Сверхпроводящие квантовые процессоры: физика, технология и перспективы

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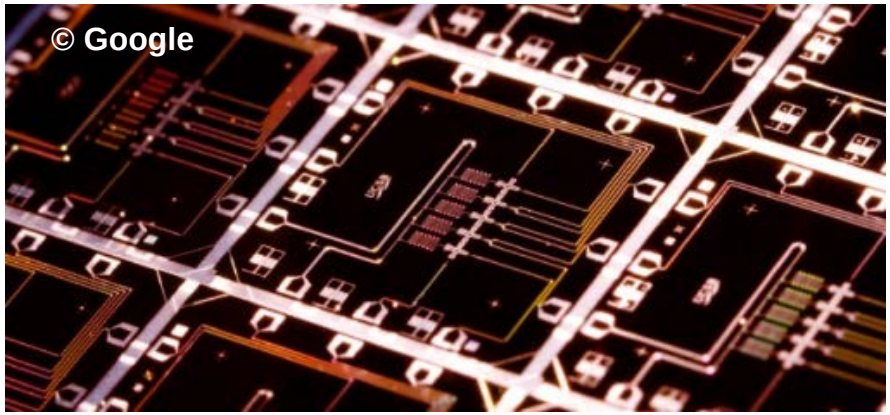
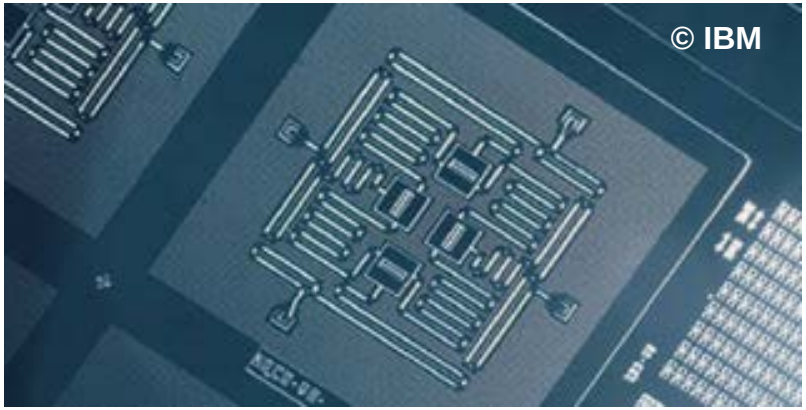
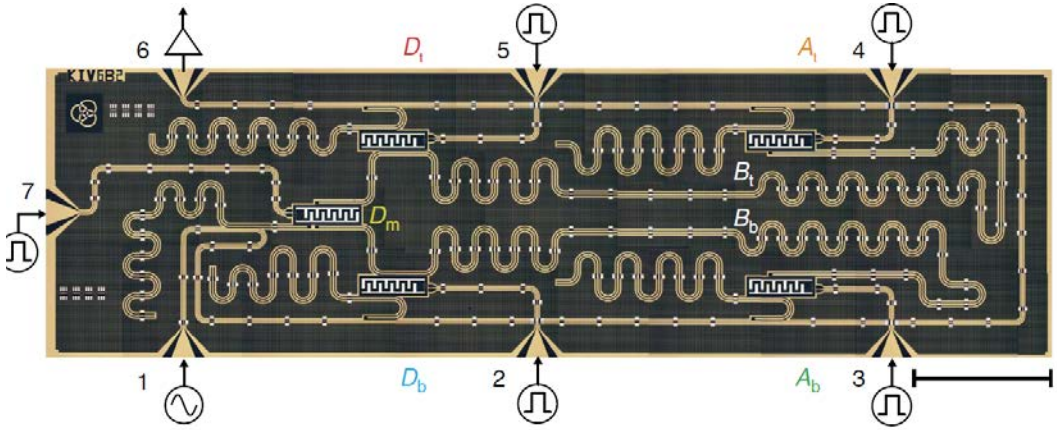




Superconducting quantum machines

- **Components**
  - **resonators**
  - **Josephson junctions**
- **Qubits**
  - **phase, charge, flux**
  - **-um's and –mon's**
  - **decoherence**
- **Quantum processors**
  - **simple algorithms**
  - **error correction**
  - **simulators vs computers**
- **Not in this talk**
  - **quantum microwaves**
  - **single-photon detectors**



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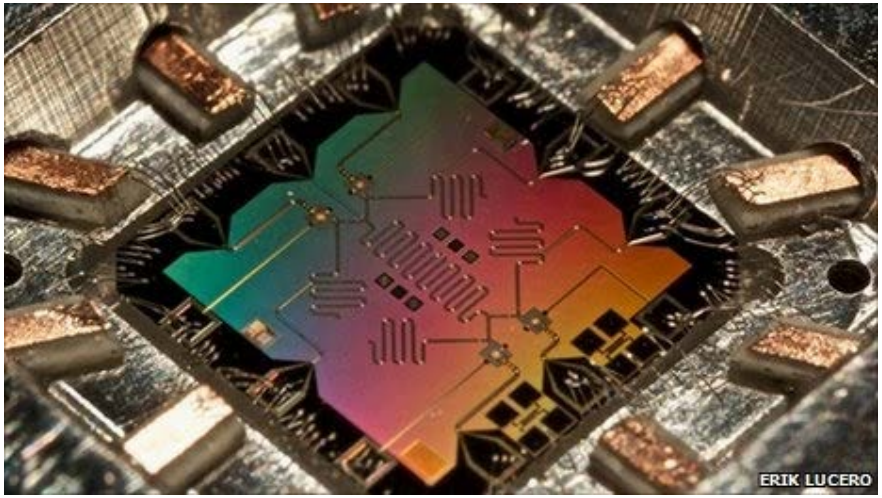

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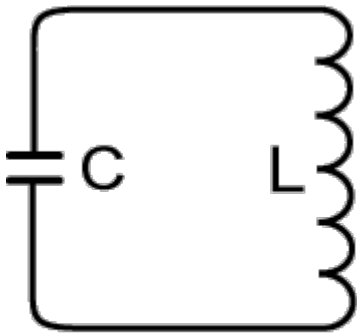
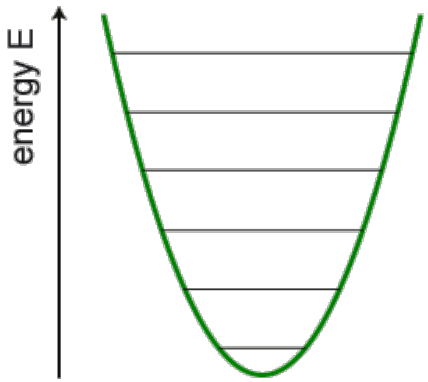
Electromagnetic resonator as a quantum system

- LC - resonator



- potential energy



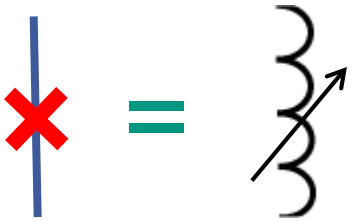
$$\hat{H} = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L}$$

conjugate operators

$$\left[\hat{Q}\,\hat{\Phi}\right] = i\hbar$$

➡ harmonic potential: equidistant energy levels

➡ way to get anharmonic potential is by using a nonlinear inductor: a Josephson junction

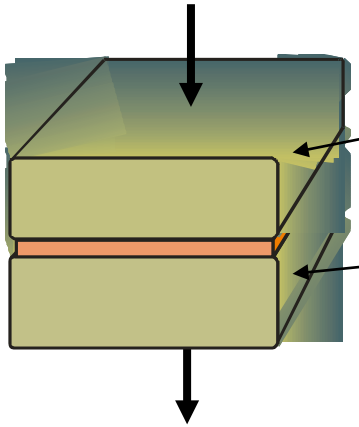


Josephson junction

superconductor

tunnel barrier

superconductor



$$\Psi_1 = |\Psi_1| \exp(i\theta_1)$$

$$\Psi_2 = |\Psi_2| \exp(i\theta_2)$$

superconducting phase difference: $\varphi = \theta_1 - \theta_2$

Josephson relations

$$\begin{cases} I_S = I_C \sin\varphi \\ V = \dfrac{\hbar}{2e}\dfrac{\mathrm{d}\varphi}{\mathrm{d}t} \end{cases}$$

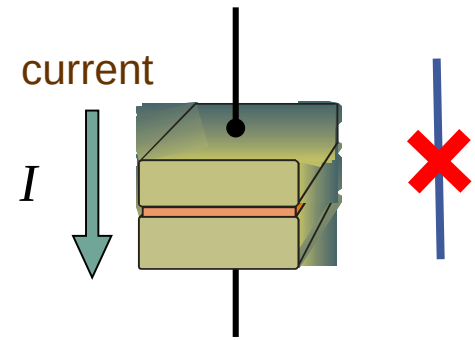
Josephson inductance

$$L_J = V\frac{\mathrm{d}I_S}{\mathrm{d}t} = \frac{\Phi_0}{2\pi I_C \cos\varphi}$$

Josephson junction: washboard potential

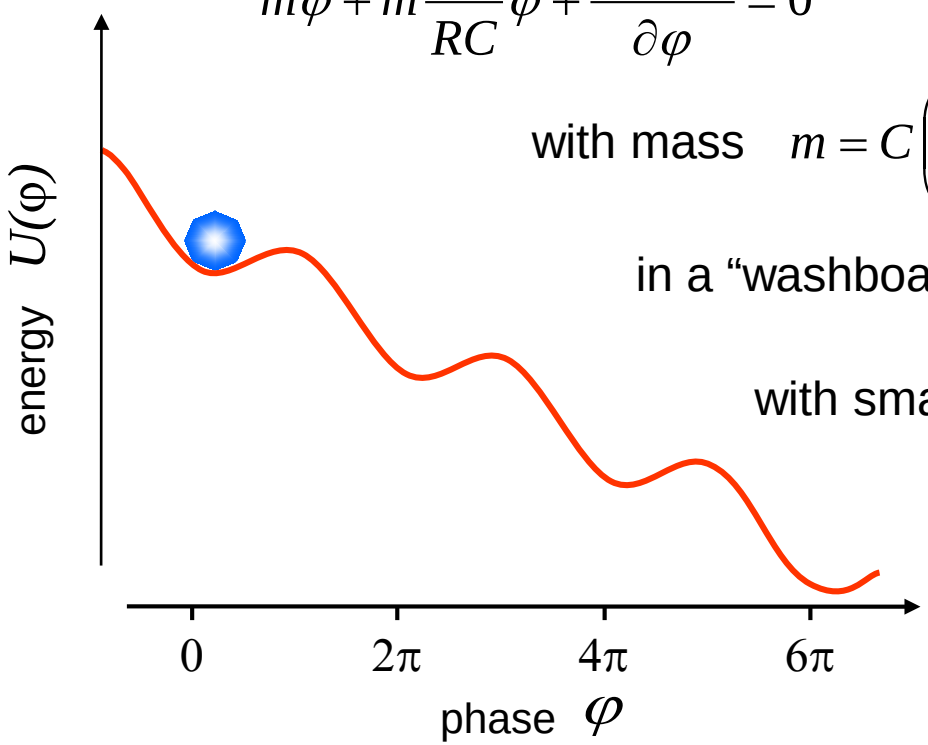
Dynamics of a small Josephson junction is equivalent to the motion of a particle

$$m\ddot{\varphi} + m\frac{1}{RC}\dot{\varphi} + \frac{\partial U(\varphi)}{\partial \varphi} = 0$$



with mass $m = C\left(\frac{\Phi_0}{2\pi}\right)^2$

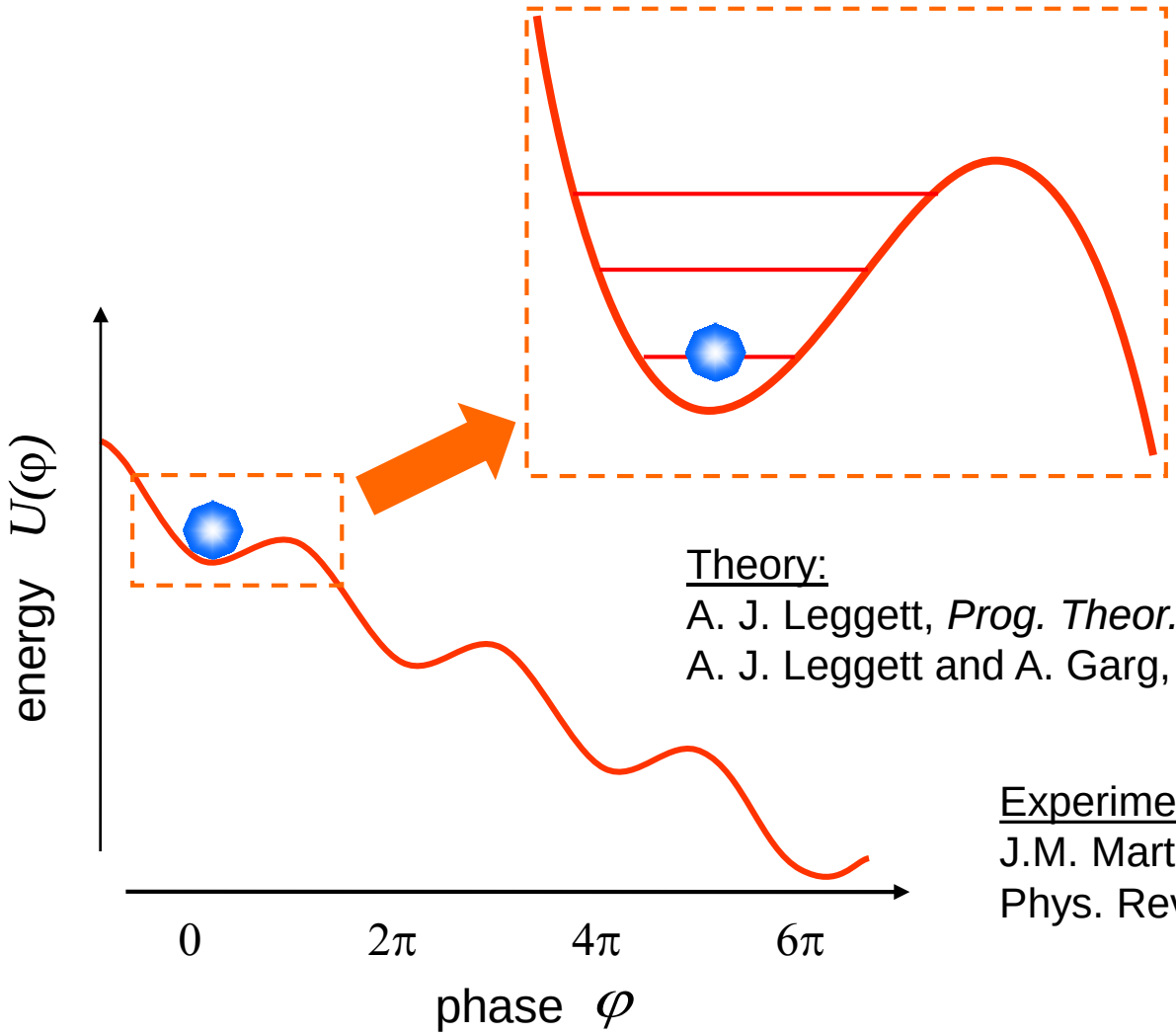
in a “washboard” potential $U(\varphi) = -\frac{I_c \Phi_0}{2\pi}\left(\frac{I\varphi}{I_c} + \cos\varphi\right)$



with small-amplitude oscillation frequency

$$\omega(I) = \omega_0 \sqrt[4]{1 - \frac{I^2}{I_c^2}} \quad ; \quad \omega_0 = \sqrt{\frac{2\pi I_c}{\Phi_0 C_J}}$$

Macroscopic quantum system



By reducing the capacitance C the ´mass`

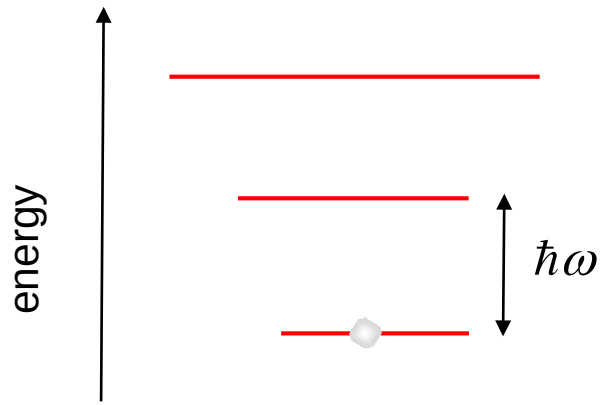
$$m = C\left(\frac{\Phi_0}{2\pi}\right)^2$$

can be made small

Theory:
A. J. Leggett, *Prog. Theor. Phys. Suppl.* **69**, 80 (1980).
A. J. Leggett and A. Garg, *Phys. Rev. Lett.* **54**, 857(1985).

Experiment:
J.M. Martinis, M. H. Devoret, and J. Clarke, Phys. Rev. B **35**, 4682 (1987).

How low should be the temperature?



To see the energy levels we need $\hbar\omega >> k_B T$.

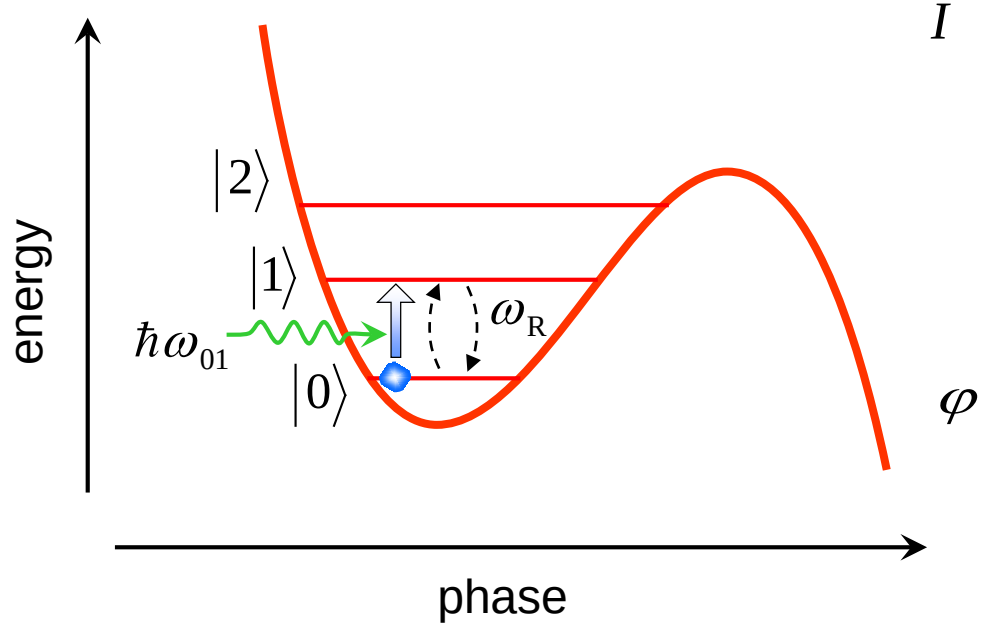
For the level separation frequency of

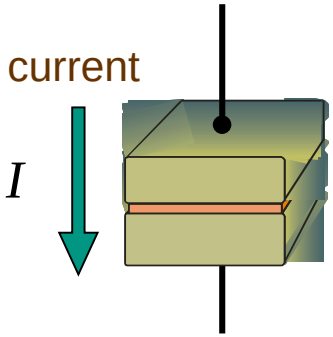
$$f = \frac{\omega}{2\pi} = 10\,\mathrm{GHz}$$

the condition $T = \frac{\hbar\omega}{k_B}$ corresponds to $T \approx 0.48\,\mathrm{K}$

i.e. $1\,\mathrm{GHz} \Leftrightarrow \sim 50\,\mathrm{mK}$

Josephson phase qubit





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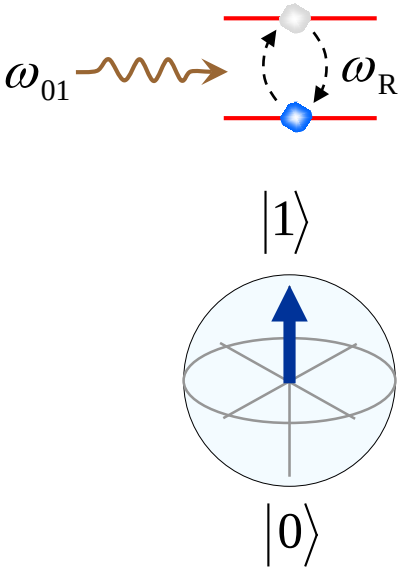


