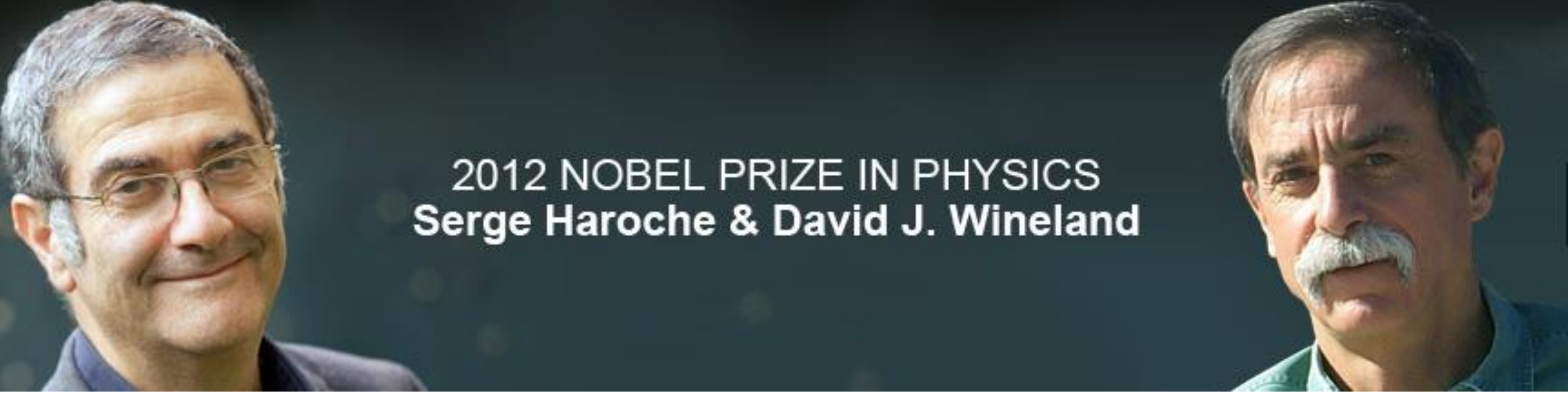


Particle control in a quantum world

Serge Haroche *and* ***David J. Wineland*** *have independently invented and developed ground-breaking methods for measuring and manipulating individual particles while preserving their quantum-mechanical nature, in ways that were previously thought unattainable.*

http://www.nobelprize.org/nobel_prizes/physics/laureates/2012

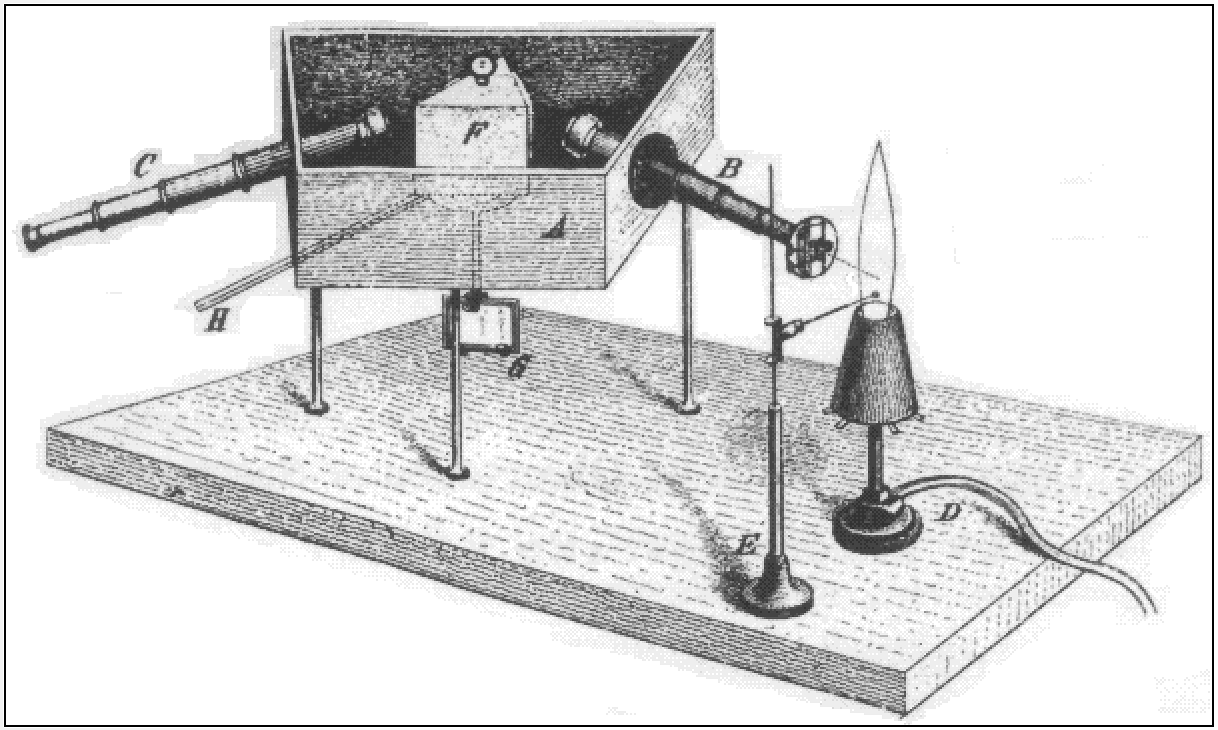
What's New in the Quantum World?

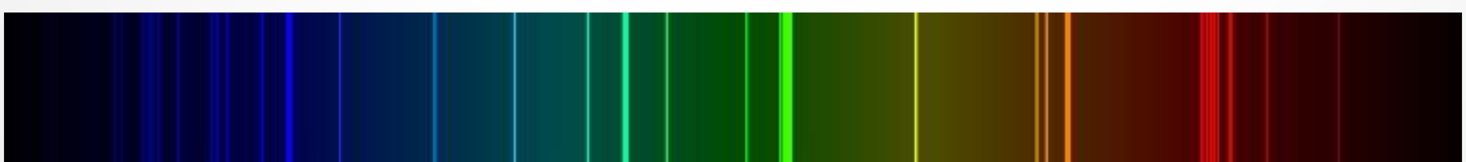
Jens Koch

NORTHWESTERN UNIVERSITY

Spectroscopy

G. KIRCHHOFF & R. BUNSEN
Annalen der Physik und der Chemie,
Vol. 110 (1860), pp. 161-189



Ca 

Spectroscopy

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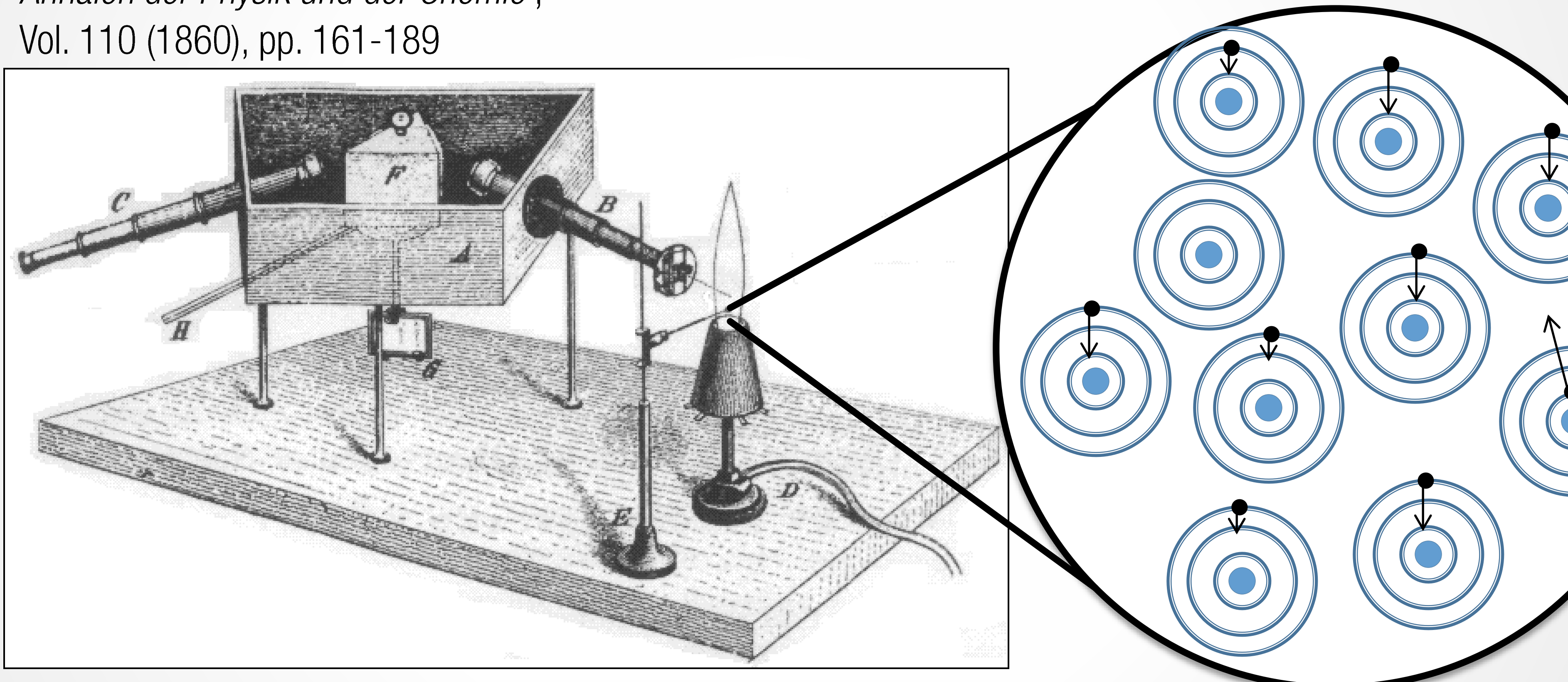
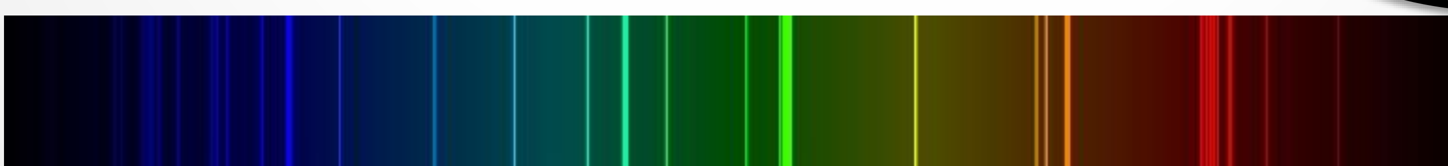
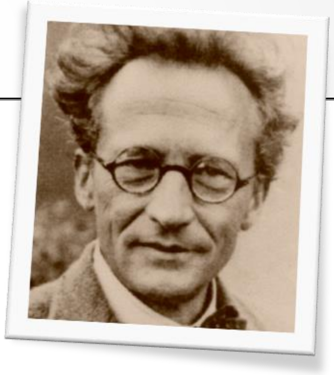


