Reliable quantum advantage in quantum battery charging precision

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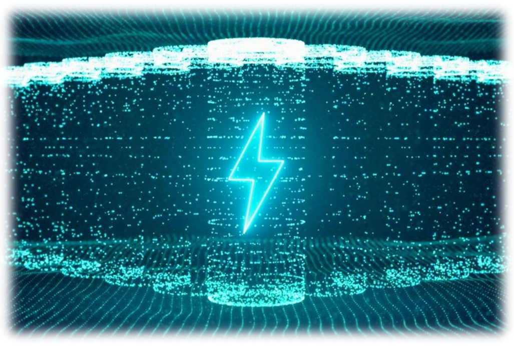
Before starting: what is a *quantum battery*?



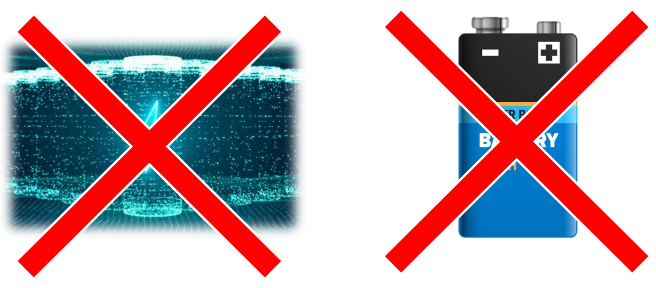
An energy supply for quantum computers?

A solid-state battery which exploits quantum properties?

$$|\text{energy}\rangle$$

A quantum system that can store and deliver precise amounts of energy?

Answer:



$|\text{energy}\rangle$

A quantum battery is a quantum object specifically designed to store energy and to deliver it when needed. A considerable number of theoretical models for quantum batteries has been developed, and the first experimental proof-of-principles have recently been implemented. However, their potential utility in future technology is presently under investigation.

Motivations

Quantum batteries (QB) can be an effective playground to test theoretical results stemming from Quantum Thermodynamics.

Quantum Thermodynamics is a research field where Quantum Mechanics meets Statistical Mechanics and Thermodynamics. For instance, this discipline studies energy fluctuations, heat currents, dissipative effects, and complex collective interactions in quantum systems. Controlling these phenomena is the key to make quantum technologies more precise and efficient.

Recent achievements

The concept of *quantum battery* has been proposed by Alicki and Fannes [1] in 2013. In the following years, several theoretical models (such as the Dicke or the Sachdev-Ye-Kitaev models) were considered as prototypical descriptions of QB [2]. Physical quantities, such as the charging power P, the ergotropy $\mathcal{E}$, and the precision $\mathrm{var}(E)$ of the charging process, have been thoroughly analyzed. Many proof-of-principle experiments have been realized on nuclear spins, quantum dots, superconductors, trapped ions, and organic microcavities [2,3].

Goal: max-precision QB charging

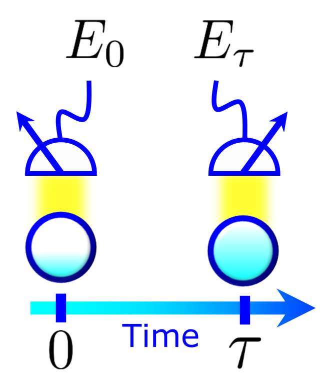
We consider M qubits (quantum systems with two energy levels) coupled to a harmonic oscillator (such as a single-mode electromagnetic field confined to a cavity). Depending on the physical process, the dynamics is determined by the following Hamiltonian:

$$\hat{H}(t) = \hbar\omega_{\text{qubit}} \sum_{j=1}^{M} \frac{\hat{\sigma}_z^{(j)}}{2} + \hbar\omega_{\text{cavity}} \hat{a}^\dagger \hat{a} + \sum_{j=1}^{M} \hbar A_j(t) g (\hat{\sigma}_+^{(j)} \hat{a} + \hat{\sigma}_-^{(j)} \hat{a}^\dagger)$$

The goal is to drive the qubit into its most energetic state acting with the e.m. field, with the maximum precision possible over the exchanged energy.