J. M. Martinis et al., Phys. Rev. Lett. **89**, 117901 (2002).

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

Flux and charge: Two extremes

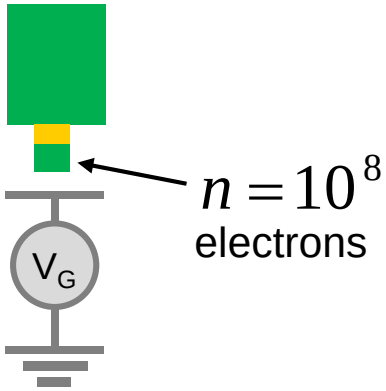
Uncertainty relation for a superconductor: $\Delta n \cdot \Delta \varphi \geq 1$

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

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

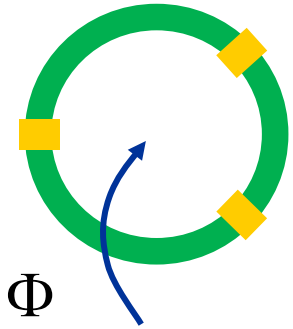
charge qubit

$E_C >> E_J$



flux qubit

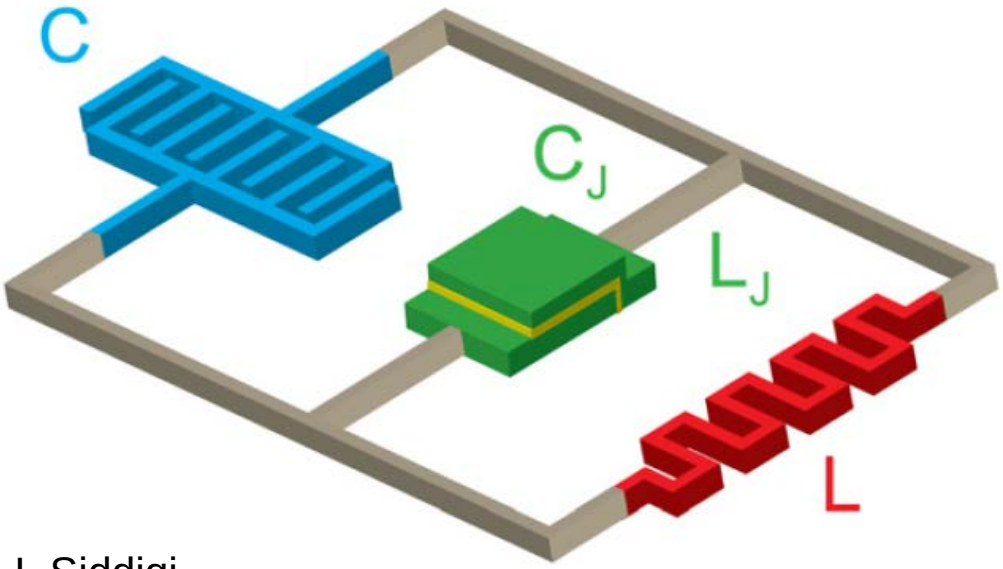
$E_C << E_J$



- Makhlin et al., Nature 398, 305 (1999)
- Nakamura et al., Nature 398, 786 (1999)

- Friedman et al., Nature 406, 43 (2000)
- van der Wahl et al., Science 290, 773 (2000)

Prototypical nonlinear equivalent circuit of a superconducting qubit



The central element is a **Josephson tunnel junction** shunted by a **capacitor** and an **inductor**. The junction has a nonlinear Josephson inductance L_J *and a* linear capacitance C_J.

© I. Siddiqi, Supercond. Sci. Technol. **24**, 091002 (2011)

|number>

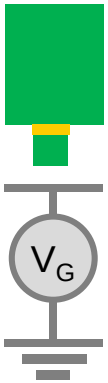
↓

|phase>

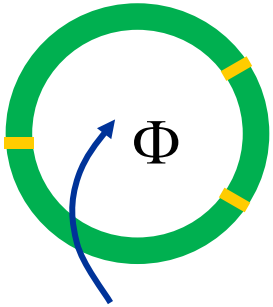
Qubit	E_J/E_C	E_L/E_J
charge	< 1	0
transmon	~ 100	0
flux	~ 100	~ 0.5
phase	~ 10^4	~ 0.2

Overview of superconducting qubits

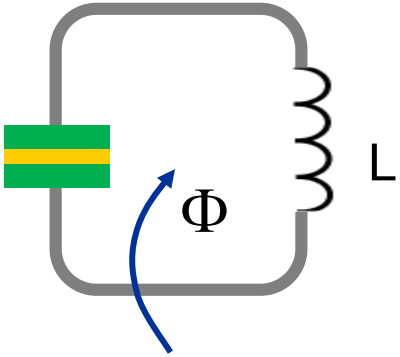
charge qubit
1999



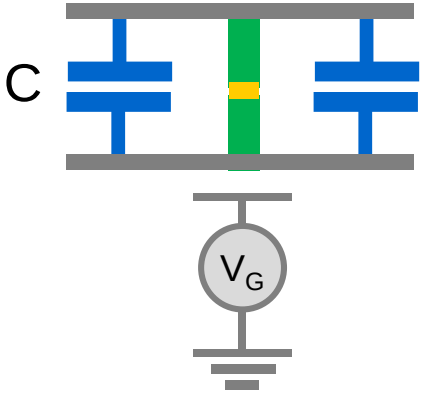
flux qubit
2000

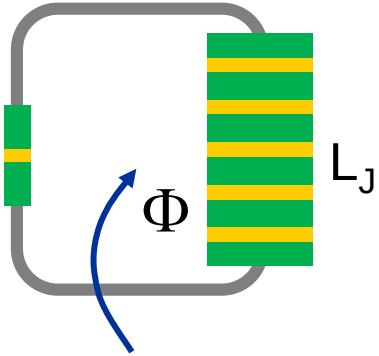


phase qubit
2002



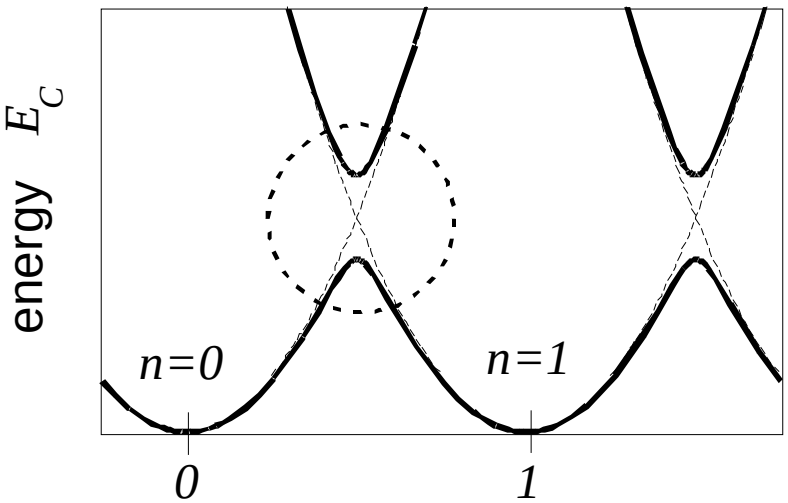
transmon
2007



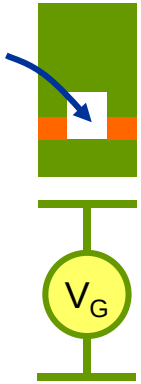


fluxonium
2008

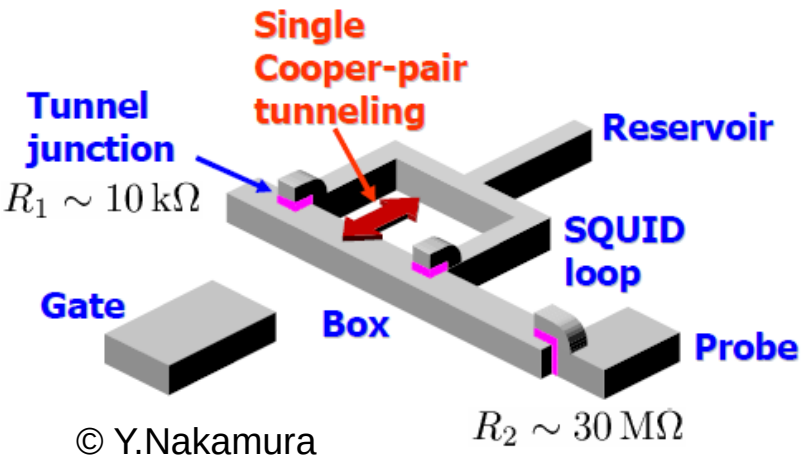
Charge qubit: NEC experiments



charge of the box $n_G=q/(2e)$



Nakamura et al., Nature 398, 786 (1999)
Nakamura et al., PRL 87, 246601 (2001)
Nakamura et al., PRL 88, 047901 (2002)



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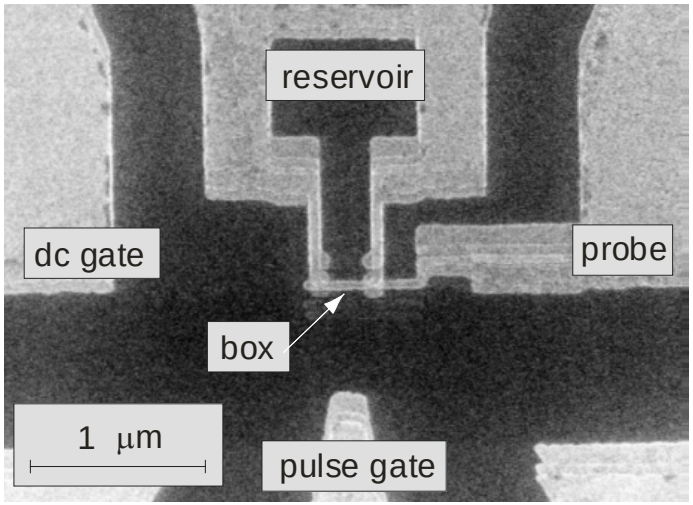
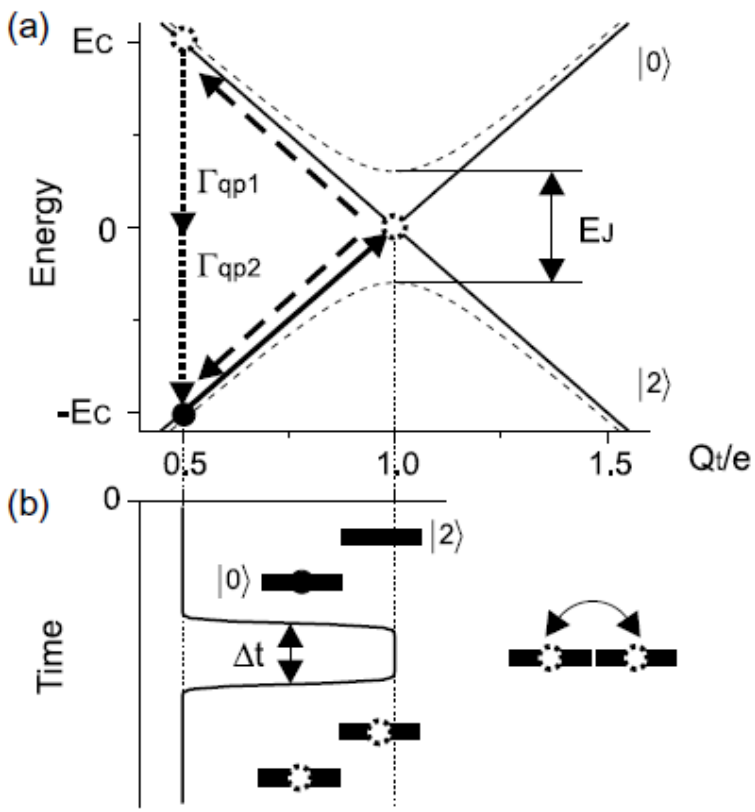
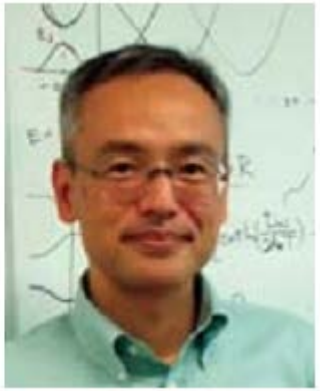
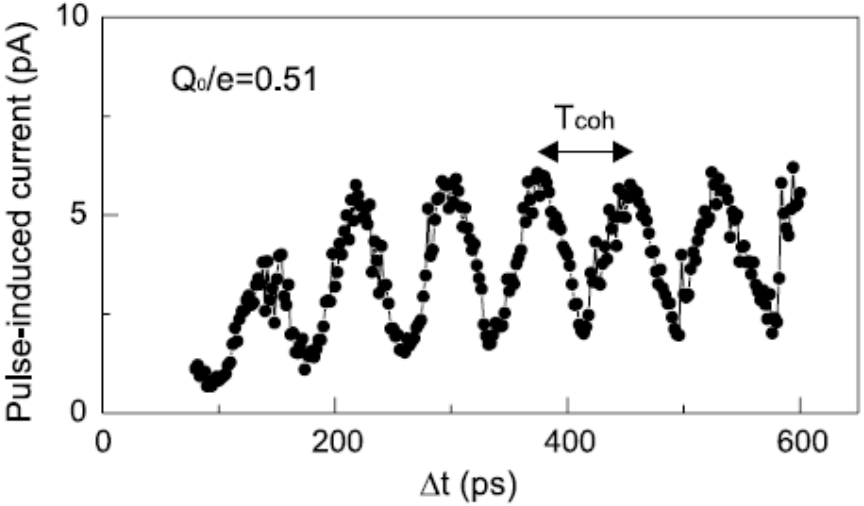


Charge qubit: NEC experiments



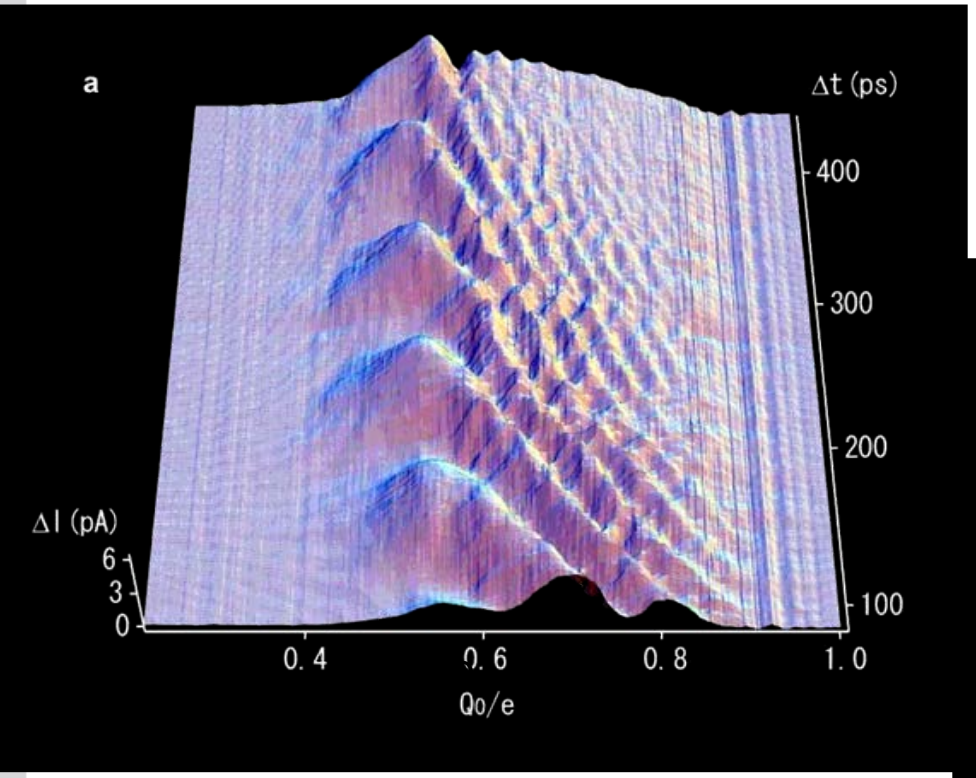
Yasunobu Nakamura





Nakamura, Pashkin and Tsai, *Nature* 398, 786 (1999)

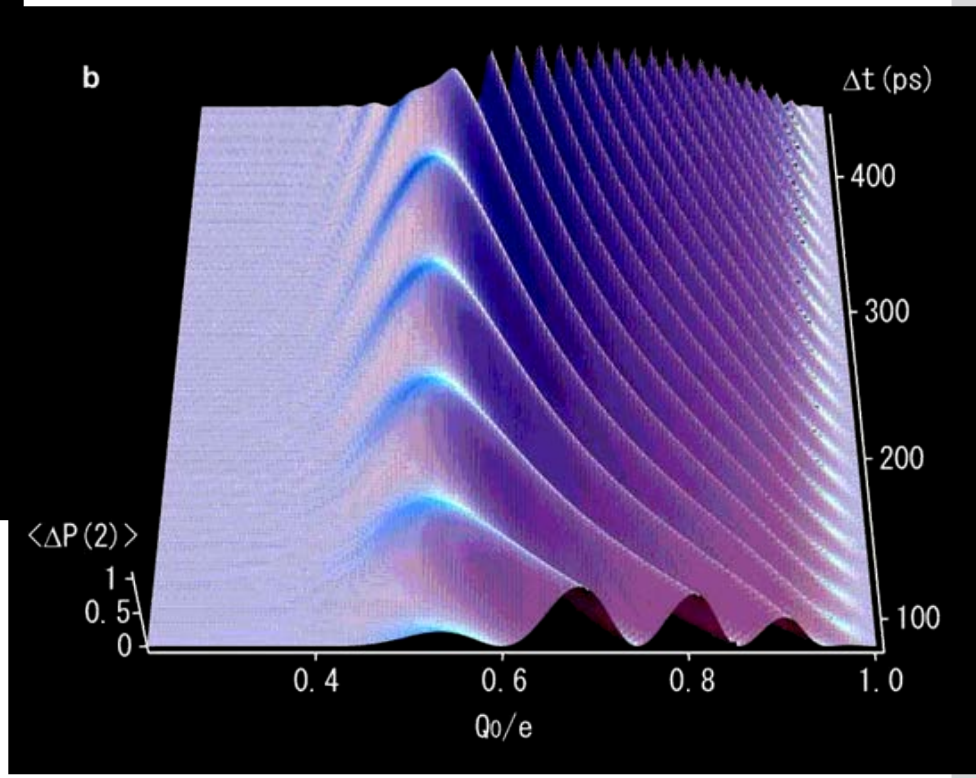
Charge qubit: NEC experiments



Measurement

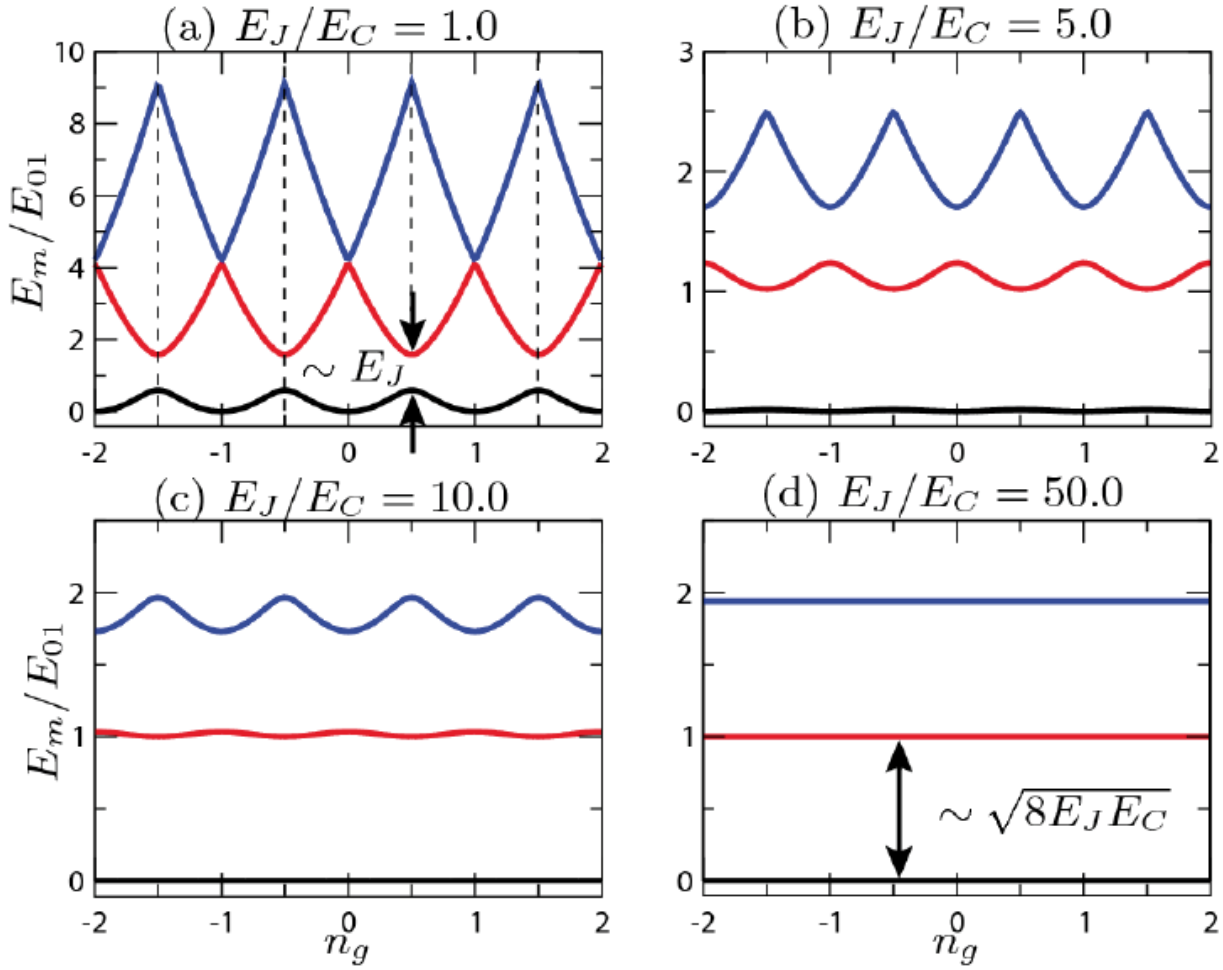
Nakamura et al.,
Nature 398, 786 (1999)

Simulation

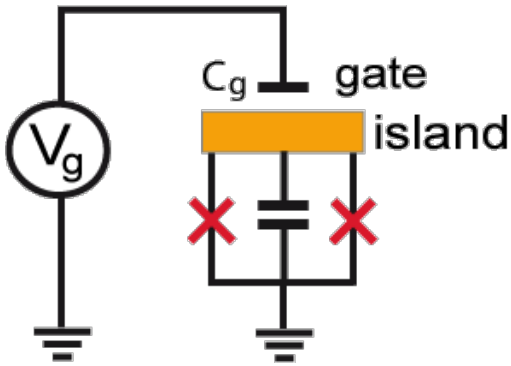


Transmon qubit

J. Koch et al., Phys. Rev. A **76**, 042319 (2007)



by **increasing E_J/E_C**
(e.g. by shunting the junction with a capacitor)
the energy bands become **more flat**



there is **a sweet spot everywhere !**

but the **anharmonicity** decreases.