Ca



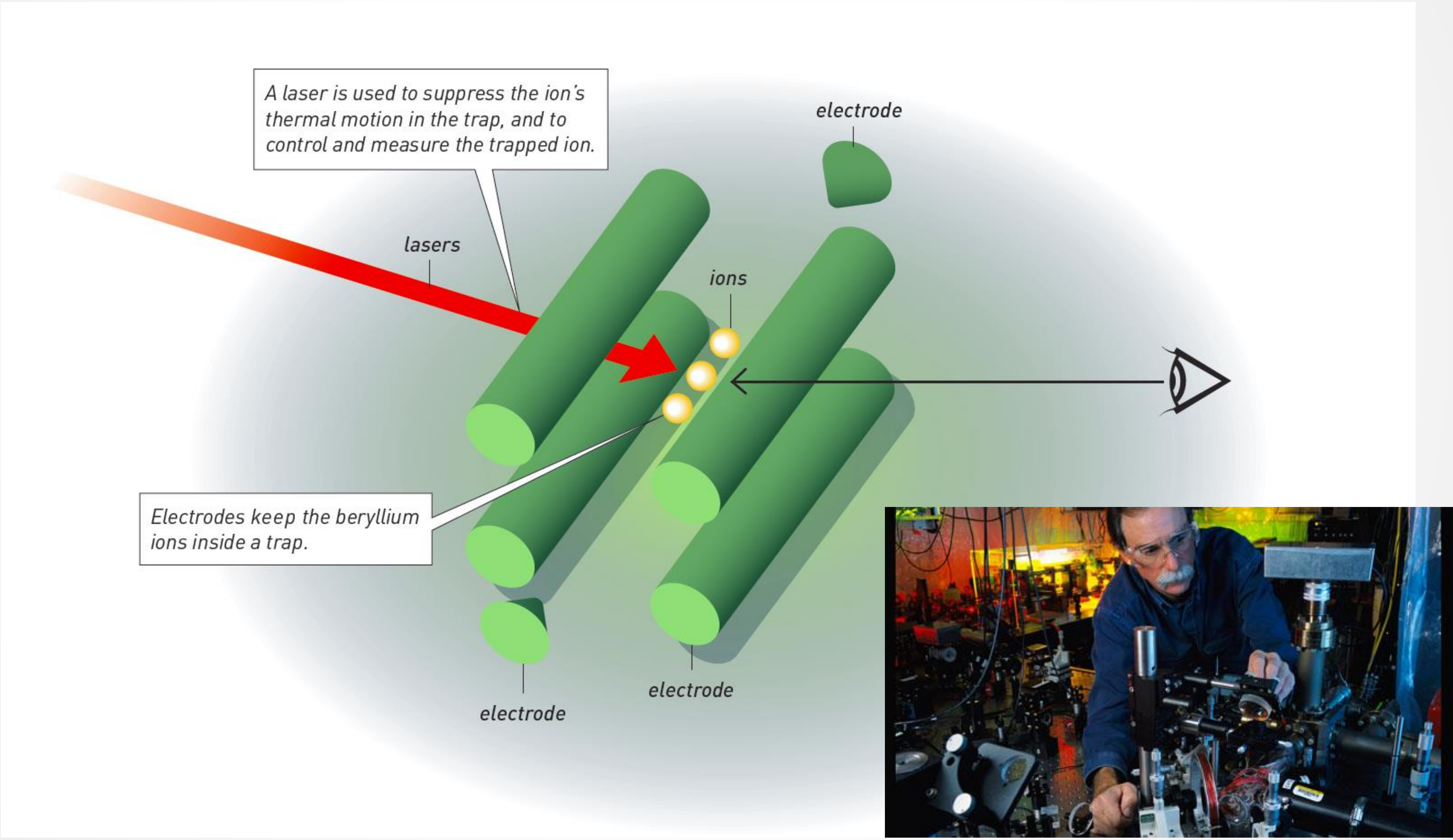
Quantum mechanics, once upon a time



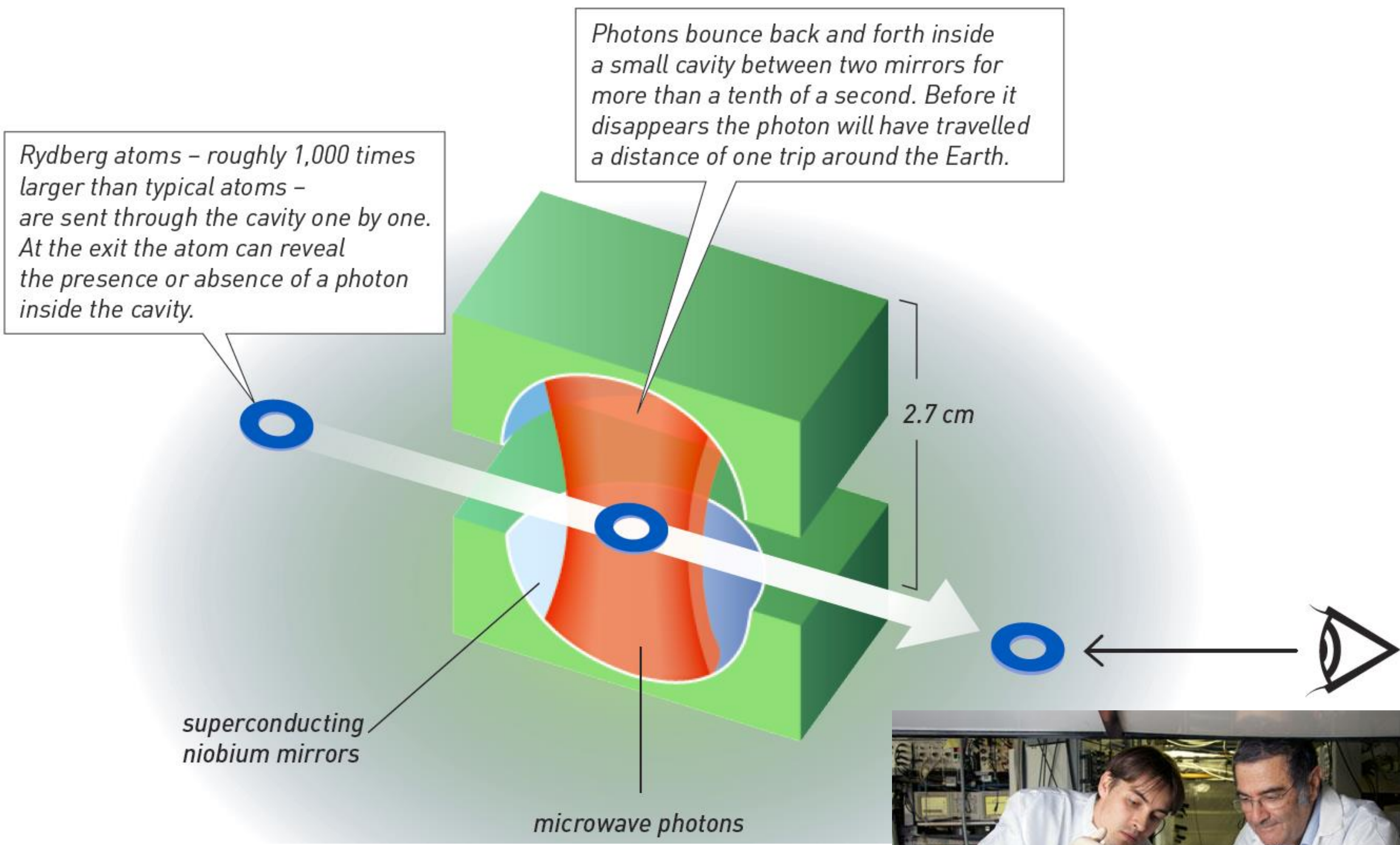
» We never experiment with just one electron or atom [...].
In thought experiments we sometimes assume that we do;
this invariably entails ridiculous consequences. «

