Московский государственный университет имени М.В. Ломоносова

Физический факультет, кафедра атомной физики, физики плазмы и микроэлектроники.

Клёнов Николай Викторович

Мир искусственных атомов

Автор признателен М.Ю. Куприянову, В.В. Рязанову, Е.В. Ильичеву, А.В. Устинову, И.И. Соловьеву, А.В. Шарафиеву, С.В. Бакурскому, В.К. Корневу за плодотворные обсуждения затронутых в рамках лекции проблем

План доклада

- Почему интересны искусственные атомы?
- Сверхпроводимость и эффект Джозефсона
- Типы джозефсоновских кубитов
- Атомная физика и квантовая оптика с джозефсоновскими кубитами
- Проблемы и перспективы
- Заключение

Квантовые биты: актуальность задачи

Основные проекты по квантовой информатике в мире:

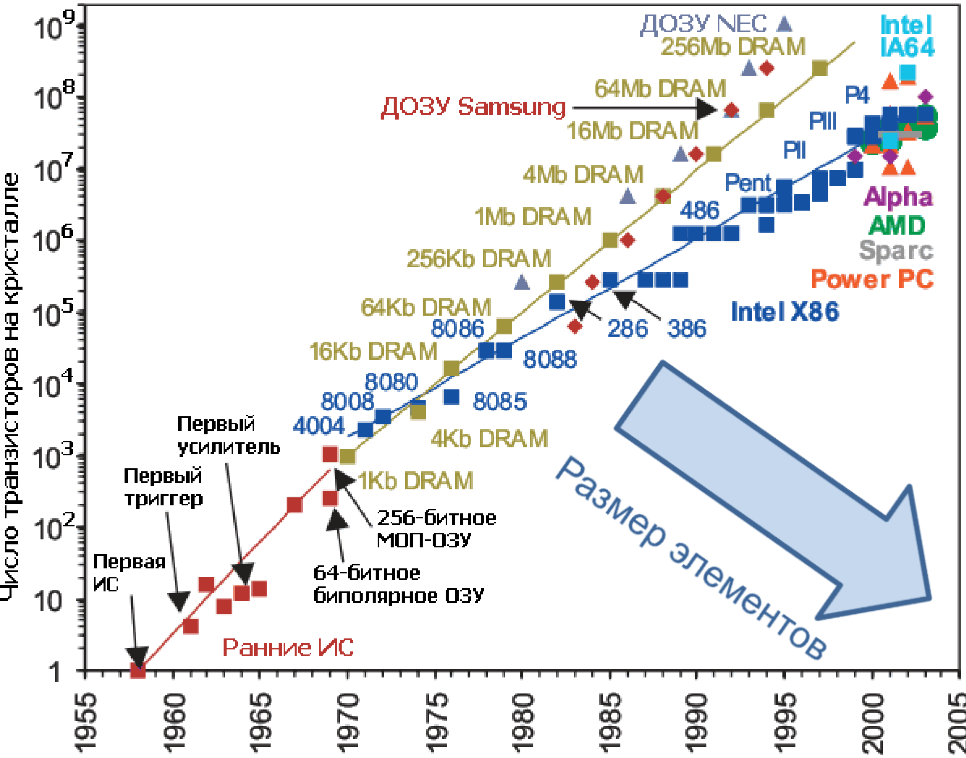
Europe, www.qurope.net, апрель 2010; ROADMAP №2, USA, www.ostp.gov, 2009

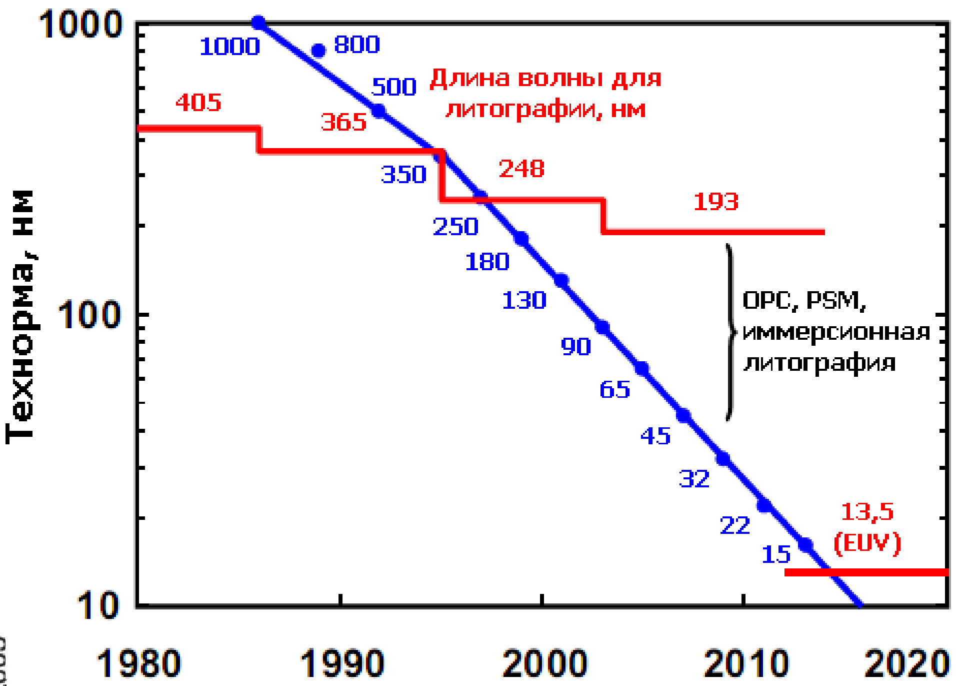
Цель 1. Квантовая криптография

Принципиально не дешифруемая передача данных, доведено до уровня готовых приборов; www.idquantique.com, www.magiqtech.com

Цель 2. Квантовый компьютер

Квантовые сверхскоростные вычисления, взлом существующих систем кодирования



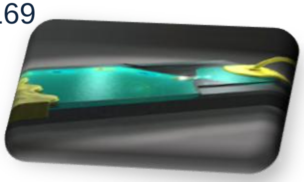


Эра квантовых технологий

Квантовые приборы

Генератор одиночных электронов

G. Feve *et al.*, Science **316**, 1169 (2007)



Графеновый транзистор

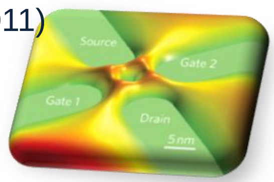
Y. Wu *et al.*, Nature **472**, 74 (2011)

Счетчик фотонов

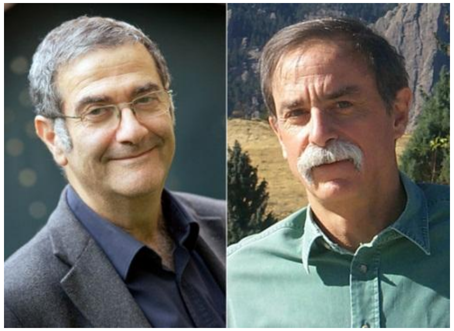
http:\\\www.lasercomponents.com

Одноэлектронный транзистор

G. Cheng *et al., Nature Nano.* **6**, 343 (2011)



Нобелевская премия в 2012 году



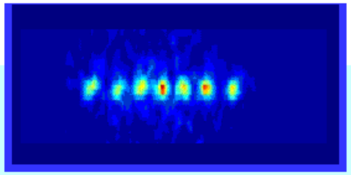
The Nobel Prize in Physics 2012 was awarded jointly to Serge Haroche and David J. Wineland *"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"*

КВАНТОВЫЙ КОМПЬЮТЕР –
Квантовые элементы памяти

REVIEWS
Quantum computers
T. D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe & J. L. O'Brien, Nature **464**, 45 (2010)

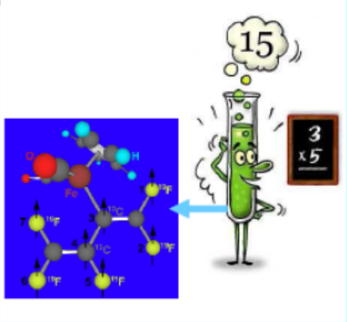
Квантовые биты

2011: Tokyo QKD Network, запутанное состояние передано на 45 км по обычному оптоволокну



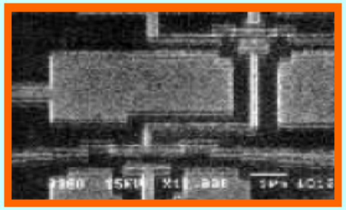
atomic

- Ions
- Neutral Atoms
- CQED



mesoscopic

- NMR
- Quantum Dot
- Superconductor SET (charge)



macroscopic

- Josephson Junctions (phase)
- 3 Junction SQUID } (flux)
- RF SQUID } (flux)

Coherence

Quantum!!

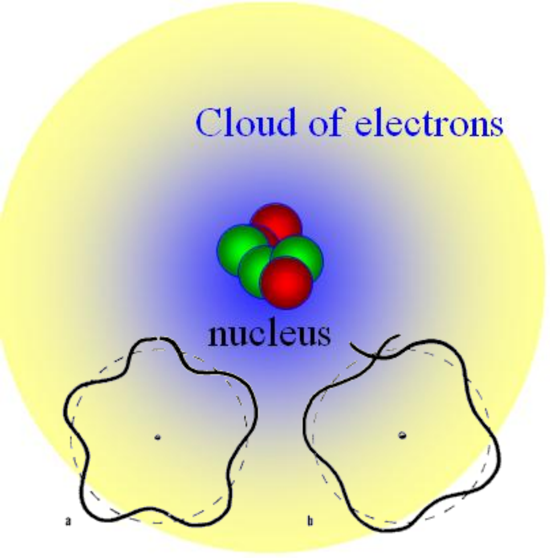
Chip?

scalability

coupling

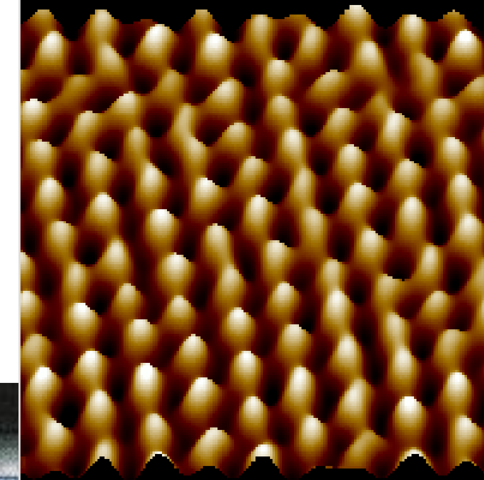
Decoherence free circuit? Quantum?

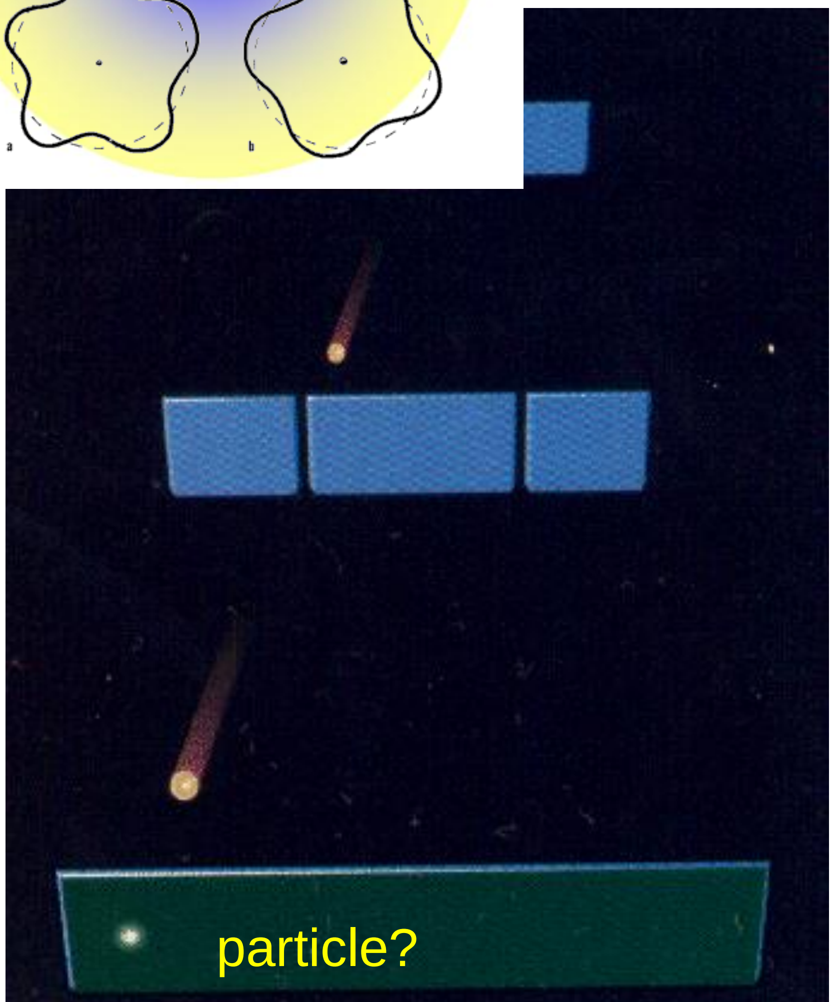
Квантовая природа

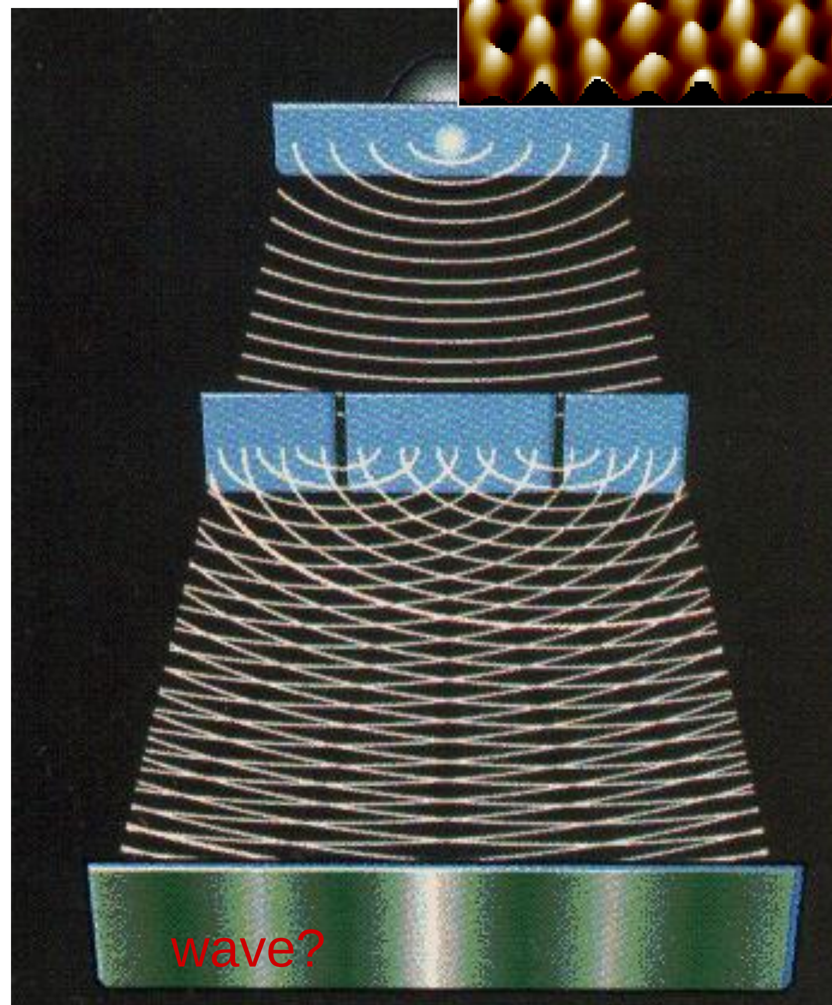


$\lambda = h/p$

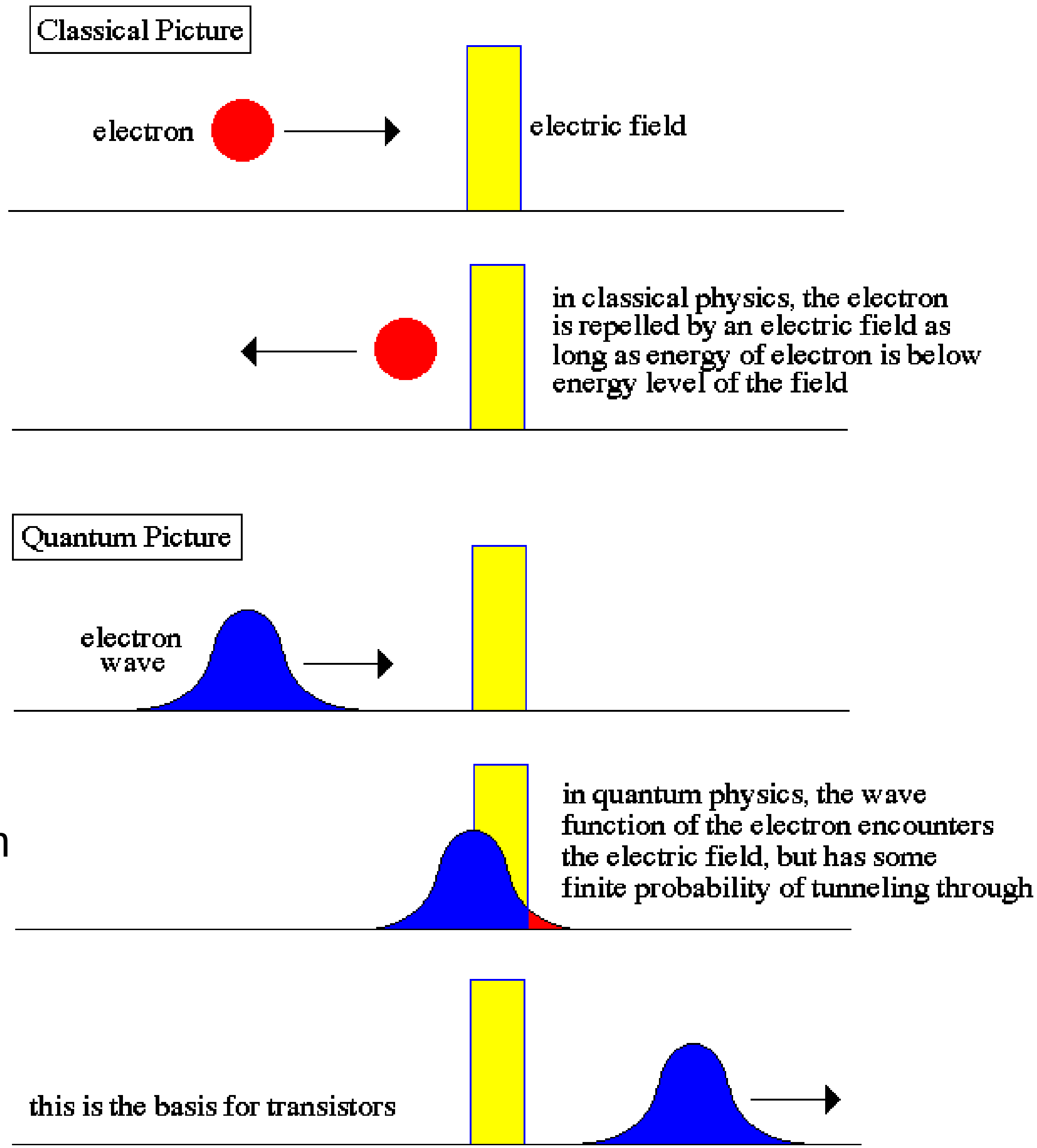
$\Delta x \Delta p \geq h/2\pi$







Quantum Tunneling



electron always repelled

electron usually repelled, but will occasionally pop out on the other side of the barrie even though it does not have enough energy t do so classically

Why do we not see tunneling in our daily lives?

If the wall is much thicker than the quantum wavelength, tunneling becomes improbable

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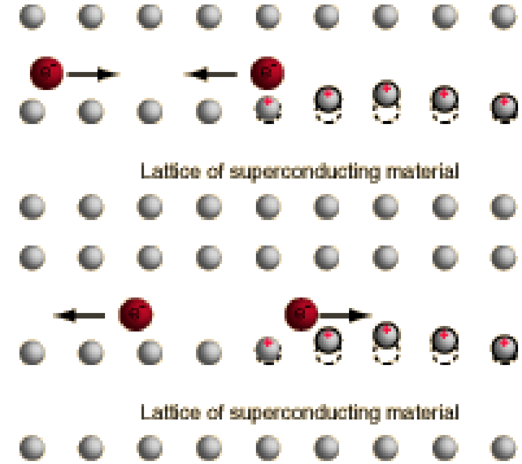
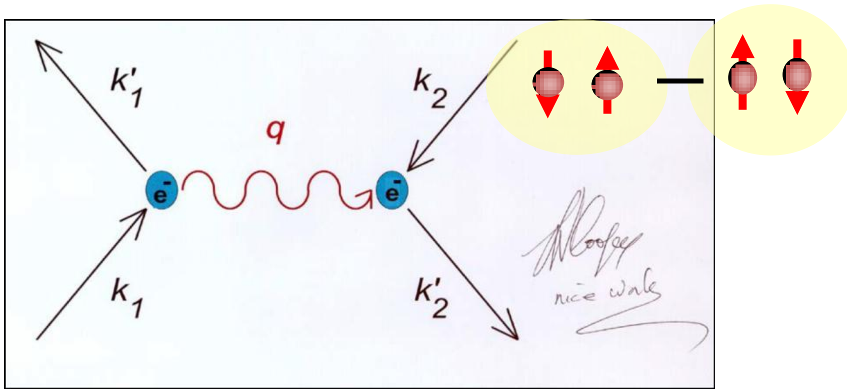


John Bardeen, Leon Neil Cooper, John Robert Schrieffer

$$\hat{H} = \sum \hbar V_F (k - k_F) a^+_{k\sigma} a_{k\sigma} + g \sum a^+_{q\uparrow} a^+_{-q\downarrow} a_{-k\downarrow} a_{k\uparrow}$$

$$\hat{H} = \sum \hbar V_F (k - k_F) a^+_{k\sigma} a_{k\sigma} + \sum \Delta^* a_{-k\downarrow} a_{k\uparrow} + \sum a^+_{q\uparrow} a^+_{-q\downarrow} \Delta$$

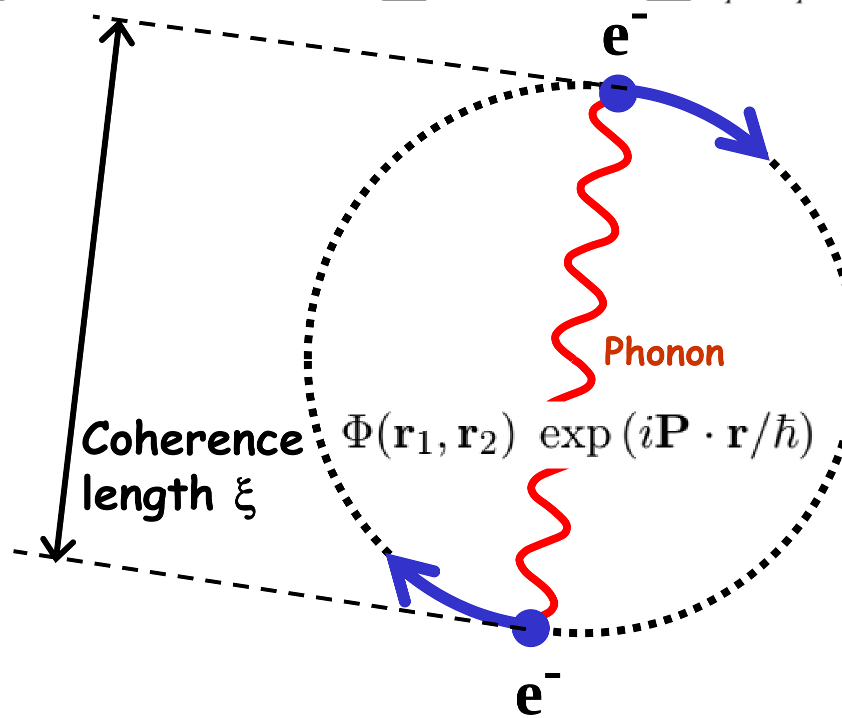


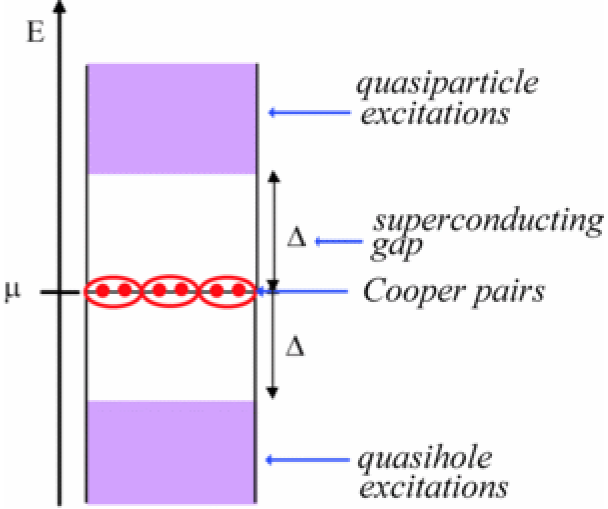
$$g \sum_k \langle a_{-k\downarrow} a_{k\uparrow} \rangle = \Delta$$

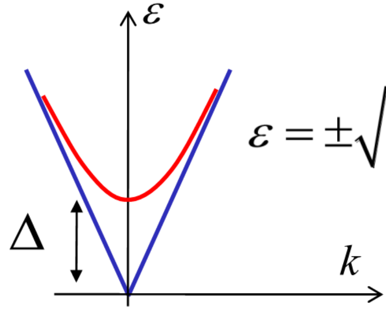
$$\Delta(\mathbf{r}) = g\langle \hat{\psi}_\downarrow(\mathbf{r}) \psi_\uparrow(\mathbf{r}) \rangle = |\Delta(\mathbf{r})| \exp[i\phi(\mathbf{r})]$$

$$\Delta^*(\mathbf{r}) = g\langle \hat{\psi}^\dagger_\uparrow(\mathbf{r}) \hat{\psi}^\dagger_\downarrow(\mathbf{r}) \rangle = |\Delta(\mathbf{r})| \exp[-i\phi(\mathbf{r})]$$

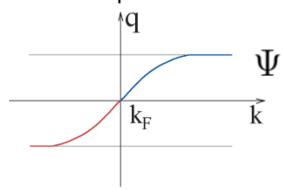
$$\Psi(\mathbf{r}) = \sqrt{n_s(\mathbf{r})/2}\, \exp[i\phi(\mathbf{r})]$$



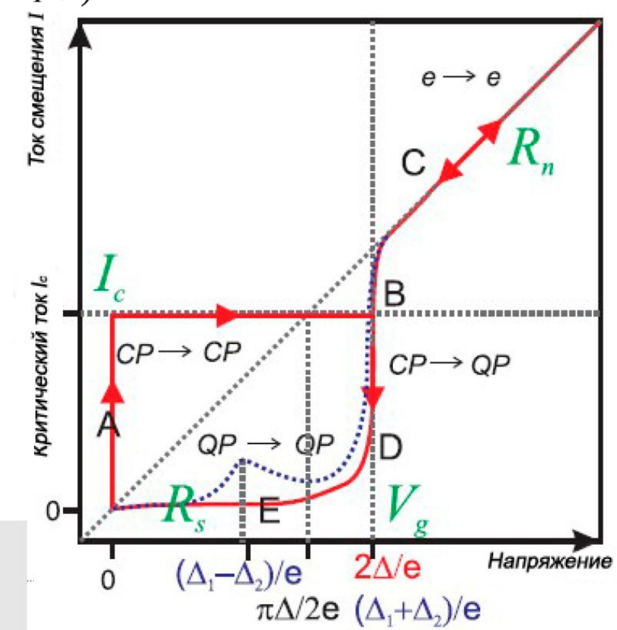


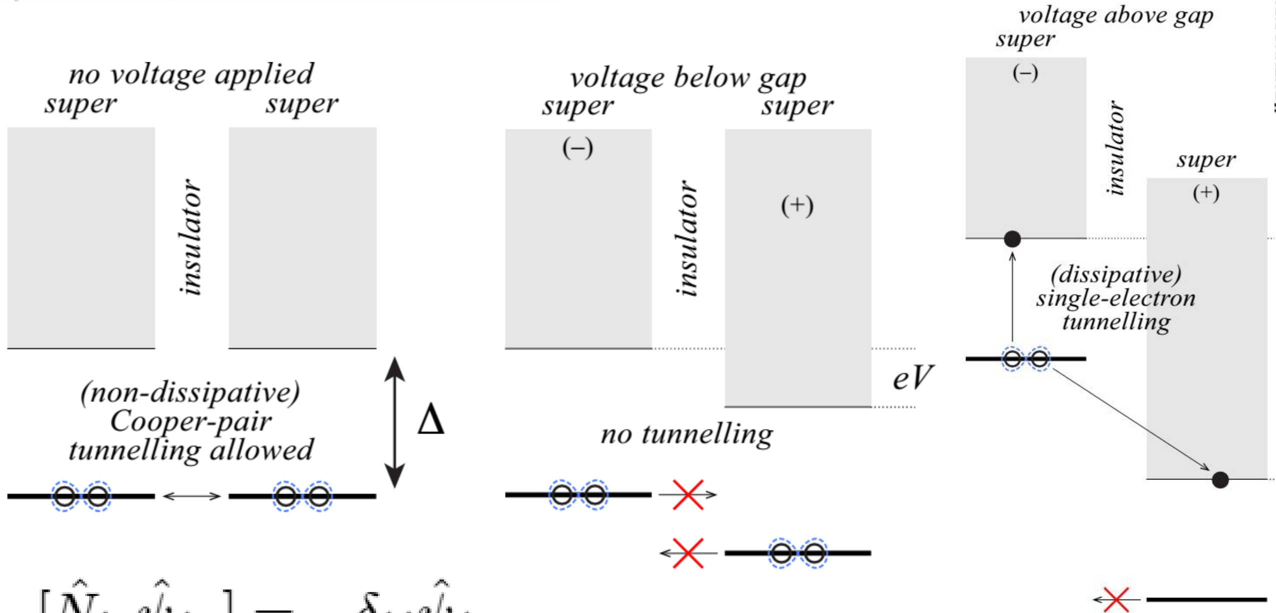


$$\varepsilon = \pm\sqrt{\Delta^2 + \left(\hbar V_F (k - k_F)\right)^2}$$



$$\Psi = \prod_k \begin{pmatrix} u_k \\ v_k e^{i\phi_k} \end{pmatrix} \otimes$$





$$[\hat{N}_i, \hat{\psi}_{j\sigma}] = -\delta_{ij}\hat{\psi}_{j\sigma}$$

$$\sin\hat{\phi}_j \simeq \hat{\phi}_j = \frac{2ig}{|\Delta_j|}\left[\hat{\psi}_{j\downarrow}\hat{\psi}_{j\uparrow} - \hat{\psi}^\dagger_{j\uparrow}\hat{\psi}^\dagger_{j\downarrow}\right]$$

$$[\hat{N}_i, \hat{\phi}_j] = -2i\delta_{ij}$$

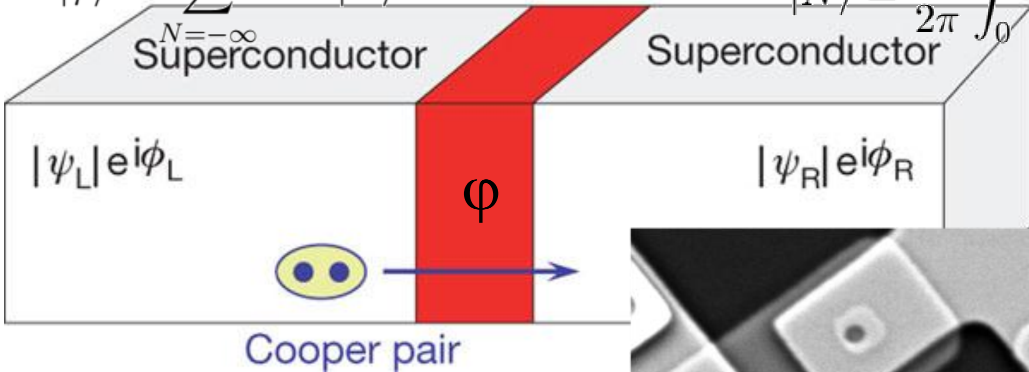
Нестац. Эффект Джозефсона

$$-i\hbar\frac{d\Delta\phi}{dt} = [H, \Delta\phi] = -i\frac{\partial H}{\partial \Delta N} = 2i\underbrace{(\mu_L - \mu_R)}_{eV}$$

$$|\varphi\rangle = \sum_{N=-\infty}^{\infty} e^{iN\varphi}|N\rangle$$

$$|N\rangle = \frac{1}{2\pi}\int_0^{2\pi} d\varphi\, e^{-iN\varphi}|\varphi\rangle$$

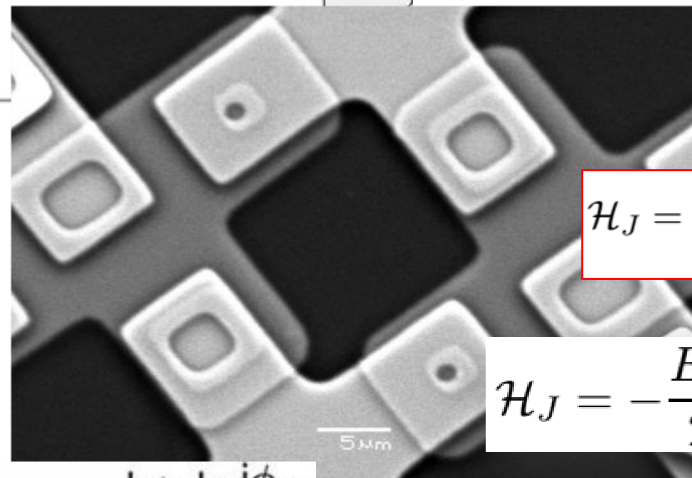
$$e^{i\hat\varphi} = \frac{1}{2\pi}\int_0^{2\pi} d\varphi'\, e^{i\varphi'}|\varphi'\rangle\langle\varphi'|$$



$$e^{i\hat\varphi} = \sum_N |N-1\rangle\langle N|$$

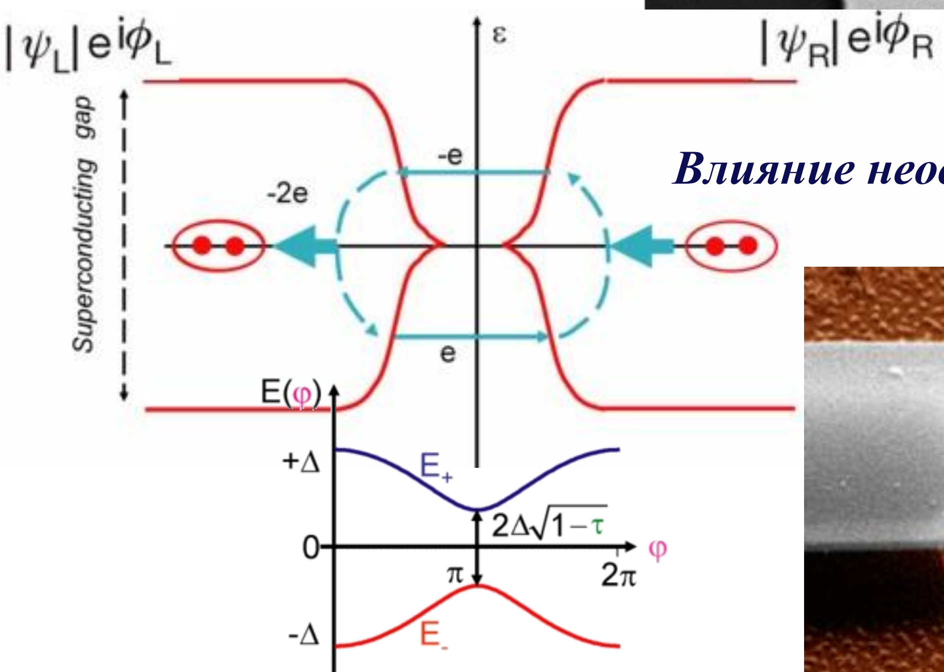
$$e^{-i\hat\varphi} = \sum_N |N\rangle\langle N-1|$$

$$I_{QP} = \frac{\pi\Delta}{2eR_N}\sin\varphi$$



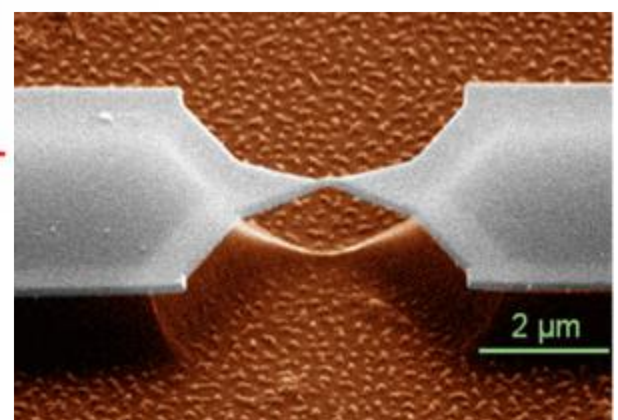
$$\mathcal{H}_J = -\frac{E_J}{2}\sum_N |N\rangle\langle N+1| + |N+1\rangle\langle N|$$

$$\mathcal{H}_J = -\frac{E_J}{2}\left[e^{i\hat\varphi} + e^{-i\hat\varphi}\right] = -E_J\cos\hat\varphi$$



