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Optimal performance of a quantum Otto refrigerator

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We consider a quantum Otto refrigerator cycle of a time-dependent frequency harmonic oscillator. We investigate the coefficient of performance at maximum figure of merit for adiabatic and nonadiabatic frequency modulations. Our results show that sudden switching of frequencies enhances the optimal performance of the refrigerator. The analyses were performed for both high- and low-temperature limits.

Thermodynamic costs of quantum measurements

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Abstract: We investigate the thermodynamic energy costs for performing a quantum measurement. For a measurement model employing a probe, we generalize and improve the results by Sagawa and Ueda [2, 3] to the genuinely quantum case where the measurement interaction generates general correlations (classical or quantum). We provide explicit gap terms, also identifying inefficiencies in the measurement and the outcome storage, and compare to other proposed information measures [1, 4]. Finally, we apply our results to analyze the full Szilard engine cycle under possibly imperfect measurements.

As computing devices approach the micro- and nano-scales, it becomes vital to analyze the fundamental energetic and thermodynamic resource requirements needed for (quantum) information processing. For the task of information erasure assisted by a thermal bath, this has been done in seminal work by R. Landauer (1961). Ideal classical measurements, on the other hand, can be performed *without* energy expenditure (C.H. Bennett 1982). However, when taking into account stability considerations or when performing imperfect or general (POVM) measurements, there will be an unavoidable energy cost. This is the question we study.

We use here the setup and notation from [3], consisting of a system S to be measured and a measurement probe device M. We do *not require any separability assumption* (as in [3, Eq. (1)], restricting their results essentially to the classical case). We derive the following general lower bound on the work expenditure necessary for the measurement:

$$\beta W^M_{meas} \overbrace{\geq}^{\text{(EFF)}} \beta \Delta F^M + \overbrace{\Big[S(\rho^S_{\text{ini}}) - \sum_k p_k S(\rho^S_{k,\text{fin}})\Big]}^{0 \leq I_{QC} \leq H \ \text{(ref. [2])}} - \overbrace{H(\{p_k\})}^{H}$$
$$+ \sum_k p_k \Big[I(S:M)_{\rho^{SM}_{k,\text{fin}}} + D(\rho^M_{k,\text{fin}} \| \rho^M_{k,\text{can}}) \Big] .$$

Note that the terms in the last line are non-negative, expressing thermodynamically inefficient use of correlations and of nonequilibrium states, respectively. Furthermore for general quantum measurements (POVMs), we identify any inefficiencies in the probe measurement and in the outcome storage, leading to a strict inequality (EFF).

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Optimal performance of quantum refrigerators

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Thermodynamics is a branch of science blessed by an unparalleled combination of generality of scope and formal simplicity. Based on few natural assumptions together with the four laws, it sets the boundaries between possible and impossible in macroscopic aggregates of matter. Close analogues of those fundamental laws are now being established at the level of individual quantum systems, thus placing limits on the operation of quantum-mechanical devices. In this respect, the analysis and derivation of general performance benchmarks is important for the design of highly optimized thermal machines operating at the quantum level. Here we study elementary refrigerators modelled as quantum "tricycles" (Fig. 1); these include quantum compression refrigerators, as well as quantum absorption refrigerators, which are driven by heat rather than by external work. We establish tight upper bounds on the thermodynamic coefficient of performance at maximum cooling power for all known models of quantum absorption refrigerators [1,2] (including single-qutrit, two-qubit, and three-qubit ones). In the particular case of endoreversible quantum refrigerators coupled to unstructured bosonic baths, the bound is refined into an exact function of the Carnot coefficient of performance [3], which might be seen as a counterpart, albeit non-universal, to the Curzon-Ahlborn bound for heat engines. We provide general design prescriptions to saturate the bounds. We further investigate how the established performance bounds may be pushed beyond what is classically achievable, by suitably introducing nonclassical environmental fluctuations (e.g. squeezing) via quantum reservoir engineering techniques [2]. The role of "quantumness" in refrigerators and other quantum heat pumps is critically discussed.

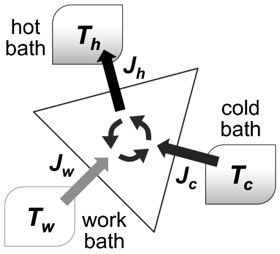

Fig. 1: A quantum tricycle in the refrigerator mode.

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Quantum Otto cycle with inner friction: finite time and disorder effects

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We investigate the effects of finite-time evolution for a quantum Otto cycle whose working medium is a qubit, or a set of noninteracting qubits, with a time dependent Hamiltonian in the adiabatic branches and coupled to two thermal baths at different temperatures in the isochoric ones.

We characterize the cycle looking at the extractable work, power, efficiency and efficiency at maximum power. We show that, when finite time evolutions are considered, there is a source of energy dissipation with respect to the quantum adiabatic case. Some of the energy is used by the system to increase its entropy and it has been named inner friction by Kosloff. It is also shown that such a inner friction appears when the Hamiltonian is the sum of at least two non-commuting operators thus giving to the inner friction a pure quantum nature.

We also discuss the effects of static disorder on the time dependent part of the Hamiltonian.

A feasible experimental proposal to implement a quantum Otto cycle with a fully optical setup is put forward.

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Non-equilibrium quantum fluctuations of work

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The concept of work is basic for statistical thermodynamics. However, it is not easy to define and interpret this concept in the quantum situation due to issues related to non-commutativity. To gain a fuller understanding of work and its (quantum) features, it needs to be represented as an average of a fluctuating quantity. Here I focus on the work done between two moments of time for a thermally isolated quantum system driven by a time-dependent Hamiltonian. I formulate two natural conditions needed for the fluctuating work to be physically meaningful for a system that starts its evolution from a non-equilibrium state. The existing definitions do not satisfy these conditions due to issues that are traced back to non-commutativity. I propose a definition of fluctuating work that is free of previous drawbacks and that applies for a wide class of non-equilibrium initial states. It allows to deduce a generalized work-fluctuation theorem that applies to any non-equilibrium state.

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Introduction. The first and second laws of statistical thermodynamics are formulated using the concept of work, i.e. the (average) energy exchanged by a system driven via a time-dependent Hamiltonian [1, 2]. In this sense the work is a basic quantity for thermodynamics. It is well-defined both in and out of equilibrium for any (quantum or classical) system interacting with external macroscopic work sources [2].

However, the work as it appears in the first and second law is an averaged quantity. There are at least two reasons why it is useful to "de-average" it, i.e. to present it as a random quantity. First, its features are understood better in this way. Recall in this context that the conservation of average energy for an isolated quantum system is just a consequence of conserving energy eigenvalues and their probabilities. Second, the current understanding of the second law is that it has a statistical character and emerges out of averaging over fluctuations [4]. Hence it is necessary to define fluctuations of work for understanding e.g. the Thomson's formulation of the second law [4–7]. Both these points are illustrated by fluctuation theorems; see [7–11] for reviews.

The existing definitions of quantum fluctuations of work can be divided into 2 groups. Time-global definitions look for the work done between two moments of time, as usual for any transfer quantity [10–21]. Time-local approaches adapt the global definitions infinitesimally along an effective quantum trajectory [22–32].

Here I focus on the time-global approaches (admittedly they are more fundamental in the quantum case) for a thermally isolated dynamics and note that they do not apply whenever the initial density matrix does not commute with the (initial) Hamiltonian. This limitation is essential, since work-extraction from non-equilibrium (e.g. non-diagonal) states is important both conceptually [5] and practically [33].

The aim of this paper is to present a definition of quantum fluctuations of work that is free of the previous drawbacks. It is based on the Terletsky-Margenau-Hill distribution [34–39]. The definition applies for a class of initial density matrices that do not commute with the (time-dependent) Hamiltonian. It leads to a generalized fluctuation theorem.

However, this definition is neither unique (otherwise there would not be the issue with non-commutativity), nor it applies for an *arbitrary* initial state, because there it leads to negative probabilities whose physical meaning is not clear. In this context, I formulate 2 conditions for fluctuating work that are closely linked to its physical meaning as the amount of energy exchanged with the source of work. They need to be satisfied for any definition of the fluctuating work and they hold for the presented one. It remains to be seen whether this is indeed the most convenient definition or there are even better ones to be uncovered in future.

To explain why I decided to focus on the concept of work, I shall compare its features to those of entropy production (EP). For a system coupled to thermal baths, EP amounts to entropy increase of baths [1, 2]. This definition does not apply more generally—for non-equilibrium baths or thermally isolated case—since the very definition of entropy is ambiguous there. For those cases, EP is defined as an effective measure of irreversibility that has to be positive and share the heuristics of entropy increase [51–53]. There is some consensus on how to define EP for classical [51, 54] and semi-classical systems [11]. But the quantum situation is ambiguous in this respect [55, 56]; e.g. Ref. [56] shows that there is a family of EPs associated with different notions of effective phase-space. They lead to different notion of the (average) EP even for the initially equilibrium (Gibbsian) initial state [57]. These features differ from those of the (average) work, which is well-defined for arbitrary (initial) states.

Set-up. Consider a quantum system with an initial state described by a density matrix ρ. The system is thermally isolated: its dynamics is described by

Seebeck Effects in Two-Dimensional Electron Gases

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We consider a two-dimensional electron system in the presence of Rashba spin-orbit interaction and under the influence of a thermal gradient externally applied to two attached reservoirs [1]. We discuss the generated voltage bias (charge Seebeck effect), spin bias (spin Seebeck effect) and magnetization-dependent thermopower (magneto-Seebeck effect) in the ballistic regime of transport at linear response. We find that the charge thermopower is an oscillating function of both the spin-orbit strength and the quantum well width. We also observe that it is always negative for normal leads. In contrast, when the contacts are ferromagnetic, the thermopower can change its sign by tuning the Fermi energy (see Figure). This effect disappears when the Rashba coupling is absent. Additionally, we determine the magneto-Seebeck ratio, which shows dramatic changes in the presence of the Rashba potential.

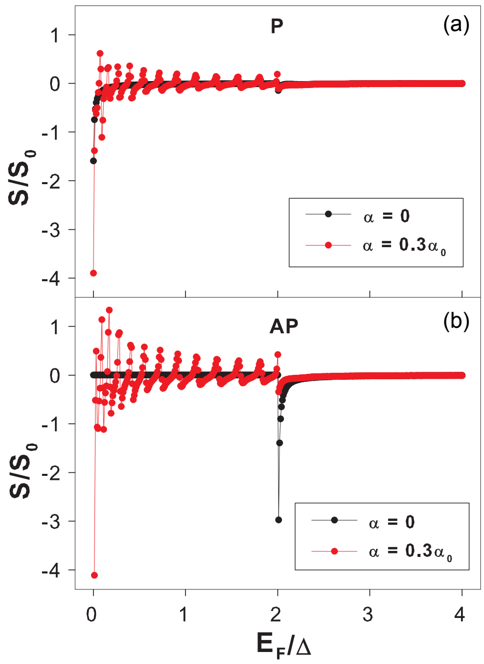

Figure: Seebeck coefficient as a function of the Fermi energy for both parallel, (a), and antiparallel, (b), configurations of leads' magnetic moments pointing along the x-direction. Grey and black curves represent the cases with and without Rashba coupling in the central region, respectively [1].

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Powerful quantum batteries

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We study unitary charging of a quantum battery described by a system with a fixed Hamiltonian H_0. Since for batteries quick charging is desirable we optimise the power of the charging process and demonstrate a non-trivial maximum. This bound on charging power depends on the energy available for driving the system. That the power possesses such a bound is indeed expected when considering that quantum processes obey quantum speed limits [1]. This first main result of the paper is analytically derived for the case of a qubit making use of recent results concerning the time-optimal driving of qubits [2]. Building on this, the second main result states that higher power can be achieved when considering an array of batteries and allowing for entangling operations. This even holds if, with cyclic operation in mind, downgrading of the state is not permitted – that is, the purity of the marginal states must not have decreased at the end of the process.

In summary, we show that whilst the power of a quantum process obeys an upper bound that bound can in fact be overcome by using entangling operations on an array of identical systems.

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D.E.Bruschi et al.

Quantum thermodynamics for a model of an expanding universe

We investigate the thermodynamical properties of quantum fields in curved spacetime. Our approach is to consider quantum fields in curved spacetime as a quantum system undergoing an out-of-equilibrium transformation. The non-equilibrium features are studied by using a formalism which has been developed to derive fluctuation relations and emergent irreversible features beyond the linear response regime. We apply these ideas to an expanding universe scenario, therefore avoiding assumptions on the relation between entropy and quantum matter. We provide a fluctuation theorem which allows us to understand particle production due to the expansion of the universe as an entropic increase.