Full Counting Statistics

To account for out-of-equilibrium thermodynamical quantities, we exploit the Full Counting Statistics, a theoretical tool drawn from Statistical Mechanics [4]. As shown here, we imagine that the qubit undergoes two energy measurements, which give as result E_0 at time 0 and E_τ after time τ.
The intimate connection between the quantum nature of the measurement outcomes and the probability distribution that govern the process, allows us to find the statistics of the random variable $\Delta E_\tau = E_\tau - E_0$, such as the mean exchanged energy, $\langle \Delta E_\tau \rangle$, and its variance, $\mathrm{var}(\Delta E_\tau)$, as well as the higher-order moments and cumulants.



Signal-to-Noise Ratio and fidelity

The primary figure of merit is the Signal-to-Noise Ratio (SNR), which quantifies how high the signal (the mean exchanged energy) is, if compared to its fluctuations (the variance):

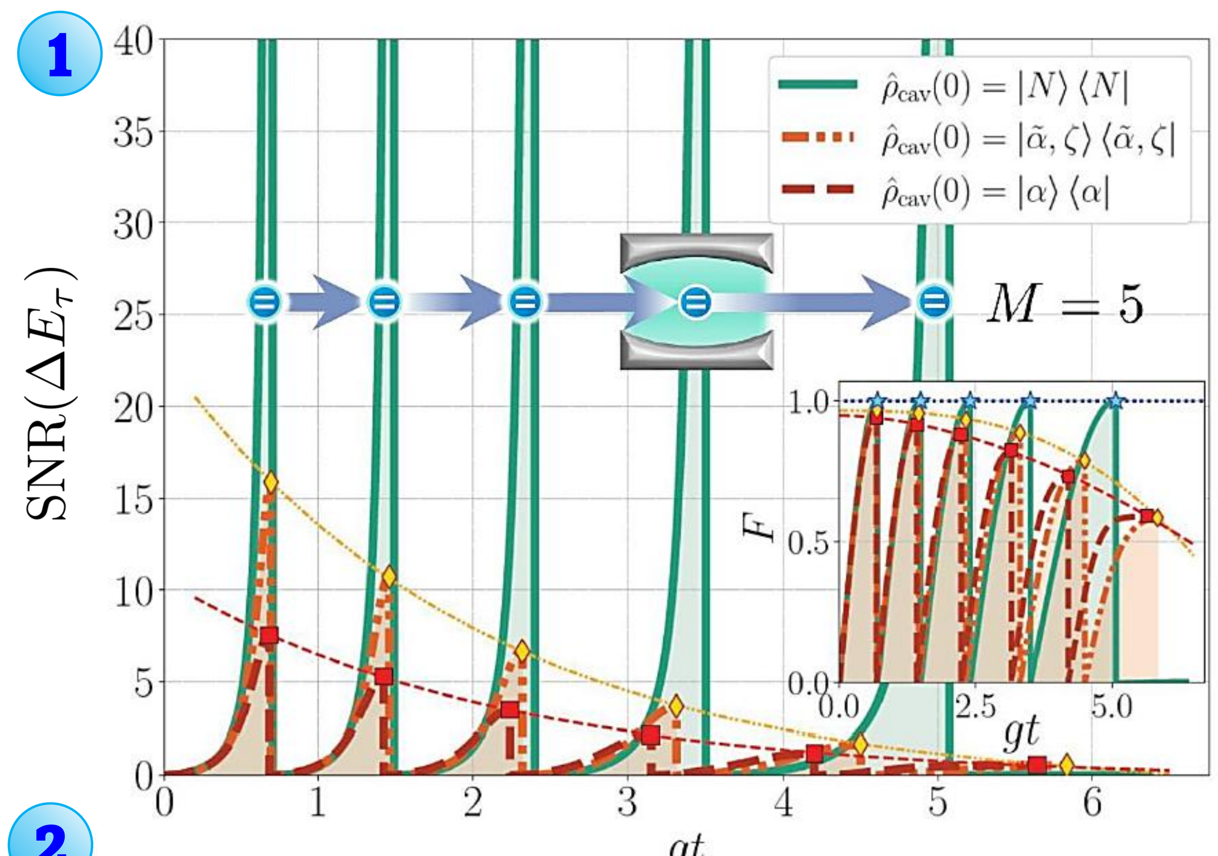
$$\mathrm{SNR}(\Delta E_\tau) = \frac{\langle \Delta E_\tau \rangle^2}{\mathrm{var}(\Delta E_\tau)}$$