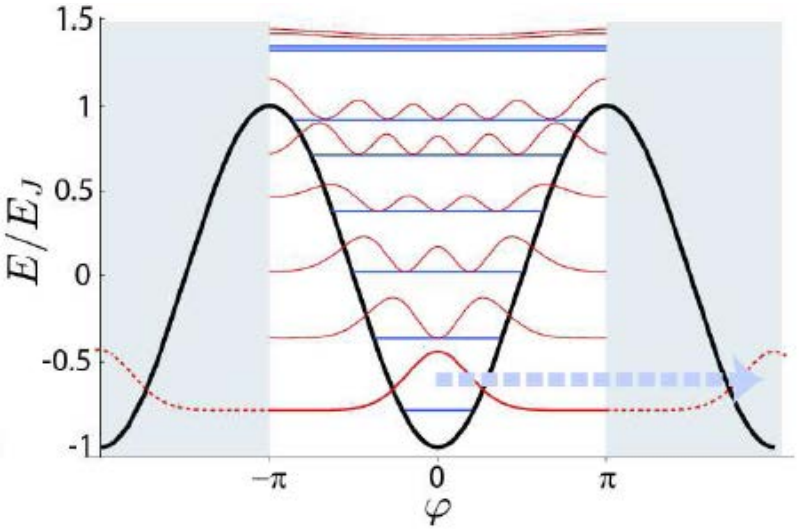
Transmon = TRANSMission-line shunted plasma oscillatiON qubit

Transmon qubit

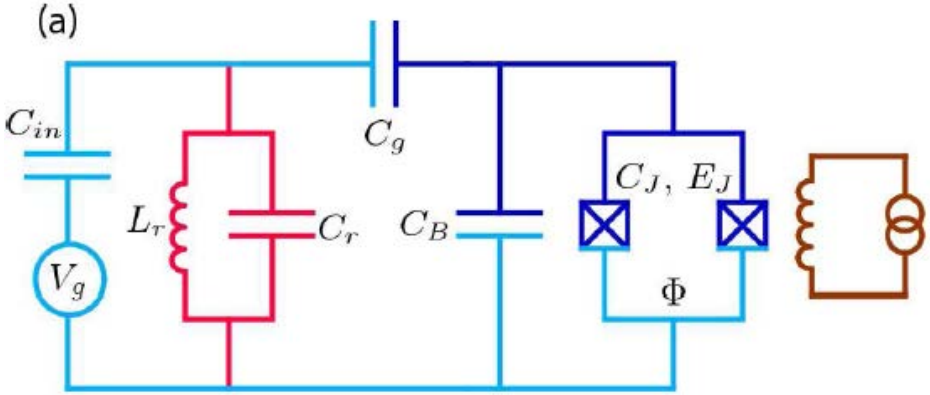
charge qubit Hamiltonian:

$$\hat{H} = E_C(\hat{N} - N_g)^2 - E_J \cos\hat{\varphi}$$

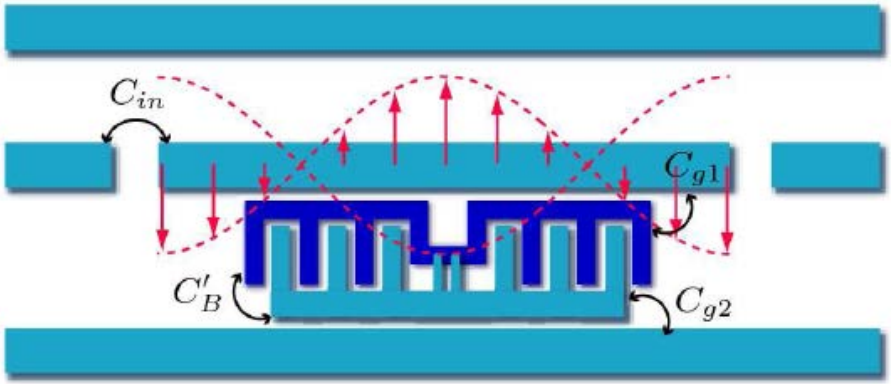
- for $E_J >> E_C$, the eigenstates are in a cosine potential:



schematic of a transmon coupled to a resonator



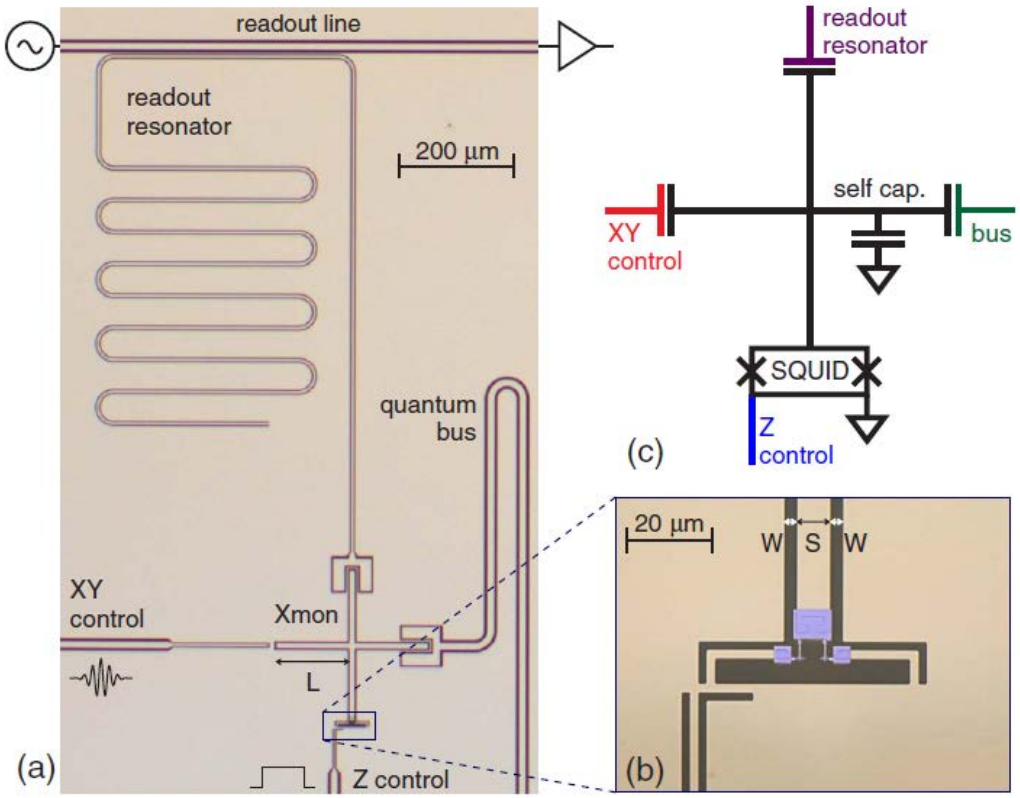
(b) transmon embedded in a coplanar resonator

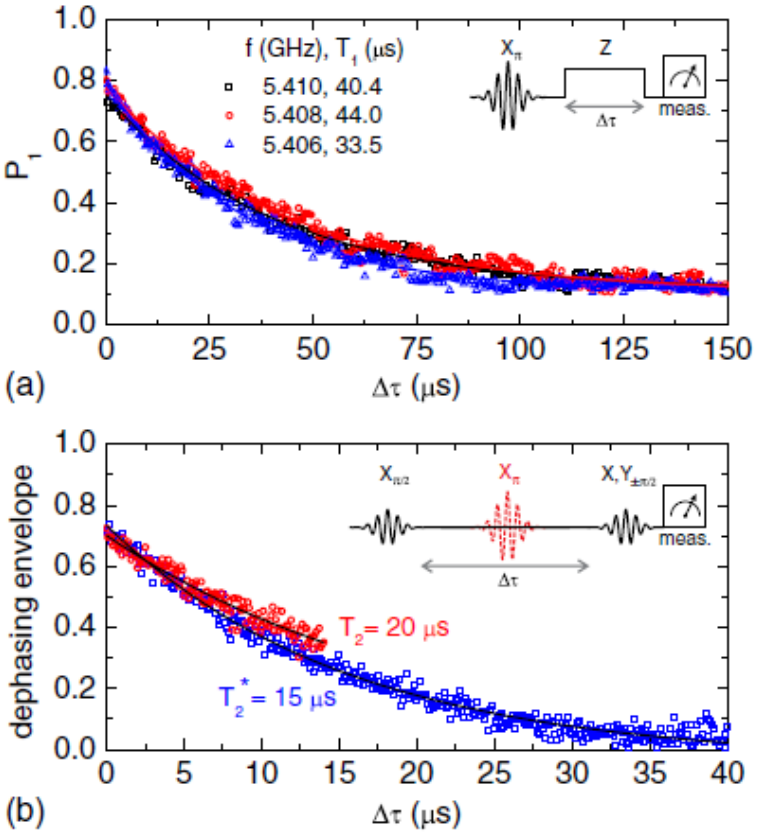


J. Koch et al., Phys. Rev. A **76**, 042319 (2007)

X-mon qubits for scalable quantum integrated circuits

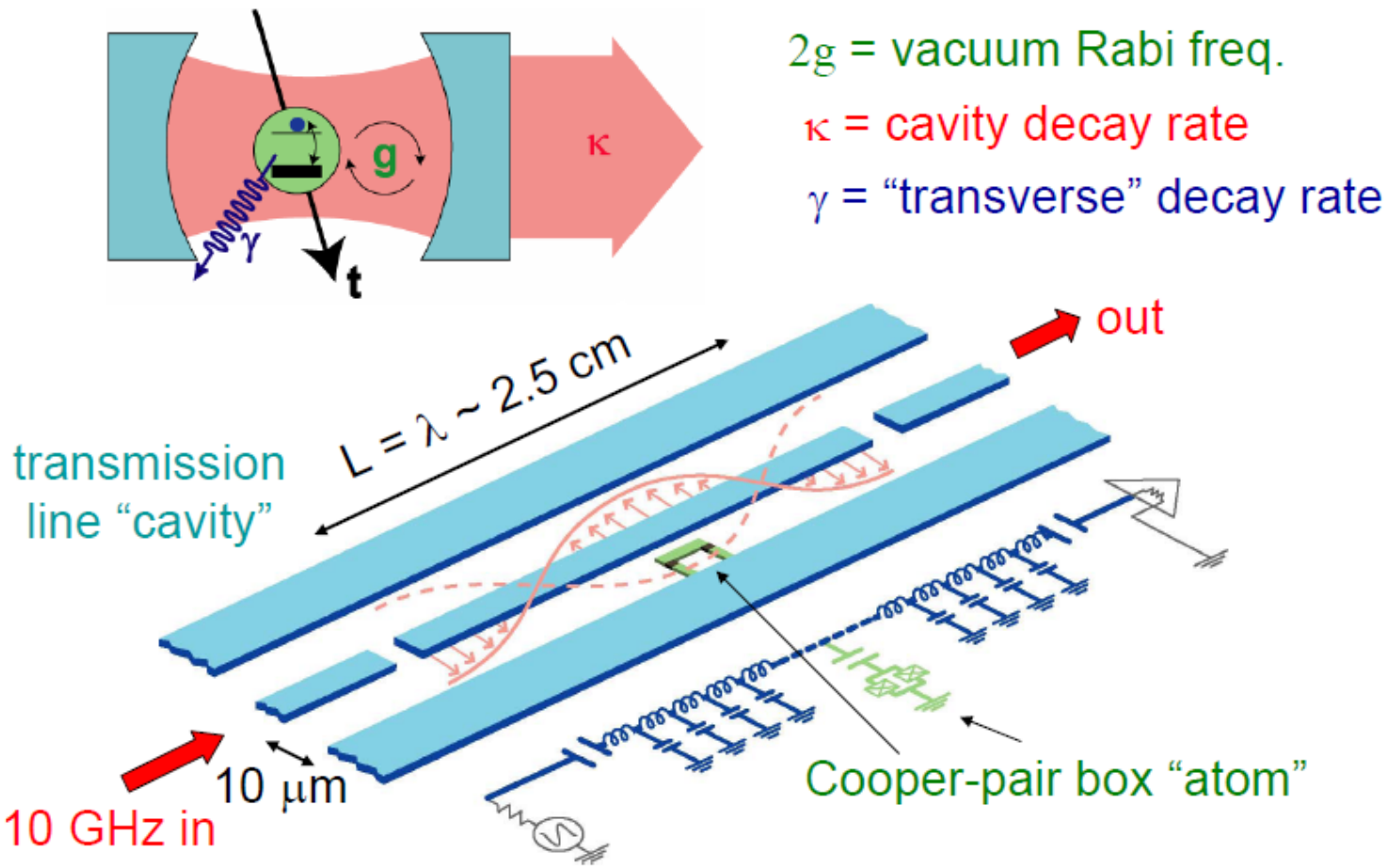
R. Barends et al., Phys. Rev. Lett. **111**, 080502 (2013)





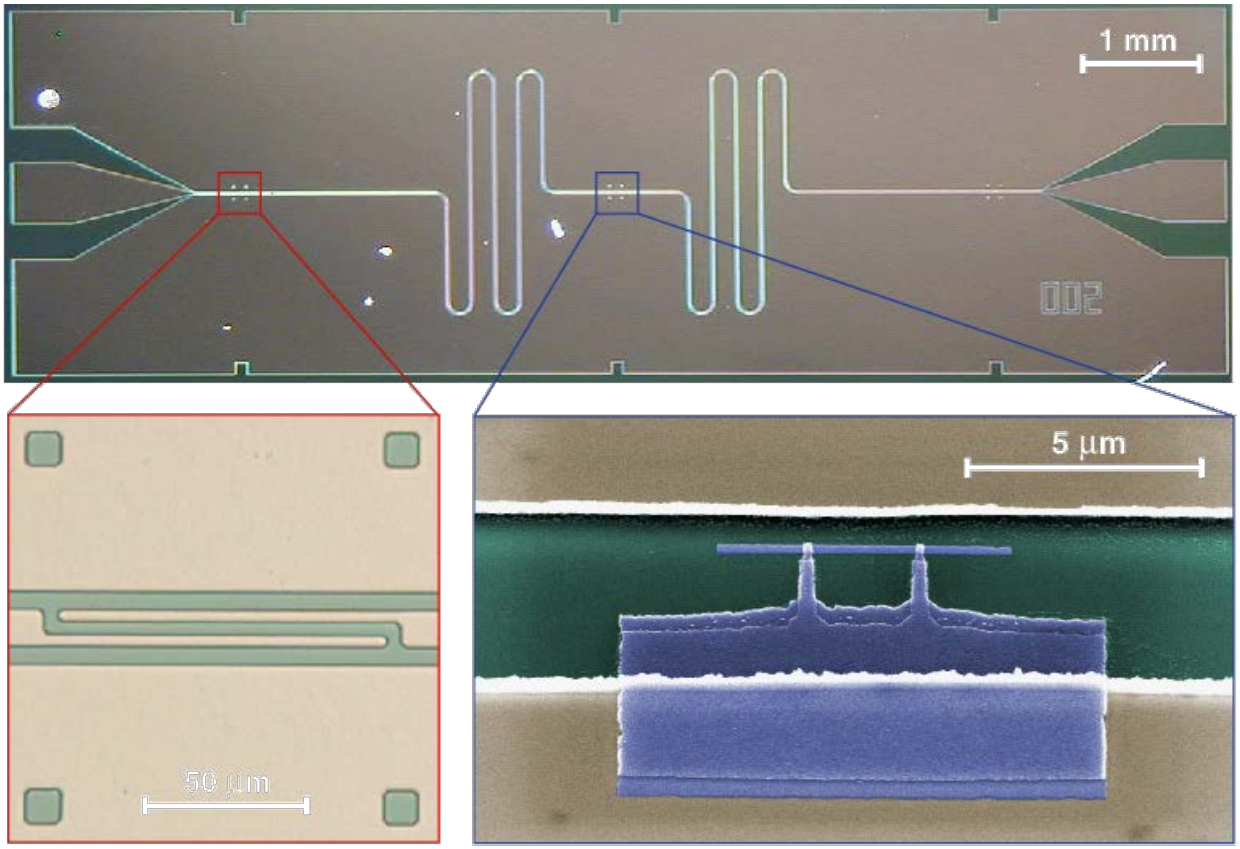
X-mon qubit

A circuit analog for cavity QED (Yale)



A. Wallraff, D. I. Schuster, A. Blais, et al., *Nature* 431, 162 (2004)

Charge qubit in a cavity (Yale)