In this work we jointly use tools from quantum field theory in curved spacetime and the recently developed concepts from thermodynamics of quantum systems to investigate a relationship between entropy production and particle creation in an expanding universe. We explore applications of this approach to a simple model for cosmological expansion. We give a thermodynamic meaning to particle creation in terms of a quantity called *inner friction*. We then show that inner friction has an entropic interpretation stemming from a quantum fluctuation relation: inner friction arises due to the quantum fluctuations of the fields. Our main result is a quantum version of the second law of thermodynamics for an expanding universe which accounts for the creation of matter. The techniques developed in this work can be used to better understand cosmological processes or scenarios based on similar mathematical descriptions.

In this work particles are excitations of a quantum field $\phi(x,t)$ with mass m that propagates on a classical spacetime with metric $g_{\mu\nu}$ and satisfy the equation of motion $(\Box+m^2)\phi=0$. The field can be decomposed in any orthonormal basis $\phi=\int_k dk[a_k u_k + a_k^\dagger u_k^*]$, with annihilation and creation operators a_k, $a_k^\dagger$ that satisfy the canonical commutation relations $[a_{k'},a_k^\dagger]=\delta(k-k')$ and all other vanish. The annihilation operators a_k define the vacuum state $|0\rangle$ through $a_k|0\rangle=0\,\forall k$.

We now specialise to the Robertson-Walker spacetime where there are two plane wave solutions to the field equation, the “in” and “out” modes whose operators are related by a Bogoliubov transformation $\tilde{a}_k=\alpha_k a_k+\beta_k^* a_{-k}^\dagger$. We can focus on one pair of modes $(k,-k)$ only in order to illustrate our techniques and define $a_k\equiv a$ and $a_{-k}\equiv b$ throughout the rest of the work. The initial and final Hamiltonian are $H=\omega(a^\dagger a+b^\dagger b+1)$ and $\tilde{H}=\tilde{\omega}(\tilde{a}^\dagger\tilde{a}+\tilde{b}^\dagger\tilde{b}+1)$ respectively.

We compute the work done by spacetime in unitarily evolving the initial Hamiltonian H to the final Hamiltonian $\tilde{H}$. A straightforward calculation gives the average work in our cosmological model: $\langle W\rangle=\tilde{\omega}\langle n_c\rangle+(\tilde{\omega}-\omega)(\langle n_i\rangle+1)$, where $\langle n_i\rangle$ is the initial average number of excitations, and $\langle n_c\rangle$ is the average number of created particles.

If the expansion occurs in a quantum adiabatic limit, the Bogoliubov coefficients β_k vanish and the final adiabatic Hamiltonian is $\tilde{H}_{ad}=\tilde{\omega}(a^\dagger a+b^\dagger b+1)=\frac{\tilde{\omega}}{\omega}H$. In this quantum adiabatic scenario, the average work done by spacetime onto the fields is defined as the adiabatic work $\langle W\rangle_{ad}$ which reads $\langle W\rangle_{ad}=(\tilde{\omega}-\omega)(\langle n_i\rangle+1)$. The difference between the average work $\langle W\rangle$ and the average adiabatic work $\langle W\rangle_{ad}$ defines the quantity $\langle W\rangle_{fric}$ called *inner friction*. In our cosmological setting the inner friction is directly proportional to particle creation

$$\langle W\rangle_{fric}:=\langle W\rangle-\langle W\rangle_{ad}=\tilde{\omega}\langle n_c\rangle. \tag{1}$$

Our final step is to show that inner friction $\langle W\rangle_{fric}$ can be interpreted as an entropic quantity.

The probability of creating $n_c=n_f-n_i$ particles in the expansion process is $p_{n_i\to n_f}=p_{n_f|n_i}p_{n_i}$, where $p_{n_i}=\langle n_i|\rho|n_i\rangle$ is the probability of starting with n_i particles, $p_{n_f|n_i}=|\langle\tilde{n}_f|n_i\rangle|^2$ is the transition probability and n_f the total number of particles. The probability of destroying $n_d=n_i-n_f=-n_c$ particles in the contraction process is $q_{n_f\to n_i}=q_{n_i|n_f}q_{n_f}$, where $q_{n_f}=\langle\tilde{n}_f|\rho|\tilde{n}_f\rangle$ is the probability of starting with n_f particles and $q_{n_i|n_f}=|\langle\tilde{n}_f|n_i\rangle|^2$ is the transition probability. Note that $p_{n_f|n_i}=q_{n_i|n_f}$. We associate entropies $-\log(p_{n_i})$ and $-\log(q_{n_f})$ to the probabilities for the expansion and contraction processes respectively. The change in the entropy is $s(n_i\to n_f)=-\log(q_{n_f})+\log(p_{n_i})$, with opposite sign for the inverse process. The fluctuation theorem tells us that: $p_{n_f|n_i}p_{n_i}=q_{n_i|n_f}q_{n_f}e^{s(n_i\to n_f)}$. This suggests the process in which the change in entropy is positive is exponentially more likely than the reversed process.

We define the distributions for entropy change in the expansion and contraction processes respectively as $P_E(s)=\sum_{n_f,n_i}p_{n_f|n_i}p_{n_i}\delta(s-s(n_i\to n_f))$ and $P_C(-s)=\sum_{n_f,n_i}q_{n_i|n_f}q_{n_f}\delta(s-s(n_i\to n_f))$. We find that $P_E(s)/P_C(-s)=e^s$ which implies

$$\langle s\rangle=K[P_E(s)\|P_C(-s)], \tag{2}$$

where $K[X\|Y]\equiv-\sum_{xy}p_x[\log(p_y)-\log(p_x)]$ is the Kullback-Leibler divergence (or relative entropy) between X and Y. This entropy $\langle s\rangle$ is positive since the relative entropy $K[X\|Y]$ is positive and vanishes only when $P_E(s)=P_C(-s)$, i.e., for an adiabatic expansion of the spacetime.

We now assume that the initial state of our mode pair is a thermal state: $\rho=\frac{1}{Z}e^{-H/T}$, where $Z=\mathrm{tr}[e^{-H/T}]$ is the partition function. For the contraction process the system is again in the thermal state ρ, but we let the initial Hamiltonian be $\tilde{H}_{ad}$. This state is a thermal state of the final adiabatic Hamiltonian $\rho'=\frac{1}{Z}e^{-\tilde{H}_{ad}/\tilde{T}_{ad}}$, where $\tilde{T}_{ad}/\tilde{\omega}=T/\omega$. Using the probabilities of ρ we can compute the change in the entropy: $s(n_i\to n_f)=\frac{\tilde{\omega}n_f}{\tilde{T}_{ad}}-\frac{\omega n_i}{T}=\frac{\tilde{\omega}}{\tilde{T}_{ad}}(n_f-n_i)$. Finally, we have an exact relationship between entropy and particle created:

$$\langle s\rangle=\frac{\langle W\rangle_{fric}}{\tilde{T}_{ad}}=\frac{\tilde{\omega}}{\tilde{T}_{ad}}\langle n_c\rangle, \tag{3}$$

implying that inner friction is positive. The positivity of $\langle W\rangle_{fric}$ can be seen as a statement of the second law of thermodynamics. This is strong evidence that $\langle s\rangle$ should be considered to be the correct entropic term to use in this cosmological context. This is the main result of our work.

We employed tools from quantum field theory and quantum thermodynamics to study the connection between entropy production and creation of particles in quantum field theoretical setups. Our main result was to provide a second law of thermodynamics for closed relativistic and quantum systems which explains how a unitary process, such as particle production, is connected to an increase of entropy. Our work is free from assumptions on the relation between matter and entropy and provides and intuitive understanding of how energy is used in the process of expansion and particle creation in a cosmological scenario. Furthermore, our formalism extends to all setups where the unitary evolution breaks down into a collection of two mode squeezing operations.

Features of Open Quantum Systems Dynamics

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The description of the dynamics of a quantum systems interacting with its physical unavoidable external environment is the central objective of the theory of open quantum systems. From microscopic models of system-environment interaction we learn that it does not lead to the famous exponential decay law, which is the result of the Born-Markov approximation, and therefore is, indeed, an approximation, valid under certain conditions.

Therefore the exact study of quantum systems interacting with structured environments, while presenting considerable difficulties from a theoretical point of view, is of crucial importance for the realistic description of a variety of physical systems. In result we discover the richness of the real systems dynamics including features such as inhomogeneity in time, non-existence of Markovian limit, and memory effects also known as non-Markovianity.

One of the fields where harnessing above features of dynamics of open quantum systems may lead to an enhancement is quantum information processing. Since it relies on the ability to coherently transfer information encoded in quantum states along quantum channels, decoherence induced by the environment sets limits on its efficiency. Generally, the longer a quantum channel is the worse its capacity. Our main result is the identification of specific features of non-Markovianity which lead to (i) revivals of the capacities of quantum channels, hence increasing the values of channel lengths over which the capacities are non zero, (ii) length-independent finite-capacity channels (residual channel capacity), i.e., channels for which the capacity remains unchanged and positive, after a certain threshold length.

We also comment on features of dynamics of open quantum systems from point of view of quantum thermodynamics. In particular we discuss their influence on the asymptotic states, problem of thermalisation and existence of equilibrium states. While for Markovian dynamics the evolution of the equilibrium state is always invariant, non-Markovian evolution, because of memory effects, can relax to an equilibrium state that is not invariant. Moreover it can happen that the asymptotic state depends on the initial state of the system, hence the equilibrium state does not exist.

Nonequilibrium fluctuations in quantum heat engines: Theory, example, and possible solid state experiments

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The stochastic thermodynamics of a quantum heat engine (including the statistics of efficiency and the compliance with the fluctuation relation) is illustrated by means of a two-qubit heat engine, where each qubit is coupled to a thermal bath and a two-qubit gate determines energy exchanges between the two qubits. We discuss possible solid state implementations with Cooper pair boxes and flux qubits, quantum gate operations, and fast calorimetric on-chip measurements of single stochastic events

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Path-integral formulation of heat exchange in open quantum systems

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The emerging field of quantum thermodynamics aims to extend basic concepts of thermodynamics at the nanoscale. Indeed lowering the dimension of a system, fluctuations and quantum effects become crucial and classical thermodynamics cannot be simply applied. The question of how a small system exchanges heat and energy with a bigger one is very important both from technological and foundamental point of view. A deep understanding of heat exchange at the nanoscale is necessary in view of the realization of quantum devices such as quantum heat engines which could have great technological impact. Despite much recent efforts, the thermodynamics of quantum systems is still poorly understood, at least when compared to its classical counterpart. Here we aim to go a step forward towards a microscopic and rigorous description of heat exchange in quantum system. We consider a quantum system coupled to a thermal reservoir and the energy flows between them.

Starting from very few and plausible assumptions, we approach the problem with the path integral technique. In this framework we can write a general heat influence functional which embodies all the dissipative mechanisms and allows us to study heat processes.

Our formalism is system-independent and allows one to access to the full dynamics of the system and the heat statistic by means of non-perturbative methods or using well-established analytical approaches, in which all necessary assumptions can be systematically controlled.

As an application we consider the so-called spin boson model. We thus concentrate on a two level system coupled to a thermal bath and we calculate, by means of the heat influence functional, the average heat and the heat power exchanged between them. Thus, we derive general expressions for the time evolution of these quantities valid also in presence of an external bias. Considering the case in which the two level system and the reservoir are weakly coupled we provide general expressions that contain also non-Markovian and memory effect. We thus demonstrate that at low temperatures these quantum corrections and non-Markovian effects have non-trivial contributions to the system dynamics and can be seen in the time evolution of the average heat and heat power.

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Toward a Thermo-Hydrodynamic Description of Quantum Mechanics

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We revisit the Madelung description of a non relativistic time dependent quantum particle as a fluid system. The compressibility of the fluid relates between its thermodynamic and hydrodynamic properties. The Bohm's potential is represented in terms of a barotropic thermodynamic pressure gradient force and the energy expectation value is composed of the fluid's kinetic energy and a positive-definite quantity that can be regarded as the fluid's thermal internal energy. The latter is proportional to the kinetic energy associated with the imaginary part of the particle's momentum whose expectation value is zero, as is required from thermal random motion. Nonetheless, we cannot relate directly the thermodynamics entropy of the fluid with quantum entropy expressions.

Next we consider the generalized thermo-hydrodynamic Madelung representation of several basic examples including the superposition of two eigenstates of a particle in a box where compressibility plays an important role. We show that incompressibility of the fluid immediately results non-spreading of the wave packet and in 1D this condition is obtained when the sum of the Bohm potential and an exterior one is either constant or linear in space. The latter yields the solutions of unbounded Airy function, quantum bouncer, and Gaussian wave packets for the cases of zero, gravitational and harmonic external potentials, respectively.