To monitor the process, we also exploit the fidelity F between quantum states, which measures how much the qubit state is similar to a target state:

$$F(t) = \mathrm{Tr}\left\{ \left[\hat{\rho}_{\text{qubit}}^{\frac{1}{2}}(t) \hat{\rho}_{\text{target}} \hat{\rho}_{\text{qubit}}^{\frac{1}{2}}(t) \right]^{\frac{1}{2}} \right\}^2$$

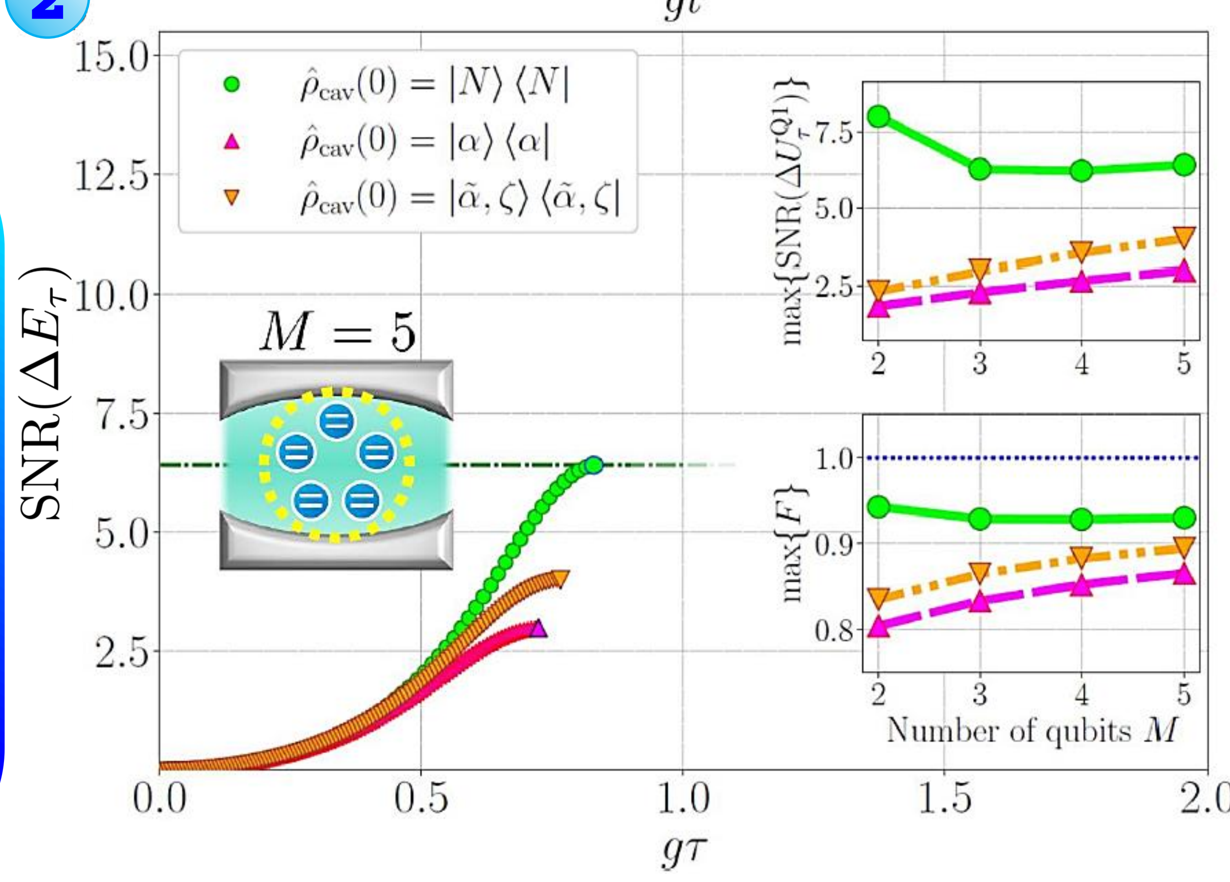
Results

1



We show [5,6] that a multi-qubit QB can achieve maximally precise charging by harnessing non-Gaussian quantum states. We compared sequential (Fig.1) and parallel (Fig.2) charging protocols of M qubits. Under ideal, noiseless conditions, an e.m. field prepared in a N-photon Fock state $|N\rangle$ (which is a quantum non-Gaussian state) can perfectly charge M=N qubits sequentially, whereas parallel charging fails to achieve perfect charging. Moreover, a Fock state field outperforms quantum Gaussian states $|\tilde{\alpha},\zeta\rangle$, as well as semiclassical states $|\alpha\rangle$.
We evaluated the robustness of the sequential protocol in the presence of noise, such as the one induced by thermal photons (Fig.3). Even in this situation, a Fock state cavity still enhances the SNR by over 150 times as compared to a cavity initialized in a Gaussian state.

