Abstract book
Quantum Carnot Workshop and QuanTEEM Winter School
Dijon, France, 25 -27 Novemner 2024

I. MONDAY 25 NOVEMBER 2024

- Speaker: Ronnie Kosloff
  Title: Quantum Carnot Engine
  Abstract: to be announced (TBA)

- Speaker: Gonzalo Manzano
  Title: Reassessing Quantum-Thermodynamic Enhancements in Continuous Thermal Machines
  Abstract:
  Quantum coherence has been shown to impact the operational capabilities of quantum systems performing thermodynamic tasks in a significant way, and yet the possibility and conditions for genuine coherence-enhanced thermodynamic operation remain unclear. We show that for steady-state quantum thermal machines —both autonomous and externally driven— that interact weakly with thermal reservoirs and work sources, the presence of coherence induced by perturbations in the machine Hamiltonian guarantees a genuine thermodynamic advantage. Such advantage applies both for the cases in which the induced coherence is between levels with different energies or between degenerate levels. On the other hand, we show that engines subjected to noise-induced coherence, can be outperformed by classical stochastic engines using exactly the same set of (incoherent) resources. We illustrate our results with three prototypical models of heat engines and refrigerators and employ multi-objective optimization techniques to characterize quantum-enhanced regimes in connection with the thermodynamic uncertainty relation and beyond it.

- Speaker: Saulo Moreira
  Title: Precision bounds for multiple currents in open quantum systems
  Abstract:
  Thermodynamic (TUR) and kinetic (KUR) uncertainty relations are fundamental bounds constraining the relative fluctuation of observables in terms of dissipation or dynamical activity in classical, non-equilibrium systems. Several works have verified, however, violations of these classical bounds in open quantum systems, indicating that they are not suitable to constrain the relative fluctuation of currents when quantum dynamics is involved. To address this, new quantum TURs and KURs have been derived for single current observables. Here, we derive multidimensional KUR and TUR for multiple currents in open quantum systems using a multi-parameter metrology approach. Crucially, our bounds are tighter than previously derived quantum TURs and KURs for single currents, because they incorporate correlations between different current observables. By considering two examples, namely a coherently-driven qubit system and the three-level maser, we demonstrate that the multidimensional quantum KUR bound can even be saturated when the currents are strongly correlated.

- Speaker: Adolfo del Campo, University of Luxembourg
  Title: Shortcuts to Adiabaticity
  Abstract:
  Shortcuts to adiabaticity provide fast protocols for quantum state preparation in which the use of auxiliary counterdiabatic controls circumvents the requirement of slow driving in adiabatic strategies. While their development is well established in simple systems, their engineering and implementation are challenging in many-body quantum systems with many degrees of freedom: the auxiliary controls involve multiple-body interactions and are highly nonlocal. This fact has motivated the introduction of a variety of schemes for approximated counterdiabatic driving, such as optimized truncations, variational methods, and Krylov subspace expansions. A novel class of counterdiabatic quantum algorithms for quantum optimization has emerged alongside experimental advancements in harnessing counterdiabatic driving in multi-particle systems. This talk will provide a comprehensive overview, ranging from foundational concepts to the most recent advancements in the field.

- Speaker: Ariane Soret
  Title: Symmetry shapes thermodynamics of macroscopic quantum systems

Abstract:
Symmetry shapes thermodynamics of macroscopic quantum systems Symmetries play a fundamental role in shaping physical theories, from quantum mechanics to thermodynamics. Studying the entropic, energetic, or dynamic signatures of underlying symmetries in quantum systems is an active field of research, from fundamental questions about entropy scalings, ground state properties, or thermalization, to the optimization of quantum computing or numerical simulation procedures, and is gaining momentum due to rapid experimental advances, particularly in cold atoms [1].
In this work [2], we derive a systematic approach to the thermodynamics of quantum systems based on the underlying symmetry groups. We show that the entropy of a system can be described in terms of group-theoretical quantities that are largely independent of the details of its density matrix. We apply our technique to generic N identical interacting d-level quantum systems. Using permutation invariance, we find that, for large N , the entropy displays a universal large deviation behavior with a rate function $s(x)$ that is completely independent of the microscopic details of the model, but depends only on the size of the irreducible representations of the permutation group SN . In turn, the partition function is shown to satisfy a large deviation principle with a free energy $f(x) = e(x) - \beta^{-1}s(x)$, where $e(x)$ is a rate function that only depends on the ground state energy of particular subspaces determined by group representation theory. We demonstrate the power of our approach by applying it to the nontrivial task of describing phase transitions governed by the interplay of quantum and thermal fluctuations in the transverse-field Curie-Weiss model.

