

Micromasers as Quantum Batteries

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Outline

Quantum advantage in new quantum technologies?
The case of quantum batteries

Rediscovering **micromasers** as a model of quantum batteries

Appealing features: **maximum extractable energy as the steady-state is pure, fast and stable charging**

What's next?

The second quantum revolution

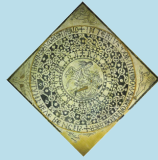
First quantum revolution: we learnt rules controlling physics at small scales

Many technological applications: transistors, lasers,...

Second quantum revolution: building real quantum machines, exploiting superposition and entanglement to develop new technologies

Quantum advantage? In computation, secure information transmission, sensing,...

Quantum computation and information is a rapidly developing interdisciplinary field. It is not easy to understand its fundamental concepts and central results without facing numerous technical details. This book provides the reader with a useful guide. In particular, the initial chapters offer a simple and self-contained introduction; no previous knowledge of quantum mechanics or classical computation is required.



Various important aspects of quantum computation and information are covered in depth, starting from the foundations (the basic concepts of computational complexity, energy, entropy, and information, quantum superposition and entanglement, elementary quantum gates, the main quantum algorithms, quantum teleportation, and

quantum cryptography) up to advanced topics (like entanglement measures, quantum discord, quantum noise, quantum channels, quantum error correction, quantum simulators, and tensor networks).

It can be used as a broad range textbook for a course in quantum information and computation, both for upper-level undergraduate students and for graduate students. It contains a large number of solved exercises, which are an essential complement to the text, as they will help the student to become familiar with the subject. The book may also be useful as general education for readers who want to know the fundamental principles of quantum information and computation.

“Thorough introductions to classical computation and irreversibility, and a primer of quantum theory, lead into the heart of this impressive and substantial book. All the topics – quantum algorithms, quantum error correction, adiabatic quantum computing and decoherence are just a few – are explained carefully and in detail. Particularly attractive are the connections between the conceptual structures and mathematical formalisms, and the different experimental protocols for bringing them to practice. A more wide-ranging, comprehensive, and definitive text is hard to imagine.”

— Sir Michael Berry, *University of Bristol, UK*

“This second edition of the textbook is a timely and very comprehensive update in a rapidly developing field, both in theory as well as in the experimental implementation of quantum information processing. The book provides a solid introduction into the field, a deeper insight in the formal description of quantum information as well as a well laid-out overview on several platforms for quantum simulation and quantum computation. All in all, a well-written and commendable textbook, which will prove very valuable both for the novices and the scholars in the fields of quantum computation and information.”

— Rainer Blatt, *Universität Innsbruck and IQOQI Innsbruck, Austria*

“The book by Benenti, Casati, Rossini and Strini is an excellent introduction to the fascinating field of quantum information, of great benefit for scientists entering the field and a very useful reference for people already working in it. The second edition of the book is considerably extended with new chapters, as the one on many-body systems, and necessary updates, most notably on the physical implementations.”

— Rosario Fazio, *The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy*

Benenti
Casati
Rossini
Strini

Principles of Quantum Computation and Information
A Comprehensive Textbook

Giuliano Benenti Giulio Casati
Davide Rossini Giuliano Strini



Principles of Quantum Computation
and Information
A Comprehensive Textbook

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Quantum thermodynamics

PRX QUANTUM 3, 020101 (2022)

Perspective

Quantum Technologies Need a Quantum Energy Initiative

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(Received 18 November 2021; revised 11 April 2022; published 1 June 2022)

Quantum technologies are currently the object of high expectations from governments and private companies, as they hold the promise to shape safer and faster ways to extract, exchange, and treat information. However, despite its major potential impact for industry and society, the question of their energetic footprint has remained in a blind spot of current deployment strategies. In this Perspective, I argue that quantum technologies must urgently plan for the creation and structuration of a transverse quantum energy initiative, connecting quantum thermodynamics, quantum information science, quantum physics, and engineering. Such an initiative is the only path towards energy-efficient, sustainable quantum technologies, and to possibly bring out an energetic quantum advantage.

What is a battery?

A mountain dam is a battery

Water wants to fall but we keep it up

Energy is stored: when water falls we can use it (a turbine will spin, ...)

What does **charging a battery** mean?

An empty dam does not store energy

Bringing water into the dam from valley we charge the battery



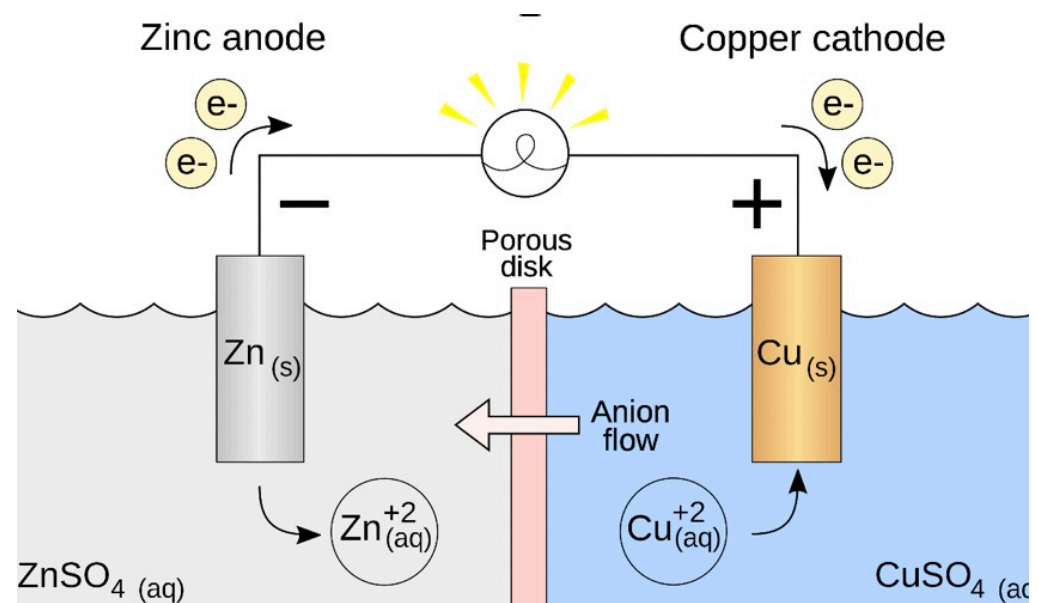
Another example: Galvanic batteries

Same principle but with electrons:

