Superconducting nanostructures for quantum technologies

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Windsor Summer School – 15 August 2012

This presentation (2 talks)

1. Introduction

2. Quantum bits with superconducting nanostructures

A. Single charge qubit

B. Coupled charge qubits (quantum beatings)

3. Charge pumping with Coulomb blockade devices

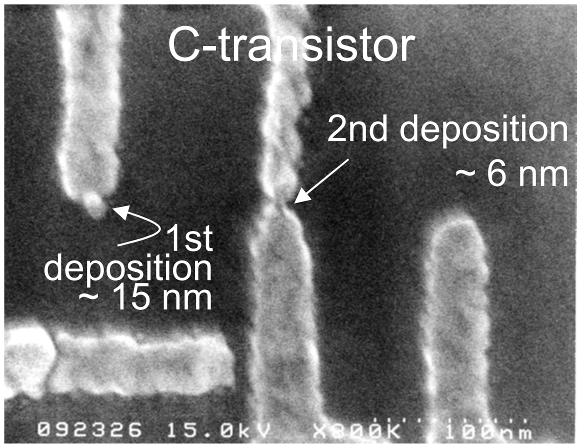
A. Incoherent charge pumping

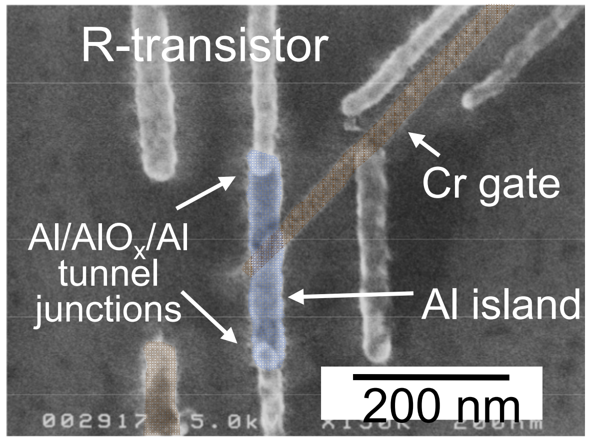
B. Coherent charge pumping

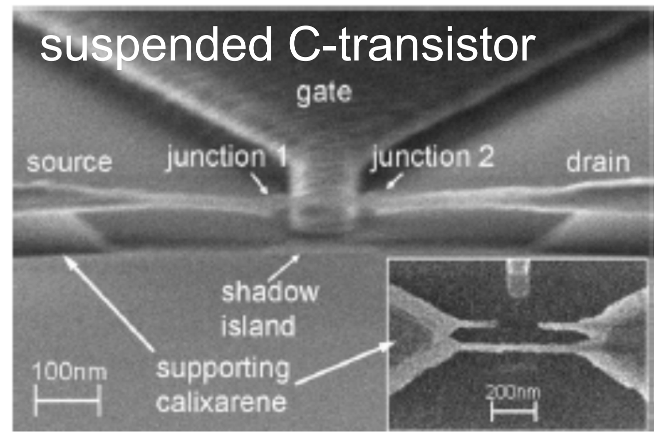
Tsukuba history 1997 - 2012

Al tunnel-junction nanoelectronic devices

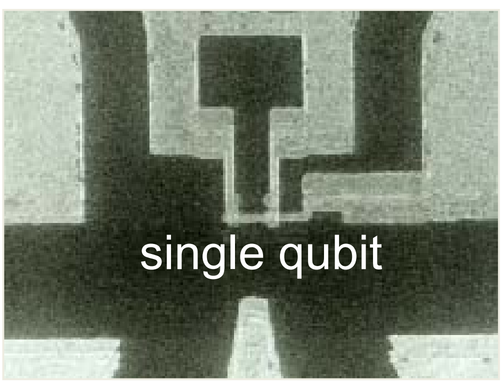
Single-electron transistors

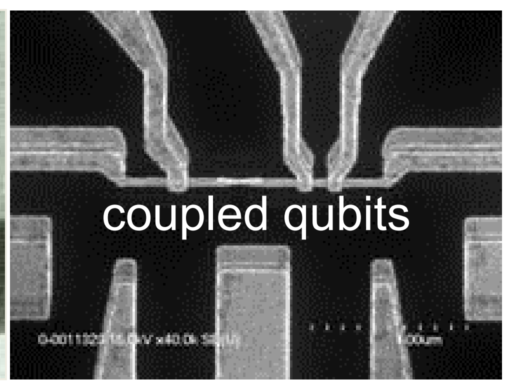




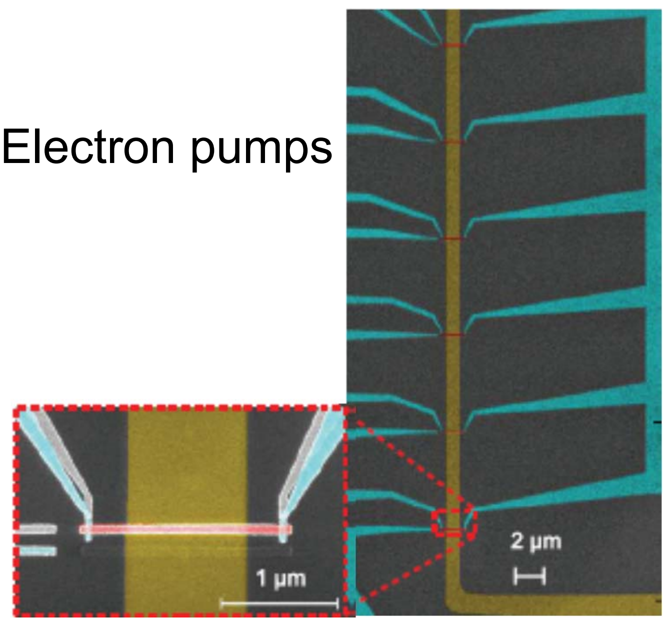


Charge qubits





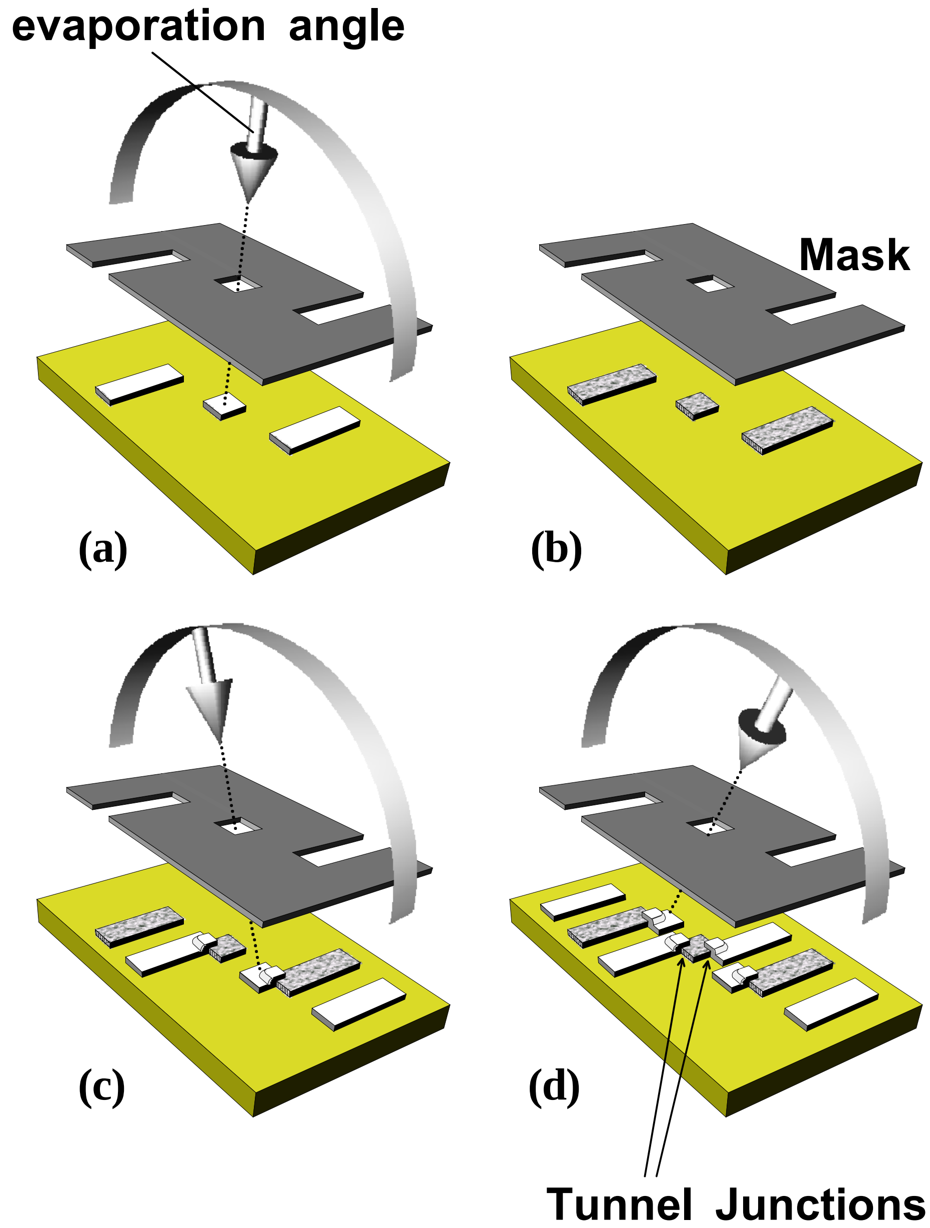
Electron pumps



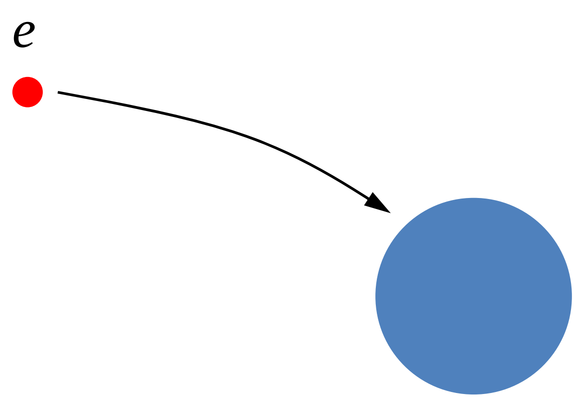
Fabrication of metallic nanostructures

Electron-beam lithography + angle deposition

Al deposition at 3 angles



Coulomb blockade

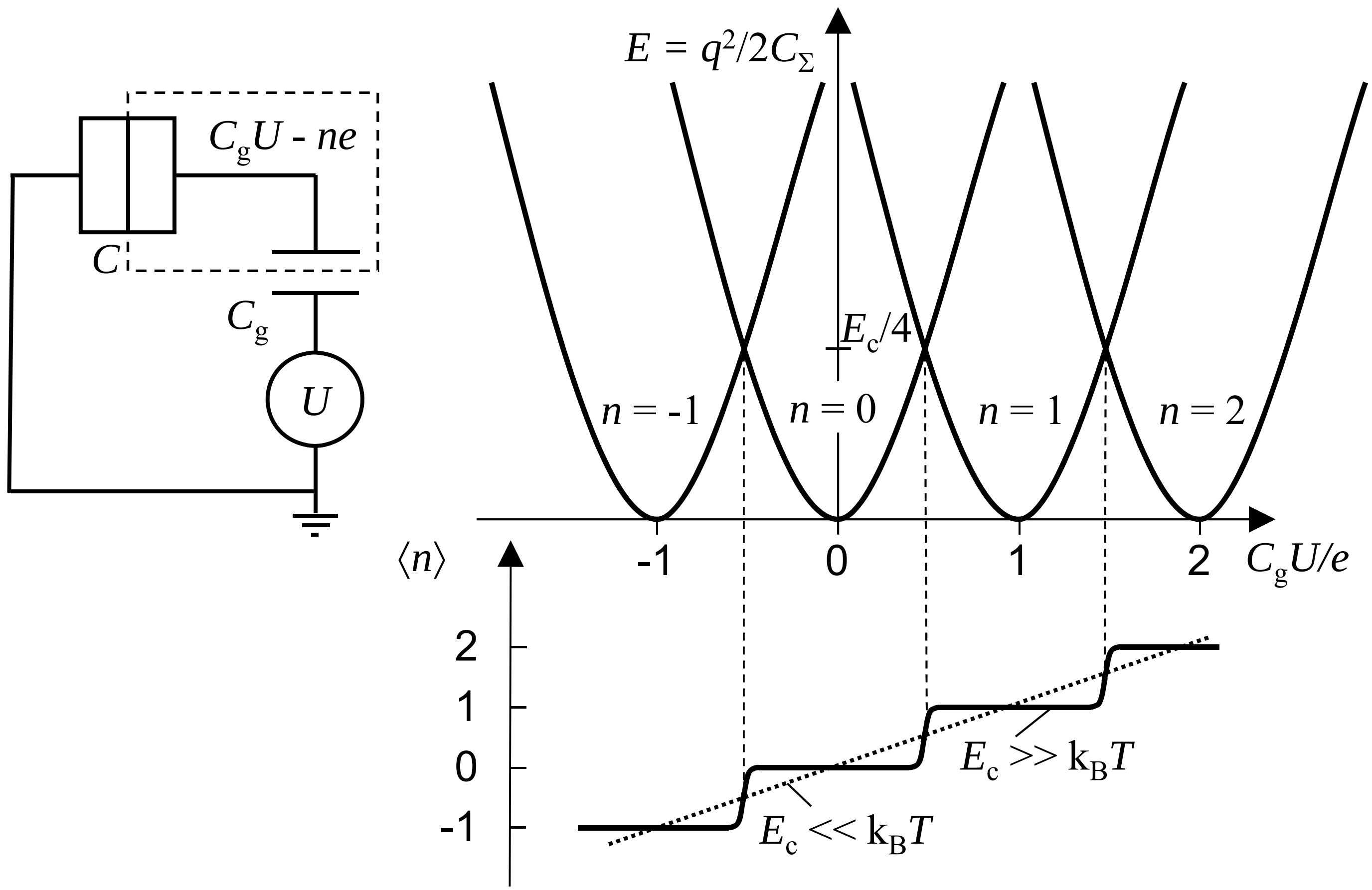


$\Delta E \sim E_c = e^2/2C$

C (F)	0.8×10^{-15}	0.8×10^{-16}	0.8×10^{-17}	0.8×10^{-18}
E_c	100 μeV	1 meV	10 meV	0.1 eV
E_c/k_B (K)	1	10	100	1000