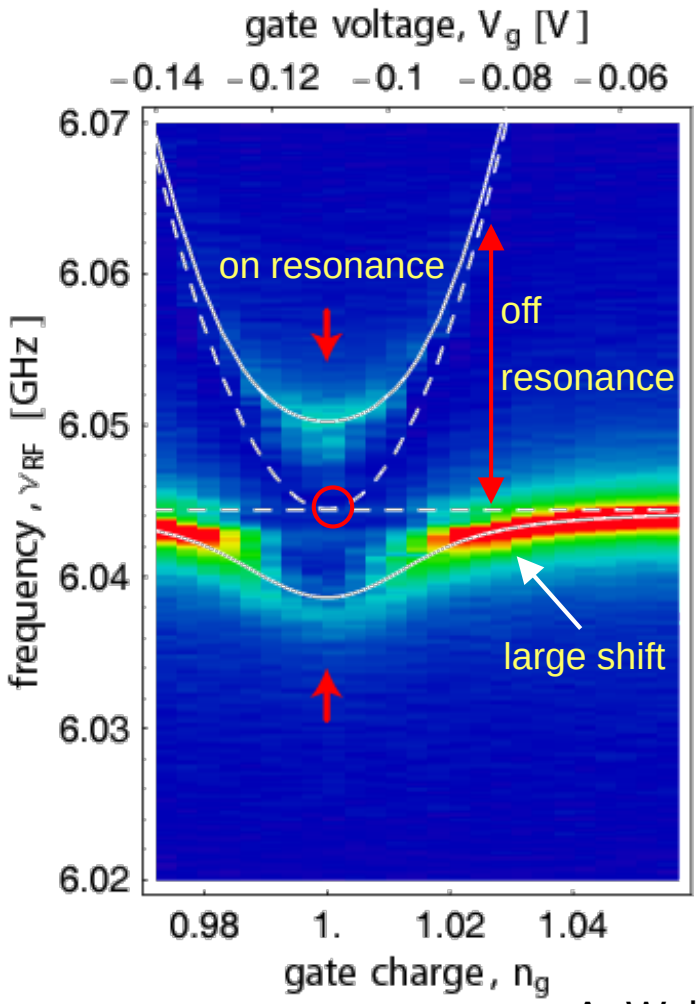


Andreas Wallraff

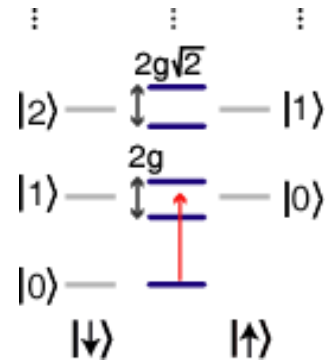
Robert Schoelkopf

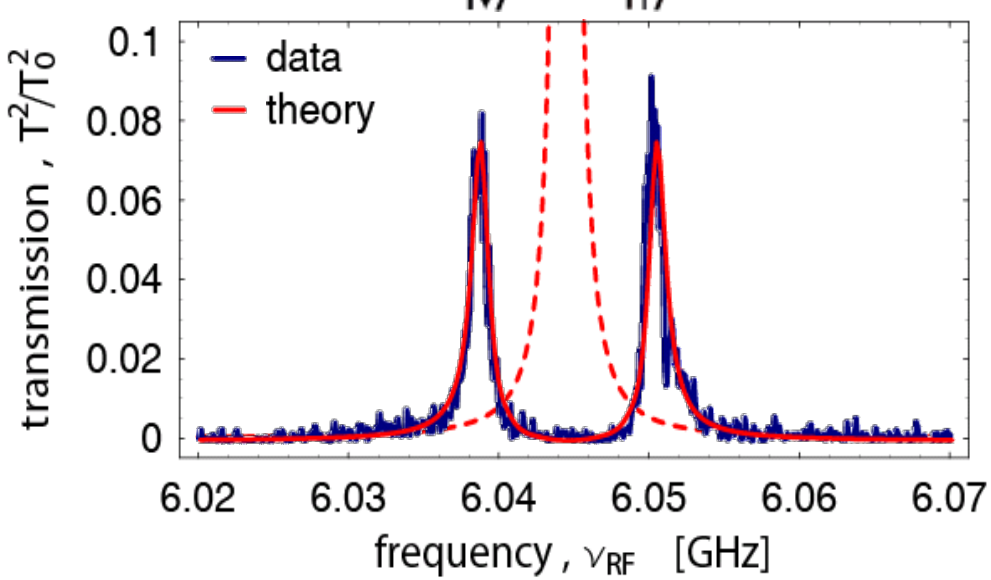
A. Wallraff, D. I. Schuster, A. Blais, et al., *Nature* 431, 162 (2004)

Dispersive qubit-field interaction



Photon-qubit anti-crossing: vacuum Rabi splitting

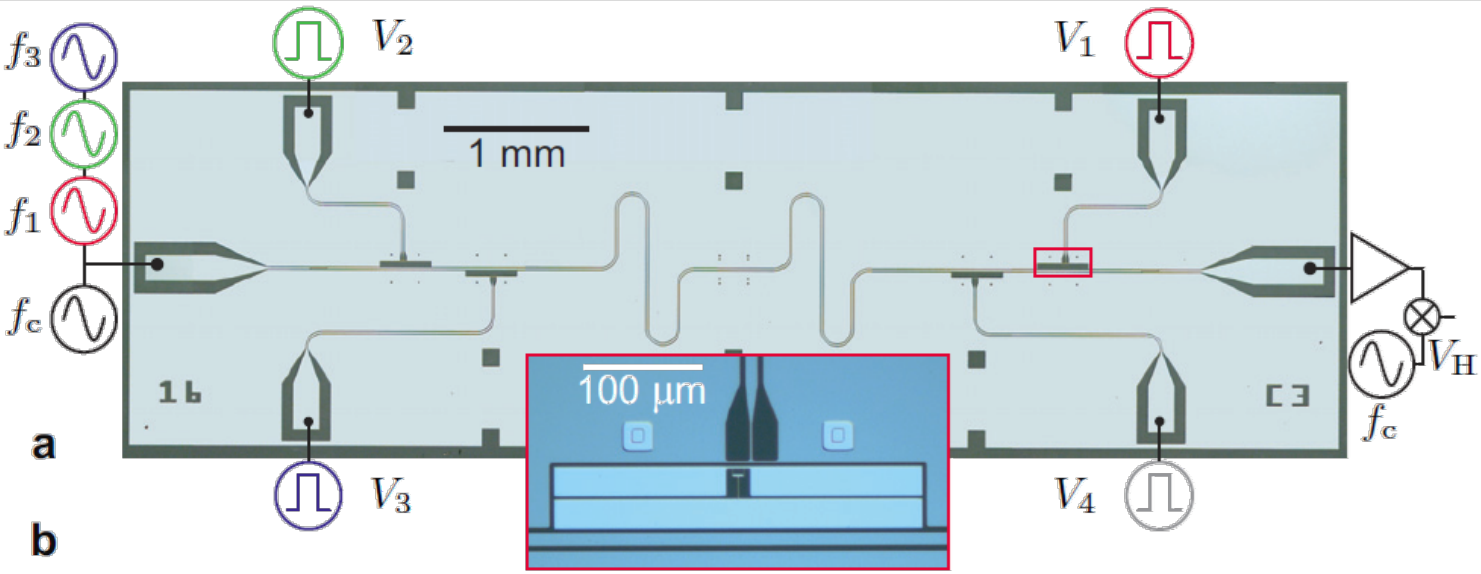




A. Wallraff, D. I. Schuster, A. Blais, et al., *Nature* 431, 162 (2004)

Circuit QED with Transmon Qubits

L. DiCarlo et al., Nature **467**, 574 (2010)



- each qubit interacts with the resonator. This is described by the **Jaynes-Cummings Hamiltonian**:

$$H = \underbrace{\hbar\omega_R\left(a^+a+\frac{1}{2}\right)}_{\text{cavity (resonator)}} + \underbrace{\hbar\omega_Q\frac{\sigma_z}{2}}_{\text{qubit}} + \underbrace{\hbar g\left(a^+\sigma^- + a\sigma^+\right)}_{\text{coupling cavity-qubit}}$$

a^+ and a are photon creation / annihilation operators.

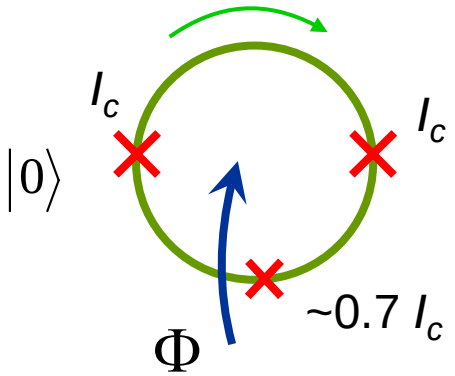
Flux qubit

quantum states:

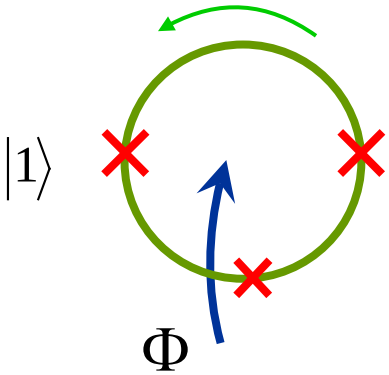
$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Hans Mooij

clockwise current

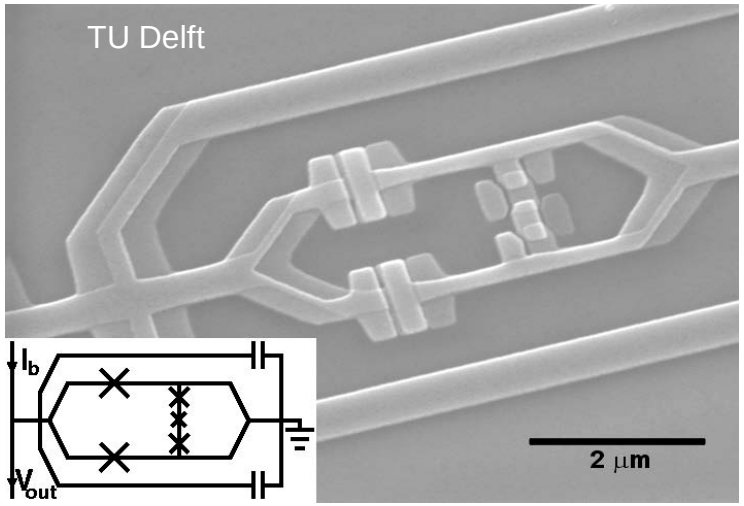


counterclockwise current



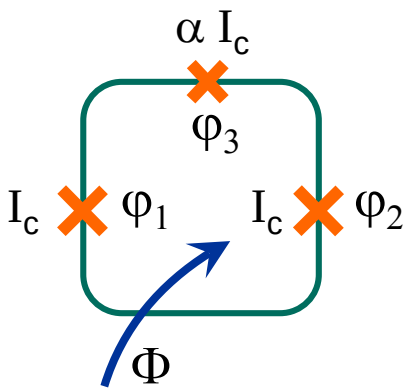
degeneracy point at

$$\Phi = \Phi_0/2$$



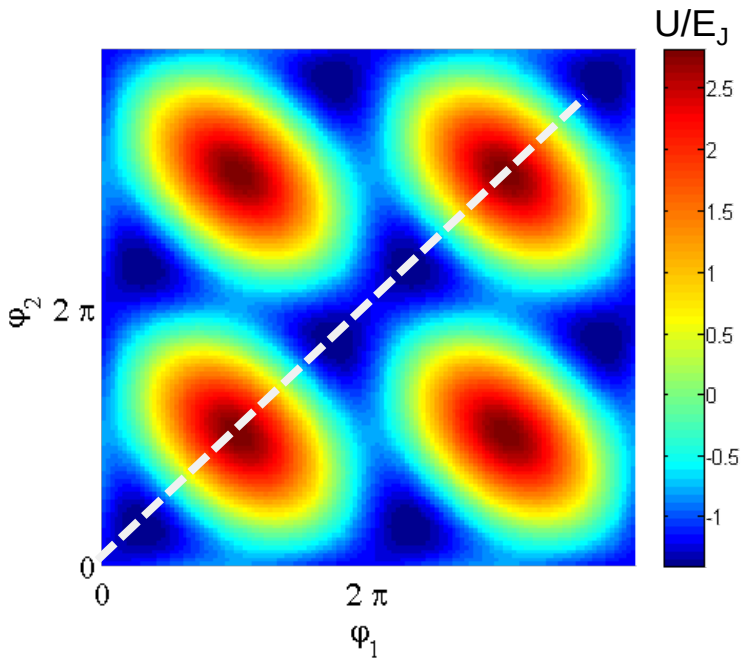
J.E. Mooij *et al.*, *Science* 285, 1036 (1999)
C.H. van der Wal *et al.*, *Science* 290, 773 (2000)

Superconducting 3-junction flux qubit



flux quantization:

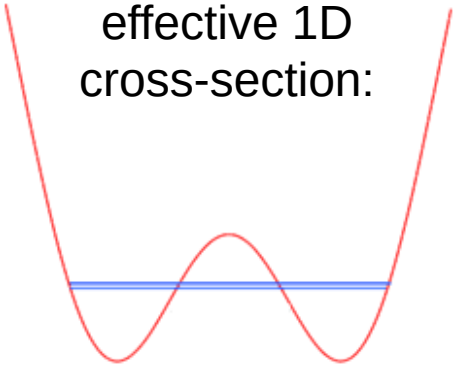
$$\varphi_1 + \varphi_2 + \varphi_3 + 2\pi \frac{\Phi}{\Phi_0} = 2\pi n$$



effective 2D potential:

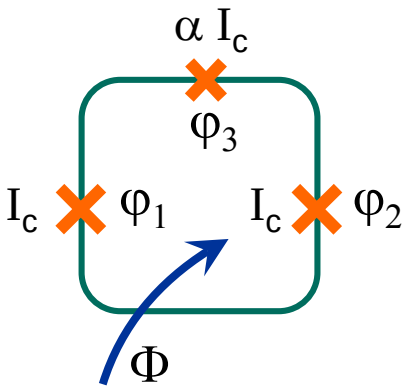
$$\frac{U}{E_J} = \cos\varphi_1 + \cos\varphi_2 + \alpha \cos\left(-\varphi_1 - \varphi_2 - 2\pi \frac{\Phi_{\text{ext}}}{\Phi_0}\right)$$

effective 1D cross-section:



Mooij et al. Science 285, 1036 (1999)
Van der Wal et al. Science 290,1140 (2000)

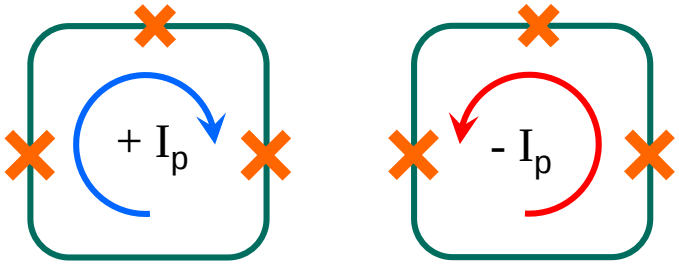
Superconducting flux qubit as a two-level system (artificial atom)

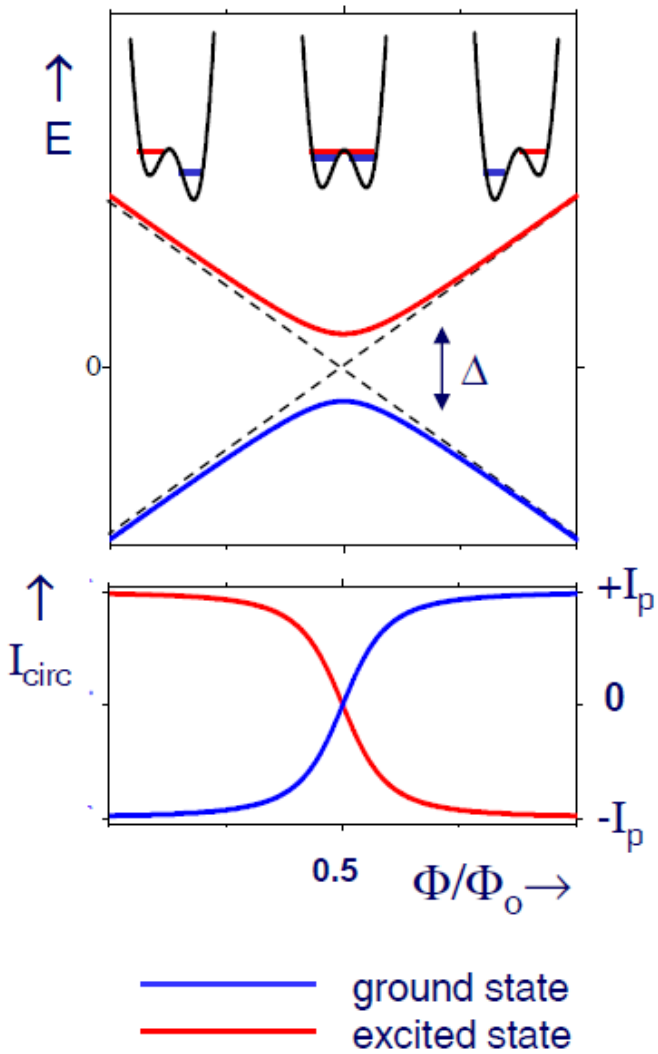


magnetic flux bias $\Phi \sim \Phi_0/2$

$$H = \frac{1}{2}\left(\varepsilon\sigma_z + \Delta\sigma_x\right)$$

persistent current states $\pm I_p$

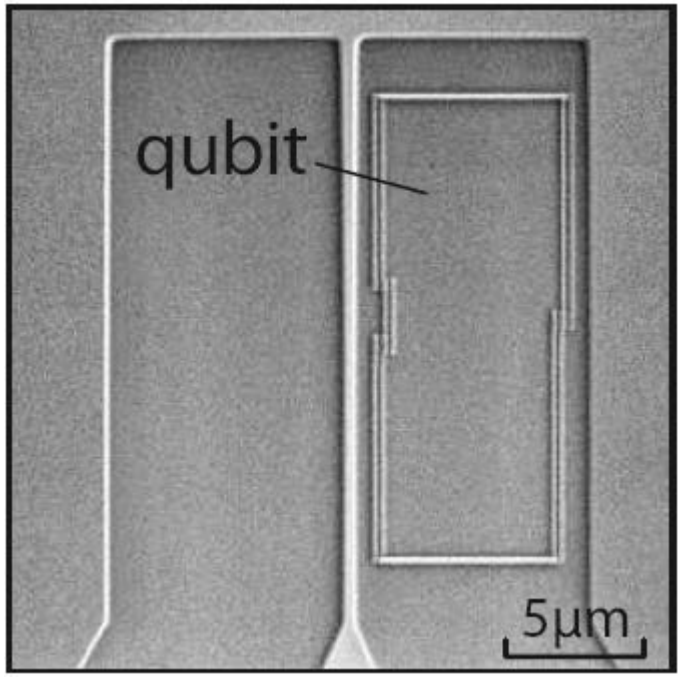


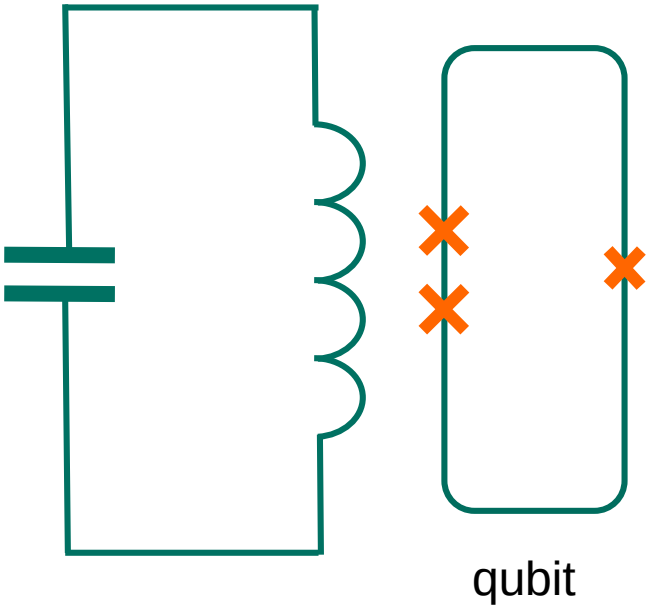


J. Clarke and F. K. Wilhelm, *Nature* 453, 1031 (2008)

QED readout of a flux qubit

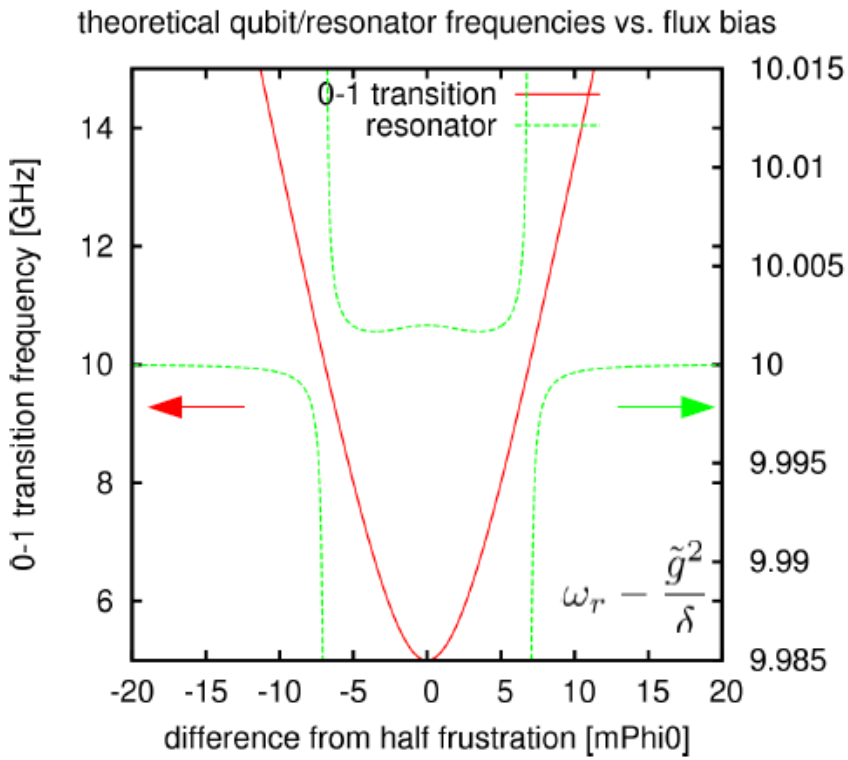
Al/AlO$_X$/Al Josephson junctions

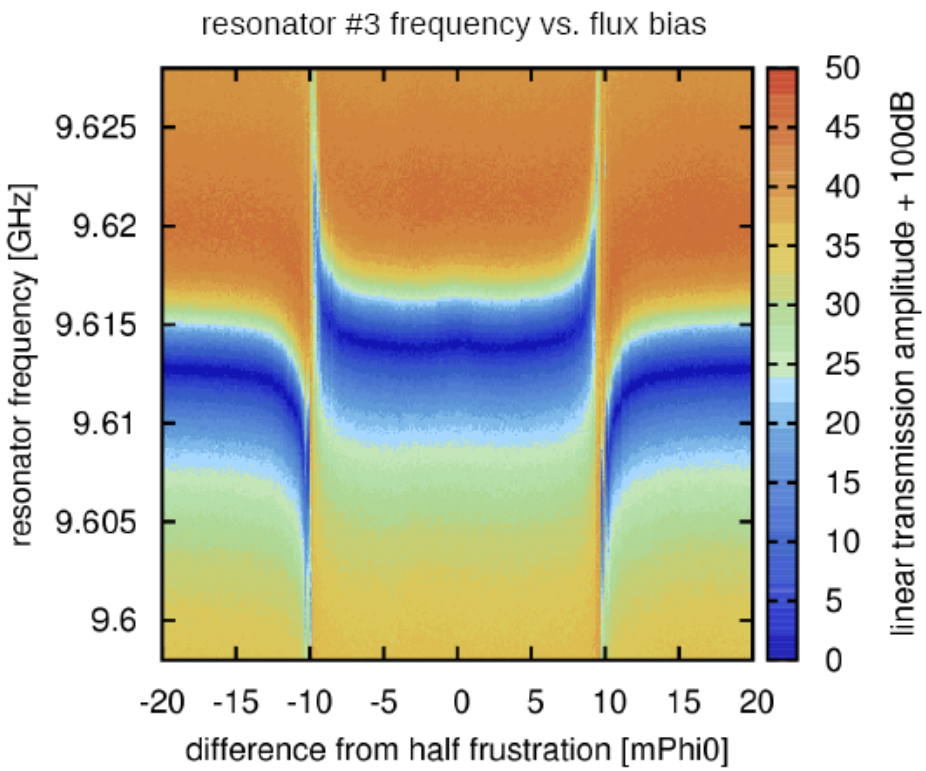




Anticrossings

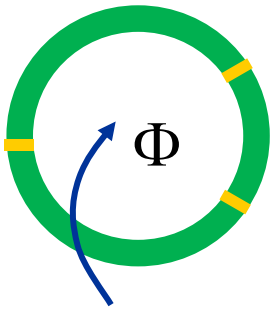
- Dispersive shift of the resonator due to the qubit in the ground state
- Evaluate qubit-resonator coupling, if gap Δ is known