- * They like Cu but they are kept on Zn
- * Energy stored and ready to be released
- * External connection: electrons flow

Recharging the battery:

- * Electrons back to Zn
- * Energy stored again



Quantum batteries

PHYSICAL REVIEW E 87, 042123 (2013)

Entanglement boost for extractable work from ensembles of quantum batteries

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(Received 20 November 2012; published 25 April 2013)



Because we are dealing with small quantum systems we may wonder whether using processes that entangle two identical copies of a given battery can yield a higher energy extraction. More generally, what happens to a large number of copies?

Quantum advantage in charging power?

PRL **118**, 150601 (2017)

PHYSICAL REVIEW LETTERS

week ending
14 APRIL 2017

Enhancing the Charging Power of Quantum Batteries

Francesco Campaioli,^{1,*} Felix A. Pollock,¹ Felix C. Binder,² Lucas Céleri,³ John Goold,⁴
Sai Vinjanampathy,^{5,6} and Kavan Modi^{1,†}

“... we demonstrate that quantum mechanics can lead to an enhancement in the amount of work deposited per unit time, i.e., the charging power, when N batteries are charged collectively ... We derive analytic upper bounds for the collective quantum advantage ...”

Quantum Charging Advantage Cannot Be Extensive without Global Operations

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(Received 13 August 2021; accepted 8 February 2022; published 4 April 2022)

Quantum batteries are devices made from quantum states, which store and release energy in a fast and efficient manner, thus offering numerous possibilities in future technological applications. They offer a significant charging speedup when compared to classical batteries, due to the possibility of using entangling charging operations. We show that the maximal speedup that can be achieved is extensive in the number of cells, thus offering at most quadratic scaling in the charging power over the classically achievable linear scaling. To reach such a scaling, a global charging protocol, charging all the cells collectively, needs to be employed. This concludes the quest on the limits of charging power of quantum batteries and adds to other results in which quantum methods are known to provide at most quadratic scaling over their classical counterparts.

VIEWPOINT

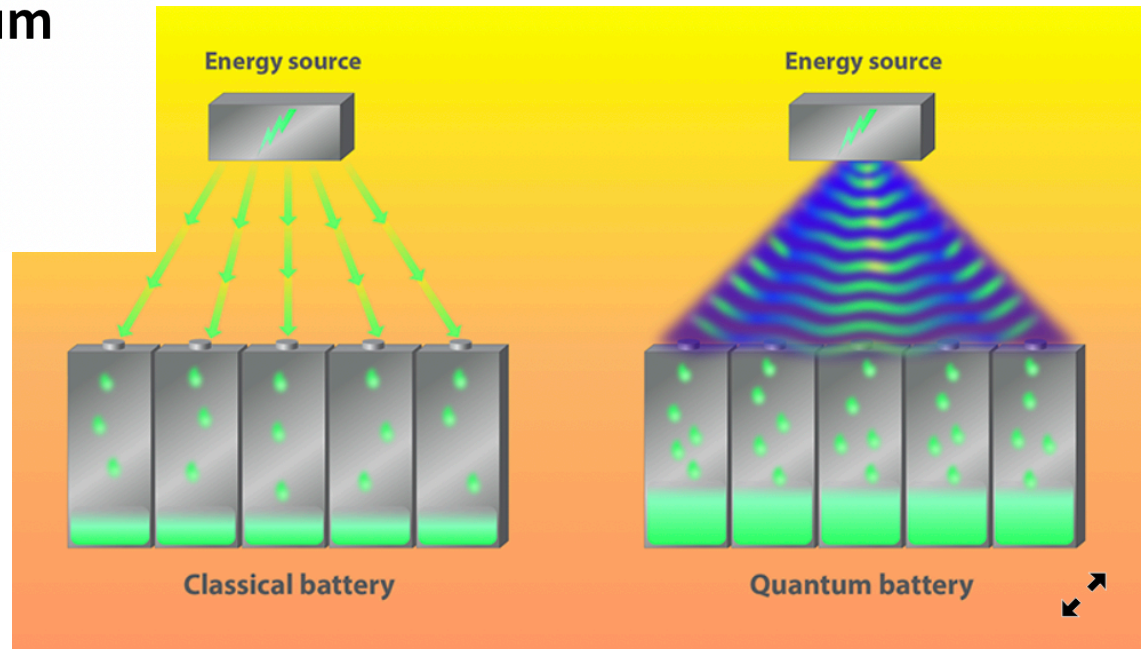
Sizing Up the Potential of Quantum Batteries

Sourav Bhattacharjee

Indian Institute of Technology, Kanpur, Kanpur-208016, Uttar Pradesh, India

April 4, 2022 • *Physics* 15, 50

A quantum battery consisting of N cells could charge up to N times faster



First experimental implementations

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Superabsorption in an organic microcavity: Toward a quantum battery

James Q. Quach^{1*}, Kirsty E. McGhee², Lucia Ganzer³, Dominic M. Rouse⁴, Brendon W. Lovett⁴, Erik M. Gauger⁵, Jonathan Keeling⁴, Giulio Cerullo³, David G. Lidzey², Tersilla Virgili^{3*}

“... we implement experimentally a paradigmatic model of a quantum battery, constructed of a microcavity enclosing a molecular dye ... Ultrafast optical spectroscopy allows us to observe charging dynamics at femtosecond resolution ...”