E. Schrödinger, 1952

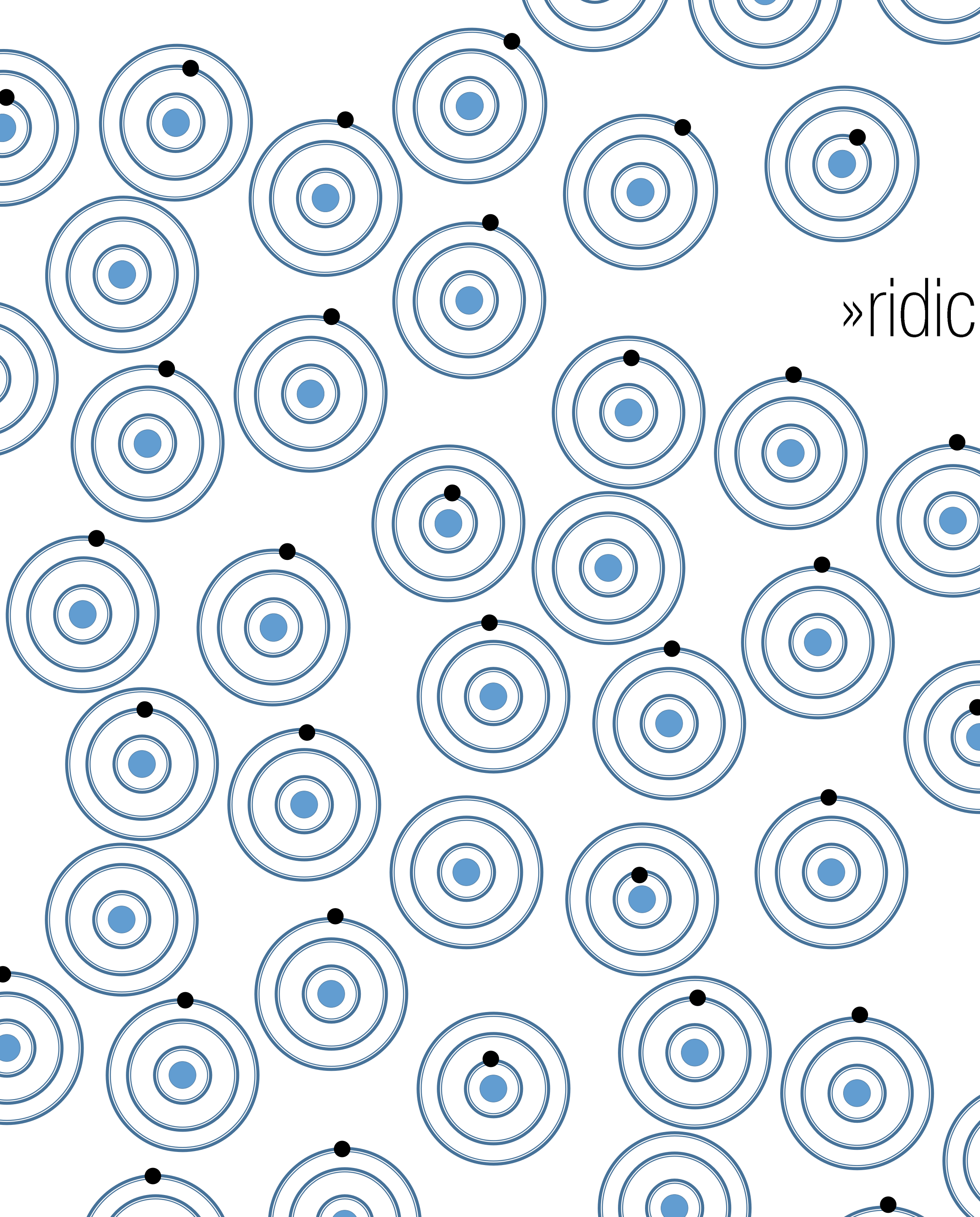
D. Wineland: trapped ions



S. Haroche: trapped photons

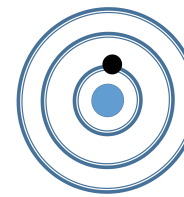


Cavity QED

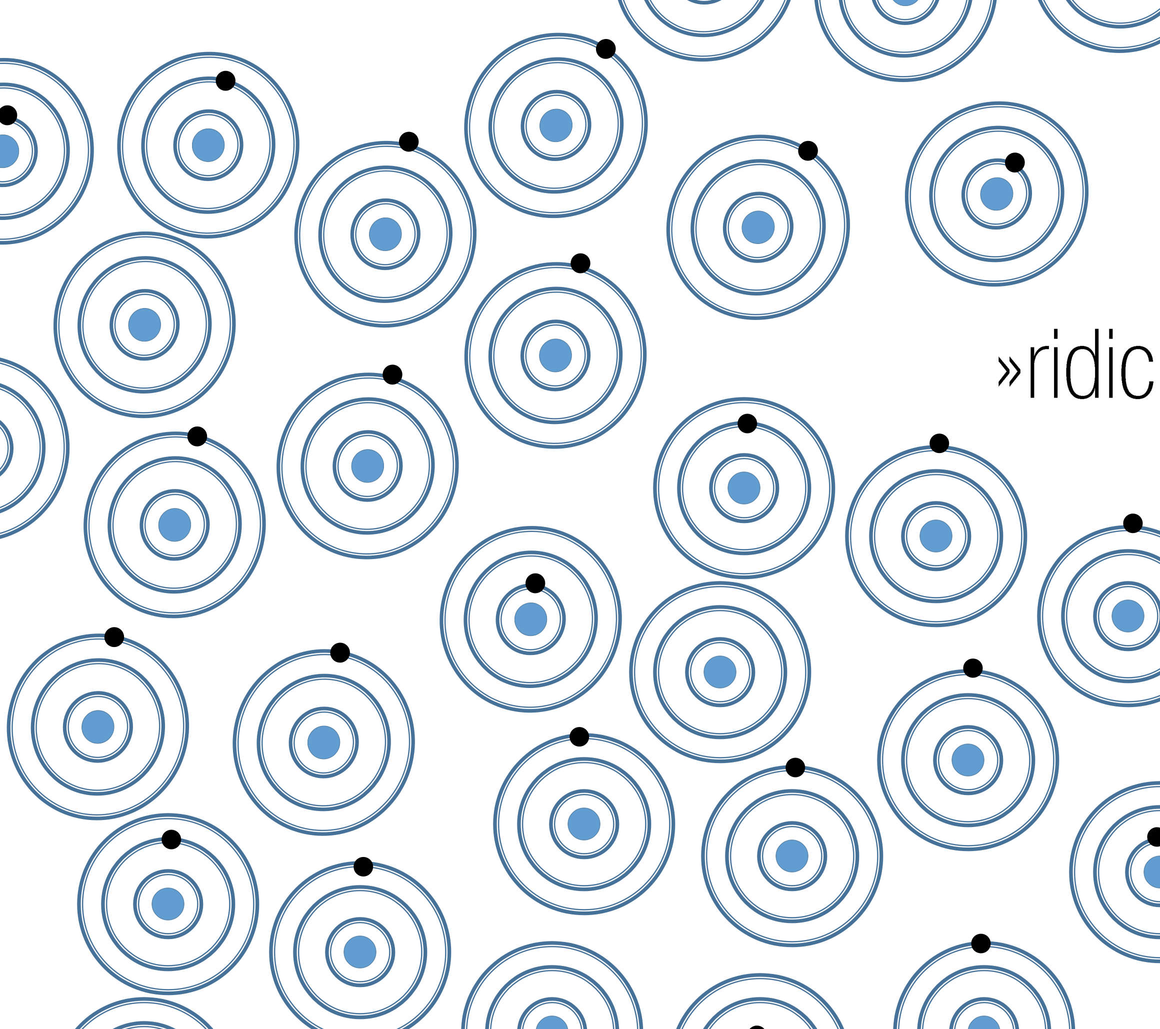


»ridiculous consequences«

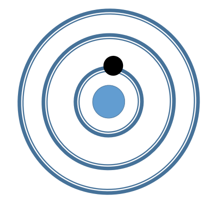
vs.



»ridiculous consequences«



vs.



- Ensemble of Atoms (or other particles)
- Measurement gives ensemble averages & may be influenced by interactions

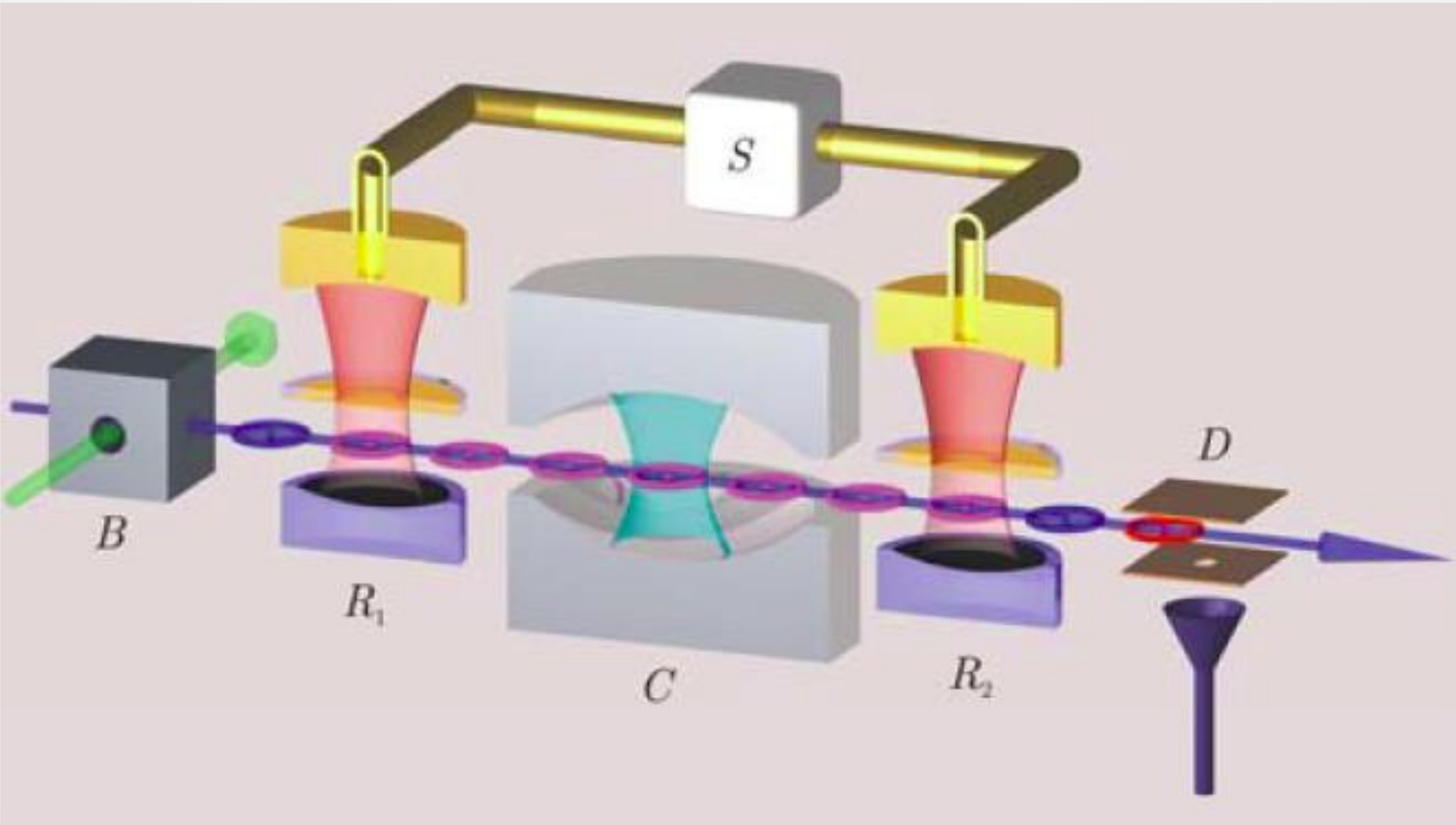
- Single Atom
- Observe stochasticity, entanglement, …