Влияние неоднородностей

Стац. Эфф. Джозефсона

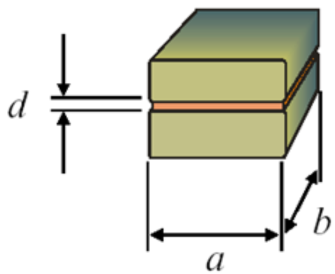


$$I_{J\pm} = \frac{2\pi\Delta}{\Phi_0}\frac{\partial E_{J\pm}}{\partial\varphi} \xrightarrow[\text{tunnel junct}]{} \frac{\pi\Delta}{2eR_N}\sin\varphi$$

Джозефсоновские контакты: итог

Josephson relations $I_s = I_c \sin\varphi$

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



tunnel barrier thickness d

junction area $A = a\,b$

Josephson energy $E_J = \frac{I_c \Phi_0}{2\pi}$

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

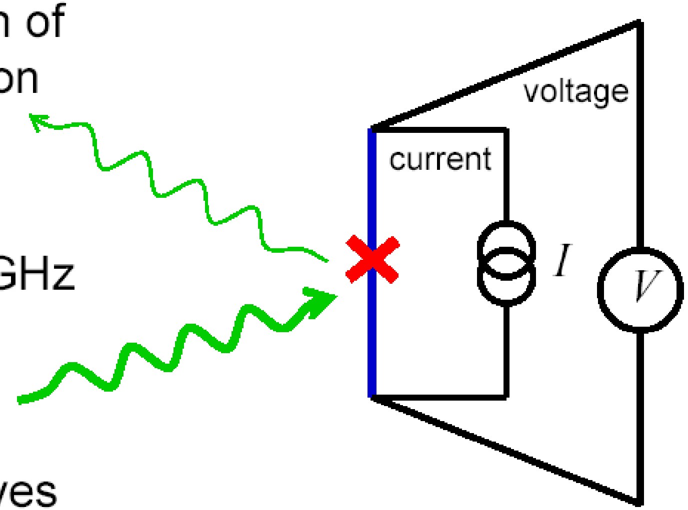
$$I_c = \frac{\Phi_0 \Delta}{2R_n} \sim A \exp\left(-\frac{d}{d_0}\right) \qquad C_J \sim \frac{A}{\varepsilon\, d}$$

$$\Rightarrow \quad \frac{E_J}{E_C} \sim A^2\, d\, \exp\left(-\frac{d}{d_0}\right)$$

Detection of Josephson radiation

10 - 600 GHz

applying microwaves



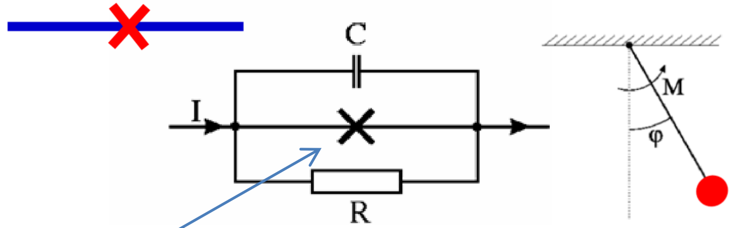
AC techniques — *expensive and difficult*

DC techniques — *cheap and easy*

Typically, achiving $\frac{E_J}{E_C} \sim 1$ requires $A < 0.001\,\mu\mathrm{m}^2$

Джозефсоновские потенциалы

$x \propto \varphi$
$v \propto d\varphi/dt \propto V$

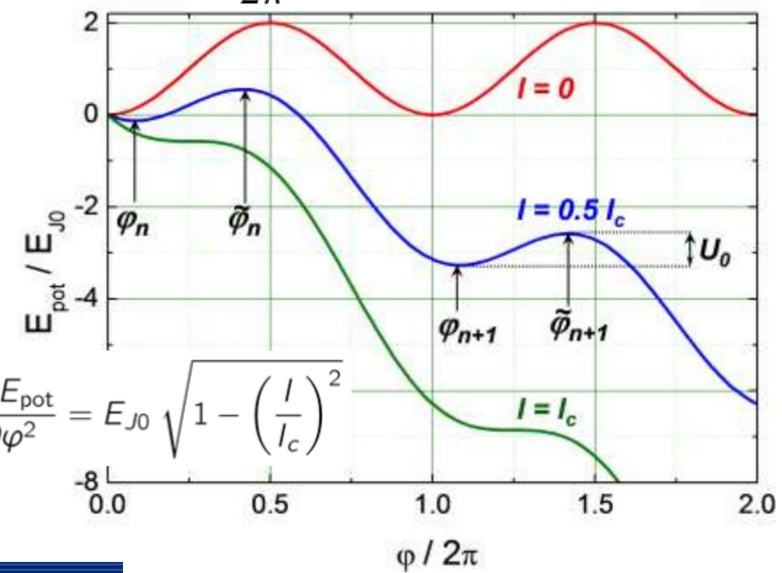


I_C ~ length
C ~ mass
R^{-1} ~ damping
I ~ ext. torque

$$L_s = \frac{\Phi_0}{2\pi I_c \cos\varphi} = L_c \frac{1}{\cos\varphi}$$

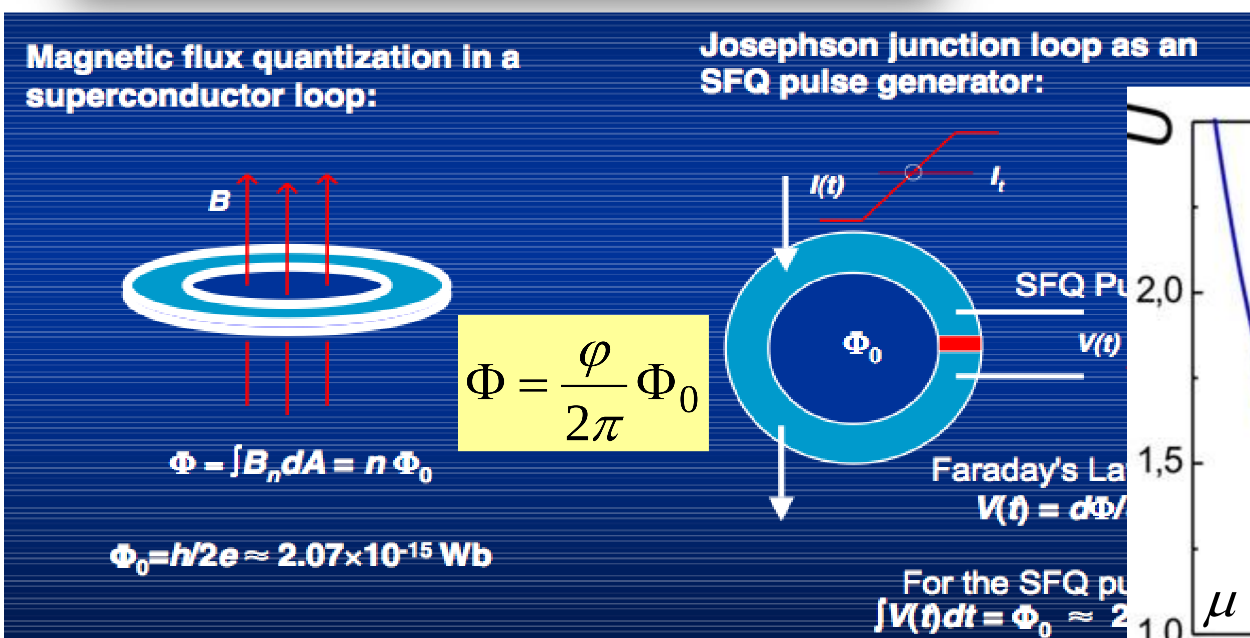
$$L_c = \frac{\hbar}{2eI_c}$$

$$-\frac{I\Phi_0}{2\pi}\varphi - E_J\cos\varphi \equiv \mathcal{U}(\varphi)$$

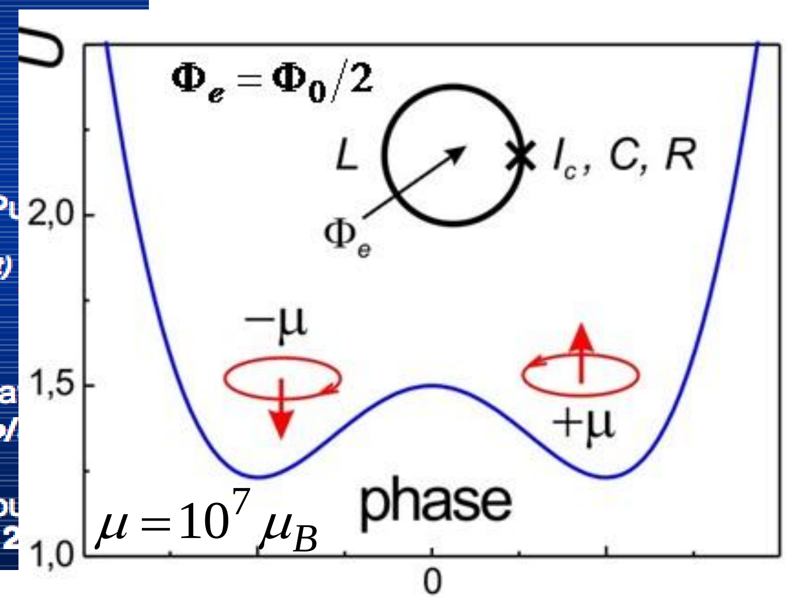


$$k \equiv \frac{\partial^2 E_{pot}}{\partial\varphi^2} = E_{J0}\sqrt{1-\left(\frac{I}{I_c}\right)^2}$$

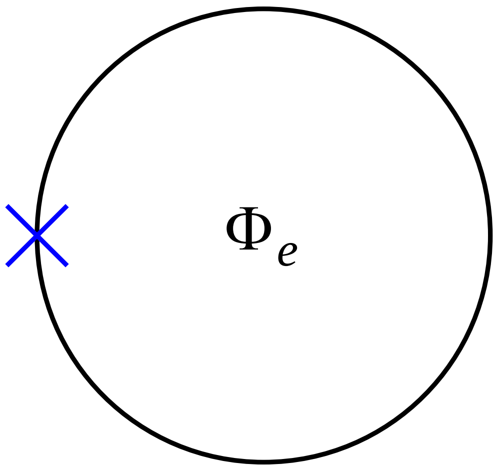
$$\mathcal{H} = \frac{\hat{Q}^2}{2C} - I\hat{\Phi} - E_J\cos\left(2\pi\hat{\Phi}/\Phi_0\right)$$



$$\Phi = \frac{\varphi}{2\pi}\Phi_0$$



Single-junction interferometer (RF-SQUID)



$$\Phi = \Phi_e - LI_c \sin\varphi$$

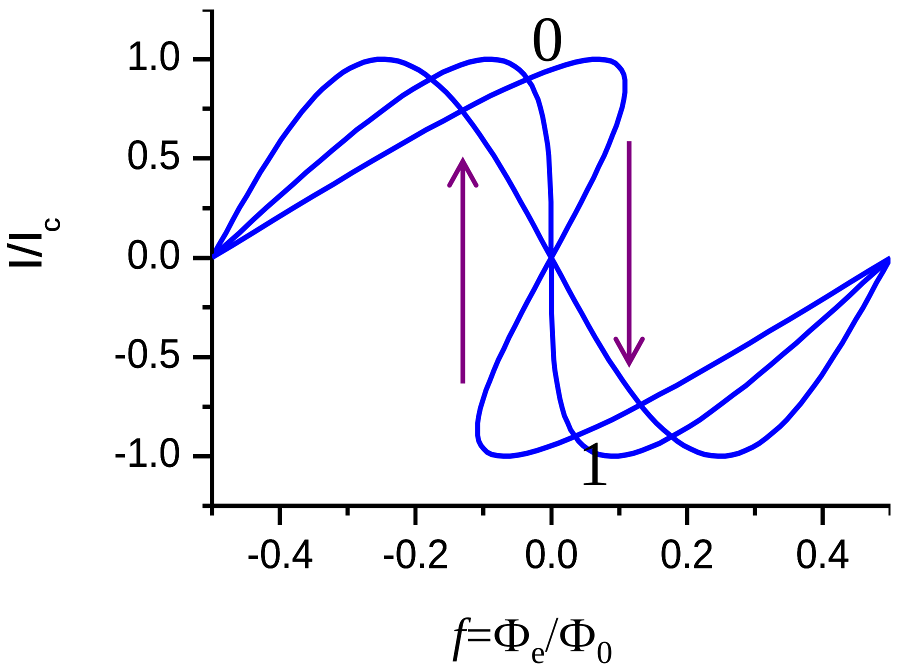
Or in normalized Units:

$$\varphi = 2\pi f - \beta_L \sin\varphi$$

$$\varphi = \frac{2\pi}{\Phi_0}\Phi$$

$$\beta_L = \frac{L}{L_C} = \frac{2\pi}{\Phi_0} LI_c$$

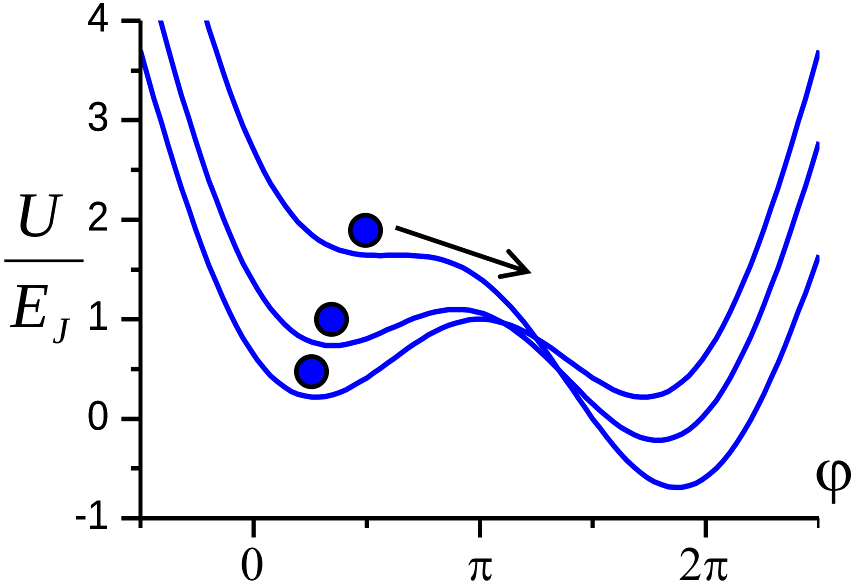
$$I(\varphi) = I_c \sin(\varphi)$$

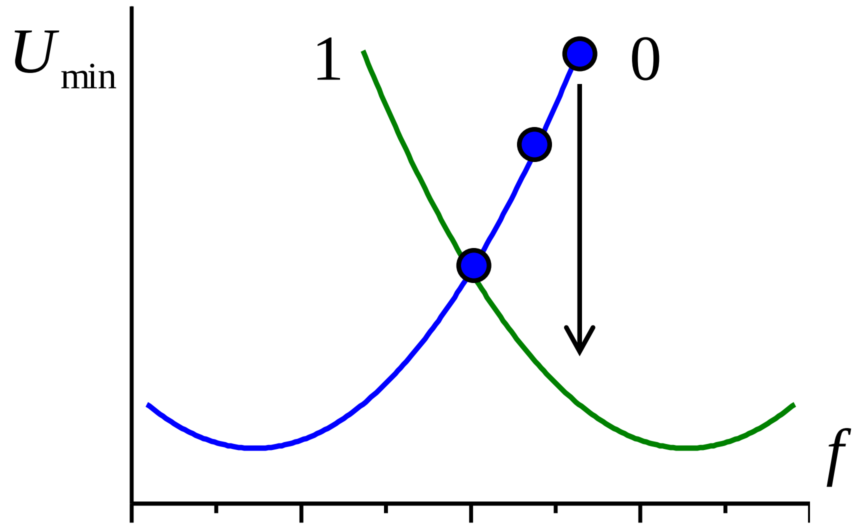


Classical two level System!

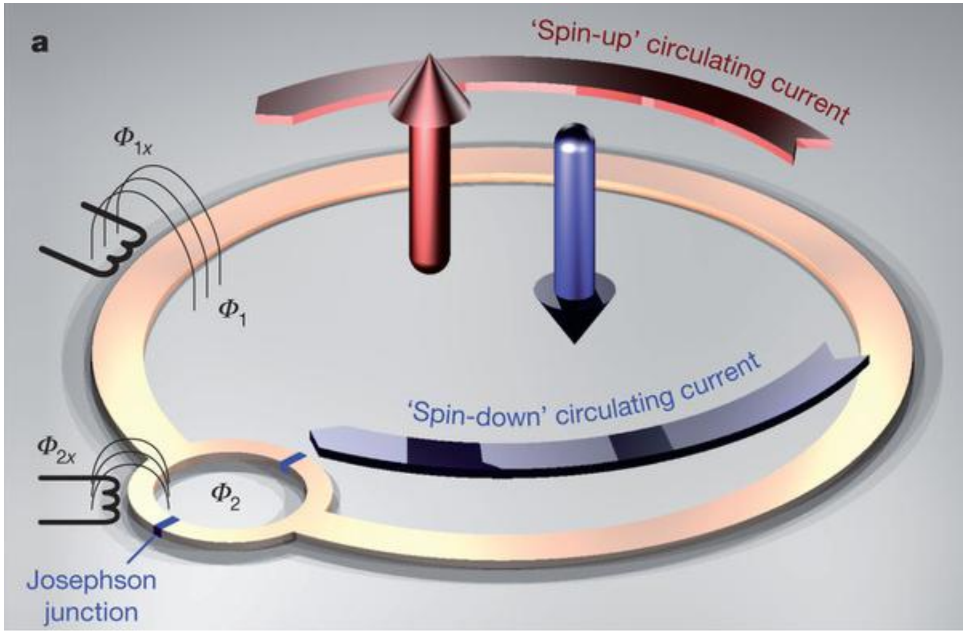
$$\beta_L > 1, \quad f = 1$$

Classical picture





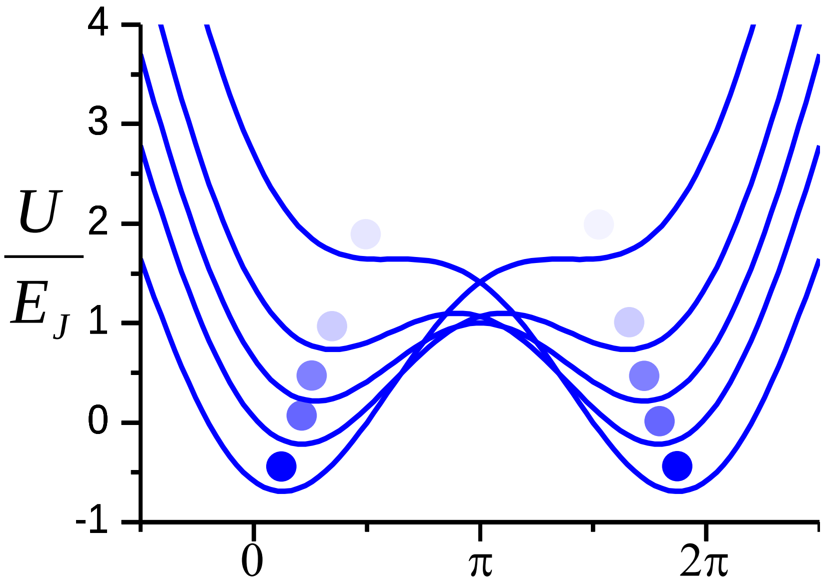
Tunable E_J (idea):

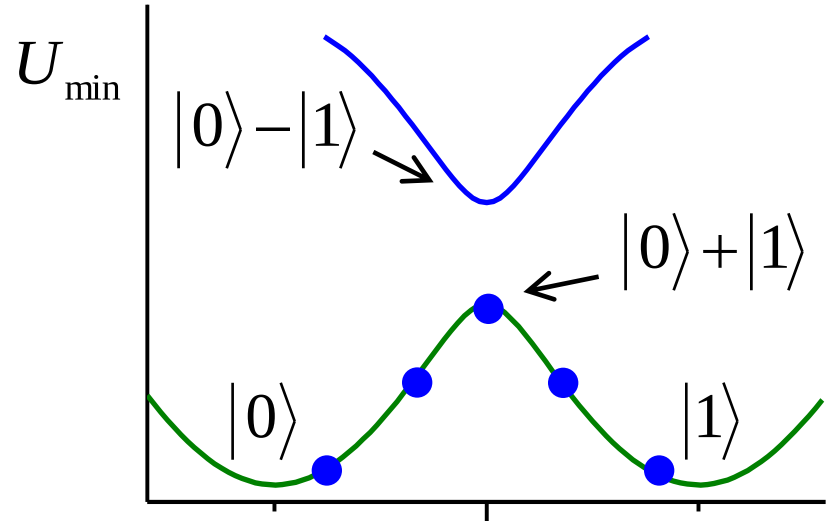


Particle with mass ~ C_J in potential:

$$\frac{U}{E_J} = -\cos\varphi + \frac{1}{2\beta_L}(\varphi - 2\pi f)^2$$

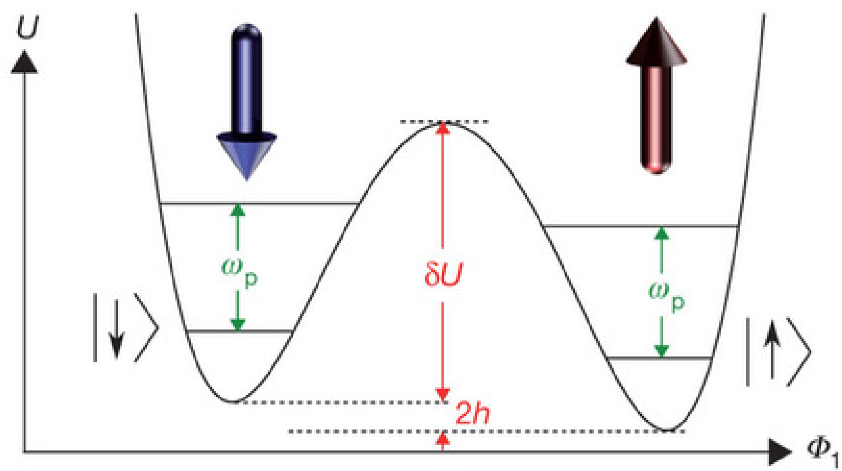
Quantum Picture





If C_J is small enough tunneling between both wells becomes possible and therefore the degeneracy is lifted.

So we need Small Josephson Junctions with E_J/E_C~10-100



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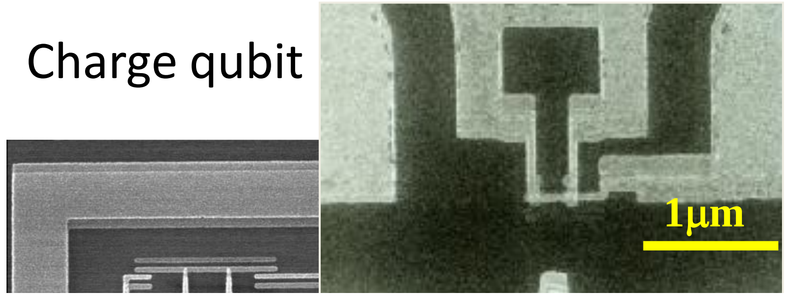
Типы сверхпроводящих кубитов

$$k_B T < \hbar\omega_{01} < \Delta$$

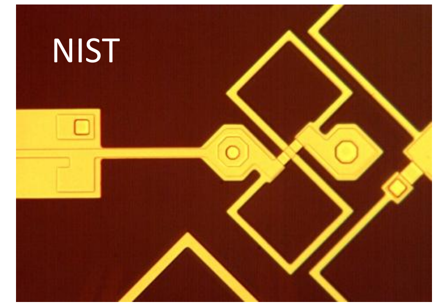
$$\frac{\omega}{2\pi} = 10\,\mathrm{GHz}$$

$1\,\mathrm{GHz} \Longleftrightarrow \sim 50\,\mathrm{mK}$

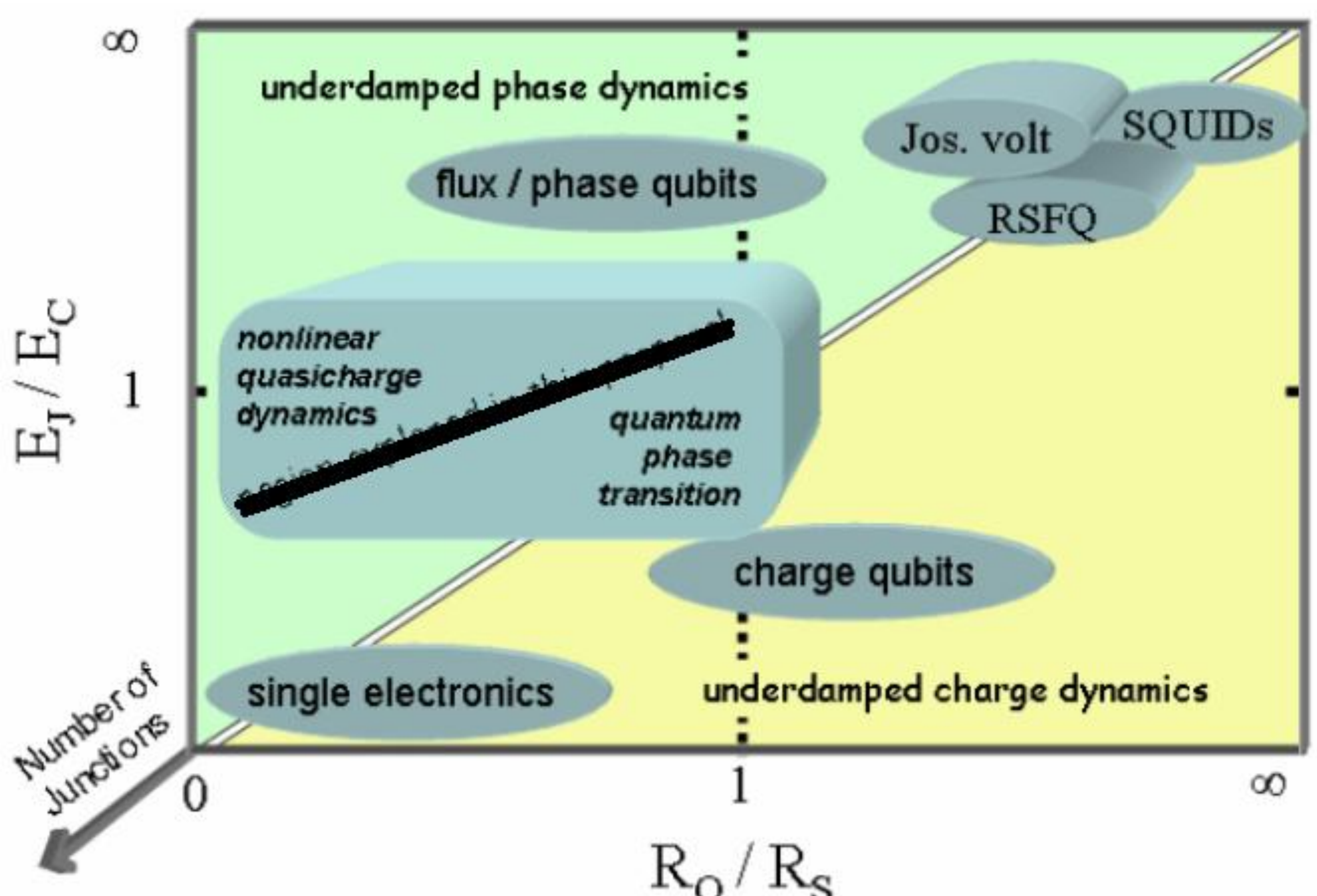
Charge qubit

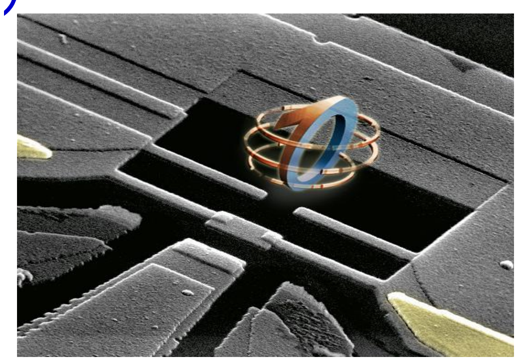


$$[\hat{\varphi}, \hat{q}] = 2ie$$



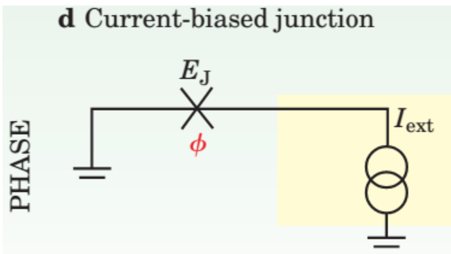
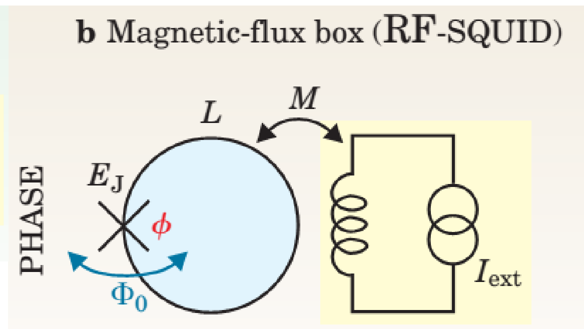
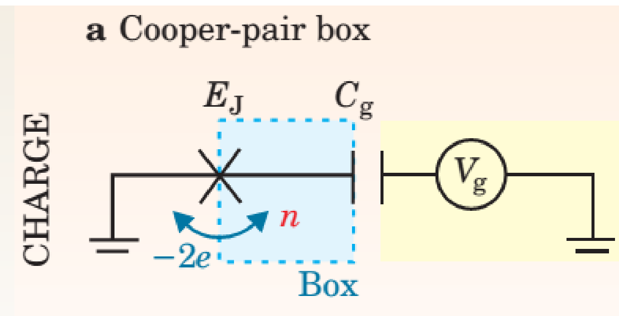
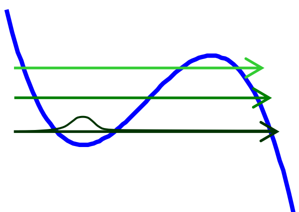
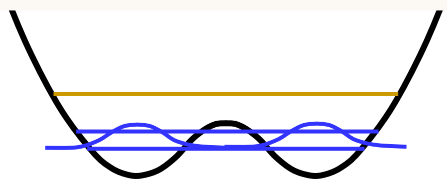
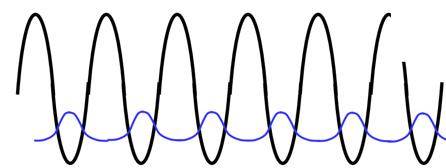
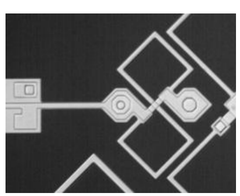
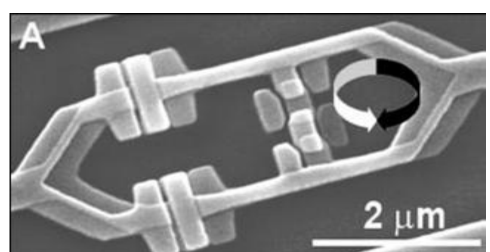
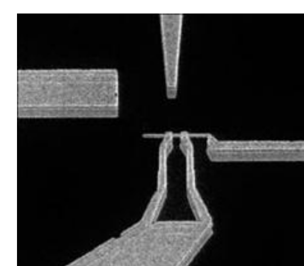
phase qubit





charge-flux qubits

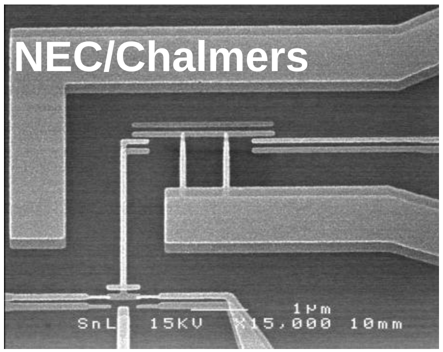
Типы сверхпроводящих кубитов

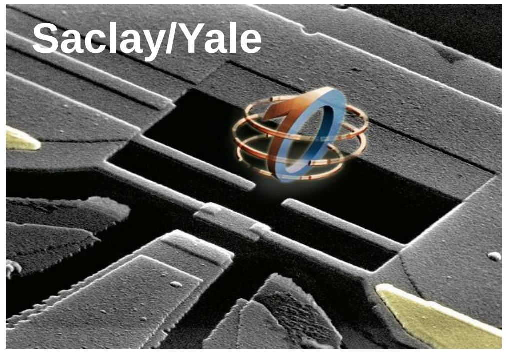
	Phase	**Flux**	**Charge**
	UCSB, NIST, Maryland	Delft, Berkeley, IPHT	Yale, Saclay, NEC, Chalmers
$\frac{E_J}{E_C} = \frac{I_0\Phi_0/2\pi}{e^2/2C}$	10^4	10^2	1
Area (μm^2):	10-100	0.1-1	0.01
Scheme			
Potential & wavefunction			
Engineering $Z_J=1/w_{10}C$	10 Ω	10^3 Ω	10^5 Ω
			

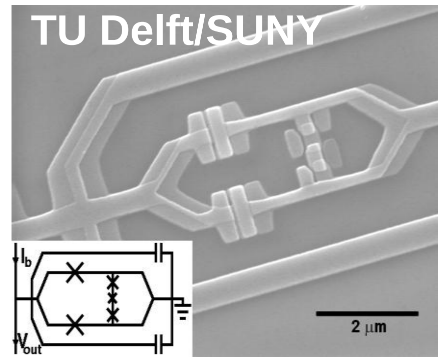
State of the Art in Superconducting Qubits at 2005

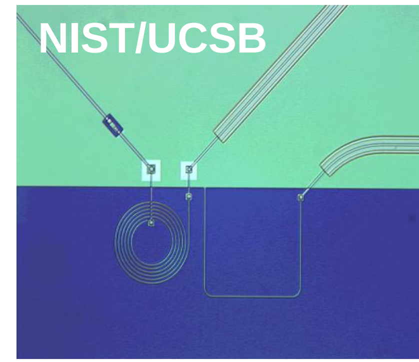
- Nonlinearity from Josephson junctions (Al/AlO_x/Al)