Organic molecules play the role of two-level systems embedded in a microcavity: super extensive energy charging

Quantum processors as quantum batteries



batteries

Article

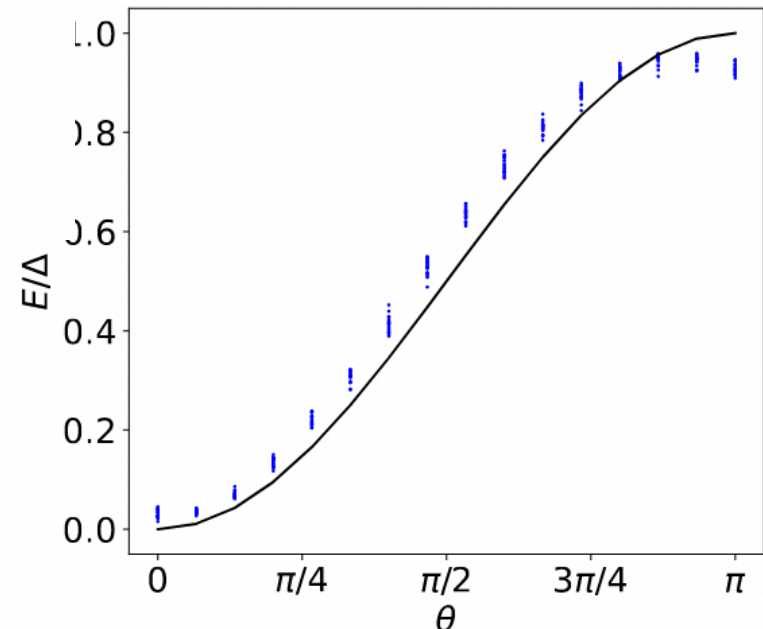
IBM Quantum Platforms: A Quantum Battery Perspective

Giulia Gemme¹, Michele Grossi² , Dario Ferraro^{1,3,*} , Sofia Vallecorsa²  and Maura Sassetti^{1,3}

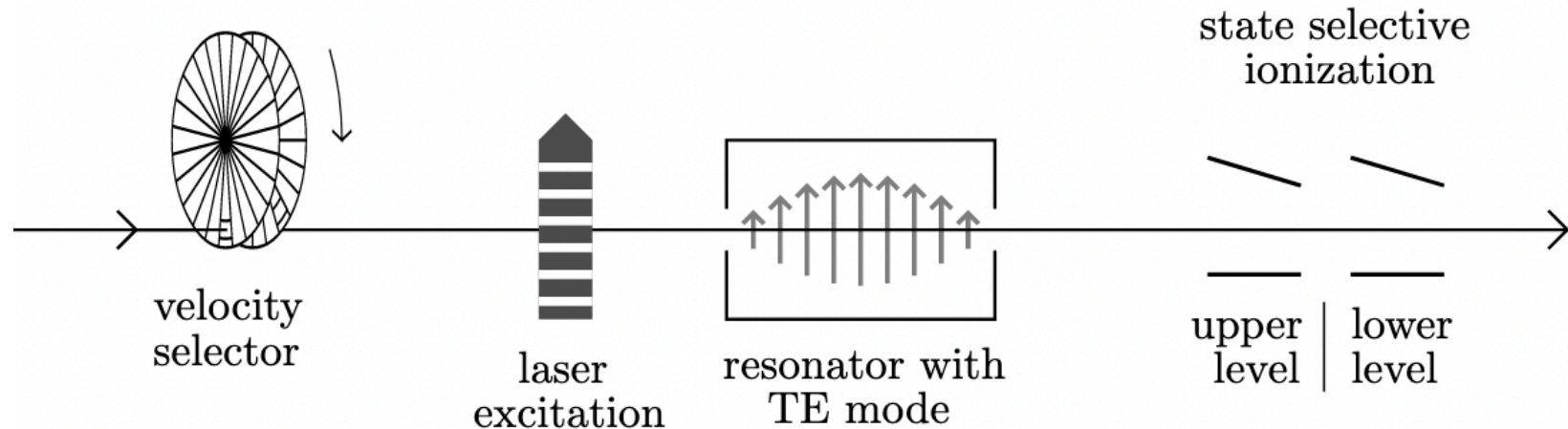
$$\begin{aligned} H &= H_{QB} + H_C \\ &= \frac{\Delta}{2}(1 - \sigma_z) + gf(t) \cos(\omega t) \sigma_x \end{aligned}$$

$$f(t) = \mathcal{N} e^{-\frac{(t-t_m/2)^2}{2\sigma^2}}$$

$$\theta(t_m) = g \int_0^{t_m} f(\tau) d\tau$$



Revisiting micromasers



(BG Englert, arXiv:quant-ph/0203052)

“Even a faint beam of atoms can pump the resonator effectively. In this way, a maser is operated in which single atoms traversing the resonator provide for an efficient pump. One is then dealing with a microscopic maser indeed, a micromaser.”

