Quantum Systems:
Entanglement, Simulations and Information
(QUANTUM)

OUTLINE

Investigation of the recent developments that have changed the status of quantum mechanics (a new "quantum revolution") and led the development of Quantum Technologies.
The major objective of QUANTUM is the investigation of typical quantum mechanical effects and phenomena via three major, interrelated avenues: Entanglement and other Quantum Correlations, Quantum Simulation, and Quantum Control.

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Milano: G. Benenti (Unins), L. Razzoli (postdoc Schwinger Foundation, till April), E. Carolan (postdoc PNRR), G. Cenedese and S. Finocchiaro (PhD students)

Quantum Thermodynamics

Fundamental questions at the interface between quantum theory and thermodynamics, vital for the development of quantum thermo-machines:

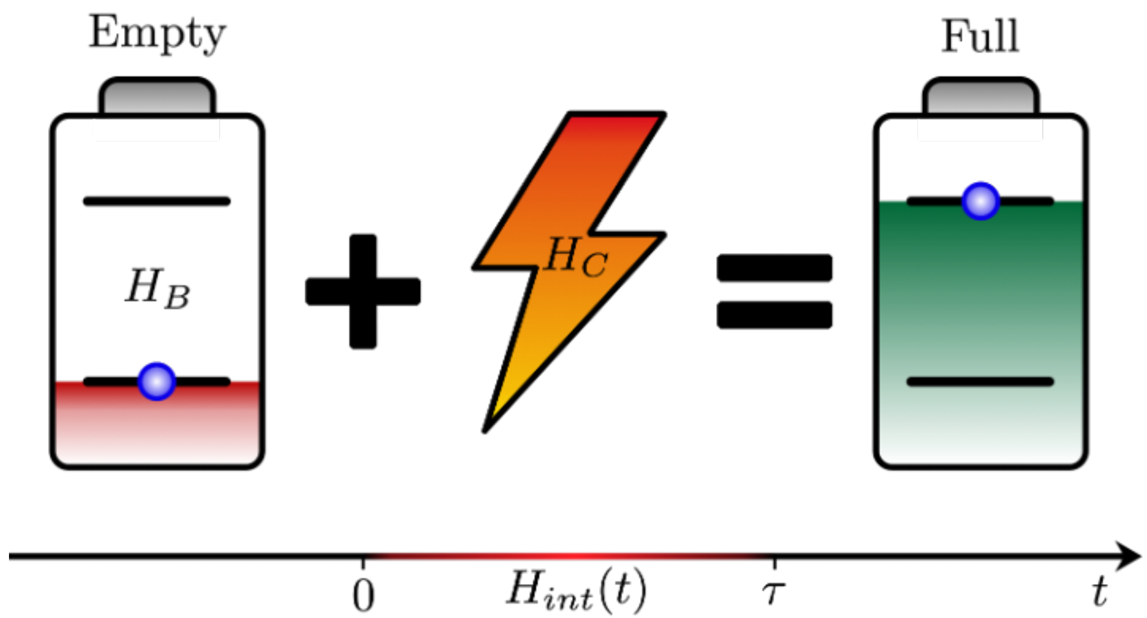
Definition of heat and work in quantum mechanics

Role of coherence, entanglement, quantum measurements and fluctuations in quantum machines and quantum batteries

Heat management at the nanoscale (cooling hot spots, thermal diodes and transistors)

Develop optimal control strategies for quantum batteries and quantum thermal machines