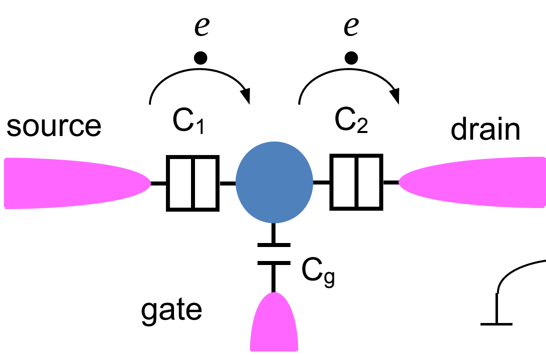
Single-electron box

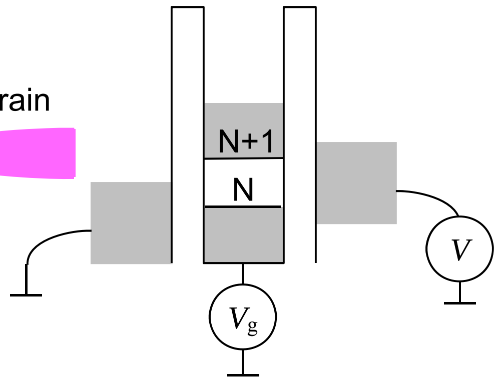
Saclay group, 1991)

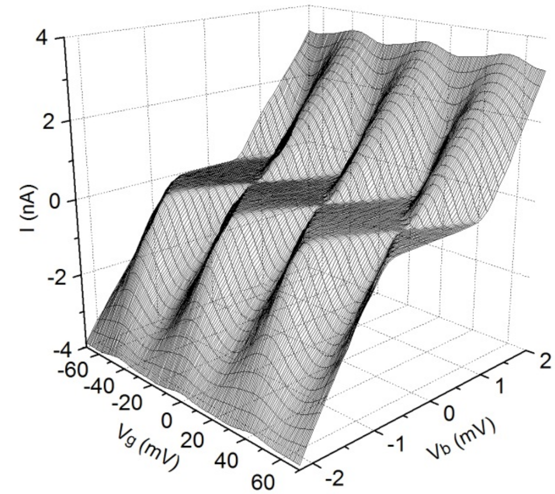


Single-electron transistor (SET)

Averin, Likharev (1986) theory
Fulton, Dolan (1987) exp.



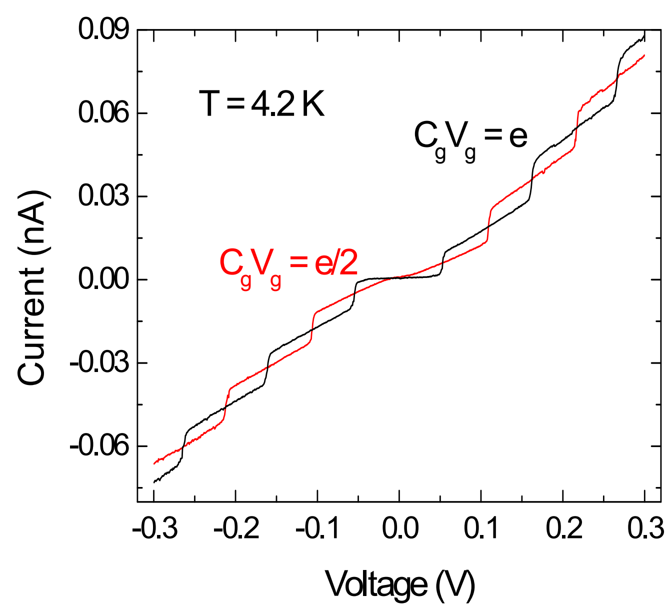




Conditions: $k_B T << E_c \equiv e^2/2C_\Sigma$
$R >> R_Q \equiv h/4e^2 \approx 6.5\ \mathrm{k}\Omega$

Features:

Coulomb blockade
e-periodic modulation on Q_g
Coulomb staircase
Charge sensitivity $10^{-3}\ e/\mathrm{Hz}^{1/2}$ in dc
$10^{-5}\ e/\mathrm{Hz}^{1/2}$ in rf



Lancaster history 2012 ~

LU Quantum Technology Centre

Research on solid-state quantum nanostructures

- looking for novel physical phenomena
- developing high-end instrumentation

Three major fields:

- quantum superconducting circuits
- quantum metrology
- quantum nanoelectromechanics

Newly built class 100 cleanroom:

- Electron-beam writer JEOL JBX-5500FS
- deposition and etching machines

Cryogenic and measurement facilities

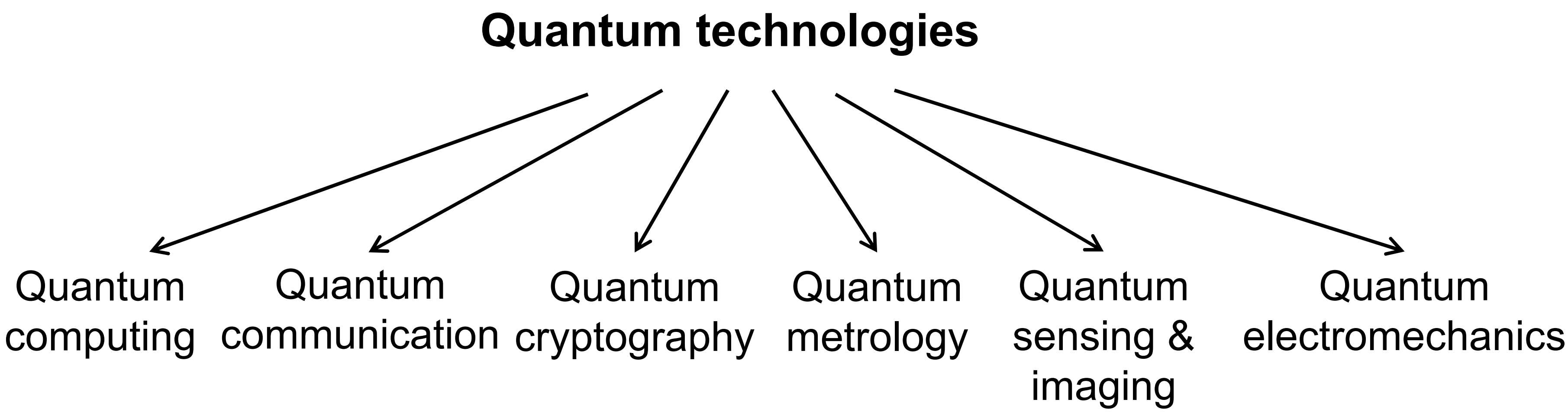
What is quantum technology?

Build and **control** quantum systems for practical purposes

Control =

- tune energy levels
- prepare a system in a well-defined initial state
- manipulate the system
- do measurement

Key areas of QT



The second quantum revolution

Jonathan P. Dowling, Gerard J. Milburn (2002)

- use the rules to develop new technologies/applications

The first quantum revolution

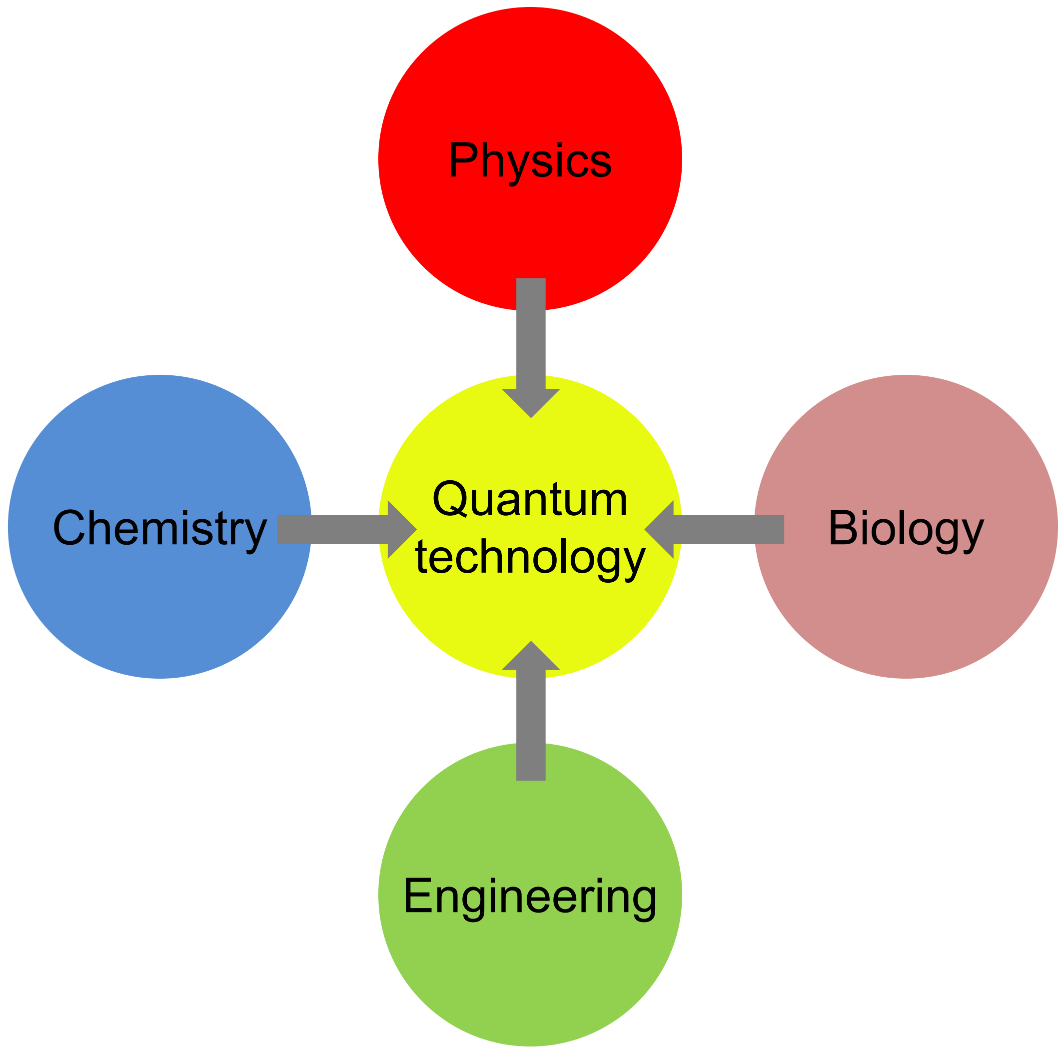
- understand new rules that govern physical reality

Two generations of quantum technologies

"Quantum technologies: an old new story", Physics World , May 2012
Iulla Georgescu and Franco Nori

Concept	Technology
1st-generation quantum technologies	
spin	• NMR, ESR • GMR (hard discs, MRAM)
tunneling	• STM • tunneling diodes • Josephson junction, SQUIDs
2nd-generation quantum technologies	
superposition and entanglement	• quantum computing • quantum simulation • quantum communication • quantum random number generation • quantum imaging

