Quantum coherence using Josephson junctions

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Josephson Tunneling

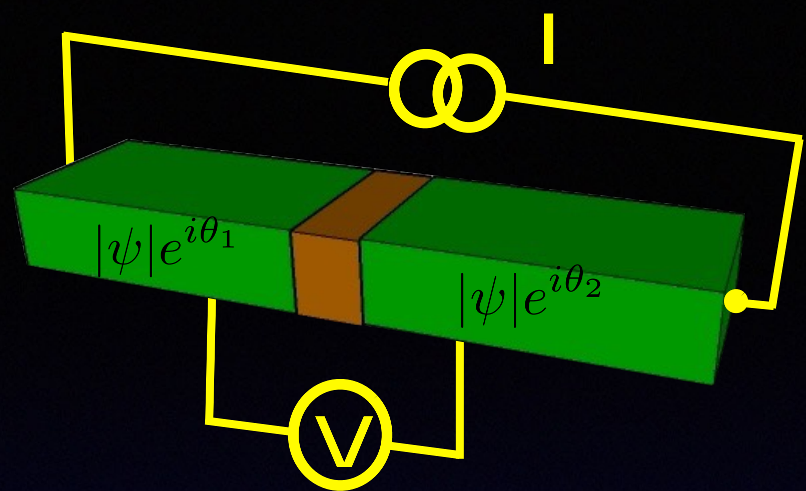
"The Noble Laureate Versus the Graduate Student"
Donald McDonald, ***Physics Today***, June 2001

- The physics of "Josephson junctions" began with a small paper, essentially Brian Josephson's MA thesis, Physics Letters (1962)
- He was trying to answer the question,

  "What is the physical significance of broken symmetry in superconductors?"

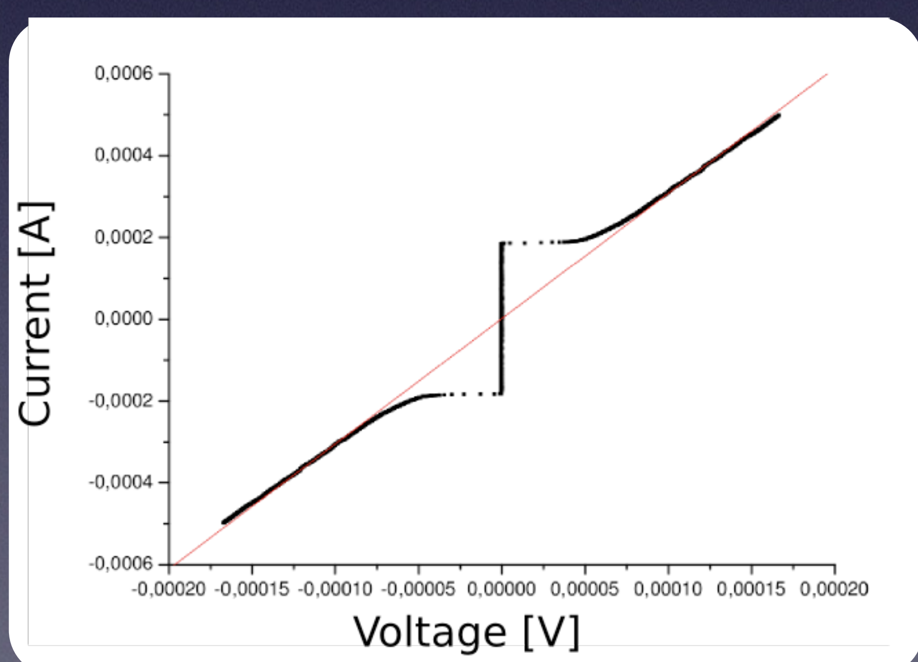
  Discovered 'The Josephson Effects' resulting from coherent tunneling of Cooper pairs

  Shared 1973 Nobel Prize (1/2) with Leo Esaki (1/4) and Ivar Giaever (1/4), one year after Nobel Prize awarded to Bardeen, Cooper and Schrieffer for BCS theory of superconductivity
- Enables metrology to one part in 10^{19}....perhaps the best test ever of the accuracy of quantum mechanics!



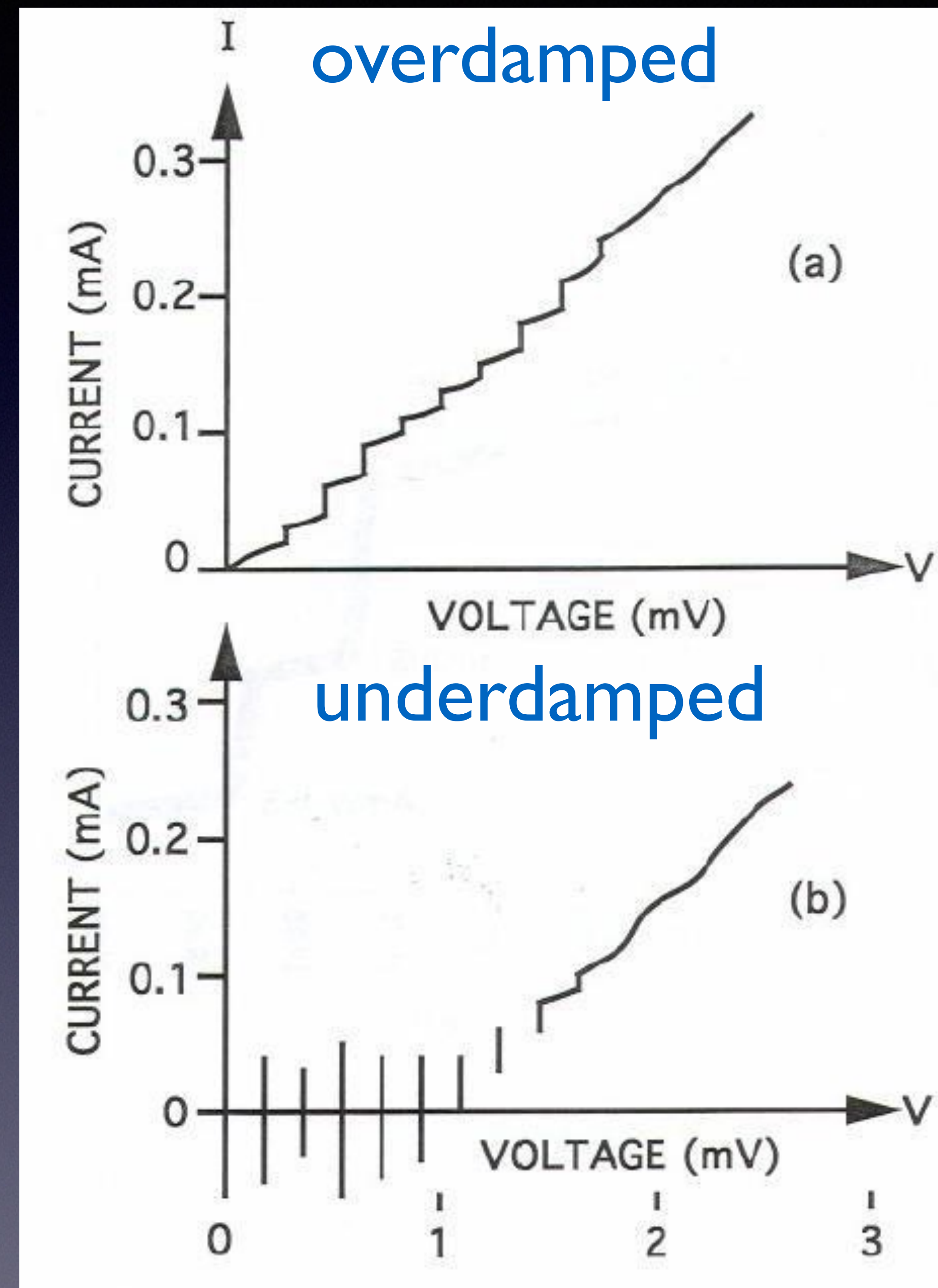
The DC Josephson effect

$$I = I_0 \sin\theta$$



$$V = \frac{\hbar}{2e}\frac{d\theta}{dt}$$

AC Josephson effect

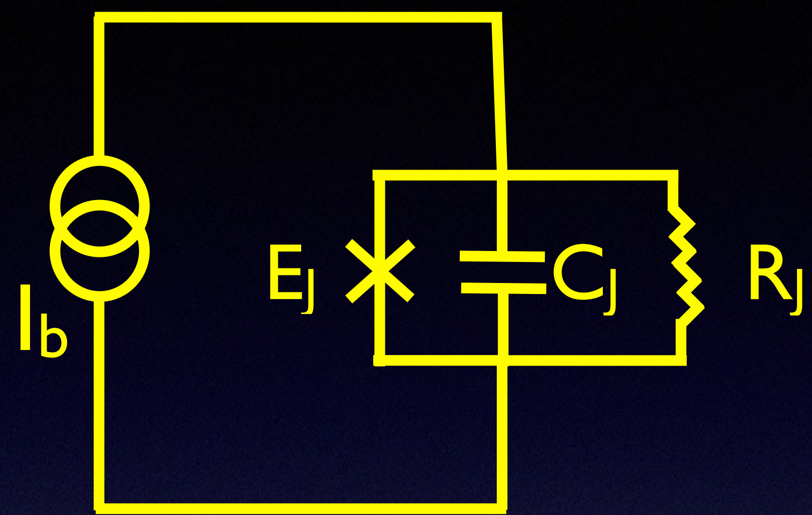


$$V = n\frac{h}{2e}\nu$$

Josephson junctions, quantum fluctuations and quantum coherence

- 1960-80's - RCSJ model, "classical non-linear dynamics"
- mid-80's - Tony Leggett, Macroscopic Quantum Tunneling (MQT) of the phase across a Josephson junction
- mid-late 80's - MQT observed by Martinis, Devoret, Esteve and Clarke
- late 80's - Likharev, Averin and Zorin 'Bloch Oscillations (small junctions)'
- 1990 - Devoret, Girvin, 'P(E) theory': write Hamiltonian for whole circuit including bias.
- 1993 - The Cooper-pair box, Lafarge, Joyez, Esteve, Urbina and Devoret
- 1999 - Nakamura et al. Coherent charge oscillations of a Cooper-pair box (first solid-state qubit)
- 2004-now - Circuit-QED, the `transmon', improved phase, flux qubits, quantum optics using microwaves, quantum phase-slips, …

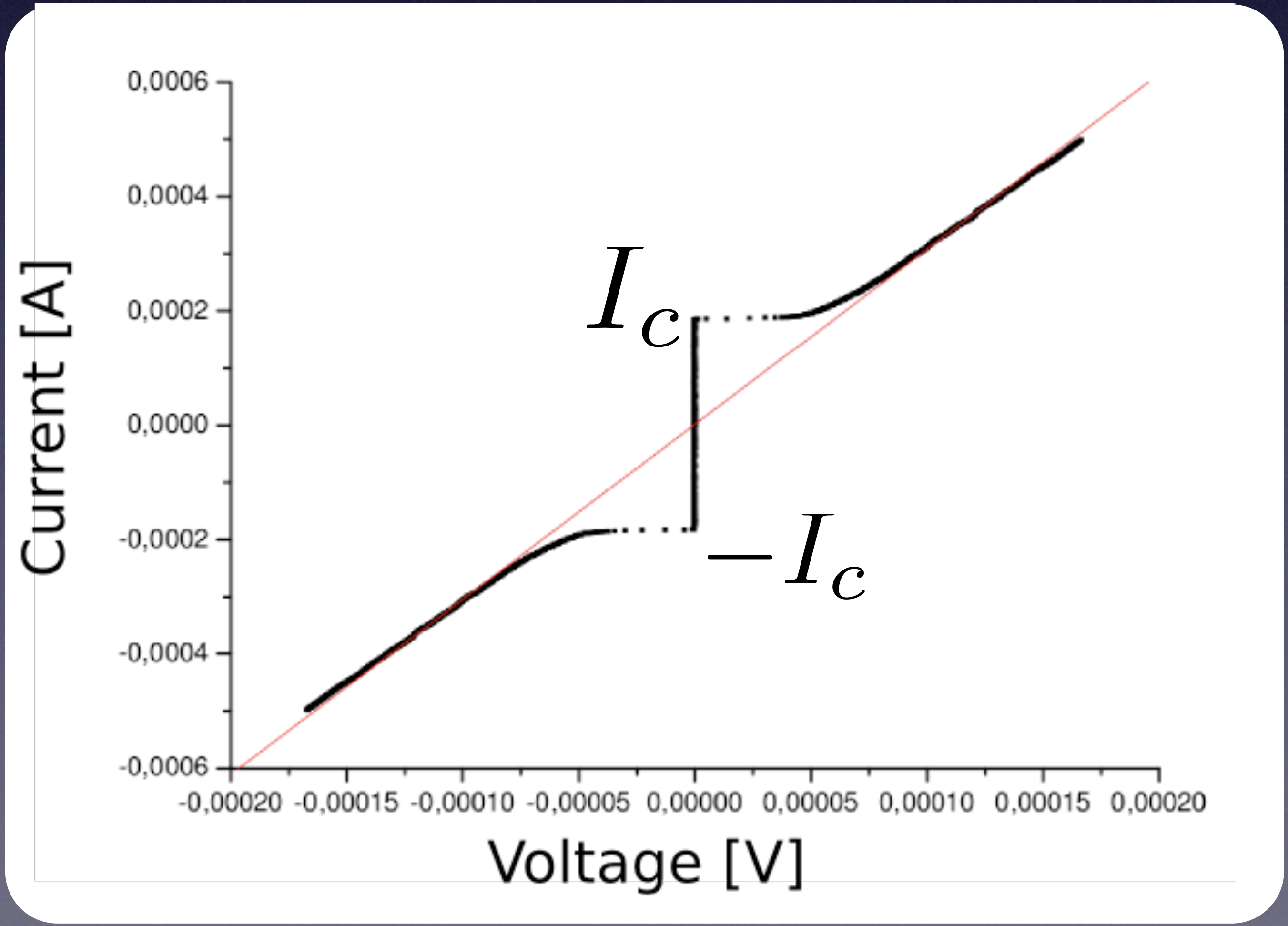
Macroscopic Quantum Tunneling of the phase (MQT)
current-biased Josephson junction



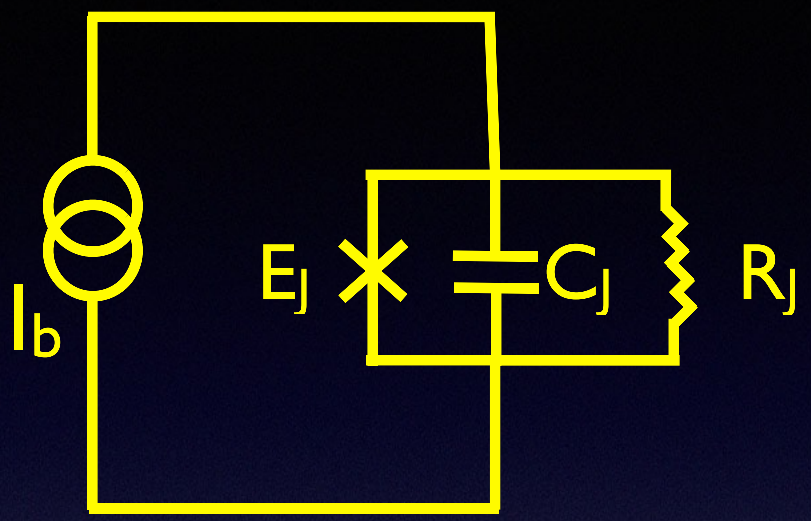
$$C_J \left(\frac{\Phi_0}{2\pi}\right)^2 \ddot{\theta} + R_J^{-1} \left(\frac{\Phi_0}{2\pi}\right) \dot{\theta} + I_0 \sin\theta - I_{\text{bias}} = \eta(t$$

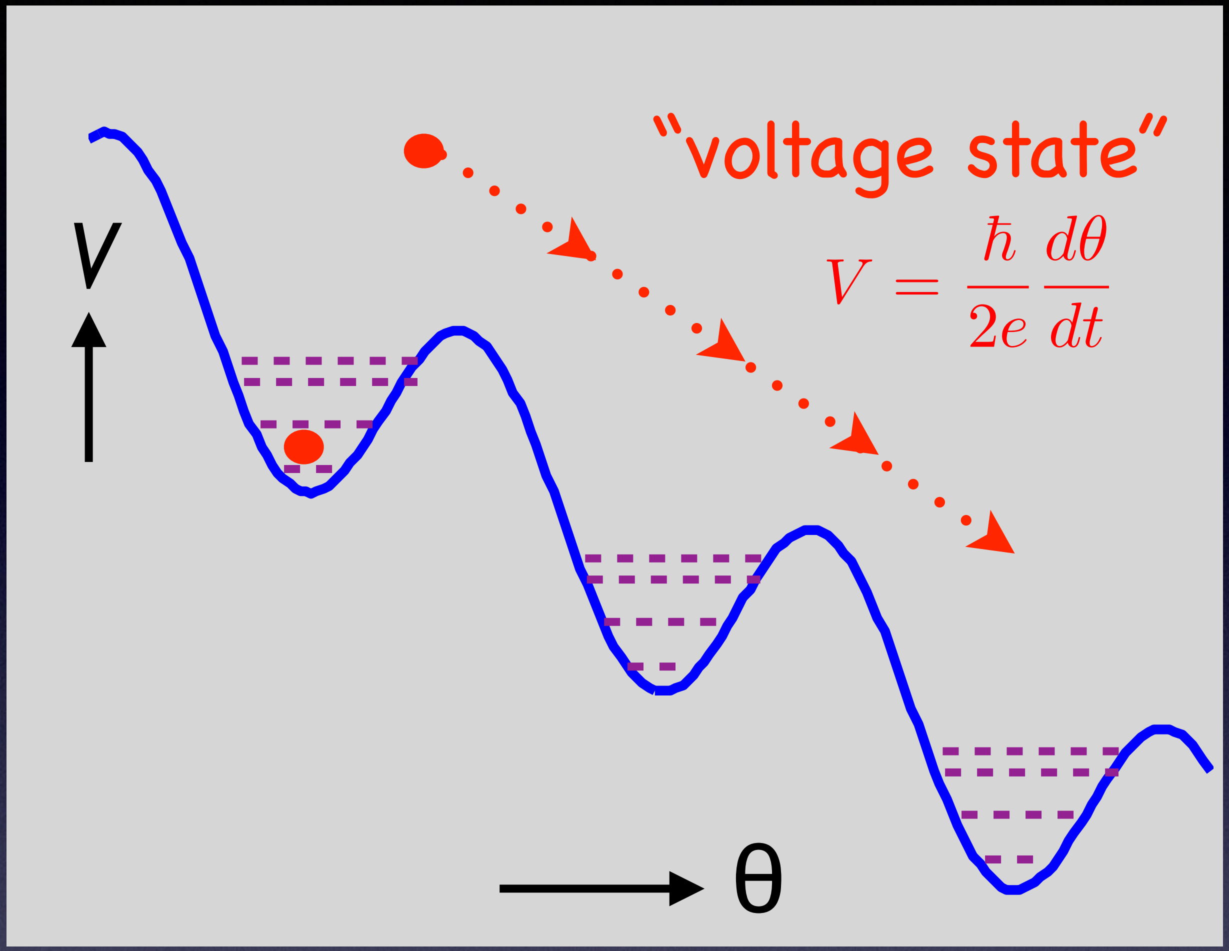
equation of motion (RCSJ model)

$$H = \frac{Q^2}{2C_J} - I_{\text{bias}}\theta - E_J \cos\theta$$



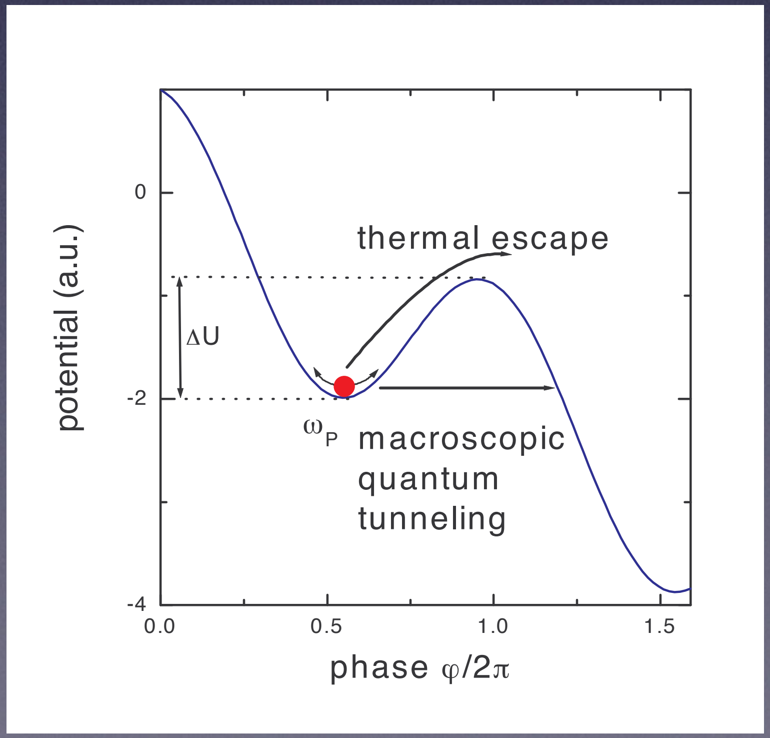
Macroscopic Quantum Tunneling of the phase (MQT) in the current-biased Josephson junction





$$H = \frac{Q^2}{2C_J} - I_{\text{bias}}\left(\frac{\Phi_0}{2\pi}\right)\theta - E_J\cos\theta$$

tilted washboard potential



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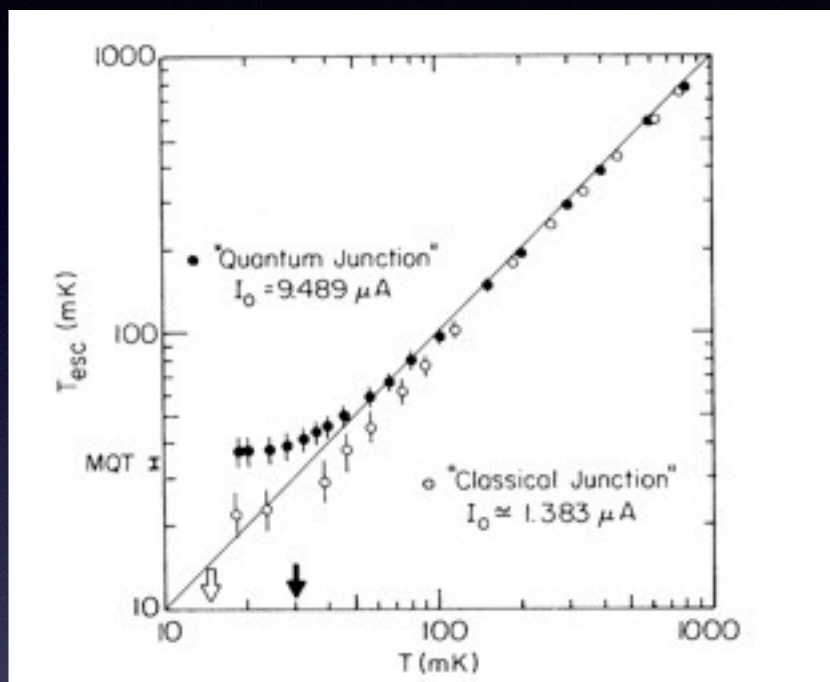
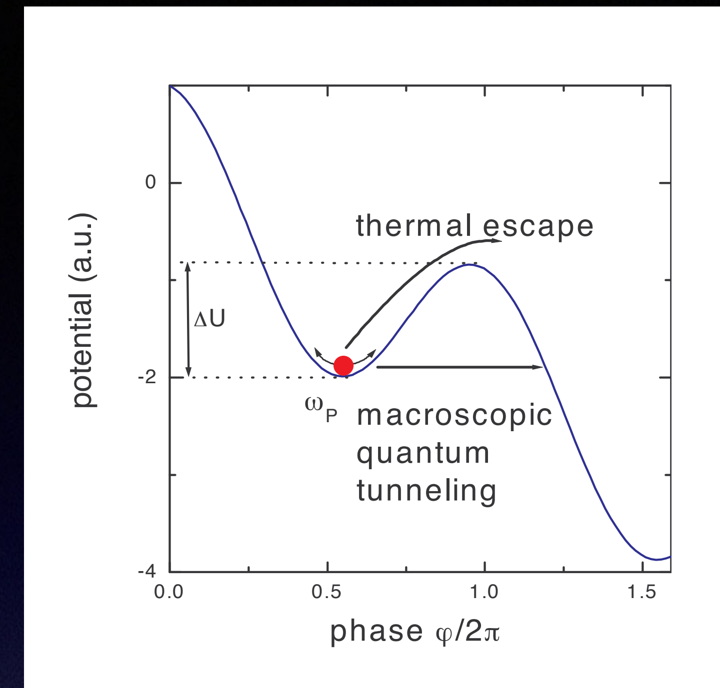
VOLUME 55, NUMBER 18 PHYSICAL REVIEW LETTERS 28 OCTOBER 1985

Measurements of Macroscopic Quantum Tunneling out of the Zero-Voltage State of a Current-Biased Josephson Junction

Michel H. Devoret,[a] John M. Martinis, and John Clarke
Department of Physics, University of California, Berkeley, California 94720, and Materials and Molecular Research Division, Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 26 July 1985)





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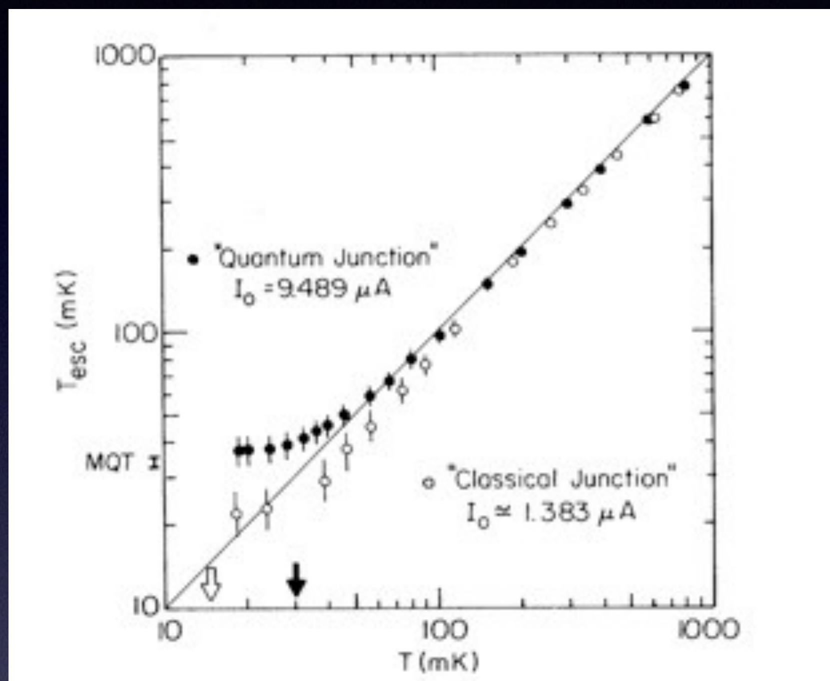

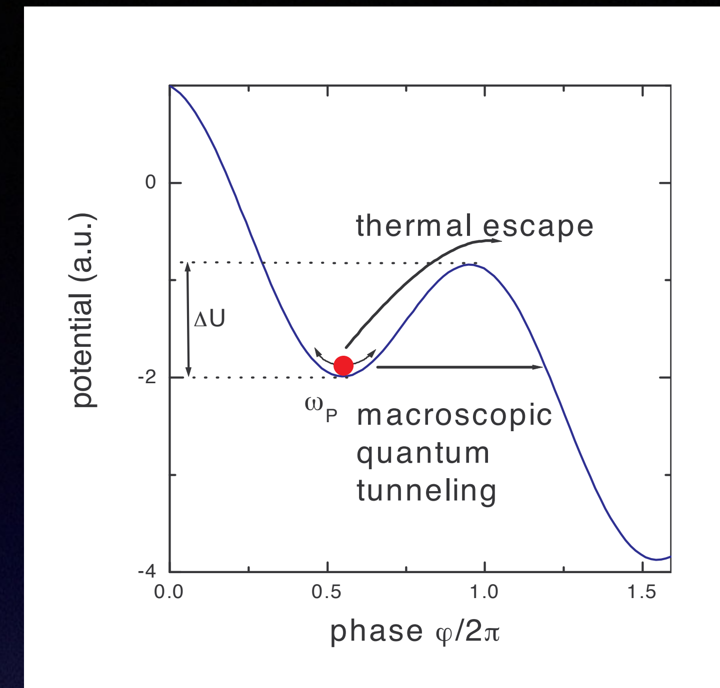

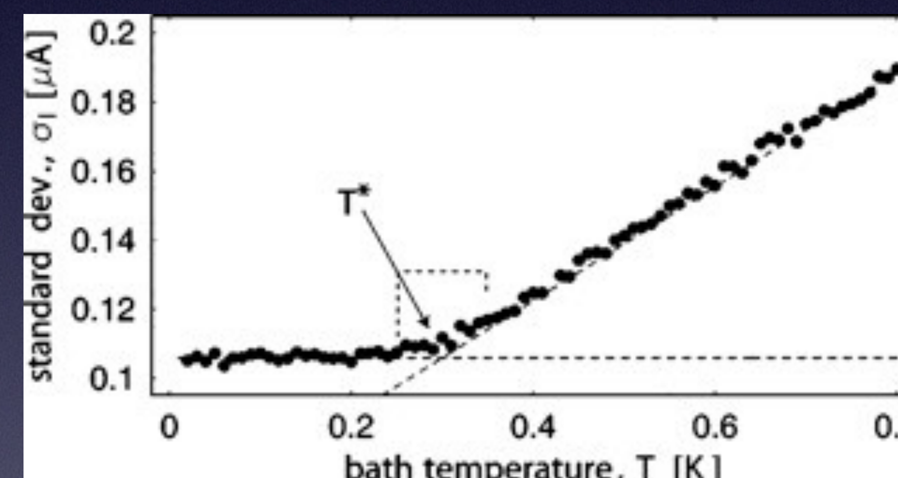

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 74, NUMBER 8 AUGUST 2003

Switching current measurements of large area Josephson tunnel junctions

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~Received 6 March 2003; accepted 21 April 2003

