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Quantum thermodynamics of long-range interacting systems

In the realm of quantum thermodynamics, one of the primary goals is to develop efficient microscopic machines that operate within the quantum regime. Such quantum devices hold promise as tools for cooling quantum processors directly at the microscopic scale. However, they encounter a fundamental challenge: the intrinsic trade-off between power and efficiency in finite-time thermodynamic cycles. This trade-off implies that increasing the speed (and thus power) of these machines often diminishes their efficiency, posing a critical limitation for practical applications.

In this talk I propose a strategy to address this issue by exploring the quantum thermodynamics of long-range interacting quantum where two-body potentials decay as a power law, $V(r) \propto r^{-\alpha}$, with r being the inter-particle distance [1]. Such systems costitute a relevant class of experimental quantum simulation platforms including Rydberg atoms arrays, cavity systems and trapped ions. Moreover, unlike their local counterparts, they exhibit distinctive resilience against external perturbations, a property that plays a crucial role in minimizing energy losses associated with defect generation during non-adiabatic evolution when the system is driven out of equilibrium.

Our study [2] identifies the conditions under which long-range interactions mitigate energy losses due to defect generation in non-adiabatic regimes, thereby enhancing the power-to-efficiency ratio of quantum thermal devices. By examining how long-range systems respond to various external driving protocols, we highlight their robustness against dynamic excitations compared to typical locally-interacting systems. This phenomenon is demonstrated through the study of the quantum work statistics, revealing insights into energy transfer efficiency and dynamical quantum criticality. Our results demonstrate the benefits of including a long-range interacting medium for quantum thermodynamics application, highlighting the potential to optimize finite-time quantum thermal cycles. To analyze these systems, we employ the effective dimension approach, a powerful method that links the scaling exponents of a critical system with long-range interactions in d-dimensional space to those of a local system in an effective fractal dimension d_{eff}. This approach facilitates the study of long-range models by leveraging established results from their local counterparts, enabling us to drawn our findings in full generality and and tailor them to experimentally relevant scenarios.

References:

[1] Nicolò Defenu, Tobias Donner, Tommaso Macrì, Guido Pagano, Stefano Ruffo, and Andrea Trombettoni, Long-range interacting quantum systems, Rev. Mod. Phys. 95, 035002 (2023).

[2] Andrea Solfanelli, Nicolò Defenu, Universal work statistics in long-range interacting quantum systems, Phys. Rev. Lett. 134, 030402 (2025).

Theme

Theme 1. Energy advantage and cost of quantum technology

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