Quantum Science and Technology

LETTER

Micromasers as quantum batteries

Vahid Shaghghi^{1,2,3} , Varinder Singh³, Giuliano Benenti^{1,2,4}  and Dario Rosa^{3,5,*} 



INDEPENDENT

Quantum battery breakthrough paves way for instant recharging

Scientists hope discovery will usher in a new era of ultra-efficient batteries

physicsworld

QUANTUM | RESEARCH UPDATE

Micromasers make a promising platform for quantum batteries

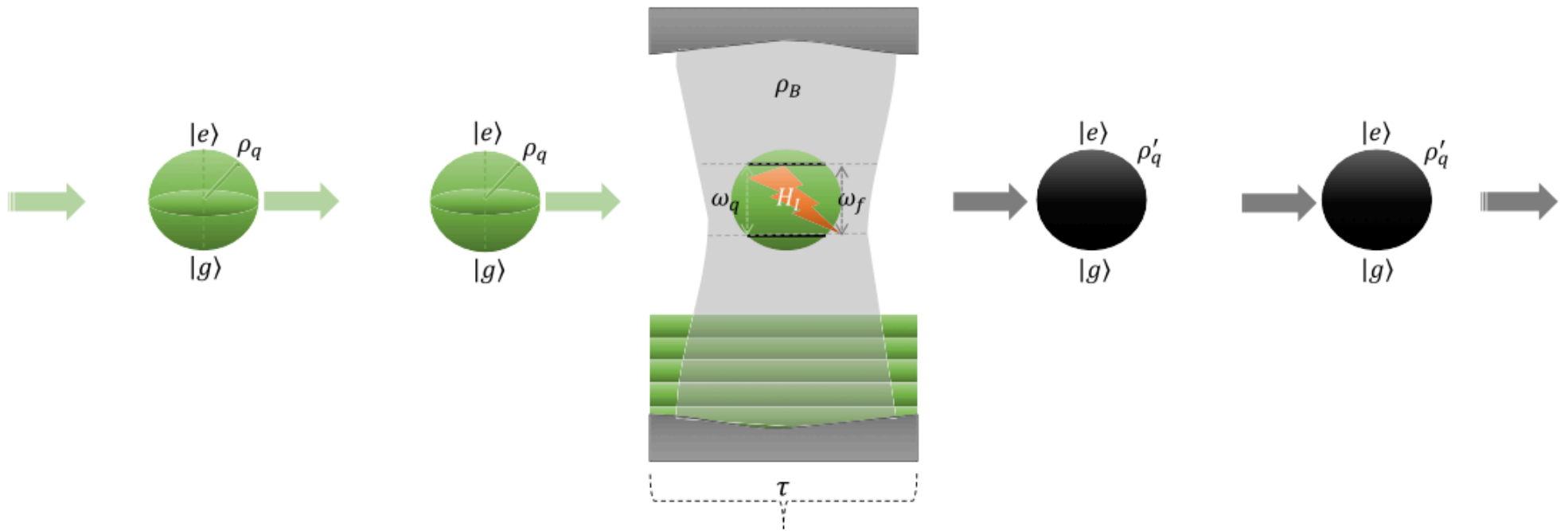


Figure 1. A pictorial view of the micromaser quantum battery. The incoming qubits are initially prepared in a superposition of ground and excited states. When entering the cavity they interact with the EM field and they decrease their energy, leaving the cavity in a low energy state (represented with a black colored Bloch sphere). In the figure, ω_q and ω_f denote the frequencies of the qubits and the fields, respectively, which in the main text have been assumed to be equal and denoted by ω (resonant condition).

Model

Initial state of the qubit (c controls degree of coherence):

$$\rho_q = q|g\rangle\langle g| + (1 - q)|e\rangle\langle e| + c\sqrt{q(1 - q)}(|e\rangle\langle g| + |g\rangle\langle e|):$$

Hamiltonian (interaction picture):

$$\hat{H}_I = g(\underbrace{\hat{a}\hat{\sigma}_+}_{\text{H_rotating}} + \underbrace{\hat{a}^\dagger\hat{\sigma}_-}_{\text{H_counter-rotating}} + e^{i2\omega t}\hat{a}^\dagger\hat{\sigma}_+ + e^{-i2\omega t}\hat{a}\hat{\sigma}_-)$$

Time-evolution operator:

$$\hat{U}_I(g, \omega, \tau) \equiv \mathcal{T} \exp\left\{-i \int_0^\tau \hat{H}_I(t) dt\right\}$$

Redefine parameters so that:

$$\hat{U}_I(g, \omega) \equiv \hat{U}_I(g, \omega, \tau = 1)$$

Energy storage

Battery state after interaction with $k+1$ qubits (trace over qubits after collisions):

$$\rho(k) = \rho_B(k) \otimes \rho_q$$

$$\rho_B(k+1) = \text{Tr}_q \left(\hat{U}_I(g, \omega) \rho(k) \hat{U}_I^\dagger(g, \omega) \right)$$

Energy stored:

$$E(k) \equiv \text{Tr}(\hat{H}_B \rho_B(k)) \quad \hat{H}_B \equiv \omega \hat{a}^\dagger \hat{a}$$