Finally we discuss, on general and in the context of the above examples, the representation of the Bohm's potential as Fisher's information and its relation to its associated thermodynamic barotropic pressure.

Individual quantum probes for optimal thermometry

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The unknown temperature of a sample may be estimated with minimal disturbance by putting it in thermal contact with an individual quantum probe. If the interaction time is sufficiently long so that the probe thermalizes, the temperature can be read out directly from its steady state. In this talk, I will prove that the optimal quantum probe, acting as a thermometer with maximal thermal sensitivity, is an effective two-level atom with a maximally degenerate excited state. When the total interaction time is insufficient to produce full thermalization, I will optimize the estimation protocol by breaking it down into sequential stages of probe preparation, thermal contact and measurement. We observe that frequently interrogated probes initialized in the ground state achieve the best performance. For both fully and partly thermalized thermometers, the sensitivity grows significantly with the number of levels, though optimization over their energy spectrum remains always crucial.

An all-optical nanomechanical heat engine

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We propose and theoretically investigate a nanomechanical heat engine. We show how a levitated nanoparticle in an optical trap inside a cavity can be used to realize a Stirling cycle in the underdamped regime. The all-optical approach enables fast and flexible control of all thermodynamical parameters and the efficient optimization of the performance of the engine. We develop a systematic optimization procedure to determine optimal driving protocols. We further perform numerical simulations with realistic parameters and evaluate the maximum power and the corresponding efficiency. Both the experimental setup and the optimization procedure have the potential of being extended into the quantum regime.

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Measuring work and heat in ultracold quantum gases

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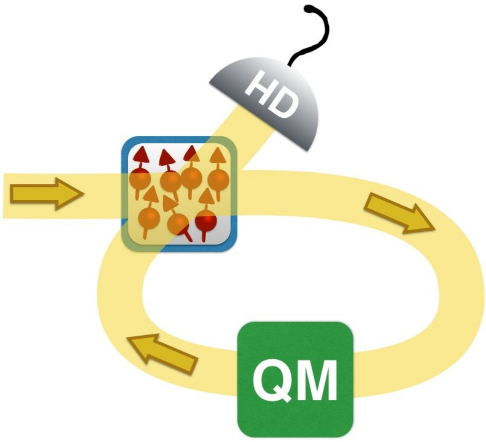

Ultracold atomic gases are one of the reference platforms for investigating fundamental physics, from few- to many-body dynamics and as a versatile system to implement quantum information processing or simulate condensed matter and high-energy physics models. So far, the interest in out-of-equilibrium quantum thermodynamics has been limited to transport problems, atoms losses and spin dynamics. In this contribution, I will present a radically new method based on Ref.[1] to measure **heat** and **work** in cold atomic gases. The scheme is based on a light-matter interface (see figure) capable of extracting information about the atomic state. Using this interaction, known as the Faraday effect, we can measure the initial and final energy of an atomic ensemble before and after a thermodynamic transformation has taken place. For isolated systems this accounts for the work done on or extracted from the system. For open systems there will also be a contribution of heat.

We showcase two examples: in the first, we consider an atomic ensemble subject to a rotating magnetic field. We find the work probability distribution and compare it with the distribution reconstructed by measuring the outgoing light. We find that the Jarzynski equality (JE) can be efficiently verified; in the second, we consider atoms in optical lattices in an open system scenario and show how, from the fulfillment of the JE, we have information about the *unitality* of the corresponding CP map.

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Temperature: a quantum estimation approach

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Some of the basic concepts of classical thermodynamics, including heat and work, still lack a univocal definition in the quantum regime. This is due to the fact that, being process rather than state variables in classical mechanics, such thermodynamical quantities have in general no quantum observables associated with them and thus cannot be directly measured. Here, we focus on the concept of temperature. In the quantum scenario, it is not always univocally defined in the sense that it may loose its intensiveness character. The theoretical efforts performed in order to close this gap shared the convention of defining a local temperature for those subsystems which can be described by canonical states [1]. By changing perspective, we feed the issue of temperature locality into the mindset of quantum estimation theory, specifically tailored for the reconstruction of physical parameters which cannot be accessed via direct measurements. More precisely, we rephrase the problem in terms of determining up to which limit-size the subsystems of a thermal state can bring information on the global temperature, thus overcoming the theoretical testbed of conserving a thermal-like structure by the subparts of a system at a given temperature. Such strategy hinges upon the computation of the quantum Cramer-Rao Bound (CRB) on the variance associated to the global temperature. Such bound enables to identify the optimal observables to be measured, so as to minimize the statistical fluctuations, thus endowing this approach with a clear operational meaning. For the case of the global temperature of a Gibbs state, the CRB has been showed [2] to be proportional to the heat capacity and the optimal quantity to be measured coincides with its total energy. We have generalized this approach to the estimation of temperature via local measurements, thus providing the explicit dependence on the dimension of the probed subsystem [3]. In the low-temperature regime, this reveals a thermodynamics-rooted scheme able to operationally quantify the state distinguishability between the ground state and the first excited level of the system Hamiltonian. Such information proves to be useful in order to determine up to which level the system is protected against local noise. We conclude by considering some prototypical models for many-body systems, such as the Ising chain in a transverse field, currently used to describe a variety of physical systems, ranging from cold atoms in optical lattices to arrays of QED cavities.

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The Quantum Hourglass – a road towards thermal clocks

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Time enters Quantum Theory in manifold ways. Since the early days of quantum theory this led to heated discussions about its nature.In a letter Heisenberg wrote to Pauli in November 1925, he commented:

„... there always will exist a coarse time sequence, like a coarse position in space - that is, within our geometric visualization one will be able to carry out a coarse description. I think it might be possible that this coarse description is perhaps the only thing that can be demanded from the formalism [of quantum mechanics].“[1]

Our inability to formulate a consistent theory with an observable for time brings along the question "how well can we observe time". This is a really important question as we don't have access to the Schrödinger parameter *t* directly. One of the first widely recognized attempts to answer this question was given by Mandelstam and Tamm in 1945 [2]. In their observable-dependent energy-time uncertainty relation they refer to time characteristics of average expectation values. This approach however has its limitations [3,4].

A different form of answer to the former question will be given more in the spirit of above Heisenberg quote. For this purpose a general non-relativistic operational framework for the description of a wide range of quantum clocks, called quantum hourglass, will be introduced. It has the ability to distinguish `coarser and finer' time sequences depending on its implementation.

We will focus on thermodynamic implementations of the quantum hourglass, as the quantum hourglass provides an adequate setting for an analysis of such possible thermal time measuring devices.

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Quantum thermodynamics:
A nonequilibrium Green's function Approach

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We will discuss the difficulties encountered when attempting to formulate quantum thermodynamics for open quantum systems strongly coupled to their reservoirs. A consistent approach resolving these problems will be presented within the framework of nonequilibrium Green's functions. The four fundamental laws of thermodynamics are verified and can be used to characterize transport in steady-state as well as in driven devices.

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Experimental realization of a Coulomb gap refrigerator

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Electronic microrefrigerators working in the temperature range of 300 - 100 mK are usually based on tunnel junctions or quantum dots [1]. These devices have received increasing attention during the past few decades and were successfully implemented in several applications. One would naturally like to explore even lower temperatures. Here we present the first proof-of-concept Coulomb blockade refrigerator (CBR) that is based on thermal transport through a fully normal single-electron transistor (SET) and intended for temperatures well below 100 mK [2, 3]. The SET has two NIN tunnel junctions in series, formed between two normal metal electrodes (N) separated by a thin insulator (I) each. The cooler is biased by voltage *V* transporting electrons from the left lead to the island and from the island to the right lead. The gate voltage controls the electrostatic potential of the island so that electrons lose energy when tunneling into the island, and experience an energy gain when tunneling to the right lead out of the island. A superconducting inclusion is placed in the middle of the island to prevent heat flow between the junctions while transporting the electrons. The heat carried by the tunneling electrons is split evenly between the two electrodes of each junction. The device is made by electron-beam lithography and lateral tunnel junction technique [4]. The observed cooling is monitored with an NIS thermometer and is rapidly increasing towards the low temperatures currently reaching 15 mK drop at a base temperature of 90 mK.

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No long-term loans from the Bank of Entropy

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I shall present a pedagogical discussion of the operation of the second law in the context of making measurements of an open classical system and exploiting the derived information. Stochastic thermodynamics has emerged in recent years as a powerful phenomenological framework for modelling irreversible processes, and attention has been given to the processes of measurement and feedback [1], and the various theoretical identities that hold [2]. Such an approach can be used to clarify an aspect of the exorcism of Maxwell's demon, in other words to refine an argument against the existence of a programme of action to reduce the total entropy of the universe [3]. In 1982, Bennett [4,5] proposed that the second law is saved in the face of such a programme by the requirement that all traces of the actions taken should eventually be removed. Measuring devices are to be reset or equivalently the demon must have his memory wiped [6]. However, such a resolution effectively puts off the reckoning of the entropy account for an arbitrary length of time. In stochastic thermodynamics, however, the entropy balance is never negative, except as temporary fluctuations, and this can be illustrated using a simple classical model. It will remain the case in a quantum setting. The second law in this framework cannot be mortgaged: there are no long-term loans from the Bank of Entropy.

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Reexamination of Pure Qubit Work Extraction

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Many work extraction or information erasure processes in the literature involve the raising and lowering of energy levels via external fields (e.g. [1,2]). But even if the actual system is treated quantum mechanically, the field is assumed to be classical and of infinite strength, hence not developing any correlations with the system or experiencing back-actions. We extend these considerations to a fully quantum mechanical treatment by studying a spin-*1/2* particle coupled to a finite-sized directional quantum reference frame, a spin-*l* system, which models an external field. With this concrete model together with a bosonic thermal bath, we analyze the back-action a finite-size field suffers during a quantum-mechanical work extraction process and the effect this has on the extractable work and highlight a range of assumptions commonly made when considering such processes. The well-known semiclassical treatment of work extraction from a pure qubit predicts a maximum extractable work $W=kT\log 2$ for a quasistatic process, which holds as a strict upper bound in the fully quantum mechanical case and is attained only in the classical limit. We also address the problem of emergent local time dependence in a joint system with a globally fixed Hamiltonian.

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Defining work and heat from operational postulates

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In phenomenological thermodynamics, work is defined as the energy that can be stored in a lifted weight. This is taken as a primitive in many operational formulations of the second law, which rely on the observation that, due to the effect of thermal fluctuations on macroscopic objects, a weight cannot be lifted just by putting it in contact with a bath.

In the quantum regime, one must account for thermal fluctuations, since they may not be negligible compared with the energy stored when it is lifted. This leads to the question of how to define work in the quantum regime in a way that is properly distinguished from heat-like fluctuations. The concept of deterministic work extraction has been put forward aiming at measuring work free from thermal fluctuations [1,2].

In this contribution, we establish an axiomatic approach to characterize the most general form of a quantifier of work that properly distinguishes it from heat.

We consider two parties: Arthur possesses an arbitrary system (a battery), that is manipulated by Merlin and returned to Arthur in a different state. They both agree upon the existence of thermal states at temperature T as a free resource, but the internal mechanism of Merlin's device is unknown to Arthur. Both want to establish a fair work value for the process implemented by Merlin as a function of the initial and final states of the battery (ρ^i and ρ^f), its Hamiltonian H and the temperature T. We propose a set of purely operationally motivated minimal postulates that any function accounting for work must fulfill: (i) if a transition could have been performed by only using free resources, then the total work is not larger than zero; (ii) if the state of the battery is unchanged, then the work is zero.

We show that (i-ii) are fulfilled if and only if the measure of work W can be written as $W = G(\rho^f) - G(\rho^i)$, where G is a monotone under free operations. This is in contrast with traditional definitions in terms of the energy difference. We also show that previous and common definitions of work do not respect postulates (i-ii), however particular choices of G lead to definitions of work that are similar in spirit to the notion of deterministic work. Finally we show that there exists choices for G such that the maximum of W under protocols implemented by Merlin is bounded by the usual second law in terms of free energy of the working system of Merlin.

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Time scales of equilibration for physically relevant measurements

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We address the problem of understanding, from first principles, the conditions under which a closed quantum system equilibrates quickly with respect to a given observable. Previously known upper bounds on the time scales of equilibration were extremely long, with times scaling approximately linearly with the Hilbert space dimension of the system [1]. Moreover, these bounds proved to be tight, since particular constructions of observables saturating the bound were found [2,3]. This implies that further assumptions are needed in order to prove reasonably fast equilibration.