QM: two types of time evolution

1. Unitary evolution under Hamiltonian H (reversible)

2. Non-unitary “collapse” of state under measurement (usually irreversible)

Haroche's cavity QED experiments



Quantum jumps

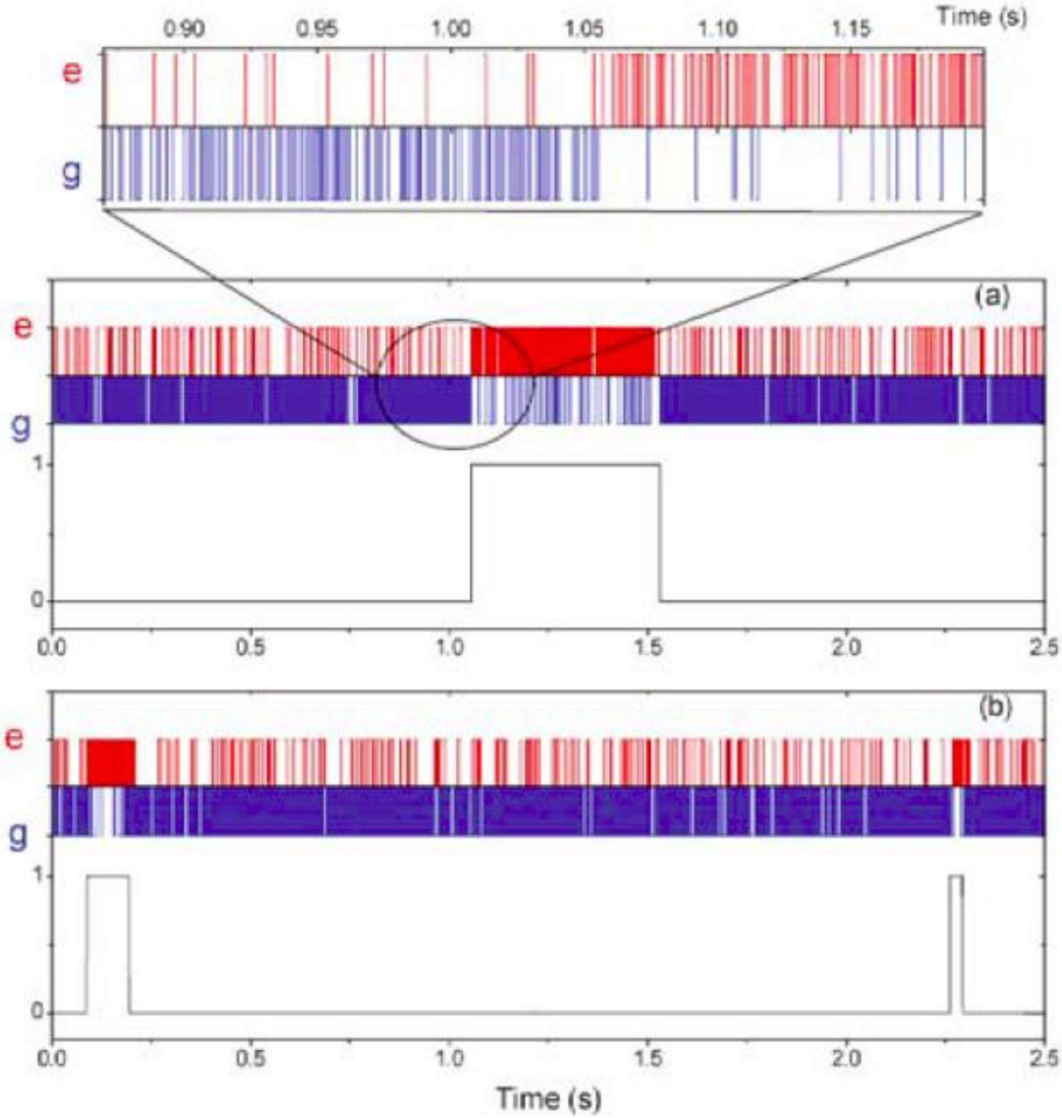
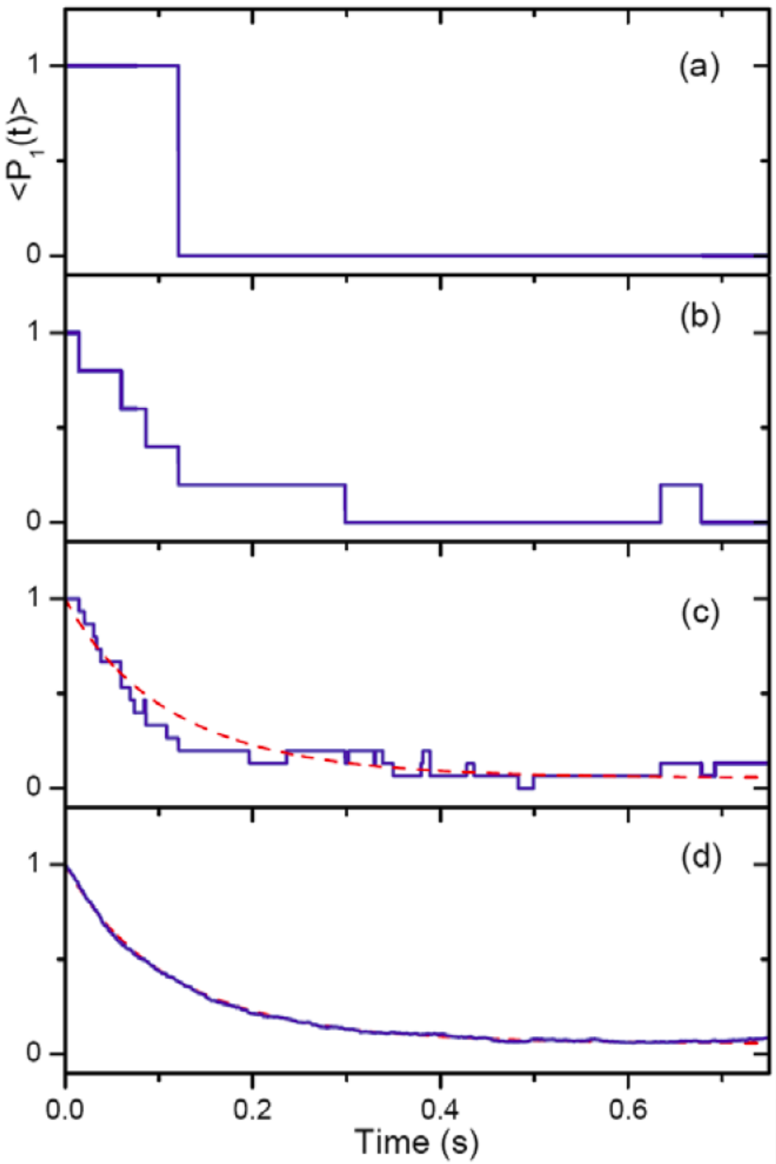


Figure 2: Birth, life and death of a photon: a QND Detection of a single photon. Red and blue bars show the raw signal, a

Gleyzes, S. *et al.*
Quantum jumps of light recording the birth and death of a photon in a cavity.

Nature 446, 297–300 (2007).

Quantum jumps



Gleyzes, S. *et al*.
Quantum jumps of light recording the birth and death of a photon in a cavity.

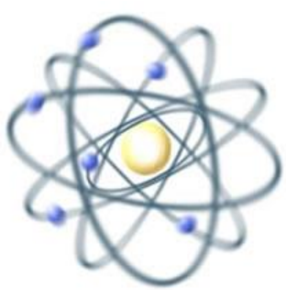
Nature 446, 297–300 (2007).

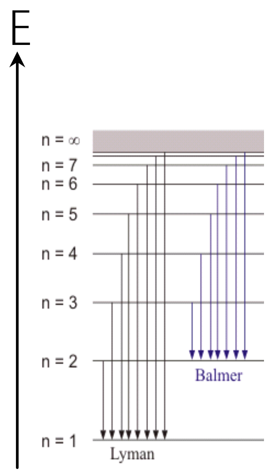
But what's the point?

