CRITICAL AGING AND RELAXATION DYNAMICS IN LONG-RANGE SYSTEMS

Valerio Pagni [1,*], Friederike Ihssen[2,1], Nicolò Defenu[1] (the presenting author underlined)

[1]Institut für Theoretische Physik, ETH Zürich, Wolfgang-Pauli-Str. 27, 8093 Zürich, Switzerland
[2]Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany
[*]vpagni@phys.ethz.ch

ABSTRACT

We investigate the dynamical scaling properties of a long-range O(N) model subjected to a sudden quench to its critical temperature [1], with a particular emphasis on the resulting aging behavior and the broader implications for non-equilibrium statistical mechanics. In systems with long-range interactions characterized by a power-law decay, the interplay between spatial correlations and temporal evolution presents rich and tunable dynamical regimes [2]. By systematically varying the range of interactions, we demonstrate that the aging exponent of the system can be effectively controlled, revealing a direct mechanism for modifying the dynamical scaling properties. This tunability offers a powerful means to explore a wide spectrum of non-equilibrium behaviors, ranging from those characteristic of short-range interacting systems to novel scaling regimes unique to long-range models.

To unravel these properties in a controlled and systematic manner, we first consider a continuous field-theoretical description of the problem and then we develop a functional renormalization group (fRG) approach specifically inspired by boundary critical phenomena. The fRG formalism provides a natural framework for analyzing systems where time-translation invariance is explicitly broken, making it particularly well suited for studying the aging dynamics of critical systems following a quench. Unlike traditional perturbative approaches, our fRG treatment allows for a non-perturbative picture, capturing crucial scaling behavior even in regimes where standard approximations break down [3]. This approach is further reinforced by benchmarking our findings against the exactly solvable large-N limit of the model, which serves as a valuable reference point for validating the predictions obtained from the renormalization group analysis.

Furthermore, we extend the so-called effective dimension [4] framework—originally formulated to establish a mapping between short-range and long-range interacting systems in equilibrium—to the non-equilibrium setting. This generalization provides deeper insight into the universality of dynamical critical phenomena and elucidates the connections between different classes of interacting systems far from equilibrium. By leveraging this framework, we gain a more comprehensive understanding of how long-range interactions modify the fundamental scaling properties that govern relaxation and aging in classical dissipative systems.

Finally, we broaden our analysis to quantum systems by incorporating the Keldysh formalism within the fRG framework. This extension enables us to study the prethermal evolution of quantum long-range systems following a quantum quench to their dynamical critical point, shedding light on the role of quantum fluctuations in shaping non-equilibrium dynamics. By systematically addressing both classical and quantum regimes, our work provides a unified perspective on long-range interacting systems far from equilibrium, offering new theoretical insights with potential implications for experimental realizations in ultracold atomic gases, trapped ions, and other platforms exhibiting tunable long-range interactions [2].

REFERENCES

[1] Janssen, H. K., B. Schaub, and B. Schmittmann, New universal short-time scaling behaviour of critical relaxation processes, *Zeitschrift für Physik B Condensed Matter*, vol. 73, pp. 539–549, 1989
[2] Defenu, Nicolo, et al., Long-range interacting quantum systems, *Reviews of Modern Physics*, 95.3: 035002, 2023.
[3] Dupuis, Nicolas, et al. , The nonperturbative functional renormalization group and its applications, *Physics Reports*, 910: 1-114, 2021.
[4] Solfanelli, Andrea, and Nicolò Defenu, Universality in long-range interacting systems: The effective dimension approach, *Physical Review E*, 110.4: 044121, 2024.