In this work we provide a new upper bound on the equilibration time scales for a given observable. Under the assumption that the initial state is spread over many energy levels, and certain assumptions about the distribution of the matrix elements of the observable and initial state, we find that for mixed initial states this new bound gives much more realistic results than previously known, with times which do not scale with the Hilbert space dimension of the system.

As a corollary the result is applied to the case of a small system interacting with a thermal bath. Unlike previously known general bounds, which only provided a scaling for the time it takes to equilibrate, we find a precise simple expression to calculate the upper bound on the time scale of equilibration for a given initial state, observable, and Hamiltonian satisfying the assumptions involved in our proof. Remarkably, this simple expression is reminiscent of the result one would get from a second order Taylor expansion for small times.

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Strongly coupled quantum heat machines

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Many different models of quantum heat machines (QHM) have been proposed and studied [1] in order to answer fundamental theoretical questions, as the validity of thermodynamics at the quantum level. Beside its theoretical importance, QHM have large experimental and technological applications, in particular in the area of cooling and nanomachines. A common denominator between these models is the weak coupling assumption [2] between the system and the baths. This supposition is grounded in the thermodynamic principle of separability between systems and allows the derivation of the evolution equation. The work or cooling power of these machines is proportional to the square of the coupling [3], limiting their output and possible realistic applications. A possible way to overcome this limitation is to consider QHM in the strong coupling regime, where the separability principle, as well as other thermodynamic principles, may no longer hold. The difficulty in solving the evolution equations, combined with the notion that thermodynamics requires some degree of separability, have left this regime virtually unexplored. Would strong coupling machines function at all or is some degree of separability needed? Would they be bounded by the Carnot bound or may the breakage of the separability principle allow a higher efficiency? Would the power increase with the coupling strength allowing the creation of machines with ultra-high output or would the power saturate at some point? Answering these questions becomes more relevant in the light of the large progress achieved in the field of strongly coupled superconductors, which makes their realizations more actual than ever. In this talk, I will explore this virtually unknown regime, showing the difference between weakly and strongly coupled quantum thermal machines, the advantage and limitations of each of them, and their relation with thermodynamic principles and bounds [4].

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Locality of temperature

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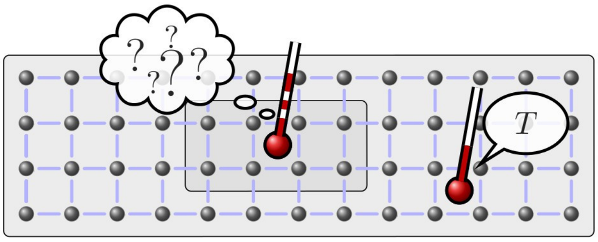

We examine the properties of systems in thermal equilibrium and essentially solve the problem of how to assign a local temperature to a small subsystem of very general globally thermal quantum lattice systems at a sufficiently high temperature.
As a first result, we show that a consistent, local, and intensive definition of temperature is possible if and only if certain correlations in a system are sufficiently short ranged. In a second step, we prove a universal upper bound on the spatial decay of these correlations, which works whenever the global temperature is above a critical value that depends only on local properties of the system. Our results show that above this value, no phase transition involving long-range order is possible. This finding implies a universal upper bound on physically relevant critical temperatures such as the Curie temperature, which is remarkable since pinning down critical temperatures is a notoriously difficult problem, and analytical results only exist for a handful of special cases. In addition, our results show that at temperatures above the critical value, thermal states are locally stable against distant perturbations of the Hamiltonian, and that expectation values of local observables can be approximated efficiently, even in the thermodynamic limit.
Our mathematical tools allow one to exploit the Hamiltonian's locality structure for the investigation of thermal states and open up new perspectives in the study of quantum systems in thermal equilibrium.

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Dissipative cooling of degenerate Bose gases

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We introduce a novel dissipative cooling schema for degenerate Bose gases based on coherent outcoupling of atoms from the condensate [1]. We show that in the universal phononic limit the system evolves towards an asymptotic dissipative state where the temperature is set by the quantum noise of the outcoupling process. The proposed mechanism supplements conventional evaporative cooling and dominates in settings where thermalization is highly suppressed, such as in a one-dimensional quasicondensate, where it can be readily observed in experiment.

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Local temperature in interacting spin systems

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Temperature is traditionally considered a local quantity: a part of a thermal system is also thermal and has the same temperature as the whole. Nevertheless, in strongly interacting systems the locality of temperature breaks down. We explore the possibility of associating effective thermal states to subsystems of infinite chains of spin-1/2 particles. We reveal the role of correlations and criticality, and discuss the implications of our conclusions for classical simulation of thermal states.

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Extractable work from correlations

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Work and quantum correlations are two fundamental resources in thermodynamics and quantum information theory. In this work we study how to use correlations among quantum systems to optimally store work. We analyse this question for isolated quantum ensembles, where the work can be naturally divided into two contributions: a local contribution from each system, and a global contribution originating from correlations among systems. We focus on the latter and consider quantum systems which are locally thermal, thus from which any extractable work can only come from correlations. We compute the maximum extractable work for general entangled states, separable states, and states with fixed entropy. Our results show that while entanglement gives an advantage for small quantum ensembles, this gain vanishes for a large number of systems.

I. INTRODUCTION

Traditional, macroscopic thermodynamics is strikingly insensitive to the underlying mechanics: its three laws remain essentially the same while switching from classical to quantum mechanics [1]. On the other hand, one would hope for the opposite, since thermodynamics is intimately connected to information theory [2], and quantum phenomena, such as entanglement, have a drastic effect on the latter, irrespective of the scale [3].

Recently much attention has been dedicated to the problem of understanding thermodynamics of small quantum systems. This has led notably to the development of a resource theoretical formulation of quantum thermodynamics [4–6] and, in a more practical vein, to the study of quantum thermal machines [7–15]. The role and significance of quantum effects to thermodynamics is still to be fully understood, although progress has recently been achieved [13–22].

A problem of particular importance in quantum thermodynamics is to understand which quantum states allow for the storage and extraction of work from quantum systems [23, 24]. Such states are called non-passive, while states from which no work can be extracted are referred to as passive. Remarkably, the latter have the property of activation: when considered as a whole, several copies of passive states can become non-passive. The only states lacking this property are the thermal (also referred to as completely passive) states [23, 24].

The situation changes when considering ensembles that can also be correlated. There, even a collection of locally thermal states can be non-passive [25–27]. The main goal of the present work is to understand how to optimally make use of correlations among quantum systems for work storage. Specifically, we consider a quantum ensemble composed of n subsystems (particles or modes). Each subsystem is assumed to be in a thermal state, at the same temperature T. The total system, however, is correlated, because otherwise its state would also be thermal hence passive. This is in fact the natural scenario to study the role of correlations for work storage, as they become the only source of non-passivity.

First, we show that if no restriction on the global state is made, then it is possible to store in the system the maximal amount of work compatible with the requirement that the reduced states are thermal. In other words, at the end of the protocol, the system is left in the ground state and, thus, all energy has been extracted. Notably this is possible thanks to quantum entanglement. It is then natural to ask if the same amount of work can be stored using a separable, or even a purely classical state diagonal in the product energy eigenbasis, that is, with no coherences among different energy levels. We will see that, although the amount of work that can be stored in unentangled states is strictly smaller than the amount that can be stored in entangled states for any finite n, the gain decreases with the size of the system and in the thermodynamic limit ($n \to \infty$) purely classical states already become optimal. In fact, quantum resources offer a significant advantage only for small n, while neither entanglement nor energy coherences are needed for optimal work storage in the thermodynamic limit. We also consider additional natural constraints on the global state, such as limiting the entropy or requiring the decohered (classical) version of the state to be thermal, and investigate the role of quantum coherence and entanglement in these cases. Finally, we show that our results are also applicable to a different framework where the system does not remain isolated but is in contact with a thermal bath.

II. FRAMEWORK

We consider an isolated quantum system which consists of n d-level subsystems. The local Hamiltonian $h = \sum_a E_a|a\rangle\langle a|$ is taken to be the same for each subsystem and, without loss of generality, it is assumed that the ground state energy is zero. We consider the situation where there is no interaction Hamiltonian between the subsystems, such that the total Hamiltonian H is simply the sum of the individual local Hamiltonians $H = \sum_i h_i$.

The class of operations that we consider is the class of *cyclic Hamiltonian processes*, i.e. we can apply any time de-

The most energetic passive state

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Passive states play a central role in thermodynamics. They are defined as states that do not allow for work extraction in a cyclic (unitary) process. For a given entropy, the least energetic passive state is the thermal state. These states consequently never admit extractable work, even if asymptotically many copies are considered [1]. The converse question is how much extractable work can be "hidden" in a passive state, that can be activated by acting on multiple copies of the system.

In an upcoming paper [2] we resolve this question, i.e., we derive the general form of the passive state with the most energy for a given entropy. We find that it is directly connected to the micro-canonical state, thus building a new connection between the two most fundamental distributions in statistical physics. In particular we prove that every most energetic passive state can be decomposed into two normalized projectors on the subspaces spanned by the first k and k' energy eigenstates, i.e. two microcanonical states of constrained dimension. The exact k and k' are determined for various Hamiltonians and corresponding energy gaps. Furthermore we provide conditions that clarify when the resulting state is indeed just a microcanonical state.

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Mutual majorization of quantum marginals and the optimal conversion of energy to correlations

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Storing extractable work in quantum systems is a paradigmatic task in quantum thermodynamics and its understanding could fuel the development of practical protocols for designing batteries at the quantum scale. While it is perfectly understood how much work can be stored in single quantum systems, a main unresolved question concerns the potential to store work in correlations of multiple batteries. As an idealized primitive of such protocols one can study single machine cycles (i.e. arbitrary unitary operations) on isolated quantum systems [1,2].

Here one is interested in the unitary orbit of states that admit no local work extraction. An optimal conversion of average energy into correlations is achieved if the final states exhibit the least possible locally extractable work after application of a unitary work storage protocol [1,2,3]. Using the maximum entropy principle one obtains an upper bound on this quantity by requiring all marginal to be simultaneously thermalized at a higher temperature. In our manuscripts [4] (and using results from [1,2]) we study the potential to attain this upper bound in general. Exploiting a decomposition of the state in maximally entangled subspaces of n qudits we arrive at a general formalism for possible transformations of the marginal distributions [4]. We show that all distributions that are circulantly majorized by the initial Gibbs distributions are attainable for any number of systems and dimensions [4]. We furthermore prove that circulant majorization is equivalent to thermal majorization in case of equal energy spacings (and thus qubits and harmonic oscillators as special cases). Using convex geometry techniques we furthermore show, that while there exist Hamiltonians whose thermal distributions don’t circulantly majorize higher temperatures, we can nonetheless always achieve an optimal energy to correlations conversion provided that a minimum amount of average energy is converted (and we give explicit bounds in terms of the energy spacing of the Hamiltonian and the temperature).

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Exchange Fluctuation Theorem for Correlated Quantum Systems

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The Exchange Fluctuation Theorem (XFT) introduced in [1] describes energy exchange between two thermal systems. It assumes (i) microscopic time-reversal symmetry and that, before their interaction, (ii) the systems are thermally distributed and (iii) uncorrelated with one another. The core strength of the XFT is that it is a statement about the thermodynamics of non-equilibrium systems: it is valid even if the systems finish arbitrarily far from equilibrium.

When applying the XFT to quantum systems, which may be highly correlated or even entangled, it is natural to bring assumption (iii) into question. In [2] we extend the XFT to describe the non-equilibrium exchange dynamics of correlated quantum states. The relation quantifies how the tendency for systems to equilibrate is modified in high-correlation environments. In fact, our XFT reveals that two correlated systems that are locally at equal temperature can exhibit large asymmetric fluctuations in energy. This feature is not predicted by the original XFT, and can be viewed as a distortion of the principle of detailed balance.

