Entropy production and thermodynamic power of the squeezed thermal reservoir

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Thermodynamic theory was developed from the analysis of real heat engines, such as the steam engine along the 19th century [1]. Those macroscopic engines have quantum analogues, whose analysis constitute an important branch of research in quantum thermodynamics [2]. Clarifying the impact of quantumness in the operation and properties of thermal machines represents a major challenge. Quantum effects can arise in the working sustance and environment, and there have been different works in the literature pointing that nonequilibrium quantum reservoirs may be used to increase both power and efficiency of the machines [2, 3]. Nevertheless, a solid understanding of these enhancements and their optimization has remained elusive, as it requires a precise formulation of the second law of thermodynamics in such nonequilibrium situations.

Using recent advances in quantum fluctuation theorems [4], we analyze the entropy production and the maximal extractable work from a squeezed thermal reservoir. The quantum nature of the reservoir induces genuine nonequilibrium features such as an entropy transfer with a coherent contribution. These nonequilibrium features allow for work extraction from a single reservoir, and are the responsible of power and efficiency enhancements for quantum heat engines operating with this kind of reservoirs. Here we consider in detail a heat engine performing a (modified) quantum Otto cycle [5], optimize it, and discuss its many striking consequences, like the appearance of multi-task regimes in which the heat engine may extract work and refrigerate a cold reservoir at the same time (see Fig. 1) [6]. Moreover, we show how our approach leads to the introduction of a *thermodynamic efficiency* based on the concept of nonequilibrium free energy, which naturally accounts for the performance of both classical and quantum thermodynamic resources. Our results hint at possible applications like squeezing-fueled batteries, multi-task thermal machines, or erasure devices operating below Landauer's limit.
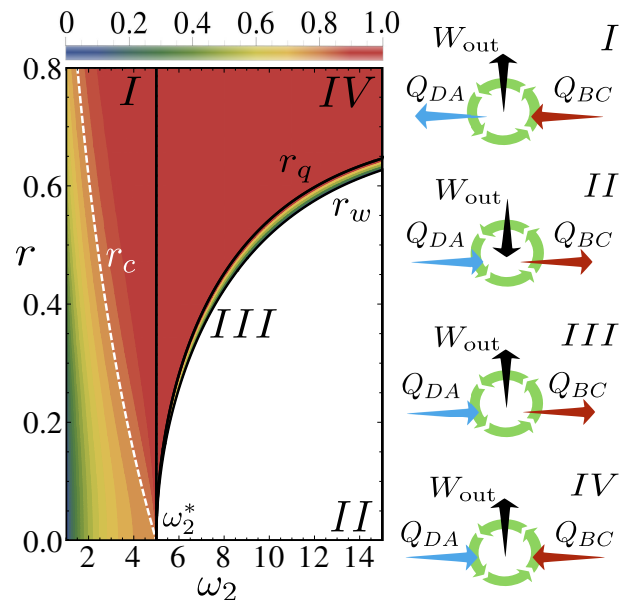

Figure 1: Phase diagram with the four regimes of operation of the cycle (I, II, III, IV) as a function of the working substance frequency modulation ω_2 and the squeezing parameter r. The color scale corresponds to the *energetic* efficiency of the cycle $\eta = W_{\text{out}}/Q_{\text{in}}$ as a heat engine, for inverse temperatures in the reservoirs $\beta_2 = 0.2\beta_1$, yielding a Carnot efficiency $\eta_c = 0.8$ (white dashed curve). In the right side the direction of the arrows represents the sign of the energy fluxes for each regime.

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