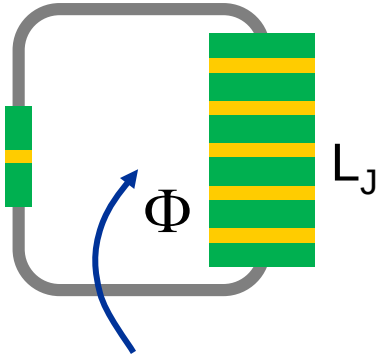




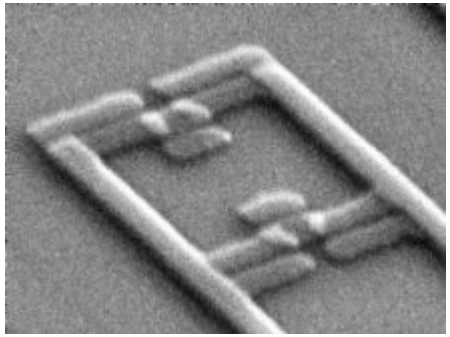
Flux qubit vs „fluxonium“

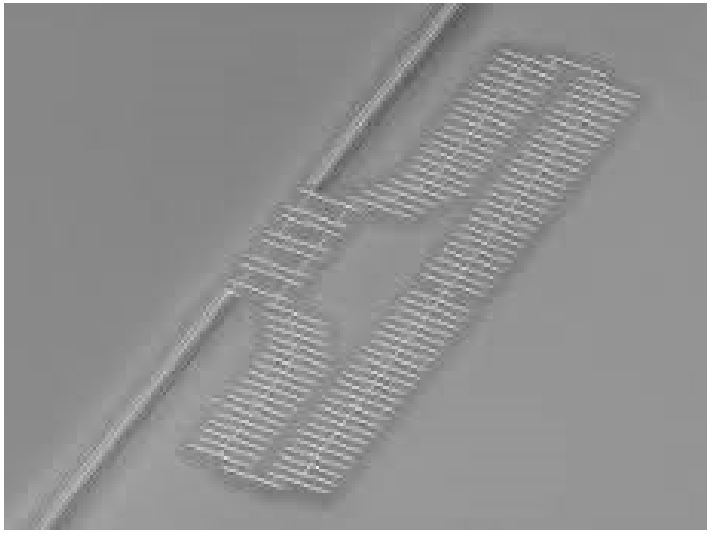
flux qubit
2000





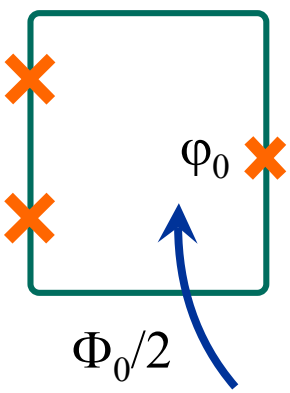
fluxonium
2008





Flux qubit vs „fluxonium“

flux qubit

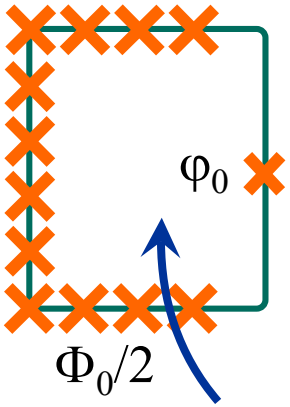


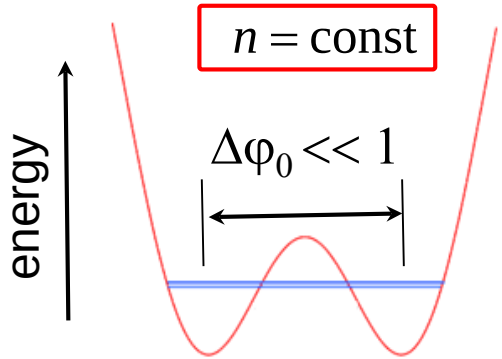
tunneling between two states separated by phase difference $\Delta\varphi_0$

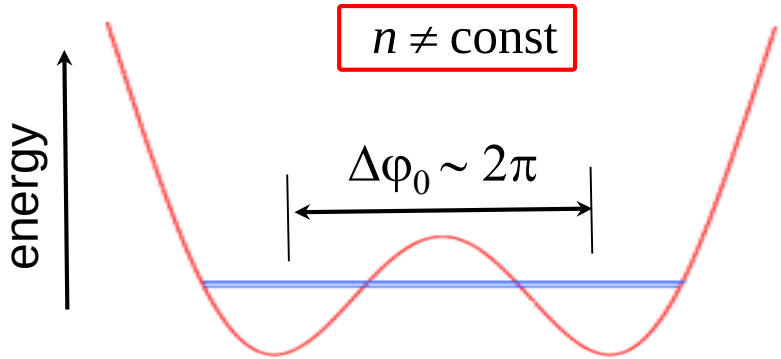
flux quantization:

$$\sum \varphi_i + 2\pi \frac{\Phi}{\Phi_0} = 2\pi n$$

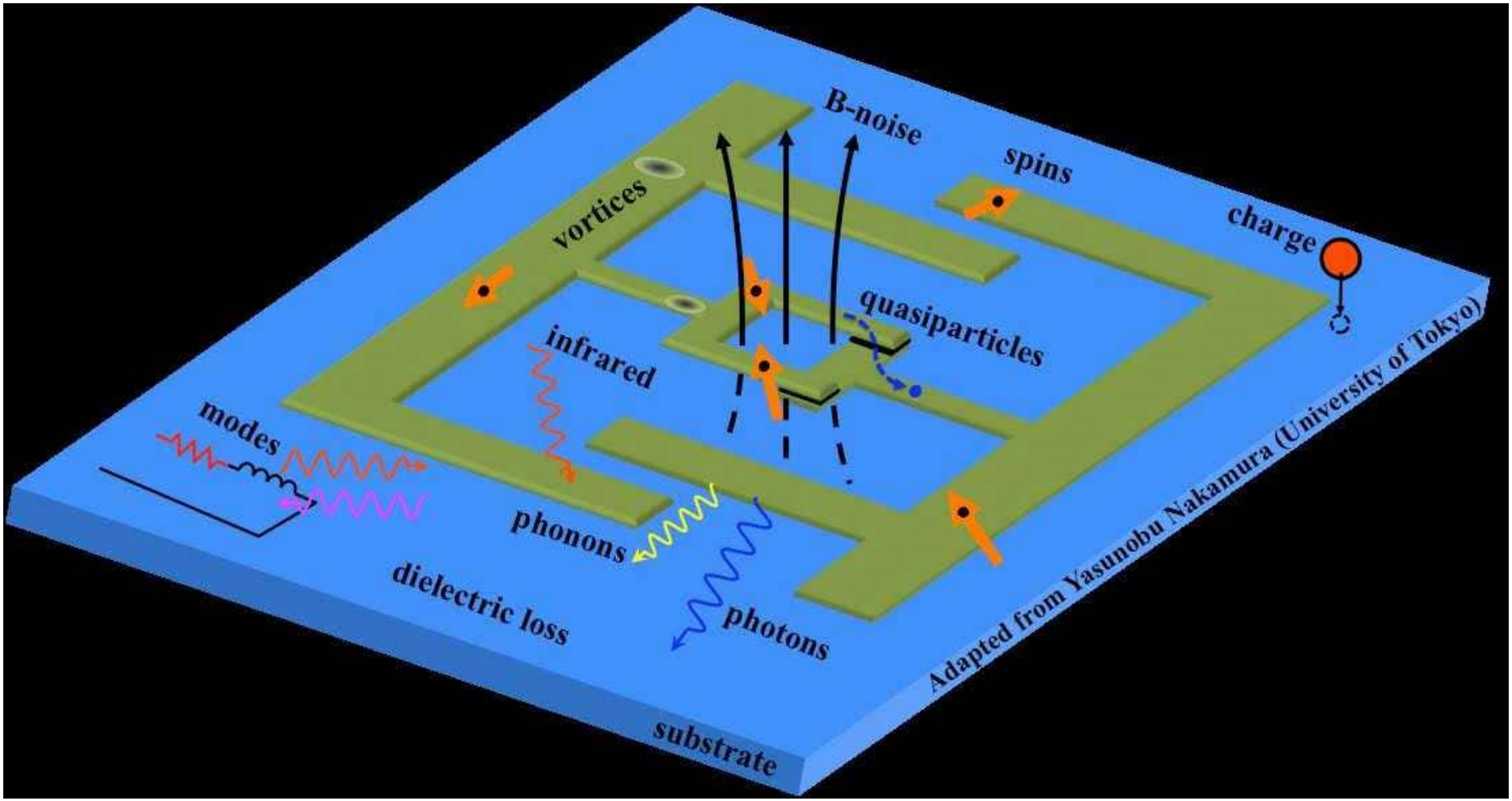
fluxonium



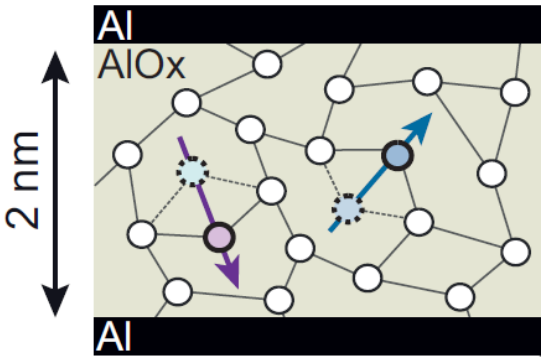


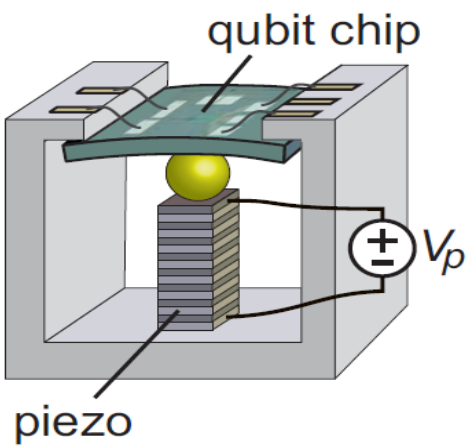


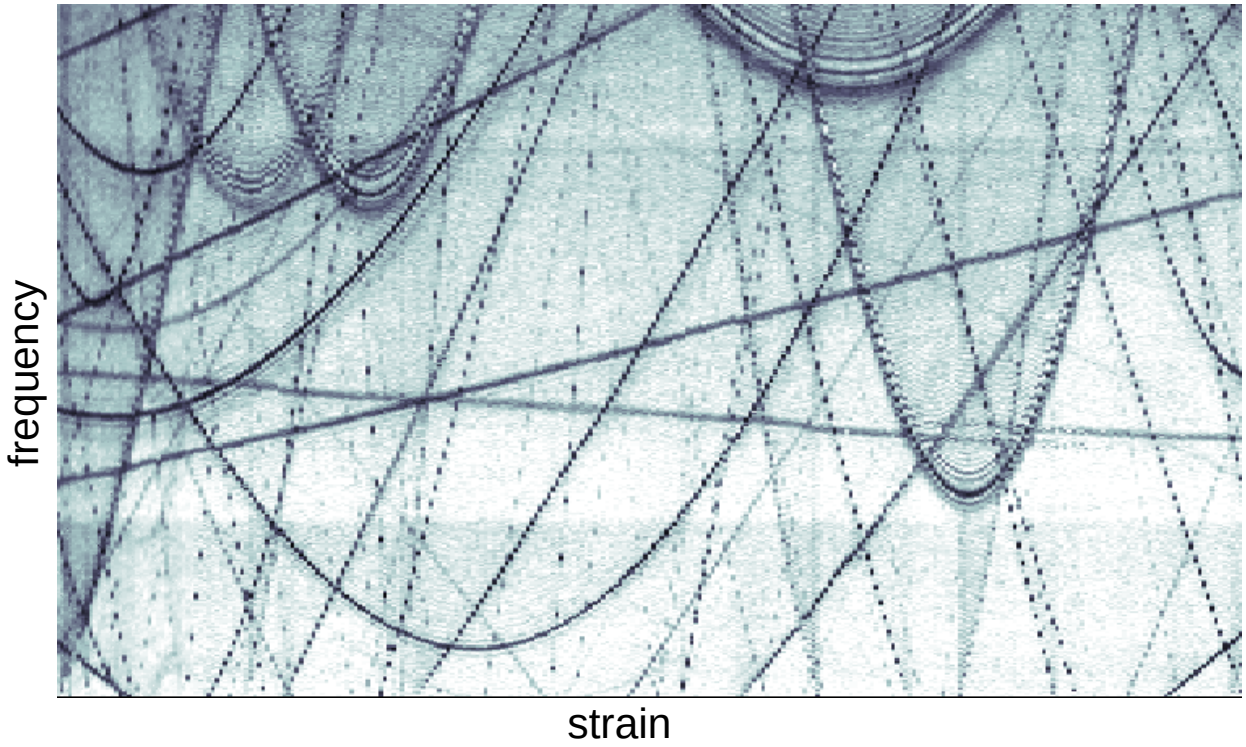
Decoherence



Microscopic defects in qubits





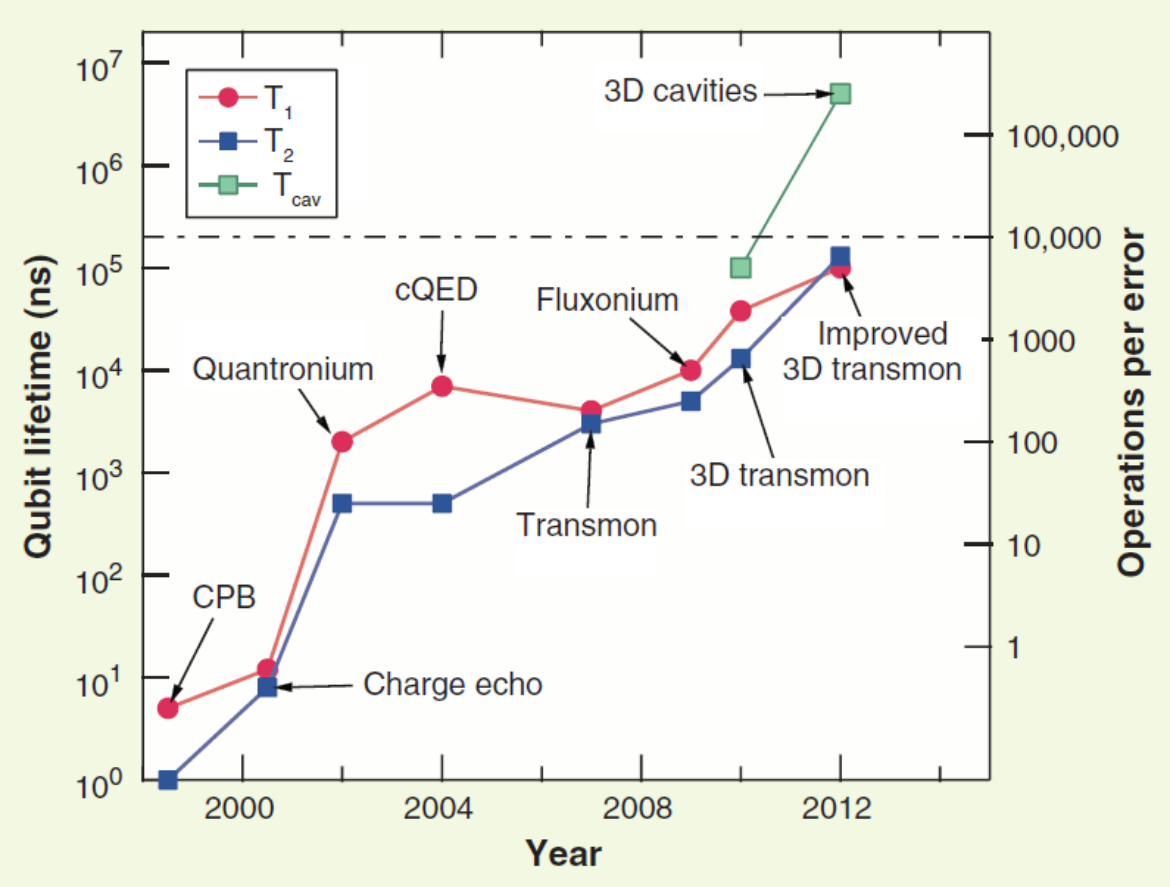


applying mechanical strain tunes the energy splitting of defects in qubits

G. Grabovskij, T. Peicl, J. Lisenfeld, G. Weiss, and A. V. Ustinov, *Science* **338**, 232 (2012)

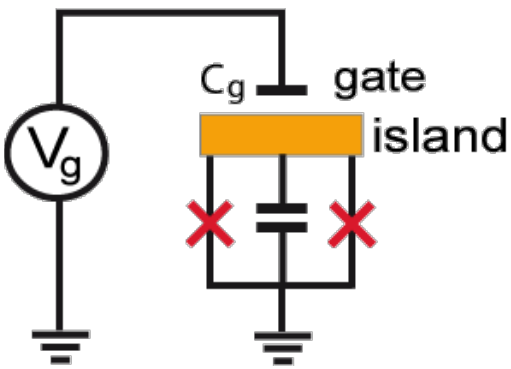
Progress of superconducting qubits

"Moore's law" of superconducting qubits

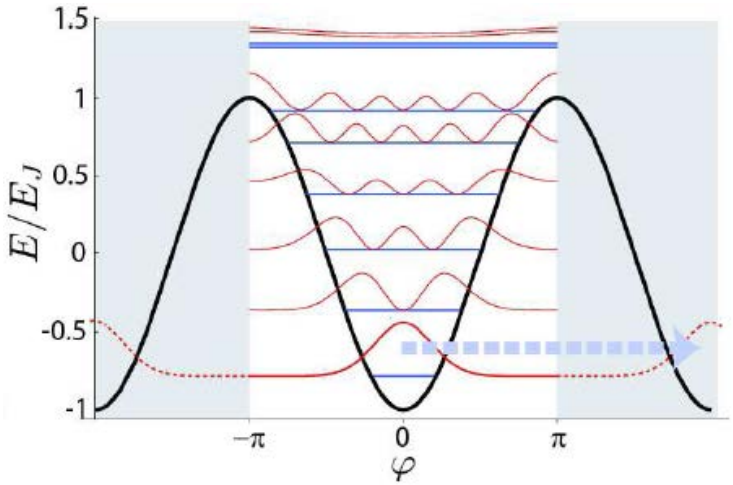


M. H. Devoret and R. J. Schoelkopf, *Science* **339**, 1169 (2013)

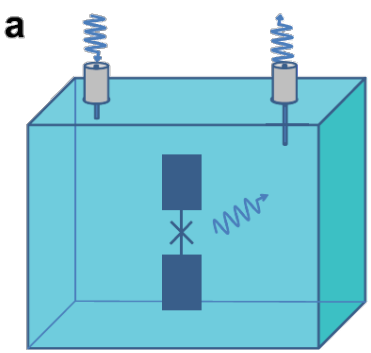
The 3D – Transmon Qubit

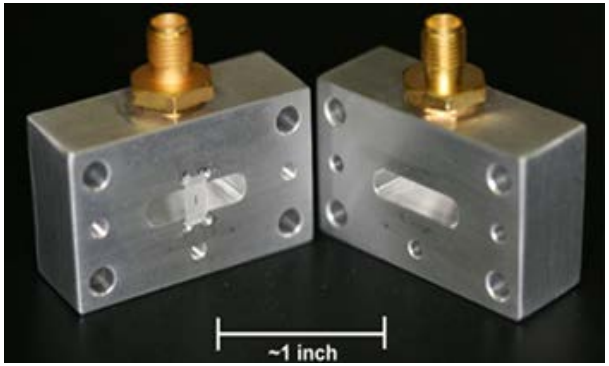


$$\hat{H} = E_C(\hat{N} - N_g)^2 - E_J \cos\hat{\varphi}$$



- no inductance ➡ minimized flux noise
- large capacitance ➡ avoids charge noise
- low field intensities ➡ no excitation of defects
- avoids dielectrics ➡ low energy dissipation