Charge | Charge/Phase | Flux | Phase









Junction size ⟶ $E_J = E_C$ ⟵ # of Cooper pairs

- 1st qubit demonstrated in 1998 (NEC Labs, Japan)
- "Long" coherence shown 2002 (Saclay/Yale)
- Several experiments with two degrees of freedom
- C-NOT gate (2003 NEC, 2006 Delft and UCSB)
- Bell inequality tests being attempted (2006, UCSB)

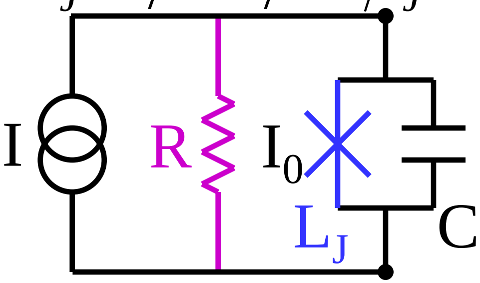
So far only classical E-M fields: atomic physics with circuits

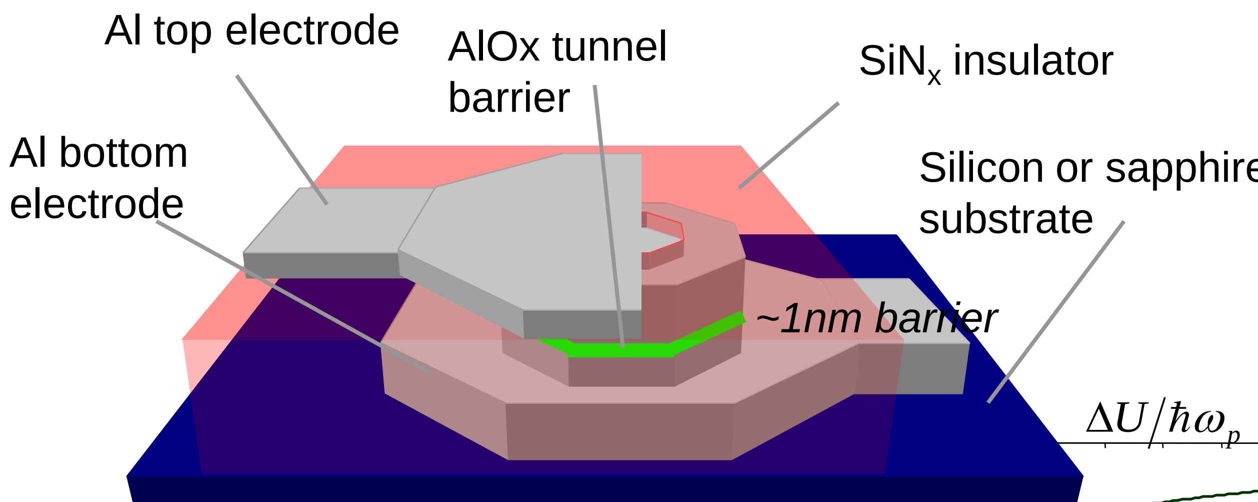
Main goal: interaction with quantized fields ⇨ Quantum optics with circuits

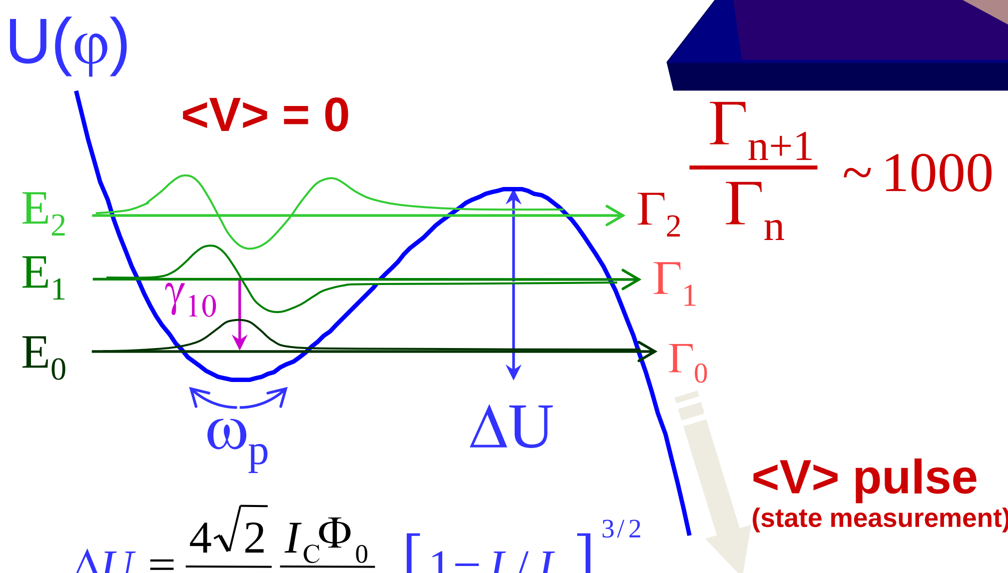
Communication between discrete photon states and qubit states

Фазовый кубит

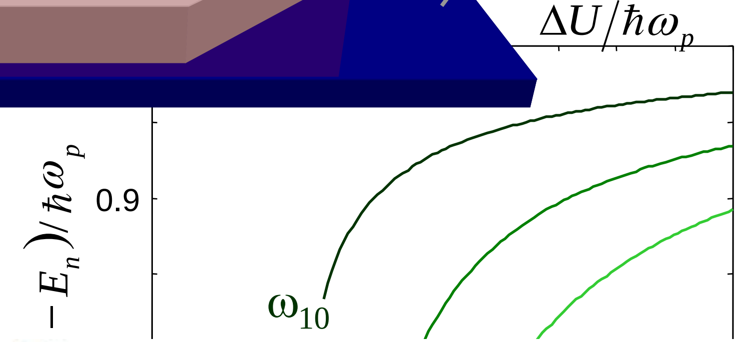
$$\dot{i}_J = \dot{\varphi}\cos\varphi = v/l_J$$

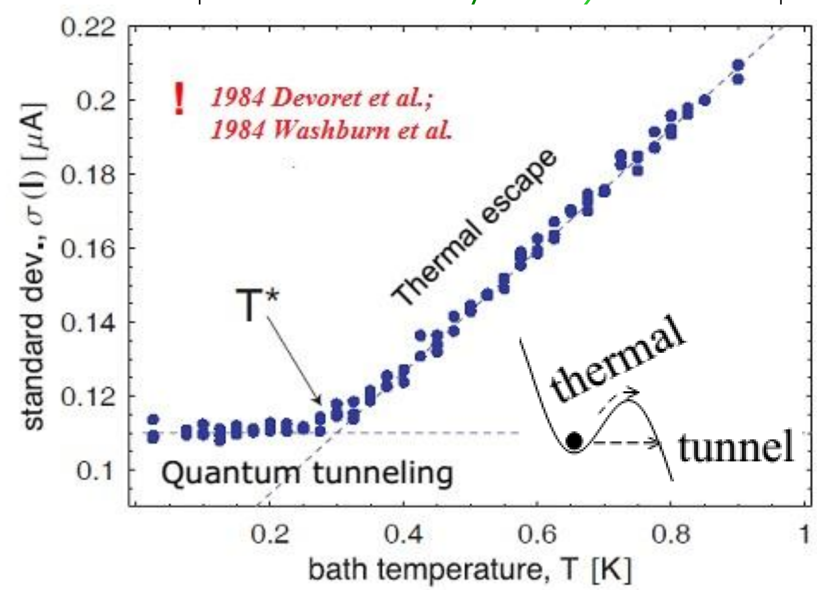






$$\frac{\Gamma_{n+1}}{\Gamma_n} \sim 1000$$





$$\Delta U = \frac{4\sqrt{2}}{3}\frac{I_C\Phi_0}{2\pi}\left[1 - I/I_C\right]^{3/2}$$

$$\omega_p = \left(\frac{2\sqrt{2}\pi}{\Phi_0}\frac{I_C}{C}\right)^{1/2}\left[1 - I/I_C\right]^{1/4}$$

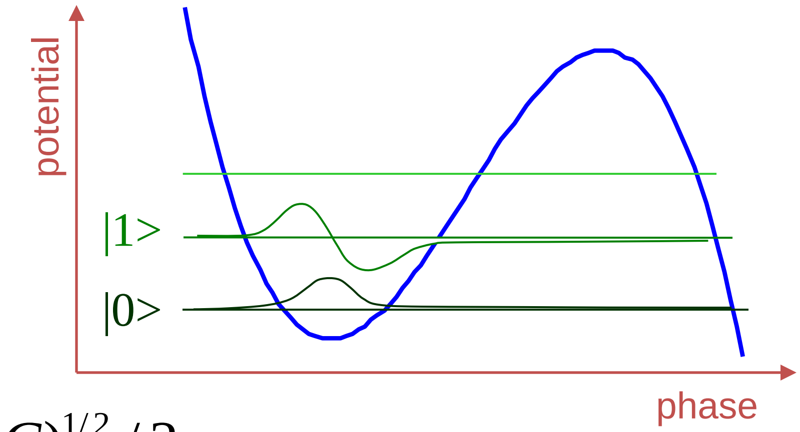
$$\gamma_{10} = (RC)^{-1}$$

Lifetime of state |1>

Фазовый кубит: считывание состояния

- State Preparation

  Wait $t > 1/\gamma_{10}$ for decay to |0>



- Qubit logic with bias control

$$I = I_{dc} + \delta I_{dc}(t) + I_{\mu wc}(t)\cos\omega_{10}t + I_{\mu ws}(t)\sin\omega_{10}t$$

$$H_{(2)} = \boldsymbol{\sigma}_x \bullet I_{\mu wc} \bullet (\hbar/2\omega_{10}C)^{1/2}/2$$
$$+ \boldsymbol{\sigma}_y \bullet I_{\mu ws} \bullet (\hbar/2\omega_{10}C)^{1/2}/2$$
$$+ \boldsymbol{\sigma}_z \bullet \delta I_{dc}(t) \bullet (\partial E_{10}/\partial I_{dc})/2$$

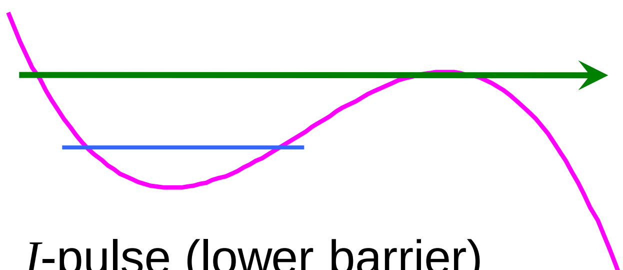
- State Measurement: $\Delta U(I+I_{pulse})$

  Single shot – high fidelity

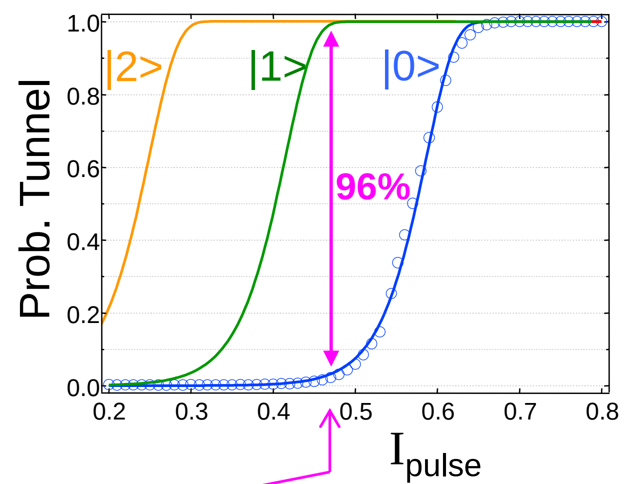
  Apply ~3ns Gaussian I_{pulse}

|1> : tunnel

|0> : no tunnel



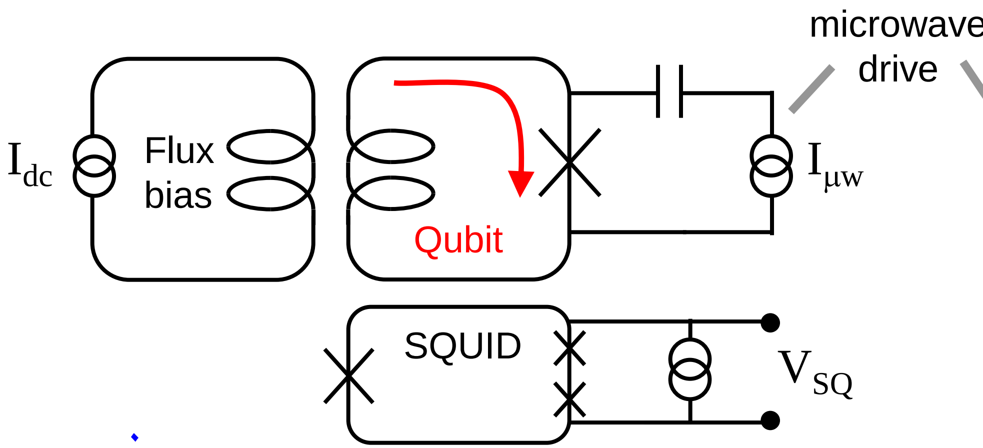
I-pulse (lower barrier)

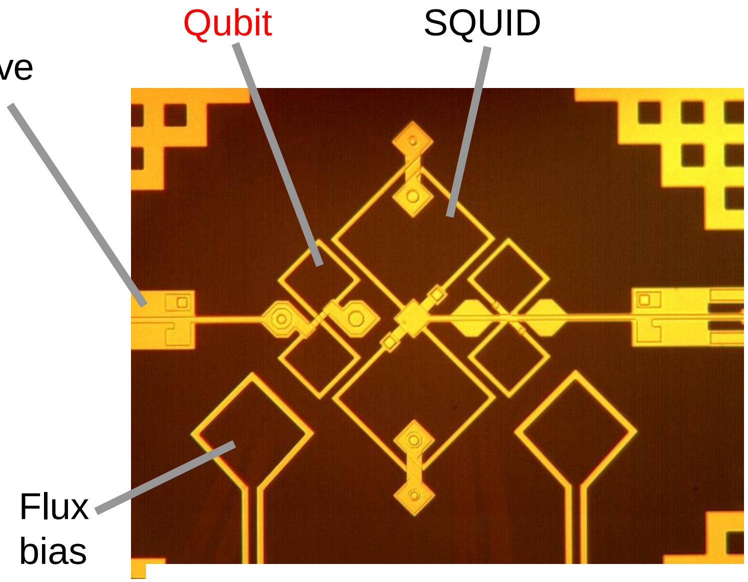


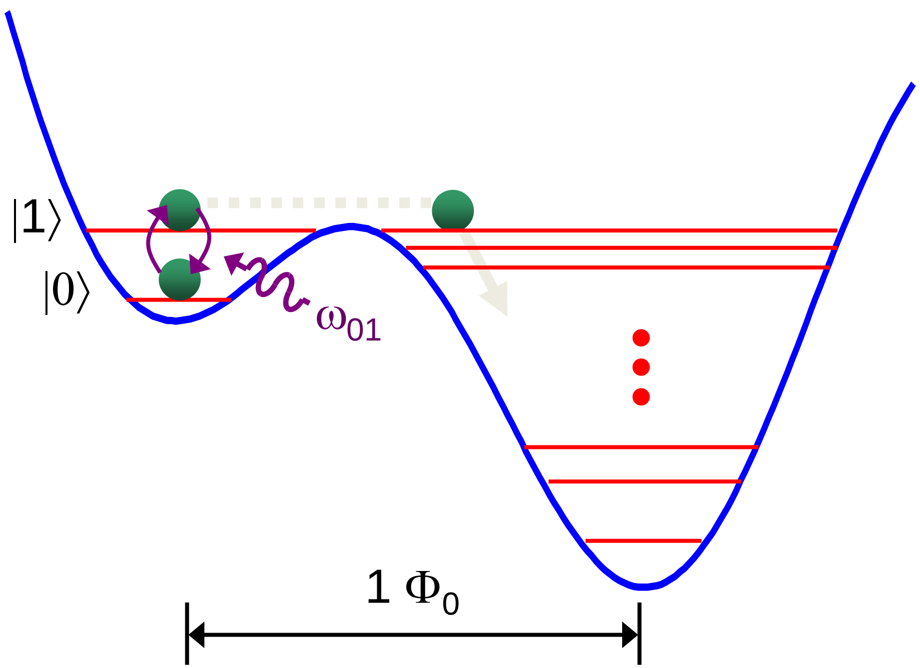
Фазовый кубит: реализация

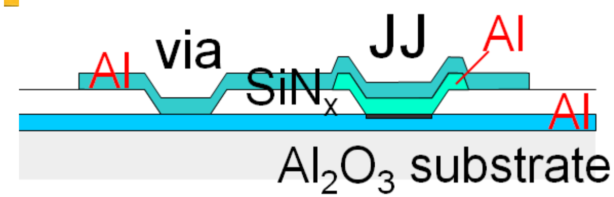
J. M. Martinis et al., Phys. Rev. Lett. **89**, 117901 (2002)

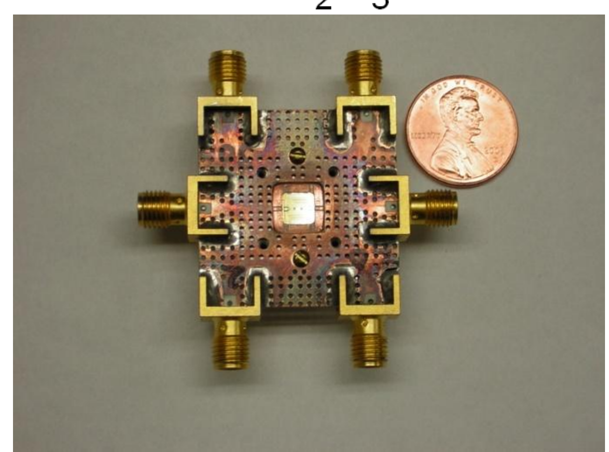
R. McDermott et al., *Science* **307**, 1299 (2005)



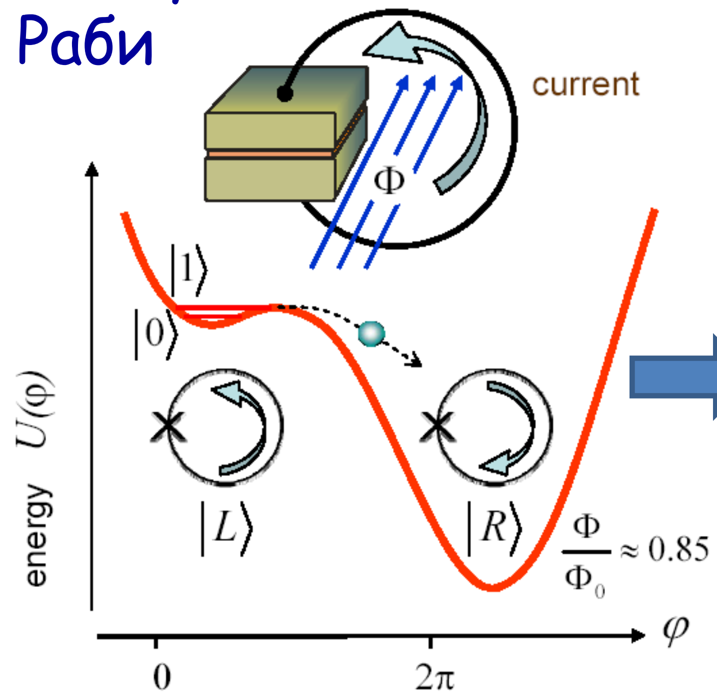


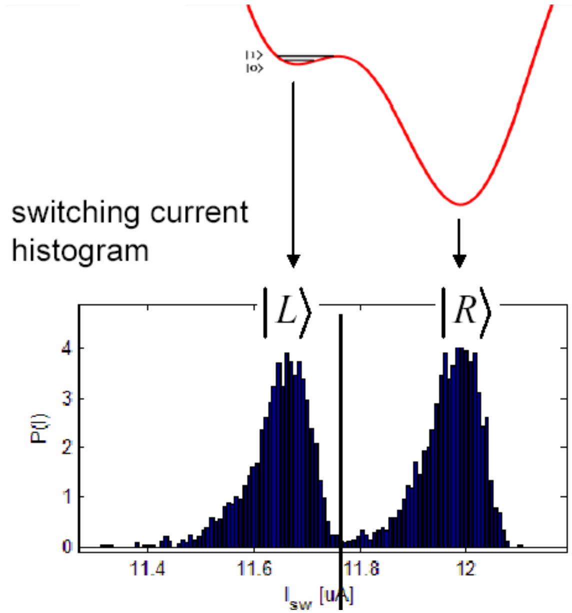


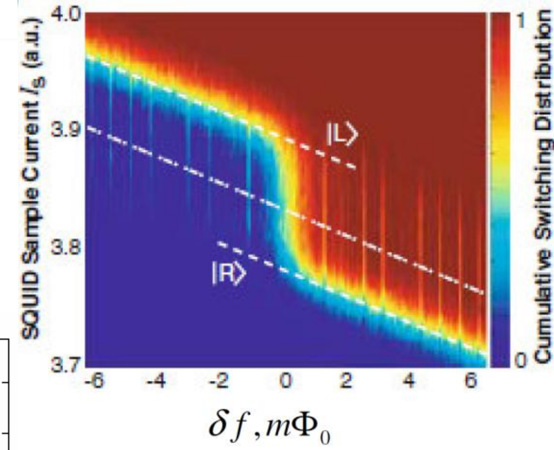




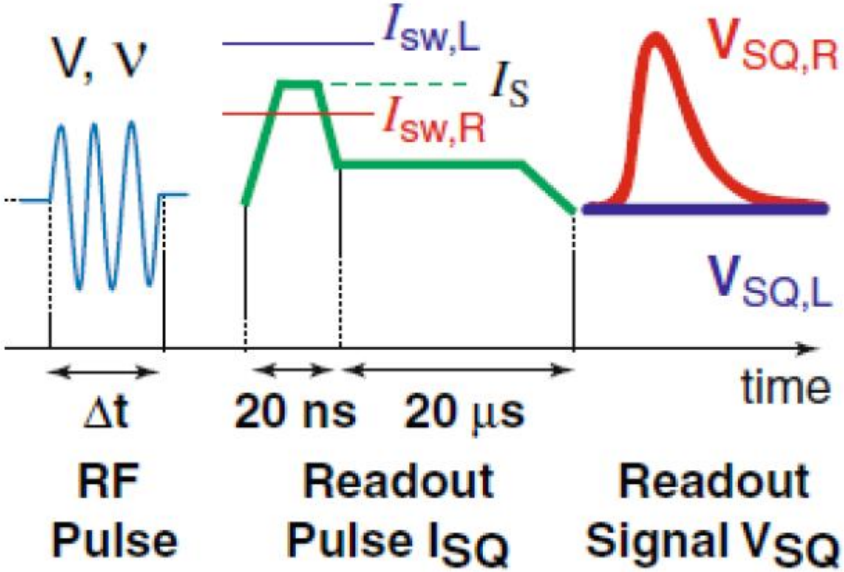
Фаз.кубит: осцилляции Раби

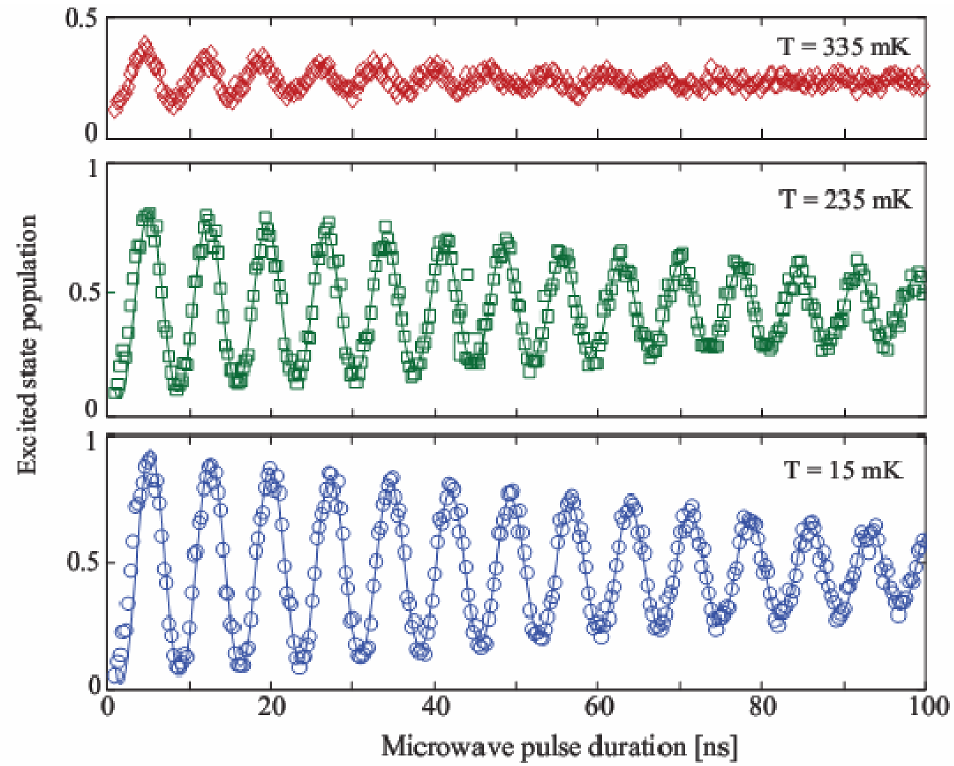




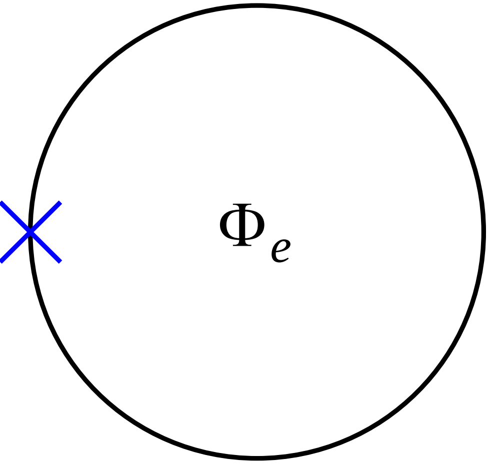


$$P_{esc} = \frac{N_{(I_{sw} > I_{tresh})}}{N_{total}}$$





Потоковый кубит



Size problem and solution

$$L \approx \mu_0 D$$

$$\frac{2\pi L I_c}{\Phi_0} \geq 1 \Rightarrow D > \frac{\Phi_0}{2\pi\mu_0 I_c} \approx \frac{250\mu\text{m}}{I_c(\mu\text{A})}$$

For quantum behavior: $E_J/E_C \sim 10\text{-}100$

Typical parameters for aluminum technology :

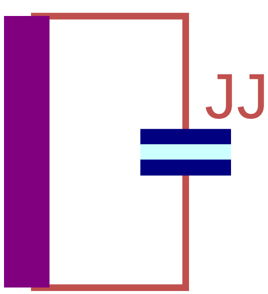
$$c_s \approx 4\times10^{-2}\,\text{F/m}^2$$

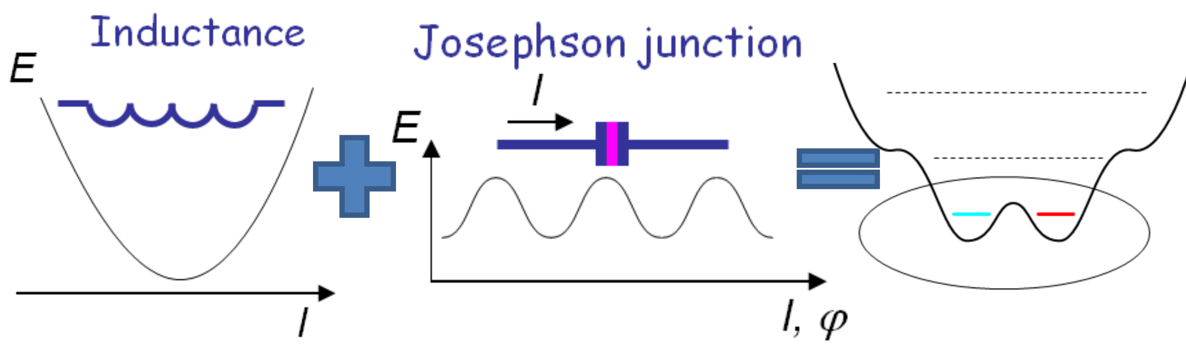
$$j_c \approx 10^6\text{-}10^7\,\text{A/m}^2$$

$$\frac{E_J}{E_C} \approx 10^4 a^4 \quad a[\mu\text{m}]$$

Possible solution: high kinetic inductance

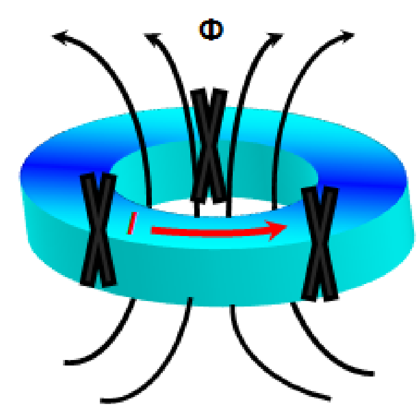
InO_x, TiN, NbN

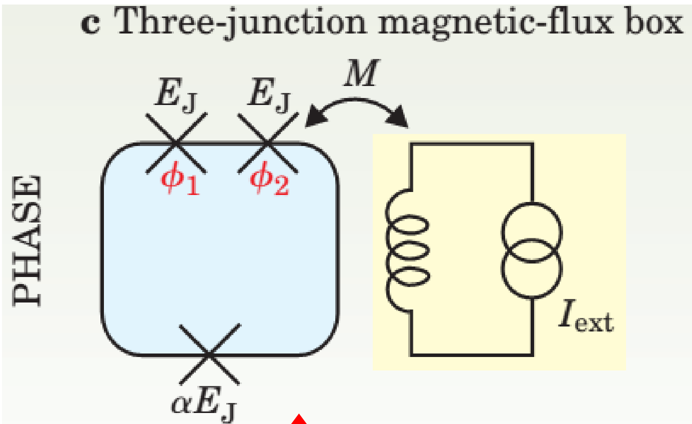




Chiorescu, van der Wal, Mooij, Orlando, S. Lloyd *et al.* *Science* **285**, **290**, **299** (1999, 2000, 2003)

3Jj-qubit. Energy surface



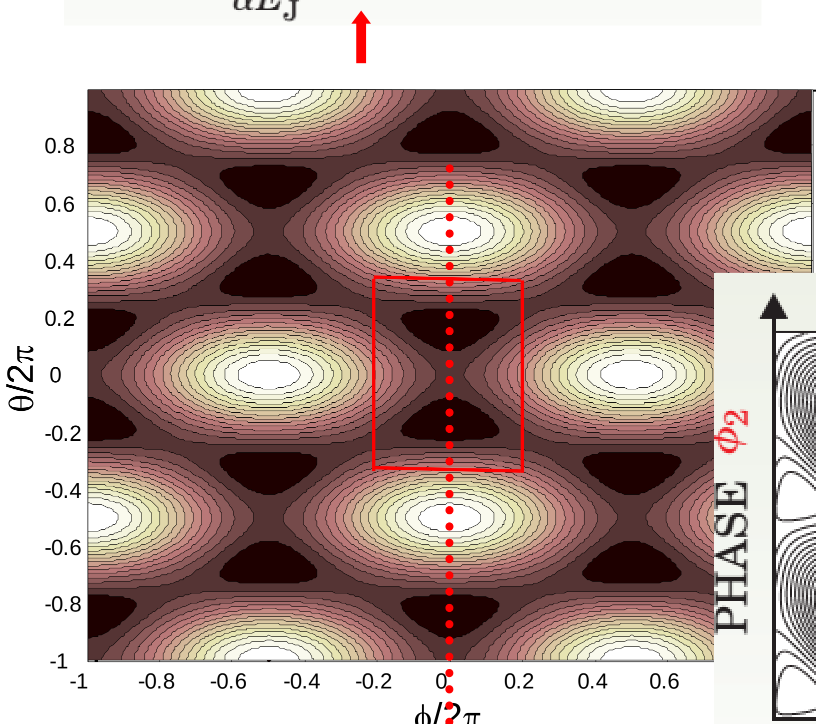


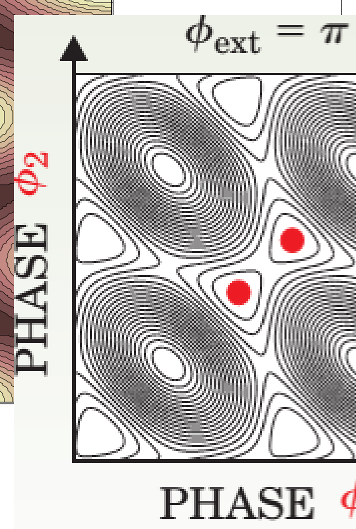
$$H_0 = \frac{P_\varphi^2}{2M_\varphi} + \frac{P_\theta^2}{2M_\theta} + U(f,\varphi,\theta),$$

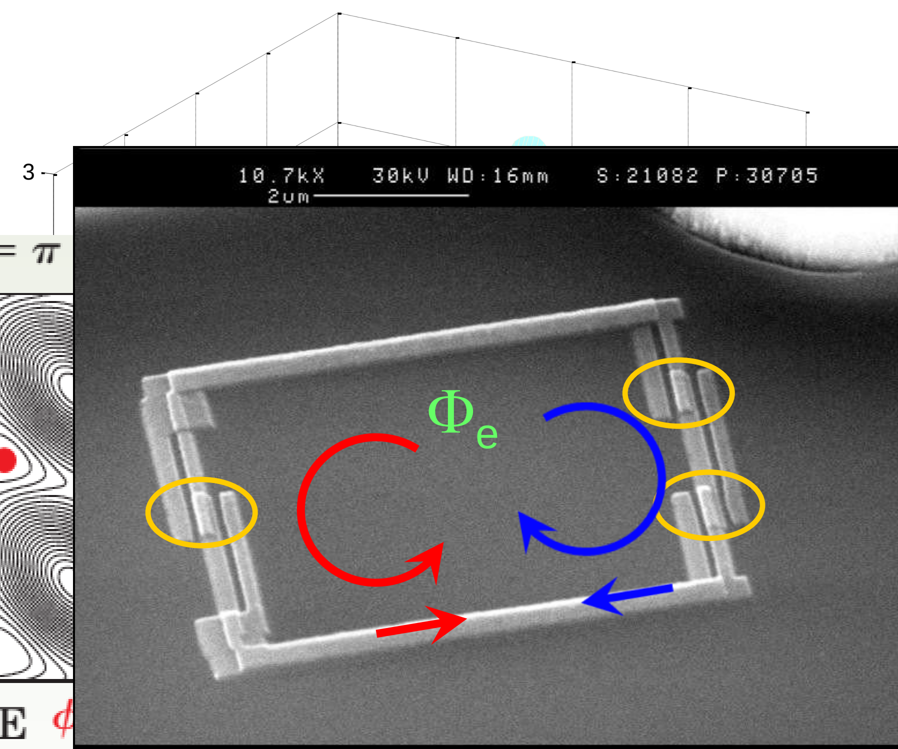
$$U(f,\varphi,\theta) = E_J(\alpha - 2\cos\varphi\cos\theta + \alpha\cos(2\pi f + 2\theta)),$$

$$\varphi = (\varphi_1 + \varphi_2)/2, \theta = (\varphi_1 - \varphi_2)/2, P_{\varphi,\theta} = -i\hbar\partial_{\varphi,\theta},$$