Quantum technology: interdisciplinary research

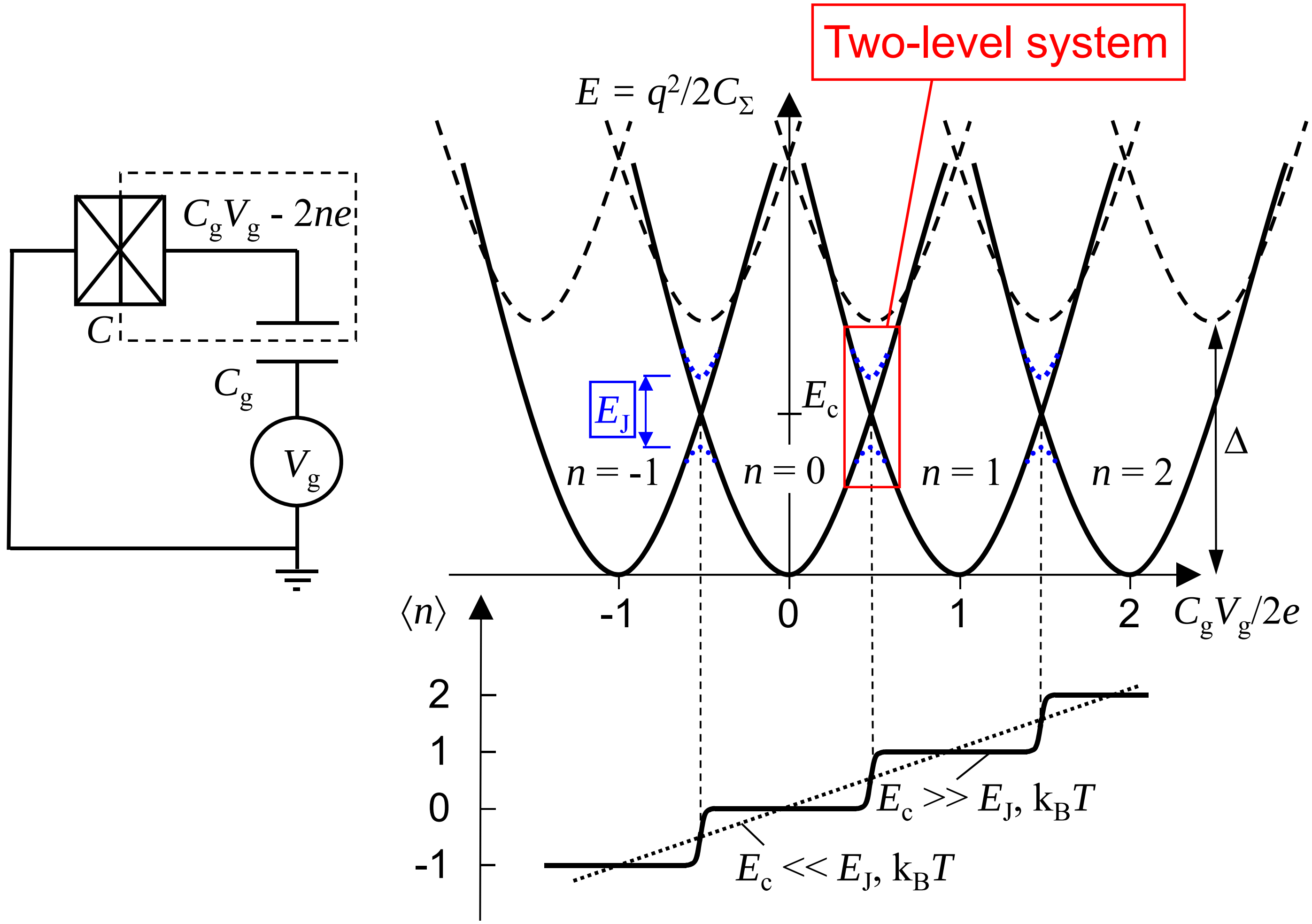


Part 2

Quantum bits with superconducting nanostructures

Cooper pair box

M. Büttiker (1987)
V. Bouchiat et al. (1995)



Charge qubit

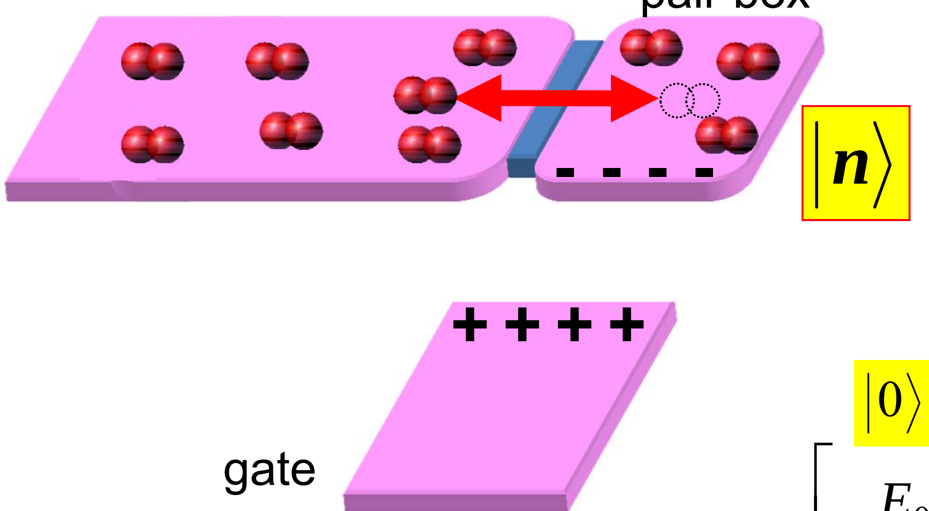
V. Bouchiat et al. (1995)

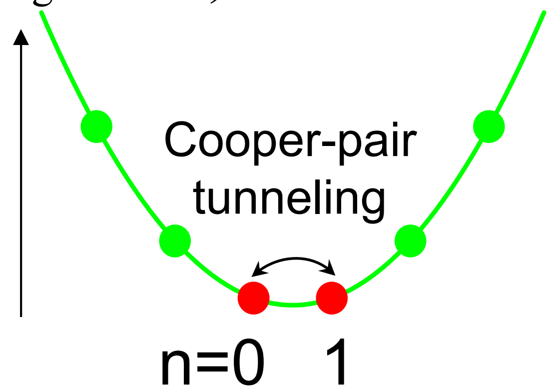
- two-level system
- ~10^8 conduction electrons

$$\Delta > E_C$$

$$4E_C > E_J >> kT$$

$$E = (C_g V_g - 2ne)^2/2C$$



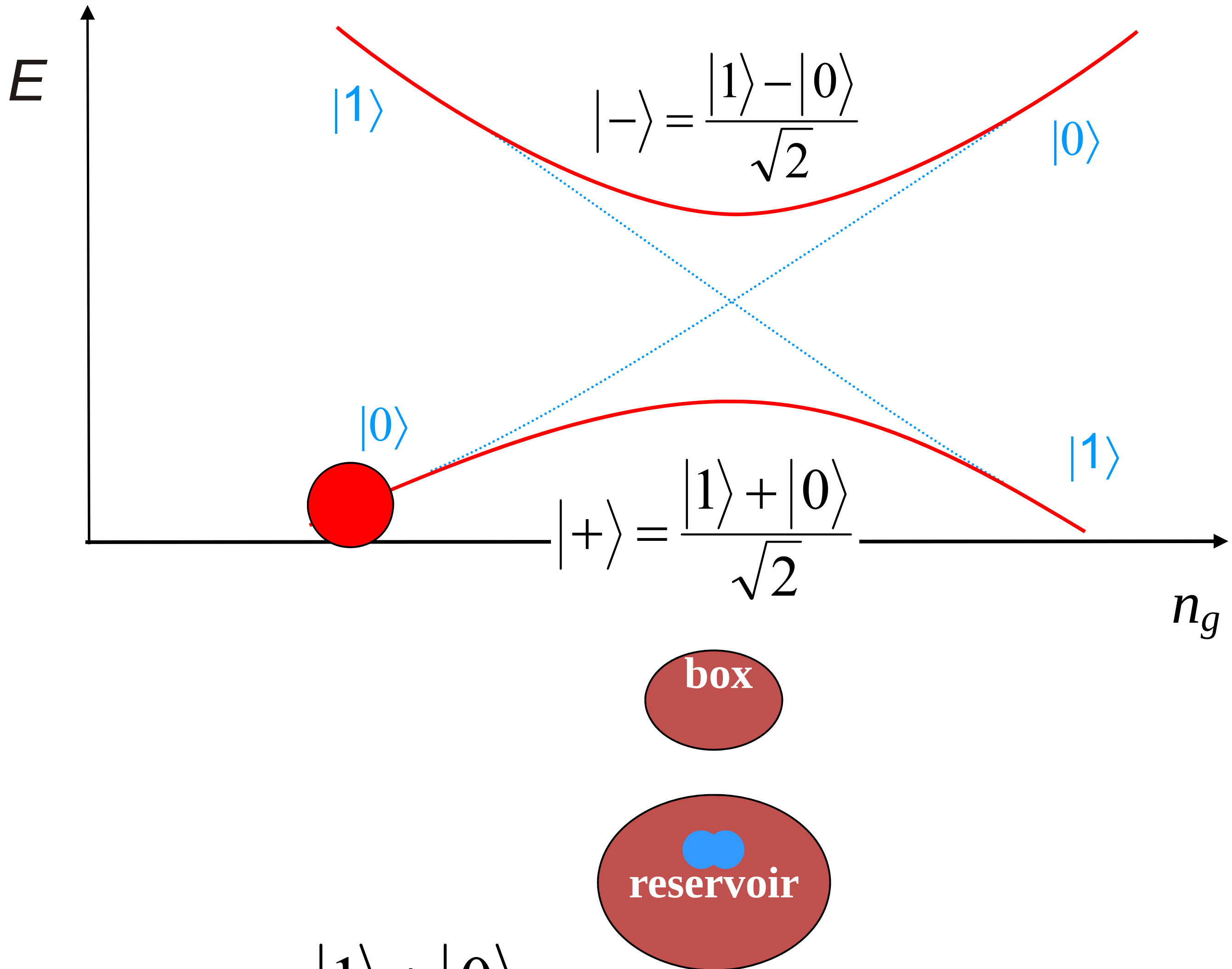


$$H = \begin{bmatrix} E_0 & -\frac{1}{2}E_J \\ -\frac{1}{2}E_J & E_1 \end{bmatrix} \quad \text{columns: } |0\rangle, |1\rangle; \text{ rows: } |0\rangle, |1\rangle$$