T_1 = 70 µs
T_2* = 95 µs

Pictures: R. Schoelkopf, Yale / IBM
Ch. Rigetti et al., arXiv: 1202.5533 (2012)

H. Paik et al., PRL 107, 240501 (2011)

Transmon basics:
J. Koch et al., Phys. Rev. A **76**, 042319 (2007)

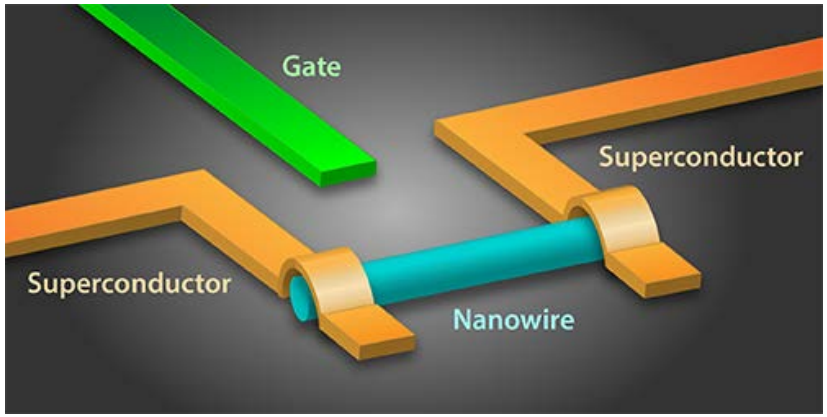
New development: gatemons

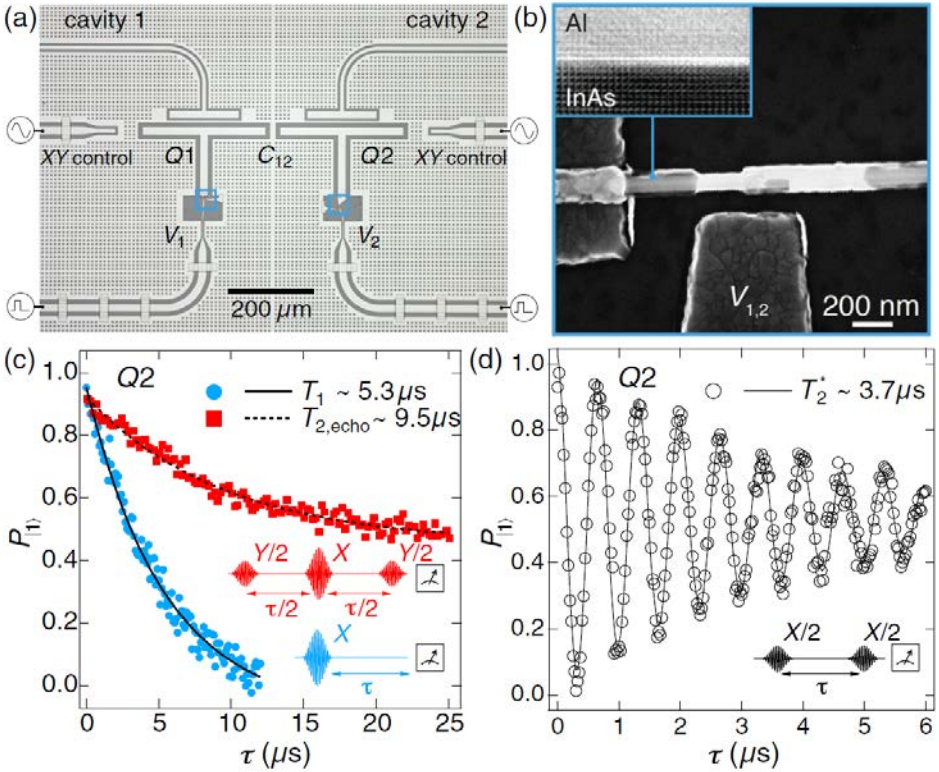
PRL **116,** 150505 (2016) PHYSICAL REVIEW LETTERS week ending 15 APRIL 2016

Gatemon Benchmarking and Two-Qubit Operations

L. Casparis,[1] T. W. Larsen,[1] M. S. Olsen,[1] F. Kuemmeth,[1] P. Krogstrup,[1] J. Nygård,[1,2]
K. D. Petersson,[1] and C. M. Marcus[1]

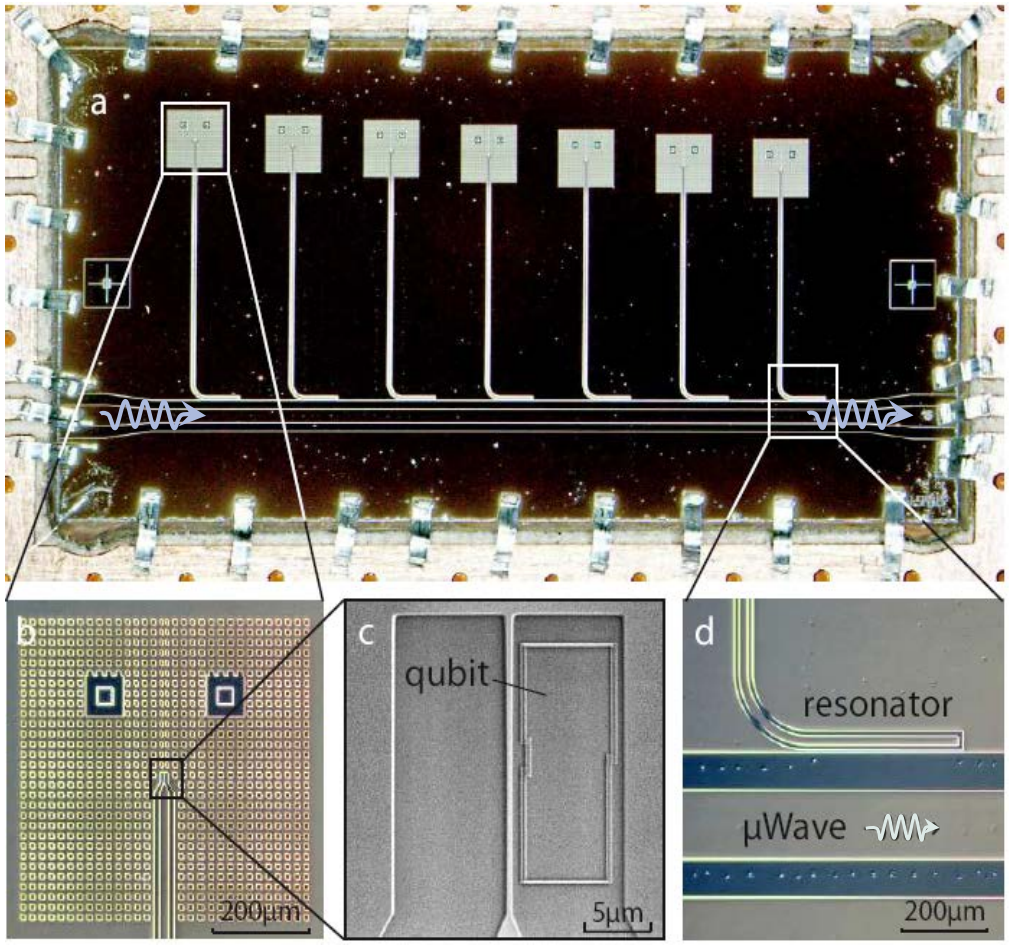
- „gatemon“ – transmon-like qubit tunable by dc voltage gate

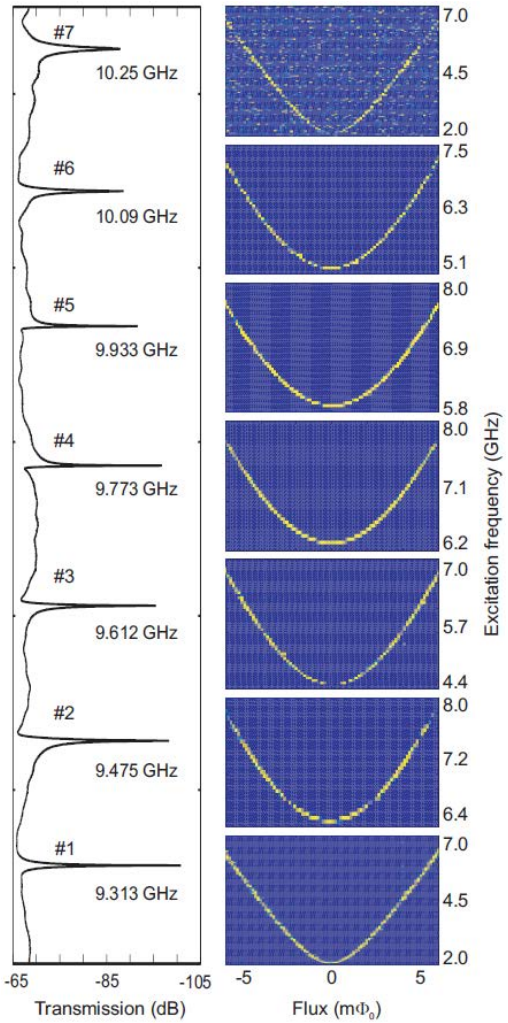




- single-qubit fidelity 99.3%
- two-qubit fidelity 91%

Multiplexed Readout of Superconducting Qubits

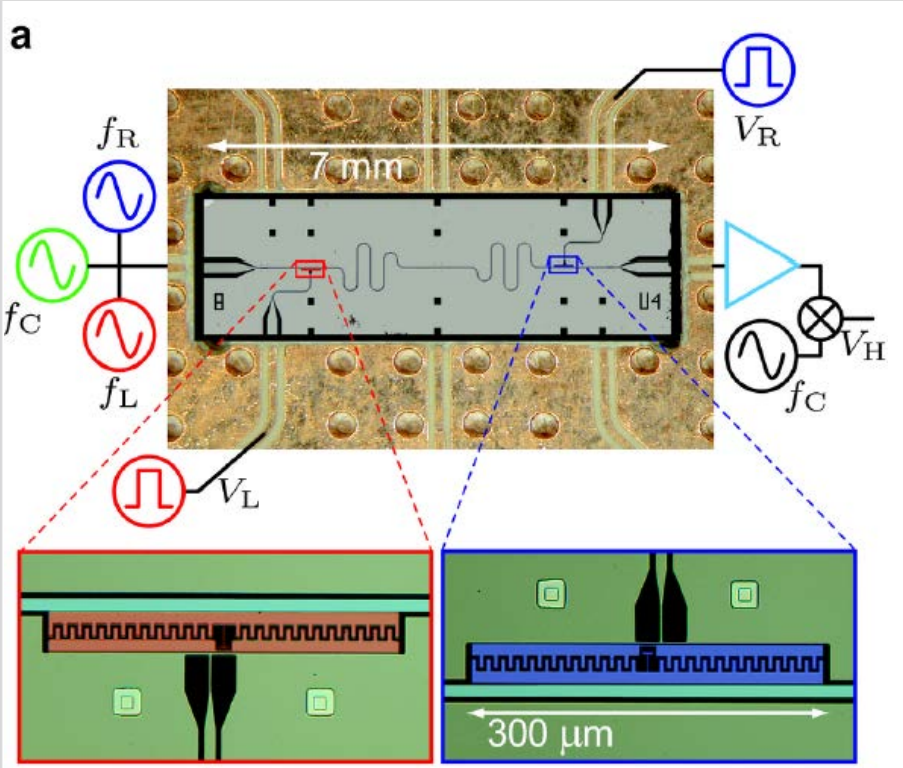


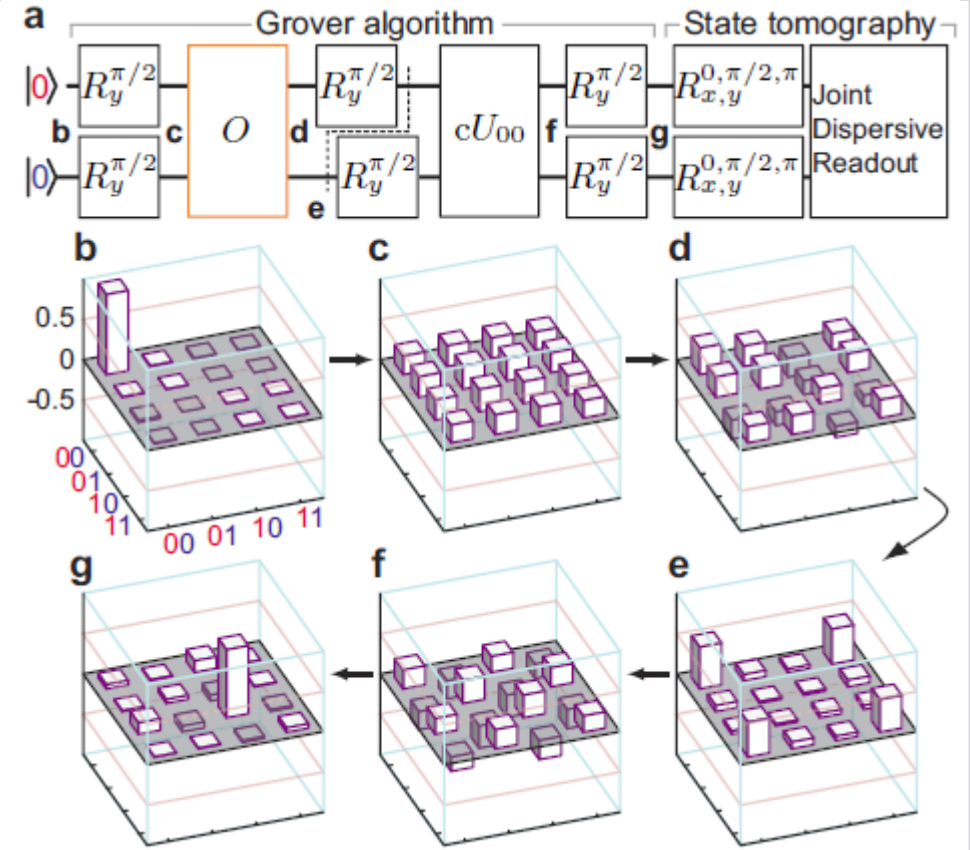


M. Jerger et al., *Europhys. Lett.* **96**, 40012 (2011)
M. Jerger et al., *Appl. Phys. Lett.* **101**, 042604 (2012)

Demonstration of 2-Qubit Algorithms

L. DiCarlo et al., Nature 460, 240 (2009)



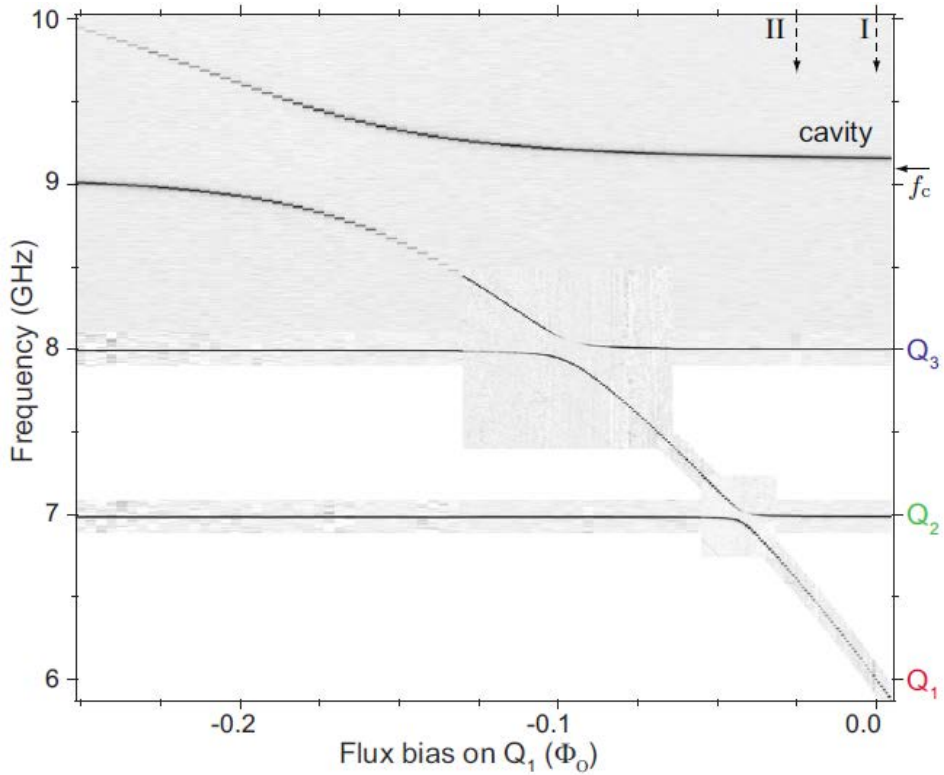


- the Grover algorithm for searching an unsorted database is demonstrated with a fidelity of 85 %.
  (b) starting state (00)
  (c) equal superposition of all 4 states
  (d) rotation of the phase of the searched state (10)
  (g) maximal amplitude of the searched state.