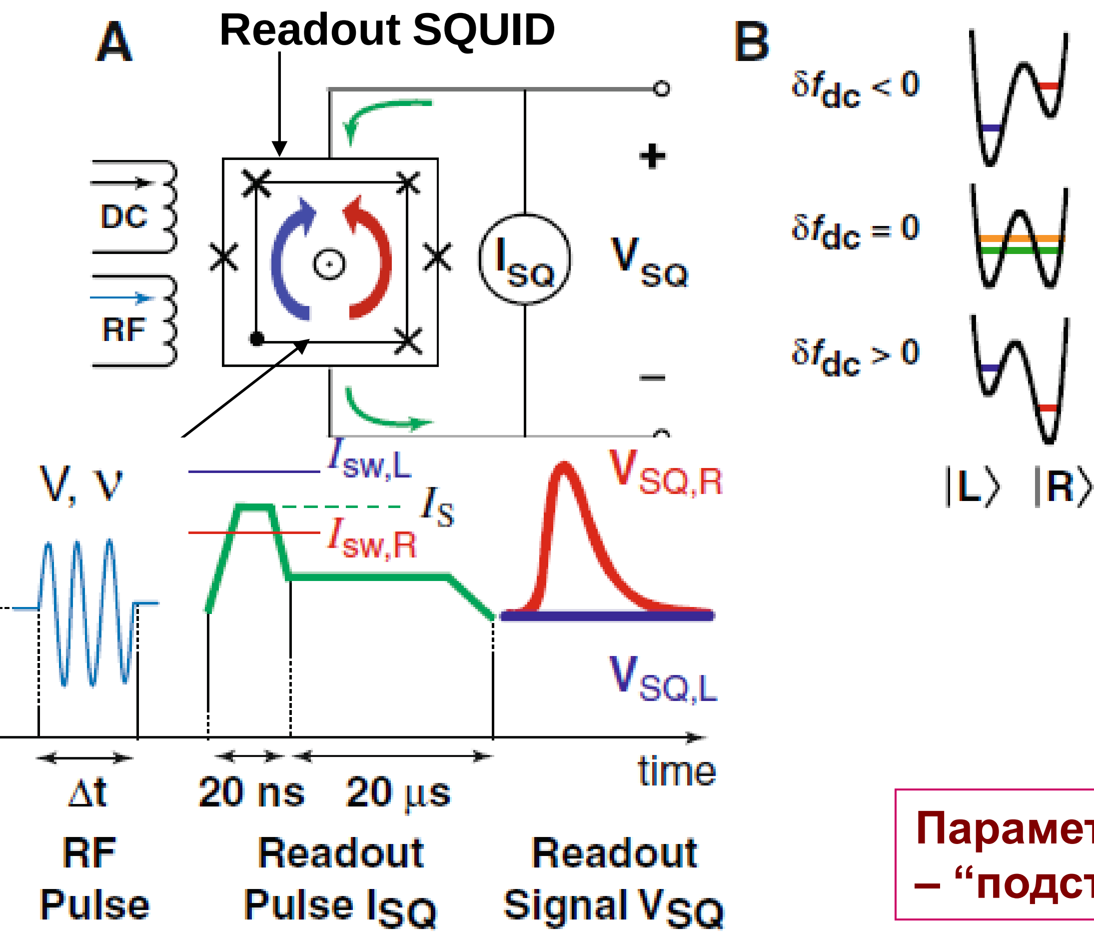
$$M_\varphi = (\Phi_0/2\pi)^2 2C, M_\theta = (1+2\alpha)M_\varphi.$$

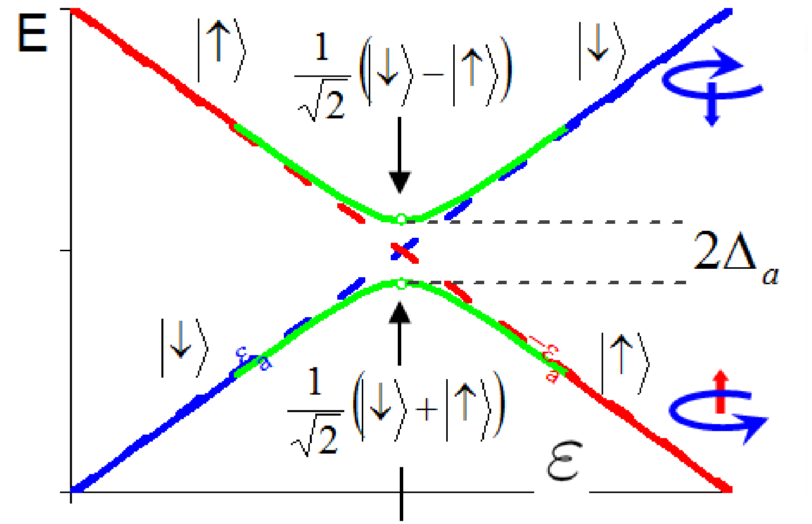






Потоковый кубит: гамильтониан, управление





$$H_s = \frac{1}{2}(\varepsilon(t)\sigma_z + \Delta\sigma_x)$$

$$\varepsilon(t) = \varepsilon_0 + A\cos\omega t$$

Параметрами кубита можно управлять – “подстраиваемый атом”

$$\delta f_{dc} = f_{dc} - \Phi_0 / 2$$

$$\varepsilon_0 = 2I_q \delta f_{dc}$$

$$f(t) = f^{dc} + f^{ac}(t)$$

$$f^{ac}(t) \propto A\cos\omega t$$

$$\Phi_0 = h / 2e \quad T = 20mK$$

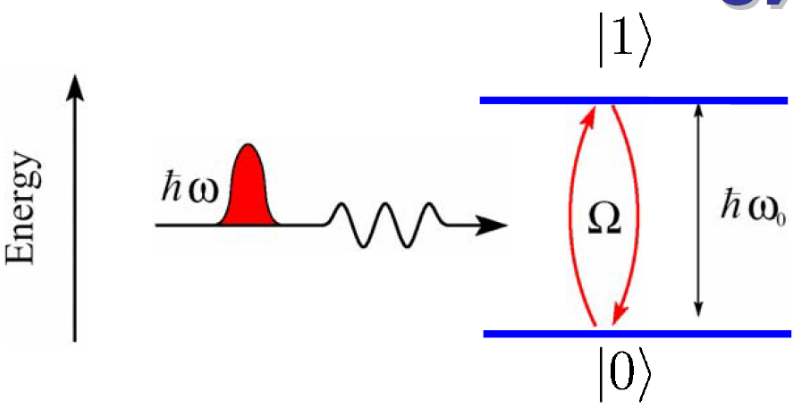
$$E_{g,e} = \pm\frac{1}{2}\sqrt{\varepsilon^2 + \Delta^2}$$

$$|g\rangle = -\sin\theta/2|\uparrow\rangle + \cos\theta/2|\downarrow\rangle$$

$$|e\rangle = \cos\theta/2|\uparrow\rangle + \sin\theta/2|\downarrow\rangle$$

$$\theta = \arctan\Delta/\varepsilon$$

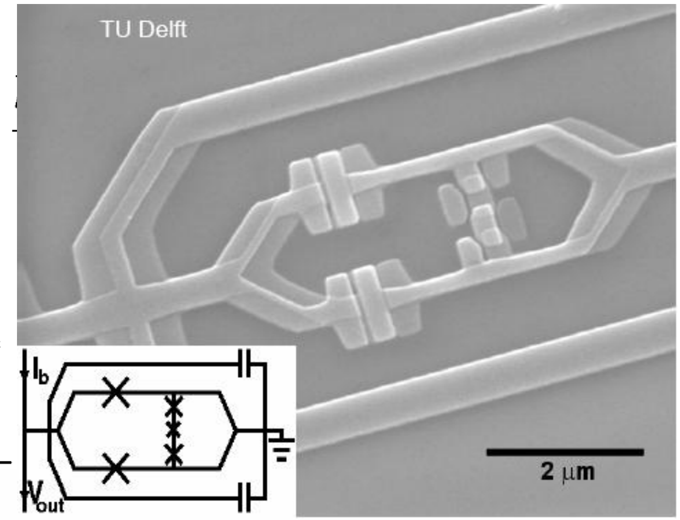
Раби осцилляции в двухуровневой системе



$H =$

$\Omega(t)$

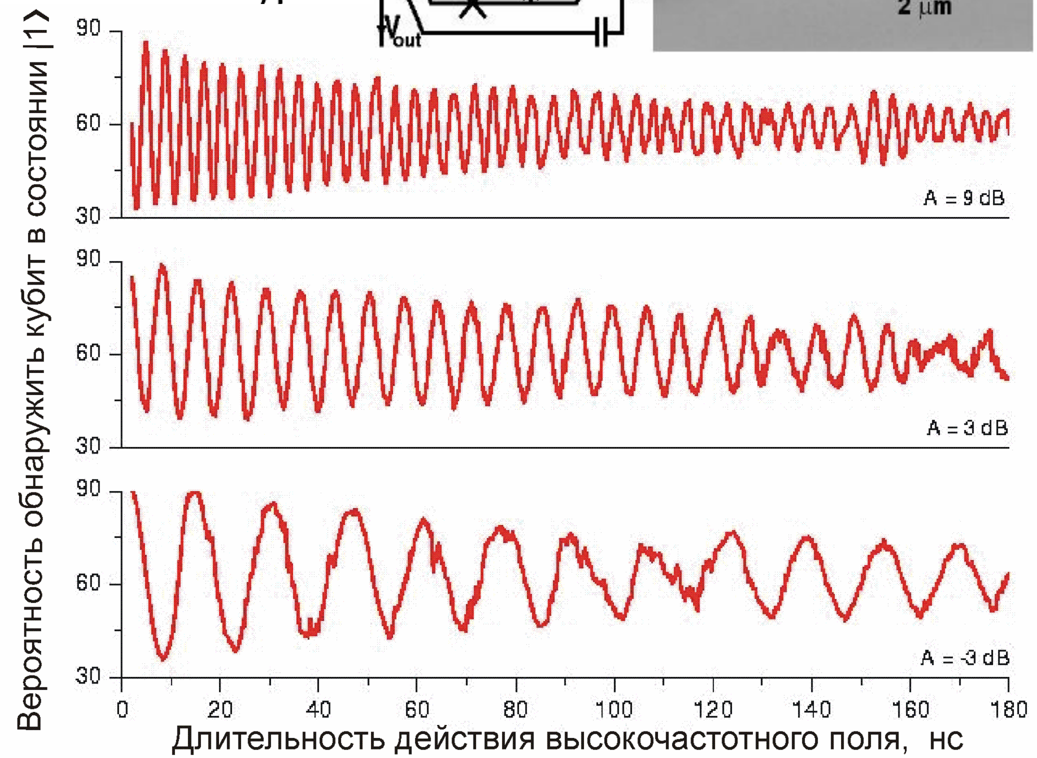
$\tau =$



При $\omega = \omega_0$ (используя приближение RWA)

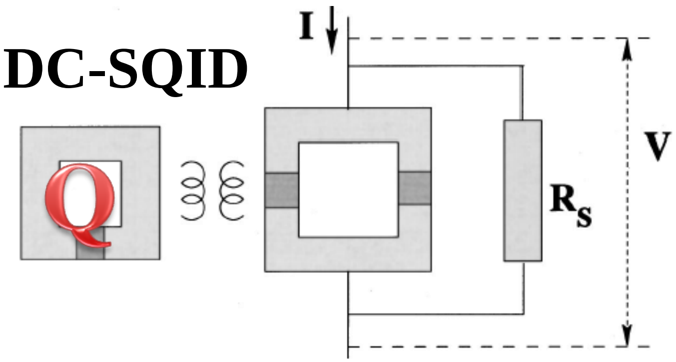
$$P_{0\to1}(t) = \sin^2\left(\frac{\Theta}{2}\right)$$

$$\Theta = \int_{-\infty}^{\tau} \Omega(t)dt$$



Measurements in flux qubit (overview)

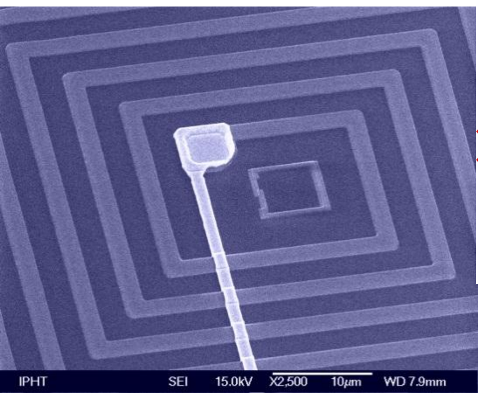
I. DC-SQUID

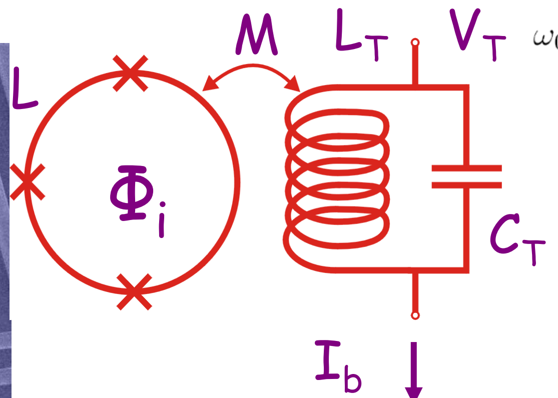


1. $R_S >> (E_J / E_C)R_Q$ — *Weak dephasing, statistical measurements*

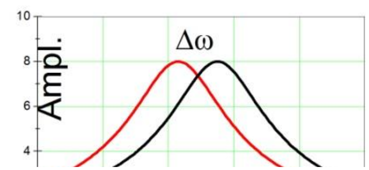
2. $R_S << (E_J / E_C)R_Q$ — *Strong dephasing*

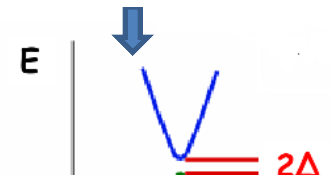
II. LC-Tank

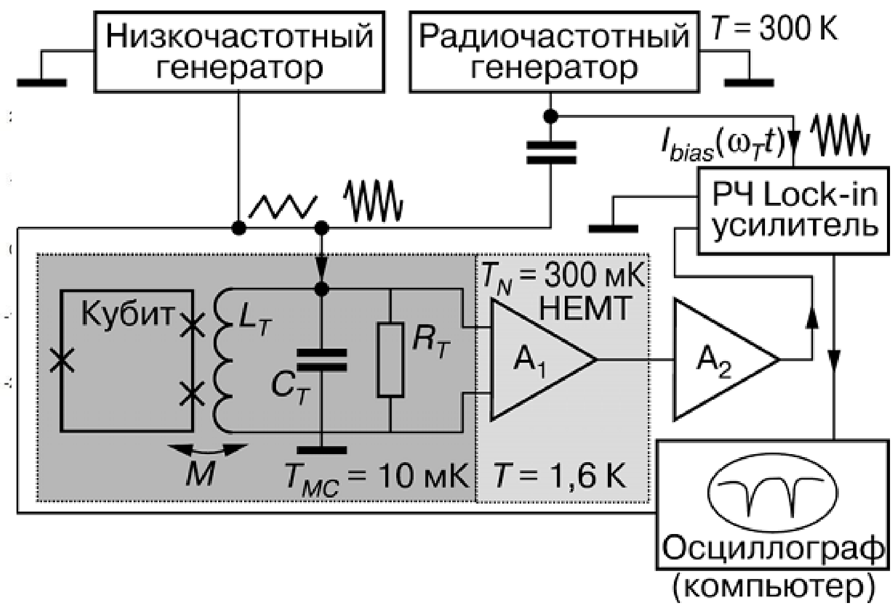




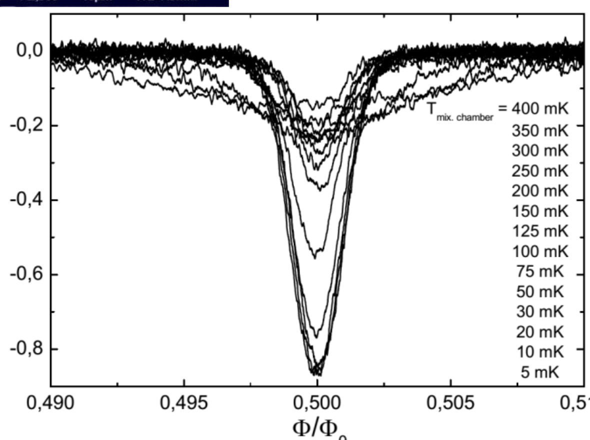
$$\omega_0 = \sqrt{\frac{k^*}{m^*}} \approx \omega_T \left(1 - \frac{M^2}{2L_T}\frac{\partial^2 E_-(\Phi_{dc})}{\partial \Phi^2}\right) \qquad \frac{\partial^2 E_-(\Phi_{dc})}{\partial \Phi^2} = -\frac{(I_p\Delta)^2}{(\varepsilon^2(\Phi_{dc}) + \Delta^2)^{3/2}}$$





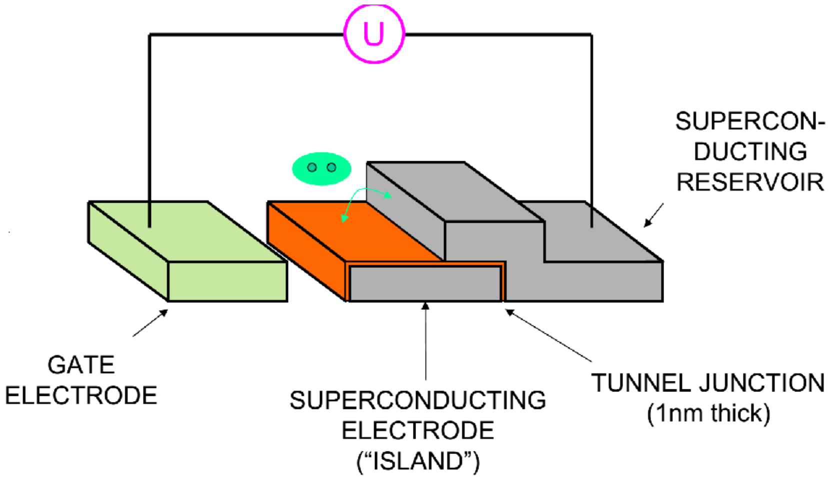


$I_p = 225$ nA



Зарядовый кубит

THE SINGLE COOPER PAIR BOX

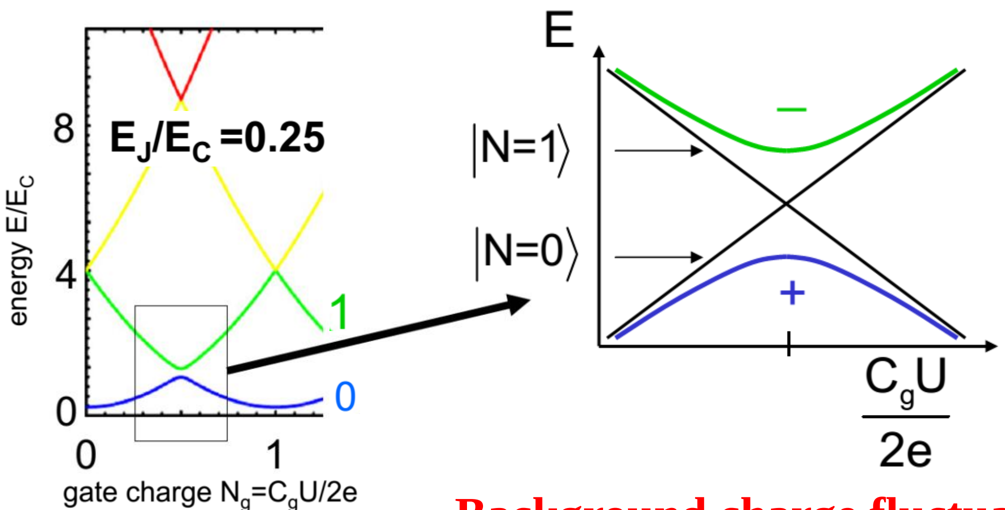


$$\widehat{N} = \sum_N N|N\rangle\langle N| \qquad \hat{\theta}:\ e^{i\hat{\theta}}\widehat{N}e^{-i\hat{\theta}} = \widehat{N} - 1$$

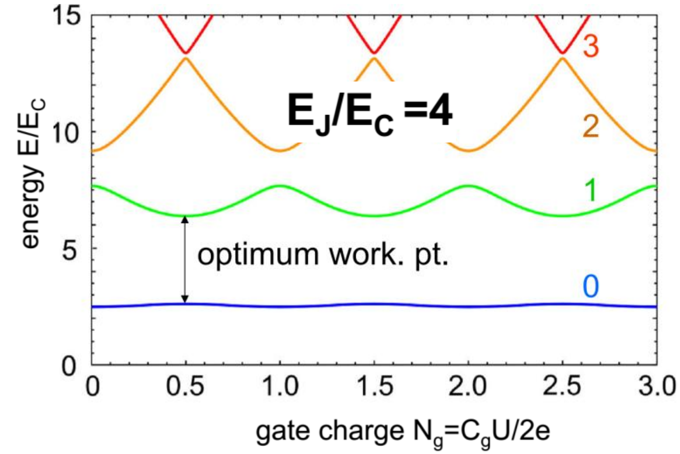
$$\widehat{H} = 4E_C\left(\widehat{N} - N_g\right)^2 - E_J\cos\hat{\theta}$$

$$\hat{V} = \frac{\hbar}{2e}\frac{d\hat{\theta}}{dt} = \frac{2e}{C_\Sigma}\left(\widehat{N} - N_g\right) \qquad \hat{I} = 2e\frac{d\widehat{N}}{dt} = I_0\sin\hat{\theta}$$

$$E_C = \frac{e^2}{2\left(C_g + C_j\right)}$$



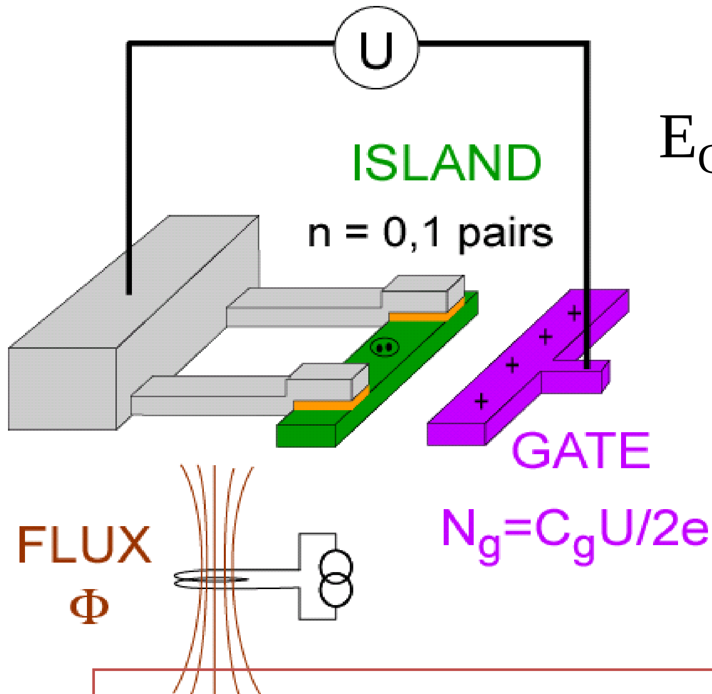
Background charge fluctuations?



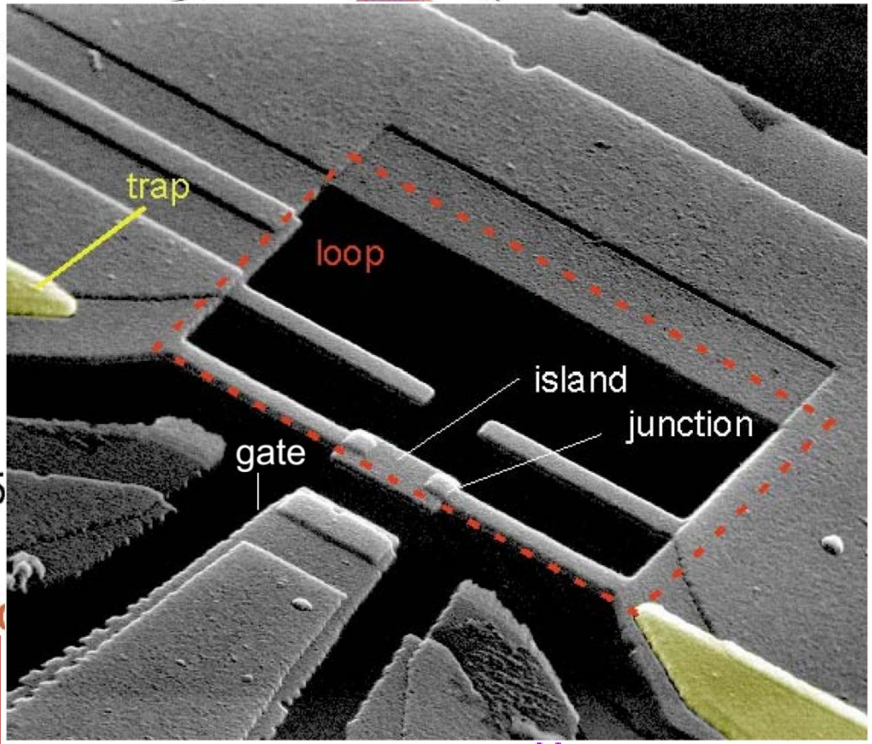
Nakamura, Pashkin, Tsai *et al. Nature* **398**, **421**, **425** (1999, 2003, 2003)

SPLIT COOPER PAIR BOX QUBIT:
THE “ARTIFICIAL ATOM” with two control knobs

*[Devoret & Martinis, QIP, **3**, 351-380(2004)]*



$E_C \approx E_J$



$$H = -\frac{1}{2} E_{ch}(V_g)\,\sigma_z - \frac{1}{2} E_J(\Phi_x)\,\sigma_x$$

$$\hat{H} = \sum_n \left[E_C (n - N_g)^2 |n\rangle\langle n| \;-\; E_j \cos\left(\frac{\pi \Phi}{\Phi_0}\right) \frac{\left(|n\rangle\langle n+1| + |n+1\rangle\langle n|\right)}{2} \right]$$

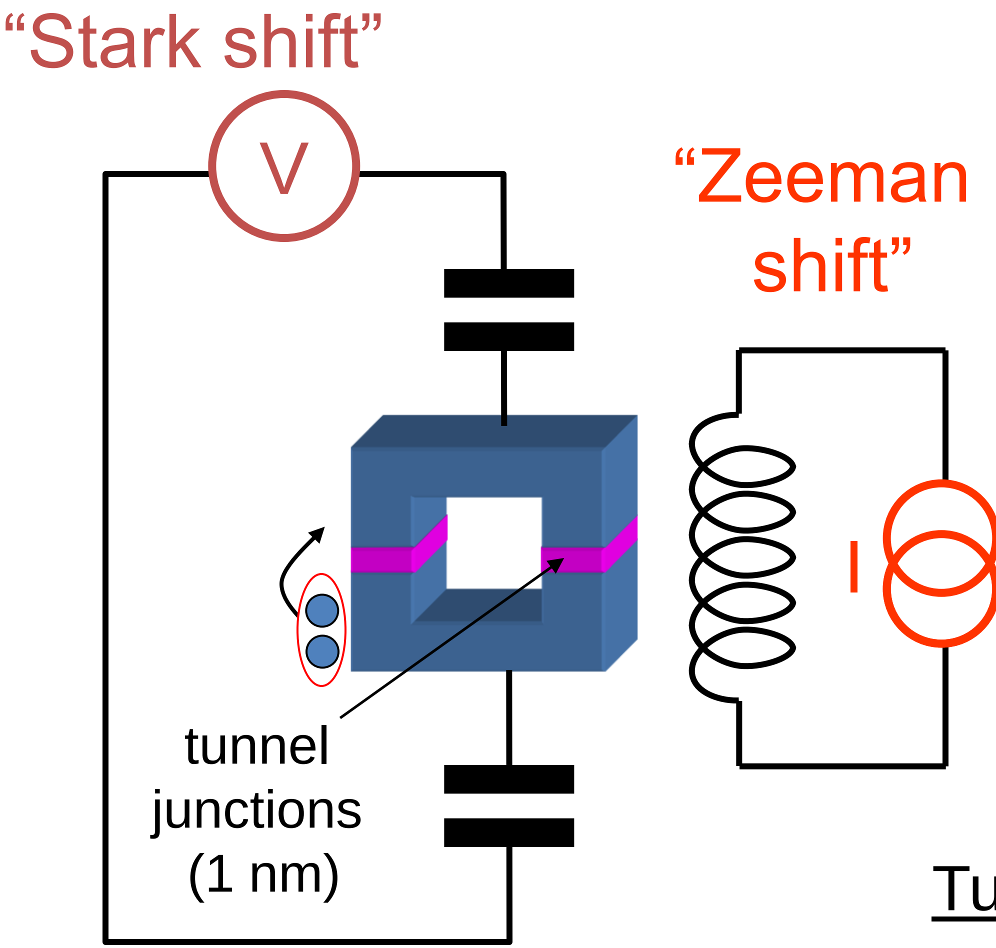
$\sigma_z = |0\rangle\langle 0| - |1\rangle\langle 1|$

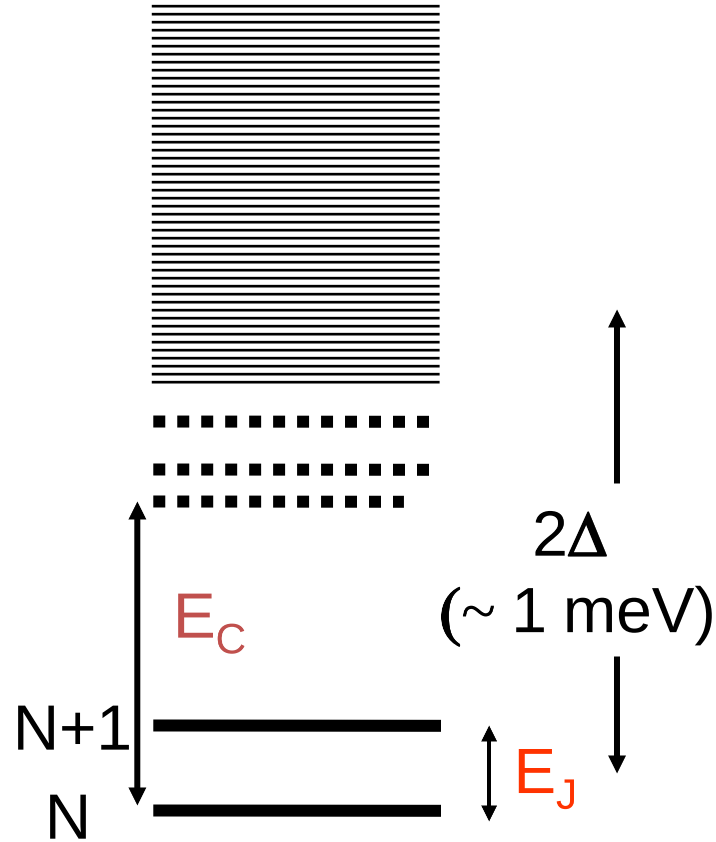
$\sigma_x = |0\rangle\langle 1| + |1\rangle\langle 0|$

Operation at optimal point (saddle)
- minimizes noise effects

- voltage fluctuations couple transversely
- flux fluctuations couple quadratically

The Single Cooper-pair Box: an Tunable Artificial Atom





$$H = \frac{E_{\text{Coulomb}}}{2}\sigma^x - \frac{E_{\text{Josephson}}}{2}\sigma^z$$

<u>Tune σ</u>

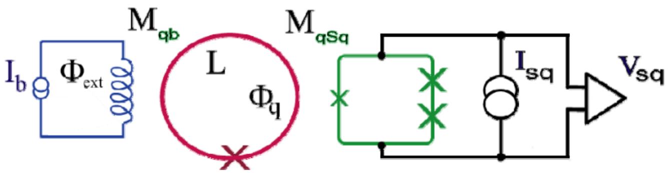
Tune σ^x with voltage: (Stark)

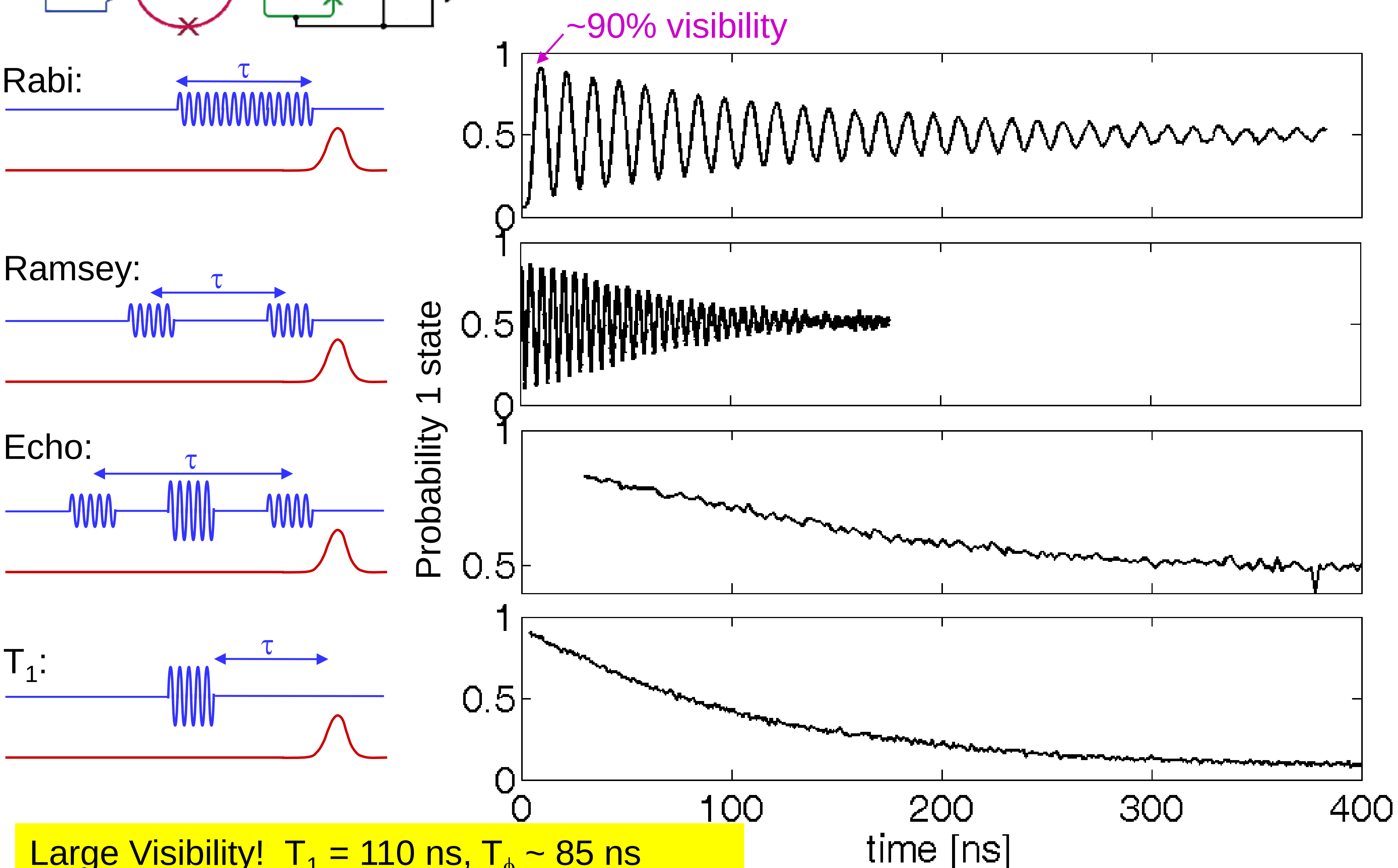
$$E_{\text{Coulomb}} = 4E_C\left(n_g - 1\right)$$