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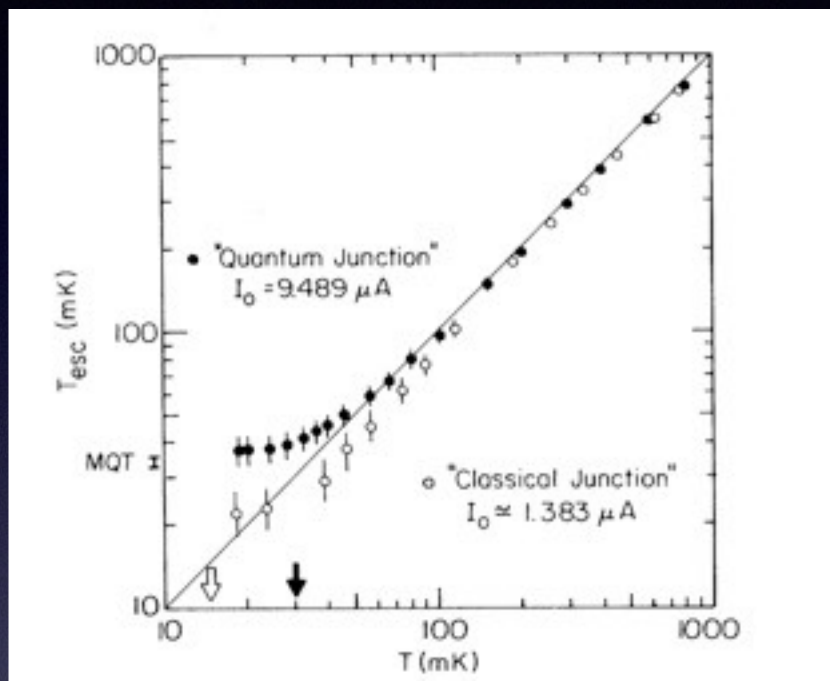

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VOLUME 90, NUMBER 3 PHYSICAL REVIEW LETTERS week ending 24 JANUARY 2003

Multiphoton Transitions between Energy Levels in a Current-Biased Josephson Tunnel Junction

A. Wallraff,* T. Duty,† A. Lukashenko, and A. V. Ustinov
Physikalisches Institut III, Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany
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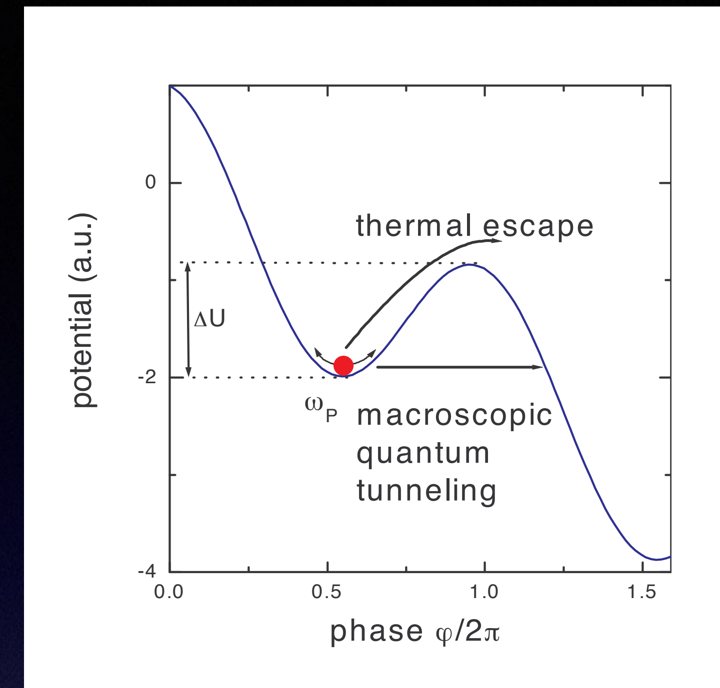
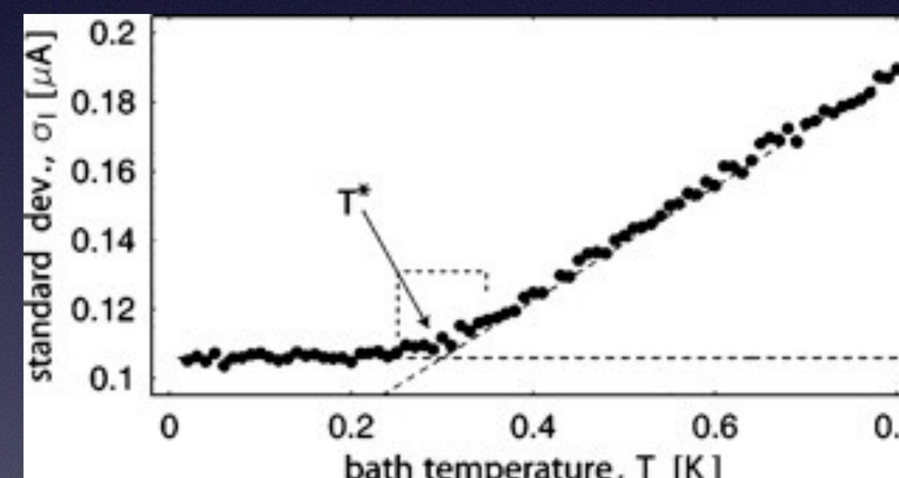
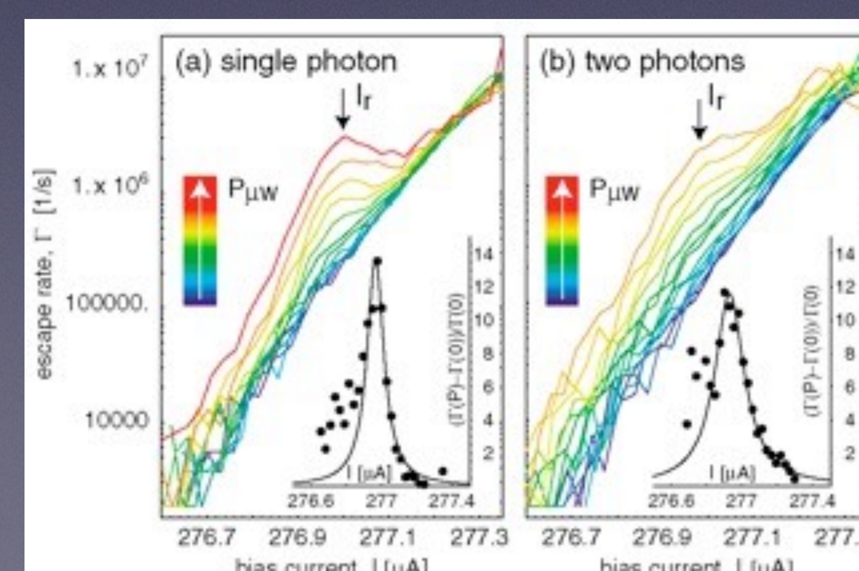
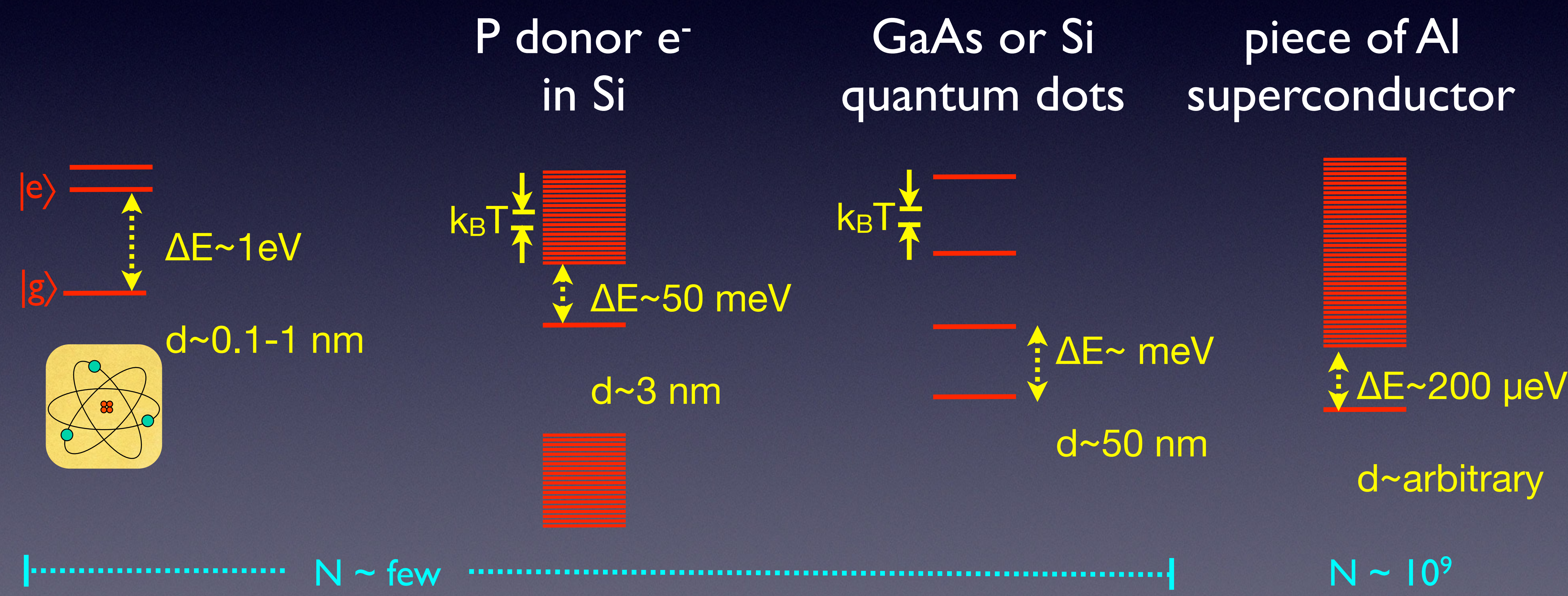




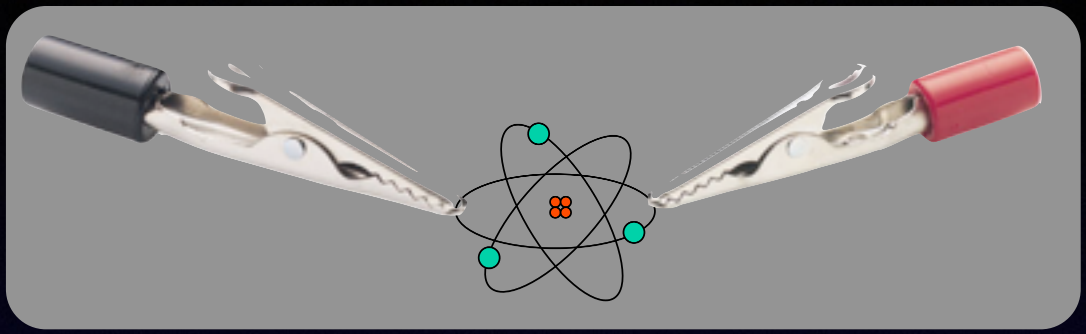


isolated "quantum" electronic levels in the solid state

atoms	solid state devices



Quantum Physics with Electrical Circuits



Further reading

"Quantum fluctuations in electical circuits"
Michel Devoret
Les Houches '95 (1997)

"Wiring up quantum systems"
R. J. Schoelkopf and S. M. Girvin
Nature **451**, 664 (2008)

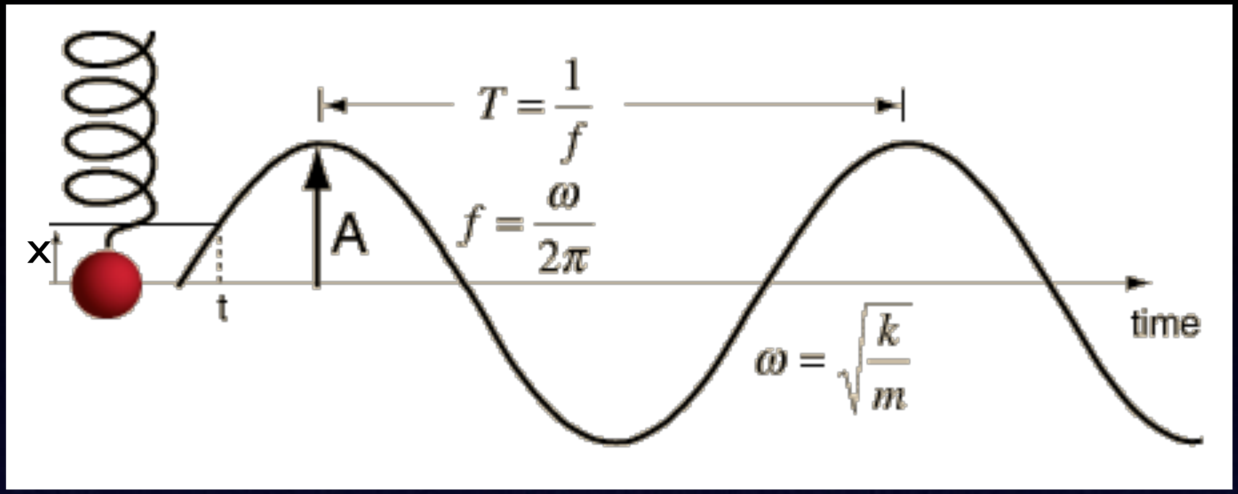
Quantum Engineering: Theory and Design of
Quantum Coherent Structures
by A. M. Zagoskin, Cambridge Univ. Press (2011)

"Superconducting quantum bits"
by John Clarke and Frank Wilhelm
Nature **453**, 1031 (2008)

"Superconducting circuits
and quantum information"
by J. Q. You and Franco Nori
Physics Today, November 2007

The harmonic oscillator (classical)

e.g. mass on a spring



linear restoring force $F = -kx$

Hamiltonian (K.E. + P.E.)

$$H = \frac{p^2}{2m} + \frac{kx^2}{2}$$

quadratic K.E. and P.E.

equation of motion $\ddot{x} + \frac{k}{m} x = 0$

or $\ddot{x} + \omega_0^2 x = 0$

solutions $x(t) = A\cos(\omega_0 t) + B\sin(\omega_0 t)$

or $x(t) = C\cos(\omega_0 t + \phi_0)$

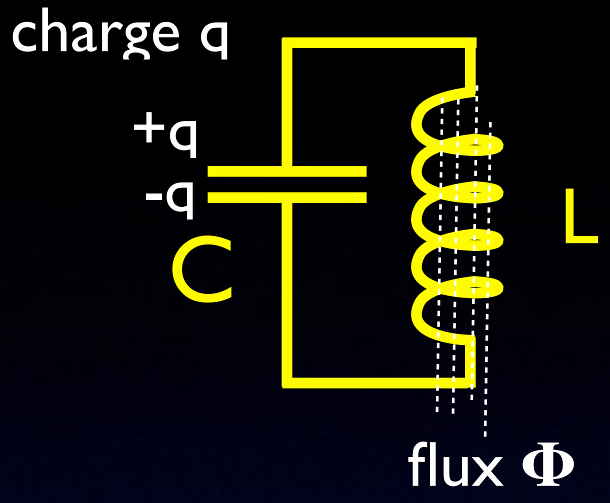
two linearly independent solution's

A linear system - the sum of any two solutions is also a solution

True also with "linear" dissipation, *i.e.*

$$\ddot{x} - \gamma \dot{x} + \omega_0^2 x = 0 \longrightarrow x(t) = Ae^{-\gamma t}\cos(\omega_0 t) + Be^{-\gamma t}\sin(\omega_0 t)$$

LC-circuit harmonic oscillator (classical)



Hamiltonian (K.E. + P.E.)

$$H = \underbrace{\frac{q^2}{2C}}_{\text{K.E.}} + \underbrace{\frac{\Phi^2}{2L}}_{\text{P.E.}}$$

$$\omega = 1/\sqrt{LC}$$

Can choose which one to be "potential energy"
and which to be "kinetic energy"

analogy between mechanical and electrical systems

Electrical	Mechanical
charge q	momentum p
voltage $V=q/C$	velocity $v=p/M$
capacitance C	mass M
flux Φ	coordinate x
inverse inductance L^{-1}	spring constant k
LC-circuit	mass on spring

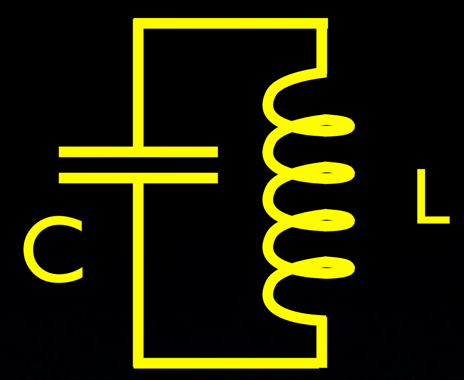
Equivalent to
mass on a spring

recall...

$$H = \frac{p^2}{2m} + \frac{kx^2}{2}$$

Quantizing the LC oscillator

(using charges and fluxes)



LC oscillator $\omega = 1/\sqrt{LC}$

$$H = T + V = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

normalized variables: $Q = 2en, \Phi = \phi_0 \phi$

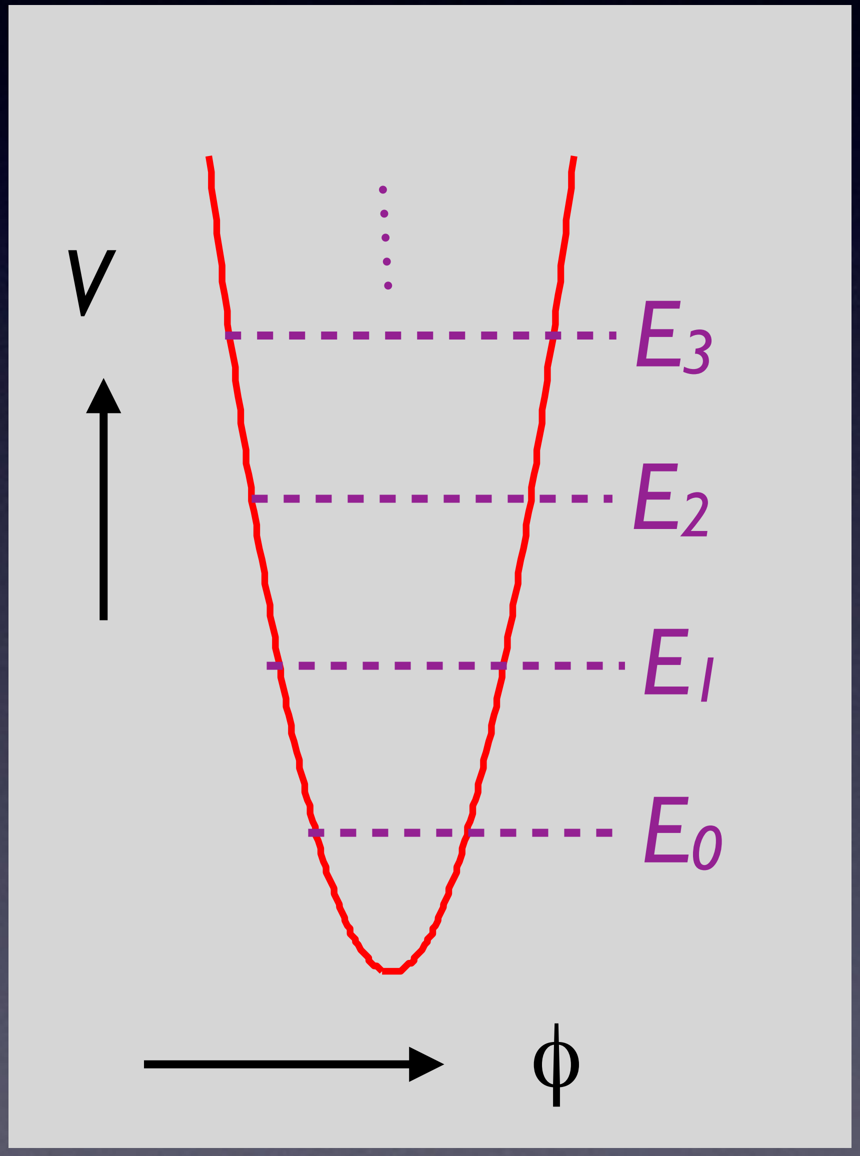
elementary charge e

flux quanta ϕ_0 $\quad \phi_0 \equiv \frac{h}{2e}$

quantization $\Rightarrow$ operators $[n, \phi] = i$

$$\boxed{H = E_C n^2 + E_L \phi^2 = \hbar\omega a^\dagger a + 1/2}$$

$$E_C = \frac{(2e)^2}{2C} \quad E_L = \frac{\phi_0^2}{2L} \quad \hbar\omega = \sqrt{2E_C E_L}$$



harmonic oscillator
equidistant levels

- Linearity --- a special property of quadratic Hamiltonians...e.g. the “ideal” harmonic oscillator
- Quantum levels are equidistant
- Response to perturbation is linear

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What about “real’ systems? Many are “non-linear”

• Linearity --- a special property of quadratic Hamiltonians...e.g. the “ideal” harmonic oscillator

• Quantum levels are equidistant

• Response to perturbation is linear

What about “real’ systems? Many are “non-linear”

• real springs harden or soften with stretching

• equivalently, inductors and capacitors can depend on voltage and current and frequency

• atomic systems (and quantum dots) have strong confinement potentials

Non-linear (non-quadratic) Hamiltonian systems

Classical mechanics → nonlinear dynamical systems
Quantum mechanics (time-independent) → non-equidistant levels

- Without non-linearities Quantum Mechanics would be quite trivial, nearly irrelevant, and even boring....

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Non-linearity in electrical circuits

- transistors and other semiconductor devices
- vacuum tubes
- iron core inductors
- transformers when operated above their saturation current

All come with substantial dissipation

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Non-linearity in electrical circuits

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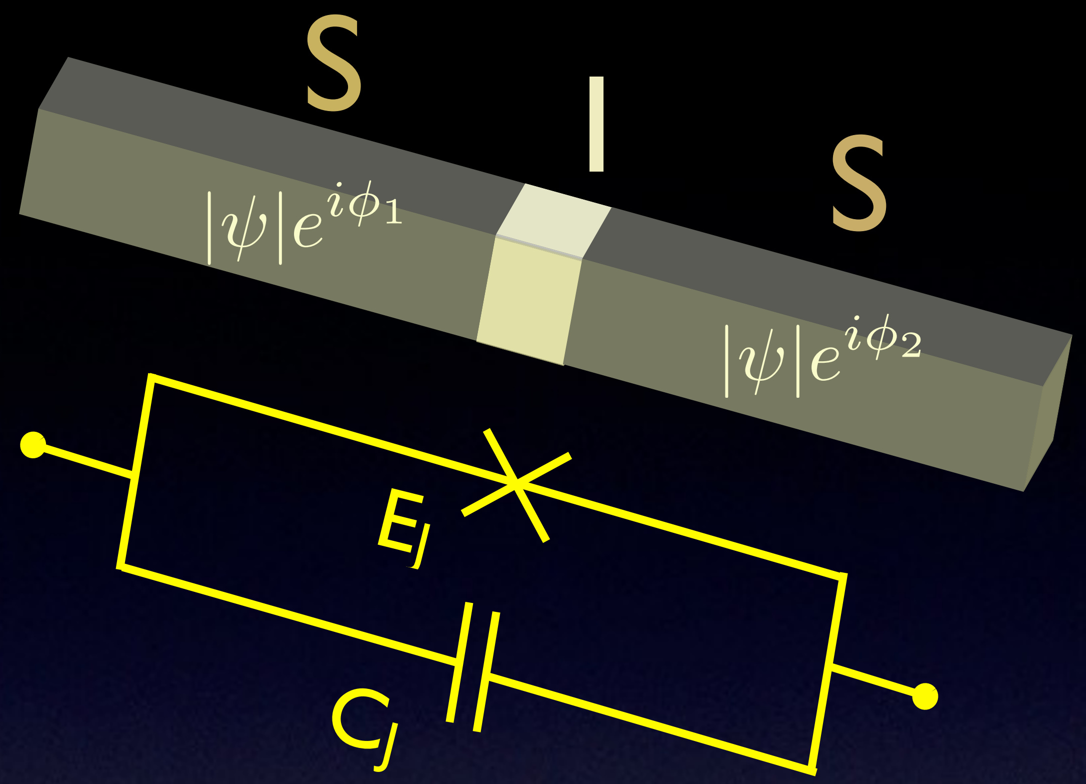
All come with substantial dissipation

The Josephson junction is a non-linear circuit element with (practically) zero dissipation!

The Josephson junction

$$H = E_C n^2 + E_J \cos\phi$$

$$[\phi, n] = i$$

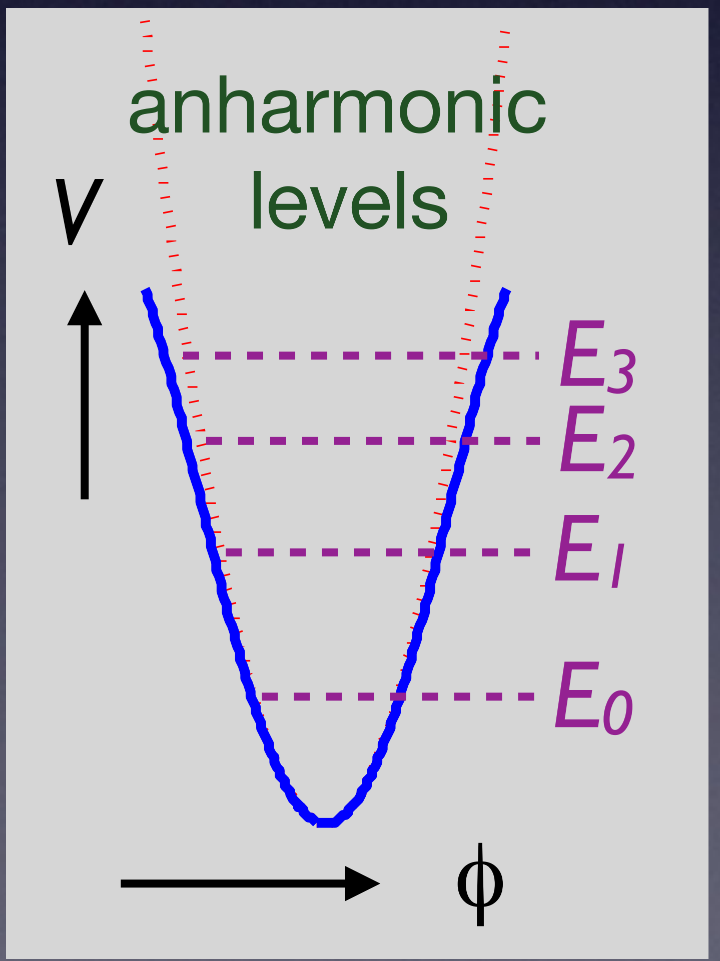


non-linear inductor when embedded in a circuit such that quantum fluctuations of ϕ are small

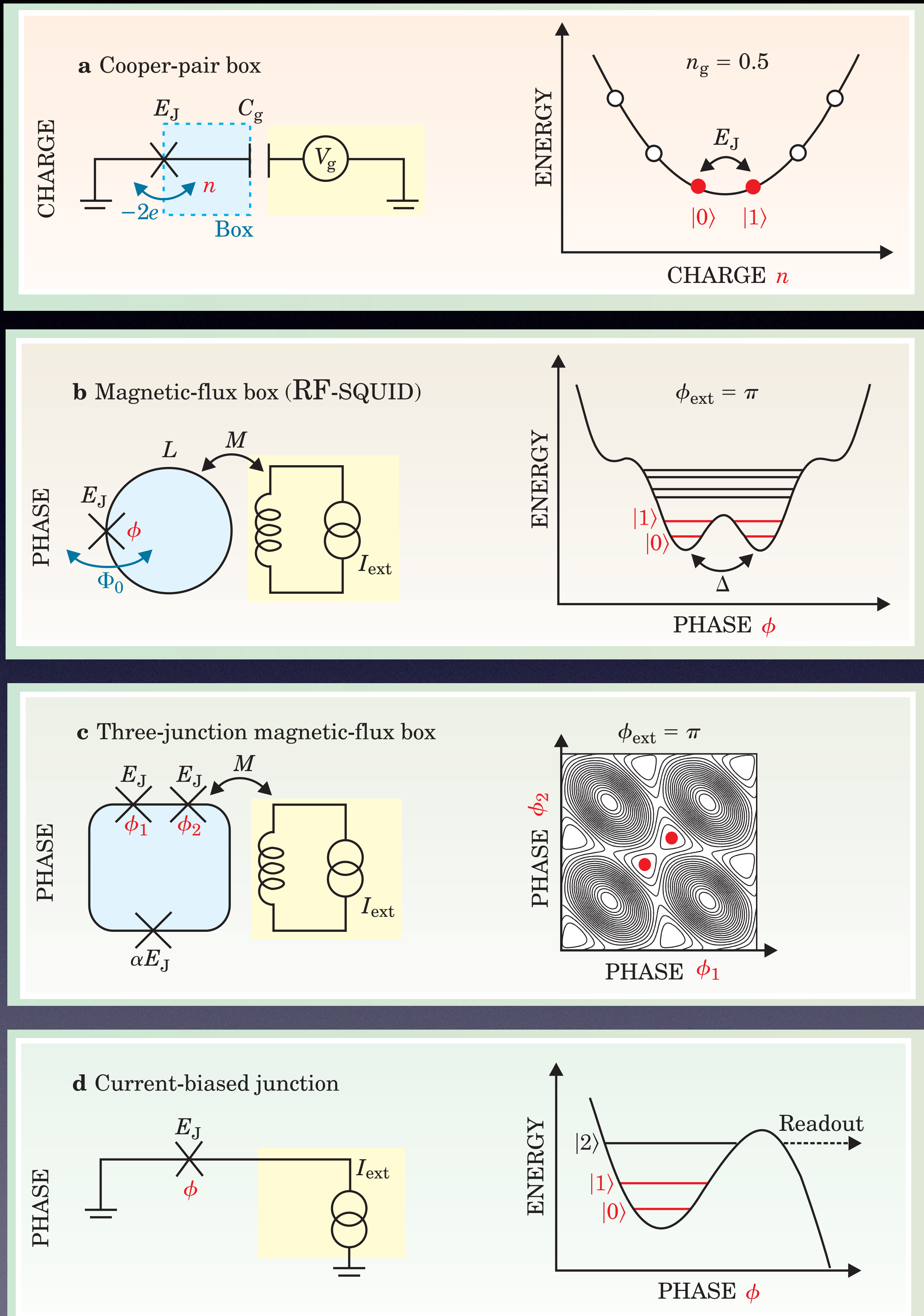
$$E_C \ll E_J$$

For $E_C \gg E_J \implies$ single charge devices

But important to consider both geometry and energy scales



Flavours of s.c. qubits



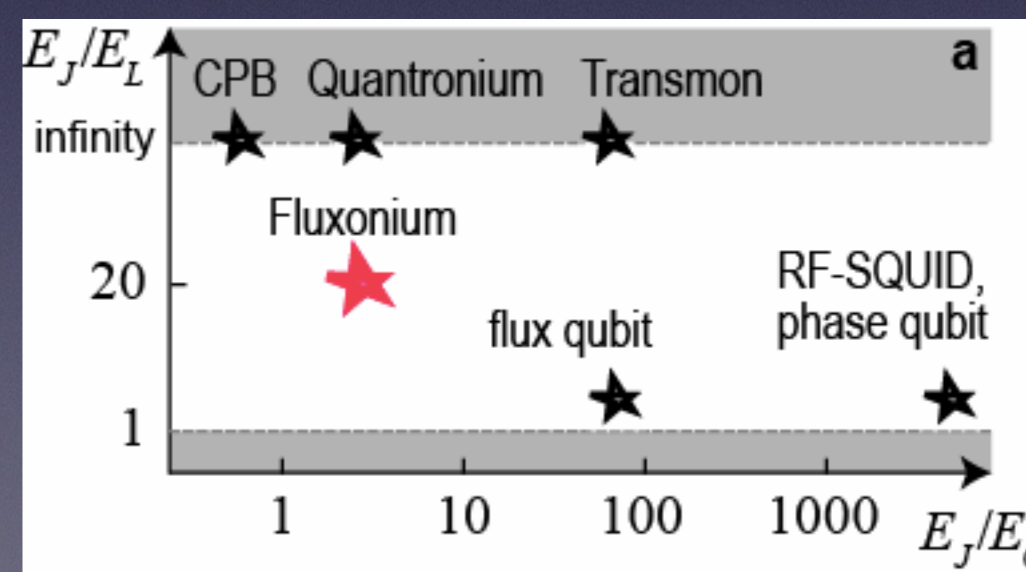
J. Q. You and Franco Nori, Physics Today, November 2007

three energy scales

E_J Josephson energy

$$E_C = \frac{e^2}{2C}$$ charging energy

$$E_L = \left(\frac{\hbar}{2e}\right)^2 \frac{1}{2L}$$ inductive energy



Manucharyan, *et al.* 2009

quantum experiments with Josephson-junction devices

- available sub-micron fabrication of Al down to ~10 nm scale using EBL provides electronic energy scales up to ~ 100 μeV (1K)