$$E_0 = E_c\left(0 - Q_g/2e\right)^2$$

$$E_1 = E_c\left(1 - Q_g/2e\right)^2$$

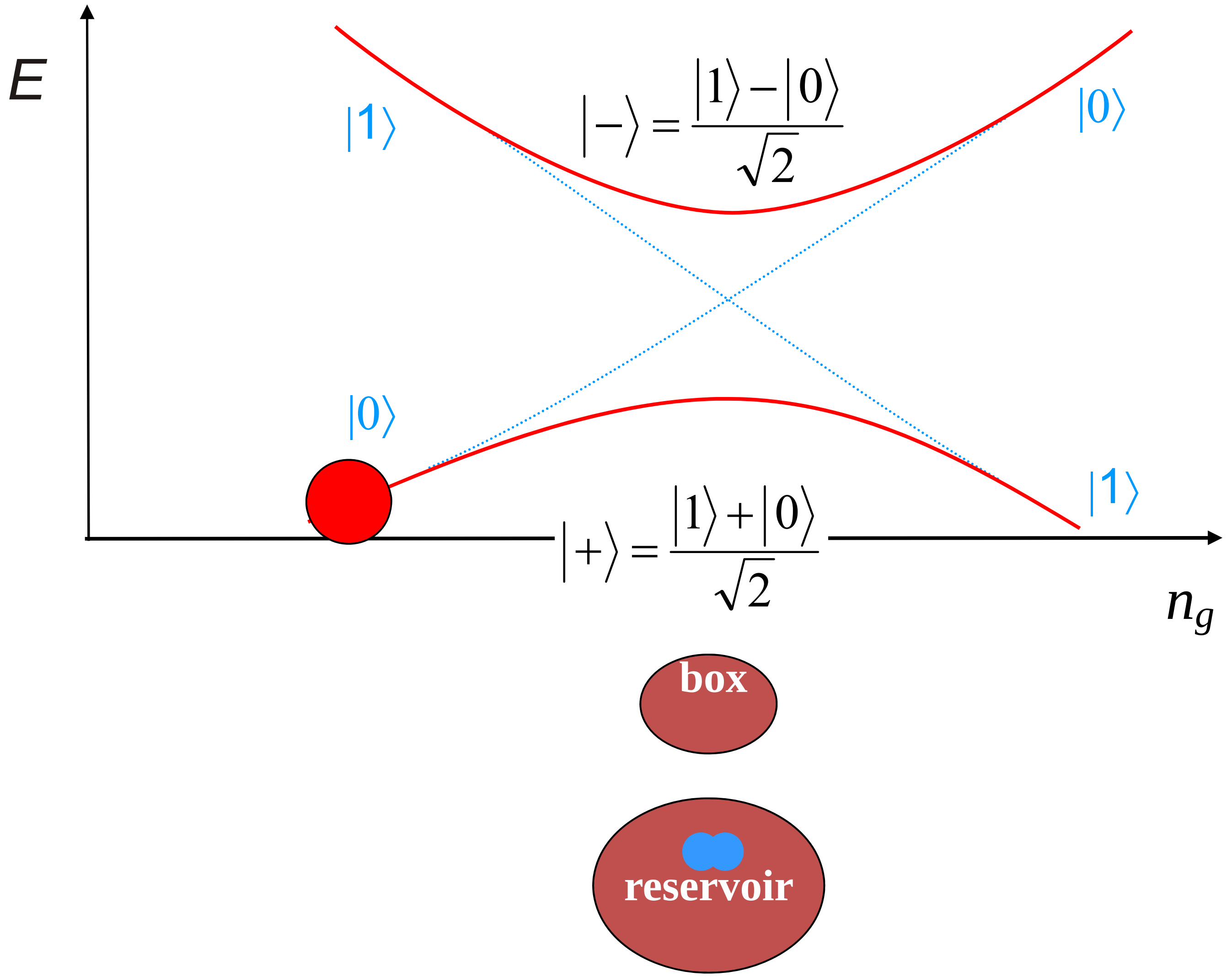
Adiabatic manipulation



$$|+\rangle = \frac{|1\rangle + |0\rangle}{\sqrt{2}}$$

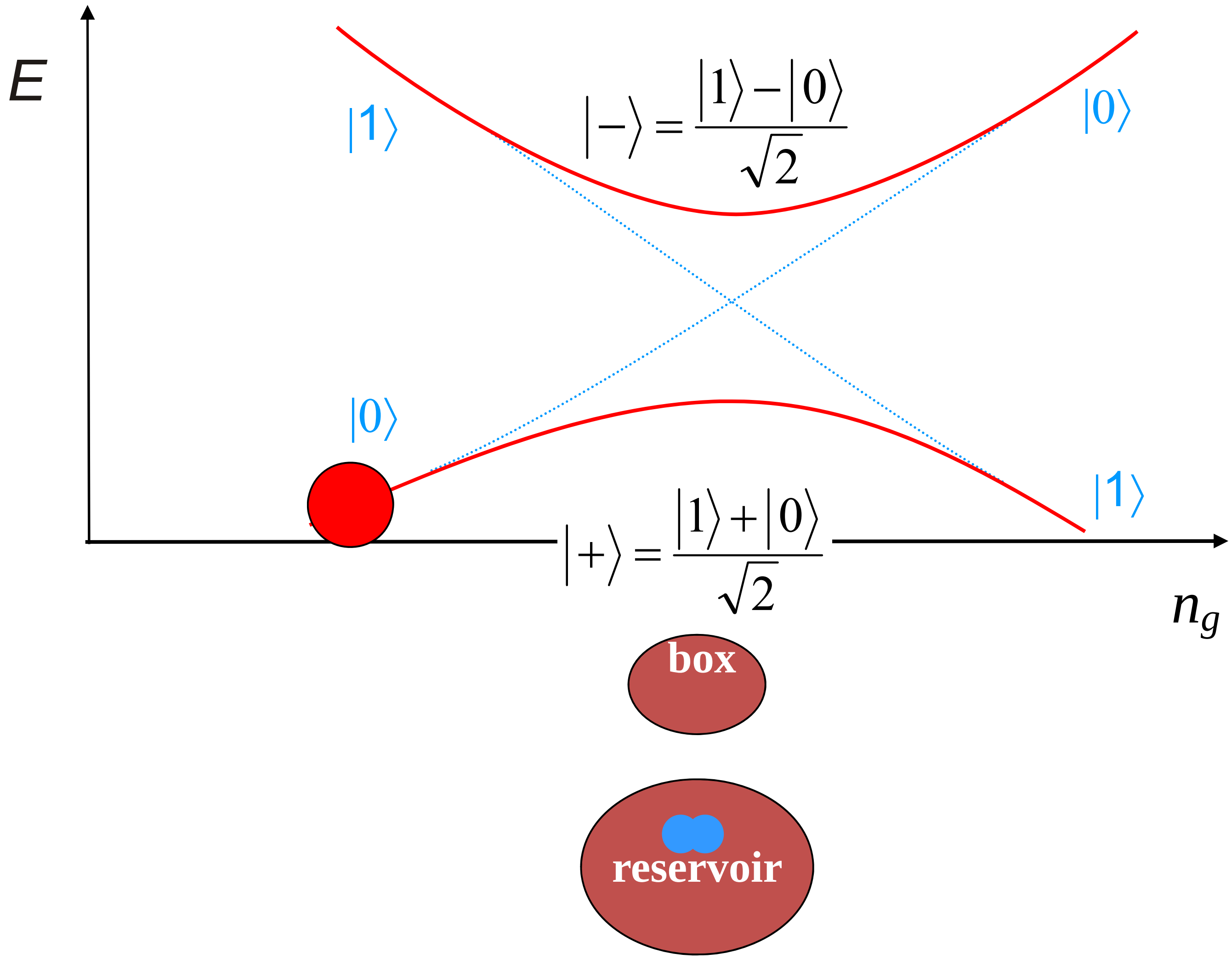
$|1\rangle$

Nonadiabatic manipulation: $\omega\Delta t = \pi + 2\pi k$



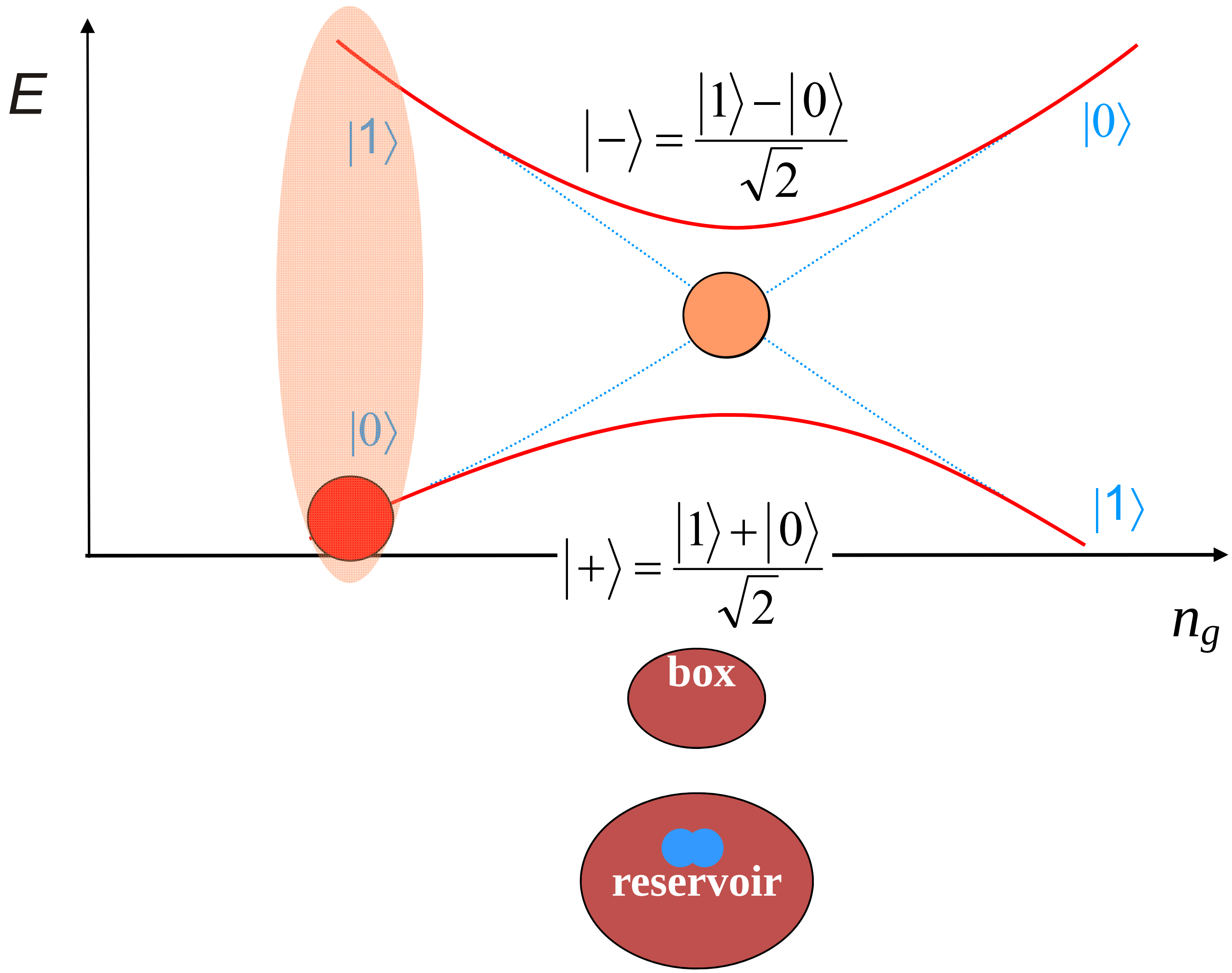
$$\cos(\omega t)|0\rangle + i\sin(\omega t)\,|1\rangle$$

Nonadiabatic manipulation $\omega \Delta t = 2\pi\, k$



$$\cos(\omega t)\,|0\rangle + i\sin(\omega t)\,|1\rangle$$

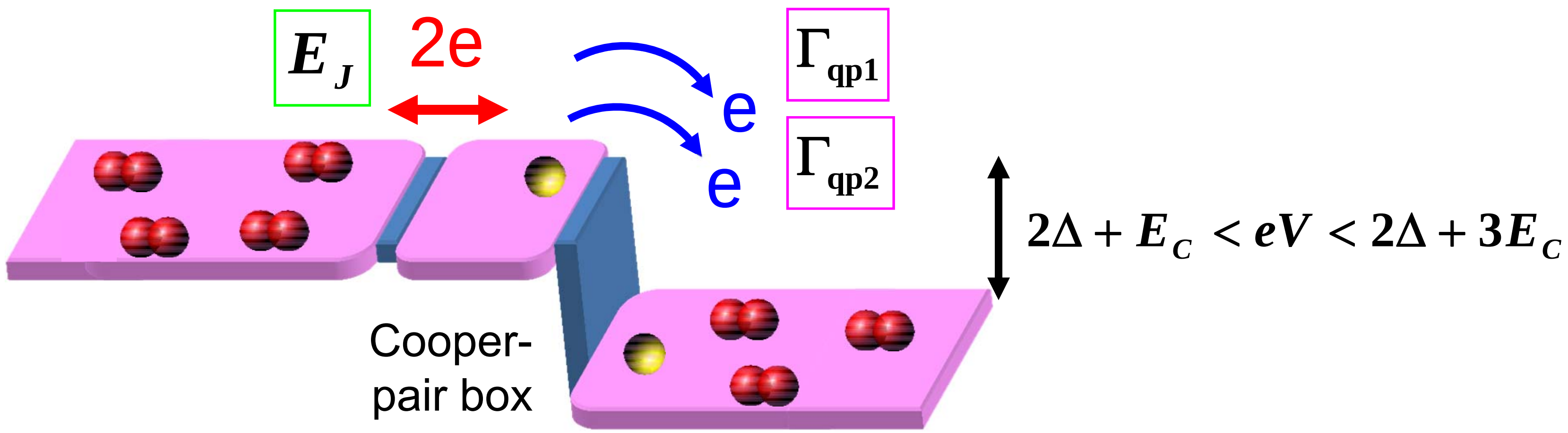
Nonadiabatic manipulation $\omega\Delta t \neq \pi k$



$$\cos(\omega\Delta t)|0\rangle + i\sin(\omega\Delta t)|1\rangle$$

Final state readout

Josephson-quasiparticle cycle (Fulton et al., 1989)

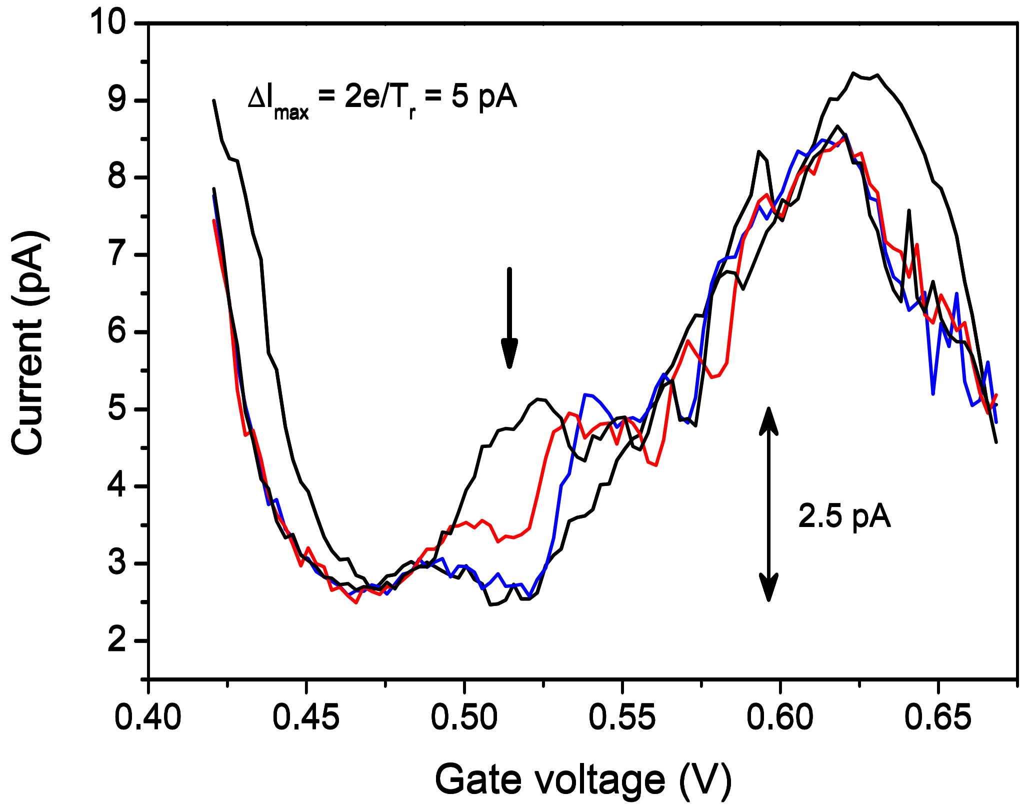


+ probe

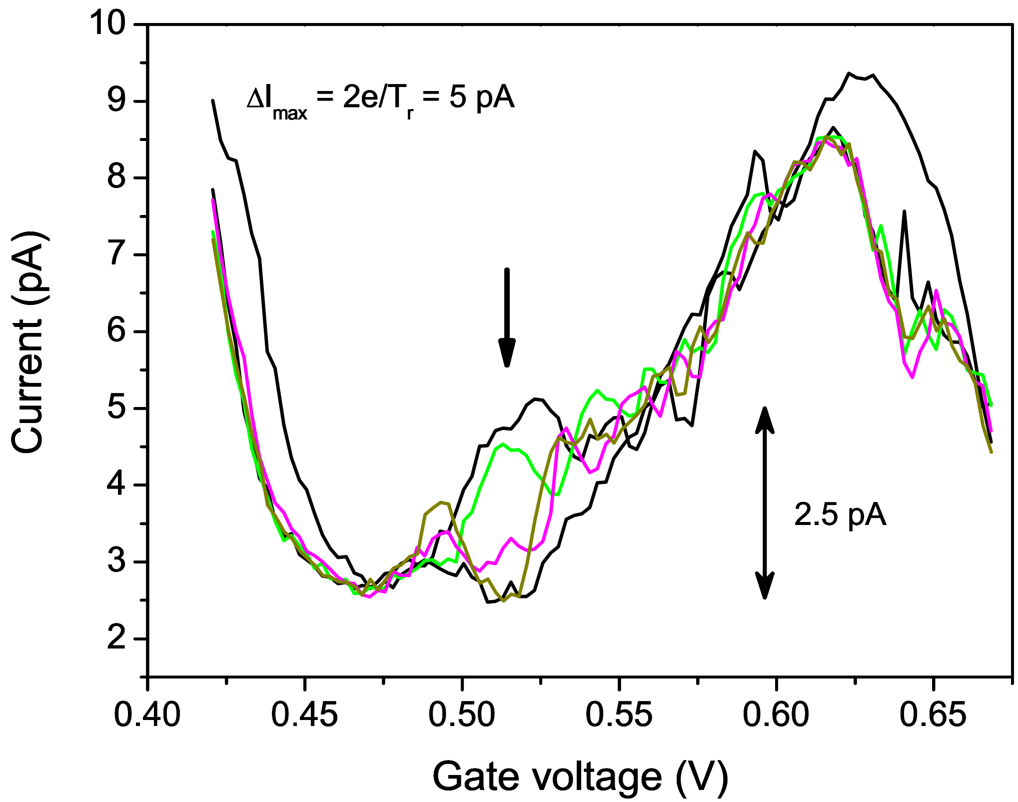
- detection of state $|1\rangle$
- initialization to the initial state $|0\rangle$

