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

Martino Lovisetto[1], Maria Chiara Braidotti[2], Radivoje Prizia[2], Claire Michel[1], Didier Clamond[1], Ewan M. Wright[3], Matthieu Bellec[1], **Bruno Marcos[1]**, Daniele Faccio[2]
*[1]Université Côte d'Azur, Nice, France, [2]University of Glasgow, Glasgow, United Kingdom, [3]University of Arizona, Tucson, United States of America*

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.

References

[1] J. Binney, S. Tremaine, Galactic Dynamics: Second Edition (Princeton University Press, 2008).
[2] I. S. Chandrasekhar, Astr. J. 93, 285 (1941).
[3] B. Anguiano et al., Astr. J. 160, 43 (2020).
[4] D. Lynden-Bell, Mon. Notices Royal Astron. Soc. 136, 101 (1967).
[5] A. Campa, T. Dauxois, and S. Ruffo, Phys. Rep. 480, 57 (2009).
[6] M. Chalony et al., Phys. Rev. A 87, 013401 (2013).
[7] F. Zwicky, Helv. Phys. Acta 6, 110 (1933).
[8] W. Hu, R. Barkana, and A. Gruzinov, Phys. Rev. Lett. 85, 1158 (2000).
[9] M. Lovisetto et al., arXiv:2205.10948 (2022).