ΣΤΑΤΙΣΤΙΚΗ ΦΥΣΙΚΗ

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STATISTICAL PHYSICS

2023

ABSTRACTS

International Conference on ΣΤΑΤΙΣΤΙΚΗ ΦΥΣΙΚΗ

Chania-Crete-Greece

10-14 July 2023

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Special Sessions

S1. Spin Glass Theory and Beyond
Special Session organized by E. Marinari and G. Parisi

S2. Entropies and Correlations in Complex Systems
Special Session organized by V.M. Ilić, J. Korbel and S. Gupta

S3. Holographic and other cosmologically relevant entropies
Special Session organized by P. Jizba and G. Lambiase

S4. Quantum Long-Range Systems
Special Session organized by A. Trombettoni, S. Ruffo and D. Mukamel

Topical Workshops

W1. Quantum Physics and Machine Learning
Workshop organized by F. Caruso

W2. Data Science and Econophysics
Workshop organized by P. Argyrakis

W3. Complex Networks: Hidden Geometry and Dynamics
Workshop organized by N. Gupte, M.M. Dankulov and B. Tadic

W4. Climate and Environments
Workshop organized by D. Hristopulos and S. Blesic

W5. Statistical Physics of Biophysical Systems
Workshop organized by A. Deutsch and B. Hatzikirou

W6. Statistical Physics Methods for Power Grids
Workshop organized by G. Odor and C. Beck

W7. Fluctuations in Physics
Workshop organized by F. Oliveira

W8. Thermalization of Nonintegrable Many-Body Systems
Workshop organized by S. Flach

W9. Fifty years of the renormalization group
Workshop organized by A. Aharony

W10. Non-Extensive Statistical Mechanics and Kappa Distributions
Workshop organized by G. Livadiotis, M. Leubner and K. Dialynas

Preface

The present volume contains the abstracts of the invited talks and the selected contributed oral or poster presentations submitted to the International Conference on ΣΤΑΤΙΣΤΙΚΗ ΦΥΣΙΚΗ held at Chania-Crete in Greece, from July 10 - 14, 2023.

The Conference is organized in the following three Areas to cover all the Topics of Statistical Physics:

Area A: Foundations and Theoretical aspects of classical, quantum and relativistic statistical physics and thermodynamics. Mathematical aspects and methods, formalism, rigorous results, exact solutions, connections with the methods of high energy physics, string theory, mathematical statistics and information theory, information geometry, classical, quantum and relativistic transport theory, Boltzmann and Fokker-Planck kinetics, nonlinear kinetics, dynamical systems, relaxation phenomena, random systems, pattern formation, fractal systems, solitons, chaotic systems, strongly correlated electrons, soft quantum matter, mesoscopic quantum phenomena, fractional quantum Hall effect, low dimensional quantum field theory, quantum phase transitions, quantum information and entanglement, power laws, stochastic optimal control, etc.

Area B: Applications to Physical Systems: quantum systems, soft condensed matter, liquid crystals, plasmas, fluids, surfaces and interfaces, disordered and glassy systems, percolation, spin glasses, structural glasses, jamming, critical phenomena and phase transitions, fluids and interfacial phenomena, molecular and ionic fluids, metastable liquids, hydrodynamic instabilities, turbulence, growth processes, wetting, surface effects, films, crystals, confined systems, surfaces and interfaces, chemical reactions, cold atoms, etc.

Area C: Applications to non-Physical Systems: Interdisciplinary applications of statistical physics, networks and graphs, applied networks, biophysics, genomics, environments, climate and earth models, seismology, linguistics, econophysics, social systems, traffic flow, algorithmic problems, complex systems, nonlinear time-series analysis, novel data analysis tools, extreme events, tipping points, prediction, classification, etc.

The Conference is organized in Symposia/Sessions dealing with general aspects and applications of statistical physics.

Some special sessions within the thematic Area A will cluster talks dedicated to the following theoretical topics: Spin glass theory and beyond; Entropies and correlations in complex systems; Holographic and other cosmologically relevant entropies and Quantum Long-Range Systems.

Furthermore, topical workshops on Quantum Physics and Machine Learning; Data Science and Econophysics; Complex Networks: Hidden Geometry and Dynamics; Climate and Environments; Statistical Physics of Biophysical; Statistical Physics Methods for Power Grids; Fluctuations in Physics; Thermalization of Nonintegrable Many-Body Systems; Fifty years of the renormalization group and Non-Extensive Statistical Mechanics and Kappa Distributions have been organized as parallel events.

G. Kaniadakis, D. Hristopulos, S.L. da Silva and A.M. Scarfone
(Editors of the Abstract Booklet)

Nonlinear ion acoustic waves in dissipative and dispersive magneto-rotating relativistic plasmas with two temperature kappa distributed electrons

Muhammad Mudassar Abbasi
University Of Wah

A study has been presented for the nonlinear features of ion-acoustic (IA) shock waves in a magnetorotating plasma consisting of warm viscous streaming ions along with kappa-distributed electrons having two different temperatures. In this regard, we have employed the reductive perturbation technique to derive the Zakharov-Kuznetsov-Burgers (ZKB) equation that governs the dynamics of IA shock waves. The solution obtained by the hyperbolic tangent method has been shown to depend on various plasma parameters such as spectral index (κc), density fraction (f), effective rotation frequency (Ωc), ion kinematic viscosity (ηo), and temperature ratio (σ). In the limiting case when the dissipative coefficient D → 0, we have also examined the solitary potential distributions, which are the solutions of the Zakharov Kuznetsov (ZK) equation. It is found that both rarefactive and compressive structures exist for the system under consideration. The transition in the nature of such profiles is due to the enhancement in the density of cold electrons. The importance of present theoretical investigations has been carried out with regard to Saturn's magnetosphere, where two temperature superthermal (Kappa distributed) electron populations have been observed by various satellite missions.

The Wilson-Fisher renormalization group after 50 years

Amnon Aharony
Tel Aviv University, Tel Aviv, Israel

In 1972, Wilson and Fisher published "Critical Exponents in 3.99 Dimensions", introducing the ε-expansion into the renormalization group studies of critical phenomena and of many other problems in statistical physics, condensed matter physics, field theory and more. This talk reviews some of the histrory in the following 50 years, including examples of recent developments.

Open questions on the random field Ising model

Amnon Aharony
Tel Aviv University, Tel Aviv, Israel

This talk reviews the 45 years history of the Ising model with quenched random ordering fields. It is now clear that the dimensionality shift (d to d-2) breaks down for d<5, where a new fixed point, which breaks supersymmetry, seems to appear. However, the details of this new behavior, and particularly the order of the transition for some field distributions, remain unclear.

[1] Some of these issues are discussed in Sec. 2.3 of arXiv:2305.13940.

A dichotomy for planar loop systems with implications for classical and quantum spin models

Michael Aizenman
Princeton University, United States

Random loop ensembles show up as a common mathematical scaffolding in a number of quantum and classical stat-mech models. In some cases a common random loop system is even found to simultaneously project onto seemingly different classical and quantum spin models. For two-dimensional loop-soup configurations of finite local density, and distribution which is ergodic under shifts, there is a natural dichotomy: the number of loops encircling any specified site is either almost surely finite or almost surely infinite. The transition between the two is found to play a role for a number of different physics phenomena. These include:

i) The discontinuity in the phase transition in planar Q state Potts models at Q > 4
[explained in this manner by G. Ray and Y. Spinka (2020).]
ii) A pair of different manifestations of symmetry breaking in the ground states of two different extension of Heisenberg's quantum anti-ferromagnetic spin chains:

* dimerization in an antiferromagnetic model of spins S > 1/2 with Hamiltonian favoring the the singlet state for each pair of nearest-neighbors', and
* Néel long range order under an asymmetric HXXZ interaction with Δ > 1.
[With (i) and (ii) linked and explained in this manner in a joint work with H. Duminil-Copin and S. Warzel (2020).]

iii) The Berezinskii-Kosterlitz-Thouless phase of slow decay of correlations in O(2) symmetric spin models.

iv) Pinning versus delocalization in a class of height functions formulated over R2.
[with (iii) and (iv) linked, and explained in this manner, in a joint work with M. Harel, R. Peled and J. Shapiro (2021).]

In the talk we shall recall a known representation of quantum Gibbs states in a manner reminiscent of (d+1) dimensional classical stat mech system, and discuss specific examples from the above list.

The predictable chaos of rare events in complex systems

Tommaso Alberti[1], Davide Faranda[2], Valerio Lucarini[3]
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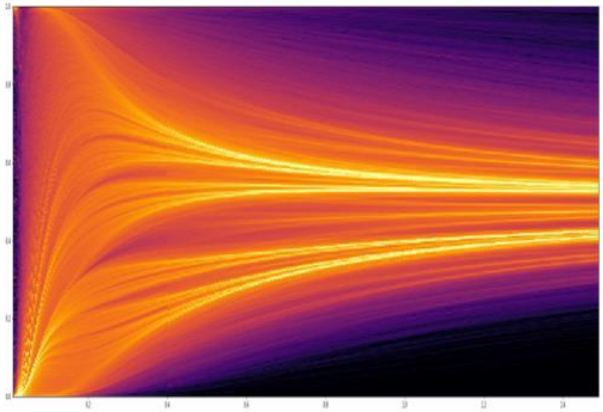
Many natural systems show emergent phenomena at different scales, leading to scaling regimes with signatures of chaos at large scales and an apparently random behavior at small scales. These features are usually investigated quantitatively by studying the properties of the underlying attractor. This multi-scale nature of natural systems makes it practically impossible to get a clear picture of the attracting set as it spans over a wide range of spatial scales and may even change in time due to non-stationary forcing. Here we present a review of some recent advancements in characterizing the number of degrees of freedom and the predictability horizon of complex systems showing non-hyperbolic chaos, randomness, state-dependent persistence and predictability. We compare classical approaches, based on Lyapunov exponents and correlation dimension, with novel approaches based on combining adaptive decomposition methods with concepts from extreme value theory. We demonstrate that the properties of the invariant set depend on the scale we are focusing on and that the proposed formalism can be generally helpful to investigate the role of multi-scale fluctuations within complex systems, allowing us to deal with the problem of characterizing the role of stochastic fluctuations across a wide range of physical systems as well as the role of different dynamical components in determining the predictability of rare events in complex systems.

Dynamical analysis of sparse Boolean networks

Alessia Annibale
King's College London, London, United Kingdom

The dynamic cavity method provides an efficient way to evaluate probabilities of dynamic trajectories in systems of stochastic units with unidirectional sparse interactions. However, the complexity of the cavity approach grows exponentially with the in-degrees of the interacting units, which creates a de-facto barrier in systems with fat-tailed in-degree distributions. We present a dynamic programming algorithm that reduces the computational complexity from exponential to quadratic, whenever couplings are chosen randomly from a discrete set of equidistant values. As a case study, we analyse the heterogeneous statistics of single node activation in random Boolean networks with fat-tailed degree distribution and fully asymmetric binary couplings. In addition, we extend the dynamical cavity approach to calculate the pairwise correlations induced by different motifs in the network. Our results suggest that the statistics of observed correlations can be accurately described in terms of two basic motifs. We then investigate models with sparse, bi-directional interactions. Bi-directional links are known to add an extra layer of exponential complexity (in the time horizon considered) to the analysis, due to the presence of retarded self-interactions arising from feedback loops, however an ad-hoc approximation, called the One Time Approximation, has been

introduced in recent years, which makes the analysis feasible. We observe that the stationary state associated with symmetric or anti-symmetric interactions is biased towards the active or inactive state respectively, even if independent interaction entries are drawn from a symmetric distribution. This phenomenon, which can be regarded as a form of symmetry-breaking, is peculiar to systems formulated in terms of Boolean variables, as opposed to Ising spins. Our study shows that a degree of bi-directionality in the interactions is conducive to having multiple attractors, when noise is sufficiently low, and the presence of multi-node interactions increases the diversity of attractors. These facts may hint at the mechanism with which gene regulatory networks sustain multi-cellular life.



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Signatures of universal criticality in the anatomic structure of the brain

Helen Ansell, Istvan Kovacs
Northwestern University, United States

Recent cellular-level volumetric brain reconstruc tions have given unrivaled access into the details of structures and connections in the brain, revealing an astronomical level of anatomic complexity [1-3]. A major challenge in analyzing this complexity is determining the structural aspects of the brain on which to focus when comparing any given brain with computational models and the brains of other organisms. Tools from statistical physics have provided powerful guidance in selecting and characterizing the key structural properties of a broad range of complex systems. Here we show evidence that such techniques can also be applied to quantify properties of the cellular structure of the brain. We analyze partial reconstructions of human [1], mouse [2] and fruit fly [3] brains. The human [1] and mouse [2] datasets consist of roughly 1 mm^3 of cortical tissue, while the fruit fly (Drosophila melanogaster) dataset [3] includes roughly half of the fly central brain. We randomly sample subregions of each dataset and examine properties of cell fragments in each sample, including their size distribution and spatial correlations. We show that the organization of brain anatomy displays signatures of being poised close to a structural phase transition, or structural criticality, including fractal-like behaviour, broad size distributions and long-range pairwise and higher-order correlations. We obtain estimates for the corresponding critical exponents and verify that they obey the expected scaling relations, providing further evidence that brain structure is at or at least close to criticality. Moreover, we demonstrate that the values of the critical exponent estimates are consistent between the different organisms, which indicates that to first approximation brain anatomy may be described by a single brain structural universality class. This framework enables extraction of relevant structural properties to study that are robust to many of the microscopic details of individual brains. This opens up the possibility of developing generative models within the brain structural universality class, from which further universal features of the brain could be inferred. Common structural features between brains may also be used to clarify the sense in which one animal brain can be considered a suitable model for another.

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The self-organization of the Sun's corona

Spiro Antiochos
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The solar corona is an amazing example of the self-organization of a complex system. The magnetic field in the corona is due to the flux at the photosphere, which has enormous structure, consisting of many bipole sources that are constantly emerging and cancelling. In addition, this magnetic field is continuously driven by the photospheric convective motions that are fully turbulent and have structure at many scales. In spite of this complexity, the coronal field is always observed to be close a minimum-energy potential (current-free) state, except for certain very specific locations. We show how chaotic reconnection in the corona, coupled with magnetic helicity conservation accounts for the observed coronal structure. Furthermore, we argue that these processes are the underlying causes of both the explosive activity and quasi-steady activity observed in the corona.

This work was supported by the NASA LWS and the NASA/GSFC ISFM programs.

A multifractional option pricing formula

Axel Araneda
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Fractional Brownian motion has become a standard tool to address long-range dependence in financial time series. However, a constant memory parameter is too restrictive to address different market conditions. Here we model the price fluctuations using a multifractional Brownian motion assuming that the Hurst exponent is a time-deterministic function. Through the multifractional Ito calculus, both the related transition density function and the analytical European Call option pricing formula are obtained. The empirical performance of the multifractional Black-Scholes models is tested and appears superior to its fractional and standard counterparts.

Kappa distribution as a description of spectrum of supra-thermal particles at collisionless shocks

Bojan Arbutina
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The departure of particle spectra from the Maxwellian is commonly observed in space plasmas, from Solar wind and Earth's bow shocks to strong collisionless shocks of supernova remnants. The similar departure is observed in kinetic particle-in-cell simulations of quasi-parallel collisionless shocks where particle distribution can be is described as a composite of thermal, supra-thermal, and non-thermal particles, the latter being accelerated in the process of diffusive shock acceleration. The supra-thermal particles are usually considered as being pre-accelerated and are treated in a similar fashion as non-thermal particles, just performing fewer diffusive shock acceleration or shock-drift acceleration cycles and having different escape probability. Describing supra-thermal and non-thermal parts as a single distribution is the basis for the so-called minimal model. However, we show that the thermal and supra-thermal parts can be alternatively described and adequately fitted with a single continuous quasi-thermal distribution – the kappa distribution, common to out-of-equilibrium astrophysical plasmas. We find that the index kappa increases with the distance from the shock, and probably over time, leading to the disappearance of supra-thermal part as lower energy particles tend to equilibrium, leaving only Maxwell's plus non-thermal distribution far downstream from the shock. Nevertheless, supra-thermal particles remain clearly present in the vicinity of the shock, at least at early times. We discuss the consequences of this for the injection of particles into diffusive shock acceleration process, assuming that non-thermal distribution, instead of Maxwellian, matches kappa distribution at some injection momentum.

A statistical approach to diffusion and waiting times in the problem of melting solids

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Melting is a common phenomenon in our daily life, and although it is understood in thermodynamic terms, the transition itself has eluded a complete description from the point of view of microscopic dynamics. Our work is oriented to the study of the melting process of superheated solids, which is believed to be caused by thermal vacancies in the crystal or by the occupation of interstitial sites. When the crystal reaches a critical temperature T_{LS} above the melting point T_m, it becomes unstable and a collective self-diffusion process is triggered. These studies are often observed in a microcanonical environment, revealing long-range correlations due to collective effects, and from theoretical models using random walks over periodic lattices. Our results suggest that the cooperative motion made possible by the presence of vacancy-interstitial pairs (Frenkel pairs) [1] above the melting temperature induces long-range effective interatomic forces even beyond the neighboring fourth layer [2]. From microcanonical simulations it is also known that an ideal crystal needs a random waiting time until the solid phase collapses. Our results also point towards a description of these waiting times using a model in which there is a positive, unspecified quantity X that accumulates from zero in incremental steps, until X exceeds a threshold value X* that triggers collapse [3]. The work proposal contemplate to incorporate the results obtained previously and study of the diffusion properties in the critical superheated phase, in particular the development of microscopic models to explain the anomalous diffusion (superdiffusion) observed in this phase [4] and studying the formalism known like continuous time random walk.

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A multifractal analysis of the rugged energy landscape of spin glasses

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The roughness of the energy landscape of spin glasses is a widely recognised property. However, it seems to be insufficiently investigated, probably because approaching it analytically raises multiple difficulties. Therefore, we have approached it numerically by theoretically relying on the so-called thermodynamic formalism of multifractals and the concept of intermittency, first highlighted by Batchelor (1953) [1]. It has become an essential characteristic, because of the structuring it generates. This research has also made it possible to model and quantify this phenomenon in various fields of physics and other disciplines (Parisi, 2022). In awarding its 2021 prize to Giorgio Parisi, the Nobel Committee for Physics has recognised both the importance of this phenomenon and the work carried out, as highlighted by Schertzer and Nicolis, 2022 [2]. Using the Metropolis-Hastings algorithm, we seek to continuously improve, site by site, the current and local minimum of the energy. At each step, we can analyse the multifractality of the Bolzman coefficient field, which is the thermodynamical analog of the energy flux density of a turbulent cascade. The spectral analysis of this field is preliminary analysis and has confirmed a scale symmetry os the second order singularities. We are currently carrying out a so-called universal multifractal analysis [3], which allows to test scale symmetries of singularities of other orders. It furthermore enables to determine significant physical parameters such as the mean intermittency, more precisely its codimension, and the multifractality parameter α.

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Statistical-mechanical consequences of the spectral properties of size-invariant shape transformations

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Changing the shape of a domain while keeping its sizes fixed under the Lebesgue measure has been realized via a geometric technique called size-invariant shape transformation, which leads to so-called quantum shape effects in the thermodynamic properties of confined particles [1, 2, 3]. In this theoretical work, we provide a detailed analysis of the spectrum under a size-invariant shape transformation in quantum thermal systems. We show that the geometric couplings between levels generated by the size-invariant shape transformations cause a nonuniform scaling in the spectra. We find that the nonuniform level scaling is characterized by two distinct spectral features: ground state reduction and modification of the spectral gaps (energy level splitting or degeneracy formation depending on the symmetries). We explain the ground state reduction by the increase in local breadth (i.e. parts of the domain becoming less confined) that is associated with the sphericity of these local portions of the domain. We accurately quantify the sphericity using two different measures: the radius of the inscribed n-sphere and the Hausdorff distance. Level splitting or degeneracy, depending on the symmetries of the initial configuration, becomes a direct consequence of size-invariance due to Weyl law. Moreover, we find that the ground state reduction causes an effect called quantum thermal avalanche causing an unusual swapping in the thermal occupation probabilities. Thermal occupation of the ground state abruptly increases while the that of excited states decrease. This is the underlying reason for the peculiar effect of spontaneous transitions to lower entropy states in systems exhibiting the quantum shape effect [4]. We also identify avoided crossing effects in the spectra which are important in determining the peculiar behaviors in the entropy of the system. From the application perspective, such unusual spectral characteristics of size-preserving transformations could be utilized to design classically inconceivable quantum thermal machines

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Symmetry-breaking motility and diffusion of a porous object immersed in an active fluid

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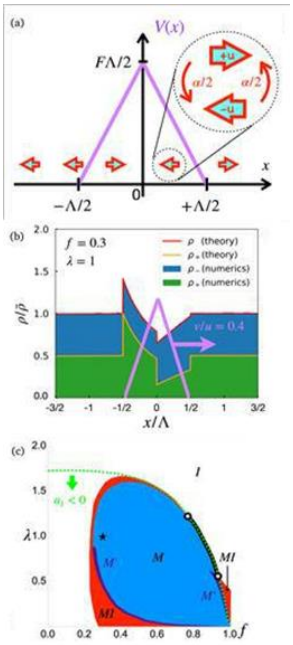
In this study, we examine the way a symmetrical, porous object, submerged in an active fluid, gains motility due to the presence of a negative drag force acting in the direction of its velocity. Past studies have proposed that this phenomenon is limited to active fluids exhibiting polar or nematic order. However, through mean-field analysis, we show that such motility can arise even in active fluids lacking any pre-existing order. The development of object motility is characterized by both continuous and discontinuous transitions linked to the symmetry-breaking bifurcation of the object's steady-state speed. Additionally, we delve into the significance of these transitions in relation to the nonmonotonic dependence of the object's diffusion coefficient on its size.



Investigation of Dynamical Complexity in Swarm-Derived Geomagnetic Activity Indices Using Information Theory

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ESA's ongoing Swarm satellite mission provides a unique opportunity for gaining better knowledge of the near-Earth electromagnetic environment by identifying and measuring magnetic signals from the Earth's core, mantle, lithosphere, oceans, ionosphere, and magnetosphere. Additionally, Swarm data are used to study the solar influence on the Earth system by analyzing electric currents in the magnetosphere and ionosphere and understanding the impact of solar wind on the dynamics of the upper atmosphere. Swarm currently offers one of the best-ever surveys of the Earth's core and crustal magnetic field as well as the near-Earth electromagnetic environment. Ground-based geomagnetic activity indices have been used for decades to monitor the dynamics of the Earth's magnetosphere, and provide information on two major types of space weather phenomena, that is, magnetic storm and magnetospheric substorm occurrence and intensity. We have been recently demonstrated how magnetic field data from the Swarm constellation can be used to derive corresponding space-based geomagnetic activity indices. Recently, many novel concepts originated in dynamical systems or information theory have been developed, partly motivated by specific research questions linked to geosciences, and found a variety of different applications. Here, we apply information theory approaches (i.e., Hurst exponent and a variety of entropy measures, including Tsallis entropy) to analyze the Swarm-derived magnetic indices from 2015, a year that includes 3 out of 4 most intense magnetic storm events of the previous solar cycle, including the strongest storm of solar cycle 24. We show the applicability of information theory to study the dynamical complexity of the upper atmosphere around storms, through highlighting the temporal transition from the quiet-time to the storm-time magnetosphere, which may prove significant for space weather studies.

Residual entropy in the repulsive one-dimensional lattice model of liquid water

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The thermodynamic and kinetics of the one dimensional lattice gas with repulsive interaction is investigated using transfer matrix technique and Monte Carlo simulations. This simple model is shown to exhibit waterlike anomalies in density, thermal expansion coefficient and self diffusion. A unified description for the thermodynamic anomalies in this model is achieved based on the ground state residual entropy which appears in the model due to mixing entropy in a ground state phase transition. Lattice models of fluid have been extensively used to investigate the above mentioned anomalous properties of water due to possibility of obtaining simple and analytically (or numerically) solvable results, while exploring a wide range of physical parameters. In this direction, both thermodynamics and kinetics [1] where investigated in lattice models with waterlike behavior. Nevertheless, approximations employed in two and three dimensions(3D), and even some analytical solutions in one dimension (1D), tend to generate complex sets of equations whose analysis is often performed numerically. Thus, it should desired to design models for which one could obtain simple analytical expressions connecting thermodynamic anomalous behavior to phase transitions and critical behavior. To achieved this goal we previously investigate 1D lattice models with pair interaction between the first neighboring molecules, with interactions spanning two [2] and three lattice sites [3]. While in Ref. [2] both van der Waals and hydrogen bond like interactions were used, resulting in a line of temperature of maximum density (TMD) associated to a ground state phase transition (GSPT), in Ref. [3] it was proposed a core-softened fluid with pair interactions up to three sites, resulting in two TMD lines associated to two GSPT. Besides obtaining exact results, in the latter work we used an analytical approximation in the neighborhood of the critical point to obtain a simple expression for Gibbs free energy, and used it mathematically study the relation between anomalous density behavior and GSPT.

In this work we proceed on this direction by investigating the repulsive 1D lattice gas (RLG1D),

which is even simpler than our previous models and presents waterlike anomalies in density, thermal response functions and self diffusion constant. The model was studied through transfer matrix technique, the Takahashi method and Monte Carlo simulations (for obtaining the self diffusion constant) and its simplicity allowed us to find a connection between temperature of maximum density and GSTP, as before [3]. In addition, it was also found that GSPT does present a residual entropy, due to phase mixing, and it is shown that this property is fundamental in determining waterlike anomalies for the model considered here. Finally, a comparison between regions with density and diffusion anomaly indicated that the present model has the so called hierarchy of anomalies.

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Boltzmann Gibbs statistics meets infinite ergodic theory

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Fermi pointed out that the Hydrogen atom in a thermal setting is unstable, as the canonical partition function of this simple system diverges. We show how a non-normalised Boltzmann Gibbs measure can still yield statistical averages and thermodynamic properties of physical observables, exploiting a model of Langevin dynamics of a Brownian particle in an asymptotically flat potential. The ergodic theory of such systems is known in mathematics as infinite (non-normalisable) ergodic theory, time permitting we will discuss these issues in the context of a gas of laser cooled atoms.

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Packets of diffusing particles exhibit universal exponential tails

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Brownian motion is a Gaussian process described by the central limit theorem. However, exponential decays of the positional probability density function P(x, t) of packets of spreading random walkers, were observed in numerous situations that include glasses, live cells, and bacteria suspensions. We show that such exponential behavior is generally valid in a large class of problems of transport in random media. By extending the large deviations approach for a continuous time random walk, we uncover a general universal behavior for the decay of the density [1]. It is found that fluctuations in the number of steps of the random walker, performed at finite time, lead to exponential decay (with logarithmic corrections) of P(x, t). This universal behavior also holds for short times, a fact that makes experimental observations readily achievable. Time permitting, we will discuss the Hitchhiker model [2] which gives a microscopical description of the observed behavior, in terms of a model describing aggregation processes, that lead to a distribution of molecule sizes and to Laplace diffusion.

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Quantum Scientific Machine Learning for Multiphysics simulations

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The natural and socioeconomic world is fundamentally governed by conservation laws and rates of change; these systems are mostly modelled by differential equations (DEs). Solving intricate DEs can be computationally challenging due to their scale and complexity. As such, recently novel methodological approaches and computational paradigms have been explored to target them efficiently and accurately. In our work, we combine the efforts made by the classical machine learning community towards Scientific Machine Learning (SciML), i.e. using machine learning to solve and optimize systems governed by DEs, and the recent developments in the field of Quantum Machine Learning (QML), to form Quantum Scientific Machine Learning (QSciML). In the talk we will focus specifically on the advancements of variational quantum algorithms in this direction, including the Differentiable Quantum Circuits paradigm, and present results of their applications in various types of physics and engineering problems towards industrial-scale relevant applications.

Stochastic dynamics on graphs and congestion in transport systems: predictive models and application to urban mobility

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Transport systems are ubiquitous in biological and social systems [1] and their optimization is one of the key issue for the sustainability of the future cities. To highlight universal statistical properties of transport systems that can be directly related to generic properties of the particle dynamics or the structure of the underlying transport network is a fundamental step to detect the behavioral aspects of the individual performing the mobility [2]. The simple stochastic dynamical systems on graphs like random walks are analytical tools to study transport systems assuming that the flows on the link depend on the dynamical states of the connected nodes (Markov Random Field). The relation between the graph structure and the dynamical properties of the considered systems gives the possibility of detecting the rising of congestion phenomena and of defining monitoring and control strategies on transport networks [3]. We consider linear and non-linear diffusion models on graph with different topological structures, and we show that the dynamic susceptibility of the stationary states can be used to reduce the network dimensionality by a node clustering mechanism, and to optimize a monitoring procedure able to detect local failures in high flow links. In this way we succeed to monitor the network state by a limited number of 'sensor nodes' and we show that the proposed methods have better performance than the usual clustering procedures base on the network topology features. The presence of nonlinear effects in the dynamics may induce the formation of congested states starting from the drop in the transport capacity along a link. Our approach provides an early warning for the congestion formation in presence of a particle knowledge of the network state. We also study the correlation properties of the fluctuations due to the finite size effects [4] to introduce a measure of the system predictability using the concept the entropy production. The possible applications of the previous results to urban mobility is considered by using GPS data from mobile phones that allow the reconstruction of individual trajectories. We discuss the possibility of realizing data-driven models for a sustainable mobility in a smart city and the possible contributions to the development of a digital twin for a city.

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Information shift dynamics described by Tsallis q=3 entropy on a compact phase space---a microscopic model of the cosmological constant

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Recent mathematical investigations have shown that under very general conditions exponential mixing implies the Bernoulli property. As a concrete example of a statistical mechanics which is exponentially mixing we consider a Bernoulli shift dynamics by Chebyshev maps of arbitrary order N≥2, which maximizes Tsallis q=3 entropy rather than the ordinary q=1 Boltzmann-Gibbs entropy. Such an information shift dynamics may be relevant in a pre-universe before ordinary space-time is created [1]. We discuss symmetry properties of the coupled Chebyshev systems, which are different for even and odd N. We provide numerical evidence that the low-energy value of the fine structure constant alpha=1/137 is distinguished as a coupling constant in this context, leading to uncorrelated behaviour in the spatial direction of the corresponding coupled map lattice for N=3. This is a kind of exotic generalized statistical mechanics model, but where could it be physically embedded? One possibility is to regard this as an underlying microscopic model of a small cosmological constant in the universe---the existence of dark energy is evidenced in the form of the observed accelerated expansion of the universe, and constant dark energy is just represented by a small cosmological constant. The type of model considered above has been previously shown to serve as a possible model of dark energy in the universe [2]. The time evolution of the information shift dynamics is not in physical time but in the fictitious time coordinate of the Parisi-Wu approach of stochastic quantization [3]. The underlying model can be used to fix and stabilize the observed numerical values of standard model parameters such as coupling constants, masses, and mixing angles. They are distinguished as states corresponding to strongest possible random properties of the underlying chaotic microscopic dynamics [4].

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Heavy-tailed distributions from superstatistics: Recent applications for power grids, air pollution statistics, and water quality time series

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The superstatistics concept, introduced 20 years ago [1], is a useful general method borrowed from statistical physics to describe driven nonequilibrium systems in spatio-temporally inhomogeneous environments that exhibit fluctuations of one or several intensive parameters. The method can be quite generally applied to heterogeneous complex systems if there is time scale separation of the underlying dynamics. This approach generates heavy-tailed probability densities in quite a natural way. After a brief introduction to the basic ideas, I will concentrate onto three examples of useful recent applications, namely the statistics of frequency fluctuations in power grid networks [2,6], the dynamics of air pollution [3,4], as well as measured time series of water quality indicators in rivers [5]. Air pollution concentration time series, as measured at a variety of measuring stations in Europe, exhibit a very heterogeneous spectrum of power-law PDFs with a wide spectrum of observed exponents, depending on location. The spectrum depends on the kind of pollution particles that are investigated. I will describe observed patterns of best-fitting parameters and the high degree of spatial heterogeneity associated with that [4]. For water quality indicators we also find that the deviations around the mean behaviour are well

described by some generalized form of superstatistics [5]. In addition, non-Gaussian fluctuations can be enhanced by correlations in the system, for example in [6] different households are not statistically independent in their time-dependent electricity consumption but strongly correlated, thus leading to non-Gaussian behaviour as the ordinary Central Limit Theorem is not valid.

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Small size, high connectance networks – the case of the artistic social network Aerowaves

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The aim of our research is to examine the structure and the evolution of specific artistic social networks, in order to identify normative patterns seen in other social or biological networks. For this purpose, we chose to study the European social network of artistic activity called Aerowaves, which aims to support new choreographers and dance companies, by promoting their artistic work across Europe. Specifically, we have analyzed the mesh of artistic connections among European countries that depicts the international mobility of dance artists who are supported by the Aerowaves network. A short description of the Aerowaves structure and operation reveals the following: The network has currently 44 partners from 33 countries who select 20 out of 600 candidate works every year. These works are performed in the annual Spring Forward Festival organized by a partner's state. Moreover, every network partner invites at least 3 works to be performed in the partner's premises. That way, the work of a choreographer from a certain country is performed in another, connecting the two countries with a (directed) network link. There are 540 directed links between pairs of European countries during the studied period October 2014 - September 2021. There are several possible representations of the above network mesh, which illuminate different aspects of the partner associations:

• In the representation where we keep the direction of the links, we observe linear rank plots for the out- and the in-degree. However, the slope of the out-degree plot is larger. This is consistent with fewer European countries producing most cultural content, compared to the countries that invite Aerowaves dance performances.

• If we consider all links in the network representation as undirected weighted edges, we find exponential degree distribution $P(k) = 10^{-k/70}$. This means that relatively few European countries dominate the cultural exchanges in Aerowaves.

• Most importantly though, we may compare Aerowaves with other studied networks if we consider all links as single-weighted and undirected. In that representation, the Aerowaves has L=225 edges and S=33 nodes, so it is of relatively small size and of high connectance C= L/S2 ≈ 0.2 (a much larger value than in other real networks as coauthors, word associations, power grid etc.). It has been reported that such complex networks have a tendency towards linear degree distributions and low clustering, as is observed in food-webs of aquatic and terrestrial ecosystems, where trophic species feed on each other in food chains [1]. We find that this is consistent with the Aerowaves degree distribution and clustering coefficient,

despite the fact that the Aerowaves is a social network, where the concept of food chain is not explicitly relevant.

The similarity of social with ecological networks suggests that general structure characteristics do exist in small, high connectance networks. Social initiatives like Aerowaves may evolve and take action to preserve and expand their activity by emulating self-preservation processes and network structures observed in nature.

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Ensemble inequivalence and negative extensibility/compressibility in semiflexible polymers with fluctuating bending stiffness

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Many semiflexible polymers exhibit fluctuations in the local bending stiffness along their contour. This may be due to intrinsic conformational changes (e.g., denaturation bubble formation in double stranded DNA, helix-coil transition in polypeptides, or reversible bundling of parallel aligned F-actin filaments) or to the reversible adsorption and desorption of molecules from the polymer's environment. In this presentation, we analyse the tensile elasticity of a strongly stretched wormlike chain which consists of N concatenated segments, where each segment can be in one of two states, A and B, which differ in bending stiffness. We call this model the reversible wormlike chain (rWLC) model. In the Gibbs (fixed-force, isotensional) ensemble, we obtain analytic expressions for the force-extension relation and the mean fraction of B segments. We show that, under certain conditions, there is a tension-induced crossover from a mostly A to a mostly B rWLC. In the Helmholtz (fixed-extension, isometric) ensemble, we obtain analytic expressions up to a summation. We show that, for finite N, there is significant ensemble inequivalence. Remarkably, in the Helmholtz ensemble, the rWLC can exhibit negative extensibility and multiple peaks. In addition, we consider a grafted rod-like semiflexible filament with two-state bending stiffness and we analyse its response to a point force exerted on the tip or to a confining wall. We show the ensemble inequivalence in the force-extension relation and the emergence of negative extensibility/compressibility for this system.

Does Maxwell's hypothesis of saturation of air near the surface of evaporating liquid hold at all spatial scales?

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The classical model of evaporation of liquids hinges on Maxwell's assumption that the vapor near the liquid's surface is saturated. It allows one to find the evaporative flux without any knowledge of what happens in the interface separating liquid and air. Maxwell's hypothesis is based on an implicit assumption that the throughput of the interface exceeds that of the air between the interface and infinity. If indeed so, the air adjacent to the liquid would get quickly saturated, making the interfacial flux decrease and adjust to that in the air. In the present paper, the so-called diffuse interface model is used to account for the interfacial physics and, thus, derive a modified version of Maxwell's boundary condition for the near-interface vapor density. It is then applied to a spherical drop floating in air. It turns out that the throughput of the interface exceeds that of air only if the drop's radius is $R \gtrsim 10\mu m$, but for $R \sim 1\mu m$, the two are comparable. If $R \lesssim 0.1\mu m$, evaporation is interface-driven, and the resulting evaporation rate is much smaller than the prediction of the classical model.

The Enskog–Vlasov equation: a kinetic model describing gas, liquid, and solid

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The Enskog–Vlasov (EV) kinetic equation has been derived to describe gas–liquid phase transitions. In the framework of the EV equation, these correspond to an instability with respect to infinitely long perturbations, developing in a gas state when the temperature drops below (or density rises above) a certain threshold. In this paper, we show that the EV equation describes one more instability, with respect to perturbations with a finite wavelength and occurring at a higher density. This instability corresponds to fluid–solid phase transitions and the perturbations' wavelength is essentially the characteristic scale of the emerging crystal structure. Interestingly, this wavelength is virtually independent of the temperature and density of the fluid state where the transition takes place – just like it is in real world. Thus, even though the EV model is not designed to describe the fundamental physics of the solid state, it can 'mimic' it – and, thus, be used in applications involving both evaporation and solidification of liquids. Our results also predict to which extent a pure fluid can be overcooled before it definitely turns into a solid.

Large scale simulations of the Ising quantum spin glass transition

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Although an Ising Quantum Spin Glass (QSG) is the prototype of disordered systems whose dynamics is affected strongly by quantum effects, there is not yet a clear picture of its critical phase, upon varying the transverse magnetic field at zero temperature whenever the spatial dimension D is ≥ 2. Currently there are two competing theories and we aim at finding out which is the correct one by providing the answer to four important questions: i) What is the value of the quantum-dynamical z exponent?; ii)How should the Finite Size Scaling analysis [2] be carried out when exponent z is unknown? iii)Does exponent z depend on the considered symmetry sector? iv) What are the critical exponents for this universality class [1,2]? These questions are addressed through a combination of exact diagonalization of the Transfer Matrix [1] (for small system sizes, up to L=6) which helps to control the $L\to\infty$ limit) and Quantum Monte Carlo (which reaches larger values of L). We highlight that a better understanding of the scaling of the spectral gap with respect to the system size, is instrumental in the assessment of the quantum computational complexity of the adiabatic quantum algorithm proposed for some classical optimization problems [3,4].

Our numerical approach pushes algorithms for Ising quantum spin glasses beyond the present limits and led us to develop two novel, highly tuned, multi GPU codes. CQSG is a Monte Carlo code for Quantum Spin Glass that relies on three levels of parallelism: multi-spin coding, multi (CUDA) threads, and multi-GPU (running simultaneously different values of the transverse field to speed up the dynamics, as required by the Parallel Tempering technique [5]). Special attention has been devoted to the implementation of a reliable and efficient parallel random number generator. EDQSG finds the first four eigenvalues (and the eigenvectors corresponding to the first two eigenvalues) of the Transfer Matrix of a 6x6 Ising Quantum Spin Glass by using up to 1024 GPU.

Our data-analysis is largely inspired by the exact diagonalization of smaller systems. In order to avoid any controversial assumption about the quantum dynamical exponent, we effectively reach the limit of zero temperature in our simulations. We find that the spin-glass susceptibility is barely divergent at the critical point, which is recognized as the crucial difficulty hampering previous works. Inspired by [6], we work-out practical alternatives to study the phase transition. In particular, we performed and now present a careful study of the energy gap.

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Innovation diffusion and Bass model on complex networks

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A milestone in the study of diffusion of innovation, the Bass model has played, since its first appearance in the Sixties, a constantly present role in marketing. It has been extensively applied for the prediction of diffusion patterns and it has also been variously generalized. The original version is expressed by a single ordinary differential equation, a Riccati equation which is, albeit non-linear, analytically solvable. Its solution describes the evolution in time of the number of adopters of a new product within a population, under the assumption that there are two types of potential adopters, innovators and imitators. The perspective is an aggregate one since, for a fixed product, the two parameters appearing in the equation, the "innovation" and the "imitation" coefficient, are the same for the whole population. A thorough investigation however (as can be tackled with today's computational tools) should take heterogeneity of individuals into account. One way to do that is to consider the network of interpersonal connections. Especially in relation to the imitative aspect of the process, it can make a big difference whether individuals who have already adopted have few or many contacts.

We here discuss how a network structure can be introduced into the model. We consider networks whose nodes have at most a number n of links. In particular, we consider scale-free networks with degree distribution of the form $P(k) = ck^{-\gamma}$ where $2<\gamma<3$, because it is into this category and with power law exponent into this range that many real-world networks fall. Of further fundamental importance in relation to network topology are the degree correlations $P(h|k)$, with $P(h|k)$ expressing the conditional probability that an individual with k links is connected to one with h links. In this connection, we devised an algorithm to build correlation matrices and get assortative or disassortative networks. Following a heterogeneous mean-field approach, we reformulate the Bass model as a system of n ordinary differential equations with each of the n equations governing the evolution in time of the number of adopters among those who have j connections (with $1\leq j \leq n$). We explore various aspects of the dynamics related to different classes of links for both correlated and uncorrelated networks. And we focus on the identification of two specific times, the takeoff time and the peak time, which play a significant role in the life cycle of an innovation/product.

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Coordinate-dependent diffusion in a heat bath: Ito-process and its consequences

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In this talk, I would present coordinate-dependent diffusion of a Brownian particle in equilibrium with a heat bath at constant temperature as a stochastic process following Ito-convention. A Brownian particle near a wall or interface, in general, gets its diffusivity re-normalized by the hydrodynamic effects arising due to the proximity to the wall. This makes the diffusivity of the particle coordinate dependent due to the fact that the diffusion is related to dynamic viscosity in equilibrium. This coordinate dependence (or state dependence) of diffusion makes the stochastic problem involve multiplicative noise in the dynamics. The method of solving such stochastic differential equations with multiplicative noise, considering the process as a Markov process with uncorrelated noise, was developed by Kiyoshi Ito around the middle of last century. However, in the standard physics literature, in this area, this Ito-process is hardly considered as the process for thermal equilibrium of a Brownian particle under confinement. The reason being that, the distribution that results for an Ito-process does not apparently look like a Boltzmann distribution. Most likely, for this reason, to consider equilibrium of such a Brownian particle, one forces some form of a Boltzmann distribution by analyzing the stochastic problem using Stratonovich or Stratonovich-like conventions. In this talk, I would make the case for the fact that Ito-distribution for equilibrium of a Brownian particle undergoing coordinate dependent diffusion is consistent with Gibbs/Boltzmann distribution. This fact could be identified by properly identifying the Hamiltonian of such a system which must be a function of coordinate dependent diffusivity of the particle because, otherwise, the Hamiltonian of the system will not be taking into account all the sources of in-homogeneity of space. Following this, I would like to demonstrate a few consequences of the Ito-distribution for equilibrium of such systems. I would show that such a process can make structural broken symmetry of interacting Brownian particles result in motion of center of mass of the system through the uniform heat bath where all currents in the configuration space of the structured object, where inter-particle forces work, vanish. Such an average directed motion of center of mass of a structured object by filtering Brownian motion will violate no principle of physics because the heat bath is on average isotropic and homogeneous. There can exist far reaching consequences of such motion of structured objects appearing spontaneously in a heat bath for biological and other systems, and I will discuss some of those.

Linear or Nonlinear Modeling for ENSO Dynamics?

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The observed ENSO statistics exhibits a non-Gaussian behavior, which is indicative of the presence of nonlinear processes. In this paper, we use the Recharge Oscillator Model (ROM), a largely used Low-Order Model (LOM) of ENSO, as well as methodologies borrowed from the field of statistical mechanics to identify which aspects of the system may give rise to non-linearities that are consistent with the observed ENSO statistics. In particular, we are interested in understanding whether the non-linearities reside in the system dynamics or in the fast atmospheric forcing. Our results indicate that one important dynamical nonlinearity often introduced in the ROM cannot justify a non-Gaussian system behavior, while the nonlinearity in the atmospheric forcing can instead produce a statistics similar to the observed. The implications of the non-Gaussian character of ENSO statistics for the frequency of extreme El Niño events is then examined.

A generalized definition of cumulants, including operators, to obtain statistical information of a broad class of stochastic processes of interest

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The possibility of obtaining a simple Master Equation (ME), such as for example a Fokker Planck Equation (FPE), for the PDF of a stochastic process of interest, is linked to the applicability of the central limit theorem (CLT), albeit under hypotheses less stringent than those of the original formulation. Ultimately, this is possible only in the case of strong separation of the time scale between the dynamics of interest and the "environmental" fluctuations (noise), i.e. in the case of effective Markovianity of the process. Alternatively, the FPE also holds for fully linear models, where the noise is Gaussian. These classical approaches to ME can all be traced back to the exploitation of the characteristics of classical cumulants, introduced in statistical mechanics starting from the first half of the 19th century. Unfortunately, Markovianity, linearity and Gaussianity are practically exceptional, rather than recurrent, conditions for real processes, particularly in fields such as climatology or the dynamics of oceanic-atmospheric systems. The extension of the concept/definition of cumulants, introduced in a recent work, which draws inspiration and formalizes an old idea of Kubo's, allows to open new paths, which lead to simple MEs, even starting from nonlinear/non-Gaussian and/or non- Markovians models. In this work, in addition to a didactic introduction to the definition and use of these new cumulants, we will present two significant applications. The first exploits the consequent natural extension of the CLT, already presented elsewhere, to obtain a FPE with memory kernel, valid for a very general class of diffusion processes. The second example shows how to obtain a general ME, valid under the sole hypothesis that asymptotically the relative dependence between noise instances, separated by a large "tau" time interval, is a function only of tau, and not of the intermediate times.

The distribution of cover times of random walks on random regular graphs

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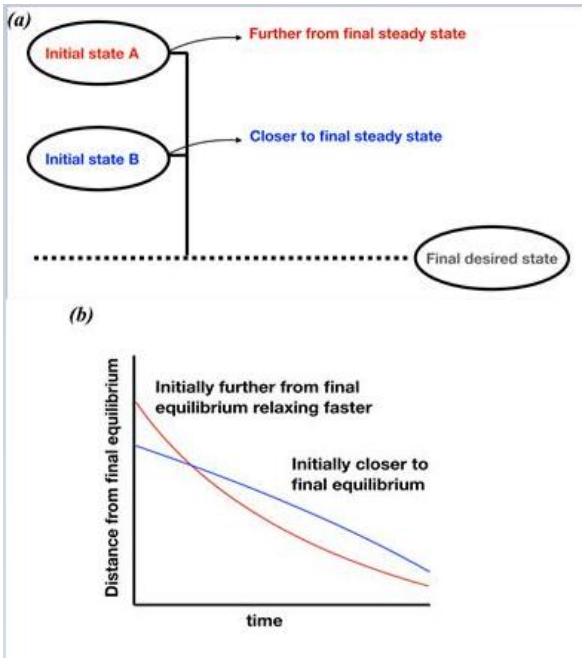
We present analytical results for the distribution of cover (C) times of random walks (RWs) on random regular graphs (RRGs) consisting of N nodes of degree c ≥3 [1]. Starting from a random initial node, at each time step an RW hops into a random neighbor of its previous node. In some of the time steps the RW visits new nodes that have not been visited before, while in other time steps it revisits nodes that have already been visited. As a result, the number of distinct nodes s visited up to time t is typically smaller than t. The cover time T_C is the number of time steps required for the RW to visit every single node in the network at least once.

In order to obtain the distribution of cover times, we first calculate the distribution $P_t(S = s)$ of the number of distinct nodes s visited by an RW up to time t. To this end we derive a master equation for the distribution $P_t(S = s)$. Using the generating function approach we obtain an analytical solution of the master equation. Inserting $s = N$ in the distribution $P_t(S = s)$ one obtains $P_t(S = N)$, which is the probability that the RW has visited all the nodes in the network up to time t. In fact, this coincides with the cumulative probability of the



cover times, namely $P(T_C \leq t) = P_t(S = N)$. The tail distribution of cover times is given by $P(T_C > t) = 1 - P(T_C \leq t)$. Therefore, $P(T_C > t) = 1 - P_t(S = N)$. Using the relations above, we obtain the tail distribution of cover times. In the long time limit the distribution of cover times converges towards a discrete Gumbel distribution, known from extreme value theory. The Gumbel distribution often emerges as the distribution of the maxima among sets of n independent random variables drawn from the same distribution. It is one of the three possible families of extreme value distributions specified by the extreme value theory.

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Mpemba effect in granular and Langevin systems

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The Mpemba effect is a counter-intuitive relaxation phenomenon in which a hotter system equilibrates faster than a colder system when both systems are quenched to the same low temperature. The effect was first discovered in the case of water [1], where it is described in terms of freezing times. However, the effect is more general and can be studied in the context of quenched relaxation dynamics of generic physical systems [2, 3]. In this talk, we describe the Mpemba effect in driven granular gases [4, 5, 6], an example of an interacting many-particle nonequilibrium system, as well as a single-particle setup of a colloidal Langevin system [8]. Both these examples allow for a strong interplay between theory and experiment. An exact analysis determining the criteria for the Mpemba effect in both systems will be presented. For granular systems, we trace the cause of the Mpemba effect to anisotropy in the kinetic energies while for Langevin systems, it is the presence of metastable states in the energy landscape. In addition, we also analyze the effect of using different measures for specifying the distance from the steady state in the study of anomalous relaxation phenomena [7].

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Characterization of meteorological drivers for incidences of malaria in South Africa

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We preformed wavelet transform (WT) cross-correlation analysis of two sets of time series of malaria incidence: of daily admissions for the disease from the two large public hospitals in Limpopo Province in South Africa (records taken in the period 2002-2017), and of weekly epidemiological reports from five districts of the same province (for the period 2000-2020). We analyzed these hospital admissions time series in relation to time series of temperature, rainfall and

evapotranspiration observational or modelled data from the same geographical area.

For the daily admissions data, we calculated both local (lCWTS) wavelet cross-correlation spectra, to monitor and characterize coincidences in daily changes of meteorological variables and variations in hospital admissions, and corresponding global wavelet cross-correlations (CWTS). All our daily admission records had CWTSs of the power-law type, indicating that those are outputs of complex systems. From the inspection of lCWTSs, we were able to confirm that malaria in South Africa is a seasonal multivariate event, initiated by co-occurrence of heat and rainfall during the summer seasons.

For the analysis of the weekly cases data, we used the WTS superposition of signals rule to delineate WTS peaks that are time lags between the onset of combined meteorological drivers and hospital admissions for malaria. We presumed that all these peaks are characteristic times connected to the periods of development, distribution and survival of either mosquitoes, as disease vectors, or the pathogens they transmit, or are the periods needed for human incubation of the disease. In this way we were able to propose a regression model for the number of admissions cases, and to provide critical values of temperature, rainfall and evapotranspiration that initiate the spread of the disease. Using the developed model, we investigated how future changes of meteorological variables and their combination can affect malaria dynamics, which is the information that can be of use for public health preparedness. This model could be further improved with the analysis of mosquito presence data from vector surveillance records, a part of our current research.

The transition to synchronization of networked systems

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Synchronization of networked units is the collective behavior characterizing the normal functioning of most natural and man made systems. As an order parameter (typically the coupling strength in each link of the network) increases, a transition occurs between a fully disordered and gaseous-like phase (where the units evolve in a totally incoherent manner) to an ordered or solid-like phase (in which, instead, all units follow the same trajectory in time).

The transition between such two phases can be discontinuous and irreversible, or smooth and reversible. The first case is known as Explosive Synchronization, which refers to an abrupt onset of synchronization following an infinitesimally small change in the order parameter, as in a thermodynamic first-order phase transition. The second case is the most commonly observed one, and corresponds instead to a second-order phase transition, resulting in intermediate states emerging in between the two phases. Namely, the path to synchrony is here characterized by a sequence of events where different functional modules (or clusters) emerge, each one evolving in unison. The structural properties of the graph are responsible for the way nodes cluterize. In particular, it was argued that the clusters formed during the transition are to be connected to the symmetry orbits and/or to the equitable partitions of the graph. In my talk, I will provide a full elucidation of the transition to synchronization in a network of identical systems. Namely, I will introduce a (simple, effective, and limited in computational demand) method which, with the only help of the eigenvalues and eigenvectors of the Laplacian matrix of a network, is able to:

i) predict the entire sequence of events that are taking place during the transition;

ii) identify exactly which graph's node is belonging to each of the emergent clusters, and

iii) provide a rigorous calculation of the critical coupling strength value at which each of such clusters is observed to synchronize.

I will also demonstrate that such a sequence is in fact universal, in that it is independent of the specific dynamical system operating in each network's node and depends, instead, only on the graph's structure. Moreover, I will clarify that the emerging clusters are those groups of nodes which are indistinguishable at the eyes of any other network's vertex. This means that all nodes in a cluster have the same connections (and the same weights) with nodes not belonging to the cluster, and therefore they receive the same dynamical input from the rest of the network.

As such, synchronizable clusters in a network are subsets more general than those defined by the graph's symmetry orbits, and at the same time more specific than those described by equitable partitions. Finally, I will show extensive numerical simulations with both synthetic and real-world networks, which demonstrate how high is the accuracy of the predictions, and also report on synchronization features in heterogeneous networks showing that the predicted cluster sequence is maintained even for networks made of slightly non identical dynamical units.

Finite-size corrections in spin glasses and combinatorial optimization problems

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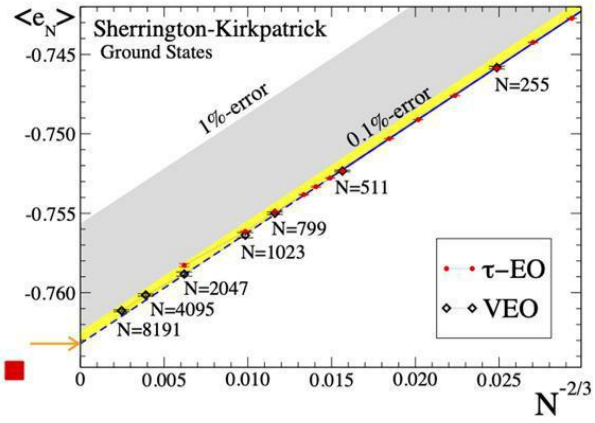
Finite-size corrections (FSC) in statistical physics are often seen as a nuisance in inevitably limited simulations that struggle to reach the (physically desirable) thermodynamic limit. For spin glasses, in particular, theoretical results (like, from replica theory) are still mostly out of reach and provide little guidance to interpret FSC. However, much insight can be gained about the nature of the physical system under investigation using FSC constructively. We will demonstrate the use of FSC in various applications to study ground states and low energy excitations in finite and infinite-dimensional spin glasses (ie, the Edwards-Anderson lattice spin glass and the mean-field Sherrington-Kirkpatrick model) as well as to assess to quality of heuristics for NP-hard combinatorial optimization problems, such as quadratic unconstraint binary optimization (QUBO) or MAX-CUT. FSC may have exponents that vary with system parameters in interesting ways [1]. Simple scaling arguments relate FSC to the energetics of domain wall excitations that characterize the stability of the glassy ordered phase [2,3]. An extrapolation plot provides a powerful means to reveal the qualities and inadequacies of recently proposed optimization heuristics based on customized hardware or the latest AI techniques for learning [4,5,6].



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Orientational ordering of molecules near a charged spherical surface

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We consider a spherical electric double layer that is formed by small mobile ions and solvent molecules captured inside a charged spherical surface. The diffusive electric double layer is a result of the competition between electrostatic attraction and translational entropy loss of the small ions results. In the theory, we incorporate solvent molecules as interacting Langevin dipoles. In addition, the surface ordering of solvent molecules is taken into account. The finite size of ions is considered. The free energy and the dielectric permittivity of the system is calculated. Finally, the entropic contribution for small number of particles is considered. This consideration has an application in the prediction of the liquid−liquid extraction efficiency for rare-earth metal cations from water.

Dependency structures in cryptocurrency market from high to low frequency

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Financial markets are complex systems characterized by strong non-stationary dynamics, feedback loops, and non-linear effects. Despite their complexity, they are governed by a rather stable and partially identified framework of rules, which, jointly with the possibility of being continuously monitored across time, makes them well-suited for statistical characterization. The unrelenting impact stemming from the implementation of new cryptocurrencies, the downfall of established ones, and modifications to existing protocols are key factors that characterize the cryptocurrency market as a peculiar category within financial systems. In this research work, we investigate logarithmic price returns cross-correlations for a set of 25 liquid cryptocurrencies traded on the FTX digital currency exchange. Exploiting two classes of information filtering networks, namely the Minimum Spanning Tree (MST) and the Triangulated Maximally Filtered Graph (TMFG) [1], we model dependency structures among crypto-assets at 6 different time horizons spanning from 15 seconds to 1 day. For each time horizon, we test the graphs' stability, statistical significance, and economic meaningfulness both at an intra-sector and pairwise level. Results provide a deep insight into the evolutionary process of the time-dependent hierarchical organization of the chosen system of cryptocurrencies. As a further step toward robustness, we compare our results with the ones achieved in the past 20 years of similar research in the field of the stock market [2, 3], uncovering comparable behaviours between the two systems. From an economic and financial perspective, the study of dependency structures among cryptocurrencies at different time scales is relevant both from a theoretical and an applicative point of view. In the first case, comparing the properties of the time-dependent hierarchical organization of the cryptocurrency market with the ones of the equity market (i) allows us to measure its degree of maturity (ii) keeping track, at the same time, of the main evolutionary phases. In the second case, such an analysis is useful as a support instrument towards achieving different goals spanning from portfolio construction tasks (e.g., diversification purposes) to developing multi-asset trading strategies acting at different time scales. Our contribution is hence twofold: (i) we propose a rigorous network-based study of the cryptocurrency market, allowing us to compare emerging dynamics to the ones observed on traditional financial markets (e.g., the "Epps effect"), and (ii) we are the first to describe the evolution of dependency structures among cryptocurrencies at time scales spanning from intra-minute to daily resolution. This study provides a crucial foundation for future research and applications in the field of cryptocurrency investment and risk management.

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Modeling hybrid economic systems - money and tokens as incentives for sustainable consumption

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In the modern context of an acute need for sustainability, the focus shifts more toward the empowerment of smaller communities than ever. Acting at a local level to help communities fight global crises like climate change is becoming an overarching goal. Risk assessment and the detailed business analysis of small and medium businesses become paramount puzzle pieces in the big picture of sustainable consumption and sustainable economic growth. Economic markets are complex systems and while their development is inherently hard to predict, econophysics offers a way to model simplified systems and still retain their main features for analysis. In this paper, we propose a chemical model that describes a wide range of market configurations involving both money and tokens for the incentivisation of sustainable consumption. Our aim is to provide a method for investigating the stability of hybrid economic systems (money and incentivising elements) in order to facilitate sustainable market interactions and sustainable business decisions. The modeling method involves the mapping of market interactions (between producers and customers) onto a sequence of chemical reactions. The mapping involves also a detailed equivalence between physical quantities e.g. steric factor or activation energy and economic concepts e.g. information available to customers or customer preference. The change in time of the concentrations of the chemical reactants is described by a set of ordinary differential equations. Solving the equations provides information on the stability of the system and describes the space of possible market configurations. The model itself is meant to simplify the complexity of the economic market by mapping it onto chemical equations. The mathematical analysis (as a next step) comes to help evolve the obtained system and when mapping the results back onto the economy, we find that we retrieve a considerable amount of detail of the real complex economic situation, making the modeling strategy general enough to be manageable and detailed enough to provide valuable insights for specific situations. Hence, the proposed chemical model reveals the stability of a business model and the optimal price correlation of goods that would ensure that the incentivizing tokens are efficiently used. It also offers an overview of the wide landscape of possible ways an economic system can develop (and the choices the customers have), of ways to devise business strategies to avoid certain outcomes, and identify the desired trading patterns. The modeling of economic systems through chemical reactions is an effective tool for scientific discovery in economics as it allows for reaching precise conclusions, not obvious at the beginning of the modeling process from an economic point of view. The theoretical model described in this paper is providing the basis for further empirical research.

Exponential tails and asymmetry relations for the spread of biased random walks

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Exponential, and not Gaussian, decay of probability density functions was studied by Laplace in the context of his analysis of errors. Such Laplace propagators for the diffusive motion of single particles in disordered media were recently observed in numerous experimental systems. What will happen to this universality when an external driving force is applied? Using the ubiquitous continuous time random walk with bias, and the Crooks relation in conjunction with large deviations theory, we derive two properties of the positional probability density function P(x,t) that hold for a wide spectrum of random walk models: (I) Universal asymmetric exponential decay of P(X,t) for large |X|, and (II) Existence of a time transformation that for large |X| allows to express P(X,t) in terms of the propagator of the unbiased process (measured at a shorter time). These findings allow us to establish how the symmetric exponential-like tails, measured in many unbiased processes, will transform into asymmetric Laplace tails when an external force is applied.

Manipulating nanoconfined charge and macromolecule transport via electrostatic strong coupling interactions

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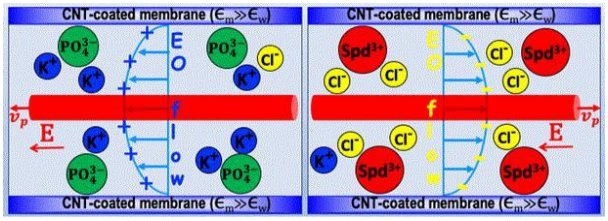
The accurate identification of the electrostatic correlation effects omnipresent in nanoconfined electrolytes is a critical task for the predictive design of nanotransport devices for energy conversion, water purification, and biosequencing purposes. The composite structure of the electrolyte mixtures involved in these processes requires the characterization of these systems via theoretical formalisms incorporating the distinct electrostatic coupling strengths associated with the constituent ion species with different valencies. I will present a unified theory of charge and polymer transport that includes on the same footing the weak- and strong-coupling interactions of mono- and multivalent ion species in confined electrolyte mixtures [1,2]. Within this formalism, I will first investigate the electrohydrodynamic mechanism driving the experimentally observed negative streaming currents in anionic nanochannels [3]. I will show that these like-charged currents triggered by multivalent cation addition into a monovalent KCl solution originate from the collective effect of the chloride attraction by the pore-adsorbed multivalent cations, and the hydrodynamic no-slip layer suppressing the contribution of these cations to the streaming current. The formalism indicates that the criterion for the emergence of these like-charge currents is the reversal of the electrostatic potential within the no-slip zone rather than the inversion of the pore surface charge. In the second part of the talk, the transport formalism will be applied to carbon-coated nanopores characterized by the giant membrane permittivity condition. In the corresponding electrostatic configuration, the theory predicts a novel molecular transport mechanism enabling the dielectric control of the polymer translocation dynamics in mixed electrolytes. Namely, in the giant permittivity regime of these engineered membranes, the emergence of attractive surface polarization forces leads to the surface adsorption of added multivalent ions with arbitrary sign. These interfacially adsorbed multivalent charges attract their monovalent counterions to the nanopore and exclude their monovalent coions from the pore into the ion reservoir. Under the effect of an externally applied voltage, the resulting monovalent ion separation induces an electroosmotic (EO) counterion flow. The shear force exerted by this EO current on the transported analyte is strong enough to cancel or invert the electrophoretic translocation velocity of the macromolecule, or equally to induce the mobility of neutral or non-uniformly charged proteins whose speed and transport direction can be tuned exclusively via the sign, charge, and amount of the added multivalent ions. Owing to the relevance of molecular transport speeds for the resolution of pore-based biosequencing techniques, this dielectric transport mechanism presents itself as a promising strategy for the extension of the mean dwell times in polyelectrolyte translocation, and also for the transport of non-uniformly charged proteins that cannot be controlled by an external voltage.



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Signal reconstruction in rough landscapes: The BBP transition and beyond

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After reviewing the Baik, Ben Arous, Pechet transition in the context of random matrix theory and its early applications in various fields, I will discuss its use in revealing relevant aspects of algorithmic transitions in inference problems, some surprising features of high dimensional cost rough landscapes associated with them, and how a new type of BBP transition emerges in specific cases.

Synchronization properties of noisy coupled Kuramoto oscillators under inhomogeneous noise intensity

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The phenomenon of spontaneous synchronization, occurring in many systems, has been extensively studied in the last decades, especially in the framework of the Kuramoto model. The original form of this model, that decribes globally coupled oscillators with distributed natural frequencies, has been extended in several directions, in order to better reproduce the features of the synchronizing systems that are found in the physical and the biological world. One of the earliest extension has been the introduction of noise, that often can modify significantly the synchronization properties. The noise, meant to modelize the fluctuations in time of the natural frequencies, from the mathematical point of view is equivalent to that due to thermal fluctuations at a given temperature. However, representing natural frequency fluctuations, it is sensible to consider the case in which different oscillators are subject to noise of different intensities, contrary to the case of thermal fluctuations, where the temperature determinig the intensity of the noise is the same for the whole system. In this work we study simple examples of Kuramoto oscillators under inhomogeneous noise, both analytically and with numerical simulations. The results show that the introduction of inhomogeneity, besides enriching the set of possible states of the system, the states being characterized by the behavior of the degree of synchronization, can also modify the nature of the transition between synchronized and unsynchronized states. The bibliography lists some earlier works where the properties of the dynamics and the statistical behavior of systems of globally coupled oscillators have been studied.

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The unconstrained ensemble and its use in the study of quantum and classical nonadditive systems

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In statistical mechanics, the unconstrained ensemble can be defined only for nonadditive systems. In this ensemble the control variables are temperature, pressure and chemical potential, namely all intensive variables, while the extensive variables, i.e., energy, volume and number of particles, are all free to fluctuate. These conditions are called completely open. Macroscopic systems with short-range interactions are additive, so that temperature, pressure and chemical potential cannot be varied independently (as evidenced by the Gibbs-Duhem relation), preventing the definition of the unconstrained ensemble. On the other hand, nonadditive systems, like small systems, or systems with long-range interactions, are inherently nonadditive, and this causes the presence of an additional thermodynamic degree of freedom, allowing, e.g., to vary independently the chemical potential at fixed pressure and temperature (apart from some particular cases that will be specified). The above considerations hold independently from the nature of the nonadditive system under scrutiny, classical or quantum. In this presentation we will give specific examples of the study of both classical and quantum systems in the framework of the unconstrained ensemble. We wil also describe the issues that arise in the definition of completely open conditions in concrete cases. The bibliography lists some earlier works in which: the peculiar thermodynamic properties of nonadditive systems are described; how it is possible to perform Monte Carlo simulation in the unconstrained ensemble; the application to a concrete model presenting phase transitions.

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The metastable state of the Fermi-Pasta-Ulam-Tsingoui (FPUT) problem

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Since the pioneering computational study of Fermi, Pasta Ulam, and Tsingou (FPUT) on the approach to thermalization in a non-integrable, nonlinear classical many-body model system, there have been numerous studies attempting to explain in detail the time evolution of the FPUT system. In particular, the existence of a long-lived “metastable” state, which slows (perhaps prevents?) the approach to a true equilibrium has been observed in this system. In this talk, we discuss the latest developments in this long saga. We treat both the α-and β FPUT models, exploring the quantitative and qualitative behavior of the metastable state in these two systems. In particular, we introduce measures quantifying the distance of this state from true equilibrium and argue that for small values of the nonlinear parameters α and β the metastable state exists for exponentially (super-exponentially?) long times. We explore the mechanism of the final decay of the metastable state as well as the possibility that it is somehow “trapped” in a small region of phase space that prevents its decay. We also analyze the relation of this state to the well-known “q-breathers” which in the limit of small α and β and stable, exactly periodic orbits in the FPUT systems. We speculate on the behavior in the true thermodynamic limit in which the size of the system (N) goes to infinity while the energy density remains finite.

The Fermi Pasta Ulam Tsingou (FPUT) Paradox: The Birth of Nonlinear Science

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In 1953, Enrico Fermi, John Pasta, Stan Ulam, and Mary Tsingou initiated a series of computer studies aimed at exploring how simple, multi-degree of freedom nonlinear mechanical systems obeying reversible deterministic dynamics evolve in time to an equilibrium state describable by statistical mechanics. Their expectation was that this would occur by mixing behavior among the many linear modes. Their intention was then to study more complex nonlinear systems, with the hope of modeling turbulence computationally. The results of this first study of the so-called Fermi-Pasta-Ulam-Tsingou (FPUT) paradox, which were published in 1955 and characterized by Fermi as a “little discovery,” showed instead of the expected mixing of linear modes a striking series of (near) recurrences of the initial state and no evidence of equipartition. This work heralded the beginning of both computational physics and (modern) nonlinear science. In particular, the work marked the first systematic study of a nonlinear system by digital computers (“experimental mathematics”) and led directly to the discovery of “solitons,” as well as to deep insights into deterministic chaos and statistical mechanics. In this talk, I will review the original FPUT studies and show how they led to the understanding of two key paradigms of nonlinear science. Specifically, I will show how a continuum approximation to the original discrete system led to the discovery of “solitions” whereas a low-mode approximation led to an early example of “deterministic chaos.” I will close with a brief indication of how the recurrence phenomenon observed by FPUT can be reconciled with mixing, equipartition, and statistical mechanics.

A mesoscopic numerical approach to active matter

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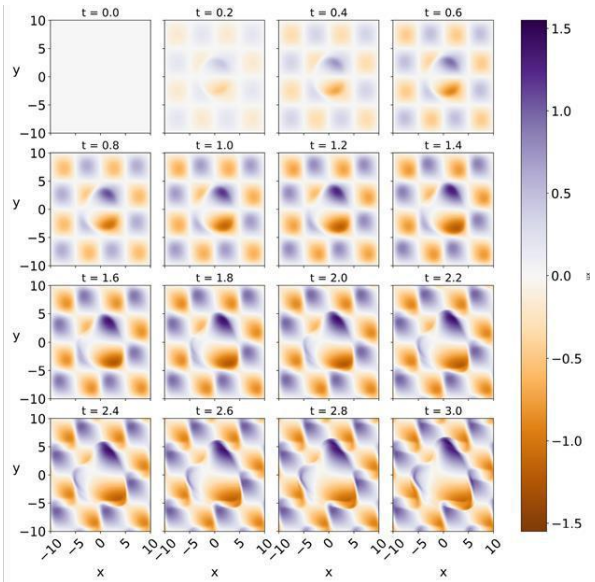
Large collections of cell-sized particles capable of self-propulsion form so-called active fluids. We investigate the stochastic thermodynamics of these systems using the mesoscopic framework first introduced by De Groot and Mazur for Brownian motion. If used with the Local Thermodynamic Equilibrium hypothesis, this approach allows the definition of thermodynamic-like quantities on the system, governed by a set of non-linear partial differential equations. Their solution is numerically hard to obtain due to instabilities that arise when using traditional integration methods. We present the derivation of these equations in the general case of active Brownian elliptical particles in a 2D domain, subject to external force and torque. We then obtain numerical solutions with a finite difference procedure (Rosenbrok Wanner method) both for Brownian and active fluids particles. For the latter case, we show that the square mean displacement of mass density follows a superlinear trend with respect to time, uncovering a superdiffusive nature of active fluids.



Information in feedback ratchets

Natalia Ruiz-Pino[1,2], Daniel Villarubia Moreno[1,3], Antonio Prados[2], Francisco Javier Cao García[1,4]
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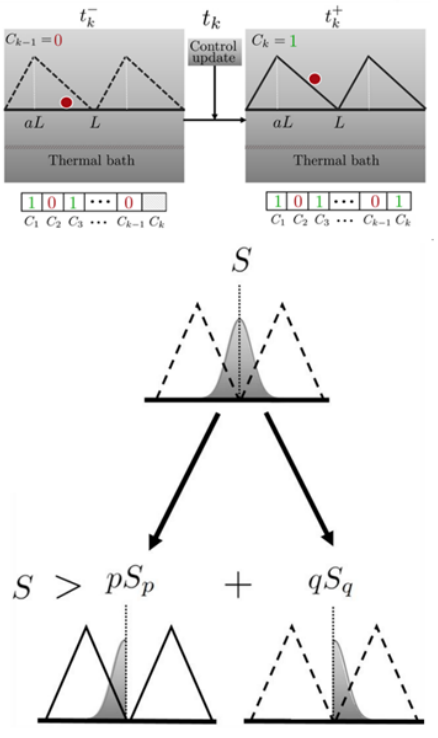
Feedback control uses the state information of the system to actuate on it. The information used implies an effective entropy reduction of the controlled system, potentially increasing its performance. How to compute this entropy reduction has been formally shown for a general system, and has been explicitly computed for spatially discrete systems. Here, we address a relevant example of how to compute the entropy reduction by information in a spatially continuous feedback-controlled system. Specifically, we consider a feedback flashing ratchet, which constitutes a paradigmatic example for the role of information and feedback in the dynamics and thermodynamics of transport induced by the rectification of Brownian motion. A Brownian particle moves in a periodic potential that is switched on and off by a controller, with the latter performing the switching depending on the system state. We show how the entropy reduction can be computed from the entropy of a sequence of



control actions, and also discuss the required sampling effort for its accurate computation. Moreover, the output power developed by the particle against an external force is investigated, which---for some values of the system parameters---is shown to become larger than the input power due to the switching of the potential: the apparent efficiency of the ratchet thus becomes higher than one, if the entropy reduction contribution is not considered. This result highlights the relevance of including the entropy reduction by information in the thermodynamic balance of feedbackcontrolled devices, specifically when writing the second principle: the inclusion of the entropy reduction by information leads to a well-behaved efficiency over all the range of parameters investigated.

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Dispersal-induced resilience to stochastic environmental fluctuations in populations with Allee effect

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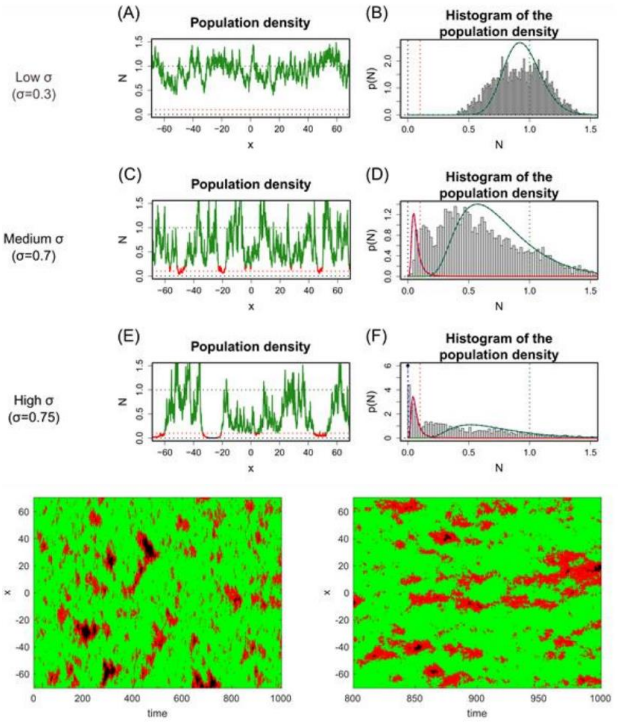
Many species are unsustainable at small population densities (Allee Effect), i.e., below a threshold named Allee threshold, the population decreases instead of growing. In a closed local population, environmental fluctuations always lead to extinction. Here, we show how, in spatially extended habitats, dispersal can lead to a sustainable population in a region, provided the amplitude of environmental fluctuations is below an extinction threshold. We have identified two types of sustainable populations: high-density and low-density populations (through a mean-field approximation, valid in the limit of large dispersal length). Our results show that patches where population is high, low or extinct, coexist when the population is close to global extinction (even for homogeneous habitats). The extinction threshold is maximum for characteristic dispersal distances much larger than the spatial scale of synchrony of environmental fluctuations. The extinction threshold increases proportionally to the square root of the dispersal rate and decreases with the Allee threshold. The low-density population solution can allow understanding difficulties in recovery after harvesting. This theoretical framework provides a novel approach to address other factors, such as habitat fragmentation or harvesting, impacting population resilience to environmental fluctuations. Environmental fluctuations can create population-depleted areas and even extinct areas for the population. This effect is more severe in the presence of the Allee effect (decreasing growth rate at low population densities). Dispersal inside the habitat provides a rescue effect on population-depleted areas, enhancing the population resilience to environmental fluctuations. Habitat reduction decreases the effectiveness of the dispersal rescue mechanism. We report here how the population resilience to environmental fluctuations decreases when the dispersal length or the habitat size are reduced. The resilience reduction is characterized by a decrease of the extinction threshold for environmental fluctuations. The extinction threshold is shown to scale with the ratio between the dispersal length and the scale of environmental synchrony, i.e., it is the dispersal connection



between non-environmentally-correlated regions that provides resilience to environmental fluctuations. Habitat reduction also decreases the resilience to environmental fluctuations, when the habitat size is similar to or smaller than the characteristic dispersal distances. The power laws of these scaling behaviors are characterized here. Alternative scaling functions with spatial scales of population synchrony are found to fit the simulations worse. These results support the dispersal length as the critical scale for extinction induced by habitat reduction.

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Spatial scales of population synchrony generally increases as fluctuations propagate in a two species ecosystem

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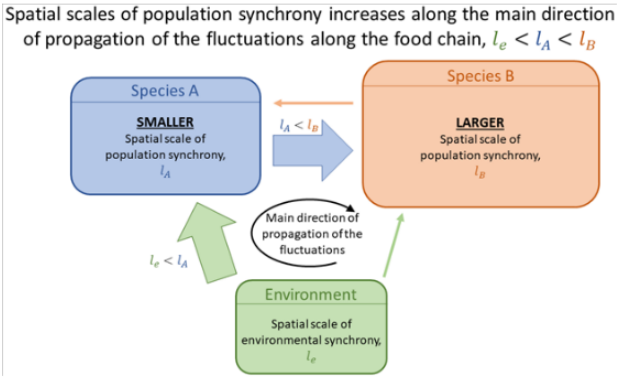
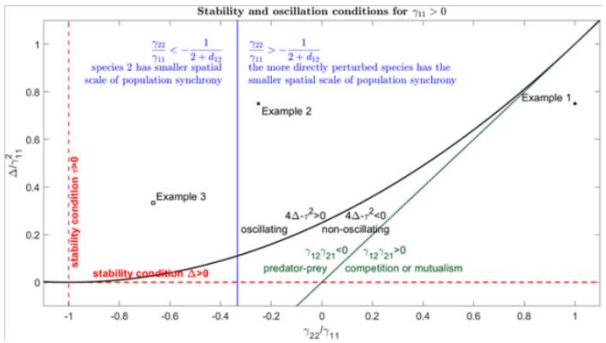
The spatial scale of population synchrony gives the characteristic distance at which the population fluctuations are correlated. Therefore, it gives also the characteristic size of the regions of simultaneous population depletion, or even extinction. Single-species previous results imply that the spatial scale of population synchrony is equal or greater (due to dispersion) than the spatial scale of synchrony of environmental fluctuations. Theoretical results on multispecies ecosystems points that interspecies interactions modify the spatial scale of population synchrony. In particular, recent results on two species ecosystems, for two competitors and for predator-prey, point that the spatial scale of population synchrony generally increases as the fluctuations propagates through the food web, i.e., the species more directly affected by environmental fluctuations presents the smaller spatial scale of population synchrony. Here, we found that this behaviour is generally true for a two species ecosystem. The exception to this behaviour are the particular cases where the population fluctuations of one of the species does not damp by its own, but requires a strong transfer of the fluctuation to the other species to be damped. These analytical results illustrate the importance of applying an ecosystem rather than a single-species perspective when developing sustainable harvestings or assessing the extinction risk of endangered species.





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Predictability of population fluctuations

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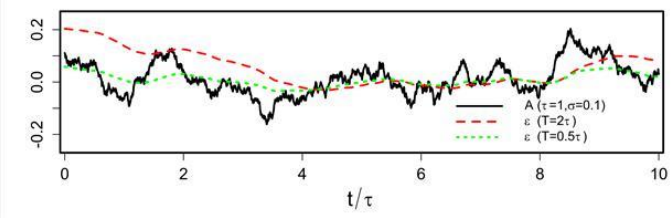
Population dynamics is affected by environmental fluctuations (such as climate variations), which have a characteristic correlation time. Strikingly, the time scale of predictability can be larger for the population dynamics than for the underlying environmental fluctuations. Here, we present a general mechanism leading to this increase in predictability. We considered colored environmental fluctuation acting on a population close to equilibrium. In this framework, we derived the temporal auto and cross-correlation functions for the environmental and population fluctuations. We found a general correlation time hierarchy led by the environmental-population correlation time, closely followed by the population autocorrelation time. The increased predictability of the population fluctuations arises as an increase in its autocorrelation and cross-correlation times. These increases are enhanced by the slow damping of the population fluctuations, which has an integrative effect on the impact of correlated environmental fluctuations. Therefore, population fluctuation predictability is enhanced when the damping time of the population fluctuation is larger than the environmental fluctuations. This general mechanism can be quite frequent in nature, and it largely increases the perspectives of making reliable predictions of population fluctuations.



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Single-stranded DNA-binding protein kinetics: theory and experiments.

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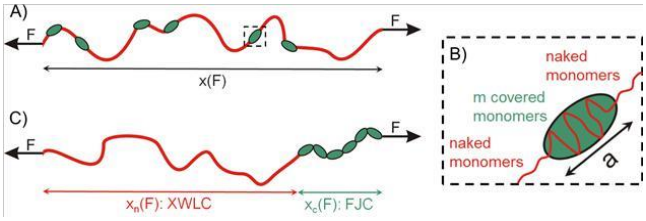
Single-stranded DNA-binding proteins (SSBs) play a key role in genome maintenance, binding and organizing single-stranded DNA (ssDNA) intermediates. Optical tweezers show that the human mitochondrial SSB (HmtSSB) (and also E. Coli SSB) binds to preformed ss-DNA in two major modes, depending on salt and SSB protein concentration [1,2]. The kinetics presents transitions between modes [1-3], which still require a full understanding at high coverages with the development of models with a correct biding site counting [4,5]. This model development has revealed two potential sources of cooperativity, enhancement of the binding or inhibition of the release due to the presence of neighboring bound SSB [5].



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Fermion mixing in curved spacetime and dark matter

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It is today accepted that neutrinos have a mass and oscillate among three flavors. They are the only known elementary particles to experience field mixing. These peculiarities place neutrinos beyond the standard model of particles. Many of the issues related to neutrino physics, including the origin of their mass, their fundamental nature and the overall number of flavors are still open. It is nevertheless clear that neutrinos play a fundamental role in the universe at all the scales. As they are abundantly produced in nuclear reactions, they carry important informations on astrophysical sources and they represent a valuable resource in multi-messenger astronomy. Relic neutrinos, as probed by experiments like PTOLEMY, may be used to test cosmological theories. Several theories envisage a crucial role of neutrinos during the first phases of the universe in producing the original baryon asymmetry. Furthermore neutrinos may be connected to the dark sector of the universe, contributing to dark matter along with hypothetical particles such as axions, and even to dark energy, for which they can also function as a probe of the underlying model. Due to these reasons, a deep understanding of neutrino physics in gravitational backgrounds is required. The topic has been analyzed primarily in quantum mechanical approaches both in vacuum and in matter. Here we wish to go beyond the quantum mechanical treatment and present a quantum field theoretical approach to fermion mixing in curved space. We limit ourselves to two flavors, but the formalism can be easily generalized to more families. The theory merges the features of mixing with the field quantization on curved space, bringing along several interesting aspects, such as a non-trivial structure of the vacuum. We introduce the flavor fields and pursue their canonical quantization. Then, we derive the transition probabilities for a generic spacetime. We apply the formalism to some specific metrics and compute the corresponding oscillation formulae, showing their departure from their quantum mechanical counterparts. Moreover, we compute the expectation value of the energy-momentum tensor of mixed fermions on the flavor vacuum. We consider spatially flat Friedmann-Lemaître-Robertson-Walker metrics, and we show that the energy-momentum tensor of the flavor vacuum is diagonal and conserved. Therefore, it can be interpreted as the effective energy-momentum tensor of a perfect fluid. In particular, assuming a fixed de Sitter background, the equation of state of the fluid is consistent with that of dust and cold dark matter. Our results establish a new link between quantum effects and classical fluids, and indicate that the flavor vacuum of mixed fermions may represent a new component of dark matter.

Scattering in quantum graphs

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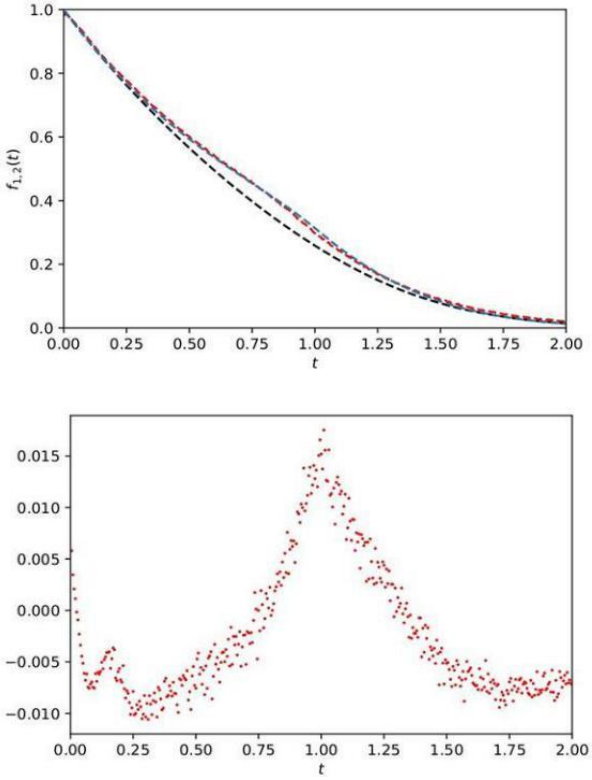
Quantum chaos is the study of quantum systems whose classical counterpart is chaotic. The conjecture of quantum chaos states that the same universal properties characterize those systems as the Gaussian random matrices [1]. Many experimental works give validity to this conjecture [2-3]. Quantum graphs turn out to be systems that due to their simplicity are useful to study quantum chaos [4-6]. Their use dates back to Linus Pauling in 1930, but they became relevant when Kottos and Smilansky introduced quantum graphs as a powerful tool to study quantum chaos, they also showed that connecting semi-infinite wires to their vertices becomes a system with dispersion. The scattering fidelity "SF" measures the sensitivity of the scattering matrix under a perturbation [7]. The SF provides a useful tool since SF can be measured experimentally (unlike fidelity). In addition, when the coupling is weak, the SF coincides with the fidelity. It is worth mentioning that SF is a powerful tool to study the nature and strength of a perturbation [9]. For quantum graphs, it is unknown what type of perturbation is introduced to the system when the length of some (or all) bounds are changed. This work presents numerical studies of the level statistics for closed graphs with the 3 types of symmetries (GOE, GUE, and GSE). In addition, we also present studies of the scattering fidelity.

Furthermore, studies of autocorrelation and cross-correlation (like [9]) of elements of the scattering matrix where we found deviations concerning the predictions made for the random matrix theory. We believe that these deviations could be due to the existence of correlations between the eigenvalues and the components of the eigenvectors of the secular matrix h.



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Measurement-induced phase transition, multipartite entanglement and critical quantum metrology

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Measurement-induced phase transition arises from the competition between a deterministic quantum evolution and a repeated measurement process. We explore the measurement-induced phase transition through the quantum Fisher information in two different metrological scenarios. We demonstrate through the scaling behavior of the quantum Fisher information the transition of the multi-partite entanglement across the phases. In analogy with standard quantum phase transition, we reveal signature of a measurement-induced phase transition in the non-analytic behaviour of the quantum Fisher information as the measurement strength approaches the critical value. Our results offer novel insights into the features of a quantum systems undergoing measurement-induced phase transition and indicate potential avenues for further exploration in the field of quantum physics.

Quantum Machine Learning: overview and perspectives

Filippo Caruso
Physics Dept., Florence University, Florence, Italy

We will give an overview on novel very promising interplays between machine learning and quantum physics, giving rise to the extremely exciting and rapidly growing field of Quantum Machine Learning. In particular, there are several ways in which machine learning could benefit from new quantum technologies and algorithms to find new ways to speed up their computations by breakthroughs in physical hardware, as well as to improve existing models or devise new learning schemes in the quantum domain. Big data analysis and image processing are just a few examples where these new hybrid classical-quantum algorithms can be applied, in domains ranging from material science to medicine, from finance to cybersecurity. This new field is indeed expected to provide remarkably huge advantages over its classical counterpart and deeper investigations are timely needed since they can be already tested on the already commercially available noisy intermediate-scale quantum (NISQ) machines, towards future scientific and industrial practical use-cases and real-world applications.

Fourth-order term effects in the Fick-Jacobs equation for diffusion in narrow channels

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Universidad Autónoma Metropolitana Cuajimalpa, Mexico City, Mexico

In some situations, such as at high densities with long-range effects, diffusivity switching process approximations, or aggregation models, the diffusive flux does not adequately describe the system's behavior, so fourth-order terms terms help model slight deviations from standard Fick behavior. We study the effect of a fourth-order derivative term in the diffusion of Brownian particles confined to a narrow 2D channel whose longitudinal coordinate is larger than the transversal one. In these cases, a Fick-Jacobs-like equation is found using the projection method. It contains a third-order, in addition to the standard first-order entropic flux. It is shown that even at the lowest order, position-dependent modifications to the longitudinal diffusivity and the drift term appear, which also depend on a new scale related to the coefficient of the fourth-order term. Furthermore, using a simplified Kalinay-Percus method, the corresponding transport coefficients are obtained depending on the longitudinal coordinate and on the new scale. The linear or conical channel is analyzed to illustrate the results. Remarkably, although small, there are non-negligible effects due to the new scale. For instance, there is a region where diffusion is enhanced. Also the stationary solution is disscused.

Phase transition in urban agglomeration and segregation

Taksu Cheon
Kochi University of Technology, Kochi, Japan

A model of the urban agglomeration and segregation is formulated, in which two types of agents move around on the square-lattice aligned cells. The model is shown to exhibit, when the density of agents are varied as the control parameter, various phase transitions representing appearance of urban aggregation, segregation and social disorder.

Application of Nonequilibrium Thermodynamics to Polymer Collapse Dynamics

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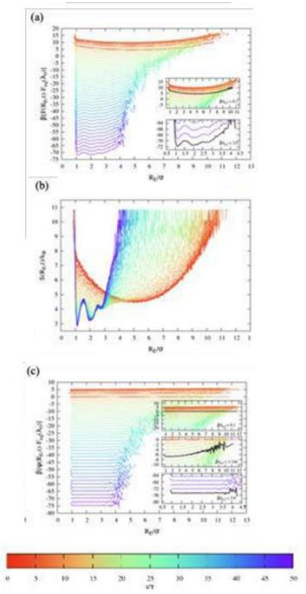
Nonequilibrium thermodynamics plays important roles in explaining various nonequilibrium processes. Various nonequilibrium theories and methodologies such as the fluctuation theorem have been developed but there still remain some difficulties in locally measuring thermodynamic properties such as energy, entropy, and the free energy in the nonequilibrium process. Recently, Jinwoo and Tanaka [Ref: Sci. Rep. 5, 7832 (2015).] provided a formalism (the JT formalism) for the local thermodynamic properties, which are expressed as the path-ensemble of local microstates over time. Herein, we investigated the JT formalism by applying it to the polymer collapse dynamics as an exemplary nonequilibrium process. We did not only verify the nonequilibrium thermodynamic relations among the local nonequilibrium variables derived in the JT formalism by additional derivations with mesoscopic variable, but we also show validity of relations for the equilibrium properties obtained by nonequilibrium local properties related with JT formalism.