- electrical control and readout with above 50 GHz becomes difficult and expensive

To reach quantum ground state one needs to cool to milli-K or use active cooling methods

some important numerical factors:

1 K = 20.8 GHz = 86.2 μeV
= 14.3 mm free space em wavelength
= 0.93 fF single electron charge
= 740 mT free electron spin

The Dilution Refrigeration

- Liquid He bath or pulse tube cooling to ~3-4.2K

- $^3He/^4He$ dilution stage cooling to mK temperatures only possible due to quantum statistics
(finite concentration of ^3He in ^4He at T=0 a property of this "quantum liquid")

- Alternative: adiabatic demagnetization

see *Experimental Principles and Methods Below 1 K*, by O.V. Lounasmaa

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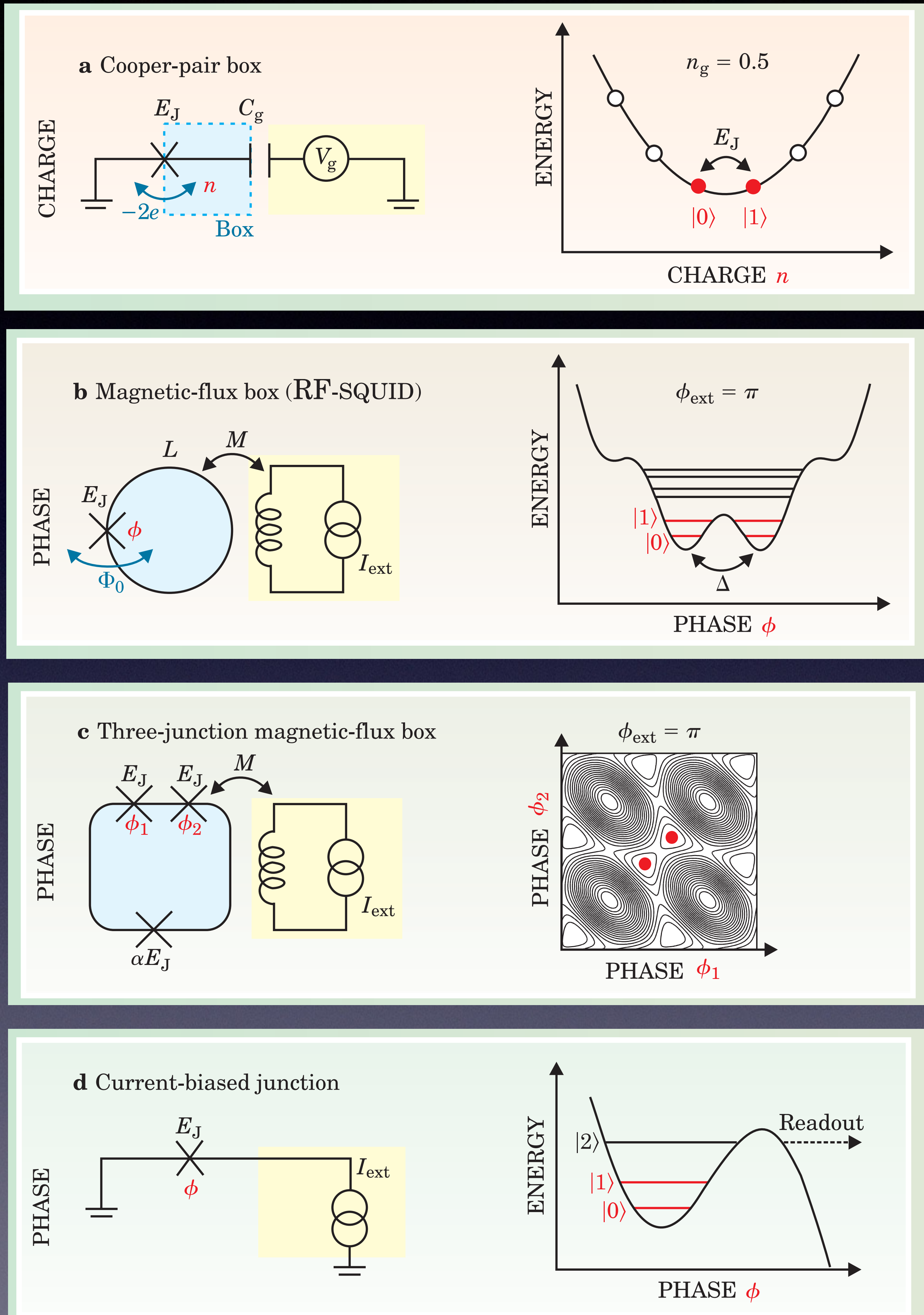

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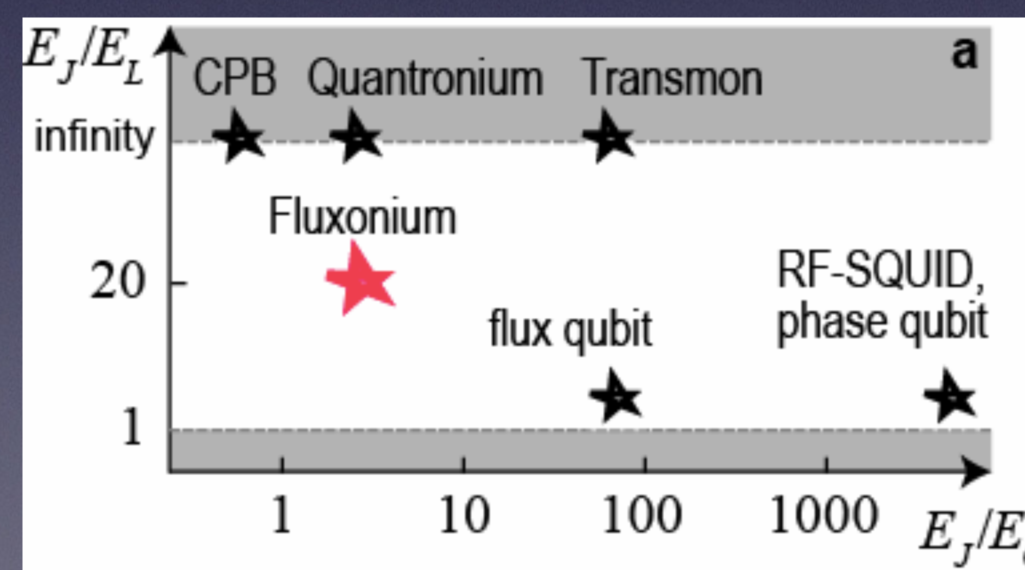
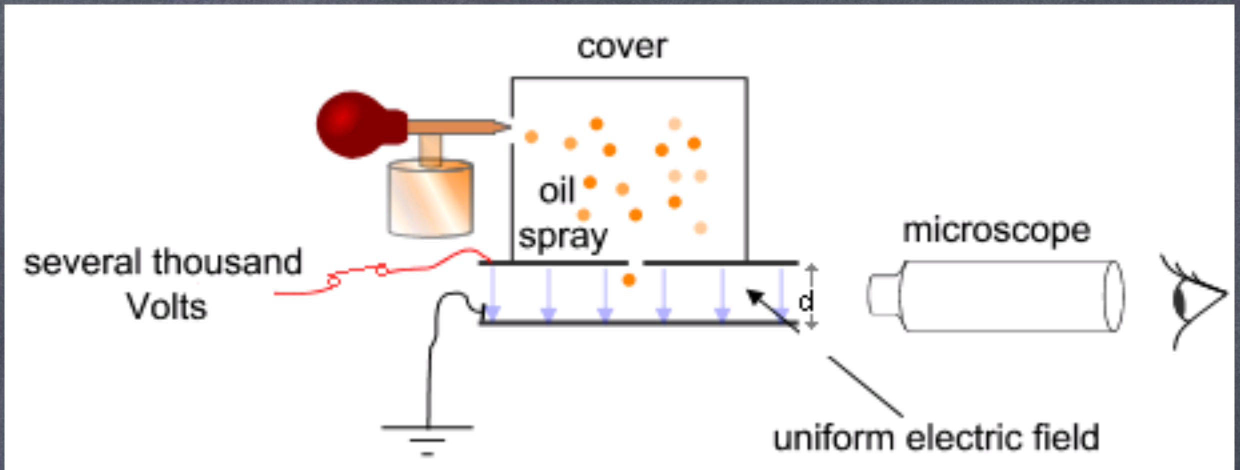


Manucharyan, *et al.* 2009

Single Charge Devices

a brief history



- Millikan's oil drops (1911)
- Single electron tunneling in solids (thin films, averaging over small grains)
  - Gorter (1951), Giaever and Zeller (1968) Lambe and Jaklevic (1969)
  - Theory: Kulik and Shekhter (1975)
- Nanolithography and thin-film processing
  - Fulton and Dolan (1989), first single-electron transistor
  - Lots of work on single-electron tunneling circuits 1990's
  - The Cooper-pair box realized, Bouchiat et al.(1997)
  - Quantum dynamics in the time domain, Nakamura et al. (1999)

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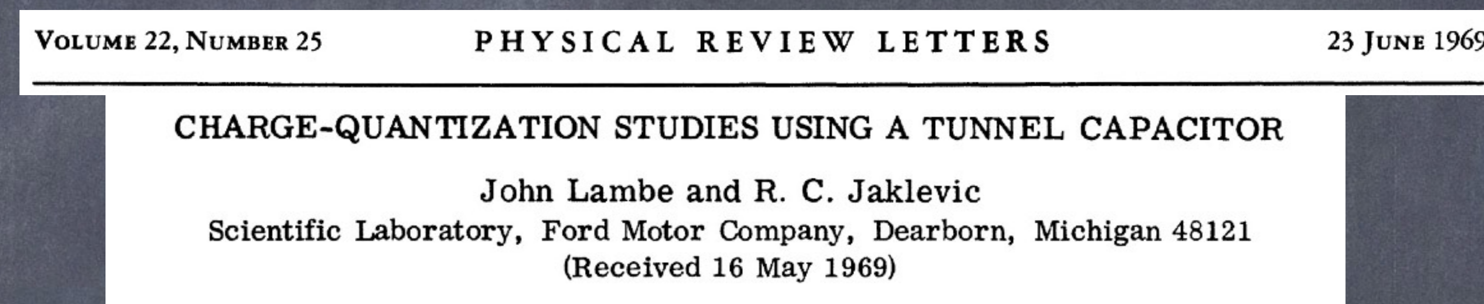
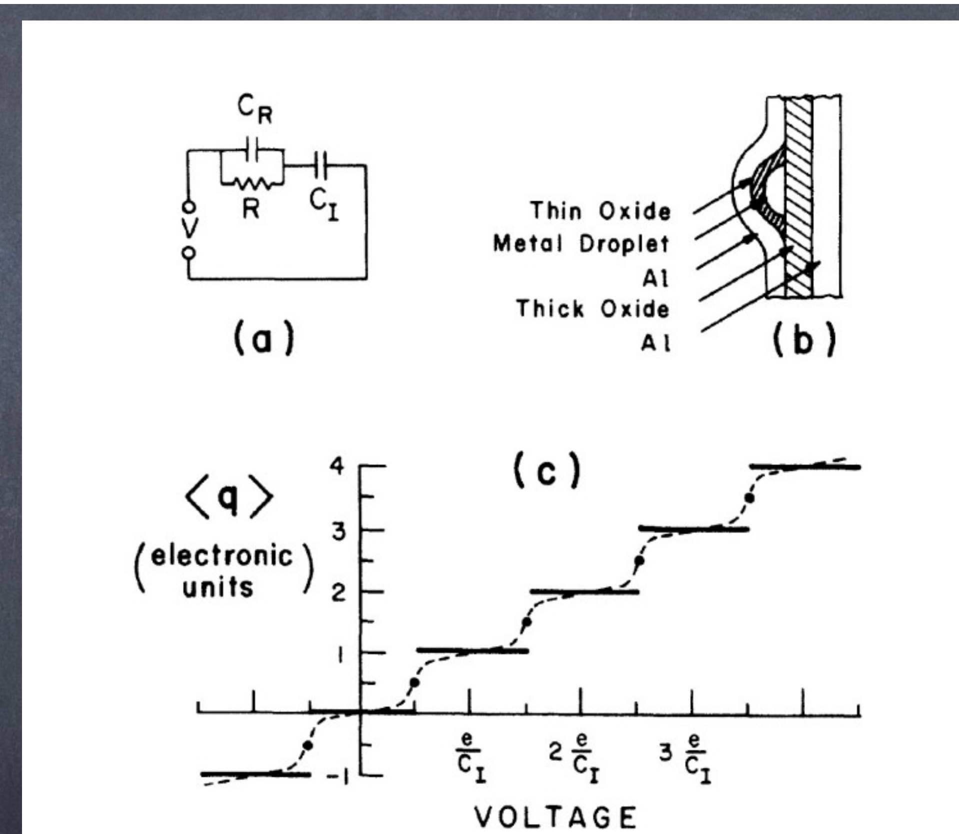


VOLUME 22, NUMBER 25 PHYSICAL REVIEW LETTERS 23 JUNE 1969

CHARGE-QUANTIZATION STUDIES USING A TUNNEL CAPACITOR

John Lambe and R. C. Jaklevic
Scientific Laboratory, Ford Motor Company, Dearborn, Michigan 48121
(Received 16 May 1969)



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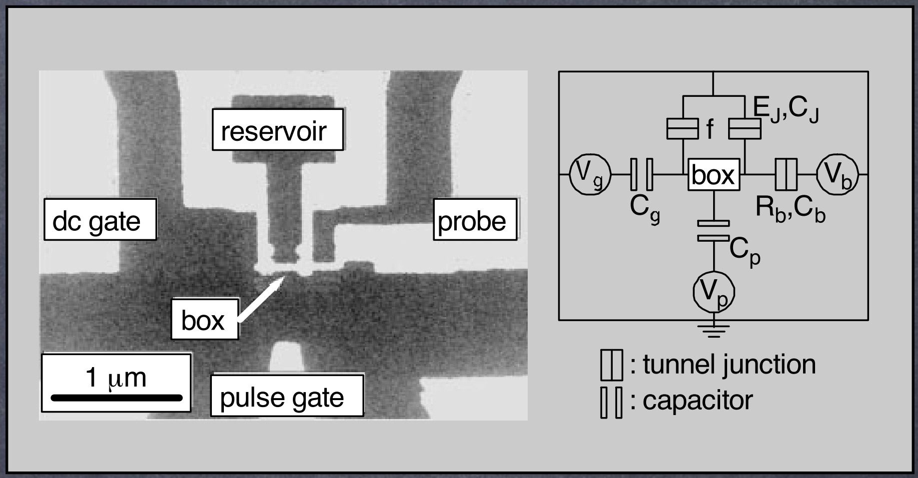
Nakamura et al. Nature 1999



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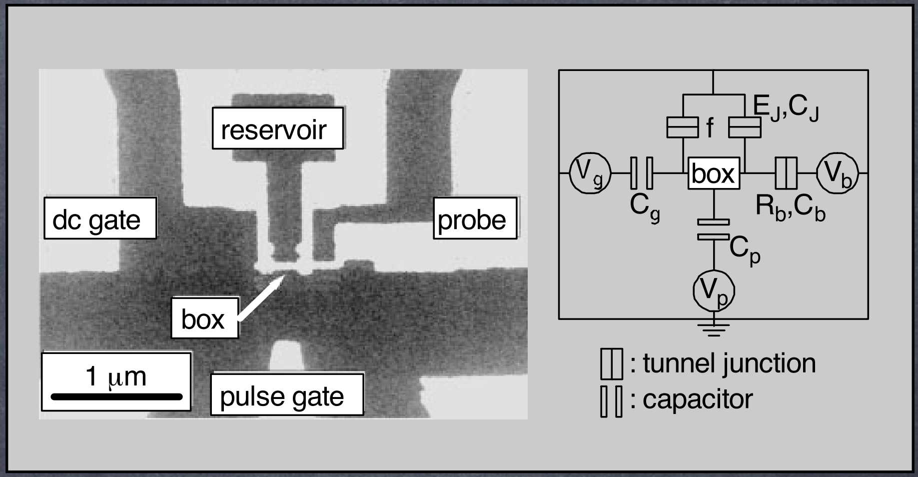
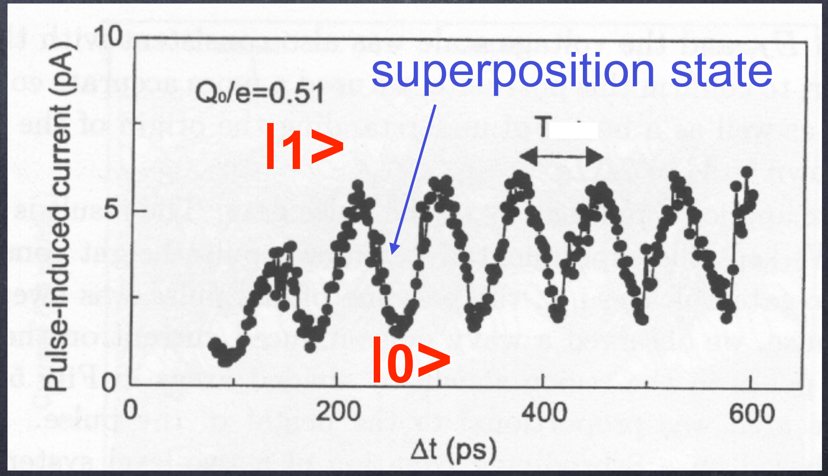


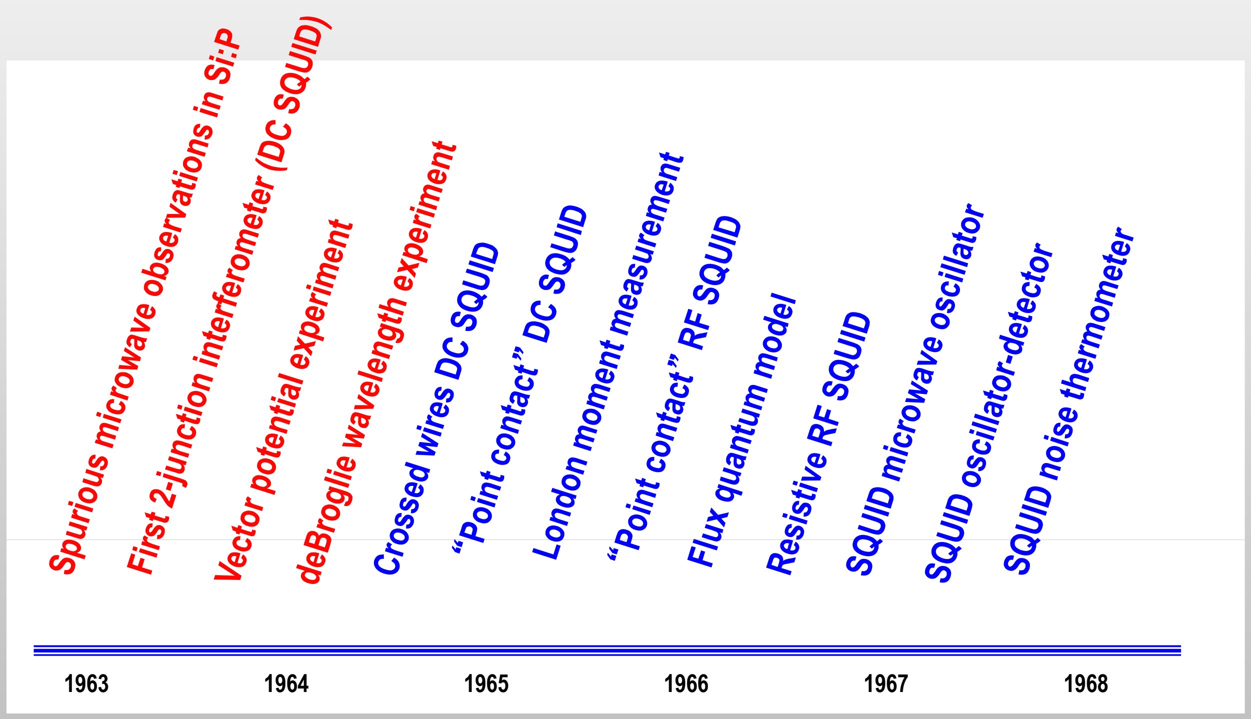


Ford Scientific Lab

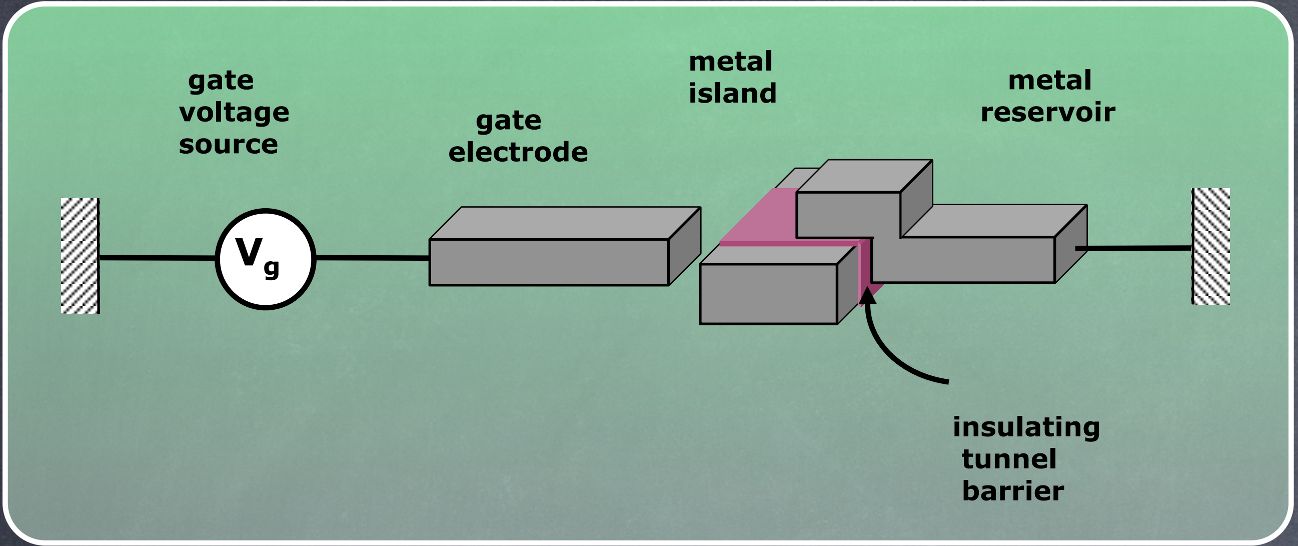
Lambe, Zimmerman, Silver, Jaklevic, Mercereau

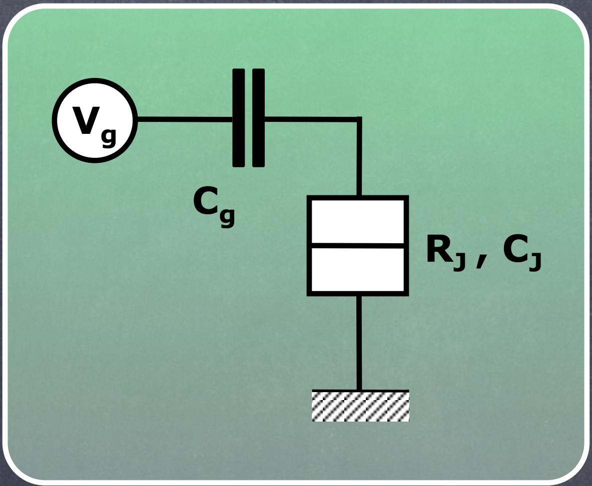
SQUID Evolution Summary

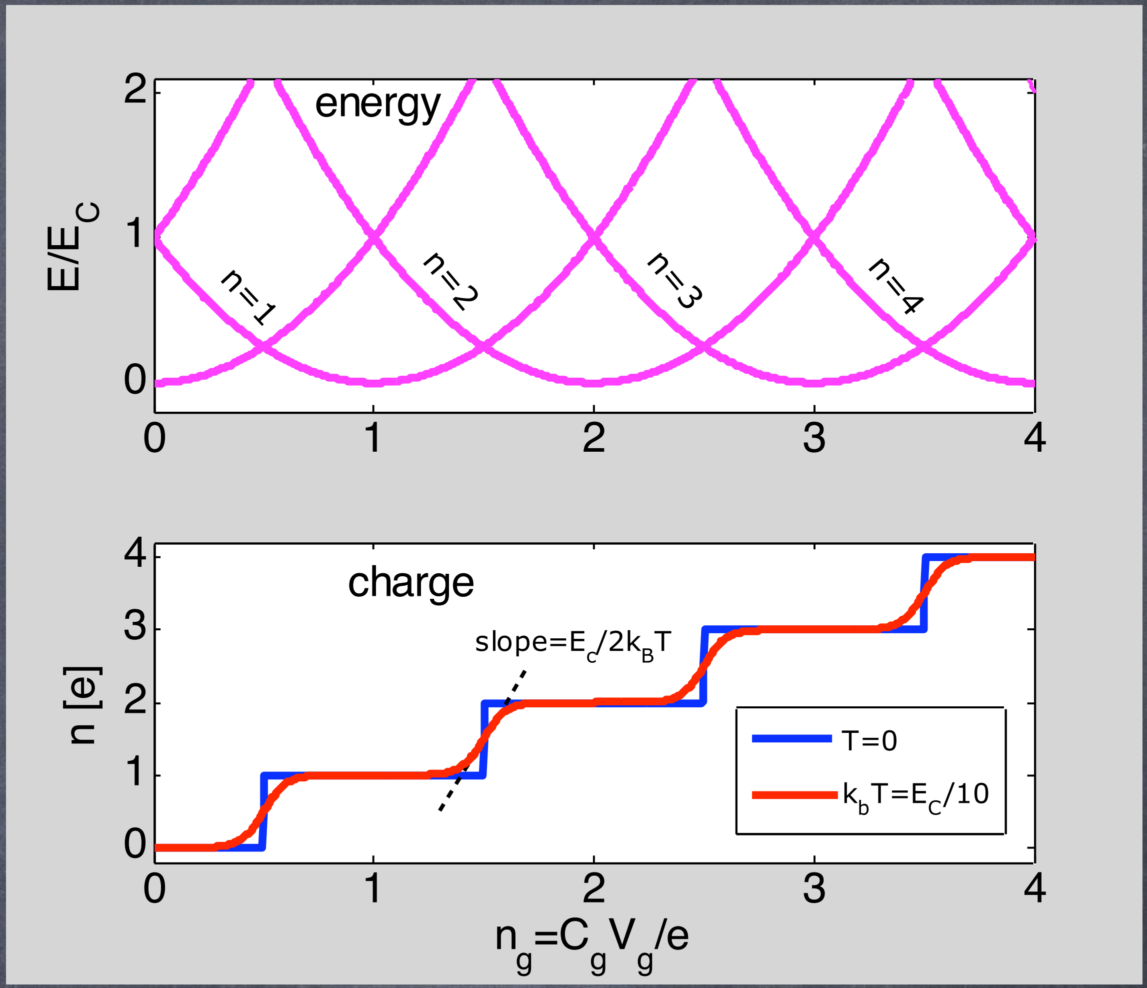
Ford Motor Company Scientific Laboratory



The single-electron box







$$E_{el} = \frac{e^2}{2C_{box}}(n-n_g)^2 = E_C(n-n_g)^2$$

$$E_C \equiv \frac{e^2}{2C_{box}} \qquad C_{box} = C_g + C_J$$

reduced (dimensionless) gate voltage: $$n_g = C_g V_g / e$$

When $E_C >> k_BT$ and $R_J > R_K = 26k\Omega$
Can polarize the island by 1 extra electron/hole in ~10^9-10^{10}

note: n-parabolas are min E,
i.e. there is a continuum of particle-in-a-box states for each n