Quantum Batteries

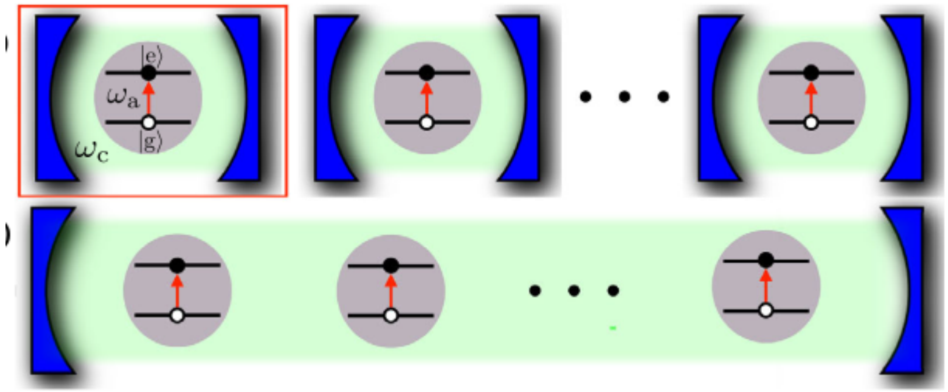


$$H(t) = H_B + H_C + H_{int}(t).$$

A quantum battery is a quantum system that can be promoted from a low energy–e.g. its ground state–to an excited state (charged battery) through the interaction with a charger

Collective advantage

Collective advantage in power, superextensive in the number of cells



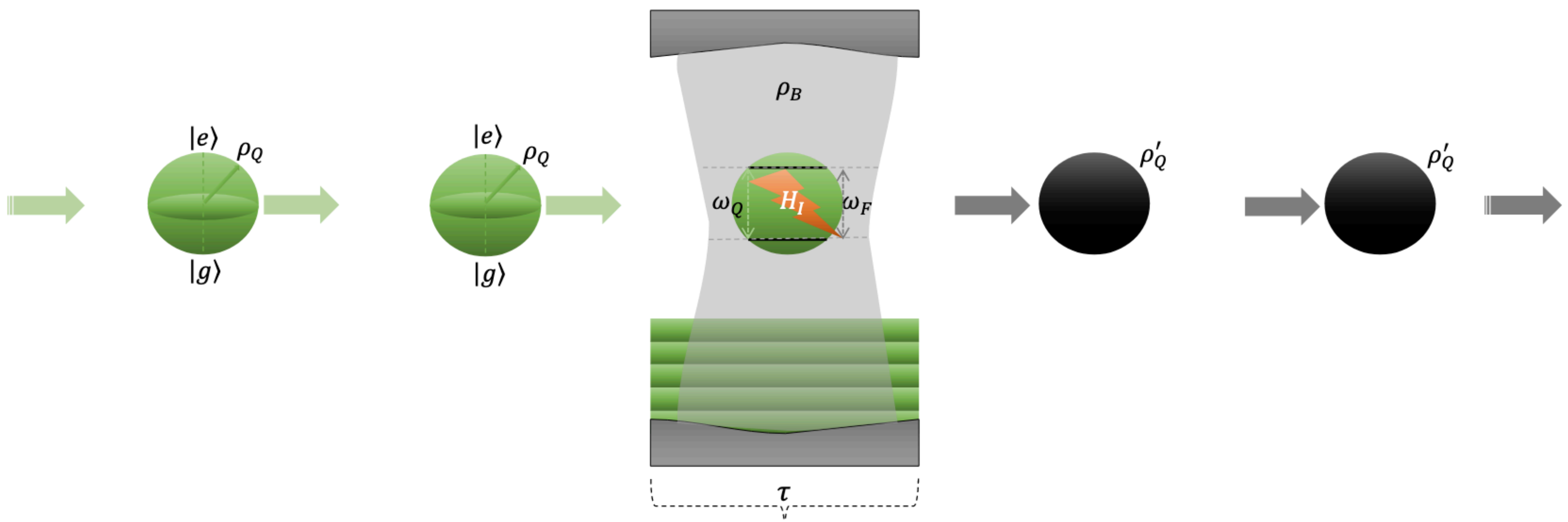
Dicke quantum battery
($\sqrt{N}$ collective advantage)

Does the advantage remains under quantum noise, e.g. cavity leakage?