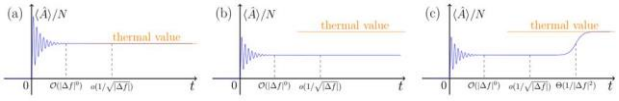


Timescale of Linear Thermalization

Yuuya Chiba[1], Akira Shimizu[2,3]
[1]Department of Basic Science, The University of Tokyo, Meguro-City, Japan, [2]Institute for Photon Science and Technology, The University of Tokyo, Bunkyo-City, Japan, [3]RIKEN Center for Quantum Computing, Wako-City, Japan

Among problems of thermalization, the timescale of thermalization is still open and is particularly nontrivial when prethermalization occurs. In this talk, we investigate the timescale of 'linear thermalization,' which is thermalization against a small change of a parameter of the system. We consider an isolated quantum many-body system prepared in an equilibrium state and its unitary time evolution induced by a small change Δf of a parameter f of the Hamiltonian. We say linear thermalization occurs for an additive observable in some timescale when its expectation value and fluctuation in that timescale are consistent with thermodynamics up to $O(\Delta f)$. As explained in Shimizu's presentation of this conference, we find that the additive observable B that is conjugate to f is the key observable for linear thermalization: Under reasonable conditions, linear thermalization of B guarantees linear thermalization of all additive observables. Examining the timescale of linear thermalization in the above result, we find the following: If linear thermalization occurs in the sense of the above result, then it occurs in some time of $O(|\Delta f|^{o})$ and lasts at least for a period of $o(1/\sqrt{|\Delta f|})$, as in Figure (a). On the other hand, if linear thermalization does not occur in the sense of the above result, then it does not occur in any timescale of $O(|\Delta f|^{o})$ and remains absent at least until any timescale of $o(1/\sqrt{|\Delta f|})$, as in Figure (b). In particular, this result, together with the result in Shimizu's presentation, implies that linear thermalization of the single key observable B in the timescale of $O(|\Delta f|^{o})$ guarantees linear thermalization of all additive observables not only in the same timescale but also in a longer timescale of $o(1/\sqrt{|\Delta f|})$. Furthermore we discuss stationarity of the system and implications for prethermalization. We show that, under the above reasonable conditions, all additive

observables take macroscopically definite and stationary values, up to O(Δf), throughout a time region from O(|Δf|^{o}) to o(1/√|Δf|). In other words, the system relaxes to a macroscopic state and stays in the same macroscopic state, up to O(Δf), throughout this time region. This result is interesting especially in a nearly integrable system where prethermalization occurs. Typically, such a system first relaxes to a nonthermal stationary state in some timescale of O(|Δf|^{o}), and then relaxes to the true thermal equilibrium state at a longer timescale of Θ(1/|Δf|²), as in Figure (c). For such a case, our results detect the nonthermal stationary state in the time region from O(|Δf|^{o}) to o(1/√|Δf|) and the absence of linear thermalization in this time region.



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Energy localisation and dynamics of a mean-field model with non-linear dispersion

Helen Christodoulidi
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Ergodicity breaking and long term stability are not rare phenomena in many-body Hamiltonian systems. There are various forms of non-equilibrium states that appear in these types of systems, like the formation of metastable states, energy localization, synchronisation, and more, which are often accompanied by a weaker form of chaos indicated by Lyapunov exponents' numerical values. In particular, the Hamiltonian systems that involve long range forces have an even more perplexed and enigmatic behaviour: they exhibit out-of-equilibrium states that persist for longer integration times, when the size of the system increases. Such well-known systems are the Mean - Field Hamiltonian (HMF) [1,2] and the Fermi – Pasta – Ulam – Tsingou model with long-range interactions (FPUT-LRI) [3]. In both systems, numerical experiments show that chaoticity wanes towards the thermodynamic limit (namely as the number of particles N increases, while the specific energy or energy per particle ε=E/N is kept constant). From Statistical Mechanics point of view, various studies show that the statistical behaviour of many-body systems Hamiltonian systems with LRI also deviates from the classical Boltzmann-Gibbs (BG) thermostatistical description. A further recent example is the ionic-crystal model which has been called "the modern form of the FPU problem" [4].

In this talk, we focus on energy localisation and non-equilibrium phenomena in a mean-field model with non-linear dispersion. In the absence of linear dispersion, the model exhibits very strong localisation phenomena, namely the initial excitation of a wave-packet will be almost preserved at all times. For generic initial conditions, we find that the maximum Lyapunov exponent decays as a power – law in terms of the system size, indicating an integrable-like behaviour in the thermodynamic limit. For a fixed N size and varying the energy, we derive an analytic estimate on the Lyapunov exponent's upper-bound λ(ε), which approximates the energy dependence in the strong nonlinearity regime. This dynamical behaviour is also reflected in the statistical behaviour of the model: we evaluate and study the evolution of the momenta distributions (which initially form a uniform distribution) as well as their distance from a Gaussian distribution, while N increases. These numerics and their analysis quantify the model's detachment from ergodicity towards the thermodynamic limit.

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Equivalence of solitonic solutions in a neuron chain and single neuron delay differential equations

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In recent years, the refinement of the technologies applied to neural imaging is making data available at finer and finer resolutions, while the amount and variety of such data has been continuously increasing [1]. These two aspects create a need for interpretable models that connect phenomena across several scales, and thus an opportunity to tackle these problems with tools from Statistical Physics. Mesoscopic models can be formulated in the framework of Dynamical Systems on Graphs, where a set of nodes, each endowed with an internal dynamics reproducing the spiking properties of neurons, is coupled according to a directed network structure. The dynamical properties of such systems are determined by the interplay of structure and dynamics, so that nonstationary stable states and emergent properties exist. For these models cycles play an important role, both as characterising structural features and as the possible origin of feedback mechanisms and self-organisation. Considering, in particular, applications to the modelling of neural phenomena, we study a periodic chain of FitzHugh-Nagumo neurons with a unidirectional gap-junction coupling. We show the existence of a regime of solitonic travelling waves, emerging through a transition that does not destabilise the fixed point of the system (corresponding to a state where all neurons are quiescent, with no activity on the network). We perform extensive numerical simulations to characterise the dependence of the solutions on the model parameters. In this regime we show that the solution of the chain is equal to the periodic solution of a single FitzHugh-Nagumo equation with an explicit time delayed feedback term of the same form of the chain coupling, once a suitable delay is set depending on the solitonic wave speed and chain size. The connection between Delay Differential Equations and spatially extended dynamical systems has already been proposed, although in a different context [2]. In the Delay Differential Equation as well as in the chain, the fixed point stability remains unaltered through the transition. This strong common feature points out to the fact that in both systems the change in the dynamics cannot be caused by a Hopf bifurcation of the stable fixed point, even though some global properties of the two systems are different. Further development of this line of work can consist in the study of two or more interacting cycles, building up to the study of network architectures. This approach can hopefully shed light on the role of cyclic structures in neural phenomena such as the emergence of memory effects, synchronisation, or even, if plasticity is implemented, learning of specific tasks.

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Markov features and Kappa distribution of magnetic field fluctuations at ion/sub-ion scales

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Magnetic field fluctuations at ion/sub-ion scales show a power law spectral density which suggests the occurrence of a novel turbulent regime. However, in this domain - as clearly discussed in several papers - the scaling features of magnetic field fluctuations are mainly mono-fractal (globally scale-invariant). This point seems to suggest that strong turbulence could not be at the basis of this spectral features. Here, we investigate the Markovian nature of fluctuations at these ion/sub-ion scales recovering some information on the nature of the scale-to-scale coupling in this domain. Furthermore, we show how the shape of the PDFs of magnetic field fluctuations can be derived from the stationary solution of the Fokker-Planck equation of the scale-to-scale coupling and that they are isomorphic to a Kappa distribution. A discussion of these findings in the framework of the small-scale plasma dynamics is presented.

On the nature of space plasma turbulent fluctuations at sub-ion scales: a Langevin approach

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Space plasmas in the Heliosphere are in a turbulent dynamical state. At large scales, say at frequencies lower than 0.1–1 Hz, magnetic field fluctuations display a power-law spectrum with spectral exponents approaching those expected from theories of fluid-like turbulence. Conversely, at scales smaller than the ion-inertial length, i.e., ion/sub-ion scales, ions' inertia decouples from that of electrons and the spectrum of the magnetic field fluctuations displays a novel dynamical regime that is still not fully understood. In this talk, we show recent results on the Markovian features of the fluctuations at these scales, recasting the scale-to-scale coupling in this regime in terms of a stochastic Langevin-like dynamics. The occurrence of a simple/global scale invariance at sub-ion scales suggests that a stochastic redistribution of energy is not relevant in this domain. A link between the Langevin drift term and the observed scale invariance of fluctuations at these scales is found in a non-diffusive limit.

The challenge of nanostochasticity: Complexity concepts and methods in the characterization and modeling of random-like nanostructured surfaces and materials

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During the last twenty years, we have been witnessing a tremendous advancement of nanotechnology with impact on several scientific and technological areas such as electronics, photonics, tribology, and composite materials to name just a few. The common basis in all cases is the novel properties and functionalities caused by the nanostructuring of surfaces and bulk of materials involved in these applications. However, the benefits of nanostructuring are challenged by the missing of understanding and controlling the stochastic effects which prevail on nanoscale dimensions. The statistical origins of these effects are coming from the small amount of materials involved in nanoprocesses which allows for enhanced fluctuations and variances in material density and compositions as well as in fabrication processes. The latter lead to random-like stochastic nanomorphologies which degrade the repeatability of nanostructured devices and undermine the ability to control and optimize their performance. A first but critical step to face with the challenge of nanostochasticity is to provide the proper mathematical and modelling tools enabling the

quantitative characterization of the random-like nanostructure morphologies promoting their understanding and the control of their fabrication and properties. The key idea of this work is that nanostochasicity is coupled with the presence of spatial correlations bringing nanostructure morphologies between fully ordered and fully random extremes. This means that the recent advances in nonlinear dynamics and complexity theory can inspire new approaches to characterize and model nanostructure morphologies and pave the way to ther deeper understanding. In particular, in this work we will try three fundamental concepts of nonlinear and complex systems in nanostructure characterization. First the essential ingredients of a chaotic system (stretching and folding of trajectories in phase space) will be properly used to build a methodology for the characterization of the spatial complexity of rough nanosurfaces which are considered the initial conditions of the chaotic system. Second, we will focus on the information content of nanostructure stochasticity and use the concept of multiscale Shannon entropy to define a measure of spatial nanocomplexity quantified by the deviation from the average spatial symmetry of nanomorphology [2]. Finally, we will highlight a hidden aspect of nanostochasticity playing though a critical role in biomimetic nanotechnology. We mean the embedding of nanostructures in morphologies with larger scales consisting what has been called hierarchical surfaces and materials. A theoretical framework and toolset for the definition, classification, characterization and modeling of hierarchy in surfaces is developed and validated. Special emphasis is given on the nonlinear character of hierarchical surfaces and the new physics of the interaction between hierarchy levels it implies [3]. The above complexity-based tools for nanostructrure modelling and characterization will be applied in a large variety of nanosurfaces produced either by plasma treatment of polymer films or wet etching of metal materials while their added value will be evaluated and discussed.

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Entropy and complexity analysis of AI-generated and human-made paintings

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Creativity is the ultimate characteristic of human intellect and expression, and it is inextricably linked to art. Previous research works attempted to analyze and parameterize the manifestations of art, but they had not escaped the human factor. However, the advent of Artificial Intelligence (AI) models has shaken up the research world, raising questions about the nature of creativity and whether in its artistic form it is a uniquely human quality. In this work [1], we aim to examine the relationship between creativity and the nature of the creator by using paintings created by both AI and humans in various artistic genres. By analysing the paintings through a mathematical lens, utilizing an entropy analysis formulated by the classic Shannon entropy (E) and a complexity (C) measure based on multi-scale entropy, we hope to gain a deeper understanding of the prowess of AI models and possible new insights into the ability to distinguish between a human-created work (H) and an AI-generated one (AI). We present findings on the general comparison between AI-generated and human-made art, as well as on the more specific analysis of 8 different genres within these two categories. Based on the results, we observe that differences between AI and human art can be found not only in the schematic representation, but also in the colour changes, with the AI finding it more complicated to represent painting styles without well-shaped objects, as well as colour changes regarding pixels of similar intensity values. AI generated paintings seem to encapsulate a general definition for the structural elements of an artistic genre, but may not fully capture the diversity of artist styles within that genre. Additionally, the AI and H differences depend on the genre of the works, thus, grouping based on art styles is possible. As for the ability of prediction with good accuracy whether an artwork is AI or H made based on the metrics of complexity and entropy, the dispersion of the C, E values exceeds the difference of the averages, offering indication that although the difference found is statistically reliable, it has little predictive power.

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Disordered systems beyond the permutation symmetry paradigm

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In this talk I will review some results obtained for the mean-field spin-glass models when the disorder is not permutation invariant or, more generally, non identically distributed. Cases include the convex and non-convex multi-species, with emphasis on the deep Boltzmann machines in the Nishimori line, and the multy-bath SK model that have some relevance in high-dimensional inference and deep learning.

Ordering kinetics in systems with long-range interactions

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Focusing mainly on one dimensional models, we discuss the kinetics after a low temperature quench of ferromagnetic systems with long range interactions between spins at distance r decaying as $1/r^{\alpha}$. In the weak long range regime with $\alpha > d$, where d is space dimensionality, coarsening of competing domains of opposite sign is observed, without development of magnetization [1]. Dynamical exponents, as the one regulating the growth of the domains size, can be obtained analytically within a scaling approach and are shown to agree well with numerical simulations of the Ising model. For $\alpha=0$, i.e. mean field, all spins evolve coherently, without formation of domains, quickly driving the system towards a magnetised state. For strong long range, i.e. for $0 < \alpha \leq d$, a mixed behaviour is observed [2] where both a mean field like or a coarsening scenario are exhibited with an α-dependent relative probability. This whole pattern of behaviors is compared with the analytical solution of the voter model with long range interactions, where an agent takes the opinion of another agent at distance r with probability $1/r^{\alpha}$. In this case, one observes coarsening of domains for $\alpha > 2$ whereas, for $\alpha \leq 2$ the system attains consensus similarly to the mean field case.

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Typicality, stochastic dynamics and generalized statistical mechanics

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The concept of typicality has not been yet explored for systems/processes with exploding or shrinking phase spaces, or processes displaying path dependent dynamics or subject to emergent internal constraints and correlations. The properties of the typical set --roughly speaking, the region of the phase space effectively occupied by a physical process--, are direct consequence of the microscopic stochastic rules underlying the system. And, interestingly, its characterization involves the entropy functional, which, consistently, arises naturally from the underlying dynamics. Therefore, the typical set connects (i) the microscopic dynamics of the system, (ii) the phase space occupancy and (iii) the entropy without imposing anything to the later. In addition, the existence of the typical set and, in consequence, typical macroscopic properties, is key for the existence of the thermodynamic limit. However, given its central role underlying the emergence of stable, almost deterministic macroscopic patterns, a question arises whether typical sets exist in much more general scenarios. In my talk I will show that the typical set can be defined and characterized from general forms of entropy for a much wider class of stochastic processes than was previously thought. This includes processes showing arbitrary path dependence, long range correlations or dynamic sampling spaces, suggesting that typicality is a generic property of stochastic processes, regardless of their complexity. Moreover, other quantities, like generalized free energies and the associated duality relations, arise from the existence of typical sets. With that, we provide a microscopic ground to the emergence of generalized entropies.

Phase transitions in embryo morphogenesis

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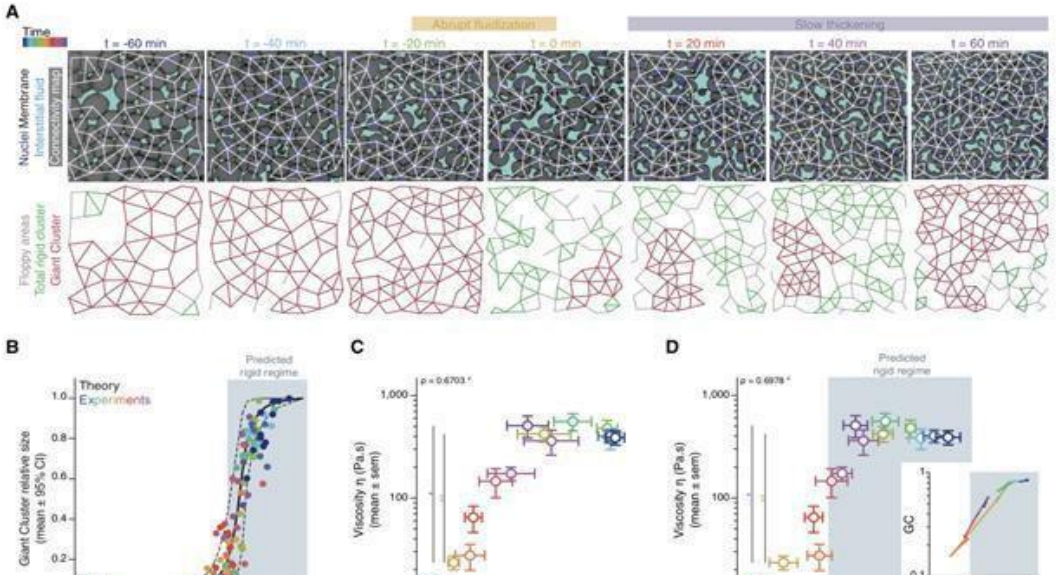
Embryo morphogenesis is impacted by dynamic changes in tissue material properties, which have been proposed to occur via processes akin to phase transitions. In this talk I will show that rigidity percolation provides a simple and robust theoretical framework to predict material/structural phase transitions of embryonic tissues from local cell connectivity. Rigidity percolation is the point in a network where the topological structure absorbs all the potential degrees of freedom of the nodes, thereby preventing the possibility of independent movements. This critical point has a dramatic impact in the material properties of the system. Combined with directly monitoring dynamic changes in tissue rheology and cell contact mechanics in real (zebrafish) embryos, I will show how the embryonic tissue undergoes a genuine phase transition, brought about by a small reduction in adhesion-dependent cell connectivity below a critical value. I will show how we quantitatively predicted and experimentally verified hallmarks of phase transitions, including traces of power-law exponents and associated discontinuities of macroscopic observables. The massive deformation occurs right after the "melting" of the tissue, which enhances such change of deformation at minimal energy cost. Consistently, when the deformation is triggered, the tissue tends to run backwards in the phase space, thereby solidifying again and fixing the deformation. Interestingly, the success of the deformation occurring right after crossing the critical point of the phase transition depends on embryonic (stem) cells undergoing asynchronous divisions causing random and, consequently, uniform changes in cell connectivity. Collectively, the theoretical and experimental findings presented here reveal the structural basis of material phase transitions, for the first time, in the context of a living organism.



(A) Exemplary 2D confocal sections at the 1st–2nd deep-cell layer of the central blastoderm with overlaid connectivity maps (top) and their rigidity profile (bottom) at consecutive time points during the fluidization/thickening process (color coded). Floppy areas are illustrated in gray, rigid areas in green, and the rigid GC in red. Shaded yellow and purple areas indicate the time period of tissue fluidization and thickening, respectively. (B) Plot of the fraction of the network occupied by the Giant Rigid Cluster (GC) as a function of normalized connectivity <k> at different time points during the fluidization/thickening process agreeing with the theoretical expectation. We observe the collapse of the GC at t=0, when the rigid-to-floppy/fluid phase transition occurs. (C) Plot of tissue viscosity as a function of the GC relative size for experimental networks of the central blastoderm at different time points during the fluidization/thickening process. (D) Plot of tissue viscosity as a function of normalized connectivity <k> for the samples described in (C) (for viscosity n = 129 embryos, N = 12 embryo batches; for normalized connectivity <k> n = 103 blastoderms, N = 11 embryo batches). The integrated plot illustrates the time trajectory (color coded) of the central blastoderm material phase state (relative size of GC) as a function of its connectivity (kc). The gray-shaded region in (B) and (D) indicates the rigid regime above the critical point of rigidity percolation kc.

Predictability of population fluctuations

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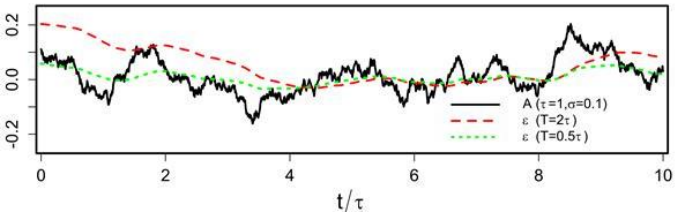
Population dynamics is affected by environmental fluctuations (such as climate variations), which have a characteristic correlation time. Strikingly, the time scale of predictability can be larger for the population dynamics than for the underlying environmental fluctuations. Here, we present a general mechanism leading to this increase in predictability. We considered colored environmental fluctuation acting on a population close to equilibrium. In this framework, we derived the temporal auto and cross-correlation functions for the environmental and population fluctuations. We found a general correlation time hierarchy led by the environmental-population correlation time, closely followed by the population autocorrelation time. The increased predictability of the population fluctuations arises as an increase in its autocorrelation and cross-correlation times. These increases are enhanced by the slow damping of the population fluctuations, which has an integrative effect on the impact of correlated environmental fluctuations. Therefore, population fluctuation predictability is enhanced when the damping time of the population fluctuation is larger than the environmental fluctuations. This general mechanism can be quite frequent in nature, and it largely increases the perspectives of making reliable predictions of population fluctuations.



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Nonequilibrium critical dynamics: upturns from surface kinetic roughening

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The collective properties that characterize dynamical complex systems often emerge via non-equilibrium analogues of phase transitions [1], at which fluctuations play an essential role. A prime example of this is generic scale invariance (GSI) [1], whereby external driving and dissipation act at comparable time scales, in such a way that criticality emerges spontaneously without parameter tuning. Thus, strong correlations pervade the spatiotemporal dynamics, being encoded in scaling behavior of observable quantities, largely irrespective of parameter values [1]. Surface kinetic roughening constitutes an important instance of GSI due to its ubiquity across system nature and physical scales [2]. Moreover, it generalizes equilibrium critical dynamics away from equilibrium, accounting for the behavior of even non-interfacial systems. For instance, in Ref. [3] the Tracy-Widom probability distribution function (PDF) ---which describes interface fluctuations in the celebrated 1D Kardar-Parisi-Zhang (KPZ) universality class [4]--- has been very recently found to also account for the statistics of phase fluctuations in the synchronization of rather generic oscillator lattices, whose evolution is demonstrated as a full-fledged instance of kinetic roughening [3]. In this talk we will address recent works [3,5-8] on kinetic roughening systems which, in spite of featuring a KPZ nonlinearity, may or may not be in the KPZ universality class, as well as systems related with these. Examples range from the stochastic Burgers [5] to Kuramoto-Sivashinsky equations [6], spreading of precursor films [7], or the KPZ equation without surface tension [8] or with columnar disorder [3]. These cases illustrate some limitations of the standard definition of universality classes via scaling exponent values [2] and the role at this of the PDF of interface fluctuations and/or interface covariance [4], and of generalizations of the standard dynamic scaling Ansatz. They also provide interesting examples on ways in which system symmetries and/or the nature of fluctuations reflect into these traits of the universality class, all of which should eventually

reflect into a comprehensive understanding of dynamic criticality away from equilibrium.

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Relativistic gas: Lorentz-invariant distribution for the velocities

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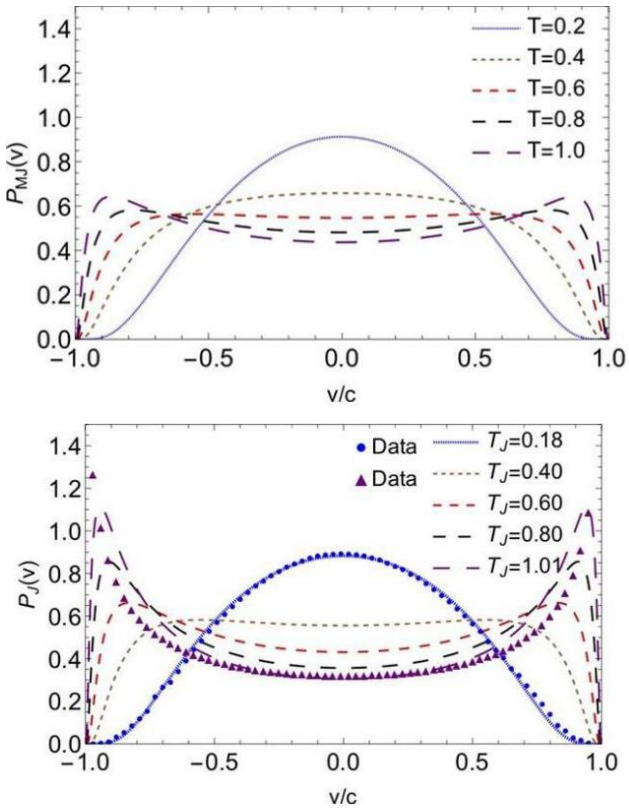
In 1911, Jüttner proposed the generalization, for a relativistic gas, of the Maxwell–Boltzmann distribution of velocities. Here, we want to discuss, among others, the Jüttner probability density function (PDF). Both the velocity space and, consequently, the momentum space are not flat in special relativity. The velocity space corresponds to the Lobachevsky one, which has a negative curvature. This curvature induces a specific power for the Lorentz factor in the PDF, affecting the Jüttner normalization constant in one, two, and three dimensions. Furthermore, Jüttner distribution, written in terms of a more convenient variable, the rapidity, presents a curvature change at the origin at sufficiently high energy, which does not agree with our computational dynamics simulations of a relativistic gas. However, in one dimension, the rapidity satisfies a simple additivity law. This allows us to obtain, through the central limit theorem, a new, Lorentz-invariant, PDF whose curvature at the origin does not change for any energy value and which agrees with our computational dynamics simulations data. Also, we perform extensive first-principle simulations of a one-dimensional relativistic gas constituted by light and heavy particles.



Space weather predictability

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The term “space weather” refers collectively to all conditions and phenomena that occur in the space environment. These conditions are influenced by the Sun's activity and can affect space-borne and ground-based technological systems and, through these, human life and endeavour. Space weather effects are multifaceted and can be acute or long-term. Several decades of research through measurements, modelling and simulations have shown the existence of some rather reliable long-

term correlations between the frequency/intensity of solar eruptions and their geospace effects. However, we have also realized that there are exceptions to such patterns, and, moreover, that similar solar eruptions and/or interplanetary disturbances can lead to geospace results of drastically different intensity. On the other hand, different types of geospace effects depend on quite different solar eruptions/interplanetary disturbances [1]. These deviations from the desired deterministic causality impose severe limitations to our efforts to accurately nowcast and forecast space weather. We will discuss selected aspects of space weather predictability, with an emphasis on the predictability of the creation of the outer Van Allen belt relativistic electrons [2].

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Space plasma physics from Moon orbit: opportunities provided by the Lunar Gateway

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The Moon is a unique location to study the deep space plasma environment. During most part of its orbit around the Earth it is directly exposed to the solar wind. Due to the absence of a substantial intrinsic magnetic field and of a collisional atmosphere, solar wind and solar energetic particles (SEPs) arrive almost without any deviation or absorption and impact directly on its surface, interacting with the lunar regolith and the tenuous lunar exosphere. Energetic particles arriving at the Moon's surface can be absorbed, or scattered, or can remove another atom from the lunar regolith by sputtering or desorption. The same phenomenon occurs also with the galactic cosmic rays (GCRs), which present fluxes and energy spectra typical of interplanetary space. During 5 - 6 days every orbit, however, the Moon crosses the tail of the terrestrial magnetosphere. It then offers the possibility to study in-situ the terrestrial magnetotail plasma environment as well as atmospheric escape from the terrestrial ionosphere, in the form of heavy ions accelerated and streaming downtail. The lunar environment offers thus a unique opportunity to study the interaction of the solar wind, the cosmic rays and the terrestrial magnetosphere with the surface and the surface-bounded exosphere of an unmagnetized planetary body, constituting a complex multi-scale interacting system. The Lunar Gateway is an orbital crewed platform that will be assembled and operated in the vicinity of the Moon by NASA and international partner organizations, including ESA, starting from the mid-2020s. It will offer new opportunities for fundamental and applied scientific research. In this presentation we we examine the opportunities provided by externally mounted payloads on the Gateway in the field of space plasma physics, heliophysics and space weather, and also the impact of the deep space environment on an inhabited platform in the vicinity of the Moon. We will then present the conceptual design of a model payload we undertook for ESA, required to perform these space plasma measurements and observations. It results that the Gateway is very well-suited for space plasma physics research. It allows a series of scientific objectives with a multi-disciplinary dimension to be addressed.

Atmospheric ion escape: contribution to the early evolution of the terrestrial atmosphere

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Understanding the evolution of planetary atmospheres, and particularly the evolution of the composition of Earth's atmosphere, is a major challenge. The evolution of the terrestrial atmosphere is driven by its interactions with the planet's crust and oceans, the biological activity, the influx from space (e.g., meteors), and the atmospheric escape to space as neutral and as ionised species. Ions outflowing from the terrestrial ionosphere and circulating in the magnetosphere play also an important role in the magnetospheric dynamics, by loading the magnetosphere with heavy ions. Some of the outflowing ions can be re-injected into the inner magnetosphere, whereas some can completely escape to outer space. The observations of the outflowing and escaping ion populations performed by the Cluster mission will be reviewed and their dependence on the solar wind parameters and on the geomagnetic activity conditions analysed. Integrating the actual ion loss rates over geological time scales (3 to 4 billion years ago), and considering that the young Sun was much more active and that the Earth's rotation period around its axis was much shorter, provides an indication on how ion escape is adequate to change the composition of the Earth's atmosphere.

Dynamical chaos in the integrable Toda chain induced by time discretization

Carlo Danieli
Sapienza University Of Rome

Integrability is one of the fundamental concept of Hamiltonian mechanics. Although rare within the space of Hamiltonian systems, integrable models play a highly relevant role in physics, as several experimentally achieved systems posses integrable limits – i.e. specific parameter regimes where an Hamiltonian turns integrable – and around such regimes novel physical phenomena have often been found. However, compute the long time propagation of integrable systems is less than trivial, as we show that time-discretization lifts integrability and induces dynamical chaos. We use the integrable Toda chain to show that even one of the most used and developed numerical method in the community – the symplectic integration scheme – induce a finite Lyapunov time TL (inverse largest Lyapunov exponent) and eventually a breakdown time TB ≫ TL where the simulations fail due to divergently large fluctuations. We discuss the dependence of these timescales on the chosen time step as well as on the chosen symplectic scheme.

Complex networks analysis of time-series data: finding patterns in socio-economic systems

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The development of information-communication technologies enabled access to large-scale data about the structure and dynamics of different socio-economic systems. The data on system elements and interactions between them are not always explicitly available but are hidden in dynamical system outputs represented by time series. The time series contain information about the dynamics of each element and its coupling with the rest of the system. Mapping time series to graphs and topological analysis of these graphs are non-trivial problems. We demonstrate our approach by analyzing the time-series data from two social systems, SARS-CoV-2 epidemics infections and death rates [1] and Meta Data for good mobility data, and USA financial sector companies [2] to uncover how different forms of crisis in these systems change their structure. We combine approaches from complex network theory, computer science, and statistical physics to study the evolutions of these systems and uncover patterns and predominant drivers of the dynamics of each system. We use correlation-network mapping to map the data onto graphs and study the spectral properties of these graphs. Eigenvector localization reveals the mesoscopic organization of these graphs and the change in the structure due to

systems evolution through the crisis. K-means clustering combined with multifractal time series analysis reveals a finer mesoscopic structure of these systems. Our analysis of two phases of SARS-CoV-2 epidemics, the outbreak and immunization phase, show the existence of robust communities of different countries and regions that further break into clusters according to similar profiles of infection fluctuations. The structure of communities and clusters in the outbreak and immunization phase differ drastically, indicating a change in epidemic dynamics due to the start of immunization. Multifractal analysis of time series reveals that persistent fluctuations around the local trend occur in intervals smaller than 14 days. Analysis of the network of relations between USA companies operating in the financial sector further confirms that the system changes during crisis periods. We find that connectivity between communities is strongly influenced by the crisis and economic measures taken by the country. Furthermore, the occurrence of crisis is also seen in the patterns of eigenvector localization. Application of described methodology on mobility data in different countries during the SARS-CoV-2 epidemic shows that a combination of epidemic measures, culture, and the infectious curve influences both mobility patterns.

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Spacecraft "clusters" for space weather studies

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Space Weather is fundamentally driven by the Solar activity and sometimes has a major impact on Earth and human lives. The consequences of severe space weather events can be disastrous for several sectors, including power, aviation and satellites. Therefore, the continuous monitoring of space weather and the accurate prediction of its impact on Earth, become vital tasks for our society.

In this presentation, we demonstrate and evaluate a concept mission, “fully dedicated” to the study of the space weather, with several assets whose low cost will allow us to replace and upgrade the assets almost continuously and at an affordable cost. The mission uses microsatellites carrying compact and fully dedicated state-of-the-art instruments. Not only will each single element of our proposed flotilla will be cheaply and quickly refreshed but also their position in the relevant part of the circum-terrestrial space could be easily modified not by complex navigation operations requiring complex and costly onboard subsystems. Indeed, by setting up a production line of very similar small and fully dedicated spacecraft, “clusters” of these spacecraft could be deployed in those parts of the Earth’s magnetosphere that will be deemed necessary to be navigated to have a fully comprehensive study and forecasts of the space weather.

Another qualifying aspect of our mission study will be the use of appropriate multivariate-multidimensional statistical analyses piloted by AI algorithms. Indeed, a major obstacle to the correct formulation of the space weather forecasts, but also of well-functioning models of the interaction of the solar wind with the Earth’s magnetosphere, require the analysis of gigantic quantities of data that are produced daily, together with need of comparing these data with those historically archived and sometimes never analyzed. We will finally discuss the scientific value of the collected data-set in the scope of multi-point studies of plasma dynamics within the inner magnetosphere.

On ensemble dependence of fluctuation-induced forces: Exact results for Casimir and Helmholtz forces

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Fluctuations are ubiquitous: they unavoidably appear in any matter either due to its quantum nature or due to the nonzero temperature of the material bodies and of the confined medium. Immersing bodies of given shapes and materials into a fluid changes its fluctuation spectrum, which has to be in accord with the geometry, the relative positions and orientations, and the material properties of the bodies. If these fluctuations are correlated in space, the dependence of their spectrum on the relative positions and orientations of the bodies generates an effective force and torque acting between them. If the excitations of the fluctuations lack an energy gap, as it is the case, e.g., for photons, Goldstone bosons, and the fluctuations of an order parameter at criticality, the fluctuation-induced force acquires an algebraic decay and, thus, becomes long-ranged.

When the degrees of freedom can enter and leave the region between the interacting objects one speaks about Casimir force. In the case of the electromagnetic Casimir force the medium is the vacuum, and the underlying mechanism is the set of quantum zero point or temperature fluctuations of the electromagnetic field. The critical Casimir force (CCF) results from the fluctuations of an order parameter. Recently, a review on the exact results available for the CCF has been published in Ref. [1].

In a recent Letter [2] we introduced the term Helmholtz fluctuation-induced force. It is a force in an ensemble in which the order parameter value is fixed. We stress that in customarily considered applications of the equilibrium Ising model to binary alloys or binary liquids the case with order parameter fixed must be addressed. In Ref. [2] via deriving there exact results on the example of Ising chain with fixed magnetization and under periodic boundary conditions, we have shown that the Helmholtz force has a behaviour very different from that of the Casimir force. It is interesting to note that the studied Helmholtz force has a behaviour similar to the one appearing in some versions of the big bang theory --- strong repulsion at high temperatures, transitioning to a moderate attraction for intermediate values of the temperature, and then back to repulsion, albeit much weaker than during the initial period of the highest temperature.

We stress that the definition and existence of Helmholtz force are by no means limited to the Ising chain and can be addressed, in principle, in any model of interest. We note that the issue of the ensemble's dependence of fluctuation-induced forces pertinent to the ensemble has yet to be studied. In the envisaged talk, we review some recent and present some new both exact and numerical results for the behaviour of the Casimir and Helmholtz force. We find that all significant results are consistent with the expectations of finite-size scaling theory.

Acknowledgments

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Glassy dynamics and jamming in persistent active matter

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In several biological systems, such as bacterial cytoplasm, cytoskeleton-motor complexes and epithelial sheets of cells, self-propulsion or activity is found to fluidize a glassy state that exhibits characteristic glassy features in the absence of activity. Recent experiments on dense systems of Janus colloids and vibrated granular systems have provided detailed information about how activity affects glassy dynamics and jamming. To develop a theoretical understanding of these non-equilibrium phenomena, we have studied, using molecular dynamics and Brownian dynamics simulations, the effects of activity in several model glass-forming liquids. The activity in these systems is characterized by two parameters: the magnitude of the self-propulsion force and its persistence time. If the persistence time is short, then the observed behavior is similar to that near the usual glass transition in passive systems. The introduction of activity reduces the glass transition temperature and decreases the kinetic fragility. Some of these effects can be understood from a generalization of the Random First Order Transition (RFOT) theory of the glass transition to active systems. For large but finite persistence times, the approach to dynamical arrest at low propulsion force goes through a phase characterized by intermittency. This intermittency is a consequence of long periods of jamming followed by bursts of plastic yielding, akin to the response of dense amorphous solids to an externally imposed shear. In the limit of infinite persistence time, the homogeneous liquid state obtained for large values of the active force and no thermal noise exhibits several unusual properties: the average kinetic energy and the width of the distribution of the kinetic energy increase with increasing system size and a length scale extracted from spatial velocity correlations increases with system size without showing any sign of saturation. This active athermal liquid evolves to a force-balanced jammed state when the self-propulsion force is decreased below a threshold value that depends on the system size. The jamming proceeds via a three-stage relaxation process whose timescale grows with the magnitude of the active force and the system size. We relate the dependence of this timescale on the system size to the large correlation length observed in the liquid state. Some of the properties of the jammed state obtained for small active force are substantially different from those of passive jammed systems. In particular, the distribution of the magnitude of contact forces in the jammed state near the jamming threshold is found to exhibit a gap for small values.

This work was carried out in collaboration with R. Mandal, S. Dutta, D. S. Bedi, P. J. Bhuyan, S. K. Nandi, P. Chaudhury, M. Rao, N. Gov and B. Chakraborty.

A κ-generalized Wasserstein metric in the graph-space for seismic waveform inversion issues

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Full-Waveform Inversion (FWI) is an advanced technique used in imaging problems to estimate the physical attributes of a medium from indirect measurements. In several geophysical applications, FWI is based on analyzing and processing seismic waves recorded at different points on the Earth's surface to reconstruct an accurate subsurface model. FWI is a robust procedure that presents significant improvements over conventional data inversion methods, as it uses all the information in seismic waveforms rather than relying solely on wave amplitudes or travel-time arrivals. This means that the FWI considers the recorded seismic waves' phase, amplitude, and complete shape, allowing a better characterization of subsurface physical parameters (e.g., conductivity, sound speed, or density). The FWI process involves several steps. In the first one, in a seismic survey, seismic waves are generated by artificial sources through controlled explosions and registered by a network of seismic receivers, composing the observed data set. Then, an initial subsurface model is produced based on prior knowledge of the region under study or conventional seismic imaging techniques. This

model is then used to generate synthetic simulations of the expected seismic waveforms by solving a wave equation. These synthetic waveforms are then compared to the observed ones employing an objective function. The next step consists of modifying the initial model to minimize the difference between the synthetic and observed data (residuals) through iterative algorithms that modify the model incrementally until the residuals are minimal. During this optimization process, phase, amplitude, and shape information from the waveforms are considered to refine subsurface physical parameter estimates. However, the so-called cycle-skipping (also known as phase ambiguity issues) poses a significant challenge in FWI applications. Such a phenomenon is mainly responsible for guiding the optimization process towards a non-informative local minimum, generating inaccurate subsurface models. This sensibility to the phase ambiguity occurs because the conventional objective functions measure pointwise (sample by sample) the misfit between synthetics and observed data, losing the convexity property regarding the time shifts between them. This work presents a robust objective function based on the κ-generalized Wasserstein metric to mitigate phase ambiguity problems. The proposed objective function is computed by solving a combinatorial optimization problem using a Kuhn-Munkres algorithm to minimize the difference between the observed waveforms and a permuted version of the synthetic waveforms. In this way, we consider the Kantorovich formulation of the optimal transport problem and the probabilistic maximum likelihood for obtaining a new κ-objective function. Since the Wasserstein metric is valid only for comparing probability functions and the seismic waveforms are not normalized quantities and not positive-defined quantities, we represent the waveforms in the graph space to satisfy the probability axioms. The results suggest that the κ-graph-space optimal transport FWI is an efficacious approach to alleviate the impact of cycle-skipping difficulties and to improve the objective function convergence, resulting in higher-resolution subsurface models when $\kappa = 0.6$.

The usage of kappa distributions in the context of accreting black hole modeling

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Recent advancements in radio astronomy opened the window for direct imaging of black holes by the Event Horizon Telescope (EHT). The historical images of Messier 87* (M87*) and Sagittarius A* (SgrA*) allow for tests of General Relativity but also challenge our understanding of plasma physics in these extreme environments. The observed emission is synchrotron radiation produced by a population of relativistic electrons whose exact emission properties depend on the shape of their distribution function. State-of-the-art EHT models rely on general relativistic magnetohydrodynamics, where the plasma fluid is assumed to be a single-temperature fluid. To model the emission from the electrons, post-processing is needed. Until recently, the status quo for EHT modeling was the usage of thermal Maxwell-Jüttner distribution functions (DF). However, this choice is unlikely since the mean-free path of an electron in the accretion flows of M87* and SgrA* is much larger than the system size. This results in the plasma being collisionless, and the electron population should have a non-thermal component. How these accretion flows accelerate the electrons and the exact shape of the DF is still a matter of active debate. In this talk, I will highlight my work exploring kappa-DF usage for EHT modeling. I will give an overview of recent numerical advancements in radiative transfer methods utilizing kappa-DFs. I will highlight the usage of the kappa-DF in the latest SgrA* results of the EHT. And give an overview of my “kappa-jet” models, which can explain the overall observables by the EHT and other multi-wavelength observatories.

Temperature and its uncertainty in nonequilibrium steady state plasmas

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The concept of temperature, which is precisely defined only for thermal equilibrium states and in systems with short-range interactions, lacks such a foundation in the case of nonequilibrium steady states. This issue is believed to be at the core of the striking effects occuring in complex systems with long-range interactions (such as space plasmas and laboratory plasmas, as well as in self-gravitating systems). Due to the long-range correlations present in these systems it is no longer possible to speak of independent, uncorrelated regions, and the presence of correlations between different regions of a system can introduce temperature fluctuations even in macroscopic systems. This issue has led to the idea of superstatistics. Superstatistics [1] is a nonequilibrium framework, an alternative to Tsallis nonextensive statistics, that assumes a superposition of equilibrium models at different temperatures and aims to describe steady states having power laws instead of the usual Boltzmann-Gibbs statistics. Despite the success and clarity of the superstatistical framework, the conceptual meaning of temperature in nonequilibrium steady states still remains to be clarified, and this provides an open challenge for the statistical mechanics community. In this work, we first provide a brief review of the main ideas behind the theory of superstatistics, and why it appears to be an attractive alternative to the framework of Tsallis nonextensive statistics in the context of nonequilibrium plasmas. In particular, we put our focus on plasmas having a kappa distribution of velocities, which is the generalization of the Maxwell-Boltzmann distribution within the Tsallis framework. Our main result is the derivation of the kappa distribution from first principles, using only the framework of superstatistics and one simple requirement on the correlation between the kinetic energy of a test particle and that of its surrounding environment. The corresponding inverse temperature distribution is the gamma distribution, which is referred to as the chi-squared superstatistics, and we show the connection between this inverse temperature distribution and the distribution of the fundamental inverse temperature [2], a property of the steady-state statistical ensemble.

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Polytropic behavior in the substructure of interplanetary coronal mass ejections

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The polytropic process is a quasi-static thermodynamic state that characterizes space plasma populations described by kappa distributions. The polytropic index, γ, is particularly important as it describes the thermodynamic behavior of the system by quantifying the changes in temperature as the system gets compressed or expands. Using Wind spacecraft plasma and magnetic field data during 02/1995 – 12/2015, we investigate the thermodynamic evolution in 336 Interplanetary Coronal Mass Ejection (ICME; [1]) events. For each event, we derive the polytropic indices (e.g., [2]) in the sheath and magnetic ejecta structures, along with the pre- and post- event regions. We then examine the distributions of these indices in the four identified regions and connect their properties with derived entropy [3,4] and turbulent heating [5] gradients. We find that in the ICME sheath region where wave turbulence is expected to be highest, the thermodynamics takes longest to recover into the original quasi-adiabatic process, while it recovers faster in the quieter ejecta region. This pattern creates a thermodynamic cycle, featuring a near adiabatic value $\gamma \sim \gamma_a = 5/3$ upstream of the ICMEs, $\gamma_a - \gamma \sim 0.26$ in the sheaths, $\gamma_a - \gamma \sim 0.13$ in the ICME ejecta, and recovers again to $\gamma \sim \gamma_a$ after the passage of the ICME. These results expose the turbulent heating rates in the ICME substructures. The lower the polytropic index from its adiabatic value, the larger the rate of turbulent energy that heats the ICME plasma. In other words,

increased energy absorption in the sheath driven by its fast expansion would result in a low polytropic index. For full details, see Dayeh and Livadiotis, 2022 [6].

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Thermodynamic bounds on correlation times

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We derive a variational expression for the correlation time of physical observables in steady-state diffusive systems. As a consequence of this variational expression, we obtain lower bounds on the correlation time, which provide speed limits on the self-averaging of observables. In equilibrium, the bound takes the form of a tradeoff relation between the long- and short-time fluctuations of an observable. Out of equilibrium, the tradeoff can be violated, leading to an acceleration of self-averaging. We relate this violation to the steady-state entropy production rate, as well as the geometric structure of the irreversible currents, giving rise to two complementary speed limits. One of these can be formulated as a lower estimate on the entropy production from the measurement of time-symmetric observables. Using an illustrating example, we show the intricate behavior of the correlation time out of equilibrium for different classes of observables and how this can be used to partially infer dissipation even if no time-reversal symmetry breaking can be observed in the trajectories of the observable.

Long-range interacting quantum systems

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The seminar is meant to present a bird's eye view on the field of long-range interacting quantum systems. The talk will start with a brief overview of critical phenomena in systems with power law interactions $1/r^{\alpha}$ showing how the equilibrium scaling depends of the power-law scaling α. Then, I will describe the peculiar out-of-equilibrium scaling dynamics observed in "strong" long-range systems with $\alpha < d$, both for sudden and slow quenches. Finally, I will show how the study of long-range interacting systems is connected to the case of non-homogeneous disordered structures.

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Effective theories in quantum dynamics: the Kibble-Zurek mechanism

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Slow quenches of the magnetic field across the paramagnetic-ferromagnetic phase transition of spin systems produce heat. In systems with short-range interactions the heat exhibits universal power-law scaling as a function of the quench rate, known as Kibble-Zurek scaling. However, the conventional scaling for the surface energy of topological defects is disrupted in long-range systems due to the influence of nonlocal effects. To investigate this, we focus on the strong long-range quantum Ising model as a concrete example. By constructing an exactly solvable low-energy theory we make an analytic prediction for the "scaling" of the heat arising after a quasi-static drive, showing perfect agreement with numerical observations obtained by exact diagolanization.

Universality in nonequilibrium quantum dynamics

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A quantum quench dynamically generates a nonequilibrium state that in the proximity of a critical point yields a time evolution exhibiting universal properties. We show how to solve the key problem of determining the nonequilibrium state for the different universality classes, and then analytically determine the behavior of local observables at large times. One result of the theory is that, for systems with interacting excitation modes, the order parameter can exhibit oscillations that stay undamped in time. In particular, this is predicted to occur for a quench of the transverse field within the ferromagnetic phase of the Ising model in more than one spatial dimension, a case previously unaccessible to analytic treatment. If the quench is performed only in a subregion of the whole d-dimensional space occupied by the system, the time evolution occurs inside a light cone spreading away from the boundary of the quenched region. In this case, the additional condition for undamped oscillations is that the volume of the quenched region is extensive in all dimensions. We also address analytically for the first time the central issue of the dependence on initial conditions in nonequilibrium quantum dynamics considering the one-dimensional ferromagnets in the regime of spontaneously broken symmetry, for the infinite-dimensional space of initial conditions of domain wall type. At large times the time evolution takes place inside a light cone produced by the spatial inhomogeneity of the initial condition. While the global limit shape in the variable x/t changes with the initial condition, the form of the space-time dependence in the innermost part of the light cone is universal. In systems with more than two ground states the tuning of an interaction parameter can induce a transition which is the nonequilibrium quantum analog of the interfacial wetting transition occurring in classical systems at equilibrium. We illustrate the general results through the examples of the quantum Ising, Potts and Ashkin-Teller models.

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Measuring the simplicity of neural networks as a function of overparametrization

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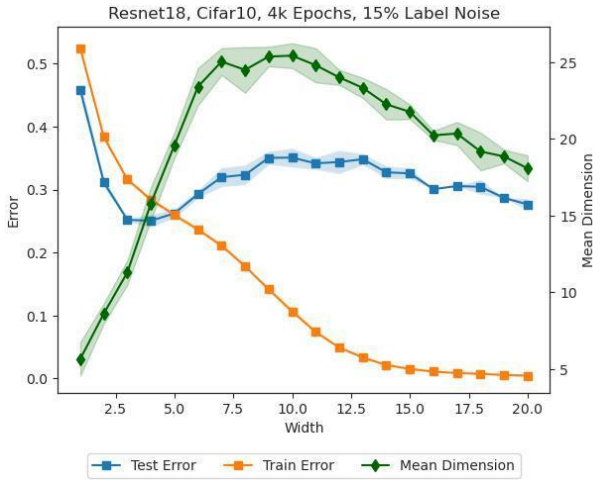
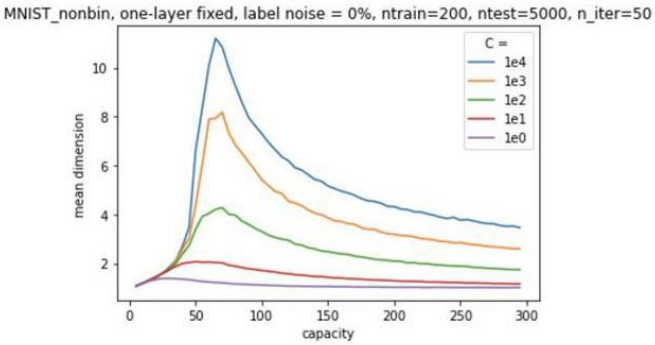
Understanding generalization properties is a crucial part of neural networks analysis. At odds with the standard bias-variance trade-off described by statistical learning theory, recent works demonstrated the existence of a double descent phenomenon for the generalization error of neural networks, highlighting a variety of settings where the test performance of these models can improve above the interpolation threshold. In the present work, we aim at building a link between the double descent phenomenon and the sensitivity of the function represented by neural networks. In particular, we characterize the susceptibility of the network with respect to the input features and their degree of ”influence” on the output of the model. To exactly quantify this influence we employ the mean dimension (MD), a metric developed in the context of boolean function analysis. The MD of a pseudo-boolean function (taking an n-dimensional





binary input and producing a scalar output) indicates the average dependency of the function on multipoint input correlations, and can be obtained from the Fourier coefficients in the decomposition of the function in the basis of 2^n polynomials, being products within all the possible sets of the features. Operationally the MD can be estimated by measuring a weighted sum of feature influences divided by the total variance of the function. In this way, the MD of a neural network can be used to measure the "simplicity" of the represented function from its response to variations in the input. We find that, as the degree of overparametrisation of the network is increased, the MD reaches an evident peak at the interpolation point, in perfect correspondence with the double descent of the generalization error, and then slowly approaches a low asymptotic value. We analyze this phenomenon for different model classes and training setups. Moreover, we demonstrate that models more robust to adversarial attacks exhibit lower mean dimension, and on the contrary, adversarially initialised models tend to show a higher mean dimension in our experiments.

Mutations in protein family networks

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To study the structural organization of a protein family we develop an approach based on the random matrix theory (RMT) and Network theory, which uses the physiochemical properties of the amino acid with multiple sequence alignment. A novel graphical technique is designed to represent protein sequences using physiochemical properties that give a fast, easy, and informative way of comparing the evolutionary distances between protein sequences. The first step is to calculate the correlation matrix associated with each property, where the noise reduction and information filtering are done employing RMT using an ensemble of Wishart matrices. The investigation of the eigenvalue statistics of the correlation matrix for the beta-lactamase family shows the universal features as seen in the Gaussian orthogonal ensemble (GOE). The statistical and spectral analysis of the Pearson correlation matrices between positions based on physiochemical properties of amino acids of several protein families is performed and compared with the random Wishart matrix model results. A detailed analysis shows that the protein families significantly diverge from the Marcenko-Pastur distribution with many eigenvalues (outliers) outside the Wishart lower and upper bound. The information content of each eigenvector of the correlation matrix is quantified by introducing an entropic estimate, which shows that for the smallest eigenvectors (low eigenmodes) are highly localized as well as informative. These small eigenvectors when processed give clusters involving positions that may have well-defined biological and structural importance. Next, we use the correlation-based threshold method to create a weighted multiplex network of evolutionary interactions between positions for the β-lactamase family. Although each network layer is derived from the same multiple sequence alignment (MSA) but is diverse from other layers by realizing a different aspect of the interaction between amino acids. In each layer, positions show a different clustering, where the clusters depend on the physiochemical properties, and the positions with similar strength of the property tend to interact with each other. This clustering gives a neighborhood of highly interconnected nodes with strong interaction, indicating a high possibility of functional and evolutionary constraints, sometimes the part of the sector that forms the important functional and structural domain. We observe a hierarchy in the physiochemical properties, some interactions in some layers are preferred over others, which can identify the property responsible for the functionality of the family. Multi degree also sets a hierarchy in the influence of properties at a given position. Patterns and regularities in the protein multiplex network are explored. The effect of mutation on a protein family is analyzed by fixing a particular amino acid at a given position of the Multiple Sequence Alignment (MSA), and taking all the sequences which have the same amino acid 'X' at that position. Multiple subsets are created with a different types of amino acid at a fixed position. We then examine and compare these subsets as this gives the effect of a particular amino acid at that position. Preliminary results on perturbating the correlation matrices and networks are discussed.

Geometrical formulation of hybrid kinetic and gyrokinetic hamiltonian field theory for astrophysical and laboratory plasmas

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Higher-order Lie-transform perturbative methods applied to Hamiltonian formulation of guiding-center motion have significant prominence in the field of plasma physics due to their ability to accurately describe the intricate dynamics of particles. The elegant and compact Lagrangian formulation plays a vital role in this process, as it enables the derivation of equations of motion from the Lagrangian two-form, or symplectic two-form. In this present work, our primary objective is to develop a comprehensive field theoretical hybrid model that incorporates the dynamics of ions within a fully kinetic framework, while simultaneously describing the dynamics of electrons using a gyrokinetic coordinate system transformation. Utilizing the Lagrangian two-form as the starting point, we execute a series of gauge transformations aimed at eliminating the theta dependence up to a predefined ordering. To guarantee theta independence in the Hamiltonian portion of the Lagrangian, a Lie transformation is performed. The dynamics of the system are subsequently derived by employing the variational principle in the action, which also encompasses the electromagnetic fields. This last step give us a complete system, and together with the Vlasov equations for the ions and electrons, can be then solved numerically. To validate our model as a first approximation, we first conduct a linear analysis and benchmark the solutions of our system against existing literature. Our examination initially focuses on linear electrostatic solutions, taking into consideration Ion Acoustic Waves and Ion Bernstein Waves as examples. Furthermore, we investigate the existence of waves with frequency much higher than ion cyclotron frequency. The lack of such waves in standard gyrokinetic frameworks is a well known barrier to its use in the study of ion frequency range turbulence in space and astrophysical plasma. Subsequently, we compare the linear solutions of our system with those obtained from a fluid and a fully kinetic solver. In summary, this study serves to introduce a field theoretical hybrid model that can effectively describe the dynamics of ions and electrons in various plasma environments. By validating our model through a linear analysis and benchmarking against existing literature, we aim to provide a valuable tool for investigating kinetic effects in solar wind, laboratory plasma, and potentially, astrophysical plasma.

Surprising spatial profiles in steady flows of living cells which polarize to move

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We study the spatial spreading of living cells in a simple model which contains the following basic ingredients: exclusion (cells cannot penetrate each other), switching between two states, namely polarized and depolarized states, and migration of polarized cells. During the process of polarization, a real cell becomes motile and asymmetric, and its shape becomes elongated. A polarized cell can move, in a direction close to its axis. During the process of depolarization, the ``motor'' of the cell is deconstructed, the cell recovers a round shape, and it looses the capacity to move. For simplicity, we assume that these changes of states are random with fixed time rates, that the shape of cells switches between a circular shape and an elongated shape with fixed aspect ratio, and that the direction of polarization is drawn uniformly at random. Cell division and cell death are of course essential phenomena in living organisms where cell migration takes place (be it during embryo development, growth, wound healing, cancerous invasion...). But we neglect them for the sake of simplicity, and to focus on the effects on the collective behavior of the cells of the migration mechanism itself. We study the settings where cells exit a spatially localized source and fall into a sink. Thanks to extensive computer simulations in two space dimensions, we observe that, because of the interplay between cell migration, change of shape, and steric interaction (excluded volume), the steady-state spatial spreading of the cells is nontrivial, much more

complicated than in a model which neglects the change of shape of the cells for instance. There is a kind of discontinuity close to the source of cells, and a continuous but highly nonlinear density profile between source and sink. To quantitatively understand the collective behavior in the low density region close to the sink, we use a mean-field like approximation with space scale separation between short-range ballistic motion and long-range diffusive motion. To understand what happens close to the source, we use an exact solution for the probabilities of the configurations of the interacting cells in the limit of maximum cell density, which we complete with a model for the diffusion of ``holes''. Finally, matching the two regimes (which is possible if the ratio width/length of the space where cells move is not too high, i.e. if the system's shape is not very thin, quasi 1D), we are able to predict the full density profile as a function of the rates of polarization, depolarization and move only. This study can be easily extended to three space dimensions and we checked that the results do not significantly depend on the lattice geometry one uses. We hope it will help to improve the precision of quantitative models of cell invasion e.g. in diffuse brain tumors.

Kinetic theory of a confined quasi-one-dimensional gas of hard disks

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In recent years, the study of transport phenomena in gases or liquids confined in spaces whose characteristic length is comparable to the molecular size, has attracted a lot of attention. This has been prompted and stimulated by the relevant new technological applications of nanofluidics. The experimental advances ask for a better understanding, at a conceptual level, of the effects that strong confinement has on the non-equilibrium behavior of fluids. Because under these conditions the particles do not explore a bulk-like environment, and because of the asymmetry generated by the confining boundaries, strongly confined systems exhibit inhomogeneity and anisotropy, that have both a great impact on their macroscopic properties. Most of the studies carried out up to now on transport in confined fluids consider, more or less explicitly, that hydrodynamics holds in all the directions, i.e. it is supposed that the length characterizing the confinement is larger that the characteristic hydrodynamic length. Then, for instance, to study diffusion in a fluid that is confined between two parallel plates, the starting point is the three-dimensional diffusion equation, with the appropriate boundary conditions confining the system. In more general transport problems, some ad hoc extrapolation of the Navier-Stokes equations to confining geometries are employed. In these works, the theoretical problem is how to project the three-dimensional dynamics on a one-dimensional or two-dimensional space, depending on the specific geometry of the system at hand. Nevertheless, when dealing with strongly confined fluids, it is not clear that hydrodynamics hold in the direction perpendicular to the confining walls. Kinetic theory and non-equilibrium statistical mechanics provide the appropriate context to investigate which is the right macroscopic description of transport under strong confinement, providing also the expressions for the needed transport coefficient. In this work we consider one of the simplest model to tackle the above mentioned general problem: A dilute gas of hard disks confined between two straight parallel lines. The distance between the two boundaries is in between one and two particle diameters, so that the system is quasi-one-dimensional. A Boltzmann-like kinetic equation, that takes into account the limitation in the possible scattering angles, is derived. It is shown that the equation verifies an H theorem implying a monotonic approach to equilibrium. The implications of this result are discussed, and the equilibrium properties are derived. Closed equations describing how the kinetic energy is transferred between the degrees of freedom parallel and perpendicular to the boundaries are derived for states that are homogeneous along the direction of the boundaries. The theoretical predictions agree with results obtained by means of molecular dynamics simulations.

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Cancer invasion and progression: insights from agent-based models

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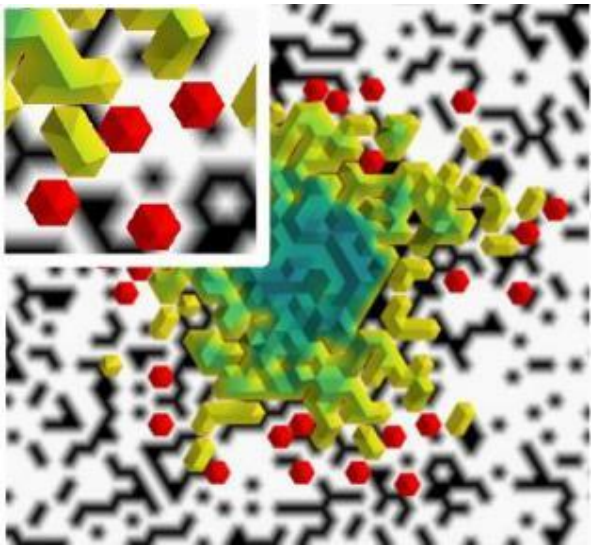
Cancer invasion may be viewed as collective phenomenon emerging in populations of normal and malignant cells. As such it can be studied with agent-based models, e.g. cellular automata. I will provide examples of such models to analyze breast and glioma invasion as well as the emergence of phenotypic heterogeneity due to cellular interactions in growing tumors. Furthermore, I will present models which shed light on cancer progression.



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Energetic H+ and O+ moments and polytropic index in the kronian magnetosphere with >20 keV Cassini/Mimi measurements

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The κ-distribution function is an essential form for analyzing the distributions of trapped ions, together with Energetic Neutral Atoms (ENAs) in planetary magnetospheres. Given that the particle populations at Saturn can have many different kinds of sources (solar wind, atmosphere, volcanic moons, etc.) and sinks (collisions with ambient neutrals or moon or ring surfaces, reconnection, etc.) and move under the influence of its dynamic magnetic field, it is advantageous to have a function flexible enough to allow the determination of the essential physical quantities of the energetic particle spectra, such as temperatures, densities, pressures, spectral indices, and convection bulk velocities. We utilize ~13 years of Cassini/MIMI observations and we model the >20 keV energetic ion (H+ and O+) energy spectra using κ-distributions [Dialynas et al. 2018]. The modeled spectra are then used to calculate the energetic ion moments for both species inside the Kronian magnetosphere, and a modified version of the Roelof and Skinner [2000] model is employed to simulate the energetic ion partial pressure, density, and temperature. Those simulations lead to extracting the polytropic index (Γ) for both H+ and O+. Our results are summarized as follows: [1] The >20 keV energetic ion spectra are consistent with κ-distributions. The energetic ion moments show day-night as well as dusk-dawn asymmetries, that can be explained by considering the multiple injections and the azimuthal energetic ion flow properties inside the magnetosphere in conjunction with charge-exchange decay and/or the noon-midnight E-field. [2] The 9.5<L<20 region corresponds to a local equatorial acceleration region, where subadiabatic transport of H+, Γ~1.25 (<1.67), and quasi-isothermal behavior of O+, Γ~0.95 (<1), dominate the ion energetics. [3] Non radiation belt energetic ions are heavily depleted inside ~8 Rs. The ion lifetimes decrease significantly (due to charge exchange), so that the ion pressure and density drop to minimum. The behavior of both H+ and O+ appears to be quasi-isothermal (Γ<1) inside ~8 Rs. [4] Energetic ion bundles within 9<L<20, and especially beyond ~17-18 Rs, that possibly result

from rotating energetic particle blobs, produce durable signatures (enhancements) in the H+ and O+ pressure and density. [5] The loss of heat from the plasma sheet is greater than the supply of new energy, which does not seem to have aground thermodynamic state. Multiple injections may account as the drivers of new energy entering the system, but a cooling mechanism does not allow the plasma sheet to behave adiabatically. The neutral gas dominates over the ion densities, has a strong influence on the magnetosphere dynamics, and may act as an effective cooling mechanism. [6] Assuming a collisionally isotropic gas, the entropy (S) becomes a conserved quantity (in a purely adiabatic processes; $S=T/n^{2/3}$, $\Gamma=5/3$). Our results indicate that S cannot be conserved in Saturn's magnetosphere, but should decrease with decreasing distance from Saturn, at least for the 9.5< L<20 region where $\Gamma < 5/3$, as it happens at Earth's magnetotail.

Non-Gaussian models of financial returns: comparisons and applications

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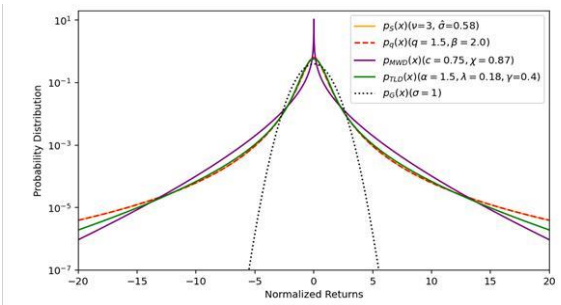
To describe the probability distribution function of returns, the normal distribution was the first suggestion. It is still a landmark and is widely used in finance, yet it is based on some hypotheses which are not empirically verified. In fact, the analysis of empirical data clearly shows that high-frequency returns follows a leptokurtic, heavy-tailed shape. Different non-Gaussian models have then been proposed to account for these features, such as the Truncated Lévy, the Student's t, the q-Gaussian and the Modified Weibull distributions. There is no consensus on what class of probability distributions should be adopted to describe financial returns, since the different models have demonstrated, to varying extent, an ability to reproduce empirically observed stylized facts. In order to provide some clarity, we perform a comparative study of the aforementioned non-Gaussian models. To introduce a coherent framework, each distribution is reported to zero mean (to model price changes with subtracted average returns), unit variance and evaluated over a bounded range (to mimic realistic outliers). The shape parameter of each model is chosen according to values of the literature which provide a good fit to empirical data, whereas the scale parameter is obtained with the constraint of unit variance. Given the above setting, we are able to implement a consistent comparison of the four models, which show a similar leptokurtic shape and a quite good agreement along the tails. To further investigate the outliers behavior, we focus on the complementary distribution functions and on the kurtosis; similarities emerge in these cases as well. By using different Monte Carlo algorithms, we generate large samples of non-Gaussian random numbers as synthetic data representations of financial fluctuations, in order to compare their statistical properties and to simulate their dynamical evolution, highlighting the differences with the normal scenario. We also present a first application to option pricing, by considering both plain vanilla and path-dependent options for a comparison of Gaussian and non-Gaussian fluctuations. To this aim, we adopt the standard risk-neutral approach to derivative pricing. We observe differences between the two scenarios in the limit of short maturities, while, as the maturity increases, our results gradually converge to the Gaussian predictions as a consequence of the limit behavior of the fat-tailed distributions.



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Hydrodynamics and rheology of fluctuating, semiflexible, inextensible, and slender filaments in Stokes flow

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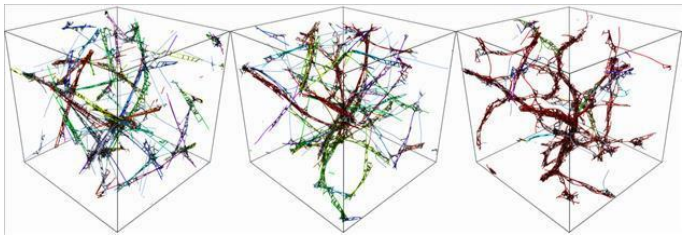
Every animal cell is filled with a cytoskeleton, a dynamic gel made of inextensible filaments / bio-polymers, such as microtubules, actin filaments, and intermediate filaments, all suspended in a viscous fluid. Similar suspensions of elastic filaments or polymers are widely used in materials processing. Numerical simulation of such gels is challenging because the filament aspect ratios are very large. We have recently developed new methods for rapidly computing the dynamics of non-Brownian and Brownian inextensible slender filaments in periodically-sheared Stokes flow [1-3] . We apply our formulation to a permanently1 and dynamically cross-linked actin mesh3 in a background oscillatory shear flow. We find that nonlocal hydrodynamics can change the visco-elastic moduli by as much as 40% at certain frequencies, especially in partially bundled networks [3,4]. I will focus on accounting for bending thermal fluctuations of the filaments by first establishing a mathematical formulation and numerical methods for simulating the dynamics of stiff but not rigid Brownian fibers in Stokes flow.4 I will emphasize open questions for the community such as whether there is a continuum limit of the Brownian contribution to the stress tensor from the filaments.



This work is supported in part by the U.S. National Science Foundation under grant DMS-2052515.

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Scale-free network architectures generated by nonlinear preferential attachment

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The preferential attachment mechanism is one of possible origins of power-law degree distributions $P(q) \propto q^{-\gamma}$ in complex networks. New vertices attach to existing ones with a probability proportional to a preference function of their degrees, $f(q)$. It is widely known that linear preference functions provide scale-free networks [1], while power-law preference functions with exponents distinct from 1 result in non-scale-free architectures [2]. It was noticed however that a linear asymptotics of the preference function turns out to be sufficient to get a power-law degree distribution, and that, for a recursive tree, even distorting a linear preference function at the smallest degree $q^* = 1$, one can vary the exponent γ of the degree distribution within the range $(2, \infty)$ [2]. Remarkably, a small distortion of this kind produces a strong effect on γ. We study the effect of the distortion of a linear preference function $f(q) = q + a$ at single degrees q^* on a shape of the degree distributions of recursive trees. Without this distortion, exponent $\gamma = 3 + a$, where $-1 < a < \infty$. We find the explicit solution of the stationary limit of the rate equations for degree distributions and show that the effect of this distortion decreases with q^*. For $q^* = 2$, varying $f(2)$ in the range $(0, \infty)$, we obtain exponent γ in the range $(2, \gamma_{max}(a))$, where $\gamma_{max}(a) \cong [(1 + \sqrt{5})/2]a$ for large a. The factor $(1 + \sqrt{5})/2 = 1.618..$ is the golden ratio. Further, for $q^* =$, varying $f(3)$ in the range $(0, \infty)$, we obtain exponent γ in the range $(\gamma_{min}(a), \gamma_{max}(a))$, where $\gamma_{min}(a) \cong 0.618 \ldots a$ and $\gamma_{max}(a) \cong 1.247 \ldots a$ for large a. For large q^ $*$, the range of possible values of exponent γ becomes quite narrow, converging to $\gamma = 3 + a$ as $q^* \to \infty$. The limiting minimum value $\gamma_{min} = 2$ is approachable only in the narrow range of a close to -1, namely for $-1 < a < -1 + 1/(\ln q^* + \gamma_e)$, where $\gamma_e = 0.577..$ is Euler's constant. These results indicate the range of scale-free architectures produced by such manipulations of a preference function.

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Different kinds of localization in complex networks

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We discuss localization effects observed in various matrix representations of complex networks and in processes taking place on networks [1]. The localization is indicated by a non-vanishing inverse participation ratio in large networks. The first basic example of localization is demonstrated by the quenched mean-field theory for the epidemic SIS model on a complex network with a hub or a cluster with high connectivity. This problem is reduced to the localization of the principal eigenvalue of the adjacency matrix of a network [2]. The explicit solution was found for a sparse random regular graphs and for Erdős-Rényi random graph with a hub. For a disease spreading, localization results in an island of infected vertices in a range of transmission rates below the endemic epidemic threshold. Localization of the principal eigenvalues of the adjacency and Laplacian matrices of complex networks with a hub significantly hinders community detection. A non-backtracking matrix is widely used as a remedy against localization on isolated hubs. Nonetheless, the principal eigenvalues of this matrices still can be localized on clusters. We describe the explicit solution for localization of the principal eigenvector of the non-backtracking matrix on an arbitrary finite graph inserted into an arbitrary infinite tree-like network [3] derived in the framework of the non-backtracking expansion approach [4]. Importantly, the quenched mean-field approximation neglects the absorbing state in the SIS model and fluctuations, due to which a finite number of infected vertices all will finally become susceptible due to fluctuations. Hence this solution with a finite number of infective vertices is meaningful only in the quasi-stationary, metastable state, and so localization on a hub in the SIS model is actually metastable [5]. This trouble disappears for localization on a large cluster still containing a vanishingly small fraction of an in infinite network. We outline the features and applications of the metastable localization.

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Acoustic metafluids based on random microstructure networks

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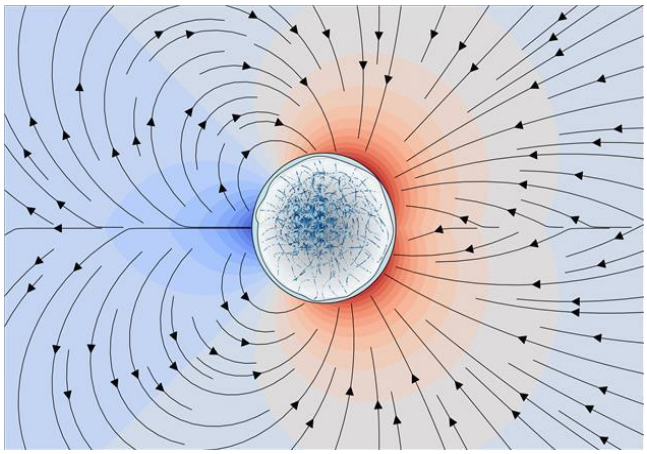
In metamaterials, the interaction between waves and matter leads to unusual wave-propagating properties of the medium, which can be used for various purposes [1]. In acoustic metamaterials, the parameters that determine sound propagation, i.e., the effective compressibility χ and density ρ of the wave-carrying medium, can become simultaneously negative in certain frequency windows due to resonance effects of sub-wavelength inclusions [1,2,3]. In our work [3] we focus on irregularly shaped inclusions - micro-oscillators – that are allowed to be randomly distributed throughout the host fluid and have irregular modal shapes. We show that the metafluid concept need not necessarily be based on position periodicity or correlation of the suspended micro-oscillators, and in this case not even on ideally designed micro-oscillators. We formulate the detailed operating principle of such a metafluid model, give explicit formulas for its effective dynamic moduli in terms of the modal structure of the micro-oscillators, and

discuss basic practical issues of performance optimization in terms of their mass and size. In our model the micro-oscillators consist of point masses connected by harmonic potentials. Further we discuss how the amount and distribution of such connections affects the effectiveness of the micro-oscillators in modification of apparent acoustic parameters of the fluid. It turns out that the so called floppy-modes, which appear at very low frequencies due to under-constrained regions in the system [4], can have a substantial effect on acoustic parameters of the medium. This makes them acoustically accessible and additionally the absence of need for an intricately designed structure brings experimental realizations that much closer.



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Decomposition of cross-correlation networks by means of the concept of q-MST

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The dynamics of complex systems is commonly accessible through the multivariate time series. They are then used to determine the correlation matrices. By introducing an appropriate distance matrix, such matrices - for transparency - are usually converted into networks which are typically reduced to the minimum spanning tree (MST) representation. Of course, the traditional correlation coefficients, by construction, considerably compress and reduce the amount of information contained in the original series. The related compression may result, at the first place, from the fact that such coefficients involve averaging correlations over the whole span of fluctuations and thus do not filter out some possible variability of the intensity of correlations at different values of their amplitudes. Within such an approach, in the case of strong correlations, the resulting MST may give rise to some false signals, such as promoting a peripheral node to play the role of a central hub. Here the generalization of the concept of cross-correlation coefficient to the q-dependent detrended cross-correlation coefficient ρ(q,s) [1] is presented such that when varying the q-parameter, it acts selectively to cross-correlations between different fluctuation amplitudes at different time scales s of multivariate data. Following such a generalization, the family of q-dependent minimum spanning trees (q-MSTs [2]) is introduced, which allows to disentangle the composition and organization of correlations graphically and thus to study their varying network characteristics. The utility of such a procedure in addressing the above indicated issues is illustrated on a recently vital subject of the world cryptocurrency market [3] and of the underlying cross-correlations [4]. During the periods of the relatively stable increases, accompanied by rather moderate cross-correlations, the overall structure of q-MSTs does not change significantly with varying q-values. This signals that the cross-correlations are rather uniformly distributed over the range of

fluctuations. Also, the anticipated central hub - the Bitcoin - remains such at different values of q. On the other hand, during the periods of violent decreases and strong cross-correlations, the structure of q-MSTs sizeably varies, and for instance, in May 2021, it is the DASH which at q=2 is seen to constitute a node of comparable multiplicity to the Bitcoin. Even more, at q=4, the latter is seen as a peripheral node, and an overall structure of the corresponding MST is much more dispersed. This indicates that here the strength of cross-correlations is more diversified at the large amplitude of fluctuations and that q-MST offers a promising tool for a systematic study of such effects in many different areas.

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Work based on cooperation with J. Kwapień and M. Wątorek.

Probability analysis of nonlinear dynamical systems driven by Ornstein-Uhlenbeck process

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The advantage of the white noise approximation as a simulation of the impact of a random environment on the considered nonlinear dynamical system is that it allows one to apply the powerful apparatus of the theory of Markovian processes and thereby obtain exact analytical results. Although the white noise approximation is a very convenient theoretical technique, in physical applications the correlation time of real noise, however small, is strictly non-zero. Any attempts to theoretically consider nonlinear systems under the influence of real external noise are faced with the fact that the evolution of the system in time ceases to be Markovian. At the same time, the noise generated by the environment can be considered for simplicity as a Markovian and, representing the combined effect of the action of many weakly coupled factors, it is distributed according to the Gaussian law by the central limit theorem. These properties of external fluctuations (ergodicity, Markovianity, and Gaussianity) limit the wide choice of models to only one possibility. Indeed, a regular stationary Gaussian Markovian process is an Ornstein-Uhlenbeck process. Thus, it can be concluded that for most applications, the Ornstein-Uhlenbeck process is a suitable model for external colored noise. In this paper a new approximate method for finding the steady-state probability distribution of a nonlinear dynamical system described by first-order differential equation with additive colored Gaussian noise (Ornstein-Uhlenbeck process) is proposed. An expansion of a stationary probability density function into a power series in a small parameter, the noise correlation time, up to second-order terms, has been obtained for the first time. The procedure is based on solving an infinite chain of differential equations for conditional moments, obtained from Fokker-Planck equation for the joint probability distribution. Based on the power series expansion obtained, the applicability of the previously proposed approximations is estimated. As shown, the previously proposed steepest-descent approximation gives an incorrect result already in the first order term of expansion, while the unified colored noise approximation and the functional-calculus approach only in the second order. At the end, an exact probability analysis of the Gompertz model of tumor cell growth with fluctuations in the form of the Ornstein-Uhlenbeck process in the growth rate is carried out. Along with the steady-state probability density function of tumor volume, the evolution of the conditional probability distribution in time is precisely found. The dependence of the stationary probability distribution on the correlation time and intensity of external fluctuations is studied in detail. As was shown, the form of this probability density function is unimodal, and the most probable value of the tumor volume, as well as its mean value, increases with increasing the correlation time of noise, but decreases with increasing its intensity.

Phase transitions in three-dimensional random anisotropy Heisenberg magnets

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We are interested in ordering of random anisotropy magnets (RAM) described by the model introduced in the early 1970s [1]. Despite extensive studies, the problem of the nature of a low-temperature phase of RAM remains a very intriguing issue. While, for large values of local anisotropy strength, the majority of studies predict a spin glass, there is much discussion about ordering for small and moderate values of such strength. It appears that the answer to this question depends also on the local anisotropy axis distribution. Field-theoretical renormalization group studies predict an absence of ferromagnetic order for uniform continuous distribution while preserving long-range order for discrete anisotropic distribution. We apply extensive Monte Carlo simulations to study phase transitions in the three-dimensional RAM with three-component (Heisenberg) order parameter and consider two different random anisotropy axis distributions for two different values of local anisotropy strength. For the case of the anisotropic distribution, we have show evidence of universality by finding critical exponents and universal dimensionless ratios independent of the strength of the disorder. In the case of isotropic distribution the situation is very involved: we have found two phase transitions in the magnetization channel which are merging for larger lattices remaining a spin glass phase transition [2].

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Effects of electron density, multiple ionization a photoionization on the ionization equilibrium the kappa-distribution in the solar corona and plasma diagnostics

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The physical conditions in the transition region and solar corona can lead to formation of non-Maxwellian kappa-distributions. The shape of the electron distribution changes individual ionization, recombination, as well as collisional excitation rates, and consequently line intensities. This allow us to diagnose non-Maxwellian distributions from spectral observations. Ionization equilibrium in the coronal conditions with low electron densities is usually approximated to be independent of electron density, as it is assumed that the ionization and recombination from the ground levels dominate. However, the metastable levels can have significant populations, leading to density-dependent effects in ionization equilibrium. Similarly, electron impact multiple ionization is commonly neglected, which again is not necessarily true for distribution with the enhanced high-energy tail. We analyzed how these effects affect the ionization equilibria for kappa-distributions. We have found that density effects on the ionization equilibrium are lower for the kappa-distributions with low kappa then for the Maxwellian one. The photoionization behaves similarly with kappa. The increase of the ionization rates for the strongly non-Maxwellian distributions leads to the suppression of the photoionization effects. Reversely, effect of double ionization on the ionization equilibrium is stronger for low values of kappa. However, density dependent dielectronic recombination shifts the ionization peaks to lower temperature similarly for the all of kappa and Maxwellian distributions. These improvements were included into the new version of KAPPA package (software and database) providing fast calculations of synthetic spectra for kappa-distributions for different kappa > 1.7, temperatures, and electron densities. Synthetic spectra calculate with improved KAPPA package enable us to diagnose electron distribution from EUV spectra of flares, active regions or quiet Sun.

Phonon modes in disordered systems

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Phonons govern a wide range of phenomena ranging from phase change to mechanical behavior and heat transport. They are characterized by the normal modes of vibrations, which are non-interacting collective excitations of atomic vibrations. Phonon modes and the corresponding dispersion relationships are typically evaluated by solving the dynamical matrix. This approach fails for disordered solids when there is a complete breakdown of translational symmetry even when there are well-identifiable dispersion relationships for such systems (from the density or longitudinal current fluctuations). In this work, we propose a new approach that makes use of the spatial Fourier component of the particle current to obtain the dispersion relationship without directly working with the dynamical matrix. First, we demonstrate that by Taylor expanding the particle current with respect to the atomic displacements and without invoking a repeating unit cell, the leading term corresponds to the normal modes of vibration. We then show that the key to extracting the phonon dispersion is to use eigen projections of the atom types in a multi-atom system.

Using atomistic simulations, we verify our approach on simple systems and then compute the dispersion relationships in glassy and radiation-damaged graphite systems. A glassy state is prepared by rapidly quenching a liquid (modeling using a binary Lennard-Jones potential) to low temperatures. The disordered state is confirmed through the radial distribution function and through the lack of long-range order. The radiation-damaged graphite system is prepared through large scale non-equilibrium cascade simulations. The carbon-carbon interaction is modeled using the Tersoff potential, which is additionally stitched with a Ziegler-Biersack-Littmark screened Coulombic potential. After equilibration, a primary knock-on atom that is placed at the center of the simulation box receives excess momentum along a certain specified direction. This initially creates a transient liquid-like state, which condenses to a solid state with a number of quasi-stable atomic scale defects following a ultra-rapid cooldown phase. We apply our methodology to both the glassy and radiation-induced disordered systems and compute their respective phonon dispersion relationships. Finally, we show how our approach can be generalized to extract the dispersion relationships corresponding to all the hydrodynamic variables including density, momentum and energy.

Entropy production rate of a nonlinear hybrid quantum optomechanical system

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We study the irreversible entropy produced in an interacting nonlinear hybrid optomechanical cavity system by stationary-driven dissipation process. The influence of the nonlinearity resulting from the optical parametric oscillators on the entropy production and quantum correlations is scrutinized in detail. We derive the modified entropy production rate of an optical parametric oscillator placed in a cavity modelled by the two-mode Gaussian system. Our findings show a substantial digression in the irreversibility and quantum mutual information for minute detuning. It is further shown that the nonlinearity effect persists for a reasonable range of cavity decay rates. The findings from our study would benefit the current effort toward the optimization of quantum thermal devices and a better understanding of the energetic cost of cooling optomechanical systems.

Evolution in spatially heterogeneous environments

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Resources and dangers are usually not evenly distributed. Thus, environmental interactions are a major factor in determining the success of a new mutant in structured populations. Spatial variations in the concentration of resources locally alter the suitability of competing strategies and can thus drastically alter the outcome of evolutionary processes in unintuitive ways. We discuss the fixation probability and fixation time for a Moran birth-death process as fitness heterogeneity and its pattern vary. Various scenarios of competition between species and also the impact of migration were also examined.

Quantum computational approach based on quantum κ-entropy

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A novel approach to the quantum version of κ-entropy that incorporates it into the conceptual, mathematical and operational framework of Quantum Computation is put forward. Various alternative expressions stemming from its definition emphasizing, computational and algorithmic aspects are worked out. For the case of canonical Gibbs states is first shown that the κ-entropy can be cast in the form of a expectation value for an observable that is determined. Further an operational method named, the two-temperatures protocol, is introduced that provides a way to obtain the κ-entropy in terms of the partition functions of two auxiliary Gibbs states with temperatures κ-shifted above, the hot-system, and κ-shifted below, the cold-system, with respect to the temperature of initial system. That protocol provides physical procedures for evaluating the entropy for any κ and density matrix. Two novel additional ways of expressing the κ-entropy are introduced. Firstly one determined by a non-negativity definite quantum channel, with Kraus like operator sum representation and its extension to a unitary dilation via a qubit ancilla. Secondly one given as simulation of κ-entropy via the quantum circuit of a generalized version of Hadamard test. Next a simple inter-relation of von Neumann entropy and quantum κ-entropy is worked out and a bound of their difference is evaluated and interpreted. Finally the effect on κ-entropy of quantum noise, implemented as a random unitary quantum channel acting in system's density matrix, is addressed and a bound on entropy's value depending on spectral properties of the noisy channel and system's density matrix is evaluated. The results obtained amount to a quantum computational tool-box for κ-entropy that enhances its applicability in practical problems as will be outlined.

Physics-informed neural network (PINN) for solving quantum master equation via Wigner function

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Quantum master equations refer to operator valued equations that describe open quantum systems via the evolution of their density matrix. Standard techniques, usually based on the associated symmetry group of the system, are applied to transform a master equation to a partial differential equation, a Fokker-Planck type equation (FPE), for a quasi-probability function defined on some underlying phase space. Quasi-probability functions, e.g. the Wigner function, the P, Q functions etc, supported by initial, boundary conditions determine the temporal evolution of the quantum system from which statistical predictions are obtained. One the other hand, the so called physics-informed neural networks, PINNs, based on deep learning ideas, is a recent kind of mathematical and computational solution methodology. PINNs are intended for solving various scientific and engineering problems involving ordinary or partial

differential equations. The computational part is based on a developed open source machine learning platform, that includes the scientific software Tensorflow and an application programming interface Keras for deep learning applications. In this work both quantum master problems and PINNs are combined to address the solution of typical master equation problem. Specifically the problem of a single boson mode interacting with a nonlinear Kerr medium yields a third order nonlinear FPE. The equation describes the evolution of Wigner function defined in phase plane with symmetry group the Euclidean group ISO(2) and its algebra of generators i.e. plane translations and rotations. An architecture of the computational model provides two inputs: the time τ and the angle φ variables, hidden layers and one output W, the Wigner function. Providing initial and boundary conditions the unique solution of FPE is obtained everywhere on (τ,φ) domain. A learning is performed through training the PINN in order to fit the FPE, the initial condition (τ=0), the boundary conditions and the normalization integral of Wigner function over the circle at collocation points (training samples). An analysis of numerical results, including a loss function, a choice of a number of hidden layers, neurons, training iterations, samples (collocation points), batch sizes is given. Figures illustrating the evolution of model accuracy, model loss (mean squared error), the output of the neural network and predicted approximate solutions in the discretized domain (τ,φ) are provided. Numerical experiments show that the accuracy of computations mostly depends of the number of training epochs and the number of collocation points. Increase of number of hidden layers and neurons improves the convergence rate, at the cost of rapid increase of computation time. Thus, NN parameters should be chosen carefully to reach desired results. These issues confirm an efficiency of the introduced, PINN-in-quantum-master-equation, methodology.

Relationships between solar wind parameters

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In the inner heliosphere, both source properties at the Sun and in the corona combined with dynamic interactions that occur as the solar wind propagates away from the Sun produce relationships amongst pairs of the solar wind and IMF parameters. The solar wind speed can correlate with the density and temperature because fast wind from coronal holes tends to have lower density and higher temperatures than slow wind associated coronal streamers or the edges of coronal holes. As the Sun rotates, different regions on the surface of the Sun emit wind of different speeds along the same radial line. This results in dynamic interactions developing en route as the wind propagates away from the Sun. For example, a fast wind parcel emitted after a slow wind region along the same radial will eventually run into the slower parcel ahead of it. Where the fast wind runs into the slow wind, a compression region forms that has elevated density, temperature, and field strength. As the solar wind continues to move away from the Sun, the interaction between the fast and slow wind structures causes these structures to merge and be worn down significantly reducing the variability of the wind in the outer heliosphere. In the outer heliosphere as the solar wind encounters an increasing amount of interstellar material the solar wind picks up interstellar material which slows and heats the solar wind. In this study we examine, the relationships between solar wind parameters and how these evolve with distance.

Transfer of quantum states and stationary quantum correlations in hybrid optomechanical network

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The hybrid systems like opto- or spin-mechanical, opto-electromechanical setups, etc., actually become more attractive for their effectiveness and usefulness for a wide range of quantum applications, from gravitational wave detectors to force microscopes, hence they are considered leading candidates for quantum metrology and sensing. In this context, the squeezing of the modes in a hybrid system, and particularly the squeezing transfer between them, is of major importance and applicability. The preparation of the mechanical and light modes in the squeezed states has been widely investigated theoretically, e.g. [1,2], and is nowadays experimentally feasible in versatile hybrid setups, e.g. [3,4]. In this work we study the effects of dynamical transfer and steady-state synchronization of quantum states in a hybrid optomechanical network. As an example of elemental network we consider two cavities with atoms inside and interacting via a common moving mirror, i.e. mechanical oscillator (MO), see Fig.1a. We found that when two external fields independently driving each atom (see Fig.1b), the squeezed and Schrödinger's cat states between the cavities can be transferred with an extremely high fidelity under the unitary dynamics. In this framework one observes dynamical generation and distribution of bipartite and tripartite entanglement. On the other hand, in case of highly dissipative dynamics of the hybrid optomechanical system together with the driving atoms and using a coherent pumping of squeezed phonons/photons in

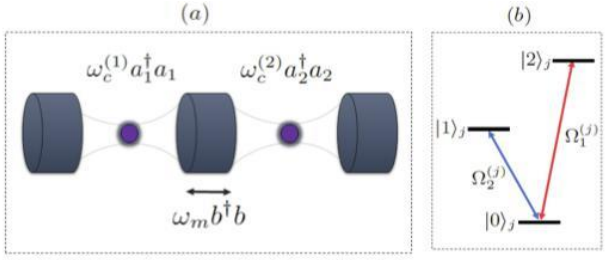

FIG. 1. (a) Schematic diagram of a cavity-atom-mechanics system. (b) Two lasers $\Omega_1^{(j)}$ and $\Omega_2^{(j)}$ are injected in the three-level j-atom, which are resonant with the transitions of the levels $|2\rangle_j \longleftrightarrow |0\rangle_j$ and $|1\rangle_j \longleftrightarrow |0\rangle_j$, respectively.

the initial stage, one can synchronize a pair of bosonic modes in squeezed steady states for the bipartite system as cavity 1 - cavity 2, cavity1 - MO and cavity 2 - MO. The effect of squeezing synchronization of the cavities and mechanical modes can be achieved regardless of the pump mechanism discussed here. When the two bosonic modes are synchronized in a squeezed stationary state, then these modes are also entangled.