2



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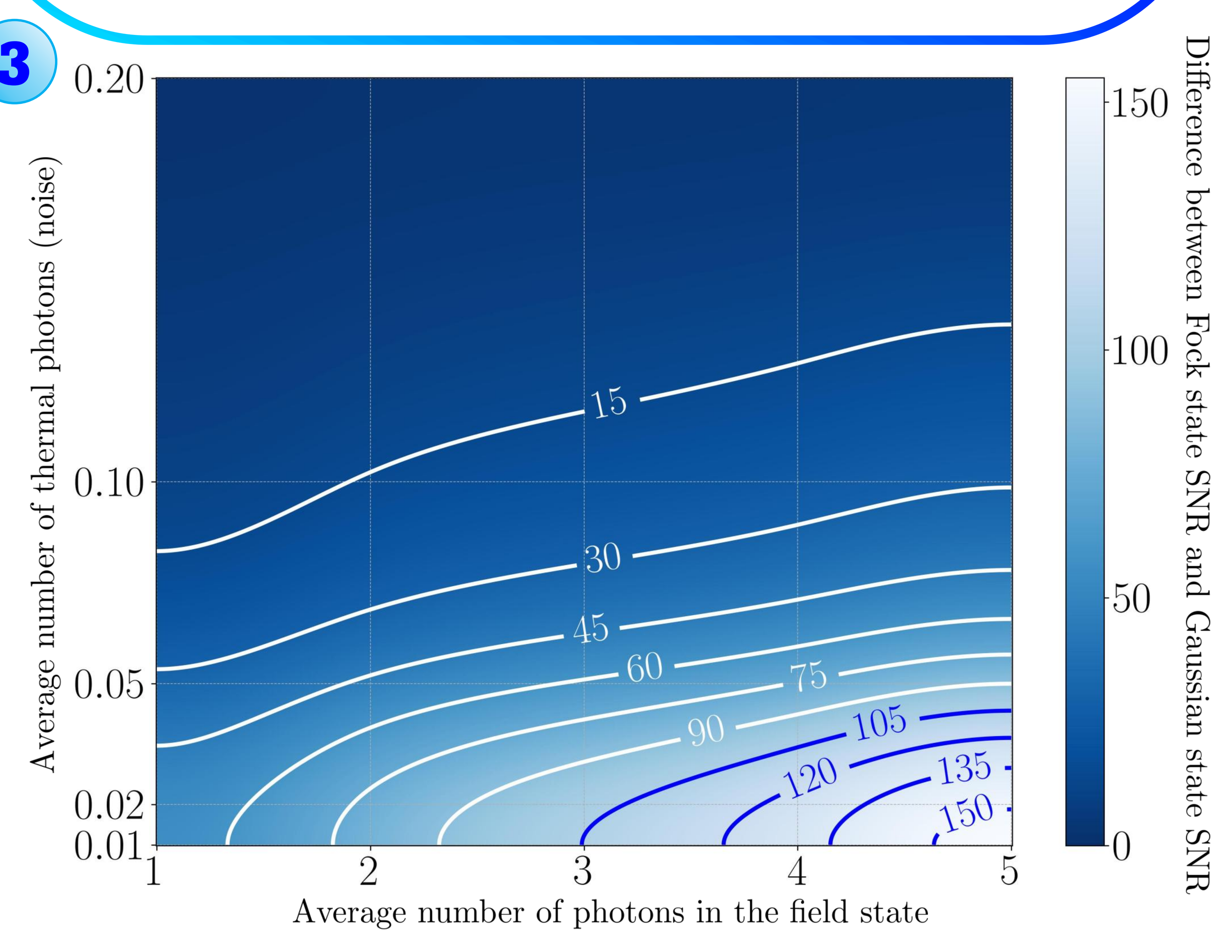

References

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