$$E_J \gg \hbar\Gamma_{qp1}$$

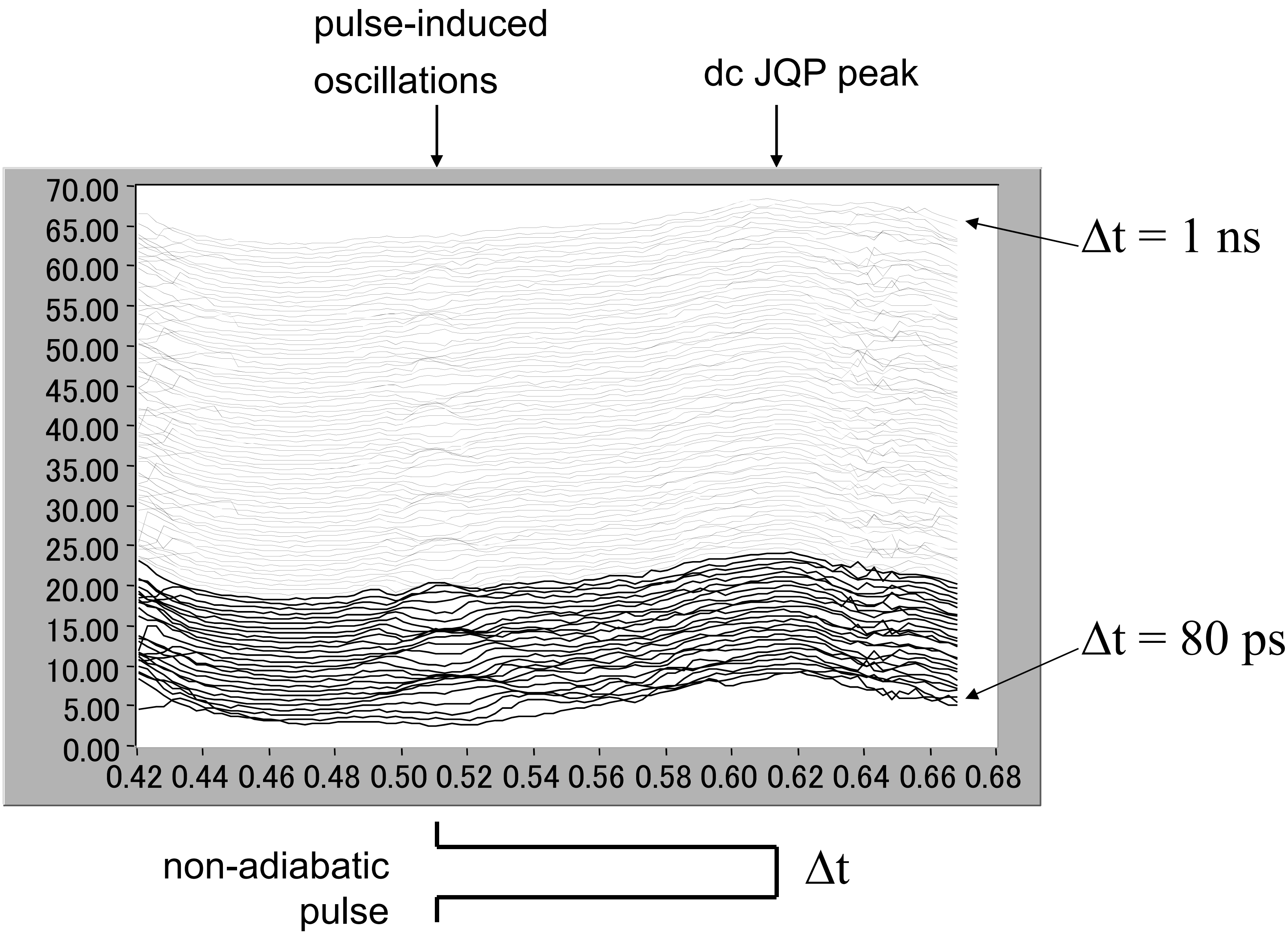
Dc sweep + pulses (1)



Dc sweep + pulses (2)

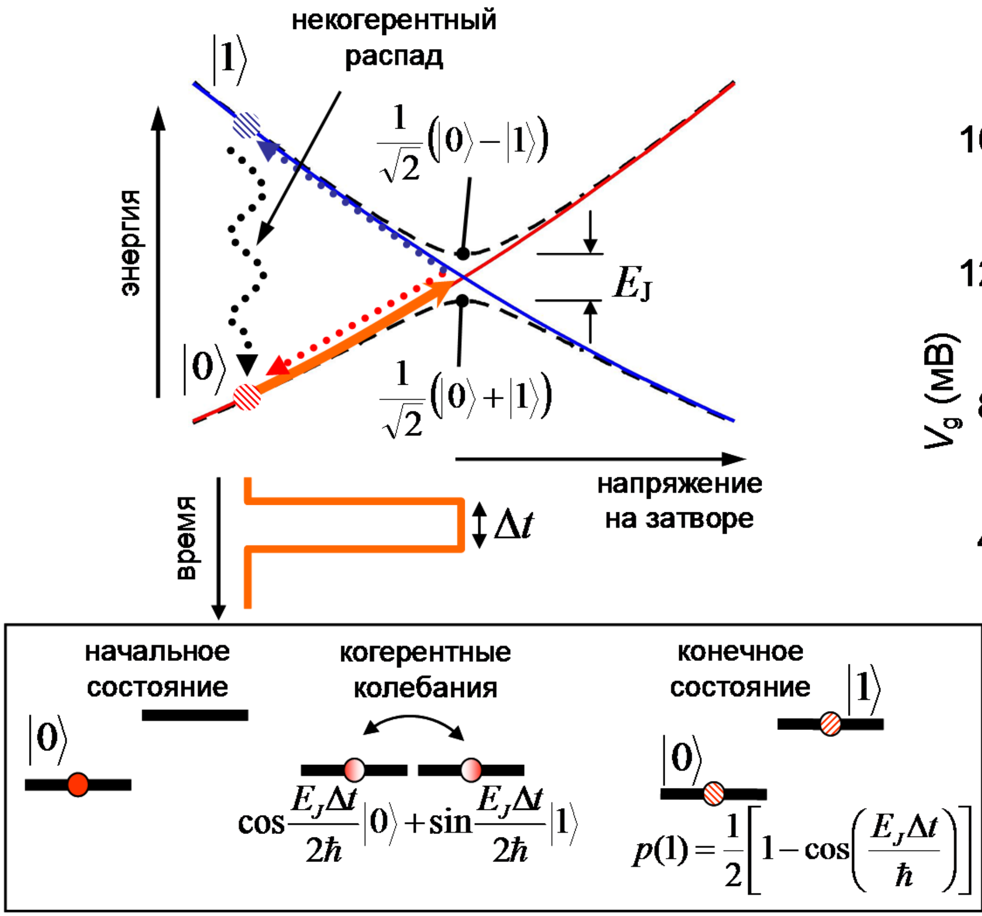


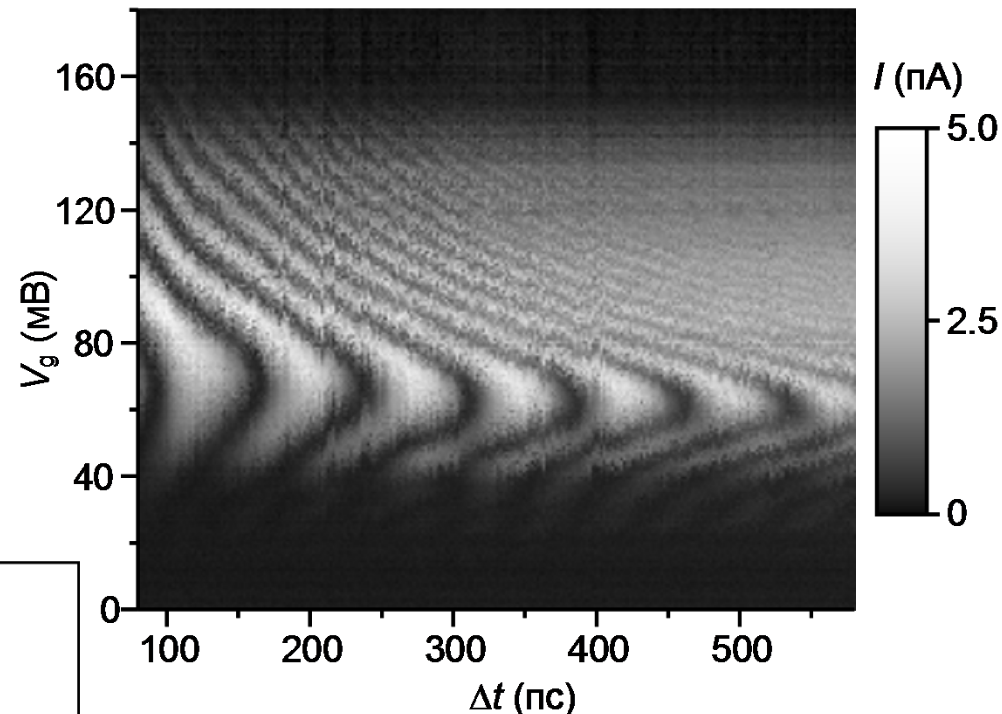
Dc sweep + pulses (3)



Observation of quantum oscillations

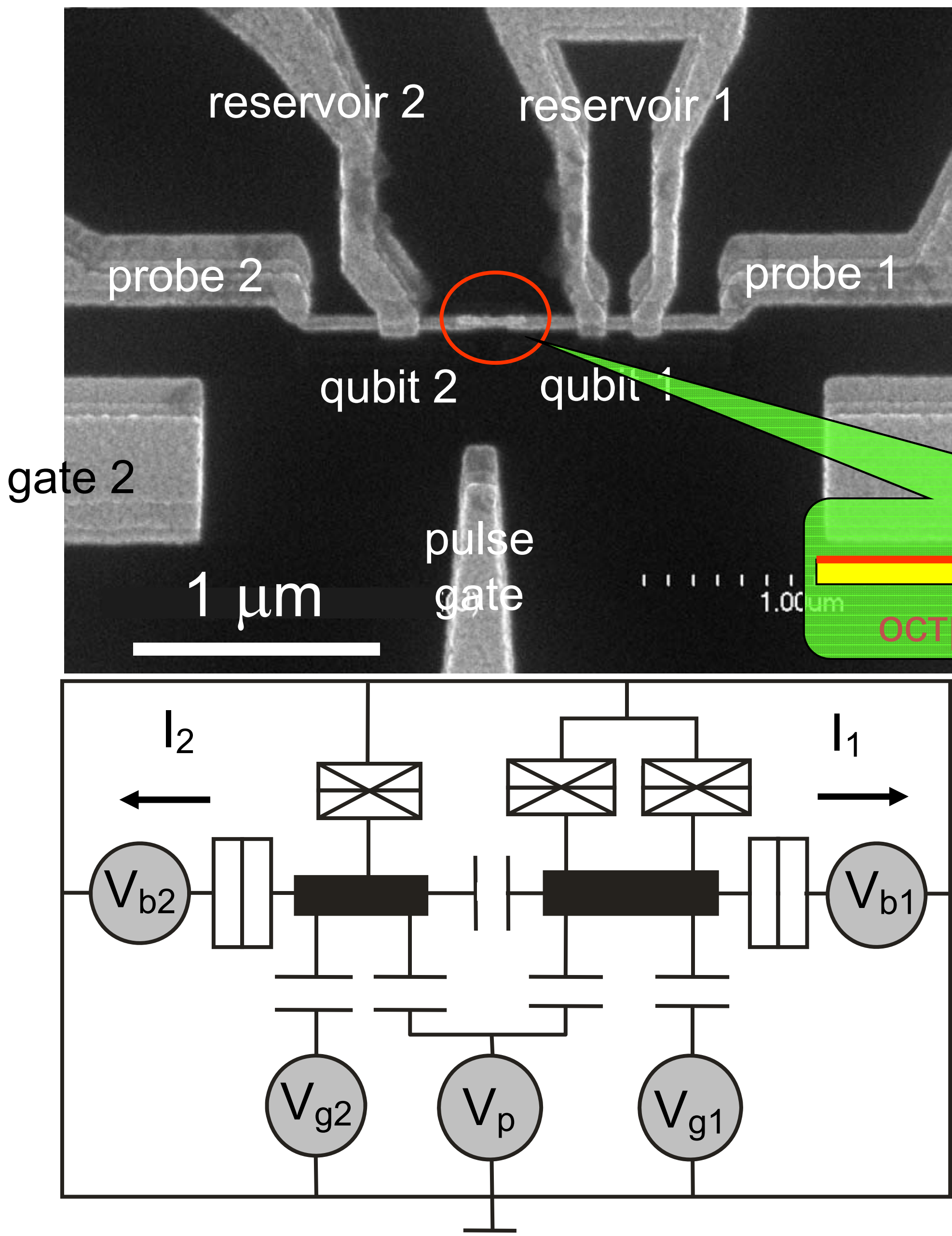
Y. Nakamura et al., Nature **398**, 786 (1999)