With measurement and feed-back possible to improve the extractable work with respect to the noiseless limit

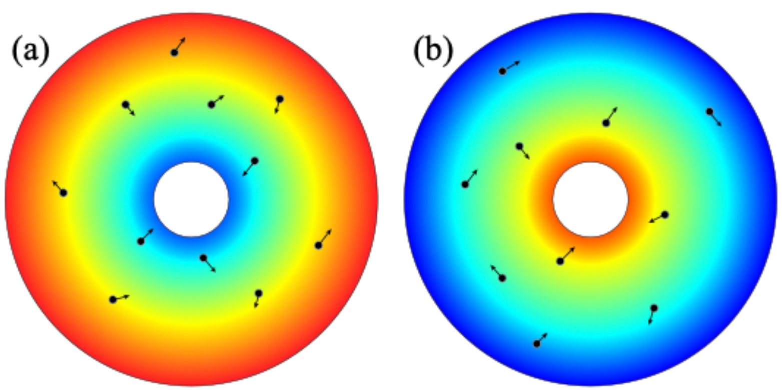
Ultrastrong coupling

In this regime, the coupling strength between matter and the electromagnetic field within a cavity becomes comparable to the cavity frequency: a road towards ultrafast quantum technologies

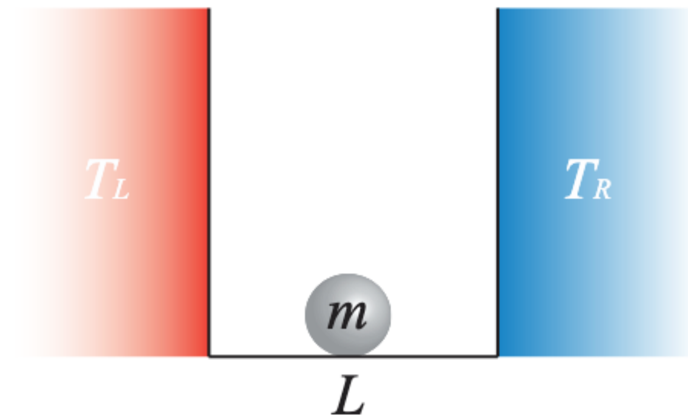


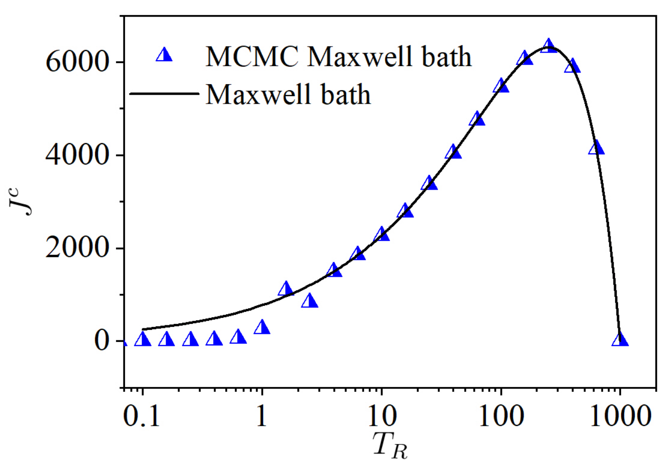
Extend optimal control to micromaser quantum battery to the USC regime, including dissipation

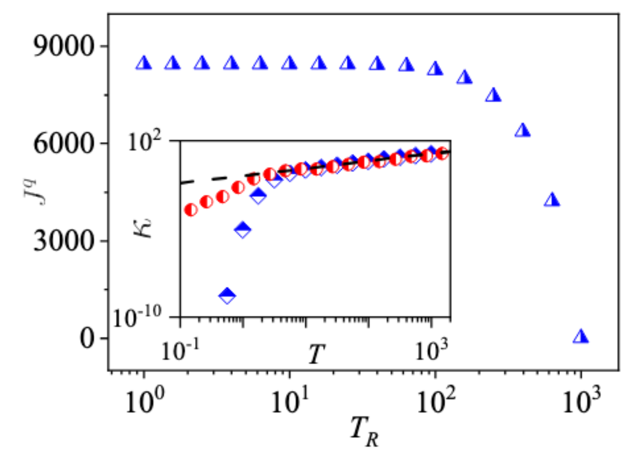
Quantum vs. classical thermal transport



Classical heat rectifier (Corbino billiard model)