[1] Masahito Ueda. Quantum equilibration, thermalization and prethermalization in ultracold atoms. Nat. Rev. Phys., 2(12):669, 2020.

[2] Vasco Cavina, Ariane Soret, Timur Aslyamov, Krzysztof Ptaszy ´nski, and Massimiliano Esposito. Symmetry shapes thermodynamics of macroscopic quantum systems. Phys. Rev. Lett., 133:130401, Sep 2024.

II. TUESDAY 26 NOVEMBER 2024

- Speaker: Benjamin Huard
  Title: Energetics of superconducting circuit gates
  Abstract: TBA

- Speaker: Laurent Vernac
  Title: Study of quantum thermalization in a lattice dipolar system from collective and bipartite measurements of quantum correlations
  Abstract:
  We measure the dynamical growing of quantum correlations of a large ensemble of dipolar chromium atoms, during an out-of-equilibrium dynamic, taking place in 3D deep optical lattice. Two-point correlators associated with the magnetization are measured from ensemble measurements, assuming homogeneity. While collective measurements show that globally anti-correlations develop in our system, the implementation of a bipartite protocol allows to investigate the correlation landscape, and to demonstrate a strong anisotropy of correlations, linked to the anisotropic nature of the dipolar interaction. Our various theoretical models offer a description of the system throughout the dynamics. In particular, at long time, where quantum thermalization leads to a stationary state with thermal properties, we can point thermalization at a high negative spin temperature.

- Speaker: Raffaele Pisano
  Title: 1824-2024: Sadi Carnot and the Birth of Thermodynamics
  Abstract:
  In 1824, Sadi Carnot (1796-1832) presented the basics of thermodynamics (2nd principle only) in his only published book–Réflexions sur la puissance motrice du feu (hereafter Réflexions). Sadi Carnot knew Watt's works. In his Réflexions he dealt with heat machines and gas theory through: a) the caloric hypothesis mixed with a weak heat concept, b) the 4-phases cycle and c) ad absurdum proof theorem (atypical for a physical science at that time). The impossibility of perpetual motion was linked to state of a system, reversible processes and cycle (four phases). In his unpublished Notes sur les mathématiques, la physique et autres sujets (s.d.) he made slight and indirect use of the hypothesis on puissance motrice conservation/heat–work (Cfr. Carnot s.d., pp. 134–135). He also provided a cycle (three phases) in his unpublished Recherche d'une formule propre à

représenter la puissance motrice de la vapeur d'eau (between November 1819 and March 1827). At the beginning of the discursive part of Réflexions – and at the end of his celebrated theorem – he claimed that work can be obtained every time there is a difference in temperature between which heat flows (Cfr. Pisano's works). He proposed a different manner to close his own cycle (displayed by cylinders only) and determined (erroneously) the mathematical function of the efficiency for an heat machine. In my talk I present an historical–genesis account of Sadi Carnot's thermodynamics in his Réflexions (1824).