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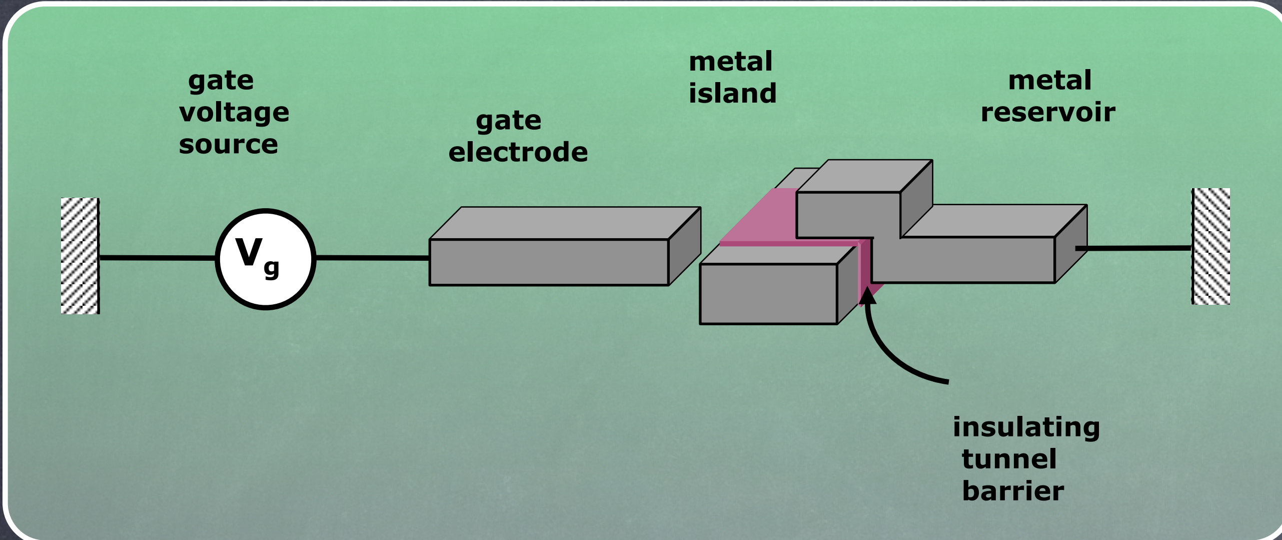

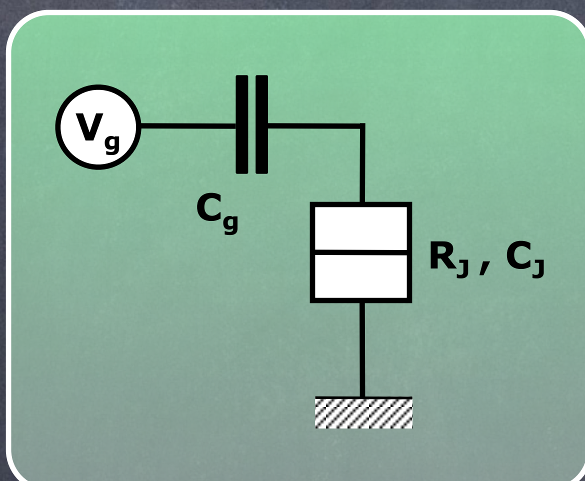

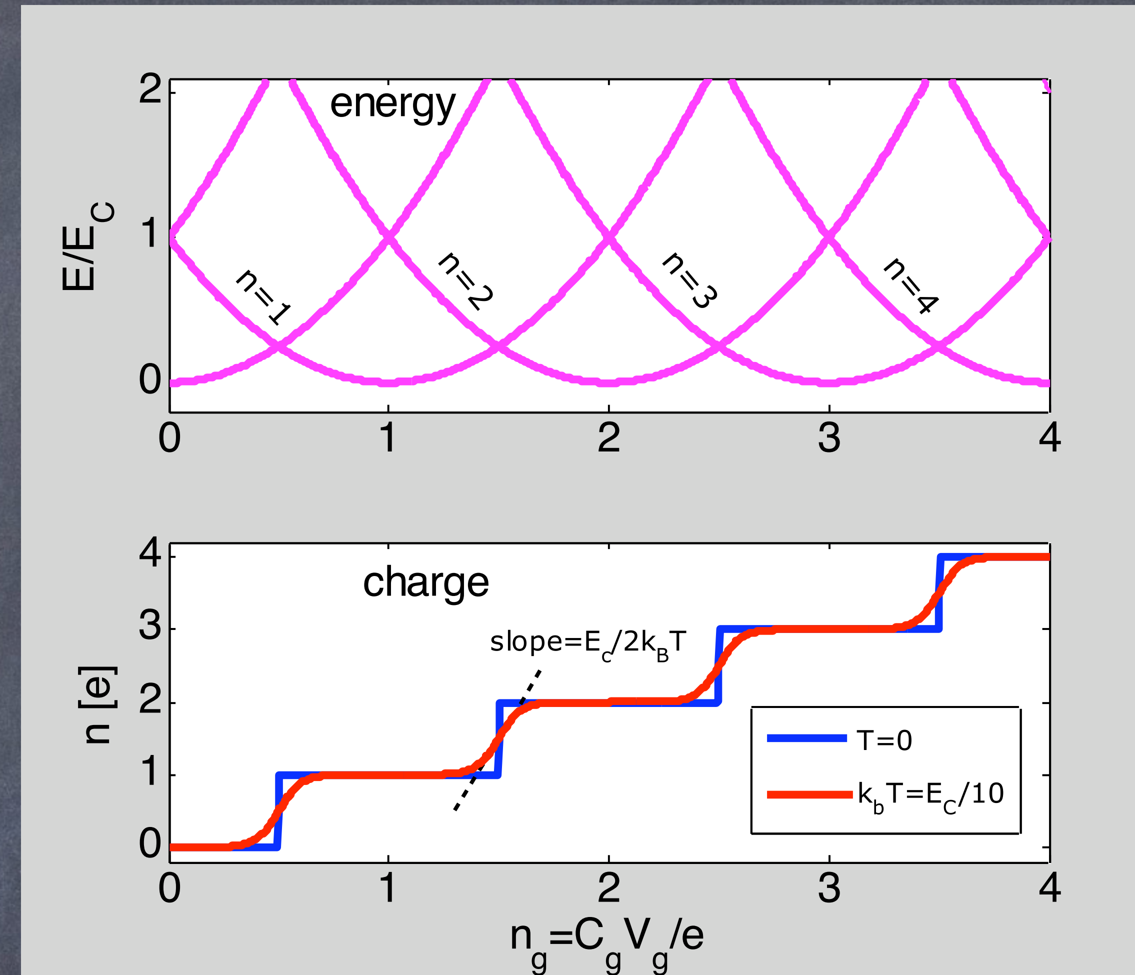

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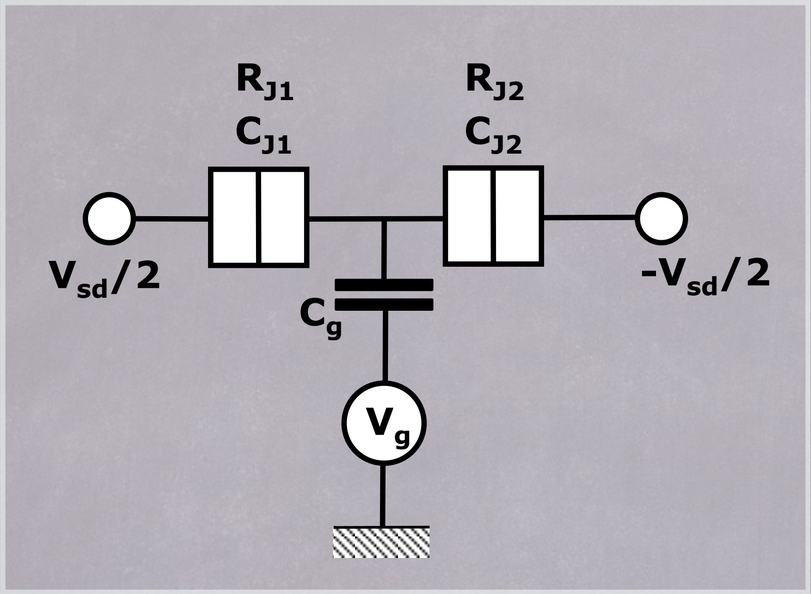
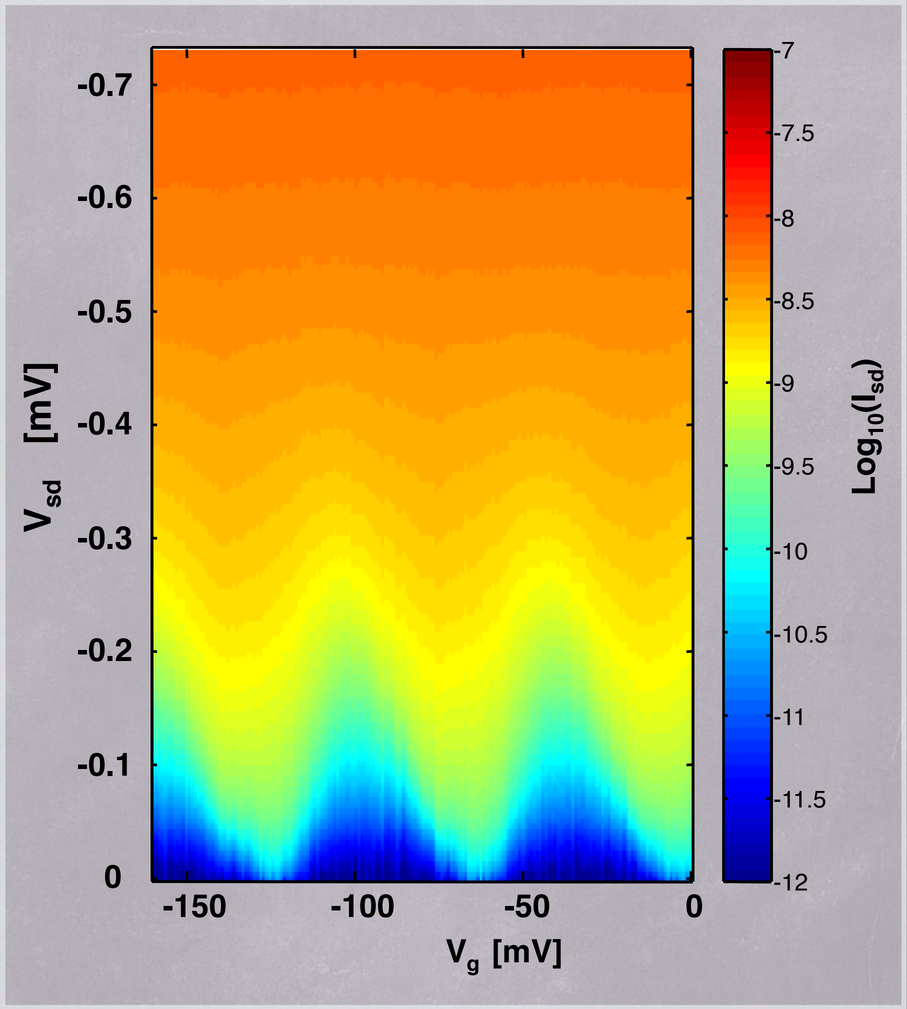
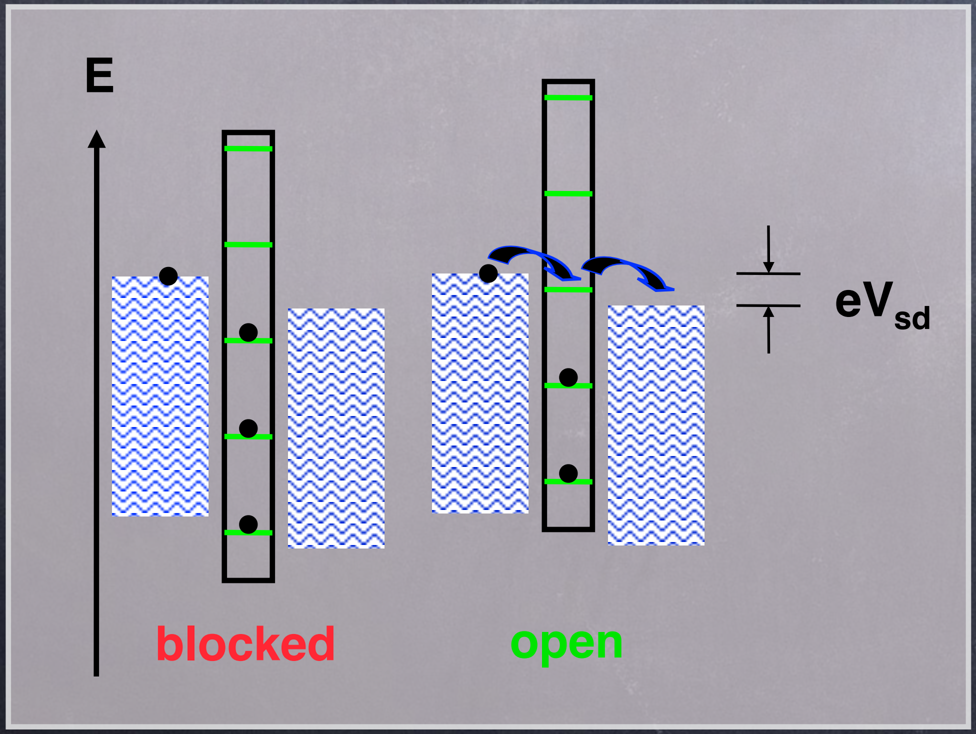
But how do can we measure sub-e charge differences?

The single-electron transistor

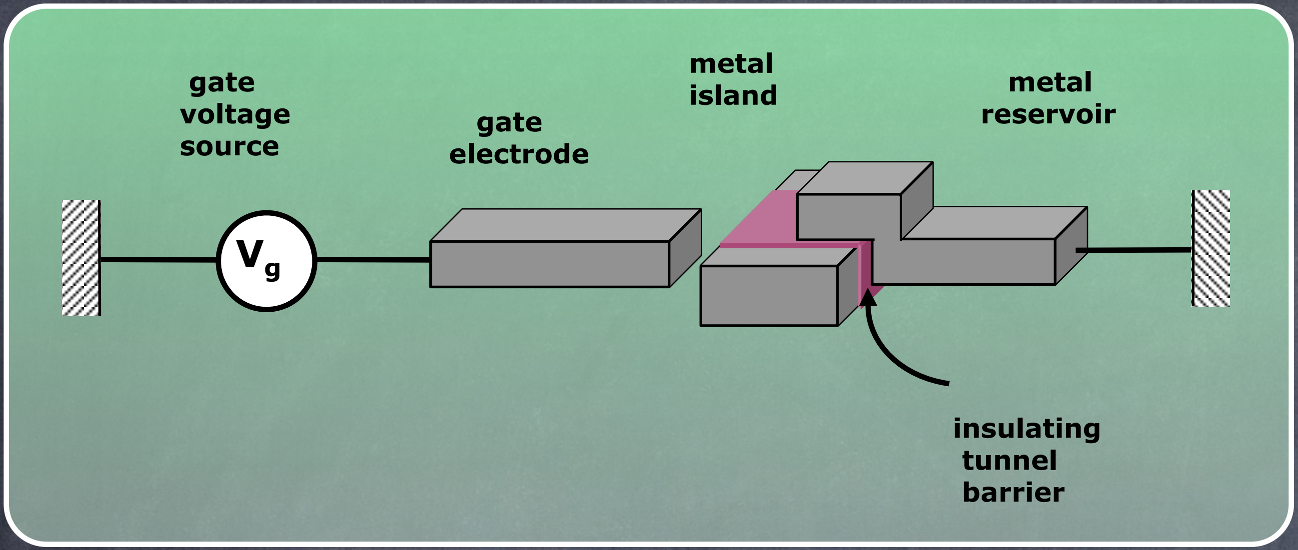


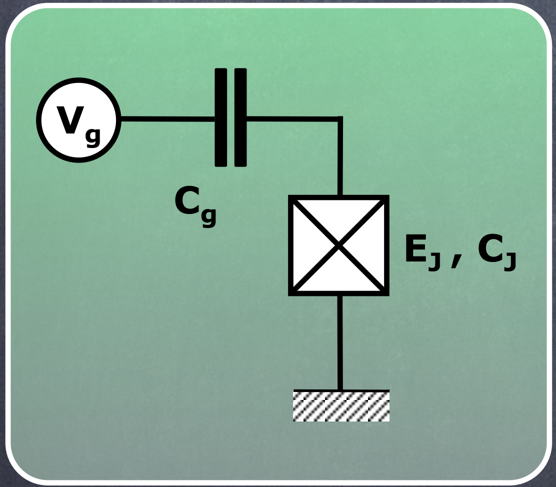




- Enables one toconstruct a very sensitive electrometer
- Can resolve small fractions of induced charge ~0.001e

The basic Cooper-pair box





- With aluminium one naturally has a Cooper-pair box and turns it into a single-electron box using a magnetic field to kill superconductivity

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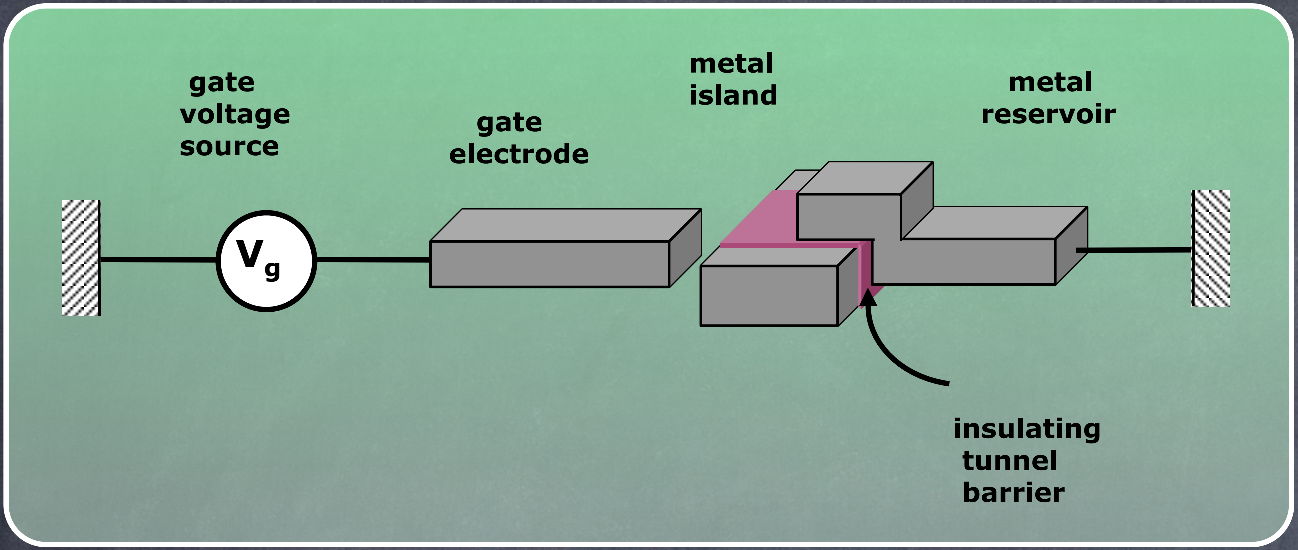

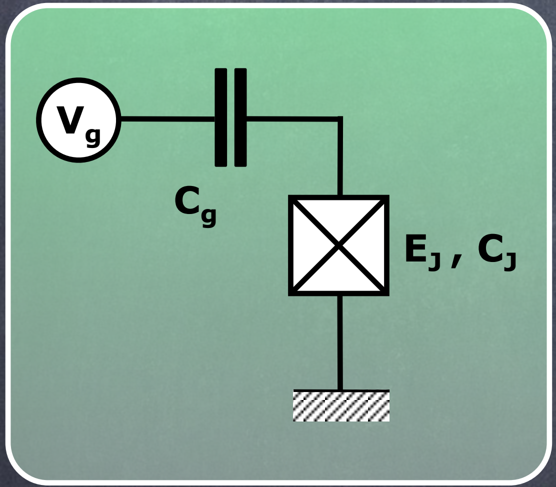

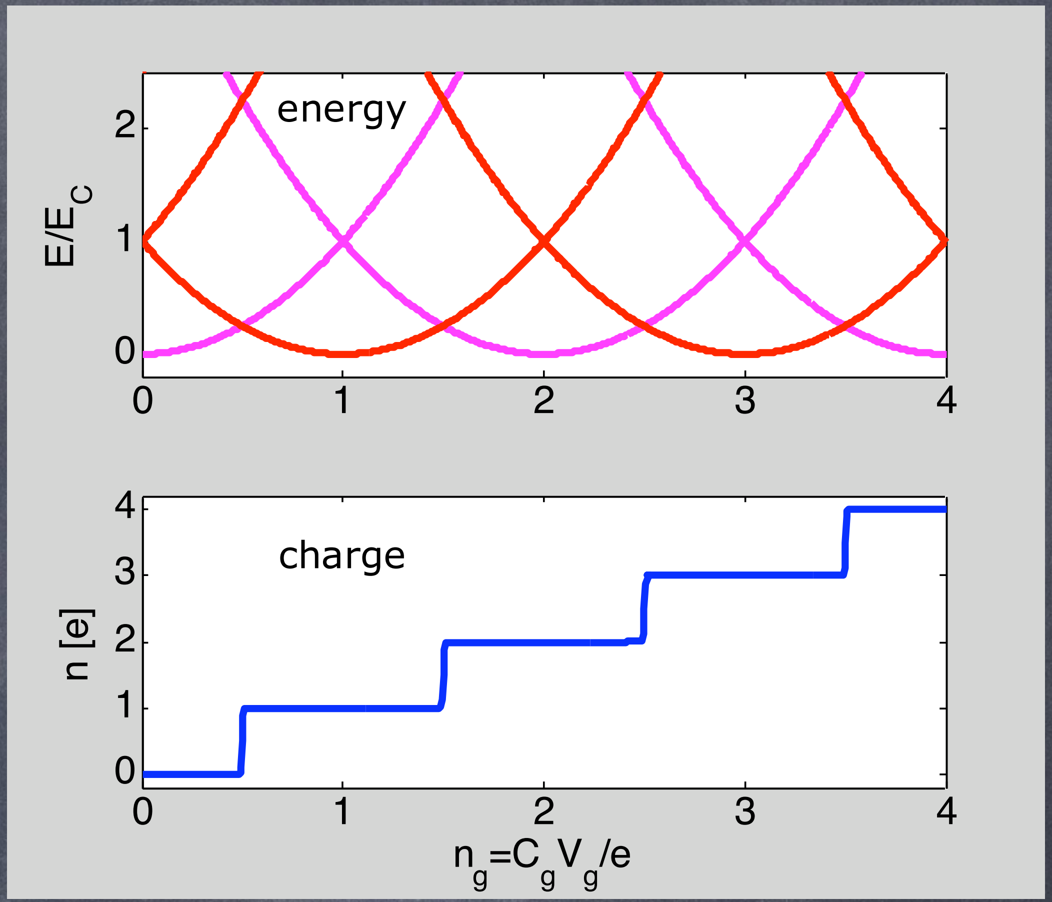

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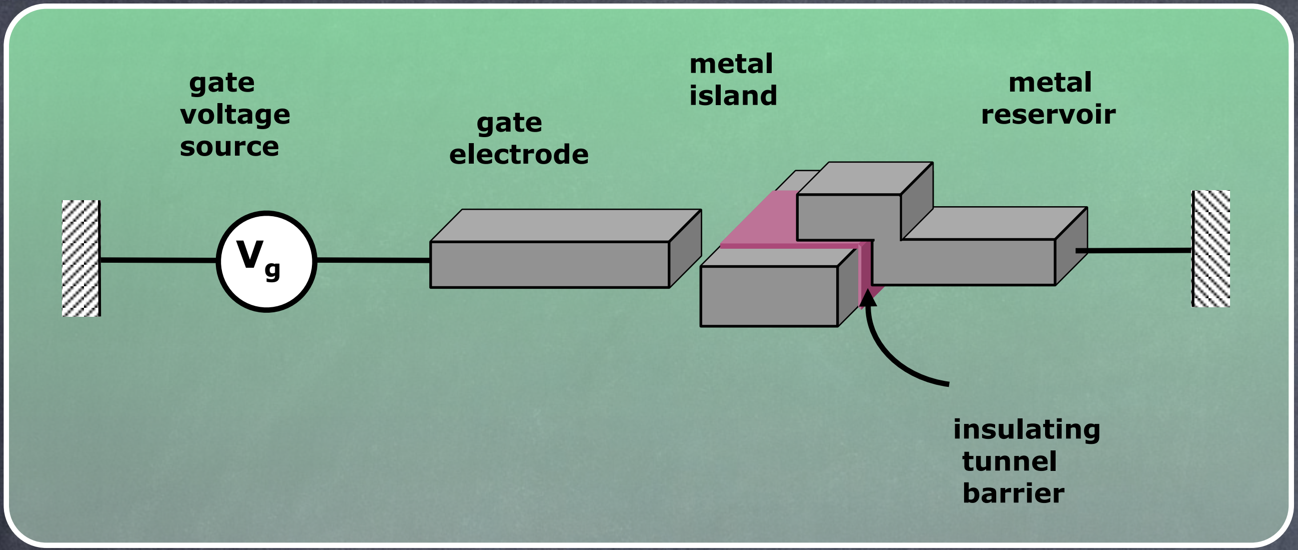

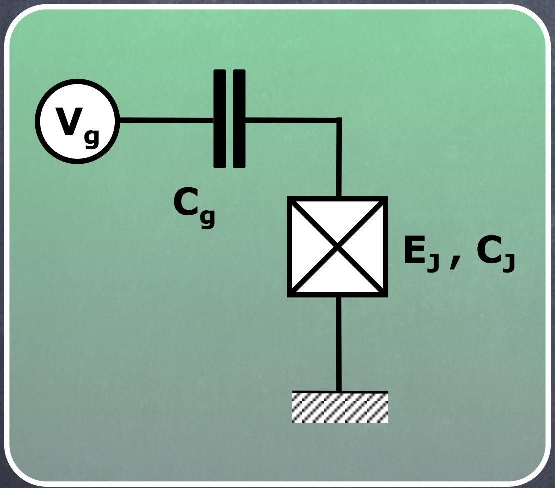

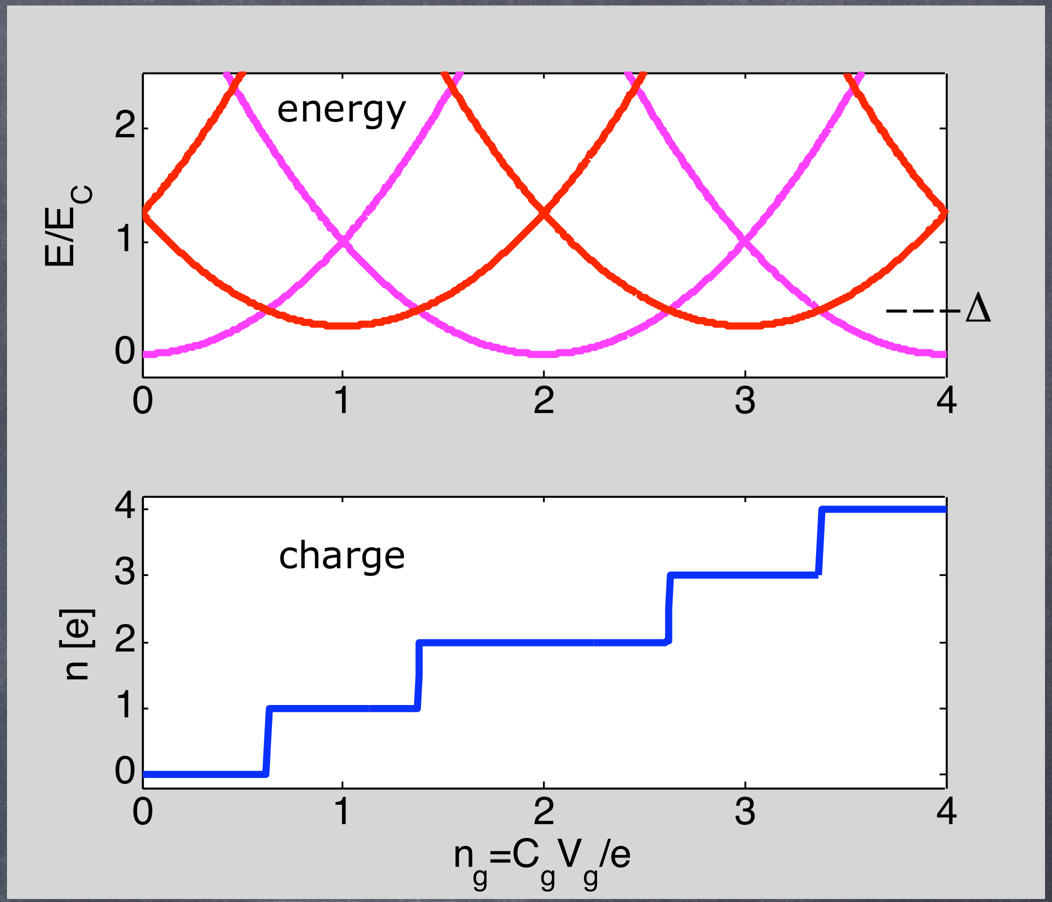

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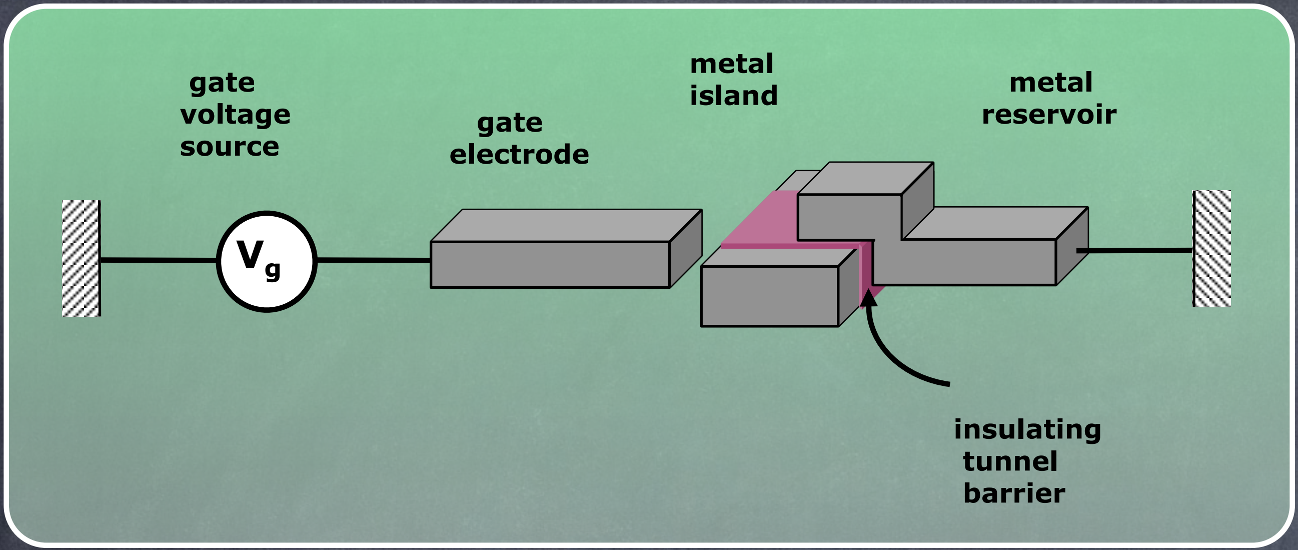