- Fundamental tests of quantum mechanics
  - entanglement
  - violation of Bell's theorem
  - …
- High precision measurements based on quantum effects
  - conductance quantization
  - voltage standards based on Josephson effect
  - detection of tiny magnetic fields with SQUIDs
- New quantum devices (q-computer, q-simulators,…)

Artificial atoms

Atom





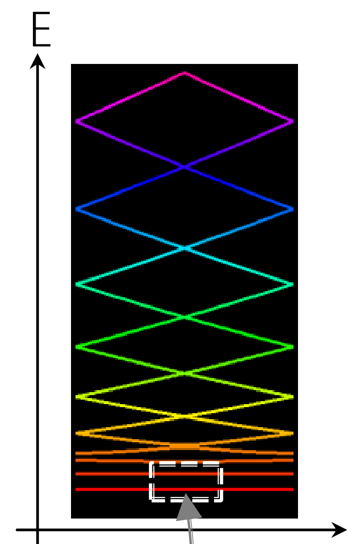
energies: ~eV, IF-vis-UV

Artificial atoms

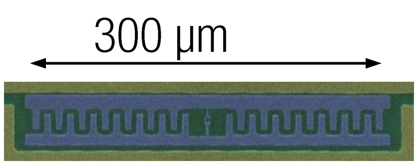
quantum systems with
discrete, anharmonic spectrum

e.g.,

- nuclear spins
- electrons on He
- spins in semicond.
- quantum dots
- sc circuits

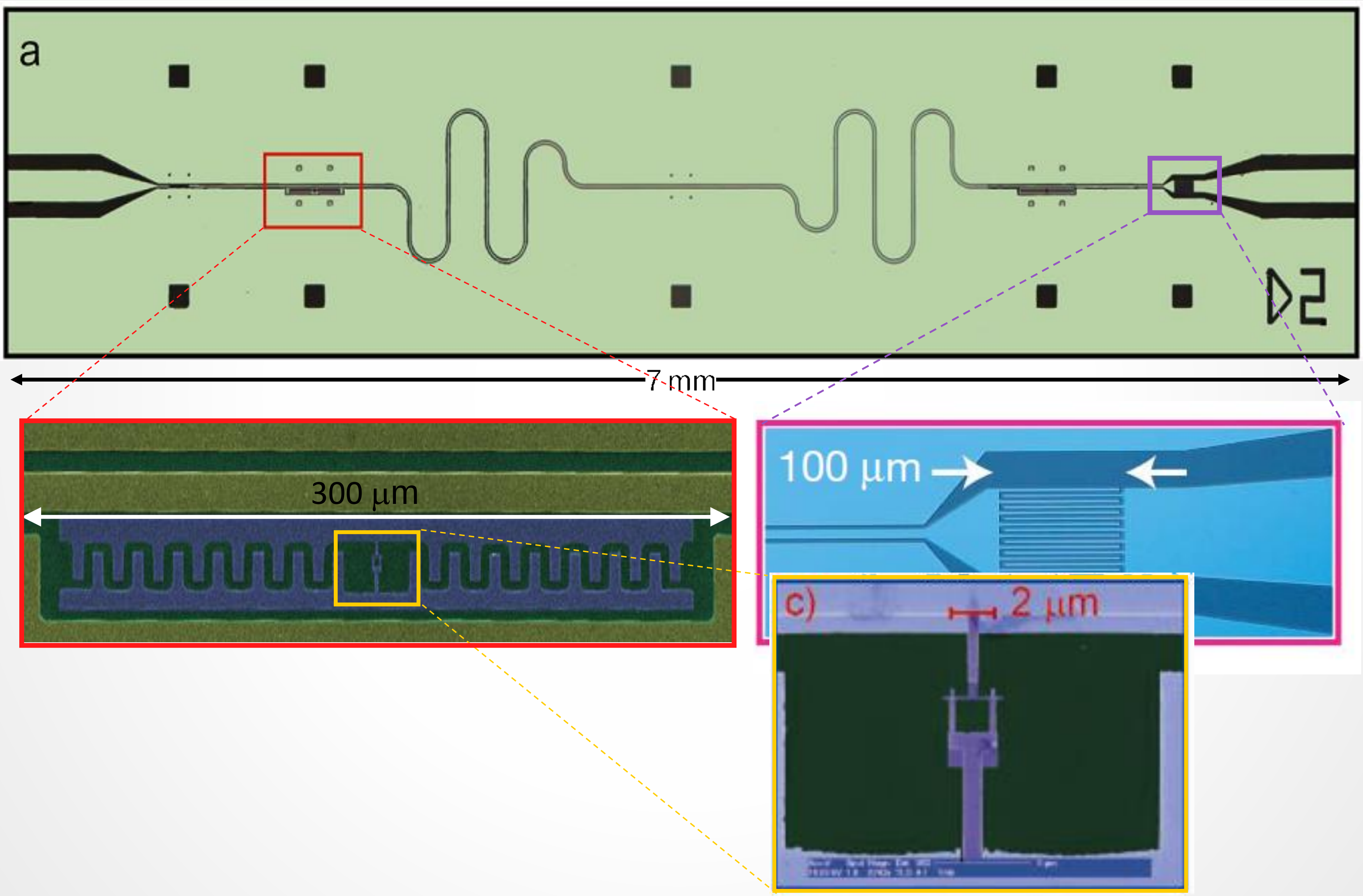


the qubit



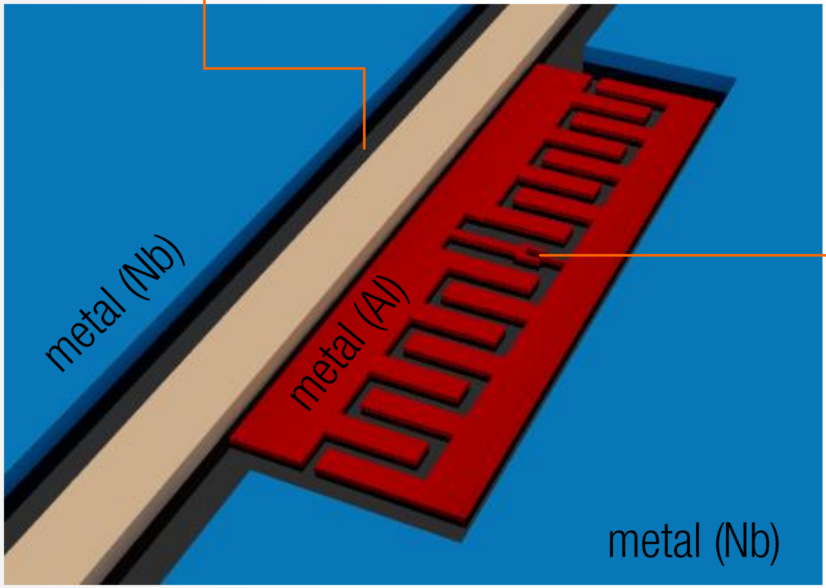
energies: ~50 µeV
≙ 10 GHz ≙ 0.5 K

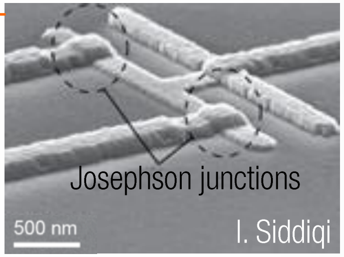
Circuit QED



Superconducting qubits 101

substrate (Si, sapphire)





circuits go quantum

1981 **Influence of Dissipation on Quantum Tunneling in Macroscopic Systems**
A. O. Caldeira and A. J. Leggett

1982 **Quantum Dynamics of Tunneling between Superconductors**
Vinay Ambegaokar and Ulrich Eckern
and
Gerd Schön

$$I = I_0 \sin\varphi$$

$$\Downarrow$$

$$\hat{I} = I_0 \widehat{\sin\varphi}$$

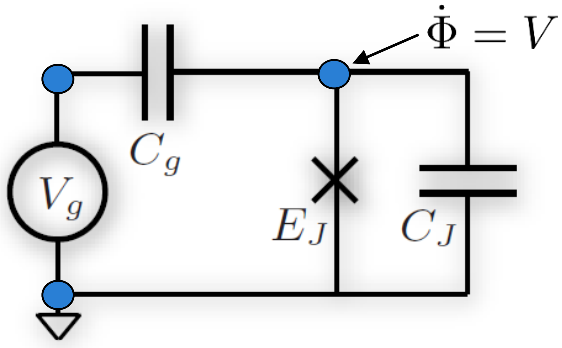
collective quantum variables

How do you quantize a circuit?

▶ **Step 1:** set up Lagrangian for circuit

$$L(\dot{\Phi}_i, \Phi_i) = E_{\text{kin}} + E_{\text{pot}}$$

Σ capacitive energies Σ inductive energies



▶ **Step 2:** Legendre transform → Hamiltonian

▶ **Final Step 3:** canonical quantization $\{\Phi_i, Q_j\} = \delta_{ij} \quad \longrightarrow \quad [\Phi_i, Q_j] = i\hbar\delta_{ij}$

⚠ with one important caveat – can you see it?

Result for Cooper pair box (circuit above):

$$\hat{H} = 4E_C(-id/d\varphi + n_g)^2 - E_J \cos(\varphi)$$

sc phase difference

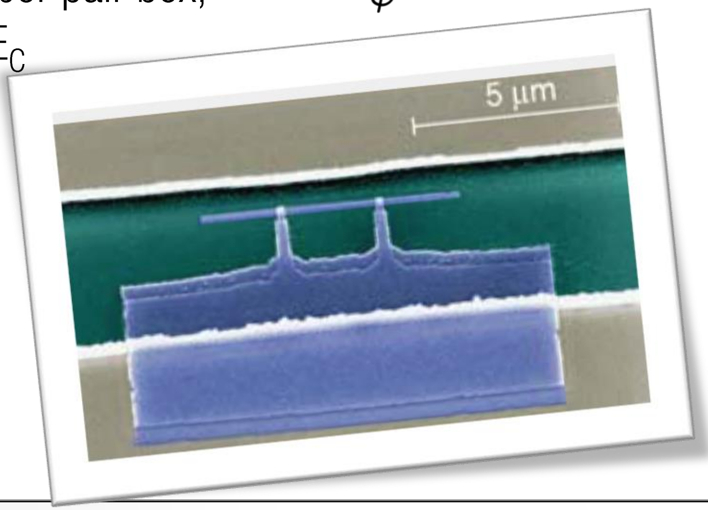
$$\hat{H} = 4E_C(\hat{n} + n_g)^2 - \frac{E_J}{2} \sum_{n=-\infty}^{\infty} \Big[|n+1\rangle\langle n| + |n\rangle\langle n+1| \Big]$$