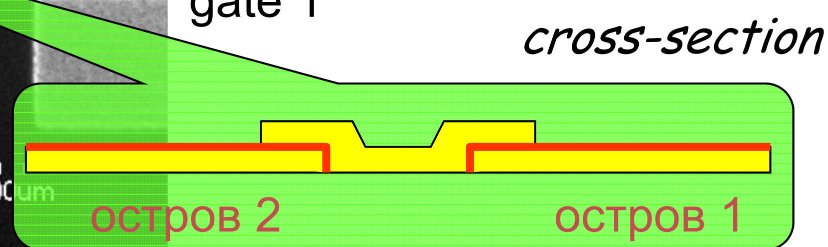




Coupled charge qubits

Yu.A. Pashkin et al.,
Nature **421**, 823 (2003)





capacitive coupling

I_1 and I_2 give info about charge states

Hamiltonian

Charge basis

$$H = \begin{bmatrix} E_{00} & -\frac{1}{2}E_{J1} & -\frac{1}{2}E_{J2} & 0 \\ -\frac{1}{2}E_{J1} & E_{10} & 0 & -\frac{1}{2}E_{J2} \\ -\frac{1}{2}E_{J2} & 0 & E_{01} & -\frac{1}{2}E_{J1} \\ 0 & -\frac{1}{2}E_{J2} & -\frac{1}{2}E_{J1} & E_{11} \end{bmatrix}$$

Columns: |00> |10> |01> |11>

Rows: |00> |10> |01> |11>

$\boldsymbol{E_{J1,2} \sim E_m < E_{c1,2}}$

initial state |00>

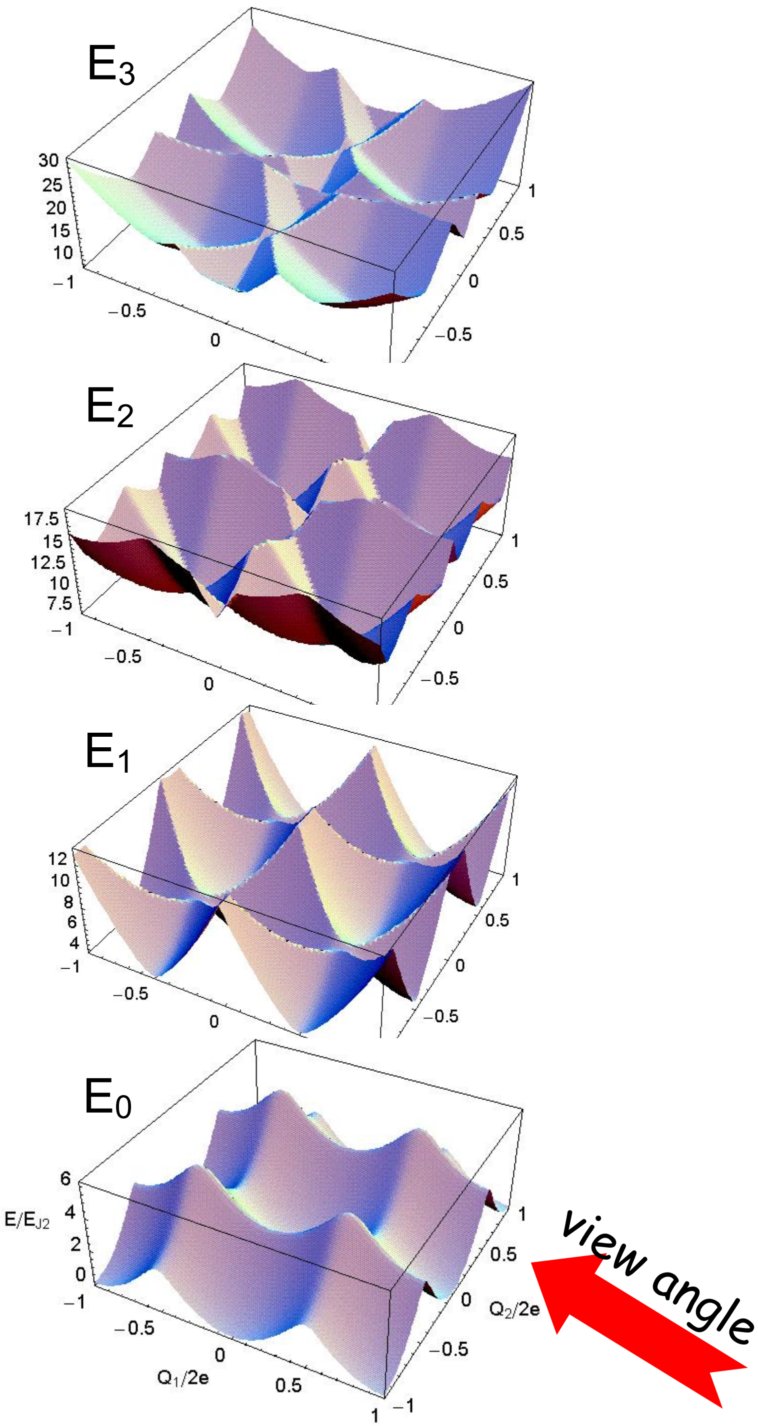
$$E_{n1n2} = E_{c1}(n_{g1}-n_1)^2 + E_{c2}(n_{g2}-n_2)^2 + E_m(n_{g1}-n_1)(n_{g2}-n_2)$$

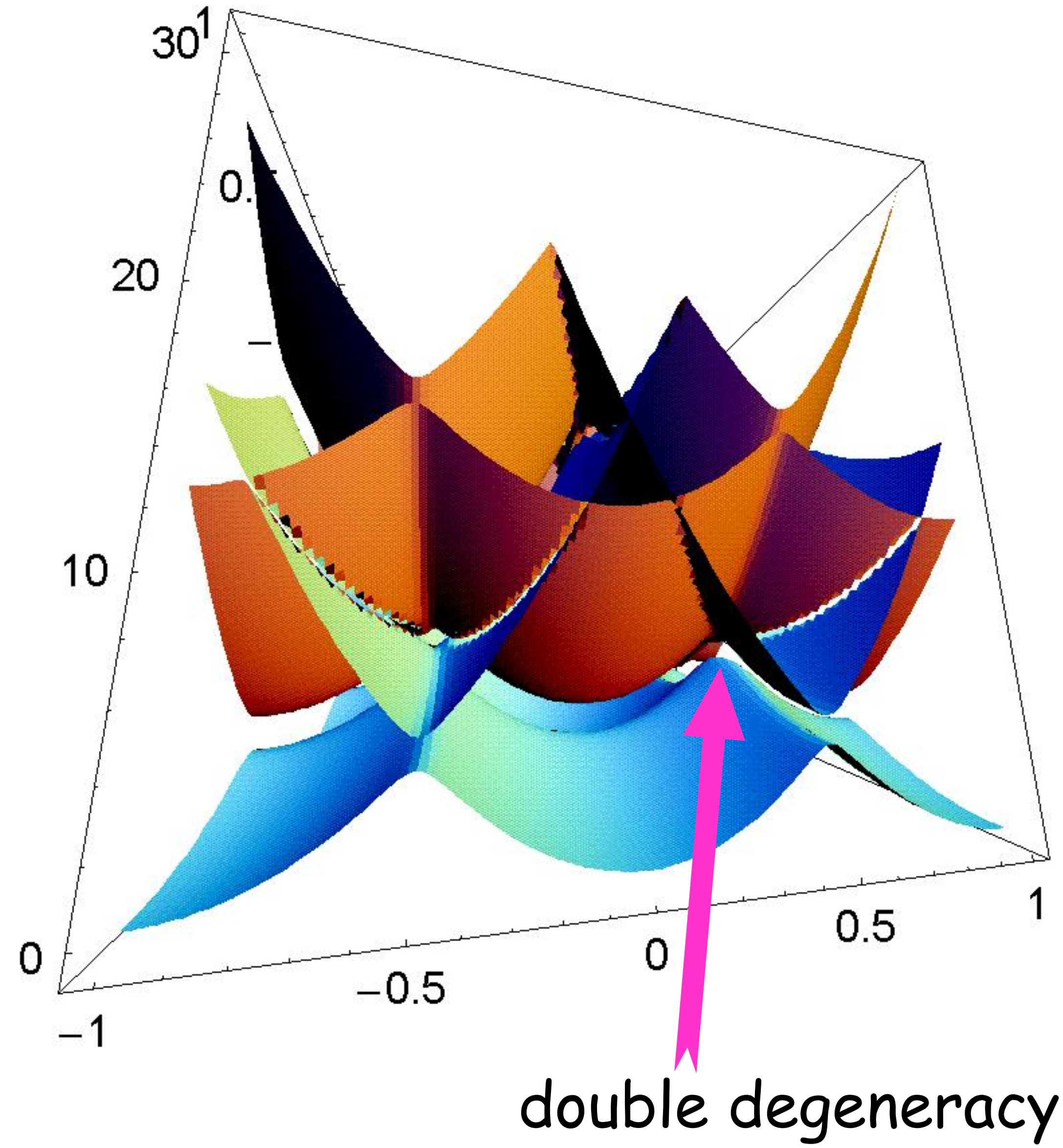
$$E_{c1,2} = 4e^2 C_{\Sigma 2,1}/2(C_{\Sigma 1,2}C_{\Sigma 2,1} - C_m^{\,2}) \approx 4e^2/2C_{\Sigma 1,2}$$

$$n_{g1,2} = (C_{g1,2}V_{g1,2} + C_p V_p)/2e$$

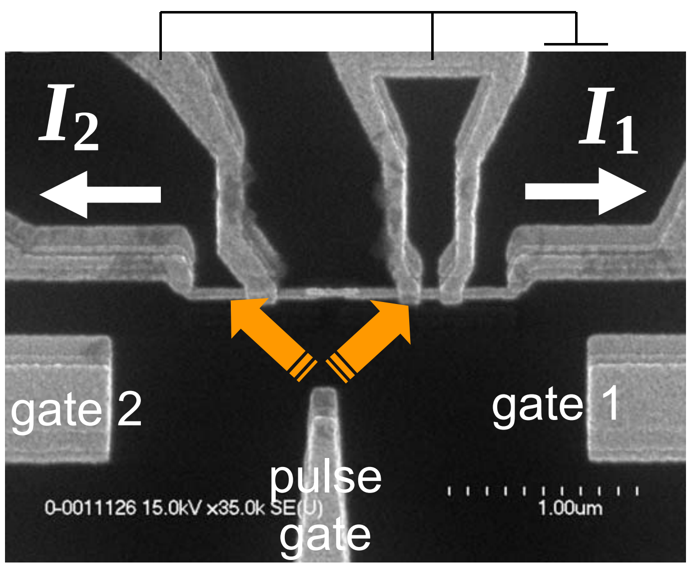
$$E_m = 4e^2 C_m/(C_{\Sigma 1}C_{\Sigma 2} - C_m^{\,2})$$