State purity (if a state is pure all energy can be in principle extracted via unitary transformations):

$$\mathcal{P}(k) \equiv \text{Tr}(\rho_B^2(k))$$

Coupling regimes

Weak coupling regime

Strong coupling regime



$$g < \gamma, \kappa$$

$$g > \gamma, \kappa$$

Ultra-strong coupling regime

Deep coupling regime



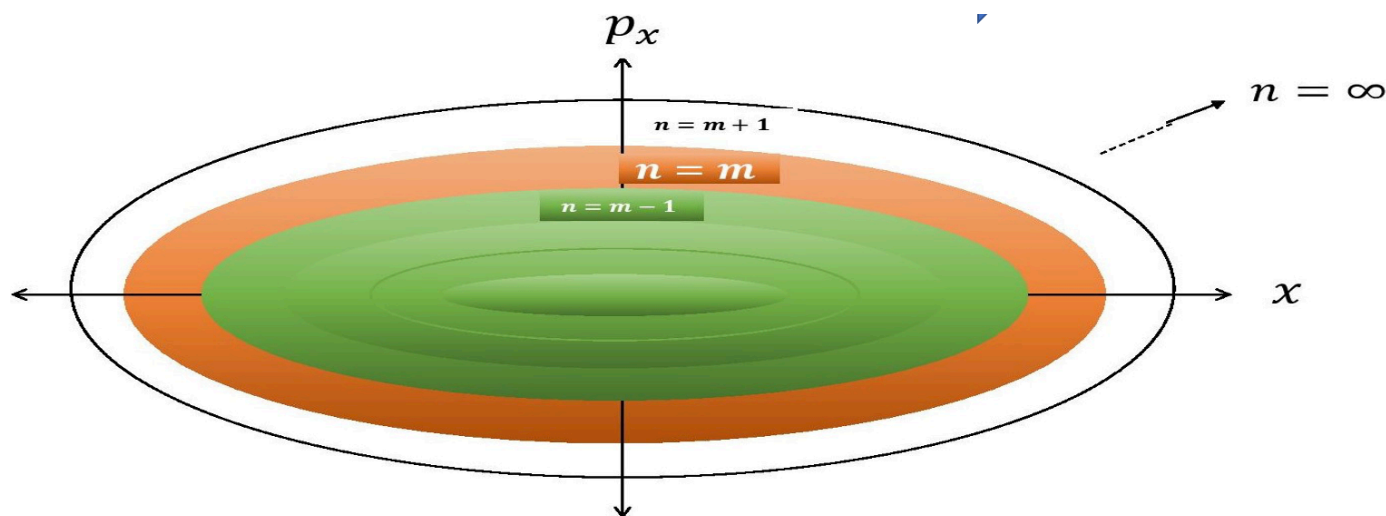
$$0.1 < \frac{g}{\omega} < 1$$

$$1 < \frac{g}{\omega}$$

Pure states in the Jaynes-Cummings model ($g \ll 1$)

Trapping states for fine-tuned g : $g\tau = \frac{\pi}{\sqrt{m}}$

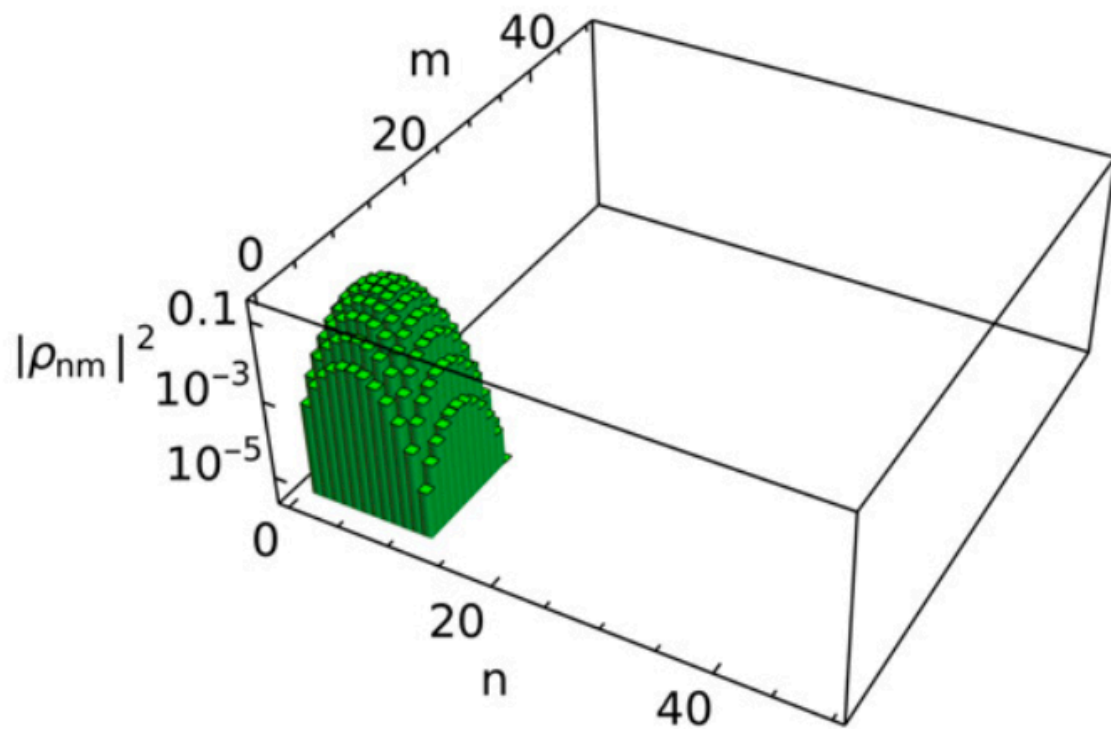
For $C=1$  superposition state $|\Psi\rangle = \sum_{n=0}^m c_n |n\rangle$