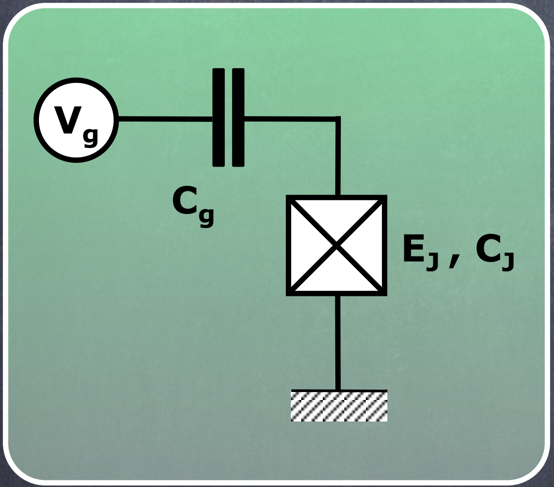

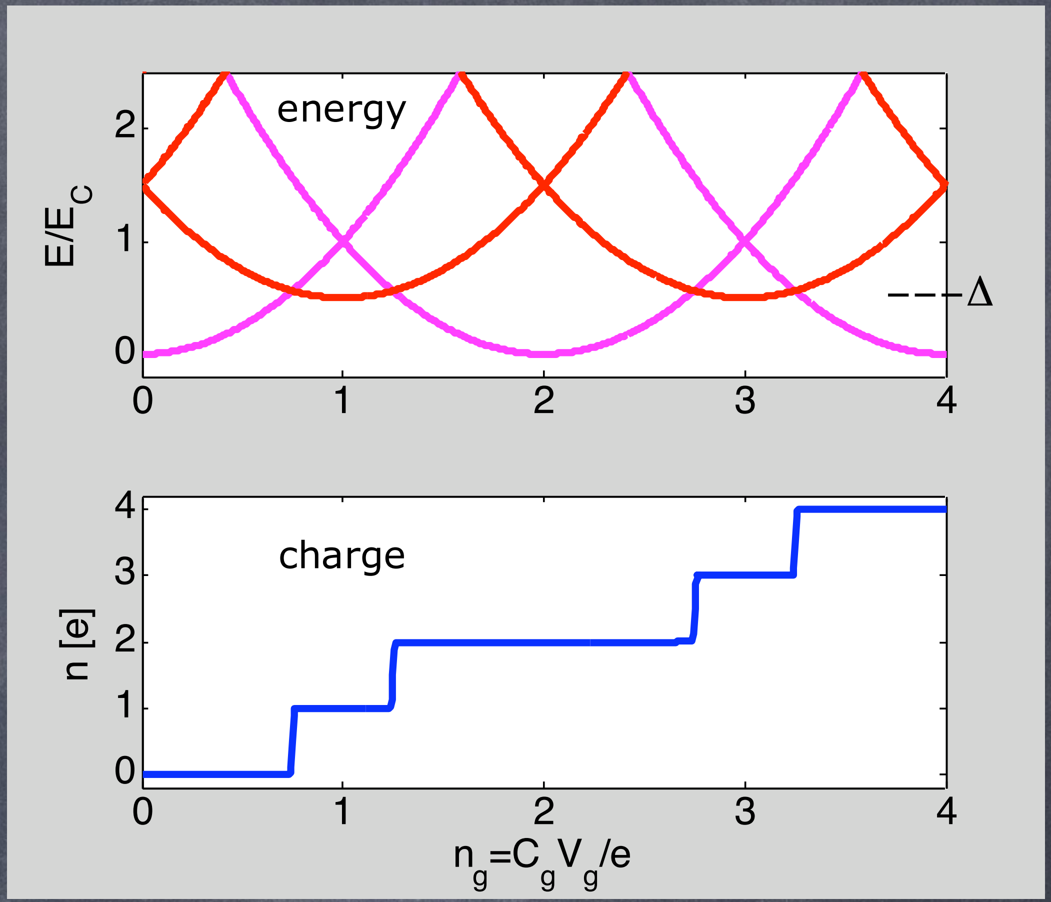

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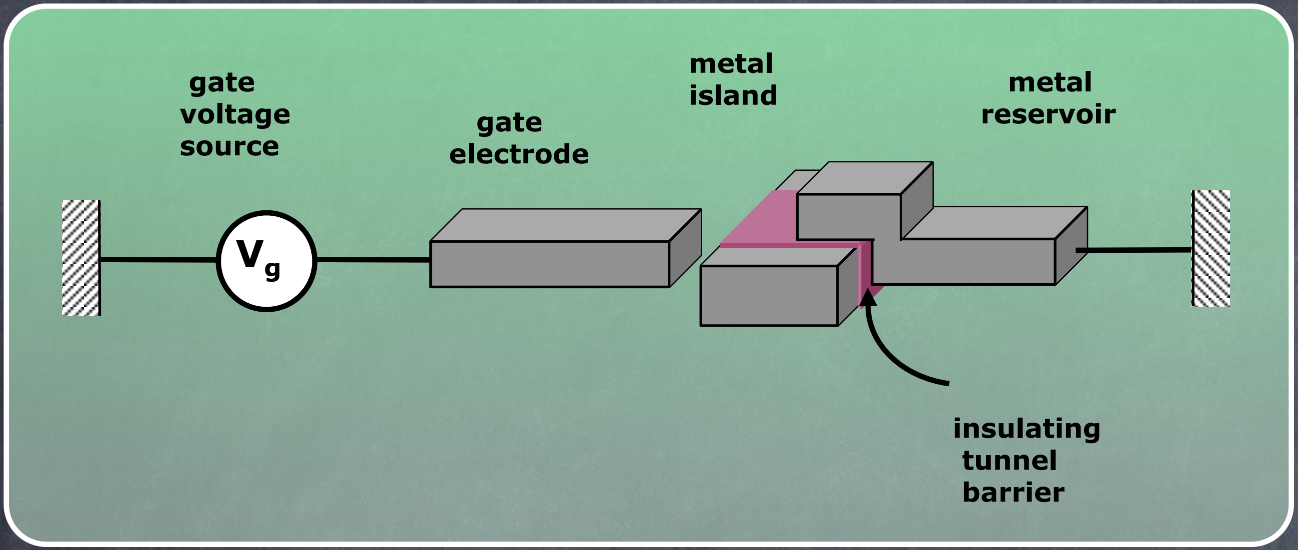

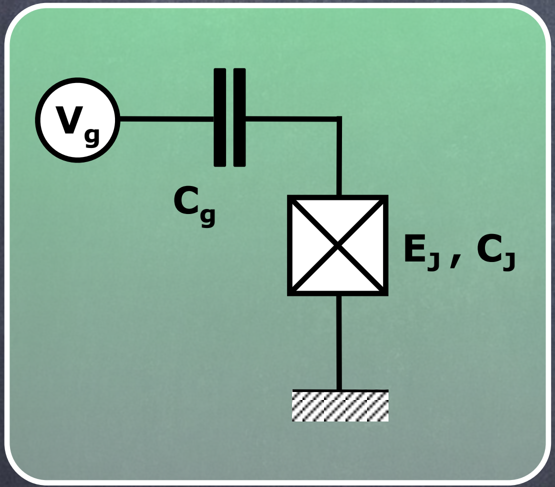

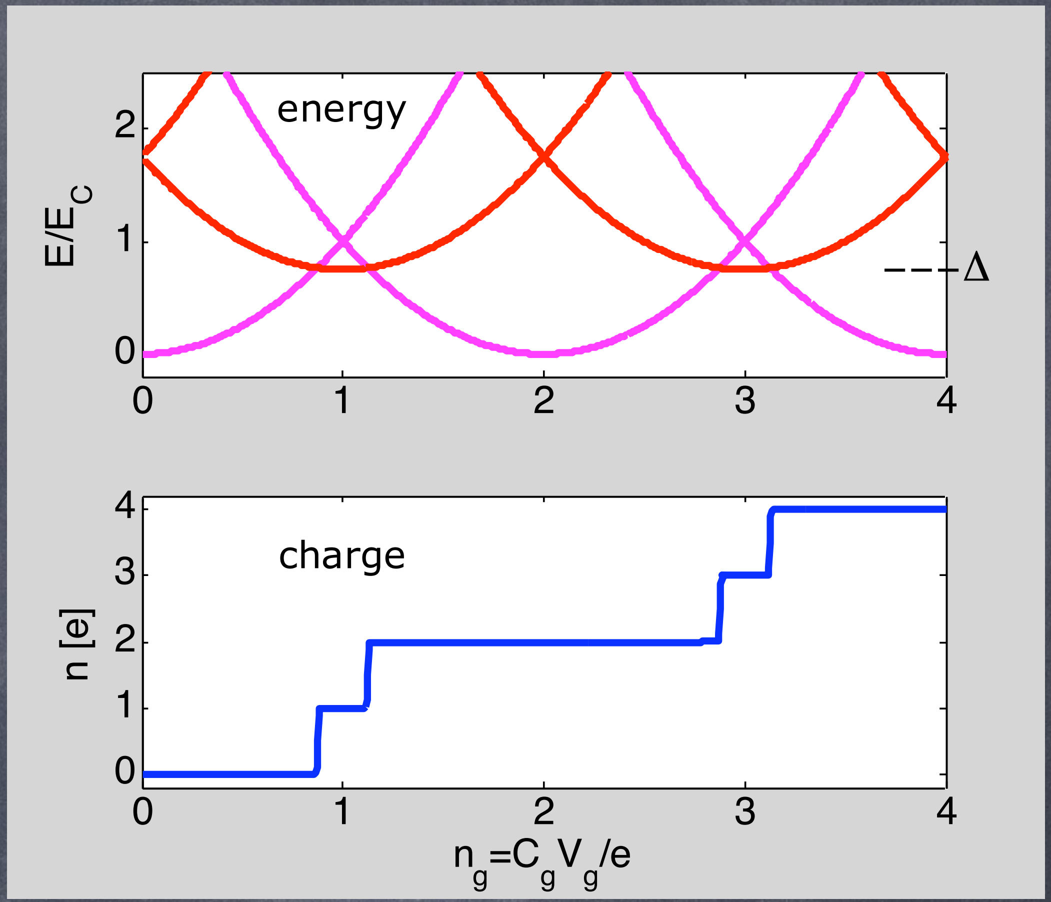

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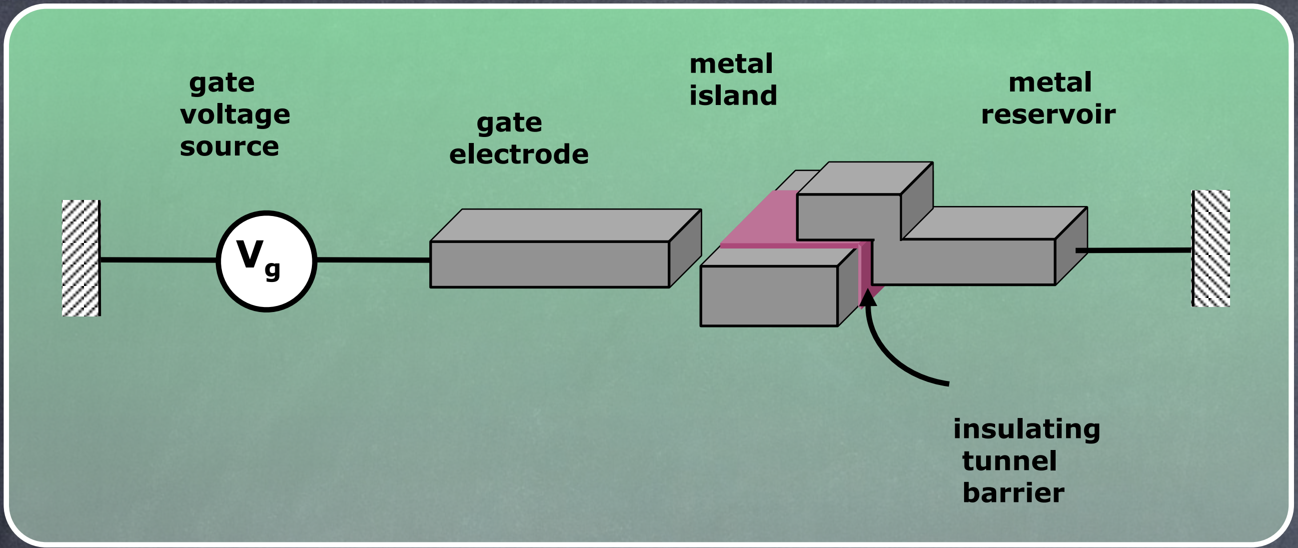

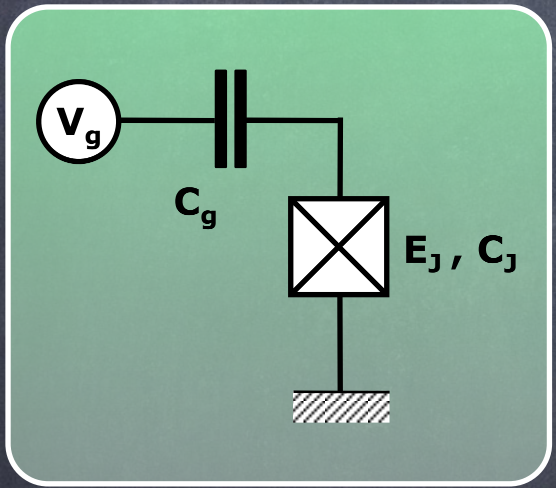

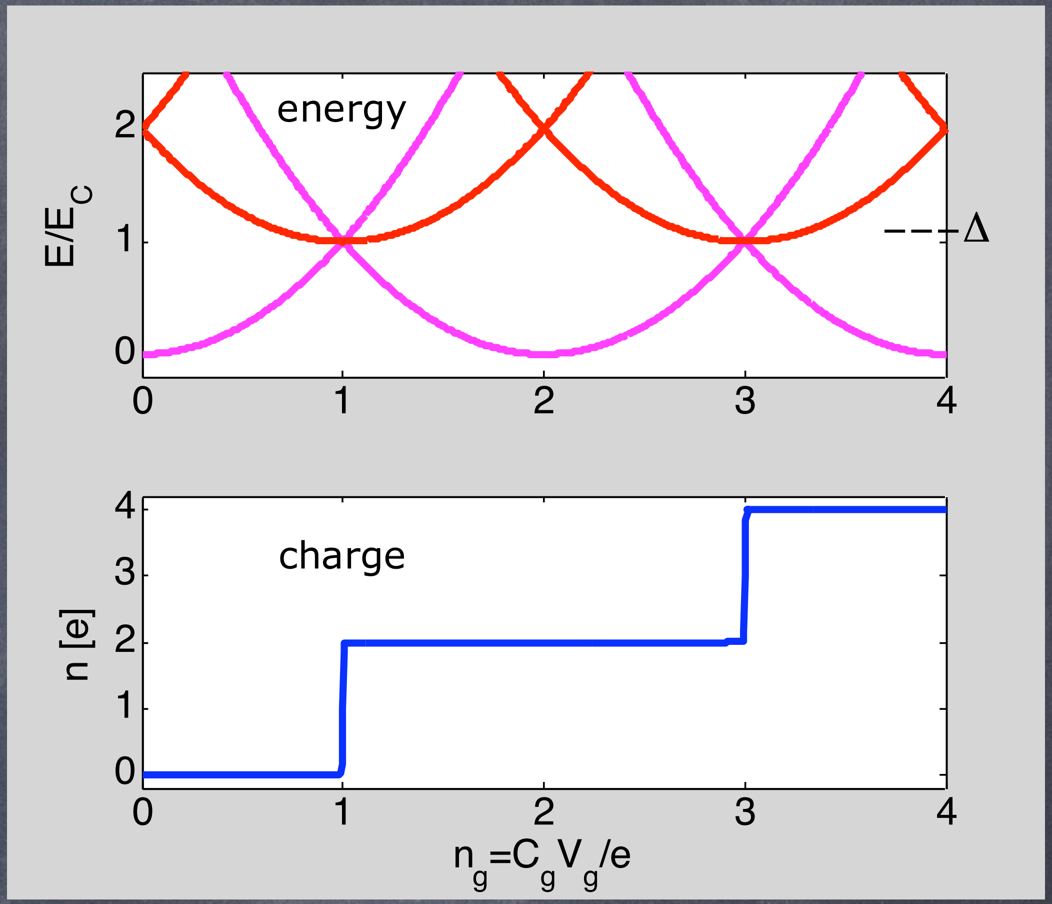

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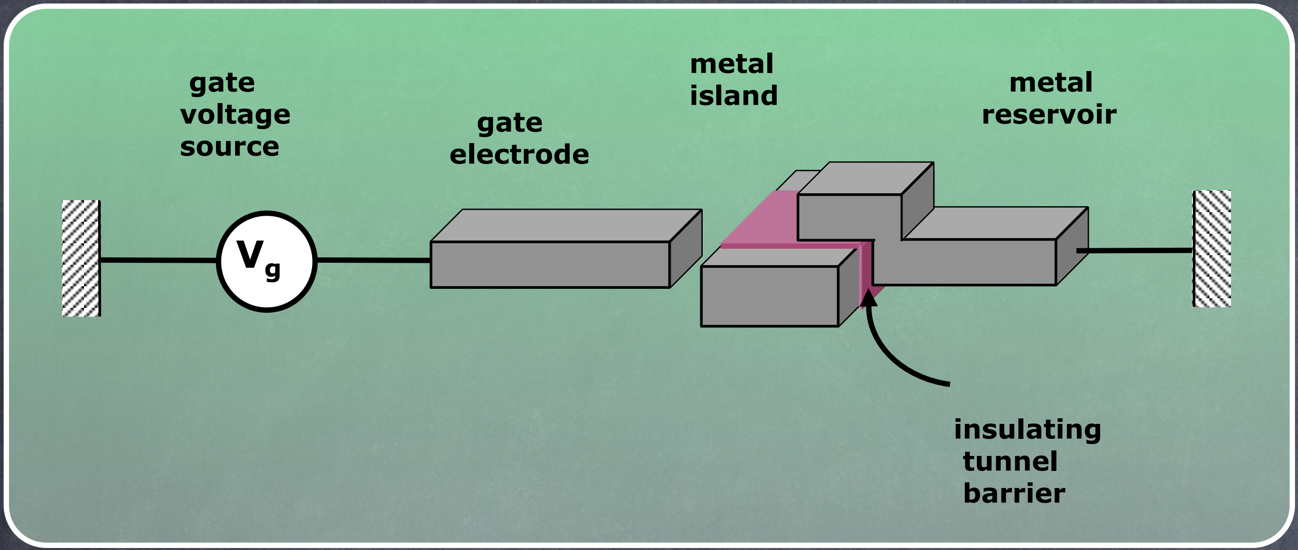

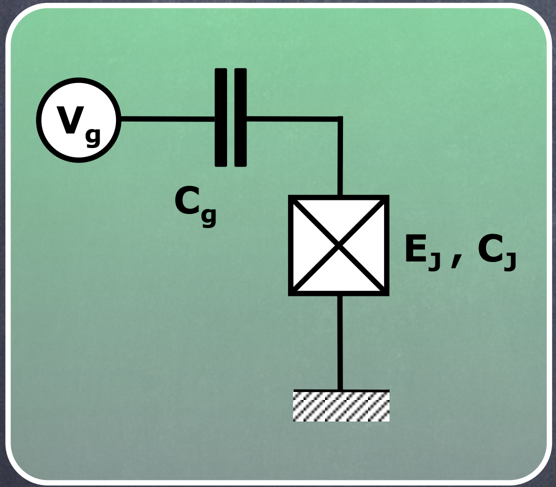

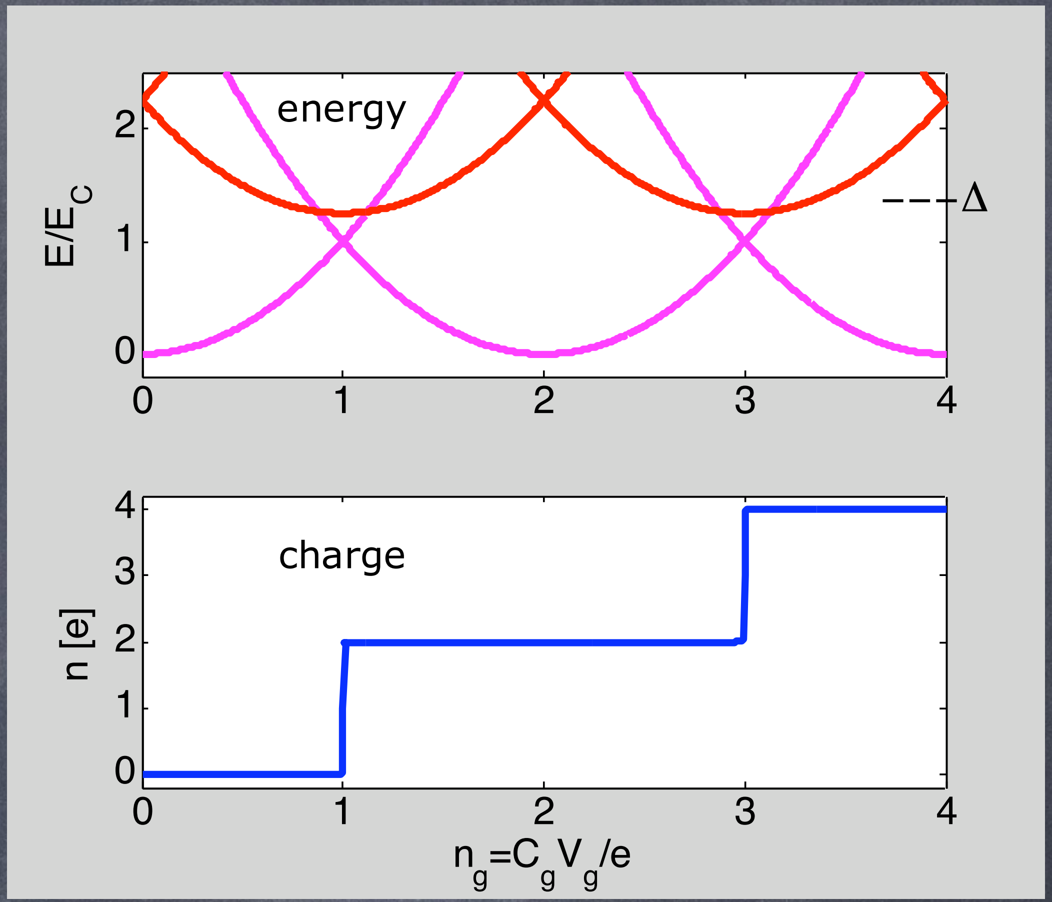

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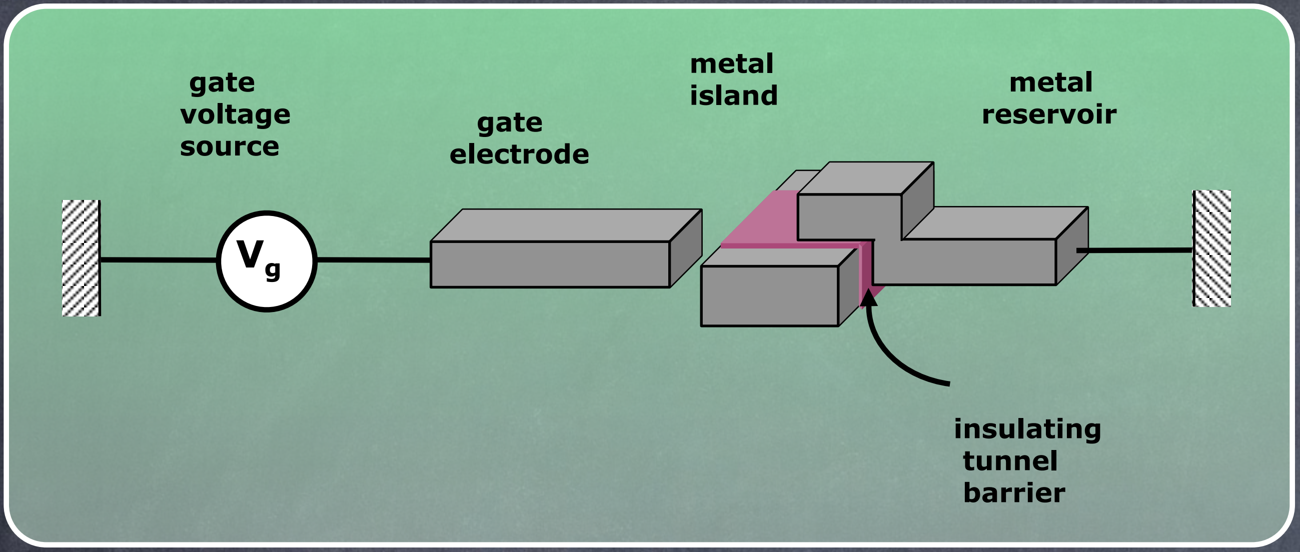

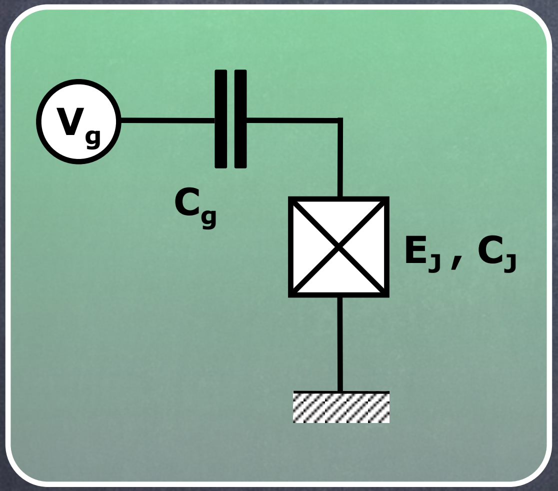

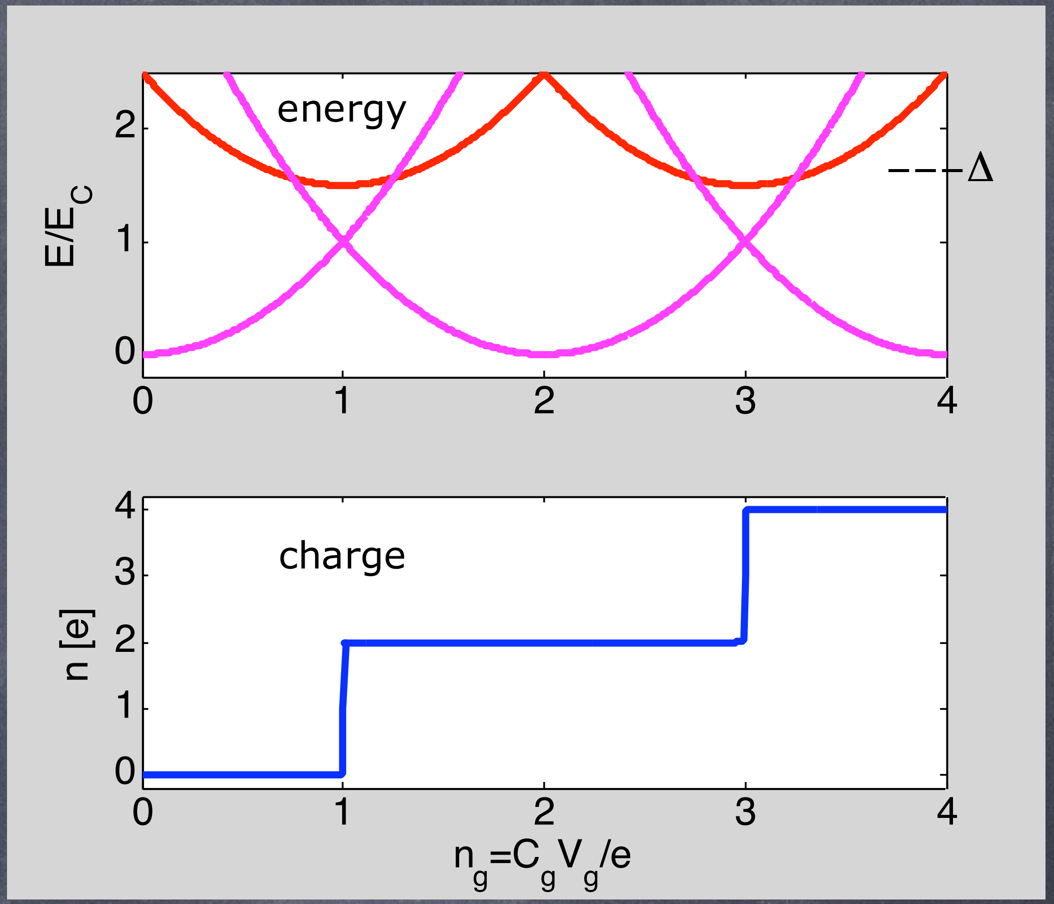

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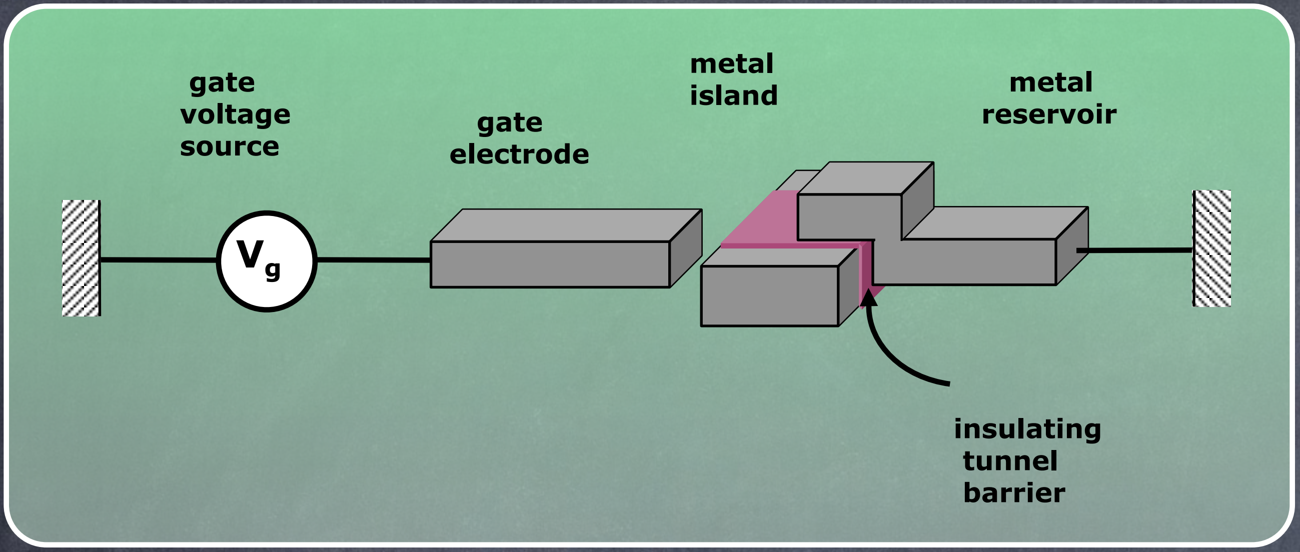