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Reconstruction of complex networks dynamics from data: Emergent higher-order interactions and critical phenomena

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Real-world complex systems such as ecological communities and neuron networks are essential to our everyday lives. These systems are composed of units that interact through intricate networks. The ability to predict sudden changes in network behavior (critical transitions) from data is essential to avert disastrous consequences of significant disruptions. Predicting such changes is a major challenge as it requires forecasting the behavior for parameter ranges for which no data on the system is available. We address this issue for networks with weak individual interactions and chaotic local dynamics by introducing a unified reconstruction scheme by blending dynamical systems theory and machine learning tools. Although our approach works perfectly under the given assumptions, the model reconstruction scheme can also surprisingly lead to recovering emergent hypernetworks with triplet and higher interactions among oscillators for slightly different settings. This appears paradoxical at first glance because, initially, such models are defined as oscillator networks with pairwise

interactions. In this work, we uncover a general mechanism for emerging hypernetworks when recovering models of nonlinearly coupled oscillators from data. We present a full description of such emergent hypernetworks using normal form theory and the local tree structure of the original network. Our findings shed light on the apparent abundance of hypernetworks and provide a constructive way to predict their emergence. Using the approach, we can create a proxy of a complex system and thereby make predictions about the critical transitions in the system.

Macroscopic stochastic thermodynamics

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Equilibrium thermodynamics emerges from equilibrium statistical mechanics as the most likely behavior of a system in the macroscopic limit. Over the last two decades, enormous progress has been achieved in formulating statistical mechanics for small systems operating far-from-equilibrium. The resulting theory is called stochastic thermodynamics. I will show that taking the macroscopic limit of stochastic thermodynamics enables to formulate a nonequilibrium thermodynamics of large systems typically described by nonlinear deterministic dynamics, which can also capture macroscopic fluctuations around it [1]. This macroscopic stochastic thermodynamics gives rise to novel fundamental results (for instance, once can bound nonequilibrium steady state fluctuations using the entropy production along deterministic relaxation trajectories [2]) and enables to recover many classical phenomenological results in macroscopic irreversible thermodynamics within well controlled approximations. It also opens the way to study the energetics of many complex nonlinear phenomena in a broad range of systems such as chemical reaction networks (CRNs), nonlinear electrical circuits, and Potts models.

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The effects of defects on mangetization reversal processes

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Defects and impurities strongly affect the timing and the character of the (re)ordering or disordering transitions of thermodynamic systems captured in metastable states. In magnetic systems, the transition driven by an external field usually occurs through the nucleation and the growth of magnetized clusters. Defects act as nucleation centres or pinning sites, respectively accelerating or hampering the passage to equilibrium. We focus on the acceleration effect by analysing the early stages of the magnetization reversal induced by sudden switching on of an external field. We consider the two-dimensional Ising model with quenched randomness, modelled in a new way as spins with a reversal lifetime considerably higher than the time of the experiment. As a result, defects are spins that remain fixed in position and with the same orientation throughout the simulation. We adapt the classical Johnson-Mehl-Avrami-Kolmogorov (JMAK) theory to account for the effects of defects on the free energy barriers, the critical droplet area, and the associated metastable time [1]. By increasing the impurity fraction in the system, both the critical area of the droplet and the free energy barrier decrease. Thus, the reversal process is favored and the metastable lifetime decreases exponentially with the defects fraction. The resulting predictions are successfully tested against Monte-Carlo simulations, performed by adopting the Glauber dynamics, to obtain reliable time-dependent results during the out-of-equilibrium transformations. Eventually, we study the pinning effect of defects during cluster growth by analysing hysteresis loops, focusing on a slow time-dependent magnetic field. We test the hypothesis that defects explain the nature of the Barkhausen noise by reproducing, with our simulations [2], the experimentally observed power law [3] in the

probability distribution of the amplitude of the magnetization jumps. The effects of temperature and fraction of defects in the system are analyzed and quantified.

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High-dimensional central limit theorem by Stein's method

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High-dimensional central limit theorem has attracted much attention both in theory and applications since the work of Chernozhukov et al. (2013, 2017). They proved that, under mild regularity assumptions, Gaussian approximation in multivariate Kolmogorov distance is valid even when the dimension d is much larger than the sample size n. Such results are crucial in high-dimensional statistical inference (Belloni et al. (2018)). The currently best known convergence rate is n subject to logarithmic terms on dimension d. It has been an open problem whether this rate can be improved. In this talk, we will introduce recent progress (Fang and Koike (2021, 2022)) in improving the convergence rate to the optimal one, namely, $n^{-1/2}$. In particular, for sums of independent and identically distributed (i.i.d.) random vectors, we obtain the optimal convergence rate assuming the correlation matrix has off-diagonal entries bounded away from 1. For sums of i.i.d. log-concave random vectors, we obtain the optimal convergence rate without any assumption on the covariance matrix. To prove our main results, we use the approach of Götze (1991) in Stein's method, together with modifications of an estimate of Anderson, Hall and Titterington (1998) and a smoothing inequality of Bhattacharya and Rao (1976).

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Temperature distribution in finite systems: Application to the one-dimensional Ising chain

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The interactions of small systems with a finite environment in thermodynamics, display an interesting statistical behavior, similar to complex non-equilibrium systems and recently gained relevance for technological applications. In the case of a small system with a finite environment, unlike standard thermodynamic treatment of systems, the subsystem presents energy fluctuations and temperature uncertainty. Conceptually, the idea of uncertainty is often confused with that of fluctuations, the latter being usually related to systems that present a particular dynamics, on the other hand, uncertainty appears in both static and dynamical models of systems. Moreover, in theories

such as superstatistics, there are cases in which the uncertainty in the inverse temperature β cannot be understood as fluctuations of an observable quantity, but instead can only be treated as lack of information about an unknown, constant parameter to be inferred. In the literature, the study of small systems with finite environment has been pursued by several authors either using the traditional techniques from statistical mechanics, or proposing suitable generalizations of Boltzmann-Gibbs statistical mechanics. A particularly interesting way to treat these types of systems is by means of the theory of superstatistics, that generalizes Boltzmann-Gibbs statistical mechanics and aims to explain the statistics of different types of complex systems, such as plasmas and self-gravitating systems. Only lately, some applications to the thermodynamics of small systems characterized by short-range interactions have been presented.

Accordingly, in this work we propose to use the properties of the ensemble and the microcanonical inverse temperatures to explore and study the necessary conditions for superstatistics in the context of small systems. As a particular case, we describe the behavior of a one-dimensional Ising subsystem as a part of an isolated Ising chain, as recently reported. Under the constraints that the superstatistical theory imposes on the two temperature functions, ensemble and microcanonical, we show that the non-canonical distribution that describes the Ising subsystem is not consistent with this theory, despite having temperature uncertainty. Our results hint at a new framework for dealing with regions of microcanonical systems with positive heat capacity, which should be described by some new class of statistical ensembles outside superstatistics but still preserving the notion of temperature uncertainty.

Ensemble self-reinforcement and strong memory effects for the anomalous transport of heterogeneous populations

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We present a random walk model that incorporates random transition probabilities among a heterogeneous population of random walkers, resulting in an effectively self-reinforcing random walk. The heterogeneity of the population leads to conditional transition probabilities that increase with the number of steps taken previously (self-reinforcement). We establish the connection between random walks with a heterogeneous ensemble and those with strong memory where the transition probability depends on the entire history of steps. We employ subordination, utilizing the fractional Poisson process to count the number of steps at a given time and the discrete random walk with self-reinforcement to determine the ensemble-averaged solution of the fractional master equation. We also find the exact solution for the variance which exhibits superdiffusion even as the fractional exponent tends to 1. We discuss the applications of this random walk model for intracellular transport and stochastic endocytosis. Given that a heterogeneous population of random walkers emulates strong memory, this opens another avenue for modeling biological processes that display strong memory properties and yet are heterogeneous ensembles of inanimate objects, such as organelles and macromolecules. Might it be that nature has developed a mechanism such as an ensemble self-reinforcement that we demonstrate in this work as a proxy for strong memory? Such questions have plagued the field of intracellular transport for decades where brainless membrane-bound vesicles seemingly engage in random walks that appear to have correlations caused by strong memory effects. Our finding also fits nicely with the emerging theory that, in biological processes, the first arrival times of a signal to a cell (or neuron) influence the subsequent system behavior far more than the average arrival times. With ensemble self-reinforcement, the cell can organize the movement of these particles such that it maintains the

efficiency of transport and overcomes the trapping that occurs in the crowded cytoplasm. We hypothesize that ensemble self-reinforcement is a way that the cell efficiently transports vesicles in a heavily crowded intracellular environment, which has been shown to be subdiffusive. Moreover, this provides another mechanism through which seemingly unintelligent systems can exhibit strong memory.

This is joint work with Dr. Daniel Han of Laboratory of Molecular Biology, Cambridge, United Kingdom.

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Analytical extension/force curve of the freely jointed chain (FJC) and the discrete wormlike chain model (DWLC) with extensible bonds

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We calculate analytically the extension under a stretching force of a polymer modeled as a freely jointed chain (FJC) with extensible bonds, the latter modeled as harmonic springs. We obtain an approximated formula for the extension/force curve that can reproduce with high precision the chain elongation. More complicated is the wormlike chain model, where a Transfer Matrix procedure allowed to calculate numerically the extension/force curve of the polymer in the presence of two elastic contributions: the longitudinal harmonic bonds giving the extensibility and the bending recoil between two consecutive bonds. Also, an analytical approximation has been calculated from the exact partition function, that results in the most accurate formulas for the semiflexible polymers at the date. In both EFJC and EDWLC models, the curves obtained have been double checked by means of numerical experiments provided by Langevin simulations. The analytical expressions revealed an excellent agreement with the numerical outcomes, also at low values of the elastic parameters where previous phenomenological proposals differ substantially.

Dynamical theory of spin noise and relaxation - Beyond the Lorentzian

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Recent developments in spin noise and relaxation and their interrelationship in terms of a modified spin density (MSD) have focused on the case of extreme narrowing where the timescale of the field fluctuations that give rise to the spin process are negligibly small. It is customary in this case to model the random magnetic field as a(n) (isotropic) white noise process and thereby formulate a stochastic differential / Langevin type equation for the spin ensemble. It is notable in this case that the usual perturbation treatment becomes exact since the perturbation expansion truncates at second order, a characteristic familiar feature of the Wiener process, which has finite quadratic variation but whose higher order infinitesimal moments vanish. In terms of the field spectrum the Larmor frequency plays no essential role here, since such a flat spectrum is invariant to frequency shifts. Of much greater experimental relevance is the non-extreme narrowed case where the field fluctuations have a finite auto-correlation time and a corresponding power spectrum with finite bandwidth. In such

cases the Larmor frequency plays a special role in terms of its situation within this narrowed spectrum. Provided the strength of the fluctuations is small it is possible to formulate the spin dynamics (perturbatively) while retaining the full spectral character of the random field - more recently a non-perturbative treatment has also been possible. This is achieved through the description of the field in terms of an (3-dimensional) Ornstein-Uhlenbeck process, consistent (via Doob's theorem) with the requirements that the process be Gaussian, Markov and stationary. The result is significant in that it predicts a non-Lorentzian spectrum - it is interesting therefore both theoretically and experimentally. In turn we derive a spin noise / relaxation process that inherits spectral features from both the amplitude and frequency characteristics of the driving random magnetic field. The intimate connections that exist between spin noise and relaxation in the extreme narrowed case persist in this more general context, whereby standard relaxation emerges as the ensemble average of spin noise, the latter being essential to describe non-ensemble averaged (real time) properties of spin systems.

Thermalization universality classes for weakly nonintegrable many-body dynamics

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We observe different universality classes in the slowing down of thermalization of many-body dynamical systems upon approaching integrable limits. We identify two fundamentally distinct long-range and short-range classes which stem from the type of nonintegrable perturbations - weak two-body interactions (nonlinearities) versus weak lattice coupling (hopping) [1,2,3]. We study the scaling properties of the full Lyapunov spectrum [4,5]. The long-range class results in a single parameter scaling of the Lyapunov spectrum, with the inverse largest Lyapunov exponent being the only diverging time control parameter and the rescaled spectrum approaching an analytical function [4]. The short-range class results in a dramatic slowing down of thermalization and a rescaled Lyapunov spectrum approaching a non-analytic function. An additional diverging length scale controls the exponential suppression of all Lyapunov exponents relative to the largest one [4].

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Solar flare science with microwave imaging spectroscopy

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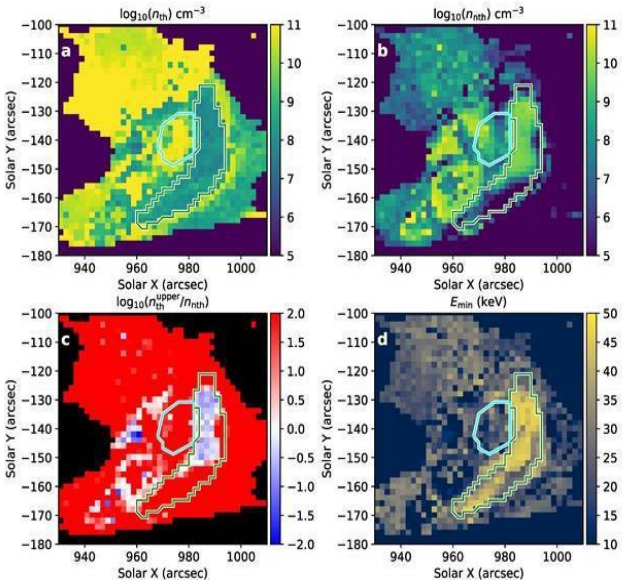
Release of magnetic energy due to reconnection is believed to drive such transient phenomena as solar flares, eruptions, and jets. This energy release should be associated with a decrease of the coronal magnetic field. Quantitative measurements of the evolving magnetic field strength in the corona are required to find out where exactly and with what rate this decrease takes place. The only available methodology capable of providing such measurements employs microwave imaging spectroscopy of gyrosynchrotron emission from nonthermal electrons accelerated in flares. Here, we report microwave observations of a solar flare, showing spatial and temporal changes in the coronal

magnetic field at the cusp region; well below the nominal reconnection X point. The field decays at a rate of ~5 Gauss per second for 2 minutes. This fast rate of decay implies a highly enhanced, turbulent magnetic diffusivity and sufficiently strong electric field to account for the particle acceleration that produces the microwave emission. Moreover, spatially resolved maps of the nonthermal and thermal electron densities derived from the same microwave spectroscopy data set allow us to detect the very acceleration site located within the cusp region. The nonthermal number density is extremely high, while the thermal one is undetectably low in this region indicative of a bulk acceleration process exactly where the magnetic field displays the fast decay. The decrease in stored magnetic energy is sufficient to power the solar flare, including the associated eruption, particle acceleration, and plasma heating. These findings are published in Science (2020) and Nature (2022) papers.



Formation and 3D dynamics of replication factories

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A key stage of the cell life is the S-phase, when DNA is replicated. It is now well established that replication of chromosomes begins with the assembly of multi-protein machines, the replisomes, at specific chromatin sites known as replication origins. The 3D dynamics of replisomes during the S-phase is not completely understood yet. Microscopy experiments showed how replisomes tend to form clusters, often called replication factories, which increase in size and decrease in number during the replication process [1,2].

Here I will present recent Molecular Dynamics simulations of a polymer model developed to understand the dynamics of replication factories and the underlying mechanisms leading to their formation and growth. We discovered a new growth pathway involving the formation of long-range chromatin loops which was not predicted by previous experiments. Moreover, a statistical mechanics calculation explains the importance of attractive interactions between replisomes and the whole chromatin fibre, not only replication origins, in order to observe the aggregation of replisomes and the formation of replication factories.

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Nonlinear response in dilute colloidal suspensions beyond the fluctuation-dissipation theorem

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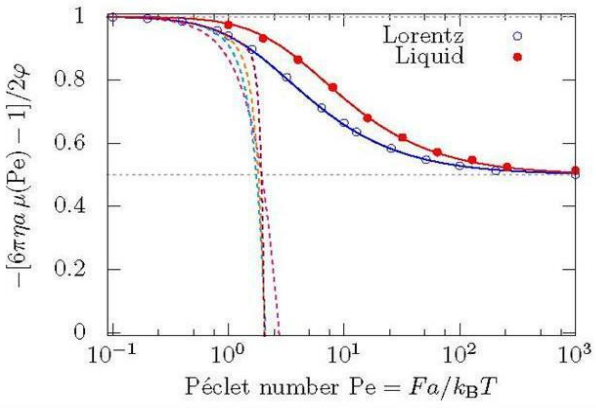
In a microrheological experiment the thermal or forced motion of a colloidal particle is monitored to obtain information on mechanical properties of the surroundings [1]. While the linear response is well-characterized in terms of the fluctuation-dissipation theorem, few exact results are available for strong driving. Here, we consider the time-dependent velocity v(t, F) of a colloidal particle immersed in a dilute suspension of hard spheres in response to switching on a finite constant force F at time zero. The dimensionless number quantifying the strength of the driving is the Peclet number Pe = F a/kB T, where a denotes the radius of the hard spheres. Our main quantities of interest are the time-dependent mobility μ(t,Pe) = v(t,Pe)/F and its approach to the stationary state mobility μ(Pe)=μ(t -> ∞, Pe). A stationary state solution for the mobility exact in first order of the packing fraction ϕ has been established earlier in terms of a power-series expansion [2]:

$$6\pi\eta a\,\mu(\mathrm{Pe}) = 1 - 2\phi\,[1 - \mathrm{Pe}^{2/30} + |\mathrm{Pe}|^{3/64} + O(\mathrm{Pe}^4)],$$

where η denotes the shear viscosity. Here, we extend this results to the case of arbitrarily strong driving including the complete time-dependence of the response upon switching on the force [3]. In the stationary state, our analytic solution recovers the anticipated limit for strong driving (see figure) 6πηa μ(Pe) = 1-ϕ and captures the nonlinear response in first order of the packing fraction for any strength of the force. The time-dependent drift velocity approaches its stationary-state value exponentially fast for arbitrarily small driving in striking contrast to the power-law prediction of linear response encoded in the long-time tails of the velocity autocorrelation function. We show that the stationary-state behavior depends nonanalytically on the driving force and connect this behavior to the persistent correlations in the equilibrium state. We argue that this relation holds generically. Furthermore, we elaborate that the fluctuations in the direction of the force display transient superdiffusive behavior.



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The entropy production rate of active matter systems

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The entropy production rate (EPR) quantifies a distance from equilibrium. It is quite a relevant concept for active particle systems which take up and dissipate energy, the process which takes the system out-of-equilibrium. We consider canonical theoretical models of non-interactive active particles. Our aim is to provide an intuitive formulation and interpretation of the concept of EPR. Based on the connection between the EPR and the dissipation of energy, we obtain several alternative formulations of EPR. For certain simple situations, such as particles confined in a harmonic trap and particles between rigid walls, we obtain exact results which provide a straightforward understanding and interpretation of emerging behaviors. In addition, we discuss the role of inertia in formulating the EPR and emphasize that a complete theoretical framework must incorporate inertia if correct limiting behaviors are to be recovered. Lastly, we point out certain circumstances where the definition of the EPR becomes ambiguous.

Can memory hysteresis in a neural network judge the continuity/discontinuity of a phase transition?

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The application of machine learning (ML) has been extended quite rapidly over many disciplines [1] and is also pervasive for solving problems in a wide area of physics. Detecting a phase transition using ML is an intriguing trial [2]. The success prompted us to apply the nonequilibrium relaxation idea to the problem to show that phase-transition detection could be finished early in the learning processes [3]. These works utilized that the sum of the weights between neurons in a convolutional neural network (CNN) behaves like an order parameter. Here, we focus on not detection but judging the (dis)continuity of a phase transition as another application of ML. The following memory hysteresis experienced in everyday life inspired us to undertake the present investigation. When we watch a series of continuously varying pictures, we recognize that the point at which the picture undoubtedly changes differs if we see the sequence in reverse order. The degree of this hysteresis depends on the degree of continuity; the better the continuity, the more significant the hysteresis. If there is a sudden change in the series, we may recognize the point uniquely regardless of the direction of variation. Because a CNN is implemented to mimic the functionality of a biological neural network, the degree of (dis)continuity would be reflected in the hysteretic behavior of the weights in a CNN in back-and-forth learning processes, i.e., when a CNN learns the phase-transition patterns in increasing (decreasing) order of the labels. We employed the two-dimensional Ising and q-state Potts (q=3 through 6) models. Equilibrium spin configurations above and below the critical temperature were generated as a function of the external field for the Ising model; those at various temperatures around the critical point were prepared for the Potts model. The external field and temperature constitute the labels. We let our CNN [4] learn the difference between the configurations with adjacent labels sequentially in increasing order (forward learning) and then decreasing order (backward learning) of the labels. The Potts' order was simplified in some way for CNN to capture the difference quickly. We monitored the weights connected to the output layer in forward and backward learning. The memory hysteresis, i.e., hysteresis in the CNN's weights, in back-and-forth learning appeared for the Ising crossover transition and the transitions of the Potts model with q=3, 4. No hysteresis was recognized for the Ising transition below the critical point and the transition of the q=6 Potts model. Interestingly, the weights behaved marginally for a weak first-order transition in the q=5 Potts model. The (dis)continuity of a phase transition could thus be adequately judged by the aspect of memory hysteresis of a CNN through sequential learning of the differences in the patterns around the transition point.

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A new universal dynamics preceding the early stage of spinodal decomposition

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The theory of spinodal decomposition has been developed in the '60s through '70s. The concept of spinodal was then reexamined for an Ising system [1]. However, no explicit discussion has been given to a fluid system, which is believed to belong to the same universality class. Ushcats has suggested [2], extending the equation of state beyond the thermodynamically stable region, that the spinodal line of the modified Lennard-Jones (mLJ) system [3] approaches the liquid–gas coexistence (binodal) line. Our prediction based on the coarse-graining limit for the coarse-grained free energy, estimated using the block spin coarsening technique, supports Ushcats' conjecture [4]. This finding suggests that a system's dynamics can also depend on a coarsening level. We conducted isothermal–isobaric molecular dynamics simulations for an mLJ system consisting of 4×10^6 particles to examine the dynamical liquid–

gas phase separation process. Length, time, and temperature are expressed in units of mLJ parameters. The critical temperature, pressure, and density of the mLJ system are Tc = 1.0762(2), pc = 0.09394(17), and ρc = 0.331(3), respectively [5]. We treated two systems with different densities: 0.02 and ρc. The fluid system well-equilibrated at 20Tc was instantaneously brought to 0.7Tc for phase separation. The lower- and critical-density systems were expected to be quenched in the metastable and unstable regions, respectively, judging from the shape of the coarse-grained free energy. The term "local density" has often been used in mesoscopic descriptions. However, it has been far unclear what is meant by "local." In this case, we can define the local density unambiguously using the length L, the coarse-graining scale based on which the coarse-grained free energy was described [4]. Based on this well-defined "local" density and its fluctuations around the average density, we defined the structure factor S and examined its time evolution after the quench. On the short-time side (t < 2), L predominantly determines the peak position of S, whereas the peak position approaches the value determined by the average density on the long-time side (t > 2). To examine in detail the L-dependence of the wavelength at which structural destabilization occurs, S was scaled by its peak position and height. The dynamical process in another state, obtained by quenching the critical-density system to 0.97Tc, was also examined. We could identify in the short-time region the new universal process, in which phase separation proceeds in a statistically self-similar fashion irrespective of the average density, quenching temperature, and coarsening length. We speculate that such a "super-early" stage precedes the early stage covered by the linear theories.

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Strong, weak or no balance? Testing structural hypotheses against real networks

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The abundance of data about social, economic and political relationships has opened an era in which social theories can be tested against empirical evidence, allowing human behaviour to be analyzed just as any other natural phenomenon. The present contribution focuses on balance theory, stating that social actors tend to avoid establishing `frustrated' network configurations where positive (friendly) and negative (hostile) interactions conflict with each other [1,2]. To make this theory testable, one needs 1) a proper representation of social networks, 2) a definition of frustrated configurations and 3) a set of null models with respect to which the amount of frustration in a given, real network can be checked for statistical significance. The first two ingredients have been already explored comprehensively: social interactions can be represented via signed graphs (where edges can be positive, negative or absent) and frustrated configurations are defined (in strong form) as having cycles with an odd number of negative links (although a weaker definition exists as well). The third ingredient, however, is way less developed in current research, since the existing null models cannot take into account the heterogeneity of individual actors, i.e. their different tendencies to establish positive and negative interactions. To reduce this gap, we extend the Exponential Random Graphs framework to binary, undirected, signed networks with both global constraints (overall numbers of positive, negative and missing links) and local constraints (node-specific numbers of positive and negative links). Moreover, we define two variants for each benchmark: one where the topology is kept fixed and one where it is left to vary along with the edge signs. When applied to real networks, the new null models show that the level of frustration crucially depends on (at least) three factors: 1) the nature of the data (e.g. biological VS socio-political networks),

2) the measure adopted to quantify balance (e.g. weak VS strong form), 3) the null model employed for the analysis (e.g. homogeneous VS heterogeneous, fixed VS varying topology). As the attached figure shows, the analysis of triangles reveals that homogeneous null models with global constraints (e.g. the Signed Random Graph Model, SRGM) tend to favour the weak version of balance theory, according to which only the triangle with one negative link (depicted in green) should be under-represented in real, social and political networks (as a comparison, biological networks are instead found to be significantly frustrated). On the other hand, heterogeneous null models with local constraints (e.g. the Signed Configuration Model, SCM) tend to favour the strong version of balance theory, according to which also the triangle with all negative links (in purple) should be under-represented in real, social networks (again, biological networks behave differently).

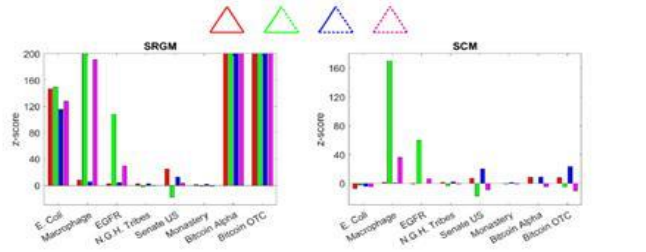

FIG. 1: z-scores of triadic motifs for three biological networks (*E. Coli, Macrophage, EGFR*) and three social and political networks (*N.G.H. Tribes, Senate US, Monastery*). While homogeneous null models (SRGM, left panel) support weak balance theory on social and political networks, heterogeneous ones (SCM, right panel) tend to favour strong balance theory. As a comparison, biological networks show a different behaviour.

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Shear viscosity of granular mixtures: Assessment of kinetic theories

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The determination of the transport coefficients of granular mixtures (namely, mixtures constituted by smooth hard spheres of different masses, diameters, and coefficients of restitution) is still a challenging target. This is due not only to the large number of parameters involved in the description of the system but also by the array of intricacies and uncontrolled approximations needed to achieve explicit results. Due to the above difficulties, most of the previous attempts for computing transport in polydisperse granular systems were restricted to nearly elastic spheres. In this limiting situation, the partial temperatures of each species (measuring their mean kinetic energies) were assumed to be equal to the global granular temperature. On the other hand, the departure of energy equipartition increases with increasing inelasticity and hence, some recent kinetic theories [1] have taken into account not only the breakdown of kinetic energy in granular mixtures but also its impact on the transport properties.

In this talk, I consider two different kinetic theories for determining the shear viscosity for moderately dense granular mixtures. These theories have been independently proposed by Solsvik and Manger [1] (hereafter referred to as the SM-theory) and by Garzó, Dufty and Hrenya [2] (hereafter referred to as the GDH-theory). The set of Enskog kinetic equations is the starting point to obtain the shear viscosity in terms of the parameters of the mixture. While the SM-theory [3] assumes that the distribution functions of each species are Maxwellian distributions defined at the partial temperatures, the GDH-theory solves the Enskog equation by means of the Chapman-Enskog method conveniently adapted to account for the inelastic character of collisions. To assess the reliability of both theories, the Enskog equation for granular mixtures is numerically solved by means of the direct simulation Monte Carlo method. The mixture is assumed to be under simple shear flow and driven by the action of an external force that exactly compensates the energy dissipated by collisions. Under these conditions, the system achieves a linear hydrodynamic regime where the Navier-Stokes shear viscosity can be identified and measured in the simulations. The results clearly show that the GDH-theory compares with simulations much better than the SM-theory over a wide range of values of the coefficients of restitution, the volume fraction, and the parameters of the mixture (masses, diameters, and concentration).

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Musicians' Synchronization and the Mystery of Swing in Jazz

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It is a widespread opinion that musicians who are interacting together in a performance should perfectly synchronize their timing. This view was challenged for the swing feel, a salient feature of jazz, which has eluded scientific clarification for a century. For much of this period it was considered arcane, arguing that swing can be felt but not explained, until the theory of 'participatory discrepancies' raised the controversial claim that swing is caused by microtiming deviations between different participating musicians [1] and put a question mark on the synchronization of jazz musicians.

In several projects we have clarified the controversy on the central role of microtiming deviations for the swing feel using data analytics [2] and experiments [3,4] in which we manipulated the timing of different instruments and measured the resulting swing feel through ratings of professional jazz musicians. We thereby showed that involuntary random microtiming deviations are irrelevant for swing [3], but found that a particular systematic microtiming deviation between musicians enhances the swing feel and is a key component of swing in jazz [4]. It consists in phase shifts, where downbeats of soloists are slightly delayed with respect to a rhythm section, but offbeats remain strictly in phase.

This effect was unknown to professional jazz musicians, who were able to perceive the differences, but unable to determine their nature. Thus musicians apparently use the effect intuitively and unconsciously, as our data analysis of 456 renowned jazz solos revealed the use of downbeat delays in almost all cases [4].

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A machine learning approach for strong aftershock forecasting by the NESTORE algorithm. Comparison of California, Italy and Greece results

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It is well known that large earthquakes are often followed by aftershocks that can affect numerous structures in cities and exacerbate the damage caused by the initial quake. In particular, the ground motion produced by strong aftershocks can cause further building collapses and fatalities. To forecast the occurrence of these subsequent large earthquakes (SLEs), we proposed a pattern recognition approach based on seismological features. The method, called NESTORE, has been successfully applied in northeastern Italy and western Slovenia (Gentili and Di Giovambattista, 2020), in all of Italy (Gentili and Di Giovambattista, 2017), in California (Gentili and Di Giovambattista, 2022), and in Greece (Gentili et al., 2023). The NESTORE algorithm has recently been optimized and made available in the form of a software called

NESTOREv1.0. This software (Gentili et al., 2023), written in MATLAB, uses a machine learning approach to produce a probabilistic forecast of clusters in which a strong mainshock is followed by at least one subsequent earthquake of comparable magnitude. In particular, the algorithm distinguishes between clusters in which the magnitude difference between the mainshock and the strongest aftershock is less than or equal to 1 (type A), and other cases (type B). NESTOREv1.0 is trained to distinguish between the two classes using cluster seismicity parameters (features) in a training dataset. Specifically, NESTOREv1.0 trains one-node decision trees on individual features at increasing time intervals, selects the best classifiers, and merges the resulting classifications using a Bayesian method. It is then able to produce type A cluster forecasting for both retrospective analyzes on a test database and for ongoing clusters. Supervised training allows NESTOREv1.0 to adapt to the region under study. On the other hand, the classification structure based on single-layer decision trees allows the definition and comparison of thresholds identified in different regions to infer the characteristics of their seismicity. In this work, we compare the results obtained in Greece, Italy and California. In particular, both the performances on an independent test set and the characteristics of seismicity found by using all available data are shown.

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On hierarchies of evolution equations for correlations of many quantum particles

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In the talk, we discuss an approach to describing the correlations in a system of many quantum particles based on the hierarchy of evolution equations for the sequence of correlation operators which are cumulants of density operators (the von Neumann hierarchy). It is established that the constructed dynamics of correlations underlies the description of the dynamics of both finitely and infinitely many quantum particles governed by the BBGKY hierarchies for reduced density operators or reduced correlation operators. The structure of expansions by which are represented non-perturbative solutions of the Cauchy problem to these hierarchies of evolution equations is established. Moreover, the problem of the rigorous description of the collective behavior of many-particle quantum systems by means of a one-particle correlation operator governed of the generalized quantum kinetic equation with initial correlations, in particular, correlations characterizing the condensed states is considered.

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Fluctuations of CO2 concentration inside a mofette long-term, high-frequency monitoring and a simple model.

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Our study investigates experimentally and theoretically the fluctuation of carbon dioxide (CO2) concentration and emission in a mofette located in Covasna city (Romania), On the experimental side, data over a period of 7 months were collected, measuring CO2 concentration at different depths, pressure, and temperature inside the mofette with a time resolution of 1 second. For the measurement of the CO2 concentration and temperature, we used 20 vertically placed STC31 sensors with a 5cm spacing. The atmospheric pressure was monitored at one point located at a depth of 1.2m from the bottom of the mofette using a BMP280 sensor. The

data is publicly available and the measured values can be consulted in real-time at the web-site dedicated to this study [http://comodi.phys.ubbcluj.ro:8087/].

Using the collected concentration data and the classical convection-diffusion equation, we estimated the CO2 flow yield. The power-spectra of the fluctuation for this flow yield shows clearly distinguishable scaling regimes. We also found correlations between the flow yield and various environmental parameters (pressure and temperature), aspects that motivated a simple theoretical model. Our model consists of a grid of chambers connected by tubes, each chamber supplied with a constant CO2 flow yield. The flow between the chambers is assumed to be proportional to their pressure difference, while the resistance between the chambers depends on the temperature. One of the chambers is connected to the atmosphere through a tube, therefore it is directly influenced by the external pressure. Using such a connected chamber ensemble, we predicted the flow yield numerically by a 4th order Runge-Kutta method. The model is characterized by some unknown physical parameters. In order to determine their optimal values, we minimized the average of the squared differences between the measured and predicted flow yields. To account also for a possible change in the system parameters over time, we divided our dataset into 14 equal parts and optimized the model parameters for each interval separately. Using the best fit parameters, the model predicts accurately the measured flow yield both in time, generating a statistically correct power-spectra in the low frequency limit.

Overall, our study provides experimental and theoretical insight into the CO2 emission in a mofette and proves the existence of correlations between the flow yield and environmental parameters. Potential applications are diverse ranging from environmental science to earth- and medical sciences. As an immediate example we recall that mofettes are widely used in medical treatment in some circulatory disease. Understanding the dynamics and predictability of CO2 emission is crucial for ensuring patient safety. Sudden jumps in CO2 flow yield can pose a significant risk to patients, therefore the ability to anticipate and respond to large fluctuations in emission levels should be critical in the medical use of mofettes. Our original experimental apparatus can provide solution for such demands as well.

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Direct nuclear cross section measures at Big Bang energies and the cosmological lithium problem

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The direct cross sections of four nuclear reactions of relevant interest for the two cosmological lithium problems at Big Bang Nucleosynthesis are presented and discussed. Two reactions have been measured at high precsion and down to energy never reach before at LUNA Underground Laboratories: 2H(α,γ)6Li and 3He(α,γ)7Li . Two neutron induced reactions, 7Be(n,p)7Li and 7Be(n, α γ), have been studied at EAR2 experimental area of n_TOF facility at CERN. There is no sign that 7Be, parent nucleus of 7Li, could be affected by a sensible production rate decrement by much smaller values of 3He(α, γ)7Be cross sections and/or an increase of its destruction rate by unknown or poorly measured resonance in 7Be(n, α γ) reaction, in order to match the standard Big Bang Nucleosynthesis predictions. 2He(α, γ)6Li latest data carries in only a slight corrections in the 6Li abundance (second lithium problem) and in the wrong side too. From the obtained results nuclear physics solutions of both lithium problems have been pinned down, leaving all the alternative physics scenario still open, with the strict constraints that deuterium and 4 He cosmological abundance must remain unperturbed.

Human health risk estimation from indoor radon measurements

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The indoor radon concentration level have been monitored in selected locations of four European countries (Iceland, Italy, Norway and Sweeden) during an yearlong measurement campaign using time integrated passive radon dosimeters containing CR-39 track detectors. The measurements were carried out in private houses and public buildings like schools for an exposure time of up to 6 months of each detector. Experimental data show a great variation between different geographic areas, and often the average levels is over the acceptable radon limit of 300 Bq/m3 recommended by International Commission on Radiological Protection (ICRP). To investigate a relationship between indoor radon exposure and lung cancer, estimating cumulative levels of exposure to indoor radon for an individual or population is necessary. We analyze the datasets and investigate the factors influencing indoor radon concentrations in order to determine the optimum use of the experimental information: the results show that the variables associated with indoor radon levels were strictly linked to the soil geology. Analyzing the datasets enables improved assessment of radon exposure in a given area. The average absorption effective dose equivalent for a person is computed and the risk of lung cancer per year is evaluated.

Anomalous relaxation of a Brownian particle in active baths

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We investigate a Brownian particle confined in an active heat bath and report on the non-monotonic cooling behavior while the system approaches the final steady state. This effect is especially pronounced as the correlation time of the active noise, associated with the random kicks by the active particles, becomes longer compared to the relaxation time of the damped harmonic oscillator in an otherwise thermal bath. Introducing the effective temperature scheme, where the fluctuation-to-dissipation ratio is the proxy for nonequilibrium temperature, we analyze the anomalous relaxation process in the light of stochastic thermodynamics.

Coupled dynamical phase transitions in driven disk packings

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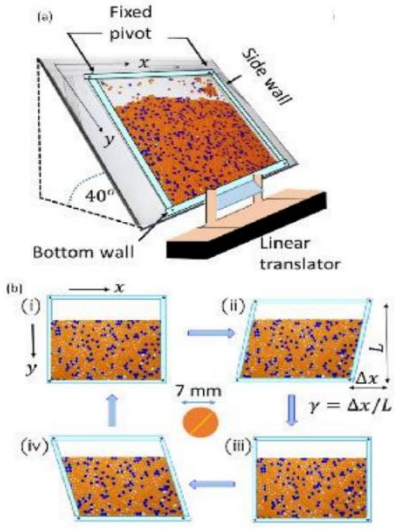
Active-absorbing phase transition has been studied in variety of models and experimentally in a system of colloids suspended in viscous medium. The transition is characterized by a critical point where long range correlations are manifested. Beyond the critical point, the system usually remains dynamic whereas below the transition, the dynamics ceases. Cessation of dynamics typically occurs when the system achieves some local goal, such as being non-overlapping or having no near neighbor. Order parameter of this transition is the fraction of particles which are active(α) between two consecutive cycles. On one side of the transition α=0, (absorbing state) whereas on the other side,

α>0 (active state). In our experiment, a two dimensional assembly of monodisperse particles driven by oscillatory shear, manifests the active absorbing transition. The entire assembly is kept at an angle with respect to the gravity to ensure that the constitutive relation of stress and strain holds true. When analyzed stroboscopically, it is observed that below a critical shear amplitude (γ_c), all the disks come to its previous position(within some error bars), whereas above the transition they don't. Trajectories of the particles also become interesting in the absorbing state as they tend to follow some non-trivial loops breaking time reversal symmetry. Number of cycles required for the system to reach the steady state follows power law with divergence at γ=γ_c. Observation of such a transition in granular systems is non-intuitive in a sense that unlike the suspension of colloidal particles, granular interactions involve dry friction and also it's impossible to avoid collisions among the particles for the system to reach the quiescent state. Since the particles are of similar size, it is expected of them to form a single crystalline state in the steady state. But surprisingly, that's not what we observed. For small shear amplitudes, the particles form polycrystalline configurations with defects forming grain boundaries across the system. As the shear amplitude approaches γ_c (≈0.065), number of defects in the system starts to decrease and eventually the entire system forms a single crystalline configuration at γ_c. Isolated clusters of defects again start appearing beyond the critical point. Number of cycles required for the system to reach the state with constant defect density also shows similar power law dependence with maximum shear amplitude.



Hence the two transitions are coupled to each other. Typically, the absorbing states studied theoretically or observed experimentally are disordered and hyperuniform, but our experiment exhibits an ordered crystalline configuration at the critical point. Since the system is kept under gravity, there exists a pressure gradient along the direction of gravity. Therefore, beyond the transition, only a part of the system become active. As we go more and more away from the transition, the length of the active region grows, eventually covering the entire assembly. The length scale of the active region grows linearly with γ .

Renormalization group irreversibility in conformal gravity

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Irreversibility of the renormalization group (RG) implies that ultraviolet (UV) and infrared (IR) fixed points of a consistent Quantum Field Theory (QFT) cannot be arbitrary conformal invariant models but must satisfy specific conditions. These are usually expressed in terms of dimensionless charges associated with the fixed points which monotonically decrease along the RG flow. Although the charges have been identified, leading to C, F, A-theorems in d=2,3,4, the physical interpretation of irreversibility is still elusive. On the other hand, one can wonder whether the number of fields in a weakly-coupled QFT can be non-perturbatively defined as a quantity whose change along RG flow can be studied. A connection between a non-perturbative analogue of the "number of fields" in weakly-coupled theories and the RG charges associated with irreversibility theorems is indeed strongly suggested by the latter's identification with the logarithmic universal coefficient of the Entanglement Entropy (EE) of a sphere. We discuss irreversibility of RG flow in the case of Weyl gravity, for which recently an interesting IR behavior was found using the Functional Renormalization Group approach. In particular, we identify a monotonically decreasing charge and discuss its relation to the degrees of freedom associated with UV and IR fixed points.

Testing the neural network approach in the presence of topological frustration

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In recent years, neural networks are establishing themselves as a very useful research tool in the quantum physics of complex systems. As with all numerical approaches, the accuracy of the results obtained with them depends on the characteristics of the system under analysis. To give an example of this dependence, consider the DMRG, where the accuracy and speed of convergence are strongly influenced by the correlation length of the system and the type of entanglement. In the case of neural networks, due to their relative novelty, it is not yet clear what these characteristics are, nor what their relative weight is. To shed some light on this problem, in the work that I am going to present, we have analyzed the accuracy of the solution provided by a neural network in the context of topologically frustrated one-dimensional systems, and then we have compared it with the results obtained in the absence of frustration. For some years now, topologically frustrated models have been attracting increasing attention. Indeed, despite their apparent simplicity, even in the case of analytically solvable models, topological frustration induces a very complex phenomenology which includes: the existence of incommensurate order parameters; the presence of a specific violation of the area law; the possibility of having mesoscopic chiral phases, etc. This phenomenology is the reflection of the change induced, at the ground-state level, by the presence of topological frustration which can be quantified through the use of various quantum resources such as entanglement, quantum coherence, or the so-called "magic". Therefore, by comparing the accuracies obtained by neural networks in the presence and absence of topological frustration, and comparing them with the changes in the value of different resources, we can analyze the influence that the latter has on the former. Our results show that neither the entanglement nor the magic value is related to the accuracy of a Restricted Boltzmann Machine. These two results are quite surprising for two different reasons. As regards to entanglement, as we have already said, it is well known that its behavior affects the precision of algorithms based on the tensor network technique. In contrast, magic is a measure of complexity. Therefore, both these quantities were the main suspects in influencing the reliability of the solutions obtained with the neural networks. On the contrary, a strong correlation exists between accuracy and quantum coherence. The greater, the latter, the worse the accuracy of the state obtained from a neural network. These results open an important discussion point on systems that can be efficiently analyzed using neural networks and on possible strategies to improve their performance.

TACTICIAN: AI-based applications for knowledge extraction from ESA's missions' scientific publications

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Scientific publications in space science contain valuable and extensive information regarding the links and relationships between the data interpreted by the authors and the associated observational elements (e.g., instruments or experiments names, observing times, etc.). In this reality of scientific information overload, researchers are often overwhelmed by an enormous and continuously growing number of articles to access in their daily activities. The exploration of recent advances concerning specific topics, methods and techniques, the review and evaluation of research proposals and in general any action that requires a cautious and comprehensive assessment of scientific literature has turned into an extremely complex and time-consuming task. The availability of Natural Language Processing (NLP)

tools able to extract information from scientific unstructured textual contents and to turn it into extremely organized and interconnected knowledge, is fundamental in the framework of the use of scientific information. Exploitation of the knowledge that exists in the scientific publications, necessitates state-of-the-art NLP. The semantic interpretation of the scientific texts can support the development of a varied set of applications such as information retrieval from the texts, linking to existing knowledge repositories, topic classification, semi-automatic assessment of publications and research proposals, tracking of scientific and technological advances, scientific intelligence-assisted reporting, review writing, and question answering. The main objectives of TACTICIAN are to introduce Artificial Intelligence (AI) techniques to the textual analysis of the publications of all ESA Space Science missions, to monitor and evaluate the scientific productivity of the science missions, and to integrate the scientific publications' metadata into the ESA Space Science Archive. Through TACTICIAN, we extract lexical, syntactic, and semantic information from the scientific publications by applying NLP and Machine Learning (ML) algorithms and techniques. Utilizing the wealth of publications, we have created valuable scientific language resources, such as labeled datasets and word embeddings, which were used to train Deep Learning models that assist us in most of the language understanding tasks. In the context of TACTICIAN, we have devised methodologies and developed algorithms that can assign scientific publications to the Mars Express, Herschel, and Cluster ESA science missions and identify selected named entities and observations in these scientific publications. These methodologies can be applied to any other mission. The combination of NLP and ML constitutes a general basis, which has proved that it can assist in establishing links between the missions' observations and the scientific publications and to classify them in categories, with high accuracy.

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Current transport properties and phase diagram of a Kitaev chain with long-range pairing

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We describe a method to probe the quantum phase transition between the short-range topological phase and the long-range topological phase in the superconducting Kitaev chain with long-range pairing, both exhibiting subgap modes localized at the edges. The method relies on the effects of the finite mass of the subgap edge modes in the long-range regime (which survives in the thermodynamic limit) on the single-particle scattering coefficients through the chain connected to two normal leads. Specifically, we show that, when the leads are biased at a voltage V with respect to the superconducting chain, the Fano factor is either zero (in the short-range correlated phase) or 2e (in the long-range correlated phase). As a result, we find that the Fano factor works as a directly measurable quantity to probe the quantum phase transition between the two phases. In addition, we note a remarkable "critical fractionalization effect" in the Fano factor, which is exactly equal to e along the quantum critical line. Finally, we note that a dual implementation of our proposed device makes it suitable as a generator of large-distance entangled two-particle states. Throughout our work, we evidence the strict connection between the emergence of a long-range topological phase and the onset of a remarkable nonzero crossed Andreev reflection at the Fermi level. On taking the complementary point of view in which one injects Cooper pairs into the circuit through the central superconducting region, this provides a potential source to generate nonlocal particle-hole highly entangled states, that is, thanks to the CAR our device can stabilize the emission of two correlated particles, one per each lead. For this reason, when working in the long-range regime, our model can be regarded as an efficient generator of pairs of strongly entangled particles, distant in real space. Finally, we consider possible practical realizations of our system with long-range correlations in cold-atom devices, as well as in solid-state platforms.

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On the energization of pickup ions downstream of the heliospheric termination shock, by comparing 0.52-55 keV observed ENA spectra to simulated ENAs inferred by proton hybrid simulations.

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As the solar system and its surrounding heliosphere move through the local interstellar medium (LISM), interstellar neutral (ISN) atoms, mostly atomic hydrogen, enter the heliosphere and undergo charge-exchange collisions with the continuously flowing solar wind (SW) protons. Newly created ions from the ISN population are advected outward with the SW under the force of the V × B electric field forming a population that is commonly known as pickup ions (PUIs). PUIs are heated in the frame of the SW with increasing distance, before reaching the termination shock (TS). At the shock, they are further heated, with a fraction of their distribution being reflected off the shock surface and undergoing additional heating. Determining the PUI distribution downstream of the Termination Shock (TS) is essential in order to understand the pressure balance and acceleration mechanisms inside the heliosheath (HS). This understanding is needed to determine the emission of Energetic Neutral Atoms from the HS because these ENAs are used to remotely sense the boundaries of our heliosphere and its interaction with the VLISM. We present here an unprecedented comparison of ∼0.52–55 keV energetic neutral atom (ENA) heliosheath measurements, remotely sensed by the Interstellar Boundary Explorer (IBEX) mission and the Ion and Neutral Camera (INCA) on the Cassini mission, with modeled ENAs inferred from interstellar pickup protons that have been accelerated at the termination shock, using hybrid simulations, to assess the pickup ion energetics within the heliosheath. This is the first study to use hybrid simulations that are able to accurately model the acceleration of ions to tens of keV energies, which is essential in order to model ENA fluxes in the heliosheath, covering the full energy range observed by IBEX and CASSINI/INCA. The observed ENA intensities are an average value over the time period from 2009 to the end of 2012, along the Voyager 2 (V2) trajectory. The hybrid simulations upstream of the termination shock, where V2 crossed, are constrained by observations. We report an energy-dependent discrepancy between observed and simulated ENA fluxes, with the observed ENA fluxes being persistently higher than the simulated ones. Our analysis reveals that the termination shock may not accelerate pickup ions to sufficient energies to account for the observed ENA fluxes. We, thus, suggest that the further acceleration of these pickup ions is most likely occurring within the heliosheath, via additional physical processes like turbulence or magnetic reconnection. However, the redistribution of energy inside the heliosheath remains an open question.

Emission Measure analysis of the transition region of solar flare structures

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We analyze an X1.6-class solar flare, observed on September 10, 2014, with the Interface Imaging Spectrograph (IRIS) and the Atmospheric Imaging Assembly onboard the Solar Dynamic Observatory (SDO/AIA). The purpose of study is to determine whether the lower transition region plasma is heated through classical thermal conduction described by Spitzer & Harm (1953) [1]. To achieve this the Emission Measure (EM) is computed for the chromosphere and low transition region spectral lines C II 1334.525Ang (formation temperature T~25000 K), Si IV 1402.770Ang (T~80000 K), and the Fe XXI 1354.066Ang flare line (T~10^7 K), all of them observed with IRIS, as well as the EM derived from the AIA 171Ang image, formed at low coronal temperatures (T<10^6K). Flare ribbons and flaring loop footpoints are sampled. The EM ratio of

1354.066 Ang over 171 Ang suggests that the energy flow from the hot ten million Kelvin plasma towards the low corona plasma is dominated by the standard thermal conduction. On the other hand, the EM ratio of 171Ang over Si IV 1402.770Ang is not compatible with a low transition region dominated by the standard thermal conduction. Moreover, the EM of the chromospheric line C II 1334.525Ang, when compared with the EM of the Si Iv 1402.770Ang is also not under the effect of the classical thermal conduction. The flare plasma is brighter than low transition region plasma structures, not thermally connected with the corona (small loops, spicules [2]). Therefore, the reason for the EM discrepancy must be found elsewhere. Effects such as variation of element abundances, ionization non-equilibrium, and the fact that Si IV 1402.770Ang is emitted by a Na-like ion are not able to explain our results. We discussed the possible influence of turbulence or non-Maxwellian free electros distributions on the thermal conduction mechanism [3-5] For more details, please consult Gontikakis, Antiochos and Young, 2023 [6].

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Understanding the nature of memory in the order flow of financial markets

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Previously we showed that the long-range memory phenomenon could be reproduced using Markov processes, such as point processes, stochastic differential equations, and agent-based models [1]. Research has led us to question whether the observed long-range memory results from the actual long-range memory process or is just a consequence of the non-linearity of Markov processes. Identifying the best possible models based on given empirical data of observed time series is challenging. The financial markets provide us with vast empirical data, but the best model selection is still problematic for researchers. The widely used long-range memory and self-similarity estimators give varying values of the parameters as these estimators are developed for specific time series models. From the general fractional Lévy stable motion perspective, we investigated the order disbalance time series constructed from the limit order book data of the financial markets [2]. Our results suggested that previous persistence findings in order flow could be related to the power-law distribution of order sizes and other deviations from the normal distribution. Nevertheless, a more detailed consideration of empirical data suggests we construct a more specific order flow model based on the power law of limit order cancel times. In the event time consideration, the limit order cancel times follow the discrete probability mass function derived from the Tsallis q-Exponential distribution [3]. The power-law distribution of the limit order volumes and power-law cancel times form the basis for our modeling of order flow in the financial markets.

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The complexity of power-grid frequency dynamics – An application in superstatistics

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Power grids constitute one of the most complex human-made systems of our time. The delivery of electrical power, centralised or decentralised, depends almost exclusively on power grid networks. The dynamics of electricity in conventional power grids follow strict physical laws. Yet, the inherent variability of supply and demand, augmented with the volatile nature of power generation, leads to inherently ever-changing statistics of power-grid-specific variables. In this presentation, we focus on power-grid frequency, the key signature of power-grid stability, and show that this exhibits known signatures of complex systems, specifically, heavy-tailed distributions. We show that we can recover the statistics of power-grid frequency increments via superstatistics. Moreover, we show that we can disentangle different 'strengths' of superstatistics – given by differing q-indices – across a synchronous power grid, yet with the current data, it is still difficult to detail exactly the type of hyper-distributions governing the statistics of the increments. We will lastly allude to the connection between multifractality and superstatistics in power-grid systems.

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Freeness in cognitive science

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Free random calculus and free random variables (FRV) are viewed as probability calculus of the XXI century, with diverse applications to many-body physics, network analysis and cognitive sciences. In the latter, the techniques like dense array encephalography (dEEG), functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG) or optogenetics, provide enormous amount of data at wide spectrum of temporal and / or spatial resolutions. The multivariate character of time series brings immediately connotations to random matrix theory (RMT), which for the rotationally invariant matrices in the large size limit can be described by free probability. We provide three examples:(i) inference of noisy signals from multivariate correlation data from the brain; (ii) distinguished role of non-normality in real neuronal models; (iii) applications to the field of deep learning in artificial neural networks. In the talk I will mostly concentrate and explain the system (ii).

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Quantum unitary evolution interspersed with repeated non-unitary interactions at random times: The method of stochastic Liouville equation

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We address the issue of what happens when the unitary evolution of a generic closed quantum system is interrupted at random times with non-unitary evolution due to interactions with either the external environment or a measuring apparatus. We adduce a general theoretical framework involving stochastic Liouville equation to obtain the average density operator of the system at any time during the dynamical evolution, which is applicable to any form of non-unitary interaction. We first provide two explicit applications of the formalism in the context of the so-called tight-binding chain (TBC) relevant in various contexts in solid-state physics, for two representative forms of interactions: (i) stochastic resets, whereby the density operator is at random times reset to its initial form, and (ii) projective measurements at random times. For (i), we demonstrate with our exact results how the particle is localized on the sites at long times, leading to a time-independent mean-squared displacement of the particle about its initial location. For (ii), we show that repeated projection to the initial state of the particle results in an effective suppression of the temporal decay in the probability of the particle to be found on the initial state. The amount of suppression is comparable to the one in conventional Zeno effect scenarios, but which does not require to perform measurements at exactly regular intervals that are hallmarks of such scenarios. For the case of the TBC subject to an external field periodic in time and being stochastically reset to the initial condition at exponentially-distributed random times, we derive using the aforementioned method of stochastic Liouville equation exact results for the probability at a given time for the particle to be found on different sites and averaged with respect to different realizations of the dynamics. We establish the remarkable effect of localization of the TBC particle on the sites of the underlying lattice at long times. The system in the absence of stochastic resets exhibits delocalization of the particle, whereby the particle does not have a time-independent probability distribution of being found on different sites even at long times, and, consequently, the mean-squared displacement of the particle about its initial loca- tion has an unbounded growth in time. One may induce localization in the bare model only through tuning the ratio of the strength to the frequency of the field to have a special value, namely, equal to one of the zeros of the zeroth order Bessel function of the first kind. We show that localization may be induced by a far simpler procedure of subjecting the system to stochastic resets.

From fireflies to power grids: The physics of spontaneous synchronization

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Crickets singing in synchrony, fireflies blinking in unison, audience clapping in unison, power grids operating at a common frequency with generator and motor shafts rotating in phase, and last, but foremost, pacemaker cells syncing up to send out electrical signals and generating regular heart beats are all examples of the fascinating phenomenon of spontaneous synchronization. In this talk, I will summarize how a physicist studies such an emergent collective behavior using tools of nonlinear dynamics and statistical physics.

In particular, in the context of the Kuramoto model of coupled oscillators with distributed natural frequencies interacting through a time-delayed mean-field, we derive as a function of the delay exact results for the stability boundary between the incoherent and the synchronized state and the nature in which the latter bifurcates from the former at the critical point. Our results are based on an unstable manifold expansion in the vicinity of the bifurcation, which we apply to both the kinetic equation for the single-oscillator distribution function in the case of a generic frequency distribution and the corresponding Ott–Antonsen (OA)-reduced dynamics in the special case of a

Lorentzian distribution. Besides elucidating the effects of delay on the nature of bifurcation, we show that the approach due to Ott and Antonsen, although an ansatz, gives an amplitude dynamics of the unstable modes close to the bifurcation that remarkably coincides with the one derived from the kinetic equation. Further more, quite interestingly and remarkably, we show that close to the bifurcation, the unstable manifold derived from the kinetic equation has the same form as the OA manifold, implying thereby that the OA-ansatz form follows also as a result of the unstable manifold expansion. This may have important bearings on their inter-relationship to be unravelled in future. As an explicit physical effect of the presence of delay, we demonstrate with our exact results that for a sum of two Lorentzians as a representative example of a bimodal frequency distribution, while absence of delay leads to a bifurcation of the synchronized from the incoherent state that is subcritical, even a small amount of delay changes completely the nature of the bifurcation and makes it supercritical.

Climate network analysis of extreme events: Tropical Cyclones

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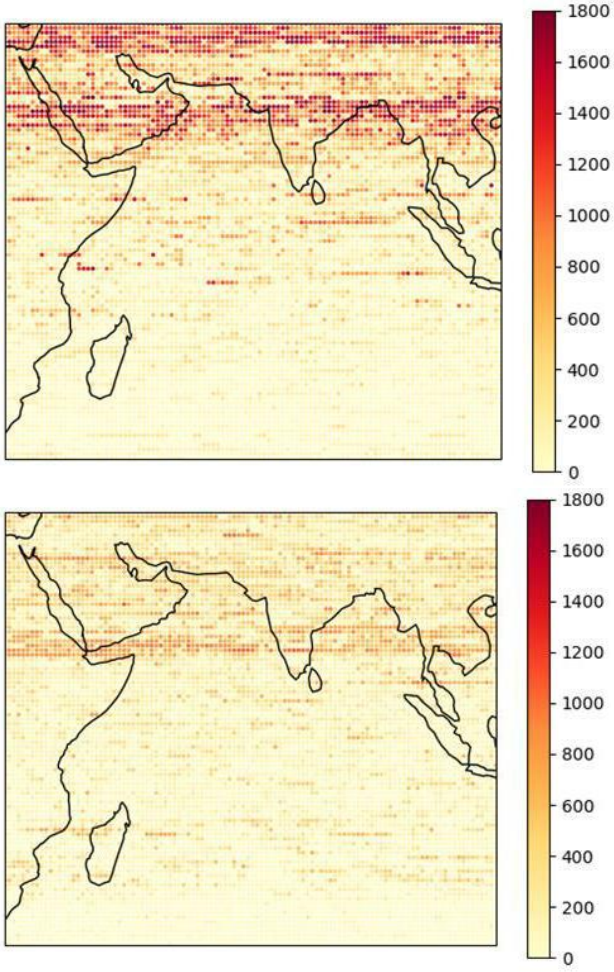
We construct climate networks based on surface air temperature data to identify distinct signatures of tropical cyclones in the region of the Indian Ocean, which have serious economic and ecological consequences. The climate network shows a discontinuous phase transition in the size of the normalised largest cluster and the susceptibility during cyclonic events. We analyze these quantities for a year (2016) which had three successive cyclones, viz Cyclone Kyant, cyclone Nada and cyclone Vardah, and compare these with years where a single cyclone, cyclone Ockhi (2017) and was seen. The microtransitions and jumps in susceptibility in these two cases show distinct patterns and scaling behaviour. The signatures of the cyclones can be seen in other quantities like the degree distributions and other network characterizers. The nodes of high degree show rough correlation with the cyclone paths, and also have potential as predictors. We discuss the implications of these results for further analysis.



(a) Degree distribution at C=0.75 before of very severe cyclonic storm Cyclone Ockhi (29 Nov-6 Dec) 16th to 30th Nov, 2017. (b) Degree distribution at C=0.75 during very severe cyclonic storm Cyclone Ockhi (29Nov-6 Dec), 1-15 December 2017.

Active XY model on a substrate: Density fluctuations and phase ordering

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We explore the generic long wavelength properties of an active XY model on a substrate, consisting of collection of nearly phase-ordered active XY spins in contact with a diffusing, conserved species, as a representative system of active spinners with a conservation law. The spins rotate actively in response to the local density fluctuations and local phase differences, on a solid substrate. We investigate this system by Monte-Carlo simulations of an agent-based model, which we set up, complemented by the hydrodynamic theory for the system (using Renormalisation Group theory framework for nonlinear terms). We demonstrate that this system can phase-synchronize without any hydrodynamic interactions. Our combined numerical and analytical studies show that this model, when stable, displays hitherto unstudied scaling behavior: As a consequence of the interplay between the mobility, active rotation and number conservation, such a system can be stable over a wide range of the model parameters characterized by a novel correspondence between the phase and density fluctuations. In different regions of the phase space where the phase-ordered system is stable, it shows phase ordering which is generically either logarithmically stronger than the conventional quasi long range order (QLRO) found in its equilibrium limit, together with "miniscule number fluctuations", or logarithmically weaker than QLRO along with "giant number fluctuations", showing a novel one-to-one correspondence between phase ordering and density fluctuations in the ordered states. Intriguingly, these scaling exponents are found to depend explicitly on the model parameters. We further show that in other parameter regimes there are no stable, ordered phases. Instead, two distinct types of disordered states with short range phase-order are found, characterized by the presence or absence of stable clusters of finite sizes. In a surprising connection, the hydrodynamic theory for this model also describes the fluctuations in a Kardar-Parisi-Zhang (KPZ) surface with a conserved species on it, or an active fluid membrane with a finite tension, without momentum conservation and a conserved species living on it. This implies the existence of stable fluctuating surfaces that are only logarithmically smoother or rougher than the Edward-Wilkinson surface at two dimensions (2d) can exist, in contrast to the 2d pure KPZ-like "rough" surfaces.

The unexpected generality of Boltzmann Entropy & its context sensitive functional representations as generalized entropy measures of information production

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In recent years so called Generalized Entropy Functionals were attracting considerable attention, with pertinent questions concerning the microscopic foundations of such functionals, their interrelations, and their correspondence to what one might identify as "thermodynamic entropy" being under debate. We will briefly discuss challenges statistical theory faces, when considering complex generative processes, [1,2]. One in particular. Different entropy concepts, including e.g. axiomatic schemes, or Boltzmann's prescription, log number of states, may differentiate with distinct functional forms and operational meaning, as one applies them outside the realm of iid and equilibrium processes [3]. However, we can show very generally that Boltzmann entropy and the information theoretic concept of information production can be unified conceptually once one shifts attention from single states a process accesses towards suitable sets of path fragments a process takes. By doing so one can in principle reversibly translate any reasonably well behaved process into an adjoined iid process [4]. For iid processes we know the triplet Shannon entropy, cross-entropy, and Kullback-Leibler information divergence completely determines the MaxEnt principle (MEP) which can be pull back entirely from the adjoined process space to the marginal distribution space of the original process class. Generalized MEP entropies turn out to be the natural functional

representations of Boltzmann entropy. They context sensitively depend on the considered process class and measure of information production. Despite theoretical and practical issues that limit our capability of inferring optimal adjoined process representations from statistical data alone the existence of such not necessarily unique representations has stunning consequences. One being, that each suitable process is self-generalizing. It implicitly carries all the information about the particular process class it belongs to. Another, that we are being provided with theoretical tools to study how "thermodynamic relations" deform as we drive processes away from equilibrium conditions [5].

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About a curious equivalence: Boltzmann Entropy as measure of information production - its functional representations and ensuing process classes

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In recent years so called Generalized Entropy Functionals were attracting considerable attention, with pertinent questions concerning the microscopic foundations of such functionals, their interrelations, and their correspondence to what one might identify as "thermodynamic entropy" being under debate. We will briefly discuss challenges statistical theory faces, when considering complex generative processes, [1,2]. One in particular.

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A statistical mechanics framework for porous media flow

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The central problem in the physics of multiphase flow in porous media is to find a proper description of the flow at scales large enough so that the medium may be regarded as a continuum: the scale-up problem. It is the same kind of problem as finding a proper description of fluids at the continuum level when we know that they consist of molecules; a problem that in this case was solved almost two hundred years ago with the introduction of the Navier-Stokes equation. So far, the only workable approach to the multiphase flow scale-up problem has been a set of phenomenological equations that have obvious weaknesses. Attempts at going beyond this relative permeability theory have so far never led to practical applications due to exploding complexity. Edwin T. Jaynes proposed in the fifties a generalization of statistical mechanics to non-thermal systems based on the information theoretical entropy of Shannon. We have used this approach to construct a description of immiscible two-phase flow in porous media at the continuum scales, which is directly related to the physics at the pore scale, and with a level of complexity that is manageable [1-6]. The approach leads to a thermodynamics-like formalism at the continuum scale with all the relations between variables that ``normal" thermodynamics has to offer.

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On a theory of cell decision-making for multicellular systems

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Cell decision-making is the process of cells changing their phenotype according to their intrinsic programming and in response to the microenvironmental cues. Currently, little is known about the principles dictating cell decision-making in multicellular systems. Regarding cells as Bayesian decision-makers under energetic constraints, we propose that organisms of all domains of life operate using a ‘Least microEnvironmental Uncertainty Principle' (LEUP) for their decision-making processes. This is translated into a free-energy principle, implying a statistical mechanics theory for cell decision-making. Here, we address three fundamental challenges: (C1) the uncertainty/stochasticity of subcellular regulatory cell decision-making mechanisms, (C2) lack of knowledge in the relative contribution of intrinsic and extrinsic cell decision-making factors to multicellular spatiotemporal dynamics, and (C3) a unified theory for different types of cell decision-making. Such a statistical mechanics reduction allows for simplifying many parameters into a low-dimensional mathematical description and circumvent the uncertainty about the underlying mechanisms.

Hidden geometry of brain dynamics revealed by persistent homology

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Characterizing the pattern of dependences between the dynamics of nodes of complex systems (such as interacting brain regions) by the tools of topological data analysis is an area of rapidly growing interest. It has been recently shown, that topological data analysis is sensitive to brain-disease-related alterations in both the structure of the functional connectivity (instantaneous statistical dependences) and effective connectivity (directed causal interactions), albeit the detectability of these alterations depends of their topological/topographical specificity [1]. In this contribution we shall discuss the practical aspects of utilization of topological data analysis to characterize the hidden geometry of brain dynamics, as well as provide methodological approaches to gain qualitative insights concerning this hidden geometry. In particular, we present an investigation of the underlying curvature of data through the lens of topology [2]. Building upon previous work [Giusti et al., 2015], we employ the tools of Persistent Homology, namely topological features derived from Betti curves. We first investigate the case of random and geometric matrices (distance matrices of points randomly uniformly distributed on manifolds of constant sectional curvature). We consider the three classical models given by the Euclidean space, the sphere, and the hyperbolic space. We show that Betti curves effectively distinguish these spaces. Thus we can use manifolds of constant curvature as comparison models to infer properties of the underlying curvature of manifold underlying real data. We analyse brain dynamics data (while comparing with financial and climate data examples) and observe that their associated topological features appear to emerge from hyperbolic underlying geometry. This result is consistent with the general belief that their underlying data manifold is of non-positive curvature, however we also discuss alternative explanations related to the data sampling and processing steps, as well as more complex possible hidden geometries.

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Energetic and suprathermal particle measurement at the inner heliosphere

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Particles that have energies of a few times the solar wind plasma energy up to 100s of keV/q are called suprathermal particles. Recent studies have revealed that these particles may a significant role as seed particles for further acceleration to higher energies. This may occur either close to the Sun in solar energetic particle (SEP) events, but also locally at 1 AU in energetic storm particle events, or even outside 1 AU as ions accelerated in Corotating Interaction Regions. The origin of these suprathermal particles is largely unknown at this time. It is therefore important to make high-time resolution measurements of the composition and spectra of this particle population in the inner heliosphere to better characterize its origins and role as a seed population in particle acceleration processes. Because of the vastly different mass-per-charge ratios of the various possible origins of suprathermal ions, we expect to see distinct difference and radial dependencies in their abundances in low-energy accelerated particles in the inner heliosphere. Here we describe the measurements on Solar Orbiter that are already making significant contributions to the understanding of the source, spectral shape and particle population in this largely unexplored energy range.

The gradient-flow equations in information geometry and electric circuits.

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Information geometry (IG) is a useful method exploring the fields of information science by means of modern differential geometry. It has been applied to some different fields including statistical physics, statistics, information theory, dynamical systems and so on. IG is invented from the studies on invariant properties of a manifold of probability distributions. The dually-flat structures are important and a statistical manifold (M, g, ∇, ∇*) is characterized by a (psuedo-) Riemannian metric g, and torsion-less dual affine connections∇ and ∇*. For a given convex function ψ(θ) together with its dual convex function ψ*(η), one can construct a dually-flat structures as follows. The affine coordinates θ^i (η_i) are obtained as the derivative of ψ(θ) (ψ*(η)). The convex functions are Legendre dual to each to other. The positive definite matrices gij(θ) and g^{ij}(η) are obtained from the Hessian matrices of the convex function ψ(θ) and ψ*(η). The product of these matrices is Kronecker's delta.The θ- and η-coordinate systems are dual affine coordinates. Since connections are not tensors, there exists a coordinate system in which the connection becomes zero and such a coordinate system is called affine coordinate. The gradient-flow equations with respect to the η-potential function are given by $d\eta_i/dt = - g_{ij}(\eta)(\partial\psi^*(\eta)/\partial\eta_j)$, in the η-coordinate system. They are equivalent to the linear differential equations $d\theta^i/dt = - \theta^i$, in the θ-coordinate system. It is worth emphasizing that the two sets of the differential equations describe different processes in general. The gradient-flow equations are useful for some optimization problems. The gradient flows on a Riemann manifold follow the direction of gradient descent (or ascent) in the landscape of a potential functional, with respect to the curved structure of the underlying metric space. In this contribution, we consider the gradient-flow equations in an electrical circuit based on the correspondence between the thermodynamic processes in equilibrium thermodynamics and the gradient-flows in IG. Specifically we have constructed the gradient-flow equations in a simple electrical resistor-capacitor (RC) circuit based on the first law of thermodynamics, which is a conservation law of energy in thermodynamical systems, and Telegen's theorem, which is a conservation law of electric powers in electric circuits. The corresponding η-potential function (negentropy) is constructed from the entropy production rate in the electrical resistor (R) by using Joule's law. Remarkably it is shown that the associated gradient-flow equation is consistent with the conventional transient analysis of the RC circuit when the dynamical evolution parameter is regarded as the time parameter.

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Energy partition of thermal and nonthermal particles for a composed spectrum of Maxwellian and kappa distribution function in magnetic reconnection

Masahiro Hoshino
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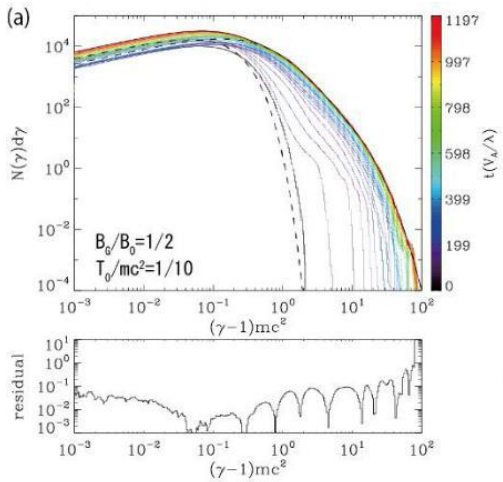
In collisionless plasmas in our space and astrophysical environments, nonthermal particles, whose energies are much higher than the thermal temperature, are often observed, yet our understanding of the energy partition between thermal and nonthermal particles remains to be elucidated. In this presentation, we discuss the energy partion by focusing on magnetic reconnection, which has long been known to be the most important mechanism as quick conversion of magnetic field energy into thermal and nonthermal energies. By using particle-in-cell (PIC) simulations, we have investigated the energy partition for hot plasmas in plasma sheet as a function of plasma sheet temperature and guide magnetic field. For simplicity, we have assumed a pair plasma, and the thickness of plasma sheet normalized by the inertia length has been fixed. We analyzed the hot plasmas heated by reconnection by fitting a model function of a composed function of the Maxwellian and kappa distribution. Shown in the left-hand panel (a) is an example of the energy spectrum obtained in PIC simulation as a function of particle energy $(\gamma-1)mc^2$. The color lines indicate the time evolution of the spectra, whose time stages are indicated in the



right-hand side bar, and the red line is the final stage. The thick solid lines represent the model fitting curve, and the two black dashed lines represent the Maxwellian part in the lower energy regime and the kappa distribution part in the higher energy regime. The bottom panel is the residual of the model fitting. We found that the heated plasmas can be well fitted by the model function. Based on this model fitting, we show the kappa index and the efficiency of the nonthermal particles against heated thermal plasma in the right-hand panels (b) and (c), respectively. The plots are depicted as a function of the initial plasma temperature T_0/mc^2 and guide magnetic field BG/B_0. The temperature and the magnetic field are normalized by the rest mass energy mc^2 and the initial magnetic field B_0, respectively. In relativistic reconnection with anti-parallel magnetic field or weak guide magnetic field, it was found that the nonthermal energy density can occupy more than 90% of the total kinetic plasma energy density with a hard energy spectrum, but strengthening the guide magnetic field suppresses the efficiency of the nonthermal particle acceleration. In nonrelativistic reconnection for anti-parallel magnetic field, most dissipated magnetic field energy is converted into thermal plasma heating with a soft energy spectrum. For a weak guide magnetic field with a moderate value, however, the nonthermal particle acceleration efficiency was enhanced, but strengthening the guide-field beyond the moderate value suppresses the efficiency.

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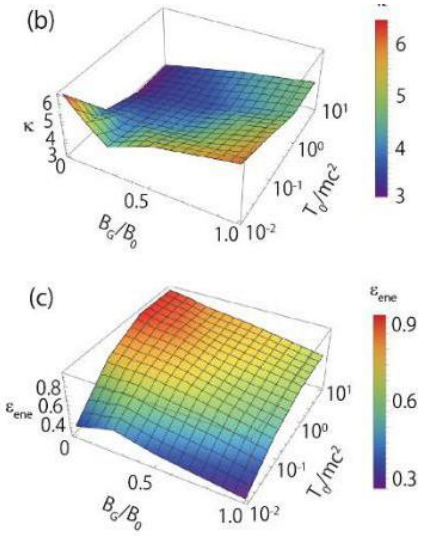

Nonthermal particle acceleration and energy partitioning of thermal and nonthermal particles in collisionless plasma universe

Masahiro Hoshino
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In hot and rarefied plasma in our universe, the mean free path is much larger than the characteristic system size of the astrophysical objects, and the collision between charged particles are rare. In such a collisionless system, the collective behavior of the plasma is governed by the interaction between electromagnetic fields and charged particles. In this system, local thermal equilibrium is not achieved in the time scale of our interests, and the velocity distribution function of plasma contains nonthermal population, whose energies are much beyond thermal energy. In fact, nonthermal particles are ubiquitously observed from various astrophysical phenomena such as solar flares, supernova shocks, pulsar wind nebulae, and black holes and so on. Those nonthermal particles are often approximated by a kappa distribution function with a power-law distribution function in high energy regime. It is important to understand the mechanisms of nonthermal particle acceleration for dynamical evolution of the high-energy astrophysical phenomena and for advancing our knowledge of plasma physics. In this talk, I focus on magnetic reconnection in both non-relativistic and relativistic plasmas, which is one of the key acceleration processes in plasma universe, and I discuss how the energy partitioning between thermal and nonthermal plasmas is realized by using electromagnetic particle-in-cell numerical simulations.

Botzmann-Gibbs distributions and applications to data-driven modeling

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Boltzmann-Gibbs (BG) models are a cornerstone of statistical physics. They are used to describe the probability functions of discrete physical systems as well as continuum field theories. In addition, they provide a useful framework for the representation of data-driven spatial or spatiotemporal processes. The structure of statistical dependence in such processes is enforced by means of near-neighbor interactions in space and/or time. The interactions contribute to a scalar energy (appearing in the exponent of the exponential BG density), and they are controlled by data-driven interaction parameters.

The BG representation can lead to sparsely connected space-time networks comprising edges that are determined according to suitable distance concepts. For Gaussian BG models, the spatial/spatiotemporal structure of the interactions determines the model's precision (inverse covariance) matrix. The latter is sparse by construction if the interactions are local. The sparsity property leads to efficient prediction algorithms for the representation of random functions. Hence, the sparsity of the precision matrix provides considerable computational gains compared to standard approaches which are based on the covariance function and require inverting the (potentially very large) covariance matrix.

This presentation focuses on recent progress in the application of Boltzmann-Gibbs models to spatial and space-time geo-referenced data. A topic that will be discussed is the construction of new temporal/spatial/spatiotemporal covariance kernels which are based on continuum-space BG models and can be used in Gaussian process regression tasks. In addition, we will discuss the extension of BG models to network-based stochastic local interaction (SLI) models which are suitable for the interpolation of scattered spatiotemporal datasets without using covariance kernels. In SLI models the interactions are

implemented via compactly supported kernel functions (not to be confused with the covariance kernels). SLI models provide a flexible statistical framework for spatiotemporal datasets; they are computationally efficient, due to the explicit precision matrix construction, and therefore useful for applications to big datasets. In addition, it is straightforward to ensure that the precision matrices of SLI models are non-negative definite. This feature enables the use of different data types and distance measures, topics which will be further investigated in future studies.

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Applications of Kaniadakis functions beyond statistical mechanics

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This talk focuses on applications of the Kaniadakis -deformed exponential and logarithmic functions in three different problems. First, we show that a pair of nonlinear transforms based on the -exponential and the - logarithmic functions are useful tools in Gaussian process regression for non-Gaussian data. This novel transformation has advantages compared to the Box-Cox transform which is a standard statistical tool for normalizing skewed data. For illustration, the new transform is applied to a censored autoregressive model for the simulation of precipitation time series. Second, we highlight the connection between the heavy- tailed -Weibull distribution and weakest-link scaling theory in the case of non-independent links. In light of this analogy, the -Weibull is suitable for modeling the mechanical strength distribution of non-homogeneous brittle materials. We provide statistical analysis of various datasets that illustrate the usefulness of the - Weibull distribution. Finally, we comment on the potential use of the novel - lognormal probability distribution as a model for the permeability of random porous media. In summary, - deformations allow modifying the tails of classical distribution models (e.g., Weibull, lognormal) and provide new directions of research in the analysis of skewed space-time datasets.

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Using percolation theory and an ecological optimum to understand water partitioning on the Earth's surface, including streamflow and vegetation response to climate change

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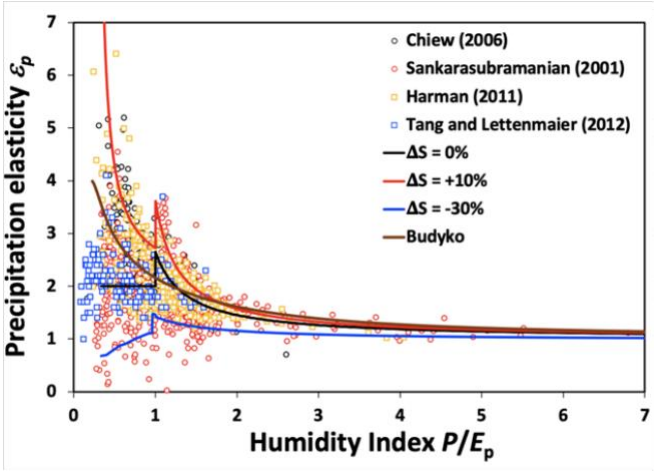
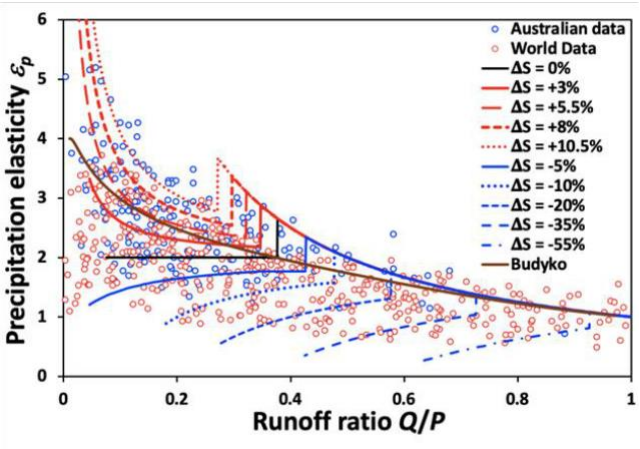
Quantifying partitioning of rainfall P into run-off Q and evapotranspiration ET at the terrestrial Earth's surface is the central problem of hydrology. ET of plants is by far the best single predictor of plant net primary productivity (NPP) since it expresses simultaneously limitations from insufficient solar energy (potential evapotranspiration, PET, equal to a depth of water that could be evaporated) and P, simultaneously. Because the input of solar energy into ecosystems limits all subsequent transformations of energy, this is a central problem

of ecology and climate change as well. Human civilization depends on run-off/streamflow for drinking, agriculture, industry, transportation, and power. The planet's thermal regulation and atmospheric composition depend on ET, the working fluid of the vegetation engine. Percolation theory governs soil formation rate through the process of solute transport-limited chemical weathering, and thus the conversion of atmospheric carbon to carbonate rock reservoirs. Percolation theory also governs the rate of ET through plants in its definition of the optimal paths for advective nutrient transport to plants and the associated paths along which roots grow in order to access these nutrients. Since lateral spreading of plant roots is thus related to the 2D fractal dimension of percolation theory and to the evapotranspiration fluxes, but the soil depth is determined through run-off by the 3D backbone fractal dimensionality, it is possible to find a maximum in plant root mass through a procedure assuming that ecosystem dominance is guaranteed by its optimal conversion of atmospheric carbon dioxide to biomass. This optimality principal is extended to arid regions by applying it only to vegetated ground, a fraction P/PET of the surface, and to humid regions by applying it only to that portion of P equal to PET. This zero-parameter result has been verified to equal the best-fit function of (PET/P) for a global FLUXNET study on evapotranspiration across climate regimes and biomes. Including storage S changes, observed behavior of elasticity (P/Q)(dQ/dP in global and continental scale studies as well as Budyko's catalogued observations of NPP as a function of P and PET simultaneously. Finally, the input relationships for soil depth and vegetation growth are verified across the world's precipitation regimes, from the Atacama desert to the tropical and temperate rainforests and for time scales of up to 130,000,000 and 100,000 years, respectively.





Irregularity of polymer domain boundaries in two dimensional polymer solution

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Domain boundaries of polymer chains comprising a polymer solution confined in strict two dimensions (2D) are irregular, and their fractal dimension (Dp) varies with the area fraction of the solution and the solvent quality. For polymers in θ solvents, Dp remains constant at Dp=4/3 from dilute to semi-dilute phase, but decreases to Dp=5/4 in dense phase. In contrast, Dp in good solvents changes non-monotonically from Dp=4/3 in dilute phase to Dp=5/4 in dense phase, maximizing to Dp≃3/2 at a critical area fraction. Using polymer physics arguments, we rationalize the values of Dp at some limiting conditions. We also put our discussion into the perspective of the Schramm-Loewner evolution (SLE). We find that the maximal irregularity of Dp≃3/2 results from "fjord"-like corrugations formed in domain boundary which also maximize at the critical area fraction. In fact, 2D random curves with Dp=3/2 correspond to the SLEκ with κ=4, which lies at a marginal point, transitioning from simple non-intersecting curves to those with self-intersections.

Statistical complexity of kappa distribution

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The statistical complexity measures represent an interplay between order and disorder levels of a complex system. In the past, different definitions of statistical complexity were introduced, but there is not a general agreement about which one is preferable [1-3], since it has still not been accepted what a set of basic properties is that a complexity measure should satisfy. In this work we provide a general treatment of the statistical complexity measures starting from a set of ineluctable properties, which are stated as axioms. These axioms state that the statistical complexity measure of a discrete system is a non-negative composition of a strongly pseudo-additive entropy [4-5], which serves as a measure of disorder, and of a generalized certainty measure [6], which serves as a measure of an order. In addition, the statistical complexity measure has to be non-negative, decomposable, equal to zero, in the case of a simple system, and to preserve consistency of discrete and continuous cases. We derived the unique class of statistical complexity measures which satisfy the aforementioned axioms and includes some of the previously considered measures as special cases. Unlike the majority of the previously proposed measures, it has a finite and non-vanishing limit when a discrete system tends to a continuous one, so that the corresponding differential statistical complexity can be defined, being invariant under rescaling, translation and replication. We derive the analytic expression for the statistical complexity of a multivariate kappa distribution and we analyze its extensivity.

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Super-additivity, generalized concavity and quasi-homogeneity in non-additive systems

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The properties of an entropy function, such as super-additivity, concavity, and homogeneity, set up the basis for the maximum entropy principle, which arises from the second law of thermodynamics [1]. According to the maximum entropy principle, the equilibrium state of a composed system is found to be the one that maximizes the sum of entropies of its subsystems, and the equilibrium conditions are found by the zeroth law of thermodynamics [2]. The standard results show that the satisfaction of two of the properties implies the third one (see [3] and references therein), which sets up the criterion for the thermodynamic consistency of the chosen entropy form. However, these results are applicable only to additive systems. On the other hand, in the case of non-additive systems, which are common in the presence of long-range interactions [4] and in black hole thermodynamics [5], the entropy is not a homogenous, but a quasi-homogenous function. Although some fundamental results, such as the zeroth law of thermodynamics and the Gibbs-Duhamel relationship, have already been established for quasi-homogenous systems [5], the relationships between quasi-homogeneity, concavity, and super-additivity of non-additive systems seem to still be unknown. In this talk, we will show that quasi-homogeneity and generalized concavity imply the super-additivity of entropy in a non-additive system. The results will be applied to the characterization of the equilibrium of the generalized Landsberg ideal gas, which represents a model of a simple system that violates homogeneity (and consequently super-additivity), while being consistent with ideal gas state equations. Applications of the results to systems with non-additive energy and non-additive volume will also be discussed. Finally, we will discuss the role of non-additive entropies [6] in the thermodynamics of quasi-homogenous systems.

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A quantum thermodynamics approach to optimization in complex systems

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An optimization problem can be translated into physics language as the quest for the energy minimum of a complex system with a Hamiltonian that encodes the problem itself. Stretching the analogy further, the optimization problem can be seen as the controlled cooling of such a complex system so as it lands in a minimum of its complex energy landscape corresponding to the optimal solution of the given problem.

I will introduce and discuss two methods for quantum cooling, and thus for optimization, entailing the use of quantum, non-Markovian baths connected to the system of interest. In the first method the bath is prepared in a suitable low energy initial state that efficiently cools down the system of interest. In the second method the bath is measured, and post-measurement excited states of the bath are selected, that correspond to low energy states for the system of interest.

Occurrence and evolution of switchbacks: PSP Observations

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Since its launch, the Parker Solar Probe (PSP) mission revealed the presence of numerous fascinating phenomena occurring closer to the Sun, such as the presence of ubiquitous switchbacks (SBs). The SBs are large magnetic field deflections of the local magnetic field relative to a background field. We investigated the statistical properties of the SBs during the first 11 encounters between 13.3 and 70 Solar Radii using data from the SWEAP and FIELDS suites onboard PSP. We find that the occurrence rate of small deflections with respect to the Parker spiral decreases with radial distance (R). In contrast, the occurrence rate of the large deflections (SBs) increases with R, as does the occurrence rate of SB patches. We also find that the occurrence of SBs correlates with the bulk velocity of the solar wind, i.e., the higher the solar wind velocity, the higher the SB occurrence. For slow wind, the SB occurrence rate shows a constantly increasing trend between 13.3 and 70 solar radii. However, for fast wind, the occurrence rate saturates beyond 35 solar radii. Sub-Alfvenic regions encountered during encounters 8-10 have not shown significant SBs. This analysis of the PSP data hints that some of the SBs are decaying and some are being created in-situ. We discuss the different possible mechanisms which could explain the observed switchbacks behavior.

How do strokes affect the brain's critical state? Structural and functional aspects of the loss of connectome integrity

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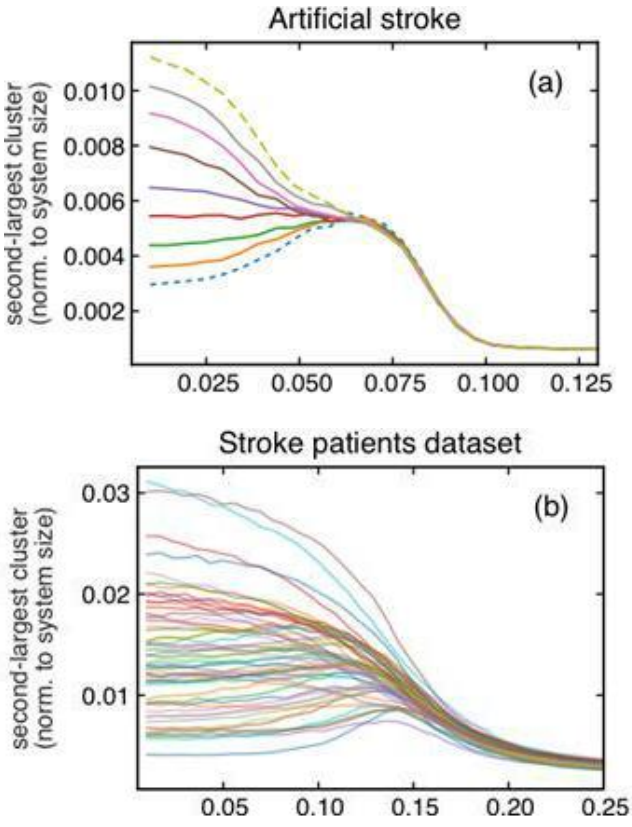
We address the problem of the brain's critical behavior in the case of a brain injury such as a stroke. The criticality provides optimal functioning of the healthy brain, hence neurological dysfunctions might be associated with its loss, which opens this area of study to clinical applications. Assessing whether a critical phase transition occurs, however, has been challenging in similar contexts. In study for a cohort of stroke patients [1] the presence and severity of the stroke reportedly were related to a loss of critical behavior in the brain. The state-of-the-art analysis of a brain's cortex activity model dynamics has been based on the time-averaged sizes of the largest clusters. However, calculation of additional criticality-aware quantities for the patients cohort, beyond the usual second-largest cluster size, and a comparison with an artificial system with known criticality status reveals an inconsistency. The criticality status of the stroke-affected brain becomes unclear due to an ambiguous behavior of the second-largest cluster size. Explaining this crucial observation is our main motivation. We introduce a model of a stroke-like modification of a healthy connectome. The Hagmann et al.'s connectome [2] serves as the base connectivity matrix representing the healthy brain. An artificial stroke changes the connectivity between a particular brain's subsystem, a resting state network (RSN), with the rest of the brain. To this end, we randomly select a fixed fraction of nodes of the RSN and completely remove connections to their neighbors not belonging to the same RSN. This way, the internal structure of the RSN remains unchanged, while effectively decreasing the connection of the RSN with the rest of the brain. The proposed minimal model of a stroke recreates the behavior of second largest cluster observed for stroke patients, see Figure 1. Furthermore, we perform the comparison using graph-theoretic methods. The connectome integrity is probed by the graph modularity. Despite the limiting assumptions, the artificial stroke model recreates quite well the overall loss of connectome integrity observed in patient's cohort. Finally, we perform a detailed study for the second-largest cluster in the Ising model. We combine the insights from connectome integrity study with the Ising model, a paradigmatic case with known criticality status. Ising spins act as the neuron nodes, and the usual two-dimensional grid takes the role of the connectome. The stroke-induced loss of integrity is taken to an edge case where the connectome is completely divided into subsystems, thus modeling a severe artificial stroke. We recreate an anomalous lack-of-peak in the second-largest cluster size and describe the underlying mechanism as a competition within the hierarchy of subsystem-wide clusters. The results presented refer to neurobiological data; however, the conclusions reached apply to a broad class of complex systems for which a critical state is identified.