Tune σ^z with Φ: (Zeeman)

$$E_{\text{Josephson}} = E_{J_{\max}} \cos\left[\pi\Phi_b / \Phi_0\right]$$

Qubit Fidelity Tests





Large Visibility! T_1 = 110 ns, T_ϕ ~ 85 ns

Superconducting Circuits for Quantum Information: An Outlook

M. H. Devoret[1,2] and R. J. Schoelkopf[1*]

relaxation T_1 τ_{relax} dephasing T_2 τ_ϕ

$$\Gamma_1 = \lim_{t\to\infty} \frac{\ln\langle S_z(t) - S_z^{eq}\rangle}{t}$$

$$\Gamma_\phi = \lim_{t\to\infty} \frac{\ln\left[\frac{\left\langle \vec{S}(t).\vec{S}_0(t)\right\rangle}{\left|\vec{S}(t)-S_z^{eq}\hat{z}\right|}\right]}{t}$$

$$T_1 = \Gamma_1^{-1}$$

$$T_2 = (\Gamma_\phi + \Gamma_1/2)^{-1}$$

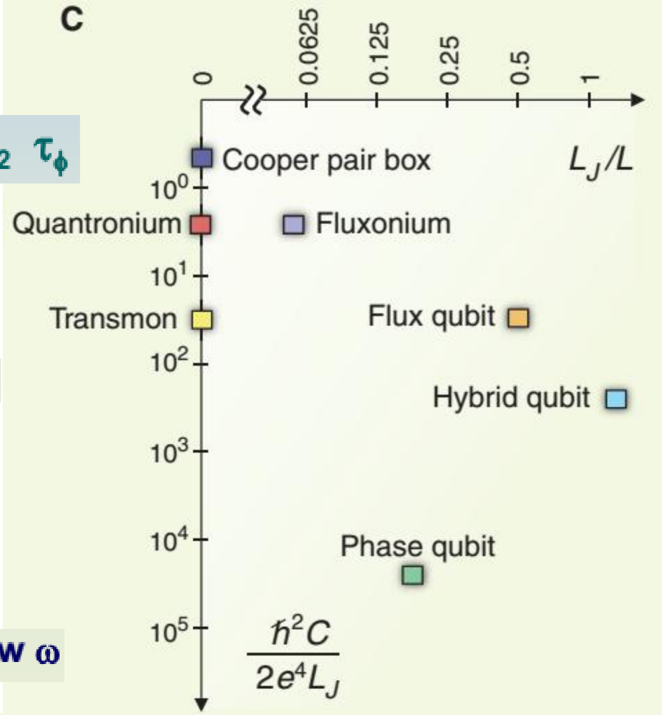
$$H = -\frac{1}{2}\Delta E\sigma_z - \frac{1}{2}X\sigma_x + H_{Bath}$$

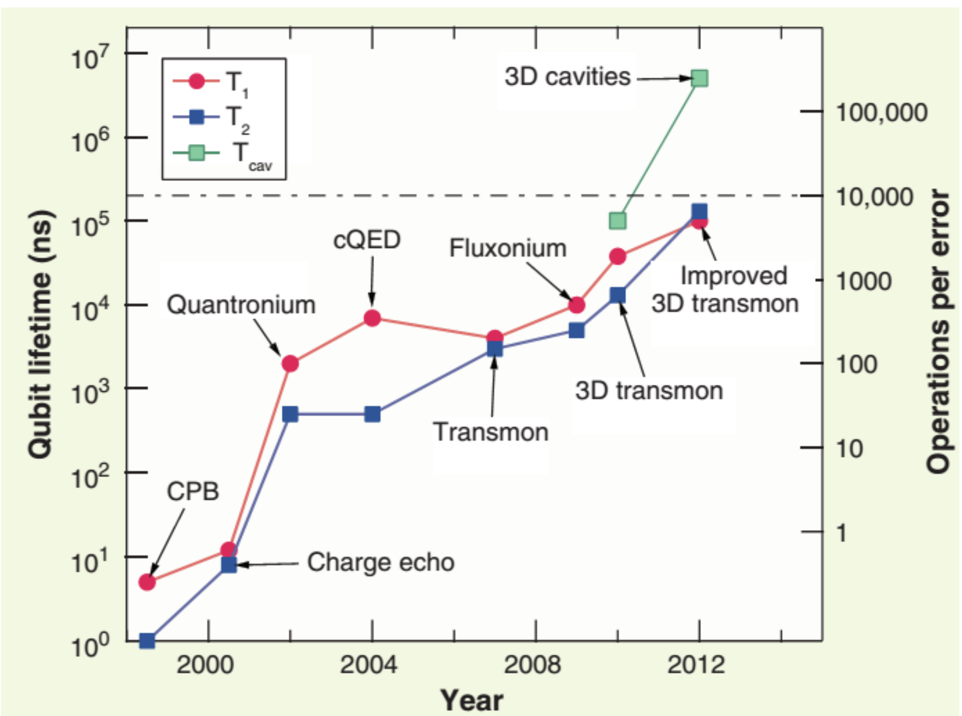
τ_{relax} determined by spectral density at ΔE

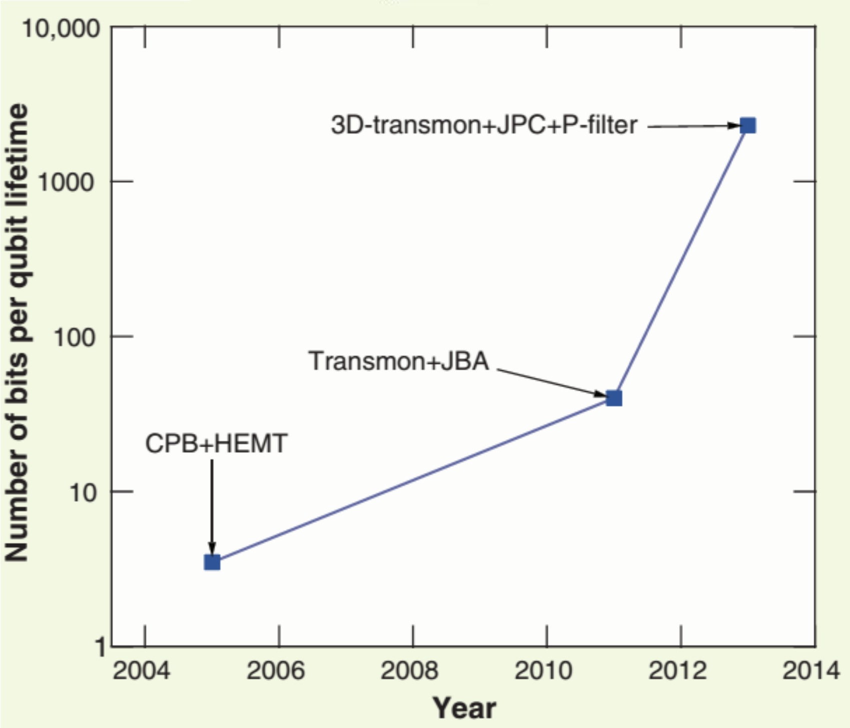
$$H = -\frac{1}{2}(\Delta E + X)\sigma_z + H_{bath}$$

τ_ϕ determined by spectral density at low ω

C



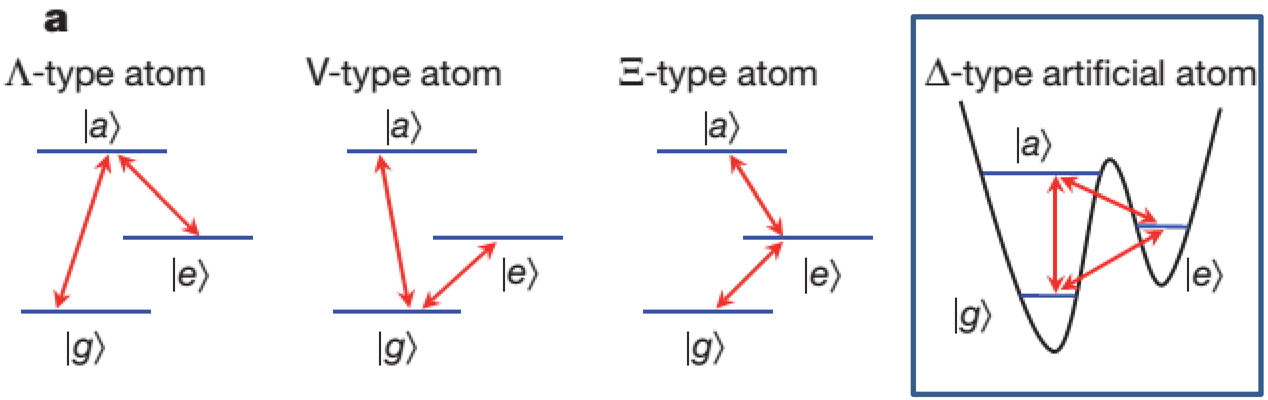


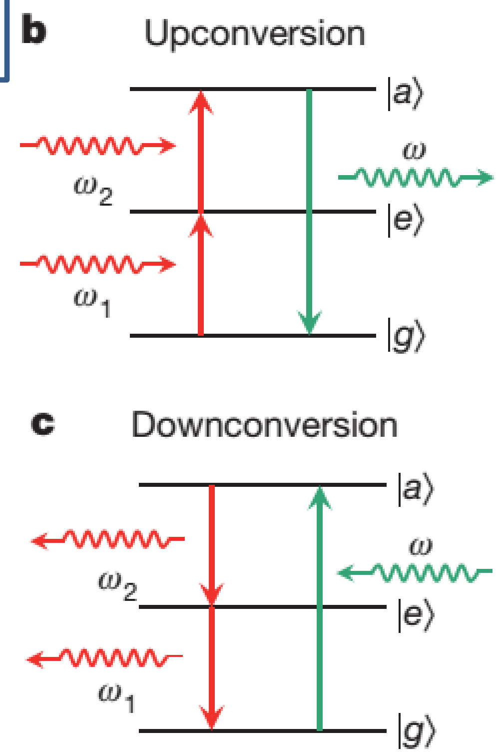


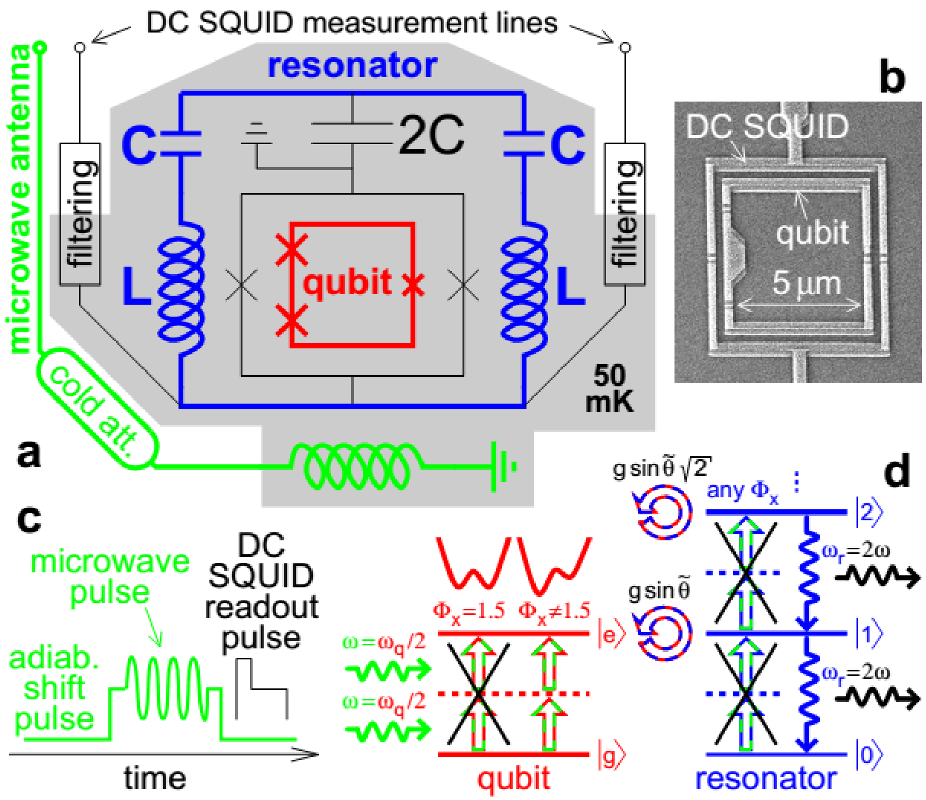
План доклада

- Почему интересны джозефсоновские кубиты?
- Сверхпроводимость и эффект Джозефсона
- Типы джозефсоновских кубитов
- **Атомная физика и квантовая оптика с джозефсоновскими кубитами**
- Проблемы и перспективы
- Заключение

Правила отбора для потокового кубита





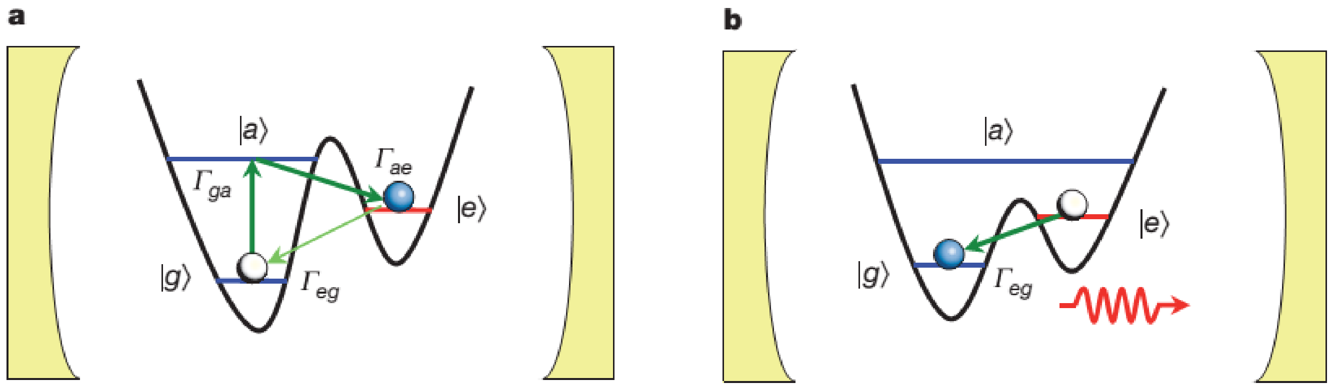


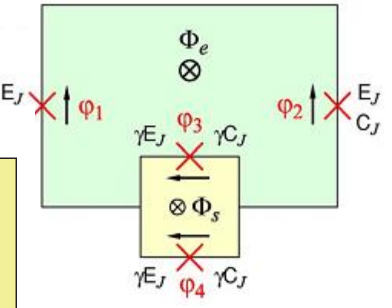
Liu, Y. X., et al. Optical selection rules …Phys.Rev. Lett.95,087001 (2005).

Deppe, F.et al. // Nature Phys.4,686–691 (2008).

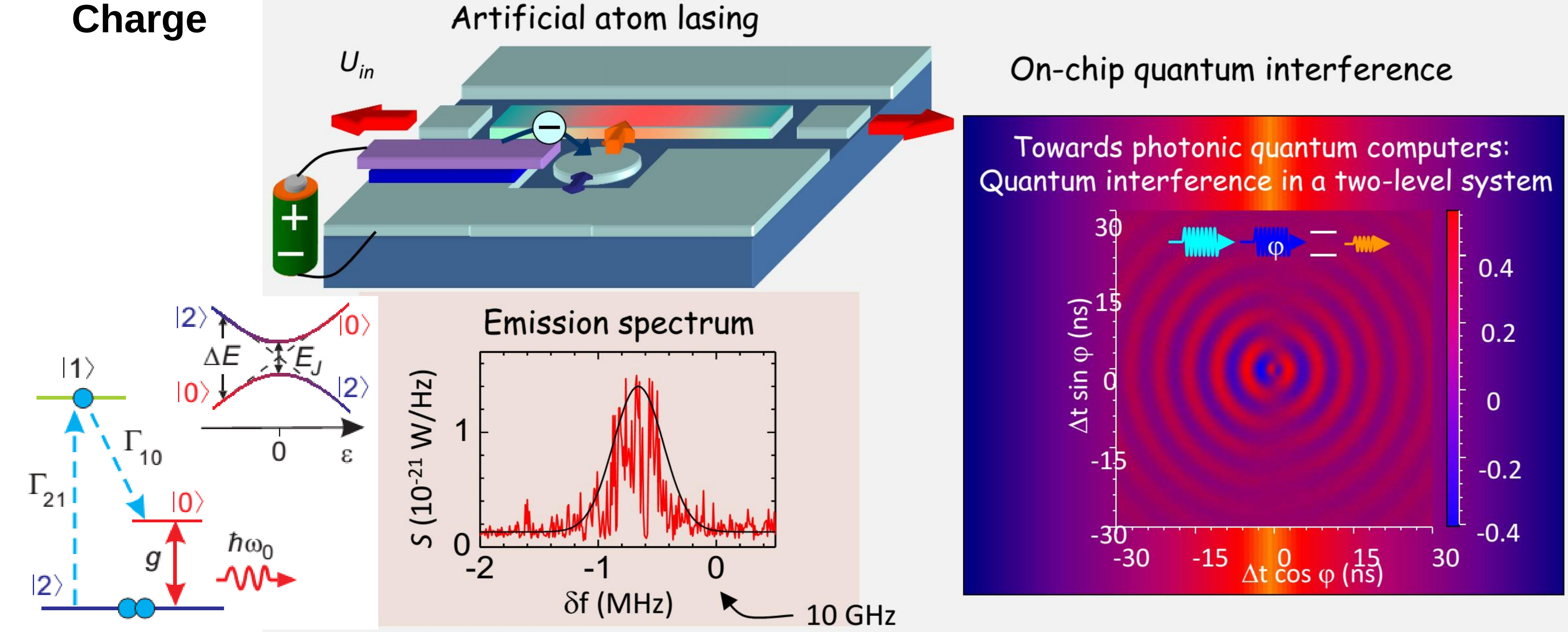
Лазер на одном атоме

Flux



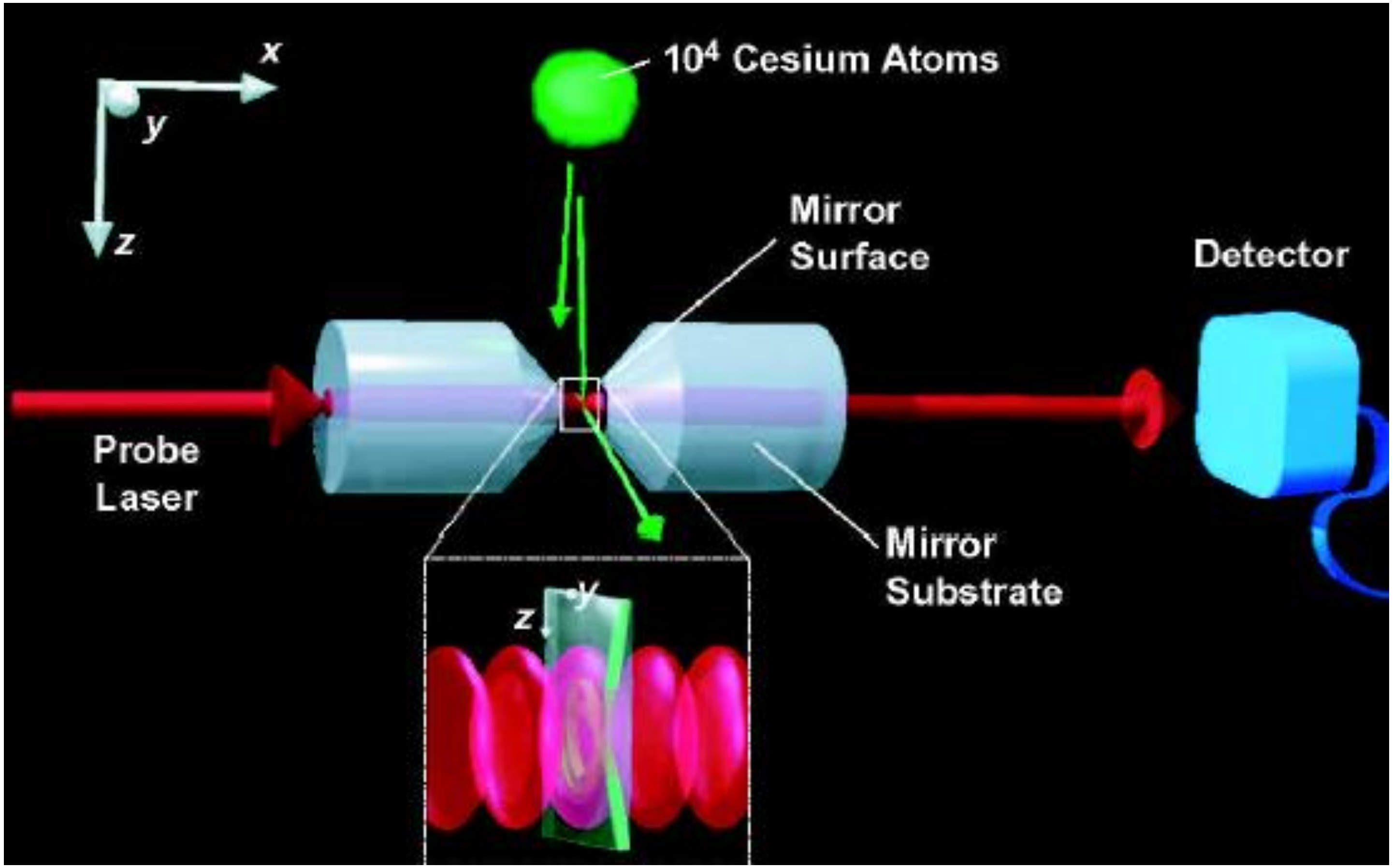


Charge



- **O. Astafiev**, et.al. "Single artificial-atom Lasing". *Nature* **449**, 588–590 (2007).
- **O. Astafiev**, et.al. Resonance fluorescence of a single artificial atom. *Science*. 327 (2010).

Optical Cavity QED

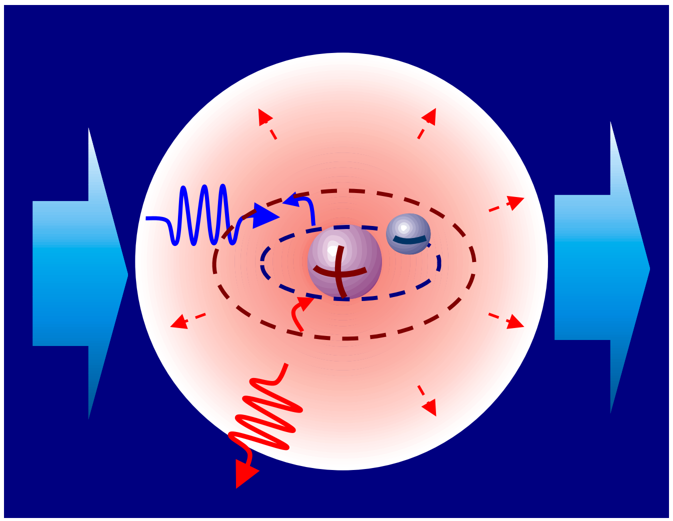


… measure changes in transmission of optical cavity

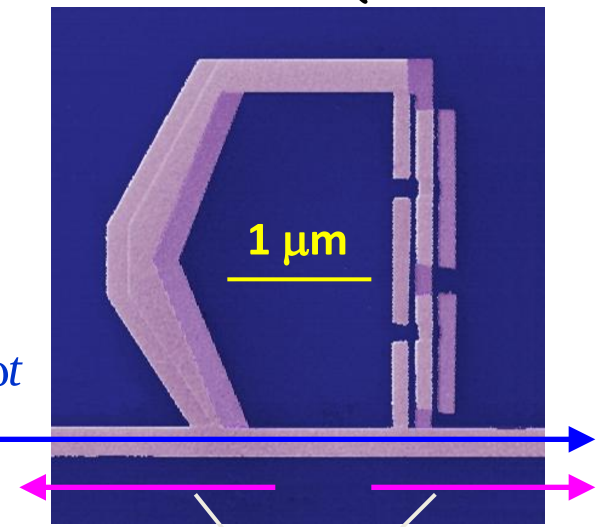
e.g. Kimble and Mabuchi groups at Caltech

Atom in open space

Light scattering by an atom



MW scattering by a macroscopic quantum scatterer (10^{10} Al atoms)



$$I_0\, e^{ikx-i\omega t}$$

$$I_{sc}(x,t) = i\frac{\hbar\Gamma}{\phi_p}\langle\sigma^-\rangle e^{ik|x|-i\omega t}$$

Dipole moment $\langle\phi(t)\rangle = \phi_p\langle\sigma^-\rangle e^{-i\omega t}$

Matrix element $\phi_p = MI_p$

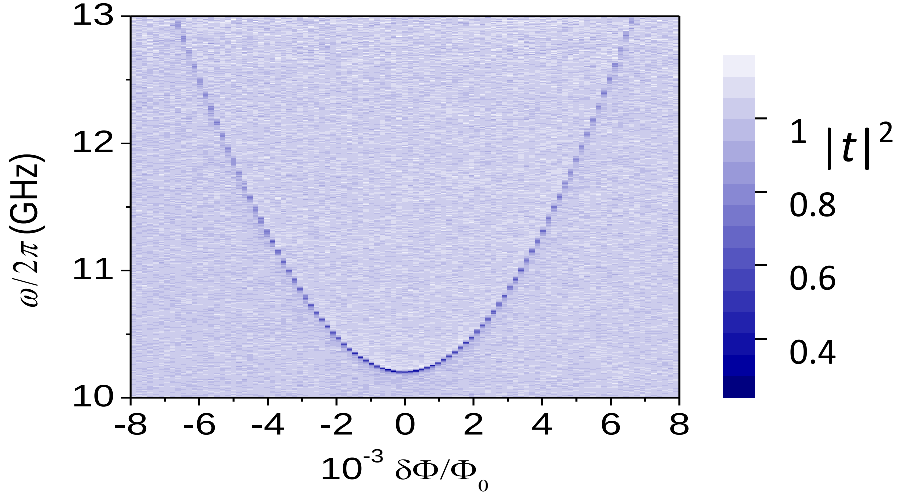
Natural atoms are weakly coupled to electromagnetic waves (weak scattering)

Artificial atoms are strongly coupled to electromagnetic waves

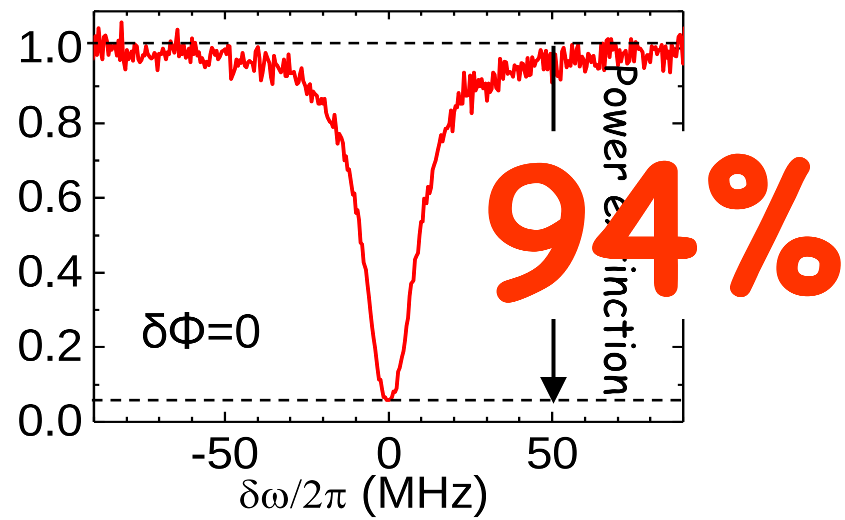
Strong scattering of propagating waves

Resonance fluorescence

Direct transmission spectroscopy



Spectroscopy of the artificial atom. Power transmission coefficient $|t|^2$ versus flux bias δΦ and incident microwave frequency ω/2π.



Previous record in optical systems was 12%

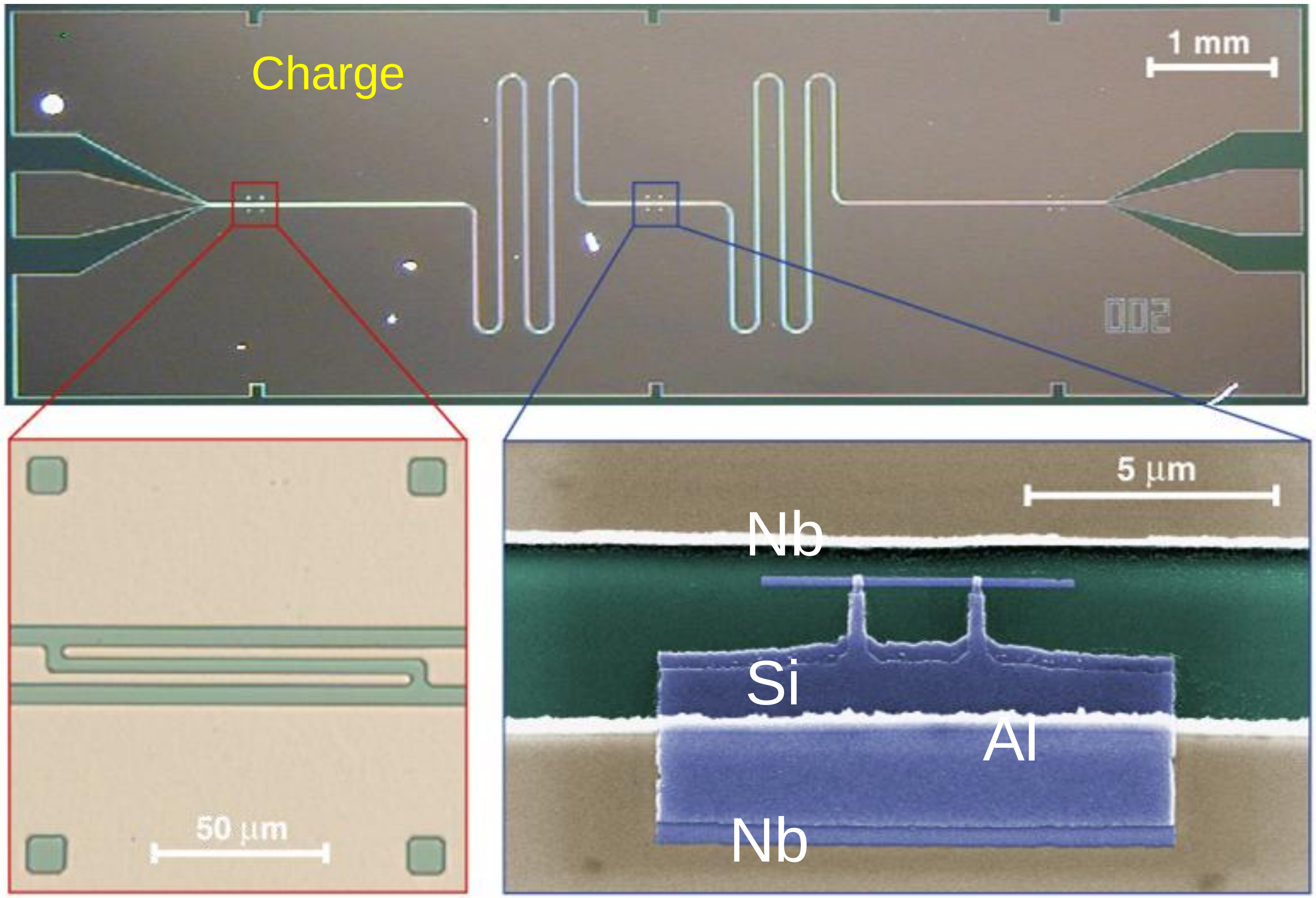
The artificial atom strongly interacts with modes of 1D open space

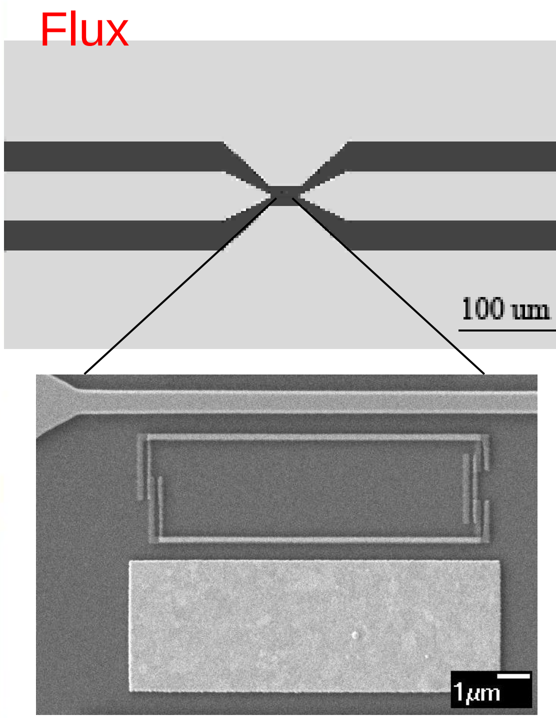
⇓

Promising candidate for quantum information processing

O. Astafiev, A. M. Zagoskin, A. A. Abdumalikov, Yu. A. Pashkin, T. Yamamoto, K. Inomata, Y. Nakamura, and J. S. Tsai. Resonance fluorescence of a single artificial atom. Science. 327 (2010).

First Generation Chip for Circuit QED





No wires attached to qubit!

<u>First coherent coupling of solid-state qubit to single photon:</u>

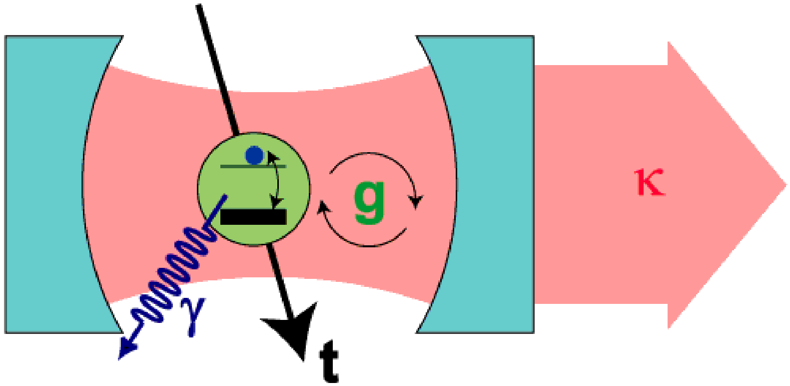
A. Wallraff, et al., *Nature (London)* **431**, 162 (2004)

<u>*Theory:*</u> Blais et al., *Phys. Rev. A* **69**, 062320 (2004)

R. J. Schoelkopf et al., Nature (London) 451, 664 (2008)

$$E_{0,\mathrm{rms}} \approx 0.2\,\mathrm{V/m}$$

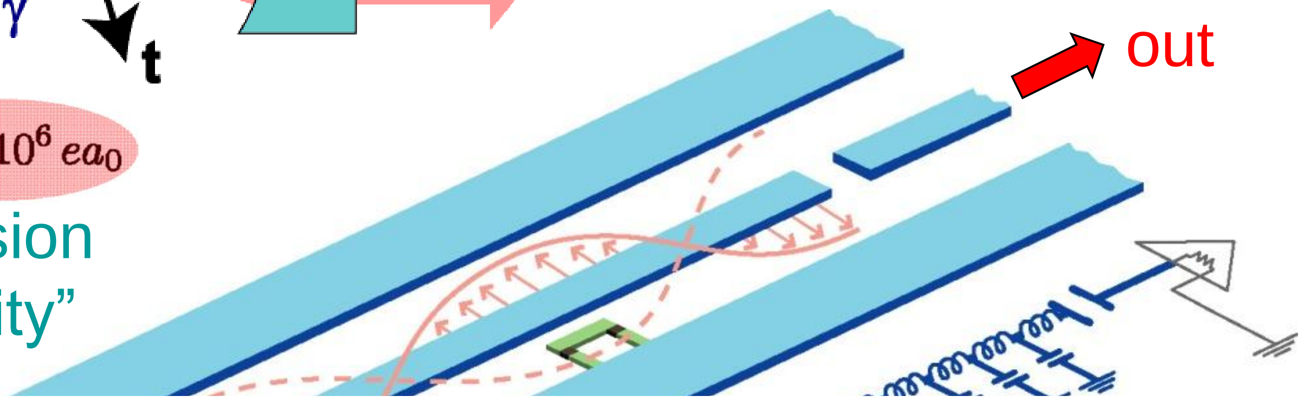
A Circuit Analog for Cavity QED



2g = vacuum Rabi freq.