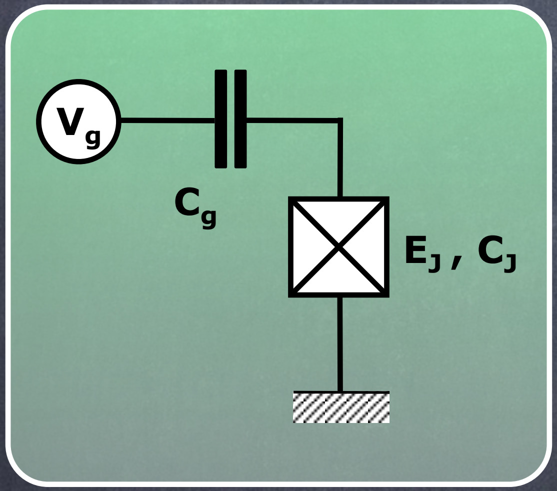

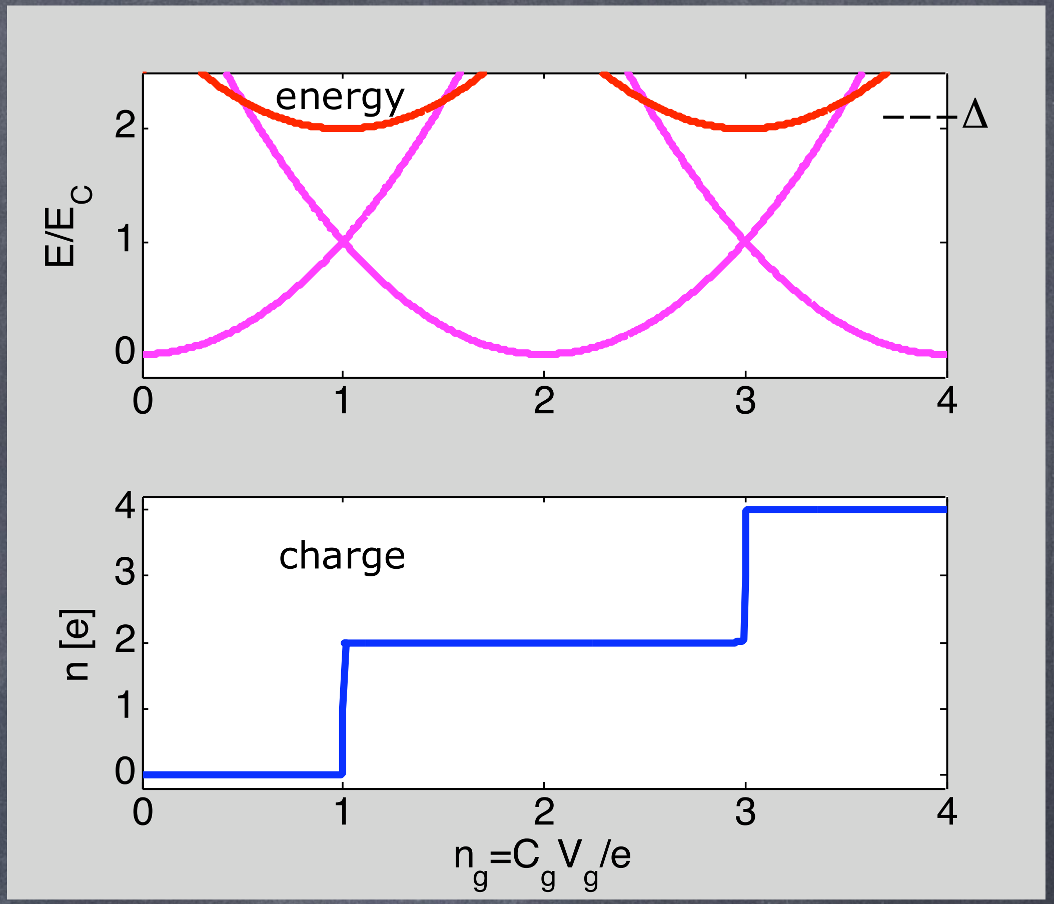

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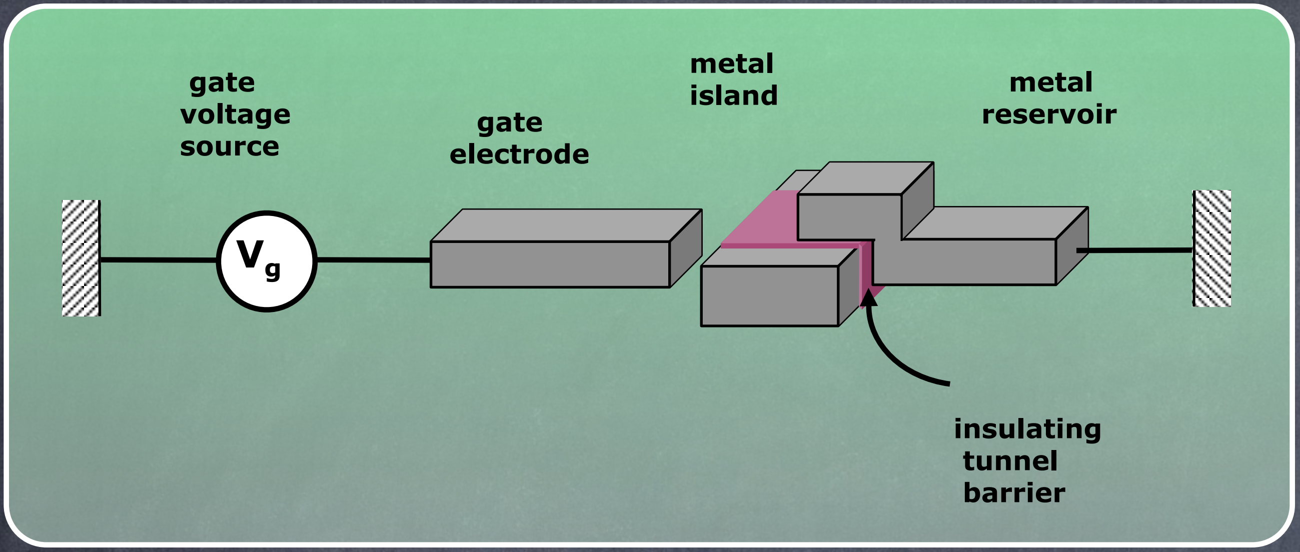
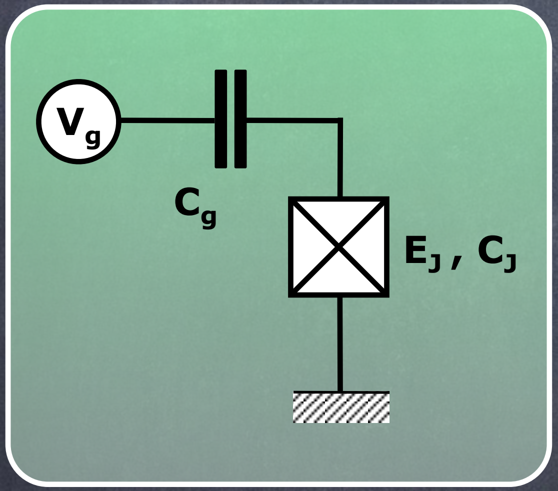
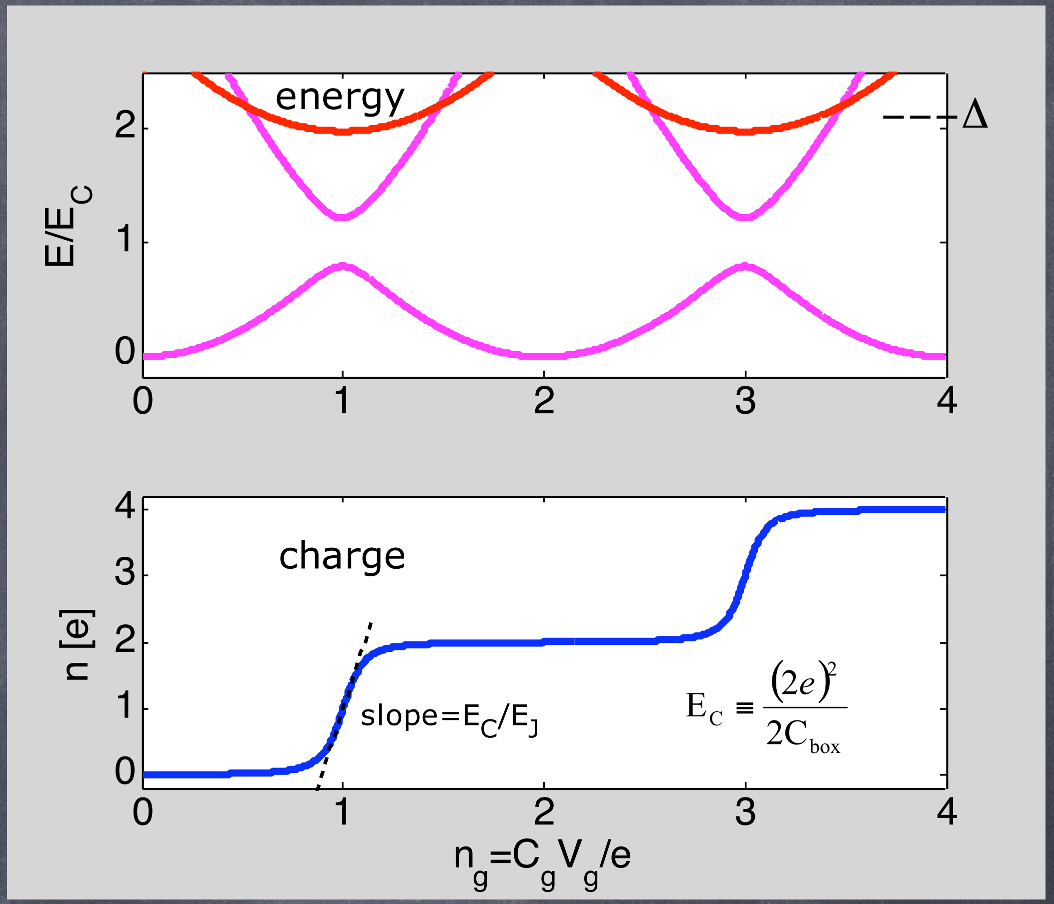
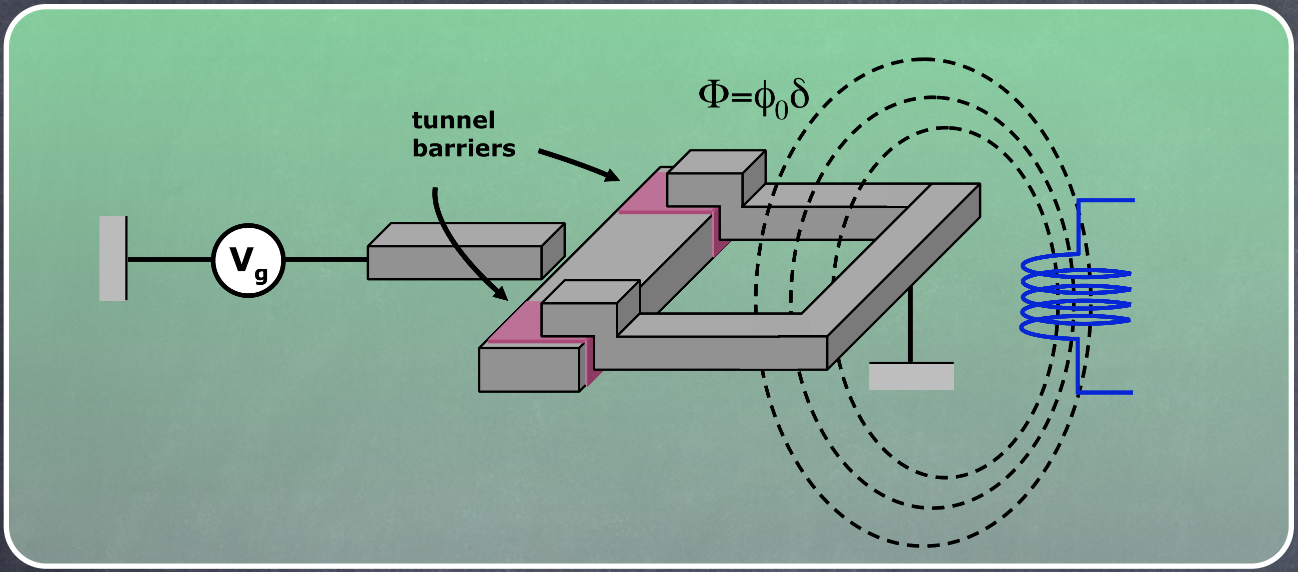






- Cooper-pair tunneling E_J removes charge degeneracy
- With aluminium one naturally has a Cooper-pair box and turns it into a single-electron box using a magnetic field to kill superconductivity
- Steps now broadened by quantum fluctuations (i.e. quantum superpositions) of charge

Split Cooper-pair box:



use SQUID configuration to tune E_J

$$E_J(\delta) = E_J^0 \sin\delta$$

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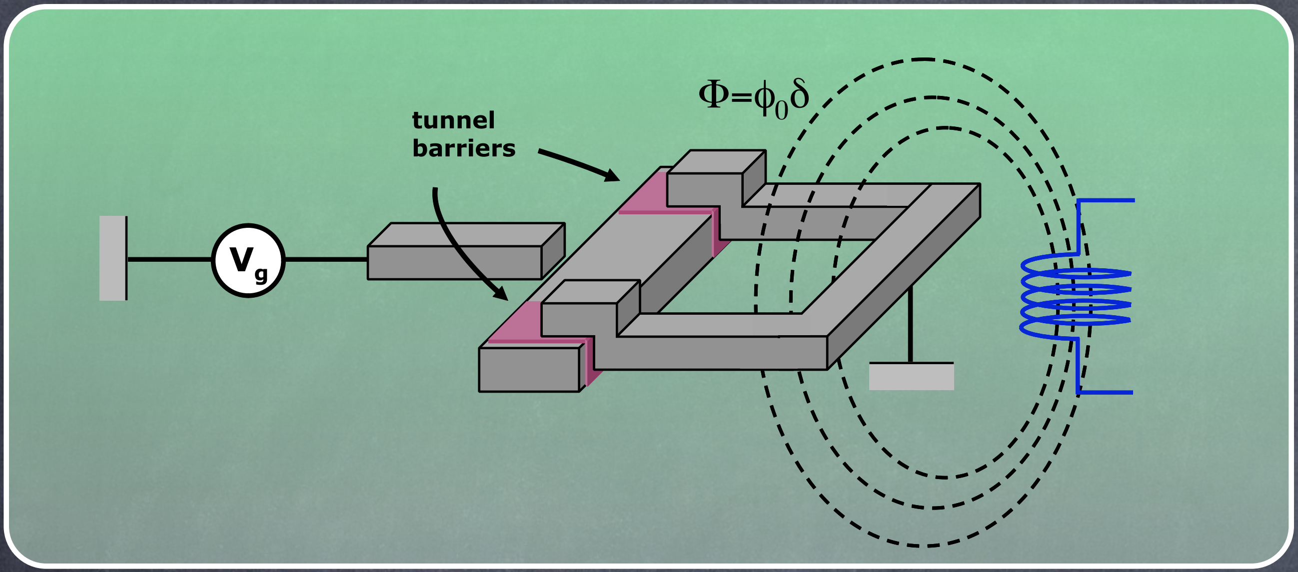

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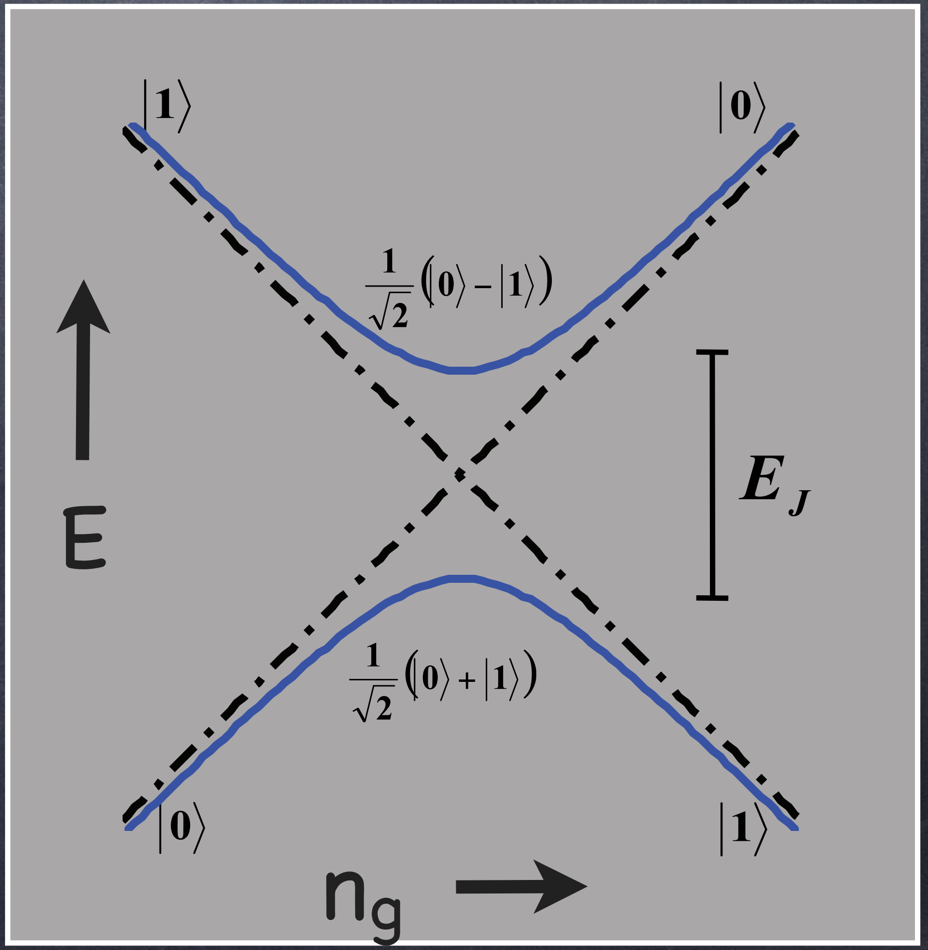
Two charge approximation for $E_J/E_Q \ll 1$

$$H = -E_Q(\frac{1}{2} - n_g)\sigma_z - \frac{E_J}{2}\sigma_x$$

$$E_Q \equiv \frac{(2e)^2}{C_{box}}, \qquad n_g \equiv C_g V_g/2e$$



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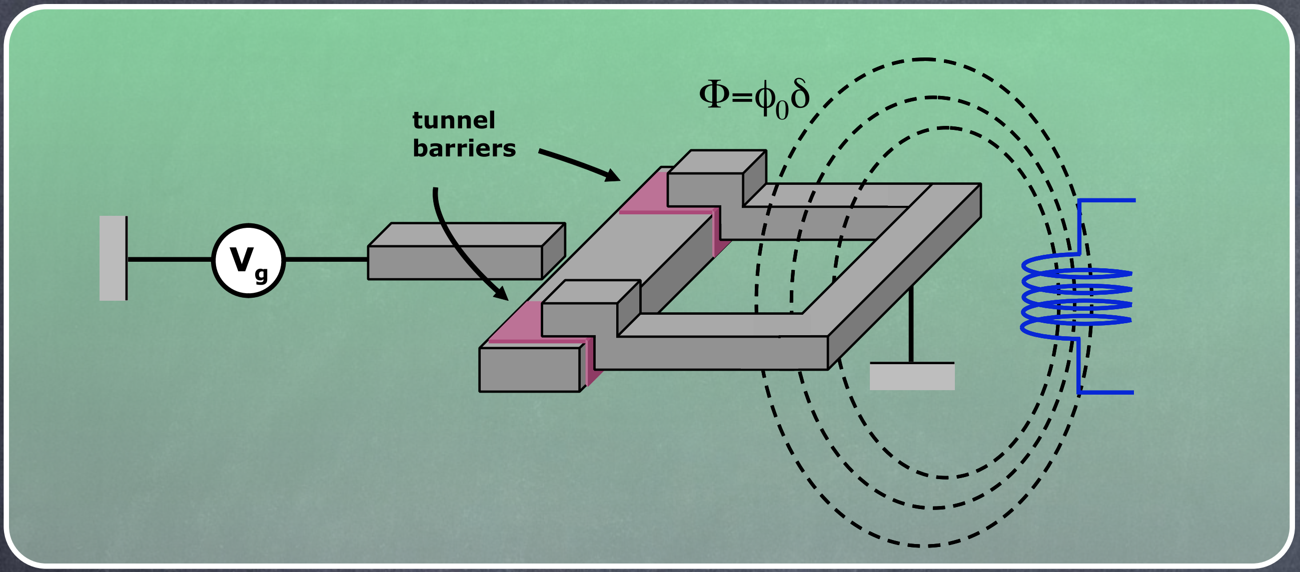

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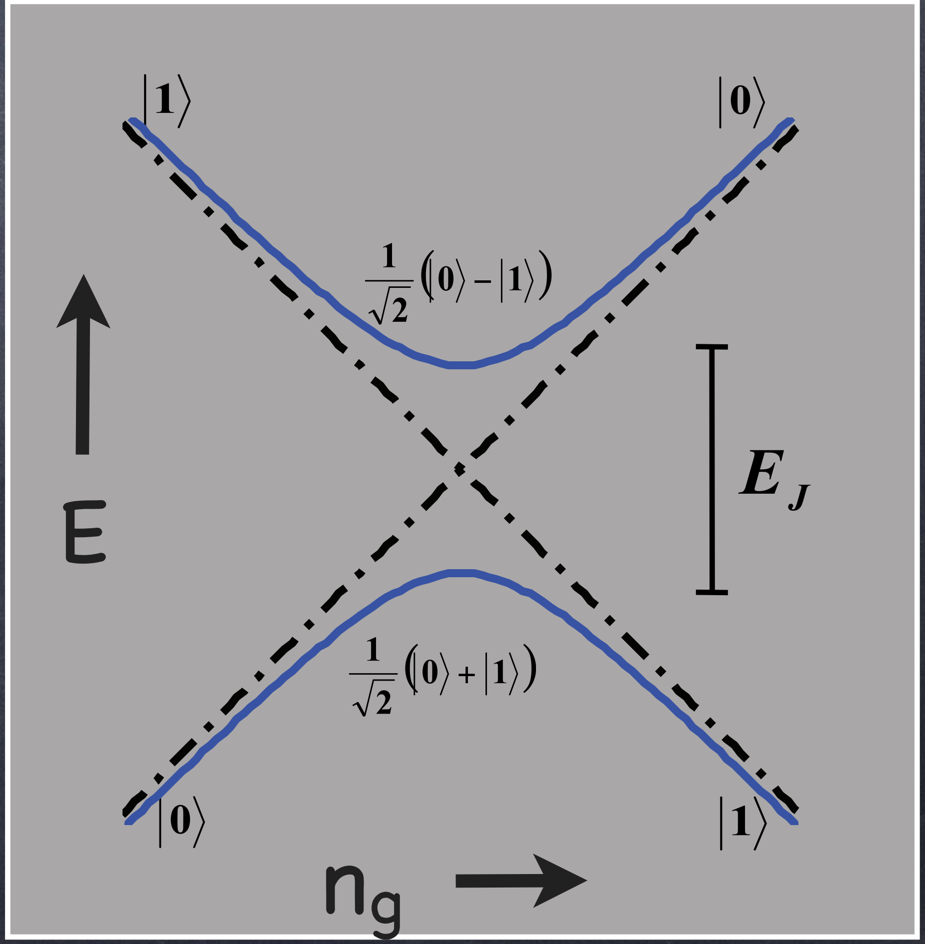
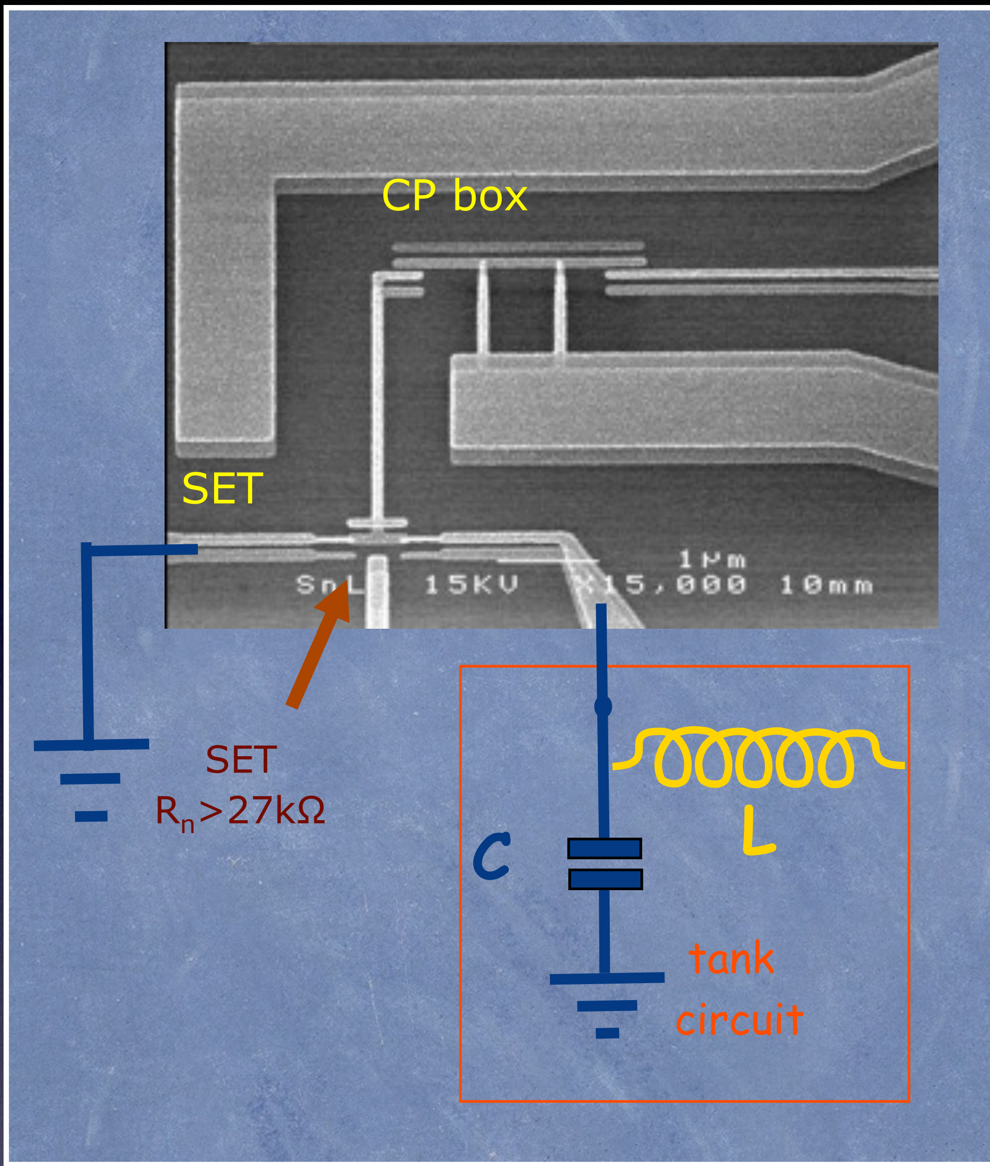
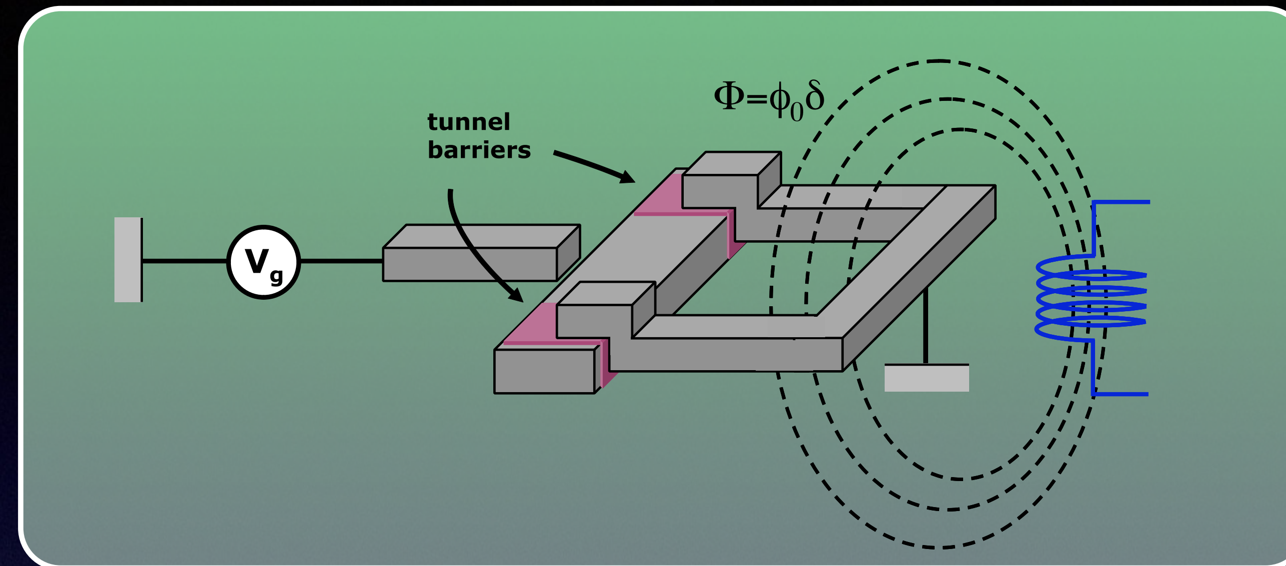
eigen-energies

