REASSESSING QUANTUM-THERMODYNAMIC ENHANCEMENTS IN CONTINUOUS THERMAL MACHINES

José A. Almanza-Marrero[1*], Gonzalo Manzano[1],

[1]Institute for Cross-Disciplinary Physics and Complex Systems IFISC (UIB-CSIC), Campus Universitat Illes Balears, E-07122 Palma de Mallorca, Spain
*joseantonio@ifisc.uib-csic.es

ABSTRACT

The role of quantum coherence in thermodynamic processes has been a subject of intense debate in quantum thermodynamics. While coherence is often claimed to enhance the performance of quantum thermal machines, the precise conditions under which it leads to a genuine thermodynamic advantage remain unclear. In this talk, we present a systematic reassessment of coherence-induced enhancements in steady-state quantum thermal machines, including both autonomous and externally driven systems operating in the weak-coupling regime. Our work critically examines different sources of coherence—whether induced by the system's Hamiltonian or generated by noise—and evaluates their respective contributions to thermodynamic performance.

We begin by distinguishing between Hamiltonian-induced coherence, which arises due to perturbations in the machine's energy structure, and noise-induced coherence, which emerges from collective dissipation effects. By constructing classical thermodynamic-equivalent models, we establish a robust criterion for assessing whether coherence provides a genuine quantum advantage beyond classical stochastic machines. Our findings reveal that Hamiltonian-induced coherence systematically improves the stability and precision of thermodynamic outputs—reducing fluctuations while maintaining efficiency and power. On the other hand, noise-induced coherence does not universally yield advantages; in many cases, we show that it leads to no net benefit or even worsens performance when compared to an equivalent classical counterpart.

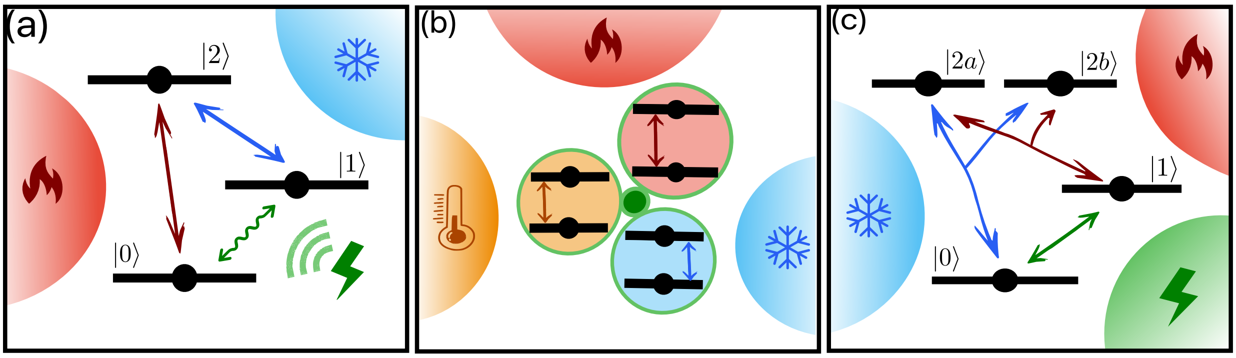

Figure 1: Schematic representation of three quantum thermal machine models. (a) The coherent three-level amplifier with couplings to baths at hot β_h(red) and cold β_c(blue) temperatures, as well as coherent external driving (green thunderbolt), (b) the three-qubit autonomous (absorption) refrigerator where each qubit is locally coupled to baths at hot (red), cold (blue), and intermediate (yellow) temperatures β_m, and (c) the noise-induced-coherence machine showing collective jumps induced by the baths at hot (red) and cold (blue) temperatures, together with a classical work source given by an infinite-temperature bath (green).

To illustrate these insights, we analyze three prototypical models of continuous quantum thermal machines: a coherent three-level amplifier, a three-qubit autonomous refrigerator, and a noise-induced coherence engine. Through multi-objective optimization techniques, we identify operational regimes where quantum coherence yields an unambiguous advantage, surpassing the classical thermodynamic limits set by the thermodynamic uncertainty relation (TUR). We also highlight cases where coherence provides no benefit, challenging previous claims of universal enhancements.

REFERENCES

[1] J.A. Almanza-Marrero and G. Manzano, Reassessing quantum-thermodynamic enhancements in continuous thermal machines, *arXiv:2403.19280v3*.