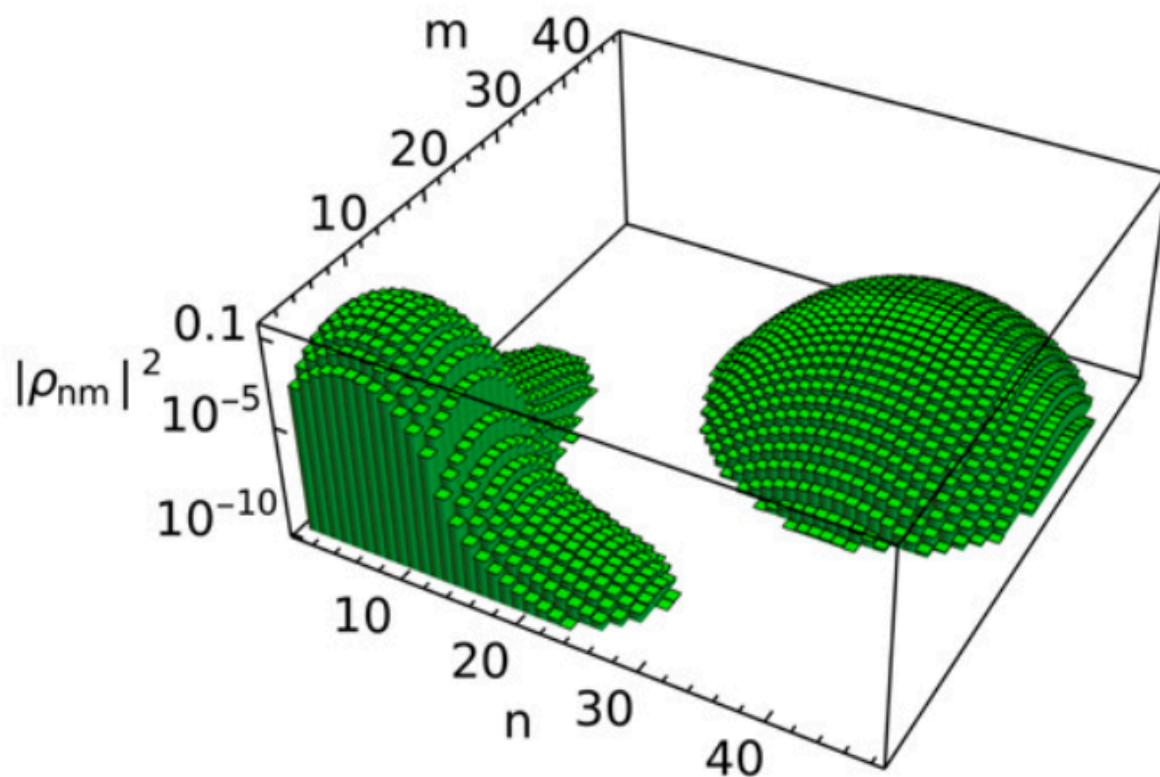
phase space is dynamical disconnected

Trapping state

John J. Slosser, Pierre Meystre, and Samuel L. Braunstein
Phys. Rev. Lett. **63**, 934 – Published 28 August 1989



Fine-tuned steady-state density matrix elements



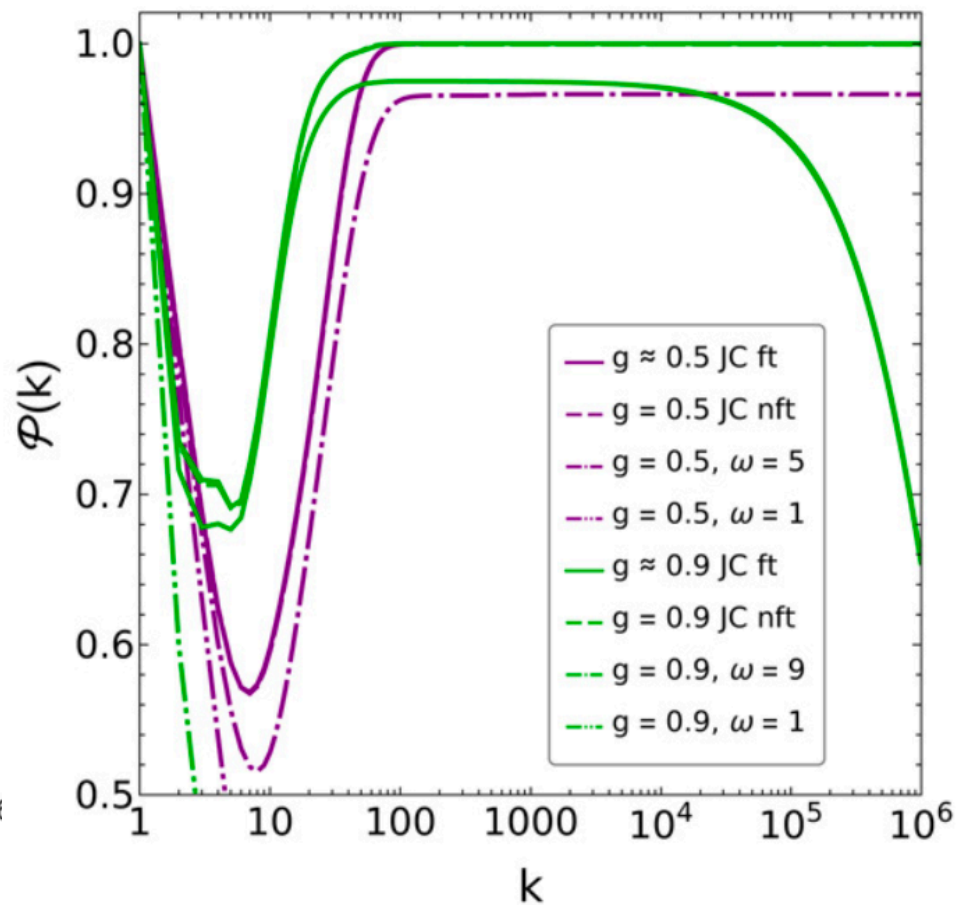
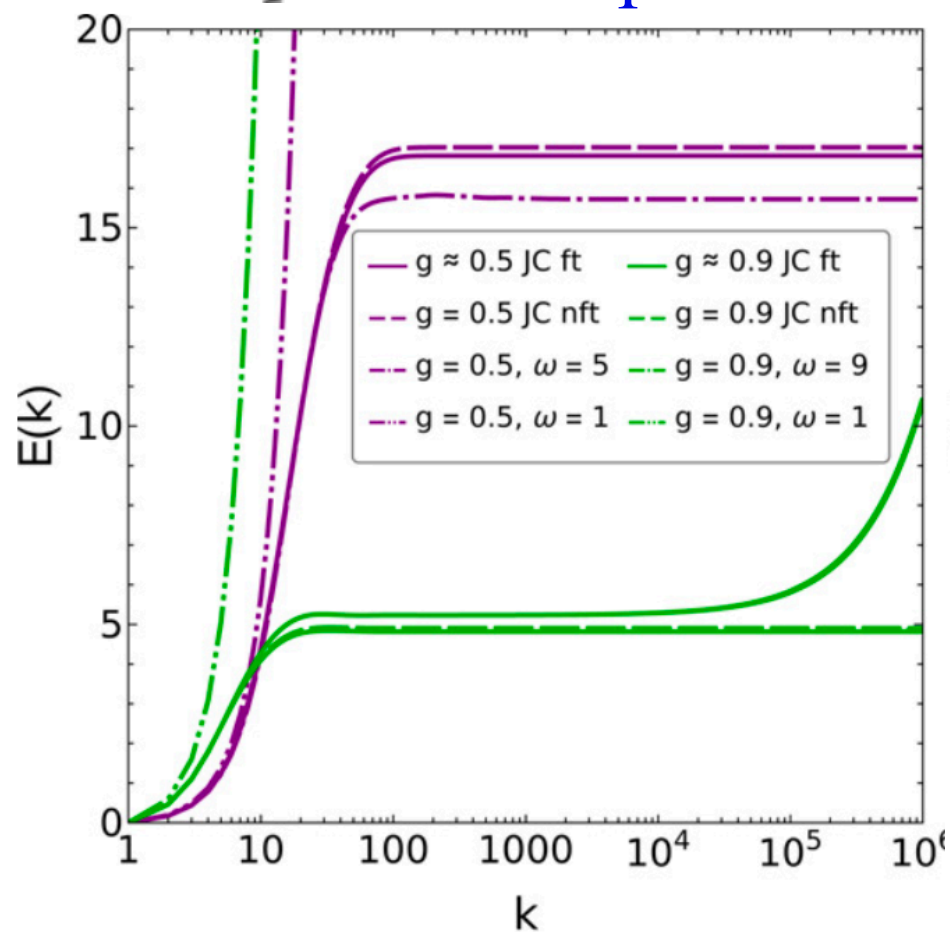
Non fine-tuned results