Selected References

- Carnot L ([1783] 1786) Essai sur les machines en général. Defay, Dijon.
- Carnot L (1778) Mémoire sur la théorie des machines pour concourir au prix de 1779 propose par l'Académie Royale des Sciences de Paris. The manuscript is conserved in the Archives de l'Academie des sciences, Institut de France, and consists of 85 sections in 63 folios. Sections 27–60 are reproduced. In: Gillispie (1971), Appendix B, pp. 271–296 — See also: Carnot L (1780) Mémoire sur la théorie des machines pour concourir au prix que l'Académie Royale des Sciences de Paris doit adjuger en 1781. The manuscript is dated from Béthune 15 July 1780. It is conserved in the Archives de l'Académie des sciences, Institut de France, and consists of 191 sections in 106 folios. Sections 101–160 are reproduced. In: Gillispie (1971), Appendix C, pp. 299–343.
- Carnot S (1878) Réflexions sur la puissance motrice du feu sur les machinés propre à développer cette puissance. Gauthier–Villars, Paris.
- Clapeyron EBP (1834) Mémoire sur la puissance motrice du feu. Journal de l'École Royal Polytechnique XXIII/XIV:153–190. [Collections École polytechnique Z 5 (1834)].
- Gillispie CC, Pisano R (2014) Lazare and Sadi Carnot. A Scientific and Filial Relationship. 2nd edition. Springer, Dordrecht [On St Robert, see Chap. X].
- Pisano R, Cooppersmith J, Australia, Peake M (2021) Essay on Machines in General (1786). Text, Translations and Commentaries. Lazare Carnot's Mechanics – Vol. 1. Springer, Cham.
- Pisano works on the subject: https://pro.univ-lille.fr/raffaele-pisano

- Speaker: Alessandra Colla
  Title: Thermodynamic roles of quantum environments: from heat baths to work reservoirs
  Abstract:
  Environments in quantum thermodynamics usually take the role of heat baths. These baths are Markovian, weakly coupled to the system, and initialized in a thermal state. Whenever one of these properties is missing, standard quantum thermodynamics is no longer suitable to treat the thermodynamic properties of the system that result from the interaction with the environment. Using a recently proposed framework for open system quantum thermodynamics at arbitrary coupling regimes [1], we show that within the very same model (a Fano-Anderson Hamiltonian) the environment can take three different thermodynamic roles: a standard heat bath, exchanging only heat with the system, a work reservoir, exchanging only work, and a hybrid environment, providing both types of energy exchange. The exact role of the environment is determined by the strength and structure of the coupling, and by its initial state.

  [1] A. Colla, H.-P. Breuer, Physical Review A 105, 052216 (2022)

- Speaker: Janine Splettstoesser
  Title: Fluctuation theorems and noise bounds for nonequilibrium nanoscale engines
  Abstract:
  Energy conversion processes in nanoscale devices are potentially strongly impacted by fluctuations. It is therefore of high interest to understand if and how these fluctuations are related to the desired outcome of the process. While in systems close to equilibrium, fluctuation-dissipation theorems exist, relating the fluctuations to the average response of the system, such relations are typically harder to find in nonequilibrium situations. More general fluctuation relations, holding also in nonequilibrium, are at the basis of recently studied bounds on the fluctuations such as the so-called thermodynamic uncertainty relation. These are however typically applicable mostly to classical or weakly coupled systems.

In this talk I will present recent progress in establishing constraints on the fluctuations in nonequilibrium, possibly strongly coupled systems. These results are obtained from scattering theory, which applies to a large class of systems, as long as particle-particle interactions are weak. For nanoscale heat engines, possible subject to a large temperature bias, we find a bound on the power fluctuations given by the power itself, which holds even when the thermodynamic uncertainty relation breaks down [1]. Furthermore, we prove a sort of kinetic uncertainty relation for quantum transport of particles, energy or entropy, which in the classical limit bounds the precision by the "activity" of the system - independently of whether the system is bosonic or fermionic and even when the contacts are nonthermal [2]. In the quantum regimes, these kinetic uncertainty relations need to be modified, where the quantum statistics (fermionic/bosonic) play an important role for the validity and shape of these bounds.

[1] L. Tesser, J. Splettstoesser: Out-of-Equilibrium Fluctuation-Dissipation Bounds. Phys. Rev. Lett. 132, 186304 (2024)

[2] D. Palmqvist, L. Tesser, J. Splettstoesser: Quantum kinetic uncertainty relations, in preparation.