κ = cavity decay rate

γ = “transverse” decay rate



$$d = \frac{\hbar g}{E_0} \sim 10^2 \ldots 10^6\, e a_0$$

transmission line “cavity”

Strong Coupling = $g > \kappa, \gamma, 1/t$

Jaynes-Cummings Hamiltonian

DC + 6 GHz

$$\hat{H} = \hbar\omega_r(a^\dagger a + 1/2) + \frac{E_{el}}{2}\hat{\sigma}_x - \frac{E_J}{2}\hat{\sigma}_z - \hbar g(a^\dagger\sigma^- + \sigma^+ a)$$

Quantized Field

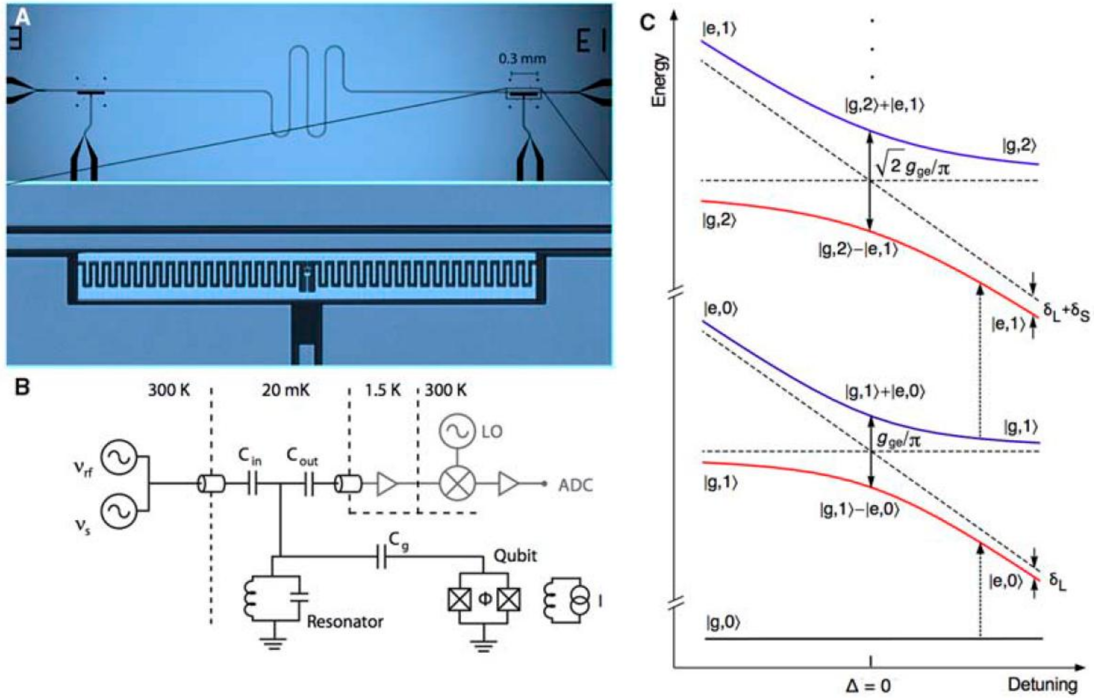
2-level system

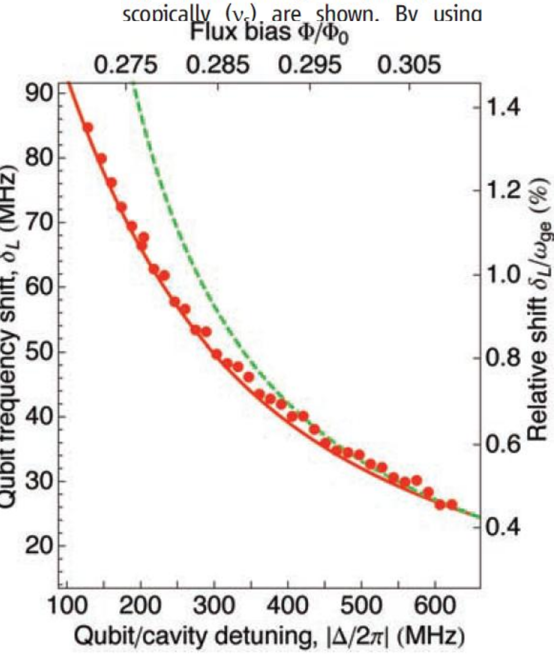
Electric dipole Interaction

Blais, Huan

Лэмбовский сдвиг

Fig. 1. Sample, experimental setup and energy-level diagram. (**A**) (Top) Optical image of the superconducting coplanar waveguide resonator with the transmon-type superconducting qubit embedded at the position shown boxed. (Bottom) Magnified view of boxed area, showing the qubit with dimensions 300 by 30 μm^2 close to the center conductor. (**B**) Simplified circuit diagram of the setup, similar to the one used in (*21*). We capacitively coupled the qubit at temperature 20 mK to the radiation field contained in the resonator through C_g. We coupled the resonator, represented by a parallel LC circuit, to input and output transmission lines via the capacitors C_{in} and C_{out}. We controlled the qubit transition frequency via a current-biased (*I*) coil generating a magnetic flux Φ threading the qubit loop. Microwave signal generators for populating the resonator with photons (ν_{rf}) and for exciting the qubit spectroscopically (ν_s) are shown. By using



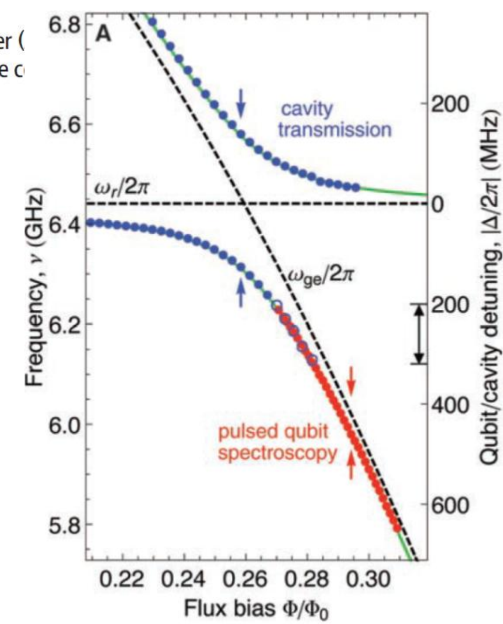


ıitted microwave signal with a local oscillator (LO) and digitized with an analog-to-digital converter (
the coupled (solid lines) and uncoupled (dashed lines) qubit/cavity system versus detuning Δ. The c
ted (see text for details).

Resolving Vacuum Fluctuations in an Electrical Circuit by Measuring the Lamb Shift

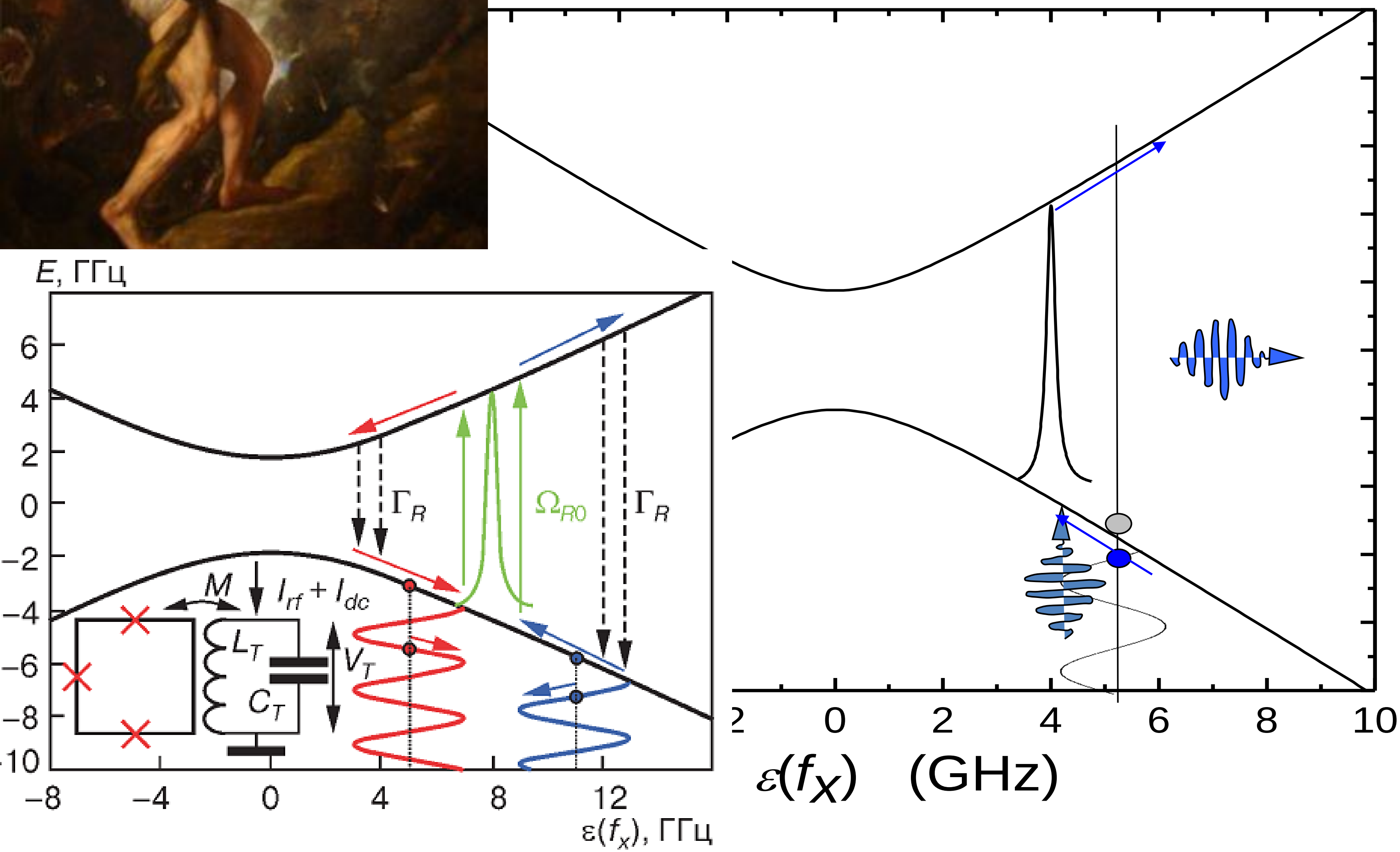
A. Fragner,[1] M. Göppl,[1] J. M. Fink,[1] M. Baur,[1] R. Bianchetti,[1] P. J. Leek,[1] A. Blais,[2] A. Wallraff[1]*

SCIENCE VOL 322 28 NOVEMBER 2008

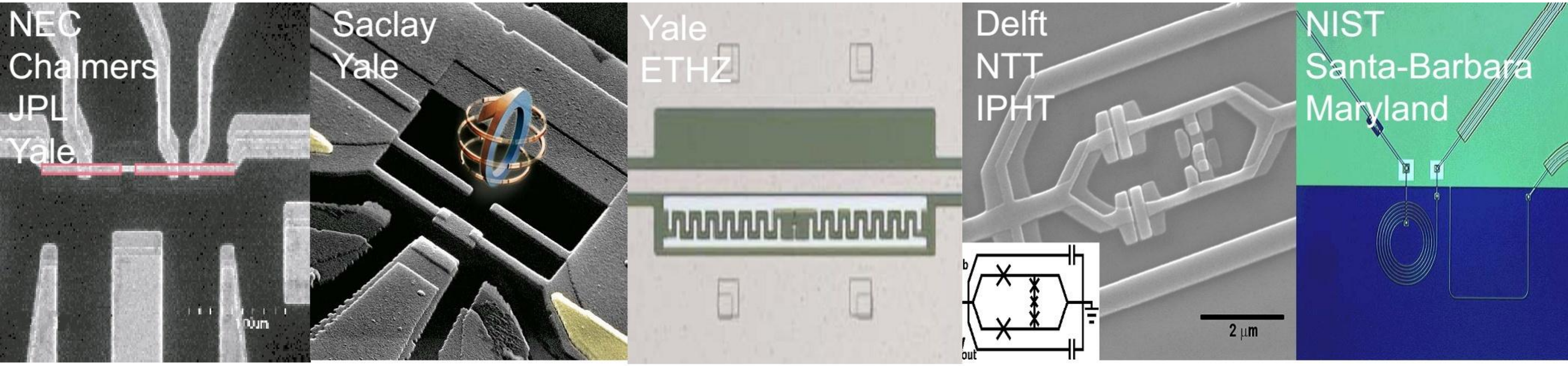


Sisyphus cooling

For qubit
Grajcar et al., arXiv:0708.0665
Nature Physics 4, 612-616 (2008).



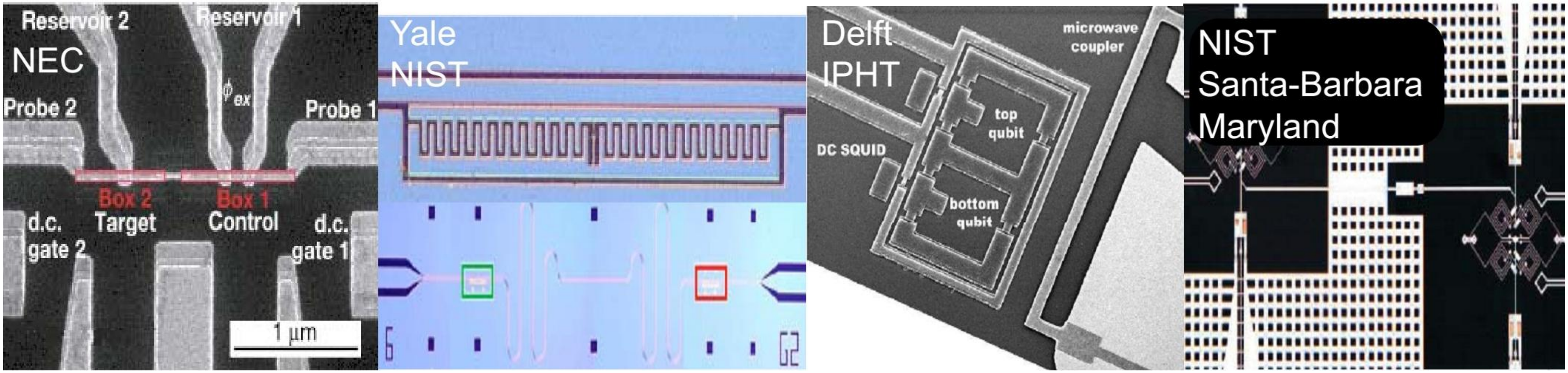
Искусственные атомы и искусственные молекулы



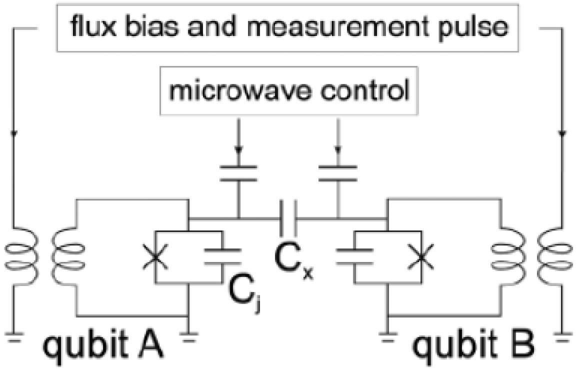
'artificial atoms' -- single superconducting qubits

'artificial molecules' -- coupled superconducting qubits

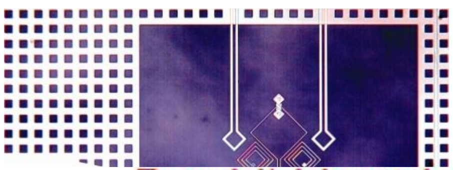
review:
J. Clarke and F. Wilhelm
Nature 453, 1031 (2008)

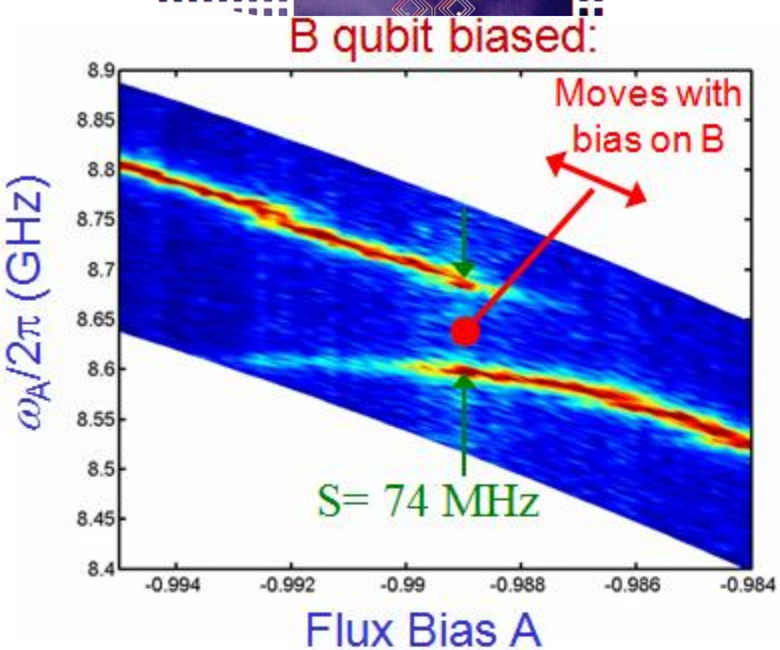


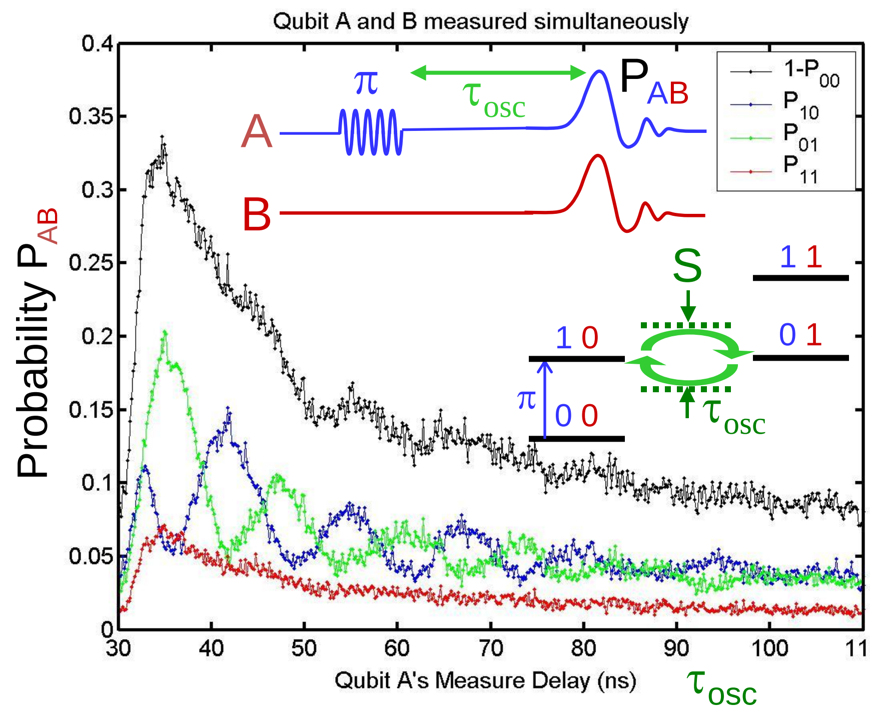
Qubit coupling: phase qubits



M. Steffen, M. Ansmann, R. C. Bialczak, *Science* **313**, 1423 (2006)



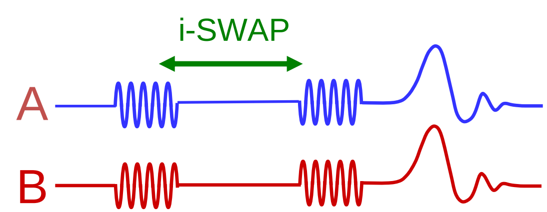




i-SWAP gate:

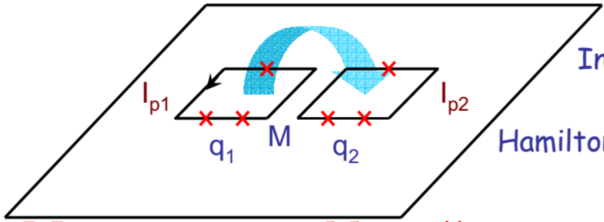
$$|\Psi\rangle = \tfrac{1}{2}\left(|10\rangle + |01\rangle\right) + \tfrac{1}{2}\left(|10\rangle - |01\rangle\right)e^{iS\tau_{osc}}$$
$$= |10\rangle\cos(S\tau_{osc}) + i|01\rangle\sin(S\tau_{osc})$$

CNOT gate with Tomography:



Turn interaction on/off with bias current

Связанные потоковые кубиты

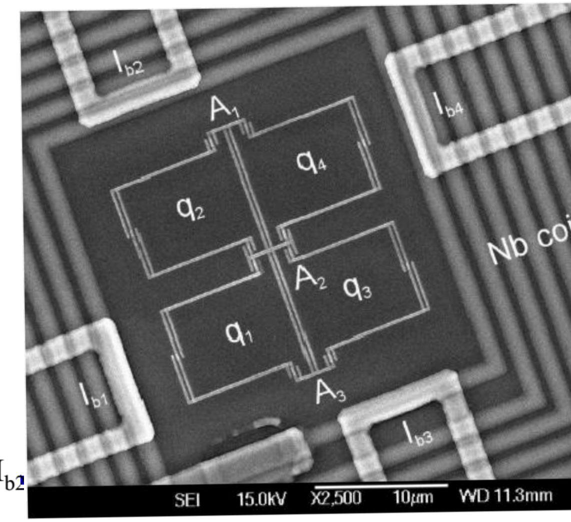


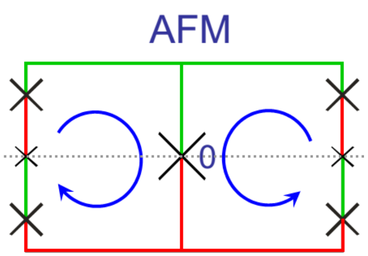
Interaction energy: $J = MI_{p1}I_{p2}$

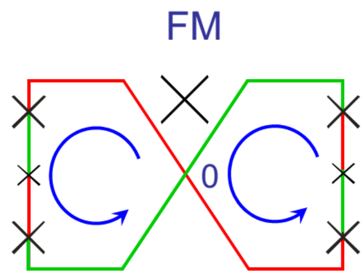
Hamiltonian: $H_\Sigma = H(q_1) + H(q_2) + J\sigma_1^z\sigma_2^z$

$H(q_i) = \varepsilon_i\sigma_i^z + \Delta_i\sigma_i^x$

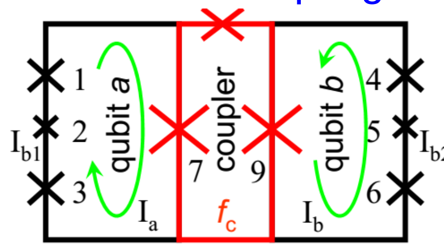
$M \ll 1$: size problem #2



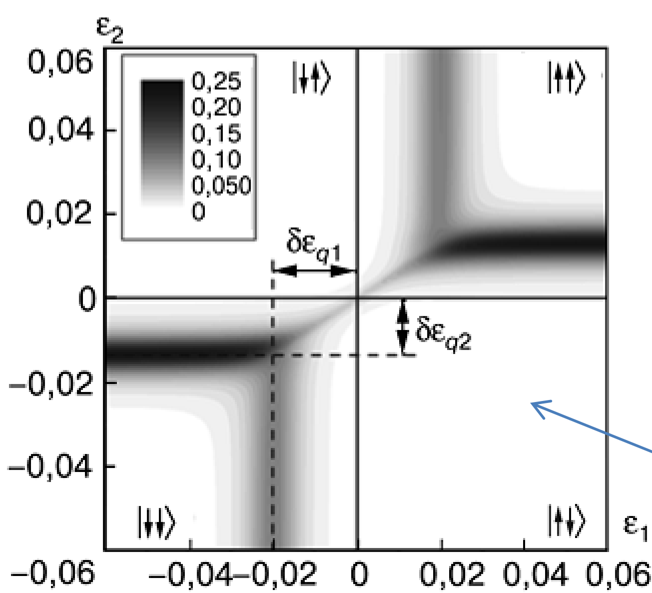




Tunable coupling



Grajcar et al., PRL 96 047006 (2006)



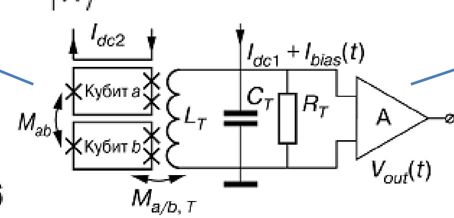
$$\Delta_a = \Delta_b = 0$$

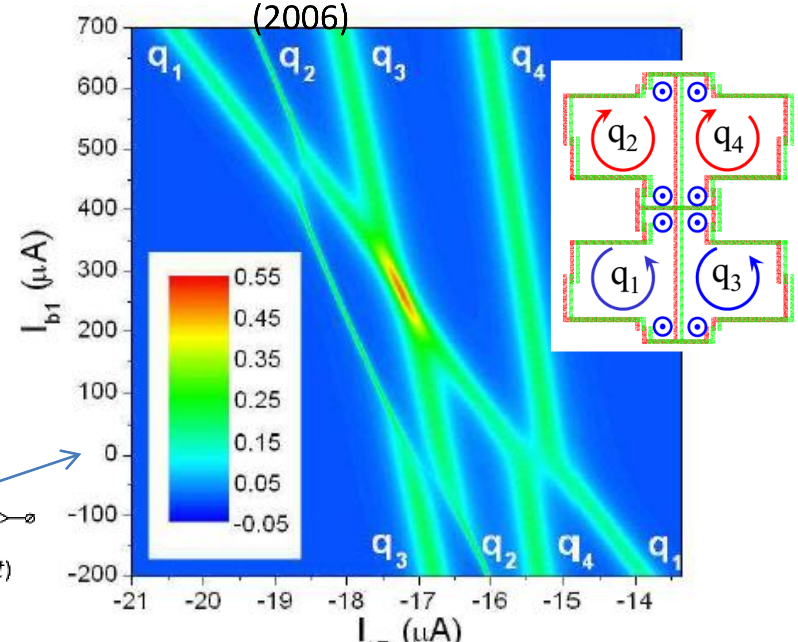
$$E_{|\uparrow\uparrow\rangle} = \varepsilon_1 + \varepsilon_2 + J,$$

$$E_{|\uparrow\downarrow\rangle} = \varepsilon_1 - \varepsilon_2 - J,$$

$$E_{|\downarrow\uparrow\rangle} = -\varepsilon_1 + \varepsilon_2 - J,$$

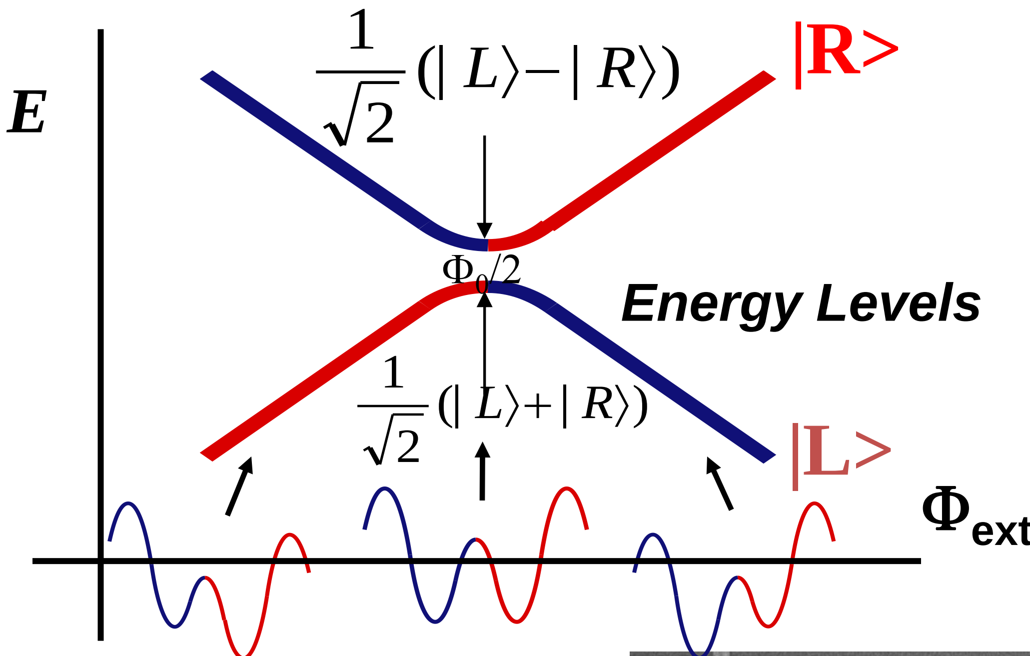
$$E_{|\downarrow\downarrow\rangle} = -\varepsilon_1 - \varepsilon_2 + J.$$

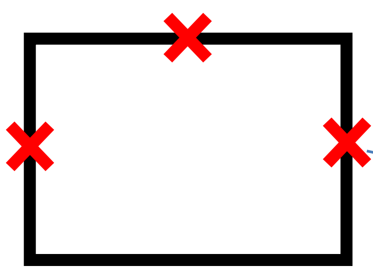


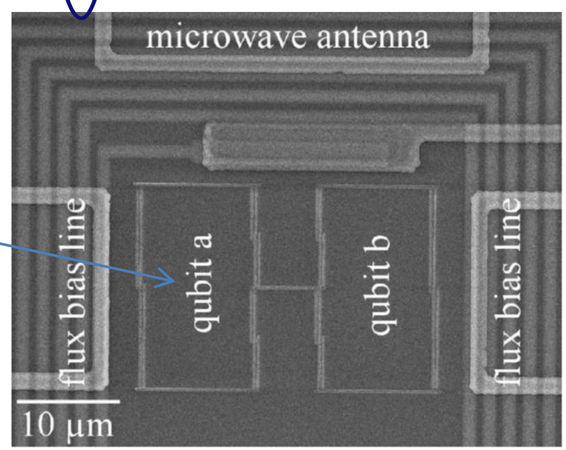


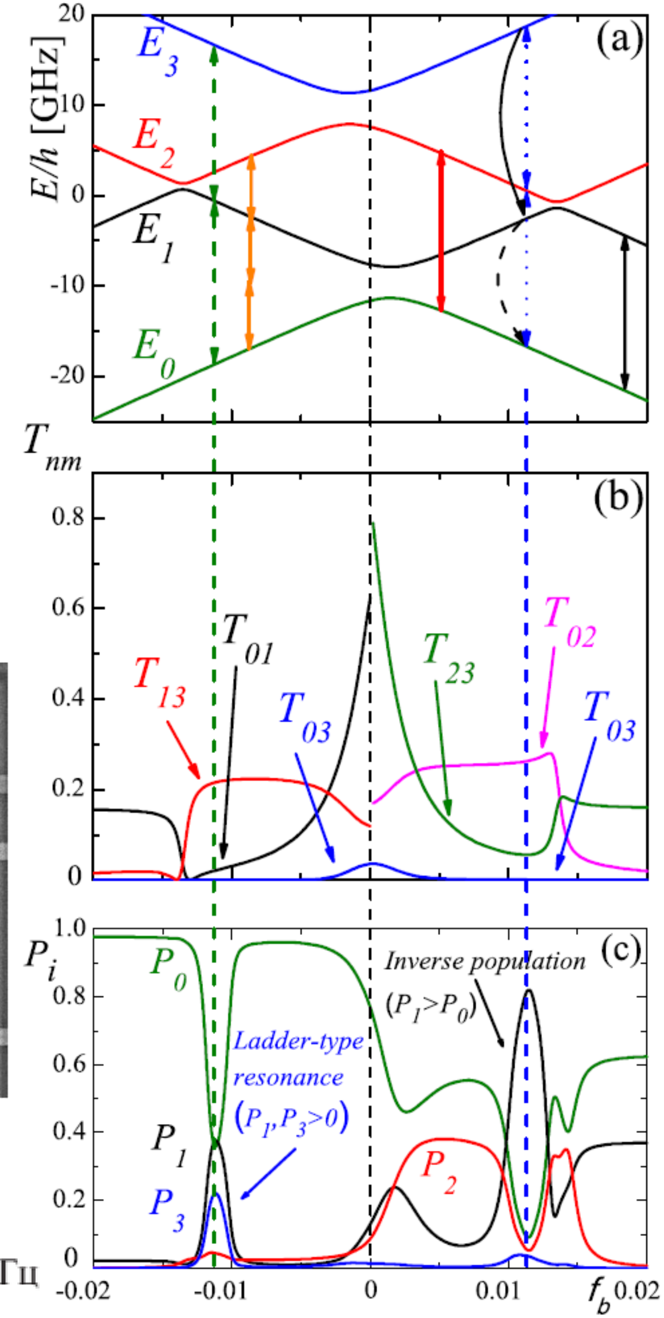
M. Grajcar M. *et al.*, Phys. Rev. B **72**, 020503 (2005); A. Izmalkov, *et al.*, Phys. Rev. Lett. **101**, 017003 (2008).