3 coupled Transmon Qubits

L. DiCarlo et al., Nature 467, 574 (2010)

- Spectroscopy:

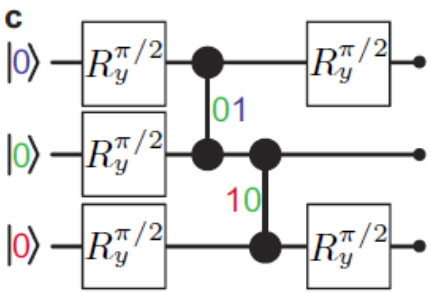


fidelity of GHZ preparation : **88%**

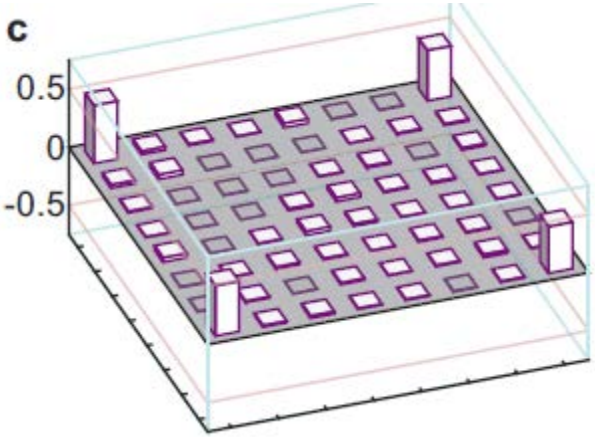
- demonstration of **GHZ** (Greenberger, Horne, and Zeilinger) state of 3 entangled qubits:

$$\Psi_{\mathrm{GHZ}} = \frac{1}{\sqrt{2}}\left(|000\rangle + |111\rangle\right)$$

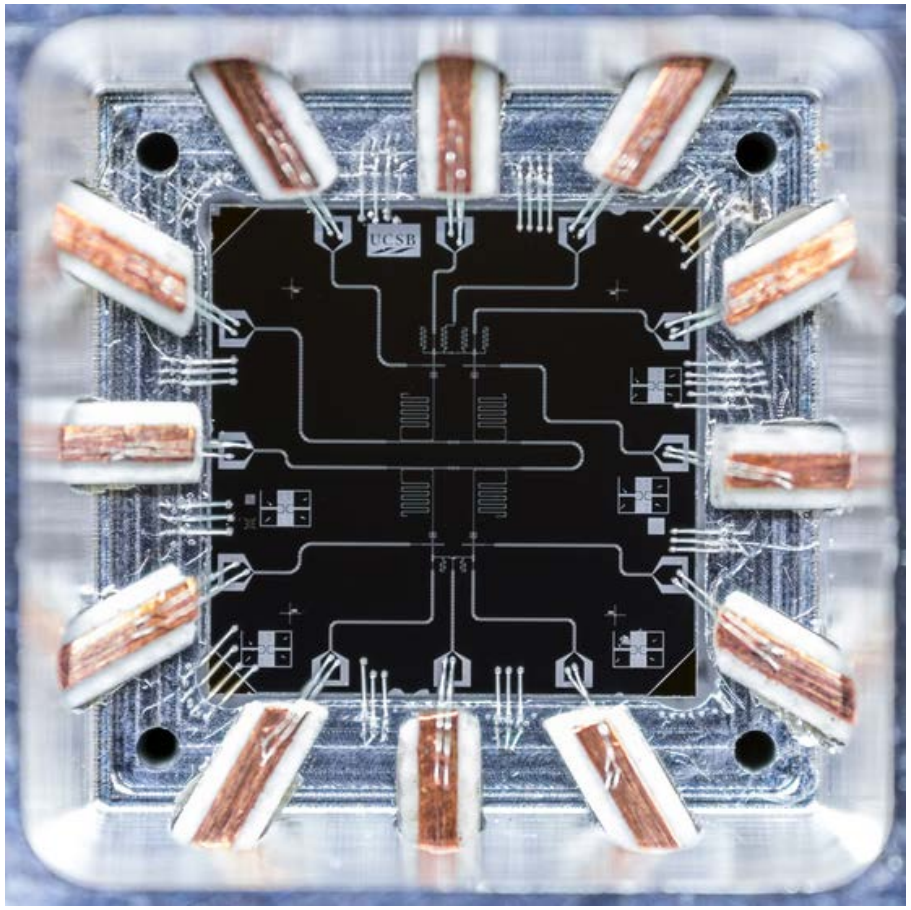
algorithm for preparation of GHZ:

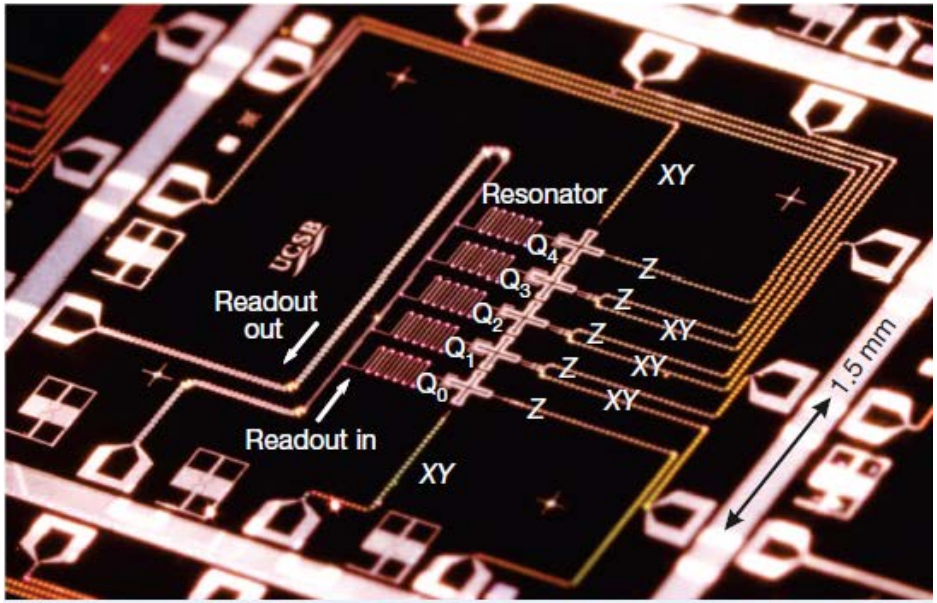


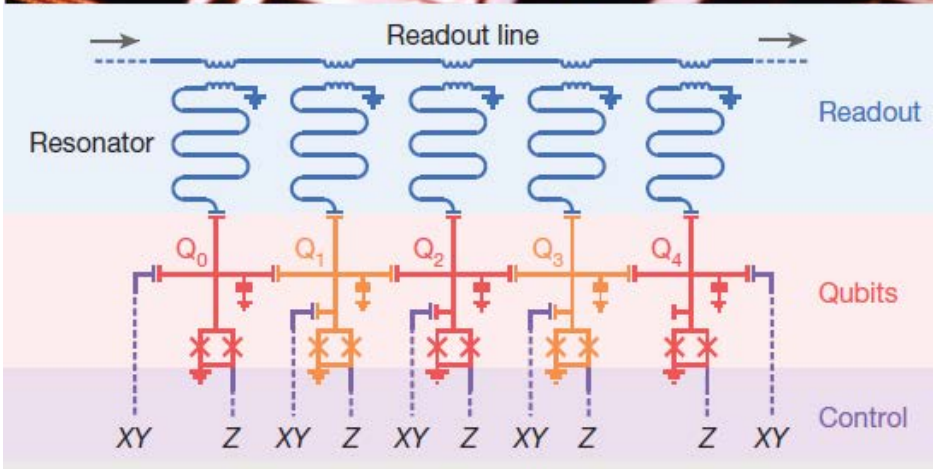
result: density matrix



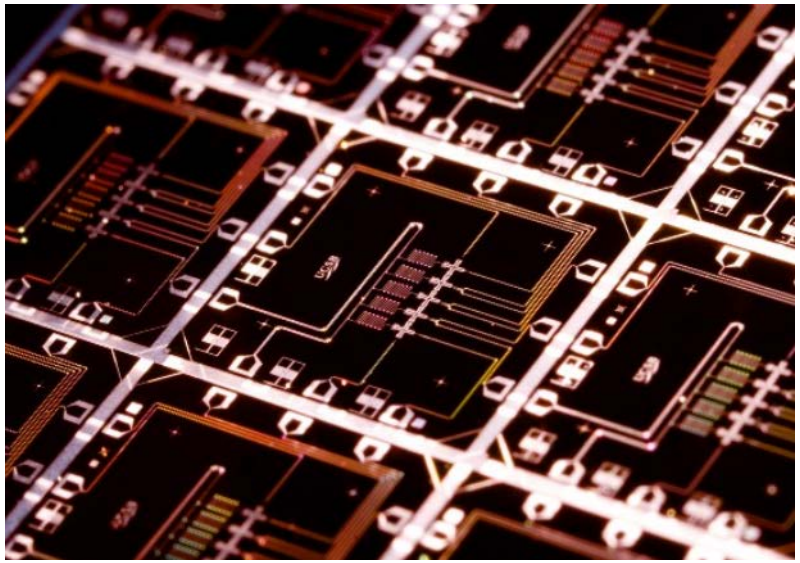
2014: Reaching the surface code threshold for fault tolerance of > 99.4% fidelity



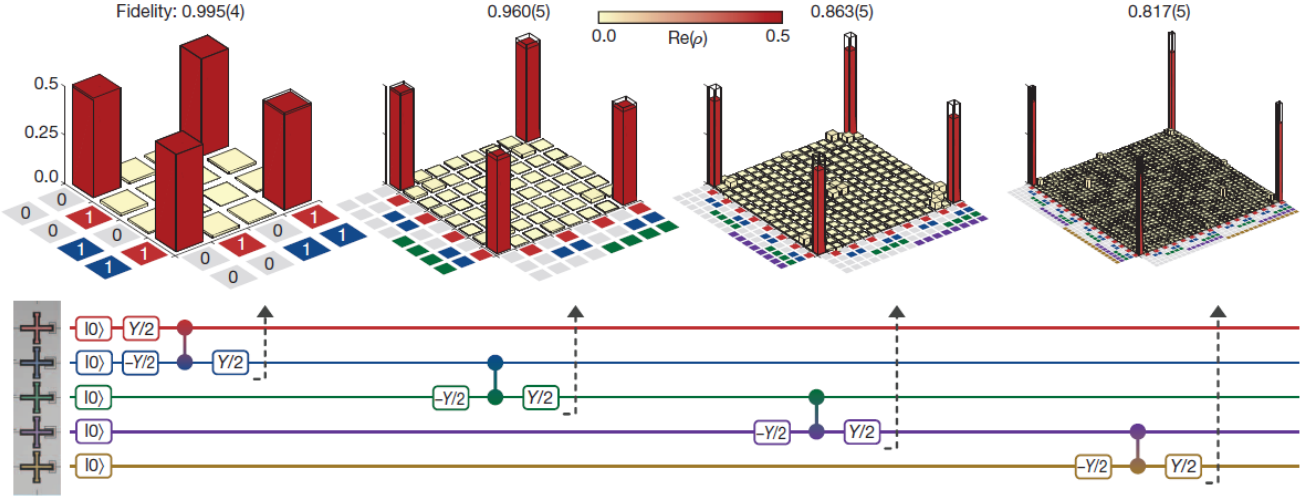




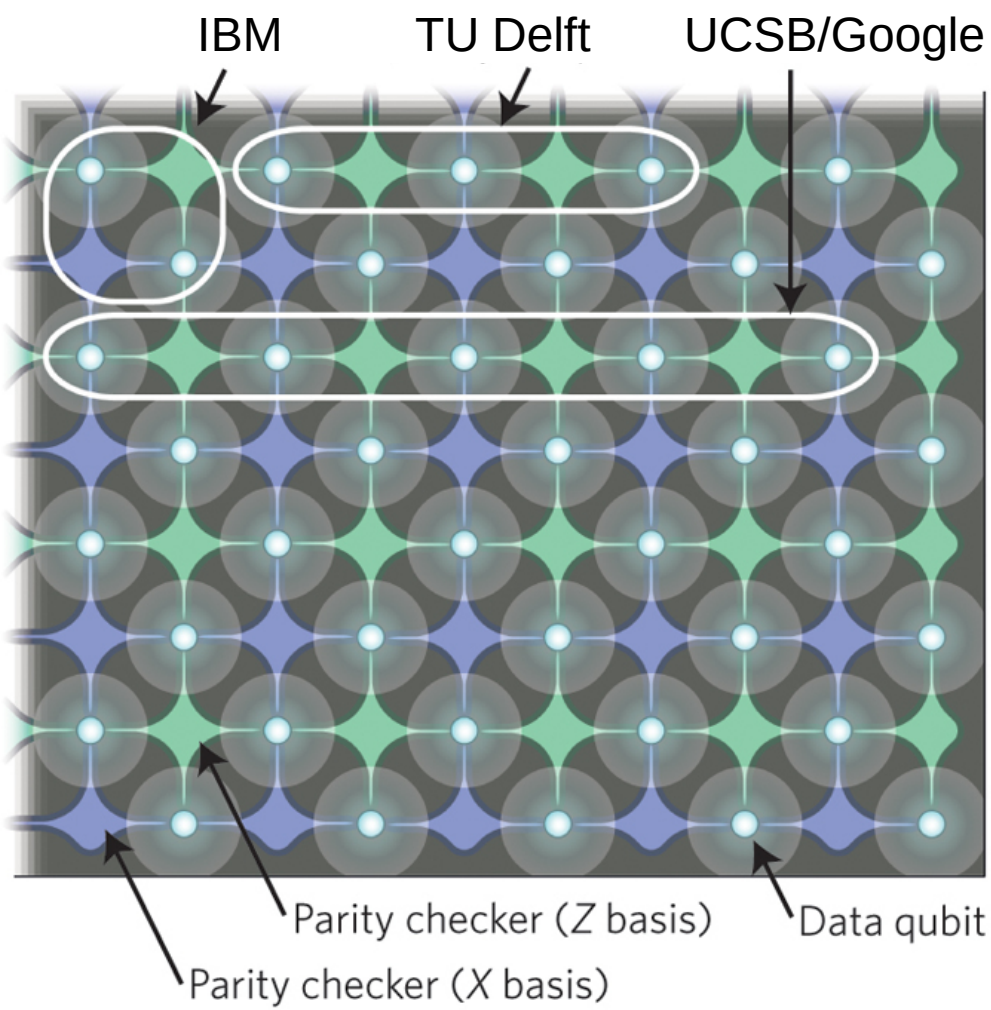
John Martinis' UCSB team hired by Google



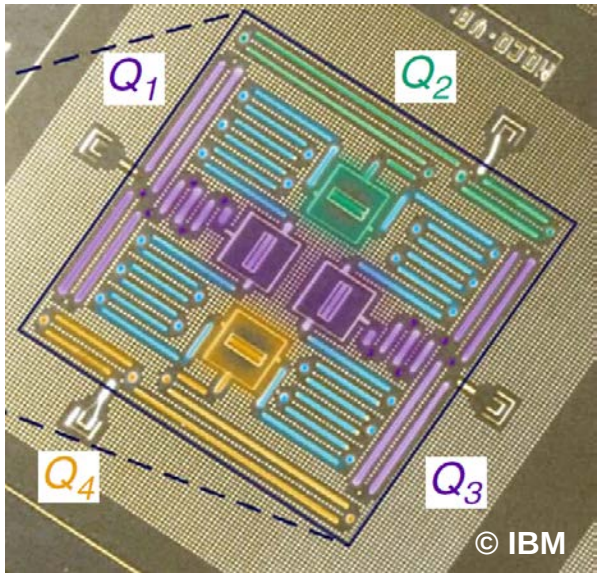
September 2014



Kitaev‘s surface code implementation

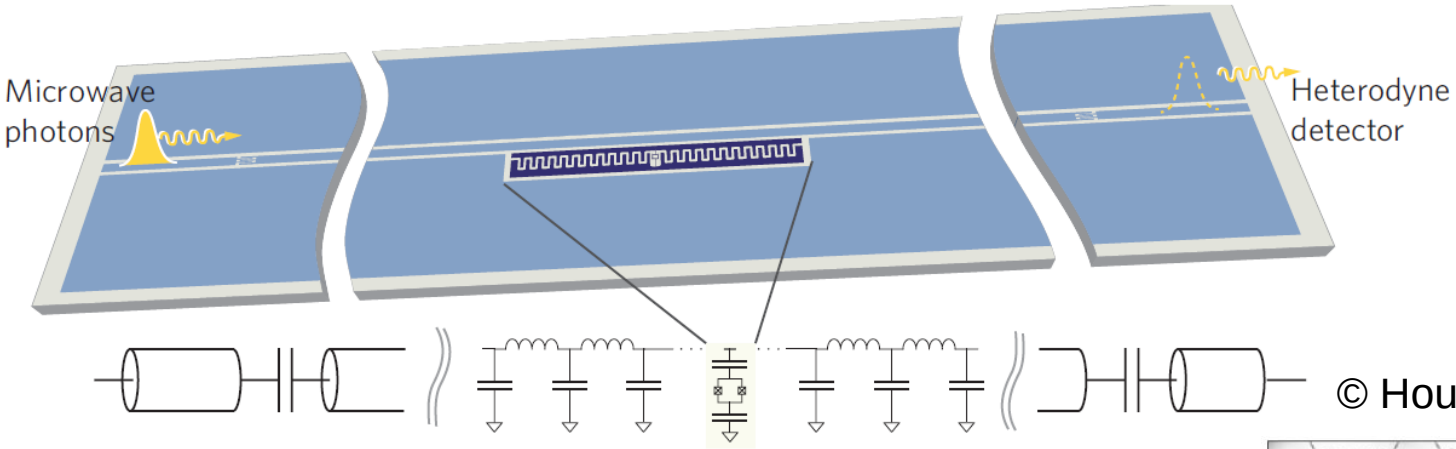


In 2015 three teams have demonstrated the basic parts of the Kitaev‘s surface code

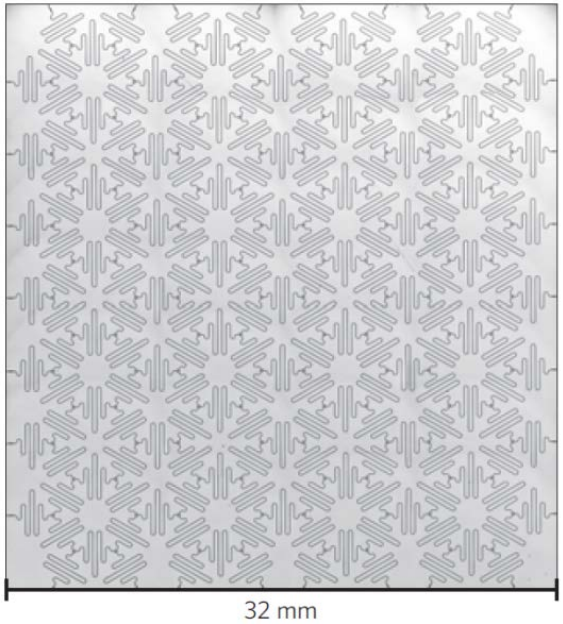


S. Benjamin and J. Kelly, *Nature Materials* **14**, 561 (2015)

Quantum simulators



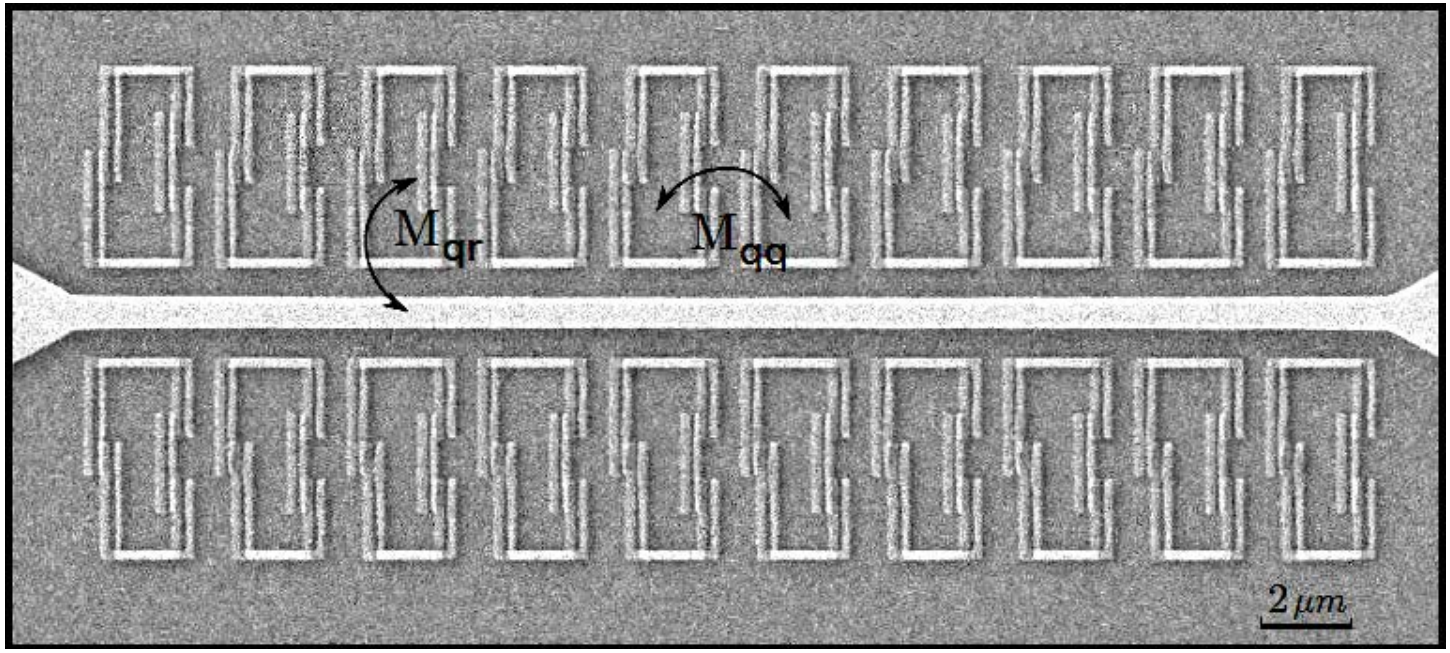
© Houck lab, Princenton



Main idea: Measure the result of interaction of a superconducting qubit with an environment composed of an array of spectrally tailored microwave resonators