- Speaker: Kark Mitchison
  Title: Thermodynamics of precision: from counting statistics to clocks
  Abstract:
  Any clock is a nonequilibrium system that consumes and dissipates energy in order to produce an ordered sequence of ticks, which are counted by a register. A good clock produces ticks that are regularly spaced in time, so that the number of counts in a given time interval fluctuates little. The problem of timekeeping is thus intimately connected to the problem of full counting statistics in nonequilibrium systems. In this talk, I will explain how the precision of a clock is limited both by thermodynamic irreversibility (quantified by entropy production) and temporal resolution (related to how active or frenetic is the underlying dynamics). I will focus on one of our recent results: the clock uncertainty relation [1], which is a tight upper bound on the precision of any time estimate constructed from sustained observations of a classical, Markovian jump process. This bound is controlled by the mean residual time, i.e. the expected wait before the first jump is observed. As a consequence, we obtain a universal bound on the signal-to-noise ratio of arbitrary currents and counting observables in the steady state. This establishes the ultimate precision limits for an important class of observables in non-equilibrium systems, and demonstrates that the mean residual time, not the dynamical activity, is the measure of freneticity that tightly constrains fluctuations far from equilibrium. I will also discuss some consequences for timekeeping in quantum systems and perspectives on potential experimental realisations.

[1] Prech, K., Landi, G. T., Meier, F., Nurgalieva, N., Potts, P. P., Silva, R., & Mitchison, M. T. (2024). Optimal time estimation and the clock uncertainty relation for stochastic processes. arXiv, 2406.19450.

III. WEDNESDAY 27 NOVEMBER 2024

- Speaker: Olivier Maillet
  Title: Probabilistic work extraction with single electron devices
  Abstract:
  Thanks to their tunability and sensitivity to thermal fluctuations, single-electron devices enable to explore nonequilibrium stochastic thermodynamics, far beyond the laws that were established two hundred years ago by Sadi Carnot. Here, we first drive a single-electron box out-of-equilibrium to allow maximal, or with maximal probability, work extraction at the limit of what is allowed by Jarzynski's equality, beyond the standard "average" second law of thermodynamics. We then devise a "gambling" strategy where, instead of performing cycles of definite duration, we stop the system's operation whenever a threshold work exerted is reached. For sufficient irreversible operation, work is, when averaged over all realizations, extracted above the free energy bound, yet in agreement with a generalized second law that we experimentally verify.

[1] O. Maillet et al., Phys. Rev. Lett. 122, 150604 (2019)

[2] G. Manzano et al., Phys. Rev. Lett. 126, 080603 (2021)

- Speaker: Milton Aguilar
  Title: Correlated quantum engines beyond the standard second law
  Abstract:
  The laws of thermodynamics strongly restrict the performance of thermal machines. Standard thermodynamics, initially developed for uncorrelated macroscopic systems, does not hold for mi- croscopic systems correlated with their environments. We here derive exact generalized laws of quantum thermodynamics for arbitrary, time-periodic, open systems that account for all possible correlations between all involved parties. We demonstrate the existence of two basic modes of engine operation: the usual thermal case, where heat is converted into work, and a novel athermal regime, where work is extracted from entropic resources, such as system-bath correlations. In the latter regime, the efficiency of a quantum engine is not bounded by the usual Carnot formula. Our results provide a unified formalism to determine the efficiency of correlated microscopic thermal devices.

- Speaker: Bruno Bellomo, Institut UTINAM, Université de Franche-Comté
  Title: Quantum thermal devices based on simple quantum systems
  Abstract:
  In the last decades the emerging field of quantum thermodynamics attracted many efforts. One of the goals is the extension of standard thermodynamics to include quantum effects in systems of small size. The rapid growth of quantum thermodynamics has been also connected to the development of the field of open quantum systems. This pushed and facilitated the study of quantum thermal machines designed using simple models and capable, as for classical thermal machines, to convert heat energy into useful work and vice-versa.

  In this talk, after an introduction about quantum thermodynamics and quantum thermal machines, I will present some results concerning the realization of quantum thermal devices by means of simple quantum systems, obtained in the context of the following studies.