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Decoherence limit of quantum systems obeying generalized uncertainty principle: new paradigm for Tsallis thermostatistics

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The generalized uncertainty principle (GUP) is a phenomenological model whose purpose is to account for a minimal length scale (e.g., Planck scale or characteristic inverse-mass scale in effective quantum description) in quantum systems. In my talk I will discuss possible observational effects of GUP systems in their decoherence domain. I first derive coherent states associated to GUP and unveil that in the momentum representation they coincide with Tsallis' probability amplitudes, whose non-extensivity parameter q monotonically increases with the GUP deformation parameter β. Secondly, for $\beta<0$ (i.e., $q<1$), I show that, due to Bekner-Babenko inequality, the GUP is fully equivalent to information-theoretic uncertainty relations based on Tsallis-entropy-power. Finally, I invoke the Maximal Entropy principle known from estimation theory to reveal connection between the quasi-classical (decoherence) limit of GUP-related quantum theory and non-extensive thermostatistics of Tsallis. This might provide an exciting paradigm in a range of fields from quantum theory to analog gravity. For instance, in some quantum gravity theories, such as conformal gravity, aforementioned quasi-classical regime has relevant observational consequences. I will discuss some of the implications.

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A new class of entropy-power-based uncertainty relations

Petr Jizba
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In my talk I will use the concept of entropy power to discuss a new one-parameter class of information-theoretic uncertainty relations for pairs of observables in an infinite-dimensional Hilbert space. This class constitute an infinite tower of higher-order cumulant uncertainty relations, which allows in principle to reconstruct the underlying distribution in a process that is analogous to quantum state tomography. I will illustrate the power of the new class by studying Schroedinger cat states and the Cauchy-type heavy-tailed wave function. Finally, I will also cast some fresh light on generalized uncertainty principle from the information theory point of view.

Related works

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Spin based Quantum Otto engines and majorization

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Quantum thermal machines exploit new thermodynamic resources such as quantum entanglement, coherence, quantum interactions, and quantum statistics. A quantum Otto engine (QOE) has been widely studied for its possible quantum advantages—both in its quasistatic formulations as well as based on time-dependent constraints. It offers conceptual simplicity by virtue of a clear separation of heat and work steps in its heat cycle. The quantum working medium used in these models may be taken in the form of spins, quantum harmonic oscillators, interacting systems, and so on. One of the prominent analytical tools in this context is the notion of majorization, which was developed to quantify the notion of disorder, in a relative sense, when comparing probability distributions. In the present work, we characterize the operation of a QOE through the notion of majorization. We focus only on quasistatic heat cycles in which the quantum adiabatic theorem is assumed to hold as well as a complete thermalization with heat reservoirs is involved. We show that a spin-based quantum working substance provides a natural platform by which the majorization conditions provide sufficient criteria for the operation of a spin-based Otto engine. In particular, for a working substance as a single spin of arbitrary magnitude, majorization yields necessary and sufficient conditions for the Otto engine, provided the canonical distribution of the working medium at the hot reservoir is majorized by its canonical distribution at the cold reservoir. It can be shown on general grounds that a greater Shannon entropy of the equilibrium distribution due to the hot temperature as compared to the cold temperature is a necessary, but not a sufficient condition for positive work extraction. Further, the total entropy generated in a quantum Otto cycle can be given as the sum of the two relative entropies. In this regard, a single spin has a special spectrum for which all the energy gaps change by the same ratio during a quantum adiabatic process. We consider a model three-level system in which the various ratios of energy gaps are not the same and have shown the usefulness of the majorization criterion to infer the regime of positive work. We extend our analysis to a bipartite system consisting of a spin 1/2 interacting with an arbitrary spin via an isotropic Heisenberg exchange interaction. We find that while majorization condition implies positive work extraction, it only yields sufficient conditions for the engine operation. Finally, we study the local thermodynamics of spins in the case of the bipartite system and infer an upper bound on the quantum Otto efficiency using the majorization relation. This presentation thus illustrates the usefulness of the majorization heuristic to infer the performance of quantum Otto engines.

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Thermoelectric generator in endoreversible approximation: The effect of heat-transfer law under finite physical dimensions constraint

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A heat exchanger is an important device that facilitates the exchange of heat between the working medium and the heat reservoirs. These devices find applications in many engineering systems, such as power plants, refrigeration, and air conditioning systems, automobile radiators, waste-heat recovery units. The real-world energy convertors perform under finite-size and finite-time constraints on the resources. Finite physical dimensions thermodynamics (FPDT) is an approach which considers the physical size of a heat exchanger to study irreversible processes in actual devices.

In this presentation, we focus on a steady-state energy convertor working on the principle of thermoelectricity which is a paradigmatic model to

study the effect on performance due to different sources of irreversibility. Here, in addition to optimizing the power output with respect to electric current, we also optimize with respect to the fractional area of a heat exchanger. With this step, it will be shown that the maximum power output should be at a proper selection of the area of the heat exchangers, in addition to an optimal value of the electric current. This selection is an important step in thermal optimization as finiteness of the total heat transfer area is a relevant constraint in the overall design of the energy converter.

Another objective of this paper is to examine the effect of heat transfer law between the working substance and reservoirs on the performance of thermoelectric generator. In particular, we investigate the endo-reversible model based on linear-irreversible law of heat transfer. The results are compared with the usual results based on Newton's law of heat transfer.

Our approach allows the engineer allocate optimal areas to the heat exchangers, apart from an optimal value of thermoelectric electric current. The approach has been earlier applied to various industrial devices, power plants, and cooling systems. The present application to a thermoelectric device shows the utility of FPDT for this class of energy conversion devices. In particular, our analysis also highlights the comparison between linear-irreversible and Newton's laws in thermoelectric engines and provides a useful toy model to analyze the interplay of different forms of the efficiency in these devices.

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Quantum and generative machine learning for molecules and materials

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The discovery of new molecules and materials with desired properties is a practical goal of chemical research. A promising way to significantly accelerate the latter process is to incorporate all available knowledge and data to plan the synthesis of the next materials. In this talk, I will present several directions to use informatics and machine learning to efficiently explore chemical space. I will first describe methods of machine learning for fast and reliable predictions of materials and molecular properties, including quantum mechanical energies and forces. With these tools in place for property evaluation, I will then present a few generative frameworks that we have recently developed to allow the inverse design of molecules and materials with optimal target properties, either in the compositional space or structural space. One general challenge in digital discovery is that many of the molecules and materials that are computationally designed are often discarded in the laboratories since they are not synthesizable. I will thus lastly spend some time to talk about the synthesizability of molecules and materials, either by predicting the synthesis pathways (retrosynthesis) or chemical reactivity. Several challenges and opportunities that lie ahead for further developments of accelerated chemical platform will be discussed.

Criticality of gene regulation networks and an exact bound on stability of Boolean systems

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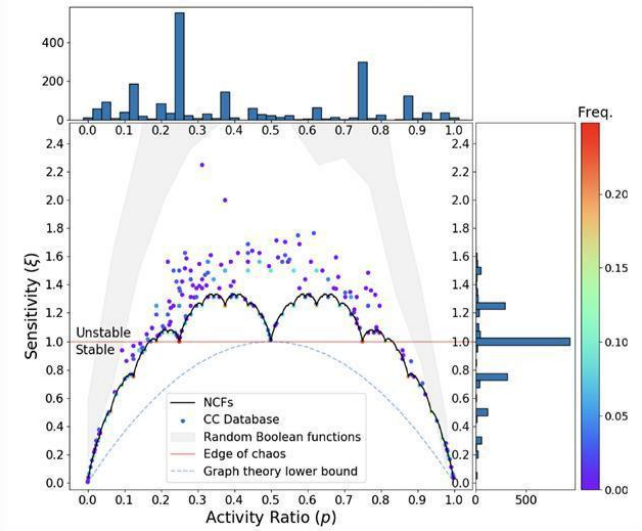
We prove that nested canalizing functions are the minimum-sensitivity Boolean functions for any activity ratio and we determine the functional form of this boundary which has a nontrivial fractal structure. We further observe that the majority of the gene regulatory functions found in known biological networks (submitted to the Cell Collective database) lie on the line of minimum sensitivity which paradoxically remains largely in the unstable regime. Our results provide a quantitative basis for the argument that an evolutionary preference for nested canalizing functions in gene regulation (e.g., for higher robustness) and for plasticity of gene activity are sufficient for concentration of such systems near the “edge of chaos.”.



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Locally driven spin collision battery

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Koc University, İstanbul, Turkey

Quantum batteries are an emerging field of research that explores the use of quantum mechanics to enhance the storage and transfer of energy [1]. Unlike classical batteries, quantum batteries exploit the principles of superposition and entanglement to increase their efficiency and capacity [2]. One promising model for quantum batteries is the collision model, which involves the transfer of energy between two quantum systems that collide with each other [3]. In this research, we were inspired by the collision model, and we are considering two spin systems that contain three spins each. Both systems are fully interacting graphs but only collide by interacting one spin from each graph. As stated, collision model is only an inspiration, the battery dynamics are solved via numerical integration of Liouville-von Neumann equation. Also adding a time dependent driving which can induce a phase transition. Our work also aims to address the question of whether it is possible to induce a phase transition in a non-uniformly interacting Hamiltonian within a finite time frame using finite-time quantum control. The shortcut to adiabaticity (STA) method was considered as a potential candidate for such control, as it has been shown to be effective in driving many quantum systems [4-6]. These attempts have been limited by the issues of level crossings and degeneracy, which are problematic for STA [6]. It is worth noting that level crossings are unavoidable in phase transitions [6]. In order to address issues related to degeneracy and level crossings, we have devised an approach that draws inspiration from collision models. This research demonstrates that incorporating non-uniformity into battery design has the potential to enhance battery performance. We have utilized work output and ergotropy as performance metrics and presented statistical information on different non-uniform Hamiltonians [2].

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Power law entropies for parabolic systems?

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The American University Of Iraq - Baghdad, Baghdad, Iraq

We present some hand-waving arguments which may lead someone to suspect that power law entropies (such as the q-entropy) may be appropriate for encoding the statistical behavior of a parabolic dynamical system. We make some comments on the case of low-dimensional collision-less, non-relativistic plasma where the effects of the magnetic field can be neglected, as a potential example for testing concretely these ideas.

On the origin of the escort distributions

Nikolaos Kalogeropoulos
The American University Of Iraq - Baghdad, Baghdad, Iraq

We present an argument which aims to justify the use of the escort distributions in non-additive statistical mechanics. We ascribe their use to the distinct role played by the metric and the measure of the coarse-grained phase space of the underlying dynamical system.

Quantitative empirical verification of the Lillo-Mike-Farmer hypothesis for the persistent order flow in the Tokyo Stock Exchange market

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Kyoto University, Kyoto, Japan

Statistical physics aims to study the macroscopic behaviour of various physical systems, and econophysics is its subfield to analyse the financial market microstructure by using recent high-frequency data in alignment with the statistical-physics program. In this talk, we focus on the persistence of the market order flow in financial markets from microscopic data analyses. In broad financial markets, market orders exhibit the long-range correlation (LRC): once a buy (sell) market order is observed, a buy (sell) order is likely to appear even in future. In addition, this phenomenon is quantitatively characterised by the power-law decay of the sign autocorrelation function (ACF). Then, a natural question will arise: what is the microscopic origin of this phenomenon? One of the promising microscopic hypotheses is the order-splitting hypothesis, stating that several large investors are splitting large metaorders into a long run of small child orders. Based on this hypothesis, Lillo, Mike, and Farmer (LMF) proposed a microscopic model in the spirit of statistical physics. This theory strongly predicts that the power-law exponent γ in the sign ACF is directly linked with the microscopic power-law exponent α in the run-length distribution for the order splitting, such that γ = α - 1. However, this statistical-physics prediction has not been quantitatively verified in the absence of appropriate microscopic datasets for almost 18 years. In this talk, we solve this long-standing problem by analysing a large microscopic dataset of the Tokyo Stock Exchange (TSE) markets based on our latest preprint (Y. Sato and K. Kanazawa, arXiv: 2301.13505). Our dataset includes the virtual server identifiers (IDs), a unit of trading accounts on the TSE market. By aggregating the virtual server IDs, we can allocate effective trader IDs to track traders' behaviour at the level of individual accounts. First, we study the run-length distributions of the order splitting to measure their microscopic power-law exponent α. We then measure the macroscopic power-law exponent γ in the order-sign ACFs. Finally, we show the scatterplot between α and γ, showing excellent and quantitative agreement with the LMF theory. Our work has provided the first quantitative support to the LMF model as the minimal microscopic model for the LRC in the order flow.

Correlated percolation of sites not removed by a random walker in 2≤d≤6 dimensions

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Mechanical properties of a gel which is degraded by few enzymes that travel through it and brake crosslinks can be modeled by the removal of sites on a lattice by a meandering random walk (RW) [1]. We studied [2] a percolation problem on a d-dimensional hypercubic lattice of size L^d with periodic boundary conditions, where a RW of $N=uL^d$ steps removed sites. Sites not visited by the RW have correlation that decays with the distance r as $1/r^{d-2}$. [However, crossing the (periodic) boundaries breaks the RW into almost uncorrelated segments.] In d≥3 for large L the RW length parameter u is simply related to the fraction of unvisited sites p=exp(-Ad u), where Ad are known constants. As u increases (p decreases) the critical value uc is reached, beyond which the unvisited sites no longer percolate. For 3≤d≤6 we found that uc≃3. Close to the percolation threshold the correlation length (mean linear size of a finite cluster) diverges as $|u-u\_c|^{-\nu}$, with ν=1/(d-2), as predicted by the theory of correlated percolation [3] This and other critical exponents (including the exponent of conductivity) differ significantly from the case of the uncorrelated (Bernoulli) percolation, but, with increasing d, their values approach the same mean field values at d=6. In d=2 the percolation probability is a smooth function of u and the problem has no percolation threshold, because the fractal dimension of the RW coincides with d. Nevertheless, the system has scaling properties [4], where the system size L plays a role resembling correlation length in higher-dimensional cases: Boundaries of the clusters of unvisited sites have fractal dimension 4/3, while the mean cluster size (mass) is proportional to L^2. Density of clusters of size s scales as s^{-t}, while the volume fraction occupied by k-th largest cluster scales as k^{-q}. We numerically measured the t≃1.8 and q≃1.2, which are outside the range of allowed values for such exponents, and we suggest that these are effective numbers that converge to their ultimate values (2 and 1, respectively) as 1/ln L. We provide a heuristic argument for their L=∞ values.

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Frustrated magnetism of a quantum mixed spin-(1, 1/2) Heisenberg octahedral chain from a statistical-mechanical monomer-dimer model

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The mixed spin-1 and spin-1/2 Heisenberg octahedral chain with regularly alternating monomeric spin-1 sites and square-plaquette spin-1/2 sites has, in a magnetic field, an extraordinarily rich ground-state phase diagram, which includes the uniform and cluster-based Haldane phases, two ferrimagnetic phases of Lieb-Mattis type, two quantum spin liquids, two bound magnon crystals in addition to the fully polarized ferromagnetic phase. In the highly frustrated parameter region the lowest-energy eigenstates of the mixed-spin Heisenberg octahedral chain belong to flat bands, which allow a precise description of low-temperature magnetic properties within the localized-magnon approach exploiting a classical lattice-gas model of hard-core monomers. Moreover, we have found a more comprehensive version of the localized-magnon approach, which extends the range of its validity down to a less frustrated parameter region involving the Haldane and cluster-based Haldane ground states. A comparison between results of the developed localized-magnon theory and accurate numerical methods like full exact diagonalization and finite-temperature Lanczos methods convincingly evidence that the low-temperature magnetic properties above the Haldane and the cluster-based Haldane ground states can be extracted from a classical lattice-gas model of hardcore monomers and dimers, which is additionally supplemented by a hard-core particle spanned over the whole lattice representing the gapped Haldane phase.

Acceleration and loss of relativistic electrons in the outer radiation belt: "recent scientific insights and modelling efforts"

Christos Katsavrias
National And Kapodistrian University Of Athens, Athens, Greece

The dynamics of the outer radiation belt are driven by a complex interplay between acceleration and loss mechanisms leading to a broad energy range of energetic electrons. In addition, these physical mechanisms depend on the electron energy, the timescale, and the various types of geospace disturbances. Electric fields and plasma waves are the main factors regulating the electron transport, acceleration and loss, yet both of them are driven directly or indirectly by disturbances originating in the Sun, propagating through interplanetary space and impacting the Earth. Here we will discuss the current understanding of the response of the outer Van Allen belt electrons to various types of solar wind and internal magnetospheric forcing, to geospace magnetic storms of different intensities and to intense magnetospheric substorms using electron phase space density calculations as well as concurrent Pc5 and chorus wave activity observations during the Van Allen Probes era. Furthermore, we will discuss recent efforts for the nowcasting/forecasting of the response of the outer belt electron population using physics-based or data-driven model and we emphasize the importance of Machine Learning methods in improving the current models.

Nonlinear and non-local FPK equation for probabilistic response of nonlinear systems under Gaussian colored noise excitation

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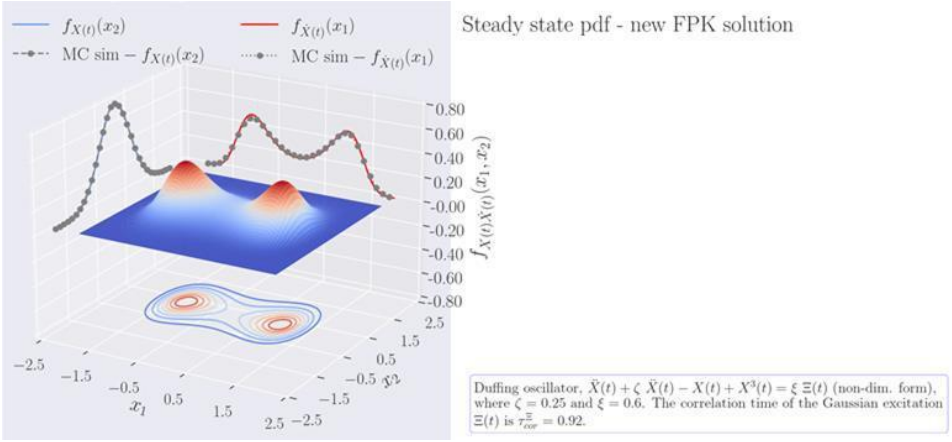
The statistical (probabilistic) response of nonlinear Random Dynamical Systems (RDS) excited by Gaussian colored noise is an important problem, arising in many applications in Physics and Technology. The loss of the Markovian character of the response, complicates the solution procedure and calls for special solution techniques. The main methods in use for treating such problems are: i) embedding the problem in a higher-dimensional Markovian one, asymptotic techniques, as e.g. the unified colored noise approximation [1], [2], which works well in a restricted domain of the parameter space (correlation time and noise intensity). Obvious drawbacks of these methods are, the increase of degrees of freedom, in the first approach, and the restricted applicability, in the second. In the present paper we present a different approach, deriving a novel efficient FPK-like equation, for the first-order probability density function (pdf), which embodies non-Markovian effects through nonlinear and history-dependent terms. A first announcement of the theory, without numerical results, has been given in [3], [4]. This equation generalizes a similar one developed for the case of scalar Random Differential Equations [4], [5] The derivation is based on the Stochastic-Liouville equation (SLE) of the RDS, which is a non-local equation containing averages over nonlinear



expressions of the time history of the response. This is further reformulated by applying the Extended Novikov-Furutsu Theorem [6], which leads to another form of SLE containing averages over the transition matrices of the variational problems associated with the given RDS (time-varying linear IVPs). This equation is exact, yet non-closed. The novel closure applied to this equation is based on a decomposition of response in its local (in time) mean value and its fluctuation around it. Then, we apply a current time approximation to the fluctuating part, keeping in full the effect of the local mean value, which is expressed as a time-history term of some moments of the response. In that way we obtain our final, efficient FPK-like equation, which is closed, yet nonlinear and nonlocal. This equation reduces to the usual multidimensional FPK equation in the case of delta-correlated excitation. Further, it reduces to a linear PDE in the case of a linear RDS, providing the well-known Gaussian solution. Numerical results for the new nonlinear, nonlocal equation are provided for a bistable Duffing oscillator under Gaussian excitation with correlation time 0.92. The obtained pdf compares well with Monde Carlo simulations.

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Handling incomplete information: Gini coefficient from coarse-grained data

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Acquiring income or wealth data at agent-level for large social systems is an experimentally challenging task [1, 2]. The absence of such exhaustive data poses significant difficulties for accurately characterizing the level of inequality in social systems, particularly when it comes to calculating the commonly used Gini coefficient. To overcome this challenge, we introduce a novel methodology that enables a better computation of the Gini coefficient using only the average income or wealth and population at a lower hierarchical level, such as settlements or communes. Our approach is based on the assumption that a one-parameter wealth/income distribution is valid at the lower organizational level, and we validate this hypothesis using various data sources. These include exhaustive income data for Cluj county, Romania and average income data at the settlement level, as well as percentile and average income data for settlements from Hungary and the United States. Our methodology provides a compact analytical formulae that allows the calculation of the Gini coefficient from datasets where only statistical information, like population and measures of general well-being (i.e. average income or wealth), are available for the lower hierarchical level. Although, the proposed approach has its limitations, it represent a significant step forward in quantifying inequality in large social systems. In contrast to traditional Gini coefficient calculation methods based on statistical data, which can often lead to coarse-graining of inequalities at lower level, our methodology provides a more accurate estimation of the inequality level.

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Towards full-network modeling of large power grids

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The renewable energy transition poses new challenges for existing power grids by introducing larger and more unpredictable fluctuation of energy production in both space and time. We model the the synchronization dynamics on large power grids using the second-order Kuramoto coupled oscillator model. Our goal is to predict both the behavior of synchronized networks as well as the resiliency of networks against perturbations such as line or node failures.

In a recent study [1], we simulate the model on real high-voltage grid data from the US and EU by direct numerical integration of the second-order Kuramoto equation. These networks, with 4194 and 13478 nodes, respectively, are highly modular with topological dimensions above two. We investigate the local synchronization in the steady state using the local Kuramoto order parameter and local power flows, revealing topological hot-spots in the networks. Considering a line failure model where links between neighboring nodes with a power flow exceeding a threshold T are cut dynamically, we investigate line failure cascades triggered by perturbations in the form of single line cuts introduced in the steady state. Near the critical value coupling parameter K the size distributions of these cascades follow power laws depending on T and an islanding effect leading to a new steady state is observed.

In the future we plan to study even model detailed representations of real power grids by including medium-and low-voltage levels into the networks to better capture topological effects present in real network, including rare regions. These studies are enabled by a GPU code, which we developed specifically to efficiently handle numerical integration on these sparse modular graphs. Here, we present the above-mentioned simulation results and the specific computational optimizations employed to obtain them on large-scale networks with an acceleration of up to two orders of magnitude over CPU. We also present our threshold extension to the Kuramoto model and the various observables computed on-the-fly.

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How to count in hierarchical landscapes: quenched complexity for the spherical models

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Complex landscapes are characterized by their many saddle points. Determining their number and organization is a long-standing problem, in particular for tractable Gaussian mean-field potentials, which include glass and spin glass models. The annealed approximation is well understood, but is generically not exact. Here we describe the exact quenched solution for the general case, which incorporates Parisi's solution for the ground state, as it should. We investigate two explicit examples, one with a 1RSB complexity, and one with a full RSB complexity.

Tradeoff of generalization error in unsupervised learning

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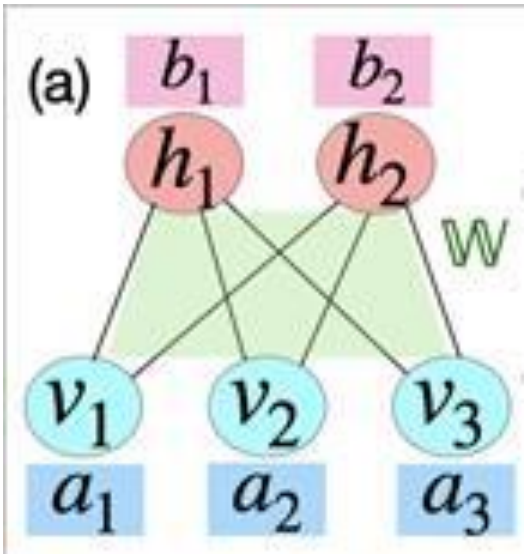
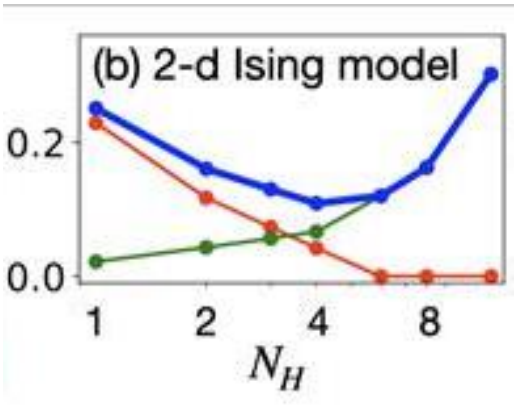
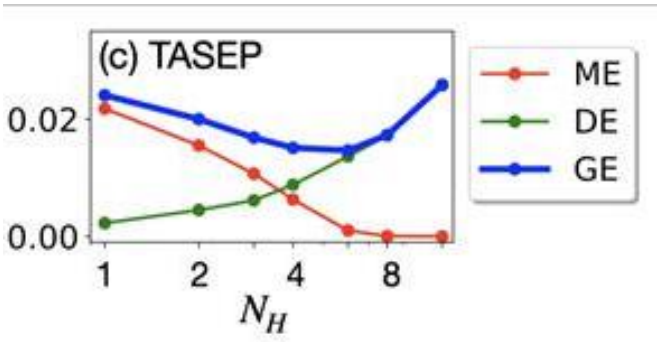
Finding the optimal model complexity that minimizes the generalization error (GE) is a key issue in many machine learning tasks. For conventional examples of supervised learning, it is well known that the GE can be decomposed into two parts, namely the bias and the variance. A too simple model may not be able to capture many features of the given data set, yielding a highly biased training result with low variance (underfitting). In contrast, a too complex model may learn even the sampling noise of the data set, which results in a highly variable training result with low bias (overfitting). In this manner, lowering the bias by making the model more complex typically entails an increase in the variance, inducing the U-shape behavior of the GE with the model capacity. This phenomenon is called the 'bias-variance tradeoff.' In this study, we investigate whether unsupervised learning also exhibits the same tradeoff behaviors by training the restricted Boltzmann machine to generate the steady-state configurations of the two-dimensional Ising model at a given temperature and the totally asymmetric simple exclusion process with given entry and exit rates. In fact, we find that a straightforward generalization of the bias-variance decomposition to unsupervised learning leads to the non-monotonic dependence of the bias on the model complexity. This indicates that the bias–variance decomposition is not useful for describing the generalization behaviors of unsupervised learning. Instead, we propose a different decomposition of the GE, which consists of the model error (ME) and the data error (DE)— the former quantifies the minimum GE achievable by the model, and the latter quantifies the excess error that mainly stems from the sampling error of the training data set. We find that using a more complex model reduces the ME at the cost of the data error, with the data error playing a more significant role for a smaller training dataset. Based on these findings, we claim that the optimal model complexity of unsupervised learning is determined by the 'ME-DE tradeoff.' We also find that the optimal model tends to be more complex when the data to be learned involve more correlations.







Monte Carlo method for active particle dynamics with thermodynamic consistency

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Active particles maintain themselves far from equilibrium by converting ambient or stored energy into self-propulsion. They are known to exhibit various novel collective phenomena, such as motility-induced phase separation, flocking, and current rectification. Recently, there has been a surge of interest in identifying the role of energy dissipation in maintaining such large-scale nonequilibrium structures. Since the models of active particles are typically very challenging to solve analytically, developing an efficient numerical method for investigating their properties is a task of great importance. Lattice-based Monte Carlo methods provide efficient means of computing the universal scaling properties of many-particle systems. For equilibrium systems, there are well-established Monte Carlo methods based on the ensemble theories. In contrast, for active particles, the lack of ensemble theories means that one must rely on the kinetic Monte Carlo (KMC) methods that properly discretize the dynamics in space and time so that the continuum description is restored in an appropriate limit. A recently proposed KMC method achieves this goal by probabilistically mixing 'passive' steps with active ones. However, the method focuses only on the kinetics of the system, completely ignoring its energetics. If one is also interested in calculating the thermodynamic cost of maintaining a certain dissipative structure, a KMC method with well-defined energetics is needed. In this study, we present a thermodynamically consistent KMC algorithm describing both kinetics and energetics of active particles. Towards this purpose, we construct a model of active lattice gas whose jump probability does not only satisfy the local detailed balance condition but also involves the prefactor which explicitly depends on the self-propulsion. The model correctly reproduces the continuum dynamics in the proper limit, all the while allowing us to quantify how far from equilibrium the system is by calculating the energy dissipation. We demonstrate that the characteristic phenomena of active matter, such as motility-induced phase separation, current rectification, and accelerated phase segregation are well reproduced by our model. Moreover, our method reveals which part of the system dissipates more energy as the active particles maintain a nonequilibrium structure. These results are compared with those of previous studies that used effective field theories.

A game-theory-inspired reinvestigation of the Blume–Capel model

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Two-player interactions in evolutionary game theory are typically represented by matrix games. Recent research into the linear decomposition of square matrices has revealed a complete set of payoff matrices that define just four fundamentally different, archetypal interaction situations: elementary self- and cross-dependent, coordination, and cyclic-dominance games [1]. The general, n-strategy elementary coordination game and its combinations with a self-dependent game component that retains its symmetry [2] – when played according to the logit strategy update rule by numerous players located at the sites of a square lattice against their nearest neighbours – can be shown to be equivalent to a Blume–Capel model with a temperature-dependent crystal-field coupling through a consistent bunching of its n-2 neutral strategies into single strategy affected by an additional noise-level-dependent self-dependent game component, making the Blume–Capel model an ideal starting point for the systematic study of the interplay of elementary games. Here, I corroborate these analytic findings with numerical results obtained using the tensor renormalization group method introduced by Michael Levin and Cody P. Nave [3] by reinvestigating the phase transitions of the Blume–Capel model along the directions that correspond to elementary coordination games. The results are in good agreement with expectations based on the literature of the Blume-Capel model [4]: They indicate that the phase transitions do indeed occur

at the expected locations and have critical exponents that are consistent with those of the two-dimensional Ising model along the line of continuous phase transitions and vanish for jump-like changes where first-order transitions are expected. I also extend my calculations to the less frequently studied case of when the Blume–Capel model is subjected to a homogeneous external magnetic field. In keeping with earlier mean-field approximation results, first-order transitions can seemingly remain of the first order for small enough magnetic fields and only become smoothed out, unlike the continuous transitions, for stronger magnetic fields.

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Probing quantum phase transitions through entropy in boundary-critical models

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National Yang Ming Chao Tung University

In this talk, we focus on the behavior of the boundary entropy in a class of quantum critical models within a dynamical large-N limit, where N is related to the symmetry group of these models. The quantum phase transitions in these models typically defy a description in terms of a Ginzburg-Landau-Wilson functional. We analyze the leading and subleading scaling behaviors of the boundary entropy across these zero-temperature phase transitions and compare the results to expectations based on the g-theorem which relates the boundary entropy to the renormalization group flow. Our findings show that the g-theorem does not apply. This is due to an anomalous contribution to the scaling function in the hydrodynamic regime, which is absent in the quantum coherent regime. We also compare our results with those obtained for the Sachdev-Ye-Kitaev model.

In collaboration with F. Zamani, P. Ribeiro, Z. Yu.

Generative deep neural networks for topological defects and their microstructure reconstruction in two-dimensional spin systems

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Topological defects and their interactions are highly relevant for many physics fields, especially in spin physics. While being a stable local perturbation of an underlying field, on larger length scales topological defects can be described as point-like particles characterised by their winding number. The range of the associated deformation field around each of their core is very large. One consequence of this is, e.g., the existence of a phase transition induced by topological defects, the so called Berezinskii-Kosterlitz-Thouless phase transition. Due to the multiscale character of topological defect structures and their long range correlation, numerically simulating a large number of them in full microscopic detail is computationally extremely demanding. As a possible solution for this problem, we propose to use generative neural networks to bridge between the macroscopic description of a model with topological defects and its underlying microscopic field. With data from a spin dynamic simulated microscopic model, we train our physics induced conditional generative adversarial network system [2] with a loss-function based on the Wasserstein-metric [3,4] (WGAN) to generate realistic spin configurations from given defect configuration inputs. The training process of the WGAN is split into two steps. An initial pretraining process and a global training with customisable physical constraints as additional input, such that the trained WGAN can generate full physically realistic spin fields from given defect position configurations. The resulting neural network backmapping tool provides the opportunity to construct representative sets of microscopic spin configurations of magnetic materials from topological defect distributions and other input parameters, such as temperature and magnetisation. Possible applications include the enhancement of large and complex simulations as

well as the more in-depth analysis of experimental data.

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Physical consequences of non-additive and non-extensive entropies

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In recent years various generalizations of entropy have been employed to examine other issues from statistical perspective. These include applications of non-extensive entropy in deriving GUPs, which are of interest due to allowing to account for minimal length scale (of relevance in quantum gravity, and modified relativity schemes); or applications of non-additive entropy to cosmological problems. In this we investigate combined impact of considering both non-additive and also non-extensive entropy on these problems. To that end we will be employing two-parameter entropic functionals $S_{q,\delta}$ introduced by Tsallis.

An improved indicator for causal interactions in non-linear systems

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Employing methodologies from the field of empirical dynamic modeling of non-linear systems, we revisit the problem of inferring a causal relationship between two variables when a delay between cause and effect is present. Using time series obtained from numerical and experimental data we demonstrate that the usual cross mapping criterion for causality, between time-delayed embedded reconstructions of the state space, can be enhanced when one takes into consideration the similarity between observed and predicted embedded vectors. We apply these methods on weekly mosquito abundances in northern Greece in order to ascertain how various environmental variables affect mosquitoes as well as the degree of interaction between spatially separated populations. Since mosquitoes can be vectors of viral diseases these results indicate the usefulness of empirical dynamic modeling techniques in guiding the construction of more realistic forecasting models as well as vector control strategies and health policy assessments.

Heterogeneous endosomal dynamics within eukaryotic cells

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Transport processes of many organelles inside living cells display anomalous diffusion defined by the non-linear growth of the mean squared displacement. This means that the movement of these organelles deviates from Brownian diffusion, but rather they move in a complicated manner. One such organelle is endosomes in eukaryotic cells. Endosomes play an essential role in the transport of molecules such as proteins and lipids within cells. However, the transport of these structures is not uniform, and they are heterogeneous in space and time. In eukaryotic cells, endosomes form a highly dynamic and heterogeneous network which is comprised of various forms of early and late endosomes, each with distinct structures and functions1. The endosomal network plays a major role in sorting and transporting proteins and lipids that are taken in from the cell surface and need to be delivered to lysosomes for degradation. Early endosomes, formed by the budding of clathrin-coated vesicles, are characterized by their high levels of Rab5, a small GTPase protein. Late endosomes, on the other hand, are characterized by lower levels of Rab5 and higher levels of Rab72. Rab5 early endosomes move towards the cell nucleus via dynein3, fuse with one another, increasing in size, and change in membrane composition. The open question remains: how does the heterogeneity of the endosomal network influence endosomal dynamics? To understand the complexity of endosomal transport, large ensembles of single particle trajectories are studied. These ensembles allow the heterogeneities to be quantified in detail and provide insights for mathematical modelling. Accurate mathematical models for heterogeneous dynamics have the potential to enable the design and optimization of various technological applications, such as the design of effective drug delivery systems. The central questions in the analysis of anomalous dynamics are ergodicity and statistical ageing. Ergodicity means that a system will eventually explore all possible states, whereas statistical ageing means that the dynamics of a system change over time. These two concepts are important in selecting the proper model for the description of anomalous dynamics. It is believed that non-ergodicity and ageing come together, but this is not always the case. Endosomal transport is paradoxical since it is ergodic but shows ageing. This behaviour is caused by ensemble heterogeneity, which is an inherent property of endosomal motion. In addition to space-time heterogeneity within a single trajectory, there is heterogeneity across the ensemble of endosomes. The discovery of the paradoxical behaviour of endosomal transport introduces novel approaches for the analysis and modelling of heterogeneous dynamics. These approaches can be used to develop more accurate mathematical models that can help design and optimize technological applications, such as drug delivery systems. The study of endosomal transport provides valuable insights into the complexities of transport processes within living cells. By understanding the heterogeneities of transport processes and developing accurate mathematical models, we can design and optimize technological applications that can greatly benefit human health.

State selection in driven out of equilibrium systems – noisy stabilized Kuramoto-Sivashinsky equation

John Michael Kosterlitz
Brown University, Providence, Rhode Island, United States

This talk discusses the problem of pattern selection in driven out of equilibrium systems by stochastic noise by two methods: (i) Computer simulation of Langevin equation and (ii) construction of a potential and minimizing this. Both methods work for a test case – a stabilized Kuramoto-Sivashinsky equation with additive stochastic noise which is essential for selecting a unique stationary state at late time. The second method is mainly analytic and the state minimizing the potential agrees with the numerical result.

Exact results from approximate theories at critical points from a renormalization group treatment

John Michael Kosterlitz
Brown University, Providence, Rhode Island, United States

In this talk I will discuss how the renormalization group can yield exact predictions from approximate theories and how some of these lead to experimentally measurable quantities. The best known are the discontinuity in the measured superfluid density in thin films of ^{4}He and in the Young's modulus of a 2D colloidal crystal trapped at an air/water interface. Some other theoretical results will be discussed but these are more difficult to test experimentally.

Application of g-subdiffusion equations with the fractional Caputo time derivative with respect to another function in modeling of anomalous diffusion processes.

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Institute of Physics, Jan Kochanowski University, Kielce, Poland, Kielce, Poland

We consider a g-subdiffusion equation with a fractional Caputo time derivative with respect to another function g [1-6]. We derive the equation by means of a modified continuous time random walk model (the g-CTRW model) [2]. An interpretation of g-subdiffusion is that it is the ordinary subdiffusion process with a changed time scale controlled by a deterministic function g. The g–subdiffusion equation is shown to be quite general. Changing of a time scale can lead to changes in diffusion parameters and/or in the type of diffusion. Thus, the g-subdiffusion equation offers different possibilities for modeling diffusion, such as a process in which a type of diffusion evolves continuously over time. The g-subdiffusion equation can be solved by means of the g-Laplace transform method; the g-Laplace transform is a generalization of the "ordinary" Laplace transform [1,2]. By defining the function g appropriately, the equation describes a smooth transition from "ordinary" subdiffusion to other processes such as ultraslow diffusion [1], "ordinary" subdiffusion with changed parameters [3], and superdiffusion [6]. In the transition from subdiffusion to superdiffusion, the fundamental solution (the Green's function) for the g-subdiffusion equation takes the form of Green's function for superdiffusion described by the equation with the fractional Riesz derivative with respect to a space variable. We conclude that for a sufficiently long time the g–subdiffusion equation describes superdiffusion well, despite a different stochastic interpretation of the processes. Then, paradoxically, a subdiffusion equation with a fractional time derivative describes superdiffusion. The superdiffusive effect is achieved here not by making anomalously long jumps by a diffusing particle, but by greatly increasing the particle jump frequency. Some methods used in modeling of "ordinary" subdiffusion processes, such as the derivation of local boundary conditions at a thin partially permeable membrane, can be used to model g–subdiffusion processes, even if this process is interpreted as superdiffusion. We also use the g-subdiffusion equation to describe anomalous diffusion of antibiotic (colistin) in a system consisting of packed gel (alginate) beads immersed in water. Experimental results show that this process cannot be described by the "ordinary" subdiffusion equation with constant parameters. However, the g-subdiffusion equation with the function g derived from empirical data can be used to describe this process which is interpreted as subdiffusion with changing subdiffusion parameter (exponent) [4]. In addition, there is considered g-subdiffusion process of molecules that can be annihilated with a constant probability independent of time; molecule anihilation equation also includes the g-Caputo fractional derivative [5]. Such g-subdiffusion-anihilation model can be used to describe antibiotic diffusion in a bacterial biofilm.

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Nonlinear electrostatic waves in non-Maxwellian Space plasmas: overview of recent advancements

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This presentation aims to provide an overview of the current state of the art in regards with the formation and dynamics of electrostatic nonlinear structures in Space plasmas. Some of the topics to be covered include electrostatic solitary waves (ESWs) in non-Maxwellian Space plasmas [1], supersolitons [2] and flat-topped solitary waves, related to different types of bipolar pulses occurring in Space observations. We will discuss the underlying mechanisms involved in the formation and propagation of these structures, and how these are manifested at different spatiotemporal scales in various plasma situations. In particular, we shall focus on non-Maxwellian planetary environments, where kappa-distributed electrons are observed, and on how suprathermal electrons statistics may affect the morphology and propagation characteristics of ESWs. Some recent results [3-5] regarding the structural characteristics of "non-conventional" ESW waveforms occurring on planetary magnetospheres (e.g. flat-top solitons, supersolitons) will be presented and discussed.

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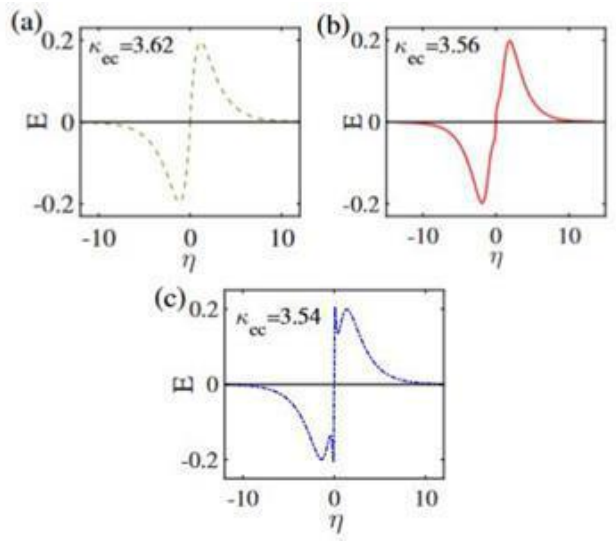

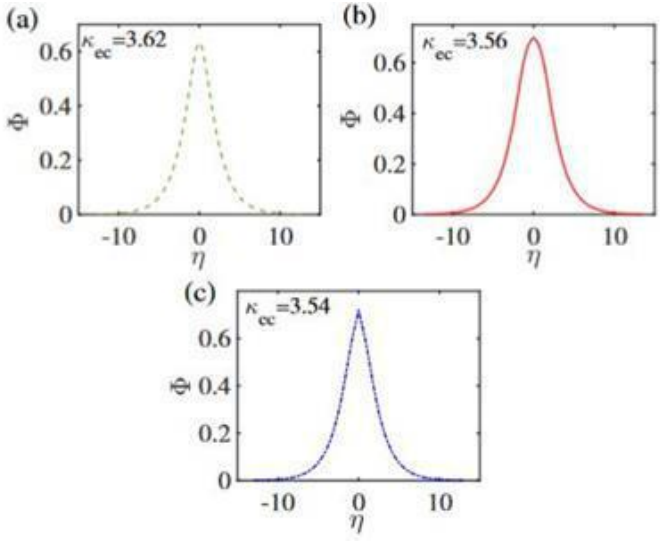

Spatial and temporal cluster tomography

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As we address systems of increasing complexity, it becomes ever more challenging to identify the relevant order parameters to characterize different phases and the corresponding transitions. At the same time, pattern formation in complex systems often leads to distinct clusters or regions. The emerging cluster structures span from magnetic domains in classical and quantum systems through flocks and brain regions to motility-induced phase separation in active matter. Here, we discuss the concept of cluster tomography, a simple and efficient geometric approach to detect phase transitions and characterize the universality class in any classical or quantum system with a relevant cluster structure, both in- and out-of-equilibrium.

Such measurements have been inspired by studying entanglement properties at quantum phase transitions, like the von Neumann entropy. On many occasions, the critical point can be located even without access to an order parameter, solely based on quantum information patterns. Subsequently, using tools from conformal field theory, we have considered the classical ‘cluster’ counterparts of such quantum methods, revealing new universal insights in variations of the Potts model in both two and three dimensions.

In the simplest application of spatial cluster tomography, we consider the N(L) number of clusters intersected by a line of length L. As expected, to leading order, N(L)=aL, where 'a' depends on the microscopic details. In this talk, we will show that in a broad range of classical and quantum systems, critical points are indicated by an additional nonlinear ‘corner term’ in the form of b*ln(L), where 'b' is universal. We also introduce the analogous concept of temporal cluster tomography, motivated by the concept of burstiness in the area of complex network dynamics. These methods are just two aspects of a unified cluster tomography framework, characterizing the geometric complexity of a system via the statistics of low-dimensional cross-sections, akin to a geometric notion of susceptibility.

In spatial cluster tomography, the corner term is an integrated statistics over the so-called gap-size statistics, n(s). Indeed, each cross-section in each cluster can be viewed as a one-dimensional ON-OFF process, where ON events correspond to sites of a specific cluster and OFF periods to the lack of them. n(s) is then the inter-event ‘time' statistics between the ON events along the cross-section. Analogously, in temporal cluster tomography, we study the inter-event time distribution between ON events, where ON events indicate that a pair of particles belong to the same cluster. By quantifying the relative width of this distribution over all particle pairs, we can detect different phases with or without dynamical complexity, quantified by the burstiness parameter $B=(\sigma-\tau)/(\sigma+\tau)$. Here τ and σ stand for the mean and standard deviation, and B quantifies the distance from a random, Poisson distributed time series (B=0) with no dynamical complexity, i.e., no memory. B>0 is known as bursty dynamics, e.g., with cascades and avalanches, leading to broad inter-event time distributions. B<0 indicates regular dynamics, with a characteristic inter-event time scale. Various phases and the corresponding transitions are expected to be characterized by different levels of burstiness.

Individual bias and fluctuations in collective decision making: analytical results and simulations

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We reconsider the spin model suggested recently to understand some features of collective decision making among higher organisms [1]. Within the model, the state of an agent i is described by the pair of variables corresponding to its opinion Si=±1 and a bias ωi towards any of the opposing values of Si. Collective decision making is interpreted as an approach to the equilibrium state within the non-linear voter model subject to social pressure and a probabilistic algorithm. Here, we push such physical analogy further and give the statistical physics interpretation of the model, describing it in terms of the Hamiltonian of interaction and looking for the equilibrium state via explicit calculation of its partition function. We show that depending on the assumptions about the nature of social interactions two different Hamiltonians can be formulated, which can be solved with different methods. In such an interpretation the temperature serves as a measure of fluctuations, not considered before in the original model. We find exact solutions for the thermodynamics of the model on the complete graph. The general analytical predictions are confirmed using individual-based simulations. The simulations allow us also to study the impact of system size and initial conditions in the collective decision making in finite-sized systems, in particular with respect to convergence to metastable states. We discuss advantages and flaws of such an approach as well as its utility to understand impact of population heterogeneity, type of local interaction and fluctuations on the collective decision making. [2].

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Potts model with invisible states: changeover to the percolation transition

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Within scarcely a decade of its appearance, the Potts model with invisible states (ISPM) [1] attracted significant interest (see a review on this model for more details [2]). This interest is due to the prominent feature of the model that allows changing the strength and even the order of the phase transition by continuously tuning the model parameters, keeping other global features like space dimensionality, interaction range and symmetry unchanged. It has been used to interpret the possible changes in the order of the percolation transition. Although the percolation transition is known to be a continuous one [3], in the real world there exist connectivity problems that are clearly abrupt and need conceptual understanding and quantitative treatment [4]. The results obtained for ISPM on the complete graph [5] and on an annealed scale-free network [6] prove that the addition of invisible states can lead a phase transition in the percolation limit $q \to 1$ of the standard Potts model to become a first order transition. In this way one more mechanism is suggested to achieve a discontinuous percolation transition. This

mechanism differs from those of explosive percolation, bootstrap percolation, cascade of failures in inter-dependent networks and hybrid percolation on multiplex interdependent Erdős–Rényi networks.

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Relaxation dynamics in classical and quantum supercooled liquids

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Supercooled state of a liquid is characterized by extremely slow and spatially heterogeneous dynamics. Being a low temperature phenomenon, the properties of supercooled liquids are expected to be affected significantly by quantum fluctuations, atleast for light molecules [1,2,3]. Quantum liquids show high degree of dynamic heterogeneity at short times, which is weakly dependent on the degree of quantumness as quantified in terms of the thermal de-Broglie wavelength associated with a particle. This is in contrast to the classical case, where the dynamic heterogeneity is zero for short times. These non-classical features arise due to the initial uncertainty in the quantum particle's position [4,5]. The dynamic heterogeneity in the intermediate time scales arises from the caging of particles by the neighbors, and the subsequent slowdown of dynamics. We compare the static and dynamic properties of cages in the classical [6] and the quantum supercooled liquids. The cage size fluctuations decrease with decreasing temperature in the classical case. A similar effect is seen in the quantum case with increasing quantumness in the moderate quantum regime.

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Ion acceleration at filamentary structures downstream of the earth' s bow shock: MMS and wind observations

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The Earth's bow shock is the place where most of the solar wind's kinetic energy is partitioned into wave energy, particle acceleration, and heating. Very recent publications provide strong evidence that current sheets at the shock ramp region and downstream may participate in the thermalization of the solar wind plasma. Their occurrence varies from single to multiple current sheets, reconnecting or not reconnecting, as well as filamentary structures. These structures are often associated with turbulence mediating particle distributions. We investigated several quasi-parallel/quasi-perpendicular bow shock crossings by the MMS spacecraft with its sophisticated instrumentation, characterizing and quantifying the occurrence of filamentary structures, current sheets, the associated magnetic field wave turbulence, and ion acceleration downstream of the shock. The associated turbulence is likely a mediator for energy partition. These MMS observation indicate that current sheets and field gradients are associated with ion acceleration. The associated turbulence is likely a mediator for energy partition. During some

traversals the shock location was changing due to variable upstream solar wind conditions. This happened during times of increasing Mach number/dynamic pressure. At these times we observe higher wave activity and broader distribution functions with suprathermal tails. Much less suprathermal ions downstream of the shock are observed at shock crossings during decreasing upstream Mach numbers. It is known that with increasing Mach numbers, the bow shock moves away from the Sun and compresses the magnetosheath that would favour reconnection of currents sheets, stronger electric field gradients and thus ion acceleration. At periods of decreasing upstream Mach numbers, the bow shock moves towards the Sun, becomes blunter, and the sheath region relaxes, making reconnecting current sheets less likely and smoothens field gradients resulting in less acceleration. Other possible acceleration mechanisms will also be discussed in the context of this presentation. The shape of and the power law of the observed distribution function with suprathermal tails. These tails and the power law index will provide us important information on the processes that cause acceleration.

Heternogeneous micro-structure of percolation in complex networks: theory and applications

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We review a message passing (or cavity) approach [1,2] that is able to uncover and analyze a considerable degree of microscopic heterogeneity in the percolation problem on complex networks. Indeed, the probability for individual nodes of a complex networks to remain part of the giant connected component (GCC) or percolating cluster, when bonds or nodes are randomly and independently removed with some given probability varies considerably across a network. Average percolation probabilities which measure the fraction of nodes that belong to a GCC are just the first moments of distributions of percolation probabilities. We evaluate these distributions, both on single large graph instances, and for configuration models in the thermodynamic limit. The underlying message passing approach can also be used to locate articulation points vertices whose removal would break the cluster on which they sit into two or more smaller components. We discuss applications in the context of SIR/SEIR epidemics and in approaches to efficient network dismantling strategies [3,4].

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Non-equilibrium statistical mechanics of dilute astrophysical plasmas

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The transport of energy and momentum and the heating of plasma particles by waves and turbulence are key ingredients in many problems at the frontiers of heliospheric and astrophysics research. This includes the heating and acceleration of the solar wind; the observational appearance of black-hole accretion flows on event-horizon scales; and the properties of the hot, diffuse plasmas that fill dark-matter halos. All of these plasmas are magnetized and weakly collisional, with plasma beta parameters of order unity or even much larger. In this regime, deviations from local thermodynamic equilibrium (LTE) and the kinetic instabilities they excite can dramatically change the material properties of such plasmas and thereby influence the macroscopic evolution of their host systems. Departing from the astronomical tradition of abstracting these physics into crude, sub-grid prescriptions, this talk outlines an ongoing programme of kinetic calculations aimed at

elucidating from first principles the multi-scale physics of waves, turbulence, instability, and transport in magnetized, weakly collisional astrophysical plasmas. Effective "collision operators" describing the interaction between plasma particles and microscale kinetic instabilities driven by departures from LTE will be presented, alongside a witches' brew of self-defeating Alfvén waves, self-sustaining sound waves, and microphysically modified magnetosonic modes.

Stability of power grid concerning tropical cyclones: Increasing resilience by protecting critical lines

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Power grids are characterized by multistability. For power grids, the strongly ongoing transition to distributed renewable energy sources leads to a proliferation of dynamical actors. The desynchronization of a few or even one of those would likely result in a substantial blackout. Thus, the dynamical stability of the synchronous state has become a leading topic in power grid research, in particular for rather strong perturbations where traditional linearization-based concepts are not appropriate. First, we discuss the concept of basin stability and its estimation even in high-dimensional systems. Considering the vulnerability of power grids against extreme wind loads and, consequently, increasing its robustness to withstand these events is of great importance. Here, we combine a detailed model of the climatic drivers of extreme events, and a cascadable model of the transmission network to provide a holistic co-evolution model to consider wind-induced failures of transmission lines in the Texan electrical network. The proposed modelling approach coulda tool so far missing to effectively strengthen the power grids against future hurricane risks even under limited knowledge.

Thermalization of weakly non-integrable Josephson junction networks

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Statistical mechanics (SM) is, in many ways, considerably more general than either classical or quantum mechanics: as long as one knows how to write a partition function, the statistical formalism can be applied. A cornerstone assumption for such generality is the ergodic hypothesis, which allows us to average over ensembles of similarly prepared systems rather than time. This is definitely not true for integrable systems, in which motion is always confined to lower-dimensional submanifolds and, therefore, thermalization is never achieved. It is then natural to wonder how thermalization is suppressed as a system approaches an integrable limit: Is integrability reached through an universal mechanism? How long does it take? Does it happen isotropically?

In this talk I will expand on results previously published by our group, namely that there appear to be two main pathways towards integrability, each with markedly distinguishable features. While previous investigations were focused on abstract discrete unitary maps, I will present results obtained for one- and two-dimensional networks of hundred(s) of coupled Josephson junctions. Such a generalization from maps to high-dimensional Hamiltonian systems is quite a formidable computational task, some aspects of which I will also briefly expose in the presentation.

A sunburst of solutions in the continuous negative perceptron

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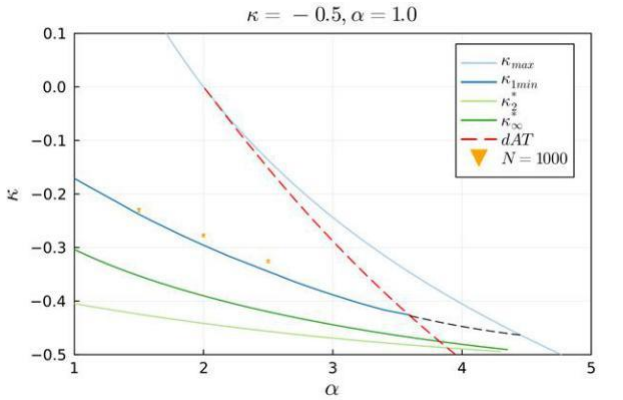
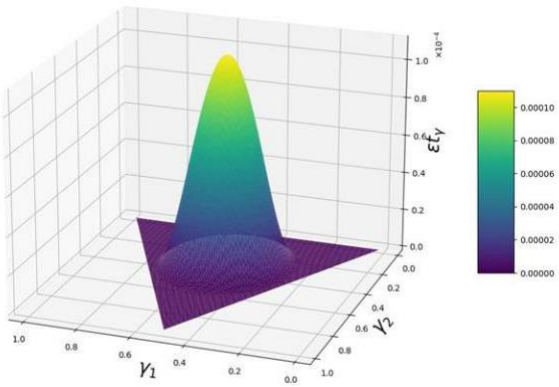
The landscape properties of high-dimensional constraint satisfaction problems (CSPs) can completely determine the type of configurations that can be efficiently sampled from their space of solutions. In recent years, empirical studies on the landscape of neural networks have shown that low-lying configurations are often found in complex connected structures, where zero-energy paths between pairs of distant solutions can be constructed. In the present work, we investigate the connectivity of solutions in the negative perceptron, a linear neural network model and a prototype of a non-convex continuous CSP. We introduce a novel analytical method for characterizing the typical energy barriers between groups of configurations sampled from the zero-temperature measure of the problem. We find that, despite the overall non-convexity of the space of solutions, below a critical density of constraints $_\star$, the geodesic path between any solution and the robust solutions of the problem, located in the interior of the solution space, remains strictly zero-energy. We study the shape and the anisotropy of the connected space of solutions, and numerically characterize a sharp transition where the simple connectivity property breaks down.





Learning through atypical “phase transitions” in overparameterized neural networks

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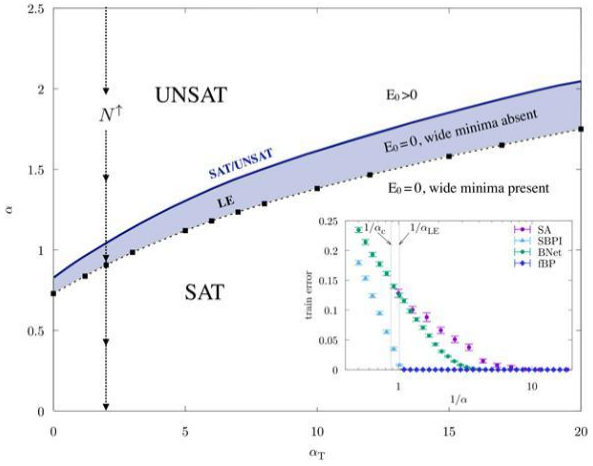
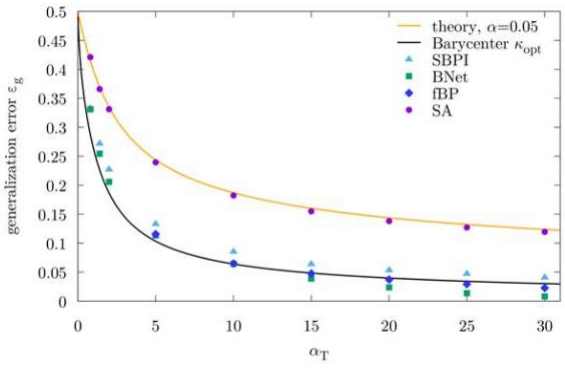
One of the most debated themes in machine learning is how to characterize deep neural network performances. These are highly overparameterized devices in which the number of parameters far exceed the number of data points whose abilities can be studied in terms of the structure of the loss landscape and by focusing on how the learning algorithms minimizing the loss affect their generalization properties. In this talk I will specialize on a non-convex model of random features (i.e. a





two layer neural network) in order to shed new light on the mistery of overparameterization: given the large amount of connection weights to be adjusted, one would expect them to overfit the training dataset but, surprisingly, this is not the evidence. Once the choice of model has been justified, I will illustrate why having a way to geometrically characterize solutions in the energy landscape in terms of their stability parameter is highly correlated with the network performances. Thus, with the support of an analytical conjecture, we identify a novel (non-equilibrium) phase transition in the geometrical structure of the error counting loss, i.e. what we call the "Local Entropy" transition. It is controlled by the degree of overparameterization of the system and is definitely different from the common SAT/UNSAT threshold. It coincides wih the detection of locally entropic minima of solutions which seems to be highly attractive to the learning algorithms exhibiting good generalization properties.

Coupled electrostatic wavepackets in plasmas: on the role of kappa-distributed electrons on the onset and growth rate of modulational instability.

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Electrostatic wavepackets in plasmas have been investigated with respect to the modulational instability (MI), a mechanism known from nonlinear optics that may lead to energy localization and to the emergence of localized structures (envelope solitons). For a single wave, the plasma fluid model can be reduced to a nonlinear Schrodinger (NLS) equation by using a multiple scale perturbation method [1]. The MI of propagating waves and the existence of localized wavepackets is then investigated within the NLS framework. However, co-propagation and interactions of two or more wavepackets in a plasma fluid remains largely unexplored. A pair of co-propagating electrostatic wavepackets with different carrier wavenumbers is considered in a 1D collisionless unmagnetized plasma, consisting of a cold (inertial) ion fluid and suprathermal, kappa (κ-) distributed electrons. The plasma fluid model is reduced by using a multiple scale (Newell) technique to an a-symmetric pair of coupled NLS (CNLS) equations for the respective wavepacket amplitudes. The dispersion, nonlinearity and cross-coupling coefficients have been calculated as functions of the plasma parameters and the electron spectral index (kappa) [2, 3]. A detailed MI analysis has been performed to determine the instability window and the corresponding growth rate [4, 5] and to investigate, from first principles, their dependence on the carrier wavenumbers and on the spectral index κ of the electron distribution. Space relevant values of kappa [2] in the range from 2 to 6 are adopted, in comparison with the large kappa regime for which

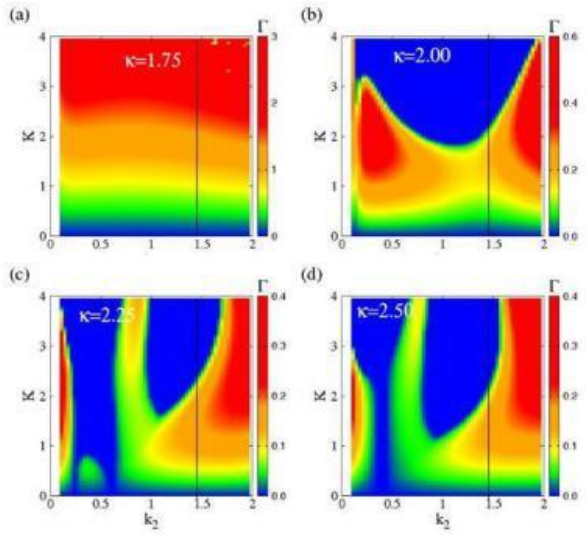

Figure 7: Maps of the growth rate Γ on the $k_2 - K$ plane for (a) $\kappa = 1.75$; (b) $\kappa = 2.00$; (c) $\kappa = 2.25$; (d) $\kappa = 2.50$. The other parameters as in Fig. 6. The vertical black-solid line indicates the boundary between two different regimes of the decoupled CNLS equations, i.e., the stable-stable regime for which $P_1Q_{11} < 0$ and $P_2Q_{22} < 0$ ($k_2 < k_r$, left from the vertical line) and the stable-unstable regime for which $P_1Q_{11} < 0$ and $P_2Q_{22} > 0$ ($k_2 > k_r$, right from the vertical line). Note that k_r depends weekly on the spectral index κ, but the differences cannot be observed in this scale.

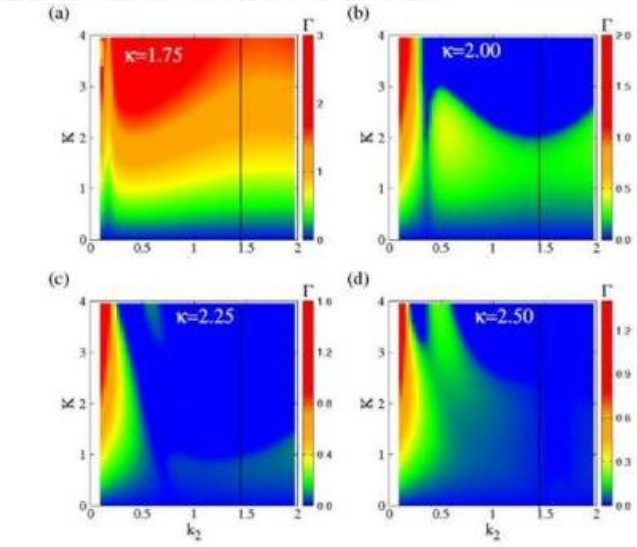

Figure 11: Maps of the growth rate Γ on the $k_2 - K$ plane for (a) $\kappa = 1.75$; (b) $\kappa = 2.00$; (c) $\kappa = 2.25$; (d) $\kappa = 2.50$. The other parameters as in Fig. 10. The vertical black-solid line indicates the boundary between two different regimes of the decoupled CNLS equations, i.e., the unstable-stable regime for which $P_1Q_{11} > 0$ and $P_2Q_{22} < 0$ ($k_2 < k_r$, left from the vertical line) and the unstable-unstable regime for

the behavior is practically of Maxwell-Boltzmann

type. A calculation of growth-rate patterns on two-dimensional parameter spaces reveals that most of the variation occurs in the range of kappa from 2 to 3. The region of kappa between 3 and 6 presents some quantitative variation but is qualitatively uniform, practically. For kappa less than 2, wave propagation is modulationally unstable in most parts of the explored parameter spaces with very large growth rates.

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Odd elasticity in disordered chiral active materials

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Chirality, first proposed as handedness of a material's shape, can also refer to motion or trajectory of a preferred helical or rotational direction. This dynamic chirality is abundant in biological systems, of which the components become active via constant energy consumption (e.g., ATPs) to generate local stresses and/or torques. Examples include microtubules twisted by motor proteins, rotary clusters formed by microorganism or bacterial flagella, microswimmers with asymmetric shape and many more. These chiral active materials can exhibit unusual dynamics and mechanics due to breaking time reversal symmetry via energy injection and breaking parity via chirality. Among them, biological active gels with chiral components are frequently encountered, e.g., cytoskeleton (biofilament network) with motor proteins. These gels are generally highly disordered in space, yet can be considered to be isotropic at large scales. In terms of mechanics, they are known to show viscoelasticity with elastic compliance in short timescale. In this talk I will discuss a minimal model for such disordered systems with local active torques as input of chirality. To this aim, I use Cosserat continuum medium for the elastic potential, which accounts for the effect of local orientation of the material components, and thus interplays with chirality (i.e., local active torques). For dynamics, I apply the Poisson-bracket formalism to derive dynamic equations for macroscopic fields from microscopic quantities. This may have the advantage to more easily design or connect with agent-based simulations. Our results show that new elastic moduli naturally emerge due to these active torques in our model. One of them is the so-called odd elasticity, which anti-symmetrically couples two different types of shear deformations and stresses, i.e, one in pure shear and the other in simple shear direction. The other two moduli couple dilation with torques and rotations with pressure, respectively. In comparison with earlier work, which used `lattice' models to obtain odd elasticity, we found this oddity from a disordered model, which shall be closer to real biological systems. I will also discuss the effects of these emergent elastic moduli on elastostatics and elastodynamics of such chiral active materials, as oddity has been shown to exhibit interesting non-reciprocal response.

Can we predict performance of diffusion source localization using navigability?

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A complex network is a network of interconnected nodes, such as a social network, a transportation network or a network of neurons in the brain. One important property of complex networks is the existence of hidden metric spaces. In a hidden metric space, the points represent nodes in the network, and the distances between them reflect the underlying structure of the network. The closer the nodes are in the hidden space, the more likely they are to be linked in the observable topology. However, this structure is not immediately visible in the network itself and may require some analysis to uncover. For example, in a social network, the true underlying metric space could be the distance between two people in terms of their interests or opinions. The most widely-known models of hidden metric spaces are the so-called S1 and H2 models [1].

It has been shown that the underlying hidden metric space gives a significant effect on several observable features of the network, including navigability in the sense of greedy routing algorithm efficiency [2]. Several real-world networks have been recognized as navigable, for instance, the Internet or the air transportation network, meaning that a message or a traveler may find its destination node without knowledge on the entire structure of the network but using only locally-available information. The studies revealed that large small-world networks with power-law degree distribution of nodes tend to be navigable if their power-law exponent is lower than 2.6, i.e., that strong clustering improves navigability metrics.

On the other hand, nowadays, there exist a large number of algorithms to find sources of diffusion or information spread in complex networks. That topic has become particularly important in the face of novel problems as fake news and fake rumors. Methods for that purpose include classes of algorithms based on epidemic models, independent cascades, or centrality measure.

Here, we posed several research questions. Is there straightforward relation between efficiency of the source-finding algorithms and navigability? How do source-finding algorithms behave depending on the hidden metric space underlying the network? Can we (specifically, to what extent and in which conditions) simply predict the performance of the source finding algorithm basing on the known navigability of the network? At first, we considered the model based on time-reversal backward spreading [3] and tested it against S1 model of hidden metric space. First results indicate that, for a small number of observers in the network (e.g., 1%), efficiency of the source localization behaves similarly as navigability, however, it not the case for large numbers of observers (e.g., 10%). Currently, we pursuit to find large-network limit of this relation. Eventual conclusions will allow to establish stronger relationship between diffusion spreading and hidden metric models.

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Coagulating systems revisited with combinatorial approach – possibilities and issues

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Coagulation processes (also known as aggregation or coalescence) are common in nature. They determine a large number of phenomena, such as cloud formation, blood coagulation, milk curdling, traffic jam formation, and even planet formation. Several technological applications are based on coagulation, including formation of polymers and aerosols, food processing, material processing, and water treatment. The classic (deterministic) approach to describing an aggregation process is the Smoluchowski aggregation equation. In this model, the explicit analytical solutions are known for several simple kernels (e.g., constant, multiplicative, and additive) [1]. However, this approach requires an infinite size of the system and continuous cluster concentrations. This model also fails in the case of the so-called gelling kernels, e.g., the multiplicative

(product) kernel. Moreover, the solutions arising from the Smoluchowski aggregation equation are stochastically incomplete describing only the average behavior of clusters and not providing any information on the deviations from the average. Later, a stochastic approach has been proposed by Marcus and developed by Lushnikov. However, being mathematically involved, it allowed to find explicit solutions only for limited number of basic coagulation processes. To overcome the abovementioned disadvantages, a combinatorial approach to finite coagulating systems has been introduced recently [2, 3]. The idea behind this approach uses combinatorial equations to derive exact expressions for cluster size distribution in time. Thus far, this combinatorial approach was used to find solutions to the basic kernels as well as for condensation, electrorheological (linear chains), and a few other kernels in case of the monodisperse initial conditions [4, 5]. It can be extended to cover any arbitrary kernel, including those with some arbitrary parameters, if only the aggregation rate K(i,j) can be written in a required form. The combinatorial approach also provides the expression for the standard deviation of the mean values of the numbers of clusters in the cluster size distribution. However, not all of the expressions obtained in this approach are exact solutions, some being approximate. A debate on this issue arose [6]. In this contribution, I will present the foundations behind the combinatorial approach and describe its application for modelling coagulation processes, with a particular emphasis on the electrorheological coagulation as an example where experimental data were available. Further possible extensions and related troubles will be mentioned.

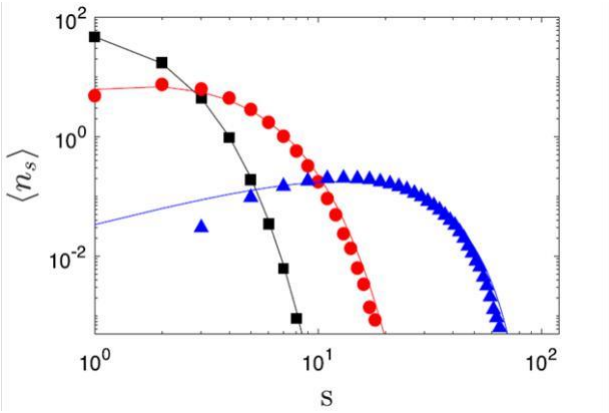

Figure 1: Average number of clusters of given size vs. cluster size for electrorheological coagulation of 100 particles. Points represent simulation, lines – theoretical predictions. Squares, circles and triangles represent three stages of the process.

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Thermalization of isolated harmonic networks under conservative noise

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We study a scalar harmonic network with pair interactions and a binary collision rule, exchanging the momenta of a randomly-chosen couple of sites. We consider the case of the isolated network where the total energy is conserved. In the first part, we recast the dynamics as a stochastic map in normal modes (or action-angle) coordinates and provide a geometric interpretation of it. We formulate the problem for generic networks but, for completeness, also reconsider the translation-invariant lattices. In the second part, we examine the kinetic limit and its range of validity. A general form of the linear collision operator in terms of eigenstates of the network is given. This defines an action network, whose connectivity gives information on the out-of-equilibrium dynamics. We present a few examples (ordered and disordered chains and elastic networks) where the topology of connections in action spaces can be determined in a neat way. As an application, we consider the classic problem of relaxation to equipartition from the point of view of the dynamics of linear actions. We compare the results based on the spectrum of the collision operator with numerical simulation, performed with a novel scheme based on direct solution of the equation of motion in normal modes coordinates.

Spin-glass models for random lasers: how to expose the inner structure of the replica symmetry breaking distribution to experimental measurements

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The experimental measure of the complete equilibrium distribution of the overlap in a replica symmetry breaking thermodynamic phase is a challenging objective since the introduction of the Parisi solution to the Sherrington-Kirkpatrick model. We tackle the problem on a spin-glass-related model in which the spins are, actually, light modes, established and coupled in an optically random medium because of multiple light scattering. In presence of external power pumping, this model reproduces the behavior of glassy random lasers. We present a short journey through the analytic, numerical and experimental properties of mode-locked glassy random lasers.

We first introduce a theory of multimode light amplification in random media. The leading model, derived from fundamental light-matter interaction, is a phasor spin-glass model with multi-mode mode-locking couplings, undergoing an overall intensity constraint induced by gain saturation. Through analytic theoretical approaches, numerical simulations, and experimental measurements we investigate this class of random laser models, displaying properties such as a mean-field lasing phase transition at high power-pumping, displaying ergodicity breaking and (pseudo-)power condensation, glassiness and nonlinear mode-locking. Indeed, Replica Symmetry Breaking theory allows to identify a laser critical point and a glassy light regime. An intensity fluctuation overlap (IFO) parameter is introduced, measuring the correlation between intensity fluctuations of light waves, that is in a one-to-one correspondence to the Parisi overlap. IFO distribution signals the laser transition and the high pumping glassy phase purely in terms of emission spectra data, the only data so far accessible in random laser experimental measurements.

Measuring the importance of individual units to the structure integrity of a complex network

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A network may fail to function due to the depression or deterioration of certain individual nodes (e.g., the 2003 great blackout that darkened much of North America). How to identify the deteriorated/depressed unit(s) is thence of great importance. This study provides an easy and faithful way to fulfill the task, by generalizing information flow, a real physical notion which has just been rigorously formulated with causality naturally embedded (see Liang, 2016, and references therein), to cumulative cases. For a network, given the time series for the units, it is shown that a natural measure is the information flowing/transferring from the unit of concern to the rest units. This flow or transfer can be rigorously derived in the setting of a continuous-time dynamical system, either deterministic or stochastic. Under a linear assumption, a maximum likelihood estimator can be obtained, allowing for an estimation of it in an easy way. As expected, this “cumulative information flow” does not equal to the sum of the information flows to other individual units, reflecting the collective phenomenon that a group is not the addition of the individual members. For the purpose of demonstration and validation, we have examined a network made of Stuart-Landau oscillators. Depending on the topology, the computed information flow may differ. In some situations, the most crucial nodes for the network are not the hubs (i.e., those with highest degrees), in contrast to the traditional point of view; they may have low degrees, and, if depressed or attacked, will cause the failure of the entire network. This study provides an easy yet effective approach to measuring the importance of individual units in producing the collective behavior of a complex network. It can allow us to understand the potential damage to the structure integrity due to the failure of local nodes, and hence help diagnose neural network problems, control epidemic diseases, trace city traffic bottlenecks, identify the potential cause of power grid failure, build robust computer networks, and so forth.

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Causality as a real physical notion ab initio, and causality analysis in climate and environmental sciences

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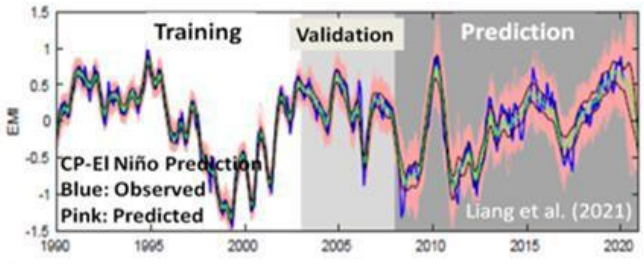
Causality analysis is an important and old problem lying at the heart of scientific research. Causality analysis based on data, however, is a relatively recent development. Traditionally causal inference has been classified as a field in statistics. Motivated by the predictability problem in physical science, it is found that causality in terms of information flow/transfer is actually a real notion in physics that can be derived ab initio, rather than axiomatically proposed as an ansatz, and, moreover, can be quantified. A comprehensive study with generic systems (both deterministic and stochastic) has just been fulfilled, with explicit formulas attained in closed form (Liang, 2016). These formulas are invariant upon nonlinear coordinate transformation, indicating that the so-obtained information flow should be an intrinsic physical property. The principle of nil causality that reads, an event is not causal to another if the evolution of the latter is independent of the former, which all formalisms seek to verify in their respective applications, turns out to be a proven theorem here. In the linear limit, its maximum likelihood estimator is concise in form, involving only the commonly used statistics, i.e., sample covariances. An immediate corollary is that causation implies correlation, but the converse does not hold, expressing the long-standing philosophical debate ever since Berkeley (1710) in a transparent mathematical expression. The above rigorous formalism has been validated with benchmark systems like baker transformation, Hénon map, stochastic gradient system, and with causal networks in extreme situations such as those buried in heavy noises and those with nodes almost synchronized (e.g., Liang, 2021), to name a few. They have also been applied to real world problems in the diverse disciplines such as climate science, dynamic meteorology, turbulence, neuroscience, financial economics, quantum mechanics, etc., with interesting new findings. For example, Stips et al. (216) found that, while CO2 emission does drive the recent global warming, on a paleoclimate scale, it is global warming that drives the CO2 emission; PNA, a teleconnection pattern related to the inclement weather in North America, may trace a part of its origin to a rather limited local marginal sea far away in Asia. Besides, with the above causality analysis, pollution sourcing (particularly PM2.5) can be conducted in an effective way via causal graph reconstruction. If time permits, I will also present an ongoing application to the development of causal AI algorithms to overcome the interpretability crisis, and a recent remarkable exercise with such an algorithm in the forecasting of El Niño Modoki, a climate mode linked to hazards in far-flung regions of the globe (cf. the figure).



El Niño prediction has become a benchmark problem for the testing of machine learning algorithms. The present wisdom is that El Niño may be predicted at a lead time of **1-2 years.** Shown here are 1000 predictions (pink) of the El Niño Modoki index (EMI) using a causal AI algorithm as mentioned in the abstract. Overlaid are the observed EMI (blue), the mean of the realizations (cyan). The light shading marks the period for validation, while the darker shading marks the prediction period---It is more than **10 years** long (from Liang et al., 2021).

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Entropy defect in thermodynamics

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We describe the physical foundations of the newly discovered "entropy defect" as a basic concept of thermodynamics. The entropy defect quantifies the decrease in entropy caused by the order induced in a system through the additional correlations among its constituents when two or more subsystems are assembled. This defect is closely analogous to the mass defect that arises when nuclear particle systems are assembled. The entropy defect determines how the entropy of the system compares to its constituent's entropies. In particular, the existence of long-range correlations between the constituents adds order to the whole system and thus decreases its total entropy, leading to the entropy defect, a term that reduces the simple summation of the constituent entropies. The entropy defect stands on three fundamental properties: each constituent's entropy must be (i) separable, (ii) symmetric, and (iii) bounded. We show that these properties provide a solid foundation for the entropy defect and for generalizing thermodynamics to describe systems residing out of the classical thermal equilibrium, both in stationary and nonstationary states.

In stationary states, the consequent thermodynamics generalizes the classical framework, which is based on the Boltzmann-Gibbs entropy and Maxwell-Boltzmann canonical distribution of particle velocities, into the respective entropy and canonical distribution associated with kappa distributions. The generalized statistical framework is suitable for describing the thermodynamics of systems residing in stationary states out of the classical thermal equilibrium, such as plasma particle populations from laboratory plasmas under extreme conditions and space plasmas throughout the heliosphere and beyond.

In nonstationary states, the entropy defect similarly acts as a negative feedback, or reduction of the increase of entropy, preventing its unbounded growth toward infinity.

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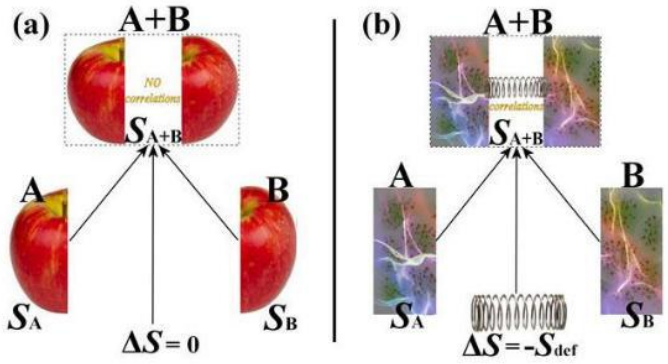

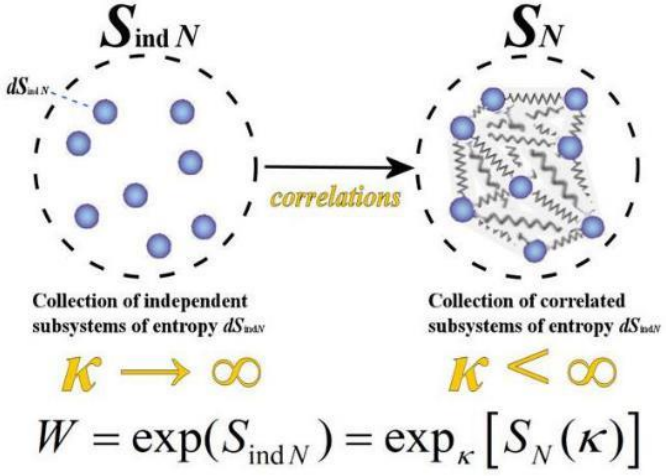

Kappa distributions: Theory and connection to thermodynamics

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Kappa distributions have become increasingly widespread in Space Physics as the power-law nature of various suprathermal tails is merged with the classical Maxwellian cores. Kappa distributions are frequently used to describe particle populations in the heliosphere, from solar wind and planetary magnetospheres to the heliosheath and beyond, the interstellar and intergalactic plasmas. Recent theoretical developments explain the origin of kappa distributions through statistical mechanics and thermodynamics, revealing the robust physical meaning of temperature and kappa that parameterize these distributions. These have been shown to be involved in numerous space plasma properties and processes, e.g., polytropic expansion, particle acceleration and circulation; pickup ions; plasma instabilities, etc. Here we review the recent developments in regards to the theory of kappa distributions and its thermodynamic origin: (1) Kappa distributions maximize the entropy of nonextensive statistical mechanics under the constraints of canonical ensemble; (2) Systems exchanging heat with each other and reaching thermodynamic equilibrium are stabilized always into the formulation of kappa distributions; (3) Polytropic flows are uniquely consistent to kappa distributions and their statistical formalism; and (4) The concept of entropy defect, that is, the decrease of entropy due to long-range correlations among the constituents is one-to-one consistent with the formulation of kappa distributions.

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Statistical physics approach in tipping point analysis

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There exist various methodologies of studying critical phenomena in climate system, ranging from bifurcation theory to machine learning applications. We demonstrate that applying statistical physics (Fokker-Planck equation) and stochastic modelling allows one to obtain early warning signals of tipping events, detect critical transitions, and forecast evolution of a dynamical system, such as the climate system, based on its trajectories (time series or data flows). These techniques follow evolution of critical transitions and constitute tipping point analysis. As a part of it, system potential analysis allows one to analyse system dynamics and detect the changes of the system states (bifurcations), which then can be extrapolated using the dynamically varying system potential. Potential dynamics can be visualised in a multiscale potential plot, where the changing

number of potential states is monitored at different scales, similarly to wavelet analysis. An interesting raising topic in tipping point analysis is the limit of control under uncertainty of early warning signals, which is directly related to climate adaptation. Can we, upon issuing an early warning signal, response in timely manner and prevent critical transitions with adaptation measures? How fast should be the mitigation response with respect to the system dynamics? What are the requirements on observational data and how can statistical physics help prevent critical transitions? We will discuss the ongoing work in this area, including controlled laboratory experiments in international collaborations. Applications include several paleo and modern climate datasets, artificial data simulations and sensor data from environmentally affected installations, in which we apply techniques for uncertainty quantification of early warning signals and for detection of statistically significant transitions. We will discuss them in the context of known climatic phenomena, as well as data-driven discovery of climate anomalies.

Related works

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Explaining the coexistence of oscillations and scale-free avalanches in resting human brain

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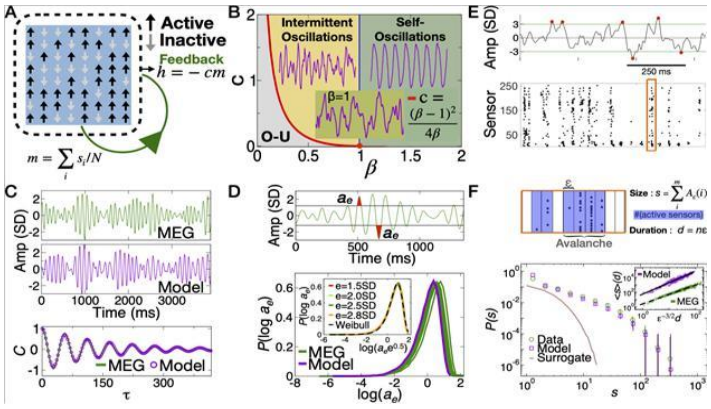
Neurons in the brain are wired into adaptive networks that exhibit a range of collective dynamics. Oscillations, for example, are paradigmatic synchronous patterns of neural activity with a defined temporal scale. Neuronal avalanches, in contrast, do not show characteristic spatial and temporal scales, and are often considered as evidence of brain tuning to quasi-criticality. While models have been developed to account for oscillations or neuronal avalanches separately, they typically do not explain both phenomena, are too complex to analyze analytically or intractable to infer from data rigorously. On the one hand, models of brain oscillations are very specific and seek to capture physiological mechanisms underlying particular brain rhythms. On the other hand, attempts to explain the emergence of neuronal avalanches almost exclusively focus on criticality-related aspects and ignore the coexisting behaviors such as oscillations, even though they themselves may be constitutive for understanding the putative criticality. Here we propose a minimal, microscopic, and analytically tractable class of models that are non-equilibrium extensions of the Ising model with an extra feedback loop which enables self-adaptation (Fig. 1A). As a consequence of feedback, neuronal dynamics is driven by the ongoing network activity, generating a rich repertoire of dynamical behaviors [1]. The structure of the simplest model from this class permits microscopic network dynamics investigations as well as analytical mean-field solution, and in particular, allows us to construct the model's phase diagram (Fig. 1B) and make direct contact with human brain resting-state activity recordings via tractable inference of the model's two essential parameters. The inferred model quantitatively captures the dynamics over a broad range of scales, from single sensor oscillations (Fig. 1C-D) to collective behaviors of extreme events and neuronal avalanches unfolding over multiple

sensors across multiple time bins (Fig. 1E-F). Importantly, the inferred parameters correlate with model-independent signatures of "closeness to criticality", indicating that the coexistence of scale-specific (neural oscillations) and scale-free (neuronal avalanches) dynamics in brain activity occurs close to a non-equilibrium critical point at the onset of self-sustained oscillations [1]. The proposed adaptive Ising model class can be seen as a natural, yet orthogonal, extension to previous maximum-entropy models that enables oscillations and furthermore permits us to explore an interesting interplay of mechanisms, for example, by having self-feedback drive Hopfield-like networks (with memories encoded in the coupling matrix J) through sequences of stable states.



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Stochastic thermodynamics of a particle in a correlated field

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Stochastic thermodynamics has uncovered general laws governing the fluctuations and energetics of mesoscopic systems that even hold far from thermal equilibrium. However, little is known about systems in environments with long-ranged spatio-temporal correlations. We introduce a theoretical framework to study the stochastic thermodynamics of a mesoscopic object which is weakly coupled to a temporal-spatially correlated environment described by a fluctuating scalar field. As a particular example, we consider a particle which is dragged at a constant speed by a harmonic trap through a fluctuating Gaussian field. Using a perturbative approach, we uncover that the dissipated power exhibits three dynamical regimes with distinct scaling laws in the dragging velocity. Furthermore, when the field is close to its critical point, the spatially resolved heat dissipation of the field displays a distinct heterogeneous pattern.

Lyapunov vectors and the energy levels of the directed polymer in random media

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The evolution of infinitesimal perturbations in spatially extended chaotic systems has been shown [1-6] to be generically described by the heat equation with multiplicative noise. After a logarithmic (Hopf-Cole) transformation, the statistical description of the dynamics of perturbations is captured by the prototypical stochastic surface growth equation of Kardar-Parisi-Zhang [7]. In the surface picture, erratic fluctuations, due to the chaotic nature of the trajectory, are treated as an effective noise. The surface picture has been shown to work also for covariant/generic Lyapunov vectors (CLVs) corresponding to sub-leading Lyapunov exponents (Oseledec splitting theorem). In Ref. [3] it was shown that surfaces associated with CLVs (other than the first one) exhibit scaling with the wavenumber k as $< |h(k)|^2 > \sim 1/k^{\delta}$ with exponent $\delta \simeq 1.20$ at long wavelengths ($k \to 0$). The crossover from KPZ scaling, $\delta = 2$, to the new universality with $\delta \simeq 1.20$ takes place at shorter length scales as one looks at higher order CLVs[3]. This new scaling exponent has been shown to be crucial to explain the universal scaling of Lyapunov-exponent fluctuations in space-time chaos [6]. While the correspondence between the main LV and KPZ universality can be understood through the multiplicative heat equation ansatz, the origin of the asymptotic $\delta \simeq 1.20$ scaling for sub-leading LVs has remained an open question for the last teen years.
Here we study the problem of the directed polymer in random media (DPRM) at zero temperature [8]. The ground state of the DPRM is known to be in the same universality class as KPZ, after a suitable correspondence between free energy of the minimal path and KPZ surface height [8]. We study, by means of numerical simulations, the excited states of the DPRM at $T = 0$, i.e. those paths with energies larger than the optimal path (ground state). We show that the DPRM energy profile E(x), which includes the energies of all paths (i.e. including excited states) starting at (0,0) and ending at (x,t), exhibits fluctuations that scale as $< |E(k)|^2 > \sim 1/k^{\delta}$, where the exponent crosses over from $\delta = 2$ for large k to $\delta = 1.2$ at long wavelengths $k \to 0$. Our results strongly support a link between the covariant LVs in space-time chaos and the excited states of the DPRM problem. We conjecture that free energies of the DPRM excited states map into surface heights of the CLVs.

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Optimal performance on neural and hybrid networks

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The decision support process in Shipping can be advanced by the AI. I test four families of neural networks an innovative classifier for the efficient portfolio selection is given to address key issues of the modern portfolio theory: i) the investors performance, ii) the incorporation of entropy dynamics in returns allocation under the new aspects of Chaos Theory and Tsallis Statistics at the Fractal Market Hypothesis, iii) the selection of the optimal classifier between 66 Modular, 60 Self Organized Feature Maps models, 14 Support Vector Machines, 1 Voted Perceptron and 46 Multilayer Perceptrons of Neural and Neuro-Genetic Hybrids optimizing portfolia.

Inertial effects in active matter

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Active particles which are self-propelled by converting energy into mechanical motion represent an expanding and flourishing research realm in statistical physics. For micron-sized particles moving in a liquid (microswimmers'), most of the basic features have been described by using the model of overdamped active Brownian motion [1]. However, for macroscopic particles (such as vibrated granules) or microparticles moving in a gas (such as a complex plasma), inertial effects become relevant such that the dynamics is underdamped. Therefore, recently, active particles with inertia have been described by extending the active Brownian motion model to active Langevin dynamics which includes inertia [2,3]. In this talk, recent developments of active particles with inertia (microflyers, hoppers or runners) are summarized. These include a fundamental inertial delay effect between particle velocity and self-propulsion direction [4] which has recently discovered by experiments on vibrated granules and by theory. Overdamped particles exhibit a nonequilibrium phase transition termed motility-induced phase separation and growth of particle clusters. Here the influence of inertia on motility-induced phase separation and the cluster growth exponent [5] is discussed. It is shown that coexisting phases can have different kinetic temperatures which is unknown from equilibrium. As an application the construction of active refrigerators [6] is put forward. Moreover the formation of active micelles (rotelles) by using inertial active surfactants [7] is proposed. All these effects document that inertia can play a significant role for active matter. Finally examples for applications in medicin for these macroscopic active inertial particles will also be highlighted.

