Two stories of metastability: Real-time dynamics of vacuum decay and long-range nucleation

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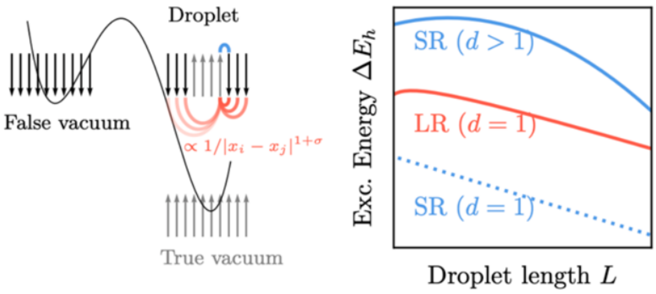
False vacuum decay is one of the characteristic phenomena of quantum field theory with a wide range of applications in physics. Examples in particle physics and cosmology include the stability of the current electroweak minimum [1], the electroweak phase transition, and inflationary models. The decay of the false vacuum has been studied in numerous works, building on Langer's theory of bubble nucleation and the foundational description by Callan and Coleman [2], which was extended to thermal field theory by Linde [3]. In general, the decay of a metastable vacuum consists of a first-order phase transition where the order parameter changes from a metastable phase to a stable phase. The transition may occur through nucleation of bubbles caused by quantum-statistical fluctuations. Bubbles below a critical size collapse due to the overwhelming surface energy cost, while larger bubbles grow rapidly and eventually fill space to complete the phase transition.

This phenomenon has attracted renewed interest, driven in particular by experiments with analog quantum simulators, which enable direct access to the real-time dynamics of the transition and have uncovered novel dynamical aspects such as oscillon precursors and time-dependent rates in non-equilibrium scenarios. At the same time, many such platforms — including trapped-ion Ising simulators with tunable power-law interactions and Rydberg-atom arrays with dipolar $1/r^3$ or van der Waals $1/r^6$ tails — exhibit genuinely long-range couplings. In these systems, non-locality can effectively alter the spatial dimensionality — much as in critical long-range systems — fundamentally reshaping nucleation barriers and droplet morphologies compared to short-range predictions. Moreover, long-range interactions can render metastable phases effectively stable, producing apparent bistability with algebraically diverging lifetimes.

In the first part of this talk, we treat false vacuum decay as a real-time, non-equilibrium problem and simulate its full dynamical evolution, extracting time-resolved decay rates and identifying genuinely quantum effects responsible for transitions beyond classical-statistical descriptions [4]. In the second part, we study how long-range interactions modify bubble nucleation — the formation of a critical droplet that triggers decay [5]. We demonstrate that long-range couplings effectively raise the spatial dimensionality: nucleation in one-dimensional long-range models proceeds analogously to short-range models in higher dimensions. To capture this, we develop a numerical method based on the fractional-Laplacian saddle-point equation, which gives direct access to the static critical-droplet profile and the corresponding nucleation rate. Focusing on a one-dimensional nonlocal ϕ^4 field theory, we find that the critical configuration develops distinctive algebraic tails, while recovering the scaling laws predicted by the exact lattice theory. Our findings are directly relevant to quantum simulation platforms and magnetic materials realizing power-law couplings.



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