  1) In this study we propose a simple protocol exploiting the thermalization of a bipartite storage system S to obtain an extraction of work from an external resource (we use a work quantifier connected to the free energy) [1]. This protocol is applied to the case of two interacting qubits and to the Rabi model. In both cases, for very strong couplings, a work extraction comparable to the bare energies of the subparts of S is obtained and its peak is reached for finite values of the temperature of the bath.

  2) Another study concerns the case of quantum thermal machines based on two-step cycles exploiting a cold and a hot thermal bath, and non-resonant interactions [2]. In particular, we focus on maximizing the power in relation to different parameters such as the waiting time between successive interactions. In the case of a heat engine where qubits are used, power peaks occur for machine efficiency values that exceed the Curzon-Ahlborn efficiency.

  3) In another study we consider a quantum system composed of three qubits interacting with each other, each coupled to a different thermal reservoir [3]. We show how to optimize this system to realize a quantum device analogous to a bipolar electronic transistor. We analyze the crucial role played by the interaction between qubits in this phenomenon. Our model extends the zone of parameters where the thermal transistor effect manifests itself.

  4) Another study concerns the realization of quantum thermal machines where driven harmonic oscillators are coupled via a collision model to thermal reservoirs at different temperatures [4]. We analyze the thermal currents and the power of the device and its different operating regimes, also in terms of the speed of modulation of the frequencies of the driven oscillators. The case in which the oscillators of one reservoir are prepared in squeezed states is also considered.

  [1] N. Piccione, B. Militello, A. Napoli, and B. Bellomo, Phys. Rev. E 100, 032143 (2019).

  [2] N. Piccione, G. De Chiara, and B. Bellomo, Phys. Rev. A 103, 032211 (2021).

  [3] A. Mandarino, K. Joulain, M. D. Gómez, and B. Bellomo, Phys. Rev. Applied 16, 034026 (2021).

  [4] H. Leitch, N. Piccione, B. Bellomo, and G. De Chiara, AVS Quantum Science 4, 012001 (2022).

- Speaker: Irene Ada Picatoste
  Title: Strong coupling quantum thermodynamics of the Otto cycle
  Abstract:
  Using an open-system approach to quantum thermodynamics at arbitrary coupling [1] we study the Otto cycle in the strong-coupling and non-Markovian regimes [2]. Our investigation is based on the exact treatment of the

dynamics of the system when coupled to a thermal reservoir, which we describe employing the Fano-Anderson model. We study the effects of strong coupling and a structured environment, and find that a non-Markovian bath can exchange both heat and work with the system. We identify a regime of enhanced efficiency occurring when the peak of the spectral density is located within the frequency range of the cycle, and explain this through an analysis of the renormalized frequencies emerging from the system-bath interaction.

[1] A. Colla and H.-P. Breuer, "Open-system approach to nonequilibrium quantum thermodynamics at arbitrary coupling", May 2022, 10.1103/PhysRevA.105.052216.

[2] I. A. Picatoste, A. Colla and H.-P. Breuer, "Dynamically Emergent Quantum Thermodynamics: Non-Markovian Otto Cycle", March 2024, 10.1103/PhysRevResearch.6.013258.

- Speaker: Sabrina Maniscalco
  Title: TBA
  Abstract: TBA

- Speaker: Martin Bowen
  Title: TBA
  Abstract: TBA

IV. POSTER SESSION - MONDAY AFTERNOON

In random order:

- Presenter: Parvinder Solanki
  Title: Steady-state tunable entanglement thermal machine using quantum dots
  Abstract: We propose a solid state thermal machine based on quantum dots to generate steady-state entanglement between distant spins. Unlike previous approaches our system can be controlled by experimentally feasible steady state currents manipulated by dc voltages. By analyzing the Liouvillian eigenspectrum as a function of the control parameters, we show that our device operates over a large voltage region. As an extension, the proposed device also works as an entanglement thermal machine under a temperature gradient that can even give rise to entanglement at zero voltage bias. Finally, we highlight a post-selection scheme based on currently feasible non-demolition measurement techniques that can generate perfect Bell-pairs from the steady state output of our thermal machine.