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Baryon asymmetry from Barrow entropy: theoretical predictions and observational constraints.

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We investigate the generation of baryon asymmetry from the corrections brought about in the Friedmann equations due to Barrow entropy, which is a quantum-gravitational driven deformation of the standard Bekenstein-Hawking entropy-area law. In particular, by applying the gravity-thermodynamics conjecture one obtains extra terms in the Friedmann equations that change the Hubble function evolution during the radiation-dominated epoch. Hence, even in the case of standard coupling between the Ricci scalar and baryon current they can lead to a non-zero baryon asymmetry. In order to match observations we find that the Barrow exponent should lie in the interval $0.005 \leq \Delta \leq 0.008$, which corresponds to a slight deviation from the standard Bekenstein-Hawking entropy. The upper bound is tighter than the one of other observational constraints, however the interesting feature is that in the present analysis we obtain a non-zero lower bound. Nevertheless, this lower bound would disappear if the baryon asymmetry in Barrow-modified cosmology is generated by other mechanisms, not related to the Barrow modification

The exponential capacity of modern associative memories

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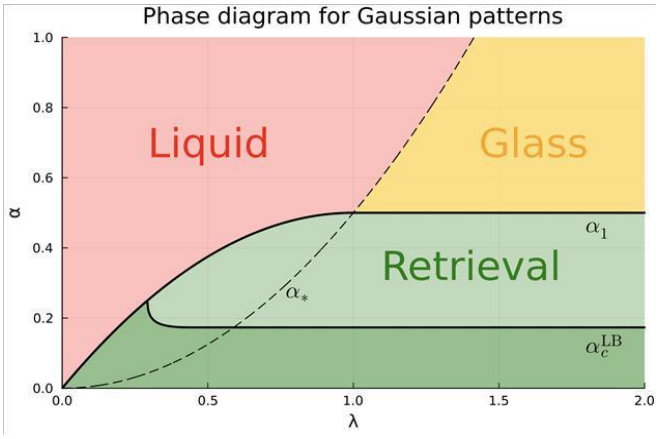
The Hopfield model is a paradigmatic model of associative memory which is able able to retrieve the stored patterns from noisy observations. Thanks to the replica method from spin glass theory, it has been shown that the model is able to store a number of uncorrelated patterns that scales linearly with the size of the system, with the asymptotic threshold that can be computed to high precision. In this talk, we present the statistical physics analysis of a recently proposed generalization of the Hopefield model, named modern Hopfield network (MHN). The MHN has an exponential capacity, i.e. it is able to store $P = exp(\alpha N)$ patterns where N is the size of the system, for an exponential rate α low enough. Besides this huge storage capacity, the MHN is linked to the attention mechanism of Transformer architectures in deep learning. In fact, one step in the dynamics of a MHN can be mapped into the forward pass of an attention layer. We provide the phase diagram of the model thanks to a large deviation analysis of a Random Energy Model (REM) related to the problem. Our framework allows the analysis of a large class of pattern ensembles, each one inducing a characteristic distribution in the related REM problem. We derive exact thresholds for single pattern retrieval and lower bounds for all patterns retrieval largely improving the existing ones. Additionally, we are able to compute the exact size of the basins of attraction, and to analyze different scaling regimes of the number of patterns and the coupling strength with N. The generic framework we present is then applied to the cases of gaussian and spherical patterns. For spherical patterns, we find that the lower bound for the full retrieval is sharp, and that one can arbitrarily increase the capacity by increasing the interaction strength. For Gaussian patterns instead we find a richer picture where the the lower bound and the single pattern retrieval threshold do not match and for any interaction strength there is a limit capacity above which the system enters either a "liquid" phase or a "condensed" spin glass phase.



Classical equipartition theorem and its universal quantum counterpart

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In classical statistical physics, the theorem on equipartition of kinetic energy is one of the most universal relation. It states that for a system in thermodynamic equilibrium of temperature T, the mean kinetic energy E per one degree of freedom is equal to $E = k\ T/2$, where k is the Boltzmann constant. E does not depend on a number of particles in the system, the form of the potential force which acts on them, the form of interaction between particles and strength of coupling between the system and thermostat. It depends only on the thermostat temperature T. On the contrary, for quantum systems, the mean kinetic energy is not equally shared among all degrees of freedom and the theorem fails. The question arises whether one can formulate a similar and universal relation for the mean kinetic energy of quantum systems at the thermodynamic equilibrium state. The answer is: Yes, if the composed quantum system (Thermostat + System) is at the Gibbs canonical state of arbitrary temperature [1]. The relation holds true for all quantum systems composed of an arbitrary number of interacting particles, subjected to any confining potential and coupled to thermostat of arbitrary strength (valid both in weak and strong coupling regimes). For a system of one degree of freedom this quantum counterpart, which can be called the energy partition theorem, has the appealing form:

$$E = \int e(\omega)\, P(\omega)\, d\omega, \quad (1)$$

where $e(\omega)$ has exactly the same form as the average kinetic energy of the quantum harmonic oscillator with the frequency ω weakly coupled to thermostat of temperature T and $P(\omega)$ is a probability density on a positive half-line of real numbers. The explicit form of the probability density $P(\omega)$ depends on the microscopic model of the Thermostat + System and has been derived for several exactly solved quantum systems like as a free particle or quantum oscillator [2-7]. The relation (1) is a generalization of the classical energy equipartition theorem for quantum systems and in the high temperature limit it reduces to its classical form $E = kT/2$. In the low temperature regime [5] it exhibits interesting properties which will be discussed in the lecture.

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Forecasting El Niño well before the spring predictability barrier

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The El Niño Southern Oscillation (ENSO) is the most important driver of interannual global climate variability and can trigger extreme weather events and disasters in various parts of the world. Existing operational El Niño predictions have been particularly hampered by the so-called spring predictability barrier, which limits the reliable pre-warning time before an El Niño to about six months.

Recently [1,2], we have developed a dynamical climate network approach for predicting the onset of El Niño events well before the spring barrier. In this network, the nodes are reanalysis grid points in the Pacific, and the strengths of the links between them are derived from the cross-correlations of the atmospheric surface temperatures at the grid points. In the year before an El Niño event, the links between the eastern equatorial Pacific and the rest of the tropical Pacific tend to strengthen such that the average link strength exceeds a certain threshold. Predictions based on this feature for the presence or absence of an El Niño onset in the following year are correct with 73% and 90% probability, respectively. The p-value of the hindcasting and forecasting phase (1981-2022) for this performance based on random guessing with the climatological average is $3.5*10^{-5}$.

We complement the climate network approach with additional forecasting methods, which can also cross the spring barrier for obtaining more specific predictions. We found that information entropy in the Niño3.4 area in the central Pacific strongly correlates with the magnitude of an El Niño that starts in the following year [3]. Additionally, the temperature gradient between the western and central Pacific provides an early predictor for the type of an El Niño event. Depending on the region of maximal warming, El Niño events can be partitioned into 2 types, Eastern Pacific and Central Pacific. The type of an El Niño has a significant influence on its impact and can even lead to dry or wet conditions in the same areas on the globe, however its prediction is currently even more limited than that of the El Niño event itself. Combining the different approaches allows not only more specific forecasts but mutually agreeing predictions increase the forecast certainty. The approaches here presented about double the pre-warning time before an El Niño and can enable early and more targeted mitigation measures.

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Continuous non-equilibrium transition driven by the heat flow

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We discovered an out-of-equilibrium transition in the ideal gas between two walls, divided by an inner, adiabatic, movable wall. The system is driven out-of-equilibrium by supplying energy directly into the volume of the gas. At critical heat flux, we have found a continuous transition to the state with a low-density, hot gas on one side of the movable wall and a dense, cold gas on the other side. Molecular dynamic simulations of the soft-sphere fluid confirm the existence of the transition in the interacting system. We formulate description of nonequilibrium stationary state of the system in terms of global thermodynamic functions and introduce a stationary state Helmholtz-like function whose minimum determines the stable positions of the internal wall. This transition can be used as a paradigm of transitions in stationary states and the Helmholtz-like function as a paradigm of the thermodynamic description of these states.

A special model of risk based on Radon Transform

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We propose a new method of determining the risk of a financial instrument [1], referring directly to the physical possibility of buying or selling it. In this sense, a financial instrument is all the more risky when there are more opportunities for it to change hands. These opportunities may change due to, for example, a change in assessment of the future profits generated by this instrument. We construct a mathematical model of risk understood in this way and a method of its measurement. In particular, we introduce the concept of a financial frame of reference based on the concept of financial time and a benchmark instrument. From these concepts we derive the definition of an instrument chart. The proposed measure of risk is based on the financial instruments with the lowest risk in a given frame of reference. We call them simple instruments. By selling (or or buying) a financial instrument, we understand its exchange with a simple instrument. Graphically, the moment of possible exchange of financial instruments is interpreted as the point of intersection between their charts. This is the moment when a simple (less risky) instrument is priced the same as the considered instrument. The owner of this instrument is thus faced with a dilemma: to replace it with a less risky one or not. The more such dilemmas, the more risky the instrument is. The measure of the number of these dilemmas is called the reachability of a financial instrument. The financial instrument A is reachable at any given time if there is a simple instrument that has a logarithmic price equal to the logarithmic price of the instrument A. Greater reachability can be associated with greater risk. We will show that simple instruments have the lowest reachability (they are the least risky). More formally, the concept of the reachability of a financial instrument can be represented by the Radon transform [2] defined on the space of simple instruments. Using this concept, we will propose a new measure of the risk of a financial instrument. The Radon transformation has led to a revolution in the field of medical imaging [3]. It is also used in astronomy, optics, and geophysics. Perhaps it will also allow us to look at the risk of financial instruments differently and to better understand the dynamics of financial markets.

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Optical thermodynamics of nonlinear systems

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In recent years, considerable effort has been devoted to the study of nonlinear highly multimoded optical systems [1]. The physical motivation behind these theoretical and experimental efforts has been the search for highpower optical sources that has been enabled by a sequence of new developments in multimode technologies pertaining to both guided wave structures and optical cavities. Understanding and predicting the complex nonlinear response of such systems especially when hundreds or thousands of modes are involved, is a challenging task. In the best case, all relevant approaches are mostly based on complicated nonlinear optical simulations, that make the description of realistic multimode fibers a formidable task. Thus a theory that explains and predicts such a complex behavior is still missing. Quite recently however, a self-consistent theoretical framework has emerged, what we call ”Optical Thermodynamics” [2–6]. In particular, optical thermodynamic theory is capable of describing such complex phenomena by means of thermodynamics of the system’s supermodes. A complete set of thermodynamical variables was determined and thus was able to describe and accurately predict the equilibrium behavior of the multimoded system. The equation of state, the entropy and the Rayleigh-Jeans modal occupancies distribution was derived axiomatically either on thermodynamical grounds [2–4] or equivalently on statistical mechanical foundations [5, 6]. Such an approach is universal since it can be applied to any weakly nonlinear optical multimode system of finite number of supermodes that involves a finite number of conserved quantities. We can derive the fundamental relations that govern the grand canonical ensemble through maximization of the Gibbs entropy at equilibrium. In this classical picture of statistical photo-mechanics, we obtain analytical expressions for the probability distribution, the grand partition function, and the relevant thermodynamic potentials. The first part of the talk is devoted to the understanding of the role of equilibrium fluctuations and the second part to develop a non-equilibrium description of the system. In order to achieve our first goal we are going to rely on the grand canonical formalism [5] and directly calculate the relevant fluctuations based on the grand partition function expression. For states far from equilibrium, we develop a Langevin type of approach for the projection modal coefficients and derive effective stochastic equations that govern every supermode. Our analytical expressions are compared with direct numerical results of system-bath simulations, in all cases, and the agreement is excellent. In conclusion, by means of statistical mechanics, we have established a solid foundation for the optical thermodynamics for equilibrium and non-equilibrium states. This formulation was carried out in the grand canonical ensemble picture and is applicable to any nonlinear arrangement involving conserved quantities such as the power, Hamiltonian, and a finite set of distinguishable modes. The equilibrium expressions for the fluctuations of power, Hamiltonian and modal occupancy number were found in excellent agreement with direct bath-system simulations. Even more interestingly, we were able to apply a Langevin type of formalism in order to understand the nonequilibrium behavior of our system. Our results universally apply to any other weakly nonlinear highly multimoded bosonic arrangement.

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Unexpected energetic particle observations near the sun by Parker solar probe and solar orbiter

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Solar Energetic Particles (SEPs) from suprathermal (few keV) up to relativistic (~few GeV) energies are accelerated at the Sun in association with solar flares and Coronal Mass Ejection (CME)-driven shock waves. Although our knowledge of the origin, acceleration and transport of these particles from close to the Sun through the interplanetary medium has advanced dramatically in the last 40 years, many puzzles have still remained unsolved due to the scarcity of in situ measurements well inside 1 AU. Furthermore, energetic particle intensity enhancements associated with high-speed streams or Stream Interaction Regions (SIRs) have been routinely observed at interplanetary spacecraft near Earth orbit since the 1960s. Since only a small sample of SIR events were observed by the Helios spacecraft inside 1 AU, additional observations well inside 1 AU were also needed to further investigate the energization and transport effects of SIR-associated ions and to compare with expectations from contemporary SIR-associated particle acceleration and transport models and theories. The Solar Orbiter (SolO) and Parker Solar Probe (PSP) pioneering missions have been providing unprecedented measurements of energetic particles in the near-Sun environment. This talk will present a review of the unexpected observations of SEP and SIR-related ion events as measured by the PSP/IS⊙IS and SolO/EPD experiments, which revealed surprises that challenge our understanding.

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Searching for universal formula for percolation threshold on two-dimensional lattices with complex neighbourhoods

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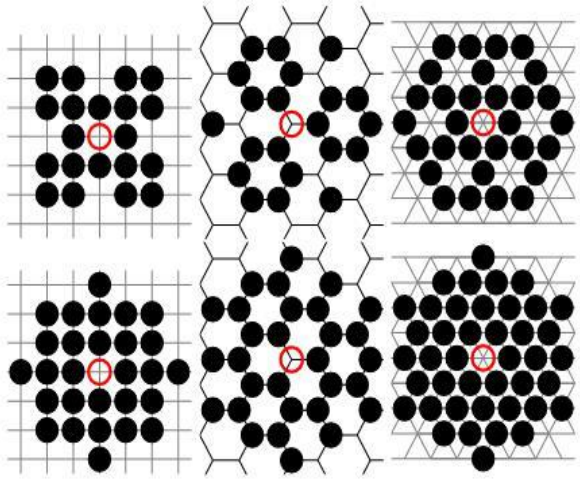
In this paper we present our recent attemps [1-6] to identify the universal formula allowing for predicting percolation thresholds on regular two-dimensional lattices. We consider complex neighbourhoods as presented in figure below. Our results [1-3] base on the scaling hypothesis regarding the probability of belonging to the largest cluster vs the occupation probability p obtained by Newman--Ziff algorithm [7]. For complex but compact (also called extended) neighbourhoods, the pc is proportional to $1/z$, where z is the total number of sites in the neighbourhood [8]. For complex (not-compact) neighbourhoods and triangular lattice pc follows the power-law with exponent close to 0.71 when ploted vs. $\xi = \sum zi \times ri\ 2\ /i\ i$, where zi and ri are the number of sites and radius of the i-th coordination zone, respectively [3]. On the other hand, similar dependence is reocvered for honeycomb lattice but in dependence on $\zeta = \sum i\ zi \times ri$ (with exponent close to 0.5) [2]. Similarly to the honeycomb lattice, the percolation thresholds for complex neighborhoods on a square lattice follow the power law $pc(\zeta) \propto pow(\zeta, -\gamma)$ with γ = 0.5454(60) [1]. The shape of universal formula for all these above mentioned complex neighbourhoods on regular two-dimensional lattices remains an open question. In this paper we present recent (more or less successful) attempts to identify such formula.



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Ranking sequences of continents and countries in affiliations of scientific papers authors

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Collaboration between scientists seems to be an important issue in the scientific world. The question is, however, what kind of cooperation are we talking about. Does it only concern colleagues from the same institution, country, or is it wider and includes people from very different research centers? To answer this question, we have selected a collection of nearly 30 million publications and are analyzing it in terms of international and intercontinental scientific cooperation.

Our analysis is based on mapping the authors to the countries and continents, where the institutions indicated in the affiliations of particular articles are located. This allows us to obtain ranks reflecting the

frequency distribution of the probability of occurrence of specific sequences describing which countries/continents people publishing together come from.

The obtained results indicate that in the most common case (~64%) the authors are associated with institutions located in one, then in two (~19.5%), then in three (~6%) countries. In the first case, the first three places in the ranking are occupied by the United States, China and Germany, respectively, so we are dealing here with countries from three different continents. When we look at the ranking of continents, the most common case is cooperation between countries from the same continent (~73.37%), the second most common case is cooperation between two continents (~18.14%), and the third most common case three continents (~4.67%). In this case, the dominant role of Europe is observed.

The detailed analysis of sequences of continents and countries in the authors affiliations by means of inverse participation ratio reveals complex probability distribution of this quantity. However, the obtained rank-frequency distribution of this index is not dissimilar to power law with exponents close to -1.36, and -0.96, for high and low ranks, respectively.

Structure and connectivity of solutions in non-convex continuous optimization problems

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The characterization of the structure of the manifold of low-energy lying states in neural networks is among the most fundamental theoretical questions in machine learning. In recent years, many empirical studies on the landscape of neural networks and constraint satisfaction problem (CSP) have shown that the low-lying configurations are often found in complex connected structures, where zero-energy paths between pairs of distant solutions can be constructed. In this talk, I will discuss the geometrical organization and the connectivity properties of solutions in the negative perceptron, a linear neural network model and a prototype of a continuous non-convex CSP. I will show that a wide flat minima arise as complex extensive structures from the coalescence of minima around “high-margin” (i.e. locally robust) configurations [1]. Moreover, I will introduce a novel analytical method for characterizing the typical energy barriers between groups of configurations sampled from the zero-temperature measure of the problem [2]. We find that, despite the overall non-convexity of the space of solutions, below a critical fraction of constraints the geodesic path between any solution and the robust solutions of the problem, located in the interior of the solution space, remains strictly zero-energy. The value of α where this simple connectivity property breaks down is compatible with the point at which the dense core of solutions fragments in multiple smaller pieces [3].

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Nonlinear topological edge states: From dynamic delocalization to thermalization

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We study a mechanical analog of the Su-Schrieffer-Heeger (SSH) tight-binding lattice [1] with Klein-Gordon-type nonlinearity. In the linear limit, the finite-size SSH chain supports localized boundary modes at the mid gap of its frequency spectrum. These edge modes originate from the bipartite

nature of the lattice and are known to be robust to deformations and/or imperfections. In particular, we discuss the two following problems: (i) what are the spectral, spatial and stability properties of the nonlinear continuation of topological edge modes in the presence of nonlinearity; and (ii) what are the characteristics of the dynamics associated with these nonlinear topological edge states. Our numerical computations rely on the Newton-Raphson scheme in the phase space which gives the shape and the frequency of the nonlinear edge states with a high degree of accuracy [2]. In this context, we carry the linear stability analysis of the obtained solutions based on the standard Floquet theory. Besides, we find energy-dependent frequencies for the nonlinear topological edge states which can be stable or unstable depending on the signs and strengths of the nonlinearity. Interestingly, the short-time dynamics of an unstable nonlinear topological edge state shows a delocalization of part of its energy toward the bulk and a tendency to restore the frequency of the linear topological edge mode [3]. Nevertheless, its long-time dynamics suggests that this delocalization of energy does not restore the linear topological edge state, but instead leads to the thermalization of the lattice, due to the presence of chaos and mode-mode interactions within the system. The obtained thermalized state is characterized by a renormalized dispersion relation whose shape is reminiscent of the symmetries of the linearized model [4].

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Experimental observation of violent relaxation and the formation of out-of-equilibrium quasi-stationary states

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Structures of the observable Universe, such as galaxies and globular clusters, appear to be macroscopically stationary which, for a long time, were thought to be at thermodynamic equilibrium [1]. However, Chandrasekhar pointed out in 1941 that the time necessary for these objects to reach thermal equilibrium is actually much larger than their age [2]. This has been confirmed by observations determining that these astrophysical structures are indeed far from thermal equilibrium (see, e.g., [3]). In 1967 Lynden-Bell proposed a mechanism, violent relaxation that leads to the formation of these out-of-equilibrium structures, called quasi-stationary states [4]. These structures are called quasi-stationary states because they evolve, towards thermodynamic equilibrium, over a much longer timescale relatively to violent relaxation [1]. It has been subsequently understood that this mechanism is generic in Hamiltonian systems with a long-range interacting potential, i.e., a potential that is not integrable because of its extension over large scales [5].

Violent relaxation has not been observed to date, neither in a repeatable or controllable experiment, nor in situ. Indeed, experimental observation of the dynamics of the formation of quasi-stationary states via violent relaxation is hindered mostly for two reasons. First, there are systems in which it is potentially present, but it is destroyed by the stochastic noise generally present in these systems [6]. Second, there are systems in which violent relaxation is actually present, but the associated timescales are too large to observe it. This is the case of astrophysical systems such as galaxies, independently if it is constituted by classical (non-quantum) dark matter particles (e.g. [7]), or composed by quantum matter (e.g. [8]). In these

systems violent relaxation occurs on time scales of the order of millions of years [1].

We develop a non-linear optics table-top experiment that allows us to directly observe violent relaxation, leading to the formation of a quasi-stationary state, i.e, an analogue of a galaxy [9]. The experiment allows us to control a range of parameters, including the nonlocal (gravitational) interaction strength, and quantum effects, thus providing an effective test-bed for gravitational models that cannot otherwise be directly studied in experimental settings. Reporting observables as the mixing of phase-space and the evolution of the distribution of energy density, we give experimental evidence of observation of violent relaxation.

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Solvable model for the decline of unconventional oil and gas

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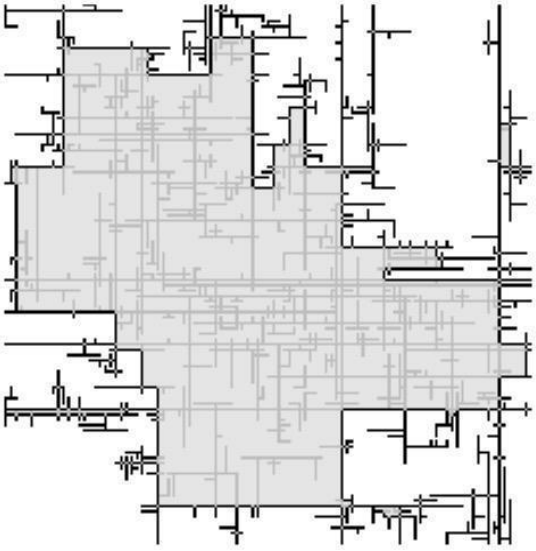
The use of horizontal drilling and hydrofracturing may represent the final stages in the extraction of hydrocarbons to meet exponentially growing world energy demands. Therefore an accurate theory for the decline of oil and gas production from unconventional wells should be of value. We found that the production rate of unconventional wells is described quite accurately as the sum of two universal curves. The first describes the early stage of production, while the second describes a stage of production so late that few wells have yet entered it. In the universal curve for the first phase, production falls first as the square root of time, and then drops exponentially. In the universal curve for the second phase the exponential drop slows, and converts to a much lower rate of decline that goes as one over a log of time. One of the implications of the late-time universal curve is that over times on the order of 30 years existing wells should yield around 30% more gas than would be expected from extrapolating behavior from the first regime. That production data fit the universal curves so well is a puzzle because the fracture networks that collect oil and gas must be highly varied and highly complex. To address this problem, we posed and then solved an analytical model for gas diffusion to complex structures. Some technical problems had to be solved in order to provide the exact solution. The method used was a T matrix formalism on a lattice, and it required computation of lattice Green's functions at arbitrary locations for energy in the complex plane, and for hopping numbers on the order of 100. The recursion relations that provide the fastest and most reliable way to find lattice Green's functions are completely unstable. This difficulty was overcome with use of arbitrary-precision arithmetic. Once exact solutions for the lattice mode of diffusion to fractured networks were in hand, it became evident that most details of the fracture network are irrelevant for the history of gas production. It takes only a few parameters, each with physical meaning, to describe the production history, and other details of the network geometry, in most cases fade away.



Memory and dreaming in the Hopfield model.

Enzo Marinari
Sapienza Università Di Roma, Roma, Italy

I will discuss dreaming in Hopfield like neural networks, as a very powerful tool to optimize memory retrieval. The Hebbian unlearning algorithm, i.e., an unsupervised local procedure used to improve the retrieval properties in Hopfield-like neural networks, is numerically compared to a supervised algorithm useful to train a linear symmetric perceptron. I discuss the stability of the stored memories, and notice basins of attraction obtained by the Hebbian unlearning technique are found to be comparable in size to those obtained in the symmetric perceptron, while the two algorithms are found to converge in the same region of Gardner's space of interactions, having followed similar learning paths. A geometric interpretation of Hebbian unlearning is proposed to explain its optimal performances. Since the Hopfield model is also a prototypical model of the class of disordered magnetic system, it might be possible to translate these results to other models of interest for memory storage in materials. I will also try to investigate more general features of learning and dreaming, and possible approaches to improve dreaming and make it more effective.

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Phase transitions in mini-batch size for sparse and dense deep neural networks

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The widespread diffusion of neural networks in many scientific fields urges for a better understanding of the processes that underlie their training. The discipline that studies how well simple devices like Turing machines or more abstract constructions, such as classifier systems, can learn and infer from observed data after the training process, is the statistical learning theory. The statistical learning theory is at the cornerstone of Machine Learning, and it deals with the statistical inference problem of finding a predictive function based on data. Even though neural networks are well analyzed from statistical learning, they have become an active subfield of research in statistical mechanics. In this area a major role is played by phase transitions that regulates what is achievable in principle (information theoretical thresholds) and what is achievable in practice (algorithmic thresholds). Such a vast field of possible applications has been found for networks, as a huge variety of systems can be described in terms of interconnected elements. Recently, statistical mechanics tools have been also applied in the realm of artificial intelligence, for building up consistent theories of deep learning. In simple words, deep learning can be seen as a fully connected neural network that takes some data, composed by input

and targets, and learns the rules for forecasting new input data. Over the last decades the practitioners of neural networks have developed many very useful tricks and smart procedures, like mini-batch, dropout and others several regularizations for speeding up the training steps. A theory justifying many of these choices is often lacking, and so it is very difficult to make optimal choices for who is not an expert. Among these "tricks" the use of the so called mini-batch, introduced as a technical requirement for dealing with huge databases, actually turns out to be crucial for the optimal training. In machine learning, a mini-batch is a subset of the full dataset that is used to train a model. Rather than training the model on the entire dataset at once, the training data is divided into smaller batches, or mini-batches, which are fed to the model one at a time. The size of the mini-batch is a hyperparameter that can be tuned to optimize the training process. A larger mini-batch size can lead to faster training times, but it can also make it harder for the model to converge to a good solution. A smaller mini-batch size can improve the model's convergence but may slow down the training process. In this work, we present the existence of phase transitions in sparse and dense neural networks, in the realm of the teacher-student scenario of deep learning. We show that the mini-batch size m plays a fundamental role in inferring the weights of the teacher neural networks. More precisely, we show that above a certain value of m, named mc, the inference is always possible, while below it the inference is impossible. This phenomenon seems to be independent of the architecture of the neural network used.

How can a machine automatically discover better feedback strategies for quantum devices?

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Many challenging tasks in the areas of quantum computing, communication, sensing and simulation require feedback strategies. Examples include state preparation and stabilization, adaptive quantum-improved sensing, and quantum error correction. In this talk I will explain how reinforcement learning can help to automatically discover elaborate feedback strategies. Reinforcement learning considers the interaction between an agent and environment, and the goal is to discover a strategy for the agent to behave in an optimal fashioning, trying to improve a reward function that encodes the overall goal. In our group, we have applied this general concept to discover better quantum error correction strategies from scratch, to train an agent that can optimize arbitrary quantum circuits, and to find good feedback strategies for quantum devices like qubit-cavity systems. Recently, we have shown how to apply these techniques directly in an experiment involving a superconducting qubit, creating a real-time neural network agent with an unprecedented reaction time. Furthermore, going beyond the so-called model-free reinforcement learning techniques, we have introduced a model-based approach, feedback-GRAPE, where we are able to take gradients through the evolution equations despite the presence of stochastic discrete quantum measurements.

The mystery of rejuvenation and memory in spin-glasses

Victor Martin-mayor
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The main focus of the talk will be describing our recent success in reproducing in a simulation (using the Janus supercomputer) the spectacular memory and rejuvenation effects of spin glasses [1]. Although memory and rejuvenation were discovered experimentally more than 20 years ago, convincingly reproducing these effects in a simulation seemed hopeless until now, and for very good reasons. Indeed, many pieces of the puzzle had to be gathered. First, we have needed to learn how to quantitatively extract the spin-glass coherence length (i.e. the size of the glassy domains) from simulations of non-equilibrium spin glass dynamics. Second, one needs to reach reasonably large coherence lengths in the simulation, a task that demands the tremendous computing power of Janus II. A third step has been learning how to extrapolate from the numerical time and length scales to the experimental ones. Fourth, Janus II has provided crucial understanding about how temperature chaos in non-equilibrium dynamics really is. These milestones have made possible undertaking a nice collaboration with the group of Ray Orbach in Texas. The collaboration with Orbach has taught us how to perform in Janus [1] true "computer experiments", in which the very same quantities are computed in the simulation and measured in a CuMn single crystal, and analyzed in a parallel way. In fact, the 2022 temperature-chaos experiment by Orbach and Zhai has produced crucial quantitative input to set up a successful simulation of memory and rejuvenation. A big surprise (at least surprising for us) is our finding that no less than three quite distinct length scales control aging dynamics.

Further experimental and numerical work is in progress [1], that explores the quantitative description of the memory effect [2].

[1] The Janus collaboration (alphabetical ordering): M. Baity-Jesi, E. Calore, A. Cruz, L. A. Fernandez, J. M. Gil-Narvion, I. Gonzalez-Adalid Pemartin, A. Gordillo-Guerrero, D. Iñiguez, A. Maiorano, E. Marinari, V. Martin-Mayor, J. Moreno-Gordo, A. Muñoz-Sudupe, D. Navarro, I. Paga, G. Parisi, S. Perez-Gaviro, F. Ricci-Tersenghi, J. J. Ruiz-Lorenzo, S. F. Schifano, B. Seoane, A. Tarancon, R. Tripiccione, D. Yllanes, Nature Phys. (in press).
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Ion-driven instabilities in the inner heliosphere

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Linear theory is a well developed framework for characterizing instabilities in weakly collisional plasmas, such as the solar wind. In this work, we analyzed 1.5M proton and alpha particle Velocity Distribution Functions (VDFs) observed by Helios I and II to determine the statistical properties of the standard instability parameters such as the growth rate, frequency, the direction of wave propagation, and the power emitted or absorbed by each component, as well as to characterize their behavior with respect to the distance from the Sun and collisional processing. We use this comprehensive set of instability calculations to train a Machine Learning algorithm consisting of three interlaced components that: 1) predict if an interval is unstable from observed VDF parameters; 2) predict the instability properties for a given unstable VDF; and 3) classify the type of the unstable mode. We use these methods to map the properties in multi-dimensional phase space to find that the parallel-propagating, proton-core-induced Ion Cyclotron mode dominates the young solar wind, while the oblique Fast Magnetosonic mode regulates the proton beam drift in the collisionally old plasma.

Effect of disorder on charging a quantum battery by collision model

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Koc University, Istanbul, Turkey

Quantum batteries are a relatively new area of research that explores the possibility of more efficient energy storage using quantum effects[1]. Several theoretical models have been proposed to investigate the potential of quantum batteries, and figures of merit, such as charging power and maximum unitarily extractable energy [2], have been analyzed. The effects of noise, imperfections, and non-markovian effects have also been studied. Quantum phase coherence and entanglement have been explored as useful resources for improving the performance of quantum batteries. One promising method for charging quantum batteries is through collision model charging [3-5], where the battery repeatedly interacts with a charging particle. However, the role of disorder [6-8 in the efficiency of collision model charging remains a largely unexplored area of research. In this study, we investigate the effect of disorder on the efficiency of the collision model [9] charging of a quantum battery and examine its impact on the optimal charging time. We model the quantum battery and the charger as (non)interacting two-level spin systems. The charging process is then simulated using the time-dependent Schrödinger equation. We investigate different strengths of interactions and their effect on the efficiency of the battery. We then investigate the impact of the degree of disorder on the efficiency of collision model charging. Finally, we investigate the effect of disorder on the optimal charging time for the quantum battery. Our study highlights the importance of controlling disorder in order to optimize the charging process and improve the efficiency of quantum batteries. In summary, our study provides a comprehensive investigation of the impact of the disorder on the efficiency of collision model charging of a quantum battery and sheds light on the optimal charging time in the presence of disorder.

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Irregular space plasmas dynamics: entropy production vs fractality

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One of the most relevant feature of turbulent fluids, included Space Plasmas, is the irregularity of the fields defining their local state (for example magnetic field, electric current and bulk velocity in the Solar Wind). In particular, time series of local quantities collected by in situ measurements, e.g. by satellites, as well as remote sensing data, e.g. those from trans-medium communications, show scale-dependent statistical behaviour suggesting the local state fields to be better represented as fractal or multi-fractal measures rather than smooth functions of time and position. While a wide literature has developed about the occurrence of these measures in irregular space plasmas, and their taxonomy, what is still lacking is a theoretical explanation predicting the geometric-topological characteristics of these measures from the continuous medium physics, or from kinetic representations of it. In this work, we investigate the possibility that some Extremal Entropy Production principle determines the multi-fractal properties of dissipative structures in space plasmas.

Thermodynamics beyond molecules – Statistical mechanics of populations

Themis Matsoukas
Pennsylvania State University, University Park, United States

The central problem in statistical mechanics is the determination of the probability of microstate based on a small number of macroscopic state variables. The solution given by Gibbs is as elegant and it is simple: maximize a special functional, entropy, under a small number of constraints that represent our knowledge of the macroscopic state. The appeal of this approach is quite undeniable, a complex dynamic problem is reduced to an equivalent yet straightforward variational problem. Can this approach be extended outside statistical physics to any problem that involves an unknown distribution? In pursuit of this problem we formulate the "cluster ensemble", an ensemble that in the asymptotic limit contains every distribution. We construct a functional, W, that assigns a probability to each distribution in the ensemble and show that in the asymptotic limit the ensemble obeys "thermodynamics": the most probable distribution is overwhelmingly more probable than all others, it is a member of the exponential family, and its parameters obey the network of Legendre relationships of familiar thermodynamics. By proper construction of the functional W (selection functional) we may pick out any distribution of the ensemble to be the most probable distribution. The implication is that any process that involves an unknown distribution can be associated with a corresponding functional W, and thus shown to obey thermodynamics. We discuss certain problems in population balances, show how to construct the corresponding selection functional and demonstrate the conditions under which phase transitions are possible.

Stochastic Processes and Statistical Mechanics

Themis Matsoukas
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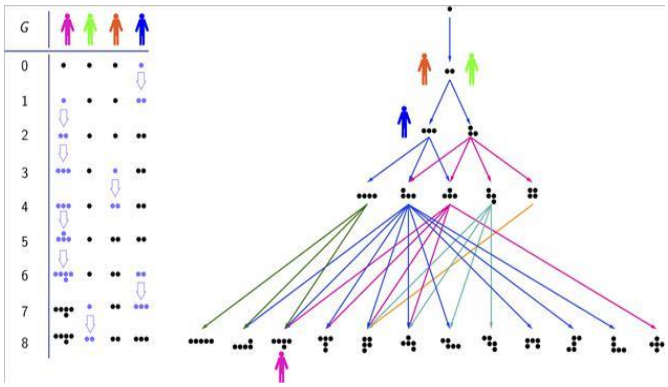
Statistical thermodynamics delivers the probability distribution of the equilibrium state of matter through the constrained maximization of a special functional, entropy. Its elegance and enormous success have led to numerous attempts to decipher its language and make it available to problems outside physics, but a formal generalization has remained elusive. Here we show how the formalism of thermodynamics can be applied to any stochastic process. At its most elementary level a stochastic process is a random walk in the event space of stochastic variable. This walk is defined by the current state of the walker and a set of rules that determine the set of feasible states in the next step. A stochastic path is a specific sequence of transitions from initial state to current state. The idea then is to count the number of paths that arrive to a particular state, then send a set of N walker to perform a walk by following any feasible path with equal probability. The state of this N-dimensional walk represents a sample of the stochastic process and the distribution of states in the sample a feasible probability distribution, and the probability of a

feasible distribution is given by the number of distinct paths that can produce it. We construct the master equation that governs the flow pf probability
–the Liouville equation of the stochastic process–and show that the ensemble of feasible distributions in the asymptotic limit obeys statistical thermodynamics: (i) the most probable distribution is overwhelmingly more probable than all others; (ii) it maximizes a homogeneous functional analogous to entropy (microcanonical functional); (iii) it is expressed in terms of parameters (canonical partition function, microcanonical partition function, generalized temperature) that obey the familiar network of Legendre relationships. Thus the formalism of thermodynamics is shown to be a stochastic calculus of stochastic processes. We present examples of simple stochastic processes and how to construct the corresponding thermodynamic functional. We are particularly interested in systems that lead to phase transitions and show how the emergence of multiple phases is governed by the same principles as vapor-liquid equilibrium in molecular systems.



Invariant and dually flat information geometric structure for deformed exponential families

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Information geometry is a mathematical framework that studies the geometry of the space of probability density functions and the geometry of statistical manifolds. It is an interdisciplinary field that combines differential geometry, statistics, information theory, machine learning theory and statistical physics. Information geometry is a research field that can be called one of the junctions of mathematical sciences. In information geometry, there are two important concepts for understanding the statistical manifold of probability density functions: invariance and dual flatness. Invariance is the property that the geometric structure of the statistical manifold formed by the family of probability density functions does not change under the transformation of random variables. For example, if we consider the logarithm of a random variable that follows the normal distribution, it follows the lognormal distribution. In this case, the geometric structure determined by the family of normal distributions and by the family of lognormal distributions are exactly the same. Invariance is a fundamental concept in physics and it seems to be related to the symmetry of physical systems. Dual flatness is the property that the Riemannian metric of a statistical manifold is not Euclidean, but the dual affine connections are flat. It is known that an exponential family, including the family of the normal distributions, is a dually flat space. Noteworthy properties include the potential of the Fisher metric being negative entropy and the dual coordinate system obtained from the Legendre transformation. Information geometry of non-additive statistical physics has focused mainly on dual flatness. Different from the usual exponential family, there are several natural dually flat structures in deformed exponential families. We have been able to clearly discuss the information geometric structures for deformed exponential families: the negative non-additive entropy can be regarded as the potential of the Riemannian metric, and divergence function can be described using escort expectations. In this talk, we consider invariant and dually flat geometric structures in deformed exponential families. Since this structure cannot be calculated directly from the non-additive entropy, it has not been studied. In this talk, we propose a new type of divergence that induces an invariant and a dually flat structure. We expect this result to be a useful development for both information geometry and non-additive statistical physics.

Dynamics of an inelastic tagged particle under strong confinement

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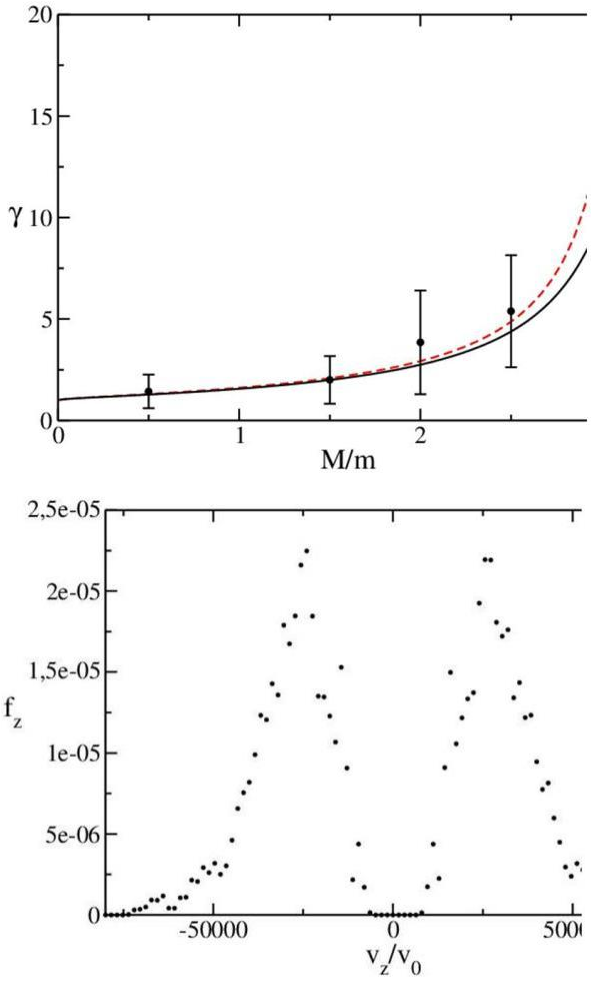
The dynamics of a tagged particle immersed in a fluid of particles of the same size but different mass is studied when the system is confined between two hard parallel plates separated a distance smaller than twice the diameter of the particles. The collisions between particles are inelastic while the collisions of the particles with the hard walls inject energy in the direction perpendicular to the wall, so that stationary states can be reached in the long-time limit. The velocity distribution of the tagged particle verifies a Boltzmann-Lorentz-like equation that is solved assuming that it is a spatially homogeneous gaussian distribution with two different temperatures (one associated to the motion parallel to the wall and another associated to the perpendicular direction). It is found that the temperature perpendicular to the wall diverges when the tagged particle mass approaches a critical mass from below, while the parallel temperature remains finite.

Molecular Dynamics simulation results agree very well with the theoretical predictions for tagged particle masses below the critical mass. In the first figure the quotient between the vertical and horizontal temperature, γ, is plotted as a function of M/m. M is the mass of the intruder and m the mass of the bath particles. The number of particles is 600, the collisions between the intruder and the bath particles are elastic and the collisions between the bath particles are slightly ineslastic. For these values of the parameters the critical mass of the intruder is of the order of 4.5.

The measurements of the velocity distribution function of the tagged particle confirm that it is gaussian if the mass is not close to the critical mass, while it deviates from gaussianity when approaching the critical mass. Above the critical mass, the velocity distribution function is very far from a gaussian, being the marginal distribution in the perpendicular direction bimodal and with a much larger variance than the one in the parallel direction [1]. In the second figure, for the same values of the parameters than in the previous figure, the marginal distribution in the perpendicular direction is plotted as a function of the velocity component perpendicular to the planes scaled with the thermal velocity. The bimodal character of the distribution can be clearly appreciated.



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The outer heliosphere: a zoo of non-equilibrium plasma's

David Mccomas, Georgios Livadiotis
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The outer heliosphere, beyond some 10s of au from the Sun, is characterized largely by particle systems, which do not reside at thermal equilibrium, and have velocity distributions that are not even close to Maxwellian. Some of these distributions can be well fit by kappa distributions, and their thermodynamics are described by non-extensive statistical mechanics. Other distributions are far more complicated. For example, pickup ion distributions are generated when interstellar neutrals are ionized in the solar wind. These distributions start as a ring with a cutoff at twice the solar wind speed (four times the energy); this ring rapidly angularly scatters in velocity space and then more slowly cools as new pickup ions are continually added to the outer shell of the distribution. Pickup ions have been well measured from ~20 to beyond 50 au by the Solar Wind and Pickup Ion (SWAP) instrument on New Horizons. While these ions do not resemble even kappa distributions, their thermodynamics can still be addressed through their entropy and the recently discovered properties of an entropy defect. This concept accounts for the entropy decrease caused by the order induced in assembling a system, such as when adding the low dimensionality of the phase-space of pickup ions or the long-range correlations among particles. Pickup ions dominate the internal pressure in the distant solar wind and are the primary population producing energetic neutral atoms (ENAs) in the heliosheath – beyond the termination shock – that are remotely observed by the Interstellar Boundary Explorer (IBEX) mission. This talk briefly summarizes the observations from SWAP and IBEX of the “zoo” of different non-equilibrium plasmas that inhabit the outer heliosphere and points to some of the work that has begun to connect them to their deeper thermodynamic properties. We also describe advances in the observations of these plasmas promised by the Interstellar Mapping and Acceleration Probe (IMAP) mission, launching in 2025.

Bosonics systems in the Canonical Ensemble

Si Khaled Mehdi, Salem Kessal
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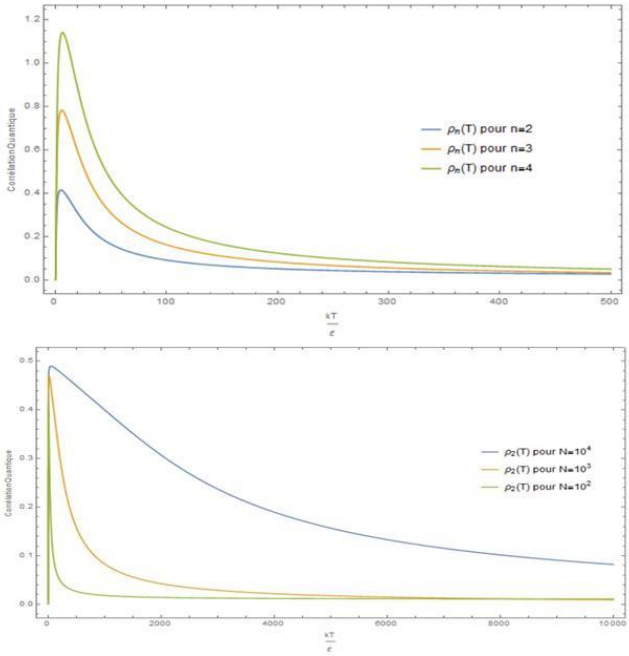
Quantum systems with infinite number of levels are difficult to treat with the canonical ensemble because of the difficulties in calculating the partition function of these systems[1]. We get to calculate the canonical partition function for these systems. We can then deduce the thermodynamic quantities such as the average energy. We have studied boson systems formed by N boson distributed over a small number of energy levels. We have considered situations where the energy levels are arbitrary and then cases where the levels are equidistant [2]. We deduced the average energy in each case. Comparing with the classical case we have given an expression of the quantum correlation for the average energy for these systems. We have plotted this correlation as a function of temperature, for different number of levels and different number of particles. We found in particular that this correlation increases with the number of levels and also with the number of particles.



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Anomalous transport and dynamic phase transitions in stochastic clustering under confinement

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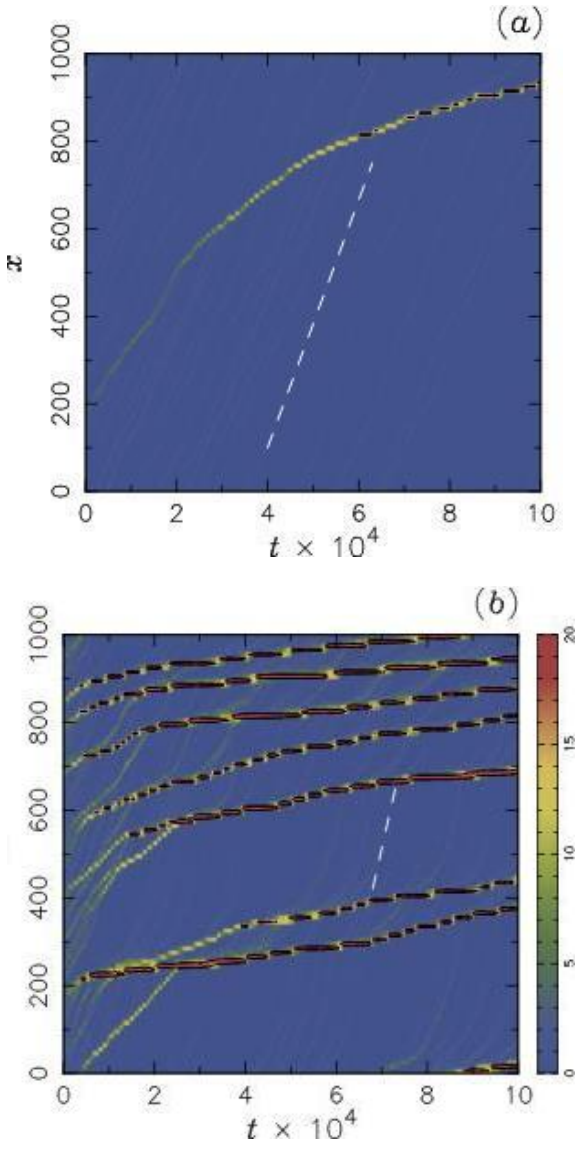
When a system of interacting particles is driven out of equilibrium macroscopic long range correlations emerge even if the interactions are local. We study the stochastic dynamics of particles driven out of equilibrium by an external force and moving in a dense quiescent bath through narrow channels. As the number of these intruders hincreases, a transition from a mixed phase to a collective pattern of dense clusters and dilute phases sets in. Clustering is mediated by the interaction with the bath and follows from a stochastic aggregation-fragmentation process. We show that the phase separation persists as confinement stabilises the thermal fluctuations, leading to large and long lived clusters that facilitate the formation of clogs. When the clogs are formed the intruders exhibits a dynamic phase transition from superdiffusion to single-file and entrain the whole system into an anomalous slow dynamics. As a result, dynamics exhibit negative differential mobility.



From financial risk measures to thermodynamic formalism

Miguel Mendes, Maria Carvalho, Paulo Varandas, Andrzej Bis *Universidade Do Porto, Porto, Portugal*

In Artzner et al. [1] an axiomatic approach to measure the risk of financial portfolios was introduced. Namely, a functional acting on the space of bounded random variables is said to be a coherent risk measure if it is invariant under translations, positively homogeneous, subadditive and monotone. Interpretations of these abstract properties in the realm of Finance were conveniently presented but the main purpose of the axiomatic setting was to obtain a robust representation theorem which establishes a one-to-one correspondence between coherent risk measures and finitely additive probabilities. More precisely, the risk of a financial position X is the maximum expected value of -X attained on a specific convex set of finitely additive probability measures. Followingly, Follmer and Scheid [2], generalized the previous result proving a robust representation theorem for convex, translation invariant and positively homogeneous functionals. In this case the risk of X is measured by the expected values of -X "penalised" by a convex and lower semicontinuous functional acting on the space finitely additive probability measures. This functional turns out to be the Fenchel-Legendre transform of the risk measure. This result is of great generality and provides a variational principle ready for use in the context of thermodynamic formalism in dynamical systems. Immediately, one notes that the

variational principle is valid for generalised pressure functions, i.e., convex, translation invariant and positively homogeneous functionals. Differentiability properties of these pressure functions are obtained analogously to the ones proved in Walters. Then we can apply the robust representation theorem given by Follmer and Schied to the topological pressure acting on the space of continuous potentials. As it is well known (see, e.g., Walters [4] p.214) the topological pressure satisfies the three properties of generalised pressure functions. We then obtain a variational principle where the Kolgomorov-Sinai metric entropy is replaced by the Fenchel-Legendre conjugate of the topological pressure. Please see Ref. [5] for more details.

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Langmuir waves in Kappa plasmas

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A detailed resource to data analysis shows that the widely known van Hoven and Derfler–Simonen laboratory results are far from reasonable agreement with the standard Bohm–Gross dispersion relation. We provide an extension of the usual notion of a polytropic index to non-Boltzmann–Gibbs statistics. Such an extension allows for the deduction of an equation of state of charged particles with the basis on the Kappa density distribution. That equation of state, in turn, enables suprathermal corrections to the standard dispersion relation. As a consequence, we prove that the employment of our suprathermal formula is in excellent agreement with the experimental data. Possible further applications of our theory are briefly addressed.

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Long-range correlated processes: confinement, heterogeneity, & tempering

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Stochastic processes driven by Gaussian yet power-law correlated noise, such as Mandelbrot's fractional Brownian motion (FBM) are ubiquitous in a range of complex systems, e.g., for the motion of tracers in viscoelastic environments, in "rough" financial data, or for the persistent motion of animals. FBM is an ergodic yet strongly non-Markovian process, with often surprising behaviour. In this talk I will briefly introduce these processes and demonstrate that in strong confinement their probability density may assume multimodal shapes, while in soft external potentials no steady state exists. An application to brain fibre growth is discussed. In heterogeneous environments the dynamics of a diffusing test particle may become a (random or deterministic) function of time. For these cases I will introduce novel extensions of FBM such as memory-multimodal FBM and FBM with a "diffusing diffusivity". Finally, I will discuss tempering of the power-law correlations, to emulate systems with a finite correlation time. This description is a good description for observed dynamics of lipid molecules in model membranes.

Methods of dimensional reduction to assess rare events of blackouts in power grids

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We discuss the frequency of blackout or desynchronization events in power grids for realistic data input, in particular with time correlations in the fluctuating power production. Our desynchronization events are caused by overloads. We propose and discuss different methods of dimensional reduction to considerably reduce the high-dimensional phase space. The first method splits the system into two areas, connected by heavily loaded lines, and treats each area as a single node. This corresponds to the so-called synchronized subgraph approximation, here applied to the swing equations. The second one considers a separation of the timescales of power fluctuations and phase angle dynamics and completely disregards the phase angle dynamics. Desynchronization events are truly rare either if the fluctuations are very small, too small to easily kick the system out of the fixed point that is stable in the deterministic limit, or, if the distance to the bifurcation point is still rather large, as the system is not heavily loaded. Such rare events are captured by the WKB-method for classical stochastic systems. We insert a WKB-ansatz into the differential Chapman-Kolmogorov equation for the probability to find certain voltage phase angles, frequencies, and power fluctuations at time t. This leads to a Hamilton-Jacobi equation. We then derive Hamilton's equations of motion to determine the optimal path with the smallest entropic barrier along which the desynchronization happens via an instanton. The obtained average desynchronization times obtained for the different versions of the dimensionally reduced system are compared with those obtained for the full system, simulated via the swing equations. The drastic approximation to neglect the phase space dynamics turns out to be justified to exponential accuracy in the strength of the fluctuations, which means that the number of rare events does not sensitively depend on inertia or damping for realistic heterogeneous parameters and long correlation times. Neither does the number of desynchronization events automatically increase with non-Gaussian fluctuations in the power production as one might have expected. We point out under which conditions the number of desynchronization events decreases. On the other hand, the analytical expressions for the average time to desynchronization do depend on the finite correlation time of the fluctuating power input. We also discuss subtleties in the very implementation of data in the numerical simulations if the artificially generated ones should reproduce real data as collected in histograms of power increments of wind data.

On a multiscale mean-field spin glass

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We will consider a mean-field disordered system with Sherrington-Kirkpatrick model Hamiltonian study its thermodynamic properties in presence of multiple thermal equilibria, namely assuming that the random coupling can be divided into a finite number of families having their own effective equilibrium temperature. The generating functional (thermodynamic pressure) of the model is constructed trough a hierarchical sequence of annealed averages, reminiscent of the Replica Symmetry Breaking interpolation [1]. The above construction can be also seen as a multiscale decomposition of the Hamiltonian viewed as a gaussian process. The measure induced by the above pressure is not Gibbsian and can be used to describes quasi equilibrium properties of systems in the small entropy production regime. Moreover it has a dynamical interpretation given in terms of Langevin dynamics where different degrees of freedom are subject to different thermal baths and have widely different timescales [2]. We will discuss the recent result obtained in [3]: the thermodynamic limit of the pressure per particle can be represented as a solution of an infinite dimensional variational principle of the Parisi type. In particular we will show that the multiscale structure acts as constraint in the space of functional order parameter. We will briefly discuss the two main ingredients of the proof: the replica symmetry breaking interpolation and synchronization mechanism. We will show that one can add a suitable perturbation to the model in order to force the overlap to be synchronized with the different thermal baths acting on the system. Finally we will briefly discuss some dynamical aspect of the model.

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Structures in a 2D colloids interacting via modified inverse-power potentials with tunable softening of inner core

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We have used classical density functional theory, HNC integral equation theory (IET) and NVT Monte-Carlo Simulation to investigated the effects of gradual softening of inverse-power repulsive interaction on the pair structure and phase transition properties of the two-dimensional system of colloidal dispersion. We aim to understand the anomalous behaviors and structure formation in a one-component 2D colloidal system using DFT by carefully examining the crossover from one-length to two-length scale characteristics of purely repulsive interaction potential. The particles are assumed to interact via modified inverse-power (MIP) potentials whose strength of the repulsion is softened in a range of distances with an interparticle separation dependent exponent. The radial distribution curves of IET are found to exhibit a non-monotonous nature with an emergence of new peak at a shorter distance. It points to the existence of two competing length scales of nearest-neighbor distance, i.e., a larger soft length fading out with increasing density in favor of the smaller hard length. At higher densities, in-contrast to the HNC IET, the RDF, obtained by MC simulation for high-softness parameter case, display a splitting of the second peak. Using DFT with structural inputs obtained by HNC IET we propose a fluid-triangular solid phase diagram in the temperature-density plane for various softness of the interparticle interaction. Comparison of the virial pressure obtained by HNC and MC simulations has been found to reveal an interesting feature. Whereas the pressure versus density curve given by HNC increases monotonically, the same due to MC simulation, on the other had, shows a discontinuity. Interestingly the line emerging at the discontinuity is found to have greater slope than the line corresponding to fluid. This suggest the possibility of the formation of amorphous glassy phase in 2D system at hand. In order to verify it further, Wendt-Abraham parameter which is a simple and yet useful empirical criterion that has been employed from both the Monte Carlo (MC) and molecular-dynamics (MD) simulations to investigate the liquid-glass transition, has been calculated. We have also calculated the bond orientational order parameter which reaffirms the presence of amorphous solid phase for the case of high softening parameter.

Decision-making with distorted memory: Escaping the trap of past experience.

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Snapshots of “best” (or “worst”) experience are known to dominate human memory and may thus also have a significant effect on future behaviour. We consider here a model of repeated decision-making where, at every time step, an agent takes one of two choices with probabilities which are functions of the maximum utilities previously experienced. Depending on the utility distributions and the level of noise in the decision process, it is possible for an agent to become “trapped” in one of the choices on the basis of their early experiences. If the utility distributions for the two choices are different, then the agent may even become trapped in the choice which is objectively worse in the sense of expected long-term returns; crucially we extend earlier work to address this case. Using tools from statistical physics and extreme-value theory, we show that for exponential utilities there is an optimal value of noise which maximizes the expected returns in the long run. We also briefly discuss the behaviour for other utility distributions as well as preliminary work extending the model to a pair of interacting agents.

Rewiring of scale-free networks vs. degree correlation properties

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We present results obtained with new algorithms which use Newman's network rewiring to achieve some target degree correlations, or to obtain assortative or disassortative mixing. In particular, Newman's rewiring has been tested by reconstructing Barabasi-Albert networks, and this procedure gives useful insights about key issues of the theory of scale-free networks, like the degree distribution of the hubs and the role of higher-order correlations. Furthermore, we have proven a new relation between the variation of r (Newman assortativity coefficient) and K (average nearest neighbor degree) valid in any degree-conserving rewiring. – This presentation is based on our works [1] and [2]. The working principle of the Newman rewiring [3] is the following. After choosing at random in the list of the links two links (a,b) and (c,d), between nodes a,b,c,d, one computes the probability E1 of these links according to the "target" correlation matrix. One then computes the probability E2 for the exchanged links, i.e. for the couple (a,c) and (b,d) and applies a sort of Metropolis-Monte Carlo criterion: if E2>E1, then the rewiring is performed with probability 1, otherwise it is performed with a probability proportional to the difference (E1-E2). These steps are repeated for a large number of times, typically at least 103 times the total number N of nodes in the network. Clearly the final product at equilibrium is a statistical ensemble of networks displaying the target correlations in an average sense.

In the reconstruction of Barabasi-Albert networks we have used the general expression for their degree correlations recently computed by Fotohui and Rabbat. For networks "BA-1" (single preferential attachment) the resulting number of isolated pairs is always zero, because the condition $P(1|1) = 0$ is enforced in an effective way. The size of the giant (connected) component is about 0.69 ± 0.01. Most of the disconnected small components are triples, whose origin is quite interesting. The correlation $P(2|1)$ is non zero for BA-1 networks. In fact, in the growth process with preferential attachment, connected tails of variable length can arise, in which the last node contributes to the correlation $P(2|1)$ and the intermediate nodes contribute to the correlation $P(2|2)$. When the network is re-constructed in the configuration model, isolated triples arise, because the non-vanishing conditional probability $P(2|1)$ allows to attach two nodes of degree 1 to a central node of degree 2 "without knowing" that on the other side of this central node there is no connection to the giant component. This is a simple demonstration of the general fact that the knowledge of the degree distribution and two-point correlations is insufficient to completely characterize a network. For BA degree distributions with multiple attachment the Newman rewiring always generates a fully connected network (giant component equal to 1).

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Improvement in Barcode analysis in Optical DNA mapping

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Optical DNA mapping (ODM), a method of generating sequence-dependent fluorescence "fingerprints" (DNA barcodes), often suffers from captured noisy images due to fluctuation of molecules inside the nanochannel, the concentration variation of dyes, non-uniform illumination, etc. We use efficient noise modelling of fluorescence cameras to generate realistic-looking synthetic barcodes of a given molecule from the database (e.g. λ DNA). These synthetic barcodes act as 'standard candles' to compare the experimental barcodes, leading to improved matching and efficient determination of the molecule species.

Skyrmion phase in a frustrated triangular lattice with next-nearest neighbours

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Skyrmions in magnetic materials are topologically protected whirled spin configurations that behave like quasiparticles and have been suggested for several practical implementations including memory devices, logic gates, and microwave resonators. Known for a while now they were first experimentally discovered in a ferromagnetic (FM) bulk sample with their stabilization attributed to the presence of the Dzyaloshinskii– Moriya interaction. The latter is very often the cause of skyrmions creation, though recently some other mechanisms came into the spotlight, one of them being the presence of frustration in the system [1]. It was shown that antiferromagnetic (AFM) next-nearest neighbours interactions on a triangular FM Heisenberg lattice favour skyrmion and antiskyrmion lattices (SkL/ASkL) with equal probability. We study AFM Heisenberg triangular lattice with second and third neighbour interactions (J1-J2-J3) in the presence of the external magnetic field [2]. First, we construct a zero-field phase diagram in J2 - J3 plane by means of Luttinger-Tisza approximation for zero-temperature calculations and massively parallelized GPU-implemented parallel tempering Monte Carlo simulations for the finite temperatures. We identify two already known phases [3] as well as several multiple-q phases and two spiral spin liquid ones according to the J2/J3 ratio. In the case of a non-zero magnetic field, we show that for a certain ratio of the coupling strengths the SkL/ASkL lattice is present in a narrow temperature-field region. Unlike in the FM case [1], the J2 and J3 magnitudes required for that are rather small. The AFM SkL/ASkL, similarly to [4], follow the three-sublattice decomposition natural for the triangular AFM lattices and form a regular hexagonal lattice on each of the three interpenetrating sublattices. Due to the presence of the rotational symmetry in the plane perpendicular to the external magnetic field antiskyrmions and skyrmions with random helicity (Bloch, Néel, and intermediate) are stabilized spontaneously. We expect that in real materials the presence of common additional interaction (single-ion anisotropy, bond anisotropy, or dipolar interactions) will lift this spontaneity, and topological objects with fixed helicity will be stabilized.

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Preserving Bifurcations through Moment Closures

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Moment systems arise in a wide range of contexts and applications as high- or even infinite-dimensional systems of coupled equations. Hence, an indispensable step to obtain a low-dimensional representation that is amenable to further analysis is in many cases to apply a moment closure. The latter is a set of approximations that express certain higher-order moments in terms of lower-order ones, so that applying those breaks the hierarchical structure of the equations and leads to a closed system of equations for only the lower-order moments. Closures are frequently found drawing on intuition and heuristics in trying to come up with quantitatively good approximations. Apart from that, from a dynamical systems' point of view, a key consideration when deriving closures has to be whether dynamical features such as bifurcations are preserved. Hence, we propose a change of

perspective where we focus on closures giving rise to certain qualitative features such as bifurcations. Importantly, this provides us with the possibility to classify moment closures rigorously and makes the design and selection of the same more algorithmic, precise, and reliable. In this talk, we will revisit two paradigmatic network dynamical systems, the SIS epidemic and the adaptive voter model, and derive conditions that a moment closure has to satisfy so that the corresponding closed systems exhibit the transcritical bifurcation that one expects in these systems coming from the stochastic particle model. Finally, we examine existing moment closures for both systems in the light of these results and show that they indeed satisfy all the conditions.

Numerical study of the six-dimensional Ising spin glass on a field

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The study of spin glasses has been tackled from many different points of view. On the theoretical side, great efforts have been dedicated to studying and classifying the phase transition. Specifically, for the Sherrington-Kirkpatrick mean field model of a spin glass, Parisi's Replica Symmetry Breaking solution[1] provides an exact description of the system. For the finite-dimensional models, however, we have no exact solution and the standard way to study them is the Wilsonian Renormalization Group[2]. Systems with no external magnetic field have been widely studied, both by theory and by simulations, and we have a good understanding of the physics of their transition. The upper critical dimension D=6 has been identified and the critical exponents for the short-range finite-dimensional model have been computed[3,4]. Nevertheless, the scenario for systems with an external magnetic field is completely different. It is not clear if there is a phase transition to a spin glass phase at all. In the literature, some results can be found that support that there is no phase transition at any dimension. Different studies defend there is phase transition only above dimension D=6. A recent publication analyzes the system by using a loop expansion around the Bethe solution finding that the upper critical dimension corresponds to D=8[5,6,7]. From the computational point of view, numerical simulations suggest a phase transition occurs for D=4[8], while the results are not conclusive for D=3[9]. The results we present here, try to add some clarity to the debate around the value of the upper critical dimension by means of massive numerical simulations for the six-dimensional spin glasses in the presence of an external field. Because of the difficulties to simulate such a system, we use sophisticated algorithms and techniques such as the Parallel Tempering Method and the Multi Spin Coding with intensive use of computational resources. We simulate the Edwards-Anderson model and study the phase transition through different estimations of the magnetic susceptibility. We identify a continuous phase transition and we also estimate the critical temperature, significative smaller than the critical temperature of the model with no external magnetic field. We also computed the critical exponents η and ν. However, their estimations are not accurate enough to determine if they are compatible with the mean-field values.

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A simple model of 1/f fluctuations from amplitude modulation and demodulation

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1/f fluctuations are ubiquitous. This fluctuation is characterized by the power-law behavior of index -1.5 to - 0.5 in the very low-frequency region of the power spectrum density (PSD). Since its discovery in 1925 in the electric current flowing through a vacuum tube (Johnson), it has been widely observed in various fields: semiconductors, biological membranes, crystal oscillators, temperature changes over very long periods, etc. Various theories have been proposed for the origin of 1/f fluctuations, but a universal mechanism has not yet been discovered.

We propose a simple model of 1/f fluctuations (pink noise) based on the amplitude modulation of accumulated frequency waves (AMAF) and its demodulation (DM) (arXiv:2301.11176, 2104.08872). This mechanism is a simple beat of many waves with accumulated frequencies. The wave beats can yield an unlimited low-frequency signal. However, on top of this AMAF, the demodulation (DM) process is also needed for 1/f fluctuations to show up. The existence of the DM process characterizes our model and is essential for its verification.

Familiar examples of amplitude modulation are the electric musical instrument theremin and the AM radio receiver. Both use high-frequency waves in the form of electric oscillations or radio waves and extract audible signals by demodulation process. The frequency accumulation can spontaneously arise in the cases of a) synchronization, b) resonance, and c) infrared divergence. We explore each of them below. Some examples of a) synchronization are as follows. A typical frequency accumulation is exponential, and the PSD shows a perfect 1/f structure. Interestingly, the exponential yields power law. If the frequency accumulation is a power law, then the PSD shows a 1/f structure with slightly modified power. Dynamical examples are the Hamiltonian Mean Field (HMF) model and the coupled macroscopic spin model. In the case of b) resonance, earthquakes, solar flares, and variable stars are typical examples. For c) infrared divergence, electric currents, and the associated nerve system show 1/f noise.

Further, there are various demodulation methods from which the diversity of 1/f fluctuations arises. For music, HMF, and electric currents, the time series of the data show 1/f fluctuations only when the original signal is squared. For seismic waves, neurotransmission signals, and solar flares, the time series of the data show 1/f fluctuations only when demodulated in the form of thresholds. The threshold mechanisms are fault rupture, neuronal firing, and magnetic reconnection. If the 1/f fluctuations are interpreted as AMAF as we propose, then it would be natural that they often appear inconsistent with various basic principles of statistical mechanics. For example, the Wiener-Khinchin theorem linking PSD and time correlation function cannot conclude the existence of long-time memory. This is because the wave beat does not appear in the PSD unless the signal is squared. Furthermore, since the beat has nothing to do with dissipation, the fluctuation-dissipation theorem does not hold. Therefore, 1/f fluctuation can appear even in HMF, a fully conserved system. We can claim that ubiquitous 1/f fluctuations do not require any elaborate stage of statistical mechanics, but they are simple amplitude modulation.

Verifications of the origin of 1/f noise - Earthquakes, solar flare, and variable stars

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We have recently proposed a simple model of 1/f fluctuations (pink noise) based on the amplitude modulation of accumulated frequency waves (AMAF). We challenge to what extent this mechanism can be universal among the variety of 1/f fluctuations reported so far. An inevitable condition of our AMAF proposal is the existence of the demodulation (DM) process for the appearance of 1/f fluctuations. This condition can be a merkmal indicator for verifying the AMAF proposal. The frequency accumulation can spontaneously arise in the cases of a) synchronization, b) resonance, and c) Infrared divergence. We explore each of them below.

We first show that the earthquake time sequence of 50 years of USGS global data shows 1/f fluctuations in its power spectrum density (PSD) if we limit the magnitude, although the whole data does not. Further, ignoring the magnitude information, the earthquake occurrence time sequence shows much clear 1/f fluctuations. According to the AMAF proposal, there must be resonant modes of Earth that cause 1/f fluctuations. We identify these modes as the Earth's free oscillation that is always excited. We found the accumulation and the superposed waves of such eigenfrequencies show 1/f fluctuations. This free oscillation may be the origin of the earthquake 1/f fluctuations. On the other hand, the demodulation (DM) mechanism should be the fault rupture. This relatively low-energy phenomenon is consistent with the fact that the 1/f fluctuations appear in low-energy earthquake events. Further, we found the 1/f fluctuations in the Earth's rotation speed, which the Earth's free oscillation may cause. Second, we show that the solar flare time sequence of 20 years RHESSI data shows 1/f fluctuations in its power spectrum. Many other time sequences of the phenomena, such as the solar wind, cosmic rays, and $_3^-$ deposition on the Antarctic ice sheet (Mochizuki et al. arxiv.2209.11330), also show 1/f fluctuations. According to the AMAF proposal, we suspect the existence of resonant modes of the Sun that cause the above 1/f fluctuations. We identify these modes as the solar five-minute oscillation. We found the accumulated frequency difference distribution and that the superposed waves of such eigenfrequencies show 1/f fluctuations. This may be the origin of the various solar 1/f fluctuations.

On the other hand, the demodulation (DM) mechanism should be the magnetic reconnection that often triggers solar activities. Third, we show that variable star light curve time sequence (AAVSO) shows 1/f fluctuations in its power spectrum. According to the AMAF proposal, there must be any synchronization mechanism in the variable stars that cause the 1/f fluctuations. We construct a model of the variable star as the coupled many convections expressed as the coupled Lorentz models. We show that this model naturally creates 1/f fluctuations according to the synchronization of convections. Thus, the origin of various 1/f fluctuations can be simple amplitude modulation (AMAF) and demodulation (DM) processes rather than any elaborate theories of statistical mechanics. If time allows, we can show more analysis: infrared divergence, volcano eruption, orchestra music, iceberg sound, and water harp caves.

From networks to spin glasses: Machine learning and statistical inference in discrete systems through the lens of random walks

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Complex, large-scale networks represent a broad spectrum of systems in nature, science, technology, and human societies [1]. Computer networks such as the World Wide Web and the Internet, social networks such as Twitter and Facebook, and online knowledge-sharing platforms such as Wikipedia exert considerable influence on our everyday lives. Many of these networks are very large and may evolve with time, making predictions of their properties a challenging task. I will describe a novel methodology, based on random walks, for the inference of various properties of complex networks with weighted or unweighted symmetric edges. I will show that this formalism yields reliable estimates of global network properties, such as the network size, after only a small fraction of nodes has been explored. I will also introduce a novel algorithm for partitioning network nodes into non-overlapping communities - a key step in revealing network modularity and hierarchical organization [3]. The problem of network community detection is similar to the well-known problem of clustering datapoints in machine learning. I will apply this algorithm to various benchmarks, including a state-of-the-art collection of synthetically generated networks with tunable community structure and a large-scale map of roads and intersections in the state of Colorado. Finally, I will demonstrate how these ideas can be used to estimate key thermodynamic quantities such as free energies in physical systems with discrete states, solely on the basis of small-size non-equilibrium samples. The main ingredient of the free energy reconstruction is so-called coincidence counting - the numbers of times the discrete states of the system are visited by random walks. In summary, random walks reveal modular organization and global structure of complex networks and at the same time provide a computationally efficient approach to inferring key statistical mechanics quantities in physical systems with discrete states.

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Converse symmetry breaking in network dynamics

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An increasing number of systems is now known to exhibit a symmetry effect that we refer to as converse symmetry breaking (CSB). It concerns scenarios where the stabilization of a symmetric state of interest requires explicitly breaking the given symmetry in the system itself. In this presentation, I will discuss recent advances in the mathematical, computational, and experimental study of this effect in the synchronization of coupled oscillators. In this case, CSB describes situations where stable synchronization requires the oscillators to be nonidentical, nonidentically coupled, or nonidentically driven. Examples will be given for networks of optoelectronic, electromechanical, and electrochemical entities as well as power generators and chaotic circuits, among others. It follows that parameter mismatches, which are ubiquitous and often unavoidable in real systems, can serve as a source of stability.

Scalable control and observability: Power grids and other large-scale networks

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A major challenge in the current study of power grids and other large-scale networks is the lack of scalability of most existing control approaches. In this presentation, I will introduce a notion of network locality that can be exploited to make the control of networks scalable even when the dynamics are nonlinear. I will also present a graph-based theory and scalable computational approach for functional observability, the important scenario in which only a subset of state variables needs to be reconstructed. Example applications will include the control of synchronization dynamics and the detection of cyberattacks in power-grid networks. These results enhance our ability to explore otherwise inaccessible dynamical processes and show how large networks can be controlled with computation and communication costs comparable to those for small networks.

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On the origin and implications of electron non-thermal distributions in the solar wind

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There is wide evidence that in many space environments as the solar wind, the Velocity Distribution Function (VDF) of electrons presents interesting non-thermal behaviors as heavy tails (power-law behavior at large energies) and skewness in the direction of background magnetic field. By separate, the origin of both properties (power-law tails and skewness), and the consequences that they produce on space plasmas have been addressed in several observational and theoretical studies. However, a complete understanding on the origin of distributions exhibiting power-law tails is and skewness has already to be done. Recently, a new model for solar wind electrons, called the "Core-Strahlo model", has been proposed. This model describes the electron VDF as the superposition of a quasi-thermal core, plus a Skew-Kappa distribution (the strahlo), representing both, halo and strahl. In this work we present the results about our two complementary studies, which aim to answer the following questions: (1) how can we model the microscopic dynamics of a magnetized, turbulent and non-collisional space plasma so that the distribution has power-law tails and skewness at the same time? For this, we show an alternative Langevin type force equation to model the first principles dynamics of electrons in a space plasma, exploring how the microscales relates to the macroscales, and we focus on quantifying the heavy tails and skewness throughout the moments of the VDF in the steady state; and (2), what is the role of these Skew-Kappa functions on the regulation of the electron heat-flux? For this, we analyze the effect of these skewed electrons on the excitation of the whistler heat-flux instability (WHFI). Our results show that the WHFI can develop in this system, and we provide stability thresholds for this instability, as a function of the electron beta and the parallel electron heat-flux, to be compared with observational data. However, since different plasma states, with different stability level to the WHFI, can have the same moment heat-flux value, it is the skewness (i.e. the asymmetry of the distribution along the magnetic field), and not the heat-flux, the best indicator of instabilities. Thus, systems with high heat-flux can be stable enough to WHFI, so that it is not clear if the instability can effectively regulate the heat-flux values through wave-particle interactions.

Phase transition in fluctuations of interacting spins at infinite temperature

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The high temperature limit of interacting spins is usually not associated with ordering or critical phenomena. Nevertheless, spontaneous fluctuations of a local spin polarization at equilibrium have nontrivial dynamics even in this limit. Here, we demonstrate that the spin noise power spectrum of these fluctuations can undergo discontinuous changes as a function of an external magnetic field. As a simple illustration, we consider a model of Ising-like long range spin-spin interactions with a transverse magnetic field as a control parameter. This system undergoes a phase transition associated with disappearance of the noise power peak responsible for the most detrimental decoherence effect of the interactions.

This work was inspired by a rapid progress with synthesis of novel Metal–Organic Frameworks (MOFs) -- the organic materials that incorporate metallic ions with uncompensated spins in a regular array. The atomic spins can be placed at a sufficient distance from each other to remove exchange interactions. Thus, the spins form a macroscopic array of qubits with considerable coherence time at cryogenic temperatures. MOFs should then provide a platform for experiments with quantum many-body physics at macroscopic scale. However, such large qubit systems induce collective decoherence effects that are absent on the level of a single qubit.

A lot about the effects of decoherence in MOFs can be inferred from the prior studies of molecular nanomagnets . The latter are molecules whose magnetic ions form relatively large net spins, which can also form regular magnetic arrays. At cryogenic temperatures the phonon-related mechanisms of decoherence in molecular magnets are generally suppressed but coherent spin dynamics is not observed due to random hyperfine, of order of a few tens of Gauss, and magnetic dipole fields from neighboring spins (a few hundred of Gauss).

The hyperfine effects can be suppressed substantially by isotopic purification, but the random long-range dipole fields in the sample represent a considerable problem for quantum control. Unlike the molecules with large spins, MOF qubits with spins-1/2 do not experience the quadratic crystal anisotropy. Hence, an external magnetic field that strongly exceeds the typical dipole fields induces coherent precession of all spins around the field axis. However, it is not convenient to use strong fields in practice.

In this work, we explore both numerically and analytically the coherent behavior of long-range interacting spins in a moderate external magnetic field. The most unfortunate effect of the dipole spin-spin interactions is the relatively slow collective relaxation of the local spontaneous spin field fluctuations. The latter mis-allign the net effective fields that act on different spins from the external field axis. Therefore, there is no possibility to define a single rotation axis for the spins in the lattice.

The main finding of our theory is that this most detrimental decoherence effect disappears at relatively week, of an order of the typical dipole field fluctuation, value of the external field. For a stronger field, the spin-spin interactions still contribute to the lifetime but they no longer mis-allign the spin precession from around the direction of the external field.

Dynamic correlations in the conserved Manna sandpile

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We study dynamic correlations for current and mass, as well as the associated power spectra, in the onedimensional conserved Manna sandpile. We show that, in the thermodynamic limit, the variance of cumulative bond current up to time T grows subdiffusively as T 1/2−μ with the exponent $\mu \geq 0$ depending on the density regimes considered and, likewise, the power spectra of current and mass at low frequency f varies as f 1/2+μ and f −3/2+μ , respectively; our theory predicts that, far from criticality, μ = 0 and, near criticality, μ = β+1 2 $\nu\perp$ z > 0 with β, $\nu\perp$and z being the order-parameter, correlation-length and dynamic exponents, respectively. The anomalous suppression of fluctuations near criticality signifies a “dynamic hyperuniformity'', characterized by a set of fluctuation relations, in which current, mass and tagged-particle displacement fluctuations are shown to have a precise quantitative relationship with the density-dependent activity (or, its derivative). In particular, the relation, $Ds(\overline{\rho})$ = $a(\overline{\rho})$ / $\overline{\rho}$, between the self-diffusion coefficient $Ds(\overline{\rho})$ activity $a(\overline{\rho})$ and density $\overline{\rho}$, explains a previous simulation observation [1] that, near criticality, the self-diffusion coefficient in the Manna sandpile has the same scaling behaviour as the activity. The main results of our work are summarized as following.

We show that, in the thermodynamic limit, $L \to \infty$ and density $\overline{\rho}$fixed, the variance of the local (bond) current $Q(T)$ grows subdiffusively. Near criticality, the current fluctuation is further suppressed, $\langle Q$ 2 $(T)\rangle \sim T$ 1/2 −μ . We find that the time-dependent (two-point) correlation function for the instantaneous current is long-ranged (power-law) and negative. The corresponding power spectrum SJ $(f) \sim f$ ψJ , vanishes at low frequency, where ψJ = 1/2 away from criticality (in the frequency regime 1 L 2 $\ll f \ll$ 1 for finite L) and ψJ = 1/2 + μ near criticality (in the frequency regime 1/L $z \ll f \ll$ 1). On the other hand, the power spectrum $SM(f)$ for subsystem-mass fluctuation, diverges $SM(f) \sim f$ −ψM at low frequency, where ψM = 3/2 away from criticality (1/L 2 $\ll f \ll$ 1) and ψM = 3/2 − μ near criticality (1/L $z \ll f \ll$ 1). These two exponents are not independent, and they are connected by a scaling relation ψM = 2 − ψJ .

The steady-state fluctuation of the subsystem current $Q(I, T)$, i.e., the cumulative (summed over bonds) current in a subsystem of size I in the thermodynamic limit ($L \to \infty$) interestingly converges to twice the activity when the infinite-subsystem-size limit is taken first and then the infinite-time limit. By deriving a fluctuation relation, we express the scaled subsystem mass fluctuation as an exact ratio of current fluctuation to twice the bulk diffusivity. Finally, we theoretically show that the self-diffusion coefficient $Ds(\overline{\rho})$ is identically equal to the ratio, $a(\overline{\rho})$/ $\overline{\rho}$, of the activity to the global number density of the system, a fluctuation relation, which connects the (scaled) tagged-particle displacement fluctuation to the density-dependent activity.

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Parametric decays of electromagnetic waves in electron-positron nonextensive plasmas

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Wave propagation in relativistic plasmas is a subject of interest in many astrophysical and space systems, where electromagnetic fields may accelerate particles up to relativistic velocities, which in turn modifies the physics of wave propagation. Besides, kinetic effects further modify the dispersion properties of waves and their nonlinear interactions with the plasma particles. Thus, it is of interest to study wave propagation, and its nonlinear decays, considering both relativistic and kinetic effects.

However, the traditional approach of equilibrium statistics, where kinetic effects are described by Maxellian velocity distributions, is not satisfactory in several environments where long range correlations, or memory effects, may lead the distributions to deviate from the Maxwellian case. Here, the proposal to describe plasma distribution functions in terms of nonextensive distribution functions, either of the Tsallis (where deviation from the Maxwellian case is given by a parameter q) or the kappa type (where deviations are parametrized by a κ factor), allows to extend the traditional formalisms, to study wave linear and nonlinear propagation for systems out of thermodynamical equilibrium. Following these ideas, in this work, parametric decays of an electromagnetic wave in an electron-positron plasma are studied. Kinetic effects are considered by means of the collisionless Vlasov equation, which is coupled to Maxwell equations. Relativistic effects on the particle motion are also taken into account. Perturbation of the system's equations lead to dispersion relations for the pump wave and for its parametric decays, which is numerically studied by considering a velocity distribution function which maximizes the nonextensive Tsallis entropy which, in the extensive limit, reduces to the Maxwell-Boltzmann-Jüttner distribution. In the weakly relativistic case, although some of the instabilities involve strongly damped, electroacoustic pseudomodes, all instabilites (of the decay and modulational type) found using fluid theory are present as well in the kinetic regime. For ultrarrelativistic temperatures and transverse velocities, the resonant decay and modulational instabilities are studied. The decay instability involves an electroacoustic pseudomode, and nonextensive effects are shown to be mainly relevant for the instability rate, whereas the real frequency of the unstable mode is essentially unchanged. Both the growth rate and the instability range are modified as the temperature and as the pump wave amplitude increase. The dispersion relation for the parametric decays is solved numerically for various values of the nonextensive parameter q. As expected, results reduce to the Boltzmann-Gibbs statistics for q close to 1.

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Random field Ising model for random single vertex origami

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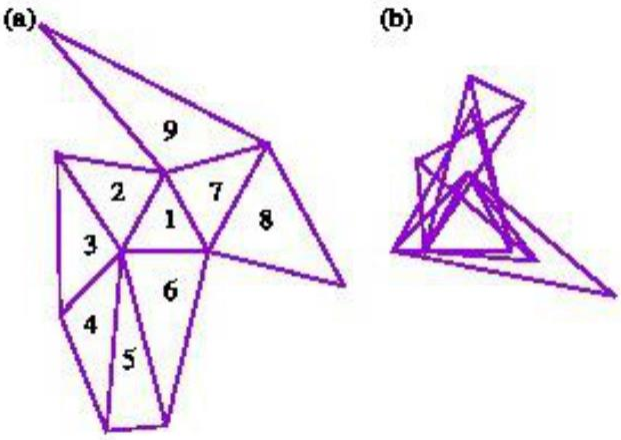
Flat-foldability problem of origami diagrams, including stamp-folding and map-folding as special cases, is a deterministic problem that asks whether it is possible to fold flat to satisfy the random allocation of mountains and valleys in the creases. These are kinds of combinatorial optimization problem and have been studied extensively in the past. For example, the stamp folding problem is known to be NP-hard to determine the maximum number of facets to be inserted, and the map folding problem is also known to be NP- hard. The classification of the computational complexity class is given by the worst-case complexity of the hardest problems in a set of various instances. On the other hand, the average-case complexity of ensembles of many instances is also interesting. The average-case complexity and the worst-case complexity sometimes exhibit different behaviors. In this research, we approach the behavior of the average-case complexity of problems related to origami. We investigate the phase transition phenomena of the flat-foldability of single vertex origami to approach better understanding of the average-case complexity of the flat foldability problem. Average behavior on the ensemble of instances of origami diagram under controlled density of imposition for folding manner, mountain or valley, of creases is observed and the thresholding value of density is obtained. We treat the problem of determining flat-foldability of the origami diagram with mapping onto a spin glass model on random graphs. A spin variable are assigned for the layer-ordering of each pair of facets which have an overlap in the pre-folded diagram. To avoid some infeasible layer-orderings some constraints are introduced. They are described as interaction terms which contain the product of two or four spin variables, while capturing the geometrical characteristics of how facets overlap. The constraints on how to overlap are classified into the following three types. 1. An intrusion of a facet into a crease which connects other two facets. 2. Some ordering among four

facets connected to each sides of the two creases which are in geometrically co- incidental position the pre-folded diagram. 3. A cyclic ordering of three facets which have areas shared with all each other in the pre-folded diagram. The flat-foldability of the diagram is closely related to the (non-)existence of frustrated loops or subgraphs on the spin model with the interactions on the random (hyper)graph. In addition, a well ordered treatment of the local-constraints with three different types reveals some collective variables, cluster spins, which reflect the locked layer-orderings of some facets generated from the cooperative work of the local constraints, which lead an efficient computation of the problem. For example, the origami diagrams shown in Figs. 1(a) and (b) are originally described by 36 spin variables, but it is found that they can be described by 11 variables by translating to cluster spin.



Cluster spin	Set of elemental spins $s_{i,j}$ included
$\mathscr{C}_1 = 1$	$\{s_{1,2}, -s_{1,3}, -s_{1,4}, -s_{1,5}, -s_{1,6}, -s_{1,7}, -s_{1,8}, s_{1,9}, -s_{2,3}, -s_{2,4}, -s_{2,5}, -s_{2,6}, -s_{2,7}, -s_{2,8}, s_{2,9}, s_{3,4}, s_{3,5}, s_{3,6}, s_{3,7}, s_{3,8}, s_{3,9}, s_{4,7}, s_{4,8}, s_{4,9}, s_{5,7}, s_{5,8}, s_{5,9}, s_{6,7}, s_{6,8}, s_{6,9}, -s_{7,8}, s_{7,9}, s_{8,9}\}$
$\mathscr{C}_2 = 1$	$\{s_{4,5}, s_{4,6}, s_{5,6}\}$
$\mathscr{C}_3 = 1$	$\{s_{1,10}\}$
$\mathscr{C}_4 = 1$	$\{s_{2,10}\}$
$\mathscr{C}_5 = 1$	$\{s_{3,10}\}$
$\mathscr{C}_6 = 1$	$\{s_{4,10}\}$
$\mathscr{C}_7 = 1$	$\{s_{5,10}\}$
$\mathscr{C}_8 = 1$	$\{s_{6,10}\}$
$\mathscr{C}_9 = 1$	$\{s_{7,10}\}$
$\mathscr{C}_{10} = 1$	$\{s_{8,10}\}$
$\mathscr{C}_{11} = 1$	$\{s_{9,10}\}$

Devil's staircase and modular invariance: from spectral statistics of random operators to phyllotaxis and the Hubbard model on a ring

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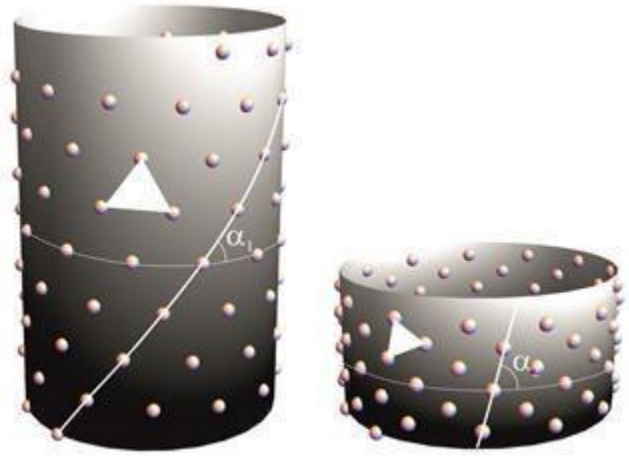
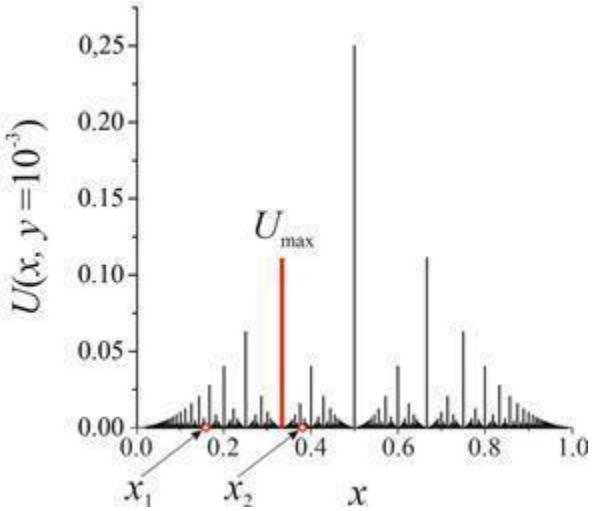
We discuss the spectral statistics of the 1D Anderson-like model with random hopping, paying attention to its relationship with some number-theoretic properties of the Riemann-Thomae function and the Dedekind eta-function exhibiting the ultrametric structure. We introduce the generalized Riemann-Thomae function and discuss its appearance in the problem of the repulsive particles packing on the cylinder (phyllotaxis). Also we show that the integral of the generalized Riemann-Thomae function has the Devil's staircase structure and coincides with the ground state of the Hubbard system of particles on a ring interacting with various long-ranged potentials.