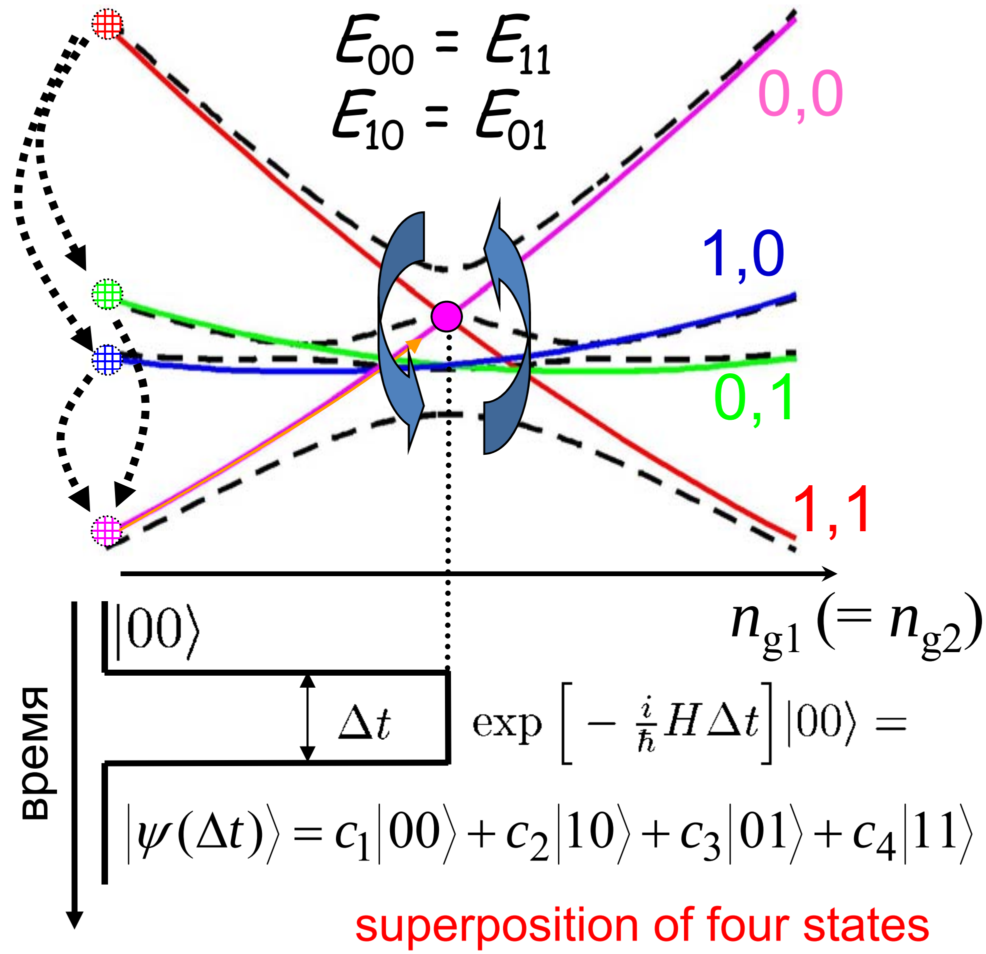
Energy bands

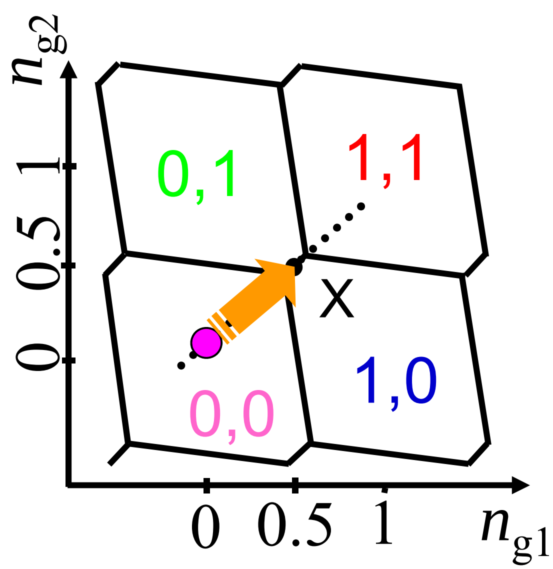




Quantum evolution at double degeneracy







Quantum beatings

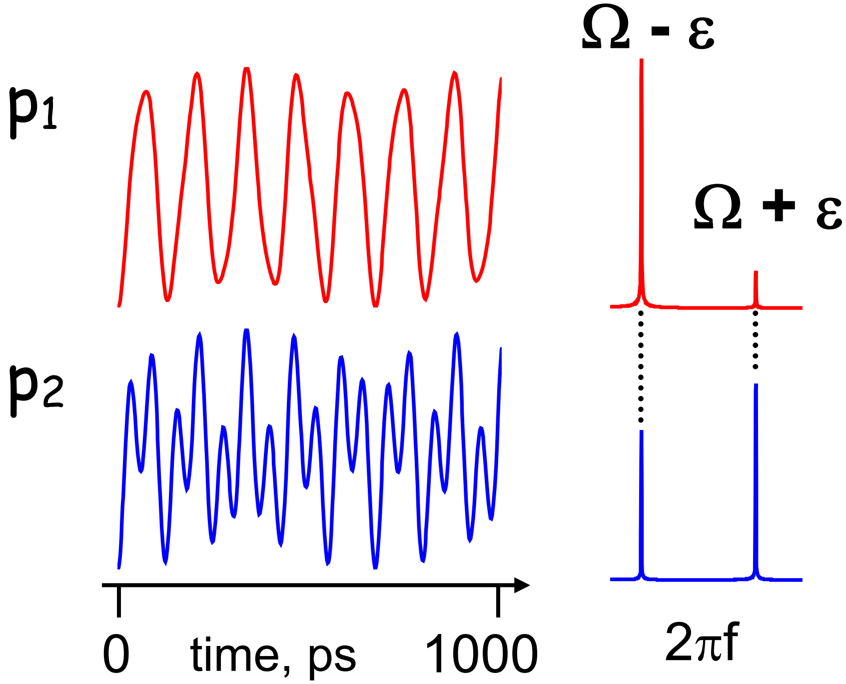
$$|\psi(t)\rangle = \exp\left[-\frac{i}{\hbar}Ht\right]|00\rangle$$

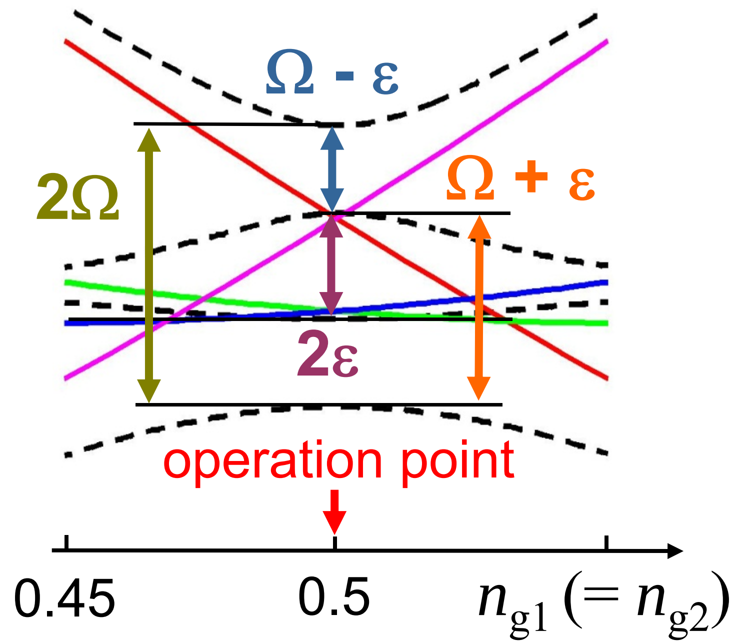
$$|\psi(t)\rangle = c_1|00\rangle + c_2|10\rangle + c_3|01\rangle + c_4|11\rangle$$

$$I_2 \propto p_2(1) \equiv |c_3|^2 + |c_4|^2 =$$

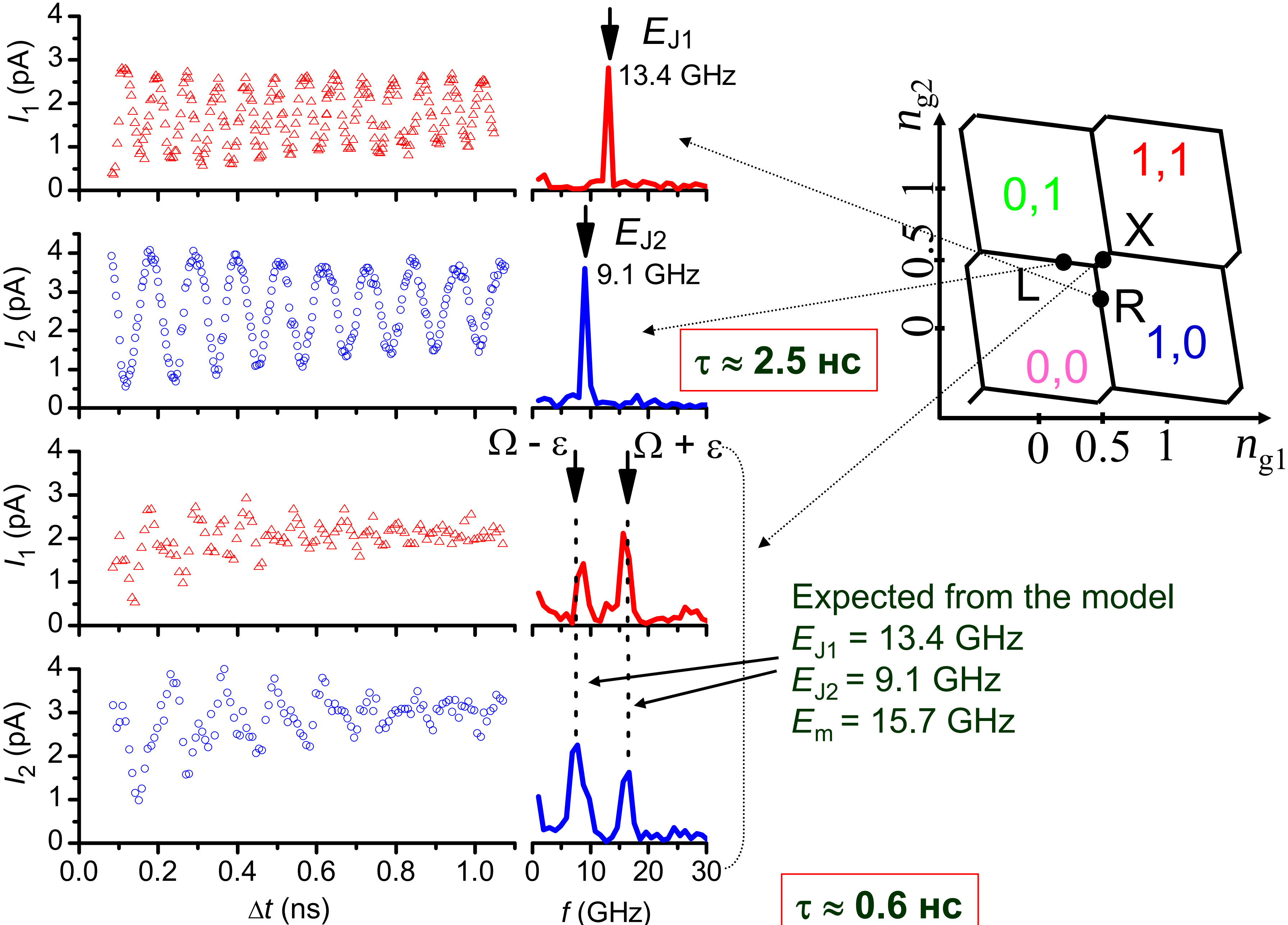
$$= \frac{1}{4}\left[2-(1-\chi)\cos(\Omega+\varepsilon)\Delta t)-(1+\chi)\cos(\Omega-\varepsilon)\Delta t)\right]$$

$$\begin{aligned}
\chi &= \frac{E_{J1}^2 - E_{J2}^2 + (E_m/4)^2}{4\hbar^2\Omega\epsilon} \\
\Omega &= \sqrt{\Delta^2 + (E_m/4\hbar)^2} \\
\epsilon &= \sqrt{\delta^2 + (E_m/4\hbar)^2} \\
\Delta &= (E_{J2} + E_{J1})/2\hbar \\
\delta &= (E_{J2} - E_{J1})/2\hbar
\end{aligned}$$