Инверсная населенность уровней в системах поток. кубитов







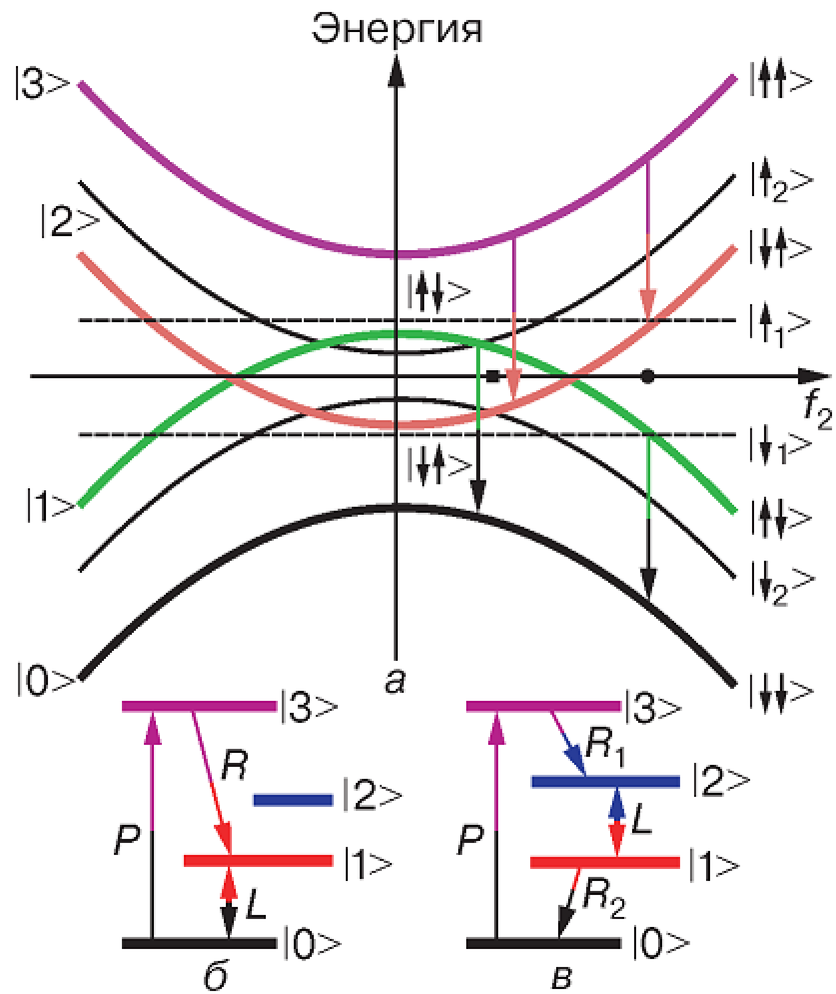


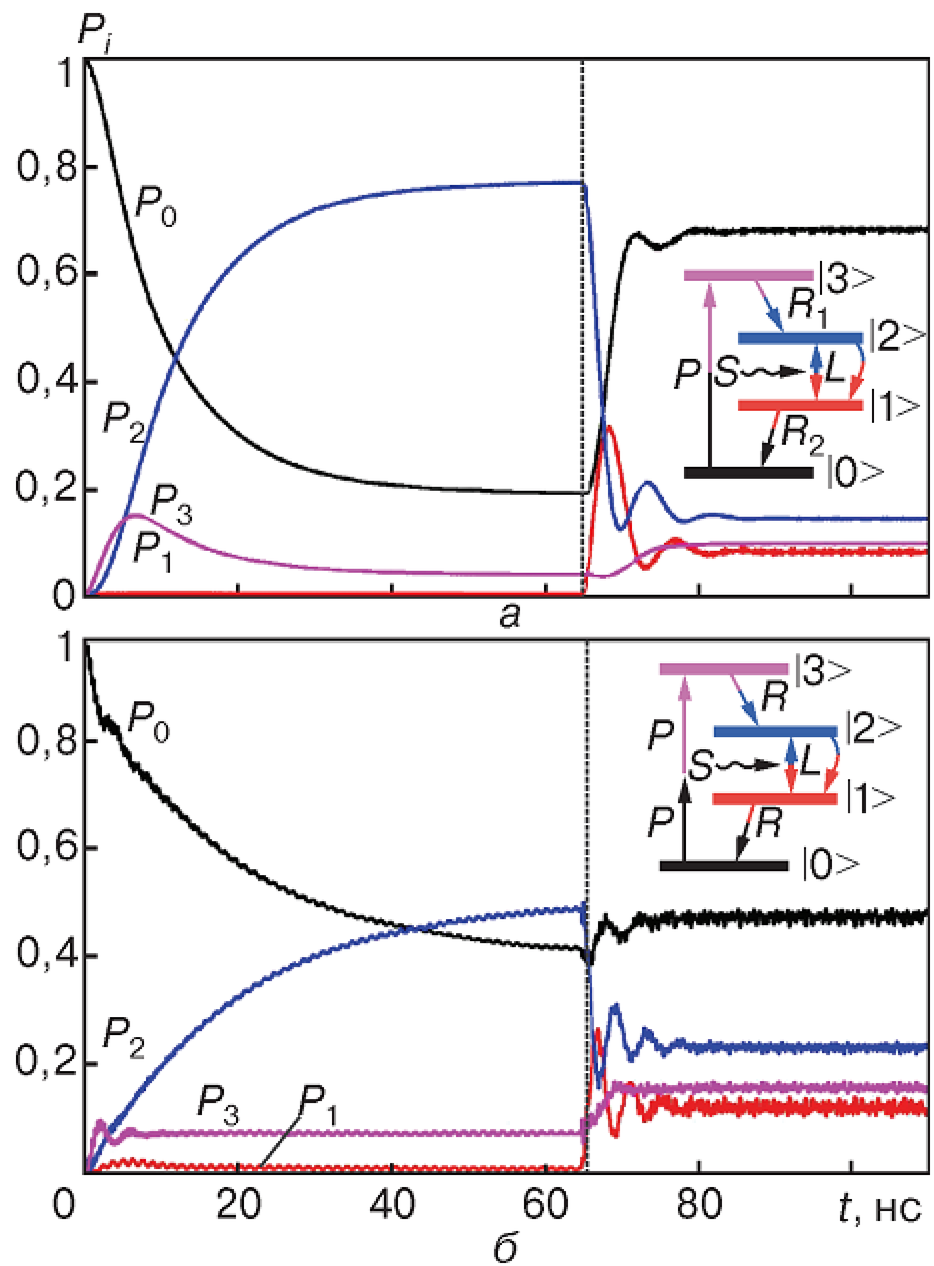
E. Il'ichev et al., Multiphoton excitations and inverse population in a system of two flux qubits // Phys. Rev. B 81, 012506 (2010).

ω/2π = 17,6 ГГц

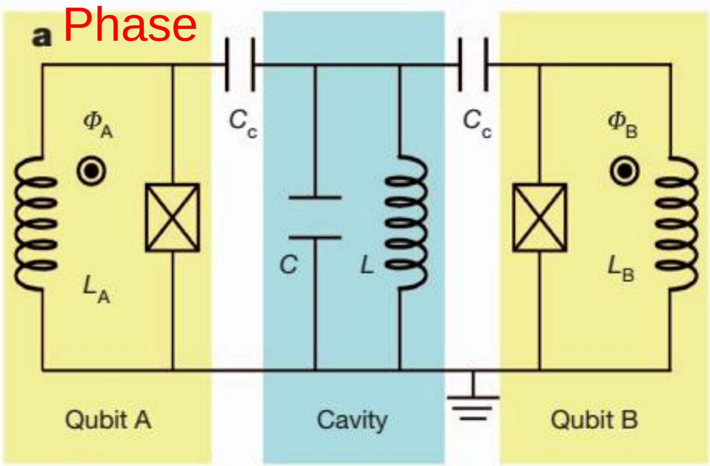
Лазеры на связанных потоковых кубитах

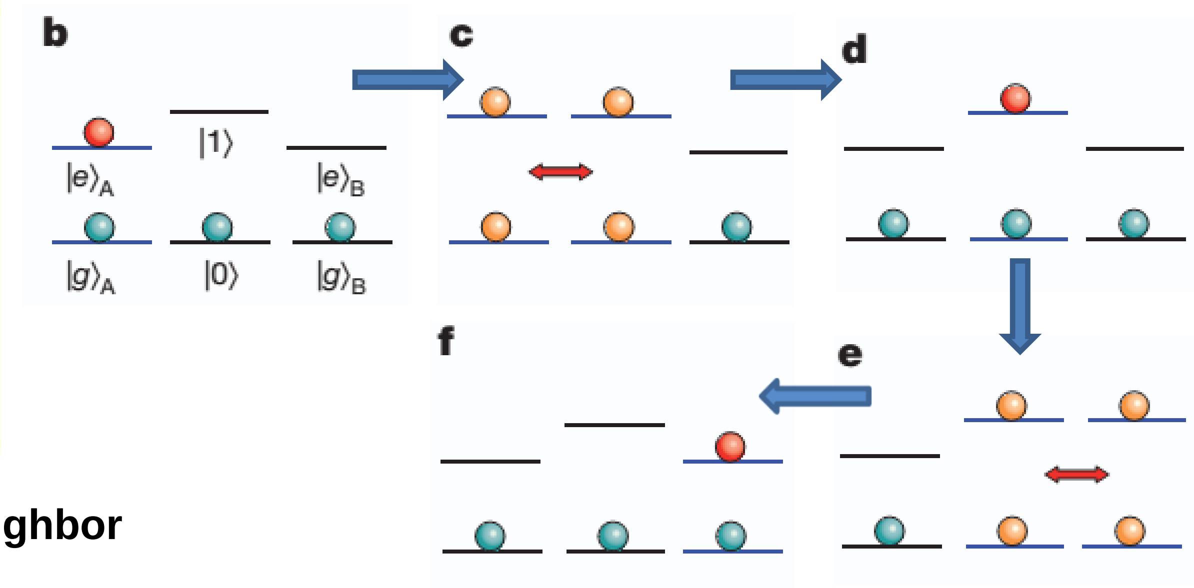
Нет связи: $E_i^{\pm} = \pm\frac{\Delta E_i}{2} = \pm\frac{1}{2}\sqrt{\varepsilon_i^{(0)2} + \Delta_i^2}$





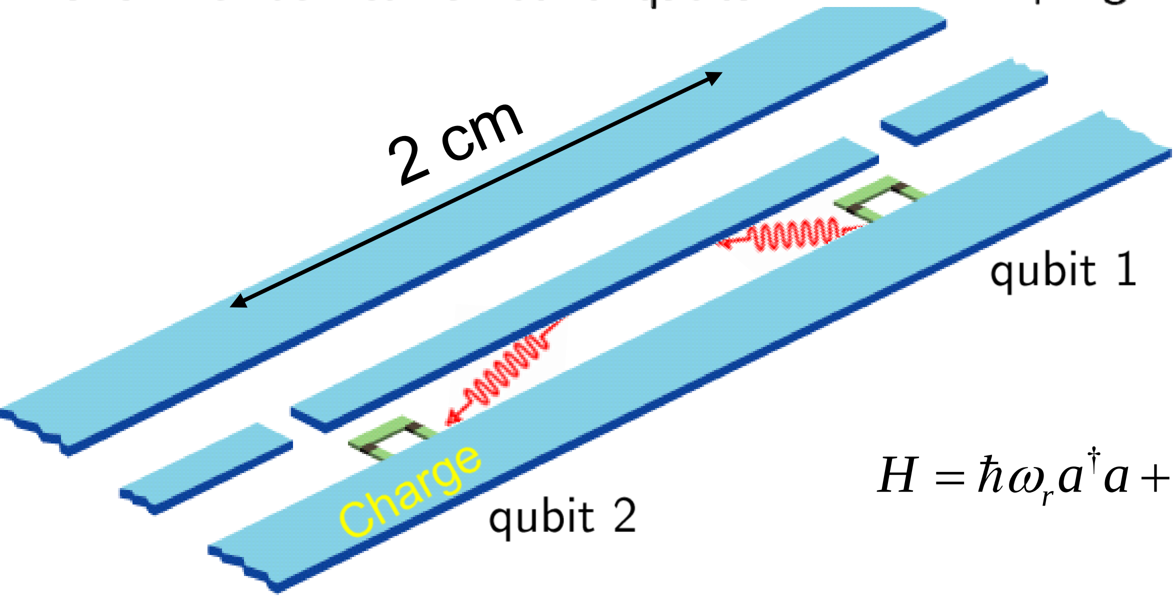
Связь кубитов через резонатор



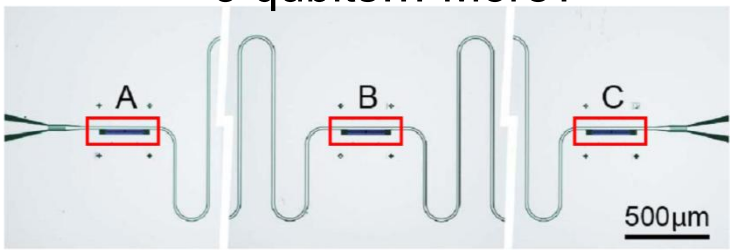


“long” range and non nearest-neighbor interactions!

- small well defined number of qubits
- fixed coupling strength
- full single qubit control



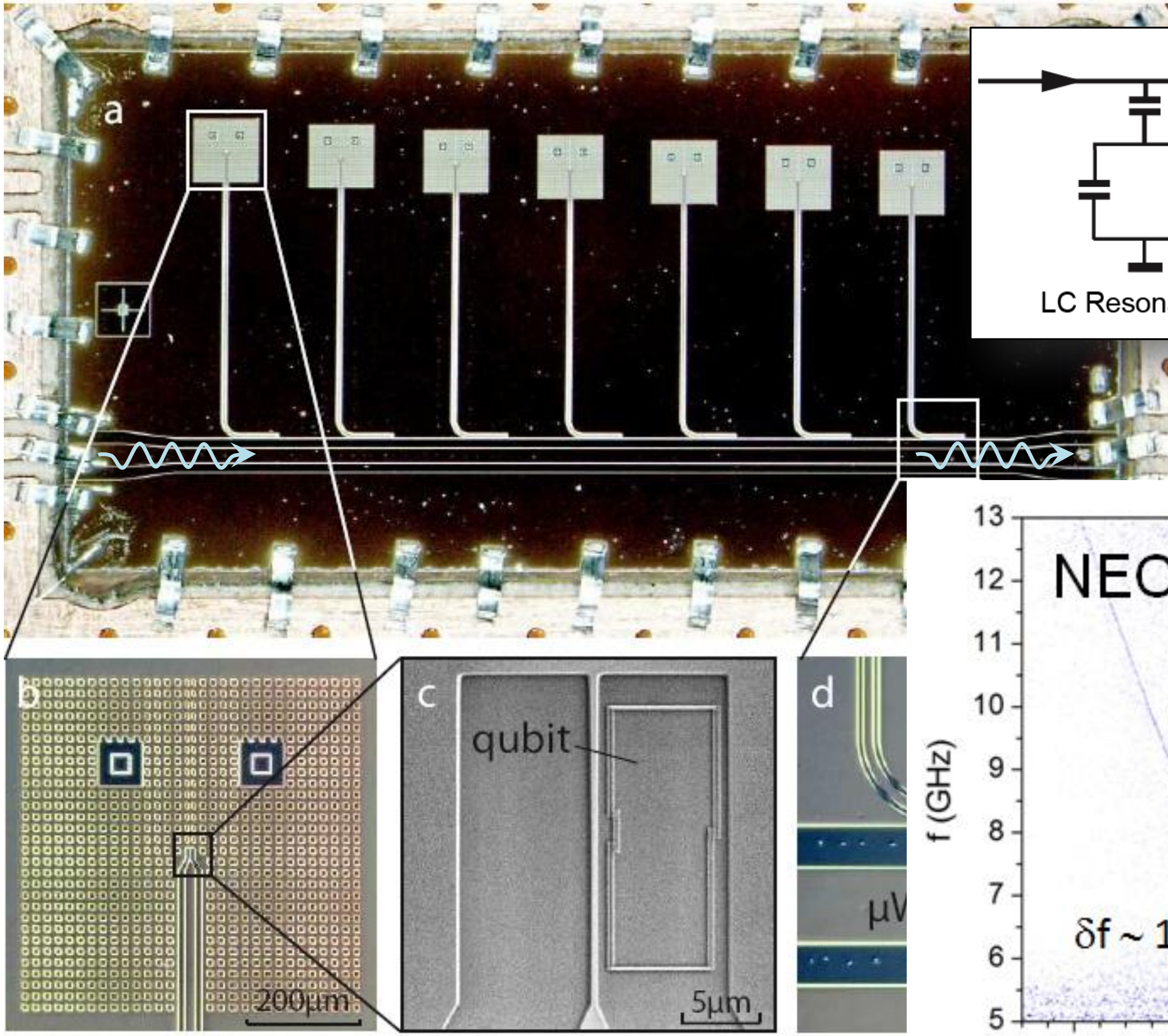
3 qubits… More?

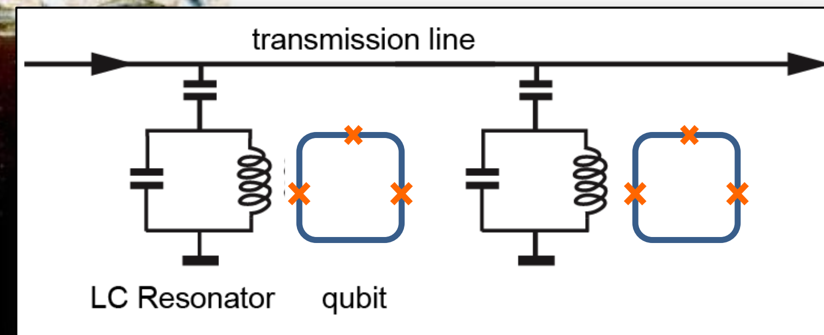


$$H = \hbar\omega_r a^\dagger a + \frac{\hbar\omega_{a1}}{2} + \frac{\hbar\omega_{a2}}{2} - \sum_{j=1,2} g_j \left(a^\dagger \sigma_j^- + a\sigma_j^+ \right)$$

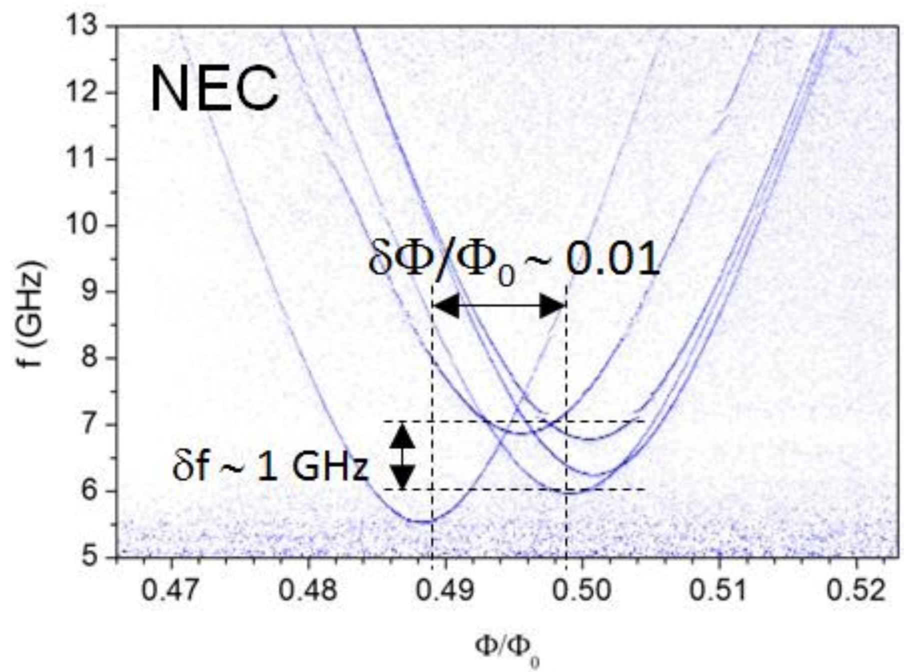
Квантовые метаматериалы

M. Jerger, S. Poletto, P. Macha, et al. EPL, **96** 40012 (2011)





• each **qubit** is **coupled** to a **resonator**,

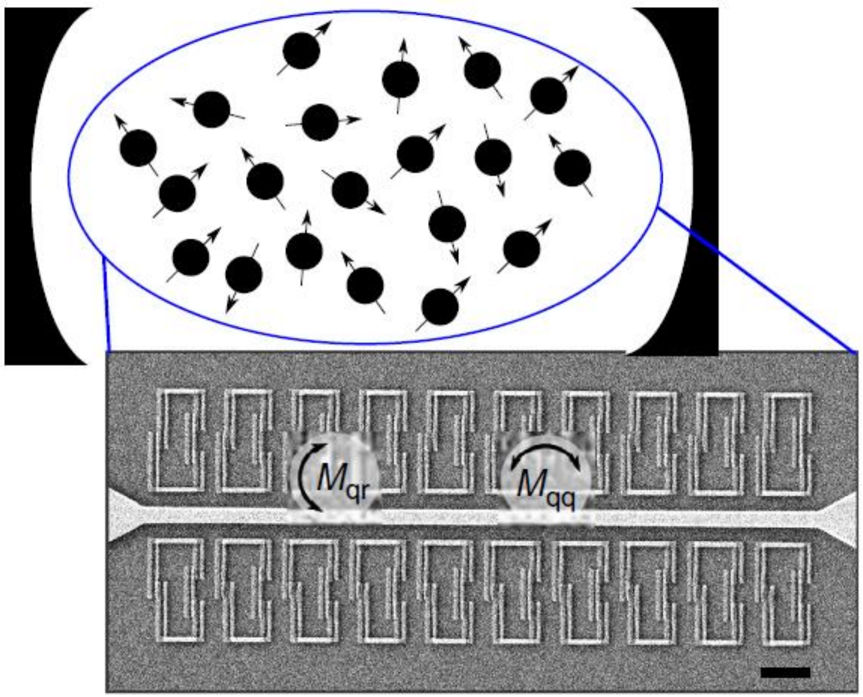


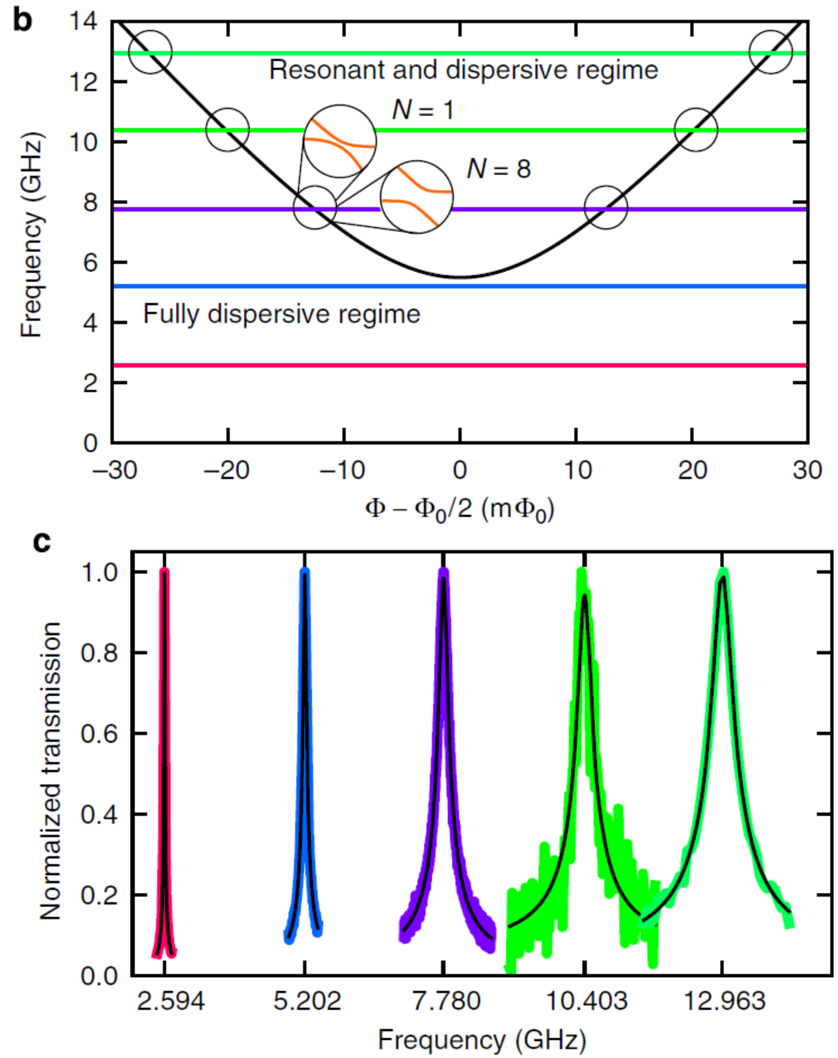
Квантовые метаматериалы (2)

Received 1 Jul 2014 | Accepted 5 Sep 2014 | Published 14 Oct 2014 DOI: 10.1038/ncomms6146

Implementation of a quantum metamaterial using superconducting qubits

Pascal Macha[1,2,3], Gregor Oelsner[1], Jan-Michael Reiner[4,5], Michael Marthaler[4,5], Stephan André[4,5], Gerd Schön[4,5], Uwe Hübner[1], Hans-Georg Meyer[1], Evgeni Il'ichev[1,6] & Alexey V. Ustinov[2,6,7]





(b) The level structure of the combined system of qubits and resonator. The horizontal lines (and their colour, as for the data traces in all subsequent figures) correspond to the modes of the resonator. The resonant phase shift expected at the crossings between qubits and resonator (encircled areas) is enhanced linearly by the number of qubits N.
(c) The transmission amplitude of the resonator at the fundamental mode frequency and the first four harmonics of the resonator. The black lines are fits to Lorentzians.

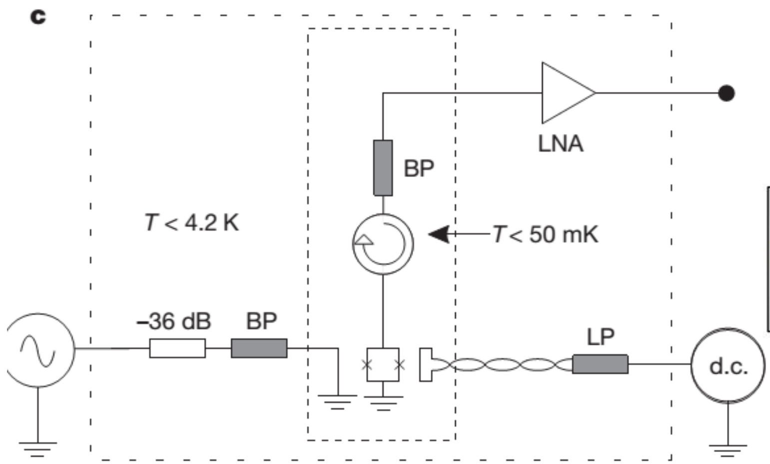
Динамический эффект Казимира

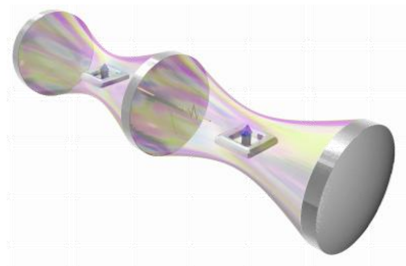
LETTER

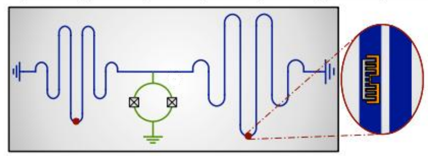
doi:10.1038/nature10561

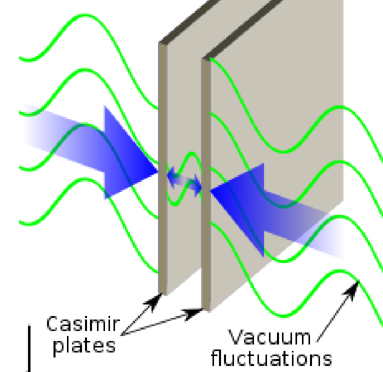
Observation of the dynamical Casimir effect in a superconducting circuit

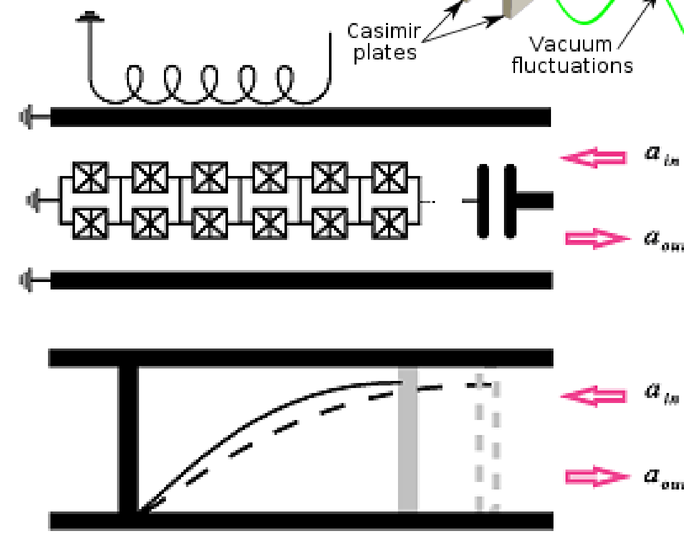
C. M. Wilson[1], G. Johansson[1], A. Pourkabirian[1], M. Simoen[1], J. R. Johansson[2], T. Duty[3], F. Nori[2,4] & P. Delsing[1]

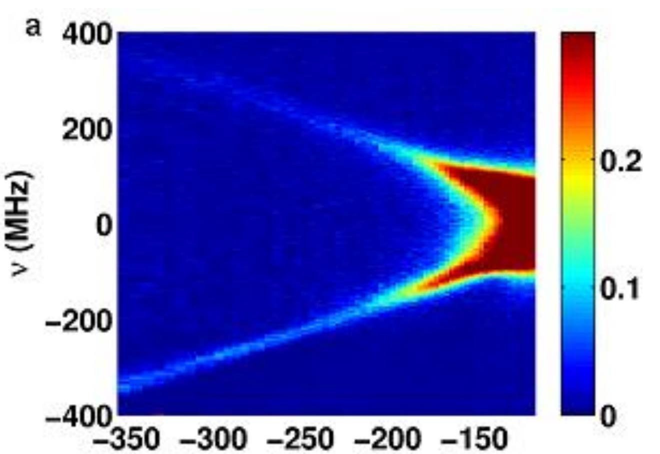




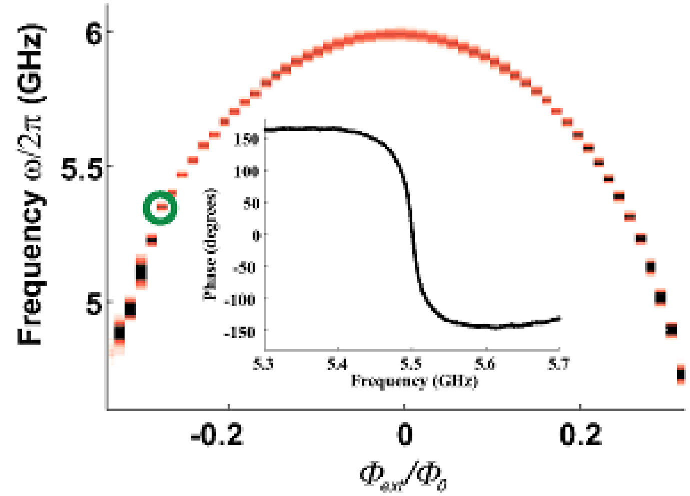








detuning of the resonator frequency with respect to half the pumping frequency



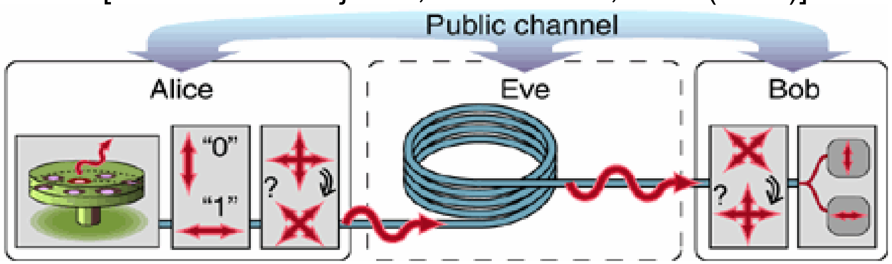
ν -- frequency measured from half the pumping frequency

План доклада

- Почему интересны джозефсоновские кубиты?
- Сверхпроводимость и эффект Джозефсона
- Типы джозефсоновских кубитов
- Атомная физика и квантовая оптика с джозефсоновскими кубитами
- Проблемы и перспективы
- Заключение

Сверхпроводящая электроника для сопряжения с закрытыми «квантовыми» каналами связи

[from Simon Benjamin, Science 290, 2273 (2000)]

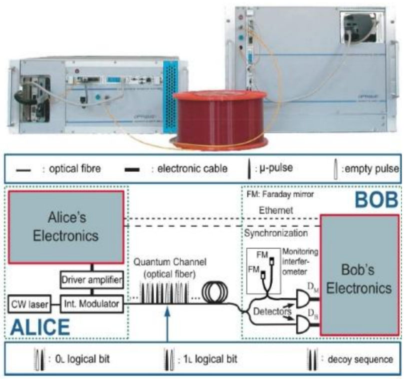


Законы квантовой механики обеспечивают защиту информации; сверхпроводниковые детекторы (SSPD) обеспечивают прием сигнала

Россия

270 км

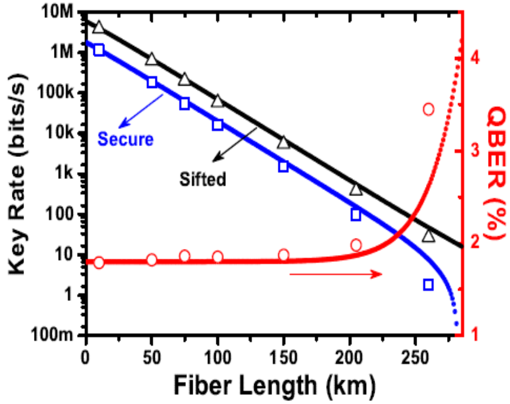
Group of Applied Physics University of Geneva



D Stucki et. al., Optics Express, Vol. 17,13326 (2009)

250 км

University of Science and Technology of China

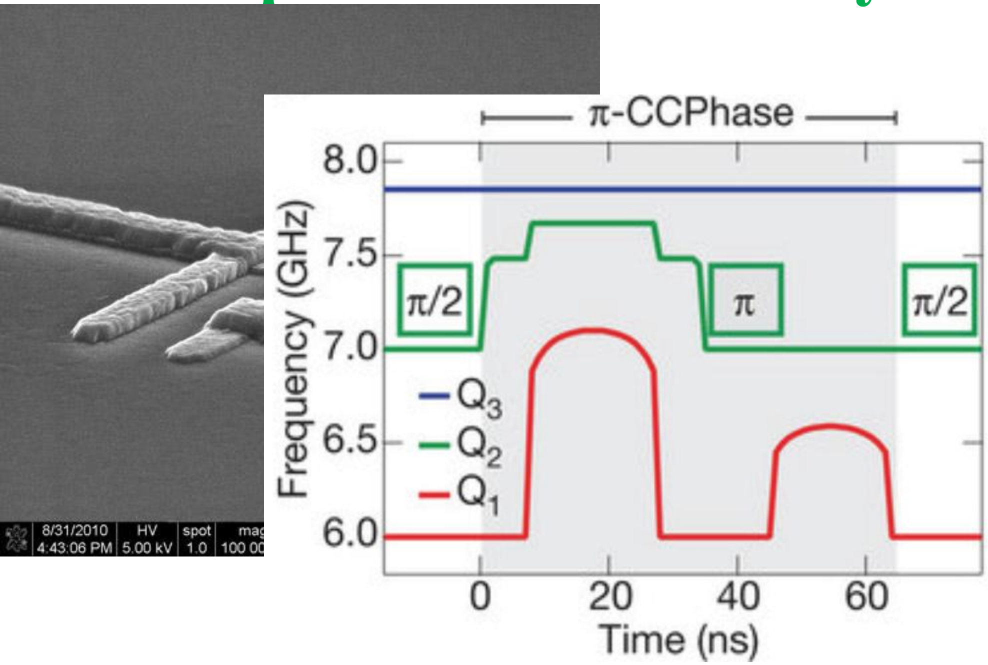


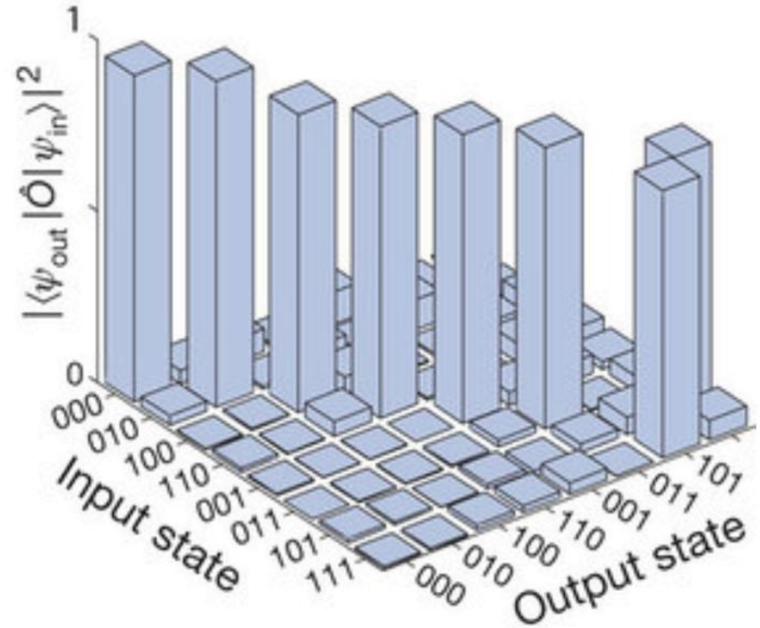
Shuang Wang et. al., Optics Letters, Vol. 37, Issue 6, pp. 1008-1010 (2012)