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Quantum Limit of Heat Flow Across a Single Electronic Channel

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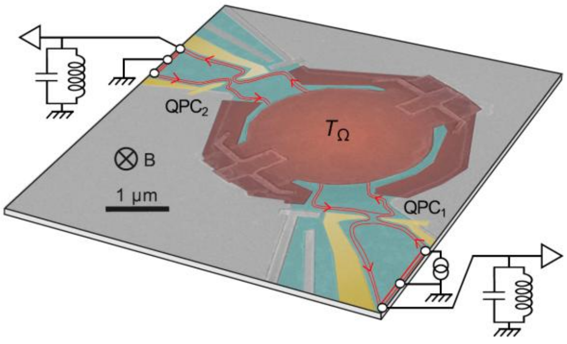
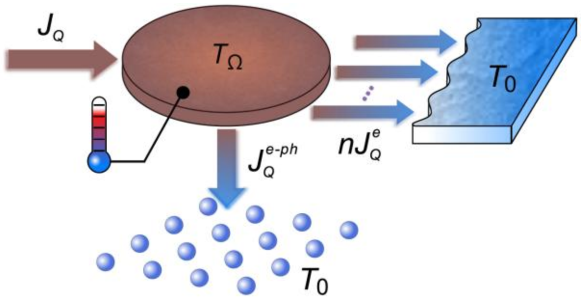
Quantum physics sets a fundamental limit, called the conductance quantum, to the maximum electrical and thermal conduction across a single transport channel. In contrast to charge transport, the thermal conductance quantum G_Q is predicted to be independent of the type of particles carrying the heat. Such universality, combined with the relationship between heat and information, signals a general limit on information transfer [1,2]. The thermal conductance quantum G_Q was previously measured for Bose particles, across the sixteen vibrational modes of narrow bridges [3]. Here, we present the quantitative measurement of the quantum limited heat flow for Fermi particles and across a single electronic channel. Using noise thermometry and quantum point contacts in a 2D electron gas, we demonstrate an experimental agreement with the predicted value of G_Q at an accuracy better than 10%. This establishes experimentally this basic building block of quantum thermal transport and opens access to new experiments involving the quantum manipulation of heat.



[Left] False-colors SEM image of the sample.



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Quantum coherence, time-translation symmetry and thermodynamics

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Fundamental laws of Nature often take the form of restrictions: nothing can move faster than light in vacuum, energy cannot be created from nothing, there are no perpetuum mobiles. It is due to these limitations that we can ascribe value to different objects and phenomena, e.g., energy would not be treated as a resource if we could create it for free. The mathematical framework developed to study the influence of such constraints on the possible transformations of quantum states is known under the collective name of resource theories.

The first and second laws of thermodynamics are such fundamental constraints that force thermodynamic processes to conserve the overall energy and forbid free conversion of thermal energy into work. Thus, a natural question to ask is: what amounts to a resource when we are restricted by these laws? It has been recently identified that apart from *athermality* (the property of a state of having a distribution over energy levels that is not thermal), also *coherence* can be viewed as a second, independent resource in thermodynamics [1]. This stems from the fact that energy conservation implied by the first law restricts processing of coherence, and so possessing a state with coherence allows for otherwise impossible transformations. It also enforces a modification of the traditional Szilard argument: both athermality and coherence contribute to the free energy, however coherence remains "locked" and cannot be extracted as work.

Since coherence is a thermodynamic resource, an open question is what kind of coherence processing is allowed by thermodynamic means. The aim of this presentation is to address this problem and ask: what are the allowed transformations of quantum states that are consistent with the first and second laws of thermodynamics? The broad approach is the analysis of coherence in thermodynamics from a symmetry-based perspective. Specifically, the underlying energy-conservation within thermodynamics constrains all thermodynamic evolutions to be "symmetric" under time-translations in a precise sense. This in turn allows us to make use of harmonic analysis techniques, developed in [2], to track the evolution of coherence under thermodynamic transformations in terms of the "mode components" of the system. This constitutes a natural framework to understand coherence, allows us to separate out the constraints that stem solely from symmetry arguments from those particular to thermodynamics, and provides results that generalize recent work on coherence [3]. This approach also implies that the existing single-shot results applicable to block-diagonal results, constrained by thermo-majorization, can be viewed as particular cases of our analysis when only the zero-mode is present. Beyond this regime, every non-zero mode obeys *independent* constraints, and displays thermodynamic irreversibility similar to the zero-mode.

Exploiting these tools we arrive at the upper bounds on final coherences in the energy eigenbasis for quantum states undergoing time-translation symmetric and thermodynamic processing [4]. A rich dynamics is allowed, in which coherence can be transferred among different energy levels within each mode. We show that similarly to heat flows, coherence flows show directionality due to the limitations imposed by the second law. This new kind of irreversibility adds up to the ones identified in work extraction [5] and coherence distillation [1]. We also present a way to find the guaranteed amount of coherence that can be preserved while transforming between two states with given probability distributions over the energy levels.

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The role of quantum correlations in measurement-based feedback cooling

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In the last decades we witnessed great improvements of the experimental techniques in manipulating quantum systems. This is of crucial importance for the implementation of quantum devices which exploit the quantum features of their constitutive units to outperform classical devices. For practical purposes, the preservation of the "quantumness" of these constitutive units is not an easy task: undesired interactions with the surrounding environment, which are unavoidable in many practical cases, are a non-negligible source of noise, responsible for the loss of the quantum features of the system of interest. An entropy increase of the latter can be seen as the fingerprint of this disturbance. It is in this context that *feedback control* plays a relevant role. Feedback control is a process useful in reducing the effects of unwanted noise on a quantum dynamical system by extracting entropy from it. This *cooling operation* can be accomplished by coupling the system we aim to control to another quantum system, hereafter dubbed *auxiliary*, and exploiting the information about the former gained by the latter [1]. In this work we focus on a particular class of feedback: *measurement-based feedback*. This class of feedback presumes the existence of a preselected (*measurement*) basis of the auxiliary, $\{|\mu\rangle_{\mathcal{A}}\}$, correlated with the useful information about the system. After a first (*measurement*) step where the correlations are built up through a joint (*measurement*) unitary U_m, a different unitary U_μ is applied to the system according to the possible outcomes of the measurement (in the measurement basis) performed on the auxiliary. We can then distinguish between two classes of measurement-based feedback: one in which the measurement is performed explicitly letting the auxiliary decohere in the measurement basis after the measurement step (*explicit measurement-based feedback*) and one in which the measurement and the feedback processes are separate and distinct but implemented coherently (*coherent measurement-based feedback*).

In this work we study, through an entropic approach, the choice of the measurement basis which allows to achieve the most effective cooling, in both coherent and explicit measurement-based feedback. The study of a simple model consisting of a single qubit system and a single qubit auxiliary led us to investigate in depth the role of quantum correlations (quantified by the quantum discord [2, 3] and by the local quantum uncertainty [4]) in feedback control processes. Following the protocol proposed in [1] we determined the optimal choice of the conditional feedback unitaries $\{U_\mu\}$ for any given measurement unitary U_m. We also found that, for this optimal protocol, the effectiveness of the cooling (the entropy reduction of the system) monotonically increases with the quantum correlations of the composite system after the measurement step. This result seems to suggest that a protocol which build up the greatest amount of quantum correlations during the measurement step cools more effectively if the chosen measurement basis is the one which minimizes, after this first step, the difference between the mutual information before and after a measurement is performed on the auxiliary in such a basis.

On a parallel line, our work aims to define a thermodynamic efficiency for measurement-based feedback control processes consistent with a tight Landauer's bound [5]. Also in this case we want to enlighten the role of quantum correlations in the thermodynamics of the protocol.

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Thermodynamics beyond free energy relations

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We are increasingly able to probe and manipulate the physics of micro and nano-scale systems. This has led to the explosion of works in the field of nanotechnology. Towards the lower-end of the nano-scale, quantum mechanical effects such as quantum coherence and entanglement increasingly make their presence felt.
The physics of these remarkable small-scale systems, displaying coherence or entanglement, constitute extreme quantum regimes. As such, a crucial question is: to what degree do traditional thermodynamic formulations and techniques encapsulate this regime? It is increasingly apparent that the traditional entropic formulation that emerges as an essentially unique description of the irreversibility of classical, macroscopic systems will only place necessary, but not sufficient, constraints on the physics of small-scale systems manifesting coherence or quantum correlations.
Rigorous derivations of the entropic form of the second law exist, such as by Caratheodory, Giles and more recently by Lieb and Yngvason [1]. The latter shows that the existence of an essentially unique entropic form of the second law is equivalent to highly non-trivial assumption on the structure of the thermodynamic partial order.
The results of [2] provide a clean characterization of non-asymptotic, thermodynamic inter-conversions of quantum states with zero coherence in terms of a set of entropic free energy functions. The present work goes beyond this, showing that even these fail to be sufficient for thermodynamic transformations involving non-zero quantum coherence. Exploiting recent results in asymmetry theory [3], we show [4] that thermodynamics can be viewed as being determined by at least two independent resources: the first is quantified by known free energies and measures how far a state is from being thermal; the second, a missing ingredient of previous treatments, measures how much a quantum state breaks time-translation invariance, i.e. the degree of coherence in the system. The theory of asymmetry provides *independent* thermodynamic that are intrinsically quantum-mechanical in nature. This removes the ``zero coherence'' assumption made in numerous recent works, e.g. [2,5-7] and extends the free energy relations to a parallel set of thermodynamic constraints for quantum coherence. We show that coherence is not directly distillable as work, but does admit activation. We uncover a second form of fundamental irreversibility that parallels the one stressed in [5] but involves coherence transformations. The same approach led to further results discussed in [8].

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Clock-Driven Quantum Thermal Engines

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So far, all frameworks describing quantum thermal engines (e.g., references [1-6]) involve the external application of discrete transformations. An interesting open question, raised by several authors [1-4], is whether this external control should carry a thermodynamic cost, and how to include this control explicitly in the framework. To describe these transformations entirely in terms of Hamiltonian evolution is the last necessary step for a completely quantum description of a quantum thermal machine. In this paper, we address this issue and describe how an explicit quantum clock can control the evolution of a completely arbitrary quantum system (the engine), thus allowing any unitary protocol to be carried out with no external control.

We consider an isolated autonomous quantum machine, where an explicit quantum clock is responsible for performing all transformations on the engine, via a time-independent Hamiltonian. In a general context, we show that this model can exactly implement any energy-conserving unitary on the engine, without degrading the clock. Furthermore, we show that when the engine includes a quantum work storage device we can approximately perform completely general unitaries on the remainder of the engine.

This framework can be used in quantum thermodynamics to carry out arbitrary transformations of a system, with accuracy and extracted work as close to optimal as desired, whilst obeying the first and second laws of thermodynamics. We thus show that autonomous thermal machines suffer no intrinsic thermodynamic cost compared to externally controlled ones.

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Quantum metrology in Lipkin-Meshkov-Glick critical systems

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Abstract: The Lipkin-Meshkov-Glick (LMG) model describes critical systems with interaction beyond the first-neighbor approximation. Here we address quantum metrology in LMG systems and show how criticality may be exploited to improve precision. At first we focus on the characterization of LMG systems themselves, i.e., the estimation of anisotropy, and address the problem by considering the quantum Cramer-Rao bound. We evaluate the quantum Fisher information of small-size LMG chains made of $N = 2$, 3, and 4 lattice sites and also analyze the same quantity in the thermodynamical limit. Our results show that criticality is indeed a resource and that the ultimate bounds to precision may be achieved by tuning the external field and measuring the total magnetization of the system. We then address the use of LMG systems as quantum thermometers and show that (i) precision is governed by the gap between the lowest energy levels of the systems and (ii) field-dependent level crossing is a metrological resource to extend the operating range of the quantum thermometer.

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Fluctuation theorems and quantum mutual information

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One signature of the second law of thermodynamics in isolated quantum systems is the creation of correlations, given by the (multipartite) mutual information, between subsystems with initial separable states [1]. This fact has been used recently as a proof of Landauer's principle in the form of a sharpened equality version [2]. Here I show how to derive detailed and integral fluctuation theorems for this quantity and discuss, from an operational point of view, their relation to the time-reversal symmetry breaking. This task is formally accomplished by constructing forward and backward thermodynamic processes related by a time-inversion of the dynamics and based on two-point measurement schemes. The role of the mutual information as an irreversible entropy production is discussed together with their complementarity to the expression given in [3].

Remarkably, the validity of our theorems do not rely on the specific form of the global (unitary) time-evolution nor on the shape of the initial (separable) states. This allows us to obtain a general relationship between forward and time-reversed Kraus operators describing the reduced dynamics of a particular subsystem. Finally, we comment on some basic examples and propose a phase estimation scheme in order to measure the characteristic function of the correlations in the same spirit as Refs. [4,5,6].

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Separation of heat and charge currents for boosted thermoelectric conversion

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February 5, 2015

Abstract

In normal two-terminal systems electrical and thermal currents are strictly interrelated since both charge and heat are transported by the same carriers: the quasiparticles. A consequence of this fact is observed in metals for low temperatures (where the Sommerfeld expansion is valid) where the ratio between electrical and thermal conductances is fixed to be a universal constant (Wiedemann-Franz law). This means that controlling separately the two currents is impossible.