- Presenter: Yashovardhan Jha
  Title: TBA
  Abstract: TBA

- Presenter: Matteo Garbellini
  Title: TBA
  Abstract: TBA

- Presenter: Mark Prusten
  Title: Quantum Clocks and Coupling with Quantum Carnot Cycles for Distributed Quantum Computing Networks
  Abstract: The Coupling of Classical Clocks and Engines can be illustrated with the Thermodynamic Carnot Cycle formulation. The synchronization and power coupling for distributed heat engine systems in the quantum regime is formulated. In the Classical regime reservoirs at absolute temperature require reservoirs of identical sign. The Quantum heat engine is not bound to these restrictions so calibrating negative absolute temperatures to positive temperatures can be investigated. An important application of this concept is the coupling of multiple quantum clocks. The Quantum Clock Synchronization (QCS) based on a quantum entanglement scheme is investigated to distribute precision time standard for future long-distance Quantum Networks. In contrast, the Quantum Asynchronous Communication (QAC) for distributed quantum machine learning as applied to quantum neural networks is presented for Asynchronous Quantum Repeaters.

- Presenter: Luca Razzoli
  Title: Cyclic solid-state quantum battery: Thermodynamic characterization and quantum hardware simulation
  Abstract: We introduce a cyclic quantum battery model, based on an interacting bipartite system, weakly coupled to a thermal bath. The working cycle of the battery consists of four strokes: system thermalization, disconnection of subsystems, ergotropy extraction, and reconnection. The thermal bath acts as a charger in the thermalization stroke, while ergotropy extraction is possible because the ensuing thermal state is no longer passive after the disconnection stroke. Focusing on the case of two interacting qubits, we show that phase coherence, in the presence of non-trivial correlations between the qubits, can be exploited to reach working regimes with efficiency higher than 50% while providing finite ergotropy. Our protocol is illustrated through a simple and feasible circuit model of a cyclic superconducting quantum battery. Furthermore, we simulate the considered cycle on superconducting IBM quantum machines. The good agreement between the theoretical and simulated results strongly suggests that our scheme for cyclic quantum batteries can be successfully realized in superconducting quantum hardware.

  Reference: Razzoli, L., Gemme, G., Khomchenko, I., Sassetti, M., Ouerdane, H., Ferraro, D., & Benenti, G. (2024). Cyclic solid-state quantum battery: Thermodynamic characterization and quantum hardware simulation. arXiv, 2407.07157.

- Presenter: Andrea Canzio
  Title: Single-atom dissipation and dephasing in Dicke and Tavis-Cummings quantum batteries
  Abstract: We study the influence of single-atom dissipation and dephasing noise on the performance of Dicke and Tavis-Cummings quantum batteries, where the electromagnetic field of the cavity hosting the system acts as a charger. For these models a genuine charging process can only occur in the transient regime. Indeed, unless the interaction with the environment is cut off, the asymptotic energy of the battery is solely determined by the environment and does not depend on the initial energy of the electromagnetic field. We numerically estimate the fundamental figures of merit for the model, including the time at which the battery reaches its maximum ergotropy, the average energy, and the energy that needs to be used to switch the battery-charger interaction on and off. Depending on the scaling of the coupling between the battery and the charger, we show that the model can still exhibit a subextensive charging time. However, for the Dicke battery, this effect comes with a higher cost when switching the battery-charger interaction on and off. We also show that as the number of battery constituents increases, both the Dicke and Tavis-Cummings models become asymptotically free, meaning the amount of energy that is not unitarily extractable becomes negligible. We obtain this result numerically and demonstrate analytically that it is a consequence of the symmetry under permutation of the model. Finally, we perform simulations for different values of the detuning, showing that the optimal regime for the Dicke battery is off-resonance, in contrast to what is observed in the Tavis-Cummings case.

- Presenter: Mayeul Chipot
  Title: TBA
  Abstract: TBA