

Kibble-Zurek Mechanism in the Open Quantum Rabi Model

Tommaso Pirozzi¹, Grazia Di Bello^{1,2}, Vittorio Cataudella^{1,2}, Carmine Antonio Perroni^{1,2}, Giulio De Filippis^{1,2}

1. Dipartimento di Fisica "Ettore Pancini", Università degli Studi di Napoli Federico II, 80126 Napoli, Italy

2. INFN, Sezione di Napoli, Complesso Universitario di Monte Sant'Angelo, Via Cintia, 80126 Napoli, Italy

Abstract: We characterize the critical non-equilibrium dynamics of the open quantum Rabi model, identifying the first dynamical signature of an environment-induced Berezinskii-Kosterlitz-Thouless transition. We further validate the Kibble-Zurek mechanism, demonstrating that universal scaling characterizes this transition driven by non-Markovian memory.

We investigate the non-equilibrium dynamics of the open quantum Rabi model driven across a phase transition, revealing the emergence of the Kibble-Zurek mechanism (KZM) [1,2]. In this system, the strong coupling to an Ohmic bath results in non-Markovian dynamics, driving a Berezinskii-Kosterlitz-Thouless (BKT) quantum phase transition. To simulate the exact open-system dynamics, we employ Matrix Product State techniques, leveraging the Density Matrix Renormalization Group (DMRG) for the ground-state characterization and the Time-Dependent Variational Principle (TDVP) for the real-time evolution.

By probing the relaxation dynamics within linear response theory, we observe a suppression of the tunnelling amplitude in the deep-strong coupling regime. As the system approaches the critical point, the non-Markovian effects drastically alter the system's response, which crosses over from damped oscillations to a stretched exponential relaxation profile. By extracting the characteristic relaxation time from this response, we demonstrate that it rigorously obeys the scaling law $\tau \sim \exp(B/\sqrt{|g - g_c|})$ Fig. 1(a) [4]. This scaling behaviour provides the first dynamical signature of BKT universality in the model. Furthermore, the critical coupling extracted from this scaling matches the value calculated at equilibrium[3].

Subsequently, we study the system response to finite-rate quenches across the phase boundary. By comparing the quench residual time with the previously extracted relaxation time, we identify the freeze-out point where the adiabatic-to-impulsive crossover occurs Fig. 1(b). We demonstrate that the excitation energy produced at this threshold obeys the universal KZM power-law scaling Fig. 1(c). Crucially, we find that since the environment defines the universality class, dissipation does not inherently compete with adiabatic dynamics, in stark contrast to Markovian regimes. These findings establish the KZM as a robust probe of criticality in open systems, and determine the exact scaling of the excitations that represent a major bottleneck for quantum simulators and adiabatic protocols.

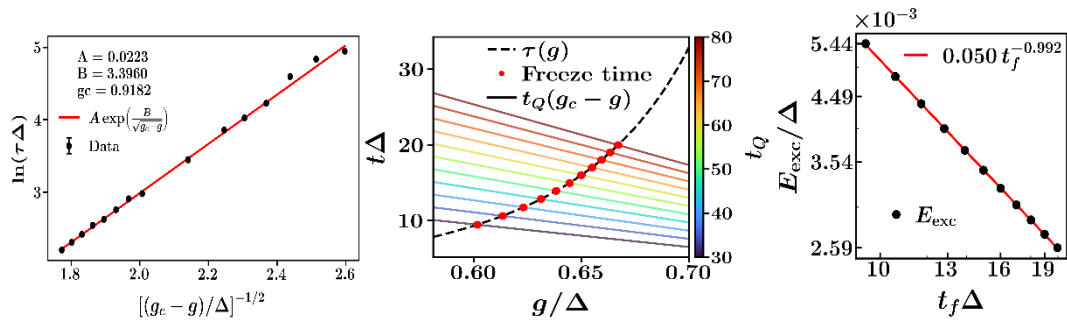


Fig. 1. (a) Relaxation time $\tau \Delta$ vs g/Δ numerical data (black dots) and fit to the BKT scaling (solid red line). (b) Comparison between quench residual time (dashed lines) and relaxation time (solid black line) identifying the freeze-out points. (c) Excitation energy E_{exc}/Δ vs $t_f\Delta$ showing universal power-law scaling $t_f^{-0.992}$.

Example References

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