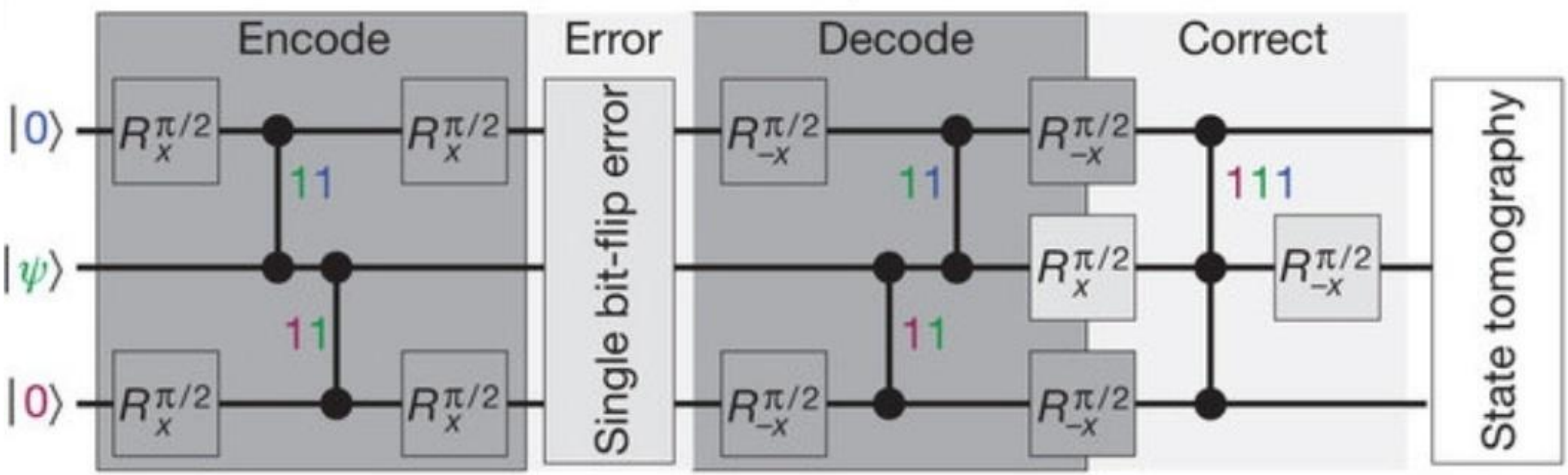
260 км

Операции над 3-мя кубитами

M. D. Reed et al, Nature, 2012
Transmons in cavity

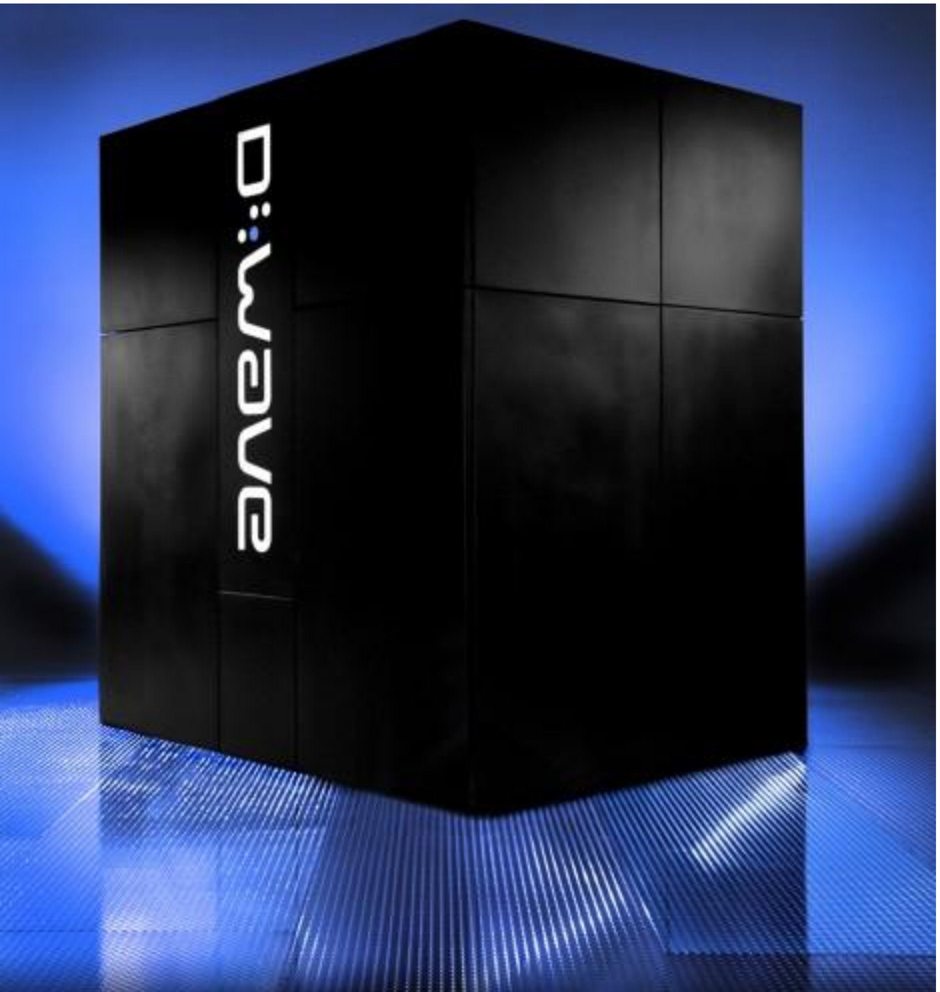




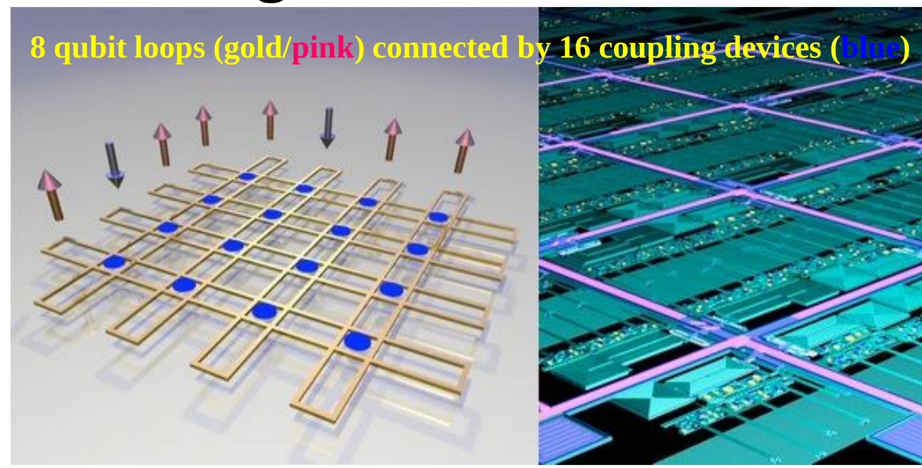


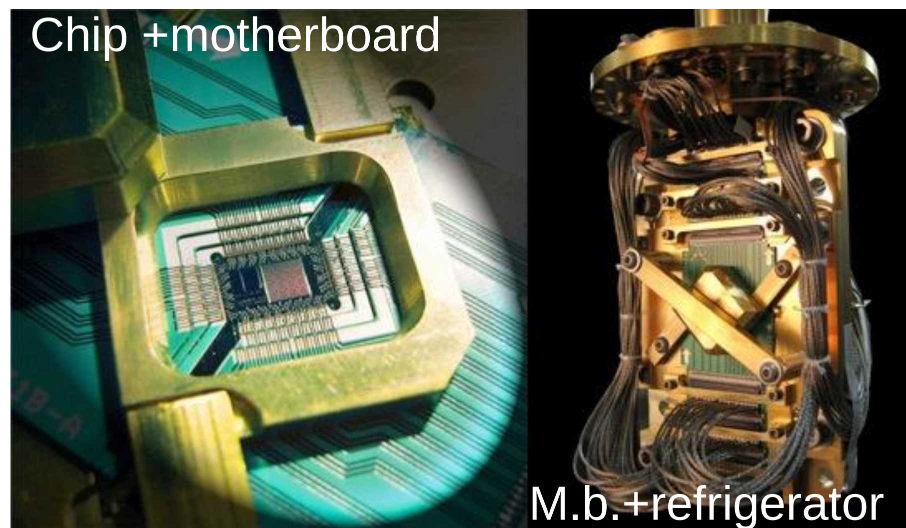
Superconducting quantum computers

Analog

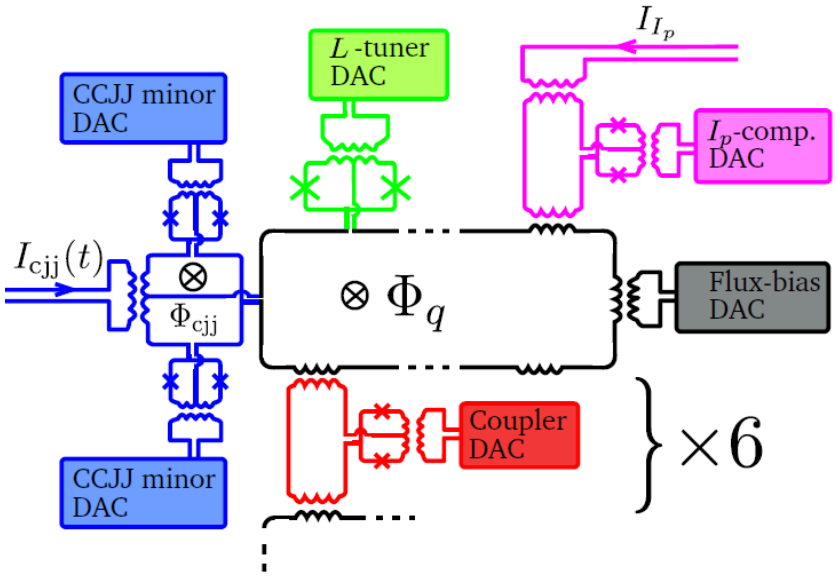


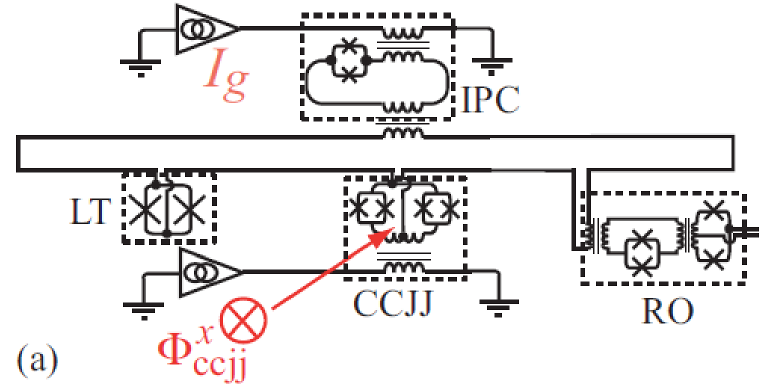
Building blocks

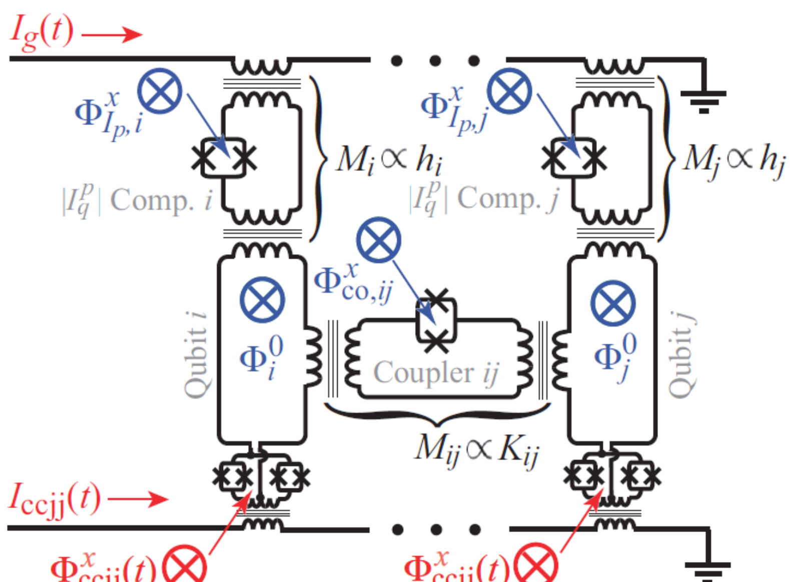


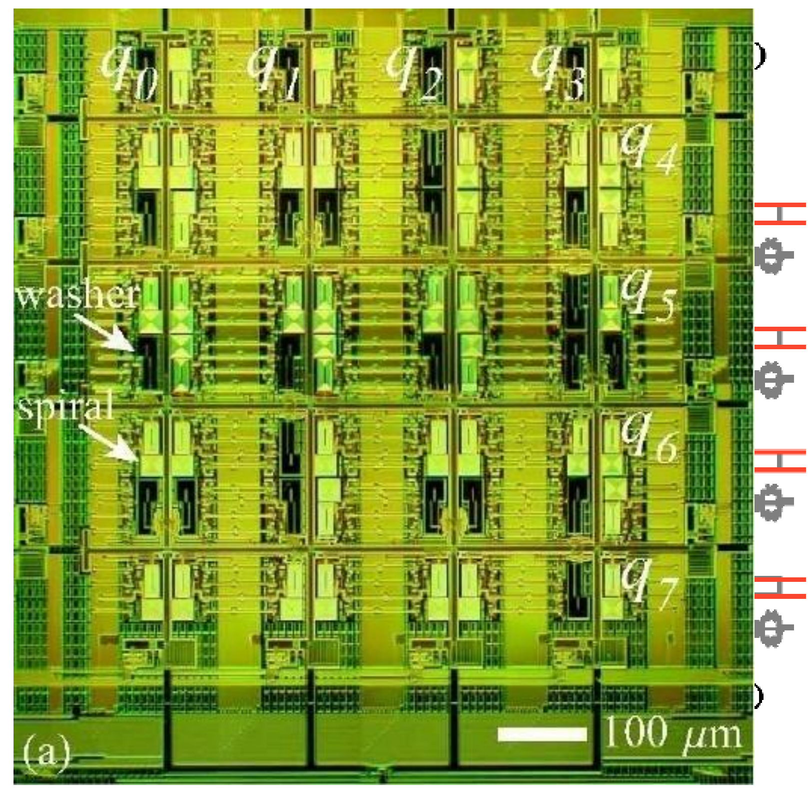


D-wave "comp"



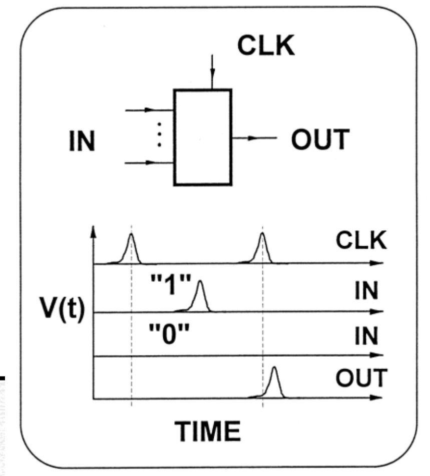


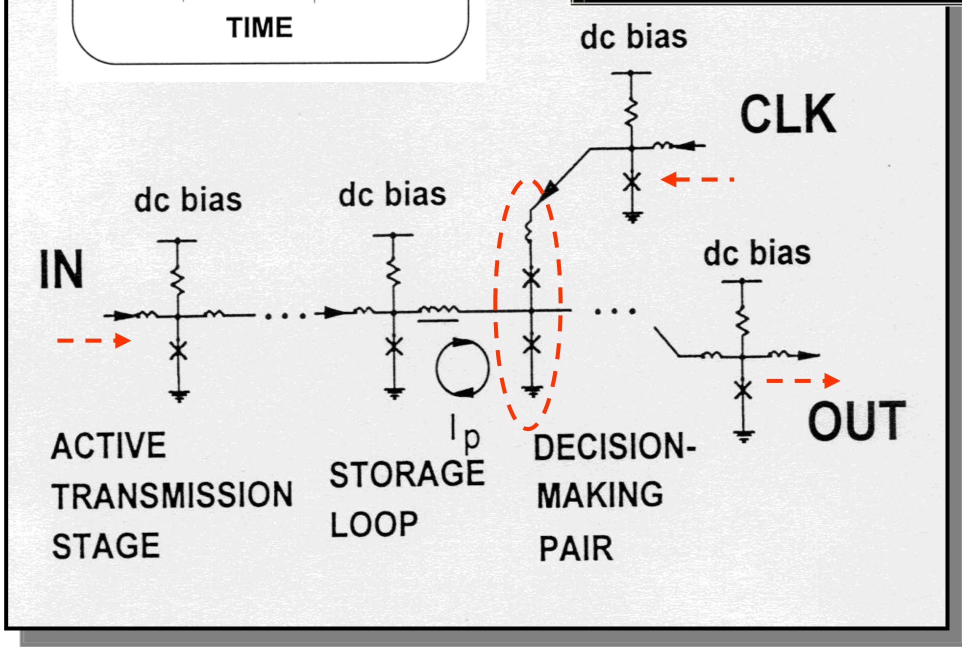




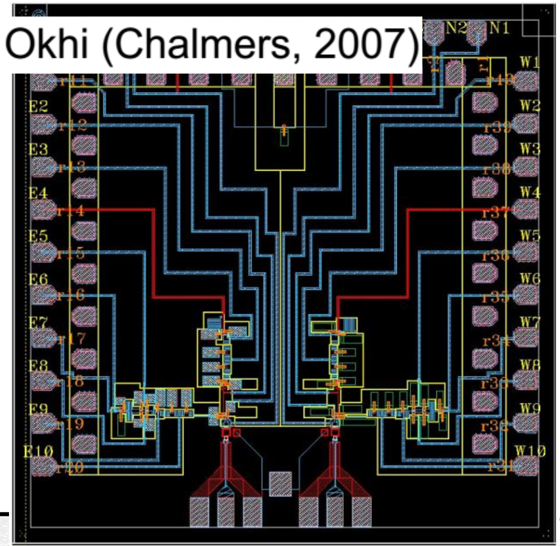
Two qubits, two Ipq compensators, and one interqubit coupler.

RSFQ-bit circuits: fundamentals





© T. Okhi (Chalmers, 2007)



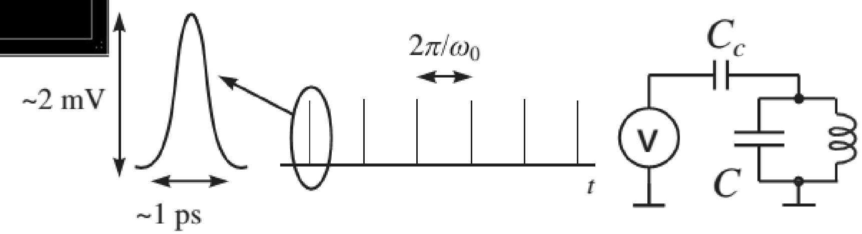
PHYSICAL REVIEW APPLIED **2,** 014007 (2014)

Accurate Qubit Control with Single Flux Quantum Pulses

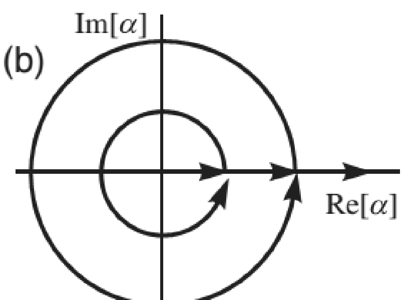
R. McDermott* and M. G. Vavilov

$$H_{\mathrm{SFQ}} = iC_c V(t)\sqrt{\frac{\hbar\omega_0}{2C'}}(\hat{a} - \hat{a}^\dagger)$$ **cavity**

$$H_{\mathrm{SFQ}} = C_c V(t)\sqrt{\frac{\hbar\omega_{10}}{2C}}\hat{\sigma}_y$$ **qubit**

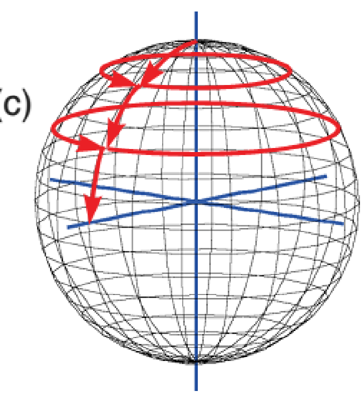


(b)



cavity

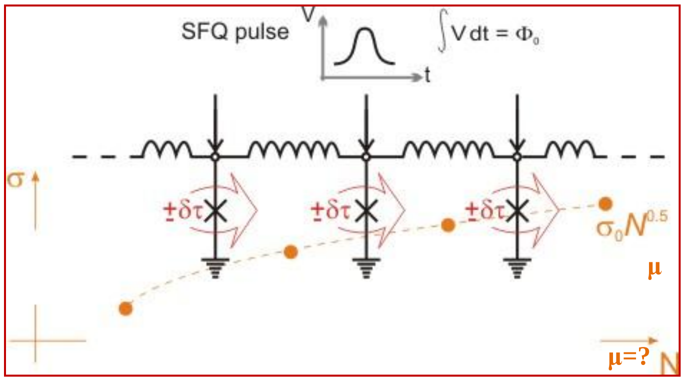
(c)



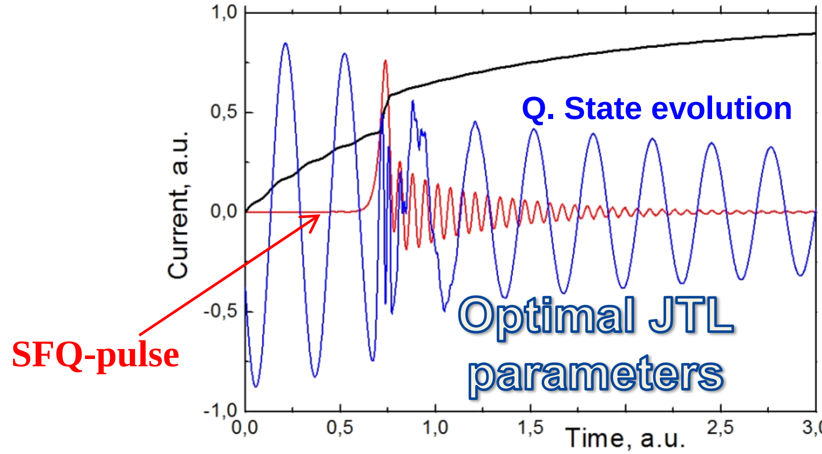
qubit

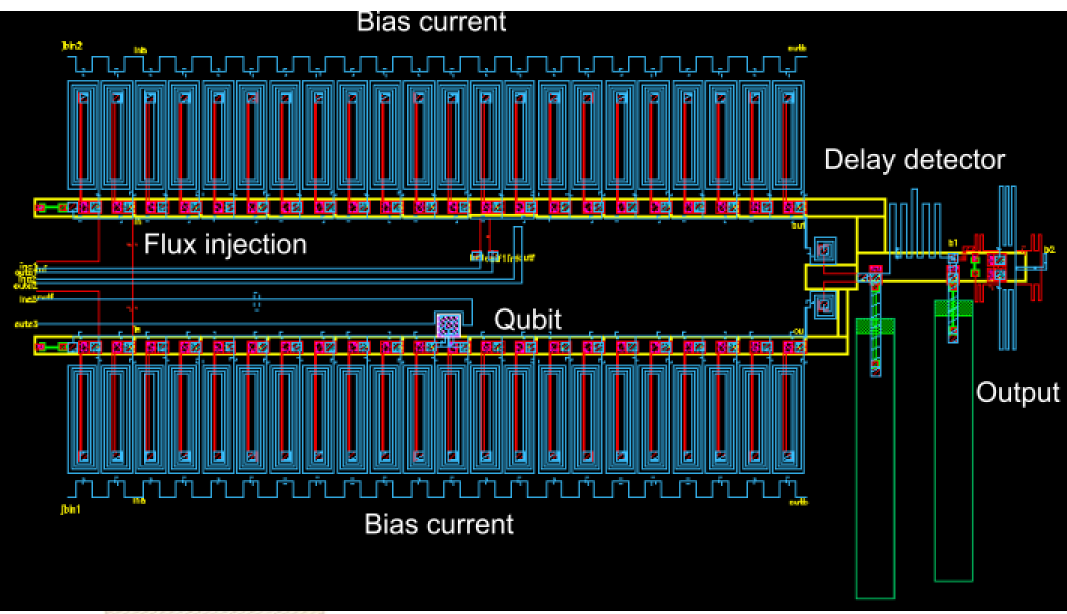
RSFQ-bit circuits: first attempts

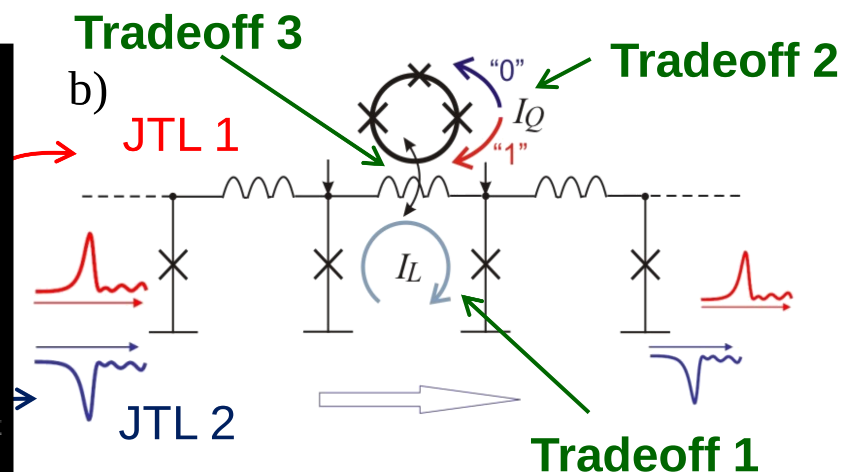
The first issue (T1) is the accumulating jitter



The second issue (T2&3) is the qubit+JTL optimization





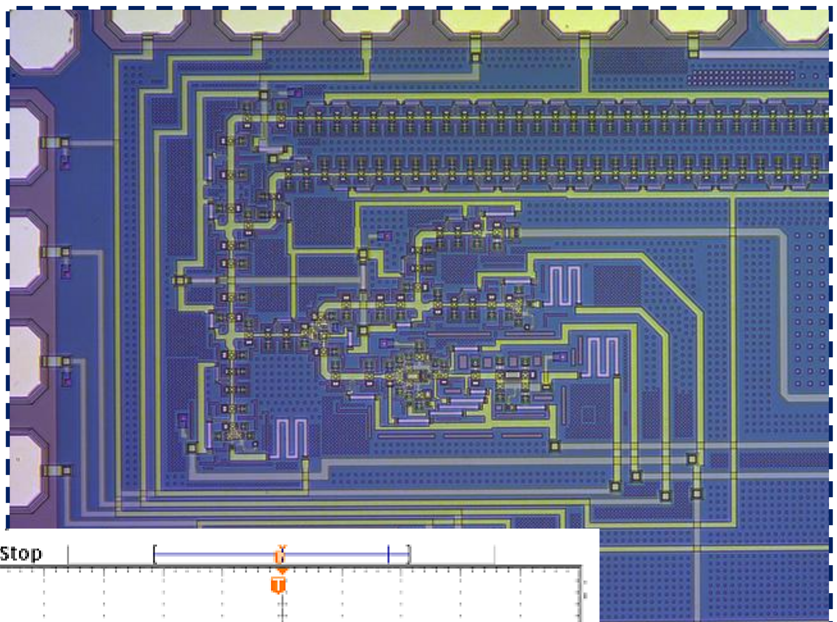


in, IEEE Trans. Appl. Supercond.13, 960 (2003)
hnirman, et al., Phys. Rev. B 75, 224504 (2007)

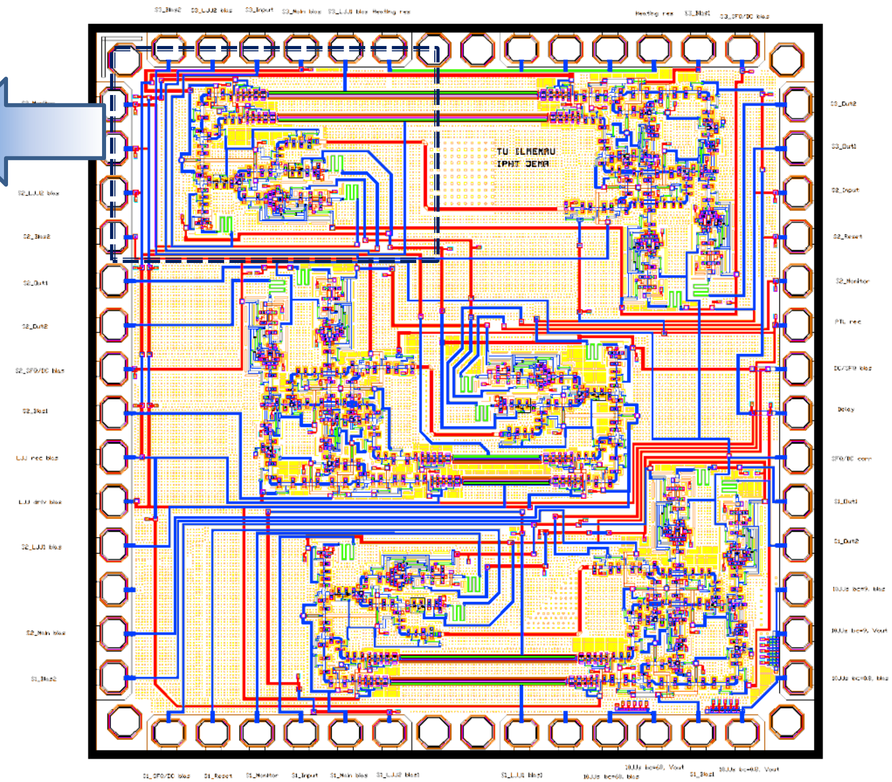
RSFQ-bit circuits: IPHT+MSU

The chips were designed in collaboration with IPHT and fabricated using IPHT foundry

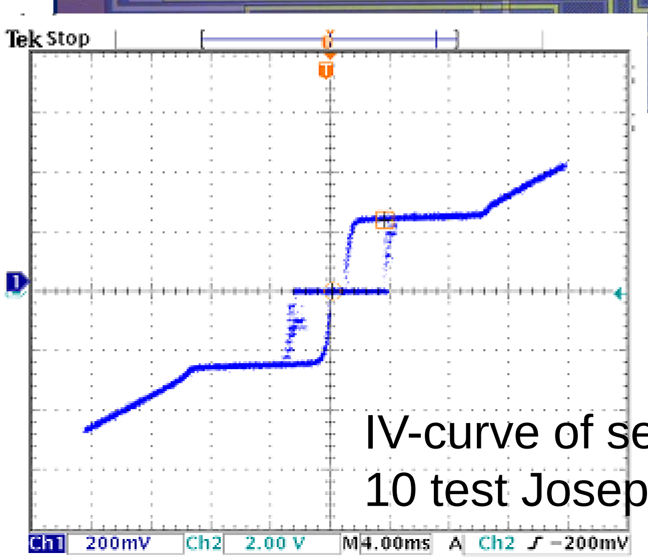
Photo of the chip fragment



Design



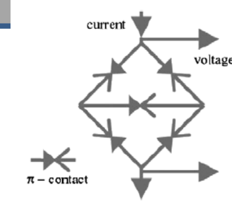
The chips were fabricated using standard IPHT Nb process with 1 kA/cm^2 critical current of JJs

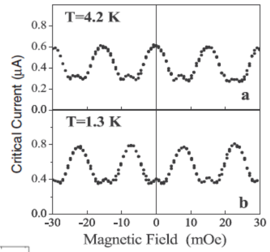


IV-curve of serial array containing 10 test Josephson junctions

Несколько наших работ

Kornev V. K., Klenov N. V., Oboznov V. A., Feofanov A.K., Bol'ginov V. V., Ryazanov V. V., Pedersen N. F., “Vortex dynamics in Josephson ladders with π-junctions”, *Superconductor Science and Technology*, vol. 17, Issue 5, pp. S355-S358 , 2004. (Импакт-фактор 2,662)

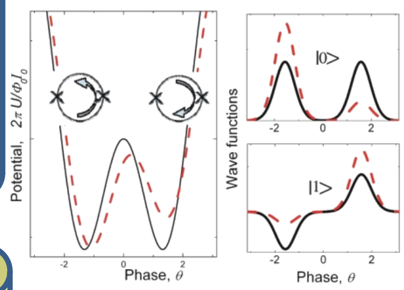




«Тихие» кубиты

N. V. Klenov, V. K. Kornev, N. F. Pedersen, “The energy level splitting for unharmonic dc-SQID to be used as phase Q-bit”, *Physica C*, vol. 435, pp. 114-117, 2006.

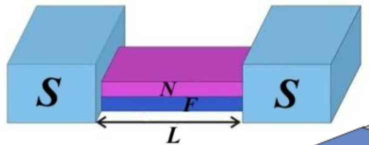
N. V. Klenov, A. V. Sharafiev, S. V. Bakurskiy, V. K. Kornev “Informational description of the flux qubit evolution”, *IEEE Transactions on Applied Superconductivity*, vol. 21, Issue 3, pp. 864-866, 2011. (Импакт-фактор **1,035**)

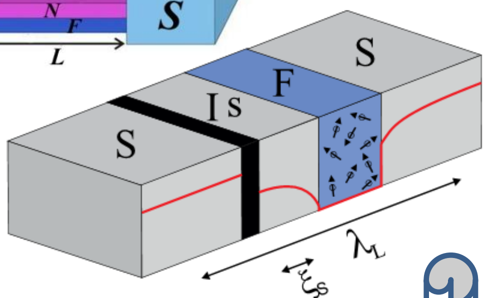


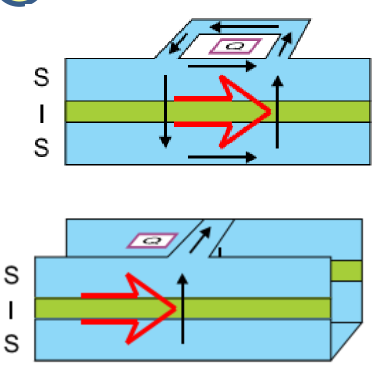
Элементы для тихих кубитов (поиск)

S.V. Bakurskiy, N. V. Klenov, T. Yu. Karminskaya, M. Yu. Kupriyanov and A. A. Golubov, "Josephson φ-junctions based on structures with complex normal/ferromagnet bilayer", Superconductor Science and Technology, vol. 25, no. 12 2012. (Импакт-фактор 2,662).

S.V. Bakurskiy, N.V. Klenov, I.I. Soloviev, M.Yu Kupriyanov, and A.A. Golubov. Theory of supercurrent transport in sisfs josephson junctions. Physical Review B - Condensed Matter and Materials Physics, 88(14):144519–1–144519–13, 2013.







RSFQ-bit circuits

I.I. Soloviev, N.V. Klenov, A.L. Pankratov, E. Il'ichev, and L.S. Kuzmin. Effect of cherenkov radiation on the jitter of solitons in the driven underdamped frenkel-kontorova model. Physical Review E 87(6):060901, 2013.

I.I. Soloviev, N.V. Klenov, S.V. Bakurskiy, A.L. Pankratov, and L.S. Kuzmin. Symmetrical josephson vortex interferometer as an advanced ballistic single-shot detector. Applied Physics Letters, 105(202602):202602–1–202602–5, 2014.

Спасибо за внимание