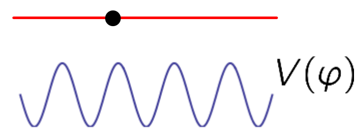
# of Cooper pairs

Thwarting charge noise

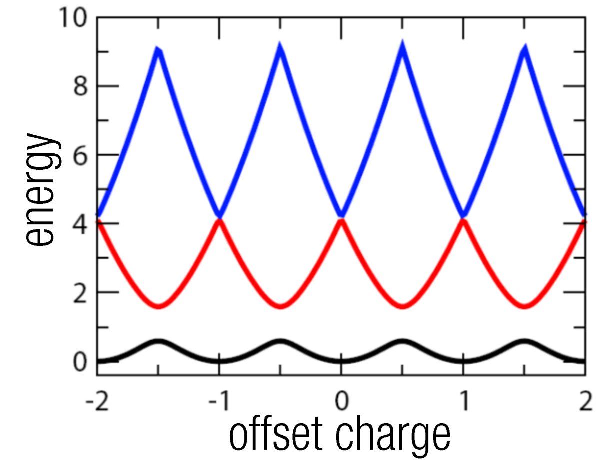
Cooper pair box,
$E_J \leq E_C$

$T_\varphi = 1\,\text{ns}$



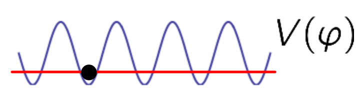


(weak potential limit)

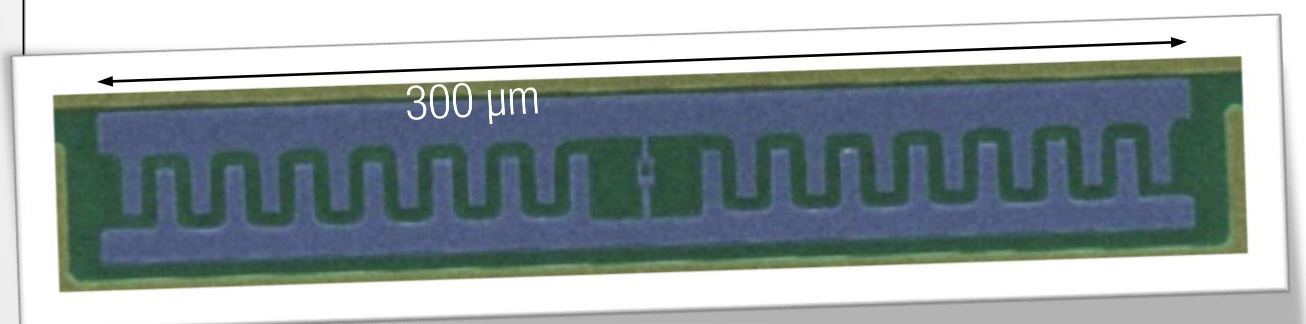


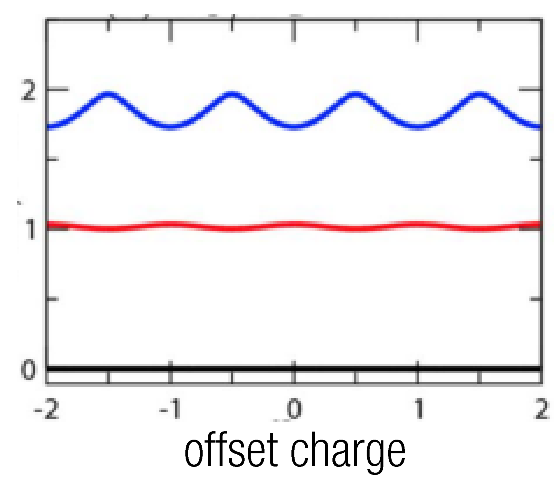
"Transmon"
$E_J >> E_C$

$T_\varphi > 5\,\mu s$



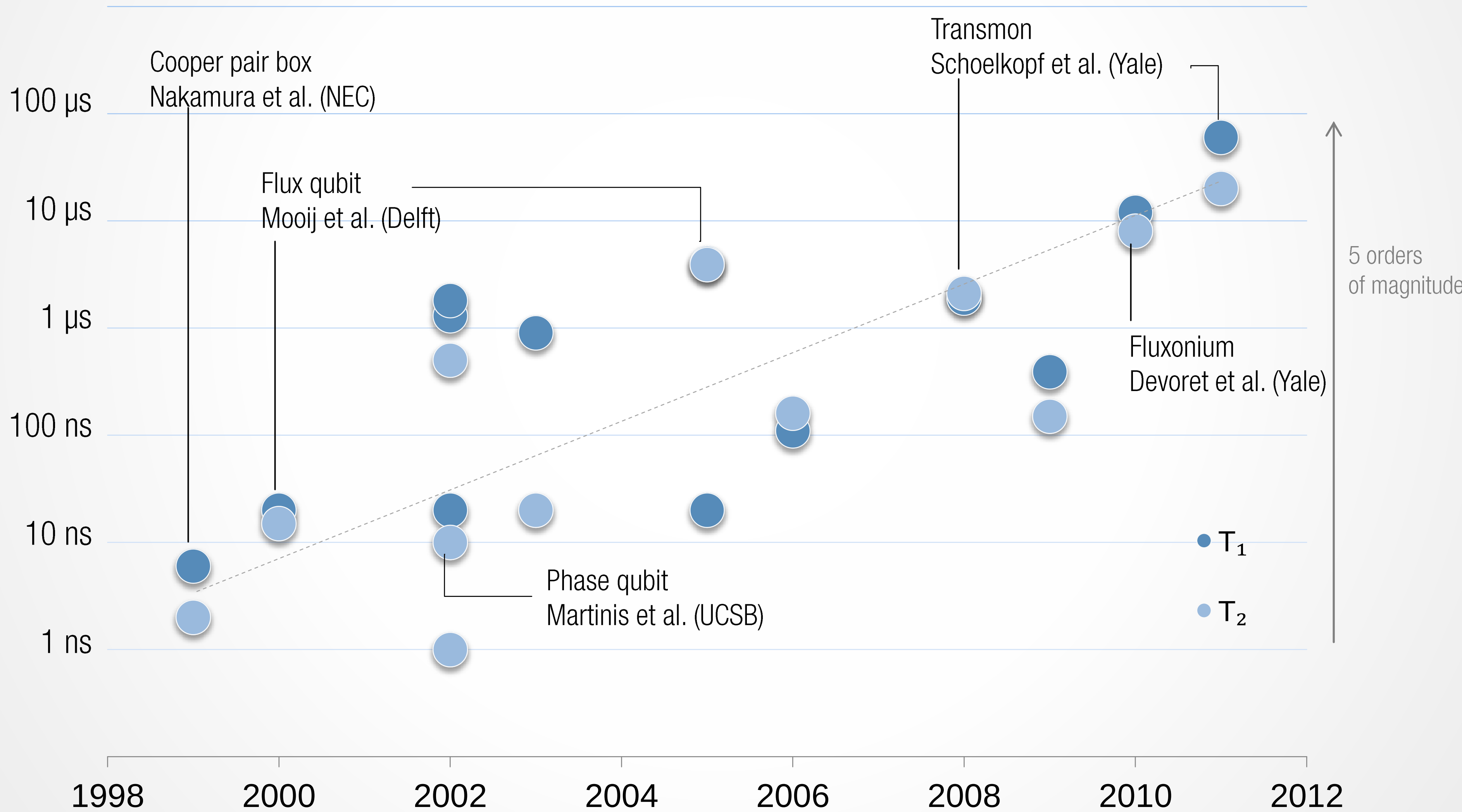
(tight-binding limit)



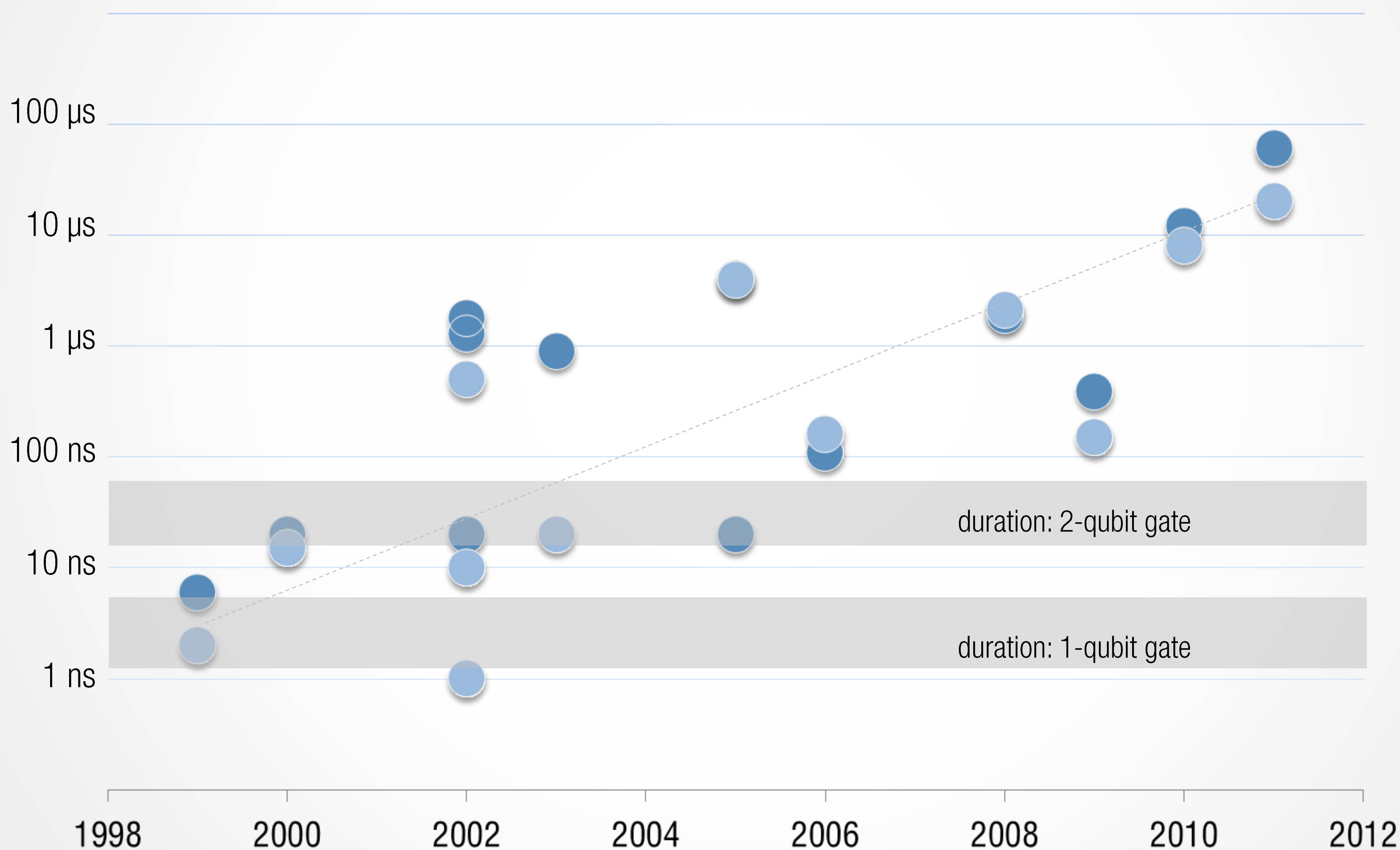


JK et al., PRA **76**, 042319 (2007) ; Schreier et al., PRB **77**, 180502(R) (2008)