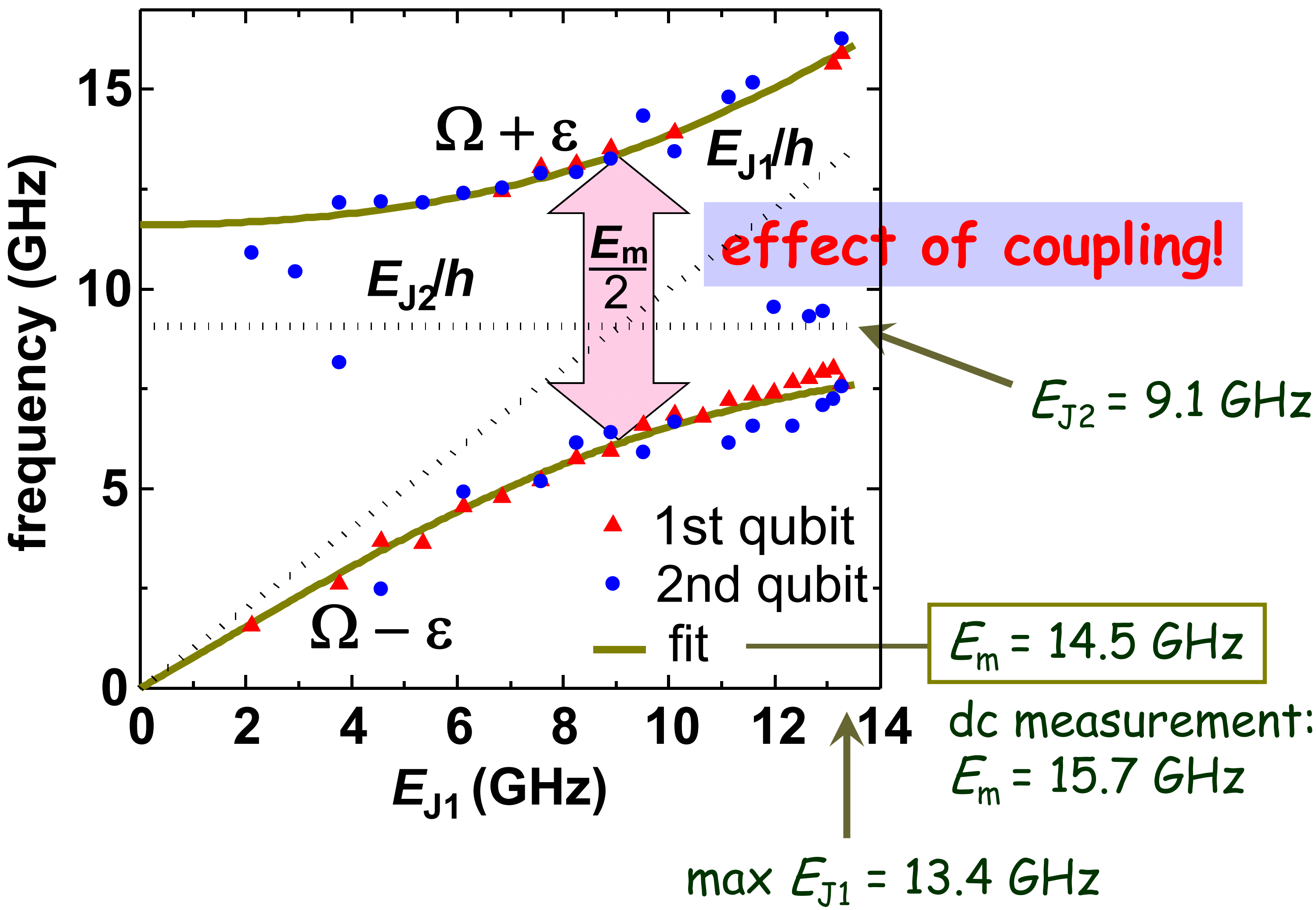
Quantum beatings: experiment



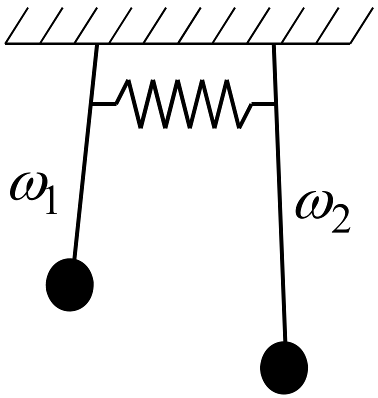
τ ≈ **2.5 нс**

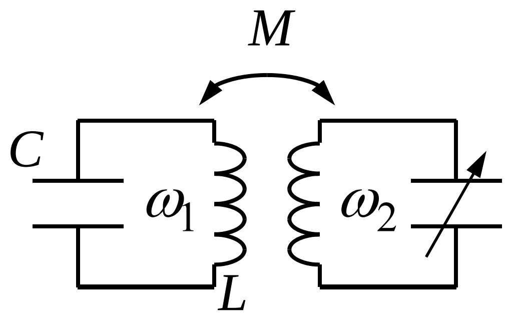
τ ≈ **0.6 нс**

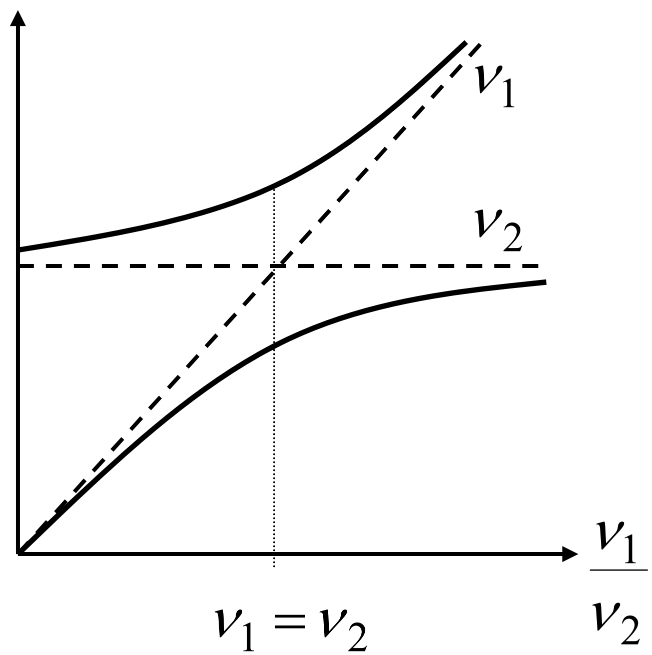
E_{J1} dependence of frequencies

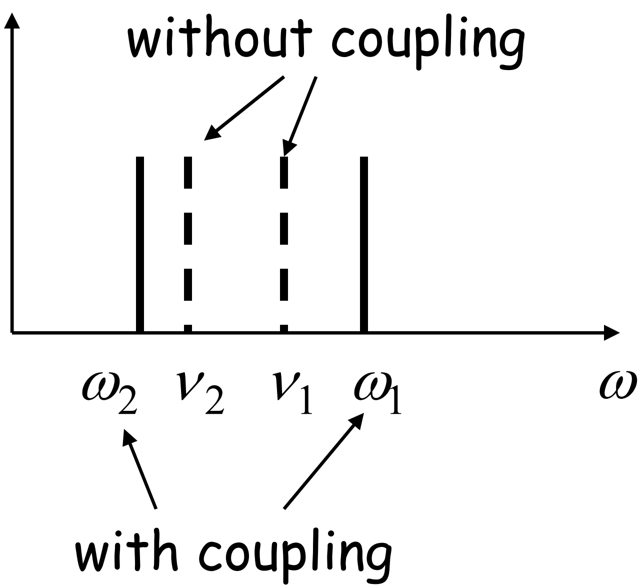


Analogy with two coupled classical oscillators









Difference?

oscillation of:

C.: physical parameter x

Q.: probability p(x) to be in 0 or 1

Entanglement of two coupled qubits

our qubits E_{J1} = 9.1 GHz
E_{J2} = 9.1 GHz
E_m = 14.5 GHz

Entangled qubits: $|\psi\rangle \neq |\psi_A\rangle \otimes |\psi_B\rangle$

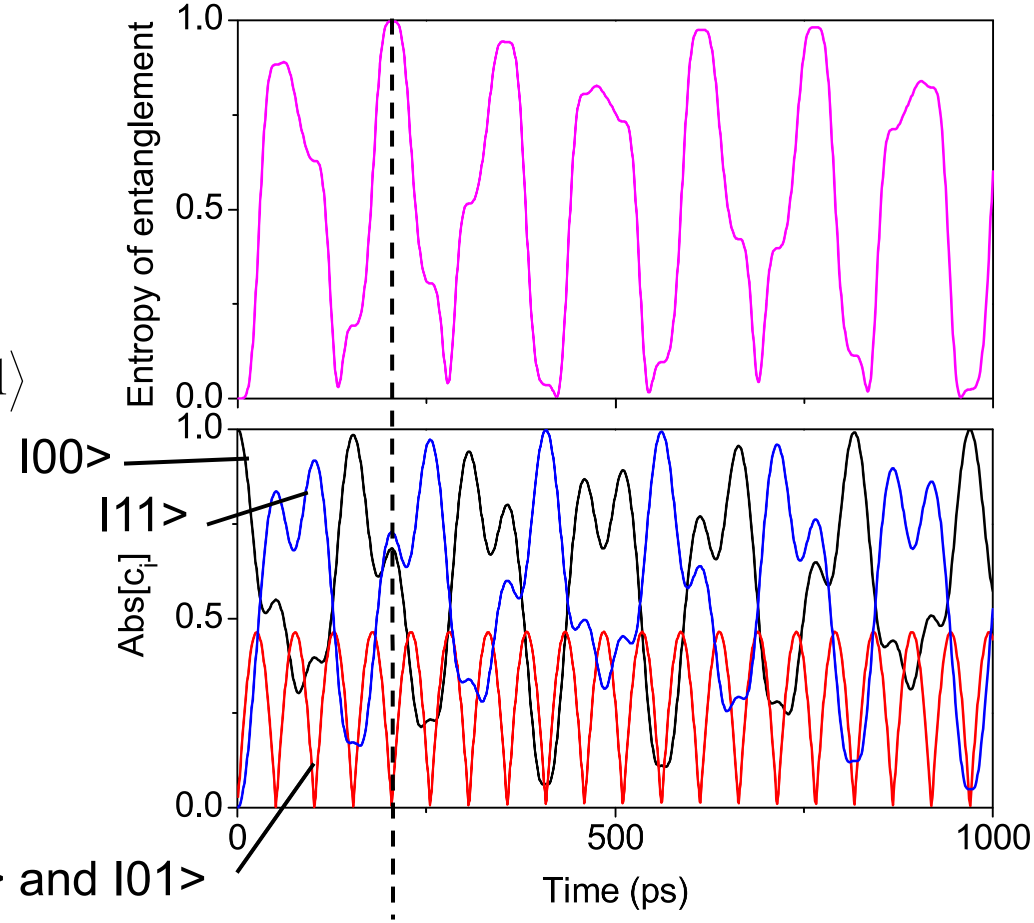
Entropy of entanglement:

$$E = -Tr\rho_A \log_2 \rho_A = -Tr\rho_B \log_2 \rho_B$$

If $|\psi\rangle = c_1|00\rangle + c_2|10\rangle + c_3|01\rangle + c_4|11\rangle$

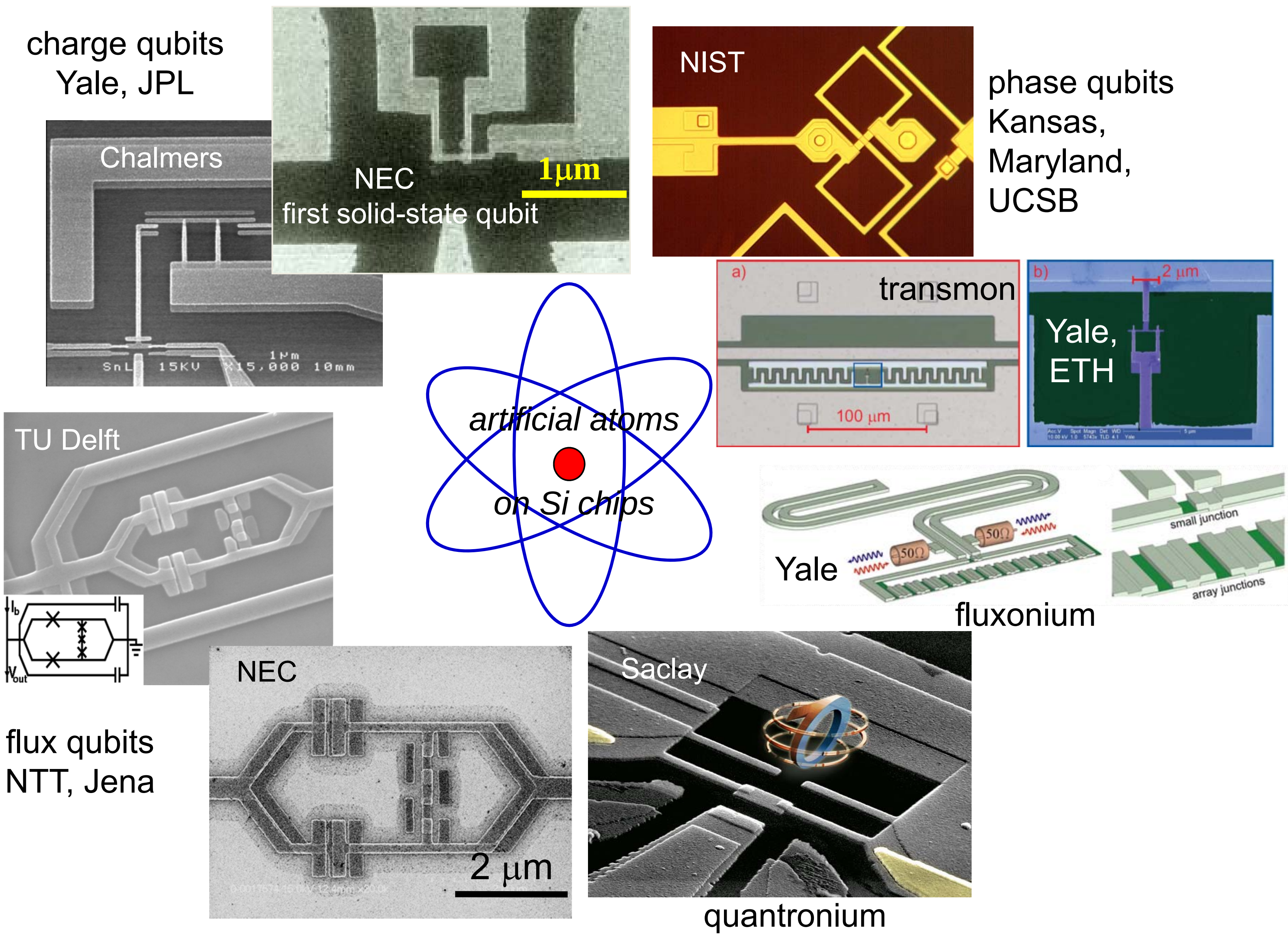
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$$
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|10\rangle \pm |01\rangle)$$

maximally entangled states, E = 1



"almost"maximally entangled state

Superconducting circuits with quantum coherence



Solid-state quantum computing

<u>Proof-of-principles phase passed</u>

- single qubits demonstrated
- interqubit coupling
- quantum logic gates
- decoherence sources identified

<u>Remaining issues</u>

- increase coherence time
- switchable interqubit coupling