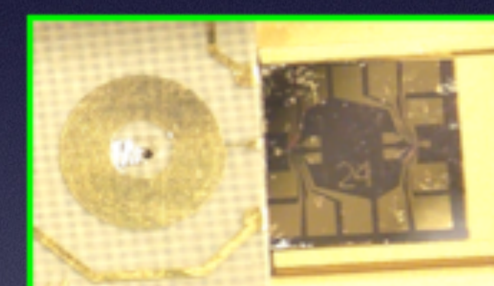
$$E_\pm = \pm\frac{E_Q}{2}\sqrt{4(\frac{1}{2} - n_g)^2 + (E_J/E_Q)^2}$$

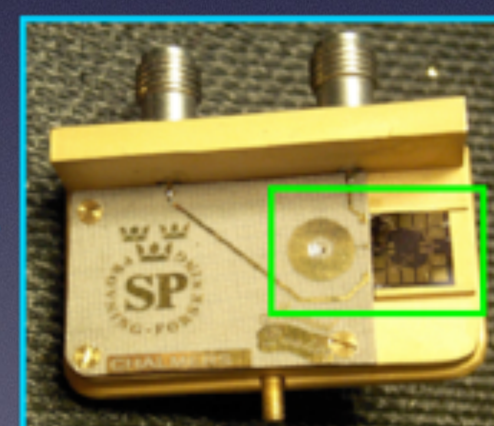


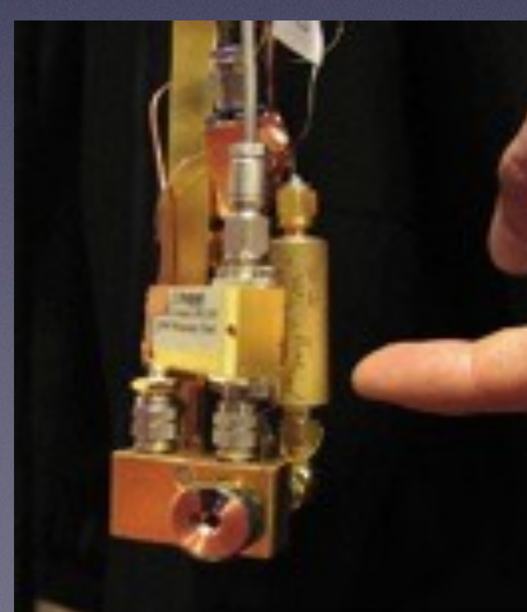
Cooper-pair box with RF-SET electrometer





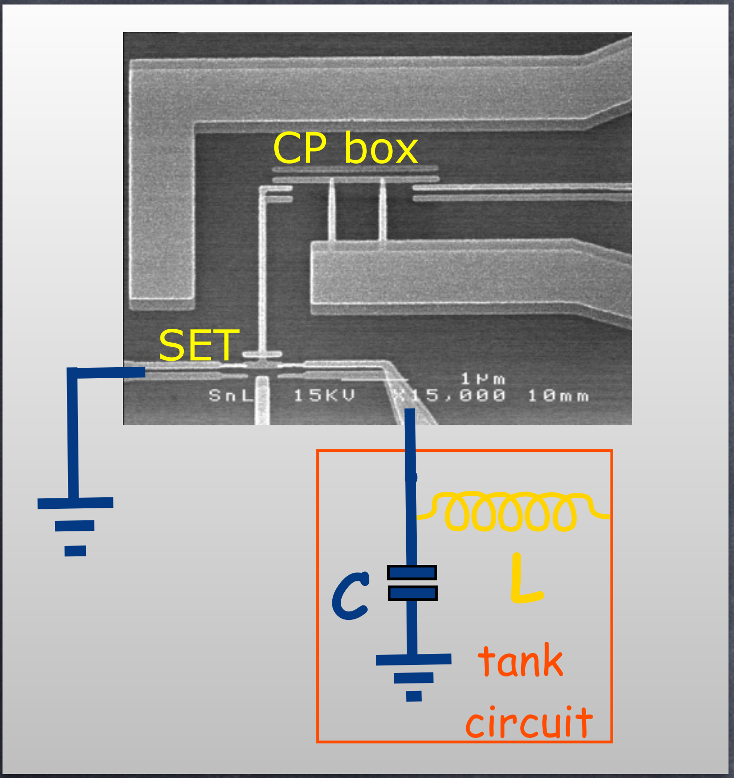


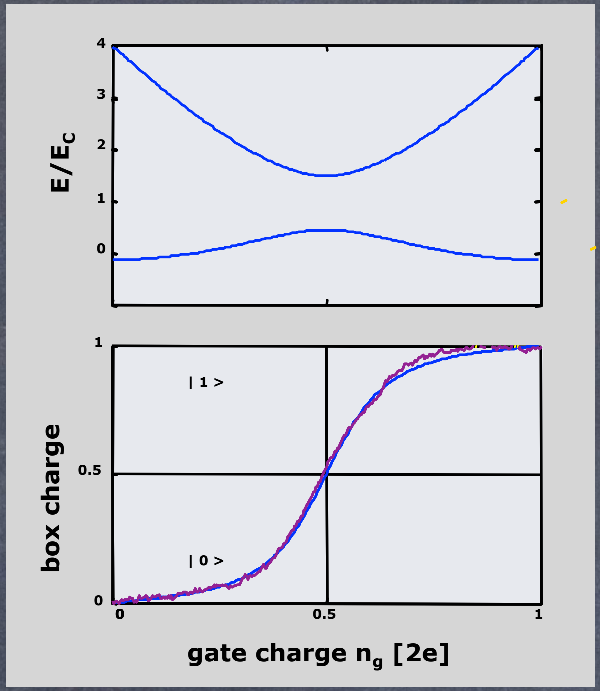




T. Duty *et al.* 2004
K. Bladh *et al.* 2005

Energy level spectroscopy of the Cooper-pair box





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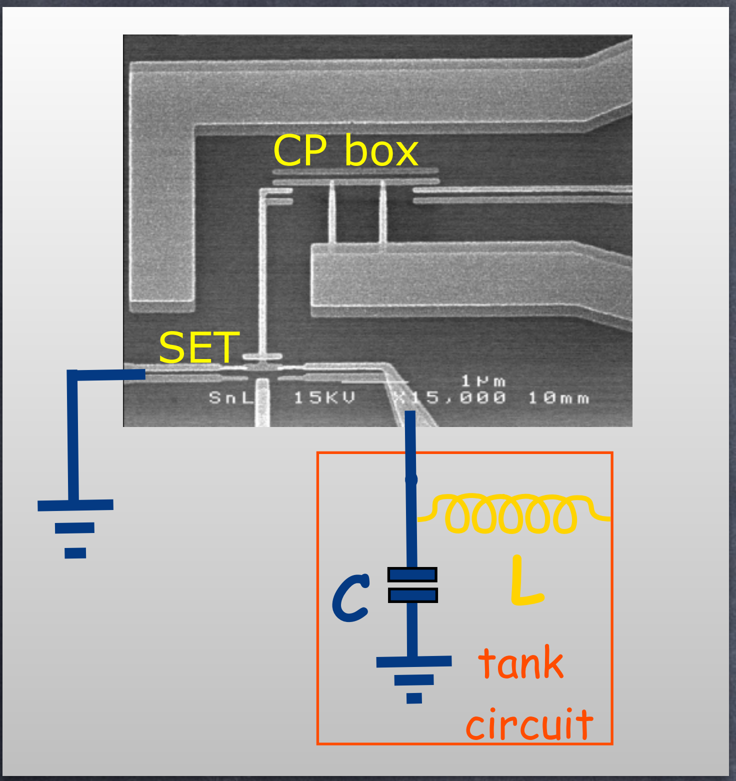

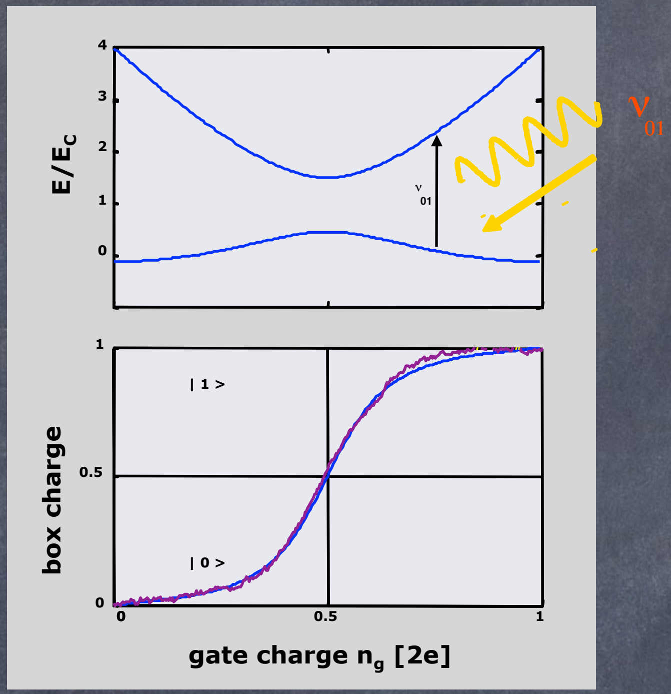

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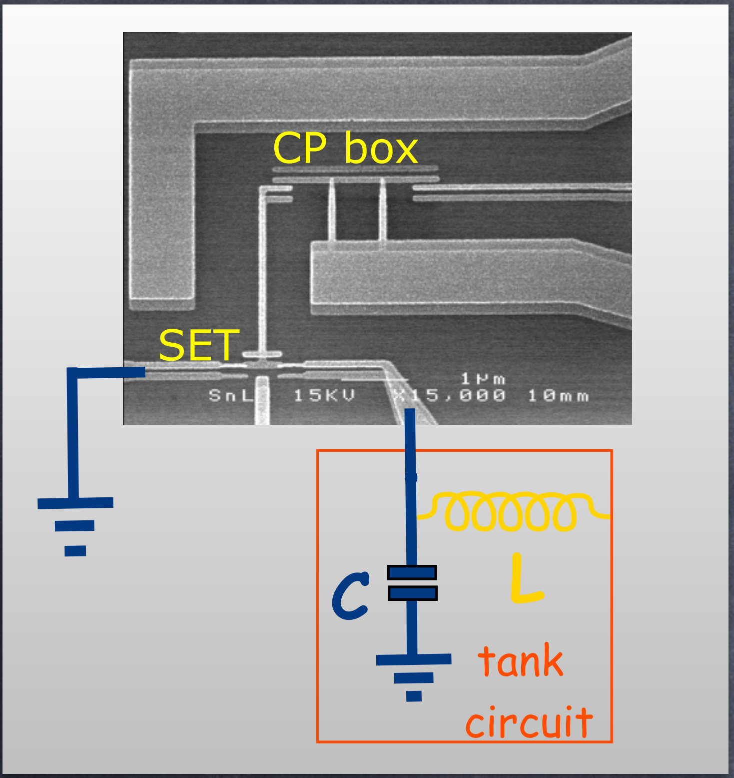

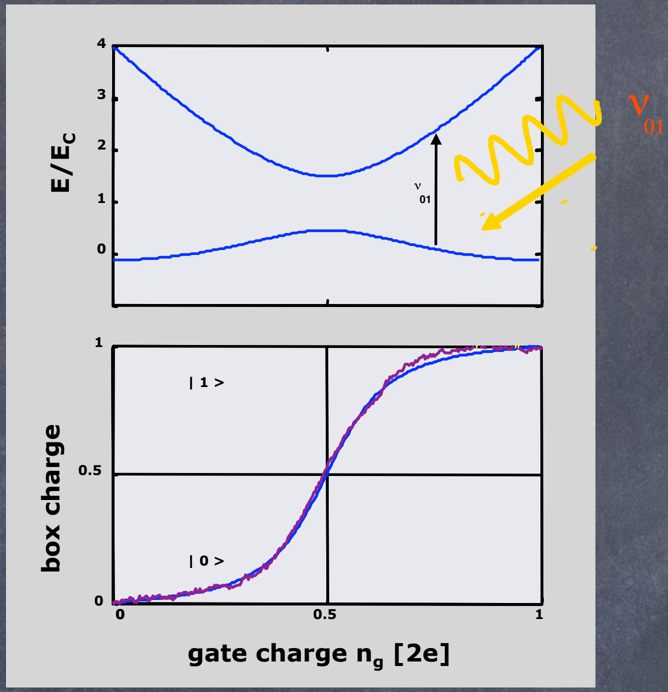

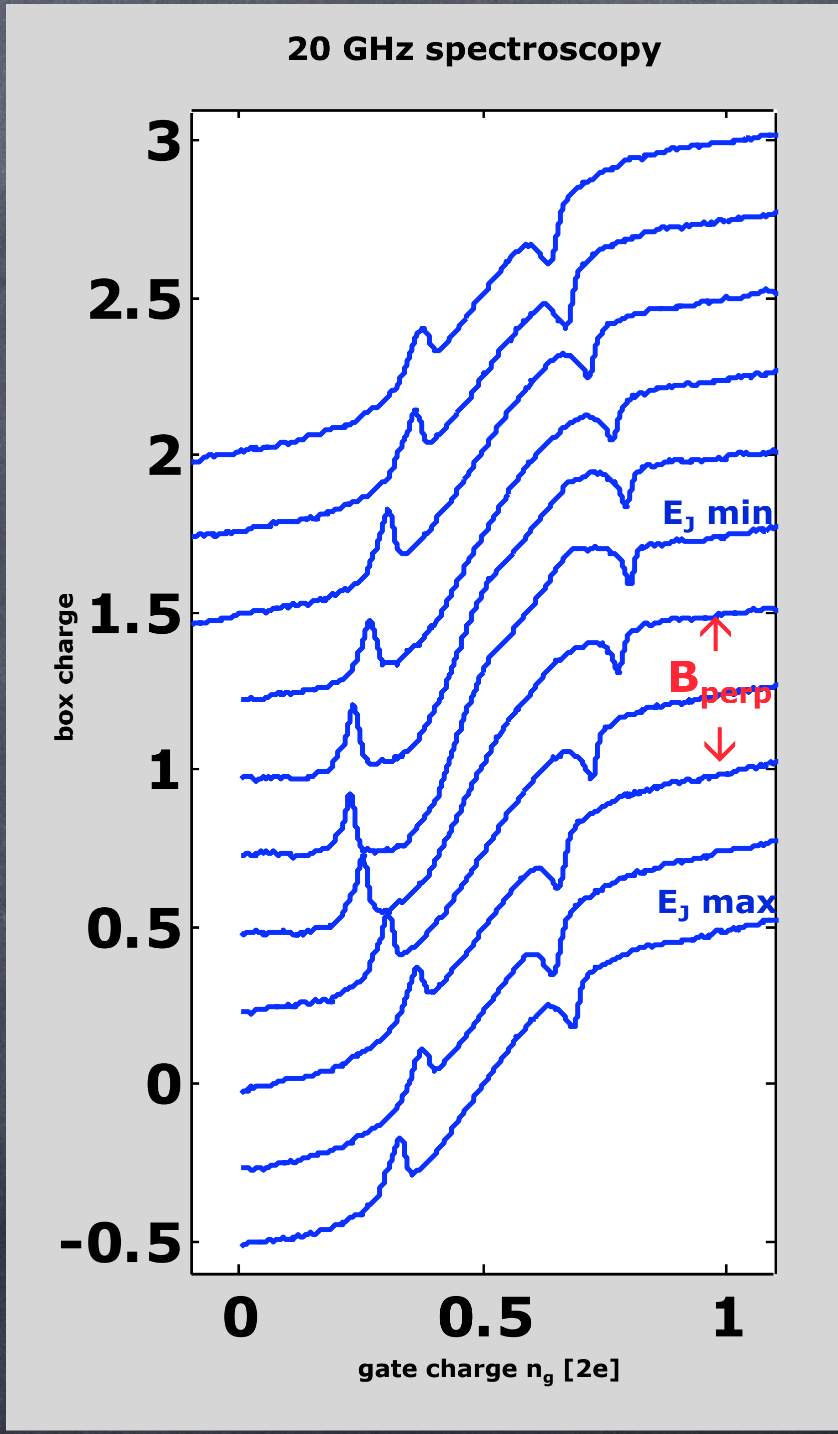

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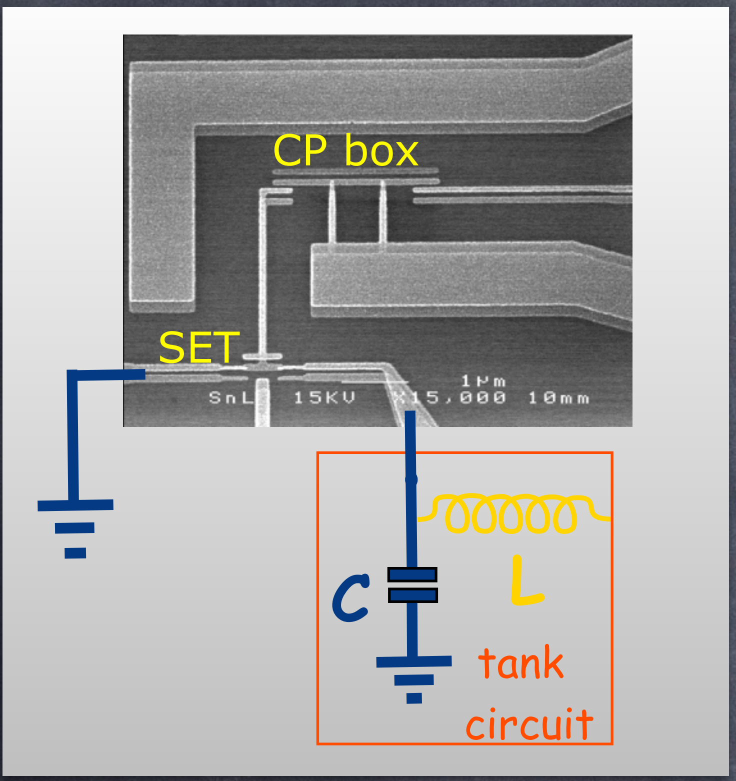
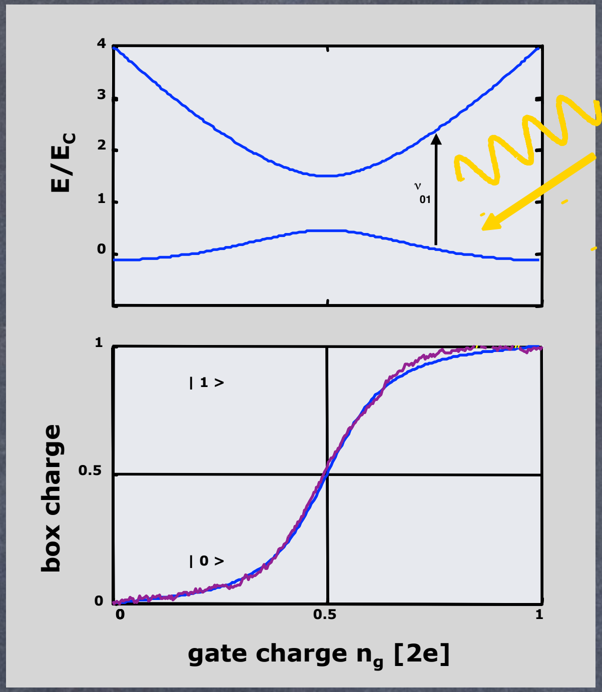
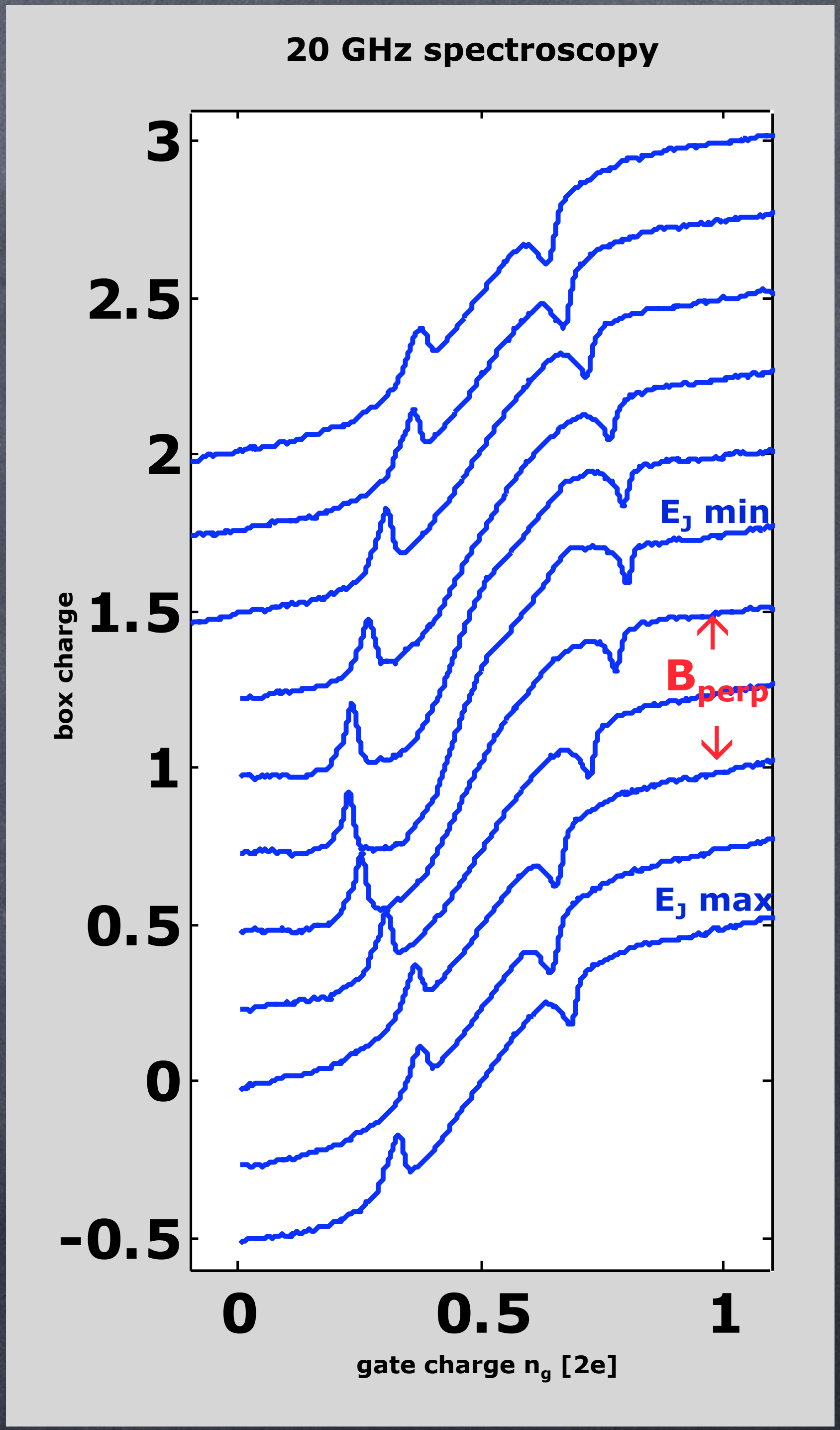
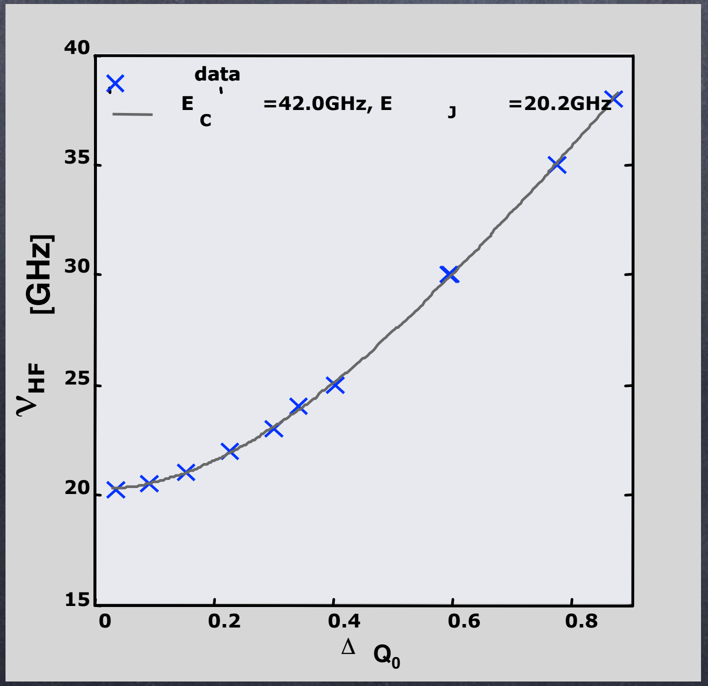




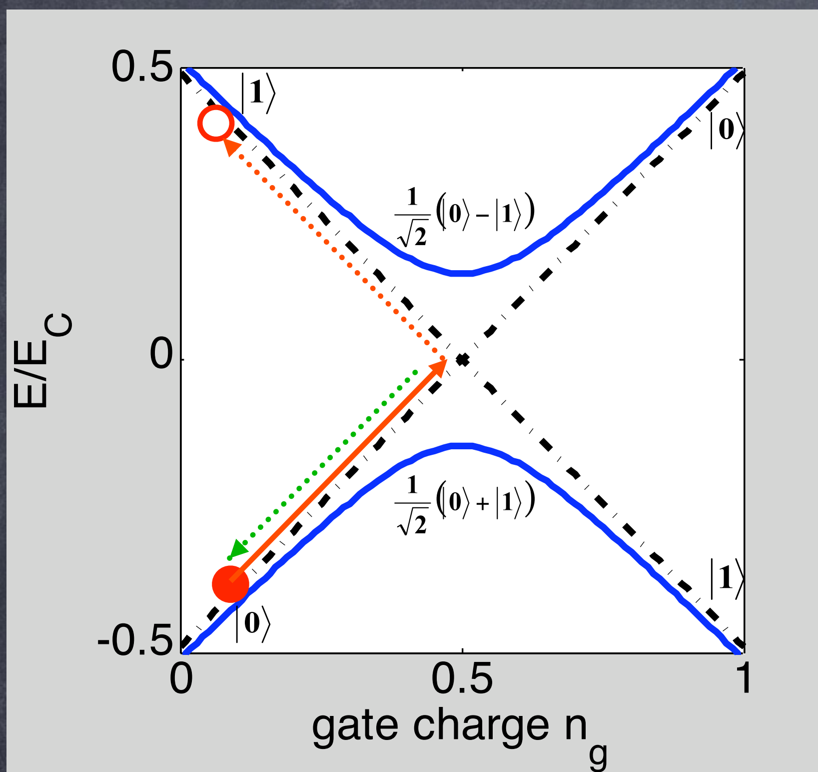


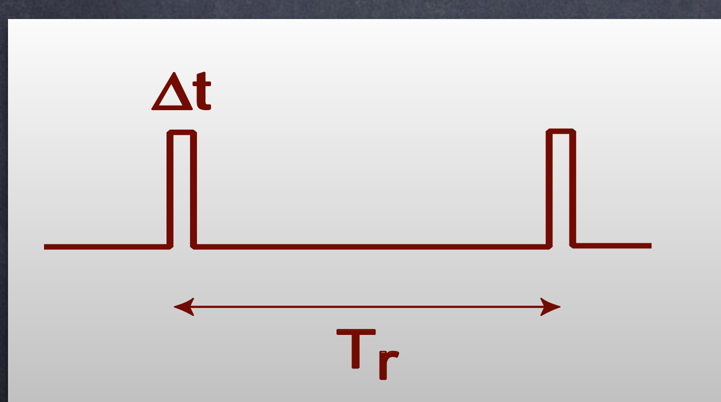
E_J, E_C determined from spectroscopy agrees with E_J/E_C from slope of staircase.