In order to overcome this restriction, we propose to spatially separate the two currents. This can be accomplished by introducing a third lead and allowing no heat current in one lead and no electrical current in another one, resulting in a situation where electrical and thermal currents can be at the same time non-negligible and controlled separately.

In this work we study how to realize a heat-charge separator and we investigate the implications on the thermoelectric performance. We found that (under the Sommerfeld approximation) the thermal and electrical conductances, and the thermopower can be separately controlled, thus leading to a controlled violation of the Wiedemann-Franz law. This implies that, for a large class of systems, the thermodynamical performance are orders of magnitude better than a two-terminal system, that we used as a benchmark.

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Heat fluxes and quantum correlations in collision models

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(Dated: December 11, 2014)

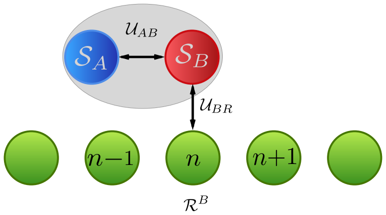

Figure 1. A schematic of the model. The quantum system S_A interacts with an ancilla S_B which then interacts with the environment via a collision model.

I. INDIRECT ERASURE

Any collision is described by a unitary evolution characterized by a collision time τ and an interaction Hamiltonian. Specifically, an $\mathcal{S}_A - \mathcal{S}_B$ collision is defined by $U_{BR}{=}e^{-igH_{BR}\tau/2}$ with $H_{BR} = \sum_k B_k \otimes R_k$ being the interaction Hamiltonian written as a sum of products of Hermitian operators B_k and R_k which act in the $B-$system's and the environment's Hilbert space, respectively. In a similar way we define $U_{AB} = e^{-iJH_{AB}\tau/2}$ with $H_{AB} = \sum_j A_j \otimes B_j$.

Assuming a weak coupling regime we can take a second order expansion with respect to the parameter $g\tau$,i.e. $U{\sim}\mathbf{I}{-}i\frac{g\tau}{2}H{-}\frac{g^2\tau^2}{8}H^2{+}O(\tau^3)$.

We now want to pass from the discrete dynamics indexed by n to a continuous-time dynamics. To perform the limit $\lim_{\tau\to\infty}\frac{\rho^{n+1}_{AB}-\rho^{n}_{AB}}{\tau}$, we set $n = t/\tau$ and we let the interaction time τ go to zero in such way that $g^2\tau$ rest constant: this means that we are watching in an exact manner the intra system dynamic and in a coarse-grained way the interaction with the reservoir.

$$\begin{aligned}\dot\rho_{AB} ={}& -\frac{i}{2}\,[\tilde H, \rho^t_{AB}]_- \\ &+ \frac{\gamma_g}{4}\sum_{kk'}\langle R_k R_{k'}\rangle_\eta \left(B_{k'}\rho^t_{AB}B_k - \frac{1}{2}\{B_kB_{k'}, \rho^t_{AB}\}_+\right)\end{aligned} \tag{1}$$

where we have defined the rate $\gamma_g = g^2\tau$ and with new Lamb shifted Hamiltonian $\tilde H = JH_{AB} + g\sum_k\langle R_k\rangle_\eta B_k$. What we obtain is a Lindblad master equation that describes a Markovian dynamics for the bipartite system.

II. EXAMPLE

In this example, the ancilla is a harmonic oscillator, but the environment remains comprised of qubits in the Gibbs state. The interactions between the system qubit and the oscillator are described by Jaynes-Cummings, as is the oscillator-environment interaction. Specifically, an $\mathcal{S}_A - \mathcal{S}_B$ interaction in qubit-oscillator ensemble, we define $U_{AB} = e^{-iH_{AB}\tau}$ with $H_{JC1} = \hbar\omega_c a^\dagger a + \hbar\omega_a\frac{\sigma^a_z}{2} + \hbar J(a\sigma^a_+ + a^\dagger\sigma^a_-)$ and for the $\mathcal{S}_B - \mathcal{S}_R$ interaction we define $U_{BR} = e^{-iH_{JCR}\tau}$ with $H_{JCR} = \hbar\omega_c a^\dagger a + \hbar\omega_r\frac{\sigma^r_z}{2} + \hbar g(a\sigma^r_+ + a^\dagger\sigma^r_-)$ the hamiltonian for the rth element interaction. J and g are the intra-system and environment coupling strengths respectively.

Taking the infinite small collisions limit with the environment as previously we obtain the master equation:

$$\begin{aligned}\dot\rho_{AB} ={}& -i\,[H_{JC1}, \rho] + \gamma_g\left(\frac{1-\xi}{2}\right)\left(a^\dagger\rho_{AB}a - \frac{1}{2}\left\{aa^\dagger, \rho_{AB}\right\}\right) \\ &+ \left(\frac{1+\xi}{2}\right)\left(a\rho_{AB}a^\dagger - \frac{1}{2}\left\{a^\dagger a, \rho_{AB}\right\}\right).\end{aligned} \tag{2}$$

This equation is a variation of Eqn. 1 using the Jaynes-Cummings Hamiltonian and the thermal state of the environment. The heat flow can be expressed as functions of density matrix elements ρ^{kj}_{nm}:

$$\mathcal{J}^{\text{tot}}_{AB}(t) = \omega\gamma_g\left(\left(\frac{1-\xi}{2}\right) - \xi\sum_{N=0}^{\infty}N\left(\rho^{ee}_{NN} + \rho^{gg}_{NN}\right)\right), \tag{3}$$

where $\omega = \omega_a = \omega_c = \omega_r$ for the resonant Jaynes-Cummings case.

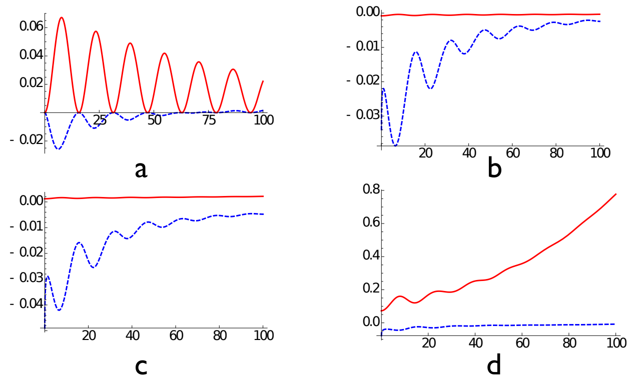

Figure 2. The heat flow $\beta\mathcal{J}^{\text{tot}}_{AB}$ (red) for the two qubit ensemble plotted against the differential entropy decrease δS (blue, dashed). This plot was done with $J = 0.1$, $\gamma_g = 0.01$ and $\omega = 1$. Each plot is for the environment at different temperature $\xi = 1, 0.2, -0.2, -1$ for a, b, c and d respectively.

Thermometry in Strongly Correlated ultracold lattice gases

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We propose the use of quantum non-demolition Faraday spectroscopy to estimate reliably the temperature of a sample of ultracold atomic gases simulating a strongly correlated system. The Faraday spectroscopy is a matter-light interface mapping atomic correlations into light quadrature fluctuations, the latter perceptible to be measured. Within this frame we analyze the paradigmatic XY model, estimating first by means of the quantum Fisher information the lowest attainable bound on the error of temperature estimation. Our results show that in the very small temperature limit the regions, which are most sensitive to temperature, are in agreement with the quantum phase transition lines. We then show, however, increasing the temperature poses these lines to move in the phase space. As a further step we identify the optimal observable and analyze those regions of the phase diagram whose thermal sensitivity is higher once this optimal observable is measured. Our analysis shows the same result as the one obtained using the quantum Fisher information. Finally, we investigate if this scheme could be realistically used for thermometry in the strongly correlated domain.

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Minimising the heat dissipation of maximal information erasure

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Information erasure in quantum mechanics is equivalent to purification, and maximally erasing the information of a system can be understood as maximising the probability of finding it in an assigned pure state. We determine the optimal unitary evolution of a system, composed of an object to be erased and a thermal reservoir, so as to minimise the heat dissipation to the latter conditional on maximising the information erasure on the former.

A simple example is considered, where the object is a qubit in a maximally mixed state, and the reservoir is a subspace of a harmonic oscillator, of frequency ω, containing the d lowest energy levels. Full information erasure is possible, whereby the entropy of the qubit is reduced by $log(2) \simeq 0.69$, in the limit as d and the reservoir's Hamiltonian norm tend to infinity, with a corresponding heat transfer to the reservoir given as $\Delta Q = k_B T+\varepsilon$; k_B is Boltzmann's constant, T the temperature of the reservoir, and ε a positive number that can be made arbitrarily small by diminishing ω. This is greater than Landauer's limit, wherein the lowest achievable heat dissipation is $k_B T\ log(2)$. Moreover we show numerically for reservoir dimensions within the range of {2,…,32}, that in the presence of energy conserving, Markovian dephasing, cases where $d = 2^n$ with $n \geq 2$ a natural number are more robust; this is in the sense that for such dimensions, the probability of bit erasure takes the largest global values (within the range considered), whilst the heat dissipation of all larger dimensions are always greater.

Finally, we consider two alterations in the assumptions upon which Landauer's principle is based, so as to attain better bounds. The first of these is the addition of an entropy sink in the form of a third, auxiliary system, with which the object may or may not be correlated. We show that the figure of merit is not the correlations, but rather the rank of the state on the object-plus-auxiliary subspace; if the rank is less than, or equal to, the dimension of the auxiliary Hilbert space, then full information erasure is achievable with at most zero heat cost. The second approach is to envisage a system, initially in a Gibbs state, a subspace of which is designated as the object. Maximal information erasure can be achieved here, with a heat cost potentially lower than Landauer's limit, if the eigenstates of the system Hamiltonian are unentangled with respect to the partition that separates the object from the other subspace.

Optical absorption of 2D Majorana nanowires

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Majorana suggested in 1937 the idea of fermionic particles that are their own antiparticles [1]. In spite of many years of research the existence of elementary particles of Majorana character is still unclear. Quasiparticle excitations, called Majorana Zero Modes (MZM), having similar properties are currently attracting much interest in condensed matter systems in general. Particular interest in nanowires is motivated by their potential applications in quantum computation and their interesting physics. In essence, MZM's are topological zero-energy states living close to the system edges or interfaces.

Majorana modes can be implemented in hybrid semiconductor-supercoductor nanowires inside a magnetic field. Recent measurements of the electrical conductance of these hybrid nanowires have provided good evidences on the existence of Majorana states in this kind of systems [2]. However, these evidences are not enough to unambiguously confirm the existence of the Majorana states. It has been suggested to consider the coupling with the electromagnetic field in photonic cavities [3, 4]. In a related direction, we have explored the absorption cross section of a 2D Majorana nanowire to a dipole field, focusing on the absorption signatures of the zero mode [5]. We use the dipole approximation to describe the optical field and consider the linear response formalism to a weak perturbation. We find that for field polarization parallel to the nanowire the Majorana state leaves no clear signature on the cross section. On the other hand, the existence of a Majorana is indicated by a low energy peak emerging for transverse polarization. This low energy feature is relatively robust when the temperature is increased and many levels become thermally activated due to the change in occupations.

We also considered the influence of optical masks, hiding parts of the nanowire to the optical excitation, as a probe of the localization character of the Majorana modes [5]. We believe that in the characterization of Majorana states in nanowires optical absorption experiments would be relevant.

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Work and correlations.

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Correlations, and particularly entanglement, are essential resources for quantum information tasks. On the other hand, work can be thought as a resource for thermodynamics. In this talk we discuss the optimal interconversion between both resources.

Considering a set of initially uncorrelated thermal quantum systems, the first question we seek to answer is how the initial temperature limits the achievable correlations. For that we characterize the maximal temperatures allowing for the creation of different types of entanglement as a function of the number of systems. In particular, we show that the strongest form of entanglement, genuine multipartite entanglement, can be generated at arbitrary high temperatures if sufficiently many systems are available [1].

Secondly, in the same scenario, we explore the energy cost of establishing correlations. Since the initial state is thermal, every transformation requires a positive amount of invested work. The question is then finding the minimal work cost of generating a certain amount of correlations. For the case of total correlations, as quantified by the mutual information, we provide exact bounds which hold for arbitrary systems, with and without the presence of an external bath, and explicit protocols saturating them [1,2]. For the case of entanglement, as quantified by the entanglement of formation, we focus our attention on bipartite systems made up of qubits, fermions or bosons. In all these systems we provide optimal protocols for energy to entanglement conversion [1,2].