$$g = \frac{\pi}{\sqrt{m + \varepsilon}},$$

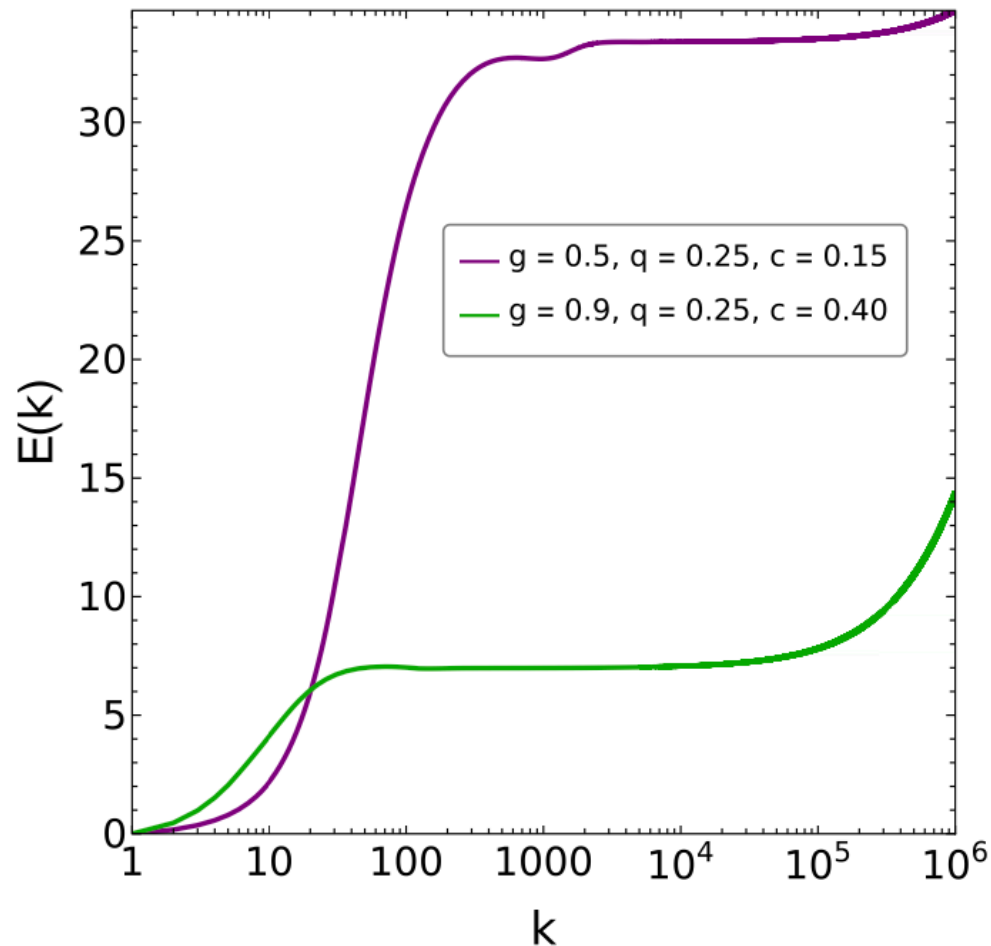
$$-0.5 < \varepsilon \leq 0.5$$

Results in the ultra-strong coupling regime

$q = 0.25$ pure states ($c=1$) for incoming qubits

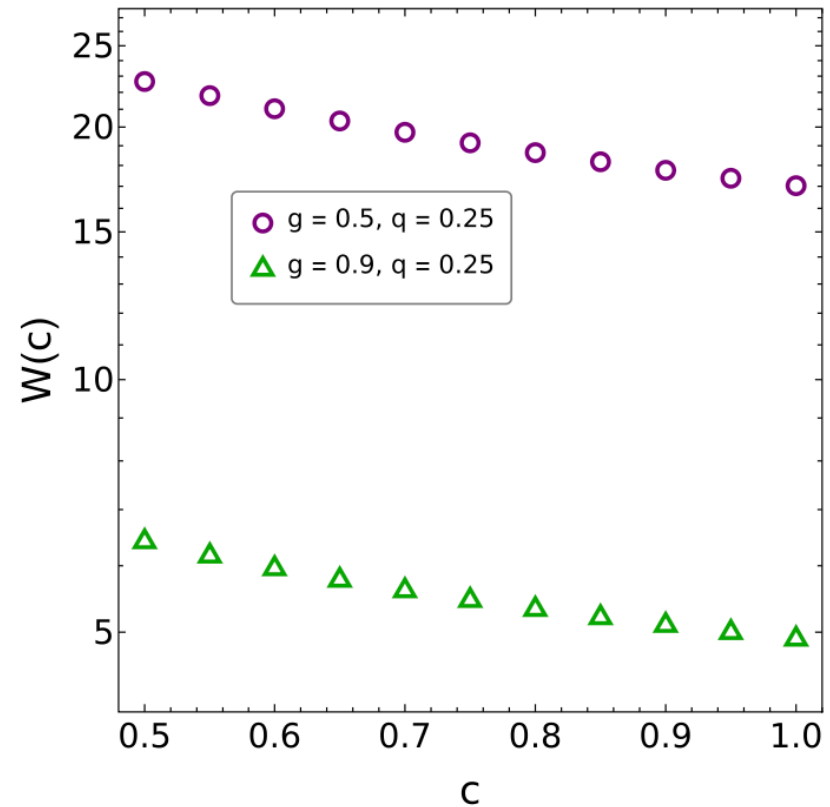
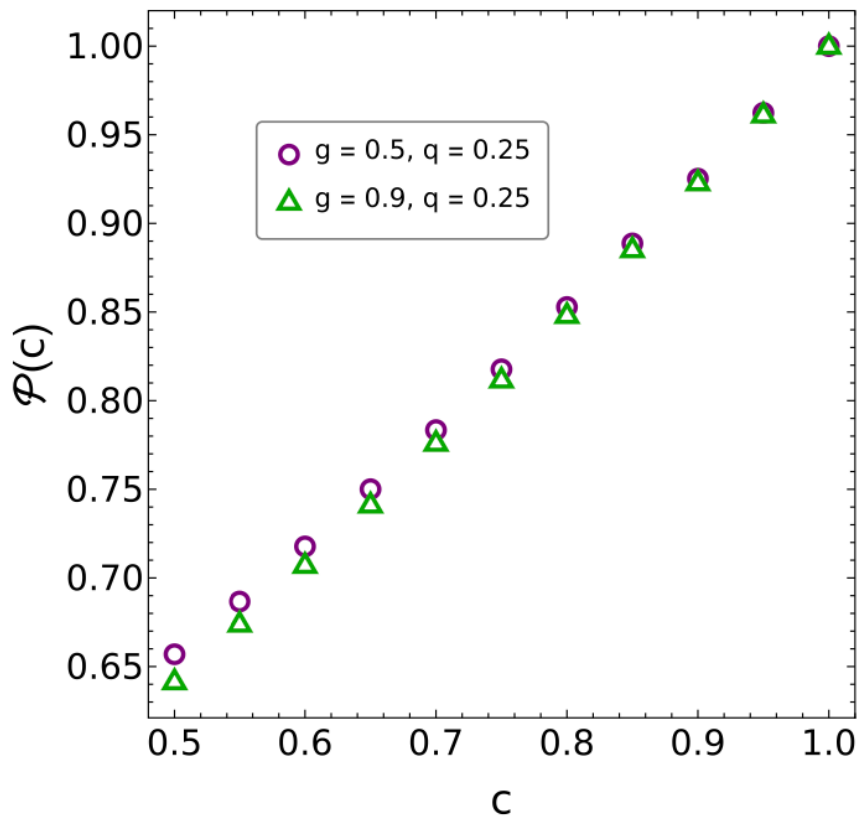


Charging with $c < 1$ (incoherent qubits)



(Jaynes-Cummings model)

Metastable states stable down to small c values (the incoherent case $c=0$ is much less stable than the coherent one $c=1$)



Mildly reduced purity but **ergotropy** (i.e., energy than can be extracted via unitary transformations) even increased

Outlook

Micromasers are an interesting model of quantum batteries since a pure steady state is built and the charging is fast and stable

Towards real implementations: take into account dissipation both in the rotating-wave approximation (Jaynes-Cummings model) and in the ultra-strong coupling regime

Is there a quantum advantage if two or more batteries are charged in series or in parallel by the stream of photons?