Gintropic limits and scaling for the Hirsch index

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Since the seminal paper of Hirsch, in 2005 [1], scientist tried to link statistically the h index to the other two basic scientometric indicators: the total number of citations received by the researcher, N(cit) and the total number of papers published, N(pub), by him/her. Empirically, it was found that $N(cit)=4\ h^2$ [2], and assuming that all allowed distributions of the N(cit) citations for the N(pub) papers are equally probable, Yong [3] proposed a theoretical scaling: $N(cit)\simeq 3.42^{\ h}$. Seemingly both approaches work well for not too high N(cit) and N(pub) values. Exploiting the Paretian form for the distribution of citations for the papers authored by a researcher, here we discuss a novel scaling relations between h, N(pub) and N(cit). The analysis incorporates the Gini index as an inequality measure of citation distributions and a recently proposed inequality kernel, gintropy (resembling to the entropy kernel). We find a new upper bound for the h value as a function of the total number of citations, confirmed on massive data collected from Google Scholar (Figure 1). Our analyses reveals also that the individualized Gini index calculated for the citations received by the publications of an author peaks around 0.8, a value much higher than the one usually reported for socio-economic inequalities.

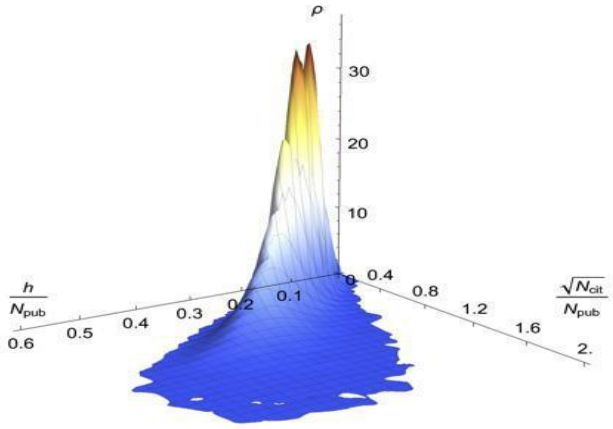

Figure 1. Distribution of the points [√N(cit)/N(pub), h/N(pub)], gathered form the profile of 43 656 researchers with N(pub)>100 and N(cit)>10 000 gathered from Google Scholar.

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Interpolation of large precipitation fields with space and space-time stochastic local interaction models

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Precipitation is the main variable used as input in hydrological models and risk assessment studies. Precipitation data of fine spatial scales contribute to a better understanding of the local effects on the hydrologic cycle, urbanization, and agriculture. At fine temporal scales, precipitation is essential for assessing weather patterns and estimating the timing and peak of floods and other hazards. At the same time, we need precipitation data over large areas, in order to better understand the global climate system and manage water resources, floods, droughts, and other climate risks. However, observations at fine spatial scales are difficult to acquire; observational stations are scarce, especially in mountainous regions, and rarely provide complete time series. Observational data at fine temporal scales (e.g., hourly or sub-hourly) are even more limited. Typically, interpolation methods are used to overcome these limitations. However, such methods usually do not take into account the spatial

and temporal dependencies of the data; the methods that do are generally computationally intensive and, therefore, not applicable to large-scale datasets. A different approach for obtaining large fields of fine-scale precipitation is the use of simulation models. Precipitation at fine spatiotemporal scales is a complex process characterized by strong dependence, anisotropy, and advection; hence, even simulation models have limits in the size of the random fields that they can generate, due to computational constraints. In this presentation we use the Complete Stochastic Modeling Solution (CoSMoS) framework to generate random fields (RFs) of precipitation having complex patterns and motion, imitating the movement of rainfall storms. This approach preserves any non-Gaussian marginal distributions and spatiotemporal correlation structure, locally varying anisotropy, and the general advection vector generated by velocity fields with locally varying speed and direction. To increase the sampling density of the generated fields in a fast and effective way, we use the Stochastic Local Interaction (SLI) model. SLI estimates the spatial (Space SLI, S-SLI) and spatiotemporal (Space-Time SLI, ST-SLI) dependence based on energy functions with local interactions that involve near neighbors. The interaction strength and the neighborhood size are defined by means of kernel functions and local bandwidths, allowing the formulation of sparse and explicit precision (inverse covariance) matrices for spatial or spatiotemporal dependence. SLI does not require matrix inversions; this feature implies modest computational requirements and allows the interpolation of large precipitation fields. We apply both S-SLI and ST-SLI to a combination of Gaussian and non-Gaussian, isotropic and anisotropic RFs generated by CoSMoS. We test the accuracy of the SLI models for predicting missing values, and we assess their ability to generate large moving fields of precipitation. The study provides a framework for the generation of large moving precipitation fields which can be used as input to large-scale hydrological models.

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Kappa distributions in space plasmas: review of methods and applications

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The valid description and understanding of physical mechanisms in space plasmas often requires the accurate determination of the velocity distribution functions of space plasma particles. Typical space plasmas are weakly collisional systems and the velocities of their particles follow non-Maxwellian distribution functions. Several studies have successfully used kappa distribution functions to describe the velocities of plasma particles in several space regimes, such us the solar wind, planetary magnetospheres, interplanetary shocks, the vicinity of a comet, the inner and outer heliosphere. The determination of the kappa index that labels and governs these distribution functions becomes a vital task, which is required for the complete description of the plasma dynamics. Recent studies demonstrated that inaccuracies in the determination of the kappa index can lead to significant misestimations of all the plasma bulk parameters. In real several applications, distribution functions are determined from particle observations obtained by space plasma instruments. Thus, the accuracy of the derived plasma parameters, depends on the quality of the plasma particle observations and it is affected by instrumental limitations. In this presentation we expose possible misestimations of the plasma bulk parameters when kappa distributions are not accurately determined. We consider realistic plasma instruments and their limitations in order to simulate observations in specific plasma conditions. We analyze the simulated observations in order to present new methods and tools we have developed in order to overcome poor sampling of the plasma distributions. For instance, we simulate the expected electron observations by Solar Orbiter mission and we quantify different fitting methods to calculate the plasma parameters in conditions of extremely low particle flux. In another example, we demonstrate the accurate determination of kappa distribution functions from the analysis of reduced data-sets. Moreover, we discuss the effects of instrument's field of view, sampling and efficiency limitations on the expected observations and the accuracy of the derived plasma parameters. We finally, report the potential use of our methods in a broad range of space plasma analyses, where kappa distribution functions play a significant role.

Low energy excitations in vector spin glasses

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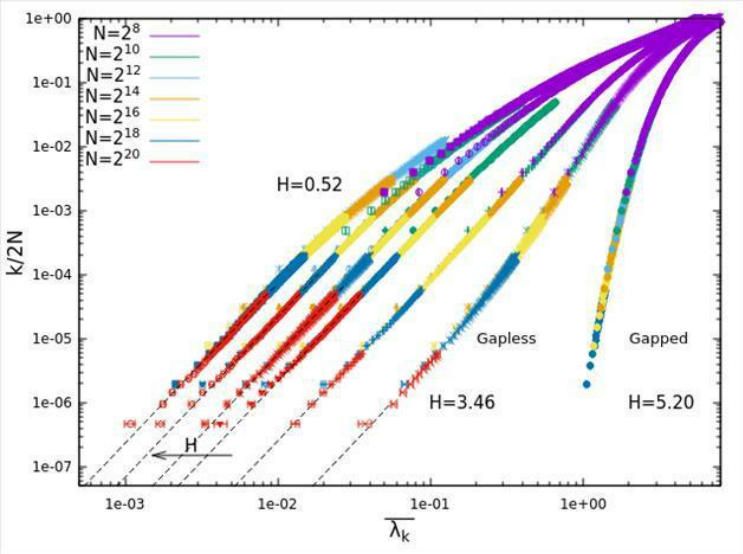
'La Sapienza' University Of Rome, Roma, Italy

The low temperature physics of glassy systems has not been yet completely understood. Glasses posses an excess of low energy excitations when compared to crystals: at low frequency, the VDoS of many glassy systems seems to follow a quartic law, understood in terms of phenomenological theories such as soft potential models. These soft excitations are found to be quasi-localised in microscopic spatial regions of the samples: they are related to soft spots of the system, showing anomalously high responses to external mechanical perturbations.

A first-principle theoretical framework where such glassy excitations emerge naturally is provided by spin glass systems. In this talk we will analyse two mean field vector spin glass models, the first with all-to-all interactions and the second with sparse interactions. We will present our analytical and numerical results at zero temperature about the spectral properties of these systems, focusing mostly on the Heisenberg model (spin with three components). We will show that these models feature quasi-localised soft excitations, which will be connected to the spin glass transition.



Glass and pseudo-localization transitions in the mode-locked p-spin model for random Lasers

Jacopo Niedda
Sapienza, Italy

Optical waves in active disordered media display the typical phenomenology of complex systems. Several spectral shots taken from the same piece of material in the lasing regime display strong fluctuations in the position of the intensity peaks, suggesting that there is no specific mode which is preferred in the amplification, but depending on the initial state, with the disorder kept fixed, the modes gaining the highest intensity change every time. In order to explain this behaviour, a spin-glass model has been developed, where the light modes are described as non-linearly interacting phasors on the so-called mode-locked diluted graph [1]. The specific mode-coupling selection rule, which naturally emerges in the study of lasing modes dynamics, impairs the analytical solution of the model out of the narrow bandwidth limit, where the interaction network is fully connected. In this talk we present recent results from numerical simulations of the mode-locked glassy random laser. A phenomenology compatible with a glass transition is revealed from the divergence of the specific heat and the non-trivial structure of the Parisi overlap distribution function [2]. By means of a refined finite-size scaling analysis of the critical region, the transition is assessed to be compatible with a mean-field universality class [2]. A pseudo-localization transition to a phase where the intensity of light is neither properly localized on a single mode nor equiparted among all the modes is revealed from the measure of the inverse participation ratio and of the spectral entropy [3]. The two transitions occur at the same temperature as different manifestations of the same underlying phenomenon, the breaking of ergodicity.

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Molecular motors and Brownian time crystals

Antti Niemi
Nordita, Sweden

Falling cats have a remarkable ability to turn in midair and land safely on their feet, even without angular momentum. The phenomenon can be explained using the mathematical framework of a connection in shape space. In this talk we argue that this connection can also explain the exceptional performance of many biomolecular motors. It organizes the thermal vibrations of individual atoms into a coordinated rotational motion of the entire molecule, enabling the molecule to evade the conclusions of Feynman's ratchet-and-pawl analysis. First, we present two molecular models that exemplify how universal directed rotational motion emerges from shape changes, even without angular momentum. We then implement an all-atom design approach for knotted polyalanine ring molecules, and find the emergence of a cooperative rotational organization of individual atom thermal vibrations that is dictated by the connection. Our molecular dynamics simulations also expose the dynamical consequences of spontaneous symmetry breakdown. The rotational motion arises so effortlessly even in ambient water, such that the molecule can be described using an effective theory time crystal.

From multiplicative matrix-valued diffusion to isometry of residual networks in deep learning

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Jagiellonian University, Cracow, Poland

We demonstrate that in residual neural networks (ResNets) dynamical isometry is achievable irrespective of the activation function used. We do that by deriving, with the help of Free Probability and Random Matrix Theories, a universal formula for the spectral density of the input-output Jacobian at initialization, in the large network width and depth limit. The resulting singular value spectrum depends on a single parameter, which we calculate for a variety of popular activation functions, by analyzing the signal propagation in the artificial neural network. We corroborate our results with numerical simulations of both random matrices and ResNets applied to the CIFAR-10 classification problem. Moreover, we study consequences of this universal behavior for the initial and late phases of the learning processes. We conclude by drawing attention to the simple fact, that initialization acts as a confounding factor between the choice of activation function and the rate of learning. We propose that in ResNets this can be resolved based on our results by ensuring the same level of dynamical isometry at initialization. The presentation is based on work [1].

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Eikonal formulation of large dynamical random matrix models

Maciej Nowak
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The standard approach to dynamical random matrix models relies on the description of trajectories of eigenvalues. Using the analogy from optics, based on the duality between the Fermat principle (rays) and the Huygens principle (wavefronts), we formulate the Hamilton-Jacobi dynamics for large random matrix models. The resulting equations describe a broad class of random matrix models in a unified way, including normal (Hermitian or unitary) as well as strictly non-normal dynamics. This formalism applied to Brownian bridge dynamics allows one to calculate the asymptotics of the Harish-Chandra-Itzykson-Zuber integrals.

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Global MHD galaxy simulations: feedback, non-equilibrium chemistry and the emergence of a mean-field dynamo

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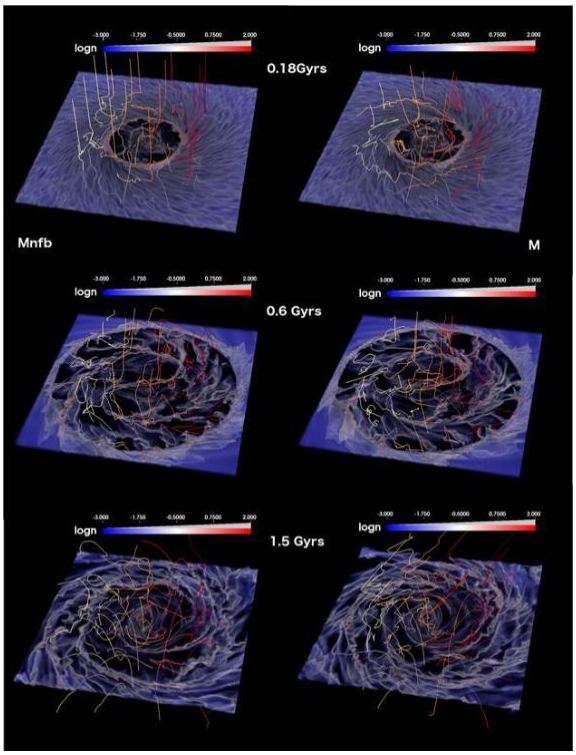
Magnetic fields are of paramount importance for understanding the evolution and dynamics of galaxies. However, even the magnetic field of our own Galaxy is still elusive, since its strength and direction are impossible to measure simultaneously. It is therefore essential that we complete our knowledge with numerical simulations of galaxy and magnetic field co-evolution. This contribution shows results from a series of high-resolution numerical models, aimed at deciphering the effect of the initial conditions and supernova feedback on the evolution of the galactic magnetic field in Milky Way-like galaxies. The models include a live potential from dark matter and stars, modeled as collisionless particles, coupled through gravity to a grid containing the magnetized gaseous disk. In models without chemistry [1,2], the gas cooling and heating is modeled based on equilibrium relations, and star formation is based on a local density criterion. Models with non-equilibrium chemistry include the physics of molecular hydrogen formation and base star formation on the molecular content of a grid cell [3]. The magnetic field of each model is either ordered on large scales, with a toroidal or poloidal geometry, or random with a power-law spectrum. Independently of these initial conditions, the galaxies quickly develop both a random and an ordered magnetic field component. An example of this evolution is shown in the accompanying figure (Figure 1), where we plot the gas number density with magnetic field lines for two models, M and Mnfb with and without supernova feedback and an initially toroidal field: both models show an increasingly complex magnetic field structure, independently of the presence of supernova feedback. This complex environment also naturally leads to a mean-field dynamo, which amplifies the magnetic field of both models by at least an order of magnitude over half a Gyr. However, the characteristics of the steady state galactic magnetic field and the magnetic-field-density relation differ for different initial conditions, indicating a possible link between observable features and initial magnetic field topology. Overall, these models highlight the importance of a systematic study of galaxy evolution including magnetisation.



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Data-driven stochastic modelling of power-grid frequency applied to islands

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Mitigating climate change requires a transition away from fossil fuels towards renewable energy. As a result, power generation becomes more volatile and options for microgrids and islanded power-grid operation are being broadly discussed. Therefore, studying the power grids of physical islands, as a model for islanded microgrids, is of particular interest when it comes to enhancing our understanding of power-grid stability [1, 2]. In the present work, we investigate the statistical properties of the power-grid frequency of three island systems: Iceland, Ireland, and the Balearic Islands using two different approaches. First, we utilise a Fokker– Planck approach to construct stochastic differential equations that describe market activities, control, and noise acting on power-grid dynamics. In particular, we propose stochastic power-grid frequency models and showcase the applicability of these new models to non-Gaussian statistics, as encountered in islands [3,4]. Second, we apply physical-inspired machine learning (PIML) to power-grid frequency data [5]. Specifically, we exploit techno-economic features to determine model parameters using neural networks. Thereby, we obtain physics-inspired trajectory forecasts for the power grid frequency in islands.

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Volterra equations to compute memory kernels and projected cross-correlation functions from molecular dynamics

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Because usual stochastic systems such as complex fluids have a large number of degrees of freedom, we use the projection operation techniques of statistical mechanics in which only a few observables are chosen to describe the system's evolution. The dynamics of such coarse-grained, or macroscopic, variables are separated from the dynamics of the other "irrelevant" microscopic variables that comprise the formers' environment. This is accomplished in the Langevin equation by dividing the coarse-grained dynamics into two components: a random one that sums up the interactions with the environment, and a dissipative one that represents the response of the macroscopic variables to their environment. The Markovian assumption is made, in which the dynamics of microscopic degrees of freedom occur on a negligible timescale in comparison to the typical one of macroscopic dynamics. Such an assumption is removed in the Mori-Zwanzig equation which becomes important as the separation of timescales is incomplete. Those memory effects are quantified by memory kernels or, more generally, by projected time correlation functions if one is also interested in decomposing

memory kernels or in the coupling between different macroscopic variables. Despite the difficulty of such a task, the calculation of memory kernels from microscopic dynamics can be performed reliably and efficiently by inverting the Volterra equations obtained from the Generalized Langevin Equation (GLE) [1]. The simple yet efficient method based on the inversion of Volterra equations has, however, only been applied to the computation of the memory kernel appearing in the GLE. The first numerical method allowing to decompose of the memory kernel, or more generally to compute projected correlation functions, has been proposed quite recently by Carof et al. [2] and is based on the reconstruction of the random force, which obeys an "orthogonal" dynamics. This method is, however, difficult to implement and computationally very expensive.

Starting from the orthogonal dynamics of any given set of variables with respect to the projection variable used to derive the Mori-Zwanzig equation, I show that a set of coupled Volterra equations is obtained that relate the projected time correlation functions between all the variables of interest [3]. This set of equations can be solved using standard numerical inversion methods for Volterra equations, leading to a very convenient yet efficient strategy to obtain any projected time correlation function or contribution to the memory kernel entering a GLE. Also, I provide a very simple derivation of the orthogonal dynamics of any variable.

Using this strategy, the memory kernel related to the diffusion of tagged particles in a bulk Lennard-Jones fluid is accurately investigated up to the long-term regime to show that the repulsive-attractive cross contribution to memory effects represents a small but non-zero contribution to the self-diffusion coefficient. Furthermore, all the memory kernel's components follow the same scaling in the long-term regime, which corresponds to the one predicted by the hydrodynamics.

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Fractal and multifractal organisation of neuroimaging signals in cognitive tasks and in disease

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In this contribution, we present A) a detrended fluctuation analysis of functional magnetic resonance imaging (fMRI) data from a working memory experiment and B) a multifractal analysis of the electroencephalography (EEG) data obtained from patients with multiple sclerosis (MS). fMRI and EEG signals are notoriously challenging to analyse due to their very low temporal and spatial resolution, respectively, and a non-trivial auto-correlation and cross-correlation structure. In A), we applied fractal analysis to investigate how a person is memorising and retrieving information in four types of experimental tasks: two visual-verbal (based on lists of semantically or phonetically associated words) and two non-verbal (pictures of similar objects). The regional brain activity was quantified with the Hurst exponent (see Fig. 1) and Detrended Cross-Correlation Analysis (DCCA) [1,2]. We clearly observe 1/f signature in most brain areas, a reduction of persistent behaviour in tasks relative to the spontaneous brain activity and regional dependence of exponents depending on the tasks and the stage of the experiment (memorising the stimuli or information retrieval). We uncover such regionally coordinated changes also by analysing eigensystems of detrended correlation matrices (which turn out to be more sensitive than Pearson correlations). In B), we compared the complexity of the EEG time series, paying particular attention to analysing the correlations between the degree of multifractality, disease duration, and level of disease progression quantified by the Expanded Disability Status Scale (EDSS). We used Multifractal Detrended Fluctuation Analysis [3], a generalisation of the DFA which is a robust tool for multilevel characterisation of time series (e.g., see [4]) and specifically other types of brain signals [5]. Based on the generalised Hurst exponents, we obtained the multifractal/singularity

spectrum of the Hölder exponents [6], f(α). To quantify the coupling between the brain regions we again used the DCCA. Our results reveal a significant correspondence between the complexity of the time series and the stage of multiple sclerosis progression. Namely, we identified brain regions whose EEG signals were characterised by a well-developed multifractality (the estimated multifractal spectra take the shape of asymmetrical parabolas with larger widths Δα) and lower persistence of the time series (spectra localised above but closer to α=0.5) for patients with a higher level of disability, whereas for the control group and patients with low-level EDSS they were characterised by monofractality and higher persistence. The link between multifractality and disease duration has not been observed. Our conclusions are supported by the cross-correlations analysis.

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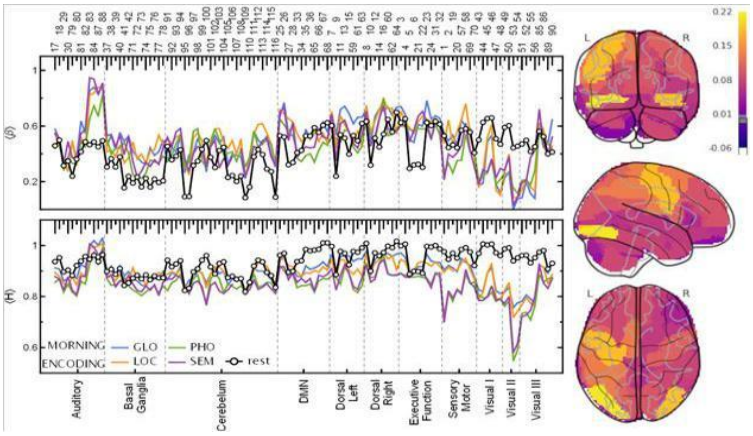

Non-local synchronization and electric power-grid outages

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Dynamical simulation of the cascade failures on the EU, USA and Hungarian [1] high-voltage power grids has been done via solving thesecond-order Kuramoto equation. We show that synchronization transition happens by increasing the global coupling parameter K with meta-stable states depending on the initial conditions so that hysteresis loops occur. We provide analytic results for the time dependence of frequency spread in the large K approximation and by comparing it with numerics of d=2,3 lattices [2], we find agreement in the case of ordered initial conditions. However, different power-law (PL) tails occur, when the fluctuations are strong. After thermalizing the systems we allow a single line cut failure and follow the subsequent overloads with respect to threshold values T. The PDFs of the cascade failures exhibit PL tails near the synchronization transition point K_c. Below K_c we find signatures of T-dependent PL-s, caused by frustrated synchronization, reminiscent of Griffiths effects [3]. Here we also observe stability growth following blackout cascades, similar to intentional islanding, but for K > K_c this does not happen. For T < T_c, bumps appear in the PDFs with large mean values, known as ``dragon king'' blackout events. We also analyze the delaying/stabilizing effects of instantaneous feedback or increased dissipation and show how local synchronization behaves on geographic maps. We demonstrate the occurrence of non-local cascade failure events at the weak points of the networks.

The size distribution of planned and forced outages in power systems have been studied for almost two decades and has drawn great interest as they display heavy tails. Understanding of this phenomenon has been done by various threshold models, which are self-tuned at their critical points, but as many papers pointed out, explanations are intuitive, and more empirical data is needed to

support hypotheses. We analyze outage data collected from various public sources to calculate the outage energy and outage duration exponents of possible power-law fits. Temporal thresholds are applied to identify crossovers from initial short-time behavior to power-law tails. We revisit and add to the possible explanations of the uniformness of these exponents. By performing power spectral analyses on the outage event time series and the outage duration time series, it is found that, on the one hand, while being overwhelmed by white noise, outage events show traits of self-organized criticality (SOC), which may be modeled by a crossover from random percolation to directed percolation branching process with dissipation. On the other hand, in responses to outages, the heavy tails in outage duration distributions could be a consequence of the highly optimized tolerance (HOT) mechanism, based on the optimized allocation of maintenance resources [4].

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Higher-order interactions generate mixed order phase transition and Griffiths phases on heterogeneous complex networks

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In d > 2 dimensional, homogeneous threshold models, involving higher order interactions, discontinuous phase transition emerge, but the mean-field approximation provides 1/t power-law activity decay and other critical power laws, thus it is called mixed-order or hybrid type [1]. This is in contrast with simple two body interaction, spreading models, where continuous transition occur [2]. Furthermore, quasi-static network heterogeneity can cause dynamical critical behavior around the transition point if the graph dimension is d < 4 [3]. We derive the mean-field approximation analytically for the K=2 threshold model and show the occurrence of the prototype of higher order interaction models. We compare these results with extensive simulations by putting this model on hierarchical modular graphs similar to the rat brain connectome. We provide numerical evidence that even in case of the high graph dimensional hierarchical modular networks a Griffiths phase in the K=2 threshold model is present below the hybrid phase transition. That means we can observe control parameter dependent, non-universal power-laws in dynamical quantities, activity avalanche sizes and duration. This happens in an extended control parameter region, where the susceptibility also diverges in the whole Griffiths phase, thus sensitivity for external input is maximal, as required by optimal neural systems. This is due to the fragmentation of the activity propagation by the modules, which are connected via single links, while the interaction requires higher number (K>1) of active neighbors. This delivers a widespread mechanism in the case of the threshold type of heterogeneous systems, modeling the brain, socio or epidemic spreading for the occurrence of dynamical criticality in extended Griffiths phase parameter spaces [4] even in the presence of discontinuous phase transitions.

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Dynamics, fractal geometry and fluctuation-dissipation relations in the Kardar-Parisi-Zhang equation

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The KPZ equation[1] is connected to a large number of processes, such as atomic deposition, evolution of bacterial colonies, the direct polymer model, the weakly asymmetric simple exclusion process, the totally asymmetric exclusion process, direct d-mer diffusion, fire propagation, turbulent liquid-crystal, spin dynamics, polymer deposition in semiconductors, and etching [2]. We present a short review of the field, some modern problems and perspectives. We discuss as well how the disordered interface geometry during growth allows a new interpretation of the fluctuation-dissipation theorem[3], exponents[4], and fractal dimension[5].

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Dynamics beyond statistics and topological supersymmetry

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Supersymmetry and chaos are among the most fundamental concepts in physics and mathematics. They had been evolving almost independently until a close relation between the two was recently established within Supersymmetric Theory of Stochastic Dynamics (STS). It turned out that all stochastic differential equations (SDE) have a hidden topological supersymmetry (TS) and the spontaneous breakdown of TS is the stochastic generalization of chaos and its various manifestations such as turbulence. That is, chaos belongs to the family of the symmetry-breaking orders just as crystallization, ferromegnetism, superconductivity etc. The TS breaking order parameter represents aspects of dynamics that go beyond traditional statistical description and it has the meaning of ethereal dynamical memory known as the butterfly effect. And the Goldstone theorem explains ubiquitous long-range dynamical behavior associated with chaos and known under the umbrella term of 1/f noise. From a more technical point of view, STS is a generalization of the Parisi-Sourlas approach to Langevin SDEs, the continuation of Ruelle theory of the generalized transfer operator, and a pseudo-Hermitian Witten-type topological field theory (TFT). Being a multidisciplinary construction it naturally sets a stage for potentially fruitful crossfertilization between a few disciplines. For example, one of the low hanging fruits of STS is the basic classification of stochastic dynamics into three major categories: thermal equilibrium, instantonic or noise-induced chaos, and ordinary chaos. In this talk, the current state of STS and its application to neurodynamics (ND) in networks of type-I neurons will be discussed. It will be shown that the basic classification of stochastic dynamics by STS has a very natural interpretation on the side of ND. The theoretical picture from STS will be supported by numerical results on a toy model of ND and experimental data from emulation of ND on neuromoprhic hardware (Spikey, Heidelberg Univ.) and clinical data (UCLA medical school).

On the nature of memory in spin glasses

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Rejuvenation and memory are common to glassy systems. We are able to extract the origin of these phenomena through an examination of rejuvenation and memory in the out of equilibrium dynamics of spin glasses, using a temperature-cycling protocol carried out in a simulation using the Janus-II supercomputer. Analogously to experiments on single crystal of CuMn, we define a memory measurement and draw out a scaling law which describes both the numerical and experimental data. Moreover, we show that the dynamics is governed by more than a single correlation lengths, and we show how to connect them to the one accessible in the lab.

On the superposition principle and non-linear response in spin glasses

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The extended principle of superposition has been a touchstone of spin glass dynamics for almost thirty years. The Uppsala group has demonstrated its validity for the metallic spin glass, CuMn, for magnetic fields H up to 10 Oe at the reduced temperature Tr=T/Tg = 0.95, where Tg is the spin glass condensation temperature. For H > 10 Oe, they observe a departure from linear response which they ascribe to the development of nonlinear dynamics. The thrust of this paper is to develop a microscopic origin for this behavior by focusing on the time development of the spin glass correlation length, $\xi(t,tw;\ H)$. Here, t is the time after H changes, and tw is the time from the quench for T>Tg to the working temperature T until H changes. We connect the growth of $\xi(t,tw;\ H)$ to the barrier heights Δ(tw) that set the dynamics. The effect of H on the magnitude of Δ(tw) is responsible for affecting differently the two dynamical protocols associated with turning H off (TRM) or on (ZFC). This difference is a consequence of non-linearity based on the effect of H on Δ(tw). In this paper, we display the difference between the zero-field cooled $\xi ZFC(t,tw;\ H)$ and the thermoremanent magnetization $\xi TRM(t,tw;H)$ correlation lengths as H increases, both experimentally and through numerical simulations, corresponding to the violation of the extended principle of superposition in line with the finding of the Uppsala Group.

Ergodicity in theory and in practice

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The term ergodicity did not originally refer to the equality of time and ensemble averages. Rather, by 'ergodic' Boltzmann referred to a dynamical property of a system that would bring about this equality. In this talk we will take a tour of the various classical attempts to pin down Boltzmann's notion from a mathematical standpoint, and why these often have limited usage in practice. Two fundamental difficulties are that a) real systems are never observed for an infinitely long time and b) real data sets are therefore limited to contain finitely many points to perform statistical analyses on them. Our work proposes a new characterisation of ergodicity intended to overcome these difficulties. This new definition, inspired in part by Khinchin, relies on the idea that, to be ergodic, any single trajectory of an observable should sample the same underlying distribution as the thermodynamic equilibrium ensemble's distribution. To implement this definition, we introduce a 2-sample metric between empirical probability distributions to assess how similar 2 finite realisations of sampled time and ensemble trajectories for a specified observable may be. Even if the underlying distributions are identical, the finiteness of the sampling implies that the measured distance between these empirical distributions will never be exactly zero. In this work, we take seriously the fact that, once a specific distance value is obtained for one trajectory, how small it is may allow one to indicate a “degree of ergodicity” rather than adopting a full binary conception of the term for an observable or even an entire dynamical system.

Some degree of ergodicity may indeed be sufficient for some purposes while other situations may require a higher degree of ergodicity. We benchmark our analysis on the Kob-Andersen model, a lattice glass former, which was shown to be non-ergodic (in the sense of metric transitivity) for all system sizes for certain parameter values of the model, but to display a non-ergodic -> "quasi-ergodic" crossover as the system size is increased at fixed particle density [2]. We find that there is a substantial dependence in the initial conditions allowing us to provide a statistical description of the ergodic character of the system.

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Approximate integral of motion for macroscopic lattice systems

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It is a well-established fact, and relevant for the workshop itself, that classical results of Hamiltonian perturbation theory, like KAM and Nekhoroshev theorems, become ineffective as the number of degrees of freedom, denoted by , increases. Indeed, for example, the threshold in the perturbative parameter, below which the results are valid, vanishes very rapidly with ; but more generically, several of the constants which are present in the perturbative estimates exhibit unfavorable behavior with respect to the dimension of the system. Therefore, within the context of the workshop, it would be interesting to present the ideas of an adapted version of Hamiltonian perturbation theory that is capable of dealing with macroscopic systems and produce results applicable in the thermodynamic limit. The existing findings of this approach pertain to the existence of approximate conserved quantities in nonlinear lattices that are finite but have arbitrarily large dimensions; these results can be proven constructively and with estimates that are valid in a weak (in measure) sense. In particular, for a Klein Gordon lattice with periodic boundary conditions with particles, denoted by the nearest neighbour coupling constant, by the specific energy / and by the inverse temperature of the Gibbs measure, for any and for a fixed and sufficiently small value of the coupling constant there exists an approximate constant of motion whose evolution is controlled up to a time scale of $^{1/}$ for any sufficiently large values of . If the coupling constant is allowed to vanish jointly with the specific energy, the time scale becomes a stretched exponential. We demonstrate the adiabatic invariance by showing that the variance along the dynamics, as calculated using time averages, is significantly smaller than the corresponding variance over the entire phase space, as calculated using the Gibbs measure, for a set of initial data with a large Gibbs measure. A key point in the construction is the possiblity to exploit, within the perturbation construction and the measure estimates, the extensive nature shared by the Hamiltonian of the system as well as by the adiabatic invariant itself. If time permits, we will also discuss the relationship between the above mentioned result and the other directions being explored in the workshop.

Bayesian expectation of the mean power of several Gaussian data

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The uniform distributions over the reals for the prior probability-density of the means of several normal data leads to an inconsistent inference of the data mean-power. For example, when estimating the power of a signal from samples affected by an additive white Gaussian noise. We reinvestigate the problem, note that the uniform prior delivers unrecognised information, and propose a solution looking at the problem in a novel way. We took the power limitedness into account by a sequence of priors converging to the uniform one, organised them into a hierarchical structure, and left the data

to choose among them. We obtained an extended James-Stein estimator averaging out the hyper-parameters and avoiding empirical Bayes techniques.

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Solar energetic particle events and elements of prediction

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Solar energetic particle (SEP) events constitute a significant component of the near Earth radiation environment and consist of protons, electrons, and heavier ions. Such events originate from particle acceleration in solar flares (SFs) and/or shocks associated with coronal mass ejections (CMEs). SEPs can last from a few hours to several days, and their relative composition varies by many orders of magnitude from event to event. They have a direct space weather impact on electronics and humans. For example, the survivability of a spacecraft is directly affected by the total energy deposited by the passage of energetic particles. Furthermore, SEP events are a major threat to human spaceflight outside the protective shield of the Earth's magnetosphere and pose a severe danger for aircrews and passengers on polar flights. Given the fact that only a small fraction of all solar flares and CMEs lead to SEP events the problem at hand becomes largely imbalanced. That said SEP prognosis is far from trivial. The scientific questions that one needs to address in such efforts are summarized as follows: *If we know the characteristics of the parent solar events, could the probability of SEP occurrence be reliably inferred, and how do the characteristics of SEP events (e.g., peak flux) map to the characteristics of their parent solar events?* In this talk elements of SEP prediction will be presented and critically assessed with a view to the future needs of human spaceflight efforts.

Entropy and complexity analysis of AI-generated and human-made paintings

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Creativity is the ultimate characteristic of human intellect and expression, and it is inextricably linked to art. Previous research works attempted to analyze and parameterize the manifestations of art, but they had not escaped the human factor. However, the advent of Artificial Intelligence (AI) models has shaken up the research world, raising questions about the nature of creativity and whether in its artistic form it is a uniquely human quality. In this work [1], we aim to examine the relationship between creativity and the nature of the creator by using paintings created by both AI and humans in various artistic genres. By analysing the paintings through a mathematical lens, utilizing an entropy analysis formulated by the classic Shannon entropy (E) and a complexity (C) measure based on multi-scale entropy, we hope to gain a deeper understanding of the prowess of AI models and possible new insights into the ability to distinguish between a human-created work (H) and an AI-generated one (AI).

We present findings on the general comparison between AI-generated and human-made art, as well as on the more specific analysis of 8 different genres within these two categories. Based on the results, we observe that differences between AI and human art can be found not only in the schematic representation, but also in the colour changes, with the AI finding it more complicated to represent painting styles without well-shaped objects, as well as colour changes regarding pixels of similar intensity values. AI generated paintings seem to encapsulate a general definition for the structural elements of an artistic genre, but may not fully capture the diversity of artist styles within that genre. Additionally, the AI and H differences depend on the genre of the works, thus, grouping based on art styles is possible. As for the ability of prediction with good accuracy whether an artwork is AI or H made based on the metrics of complexity and entropy, the dispersion of the C, E values exceeds the difference of the averages, offering indication that although the difference found is statistically reliable, it has little predictive power.

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Synchronization and criticality in brain models

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The criticality hypothesis for neural systems has been roposed because information processing, sensitivity, long-range and memory capacity is optimal in the neighborhood of criticality. Real neural systems are expected to self-tune themselves close to the critical point, but heterogeneity may extend this region is a same way as in case of Griffiths phases of condensed matter [1]. We investigate the synchronization transition of the Shinomoto-Kuramoto (SK) model on networks of the fruit-fly and two large human connectomes. Besides the exactly known largest brain network of the fruit-fly we consider large connectomes, obtained by diffusion MRI, representing the white matter of the human brain, showing some degree of universality [2]. Earlier we have shown nontrivial critical behavior with continuously changing exponents, frustrated synchronization and chimera states in the resting state [3,4,5]. The SK model contains a force term, thus is capable of describing critical behavior in the presence of external excitation. By numerical solution we determine the crackling noise durations with and without thermal noise and show extended non-universal scaling tails characterized by the exponent $2 < \tau < 2.8$, in contrast with the Hopf transition of the Kuramoto model, without the force $\tau = 3.1$ (1). Comparing the phase and frequency order parameters we find different transition points and fluctuations peaks as in case of the Kuramoto model. Using the local order parameter values we also determine the Hurst (phase) and β (frequency) exponents and compare them with recent experimental results obtained by

fMRI. We show that these exponents, characterizing the auto-correlations are smaller in the excited system than in the resting state and exhibit module dependence [6].

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Study of heterogeneity effects in power grid networks on the community level

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Cascade failures in power grids occur when the failure of one component or subsystem causes a chain reaction of failures in other components or subsystems, ultimately leading to a widespread blackout or outage. Controlling cascade failures on power grids is important for many reasons like economic impact, national security, public safety and even rippled effects like troubling transportation systems. Monitoring the networks on node level has been suggested, either controlling all nodes of a network or a well defined subset
It has also been shown that too strong heterogenity destroys synchronization in the powergrid system Heterogeneity ussually can be decreased in multiple ways, for example regulating the node attributes, edge attrbutes, modifying the network topology with edge adding or removing or even complete rewiring. We show new results for the distributions of edge admittances and weights of the European and Hungarian networks, as well as for the measured frequency heterogeneities [2]. Than we provide community detection algorithms and show the level of synchronization in them, by solving the set of swing equations. Detecting communities in networks aims to identify groups of nodes in the network that are more densely connected to each other than to the rest of the network. While several clustering methods exist, they split into hierarchical and non-hierarchical methods. Hierarchical methods build a hierarchy of communities by recursively dividing the network into smaller and smaller subgroups, while non-hierarchical methods directly assign nodes to communities. We chose the hierarchical Louvain method for its speed and scalability, this algorithm runs almost in linear time on sparse graphs [4], therefore it can be useful on generated test networks with increased size. It is based on modularity optimization. Furthermore, we suggest that the most problematic nodes in terms of synchronization lie on the edges of their communities, and by simple bridge fortification between the communities in the network, we can increase stability. The resulating order parameters come close to the results of a more complicated bypass technique selection of nodes, fortifying the connection of "weak" nodes. It is worth mentioning that the network's modularity score increases by around 0.02 with the bypass technique. Finally, we compare the results with the same randomly selected number of nodes.

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Modeling the number of sunspots using machine learning

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Solar activity has a significant impact on various aspects of human life, including satellite communications, power distribution systems, and climate change. Sunspots are the fundamental indicators of solar activity. Accurate prediction of sunspot activity can help mitigate potential hazards and improve the understanding of solar dynamics. In this study, we present a comparative analysis of three supervised machine learning models for predicting sunspots: Gaussian Process Regression, Long Short-Term Memory neural network, and LightGBM. We used a time series of the yearly mean total number of sunspots to train and evaluate the performance of each model. The sunspot data exhibit a long-term periodicity (solar cycle) of 11 years. The dataset was split into training, validation, and testing sets, and various well-known performance metrics were employed to assess the prediction accuracy. Gaussian Process Regression (GPR) is a non-parametric, probabilistic approach that is particularly useful for data with complex patterns. A Gaussian Process (GP), $f(x)$, is completely specified by its mean function $m(x)$ and covariance (kernel) function $k(x,x')$. We experimented with two different kernels: (i) the product of an exponential and a periodic kernel, and (ii) a linear stochastic oscillator kernel. We also tested warped GPR by applying the κ-logarithmic transformation. We optimized the model hyperparameters using Maximum Likelihood Estimation (MLE) and RMSE minimization on a validation set. A Long Short-Term Memory (LSTM) Recurrent Neural Network (RNN) employs a deep learning architecture to learn patterns. It consists of cells, each of which is connected to three gates (input, forget, and output) responsible for information flow. We implemented an LSTM model with multiple layers and optimized its architecture and hyperparameters using grid search and validation loss minimization. We also employed LightGBM, a gradient-boosting framework of regression trees, that is well-known for its efficiency and accuracy in regression tasks. Our results show that all three models exhibit strengths and weaknesses. GPR delivers uncertainty estimates and can capture complex patterns using different kernels, but it requires the computationally intensive inversion of large covariance matrices. LSTM performs well in capturing long-term dependencies, but it needs large amounts of data, time, and resources for tuning and training, and it suffers from error accumulation on long-term predictions. LightGBM delivers the same characteristics, except that it is more computationally efficient and its training is faster. In conclusion, this study provides insights into the performance and characteristics of three powerful machine learning methods, GPR, LSTM-RNN, and LightGBM, for sunspot number prediction.

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Classical speed limit and finite-time Landauer's bound

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Landauer's bound is the minimum thermodynamic cost for erasing one bit of information. As this bound is achievable only for quasistatic processes, finite-time operation incurs additional energetic costs. We find a tight finite-time Landauer's bound by establishing a general form of the classical speed limit. This tight bound well captures the divergent behavior associated with the additional cost of a highly irreversible process, which scales differently from a nearly irreversible process. We also find an optimal dynamics which saturates the equality of the bound. We demonstrate the validity of this bound via discrete one-bit and coarse-grained bit systems. Our work implies that more heat dissipation than expected occurs during high-speed irreversible computation.

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Theory of kinetically-constrained-models dynamics

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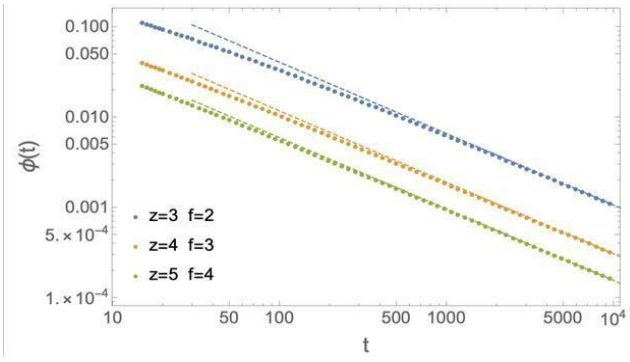
The question of whether glassy behavior is a result of a genuine thermodynamic transition has long been a topic of debate in the field of glass physics. In this debate, Kinetically-Constrained-Models (KCMs) are frequently cited as models capable of reproducing the essential features of glasses without exhibiting a thermodynamic transition. However, up to now their knowledge was mainly based on numerical simulations, which are complicated by the divergence of equilibration times and large finite size effects. In this work [1], using certain properties of the dynamics observed in actual numerical experiments, we provide the first analytical solution of the mean-field dynamics of a class of KCMs, by considering the Fredrickson-Andersen model (FAM) on the Bethe lattice. We derive asymptotic dynamical equations that are equivalent to those of Mode-Coupling-Theory (MCT). In this way we resolved the long-standing issue of proving that MCT provides the correct description of the long-time dynamics in these models. We present analytical predictions for the dynamical exponents, which are successfully verified by new numerical data, and explain earlier numerical results. Our analytical predictions are validated through numerical simulations in a wide range of models, including cases with generic values of connectivity and facilitation, random pinning, and fluctuating facilitation. Our theory is thus confirmed for both continuous and discontinuous transitions, as well as in the case of higher order critical points characterized by logarithmic decays. The possible extension of our analysis to models with conserved dynamics, notably the Kob-Andersen model, is an interesting open problem and it is left for future work. In the attached figure we show the persistence function in the case of the FAM for different values of the facilitation f, which is the parameter defining the kinetic constraint of the model. The persistence function plays the role of ergodicity breaking parameter for the FAM. At a critical value of the temperature, below which the ergodicity is broken and the system enters a glassy phase, the persistence goes to a plateau value with a power-law behavior. The numerical data, represented by the points, are in excellent agreement with our analytical predictions, which are denoted by the dashed lines. The numerical simulations are performed on Bethe lattices with coordinations z=3,4,5, and a number of nodes $N=16\times10^6$.



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Information propagation in active system

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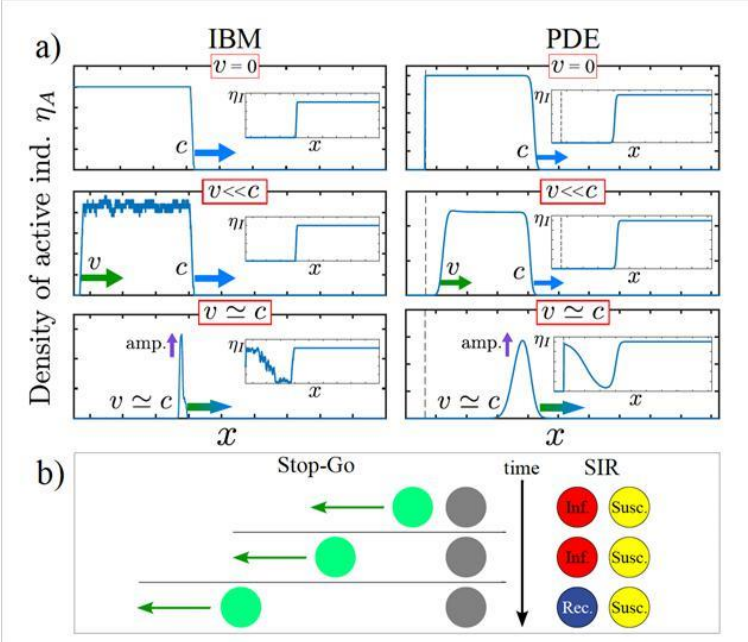
Collective motion is generally not a continuous process, and collectives display repeated transitions from static to moving phases. The initiation of collective motion -- of an initially static group -- is a crucial process to ensure group cohesion and behavioral synchrony that remains largely unexplored. Here, we investigate the statistical properties of the initiation of collective motion. We find that the information propagates as an activation wave, whose speed is modulated by the velocity of the active agents, where both, the magnitude and direction of the agents' velocity play a crucial role. The analysis reveals a series of distinct dynamic regimes, including a selfish regimes that allow the first informed individuals to avoid predation by swapping position with uninformed individuals. Furthermore, we unravel the existence of a generic and intimate connection between the initiation of collective motion and critical phenomena in systems with an absorbing phase, showing that in a range of agents' velocities the initiation process displays criticality. The obtained results provide an insight in the way collectives distribute, process, and respond to the local environmental cues.



Double-replica theory for evolution of genotype-phenotype interrelationship

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The relationship between genotype and phenotype plays a crucial role in determining the function and robustness of biological systems. Here we study this relationship within the context of an evolution model, where phenotypes are given by spin configurations; genotypes are interaction matrix for spins to give the Hamiltonian, and the fitness depends only on the configuration of a subset of spins called target. We describe the interplay between the genetic variations and phenotypic variances by noise in this model by our new approach that extends the replica theory for spin-glasses to include spin-replica for phenotypes and coupling-replica for genotypes. We obtain a phase diagram of the evolved phenotypes against the noise and selection pressure, where each phase is distinguished by the fitness and overlaps for genotypes and phenotypes. Among the phases, robust fitted phase, relevant to biological evolution, is achieved under the intermediate level of noise (temperature), where robustness to noise and to genetic mutation are correlated, as a result of replica symmetry. We also find a trade-off between maintaining a high fitness level of phenotype and acquiring a robust pattern of genes as well as the dependence of this trade-off on the ratio between the size of the functional (target) part to that of the remaining non-functional (non-target) one.

The energy cost of local rearrangements makes glasses solid

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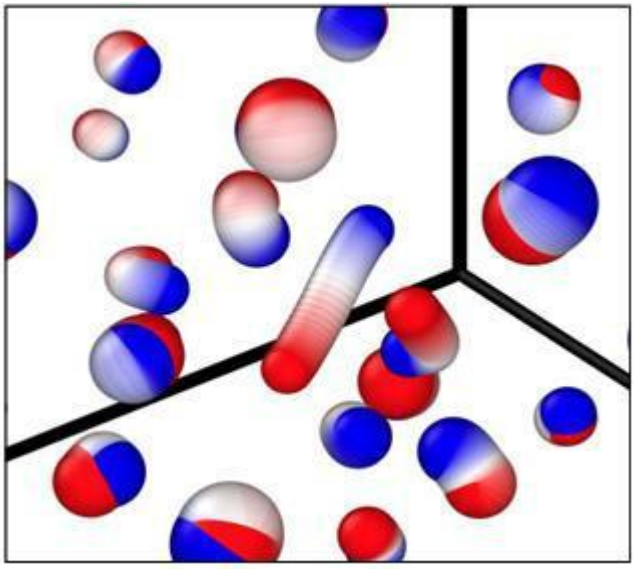
Which phenomenon slows down the dynamics in super-cooled liquids and turns them into glasses is a long-standing question of condensed-matter. Most popular theories posit that the dynamics becomes cooperative as the temperature decreases: many events must occur in a coordinated fashion on a growing length scale for relaxation to occur. Instead, other approaches consider that local barriers associated with the elementary rearrangement of a few particles or `excitations' govern the dynamics. Here we resolve this conundrum by introducing a new algorithm, SEER, that can systematically extract hundreds of excitations and their energy from any given configuration. Remarkably, we find at low temperatures that the excitation density of states is essentially shifted to higher energy under cooling. This observation directly predicts how local barriers slow down the dynamics, assuming no cooperative effects. We test this prediction in numerical super-cooled liquids using swap algorithms, allowing us to measure the relaxation time up to milliseconds. The agreement is quantitative, revealing that cooperative effects are absent and leading to new perspectives on the glass transition.



Regularized Kappa distributions to model the solar wind electrons

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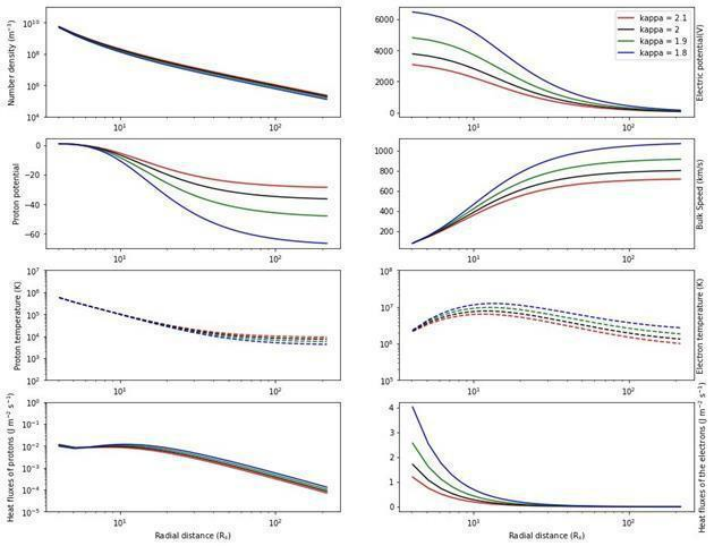
The kinetic exospheric model of the solar wind has been improved by considering regularized Kappa distributions valid even for kappa indices lower than 2. Indeed, with an exponential cutoff introduced to regularize the Kappa function for velocities reaching the light velocity, non-divergent moments of order l can be calculated even for $\kappa < (l + 1)/2$. Low values of kappa are often observed in the solar wind, especially for the electron distributions, but also for ions. We use the new Parker Solar Probe PSP) observations at low distances (down to 15 Rs) to improve the boundary conditions of the model and estimate the characteristics of the plasma in the solar corona and their average radial evolution with the distance. Results of the exospheric model are compared with different solar wind observations of Solar at different radial distances to explore the formation of the suprathermal electrons at low distances using PSP measurements.



Economic fitness: Concepts, methods and applications

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Economic Fitness and Complexity (EFC) is the recent economic discipline and methodology which makes use and develops the modern techniques of data analysis to build economic models based on a scientific methodology inspired by the science of Complex Systems with special attention to quantitative tests to provide a sound scientific framework. It consists of a *data based* and *bottom up* approach that considers specific and concrete problems without economic ideologies and it acquires information from the previous growth data of all countries with methods of Complex Networks, Algorithms and Machine Learning. Its main characteristics are the scientific rigor, the precision in the analysis and in the forecasting, transparency and adaptability. The new Fitness algorithm overcomes the conceptual and practical problems of the early attempts in this field and sets the basis for a testable and successful implementation of the field of Economic Complexity. According to Bloomberg Views: "*New research has demonstrated that the "fitness" technique systematically outperforms standard methods, despite requiring much less data*" In addition EFC has provided a detailed understanding and forecasting of the fantastic growth of China in the past thirty years which has been a major mystery for most of the standard economic analysts. The Economic Fitness represents a synthetic measure of the degree of competitivity in terms of the capabilities to produce products and services. Mathematically the Fitness corresponds to the diversification weigthed by the complexity of the products. The diversification provides stability and resilience while the complexity of the products represents the exclusivity and the relative wealth. The European Commission (Joint Research Center) has recently adopted these methods for the study of the 27 EU countries. It will be used to evaluate the best planning and the impact of the recovery fund projects (PNRR) to stimulate the economy of EU in the era post COVID-19 In the WEBsite: https://publications.jrc.ec.europa.eu/repository/handle/JRC124939 one can find a general methodological document together with the analysis of the situation for each of the 27 countries performed with EFC methods that identify the present situation together with the possible paths of evolution in relation to the PNRR projects. With these methods it is also possible to extend these analysis in various directions and optimize the projects accordingly. Since a few years it has been used by IFC-World Bank Group to define specific economic actions tuned for specific countries, in particular for developing ones. One of the main targets is to identify the products or technologies which will enable to open new markets, considering the specific situation of each country. The IFC-WB has also supported the development of these methodology which is now officially adopted for the planning of its interventions. An example for African countries can be found here: https://www.ifc.org/wps/wcm/connect/fb4761f5-809b-4685-8fd7-24bd23bad6d3/EMCompass-Note-88-West-African-Industrial-Development.pdf?MOD=AJPERES&CVID=ngxrg.e . In this lecture we present an overview of the field and the present challenge to extend these methods, developed up to now mostly for countries, also to the analysis of individual companies.

The maximum of financial greed for the algorithm of two agents cooperation

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Knowing the computational complexity of an algorithm makes it possible to calculate its speed accurately. This also applies to algorithms operating on financial markets. However, this measure will not tell us anything about the value of financial operations performed by such algorithms. It is not only the time that counts, the profits achieved by the algorithm in that time are equally important. The measure expressing the financial attractiveness of an algorithm operating in the market (hereinafter referred to as the financial greed of the algorithm) depends both on how the algorithm operates and on the supply and demand situation in the market.

We propose a definition of the measure of financial greed of a market algorithm that somewhat resembles Newton's second law of motion. It is interesting to study the conditions at which financial algorithms reach the maximum values of their greed. In the case of a single trader, the maximum of the greed function of its action turns out to be at a fixed point of this function, see [1-3].

We will present an extension of this model to a two agents cooperation. It turns out that such an algorithm reaches a maximum of its greediness below the fixed point of this function. Each participant in the cooperative individually always achieves a profit lower than the highest profit of a single trader operating on the same financial instruments. However, as a result of the correlation of the relevant transactions, the cooperative leads to profits that exceed the performance of a single trader operating in the same market. It is oriented towards lower individual profits and single trades more frequently (it has a lower trading margin). This is an interesting aspect of the benefits of synchronized cooperation. Algorithms that exhibit maximum greed are not only attractive to entities (including complex ones) operating in financial markets. For example, such algorithms can most effectively distill knowledge base corpora, increasing the quality of the information they contain [4]. The greed measure presented here therefore appears to be a universal measure, relevant to different types of environments that are characterized by well-defined utility for the entities operating in them.

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Loss landscapes of neural networks through the lens of flat regions and symmetries

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We systematize the approach to the investigation of deep neural network landscapes by basing it on the geometry of the space of implemented functions rather than the space of parameters. In the space in which all symmetries are removed, we explore the error landscape rather than the loss. This lets us derive a meaningful notion of the flatness of minimizers and of the geodesic paths connecting them. Using different optimization algorithms that sample minimizers with different flatness we study the mode connectivity and relative distances. Testing a variety of state-of-the-art architectures and benchmark datasets, we confirm the correlation between flatness and generalization performance; we further show that in function space flatter minima are closer to each other and that the barriers along the geodesics connecting them are small. We also find that minimizers found by variants of gradient descent can be connected by zero-error paths composed of two straight lines in parameter space, i.e. polygonal chains with a single bend. We observe similar qualitative results in neural networks with binary weights and activations, providing one of the first results concerning the connectivity in this setting. Our results hinge on symmetry removal, and are in remarkable agreement with the rich phenomenology described by some recent analytical studies performed on simple shallow models: through the lens of statistical physics, we investigate the paradigmatic example of the spherical negative perceptron as the simplest model of neural network landscapes.

Instantaneous Lyapunov vectors in DNA

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We define the notion of an Instantaneous Lyapunov Vector (ILV), a tool which we introduce for the investigation of spatiotemporal chaos. These ILVs are related to covariant Lyapunov vectors (CLVs), which are intrinsic directions in phase space along which perturbation growth rates are governed by corresponding Lyapunov exponents [1]. We show that ILVs can be computed from eigenvectors of the symmetric part of the dynamical system's Jacobian matrix, and we use these vectors to probe the spatial characteristics of chaotic dynamics at an instant in time. We compare the behaviour of ILVs to that of the long-term averaged dynamics of CLVs, which we compute using the efficient algorithm of Ginelli et al. [2, 3]. By making use of a well-known Hamiltonian model of DNA, namely the Peyrard-Bishop-Dauxois (PBD) model [4], we study the spontaneous thermal openings of base pairs in strands of DNA which are known as "bubbles" and have been linked to transcription [5]. The relationship between chaos and the appearance of bubbles in DNA has been investigated by Hillebrand et al. [6] and we use ILVs to explore this further. In particular, we show that the relationship between sensitive dependence on initial conditions at an instant in time and the presence of bubbles in DNA is significantly determined by the on-site Morse potential governing individual base pair interactions in the PBD model.

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Pairwise and high-order dependencies in the cryptocurrency trading network

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In this work we analyse the effects of information flows in cryptocurrency markets. We first define a cryptocurrency trading network, i.e. the network made using cryptocurrencies as nodes and the Granger causality among their weekly log returns as links, later we analyse its evolution over time. In particular, with reference to years 2020 and 2021, we study the logarithmic US dollar price returns of the cryptocurrency trading network using both pairwise and high-order statistical dependencies, quantified by Granger causality and O-information, respectively. With reference to the former, we find that it shows peaks in correspondence of important events, like e.g., Covid-19 pandemic turbulence or occasional sudden prices rise. The corresponding network structure is rather stable, across weekly time windows in the period considered and the coins are the most influential nodes in the network. In the pairwise description of the network, stable coins seem to play a marginal role whereas, turning high-order dependencies, they appear in the highest number of synergistic information circuits, thus proving that they play a major role for high order effects. With reference to redundancy and synergy with the time evolution of the total transactions in US dollars, we find that their large volume in the first semester of 2021 seems to have triggered a transition in the cryptocurrency network toward a more complex dynamical landscape. Our results show that pairwise and high-order descriptions of complex financial systems provide complementary information for cryptocurrency analysis.

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Inferring structure from firing patterns of cortical neural networks

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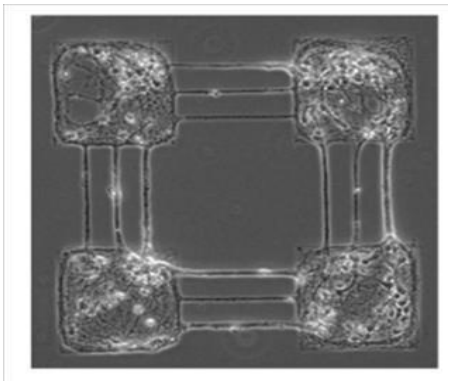
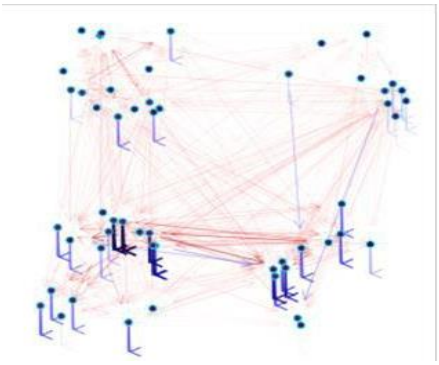
There has been growing interest recently in biological machine learning, specifically the use of cortical brain organoids as processing units for non-linear curve prediction [1], and in using cortical neural networks for playing in a simulated gaming environment [2]. These research activities rely on the assumption that plasticity takes place in cortical neural networks and that, with appropriate stimulation of neurons, the neural network will evolve to a structure capable of performing specific tasks. Revealing the emerging effective cortical network structure is crucial for understanding the mechanism behind these biological learning devices. However, there are few studies using principled methods for inferring the effective structure of cortical neural networks from their spiking patterns. Common techniques in the neuroscience community for identifying effective connections, such as measuring transfer entropy [3], are heavily affected by the sparsity of firing rate, and on setting the appropriate threshold for identifying the existence of connections; both are somewhat heuristic. Techniques for inferring the underlying interaction strengths between neurons have been developed in the statistical physics community, such as mapping neural activities onto the kinetic Ising model with inference using mean-field approximation [4]; however, these approaches are based on unrealistic assumptions, such as that the network is fully connected, and synaptic strengths are homogeneously and Gaussian distributed with small variance. More importantly, a principled technique for identifying excitatory and inhibitory connections, the existence of links between neurons, and take structural considerations into account, is still lacking. In this study, we developed an algorithm for inferring the effective structure of biological neural network using Bayesian techniques, principled machine learning methods and models from statistical physics. Based on binary spiking activity data and the prior distribution we impose, the algorithm allows one to obtain effective directional connectivity, the nature of the neurons (inhibitory or excitatory) as well as the synaptic strength between them. Moreover, based on the inferred structure, one can predict the neural activities using the probabilistic model we developed. We tested our method on both in-silico experiments using neural activity emulator data that fits realistic scenarios, and in-vitro experimental data of mouse cortical neural activities with specific structures. We extracted effective connectivity and the predictions of neural activity show good similarity with the original data. By obtaining reliable in-silico predictions of activities, we can greatly reduce the waiting time for results and improve the efficiency of in-vitro experiments by understanding the physical properties. Additionally, we expect the approach to provide insight and quantitative understanding of learning properties in cortical tissues.





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The new wealth of nations: How STEM fields generate the prosperity and inequality of individuals, companies, and countries

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Fundamental research in physics has long been a prerequisite for computer scientists and engineers to design innovative products, such as laptops and cell phones. Technological innovations and fundamental research are both part of the so-called STEM fields (Science, Technology, Engineering, and Mathematics), which are known to substantially contribute to economic growth. However, the questions still remain: how much contribution do these fields make to both wealth accumulation and inequality at different levels of analysis? First, analyzing the lists of world's wealthiest individuals, the Zipf plot analysis demonstrates that STEM billionaires contribute more to wealth inequality than their non-STEM counterparts. Analyzing the companies in the S&P500, we find that STEM firms contribute more to wealth inequality and have larger growth rates on average than the non-STEM firms. Finally, we show that the more STEM graduates in a country, the larger its GDP growth rate. In combination, we demonstrate that STEM is a fractal mechanism that drives wealth accumulation—and the wealth inequality— at different scales of economy—from individual wealth to firm valuation to country GDP. This insight is particularly useful for the financial sector. We demonstrate a functional dependence between a country's number of patents and its STEM graduates. Finally, motivated by the fact that the U.S. heavily surpasses the E.U. in terms of Venture Capital, we model wealth inequality at different scales of the economy.

Global in time existence theorem for the full revised Enskog equation

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I prove global in time existence of solutions to the full revised Enskog equation. This equation generalizes the Boltzmann theory to dense gases in two ways:
1. by taking into account the fact that the centers of two colliding spheres are at a distance a, equal to the diameter of hard spheres.
2. by increasing the collision frequency by a factor $Y0$ which nowadays is identified with the radial pair correlation function $g2$ for the system of hard spheres at a uniform equilibrium.

In contrast to the dilute gas mode described by the Boltzmann equation, the Enskog equation includes spatial pair correlation function for hard-spheres potential and depends in a highly nonlinear way on the local density of dense gas. The full revised Enskog Equation refers to the case where $g2$, the pair the correlation function (for non-uniform equilibrium of hard-spheres) is in general form. In terms of the virial expansion (in local density n, spatially dependent) at contact value, $g2$ reads:

$$g2\ (n) = 1 + V1(n) + V2(n) + \ldots + VN(n) + \ldots,$$

where the term $V1(n)$ depends on n linearly, $V2(n)$ depends on n quadratically, $VN(n)$ depends on n as $n\,N$, ad so on. Circa 30 years ago Arkeryd-Cercignani proved the result for the truncated i.e., $g2$ = 1 (no density dependence). The case with $g2$ = 1 refers to the so called Boltzmann-Enskog equation. It differs from the Boltzmann equation only by existence of the shifts in the spatial variable in the collisional integral. Since then, many researchers tried/wanted to prove the result for general form of $g2$. Dependence of $g2$ on n requires a different approach and new tools as compared to Arkeryd-Cercignani proof ([1]). Additionally, this result finally completes and fulfills the existence result for the revised Enskog Equation.

The proof of existence of solutions to the revised Enskog equation is based on two constructions:

1. Construction of an H-functional (see [2]), where the full expansion of $g2$ is used, but convergence of the series was not addressed.
2. Construction of a special sequence of stochastic kinetic equations (studied in [3]) and the proof that their solutions converge to weak solutions of the revised Enskog equation.

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On integrable parametric generalization of the Kardar-Parisi-Zhang equation of spin glasses theory and related thermodynamic stability

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Amongst the revealed new universally behaving stochastic systems we meet such important ones as directed polymers in random media and spin glasses, whose characteristic thermodynamic parameters display non-Gaussian limiting distributions and described by means of the well known Kardar-Parisi-Zhang equation:

$$\frac{\partial v}{\partial t} = \frac{\partial^2 v}{\partial x^2} - \frac{u\left(\frac{\partial v}{\partial x}\right)^2}{2} := K[v,u], \qquad (1)$$

describing the distribution function of a related random variable and $u \in M_u$ is a parameter, which can often be (heuristically) computed for a particular growth model directly from the microscopic dynamics, specified by a statistical physics model under regard. As it was demonstrated in the KPZ equation well describes the long-time thermodynamics of the spin glass substrate growth owing to the competition between the surface tension smoothing forces and internal aggregation phase state, giving rise to the tendency preferentially in the direction of the local normal to the surface, represented by the corresponding nonlinear term. Thus, the following problem arises: to describe the corresponding evolution constraints

$$\frac{\partial u}{\partial t} \stackrel{?}{=} F[v,u,r], \ \ \frac{\partial r}{\partial t} \stackrel{?}{=} R[v,u,r] \qquad (2)$$

on a functional parameter $u \in M_u \subset C(\mathbb{R};\mathbb{R})$, which would ensue to the existence of a nontrivial hierarchy of conservation laws for the combined Langevin type evolution system

$$\left.\begin{array}{c} \partial \mathrm{v}/\partial \mathrm{t} = \partial(\mathrm{r}\,\partial \mathrm{v}/\partial \mathrm{x})/\partial \mathrm{x} - \mathrm{u}(\partial v/\partial x)^2/2 \\ \partial \mathrm{u}/\partial \mathrm{t} = \mathrm{F}[\mathrm{v},\mathrm{u},\mathrm{r}] \\ \partial \mathrm{r}/\partial \mathrm{t} = \mathrm{R}[\mathrm{v},\mathrm{u},\mathrm{r}] \end{array}\right\} := \mathrm{K}[\mathrm{v},\mathrm{u},\mathrm{r}], \qquad (3)$$

considered as a smooth vector vield K on the combined functional manifold $M_{v,v,r}$ and which could be used for normalizing the corresponding distribution function $v \in C^2(\mathbb{R}\times\mathbb{R}_+;\mathbb{R})$ for suitably chosen initial data $v(\cdot\,,0) \in M_v$ and supplying the related thermodynamic stability of the spin glasses growth. To solve this problem effectively, we applied the gradient-holonomic algorithm to the parametrically extended KPZ equation (1) and in the special case $r = 1$ there was stated that the parametrically extended system of equations (3) reduces to evolution flow

$$\left.\begin{array}{c} \mathrm{v_t} = \mathrm{v_{xx}} - \mathrm{uv_x^2}/2 \\ \mathrm{u_t} = -\mathrm{u_{xx}} - (\mathrm{u^2 v_x})_\mathrm{x}/2 \end{array}\right\}, \qquad (4)$$

possessing an infinite hierarchy of the conserved quantities, providing thermodynamically stable spin glass growth process, being a Lax type integrable Hamiltonian system. This result, in particular, says that the parametrically extended Kardar-Parisi-Zhang equation (1) possesses a rich internal hidden symmetry, allowing to immerse it into an infinite hierarchy of Lax type completely integrable dynamical systems on a functional manifold. Moreover, it also demonstrates that the paramatrized Kardar-Parisi-Zhang equation (1) can present some interesting applications to describing thermodynamical properties of polymers structures in random media and spin glasses.

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Stochastic modelling of age-structured populations

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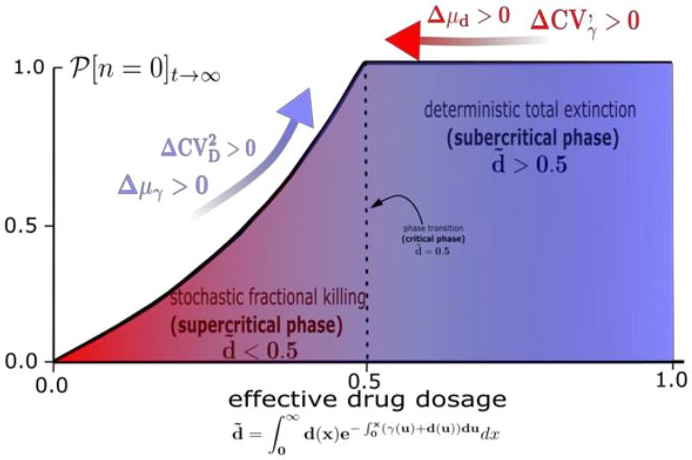
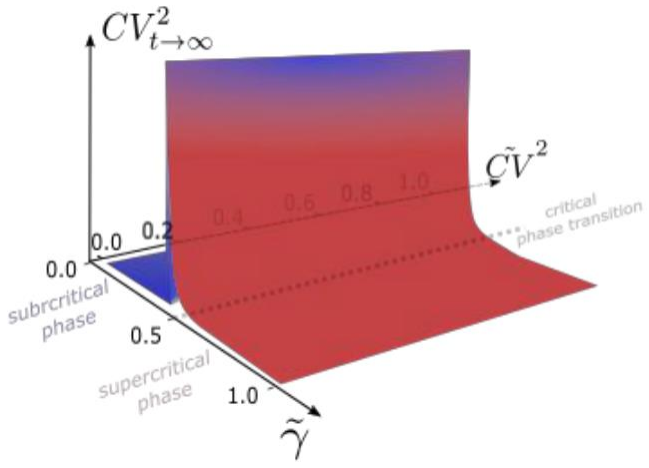
Quantifying cellular growth is crucial to understanding cell populations' dynamics such as microbes and cancer cells. The standard behaviour of batch cultures is well known and it is usually characterised by a delay before the start of exponential growth, an exponential phase, and a steady phase; however, at the single-cell level, growth varies drastically from cell to cell due to the fluctuations in the cell cycle duration, variability caused by changing environments, and cells interactions. At the present time, understanding how cell-to-cell variability affects the evolution of the entire population is still a challenge; de facto, there is still lacking solid theoretical and simulation methods to forecast the effects of cell heterogeneity on population dynamics. We propose a novel stochastic model where the cell is represented by agents who divide, die, convert to other species, and rejuvenate in response to an internal continuous state which increases with time. While such models are usually only amenable to simulations, we show that the population structure can be characterized by a functional master equation which can be manipulated to obtain a novel integral renewal equation. Compared to the classic results of renewal theory, as the Bellman-Harris branching process, the latter equation takes a step further. In fact, it provides a solid and compact stochastic description of the role played by cell heterogeneity on population dynamics. The analytical framework allowed us to fully describe the population size distribution, population growth rate, and ancestor and division times distributions. Moreover, we provide an analytical and numerical characterization of the extinction probability and first extinction times distribution for any cell-to-cell heterogeneity range. We also propose a novel way to simulate the evolution of cell populations affected by the variability of the individuals. Such computational tools allowed us to substantiate the analytical and numerical results obtained during this investigation. Our last results also provide novel methods to address the role of cell-to-cell variability in time-dependent environments. We showed that the stochastic description of agent-based population dynamics could be obtained in scenarios where the reaction network rates depend explicitly on time in addition to the internal traits of the cells. In conclusion, the following research project proposes a novel methodology to describe the stochastic behaviour of cell structured population with numerical, computational and analytical methods. Our results open a new theoretical path to understanding stochastic mechanisms underlying fluctuations in various biological and medical applications as the extinction of cancer cell populations under treatment, cell population growth in adverse environments, dormancy-awakening transition in breast cancer and microbial quiescence.





Dynamics of an entangled state under random magnetic fields

Venkata Satya Surya Phaneendra Pydimarri, Timothy R. Field *McMaster University, Hamilton, Canada*

Entanglement is an interesting aspect of quantum mechanics useful in quantum communication. The quantum communication protocols like quantum teleportation and superdense coding enable the sender and the receiver sharing maximally entangled pair of qubits to communicate information [1]. The property of entanglement, however, cannot survive indefinitely owing to disturbances. It is therefore necessary to understand the behavior of entangled states in the presence of disturbances. Among various objects that behave as qubits, we are interested in the spin-1/2 states of a particle and the random magnetic field that can cause disturbances. The dynamics of a single spin-1/2 particle in its pure state were already obtained in the presence of a random magnetic field due to which the pure state evolves into a random pure state [2]. The random magnetic field is modeled as Gaussian white noise process and the dynamics are derived using stochastic calculus. The relaxation times are obtained in the context of nuclear magnetic resonance. This idea is extended to the case of a pair of maximally entangled spin-1/2 particles that are spatially separated. The spins are subjected to random magnetic fields at their respective locations due to various sources which are in general different. We consider the most general case in which the components of the random fields are correlated [3]. This is inclusive of two special cases in which the random fields are same and independent. The dynamics are derived in terms of the joint density matrix assuming that initially the qubits are maximally entangled. This helps to understand how the entangled state behaves asymptotically and how long the entanglement survives when the constituent spins are subjected to disturbances. The timescale obtained from the dynamics is helpful to assess the possibility of implementation of the quantum communication protocols taking into consideration of the survival time of the entanglement. For instance, the pair of spins in the presence of independent random magnetic fields become totally disentangled asymptotically and the timescale associated with it, called the disentanglement time, helps to analyze how entanglement can be used effectively while implementing the protocols within the disentanglement time.

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Integrable peakon models -- Scalar case

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In this talk, I will majorly focus on the scalar peakon models developed in last 30 years. Most integrable peakon equations come from the negative order flow in the hierarchy. The key path for constructing the negative order flows is how to figure out the inverse of the recursion operator. I will take some example to explain this, and then introduce higher order models with peakons or pseudo-peakons we proposed recently. Some open problems will also be addressed for discussion in the end.

Axion-like particles and fifth force with neutron interferometry

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Università Degli Studi Di Salerno, Salerno, Italy

Phenomena, ranging from neutrino mixing to the dark matter and energy, to the muon g-2 anomaly, together with the strong CP problem (i.e. the absence of CP symmetry violation in strong interaction, for which an elegant solution was put forward by Peccei and Quinn through the introduction of pseudo–scalar particles known as axions) show the necessity of physics beyond the standard model of particles. Axions and axion– like particles (ALPs) with masses from the ultralight to the heavy axions, could represent a possible dark matter component. Not only are they capable of solving the strong CP problem in a natural way, but they also have small coupling constants to ordinary matter, and arise in the spectrum of string theories, thus representing a natural candidate for the missing matter in the universe. Many experiments have searched for ALPs, however, up to now no evidence for ALPs has been found. ALPs interact with the electromagnetic field, and moreover, they are expected to play the role of a mediating boson in a new fermion–fermion interaction ("fifth force"). Therefore, different experiments were designed to probe such interactions, which may be induced by ALPs and generic (pseudo)-scalar fields beyond the standard model. Another extremely thriving field of physics is the neutron interferometry. It has allowed to verify many theoretical effects, such as the Sagnac effect, the geometric phase and the wave–particle duality in quantum mechanics. Here, we report on a new approach to detect ALPs (and more generally bosons capable of mediating a new force among standard model particles), which suggests the use of a neutron interferometer in which two sub–beams are subject to external magnetic fields of equal strength but different direction, as a device to reveal fermion-fermion interaction mediated by axions. Indeed, we show that a detectable neutron phase difference, depending only by the axion–induced interaction between neutrons, can be achieved by setting the magnetic fields in the arms of the interferometer, one in the direction of propagation of the relative sub-beam and the other one orthogonally to the propagation. We fix the experimental parameters in order that the phase difference depends only on the axion–mediated interaction and the contributions given by the other interactions are removed. Then we show how a neutron interferometer is sensible to the presence of ALPs in a significant portion of parameter space.

Quasi-homogeneous black hole thermodynamics

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National Autonomous University Of Mexico, Mexico

We present several arguments which indicate that the fundamental equations of black hole thermodynamics should belong to the class of quasi-homogeneous functions of degree different from one. Arguments include the non-extensitivity properties of black holes as well as compatibility conditions in geometrothermodynamics. We show that the quasi-homogeneity of black holes in alternative gravity theories such as Born-Infeld, Gauss-Bonnet, etc., implies that coupling constants should be considered as thermodynamic variables, leading to natural extensions of thermodynamics.

Electromagnetic ion cyclotron waves and associated ion velocity distributions: Cluster observations

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This study presents the observations of electromagnetic ion cyclotron (EMIC) waves in the solar wind and Earth's magnetosphere using the Cluster observations. We also present the observations of ion velocity distribution functions (VDFs) at the time of enhancement of the wave. It is found that the observed ion VDFs possess low-dense ion beams in addition to the high energy tails as compared to the Maxwellian distribution. By using the observed plasma parameters at times when wave activity is at his peak, we numerically solve the full dispersion relation of EMIC waves and obtained the real frequency and growth rate expressions. We then investigate the effect of superthermal particles and ion beam on the growth rates of the EMIC waves.

A universal method for analysing copolymer growth

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Copolymers are polymers consisting of more than one type of monomer and are ubiquitous in biology, including, for example, DNA, RNA and proteins. Producing copolymers with a specific sequence is thermodynamically challenging, and in living systems copolymers without repetitive sequences are typically produced with the aid of a template copolymer. Templated copolymerisation reactions often feature complicated pathways with multiple sub-steps in order to ensure accurate reproduction of the sequence encoded in the template. Information is embedded in the sequence of monomers of these copolymers; this information is transferred through templated copolymerisation, and used to direct molecular folding and cellular function in the vital processes of transcription, translation and replication. In this work, we consider a general class of copolymerisation models in which monomers are added to or removed from the end of a growing polymer via an arbitrary Markovian reaction network. Such a class of models can be used to study both non-templated and templated copolymerisation. Hitherto, analysis of these models has either required restrictive assumptions, such as irreversibility, or brute force simulation. We introduce a methodology that allows for properties such as the sequence distribution, polymerisation speed and entropy production to be obtained either analytically or via simple numerical calculations. This methodology makes use of techniques from absorbing Markov chains, graph theory and statistical mechanics in order to map the complex copolymerisation process onto a simpler coarse-grained process that may then be solved. Crucially, using our method, fine-grained, kinetic details of the full process, such as time spent and work done, are not lost and may be inferred exactly from using the solution to the coarse-grained process. With access to these kinetic and thermodynamic quantities, we study trade-offs between accuracy, speed and the thermodynamic cost of copolymerisation systems, and define the efficiency with which work is converted to accuracy of the copolymer. Interesting properties of these copolymerisation systems emerge from this analysis. For example, there exists a minimum driving required to create copolymers; below this driving the copolymerisation process stalls. For some systems, this stall point corresponds to equilibrium; in general, however, the stall point need not be at equilibrium. This stall point cannot be accessed directly by simulation, as simulation time diverges at this point, but can be analysed straight-forwardly within our framework. Finally, we demonstrate the power of our method by analysing a family of previously intractable Hopfield-style kinetic proofreading mechanisms embedded in a copolymerisation process, and show that our method particularly excels when analysing reaction networks with recursive structures.

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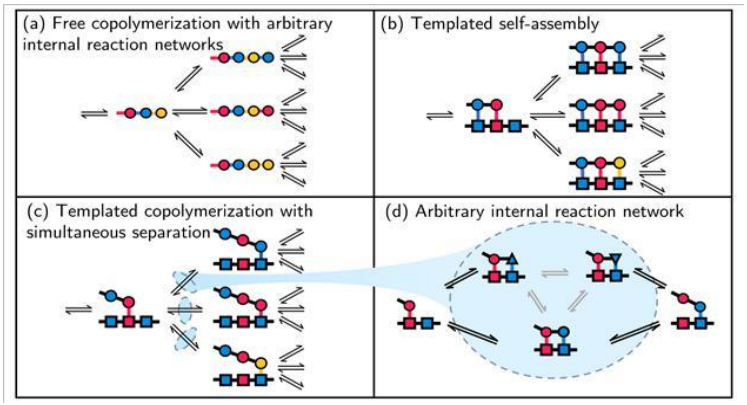

Possible explanation for power law tails of the solar wind ion distribution function: Study of the Liouville-Coulomb system

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Velocity distribution functions (VDFs) of solar wind particles are often seen to exhibit non-thermal features: a "kappa"-distributed core (a statistical distribution that has a Gaussian-like peak which transitions smoothly to a power-law tail), as well as an additional tail that does not connect smoothly to this core (see, e.g., Chotoo et al., 2000). Here, we present an explanation as to how these features come about based on a self-consistent theory of suprathermal particle acceleration from mutual Coulomb interactions. For the results presented here, we employ the simulations described in Randol & Christian (2014, 2016) and discussed further in Randol (2019, 2021), except with higher accuracy. The main result is that for a plasma that has just undergone ionization (for moderate Coulombic energy density), a "sharp" tail (that is, one that does not connect smoothly to the Gaussian core) is formed quickly, and over time, this tail rises in intensity while the Gaussian core simultaneously forms a kappa distribution. Results at longer times as well as dependence on initial Coulombic energy density are also discussed.

Thermodynamic efficiency of autocatalytic networks

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Autocatalytic networks are reaction networks suggested to be at the basis of life. The reflexively and food-generated theory provides a formal definition of this system in terms of graphs with peculiar topological characteristics, and helps to elucidate both their structural and dynamic properties. In this work, I use recent results on the nonequilibrium thermodynamics of chemical reaction networks to study the connection between the constrains a network must satisfy to be autocatalytic and its thermodynamics properties, and I show that these systems can exhibit a wide variety of thermodynamic behaviours.

First-passage time below the diagonal for the Brownian maximum

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Ecole Normale Supérieure, Univ. Paris-saclay, Paris, France

For $t \geq 0$, let St be the running maximum of a standard Brownian motion Bt and let $Tm := inf\{t; mSt < t\}$, $m > 0$. In this talk I will discuss the calculation of the joint distribution of Tm and BTm . The motivation for this work comes from a mathematical model for animal foraging. The toy-model which we have in mind was imagined by P. Krapivsky. It deals with the simplified, stylized case of an animal foraging in a one dimensional space. The animal's initial position coincides with the origin, and we model its position as time t elapses by a standard Brownian motion (Bt), $t \geq 0$. For the sake of simplicity, we suppose that the forager's metabolism is basic: to survive, the animal needs one unit of food per unit time, and it may stockpile any extra supply for future use, without any upper limit on the size of the stock nor any expiry date for the consumption thereof. Assume that only half of the space (say, the positive half-line) is initially filled with one unit of food per unit length, and that there is no replenishment. Thus, if the animal's motion is modelled by a Brownian motion, after a time t the forager has absorbed an amount of food equal to St , its maximal displacement in the positive direction. For the forager to survive up to a time t, it should be the case that, at every time $s \leq t$, the amount of food it had absorbed was not less than s. In other terms, the probability that the forager survives up to a time t is given by the probability that $Ss \geq s$ for all s in,[0,t]. Equivalently, this is the probability that the first (downward) hitting time T of the maximum process St on the diagonal barrier occurs after t-- which relates directly to the problem stated at the beginning of this abstract. I will show a path transformation that allows to calculate the joint distribution of Tm and BTm . Time-permitting, I will also present results for Brownian motion with drift.

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Investigating the role of talent and chance in individual sports: from Fencing to Tennis Tournaments

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It is a widespread belief that success is mainly due to innate qualities, rather than to external forces. This is particularly true in sport competitions, where individual talent is considered the only ingredient in order to reach success. In this talk, following a line of research started in [1-2] I will discuss the results of recent papers [3-4], where the relative weight of talent and chance has been explored in fencing and tennis by means of statistical analysis of real data and agent-based models. Numerical simulations approximate very well real data for values of chance almost equal or greater than that of talent. It seems then, that the role of chance in individual sports is heavily underestimated. Keep assessing merit without considering the bias of chance is risky, as it creates a huge disparity between comparable talents and it consequently influences not only sports results but also future career development.

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Modeling the deep abiotic weathering of pyrite

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Pyrite (FeS) is the most abundant sulfide mineral in the Earth crust. It is oxidized in contact with water and the atmosphere, but this reaction is catalyzed by microorganisms, which may cause acidification of the landscape. This phenomenon is frequently observed in mined regions where pyrite is artificially exposed. In this work, oxidative weathering of pyrite (OWP) was studied in shale fragments collected at depths from 15m to 16m in a ridge of the Shale Hills critical zone observatory (Pennsylvania, USA). Considering the rates of topsoil erosion and regolith production, full OWP occurs is estimated to occur in a geological time of ~50kyr. The low porosity of those fragments and the presence of pore throats with 10--20nm indicate that bacteria are not likely to play a role in this process. Thus, chemical analysis and transmission electron microscopy images showing ferrihydrite [Fe(OH)_3] layers around partially weathered grains were used to determine the main reaction of pyrite. However, the estimated time of full OWP is several orders of magnitude longer than the time predicted by the laboratory rates of oxidation and by the oxygen concentration in water flowing at the observed depths, implying an effectively very small field rate. This apparent contradiction is solved with the proposal of a reaction-diffusion model in which the OWP is limited by oxygen diffusion in the rock fragments of sizes ~11.6cm. The solution of that model leads to a diffusion coefficient consistent with laboratory estimates on shale with the same porosity (~4.5%) and leads to a reaction front thickness ~0.5-1cm, which is consistent with the width of the zone of partial OWP in a rock fragment. When the model is extended to shales from other two watersheds, it also explains the OWP at depth. However, when the estimate of atmospheric oxygen concentration before the great oxidation event (GOE; 2-2.4 billions of years ago) is used, the model predicts that pyrite was exposed at the land surface in the three sites. This result quantitatively confirms the proposal of previous works that pyrite oxidation at the land surface before the GOE was responsible for events of enhanced sulfate delivery to the oceans and their consequent acidification. [Science 370, eabb8092 (2020)]

Universal superdiffusion of random walks on lattices with low diffusivity fractal networks

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Superdiffusive phenomena are frequently observed in systems with Lévy flights or with active motion because these are some mechanisms that enhance the transport relatively to normal diffusion. Instead, random walks on fractal media usually show subdiffusion because the self-similar distributions of obstacles restrict the transport; in these cases, the random walk dimension Dw (>2) is non-universal, in the sense that it does not depend only on the dimension Df of the fractal medium. In this work, we show that superdiffusion with universal exponents can be obtained in a random walk model on Euclidean lattices containing embedded fractal networks where the transport is slow. The model is defined with hopping rates proportional to p<<1 in the fractal sites and proportional to 1 in the remaining lattice sites. A scaling approach predicts the superdiffusive regime at short times, with a random walk dimension Df-E+2, where E is the dimension of the lattice, under the condition that the walks begin on the fractal. A crossover to the asymptotic normal diffusion is then predicted at a time of order p^{-δ}, where δ=2/(E-Df), and the anomalous root mean square displacement reaches values of order p^{-δ/2}. Numerical simulations are performed in square lattices with embedded DLAs and Sierpinski carpets (Df~1.7--1.8) and in cubic lattices with embedded percolation clusters and Menger sponges (Df~2.5--2.8). By properly avoiding finite size effects, the simulation results for several p confirm a predicted dynamic scaling relation and show that the superdiffusion can be observed in several decades of time and length for $p\sim10^{-3}$ in the studied fractals. In one dimension, the model is equivalent to that of horizontal fluid infiltration in a matrix with fractal distributions of low conductivity inclusions, in which the superdiffusive scaling is expected with geological materials whose hydraulic conductivities may differ by a factor ~50, such as medium and coarse sand [Adv. Water Resour. 172, 104365 (2023)]. This work shows that superdiffusion can be obtained with a simple random walk mechanism, without long jumps or active motion, and that the random walk dimensions may be used to estimate the fractal dimensions of sets of low diffusivity or low conductivity inclusions.

Surprises from the out-of-equilibrium dynamics of mean-field spin glasses

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Almost 30 years after the solution to the off-equilibrium dynamics of long-range spin glasses based on the weak ergodicity breaking hypothesis, we are finding several pieces of evidence that such an assumption is not always correct. I will present this evidence and discuss the new physics that is emerging from the out-of-equilibrium dynamics of mean-field spin glasses.

Stochastic resonance for an optimal transport of active particles

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We show the existence of a stochastic resonant regime in the transport of active colloidal particles under confinement. The periodic addition of substrate to the system causes the spectral amplification to exhibit a maximum for an optimal noise level value. The consequence of this is that particles can travel longer distances with lower fuel consumption. The stochastic resonance phenomenon found allows the identification of optimal scenarios for the transport of active particles, enabling them to reach regions that are otherwise difficult to access, and may therefore find applications in transport in cell membranes and tissues for medical treatments and soil remediation.

Normal quantum channels

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We study general normally (Gaussian) distributed random unitary transformations acting on finite-dimensional quantum systems. These distributions can be understood in terms of a diffusive random walk in a compact Lie group, formally underpinned by the concept of infinite divisibility for probability distributions [1,2]. These normal distributions are completely defined by a diffusion matrix A and a drift vector b . We call a quantum channel "normal" if it is generated by such normally distributed operations. We show that there is a surjective correspondence between the normal distributions and the Lindblad-divisible quantum channels [3], i.e. quantum channels which can be generated by a Lindblad master equation. We study the one-qubit case and then consider normal quantum channels with correlations for two qubits. In the one-qubit case, we show that different normal distributions can generate the same quantum channel (Fig. 1). In the two-qubit case we use the normal distributions for modeling correlated quantum errors. We propose two models for two qubit errors Λ2 and Λc that use linear correlations modeled by the parameter m and correlations from the diffusion matrix A that use the correlations coefficient ρ respectively. We compare our proposed models with the two qubit correlated Pauli error ΛcP from the literature [4,5] on an entanglement distillation protocol and found that the distillation is more effective for the normal channels as seen in figures 2. We expect our work to find applications in the tomography and modeling of one- and two-qubit errors in current quantum computer platforms, as well as in imperfect communication channels, where it is conceivable that subsequently transmitted qubits are subject to correlated errors.