Finally, we consider the reverse question: given a correlated state, how much work can be extracted? We explore this problem for a collection of quantum systems which are locally thermal, thus from which any extractable work can only come from correlations. For that scenario we quantify the extractable work (with and without access to a bath) from entangled, separable and states with fixed entropy; identifying the gain due to genuine quantum resources [3].

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Non-adiabticity and irreversible entropy production

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The out-of-equilibrium thermodynamic properties of closed quantum systems driven by a change in a control parameter and undergoing a unitary transformation have been the subject of an intense research activity. We study the work actually done on the system and compare it with the adiabatic one, that would be performed following an ideal adiabatic protocol. The non-adiabatic work, or *inner friction*, can be used to reveal irreversibility in the process and it is intimately linked to the non-equilibrium entropy production. Indeed, it is linked with the heat exchanged in a suitable thermalization process, and it can be expressed as the relative entropy between the actual state of the system and the ideal equilibrium one. Furthermore, it is associated to a specific fluctuation relation for the entropy production, which allows the inner friction to be expressed in terms of its cumulants. We apply this formalism to various cases of experimental relevance, including a qubit and an harmonic oscillator. In such cases, we show explicitly that the inner friction is linked to the speed at which the thermodynamic transformation is performed and to the diabatic transitions that occur in the system.

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Non-equilibrium dynamics of a one-dimensional Bose gas

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Relaxation dynamics in isolated quantum many-body systems is a highly active research topic with relevance for many different fields of physics. Despite important theoretical effort, no generic framework exists yet to understand when and how a quantum system relaxes to a steady state. In the last years we have developed techniques to characterize relaxed states and the dynamics leading to them.

Our model system is a quantum degenerate 1d Bose gas which we take out of equilibrium by coherently splitting it into two parts. In the subsequent evolution the relative phase field of the two condensates is monitored, providing a local probe for the system. This allows us to directly observe how the initial coherence between the two many-body systems is lost and how a steady state emerges. We explicitly show that this steady state is described by a generalized Gibbs ensemble.

Furthermore, we study the effects of uniform particle dissipation on the system. We observe a cooling process which is reminiscent but distinctly different from standard evaporative cooling.

Emergence of the Gibbs state in local Hamiltonians

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In this work we exploit scaling arguments in the system size to derive statements for the thermalization of subsystems of local short ranged spin Hamiltonians. First, we connect the amount and the decaying of the correlations present in a quantum state with its energy distribution with respect to a local Hamiltonian. We show that if the correlations of the initial state decay either exponentially or algebraically (with an exponent strictly larger than the spatial dimension of the lattice of the model), then the energy distribution becomes narrow in the thermodynamic limit in a double sense: (i) the energy fluctuations compared to the total energy vanish and (ii) the width of the energy distribution becomes much smaller than the width of the density of states of the system.

With similar scaling arguments, we also prove that all the standardized moments of the density of states of any local Hamiltonian converge to the moments of a Gaussian in the thermodynamic limit, proving in such a way convergence in distribution of the standardized density of states to a Gaussian. Unlike the approach taken in Ref. [1] where a very similar result is proved, our strategy of showing convergence in moments allows for a much simpler proof and makes the result valid to any local upper bounded model from the beginning.

We study then implications of the previous ideas for the thermalization of subsystems of local Hamiltonians that are weakly interacting with its environment. We show that most of all initial states that have clustering of correlations in the sense described above and that evolve under a Hamiltonian with a Gaussian density of states equilibrate towards the Gibbs state in the thermodynamic limit.

Finally, we consider the question of how the size of the subsystem can scale compared to the size of the bath. Unlike what one would expect, that the size of the subsystem can increase linearly with the bath's size, we find that the canonical population are only obtained when the system is scaled at most sublinear with the square root of the bath's size.

In this ongoing work, we are now applying the above ideas to systems with unbounded Hamiltonians for which the density of states is not Gaussian.

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Kramers' Turnover measured with a vacuum levitated nanoparticle.

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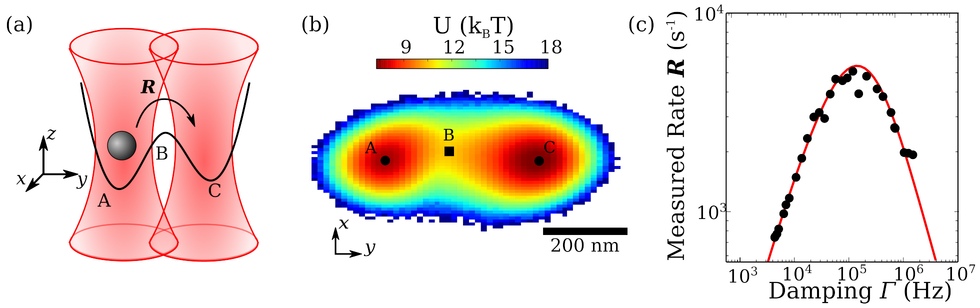
Understanding the escape from a metastable state is at the heart of phenomena as important as the folding dynamics of proteins, the kinetics of chemical reactions or the stability of mechanical systems. In 1940 Kramers, already foreseeing the implications of such a process, presented a framework for its theoretical understanding. His work described escape rates both in the high damping and the low damping regime and suggested that the escape rate must have a maximum.
This phenomenon, today known as the Kramers' turnover, has triggered important theoretical and numerical studies. However, to date there is no direct and quantitative experimental verification of this turnover. Using a nanoparticle trapped in a bi-stable optical potential we experimentally measure the nanoparticle's transition rates for variable damping, which is tuned by changing the environmental gas pressure inside a vacuum chamber. This allows us to directly resolve the Kramers' turnover. Our measurements are in agreement with an analytical model that is free of adjustable parameters. This demonstrates levitated nanoparticles as an experimental platform for studying and simulating a wide range of stochastic processes and testing theoretical models and predictions. In addition, this work will benefit from ongoing efforts toward quantum ground state cooling of vacuum-trapped particles, and we expect that our system will provide a way to shed light on rate theories in the classical to quantum transition.



(a) Scheme of a nanoparticle optically trapped in a double well potential, jumping at a rate ***R*** *between the stable points A and C. (b) - Experimentally measured optical potential. (c) - Measured jumping rate as a function of damping. Experimental data are compared with an analytical model free of adjustable parameters (red solid line).*

Three terminal quantum Hall thermoelectrics

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In an electronic circuit, current can be generated by the conversion of heat absorbed from a hot region. In the absence of a magnetic field, such thermoelectric response requires broken left-right and particle-hole symmetries. We investigate the thermoelectric properties of a three-terminal quantum Hall conductor. We identify a contribution to the thermoelectric response that relies on the chirality of the carrier motion rather than on spatial asymmetries [1]. The Onsager matrix becomes maximally asymmetric with configurations where either the Seebeck or the Peltier coefficients are zero while the other one remains finite. Reversing the magnetic field direction exchanges these effects. Our results show that thermoelectric measurements are sensitive to the chiral nature of the quantum Hall edge states, opening the way to control quantum coherent heat flows. In particular, powerful and efficient energy harvesters can be proposed [1,2]. The possibility to generate spin-polarized currents in quantum spin Hall samples is also discussed.

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Work and heat for two-level systems in dissipative environments: Strong driving and non-Markovian dynamics

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In the last years there has been a substantial interest in thermodynamical properties of small systems, where fluctuations are essential and provide deeper insight in the changeover from microscopic to macroscopic behavior. From a theoretical point of view, the description of these systems gives rise to some challenges, in particular, how to define and calculate physical quantities of the system which are not quantum mechanical observables [1], like work or heat. Also, there is the issue of describing dissipative quantum system at very low temperature and in presence of also strong driving, i.e. in the regime, where non-equilibrium steady states emerge. Interestingly, detailed studies for work, its moments, and heat flux between a system of interest and thermal reservoirs in presence of moderate to strong driving and for low temperatures have not been performed yet. Here, we present first results to close this gap by providing benchmark data for the generic case of a dissipative two level system [2] subject to an external time-dependent driving. Exact numerical simulations within the stochastic Liouville-von Neumann scheme (SLN) [2] are compared to perturbative ones obtained within a simple Lindblad type of master equation and a quantum jump treatment. Analytical calculations allow for a qualitative and in certain cases also quantitative understanding of the subtle interplay between quantum dynamics, dissipation, and driving. In addition, the SLN allows to analyze the impact of correlations between system and bath in the initial state (thermal equilibrium) and to quantify the heat flux associated with these correlations [3] when one starts from an initially factorized state as the typical assumption in perturbative treatments.

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Nonlinear thermoelectric transport in Coulomb-blockaded quantum dots

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Thermoelectric effects arise from the response of some materials under temperature gradients (voltage bias) generating electric (heat) currents. Several experiments have recently reported a remarkable nonlinear behaviour in the thermovoltage of Coulomb-blockaded quantum dots [1-2]. We have investigated theoretically the nonlinear transport in interacting quantum dots using the Anderson model in the Keldysh-Green function formalism [3]. We discuss the transport properties when both thermal gradients and voltage differences are applied. The differential thermoelectric conductance shows a characteristic butterfly structure in contrast with the Coulomb diamond seen in the conductance. Notably, we show that the dot resonances induce a change of sign in the thermocurrent and thermovoltage giving a nontrivial zero with a nonvanishing temperature bias. Additionally, we have studied thermoelectric effects in the heat transport [4]. We show that the nonlinear terms to the Peltier effect dominate over the Joule heating. We find an asymmetric behaviour due to the quantum dot level position which modifies also the position of the extrema in the differential thermal conductance. Finally, we show that the Kelvin-Onsager relation is broken beyond linear response.

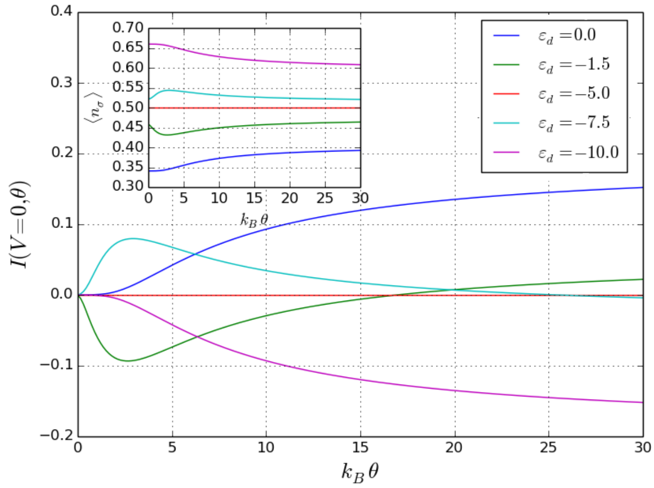

Fig 1. Thermocurrent as a function of the temperature bias for several dot energies in the model explained in [3]. A nontrivial zero appear for some values of the energy level. Inset: Occupation of the dot as a function of the temperature bias.

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Emergence of quantum-classical interplay in 1D dynamical quantum phase transitions

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A numerical simulation of the real-time dynamics for a quasi one-dimensional chain of trapped ions is performed in the fully quantum regime via an expanded time-evolved block decimation scheme. Dynamical quenches through the linear-zigzag quantum phase transition [1,2] are explored, and the Kibble-Zurek mechanism for the formation of defects is investigated. Remarkably, the interplay [3] between a regime where the fully quantum behavior is reproduced and one where a mean-field semiclassical scaling emerges, is identified and studied as a function of the effective $\hbar$ of the model and the quench parameter interval.

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Heat currents and dephasing in flux qubits

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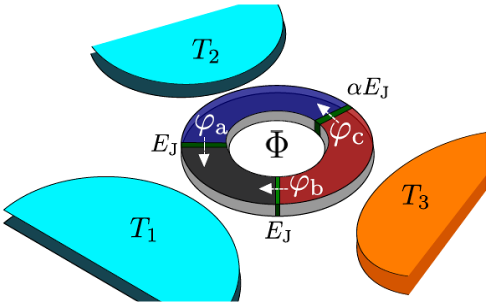

Heat currents through Josephson junctions are carried by quasiparticles above the gap and depend on the superconducting phase difference across the junction through Andreev reflection processes. This has been experimentally verified a few years ago, where the heat current due to a temperature gradient across a two-junction SQUID has been measured [1]. While this is of relevance for the coherent tunability of heat currents on one hand, we have shown that it also has an impact on devices containing Josephson junctions, where accidental temperature gradients can occur [2,3].