SC qubits: coherence

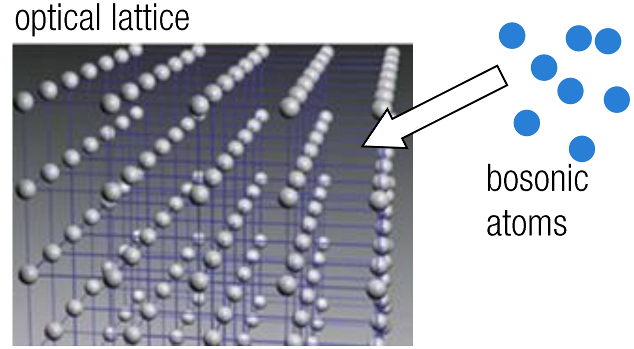


SC qubits: coherence



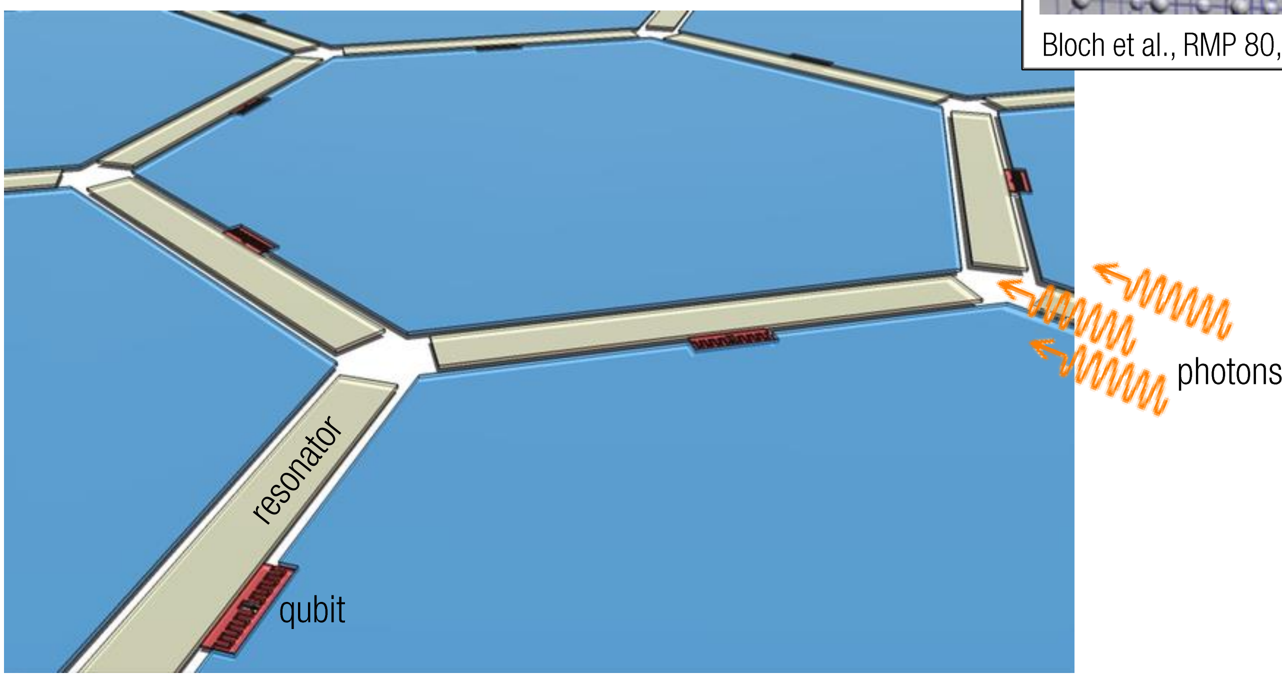
Simulating matter

optical lattice

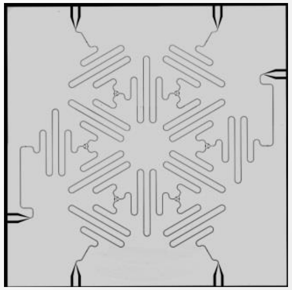


Bloch et al., RMP 80, 885 (2008)

lattice composed of resonators & qubits



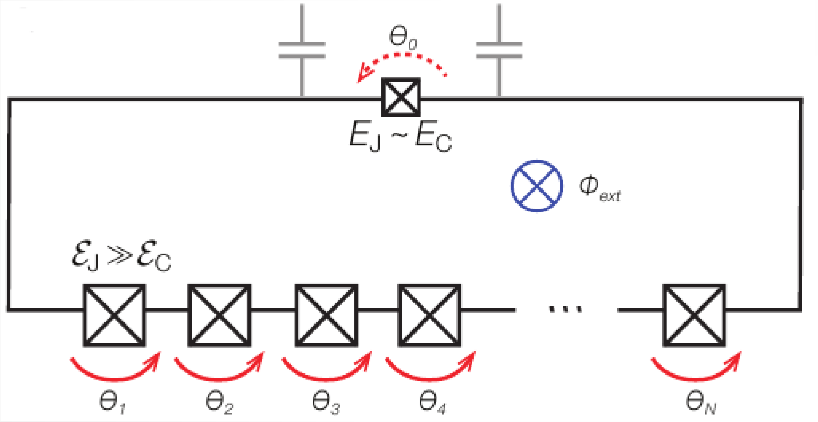
Greentree et al., Nat. Phys. 2, 856 (2006), JK and Le Hur, PRA 80, 023811 (2009)
Hartmann et al., Laser & Photonics Rev. 2, 527 (2008)