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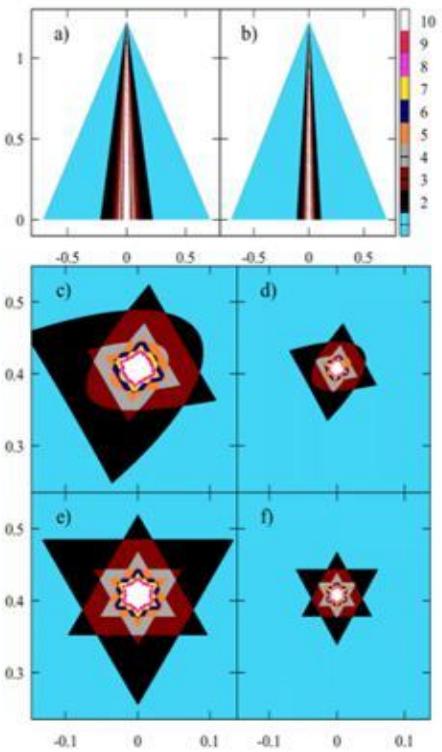

Fig.1: Plot of how many possible normal distributions can generate the same quantum normal channel. The plot is done on the space of the parameters of the diffusion matrix A restricting them to two dimensions with the vector $\vec{b}$ fixed. In other words, a point the chosen normal channel and the color how many normal distributions can generate it.

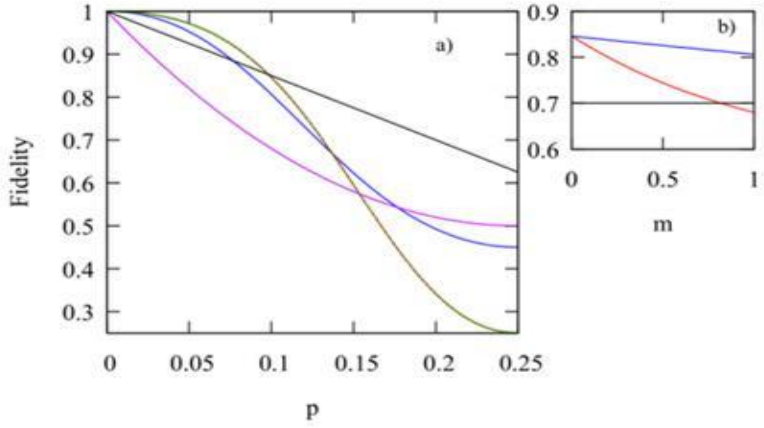

Fig.2: Left: This figure shows the fidelity of a state after the distillation for different error rates p and correlations m. The error channels used are: blue Λc (m = 1), red Λc(m = 0), purple ΛcP (m = 1), green dotted line ΛcP(m = 0). In black the fidelity when no distillation is done is shown. Right: Fidelity as a function of the correlation m when p=0.1. The red and blue lines show are the fidelity when distillation is done. The red line use ΛcP and the blue ΛcP as errors. The black line is when no distillation is done.

Stochastic equations and dynamics beyond mean-field theory in Spin-Glasses

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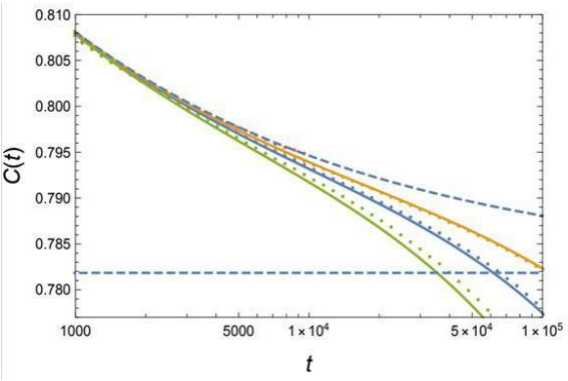
The dynamical transition occurring in spin-glass (SG) models with one step of Replica-Symmetry-Breaking (1RSB) is a mean-field artifact that disappears in finite systems and/or in finite dimensions. The dynamical transition has the features of a second-order phase transition and thus it is to be expected that the fluctuations are naturally described by a simple effective theory. Due to certain non trivial features of the corresponding theory it turns out that it is equivalent to a set of dynamical stochastic equations called stochastic-β-Relaxation (SBR) equations in [1]. Overall SBR predicts not only that the transition at the dynamical temperature is avoided or that the fluctuations deviate from mean-field theory but also that there is an essential qualitative change in the structure of the fluctuations with the appearance of dynamical heterogeneities [2-4]. We demonstrate the validity of SBR in 1RSB SG by comparing its predictions, as obtained solving numerically the stochastic equations, with Monte-Carlo simulations for the paradigmatic Ising p-spin glass model [5]. More precisely we consider a system of N spins each of which interacts with a fixed number c = 6 of p-spin interactions with p = 3 and evolve with Metropolis dynamics. The (random) lattice is such that in the large N limit loops are increasingly rare and it tends to the corresponding c = 6 and p = 3 Bethe lattice. In order to obtain parameter-free predictions we computed analytically the model-dependent parameters entering into the stochastic equations using existing and novel techniques based on the mean-field cavity method on the glassy phase of the transition. These parameters were then plugged into the code for the numerical solution of the equations. The predictions are in excellent agreement with numerical simulations for both the correlation (as seen in the figure) and its fluctuations and this demonstrates that SBR correctly describes how the sharp transition predicted by mean-field theory is turned into a crossover in 1RSB SG models with finite size. In the figure we plot the average correlation with initial equilibrium condition vs time at the dynamical temperature. Points from bottom to top are numerical data for $N = 4.5 \times 10^5$, $N = 9 \times 10^5$, $N = 1.8 \times 10^6$ (Sample numbers are respectively 9554, 8048, 7701, error bars are negligible on the scale of the plot). The data follow the Bethe lattice $N = \infty$ curve (dashed blue) at initial times and deviate from it at later times increasing with N eventually crossing the plateau value q = 0.78184. The solid lines are the corresponding SBR predictions describing the data when they start to deviate from the mean-field curve.



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Non-gaussian diffusion and long-time correlations in the magnetosphere-ionosphere system

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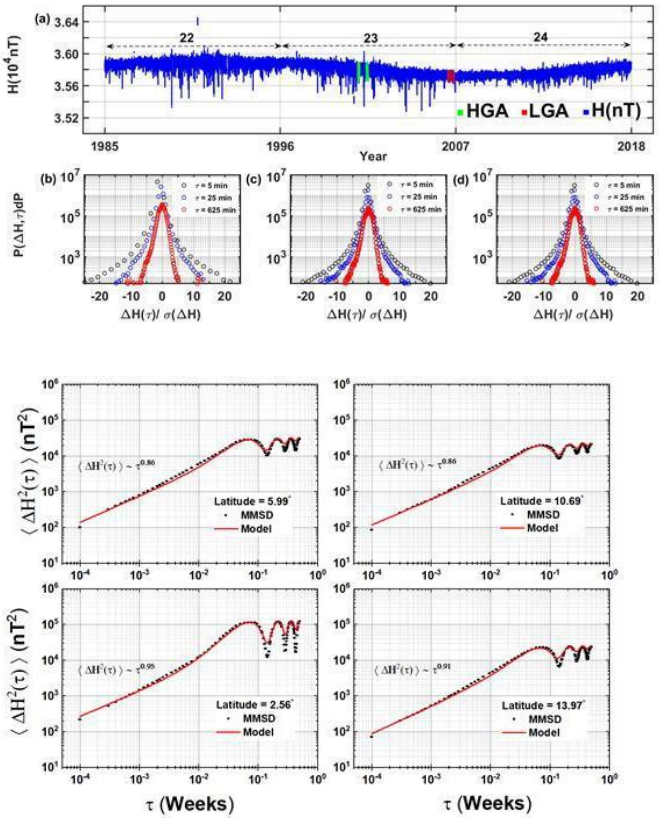
The magnetosphere-ionosphere (MI) system hosts different concentrations of cold plasma. The magnetosphere interaction with the solar wind, the Earth's rotation, and the interactions of protons, ions, and electrons with the electromagnetic fields drive the behavior of plasma dynamics [1]. Since the interactions of the magnetosphere with the solar wind are chaotic [2], this produces substantial random alterations in the plasma densities, temperatures, and velocities of the particles immersed in it, thus inducing random fluctuations in the electrical currents present in these regions. These random fluctuations in the MI system could wreak havoc on many technologies, such as satellite communications and power grids. We study the statistical properties of the temporal displacements of the magnitude of the horizontal Earth's magnetic field H over three solar cycles. The probability distribution function (PDF) of these temporary displacements allows us to characterize the dynamics of the MI system during the different solar cycles (Figure 1) [3]. All the PDFs for different solar cycles have the same form: at short times, they show a stretched Gaussian shape, and at long times, non-Gaussian tails (nGTs) are observed. nGTs are associated with "long-time tail correlations" that generate a system with non-Markovian dynamics. Likewise, at long times, there is a persistent peak associated with trajectories of random walks that never leave their local paths and with processes of the Fickian, yet non-Gaussian diffusion type [4]. Moreover, we calculate a robust statistical observable, the magnetic mean squared displacement (MMSD), using data from several geomagnetic stations in the northern and southern geomagnetic latitudes. We propose a physical model to describe the MMSD system using the Generalized Langevin Equation (GLE), provided with a smoothly decaying kernel memory γ(t) [3], and Alfvén's ideas for space plasmas in terms of electrical circuits [5]. We describe electrical currents in the MI system by an ensemble of serial electric circuits (RCL) fed by one random voltage source. Finally, we successfully compare calculated MMSD with our model (Figure 2), finding the following key results: (i) the MI system exhibits long-time tail correlations, and (ii) these correlations are explained by a memory kernel that arises from a two power-law.



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Dynamics of tagged particles in a biased A + A → Ø system in one dimension: result for asynchronous and parallel updates

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Dynamical features of tagged particles are studied in one dimensional A + A →Φ system on a periodic lattice, where the particles A have a bias ε to move towards its nearest neighbouring particle and two particles are annihilated on contact. For asynchronous dynamics, at each update a site is selected randomly and if there is a particle on it, it makes a movement. The fraction of walkers ρ(t) at time t was found to decay as $\rho(t) \sim t^a$, with a=-1 when the bias, however small, is introduced. In the absence of the bias, it is known that a = 1/2, which suggests that in the presence of the bias, the walkers, in the long time limit, behave as ballistic walkers [1-3]. To get a better understanding we study the dynamics of a tracer walker in the biased case specifically to check whether they perform ballistic motion or not. We show that for ε > 0, probability distribution of the particles π (x, t) shows a double peak structure with a dip at x = 0 and at late time regime it assumes a double delta form. For any ε, there is a time scale t* which demarcates the dynamics of the particles. Below t*, the dynamics are governed by the annihilation of the particles and the particle motions are highly correlated, while for t>> t*, the particles move as independent biased walkers. t* diverges at ε = 0.5 which is the critical point of the dynamics. At ε=0.5, the probability S(t), that a walker changes its direction of motion at time t, decays as $S(t) \sim t^a$ with a=-1, and the distribution D(τ) of the time interval τ between consecutive changes in the direction of a typical walker decays with a power law as $D(\tau) \approx \tau^a$ with a=-2. When the system is updated using parallel dynamics, all the particles are updated simultaneously. If the particles are found to occupy same site after the completion of a single MC step, then both of them are annihilated. π(x,t) shows a non Gaussian single peaked structure and the scaling variable is different from the usual random walker case. Here, the fraction of surviving particle ρ(t) shows a unsual (a ln t/t) behaviour. For ε = 0.5, a pair of neighbouring particles, termed as dimers, can survive indefinitely in the system which is exclusive for parallel dynamics only. When the bias ε becomes negative, π(x,t) retain its Gaussian nature as for ε = 0; however, the scaling factor is ε dependent. Finally, a comparative analysis for the behaviour of all the relevant quantities for the system using parallel and asynchronous dynamics shows that there are significant differences for ε > 0 while the results are qualitatively similar for ε< 0.

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Entropic transport in confined soft-matter and biological systems

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To know how particles move in small cavities, micro-channels and in general in crowded media currently constitutes a challenge for the understanding of basic mechanisms governing the behaviour of small-scale soft-matter and biological systems. The presence of obstacles, constrictions and irregularities in the shape of these structures significantly alter their trajectories thus modifying their transport properties. An analysis of these properties based on the use of diffusion and stochastic equations faces the problem of solving these equations for very complex boundaries which may constitute a formidable task. Recent studies on transport through confined media have shown that this problem can be considerably simplified if one assimilates spatial restrictions to the entropic barriers which particles must surmount in order to proceed. A wide variety of situations can be studied in this way, including many that were thought to be beyond the reach of classical transport theories, such as diffusion through deformable channels, motion of ions at very small length scales and behaviour of condensed active matter.

Cold discrete breathers

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Discrete breathers are spatially localized modes of nonlinear lattices that are relevant in a many physical systems such as crystals and coupled optical fibers [1]. Since the demonstration of their existence [2] for a broad class of weakly coupled nonlinear lattices they have also been an important field of studies for the dynamics and statistical mechanics of nonintegrable Hamiltonian systems. Their persistence in time may appear surprising from the viewpoint of statistical mechanics as localization of energy in a few high-amplitude structures seems to be opposed to what is expected in the thermalization of nonintegrable systems. For systems with a second conserved quantity (e.g. the magnetization in the Landau-Lifshitz equation [3], the wave action (or modulus-square norm) in the discrete nonlinear Schrödinger equation [4-8]), the statistical analysis has shown that the thermal equilibrium state consists of two phases, one of low-amplitude phonons and one of high-amplitude discrete breathers in a certain energy range [3-8]. This statistical explanation of discrete breathers is not directly applicable to Hamiltonian systems without a second conserved quantity. One statistical approach [9] to explain the formation of breathers in such systems (in particular the discrete nonlinear Klein-Gordon equation) is based on an envelope equation (again of Schrödinger type) that possesses a second "almost conserved" quantity. From this, the formation of breathers can be explained in the same way as for systems with a conserved quantity. At variance to this approach, I will suggest a new statistical explanation of breathers in such systems without invoking a second conserved quantity.

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Pure fluids to black holes: thermodynamics probes microstructures

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What can the thermodynamic entropy tell us about the microstructures in a thermodynamic system? As I argue in this talk, the answer is a surprising amount. Simple fluctuation theory provides a thermodynamic metric based on information geometry. This metric carries with it a curvature function R, which plays a special role as the only thermodynamic invariant. The magnitude of R is the correlation length, and its sign is positive/negative for systems with interparticle interactions repulsive/attractive. I discuss a number of basic examples of pure fluids and magnetic systems. Another essential scenario consists of black holes, where there is no currently accepted microscopic theory. But there is a well-established black hole thermodynamic structure, and I will discuss the considerable work that has been done exploring what R has to tell us about black hole microstructures.

Persistence, multifractality, and complexity of the German weather-driven electricity spot prices

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The integration of volatile renewable power sources can prove a central challenge in the transition to a sustainable energy system. Electricity markets are central in coordinating electric power generation across Europe. These markets rely evermore on short-term trading to facilitate the balancing of power generation and demand and to enable systems integration of small producers. Electricity prices are themselves afflicted by volatility induced endogenously from evolving market structures and schemes, as well as exogenously by varying power generation from different renewable and non-renewable generation. Electricity prices in these spot markets show pronounced fluctuations, featuring extreme peaks as well as occasional negative prices. In this presentation, we highlight a few distinct statistical properties of electricity prices from the European Power Exchange market, in particular the hourly day-ahead, hourly intraday, and 15-min intraday market prices. We utilise various statistical physics methods to quantify the fluctuations, correlations, and extreme events and reveal different time scales in the dynamics of the market. The short-term fluctuations show remarkably different characteristics for time scales below and above 12 hours. Fluctuations are strongly correlated and persistent below 12 hours, which contributes to extreme price events and strong multifractal behaviour. On longer time scales, they get anticorrelated and price time series revert to their mean, witnessed by a stark decrease of the Hurst coefficient after 12 hours. The long-term behaviour is strongly influenced by the evolution of a large-scale weather pattern with a typical time scale of four days. We elucidate this dependence in detail using a classification into circulation weather types. The separation in time scales enables a superstatistical treatment, which confirms the characteristic time scale of four days, and motivates the use of q-Gaussian distributions as the best fit for the empiric distribution of electricity prices.

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The complexity of power-grid frequency dynamics – An application in superstatistics

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Power grids constitute one of the most complex human-made systems of our time. The delivery of electrical power, centralised or decentralised, depends almost exclusively on power grid networks. The dynamics of electricity in conventional power grids follow strict physical laws. Yet, the inherent variability of supply and demand, augmented with the volatile nature of power generation, leads to inherently ever-changing statistics of power-grid-specific variables. In this presentation, we focus on power-grid frequency, the key signature of power-grid stability, and show that this exhibits known signatures of complex systems, specifically, heavy-tailed distributions. We show that we can recover the statistics of power-grid frequency increments via superstatistics. Moreover, we show that we can disentangle different 'strengths' of superstatistics – given by differing q-indices – across a synchronous power grid, yet with the current data, it is still difficult to detail exactly the type of hyper-distributions governing the statistics of the increments. We will lastly allude to the connection between multifractality and superstatistics in power-grid systems.

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Message passing for routing and network design in optical communication

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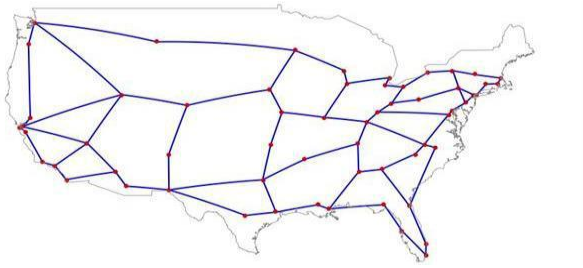
Optical communication networks underpin the global digital communications infrastructure and carry most of the Internet traffic. They comprise thousands of kilometres of optical fibres, organised in a complex web of constituent sub-networks. The exponential growth in Internet traffic and energy consumption threatens to overload the existing infrastructure. One of the key requirements is the routing and wavelength assignment (RWA) for all traffic demands across this complex heterogeneous network in a way that optimises a given objective function, be it low latency, high throughput or resilience. The main constraint in RWA is that any complete individual route, from source to destination, uses the same single wavelength and that separate routes using the same wavelength cannot share the same fibre. This constraint makes the general hard computational routing problem even harder. Given that routes are constrained to be contiguous and interaction between paths is non-localised, local optimisation methods are insufficient and global optimisation is required. However, global RWA of multiple communication requests is computationally-hard and is currently addressed in small systems by integer/linear programming and its variants, Monte Carlo search, greedy algorithms and various heuristics. The main challenge we address is the RWA under heavy traffic using multiple wavelengths and a large number of origin-destination pairs for various objective functions. This is carried out by mapping the RWA task in the presence of multiple wavelengths onto multi-layer replica of the original graph and utilising probabilistic message-passing techniques, developed independently in several fields including statistical physics, to solve it. These methods allow for messages, in the form of conditional probability values to be passed between nodes and the replicated networks representing the different wavelengths, in a way that keeps the algorithms scalable even for a large number of wavelengths, transmission requests (corresponding to source-destination pairs) and nodes. The algorithm has been tested for a variety of sparse network topologies, both synthetic random graphs and real optical communication networks, and for different objective functions, showing excellent results in obtaining high quality approximate solutions. Another major task in designing and maintaining optical communication networks is the removal of unnecessary edges or adding new ones in a manner that minimises the impact on throughput in the former and maximises the benefit in the latter. Many edges in operational optical communication networks are legacy fibres that are costly to maintain but are not removed due to the possible operational impact; similarly, adding fibres is expensive and one clearly would like to maximise the benefit from it. Many of the methods used currently for these tasks are topological in nature without considering the typical communication requests, while others rely on simulations or heuristics. We consider the two-level optimisation tasks, of edge removal/addition in parallel to optimal multi-user routing in order the identify the best edges to be removed/added with minimal/maximal impact on a given objective (e.g., throughput, latency or resilience). The methodology used is based on message passing and the resulting algorithms have been tested on synthetic and real networks, showing excellent results compared to existing heuristics.



Pandemics, marketing and opinion formation – the power of spreading processes

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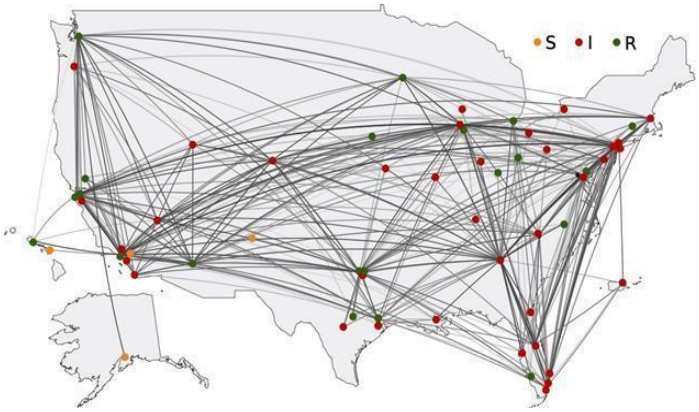
The modern world comprises interlinked networks of contacts between individuals, computing devices and social groups, where infectious diseases, information and opinions propagate through their edges in a probabilistic or deterministic manner via interactions between individual constituents. The spread of information, opinions and marketing material can be modelled and analysed in a similar manner to that of epidemic spreading among humans or animals. To contain and mitigate the spread of infectious diseases one would like to model the spread accurately, implement effective prevention and mitigation policies and deploy vaccines in a way that minimises the spread. This is a difficult problem and becomes even harder in the presence of infectious but asymptomatic individual states. In the world of marketing and opinion setting, winners are those who maximise the impact by deploying resource to the most influential available nodes at the right time, occasionally in competition (or collaboration) with adversarial (supportive) spreading processes. These can represent opinion formation by political parties (competitive) or diseases that increase the susceptibility to mutual infections (collaborative). I will explain the modelling of epidemic spreading processes and present the probabilistic analytical framework for impact maximisation/minimisation we have developed, addressing the questions of vaccine (budget) deployment and spreading maximisation in single and competitive/collaborative processes. I will also present the analysis for epidemic spreading processes with infectious but asymptomatic states and the effectiveness of containment and mitigation steps in this case.



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Ion-acoustic nonlinear structures in electron-beam superthermal plasmas

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A number of satellite observations have confirmed the presence of electron beam in the upper layer of the Earth's magnetosphere, where a coexistence of two different temperature electron populations occur. In the presence of electron beam, stationary nonlinear localized electrostatic structures are excited in a plasma system. Numerous theoretical investigations have confirmed the existence of nonlinear electrostatic structures in various space and astrophysical environments in the presence of electron beam. It has also highlighted in different findings that the nonlinear potential structures (solitons, shocks, double layers, freak waves etc.) are significantly modified by the presence of electron beam and other plasma parameters. It has been reported that the investigation of the velocity distributions observed in the solar wind, planetary magnetosphere and magneto-sheath by the spacecraft showed that superthermal distribution of charged particles is very common. Owing to the existence of electron beam and superthermal particles in different space environments, it is interesting to derive nonlinear equations taking into account presence of electron beam and derive their solutions for study of nonlinear solitary structures. Main focus of this talk is to discuss about study of investigation of various kinds of nonlinear structures (viz. solitons, Freak waves, and Peregrine solitons) in multicomponent space plasma having species (cold electrons, ions, hot electrons) obeying kappa distribution and embedded with electron beam. The

reductive perturbation method is employed to derive Korteweg-de Vries (KdV) equation and nonlinear Schrodinger equation. Further, using single variable transformation, solutions of these equations have been derived to study the characteristics of KdV solitons and freak waves as well as Peregrine solitons. It is observed that various plasma parameters have great influence on the propagation properties of solitons, freak waves and Peregrine solitons. This study may have variety of potential applications for better understanding of nonlinear phenomena in various space/astrophysical environments.

Polymer translocation driven by transversal and time-dependent end-pulled forces.

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Polymer translocation has long been a topic of interest in the field of biological physics given its relevance in both biological (protein and DNA/RNA translocation through nuclear and cell membranes) and technological processes (nanopore DNA sequenciation, drug delivery) [1,2]. In this work, we simulate the translocation of a semiflexible homopolymer through an extended pore, driven by both a constant and a time-dependent end-pulled force, employing a model introduced in previous studies [3]. The time dependence is simplistically modeled as a cosine function, and we distinguish between two scenarios for the driving -- longitudinal force and transversal force-- depending on the relative orientation of the force, parallel or perpendicular, with respect to the pore axis. We investigate the effects of this periodic driving on the translocation times. We find a large minimum region of the mean translocation times as function of the frequency of the force that is typical of the Resonant Activation effect [4], with key differences between the two considered driving regimes. This minimum is present independently of the physical characteristics of the polymeric chains and reveals a linear relation between the optimum translocation time and the corresponding period of the driving. We propose an explanation for the mechanism behind this relation, its connection to the driving regime considered, as well as the values of the coefficients involved. The behavior of the translocation times when changing parameters of the chains were recorded, finding key differences in the responses between both driving regimes, and revealing a scaling law of the translocation times for chains of different lengths. Lastly, an analytical expression for the low frequency range of the translocation curves is derived, in clear agreement with the simulation results.

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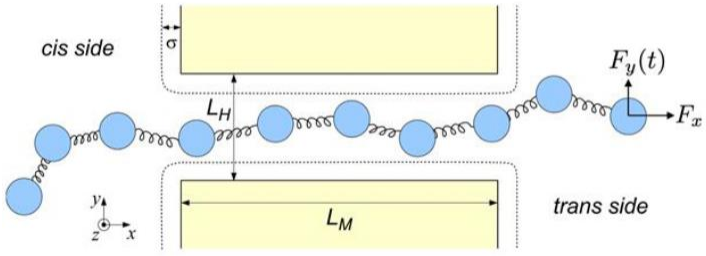

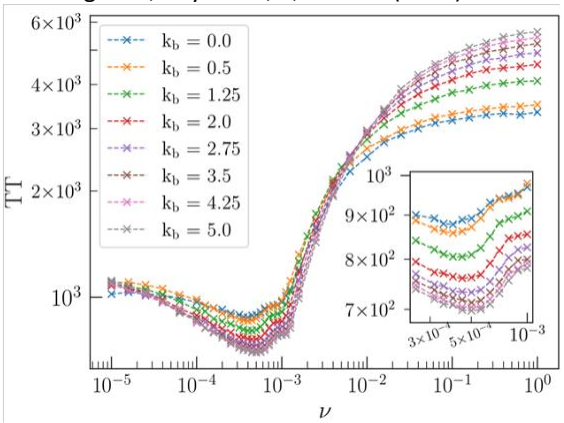

New insights on solar wind electrons at 1 AU: Collisionality, heat flux, and thermal force

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The origin and evolution of non-equilibrium characteristics of electron velocity distribution functions (eVDFs) in the solar wind are still not well understood. They are key in understanding heat conduction and energy transport in weakly collisional plasma, as well as in the scenario at the origin of the solar wind. Due to low collision rates in the solar wind, the electron populations develop temperature anisotropies and velocity drifts in the proton frame, as well as suprathermal tails and heat fluxes along the local magnetic field direction. These non-thermal characteristics are highly variable, and the processes that control them remain an open question.

We present here a recent work on enhanced measurements of solar wind eVDFs from Wind at 1AU. This work is based on a sophisticated algorithm that calibrates eVDFs with plasma Quasi Thermal Noise data in order to accurately and systematically characterize the non-thermal properties of the eVDFs, as well as those of their Core, Halo and Strahl components. Indeed, the core, halo and strahl populations are fitted to determine their densities, temperatures and temperature anisotropies as well as their respective drift velocities with respect of the ion velocity (or solar wind speed). The density, temperature and temperature anisotropy, as well as the parallel heat flux of the total eVDFs are also computed.

We use a 4-year-long dataset composed of all these parameters at solar minimum to enable statistically significant analyses of solar wind electron properties. We estimate collisional proxies such as collisional age and Knudsen number, and discuss usually neglected effects. In addition to the total electron heat flux, we also compute the heat flux contributions from the core, halo and strahl and discuss the interplay between these three components. We finally show estimates of the so-called Thermal Force, a drag or Coulomb friction between ions and the electron components that arises naturally from the non-thermal character of the eVDFs, even in the absence of current. This TF enhances the parallel electric field and plays an important, but usually neglected, role in two fluid energy transfers between electrons and ions. It is parallel to the heat flux that causes it, however its role in understanding the observed heat flux remains to be explored. This statistically-significant work allows a local, quantitative measure of Coulomb coupling that maybe important with possibly other microphysical processes to locally control non-thermal properties.

Gravity-thermodynamics connection and holographic dark energy, with generalized entropies

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National Observatory of Athens, Greece

We review spacetime thermodynamics and the gravity-thermodynamics conjecture, showing that the Friedmann equations in any cosmology can arise from the first law of thermodynamics applied at the Universe horizon with the standard Bekenstein-Hawking entropy relation. Additionally, we review the paradigm of holographic dark energy based on standard entropy. Then we present various extensions of the above constructions, based on generalized entropies, such as Kaniadakis, Tsallis, Barrow, power-law and logarithmically-corrected ones.

Anomalous sedimentation of erythrocytes in dilute solutions

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The understanding of the sedimentation properties of asymmetric objects in an inactive liquid is still far from complete. For example, Caflisch and Luke [1] state that the magnitude of the sedimentation velocity fluctuation of individual objects grows with the size of the system. Moreover, sedimentation of asymmetric objects generally involves rotations and translations of the particles due to drag forces. In irregular objects, with a strong tendency to align with the force of gravity, translation velocities emerge that generate advective terms with nonzero divergence [2,3].

We investigate erythrocytes' sedimentation dynamics in different saline solutions, which strongly tend to self-align [4]. We use Differential Dynamic Microscopy (DDM) to obtain the power spectrum, g(q, t), of a sequence of digital images. g(q, t) is directly related to the intermediate scattering function f(q, t), or temporal density-density time correlation function, which represents a measure of the spatial dynamics of the system on length scales of the order q-1 [5]. We report that the sedimentation process is anomalous, whereby a simple exponential does not describe f(q, t). Instead, in our case, f(q, t) is better described by a stretched exponential. To describe this behavior, we propose a Fractional advection-diffusion equation for the fluctuations of object concentration [2, 6], finding that f(q, t) can be described in terms of the generalized Mittag-Leffler function (Figure 1). Moreover, our model allows us to estimate the objects' effective diffusion coefficient and a parameter associated with the erythrocyte's morphology (Figure 2). Our approach allows us to unambiguously identify changes in the morphology of erythrocytes in different saline solutions, thus opening the possibility of being used in the medical diagnosis of blood diseases as sickle cell anemia.

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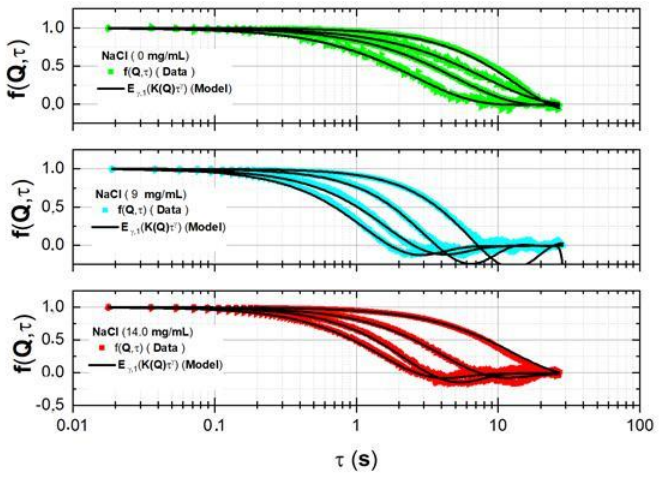

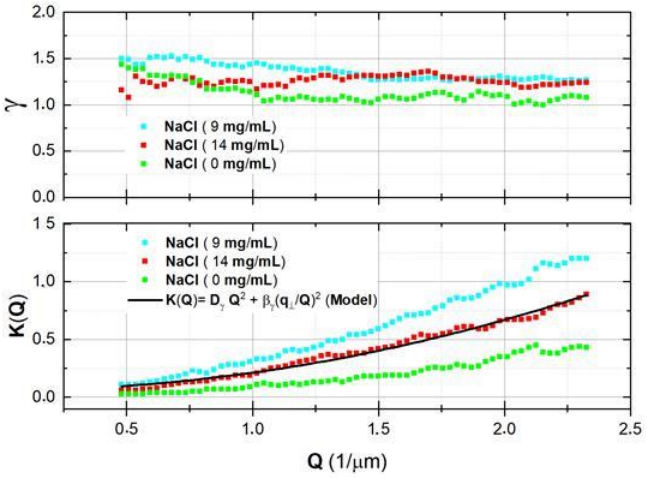

Recent advances on statistical physics of earthquakes by combining natural time analysis and Tsallis non-additive entropy

Nicholas Sarlis[1,2], Efthimios Skordas[1,2], Panayiotis Varotsos[1,2]
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Several advances in the study of earthquakes have been recently achieved [1] by means of natural time analysis introduced in 2001 [2] as well as by Tsallis non-additive entropy [3] in the frame of which kappa distributions arise [4]. Applications are presented for various seismic prone areas, including major earthquakes that occurred in Japan and Mexico. Examples treated are: First, before the Tohoku earthquake of magnitude (M) 9.0 that occurred on 11 March 2011 in Japan, the Tsallis entropic index q exhibits a precursory increase along with the fact that the Lifshitz–Slyozov–Wagner (LSW) theory for phase transitions is applicable. Moreover, upon analyzing the Japanese seismic data in natural time, we find a similar behavior for a precursory change of seismicity and in particular by the fluctuations of the entropy change ΔS of seismicity under time reversal [5]. In addition, the M7.3 foreshock at 11:45 LT on 9 March 2011 of the Tohoku earthquake, leads to a scaling behavior with a characteristic exponent 1/3 that conforms to the LSW theory for phase transitions [6]. Second, upon analyzing the seismicity during the 6-year period 2012–2017 in natural time in the Chiapas region in Mexico, where the M8.2 earthquake occurred on 7 September 2017 (Mexico's largest earthquake in more than a century), we find [7] that almost three months before the M8.2 earthquake, i.e., on 14 June 2017, the complexity measure Λ associated with the fluctuations of the entropy change ΔS under time reversal shows an abrupt increase. On the same date, ΔS has been previously found [8] to exhibit a minimum accompanied by a simultaneous increase of the Tsallis entropic index q.

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Multifractal operators to analyse and simulate complex and intermittent systems, such as weather and climate

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The 2021 Nobel Prize in Physics was awarded jointly to Syukuro Manabe, Klaus Hasselmann and Giorgio Parisi "for revolutionary contributions to our understanding of complex physical systems". Common to these contributions is the complexity and intermittency of our planet's weather and climate [1]. With the key notion of multifractals, intermittency has become understood as resulting from an infinite hierarchy of fractal supports of the singularities of the underlying equations. However, this has been done mainly for scalar fields such as temperature and precipitation (e.g. [2-4]), whereas the velocity field that plays a major role in generating the inhomogeneity of other fields is a vector field. To solve this methodological shortcoming, we were led to introduce multifractal operators acting on vector fields [5,6]. This has revealed the crucial role of the Lie algebra of their generators. A generic case has been pointed out: that whose stochastic generators of these operators are stable Levy vectors on the Clifford algebra. This presentation refines the analysis of their structural robustness and confirms the univsality of their statistics. Hence we push the analysis to those of

their multivariate properties. This presentation also highlights the development of applications of this approach in wind energy and rainfall nowcasting.

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A multifractal analysis of the rugged energy landscape of spin glasses.

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The roughness of the energy landscape of spin glasses is a widely recognised property. However, it seems to be insufficiently investigated, probably because approaching it analytically raises multiple difficulties. Therefore, we have approached it numerically by theoretically relying on the so-called thermodynamic formalism of multifractals and the concept of intermittency, first highlighted by Batchelor (1953) [1]. It has become an essential characteristic, because of the structuring it generates. This research has also made it possible to model and quantify this phenomenon in various fields of physics and other disciplines (Parisi, 2022). In awarding its 2021 prize to Giorgio Parisi, the Nobel Committee for Physics has recognised both the importance of this phenomenon and the work carried out, as highlighted by Schertzer and Nicolis, 2022 [2]. Using the Metropolis-Hastings algorithm, we seek to continuously improve, site by site, the current and local minimum of the energy. At each step, we can analyse the multifractality of the Bolzman coefficient field, which is the thermodynamical analog of the energy flux density of a turbulent cascade. The spectral analysis of this field is preliminary analysis and has confirmed a scale symmetry os the second order singularities. We are currently carrying out a so-called universal multifractal analysis [3], which allows to test scale symmetries of singularities of other orders. It furthermore enables to determine significant physical parameters such as the mean intermittency, more precisely its codimension, and the multifractality parameter α.

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Ensemble dependence of the critical behavior of a system with long range interaction and quenched randomness

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A system with long range interaction (LRI) is usually characterized by a non-extensive energy. While, by properly scaling the Hamiltonian of the system, the energy can become extensive, it may still suffer from nonadditivity. In other words, such a system with volume V and (rescaled) energy E, cannot be divided into two subsystems with energies $E1$, $E2$, where $E = E1 + E2 + o(V)$. A system is expected to have equivalent thermodynamics within the canonical and the microcanonical ensembles, provided that its energy is additive. Conversely, non-additivity of the energy may result in peculiar microcanonical phenomena (that are not observed in the canonical ensemble) such as negative specific heat or the presence of microstates that are inaccessible to the system, leading to breaking of ergodicity. The Blume-Emery-Griffiths (BEG) model with mean-field-like interaction is a simple example of a model with LRI. We employ that model to propose a mechanism which leads to an inequivalence of the two ensembles, without interfering with the interaction content. To be more specific, we consider a hybrid system governed by the BEG Hamiltonian, where the spins are randomly quenched such that some of them are ``pure'' Ising and the others admit the BEG set of states. It is found, by varying the concentration of the Ising spins while keeping the parameters of the Hamiltonian fixed, that the model displays different canonical and microcanonical phase portraits in concentrationtemperature space. Phenomenological indications that these portraits are rich and rather unusual are found.

Are “hubs” in beta-cell clusters an emergent network property or do they exist independently?

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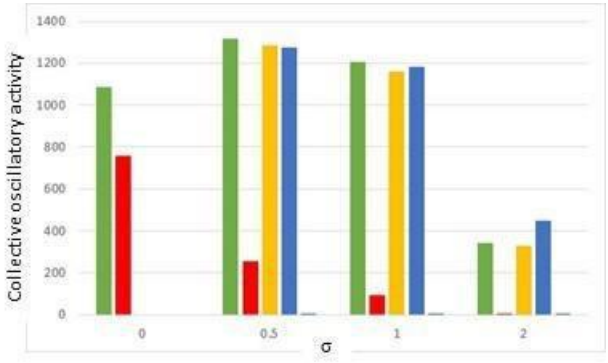
The cell network structure of the pancreatic islets of Langerhans has been the subject of numerous studies. A long-standing dilemma is whether the collective oscillations of beta-cells require the presence of specialized pacemaker cells, named “hubs”, or synchronization occurs through a “democratic” mechanism, where the collective network behavior is a nonlinear average of the properties of its elements. The topic has received so much attention to justify a review focused on the “hub” dilemma [1]. In a recent work [2] we mimicked the architecture of a beta-cell network by a cubic lattice of heterogeneous FitzHugh-Nagumo elements. This topology resembles the experimentally known features of a beta-cell islet. We introduced heterogeneity in the network through a diversified set of external currents Ji, drawn from a Gaussian distribution with standard deviation sigma, which we varied between sigma=0 and sigma=2. Our simulations showed a clear “Diversity-induced resonance”, with a maximum at sigma=0.5, corresponding to a 5% fraction of hubs (the units with Ji corresponding to an intrinsic oscillatory state), in good agreement with experiments [3]. While the above results support the existence of hubs, they do not allow us to decide whether these hubs are an emergent network property or they exist independently of the network. Trying to dig deeper into this, here we present the results of new simulations where we selectively disconnected either hubs or nonhubs from the network. We found rather surprising results, summarized in Fig. 1. We disconnected from the network 1/3 of the hubs, by setting their coupling constant C=0 in the coupled FHN equations. This means the corresponding FHN units had no interaction with other network units. As shown by the red bars in Fig. 1, this caused a dramatic drop of the collective oscillations vs. the reference network configuration, where no elements were disconnected, shown by the green bars. On the other hand, upon disconnecting the

same number of nonhubs, we found virtually no change in oscillatory activity, as shown by the yellow bars. This suggests that hubs do play a crucial role as a distinct subset of network elements. However, if we build a truncated distribution of Ji values, where the central range corresponding to oscillatory FHN states is missing, therefore the network is formed by nonhubs only (without any disconnected units), then the global oscillatory activity is also maintained vs. the reference system (blue bars). Therefore, hubs seem to be crucial for global network oscillations if they are initially present and get disconnected, whereas their complete absence does not prevent the network from being in a resonant oscillatory state. In our contribution we will present additional data and hypotheses to explain this apparent contradiction. Our learnings help shed light on the "hub" dilemma but, at the same time, raise new questions that require more work to be fully understood.



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Nucleation kinetics in supercooled ZnSe: Computer simulation data corroborate the validity of the Classical Nucleation Theory

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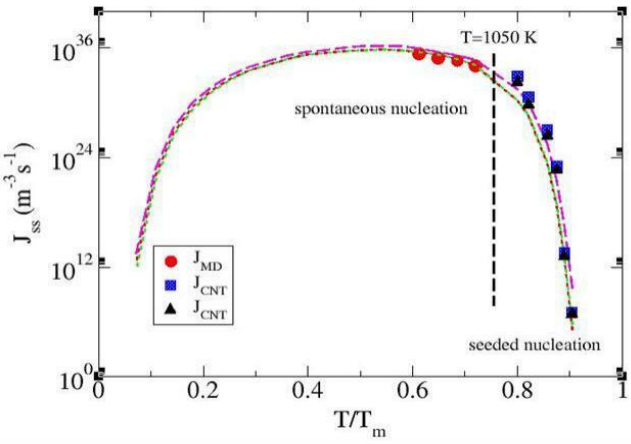
Understanding and controlling the liquid to crystal transformation is a central topic for numerous natural phenomena and technological applications. The first step of crystallization is the birth of critical nuclei. Their size, structure and rate at which critical nuclei appear and grow are fundamental parameters for understanding and controlling crystallization. Although nucleation rates can be measured experimentally in a few systems due to the very small nucleus size (nm) and either a too short or too long lifetime, it is extremely difficult to understand and describe the microscopic mechanism of nucleation, which remains elusive. To this end, computer simulation techniques provide, in principle, a suitable tool to dig deeper into this process. At least three main methods are available to obtain crystal nucleation rates via molecular dynamics simulation: 1) the mean lifetime method, 2) enhanced-sampling methods and 3) the seeding method. The Classical Nucleation Theory (CNT) is one of the most well-known models to describe the nucleation process. This theory assumes that the formation of crystal nuclei takes place as a result of thermal fluctuations in a supercooled liquid (SCL). If an embryo overcomes a certain threshold size, it becomes a critical nucleus that spontaneously grows until it meets other growing crystals and the liquid solidifies. According to this theory, the interplay between the supercooled liquid/nucleus interfacial free energy, γ, and the difference between the chemical potentials of the crystal phase and the supercooled liquid describes the thermodynamics of crystal nucleation. The third key property is the effective diffusion coefficient, which controls the atomic transport rate at the liquid/crystal interface. The independent determination of these three quantities allows CNT calculations and comparison with experimentally determined or simulated nucleation rates. Owing to the scarcity of direct measurements of these

properties, often questioned the validity and accuracy of the CNT. In this work, we were able to deeply supercool Zinc Selenide (ZnSe), and determine spontaneous homogeneous steady-state nucleation rates by molecular dynamics simulations (MD) using the mean lifetime method. At moderate supercoolings, where the nucleation rates are much smaller, we used the seeding method to compute the nucleation rates by the classical nucleation theory formalism, , without any fitting parameter, using the physical properties obtained by MD simulations: the melting temperature, density, melting enthalpy, diffusion coefficient, and the critical nucleus size, combined with two expressions for the thermodynamic driving force. The values of γ calculated by the CNT expression using the MD simulation data, via both the seeding method and the mean lifetime method at moderate and deep supercoolings show a weak temperature dependence, which is in line with the Diffuse Interface Theory. The extrapolated values of γ, from the spontaneous nucleation regime to the seeding nucleation region cover the range of values of γ calculated via the seeding method and the CNT formalism. Finally, the extrapolated from moderate supercoolings to deep supercoolings are in good agreement with the . These results confirm the validity of the CNT.



Phenomenological implications of nonlocal electrodynamics

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In recent years many phenomena, ranging from the strong CP problem, particle mixing and oscillations, matter-antimatter asymmetry, to the nature of dark matter and dark energy, as well as the lack of a quantum theory of gravity, have lead to the development of theories beyond the Standard Model (SM) of particles. An example of a phenomenon which cannot be described within the SM may be represented by the muon magnetic moment anomaly. The successful prediction of the magnetic moment of the charged leptons is one of the most celebrated accomplishments in Quantum Field Theory. The Dirac theory predicts a g-factor $gDirac$ = 2, whereas the radiative corrections shift the actual value slightly above 2. This allows one to define the anomalous magnetic moment α as the difference between the quantum field theoretic prediction and the Dirac value $\alpha = g - 2/2$. For the electron, the anomalous moment $\alpha e = (g - 2)e/2$ computed from Quantum Electrodynamics matches with the experimental value up to a striking precision of 10−12 . However recently, new experimental results from the Muon g-2 collaboration have confirmed a discrepancy between the observed value of the muon anomalous moment $\alpha\mu$ and the standard model prediction. The combined data from the Brookhaven and the Fermilab Muon g-2 experiments lead to a 4.2σ discrepancy $\Delta\ \alpha\mu = \alpha\mu,EXP - \alpha\mu,SM$ = (251 ± 59) × 10−11. The discrepancy has fueled the discussion upon the need for new physics, since, if confirmed, it would be a clear indication of physics beyond the SM. Many speculations about the origin of this discrepancy have been made in the last years. On the other hand, nonlocal theories have proliferated since the seminal work of Yukawa. Nonlocal theories of gravity have been developed as an extension of general relativity. Here nonlocal (i.e. non-polynomial) form factors in the gravitational action can help to solve the problem of ghosts as well as to improve the ultraviolet behavior of the quantized theory. In particle physics, nonlocal theories are

closely tied to string theories, as well as noncommutative field theories. Recently, a nonlocal extension of the standard model has been proposed. In this work we speculate about the possibility that the g−2 discrepancy for the muon be induced by a string-field-theory inspired nonlocal theory. We compute the lowest order nonlocal correction to the anomalous magnetic moment αNL, and we find that it depends in a simple fashion on the nonlocality scale Mf and the fermion mass mf as $\alpha NL \propto mf\ 2\ /Mf\ 2$. We then compare the known experimental anomaly $\Delta\ \alpha\mu$ with the nonlocal prediction αμ,NL in order to find a lower bound on the nonlocality scale. Our results indicate that the nonlocal theory might explain the discrepancy observed in the muon moment, and then αμ,NL might represent an important contribution to Δαμ . Moreover the nonlocal contribution provides a very high discrepancy in the tau moment. In addition we discuss some preliminary results about the phenomenological impact of nonlocality in atomic spectra.

Detecting the ultra low dimensionality of real networks

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Reducing dimension redundancy to find simplifying patterns in high-dimensional datasets and complex networks has become a major endeavor in many scientific fields. However, detecting the dimensionality of their latent space is challenging but necessary to generate efficient embeddings to be used in a multitude of downstream tasks. We have introduced models and methods to infer the dimensionality of real networks based on the ability of hyperbolic geometry to capture their complex connectivity. Our analysis has revealed ultra low dimensionality as an ubiquitous feature, and unexpected regularities across different domains, including extremely low dimensionality in tissue-specific biomolecular networks, close-to-three-dimensional brain connectomes, and slightly higher dimensionality in social networks and the Internet.

Renormalization of complex networks

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The renormalization group is a useful tool for studying physical systems at various length scales. However, applying this approach to complex networks can be challenging due to the small-world property, which introduces correlations between different scales. To overcome this challenge, the network geometry paradigm provides a powerful framework. Specifically, we have developed a renormalization group technique that coarse-grains and rescales geometric network representations to unfold them into a multiscale shell of layers. Our analysis revealed that real networks are self-similar under the renormalization transformation, implying that short and long-range connections follow the same connectivity rule across length scales. Moreover, this result explains the self-similarity observed in empirical multiscale reconstructions of human brain connectomes. Additionally, the growth over time of some real networks also exhibits self-similarity, suggesting that their evolution can be modeled using a reverse renormalization process. The practical applications of self-similar multiscale unfolding of real networks include producing scaled (up and down) replicas that can be used in a variety of downstream tasks, such as the study of processes where network size is relevant.

Bak-Tang-Wiesenfeld sandpile as the mechanism that generates the 1/x power-law and the 1/f spectrum

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Bak, Tang, and Wiesenfeld introduced the phenomenon of self-organized criticality with a sandpile model and positioned their model as the key to understanding the flicker noise. However, the BTW sandpile and its modifications are primarily known for the power-laws describing state variables, where a few power-law exponents characterize a great many isotropic model modifications defined on the square lattice. The BTW sandpile itself generates the power-law size-frequency relationship with the exponent equaled to 1.20, and the models with the exponent located closer to 1 are not known. The spectrum of basic quantities in sandpiles exhibits a constant at low frequencies, the $1/x^2$ decay at high frequencies, and, for some models, the 1/x part in-between. This spectrum structure does not elucidate specific features underlying many processes including, for example, the superposition of pulses. Therefore, researchers created additional constructions to produce the "pure" 1/f spectrum with sandpiles.

In this talk, I'll show that the departure from the original BTW sandpile was premature, and the reciprocal function in both size-frequency distribution and spectrum is attained with the BTW mechanism. The 1/x size-frequency relationship is obtained with clustering of events in space and time in the BTW sandpile. The precise definition of the clustering, affecting the cluster volume, gives the tool to control the exponent of the size-frequency relationship. This clustering allows to fill in the range of exponents from 1.20 to 1 and, possibly, to values being smaller than 1.

In the case of spectrum, I'll focus on the dynamics of the average system stress in contrast to the sequence of event sizes, which is typically analyzed. The spectrum of the average system stress indeed exhibits a constant at low frequencies that turns to 1/x at moderate frequencies and finally to the $1/x^2$ decay at high frequencies. However in the thermodynamic limit, the role of the parts precisely matches the expectations of researchers. The 1/f part extends over all time scales that represent the dynamics at the critical level of stress. The 1/f spectrum transits to a constant at the time scales that correspond to extremely rare drops of the system to the subcritical state. Finally, the $1/x^2$ part is insignificant because it covers the time scales up to the system size, whereas only the scales related to the system area "survive" in the thermodynamic limit. I also note that this insignificant spectrum part is associated with the power-law segment of the size-frequency relationship, whereas the 1/x spectrum is associated with the tail of the event distribution.

Effect of anisotropy on critical temperature estimation using machine learning

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We check how aspect ratio and interaction anisotropy can affect the accuracy of the critical temperature estimate using a neural network. We study two cases of the Ising model. We have trained a model for the classification of paramagnetic and ferromagnetic phases, which makes it possible to predict the phase to which the test sample belongs [1]. Supervised learning was carried out for the Ising model on a square lattice with the same couplings . There are two sets of testing tasks. We first test the classical Onsager case with different horizontal and vertical couplings on a square lattice [2]. Second, we test Ising model on a square lattice with couplings equipped with couplings in one of the diagonal directions. The critical temperature is known for both cases [2, 3].

The first result is that the bond aspect ratio / does not affect the accuracy of the temperature estimate for the Onsager case. The second result is that the anisotropy caused by the diagonal ratio / leads to a systematic deviation of the calculated critical temperature from a well-known critical

temperature. It is well known that anisotropy changes the value of the Binder cumulant [4] and thus determines the limitations of universality [5]. Instead, we demonstrate the limitations of knowledge transfer in machine learning due to anisotropy. This result is very practical - if randomly tested samples contain anisotropy, the trained neural network will predict the wrong critical temperature of the sample. However, we have a good message - the extracted correlation length critical exponent is still reliable and does not seem to be biased by the anisotropy parameter.

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The simulations were done using the computational resources of HPC facilities at HSE University.

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Non-thermal broadening of IRIS Fe XXI line caused by turbulent plasma flows in the magnetic reconnection region during solar eruptions

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Magnetic reconnection is the key mechanism for energy release in solar eruptions, where the high-temperature emission is the primary diagnostic for investigating plasma properties during the reconnection process. Non-thermal broadening of high-temperature lines has been observed in both the reconnection current sheet (CS) and flare loop-top regions by (E)UV spectrometers, but its origin remains unclear. In this study, we used a three-dimensional magnetohydrodynamic (MHD) simulation to model magnetic reconnection in solar flares and to reveal highly dynamic plasma flows in the reconnection regions. We calculated synthetic profiles of the Fe XXI 1354 Å line observed by the Interface Region Imaging Spectrograph (IRIS) spacecraft using the MHD results. Our model shows that turbulent bulk plasma flows in the CS and flare loop-top regions are responsible for the non-thermal broadening of the Fe XXI emission line, with modeled non-thermal velocity ranging from tens of km/s to over two hundred km/s, consistent with IRIS observations. Simulated two-dimensional spectral line maps around the reconnection region also reveal highly dynamic downward flow structures where high non-thermal velocity is large, which is also consistent with the observations.

Quantum computer health check via quantum random number generation

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All computing devices, including quantum computers, must exhibit that for a given input, an output is produced in accordance with the program. The outputs generated by quantum computers that fulfill these requirements are not temporally correlated, however. In a quantumcomputing device comprising solid-state qubits such as superconducting qubits, any operation to rest the qubits to their initial state faces a practical problem. On the implementation of the scalable quantum computers, the health check (or stability check) algorithms are needed. We propose that the quantum random number generation is one of the candidates of the health check algorithms in any quantum computing devices.

A key observable that guarantees linear thermalization of all macroscopic observables

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It has been attracting much attention to determine whether a given quantum many-body system thermalizes or not. However, such studies have usually examined thermalization of only a small number of observables, and it was unclear whether other observables thermalize. In this talk, we investigate 'linear thermalization,' which is many-body thermalization against a small change of a physical parameter of the system, and show that there exists a key observable whose linear thermalization guarantees linear thermalization of all macroscopic observables. Suppose that an isolated quantum many-body system is prepared in an equilibrium state, and then a parameter f of the Hamiltonian is changed by a small amount Δ f, which induces the unitary time evolution. We say linear thermalization occurs for an additive (macroscopic) observable when its expectation value and fluctuation after a long time are consistent with thermodynamics up to the linear order in Δ f. We find that the additive observable B that is conjugate to f is the key observable for linear thermalization: If the long time average of the expectation value of B coincides with its equilibrium value predicted by thermodynamics up to O(Δ f), so do all additive observables. In addition, we find that, under a reasonable condition on the energy eigenvalues, the time fluctuations of the expectation values of all additive observables are macroscopically negligible up to O(Δ f). We also find that, under a reasonable condition that the fluctuations of additive observables in the initial state are sufficiently small, they remain so up to O(Δ f), for all additive observables. Thus linear thermalization of B guarantees linear thermalization of all additive observables. Furthermore we consider the dynamics induced by small changes of other parameters, which are not conjugate to B. We find that linear thermalization of B occurs against the change of any other parameter if it occurs against the change of the conjugate parameter f. Moreover, we investigate the generalized susceptibilities for cross responses, and their consistency between quantum mechanics and thermodynamics. We demonstrate the main results numerically in nonintegrable and integrable spin models. Our results will dramatically reduce the costs of experiments and theoretical calculations of linear thermalization and cross responses because testing them for a single key observable against the change of its conjugate parameter gives much information about those for all additive observables and about those against the changes of any other parameters. The time scale of linear thermalization will be discussed in Chiba's presentation of this conference.

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Bekenstein bound from the Pauli principle

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Assuming that the degrees of freedom of a black hole are finite in number and of fermionic nature, we naturally obtain, within a second-quantized toy model of the evaporation, that the Bekenstein bound is a consequence of the Pauli exclusion principle for these fundamental degrees of freedom. We show that entanglement, Bekenstein and thermodynamic entropies of the black hole all stem from the same approach, based on the entropy operator whose structure is the one typical of Takahashi and Umezawa's Thermofield Dynamics. We then evaluate the von Neumann black hole--environment entropy and noticeably obtain a Page-like evolution. We finally show that this is a consequence of a duality between our model and a quantum dissipative-like fermionic system.

Interplay between algorithmic bias and external information effects in opinion dynamics with bounded confidence

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Opinion formation in society is a complex process with multiple contributing mechanisms. At the base there are individual traits, peer interactions and interaction with mass media. In recent years, peer and mass media interactions have changed in nature, as we increasingly consume information through social networks. Due to their business oriented nature, social network platforms embed recommender systems to enhance user experience and maximise platform usage. These propose to users information that they are more likely to enjoy, which also means that they are more likely to agree with or approve the messages shown, a mechanism known as “algorithmic bias”. This may result in the formation of information bubbles, and appearance of fragmentation and polarisation of the public discourse. From the point of view of opinion dynamics, algorithmic bias in social networks have an important effect on two mechanisms: peer interaction and mass media consumption. In previous work [1] we have introduced a bounded confidence model in which algorithmic bias acts on peer interaction, by modifying the probability of selecting a peer to discuss with, changing from an uniform distribution to a distribution that depends on the distance between the agent’s opinions. We showed that this mechanism can increase fragmentation and polarisation, and slow down the dynamics. This applies both to complete social networks and to complex network topologies, where dynamics are further slowed down and fragmentation enhanced [2]. In this work we extend the previous model by introducing mass media (external) effects. The agents are endowed with a probability to interact with mass media, and they select among the available media using algorithmic bias, which makes it more probable to consume media that is closest to one’s opinion. We study several settings, ranging from one polarised or moderate external media to two and three media settings. Our results show that aggressive media campaigns (extreme message or higher probability to interact with a moderate message) tend to cause polarisation, agreeing with previous literature. The effect is enhanced in general by algorithmic bias. There are however settings where algorithmic bias appears to have a protective effect against polarisation and fragmentation: when the media landscape contains both polarised and moderate media outlets and the population is open minded (confidence bound is large). In this case, higher algorithmic bias impedes agents to interact with extremist media, facilitating consensus on the moderate media, albeit with much slower dynamics.

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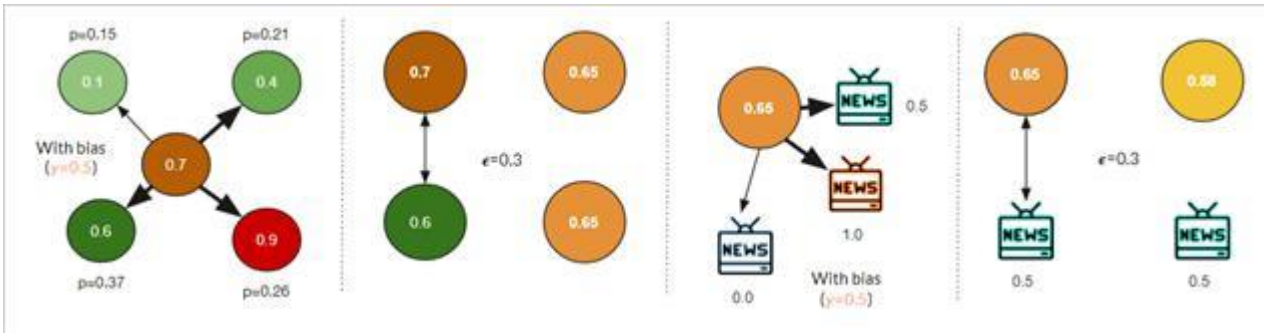

Numerical investigation of spatiotemporal chaos in nonlinear lattice models

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We discuss various numerical approaches for studying the chaotic dynamics of multidimensional Hamiltonian systems, focusing our analysis on the chaotic evolution of initially localized energy excitations in the disordered Klein-Gordon (DKG) oscillator chain in one spatial dimension. The system's linear modes are exponentially localized by disorder and consequently Anderson localization [1] is observed in the absence of nonlinearity. On the other hand, nonlinear interactions result to the destruction of the initial energy localization, leading to the eventual subdiffusive spreading of wave packets in two different dynamical regimes (the so-called 'weak' and 'strong chaos' spreading regimes), which are characterized by particular power law increases of the wave packet's second moment and participation number [2-6]. Quantifying the strength of chaos through the computation of the maximum Lyapunov exponent (MLE, see for example [7] and references therein), we observe that the index exhibits power law decays, with different exponents for the weak and strong chaos regimes, whose values are distinct from -1 seen in the case of regular motion [8-10]. The spatiotemporal evolution of the coordinates' distribution of the deviation vector used to compute the MLE (the so-called deviation vector distribution – DVD) reveals that chaos is spreading through the random oscillation of localized chaotic hot spots in the excited part of the wave packet [8-10]. Furthermore, the implementation of the SALI/GALI2 chaos indicator [11-13] permits the efficient discrimination between localized and spreading chaos, with the former dominating the dynamics for lower energy values, for which the system is approaching its linear limit [14]. In addition, by computing the time variation of the fundamental frequencies of the motion of each oscillator in the lattice, i.e. the so-called frequency map analysis (FMA) technique [15-17], we reveal several characteristics of the dynamics for both the weak and strong chaos regimes [18], related to the location of highly chaotic oscillators and the propagation of chaos.

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Exponential increase of transition rates in metastable systems driven by non-Gaussian noise

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Noise-induced escape from metastable states governs a plethora of transition phenomena in physics, chemistry, and biology. While the escape problem in the presence of thermal Gaussian noise has been well understood since the seminal works of Arrhenius and Kramers, many systems, in particular living ones, are effectively driven by non-Gaussian noise for which the conventional theory does not apply. Here we present a theoretical framework based on path integrals that allows the calculation of both escape rates and optimal escape paths for a generic class of non-Gaussian noises. We find that non-Gaussian noise always leads to more

efficient escape and can enhance escape rates by many orders of magnitude compared with thermal noise, highlighting that away from equilibrium escape rates cannot be reliably modelled based on the traditional Arrhenius–Kramers result. Our analysis also identifies a new universality class of non-Gaussian noises, for which escape paths are dominated by large jumps. Our results demonstrate that non-Gaussian noise can induce qualitatively very different escape behaviours. The instantons (optimal escape paths) with jump sections indicate an escape strategy that is fundamentally different from the one we find in thermal equilibrium systems: instead of completing the entire escape using a rare sequence of small fluctuations, the system prefers to wait for a single rare fluctuation that is large enough to carry it across the steepest section of the potential barrier. Remarkably, the prefactor of the escape rate highlights the existence of two universality classes associated with these two types of escape: the Kramers prefactor, which also applies to non-Gaussian noise in the parameter range where the escape path is smooth; and a distinct prefactor for the jump case. The theoretical analysis shows that the exponential speed-up of transition rates can persist and in fact become more pronounced even in the regime where non-Gaussian noise kicks are so rare in relative terms that their contribution to the noise intensity is vanishingly small. It might be possible to exploit this effect to optimize switching behaviour in artificial systems driven by non-Gaussian noise such as colloids interacting with an active microbial heat bath on which thermodynamic cycles can be imposed; indeed, recent experiments have shown that non-Gaussian noise can be used to tune the performance of a colloidal Stirling engine by shifting the operating speed at which power is maximum. Time permitting we will discuss applications to escape problems for highly persistent active matter, as well as extensions to non-Gaussian noise with memory.

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Learn your entropy from informative data: an axiom ensuring the consistent identification of generalized entropies

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Shannon entropy, a cornerstone of information theory, statistical physics and inference methods, is uniquely identified by the Shannon-Khinchin or Shore-Johnson axioms. Generalizations of Shannon entropy, motivated by the study of non-extensive or non-ergodic systems, relax some of these axioms and lead to entropy families indexed by certain 'entropic' parameters. In general, the selection of these parameters requires pre-knowledge of the system or encounters inconsistencies. Here we introduce a simple axiom for any entropy family: namely, that no entropic parameter can be inferred from a completely uninformative (uniform) probability distribution. When applied to the Uffink-Jizba-Korbel and Hanel-Thurner entropies, the axiom selects only Rényi entropy as viable. It also extends consistency with the Maximum Likelihood principle, which can then be generalized to estimate the entropic parameter purely from data, as we confirm numerically. Remarkably, in a generalized maximum-entropy framework the axiom implies that the maximized log-likelihood always equals minus Shannon entropy, even if the inferred probability distribution maximizes a generalized entropy and not Shannon's, solving a series of problems encountered in previous approaches

Bringing together two paradigms of non-equilibrium: Driven dynamics of aging systems

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Non-equilibrium behaviour can be broadly split into two categories. The first is aging (see e.g. [1]), where a system can in principle reach an equilibrium state but its slow dynamics leads to extremely long transients during which the properties of the system depend on its age since preparation. In the second category are driven systems, whose dynamics breaks detailed balance leading to non-equilibrium steady states. An attractive way of constructing descriptions of such driven systems is based on maximum entropy arguments in trajectory space, leading to so-called biased trajectory ensembles (see e.g. [2]). We investigate how these two non-equilibrium scenarios interact, by studying the bias-driven dynamics of two simple models that are inspired by the physics of glasses and exhibit aging at low temperatures. The analysis allows one to reveal dynamical phase transitions, which are related to unexpected qualitative differences in the robustness of aging to additional driving. Specifically, we investigate how the interplay between aging and driving by trajectory biasing works in two mean field models of glassy dynamics, widely known as trap models [3,4]. We show that similarly to kinetically constrained models, the equilibrium state of the unbiased system above the glass transition temperature is located at the coexistence of two dynamical phases (active and inactive). In contrast, below this temperature, we find two different nonequilibrium scenarios: energetic (or activated) aging that is destroyed by any dynamical bias towards low activity, which we call "fragile aging", with the system freezing after a finite number of state transitions; and entropic aging that is stable against the existence of such a dynamical bias, which we refer to as "robust aging". We conjecture that these categories have broader relevance as universality classes for aging dynamics in glassy systems. Time permitting, extensions to dynamics on glassy networks with sparse connectivity will be discussed, where new dynamical phases appear, related to localisation transitions in the leading eigenvectors of the master operators.

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Universal dipole correlation in homogeneous bulk and interfacial water

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Understanding electrostatic interactions near surfaces and interfaces is of critical importance in various fields of science. The interplay of electrostatic interactions through the symmetry-breaking boundaries plays the major role in thermodynamic and dynamic behavior of the system. Recent advances in surface specific spectroscopic techniques have greatly enhanced our understanding on these interfacial phenomena, although precise molecular understanding of these complex systems is still challenging. Strong confinement induced by two of such dielectric interfaces provide unique environment for novel materials synthesis and manipulation. This study investigates the anomalous behavior observed in strongly confined water, specifically the significant reduction in its dielectric constant that has been confirmed through experimental and simulation studies. Using molecular dynamics simulations that fully incorporate the dielectric response of confining walls, we aimed to identify the molecular mechanisms governing the dielectric reduction. Our simulations revealed that the reduction in dielectric constant occurs independently of the electronic polarization at the surface, which contradicts previously proposed mechanisms. We also found that the local fluctuation in the dipole of a water slab does not vary significantly from the locally aligned interfacial region to the homogeneous bulk region. Instead, we discovered that a small, positive

dipolar correlation between a set of water slabs plays a critical role in determining the total dielectric response of the confined water. We found that the long-range correlation is independent of the confinement size and the interfacial structure, resulting in a linear correspondence between the confinement length and the total dielectric constant in the direction orthogonal to the confining wall surface. Furthermore, our simulation suggests that allowing capillary fluctuation on the interfacial water structure mitigates the dielectric reduction. Our findings provide novel insights into the nature of the observed anomalous behavior and have important implications for controlling and designing interfacial electrochemical systems.

Cross-diffusion-induced instability on networks

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The concept of Turing instability, namely that diffusion can destabilize the uniform steady state, is well known either in the context of partial differential equations (PDEs) or in a network of dynamical systems. Recently, reaction-diffusion equations with cross-diffusion terms have been investigated, showing an analogous effect known as cross-diffusion-induced instability [1]. In [2], we extend this concept to a network of dynamical systems, showing that the spectrum of the graph Laplacian plays the role of the Laplace operator in reaction-diffusion equations and determines the instability appearance. In particular, we consider a network model for competing species, coming from the PDEs context. The influence of the topological structure on the cross-diffusion induced instability is highlighted, considering different topologies, both regular rings or lattices, but also small-world and Erdős-Rényi networks.

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A master stability function for cluster synchronization in networks with adaptation

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Networks of neurons display many features that are sometimes hard to incorporate in dynamical models and numerical simulations. One of these is the presence of adaptation or synaptic plasticity, i.e., a mechanism by which the strength of a connection increases or decreases based on the activity of the neurons at its endpoints. Another one is the emergence of cluster synchronization, which is an intermediate state between complete synchronization (state of highest order) and lack of synchronization (state of lowest order.) We consider a general dynamical model that incorporates adaptation and allows for the emergence of cluster synchronization and develop a dimensionality reduction approach to study the stability of the emerging cluster synchronous states. We show how the method can be used as an effective replacement for time and memory intensive numerical simulations.

Adaptation and cluster synchronization in networks of neurons: a dimensionality reduction approach to the study of stability of the synchronous solution

Francesco Sorrentino
University Of New Mexico, Albuquerque, NM, United States

Networks of neurons display many features that are sometimes hard to incorporate in dynamical models and numerical simulations. One of these is the presence of adaptation or synaptic plasticity, i.e., a mechanism by which the strength of a connection ('synspsis') increases or decreases based on the activity of the neurons at its endpoints. Another one is the emergence of cluster synchronization, which is an intermediate state between complete synchronization (state of highest order) and lack of synchronization (state of lowest order.) We consider a general dynamical model that incorporates adaptation and allows for the emergence of cluster synchronization and develop a dimensionality reduction approach to study the stability of the emerging cluster synchronous states. We show how the method can be used as an effective replacement for time and memory intensive numerical simulations.

The effect of strong electric field in case of acetonitrile and water mixtures

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This study reveals the hydrogen bond network as a key tool analysis to study the formation of water in nano-domains. The linear response of the system's polarization via the external electric field was analyzed for the binary mixture of water and acetonitrile. The study closes with some remarks on the non linear effects reviewed by the structural deformation between the acetonitrile molecules in the case of high external electric fields.

Non-equilibrium dynamics of open systems, fluctuation-dissipation theorems and quantum transport theory

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The talk will address the problem of a description of electron dynamics of open systems when initial conditions, quantum interference and decoherence processes play important roles. The aim is to understand the full time development of many-body open systems out of equilibrium from its initial state over its transient dynamics to its very long time (if e.g. steady state exists) dynamics.

First, the non-equilibrium Fluctuation-Dissipation Theorem is formulated within the Non-Equilibrium Green Function (NEGF) formalism [1]. The relation of this theorem to a simplified kinetic theory of non-equilibrium dynamics will be addressed. The components of the NEGF retain some inner interconnection which may be termed the fluctuation-dissipation structure out of equilibrium; there is an exact formulation in terms of reconstruction equations generating the correlation components in terms of the propagators and the non-equilibrium distribution function either of particles, or, under restrictive conditions, of the non-equilibrium quasi-particles. These equations can lead to a Non-Markovian Generalized Master equation or even to a Markovian master equation without memory. To deal with the task to find out a proper description of the dynamics of open systems and to test the used approximations, we consider a simple structure which represents well open quantum systems: a molecular bridge between two leads [1, 2].

Second, we will discuss the transport in neural networks. We have developed an approach to the transfer of electrical signals via neural network [3, 4] that is alternative to the standard theories of Hodgkin, Huxley and Rall. Our theory, which is based on generalized Ohm-Kirchhoff's law and a modified model of submarine cable, enables one to extend the description into the microphysical domain. In contrast to the standard theory, but in agreement with the experimental evidence, the transfer of the signal front has a character of diffusion with diffusion constant DE. It has been further shown that this process, actually the forming of a current carrying sphondyloid, is physically realized by quantum diffusion of Na+ and K+ cations in axoplasm with diffusion constant $D\Omega \ll DE$. According to our approach $DQ \rightarrow \hbar / 2M$, where M is ion mass and ħ Planck's constant; a signal transfer through nerves is thus essentially a quantum process.

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Periodic potential can enormously boost free particle transport induced by active fluctuations

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Active fluctuations are detected in a growing number of systems due to self-propulsion mechanisms or collisions with an active environment. They drive the system far from equilibrium and can induce phenomena that are forbidden at equilibrium states by, e.g., fluctuation-dissipation relations and detailed balance symmetry. Understanding their role in living matter is emerging as a challenge for physics. Here we demonstrate a paradoxical effect in which a free-particle transport induced by active fluctuations can be boosted by many orders of magnitude when the particle is additionally subjected to a periodic potential. In contrast, within the realm of only thermal fluctuations, the velocity of a free particle exposed to a bias is reduced when the periodic potential is switched on. The presented mechanism is significant for understanding nonequilibrium environments such as living cells, where it can explain from a fundamental point of view why spatially periodic structures known as microtubules are necessary to generate impressively effective intracellular transport.

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Combining topological data analysis with equation-free methods to analyse macroscopic dynamics of a complex network neuronal model

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We combine topological data analysis with equation-free methods to identify and study the macroscopic dynamics of a complex network neuronal model. Initially, we project the network dynamics of activated neurons on a circle S^1. Then, the filtration process of witness simplicial complexes [1] is applied to reduce the dimensionality of the system dramatically and to compute the minimum filtration radius where the Betti one number appears [1-3]. The minimal filtration radius is related to the density of activated nodes in the network. Using simulating annealing [4] as a minimising procedure, a method to express the state of the network as a function of minimal filtration value is defined. Furthermore, using the equation-free framework [5-7], we identify the macroscopic network dynamics as a function of the minimal filtration radius of the underlying persistence topology. Additionally, we perform a numerical bifurcation and stability analysis of the macroscopic network dynamics. To our knowledge, this is the first time where such a type of analysis has been made, identifying the network behaviour in terms of topological properties of dimensionally reduced data that the network model produces.

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Rényi entropy of quantum anharmonic chain at non-zero temperature

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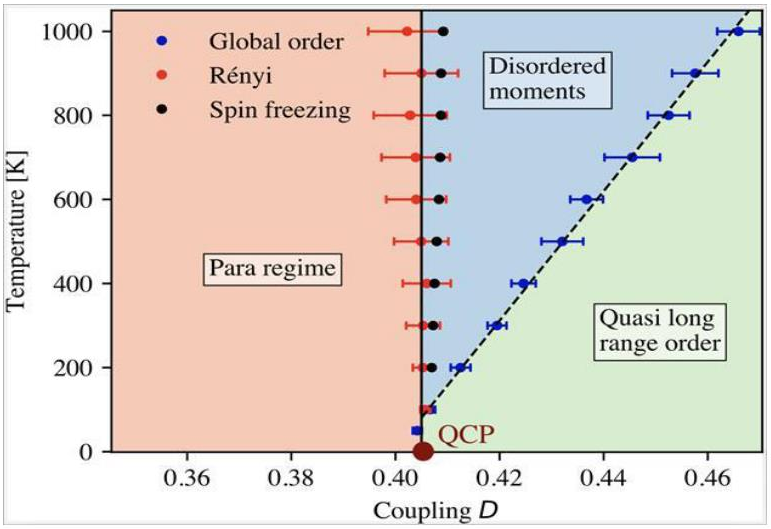
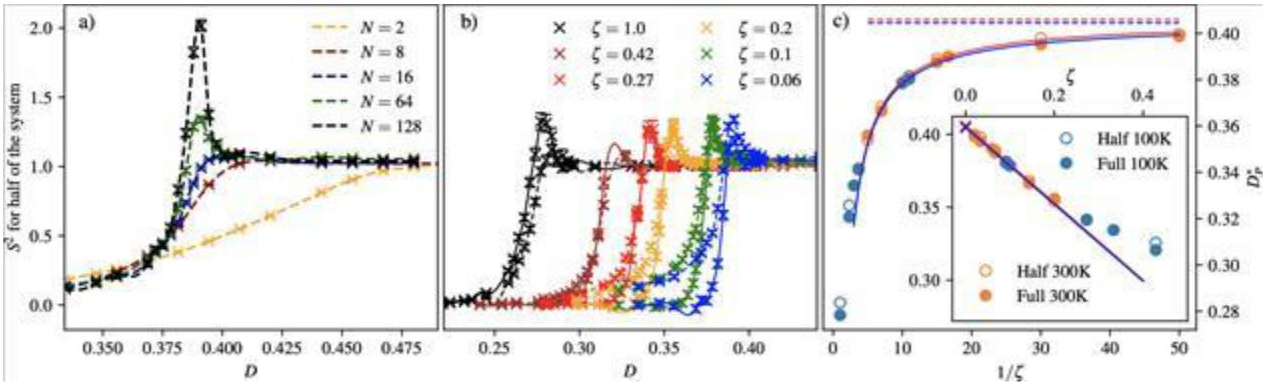
The interplay of quantum and classical fluctuations in the vicinity of a quantum critical point (QCP) gives rise to various regimes or phases with distinct quantum character. In this work, we show that the Rényi entropy is a precious tool to characterize the phase diagram of critical systems not only around the QCP but also away from it, thanks to its capability to detect the emergence of local order at finite temperature. For an efficient evaluation of the Rényi entropy, we introduce a new algorithm based on a path integral Langevin dynamics combined with a previously proposed thermodynamic integration method built on regularized paths. We apply this framework to study the critical behavior of a linear chain of anharmonic oscillators, a particular realization of the ϕ^4 model. We fully resolved its phase diagram, as a function of both temperature and interaction strength. At finite temperature, we find a sequence of three regimes - para, disordered and quasi long-range ordered -, met as the interaction is increased. The Rényi entropy divergence coincides with the crossover between the para and disordered regime, which shows no temperature dependence. The occurrence of quasi long-range order, on the other hand, is temperature dependent. The two crossover lines merge in proximity of the QCP, at zero temperature, where the Rényi entropy is sharply peaked. Via its subsystem-size scaling, we confirm that the transition belongs to the two-dimensional Ising universality class. This phenomenology is expected to happen in all ϕ^4-like systems, as well as in the elusive water ice transition across phases VII, VIII and X.





Polytropic behavior in the compressed solar wind

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The polytropic process in a thermodynamically closed system is a quasi-static change of state in which the specific heat is held constant (e.g., Ref. [1]). Pressure and mass density are related as P / ρ $\alpha = constant$. Here, $\alpha = (cp - c)/(cv - c)$, cp and cv are the specific heats at constant pressure and volume, and $c = dQ/dT$, where Q is the heat and T is the temperature. α is then an indicator for the type of thermodynamic processes taking place within the closed system. For instance, α = 0 for isobaric process (i.e., pressure remains constant), α = 1 for isothermal process (i.e., temperature remains constant) and $\alpha = \gamma$ for the adiabatic process (i.e., entropy remains constant), where $\gamma = cp/cv$. For $\alpha > 1$, as the gas in the system expands or compresses, the temperature correspondingly decreases or increases. For $\alpha < \gamma$, heat must be supplied to the system for the plasma to expand. Recent results obtained by examining the polytropic process in the substructures of interplanetary coronal mass ejections (ICMEs; [2]) showed that the thermodynamics within ICME sheath regions take the longest time to recover towards the pre-ICME quasi-adiabatic state. On the other hand, the system recovers faster in the quieter ejecta region. The authors interpreted these results as due to enhanced turbulent rates in the sheath region which heats the plasma. Using the same spacecraft data (Wind SWE, [3]; Wind MFI, [4]), we expand their analysis to include compressions from stream interaction regions and corotating interaction regions. In particular, we investigate the polytropic behavior inside and around compression regions and compare with that found in ICME substructures.

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Ising-Heisenberg diamond-decorated square lattice in a magnetic field: exact results for phase transitions and critical points

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The thermal phase transitions of a spin-1/2 Ising-Heisenberg model on the diamond-decorated square lattice in a magnetic field are investigated by making use of a decoration-iteration mapping transformation and classical Monte Carlo simulations. A generalized decoration-iteration transformation exactly maps this classical-quantum lattice-statistical model onto an effective classical spin-1/2 Ising model on the square lattice with temperature-dependent effective nearest-neighbor interaction and magnetic field. The effective magnetic field vanishes along a ground-state phase boundary of the original classicalquantum model, separating a classical ferrimagnetic phase and a quantum monomer-dimer phase. At finite temperatures this phase boundary gives rise to an exactly solvable surface of discontinuous (firstorder) phase transitions, which terminates in a line of Ising critical points. The existence of discontinuous reentrant phase transitions emergent within a narrow parameter regime is reported and explained in terms of the low-energy excitations from both phases. These exact results, obtained from the mapping to the zero-field effective Ising model, are independently corroborated by classical Monte Carlo simulations of the effective classical spin-1/2 Ising model on the square lattice with temperature-dependent effective nearest-neighbor interaction and magnetic field.

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Exact calculation of the probabilities of rare events in cluster-cluster aggregation

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Cluster-cluster aggregation (CCA) is a non-equilibrium, irreversible process, of importance in many physical systems, where a particle of mass i and a particle of mass j coalesce to form a larger particle of mass i+j, with a collision rate dependent on a collision kernel K(i,j). This problem has been studied avidly for more than a century, beginning with the Smoluchowski coagulation equation, postulated by Smoluchowski in 1917. This equation, which is a mean field, first order differential equation for the rate of change of number of particles of mass m, i.e., the typical mass distribution, with time, can only be solved exactly for a few kernels. In our work, we study the probabilities of atypical or rare events in CCA analytically for arbitrary K(i, j). We develop a formalism which expresses the probability in terms of an action, which corresponds to a large deviation function for arbitrary kernels. From the large deviation function, we recover the result that the Smoluchowski equation describes typical trajectories. We have also explicitly calculated the action for the constant, sum and product kernels. Further, we have calculated the instanton trajectories for typical as well as atypical times. We find that the action and the instanton trajectories are in excellent agreement with numerical simulations, for the constant and sum kernels for all time. For the product kernel, the action matches with the numerical simulations when the fraction of particles remaining at the final time is greater than half, but deviates when the fraction of particles remaining at the final time is less than or equal to half.

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Kappa distributions and power-law spectra in space plasmas

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One of the first studies in the literature to provide a theoretical justification for the formation of kappa distributions in space plasmas was by Ma and Summers (1998). Their study involved a non-relativistic kinetic equation for the electron distribution function incorporating the effects of stochastic acceleration by whistler mode waves. Importantly, Coulomb collisions, which result in both friction and momentum diffusion, were included. The resulting kinetic equation was shown to permit an exact solution for a kappa distribution, under certain conditions, and the spectral index kappa was found to depend on the power of the wave turbulence. The Ma and Summers (1998) study was linked to the Earth's plasma sheet, Saturn and Jupiter. Recently, Summers and Stone (2022) carried out an analysis of energy spectra of "killer" electrons in Earth's outer radiation belt. These highly energetic (relativistic) electrons can seriously damage orbiting satellites. Killer electron generation was modelled by means of chorus wave diffusion in a 1-D relativistic Fokker-Planck equation incorporating an electron loss term. Various forms of wave spectral density were used including Gaussian and power-law (with index q). The resulting model equations depend on the important controlling parameter k = DT where D is a diffusion parameter and T is the timescale for electron loss.We solve the equations numerically and demonstrate that net electron energization occurs when k exceeds a critical value.We use classical methods to obtain analytic solutions for the electron distribution f(E) that are valid for large energy E. Specifically,we obtain simple analytic forms for the electron spectra for the cases (a) a full-band whistler-mode spectrum, and (b) a lower-band chorus spectrum for both a Gaussian spectrum and a power-law spectrum. The analytic spectra are found to test well against the full numerical solutions. Typically, the spectra involve inverse exponentials in energy rather than inverse power-laws. Exceptionally, for a full-band whistler spectrum, in the case that q = 4, we obtain an exact

inverse power-law spectrum in energy where the power is a specified function of the parameter k. We carry out comparisons of our model spectra with experimental satellite data. We show comparisons of the analytic and numerical solutions with four selected "events", namely Magnetic Storm 1 (October 9, 2012), Magnetic Storm 2 (March 17,2013), Non-Storm (February 23,2013), and Average Geosynchronous conditions. We find good agreement between both analytic and numerical solutions with the experimental spectra for all four events. Kappa distributions were not readily found in the relativistic Fokker-Planck models examined by Summers and Stone(2022). However, as a further project it would be interesting to generalize these models by including additional physical effects such as frictional or collisional terms to see if kappa distribution solutions then naturally occur.

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The non-equilibrium nature of the packaging and the ejection processes of viral DNA

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DNAs are packaged into and ejected from a small viral capsid during the virus replication process. Single molecule experiments were performed to understand how the DNA could overcome a large entropy loss and a strong pressure during packaging. Theoretical studies also reported how the DNA was jammed in non-equilibrium states inside the capsid. It is also an issue how such non-equilibrium jammed conformation would affect the DNA ejection from a viral capsid. Unfortunately, however, packaging and ejection processes have been treated as independent processes under the assumption that the DNA would reach an equilibrium conformation. In this presentation, I would like to report that the ejection process of DNA from the viral capsid should depend significantly on how the DNA was packaged into the viral capsid. We perform Langevin dynamics simulation to package the DNA into a viral capsid and let the DNA eject from the capsid spontaneously. There should be three different regimes depending on the packaging rate: (1) knot dominant, non-equilibrium dominant, and (3) intermediate regimes. When the DNA is packaged slowly, the DNA forms a complex knot easily during the packaging such that the ejection slows down (knot dominant regime). When the DNA is packaged quickly, the DNA is more likely to be jammed in non-equilibrium states, slowing down the ejection process (non-equilibrium dominant regime). When the packaging rate is intermediate, the probability of knot conformation is relatively low, and the DNA conformation may also relax easily, which facilitate the ejection most (intermediate regime).

Nonclassical chemical dynamics in living cells and complex material systems

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We will present novel chemical dynamics models and theories that enable an effective, quantitative description of biochemical reaction processes and their networks in living cells. Specifically, we will introduce the chemical fluctuation theorem (CFT), a general mathematical equation that links stochastic dynamics of mRNA and protein concentrations to gene expression mechanism and dynamics of elementary processes composing gene expression. We will demonstrate the successful applications of the CFT and its recent generalization in understanding of signal propagation and signal-induced gene expression dynamic in living cells. We will also discuss the mystery of stationary, monodisperse nuclei formation and multiphasic growth dynamics of small nanoparticles. These phenomena cannot be explained by the classical nucleation theory (CNT) or other currently available theories. We will present a new statistical mechanical theory of nucleation that sheds light on the origin of monodisperse nuclei formation and provides a unified, quantitative explanation of the complex growth dynamics of various metal nanoparticles.

Natural selection under the go-or-grow dichotomy leads to the emergence of phenotypic and genetic heterogeneity

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Cancer is a significant global health issue, with treatment challenges arising from genetic and phenotypic heterogeneity in tumors. In this study, we examine the complex relationship between evolutionary processes and phenotypic plasticity, specifically focusing on the interplay between cell migration and proliferation. Our novel cellular automaton model takes into account the movement, growth, and death of cells, as well as a change between mobile and growing states controlled by inherited and mutation-driven genotypes and the cells' microenvironment, specifically the local cancer cell density. We observe that cells at the tumor edge evolve to favor migration over proliferation and vice-versa in the tumor bulk. However, we show that this phenotypic heterogeneity can be realized by completely distinct regulations of the phenotypic switch, and that parameters such as the apoptosis rate determine which go-or-grow strategy is most effective. We estimate the transition between the different evolutionary regimes using a mean-field approximation of the evolutionary dynamics. This new approach demonstrates that a specific pattern of phenotypic heterogeneity can result from different cell decision making processes that need to be distinguished in different microenvironments. It also indicates that equating phenotypic traits and genotype in theoretical models can hide the underlying complexity of the cell decision-making process required to produce any observed phenotypic heterogeneity. We expect that the explicit incorporation of decision-making processes in evolutionary models can shed light on various topics in the field of tumor ecology and evolution, such as the plasticity of metabolism, cell migration, and treatment resistance in the future.

Implementation of an autonomous Maxwell demon in a quantum motor

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The relationship between thermal fluctuations and irreversibility has been the subject of much debate since the time of James Clerk Maxwell (1867). It was Maxwell himself who proposed that an observer capable of measuring the velocity of individual particles in a gas, the Maxwell's demon, could completely extract all the energy from the gas, contradicting the second law of thermodynamics [1]. To resolve this paradox, Rolf Landauer postulated in 1961 that any logically irreversible operation performed on a system [2] leads to a dissipation of thermodynamic entropy. For example, the entropy dissipated by deleting a single bit of information from a memory (an irreversible logical operation) is associated, according to Landauer's principle, with a thermodynamic entropy dissipation S = T log 2. Accordingly, Maxwell's demon would also dissipate heat when measuring particles, limiting its efficiency. In this work, we try to relate the previous theory with the new experimental implementations developed in nanoscience. A recent example is quantum nanomotors based on carbon nanotubes, where electrical conduction through the nanotube produces mechanical oscillations in it [3]. At very low temperatures, this class of devices is extremely sensitive to the conditions of its environment. Using a simple model, we demonstrate how this system is capable of extracting energy from the environment in the form of useful work, forming a true autonomous Maxwell's demon. In the same way, we relate the efficiency of the process to the ability of the system to correlate with its environment and compute each fluctuation. Interestingly, the main consequence of our results affects the thermodynamic efficiency of computers manufactured at the nanoscale, where due to fluctuations in the environment, the entropy dissipated when deleting, creating or manipulating information is greater than Landauer predicted.

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Emergence of modulated cycles in critical dynamics

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In complex systems, the existence of critical fluctuations, either near a nonequilibrium phase transition or a self-organized criticality attractor in dynamical systems driven out of equilibrium, indicate the states where the emergence of new features at a larger scale can occur. These stationary states are characterized by long-range spatiotemporal correlations and collective avalanching dynamics in response to endogenous or external forces. A closer inspection of state variables reveals a tendency towards cyclical trends in their temporal fluctuations, which can be related to the gradual accumulation and release of energy through a cascade of avalanches of different sizes, for example, in sandpile automata. Here, we investigate such cycles in two types of critical states, particularly near a jamming transition in traffic on complex networks [1] and in self-organized critical states observed in the empirical data of emotional messages in online social networks [2]. Even though their origins differ, our results show that the emergent cycles in both cases are irregular and modulated by the collective critical dynamics; they attain higher harmonics that can be appropriately described by multifractal analysis. The observed variations in the corresponding singularity spectra correlate with the nature of collective dynamics.

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Correlation aspects of interacting quantum systems in one dimension

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In this work we inspect different correlation aspects of interacting quantum systems in one dimension. We will address the Lieb-Liniger model and focus on its one-body correlation function and try to understand its important excitations. We also talk about the single impurity immersed in a free Fermi gas and its correlation features. Adding a trap breaks the system's integrability, which can be restored in the infinite coupling limit, where the hard-core bosons regime is achieved.

Droplet spreading on reactive substrates

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Droplet spreading on reactive substrates is different from spreading on non-reactive substrates. We review the non-trivial spatio-temporal patterns observed for spreading of metal on metal-on-glass in room and high temperatures and discuss their universal features. The spreading exhibits two main regimes, bulk propagation regime followed by kinetic roughening of the advancing interface. The bulk propagating dynamics is qualitatively different from classical wetting characteristics. The rich spatio-temporal patterns observed in the kinetic roughening regime are studied and characterized using statistical physics tools, such as the growth, roughness and persistence exponents, as well as relevant Ising models. We also discuss recent results of structural instability of the reactive substrate due to the spreading, resulting in DLA-like finger patterns.