We have investigated the impact of temperature gradients on flux qubits [2,3], which are superconducting qubits consisting of SQUIDs with multiple Josephson junctions. Their quantum states representing “0” and “1” are related to counter-propagating persistent currents in the SQUID and directly depend on the phase-difference across the junctions. As a result, whenever the operation of the qubit leads to temperature gradients in the device (or nonequilibrium quasiparticle distributions which can be captured by an effective temperature gradient), as shown in the figure, heat currents flowing across the Josephson junctions are sensitive to the qubit state. This qubit-state sensitivity in turn leads to a dephasing of the qubit [2,3]. For large temperature gradients, the dephasing time is equal to the time it takes until the difference of heat currents flowing in the two different qubit states has transferred an amount of energy equal to the superconducting gap. Furthermore we argue, that for vanishing temperature gradients the study of the heat conductance can be used as a phenomenological approach to extract the dephasing time due to quasiparticle tunneling.

We have shown that for flux qubits in the Delft design [4], this dephasing can be of the order of microseconds. In contrast, the Fluxonium qubit [5] is well protected against this dephasing mechanism due to the small inductive energy of its superinductance.

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Coupled Nonlinear Thermoelectric Transport in Normal-Quantum Dot-Superconductor Junctions

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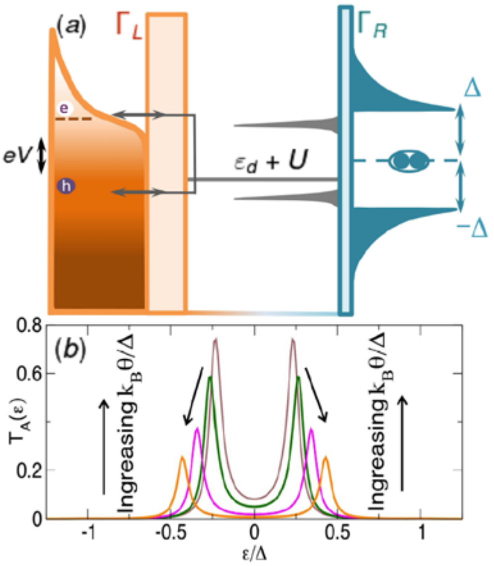
We explore the coupled nonlinear thermoelectric current of an interacting quantum dot attached to normal and superconducting reservoirs with applied voltage and temperature bias [1]. Inherent particle-hole symmetry introduced by the superconductor cancels out the pure subgap thermoelectric response. However, we show that the Andreev bound states shift as thermal gradient increases (see Figure below). Hence, the *I-V* characteristic can be tuned with a temperature when the system is simultaneously voltage biased. This is a cross effect that only occurs beyond the linear response regime. We also reveal the importance of quasiparticle tunneling processes in the generation of high thermopower sensitivities.



(a) Schematics of our setup
(b) Shift of Andreev transmission in response to a thermal gradient

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Transient quantum fluctuation relations

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The statistics of work performed on a system that initially stays in equilibrium is constrained by so-called transient fluctuation relations known under the names of Jarzynski equality and Crooks relation. We shall introduce these relations and discuss their main prerequisites both for closed and open quantum systems. These prerequisites embrace the way how the work is determined, the time-reversal invariance of Hamiltonian systems as well as the proper identification of the system's free energy. The latter point being relevant for open systems.

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Equivalence of different engine types in the quantum regime and quantum thermodynamic signatures

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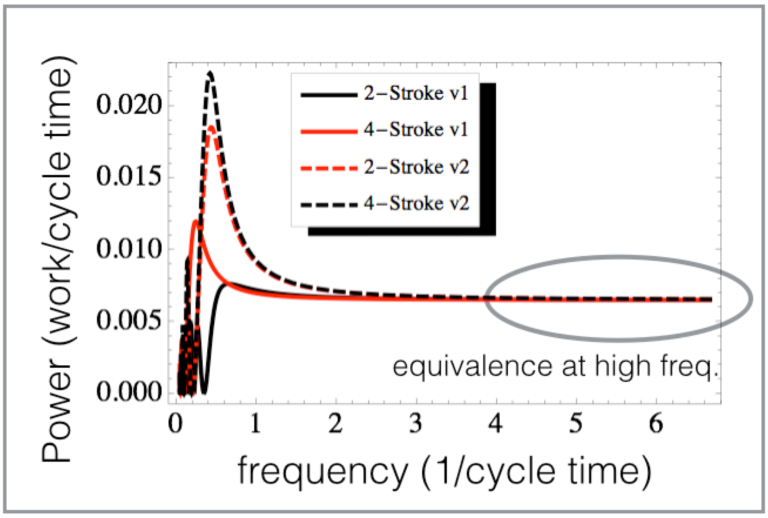
Quantum heat engines (QHE) are thermally driven engines where the working substance is a single particle or a finite-level quantum system. Despite the progress made over the last few decades, the question what exactly is quantum in QHE operation remains unclear. Stated differently, can quantum effects lead to thermodynamic features that cannot exist in classical systems? To address this question we will present two main results. The first result is that in the quantum regime different engine types such as four-stroke, two-stroke and continuous engines are all thermodynamically equivalent. They all have the same power, the same heat, the same efficiency and even the same relaxation to steady state. The equivalence appears in the limit of short cycle times. Although thermodynamically equivalent, the engine types are not identical, and they can be resolved by monitoring other quantities. The figure below shows how the power of four different engines converges to the same value in the high frequency equivalence regime. The curves correspond to two variants of a two-stroke engine and two variants of a four-stroke engine. The discussion of the continuous engine is considerably more complicated but in the end it is equivalent to the other engine types (two-stroke and four-stroke).



Our second result is that QHE have a quantum-thermodynamic signature. In a certain regime, “blind” thermodynamic measurements of work or heat as a function of the cycle time contain information on the level of quantum interference in the engine. This coherent dynamics enables work extraction far beyond the capabilities of a stochastic, dephased engine working at the same parameters.

A Framework for Information Theoretic and Thermodynamic Entropies

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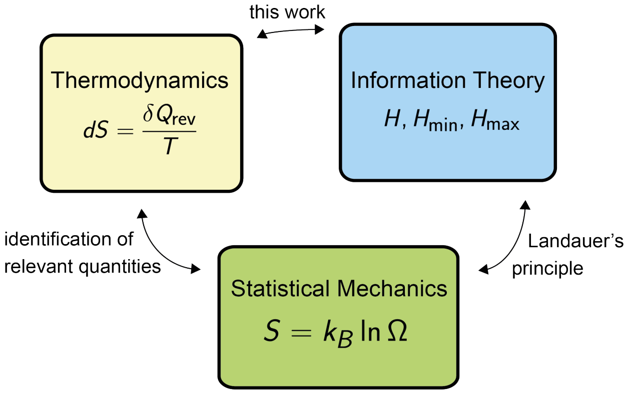
Entropy plays a central role in the understanding of processes in thermodynamic as well as in information theoretic systems. Due to the strong conceptual difference of thermodynamic and information theoretic entropy, however, their connection for microscopic systems is still not well understood. In this work we establish a direct link between information theoretic and thermodynamic entropy. The positioning of this contribution in the scientific context is illustrated by the following diagram.



Our approach is based on an axiomatisation of thermodynamics by Lieb and Yngvason, who consider an order relation on the state space of an isolated system and derive a unique entropy function characterising equilibrium states as well as bounds on the extension of this entropy function to nonequilibrium states [1].

Applying this macroscopic framework to microscopic quantum systems, we prove that in an information-theoretic context the thermodynamic entropy, defined by means of thermodynamic concepts, corresponds to the von Neumann entropy. Furthermore, the bounds on the entropy for thermodynamic nonequilibrium states correspond to the min- and the max-entropy known from information-theoretic single-shot scenarios. Additionally, we observe that Lieb and Yngvason's approach can actually be applied to a range of thermodynamic scenarios, leading to other thermodynamic potentials such as the free energy and its single shot versions.

The flexibility of the presented approach allows for further extension. Including processes with probabilities of error into the framework we are likely to obtain a corresponding framework for smooth entropy measures.

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Maximum efficiency at given power output in 2 or 3 terminal thermoelectrics

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Carnot efficiency is only achievable at zero power output. We ask what is the maximum efficiency at some given finite power output. It appears that this question is ill-defined in classical thermodynamics, but can be answered with a quantum theory.

We use the Landauer-Buttiker scattering theory to find this maximum efficiency for heat engines and refrigerators made of thermoelectric quantum systems. We initially find the exact maximum efficiency for two-terminal systems without energy relaxation [1]. We then use phenomenological models to explore whether this maximum can be exceeded by two-terminal systems with relaxation [2], or by three-terminal systems. We have not yet found a system which can exceed the maximum efficiency given in Ref. [1], although open questions remain.

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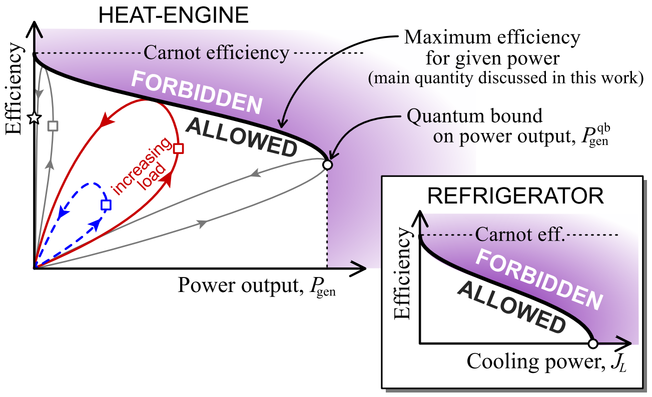

Figure 1: Taken from Ref. [2]. The thick black curves are qualitative sketches of the maximum efficiency as a function of heat-engine power output (main plot), or refrigerator cooling power (inset), with the shaded regions being forbidden. The colored loops (red, grey and blue) are sketches of the efficiency versus power of *individual* heat-engines as we increase the load resistance.

Weak thermal contact is not universal for work extraction

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Thermodynamics aims at formulating fundamental laws that govern energy-preserving processes. In particular it gives rise to bounds on what can be achieved using heat baths at a given temperature.

One such bound is given by the free energy difference, which limits the amount of work that can be extracted on average from a system out of thermal equilibrium. This bound can be saturated by protocols putting the system and a bath into weak thermal contact (WTC), i.e., bringing the system into a thermal state at the bath's temperature [1,2].

Surprisingly, the same bound holds true when the contact to the heat bath is modeled by more general processes, which have the only restriction that when the system already is in equilibrium it cannot be brought out of it [3]. Such processes are the most general that do not violate the second law and include the framework of thermal operations [4]. Thus WTC is already universal for work extraction, since it allows to extract the same amount of work as those general processes.

In our work [5], we introduce the study of work-extraction protocols under restrictions encountered in realistic devices at the nano-scale. We consider limitations on the maximum energies in the system and on the local structure of many-body Hamiltonians. Remarkably, we find that WTC then loses its universality. We do so by first proving a general bound for the extractable work in such restricted scenarios. This is then used to show a gap between the work that can be extracted with WTC and with more general operations. Indeed we can show that in both restricted scenarios there exist situations in which no work can be extracted using WTC but work can be extracted using more general operations that respect the second law.

Our work highlights the relevance of operational frameworks such as those of thermal operations and Gibbs preserving maps, as they can improve the performance of thermal machines. Furthermore, it provides a unifying framework of incorporating natural restrictions in quantum thermodynamics.

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Thermodynamics of trajectories of a quantum harmonic oscillator coupled to N baths

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Finding a concise description of the dynamics of a quantum system connected to an environment is one of the challenges of modern quantum physics. Even when the unitary evolution of a quantum system is well-known, its open dynamics is often less clear [1]; the full description of the exchange of excitations between a system and its environment would find much application in both experimental and theoretical analysis of open quantum systems. The primary tools one has access to in analysing such dynamics efficiently are input-output theory [2] and full counting statistics [3]. More recently, a promising approach came to light based on large-deviation theory [4]. We consider a paradigmatic system in quantum mechanics, a quantum harmonic oscillator connected to *N* arbitrary baths whose dynamics is governed by a master equation in Lindblad form. This system is a fundamental building block of quantum optics and is used to describe a large variety of quantum degrees of freedom, including the motion of trapped ions and molecules, cavity and circuit quantum electrodynamic systems, and many–body systems. One of the key results of this paper is an analytical expression for the large-deviation function of this frequently-encountered infinite Hilbert space dimension problem (e.g., continuous-variable system). In the simple case where the harmonic oscillator is coupled to two thermal baths, we will compare our result to its classical counterpart, showing perfect agreement at high temperatures and an unexpected quantum suppression at low temperatures. Following this, we will explore the case of a driven harmonic oscillator, once more presenting analytical results for the large-deviation function. Far from being an exclusively descriptive approach, we show how to engineer the output of a quantum harmonic oscillator to read physically meaningful internal quantities.

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