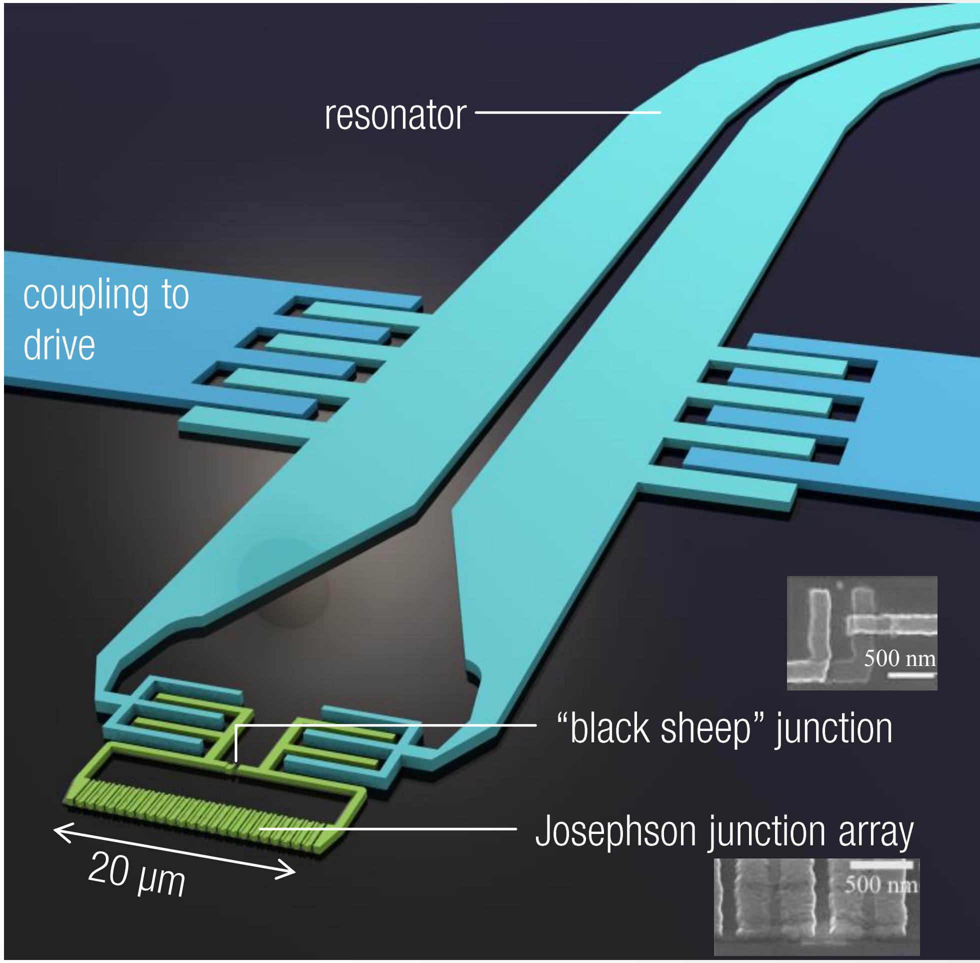


A. A. Houck, Princeton

Fluxonium

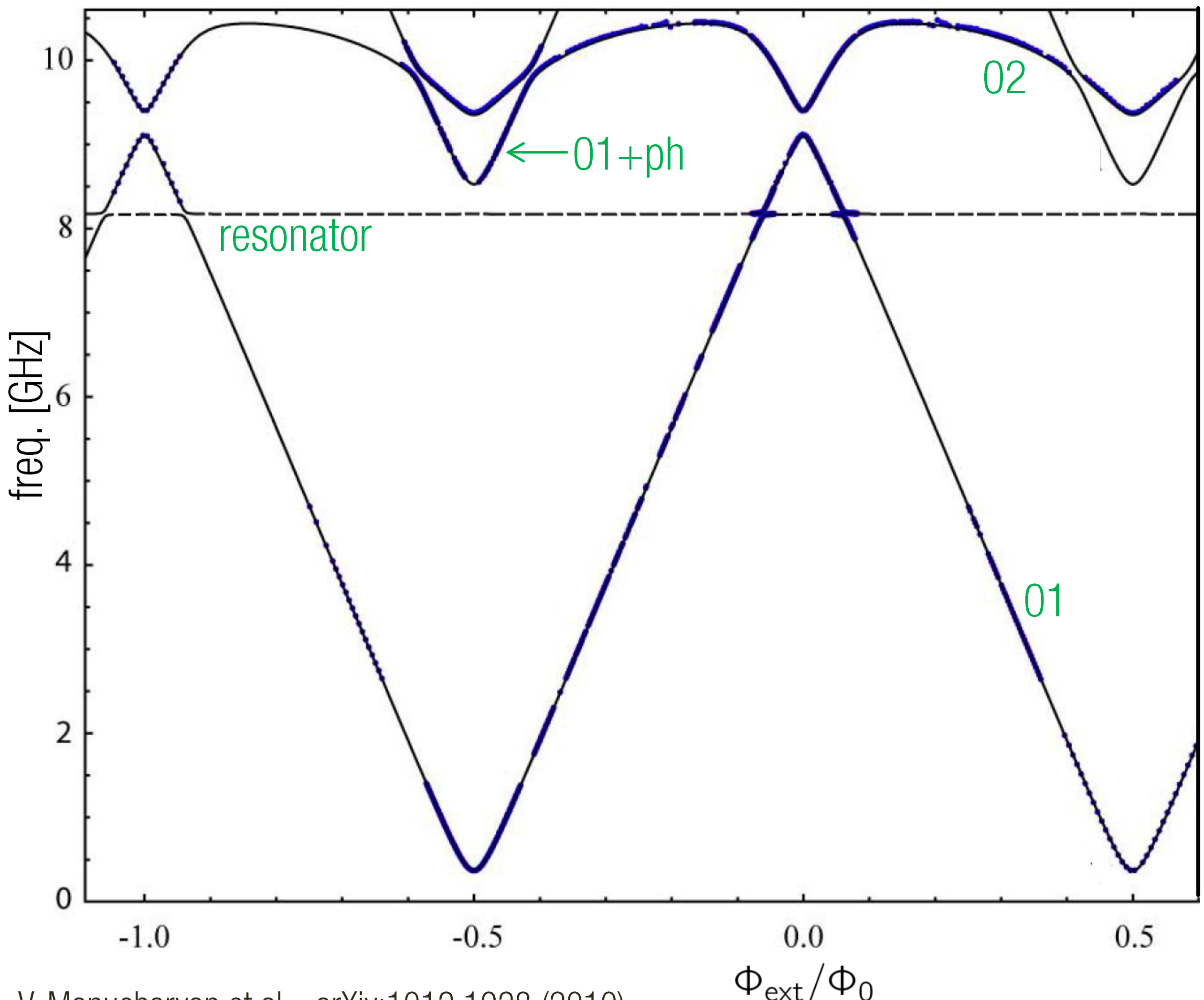
- Weak junction shunted by JJA: 43+1 junctions





Superinductor model: theory vs. experiment

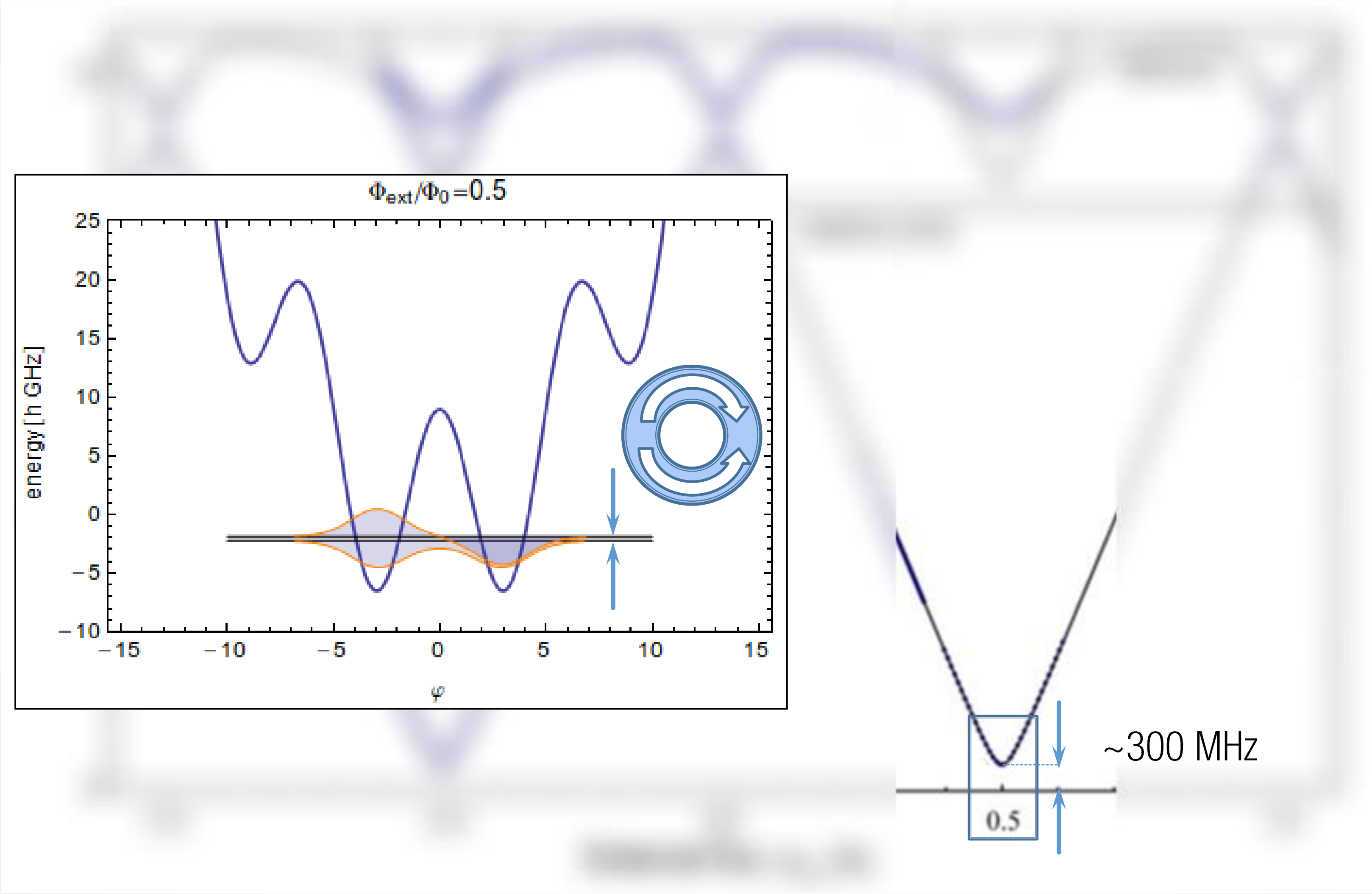
Spectroscopy (Yale sample 2010)



V. Manucharyan et al., arXiv:1012.1928 (2010)

Persistent current states @ half-int. flux

Yale sample (2010)



V. Manucharyan et al., arXiv:1012.1928 (2010)

Does quantum mechanics make sense?

quantum: open questions?

- getting beyond the "shut up and calculate!"† directive of QM

†David Mermin, summarizing the Copenhagen interpretation, Physics Today (04/1989)

- is there anything fundamentally wrong with

$\frac{1}{\sqrt{2}}\Big(|$  $\rangle \pm e^{i\varphi} |$  $\rangle \Big)$?

[Rumor has it that this state emerged in a discussion between G. Baym and A. Leggett.]

quantum: open questions

- How far can we push quantum/classical boundary?

➞ intimately related to role of measurements in quantum mechanics

Macroscopic Quantum Systems and the Quantum Theory of Measurement

A. J. LEGGETT

Supplement of the Progress of Theoretical Physics, No. 69, 1980

»The real trouble [is] the fact that the measuring apparatus […] is itself a physical system […] and therefore should in principle be describable in quantum-mechanical terms. «

quantum: other open questions

- What makes quantum computers powerful?

or, are they actually?

must prove P≠NP
& win $1,000,000 millennium prize

prize.problems@claymath.org

http://www.claymath.org/millennium/P_vs_NP/

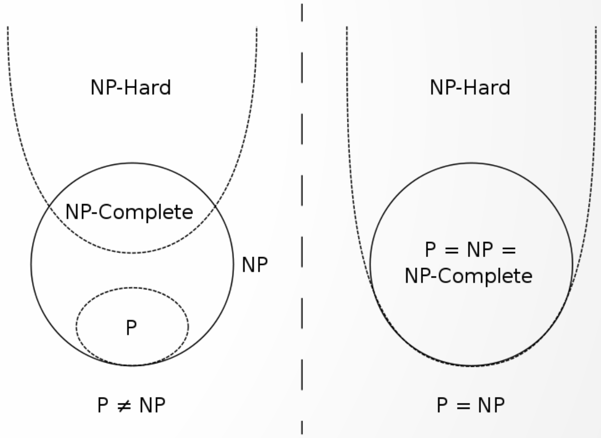


Fig: Wikipedia

recently on TED

TEDx Caltech

www.tedxcaltech.com

»The effort to build QCs [… could] lead to
a major conceptual advance
in our understanding of QM.

You'll recognize the advance
because it will look
like science, not philosophy --

-- so it won't just be
putting lipstick on a pig.«