Negative differential thermal conductance in classical but not in quantum physics

Summary (keywords)

Optimizing the performances of nanoscale quantum thermal engines and quantum batteries: trade-off between efficiency, power, and fluctuations

Heat management in nanodevices: explore possible strategies for the development of heat diodes and transistors

Quantum thermodynamics and quantum information protocols in the ultra-strong coupling regime of light-matter interaction, where the coupling strength becomes comparable to, or even exceeds, the resonator frequency.

Moreover: variational quantum algorithms, energy transfer in quantum networks, complexity of quantum walks

QUANTUM-MI publications (2024)

1) L. Razzoli, F. Cavaliere, M. Carrega, M. Sassetti and G. Benenti, Efficiency and thermodynamic uncertainty relations of a dynamical quantum heat engine, Eur. Phys. J. Spec. Top. 233, 1263 (2024).
2) L. Razzoli, G. Cenedese, M. Bondani and G. Benenti, Efficient implementation of discrete-time quantum walks on quantum computers, Entropy 26, 313 (2024).
3) M. Carrega, L. Razzoli, P. A. Erdman, F. Cavaliere, G. Benenti and M. Sassetti, Dissipation-induced collective advantage of a quantum thermal machine. AVS Quantum Sci. 6, 025001 (2024).
4) Z. Zou, G. Casati, G. Benenti and J. Wang, Rectification of heat current in Corbino geometry, Phys. Rev. E 109, L062104 (2024).
5) L. Razzoli, M. Carrega, F. Cavaliere, G. Benenti and M. Sassetti, Synchronization-induced violation of thermodynamic uncertainty relations, Quantum Sci. Technol. 9, 045032 (2024).
6) V. Singh, V. Shaghaghi, T. Pandit, C. Beetar, G. Benenti and D. Rosa, The asymmetric quantum Otto engine: frictional effects on performance bounds and operational modes, Eur. Phys. J. Plus 139, 1020 (2024).

QUANTUM-MI publications (2025)

1) L. Razzoli, G. Gemme, I. Khomchenko, M. Sassetti, H. Ouerdane, D. Ferraro and G. Benenti, Cyclic solid-state quantum battery: Thermodynamic characterization and quantum hardware simulation, Quantum Sci. Technol. 10, 015064 (2025).
2) F. Cavaliere, G. Gemme, G. Benenti, D. Ferraro and M. Sassetti, Dynamical blockade of a reservoir for optimal performances of a quantum battery, Commun Phys 8, 76 (2025).
3) S. Finocchiaro, D. Ferraro, M. Sassetti and G. Benenti, Hybrid interacting quantum Hall thermal machine, Phys. Rev. B 111, 205420 (2025).
4) G. Cenedese, M. Bondani, A. Andreanov. M. Carrega, G. Benenti and D. Rosa, Shallow quantum circuits are robust hunters for quantum many-body scars, Eur. Phys. J. Plus 140, 517 (2025).

QUANTUM-MI preprints (2025)

1) G. Cenedese, S. T. Mister, M. Antezza, G. Benenti, and G. De Chiara, Thermodynamics and Protection of Discrete-Time Crystals, preprint arXiv:2503.15134 [quant-ph].
2) L Razzoli, A Pozzoli, A Allevi, Hybrid discrimination strategy based on photon-number-resolving detectors and mesoscopic twin-beam states, preprint arXiv:2506.10160.