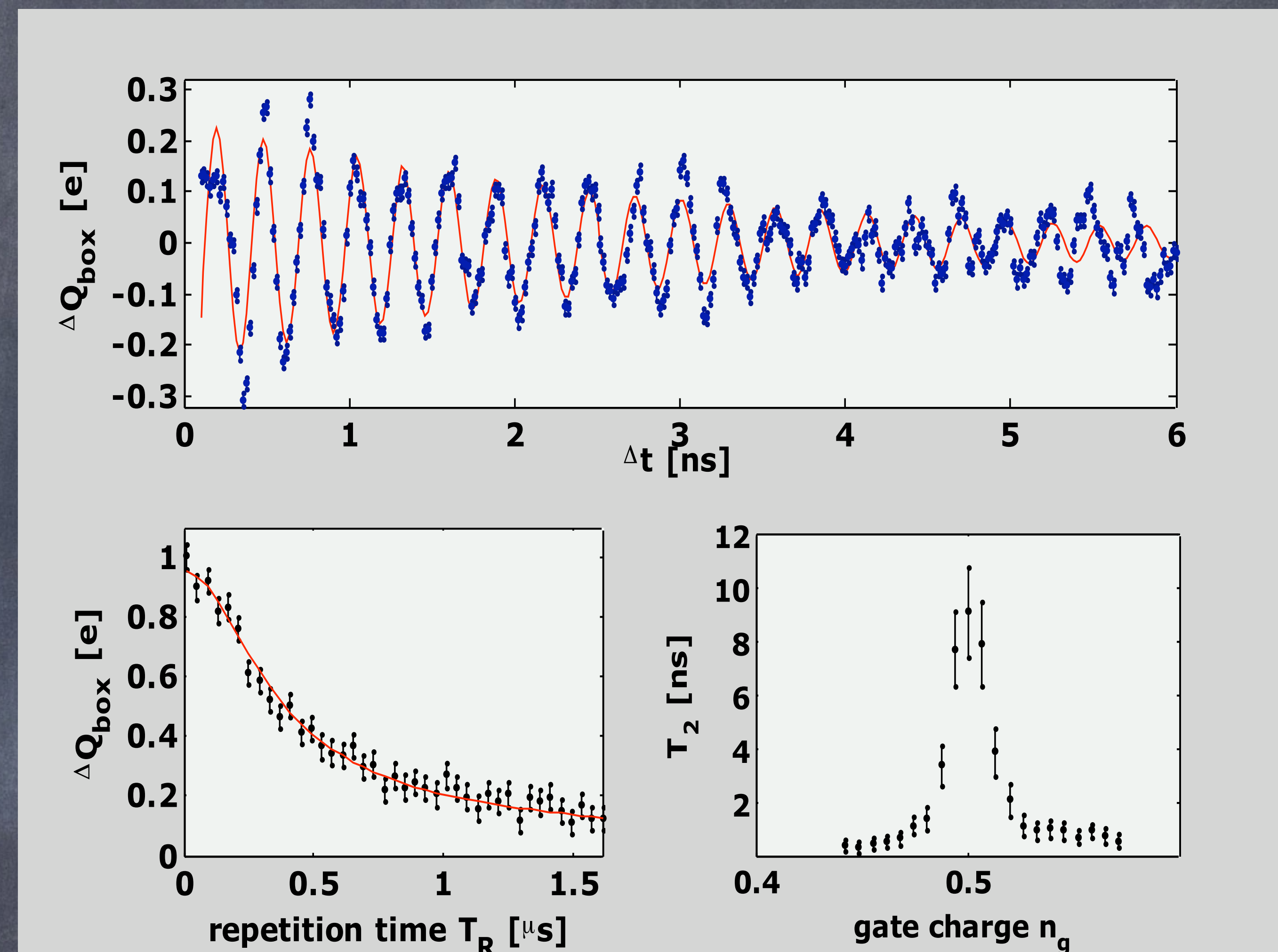


D. Gunnarsson, T. Duty, K. Bladh and P. Delsing, *Phys. Rev. B* **(2004)**

Coherent charge oscillations measured using the rf-SET





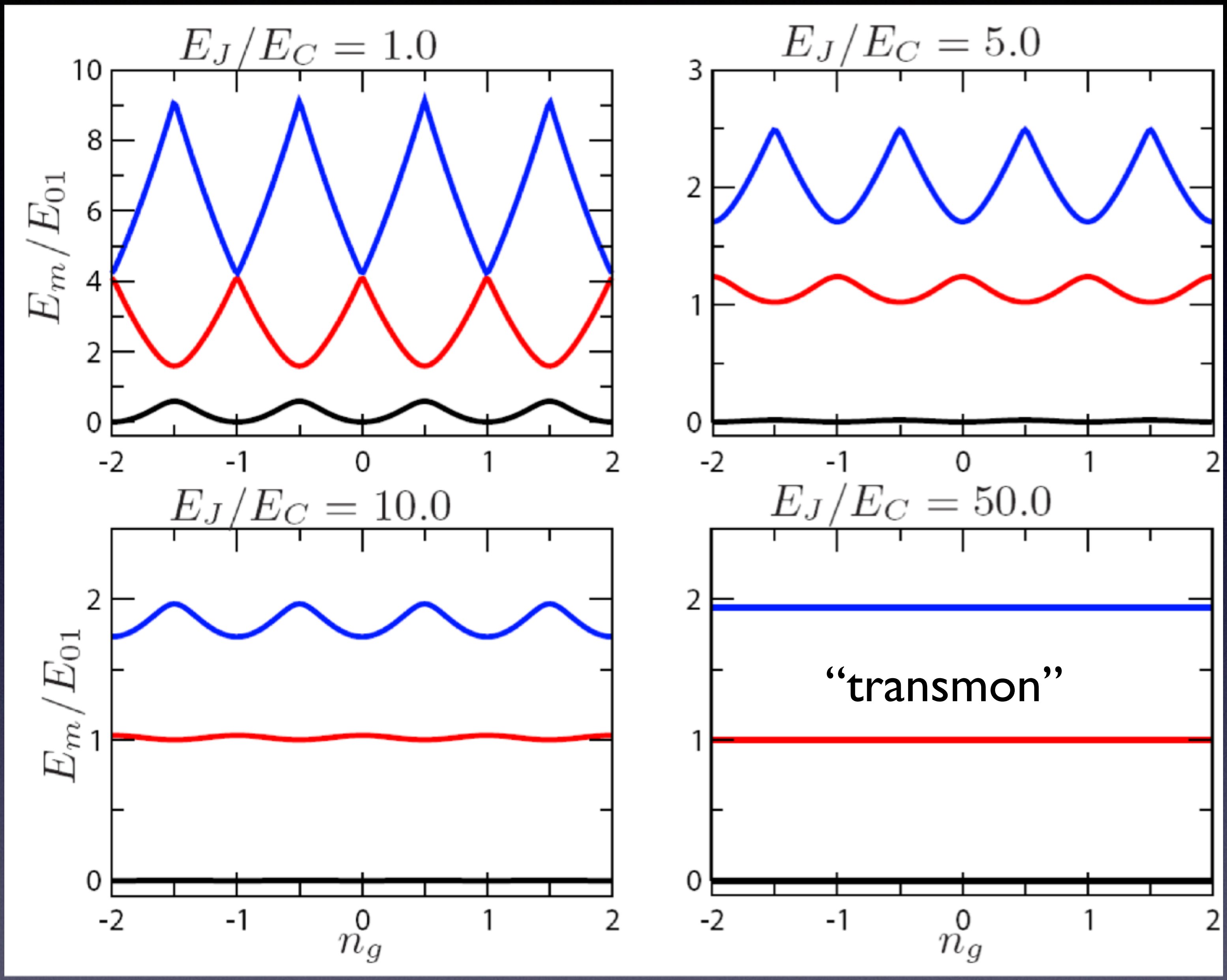


T_2 longest at charge degeneracy

T_1~10ns, but very **high fidelity**

T. Duty, D. Gunnarsson, K. Bladh and P. Delsing, ***PRB*** **(2004)**

Cooper-pair boxes for increasing E_J/E_C

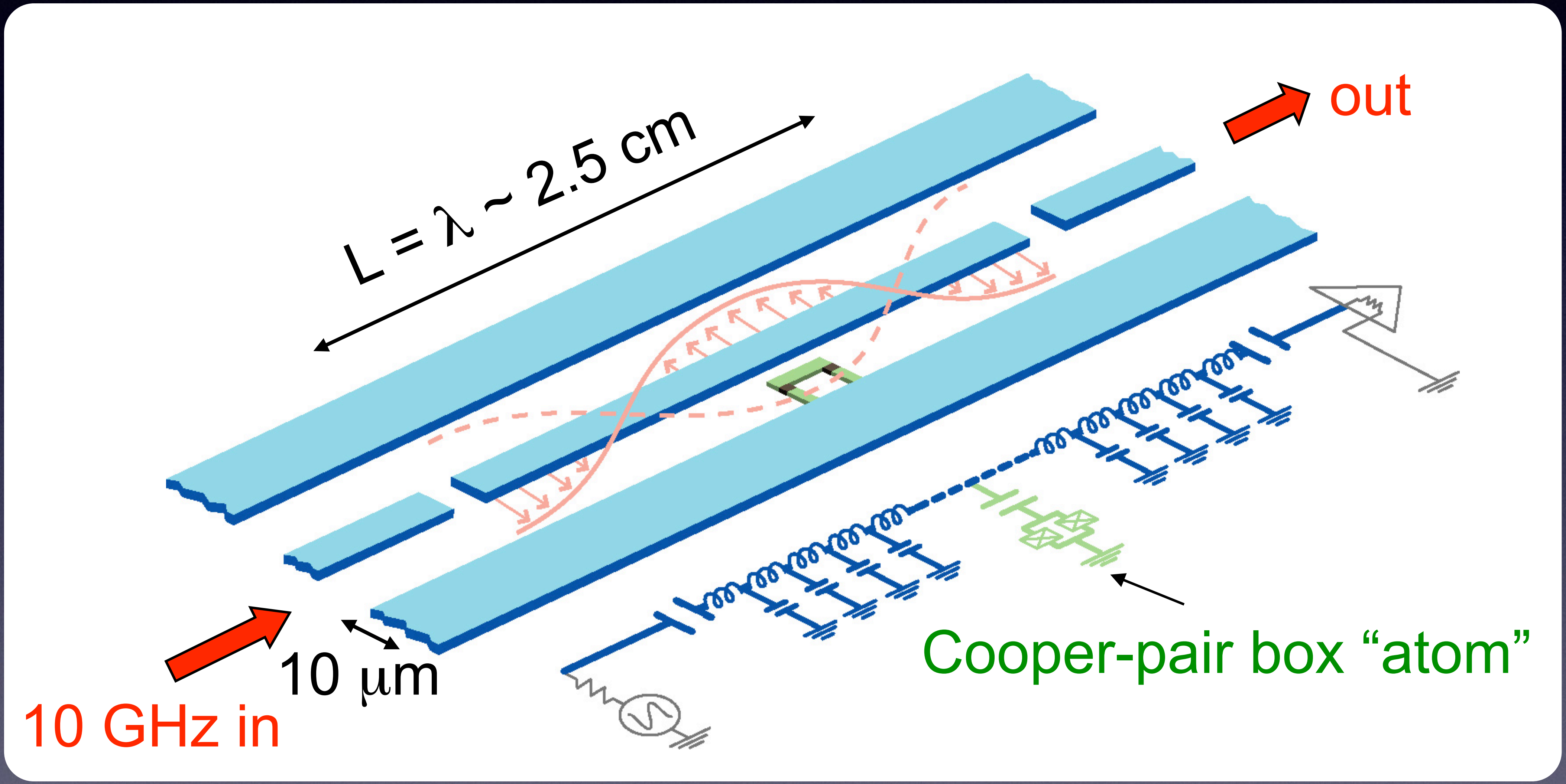


For $E_J \gg E_C$, insensitive to low-frequency gate charge noise,
but still have strong coupling to nearly resonant charge modulation
a.c. dipole moment ≠ d.c. dipole moment!

A circuit implementation of cavity QED

transmission line cavity + Cooper-pair box

two level system coupled to microwave photons



theory: Blais et al. Phys. Rev. A (2004)

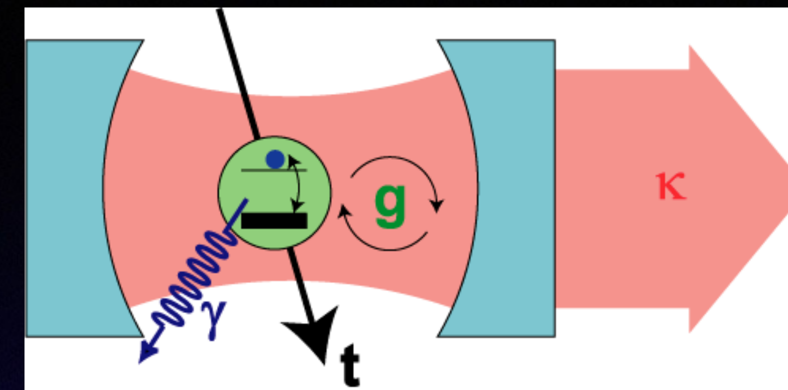
experiment: Wallraff et al., Nature (2004)

Cavity QED: two-level atom plus photon

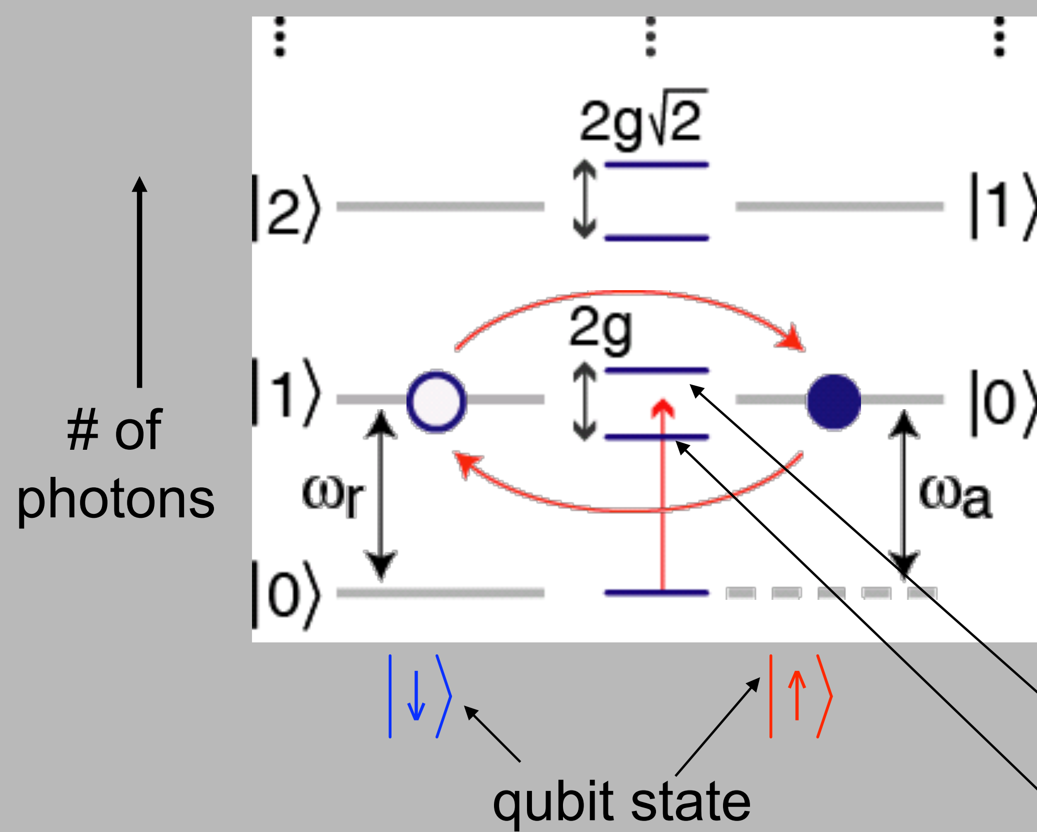
$2g$ = vacuum Rabi freq.

κ = cavity decay rate

γ = “transverse” decay rate



Cavity QED: Resonant Case



$\boxed{\omega_r = \omega_a}$

vacuum Rabi oscillations

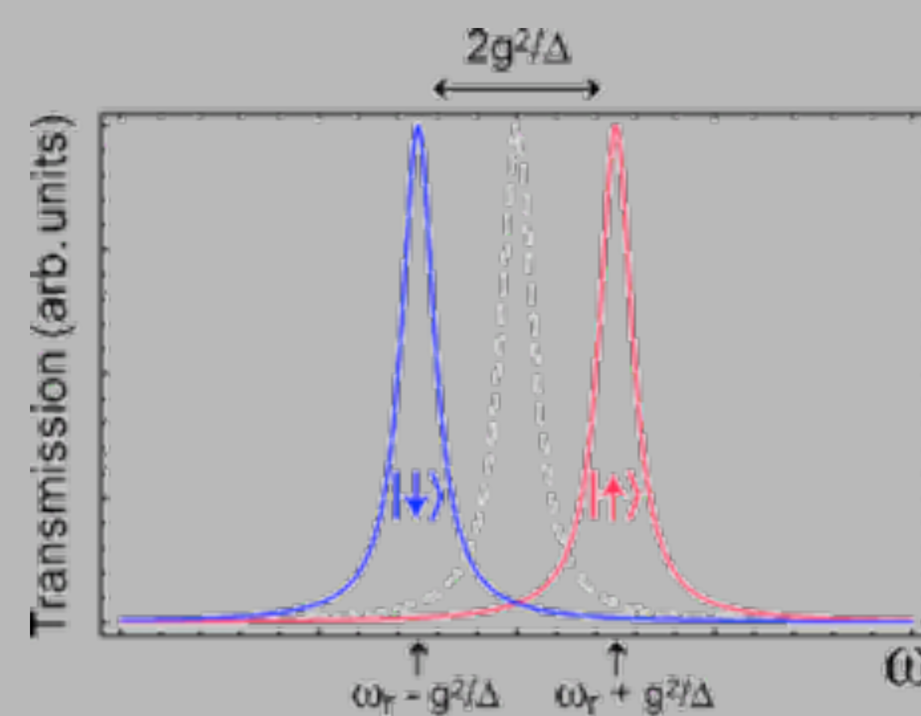
$|+\rangle = |\uparrow,0\rangle + |\downarrow,1\rangle$

$|-\rangle = |\uparrow,0\rangle - |\downarrow,1\rangle$

“dressed state ladders”

(e.g. Haroche et al., Les Houches notes)

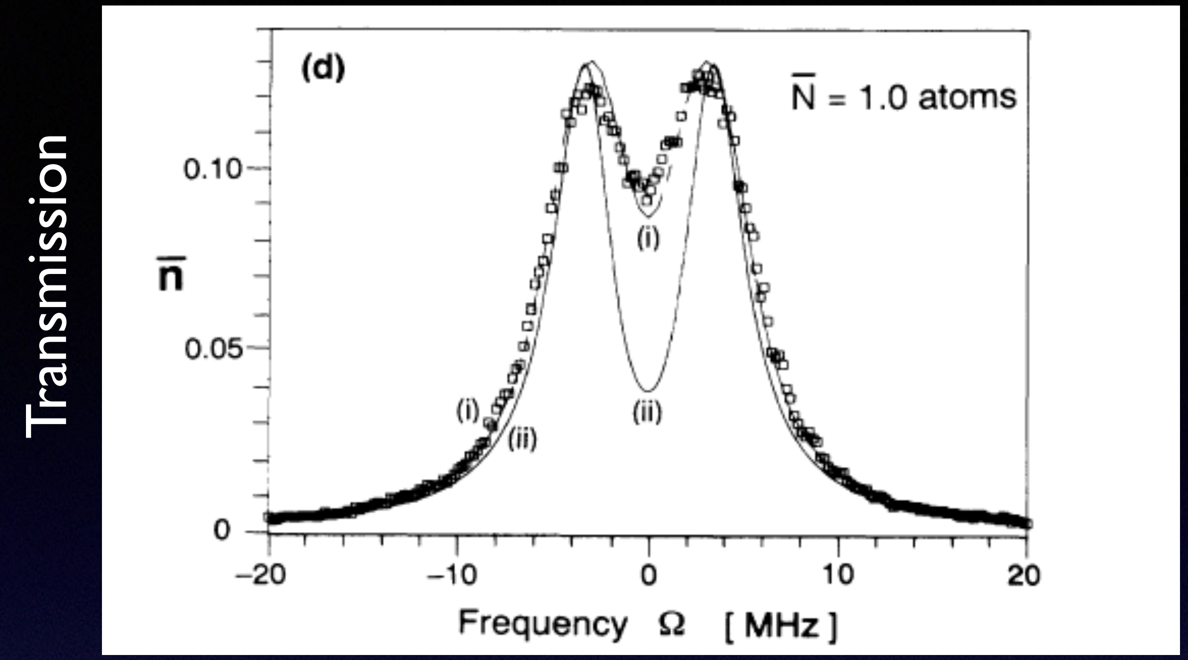
off-resonant



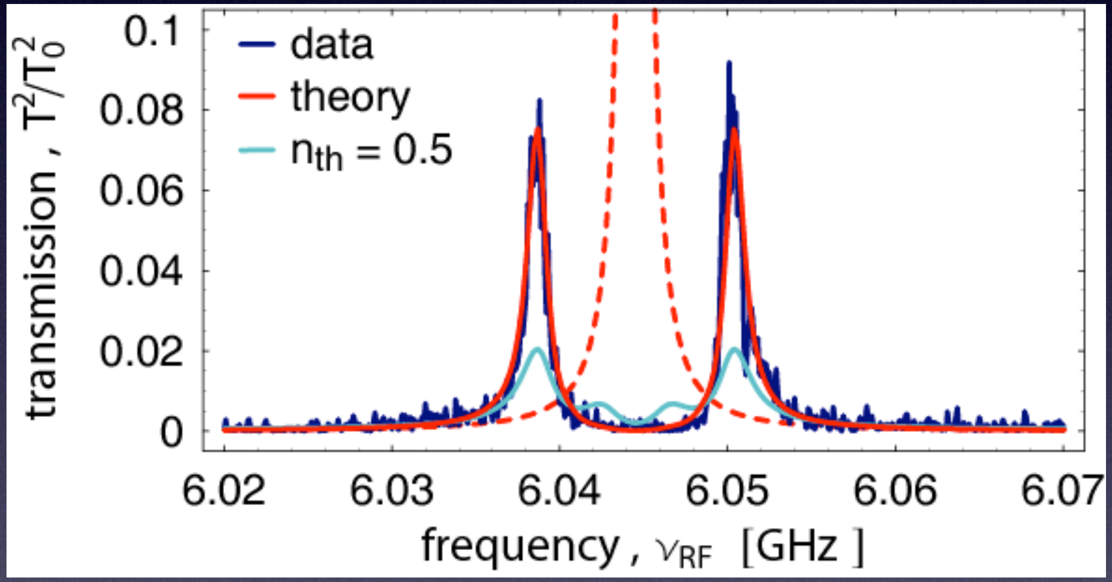
From c-QED to circuit-QED

Cs atoms in an optical cavity

First observation of vacuum Rabi splitting for a single 'real' atom



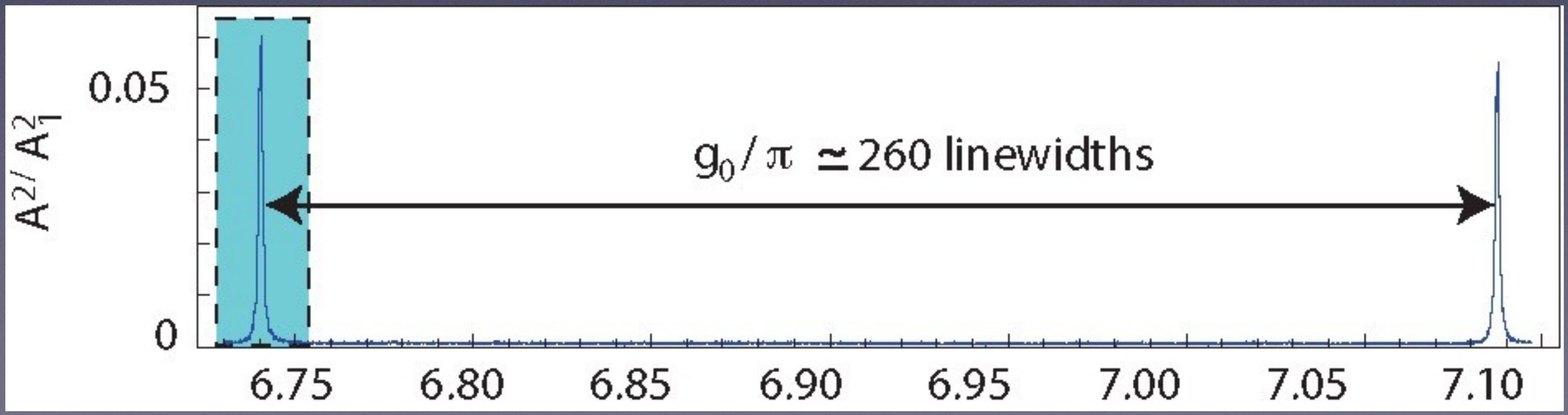
Thompson, Rempse & Kimble 1992



First Yale charge qubit in resonator
Wallraff et al. 2004

large effective dipole moment
$d \sim [e \cdot \mu m] \sim 2 \cdot 10^4 a_0$

Optimized transmon
Bishop et al. 2008

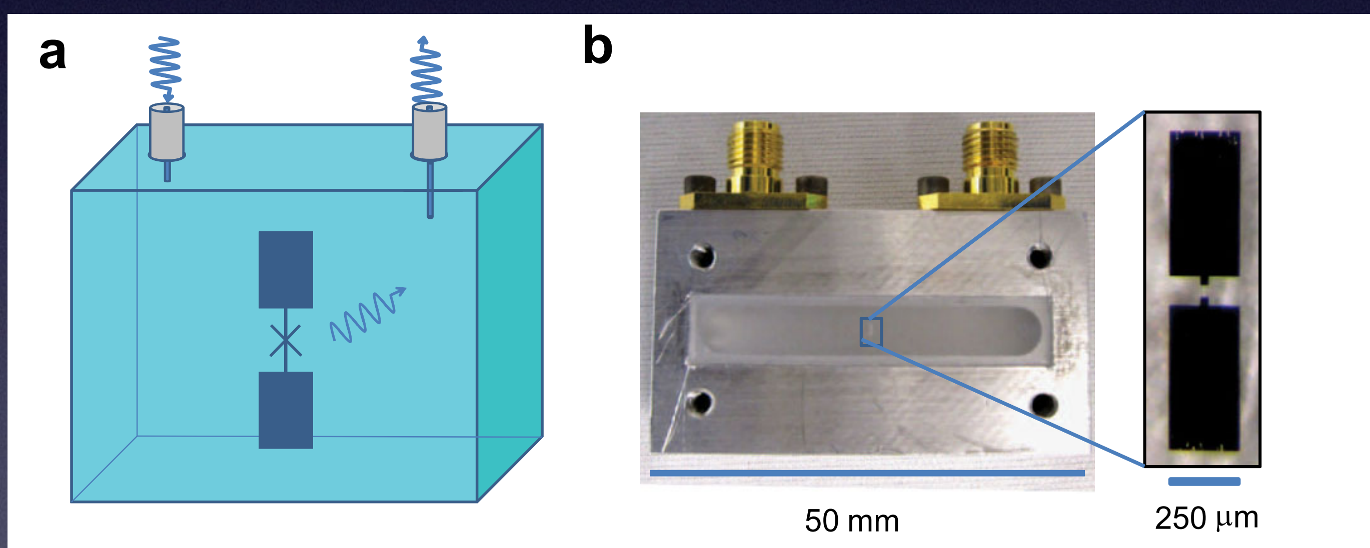


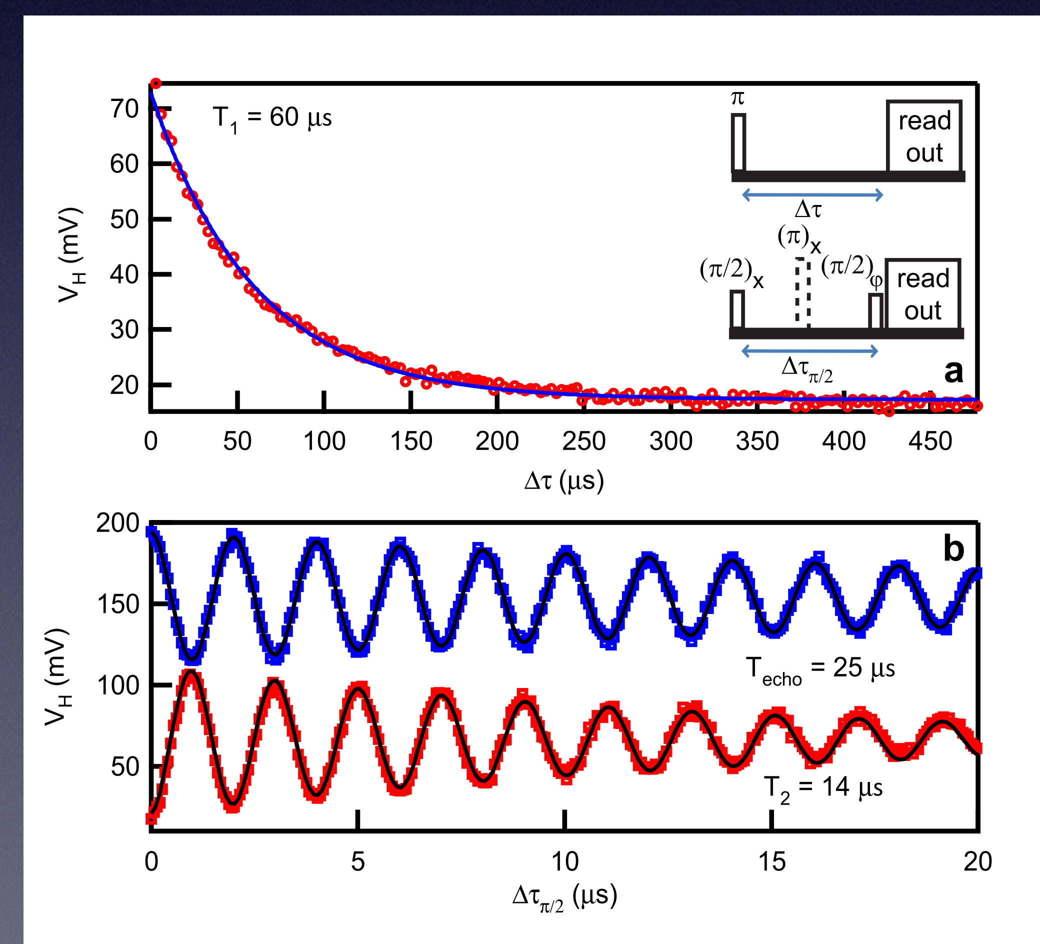
circuit-QED highest coherence times are found using "transmon" qubits and machined cavities

PRL 107, 240501 (2011) PHYSICAL REVIEW LETTERS 9 DECEMBER 2011

Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture

Hanhee Paik,[1] D. I. Schuster,[1,2] Lev S. Bishop,[1,3] G. Kirchmair,[1] G. Catelani,[1] A. P. Sears,[1] B. R. Johnson,[1,4] M. J. Reagor,[1] L. Frunzio,[1] L. I. Glazman,[1] S. M. Girvin,[1] M. H. Devoret,[1] and R. J. Schoelkopf[1]





"transmon" - Cooper-pair box in the limit of $E_J \gg E_C$