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Application of statistical physics to agroecology: an adsorption-desorption model of plant intercopping

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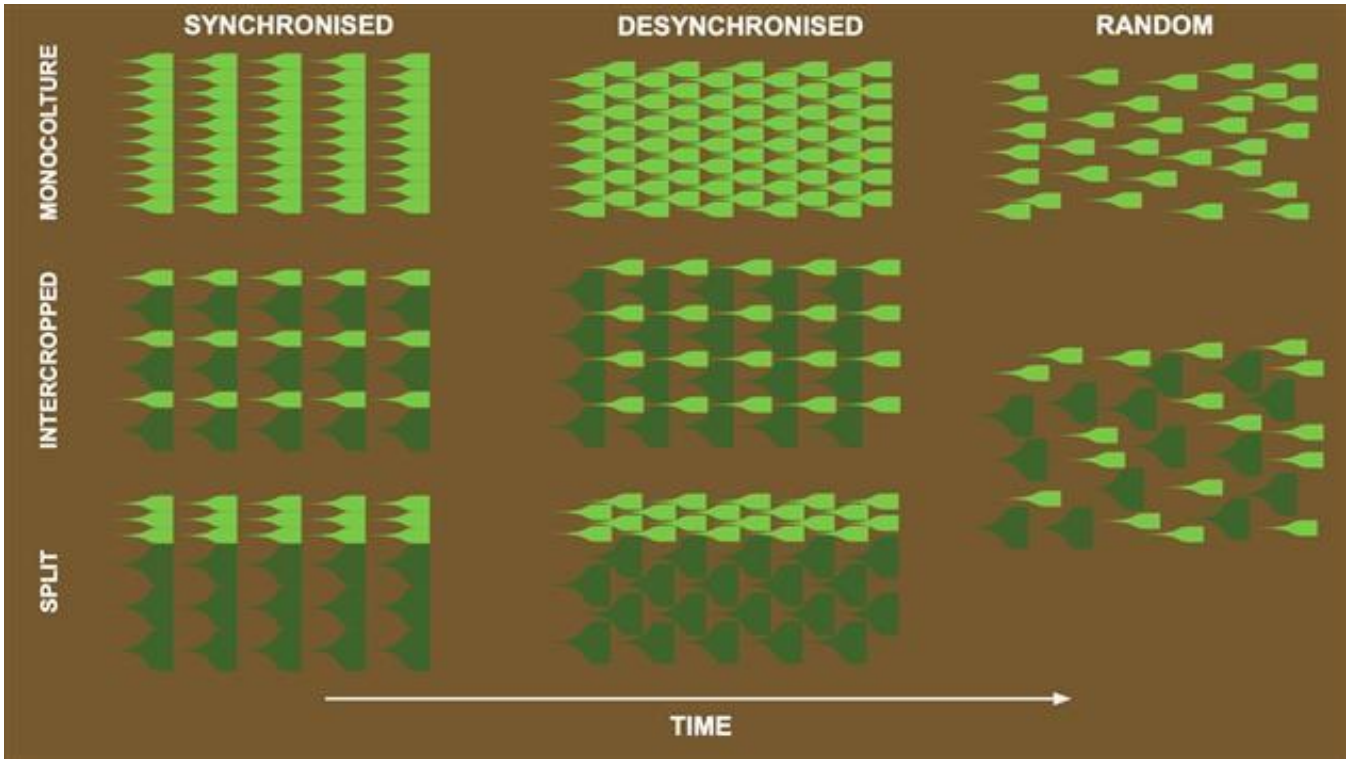
The French Intensive Method involves cultivating plants in a smaller space and with higher yields than traditional gardening methods. Typically, diversified crops are planted as densely as possible. Models in computational agroecology may assist farmers in the maintenance of such farms. Various planting strategies are used including batch with regular spacing, synchronised or desynchronised. We propose a phenomenological model in which the plants are represented as disks with a growing radius. The plant volume or biomass can be estimated as a half-sphere of radius R(t). In the simplest model we consider the growth to be linear in time $R(t) = \alpha(t-t0)$ with $t0 \le t \le tb$, when the plant is planted at time t0 and harvested at time tb. In a more refined model the time-dependent radius is modeled as a sigmoidal function corresponding to slow growth in the initial and final stages. We consider a monoculture and a mixture of two vegetables, for example lettuces and cabbages, with different maximum radii and growth rates. In addition to regularly spaced planting, we explore an alternative strategy consisting of randomly selected the planting positions and times. These models take inspiration from random sequential adsorption and parking lot models with the additional constraint that a newly sown plant must be placed so that it does not overlap with others over the course of its growth. We describe different event-driven algorithms (1D and 2D) to simulate the dynamics of this system. At low planting rates the position of a new plant may be selected randomly, but at high plant coverage the method is inefficient so in 1D we employ a rejection free algorithm. The steady state of the field consists of disordered configurations of the plants. We study the evolution of the effective planting rate as a function of the nominal planting rate, the fraction and distribution of each species in the steady state. When both vegetables are planted with equal probability, simulations show that the proportion of big plants starts decreasing above a given threshold. This model and the algorithms may be extended to more species and other planting strategies to examine original farm designs and to help manage a complex rotation plan.



Non-equilibrium statistical mechanics tool for the study of space plasma; The Ehrenfest procedure in Earth's radiation belts and Superstatistics in magnetized plasma.

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An interesting problem in plasma physics, when approached from the point of view of non-equilibrium Statistical Mechanics, is to obtain properties of collisionless plasmas, through the Vlasov Equation[1]. From Classical and Statistical Mechanics, this equation corresponds to a fluid version of the Liouville theorem for the phase space density, when the Hamiltonian describes electromagnetic interactions and the effect of Coulomb collisions can be neglected. Even though the Vlasov Equation is a well-known theoretical approach in plasma physics, the obtention of solutions is a very difficult task, usually addressed using perturbative methods. In this work we present two ways of approaching the problem. First, from the point of view of obtaining macroscopic properties of the system. Through theoretical analysis and numerical calculations we show that starting from the Vlasov equation, and using a classical analog of Ehrenfest theorem[2,3], it is possible to derive relations for the expectation values of time-dependent observables[4]. For this case, considering charged particles trapped in a magnetic field dipole, the three adiabatic invariants are studied indirectly. Considering expression for pitch angle, average radius and magnetic moment we found dynamical equations that we contrast using test-particle simulations. Second, considering the origin of empirical distributions in modeling space plasma phenomena is not a settled issue, we also approach the problem from a microscopic point of view. We start from a linear approximation of the Vlasov Equation, and apply Superstatistics considerations to explore its scope and possible interpretation on dispersion relations for a magnetized plasma, extending Ourabah's previous analysis on electrostatic plasma waves[5].

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Two lane coupled exclusion process with extended Langmuir Kinetics

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In nature, most of the essential activities are performed employing various kinds of stochastic transportation processes. Understanding the behavior of such a system is more complicated owing to its random nature. In physics, this kind of system belongs to the category of a non-equilibrium system. Comprehending the stationary characteristics of a system is also intricate because of the continuous movement of particles. Since we do not have any fundamental theories to study the behavior of these systems. So, the scientists modeled the problem with various scenarios, gaining knowledge from there; they tried to understand the nature of the system. A Totally Asymmetric Simple Exclusion Process (TASEP) is a pragmatic model commonly used to elucidate the features of the stochastic transport process. Inspired by the crowded multi-lane transportation phenomena, where the particle movement, adsorption, and desorption rely on the occupation state of the surroundings, we construct the asymmetrically coupled multi-lane TASEP model with the incorporation of modified hopping and extended Langmuir kinetics dynamical rules. The influence of the implemented dynamics on system properties has been scrutinized through phase diagrams, density profiles, phase transitions, and finite-size effects. The obtained theoretical results from the mean-field theory have been validated through Monte Carlo simulations outcomes.

Squeezing in Bose-Einstein condensate of weakly interacting atoms: non-Gaussian fluctuations of the order parameter and #p-complexity of the joint particle-occupation statistics

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The talk is devoted to new results on the statistics of Bose-Einstein condensate (BEC) in a weakly interacting gas confined in a mesoscopic trap in an equilibrium state. Detailed analysis of such statistics in presence of interparticle interactions constitutes a rather complicated problem, mainly due to the nontrivial relation between bare atoms (quantity of which is measured in experiments) and quasiparticles, which occupation numbers determine the probabilities of microstates. For a cold, partially condensed equilibrium gas, we find the universal analytic formula for a characteristic function (Fourier transform) describing the statistical properties of BEC. The analysis employs the Hartree-Fock-Bogoliubov-Popov approximation describing the condensate and quasiparticles by means of the nonlinear Gross-Pitaevskii and Bogoliubov - de Gennes equations treated in a self-consistent manner. It consistently takes into account the nontrivial Bogoliubov transformation between particles and quasiparticles which enables squeezing-of-quantum-state effects, and allows us to see how these effects are reflected in the BEC statistics. Via the method of characteristic function we, for the first time, describe an evolution of the statistics of the total number of condensed particles as the interparticle interaction increases from an ideal gas regime to the Thomas-Fermi limit. Such evolution is governed by the interplaying effects of squeezing of fluctuations and restructuring of the Bose-Einstein condensate and quasiparticle wave functions and spectrum. We find that there are two essentially different – the quantum-dominated and the thermally-dominated, – regimes of fluctuations, and specify a range of system parameters where the transition between these regimes happens. We clearly show that the thermally-dominated BEC statistics may be essentially non-Gaussian and dependent on boundary conditions, and explain why these effects are still present even in the thermodynamic limit and even in the Thomas-Fermi limit (where one may expect that the condensate screening should disable the influence of the boundary conditions on the macroscopic properties of the system) [1]. The proposed method also allows us to address a deeper problem of calculating a joint probability distribution for the particle occupation numbers in a set of different excited states of BEC [2]. Here we find interesting connections to quantum computations and simulations. We show, via the newly discovered combinatorial theorem [3], that the considered probabilities are proportional to matrix hafnians. In the general case, calculating a hafnian is a ♯P–hard problem, which means the corresponding runtime of a classical computer grows exponentially with the size of the matrix. This is a key property for the well-known and widely discussed concept of GaussianBosonSampling quantum simulators, where the outcome probabilities of multi-photon detecting events are also encoded via matrix hafnians. We elaborate on the discovered analogy and discuss how the squeezing effects induced by the Bogoliubov transition lead to a computational complexity of the excited particles' statistics calculations.

The support from the Russian Science Foundation (project no. 21-12-00409) is acknowledged.

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Permutation group entropy: A new route to complexity for real-valued processes

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Generalized entropies can play a crucial role in the characterization of the complexity of a large class of deterministic and random processes. In the first part of this talk, we will propose the notion of group entropy as a class of information measures possessing an intrinsic group-theoretical structure. This structure emerges when imposing the requirement of composability of an entropy with respect to the union of two statistically independent systems. A generalization of the celebrated Shannon-Khinchin set of axioms is proposed, obtained by replacing the additivity axiom with that of composability. This formulation, which makes use of the theory of formal groups of algebraic topology, leads to the new, infinite family of non-trace-form entropies called group entropies. The first example of this class is represented by the standard Rényi entropy. We will show that complex systems can be classified into universality classes, each characterized by a specific phase space growth rate, and described by a suitable group entropy, representing the complexity measure associated to the given universality class. As a nontrivial application, we shall present a generalization of the permutation entropy approach to data analysis by Bandt and Pompe, which has been very successful since its inception 20 years ago. Nevertheless, the theoretical aspects have remained somehow limited to noiseless deterministic time series and dynamical systems, the main obstacle being the super-exponential growth of allowed permutations with length when randomness (also in form of observational noise) is present in the data. To overcome this difficulty, we propose a new methodology based on complexity classes, which are precisely defined by the growth of allowed permutations with length, regardless of the deterministic or noisy nature of the data. We consider three major classes: exponential, sub-factorial and factorial. Our main results is a novel family of generalized permutation entropies which widely extend the standard notion of permutation entropy. They represent new complexity measures which possess many interesting group-theoretical and analytic properties. Besides, our information measures can be considered as the topological analogue of the family of group entropies. The conceptual framework proposed provides us with a unified approach to the ordinal analysis of deterministic and random processes, from dynamical systems to white noise.

Joint work in collaboration with J. M. Amigó (CIO-Elche), R. Dale (CIO-Elche), H. Jensen (Imperial College, London).

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Characterization of degree and energy distributions in asymptotically scale-free d-dimensional random networks

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It has already been reported in the literature [1,2] that a large class of preferential-attachment-based random d-dimensional growing networks exhibits q-exponential degree (k_i, defined as the number of sites that are already attached to site i) or energy (ε_i, defined as $\varepsilon_i = \Sigma_j^{k_i} w_{ij}/2$) distribution, where the link weights w_{ij} are random variables drawn from a quite generic distribution. The corresponding asymptotic power-law behavior is determined by the ratio α_A/d where α_A characterizes the distance-dependence in a preferential-attachment rule $\Pi_{ij} \propto \varepsilon_i/d_{ij}^{\alpha_A}$ $(\alpha_A \geq 0)$, where d_{ij} being the Euclidean distance between i and j. In order to cover more complex and realistic phenomena, we consider here a more general form, namely $\Pi_{ij} \propto \varepsilon_i / [d_{ij}^{\alpha_A} + c\, d_{ij}^{\gamma_A}$ $(\gamma_A > \alpha_A, c \geq 0)$. An interesting crossover is then observed and studied in the power-law behavior of the energy distribution [3].

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Marginal stability in the spherical spin-glass: on the competition between disorder and (ordered) non-linearity.

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Since the 1970's spin glasses have been a rich source of techniques and ideas that provided a theoretical foundation and universal paradigm for the emergence of ergodicity broken phases at low temperature in many-body systems with frustration. What was evident from the beginning is that the behaviour of disordered models in statistical mechanics depends on the nature of the variables, whether they are continuous or discrete. Let us consider for instance the celebrated Sherrington-Kirkpatrick model, which is a sort of mean-field Ising model with random Gaussian couplings. What is remarkable is the difference between the low temperature equilibrium phase of this model, characterized by a fractal free-energy landscape and by the so-called full replica-symmetry breaking scenario [1], and the behaviour of a model with the same Hamiltonian, but where "spins" are locally unbounded continuous variables, known as spherical spin glass [2], where a transition to a low temperature non-ergodic phase occurs at the same critical temperature of Sherrington-Kirkpatrick, but the nature of this low-temperature phase is completely different. It is a trivial spin-glass phase with only one big connected component of the phase space, which is not broken down into an infinite hierarchy of sub-clusters as in Sherrington-Kirkpatrick. The stability analysis of this "trivial spin-glass" phase, which is "marginally stable", suggests that it might be driven to a different phase by arbitrarily small perturbations. On the top of a historical briefing on the differences between disordered models with discrete or continuous variables, the goal of the present communication will be the description of how the addition of non-linear terms to the spherical spin-glass solved by Kosterlitz et al. in 1976 modifies the nature of the low-temperature phase. Motivated by the idea of investigating the competition between disorder and non-linearity, we have analytically studied the effects of different kinds of non-linear perturbations, i.e. those corresponding to the following kind of distributions for the random coefficients of the non-linear couplings: first, purely ordered coefficients; second, purely disordered coefficients; and third, a competition between ordered and disordered interactions. The main outcome of our investigation, detailed by the presentation of complete phase diagrams, is that the marginally stable trivial spin-glass phase of a model with two-body interactions (soft spins) cannot be destabilized by any perturbation: randomness looks like a necessary ingredient. In particular, consistently with previous works [3], we find that the spherical spin glass with 2+4 body disordered interactions, is characterized by full replica symmetry breaking in its low temperature phase when the non-linearity is not too strong. We emphasize how and why the transition to this phase with an infinite hierarchy of nested disjoint ergodic components is different from the case of Sherrington-Kirkpatrick model.

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Estimation of Shannon entropy with applications to systems with memory

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The estimation of entropy for very short discrete sequences is a significant challenge with broad applications in fields such as statistics, linguistics, ecology, and neuroscience. Although numerous attempts have been made to develop an unbiased estimator with minimal mean squared error, the performance of proposed estimators varies widely depending on the system being studied and the available data size. In this study, we analyzed commonly used entropy estimators for two types of Markovian systems: binary sequences and undersampled Markovian systems. Our approach centers on the block Shannon entropy, where data is grouped into blocks of a specified size, and the

entropy is derived from the probability of each block. The maximum likelihood estimator for entropy works well when the sequence length is much greater than the number of possible blocks. However, many entropy estimators in the literature are limited to independent systems and have not been applied to correlated systems. Here we have extended this analysis to Markov chains, which have many applications across disciplines. To address these issues, we propose a new method to determine the order of a Markov chain that best represents a given dataset. Our method is model-independent and sufficiently precise, even in the undersampled regime. We introduce an estimator that can be used for any observable, such as entropy, to provide information on correlated systems. Importantly, the method is valid for both Markovian and non-Markovian systems. We compare the performance of our proposed estimator with those designed for independent systems and find that it significantly increases the accuracy of entropy estimation for systems with memory. We tested our method on both numerically generated and real-world datasets and observed promising results. These successful results will certainly encourage further applications of the proposals discussed in this work. Additionally, our improved estimator can be applied to any model of correlations (not necessarily a Markov chain) and is thus of interest in situations where entropy is fundamental to understand the system's properties.

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Inference of Boolean networks from perturbation data

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Gene regulatory networks (GRNs) identify models of genes that regulate their state via activator or inhibiting signaling propagated via a network. Recent experiments perturb the state of genes and record the effects, providing rich information on the connectivity of the GRN. The inference of GRNs is the problem of inferring interactions between genes from available measurements about genes' state. It can be mapped to a problem of link prediction in the presence of node perturbations. To address this challenge, we develop a Bayesian model of the GRN that takes as input the states of nodes after perturbation experiments involving both node activation and inhibition, i.e., Crispr-a and Crispr-i experiments. To predict the effect of node perturbation, we define how the state of every node is controlled by the others. We model the node state in terms of a linear interaction model for Boolean variables in the presence of noise. The dynamics has been studied in literature using the dynamic cavity method for sparse random graphs and recent implementation of the dynamic cavity method using dynamic programming allows to apply to networks with realistic degree distributions, see ref. [1,2]. The network inference problem lays on a space that grows exponentially with N^2, with N the number of nodes of the network. We design an approximate algorithm that solves our Bayesian inference model and scales as N^3. Our solver uses the message-passing technique, and we design a dynamic programming method to compute the messages. Our dynamic programming method is optimised such that it takes advantage of the discrete nature of both couplings and Boolean variables. We evaluate the effectiveness of our method on synthetic networks and quantify its reconstruction error. We also apply to a real dataset performing Crispr-a and Crispr-i experiments on K562 cell line. Overall, our work provides a new tool for GRN inference that is based on disordered systems techniques and informs the design of future experiments by highlighting the importance of including both inhibition and activation perturbations for a more comprehensive understanding of gene interactions.

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Criticality and phase diagram of quantum long-range systems

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S everal recent experiments in atomic, molecular and optical systems motivated an huge interest in the study of quantum long-range spin systems. The goal of the talk is to present a general description of their critical behavior and phases, devising a treatment valid in d dimensions with an exponent d+σ for the power-law decay of the couplings in the presence of an O(N) symmetry. By introducing a convenient ansatz for the effective action, one can determine the phase diagram for the N-component quantum rotor model with long-range interactions, with N=1 corresponding to the Ising model. The phase diagram in the σ− dplan shows a non trivial dependence on σ. As a consequence of the fact that the model is quantum, the correlation functions are genuinely strongly anisotropic in the spatial and time coordinates for σ smaller than a critical value and in this region the isotropy is not restored even at the criticality. Results for the correlation length exponent ν & the dynamical critical exponent z and a comparison with numerical findings for them are presented.

Tilted 1D Bose gases and atomtronics

Andrea Trombettoni
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After an introduction to atomtronics and 1D ultracold gases, I discuss how to implement an integrable Floquet Hamiltonian for a periodically tilted 1D Bose gas. In general, an integrable model subjected to a periodic driving gives rise to a non-integrable Floquet Hamiltonian. Here we show that the Floquet Hamiltonian of the integrable Lieb-Liniger model in presence of a linear potential with a periodic time-dependent strength is instead integrable and its quasi-energies can be determined using the Bethe ansatz approach. To conclude, a discussion of the applications to atomtronics is presented.

Ultracold atoms for quantum sensing and quantum technologies

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I will discuss applications of interacting quantum gases to atomtronics, quantum sensing and quantum technologies, focusing on interferometric guided schemes with one-dimensional systems.

Extensive nonadditive entropies for black holes and cosmology

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No empirical indication exists that classical thermodynamics needs to be violated for any system, including cosmological ones, either quantum or not. Consistently, the Legendre structure of thermodynamics remains valid for all macroscopic systems. This implies that -- in contrast with the total energy, which typically is either extensive or superextensive -- the total thermodynamical entropy S must -- like the volume, magnetization and similar quantities -- always be, extensive, i.e., asymptotically proportional to the number of particles. This requirement severely constrains the admissible entropic functionals to be used for the statistical-mechanical approach to the system. The appropriate entropic functional to be used definitively depends on the particular occupancy of the corresponding phase space or Hilbert space, as determined by its dynamics. These issues will be illustrated in concrete systems where the nonadditive entropic functional , introduced in Tsallis and Cirto, Black hole thermodynamical entropy, Eur. Phys. J. C 73, 2487 (2013) and similar entropies [Zamora and Tsallis, Thermodynamically consistent entropic-force cosmology, Phys. Lett. B 827, 136967 (2022); Zamora and Tsallis, Thermodynamically consistent entropic late-time cosmological acceleration, Eur. Phys. J. C 82, 689 (2022); Jizba and Lambiase, Tsallis cosmology and its applications in dark matter physics with focus on IceCube high-energy neutrino data, Eur. Phys. J. C 82, 1123 (2022)] have been successfully used with regard to the available observational data.

Statistical mechanics for complex systems – News and views

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Boltzmann-Gibbs statistical mechanics is grounded on the celebrated Boltzmann-Gibbs-von Neumann-Shannon additive entropic functional. This outstanding theory is typically based on generically short-range space-time correlations and has been successfully verified along 150 years. However, during recent decades, experimental, computational and analytic evidences have grown up that it loses its applicability in the presence of generic long-range correlations. It was proposed in 1988 that, for such complex cases, statistical mechanics should be grounded on nonadditive entropic functionals, for instance Sq which depends on an index q and, for q=1, recovers . Recent applications of this generalized theory include (i)Tunnelling chemical reaction [Wild, Notzold, Simpson, Tran and Wester, Tunnelling measured in a very slow ion-molecule reaction, Nature (1 March 2023), doi: 10.1038/s41586-023-05727-z]; (ii)The numerical approach of the thermal transport properties of the n-vector d-dimensional inertial ferromagnet (n=1, 2, 3 for the Ising, XY and Heisenberg models respectively; d=1, 2, 3) and first-principle validation of Fourier's 1822 law [Tsallis, Lima, Tirnakli and Eroglu, First-principle validation of Fourier's law in d = 1, 2, 3, Physica D 446, 133681 (2023); Lima and Tsallis, Ising chain: Thermal conductivity and first-principle validation of Fourier law, arXiv 2303.13432]; (iii)The distribution of inter-occurrence times in human EEG [Abramov, Tsallis and Lima, Neural complexity – Statistical-mechanical approach of human electroencephalograms, arXiv 2303.03128 [q-bio.NC]]; (iv)Asymptotically scale-free networks with weighted links [Oliveira, Brito, Silva and Tsallis, Statistical mechanical approach of complex networks with weighted links, JSTAT 063402 (2022); Tsallis and Oliveira, Complex network growth model: Possible isomorphism between nonextensive statistical mechanics and random geometry, Chaos 32, 053126 (2022)]; (v)COVID-19 computer tomography [Al-Azawi, Al-Saidi, Jalab, Kahtan and Ibrahim, Efficient classification of COVID-19 CT scans by using q-transform model for feature extraction, PeerJ. Comput. Sci. 7, e553 (2021)]; (vi)AE in rock fractures [Vinciguerra, Greco, Pluchino, Rapisarda and Tsallis, Acoustic emissions in rock deformation and failure: New insights from q-statistical analysis, Entropy (2023), in press, doi: 10.20944/preprints202303.0462.v1]; (vii)q-generalized algebras and prime numbers [Borges, Kodama and Tsallis, Along the lines of nonadditive entropies: q-prime numbers and q-zeta functions, Entropy 24, 60 (2022)]; (viii)Decreasing entropy while increasing time [Tsallis and Borges, Time evolution of nonadditive entropies: The logistic map, arXiv 2211.03261 [cond-mat.stat-mech]]; (ix)Heavy quark dynamics [Megias, Deppman, Pasechnik and Tsallis, Comparative study of the heavy-quark dynamics with the Fokker-Planck Equation and the Plastino-Plastino Equation, arXiv 2303.03819 [hep-ph]]. Selected applications will be presented during the talk.

Application of machine learning methods in the targeted energy transfer nonlinear model

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The Targeted Energy Transfer (TET) mechanism involves resonant transfer of energy in a non-resonant but nonlinear system [1]. The original idea was motivated by ultrafast electron transfer in chlorophyl molecules and was formulated in the context of the Discrete Nonlinear Schroedinger (DNLS) equation. The transfer is perfect when a specific constrain is fulfilled that connects nonlinearity with energy disparity in the context of a two state model. While it applies to classical models it can be readily extended to quantum systems as well. In both classical and quantum cases it is very important to find the constrain that enables efficient transfer. While this is possible in simple dimer units it becomes a very challenging task in more extended systems. In order to bypass this difficulty we may apply techniques from Machine Learning (ML). Specifically, by selecting appropriate

loss function and minimising it in the system parameter space one may obtain a direct formulation of the appropriate constrain that leads to resonant transfer. In the classical oscillator case we can find easily the TET transfer condition by employing this method in the dimer case that is known analytically [3]. Furthermore, we can use the method in more complex geometries such as the a trimer that involves a nonlinear dimer unit that is separated by a linear state. While this trimer model is not analytically tractable the application of the ML approach gives readily the resonant transfer parameter landscape. Similar approach can be applied to the quantised version of the DNLS model [4]. Extension of the classical loss function to the quantum case and subsequent minimisation through learning and back-propagation results in the precise analytical TET result for the quantum system. The method is then applied to the fully quantum trimer case where the intermediate stat is in general nonlinear. Assuming that two of the oscillators fulfil the quantum TET condition leads to optimisation of transfer through the third state. This transfer enables movement of arbitrary number of bosons in unison from the donor to the acceptor state. The successful application of ML techniques in this model is now being extended to the cases where in addition to the electronic degrees of freedom we also have vibrational degrees as well [5]. We show analytically and numerically that TET works quite efficiently also in this more complex case. We focus on the temperature dependence of the phenomenon and apply our ML technique in order to find parameter regimes for optimal transfer. In conclusion the TET model is quite general and through the application of ML methods one may uncover its full applicability.

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Generic mean-field model for phase transitions in nonuniform forces

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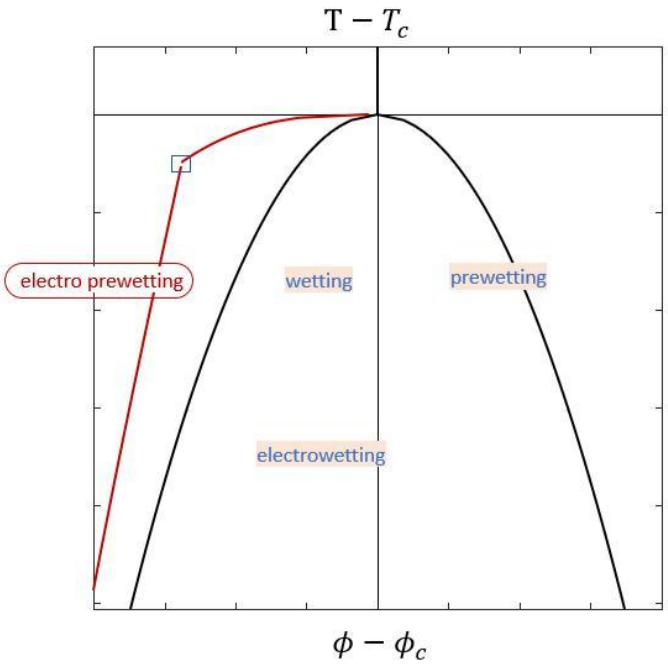
We look at the influence of external fields on systems described by generic free energy functional of the order parameter. The external force may have arbitrary spatial dependence, and the order parameter coupling may be nonlinear. The treatment generalizes seemingly disparate works, such as pure fluids, liquid and polymer mixtures, lipid monolayers, and colloidal suspensions in electric fields, fluids, and nematics in gravity, solutions in an ultracentrifuge, and liquid mixtures in laser radiation. The phase lines and thermodynamic behavior are calculated at the mean-field level. We find a ``surface'' critical point that can be shifted to higher or lower temperatures than the bulk critical point. Below this point, the transition from a ``gas'' phase to a ``liquid'' phase is first-order, while above it, the transition is second-order. The second-order line is affected by the spatial dependence of the force, while the first-order line is universal. Moreover, the susceptibility may diverge at a finite location. Several analytical expressions are given in the limit where a Landau expansion of the free energy is valid.



Quantum superposition states: Spin-glasses and magnetic classification over entanglement

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Spin glasses have been the subject of many studies due to their very interesting microscopic properties. The most important feature that distinguishes spin glasses from other systems is that they contain random disorder and, accordingly, many possible states of the system at the electronic level occur with very close probabilities [1]. This cause many local minima to occur in the free energy. However, since it is almost impossible to choose any of these almost equally probable configurations that is called frustration effect then the system cannot reach to equilibrium at least in laboratory time. We defined that spin-glass quantum superposition states as equiprobable superposition of possible electronic configurations so called cat states. The cat state is defined as a quantum state composed of two diametrically opposed conditions at the same time [2, 3]. By utilizing the Edward-Anderson type spin-glass order parameter [4] and magnetization, we have demonstrated that our superposition states can be classified based on their contribution to distinguishing magnetic order (disorder), such as spin-glass, (anti)ferromagnetic, and paramagnetic phases. Additionally, we have generalized these superposition states based on the system size. Then we focused on the entanglement of these phase-based superposition states using the negativity [5] measure. We have shown that the spin glass order parameter can be utilized to determine the entanglement of magnetically ordered (disordered) phases, or vice versa, with negativity signifying magnetic order. In conclusion, quantum superposition states are the great interest of quantum computation and quantum information [3] moreover our findings provide further insight into the nature of quantum superposition states and their relevance to quantum spin-glasses and quantum ordered and disordered phases.

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Classification of short-term memory tasks in ROI-based fMRI data

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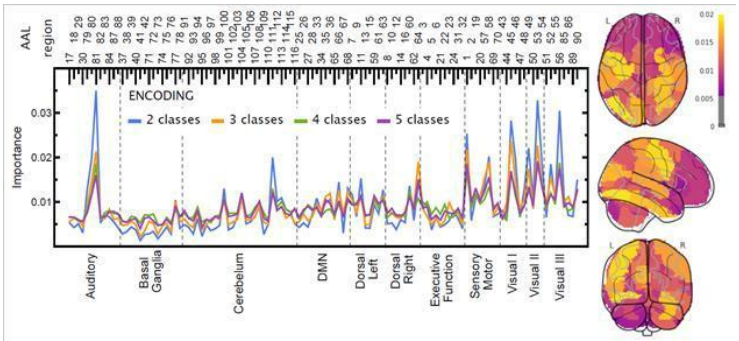
With the advance of experimental techniques, functional magnetic resonance imaging (fMRI) being one of them, measuring neural activity while a person is memorising and retrieving information has become possible. In recent years, functional activations have been intensely analysed by a range of machine learning [1] and deep learning [5] methods to study brain disorders. However, fMRI signals are notoriously challenging to analyse due to their very low temporal resolution and a non-trivial auto-correlation and cross-correlation structure. In this work, we apply several linear and non-linear classification methods to fMRI signals from the short-term memory distortion experiment [4]. The experiment consisted of two visual verbal tasks (based on semantically or phonetically associated words), two non-verbal tasks (local and global processing of pictures of similar objects), and spontaneous brain activity (resting state, RS), with matching, non-matching and intentionally confusing stimuli. The classification methods included among several others: Quadratic Discriminant Analysis (QDA), Random Forests, hyperparameter tuned Light Gradient Boosting Machine [3] (LGBM), and ResNets [2] of several depths. With these methods, we classified very short segments of brain activity (1-6 samples, corresponding to 2-11 seconds) from information encoding (memorisation) and retrieval (recollection) phases into stimuli types (2, 3, 4, or 5

classes). We show that the best classifiers reach F1-scores up to .834 for the 2-class and up to .603 for the 5-class problem, see Fig. 1. The nonlinear classifiers (such as QDA, LGBM or ResNets) clearly beat linear ones, but none of them is universally best in our experiment. Most interestingly, our tests showed that information crucial for producing good classification results (aka explanations) is localised in a small number of ROIs. We also show how important it is for such explanations (like SHAP) to scrutinise time series for cross-correlations (e.g., the right inferior occipital gyrus, 54 in Fig. 2, has a low importance score due to a large correlation with the left inferior occipital gyrus, 53). The presented findings increase the efficiency of fMRI signal classification in cognitive experiments and give rise to the understanding of the cognition process related to short-term memory performance and distortions.



Coherence-enhanced quantum-dot heat engine

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We show that quantum coherence can enhance the performance of a continuous quantum heat engine in the Lindblad description. We investigate the steady-state solutions of the particle-exchanging quantum heat engine, composed of degenerate double quantum dots coupled to two heat baths in parallel, where quantum coherence may be induced due to interference between relaxation channels. We find that the engine power can be enhanced by the coherence in the nonlinear response regime, when the symmetry of coupling configurations between dots and two baths is broken. In the symmetric case, the coherence cannot be maintained in the steady state, except for the maximum interference degenerate case, where initial-condition-dependent multiple steady states appear with a dark state.

Gutenberg-Richter, Omori and Cumulative Benioff strain patterns in view of Tsallis entropy and Beck-Cohen Superstatistics.

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The corner stones of Statistical seismology as that of Gutenberg-Richter (GR), Omori and Benioff laws analysed using the ideas of Tsallis entropy and its dynamical superstatistical interpretation offered by Beck-Cohen. The earthquake generation process is a complex phenomenon, manifested in the nonlinear dynamics and in the wide range of spatial and temporal scales that are incorporated in the process. Despite the complexity of the earthquake generation process and our limited knowledge on the physical processes that lead to the initiation and propagation of a seismic rupture giving rise to earthquakes, the collective properties of many earthquakes present patterns that seem universally valid. The most prominent is scale-invariance, which is manifested in the size of faults, the frequency of earthquake sizes and the spatial and temporal scales of seismicity. A variety of fault attributes, such as the distribution of fault trace-lengths or fault displacements, exhibit power-law scaling and (multi)fractal geometries. The frequency-size distribution of earthquakes generally follows the Gutenberg-Richter (GR) law that resembles power-law scaling in the distribution of dissipated seismic energies and fault rupture areas, limited in each case by the size of the seismogenic system. The aftershock production rate following a main event generally decays as a power-law with time according to the modified Omori formula. The modified Omori formula expresses a short-term clustering effect associated with the occurrence of large events and their triggered aftershock sequences.

Based on statistical physics and the entropy principle, a unified framework that produces the collective

properties of earthquakes from the specification of their microscopic elements and their interactions, has recently been introduced. This framework, called nonextensive statistical mechanics (NESM) was introduced by Tsallis (1988), as a generalization of classic statistical mechanics due to Boltzmann and Gibbs (BG), to describe the macroscopic behaviour of complex systems that present strong correlations among their elements, violating some of the essential properties of BG statistical mechanics. Such complex systems typically present power-law distributions, enhanced by (multi)fractal geometries, long-range interactions and/or large fluctuations between the various possible states, properties that correspond well to the collective behaviour of earthquakes and faults. Here, we provide an overview on the fundamental properties and applications of NESS. Initially, we provide an overview of the collective properties of earthquake populations and the main empirical statistical models that have been introduced to describe them. We describe the main statistical physics models that have been introduced to describe earthquake occurrence and we summarize the classic (BG) statistical mechanics approach to the phenomenology of earthquakes. We provide an analytic description of the fundamental theory and the models that have been derived within the NESM framework to describe the collective properties of earthquakes.

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Extensivity of thermodynamic bodies, weak nonlocality of continua and long-range interactions

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Extensivity is defined as first-order Euler homogeneity of the thermodynamic entropy. Therefore it is the key concept that connects bodies with continua, more properly thermodynamic bodies with thermodynamic continua. Nonextensivity and nonadditivity are body concepts and are often connected to long-range forces and to nonlocal interactions. Nonrelativistic gravity and heat conduction are nonlocal in the sense, that the speed of propagation of a perturbation is infinite. However, their field equations, the Poisson and Fourier ones, are local nonrelativistic evolution equations. In the presentation, it is shown that nonextensive thermodynamic bodies may be modelled as extensive ones. My primary example will be the thermodynamics of a Schwarzschild black hole, where the thermodynamic volume coincides with the Christodoulou-Rovelli volume and the body entropy can be transformed to and extensive one, with nonnegative heat capacity [1]. Moreover, I demonstrate that weakly nonlocal gradient extensions of well-known continuum equations result in nonextensive homogenous thermodynamic bodies because body quantities become shape and boundary dependent. The simplest example is the thermodynamics of elasticity [2], but there are many gradient theories in fluid mechanics, too, both in nonrelativistic and relativistic ones. Therefore, our fluid-based intuition in thermodynamics and thermostatistics should be generalised and properly analysed when applied in weakly nonlocal continua. Also, the natural starting point of theory building is the continuum part. Finally, I argue that a meaningful body-continuum transition in mechanics requires the classical holographic property: in ideal continua without dissipation, body forces can be represented by surface tractions [3,4]. Classical holographic property is the consequence of thermodynamic principles of second law compatibility. The transition from body to continua, from mass point representation to field theory is the general aspect of extensivity and nonextensivity in thermodynamics.

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Classical holography

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Quantum mechanics, superfluids, and capillary fluids are closely related: it is thermodynamics that links them. Newtonian gravity can be formulated in the framework of nonequilibrium thermodynamics, introducing a scalar field, the gravitational potential, as a thermodynamic state variable. In both cases, a general method validates the requirements of the Second Law of Thermodynamics for continua and calculates the consequent restrictions on the evolution equations and constitutive relations. A simple Galilean relativistic spacetime model and a clear concept of the role of entropy inequality are in the background. Both in quantum mechanics and in Newtonian gravity, perfect fields are holographic in the sense that the volumetric force density can be expressed as pressure divergence: the equation of field momentum conservation can be transformed into the form of a Newton equation. This classical holographic characteristic of perfect fields follows due to thermodynamic compatibility.

There is a bridge between field and particle representations of a physical system, the bridge is holography, and the key to holography is the Second Law of thermodynamics.

Glass transition as a topological phase transition

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The microscopic mechanisms that give rise to the glassy state of matter are still the subject of debate. In particular, it remains a debatable question: whether glasses can be considered as ultimate viscous liquids, or the glass phase is a result of a true thermodynamic phase transition to the solid state [1]. The presented work argues in favour of the second statement and shows that the transition to the glass phase can be fully described as a phase transition in a system of topological defects, i.e., as a topological phase transition.

This approach is not new. The theoretical description of the glass phase as a frozen system of topologically stable defects was actively developed at the end of the last century (see, for example, [2,3]). At that time, it was suggested that the transition to the glassy state is a topological phase transition [4]. In the presented work, a development of this approach is proposed.

It is shown that in the three-dimensional system of topological defects the phase transition can occur, the description of which is reduced to a simple model with the effective Hamiltonian of effective (gauge) field describing the interaction between topological defects [5,6]. Such a system is characterized by the presence of two spatial scales: the interaction radius, which is inversely proportional to the gauge field mass, and the correlation length of topological defects, which grows much faster than the interaction radius as the system approaches to the topological phase transition point. Using methods of nonequilibrium (critical) dynamics it is shown that the correlation length is proportional to the relaxation time, which divergence is described by the Vogel-Fulcher-Tammann law, and the glass transition temperature depends on the cooling rate [5,6]. The theory reproduces the most of characteristic thermodynamic and kinetic properties of glass transition: the behaviour of susceptibility, and non-linear susceptibilities; heat capacity behaviour; and ``boson peak'' near the glass transition temperature.

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Approximation of functional differential equations

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The fundamental importance of functional differential equations (FDEs) has been recognized in many areas of mathematical physics. A classical example is the Hopf characteristic functional equation of turbulence (Hopf, 1952). Such functional equation encodes the full statistical information of the stochastic solution to the Navier-Stokes equation, including multi-point statistical moments, cumulants, and multi-point joint probability density functions. For this reason, the Hopf characteristic functional equation was deemed by Monin and Yaglom (1972) to be ``the most compact formulation of the general turbulence problem'', which is the problem of determining the statistical properties of the velocity and the pressure fields solving the Navier-Stokes equations, given statistical information on the initial state. Another well-known example of functional differential equation is the Schwinger-Dyson equation of quantum field theory. Such equation describes the dynamics of the generating functional of the Green functions of a quantum field theory, allowing us to propagate quantum field interactions in a perturbation setting (e.g., with Feynman diagrams), or in a strong coupling regime. FDEs have recently appeared also in mean-field games, and mean-field optimal control. Mean-field games are optimization problems involving a large (potentially infinite) number of interacting players. In some cases, it is possible to reformulate such optimization problems in terms of a nonlinear Hamilton-Jacobi-Bellman FDE in a Wasserstein space of probability measures. This opens the possibility to formulate, e.g., deep learning as a mean-field optimal control problem via a functional HJB equation (E, Han & Li 2018).

Computing the solution to FDEs such as the Hopf characteristic functional equation or the functional HJB equation is a long-standing problem in mathematical physics. Back in 1972 Monin and Yaglom stated that: ``When we tried to develop a complete statistical description of turbulence with the aid of the Hopf equation for the characteristic functional we found that no general mathematical formalism for solving linear equations in functional derivatives was available.'' Since then there were of course advances in the theory of existence and uniqueness of solution to both linear and nonlinear FDEs, and also their approximation.

In this talk, I will present recent results on approximation theory of nonlinear functionals, functional derivatives, and functional differential equations (FDEs) in Hilbert and Banach spaces. The purpose of this analysis is twofold: first, we prove that continuous nonlinear functionals, functional derivatives and FDEs can be approximated uniformly on any compact subset of a real Banach space admitting a basis by high-dimensional multivariate functions and high-dimensional partial differential equations (PDEs), respectively. Second, we show that the convergence rate of such functional approximations can be exponential, depending on the regularity of the functional (in particular its Frechet differentiability), and its domain. We also provide necessary and sufficient conditions for consistency, stability and convergence of approximations to linear FDEs. These results open the possibility to utilize numerical techniques for high-dimensional systems such as deep neural networks and numerical tensor methods to approximate nonlinear functionals in terms of high-dimensional functions, and compute approximate solutions of FDEs by solving high-dimensional PDEs.

Single-stranded DNA-binding protein kinetics: theory and experiments.

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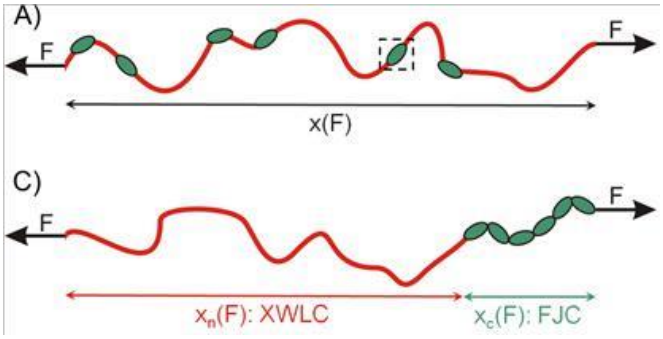
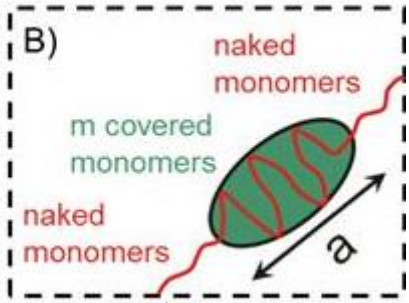
Single-stranded DNA-binding proteins (SSBs) play a key role in genome maintenance, binding and organizing single-stranded DNA (ssDNA) intermediates. Optical tweezers show that the human mitochondrial SSB (HmtSSB) (and also E. Coli SSB) binds to preformed ss-DNA in two major modes, depending on salt and SSB protein concentration [1,2]. The kinetics presents transitions between modes [1-3], which still require a full understanding at high coverages with the development of models with a correct biding site counting [4,5]. This model development has revealed two potential sources of cooperativity, enhancement of the binding or inhibition of the release due to the presence of neighboring bound SSB [5].





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The gradient-flow equations in information geometry: some approaches from geometrical optics to Randers-Finsler geometry

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Information geometry (IG) is a useful and powerful framework for studying some families of probability distributions by identifying the space of probability distributions with a differentiable manifold endowed with a Riemannian metric and an affine connection which is not necessarily Levi-Civita connection. In IG, a Riemann metric is obtained from the Hessian of a potential function, and the fluctuations play important role. Especially so-called fluctuation-response relations are related with the Hessian metric.

On the other hand it is known that the gradient-flow equations are useful for some optimization problems. The gradient flows on a Riemann manifold follow the direction of gradient descent (or ascent) in the landscape of a potential functional, with respect to the curved structure of the underlying metric space. The information geometric studies on the gradient systems were originally done by independently Nakamura, and Fujiwara and Amari. A remarkable feature of their works is that a certain kind of gradient flow on a dually flat space

can be expressed as a Hamilton flow. Later, several works on this issue have been done from the different perspectives. Boumuki and Noda studied the relationship between Hamiltonian flow and gradient flow from the perspective of symplectic geometries. The same issue was studied in from the perspective of geometric optics. The gradient-flows in IG are related to the thermodynamic processes. The analytical mechanical properties concerning the gradient-flow equations in IG are studied and discussed the deformations of the gradient-flow equations which lead to Randers-Finsler metrics.

In this contribution, we first explain some basics of the gradient-flow equations in IG. Then we show the geometrical optics approach based on the generalized eikonal equation, which is equivalent to Hamilton-Jacobi equation. Here null (or light-like) geodesics play central role. It is shown that the gradient-flows in IG are related to the Hamilton-flows associated with the so-called geodesic Hamiltonians. In conventional way of IG, the natural coordinate (θ- and η-) spaces are characterized with α-connections, which provide the parallel translation rule in these spaces. In addition, unlike Riemann geometry, the Hessian metrics g are used to determine the orthogonality only. The θ- and η-coordinate systems are regarded as the different coordinates on the same manifold. In contrast, in our perspective, the θ- and η-coordinate systems are regarded as the different spaces or manifolds. We will show some examples, e.g., the gradient-flows for the normal (Gaussian) probability distribution functions.

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Nonlinear constitutive relations by using some deformed functions

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Constitutive relations are fundamental and essential to characterize physical systems. They are combined with the other equations of the physical laws to solve physical problems. Some well-known examples of linear constitutive relations are as follows: Hooke's law ($F = k\ x$) for the tensile or compressive force F of a spring with a spring constant k against the change in its length x; Ohm's law ($V = R\ I$) for the voltage V of an electrical conductor with resistance R under an electric current I; and the relation $p = mv$ in analytical mechanics between the momentum p and the velocity v of a classical particle. However, as a real spring deviates from Hooke's law and as a real electrical resistance deviates from Ohm's law, we know that any linear constitutive relation describes an idealized situation, and it is merely a linearized-and/or approximatedrelation to describe some real physical properties. Hence, in general, a nonlinear constitutive relation plays a crucial role to describe more realistically physical systems and complex systems. It is known that some deformed functions are useful to describe a physical phenomenon which obeys an asymptotic power-law distribution, which maximizes an appropriate deformed entropy, e.g., Tsallis- or Kaniadakis-entropy, under the relevant constraints. In our previous work, we studied a thermal particle under a velocity-dependent potential which can be regarded as a deformation of Rayleigh's dissipation function, from which we can obtain the nonlinear constitutive relation between the dissipative force and the velocity of the thermal particle. We showed that the probability distribution function (pdf) for the stationary-state of this thermal particle is a κ-deformed Gaussian pdf. In this contribution we introduce the nonlinear constitutive relation which is deformed from a linear constitutive relation by using a deformed exponential or logarithmic function. For example, the linear constitutive relation of Ohm's law can be deformed as $V = R\ ln\ [exp\kappa\ (I)]$ by using the κ-exponential function $exp\kappa(x)$. For $\kappa \neq 0$, this

constitutive relation is nonlinear and reduced the original $V = R\ I$ in the limit of $\kappa \to 0$. In addition we show some basics of Rayleigh's dissipative functions and the related variational principle based on the so-called Rayleighians. We show some examples from the different fields, e.g, the velocity-dependent dry friction coefficients and Toda's nonlinear oscillators.

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Assessing the impact of climate change on fungal pathogens and insect pests in wheat: A joint species distribution model approach.

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Ecosystems are complex systems in which species do not exist in isolation; they co-occur and interact among others via competition, predation, and facilitation. These ecological interactions are critical to the functioning of ecosystems and provide the basis for biodiversity. In the face of ongoing climate change, these ecological interactions are also expected to change, including economically important interactions, such as those between a crop and its multiple fungal pathogens and insect pests. Wheat is the world's most important staple crop, and it is threatened by a range of fungal pathogens and insect pests. Acknowledging and accounting for multi-species interactions remain a challenge for species distribution models. Joint Species Distribution Models (JSDMs) are a relatively new statistical approach for analyzing multiple coexisting species in an assemblage or community. By using JSDMs, we can better understand the global distributions and co-occurrence patterns of fungal pathogens and insect pests in wheat and predict how these threats may affect wheat in the future.

In our study, we used JSDMs to analyze the distributions of wheat, its fungal pathogens, and insect pests globally. We incorporated climate change scenarios into our analyses to make predictions about the future. Our analyses can identify potential shifts in the hotspots of wheat pathogens and pests, revealing co-occurrence patterns in agro-ecosystems that have important ramifications for optimal control strategies. Our results showed that the distributions of fungal pathogens and insect pests in wheat are influenced by a complex set of factors, including climate, crop management practices, and geographic location. We found that certain regions, such as Europe and South Asia, are particularly vulnerable to multiple fungal pathogens and insect pests. Our analyses also revealed that the co-occurrence patterns of fungal pathogens and insect pests in wheat are likely to change in response to climate change, with some regions becoming more favorable for pests and pathogens, while others become less so. Our study highlights the importance of considering multi-species associations in species distribution models to better understand the impacts of climate change on ecosystems and to develop effective control strategies for pests and pathogens. By analyzing together crop, pathogen, and pest distributions, our work provides a valuable tool for predicting the effects of climate change on agro-ecosystems and can help inform strategies for sustainable food production.

Empirical observations of ultraslow diffusion driven by the fractional dynamics in languages: Fluctuation and dynamical properties of word counts of already popular words

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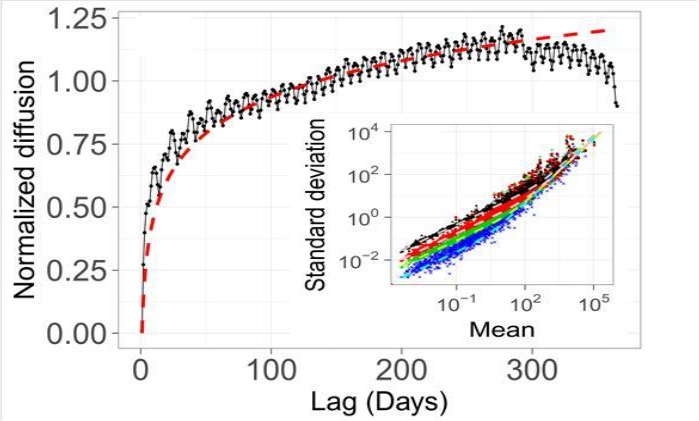
Ultraslow diffusion (i.e., a kind of logarithmic diffusion; the diffusion where the mean squared displacement is a power of the logarithm) has been extensively studied theoretically, but has hardly been observed empirically. In this research, firstly, we find the ultraslow-like diffusion of the time-series of word counts of already popular words by analysing three different nationwide language databases: (i) newspaper articles (Japanese), (ii) blog articles (Japanese), and (iii) page views of Wikipedia (English, French, Chinese, and Japanese). Secondly, we use theoretical analysis to show that this diffusion is basically explained by the random walk model with the power-law forgetting with the exponent $\beta \approx 0.5$, which is related to the fractional Langevin equation. The exponent β characterises the speed of forgetting and $\beta \approx 0.5$ corresponds to (i) the border (or thresholds) between the stationary and the nonstationary and (ii) the right-in-the-middle dynamics between the IID noise for $\beta = 1$ and the normal random walk for $\beta = 0$. Thirdly, the generative model of the time-series of word counts of already popular words, which is a kind of Poisson process with the Poisson parameter sampled by the above-mentioned random walk model, can almost reproduce not only the empirical mean-squared displacement (MSD) but also the power spectrum density (PSD) and the probability density function. In our presentation, in addition to the above, we will also report on the relationship between the ultraslow diffusion and the fluctuation scaling (FS). The FS is also known as “Taylor’s law” in ecology, is a power-law relation between the system size (e.g., a mean) and the magnitude of fluctuation (e.g., a stan-dard deviation). FS is observed in various complex systems, such as a random work on a complex network, internet traffic, foreign exchange markets, crimes etc. In particular, we will show that the time-scale-independent FS corresponds to essentially a logarithmic diffusion (i.e., a kind of ultraslow diffusion). The figure attached to this abstract shows the logarithmic diffusion in the 1771 main Japanese adjective ensembles (main figure) and the time-scale dependence of the scaling of their fluctuations (inset figure). In the main figure, the black circles are the logarithmic MSD in empirical data and a red dashed curve is theoretical curve (i.e., approximately logarithmic function). Colors and shapes in the inset figure represent the FS of the time series with difference time scales. Black triangles indicate for daily, red circles for weekly, green plusses for monthly and blue crosses for annual time series. Details of the figure are given in the Refs. [1] (the main figure) and [2] (inset figure).



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Nonlinear correlations in EEG signals

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The multiscale methodology is one of the primary methods for studying complex systems and analyzing complex time series, which are undoubtedly EEG signals from the human brain [1]. In the study, statistical analysis of the EEG data recorded during the resting state was performed for patients of the same age 30-40 with multiple sclerosis and the corresponding control group. The idea of the research was to examine differences in nonlinear cross-correlations, measured by the q-dependent detrended cross-correlation coefficient ρ(q,s) [2], between brain regions represented by electrodes for various factors such as the duration of the disease, the stage of the disease, which is measured by the Expanded Disability Status Scale (EDSS), and medications administered during treatment. The results presented in Fig contain the connections between two electrodes that exist, when the difference between the two groups for these electrodes is statistically significant. The most significant differences are observed in the case where correlation matrices for patients in different stages of the disease (quantified by EDSS) with EDSS>1 and with EDSS<=1 are compared. Differences between groups of patients who were being treated with Tecfidera, and patients who were being treated with Interferon. Furthermore, the the fractal and multifractal properties of the EEG time series for 20 representative electrodes were also studied by using a multifractal detrended fluctuation analysis [3]. These measures can quantitatively describe the persistence and complexity of the considered time series [4,5]. Looking at the differences in the width of the multifractal spectrum and Hurst exponent values, it was possible to distinguish between the stage of the disease and the type of drug. There was almost no difference when the duration of the disease was taken into account. All observed differences were stronger in the phase of the experiment with closed eyes, which may be related to the delta waveform. It is also worth noting that the highest differences were observed in the time scale range s = 200ms−2500ms (5Hz−0.4Hz), which corresponds to the delta wave.

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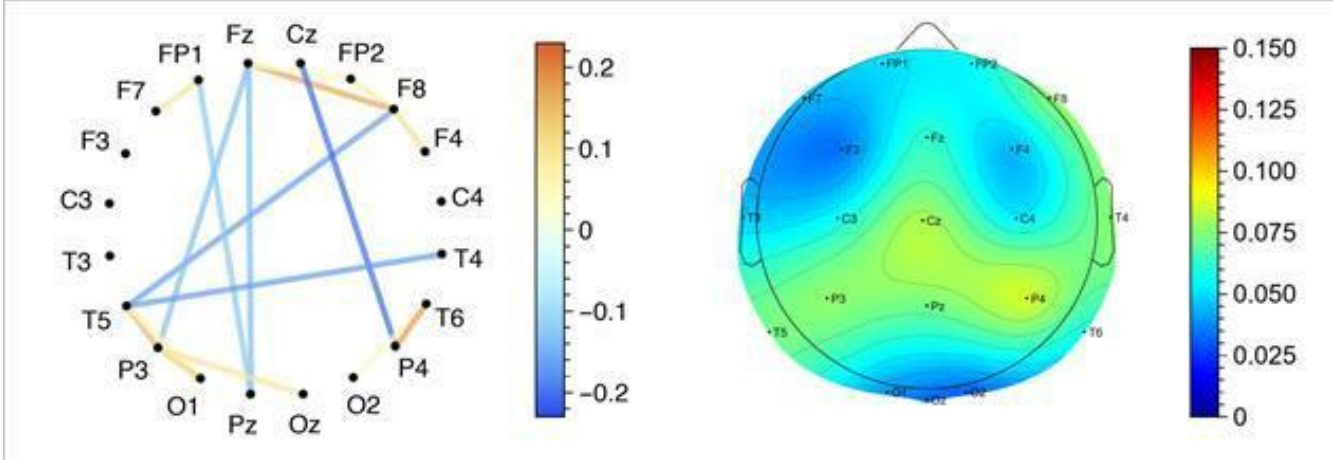

Whistler waves and magnetotail bursty bulk flows as a source for earth's diffuse aurora

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Electron cyclotron harmonic (ECH) and whistler chorus waves are the two primary mechanisms underlying the resonant wave-particle interactions that precipitate plasma sheet electrons into the Earth's ionospheric diffuse Aurora. Previous work has demonstrated that ECH waves dominate scattering of plasma sheet electrons further from Earth (at L shells > 8), while whistler chorus emissions dominate scattering closer to the Earth (at L shells L < 8). However, we find from the THEMIS (Time History of Events and Macroscale Interactions) constellation of spacecraft at L = 12 that, during substorms in the magnetotail, bursty bulk flows produce oblique whistler chorus emissions that surpass the scattering efficiency of parallel whistler waves and the local ECH waves. Previously, researchers have observed that betatron acceleration in the magnetotail creates the electron temperature anisotropy Te,⊥/Te,||> 1 that serves as the free energy source for whistler- mode waves. Here, however, we find parallel electron beams and Te,⊥/Te,||< 1. The parallel electron beams are produced by Fermi acceleration at magnetic dipolarization fronts in the bulk flows. The parallel electron beams provide an effective energy source for oblique whistler chorus waves, and the whistler waves' oblique propagation direction enhances the efficient scattering of lower-energy electrons into the diffuse aurora. We conclude that Fermi acceleration of electrons provides one important free-energy source for the wave- particle interactions responsible for coupling plasma sheet electrons into the diffuse aurora during magnetotail substorm conditions. It is likely that the Fermi acceleration results from magnetotail magnetic reconnection.

Network reconstruction from noisy and incomplete spreading dynamics

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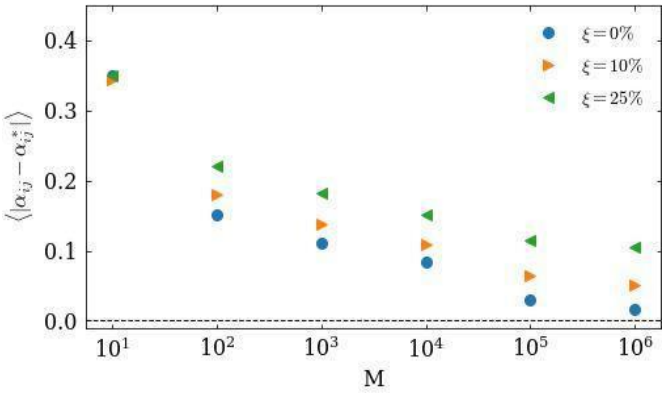
Long distance connections in modern interconnected world play an important role in many areas of life, such as information spreading, epidemics, financial contagion or opinion dynamics. This drives the need for proper understanding of diffusion processes on networks. Another unprecedented feature of current era is the data availability, which, together with rapid development of machine learning tools, allow to learn and predict models from observed processes. In reality, however, these large amounts of data are often incomplete, noisy or biased. We address this problem in the case of spreading processes on networks and propose a general framework, which allow to learn spreading models from data, when the latter is incomplete or subject to uncertainty. Starting from an algorithm based on dynamic message passing, we propose an extended methodology, which allows to learn spreading parameters, together with the network structure, when not only part of the nodes is unobserved, but there is an additional uncertainty regarding the observed part. Since the algorithm is based on a message passing inference procedure, it is particularly useful in the case of locally treelike graphs. Additionally, we present an effective implementation of the algorithm, which assures linear complexity even for heterogeneous networks and show how the procedure can be more effective when an additional information about the process is known. The approach can also be extended towards building effective models, which can have significant predictive power, even in the case where the graph is loopy. We show the effectiveness of our algorithm both on different types of synthetic networks, including scale-free and regular graphs, as well as on real-world networks. We test different scenarios of data incompleteness and uncertainty, together with their combinations. We also explore the limits of the algorithm and its dependence on the network structure. Finally, we present a full derivation of the dynamic message passing equations from the canonical dynamic belief propagation, utilizing the

knowledge about particular type of dynamics. Quality of results in the case of a Facebook subgraph with both unobserved nodes and noisy observations, is shown in the attached figure. It shows the expected error of reconstructed spreading parameters as a function of the sample size and for different percentage of unobserved nodes.



Particle velocity distribution function measurements in the solar wind: Why we need to do better

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The solar wind is a supersonic flow of ionized particles, called a plasma, streaming away from the Sun. These particles are not observed to be in thermal or thermodynamic equilibrium. This is because nearly all particle dynamics are governed by non-collisional processes and the particles experience long-range forces (i.e., Coulomb potentials of nearby, charged particles). There are multiple particle species in the solar wind as well, including but not limited to electrons, protons, alpha-particles, and multiple charge states of heavier ions up past uranium. When we observe particle velocity distribution functions (VDFs), they exhibit non-Maxwellian features. In fact, we do not see any VDFs that are consistent with Maxwellian or even bi-Maxwellian distributions. All electron VDFs observed to date in the solar wind have nonthermal tails and/or multiple phase space density peaks and/or self-similar profiles. Presumably the proton and alpha-particle core populations of the solar wind exhibit similar subpopulations but we lack the measurement resolution to observe them. There is evidence of this much closer to the Sun observed by Parker Solar Probe, where the solar wind speed is lower and temperature much higher (i.e., effective velocity resolution of measurements increases). Near-Earth solar wind measurements, however, are all under-resolved. We discuss the consequences of these limitatiions using numerically integrated velocity moments.

Related works
Wilson et al., Astrophys. J. Suppl. 243 (2019).
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Magnetospheric multiscale observations of Kappa distributions in the magnetosheath on small scales

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We discuss the results of statistical analysis of magnetic field fluctuations in the magnetosheath using the data from the Magnetospheric Multiscale (MMS) mission on extremely small kinetic scales [1]. We have shown that the turbulence cascade exhibits features characteristic for Markov processes. The solutions of the Fokker-Planck equation agree with experimental probability density functions, from the kappa distributions to the normal Gaussian distribution for large inertial scales, which exhibit a universal global scale invariance through the kinetic domain. We compare the characteristics of turbulence at various regions in Earth's space environment: behind the bow shock, inside the magnetosheath, and near the magnetopause. It is interesting to note that on kinetic scales magnetic turbulence is consistent with a generalized Ornstein-Uhlenbeck process. The obtained results especially on kinetic scales could be important for a better understanding of the physical mechanism governing turbulent systems in laboratory and space plasmas.

Acknowledgments: This work has been supported by the National Science Center, Poland (NCN), through grant No. 2021/41/B/ST10/00823.

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Spatial effects on epidemics diffusion: Network topological characteristics leading to power-law time-dependent growth

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During the initial phase of the covid-19 epidemic, it has been observed that the pathogen diffusion is characterized by a power-law growth [1, 2]. This sub-exponential increase appears independent of geographical or socio-economic parameters, given that it is shown for several China provinces and European countries. Historically, a quadratic diffusion has been also reported for other epidemics, such as AIDS. The persistence of such scaling in diverse systems sets a challenge for epidemiological modeling. In the current work, we first note that power-law scaling is a general diffusion characteristic not restricted to epidemics among humans. In particular, we juxtapose the Covid-19 and the AIDS epidemics to highly contagious disease in animal livestock, by revisiting foot-and-mouth data from the 1967 and 2001 outbreaks in the UK. We find similar power exponents over the initial diffusion period, even before mitigation measures been taken to reduce contagion. Traditionally, efforts to address diffusion characteristics like the sub-exponential growth or a reduced population size in herd immunity are considered in the framework of "fully mixed" models (such as SIR or SEIR). The aim is to reduce the presumed efficiency of the susceptible "S" or infected "I" populations in the contagion process in a variety of ways, such as: By introducing nonlinearity in the S and/or I interaction terms of the model [3]; by assuming heterogeneity in the susceptibility or the transmissivity of the populations [4]; by inferring a particular generic transmission mechanism [1, 5]. In our approach, however, in the framework of "agent based models", we note that such assumptions may not be needed: A power-law scaling may well be a purely geometric effect, resulting from spatial/topological characteristics of the associations among the involved agents [6]. We demonstrate this in numerical simulations on 2-D Cartesian lattices, with and without small world structure, where contagion is spread in various ways: When infection progresses from nearest and next nearest neighbors; from long-distant neighbors; due to external influence that infects random sites. In all cases studied, we find a Weibull closed form for the aggregated disease propagation, which is reduced to a power-law growth at small times. Using this analytic tool we also discuss the spatial disease spread in interconnected geographical regions, where a Pareto distribution has been observed [7]. We thus argue that spatial/topological characteristics of the associations among agents involved in the contagion should be explicitly taken into account when analyzing basic features of the epidemics diffusion.

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Economic inequality from a statistical physics point of view

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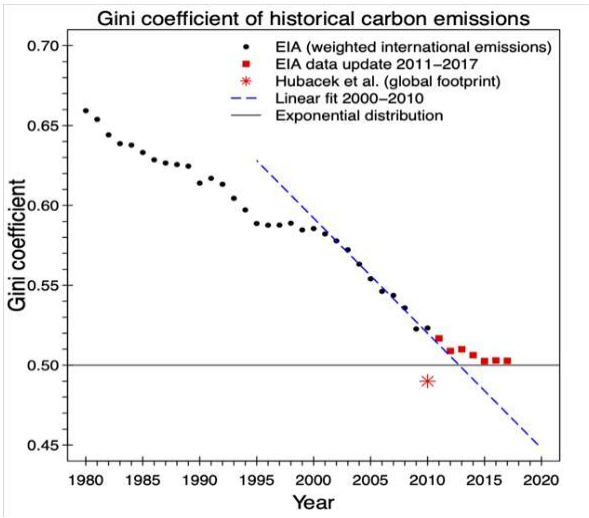
Inequality is an important and seemingly inevitable aspect of the human society. Various manifestations of inequality can be derived from the concept of entropy in statistical physics. In a stylized model of monetary economy, with a constrained money supply implicitly reflecting constrained resources, the probability distribution of money among the agents converges to the exponential Boltzmann-Gibbs law due to entropy maximization. Our empirical data analysis [1] shows that income distributions in the USA and other countries exhibit a well-defined two-class structure. The majority of the population (about 97%) belongs to the lower class characterized by the exponential ("thermal") distribution, which we observed in the data for 67 countries around the world [2]. In contrast, the upper class (about 3% of the population) is characterized by the Pareto power-law ("superthermal") distribution, and its share of the total income expands and contracts dramatically during booms and busts in financial markets [1]. In Ref. [3], we found that global inequality in energy consumption and CO2 emissions per capita around the world has been steadily decreasing in 1980-2010, and the corresponding distributions became approximately exponential by 2010. We attributed this outcome to globalization of the world economy, which mixes the world and brings it closer to the state of maximal entropy. In Ref. [3], we predicted that global inequality will soon stop decreasing and will saturate at the Gini coefficient G=0.5 corresponding to the exponential distribution. This prediction has been remarkably confirmed in Ref. [4] after the more recent data up to 2017 became available, as shown in the Figure. The black circles for 1980-2010, analyzed in Ref. [3], manifest a decreasing trend and no sign of saturation yet. But the new data points for 2011-2017, shown by red squares, exhibit the predicted saturation at G=0.5. The Figure demonstrates that the decrease of global inequality has stopped once the exponential distribution, corresponding to maximal entropy, had been reached. This observation has profound consequences for strategies and scenarios dealing with the climate change [4].



All papers are available at:
http://physics.umd.edu/~yakovenk/econophysics/

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Studying the stability of a quantum chaotic system at finite temperature via coupling to a 2-level probe

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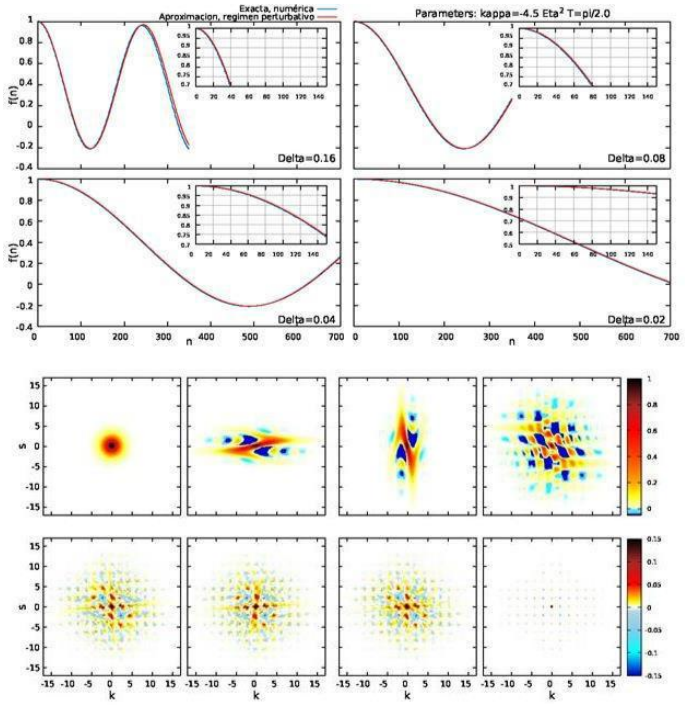
We start by considering the kicked harmonic oscillator (KHO) as a closed quantum chaotic system with unitary dynamics. In this case, the dynamics is given in terms of a Floquet operator. Then we calculate the fidelity amplitude as a function of time, where we perturb the system by small changes of the kick strength. Our results for this part show that we can go from the perturvative regime to the Fermi Golden Rule regime via changing the Lamb-Dicke parameter (effective Plank constant) and/or the perturbation strength [Fig 1]. In the second part of the work, we consider the KHO in thermal contact with a finite temperature heat bath and coupled to a two-level system. The latter is done in such a way (dephasing coupling) that the coherence in the two-level system becomes equal to the fidelity amplitude in the limit of the closed system (reducing the coupling to the heat bath to zero). For the simulations, we use the "chord function", the double Fourier transform of the Wigner function as introduced in Prado et al PRA(2017). There we find an interesting crystalline structure, despite the system is chaotic in the sense of quantum chaos [Fig 2]. In the presence of the heat bath, the decay of the coherence in the 2-level system has no longer an immediate interpretation as a fidelity for the non-unitary dynamics with and without perturbation. Never the less, the quantity can give relevant information about the properties of the KHO at finite temperature [López et al J.Phys.A(2020)]. In particular we verify the RMT prediction [Moreno et al PRA(2015)] that an increasing the coupling to the heat bath, slows down the decay of the coherence in the 2-level system.



Generation of Kappa-like electron velocity distribution function by Whistler and Langmuir mode wave spectra

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Charged particles in magnetized plasma environment such as the solar wind or planetary magnetosphere pervasively feature non-thermal energetic (tail) population. Such a feature has been modeled by the so-called Olbert-Vasyliunas Kappa distribution since the 1970s, which is a purely empirical model. However, since the trail-blazing work by Tsallis in the late 1980s, the space plasma community has adopted the Tsallis non-extensive statistical theory as a fundamental explanation for the Kappa model. Such an effort, which began in the early 2000s, was led by, among others, Leubner, Livadiotis, Lazar, and others. While the non-extensive statistical framework provides a conceptual foundation for the Kappa distribution, it is true that the physical mechanisms that undergird the notion of non-extensive nature of a statistical system are not widely available. One of them is the asymptotic theory of Langmuir turbulence by Yoon, proposed in a series papers published in mid 2010s. According to this theory, the long-time steady-state Langmuir turbulence spectrum is commensurate only with the electron Kappa distribution and no other velocity distribution functions. While such a theory represents one of the few physical mechanisms that actually leads to the formation of

Kappa distribution, the theory assumes an unmagnetized plasma. Space and laboratory plasmas are usually immersed in the background of ambient magnetic field. The extension of Yoon's asymptotic weak turbulence theory to magnetized plasmas is yet to be done. Instead, for magnetized plasmas, a number of approaches are taken in the literature to explain the formation of Kappa distribution. These models usually assume a background of wave spectrum, with which, one solves the quasilinear kinetic equation in order to obtain a Kappa-like solution for the particle distribution function - see, for instance, the paper by Ma and Summers (1998), or Kim et al. (2016). The present paper also takes a similar approach, but in the present model, the quasilinear kinetic equation that includes the effects of spontaneously-emitted wave fluctuations are also included. By adopting such a model, it is demonstrated that a steady-state Kappa-like electron velocity distribution function in magnetized plasma emerges when the electrons are immersed in the background permeated by a constant magnetic field plus the spectra of whistler-mode and Langmuir-wave fluctuations. It can be shown that steady-state solution of the quasilinear Fokker-Planck equation leads to a Kappa-like model with an exponential cutoff factor. Such a model is equivalent to the recently proposed regularized Kappa distribution by Scherer et al (2018). While Scherer et al.'s motivation was to put forth a mathematical model to avoid the divergence of higher-order velocity moments in Kappa model, such a model is a natural consequence of the present theory.

On the global warming projection: a new approach based on scaling theory

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Global warming exerts a strong impact on the Earth system. Despite recent progress, the current Earth System Models (ESMs) still project a large range of possible warming levels. Particularly, the most recent generation of the ESMs from the Coupled Model Intercomparison Project Phase 6 (CMIP6) have been found to have the so-called "hot-model" problem. That is, many CMIP6 models may have overestimated the future warming trend under a given scenario (e.g., SSPs). In order to cope with the impacts of global warming, an improved projection of the future warming trend would thus be highly required. In addition to further developing the ESMs, alternative ways would be also worth a try. Here in this talk, I will show that the future global warming trend may be reliably projected from the perspective of statistical physics. It has been well recognized that the variability of many climatic variables (including the global mean surface temperature, GMST) has scaling behavior ranging from months to decades. This scaling behavior may induce long-term memory, which has been widely detected in the climate system. By introducing fractional integrals, recently a generalized stochastic climate model, namely the fractional integral statistical model (FISM), has been proposed to simulate the scaling behaviors revealed in many climatic records. One advantage of the FISM is that it can quantify the climate memory signal and further decompose a given timeseries into the memory part and the non-memory part. By employing this model, the GMST can be decomposed into the "direct-forcing-response" and the "indirect-memory-response". In this way, a response operator was derived, with which one can compute the global mean surface temperature given specific forcing scenarios to quantify the impact of past emissions on current warming. Based on historical records, the trend of the direct-forcing-response is found to be weak, while the major portion of the observed global warming trend was attributed to the indirect-memory responses that are accumulated from past emissions. Compared to CMIP6 simulations, this approach projects lower global warming levels over the next few decades. The results suggest that CMIP6 models may have a higher transient climate sensitivity than warranted from the observational record, due to them having larger long-term memory than observed.

Diffusion of an intruder in a molecular/granular gas as a random walk

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It is well known that by using elementary random walk (RW) arguments it is possible to obtain a rough estimate of the mean square displacement (MSD) of a molecule moving in a gas of elastic hard spheres. However, this result is not very good: the difference between the diffusion coefficient thus obtained, $D=\lambda v/3$, and the diffusion coefficient obtained from the standard kinetic theory (e.g. Chapman-Enskog expression in the so-called first Sonine approximation) or simulation results is remarkable, exceeding 40%. (Here λ is the mean free path of the molecule and v is its mean speed.) The origin of this large discrepancy lies in the fact that the above simple random walk calculation neglects the correlation between the directions of the particle velocities before and after each binary collision. In fact, it is known that if this sort of correlation were rigorously taken into account, the results derived from the RW theory would be consistent with those obtained by solving the Boltzmann equation with the Chapman-Enskog method. Here we estimate the MSD of an intruder (or walker) immersed in an ordinary gas using a RW (or free path) method that considers the correlations between the directions of the molecules before and after each collision. In the case of an elastic intruder moving in an ordinary gas of elastic hard spheres, our method gives results for the self-diffusion coefficient that differ by less than 4% from those obtained by the Sonine approximation of order 9. When the intruder and particles of the gas are mechanically different, we find that the RW results for the corresponding diffusion coefficient do not differ by more than 15%, and this happens only in the extreme case when the mass of intruder is much larger than that of the particles of the gas. Our procedure can also be generalized to the case of a grain moving in a gas of elastic hard spheres (i.e., when grain-gas particle collisions are inelastic and characterized by a constant coefficient of restitution). In this case, the difference between the RW results and those derived in the second Sonine approximation is typically a few percent units. Finally, it is also possible to extend the method to the case of an intruder (grain) moving in a freely cooling granular gas (modelled as a gas of smooth inelastic hard spheres). In this situation, we analyze how the inelasticity of collisions modifies the MSD of the intruder. The results are generally very good (in some cases even excellent) when compared with simulation results and with the first and second Sonine approximations.

Thermodynamical consistency of entropic cosmological models

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Entropic-force cosmology provides, in contrast with dark energy descriptions, a concrete physical understanding of the accelerated expansion of the universe. The acceleration appears to be a consequence of the entropy associated with the information storage in the universe. In this presentation, I analyze the thermodynamical consistency of entropic-force cosmological models based on a generalized entropy scaling with an arbitrary power of the Hubble radius. The Bekenstein-Hawking entropy, proportional to the area, and the nonadditive-entropy, proportional to the volume, are particular cases. Two points to be solved by entropic-force cosmology for being taken as a serious alternative to mainstream cosmology is 1-to provide a physical principle that points out which entropy and temperature have to be used, and 2-explain the different periods of acceleration and deceleration. In this work, a simple physical principle is proposed: the temperature of the universe horizon is determined by requiring that the Legendre structure of thermodynamics is preserved. Since these cosmological models are unable of explaining the different periods of acceleration and deceleration unless a correction term is considered, we also study the effects of including a subdominant power-law term. I show that the introduced correction term is capable of explaining different periods of acceleration and deceleration in the late-time universe and I compare

the performance of thermodynamically consistent entropic-force models with regard to the available supernovae data. The results point out that the temperature differs from the Hawking one, and that some entropic-force cosmological models previously available in the literature are not thermodynamically consistent.

Periodicities in solar activity, solar radiation and their links with terrestrial environment

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In this paper, a spectral analysis of the averaged sunspot numbers, solar irradiance, and the summary curve of eigenvectors of SBMF was carried out using Morlet wavelet and Fourier transforms. We detect a 10.7-year cycle from the sunspots and modulus summary curve of eigenvectors as well a 22 years cycle and the grand solar cycle of 342-350-years from the summary curve of eigen- vectors. The Gleissberg centennial cycle is only detected on the full set of averaged sunspot numbers for 400 years or by adding a quadruple component to the summary curve of eigen- vectors. Another period of 2200-2300 years is detected in the Holocene data of solar irradiance measured from the abundance of 14C isotope. This period was also confirmed with the period of about 2000-2100 years derived from a baseline of the so- lar background magnetic field, supposedly, caused by the solar inertial motion (SIM) induced by the gravitation of large planets. The implication of these findings for different deposition of solar radiation into the northern and southern hemispheres of the Earth caused by the combined effects of the solar activity and solar inertial motion caused by the gravitation of large planets on the terrestrial temperature are discussed.

Generalized entropy production and nonthermal particle acceleration in collisionless plasmas

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Collisionless plasmas develop nonthermal particle distributions after being energized, and thus enter a state of non-maximal Boltzmann-Gibbs entropy. While the Vlasov equation predicts that Boltzmann-Gibbs entropy is formally conserved (along with an infinite set of other Casimir invariants), coarse-grained entropy production is enabled by phase mixing and nonlinear entropy cascades. Characterizing the nature and extent of entropy production for various irreversible processes is a key problem in plasma physics. I will describe a theoretical framework for representing entropy production via an infinite set of dimensional quantities, the "Casimir momenta", which generalize the Boltzmann-Gibbs entropy. Evolution of the Casimir momenta indicates violation of the Vlasov equation (and therefore irreversibility) at the corresponding energy scales. I will describe how Casimir momenta can be used as a diagnostic to demonstrate efficient entropy production (skewed toward high energies) in particle-in-cell simulations of relativistic turbulence. I will also describe the application of Casimir momenta to modeling nonthermal particle acceleration in turbulence and magnetic reconnection, where kappa distributions are obtained by maximizing the Casimir momenta subject to the energy constraint. This framework may be applied to model astrophysical and space systems, such as the solar wind and Earth's magnetosphere.

Pitch-angle distribution of accelerated electrons in 3D current sheets with magnetic islands

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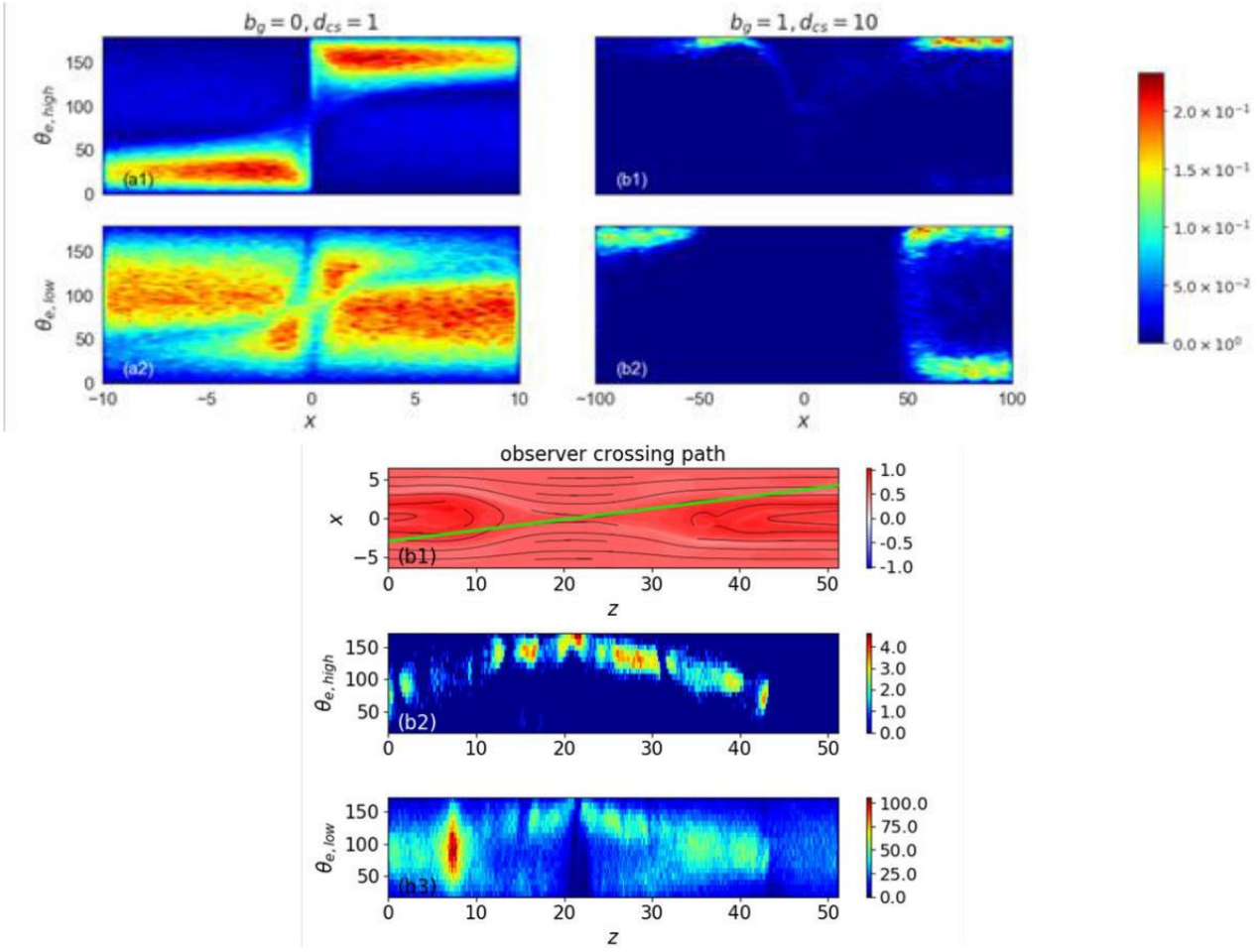
We will explore variations of electron pitch-angle distributions (PADs) during spacecraft crossing of reconnecting current sheets (RCSs) with magnetic islands. Our results can benchmark the sampled characteristic features with realistic piych-angle distributions (PADs) derived from in situ observations. Particle motion is simulated in 2.5D Harris-type RCSs using the particle-in-cell method and considering the plasma feed- back to electromagnetic fields induced by accelerated particles. We evaluate particle energy gains and PADs in different locations with virtual spacecraft passing the current sheet while moving in the different directions. The RCS parameters are comparable to heliosphere and solar wind conditions. We will report the simulated energy gains and PADs of particles depending on the specific topology of the magnetic fields. In addition, we demonstrate that the observed PADs depend on the crossing paths of the spacecraft. It was found that when the guiding field is weak, there are the bi-directional electron beams (strahls) are located just above or below the X-nullpoints in the inflow regions. The magnetic field relaxation near the X-nullpoint alters the PADs towards 90◦. As the guiding field becomes larger, the regions with bi-directional strahls are compressed towards small areas in the exhausts of RCSs. Mono-directional strahls are quasi-parallel to the magnetic field lines near the X-nullpoint due to the dominant Fermi-type magnetic curvature-drift acceleration. Meanwhile, the high-energy electrons confined inside magnetic islands create PADs of around 90 degrees. The simulated PADs can help to explain a variety of the electron features reported in recent observations in the solar wind and the Earth's magnetosphere.



Dimensional measures of generalized entropy for statistical physics

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Entropy is useful in statistical physics as a measure of irreversibility, randomness, mixing, dispersion, and number of microstates. However, there remains ambiguity over the generalization of entropy beyond the additive definition pioneered by Boltzmann, Gibbs, and Shannon. For generalized entropies to be applied to their full potential in nonequilibrium statistical mechanics, there is a need for a physically interpretable (dimensional) framework that can be connected to dynamical processes operating in phase space. To this end, I will present dimensional measures of entropy that admit arbitrary invertible weight functions (subject to curvature and convergence requirements). These ``dimensional entropies'' represent the phase-space volume occupied by level sets of the distribution function. For sufficiently structured distributions, they are sensitive to perturbations at a similar phase-space scale. Dimensional entropies may be useful as a diagnostic (for irreversibility) and for theoretical modeling (if the underlying irreversible processes in phase space are understood) in chaotic and complex systems.

Turbulence magnetic reconnection experiments driven by intense lasers

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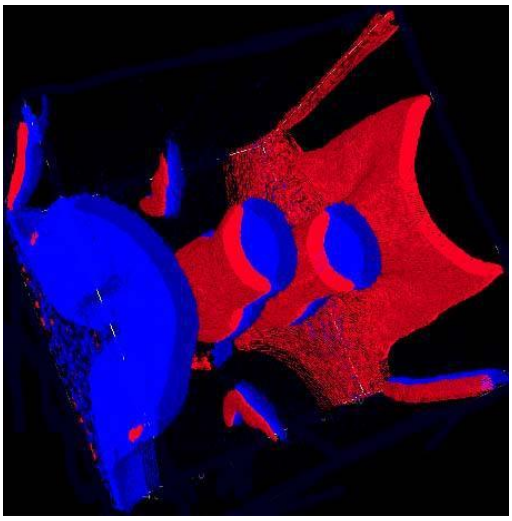
Turbulent magnetic reconnection is believed to occur in astrophysical plasmas, and it has been suggested to be a trigger of solar flares. It often occurs in long stretched and fragmented current sheets. Recent observations agree with signatures expected from turbulent reconnection. However, the underlying mechanisms remain unclear, including how magnetic energy stored in the Sun's magnetic field is dissipated. We demonstrate turbulent magnetic reconnection in laser-generated plasmas created when irradiating solid targets. Turbulence is generated by strongly driven magnetic reconnection, which fragments the current sheet, and we also observe the formation of multiple magnetic islands and flux tubes. Our findings reproduce key features of solar flare observations. Supported by kinetic simulations, we reveal the mechanism underlying the electron acceleration in turbulent magnetic reconnection dominated by the parallel electric field. In contrast, the betatron mechanism is cooling, and Fermi acceleration is negligible. As the conditions in our laboratory experiments are scalable to those of astrophysical plasmas, our results apply to the study of solar flares.



Hamiltonian operators in quantum-statistical formalism: Is it time to move on from hermiticity to normality?

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In the conventional quantum mechanics, Hamiltonian is usually assumed to be a Hermitian operator. This assumption is certainly sufficient in a case of conservative systems. But what if our Hamiltonian acquires an anti-Hermitian part thus becoming strongly non-Hermitian? At first glance, this generalization might bring imaginary parts into energy (eigen)values, which would be in an obvious contradiction with energy's physical meaning. It turns out however that non-Hermitian Hamiltonians

do not act that way in, if they are being properly implemented, therefore strict hermiticity is nor longer necessary. Instead, anti-Hermitian parts of Hamiltonian can be used to describe the effects of dissipative environment and/or noise, whereas their Hermitian parts refer to subsystems' energies, similarly to conserved systems. Within the framework of the standard quantum-statistical approach to dissipative phenomena based on a master equation for the reduced density operator, we discuss replacement of the hermiticity condition by a more general condition of normality, i.e., commutativity between Hermitian and anti-Hermitian parts of a Hamiltonian operator. Some introductory reading can be found in [1], full bibliography [2].

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Spin models for efficient prediction of massive spatial data

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The steadily increasing volume of Earth observation data collected by remote sensing techniques requires the development of new methods capable of efficient (preferably real time) and automated processing. Such processing includes filling gaps with missing values, which often occur due to different reasons. Application of standard kriging methods in such situations is hindered by their high computational complexity and also necessity of certain user-specified inputs. As an alternative to the traditional methods, a computationally efficient approach inspired from statistical physics has been proposed [1]. Instead of the empirical variogram used in geostatistics it employs Boltzmann-Gibbs random fields with joint densities that model spatial correlations by means of short-range interactions. It can be applied to both gridded and scatted data, nevertheless, is still relies on the assumption that the data follow Gaussian distribution.

In this presentation, we extend the concept of deriving correlations from local interactions to non-Gaussian data by means of classical spin models [2]. Special focus is laid on the application of the planar rotator (or XY) model, modified [3] and generalized [4] to account for spatial correlations and data distributions characteristic for geophysical and environmental data sets. The proposed methods include both non-parametric and parametric approaches and employ efficient hybrid conditional Monte Carlo (MC) simulations. They turn out to be competitive with more traditional approaches in terms of the prediction performance but at the same time computationally very efficient with only roughly linear increase of the CPU time with the data size. Generalization of the methods proposed for 2D regular grids to scattered data in arbitrary dimension will be outlined.

Further, it will be demonstrated how the short-range nature of the interactions between the spin variables can be utilized to parallelize the algorithm on graphics processing units (GPUs) and thus dramatically improve its computational performance [5]. The achieved computational speedups (up to almost 500 times on large grids) compared to single-processor calculations, allow processing of massive data sets comprising millions of points automatically in less than one second on an ordinary GPU-equipped PC. Another advantage of the GPU implementation is that it facilitates a rather simple but general approach to modelling spatial heterogeneity by introducing spatial variability to model parameters. Then the predictions can be obtained based on "local-equilibrium" conditional MC simulations.

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