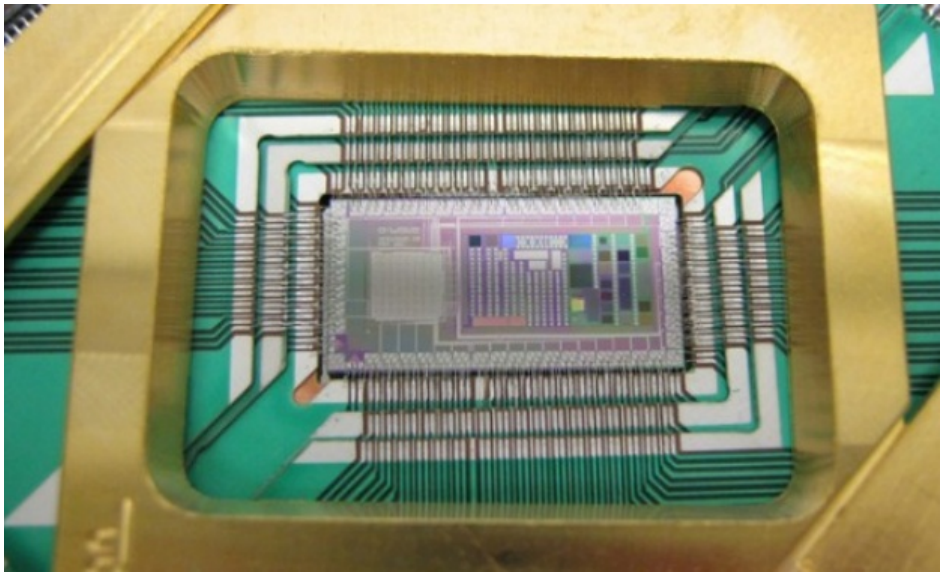
Superconducting quantum metamaterial: the simplest quantum simulator

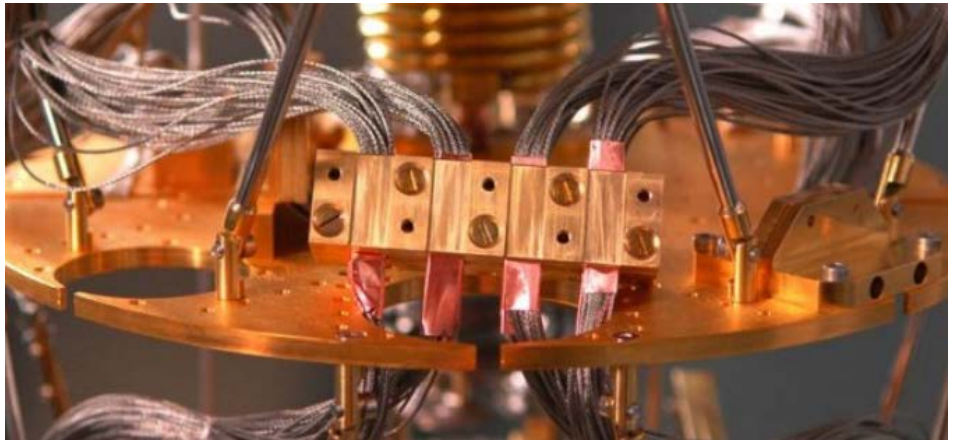
20 flux qubits



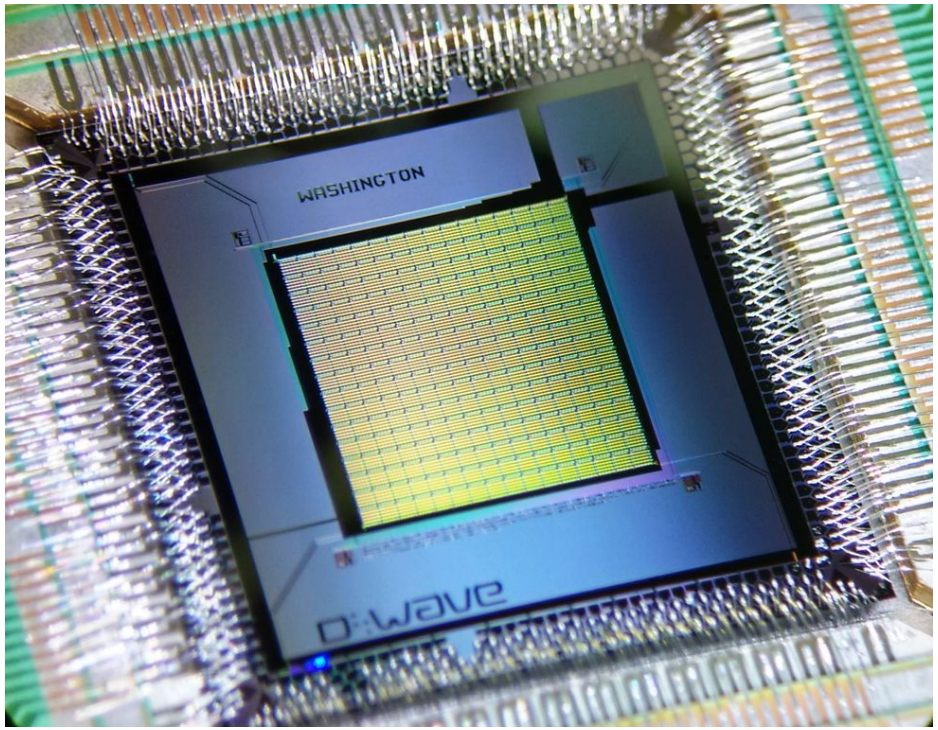
P. Macha, G. Oelsner, J.-M. Reiner, M. Marthaler, S. André, G. Schön, U. Huebner, H.-G. Meyer, E. Il'ichev, and A. V. Ustinov, *Nature Commun.* **5**, 5146 (2014)

D-Wave quantum computer: adiabatic quantum annealer-simulator





D-Wave Quantum Computer controversy



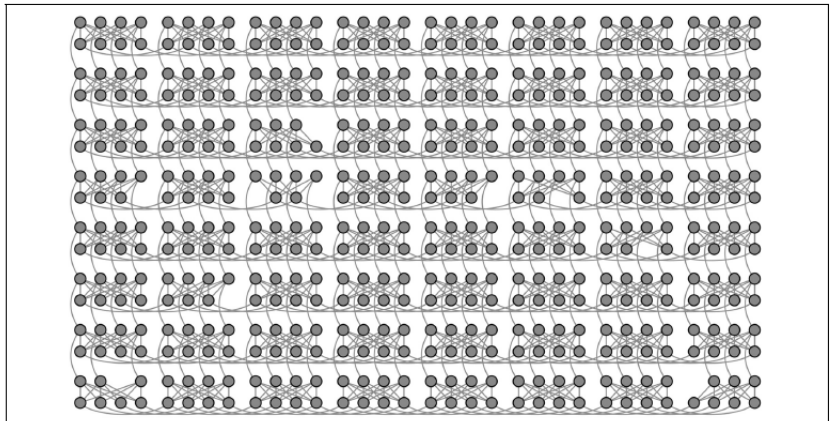


FIGURE 1 | D-Wave's recent generation Chimera connectivity graph $\mathcal{G}$. Vertices indicate spin-valued variables represented by programmable qubits (h_i's), and edges indicate programmable couplers ($J_{i,j}$'s). $\mathcal{G}$ is a lattice of $K_{4,4}$ unit cells where missing qubits are the result of fabrication defects.

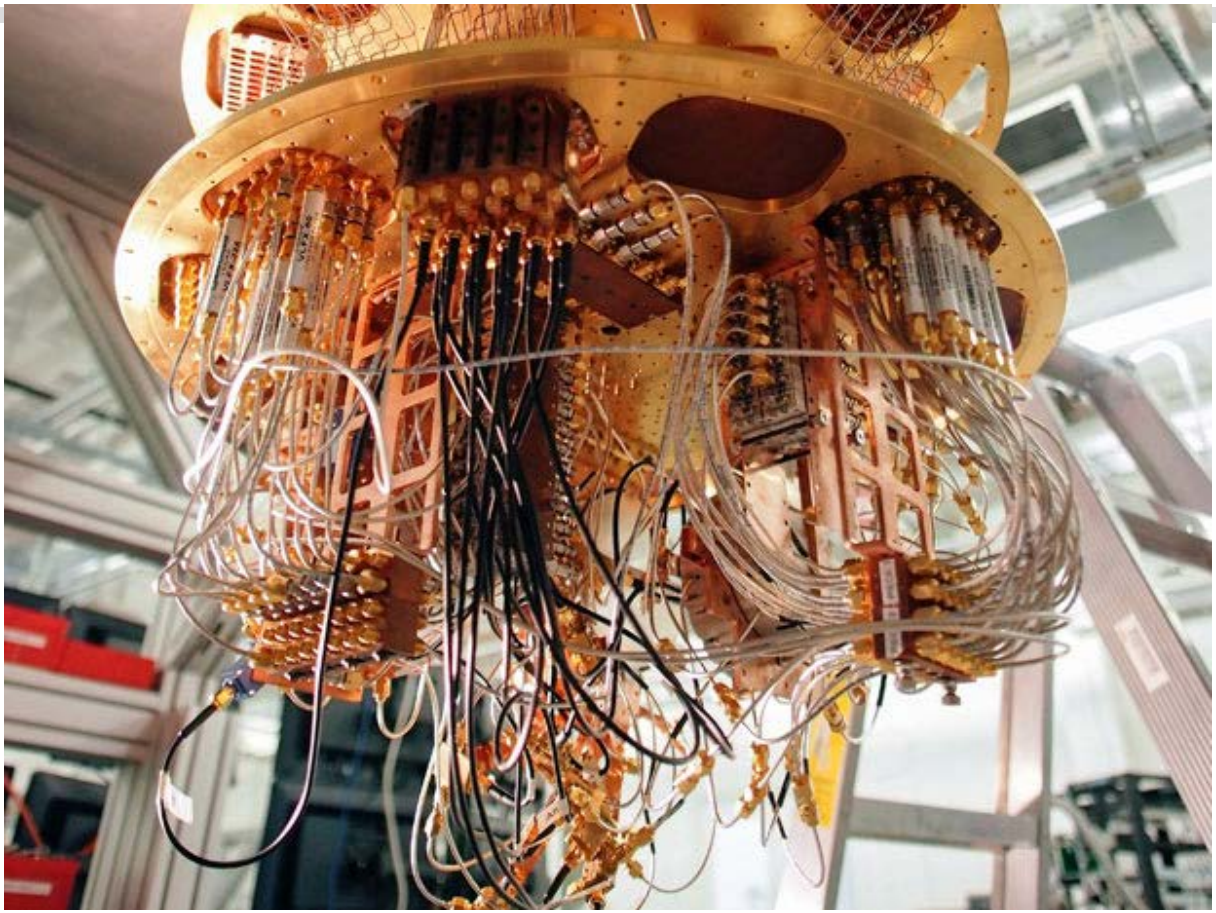
D-Wave
The Quantum Computing Company™

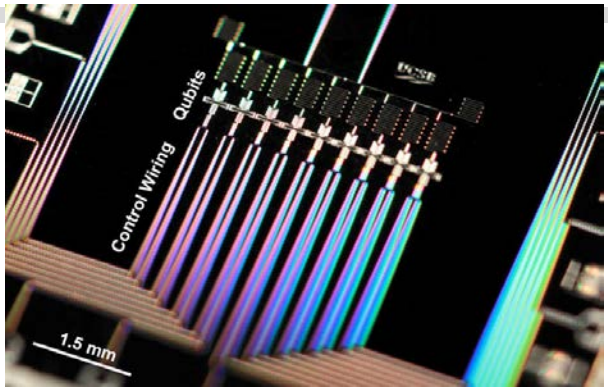
- **Washington world-largest QC: 1152 qubits, 933 operational**
- **Quantum operation confirmed for 8-qubit register**
- **Consistent with either quantum or classical operation**

State of the art for superconducting qubits

- Superconducting qubits are currently the most advanced technology for building scalable quantum circuits
- Gates and simple algorithms have been reported with up to 19 qubits (charge, flux, phase, and transmon qubits)
- Quantum gates take time 10-50 ns
- Coherence times T_1, T_2 are currently in the range 10-50 μs (2D) and up to several 100 μs (3D)
- D-Wave is marketing superconducting quantum annealer (simulator)
- Google, IBM, Microsoft enter the race towards building a scalable quantum computer

КВАНТОВЫЙ ПРОЦЕССОР GOOGLE





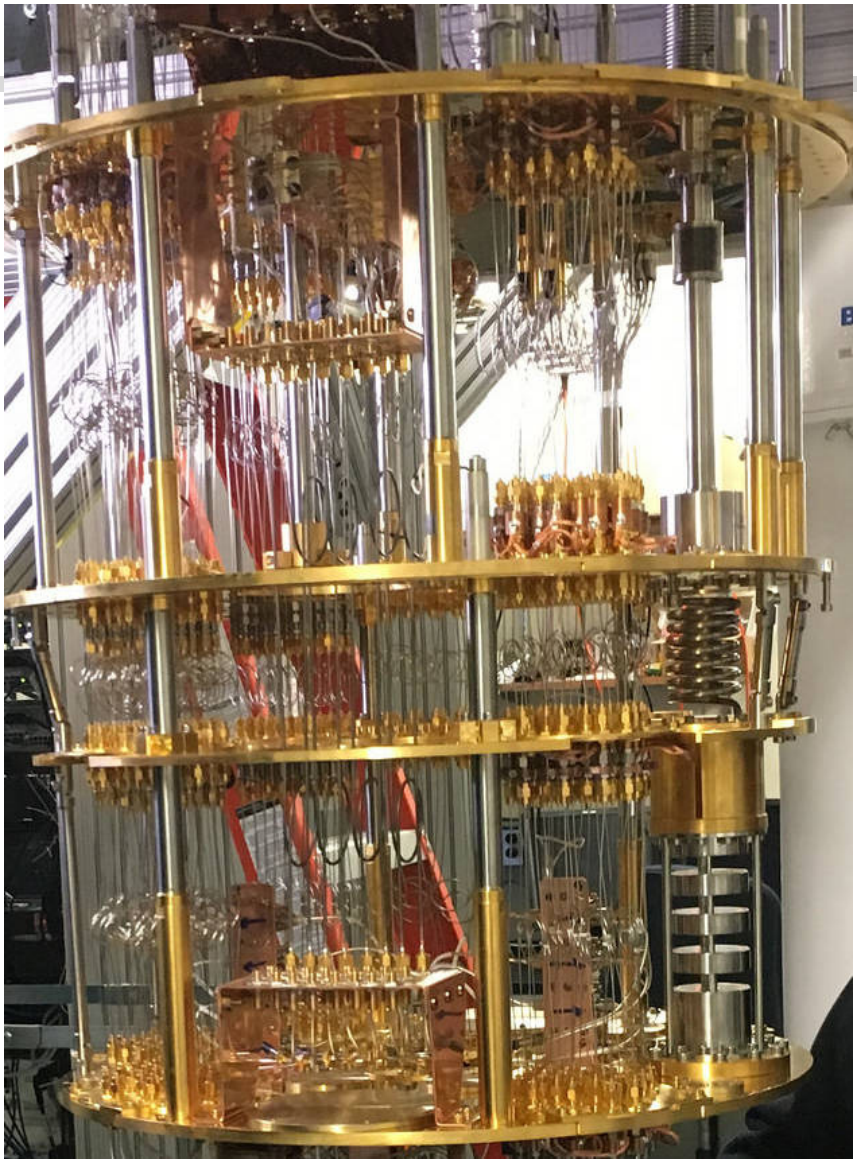
9 кубитов
Google
(2015)

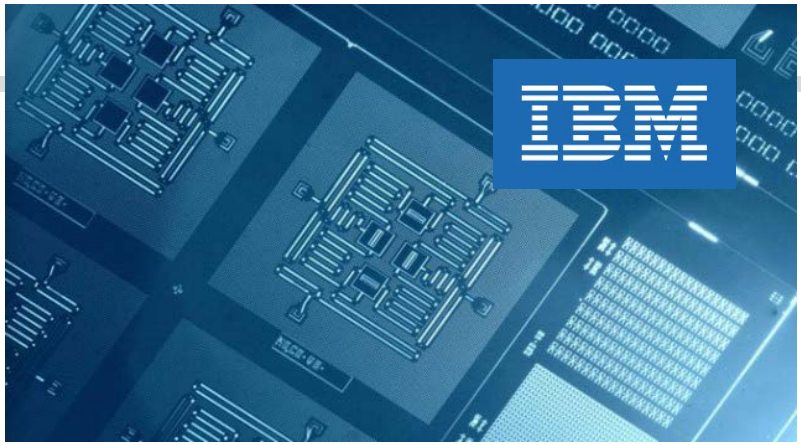
Google

John
Martinis

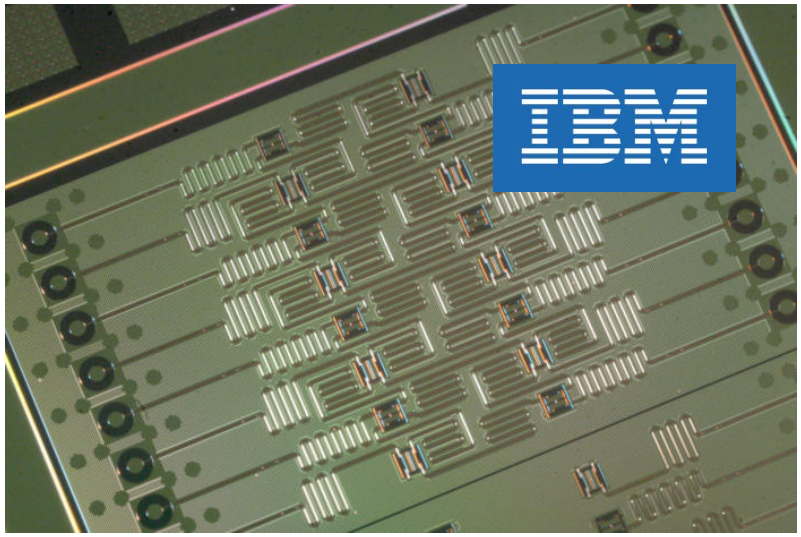
Google планировал к концу 2017 года продемонстрировать квантовый процессор на 49 кубитах. Цель - продемонстрировать „quantum supremacy".

КВАНТОВЫЙ ПРОЦЕССОР IBM





5-кубитый процессор IBM (2015)



16-кубитый процессор IBM (2017)

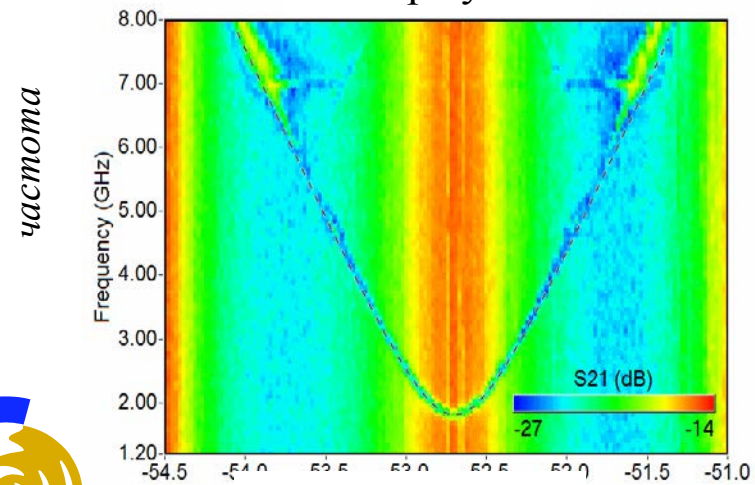
СВЕРХПРОВОДЯЩИЕ КУБИТЫ В РОССИИ

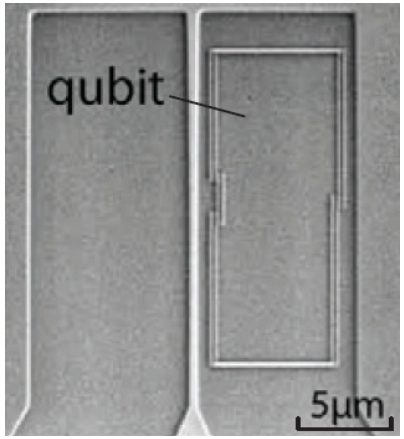
Начало: 2013-2015 гг.

июль 2013 г.
Первый кубит, измеренный в России, МИСиС и РКЦ

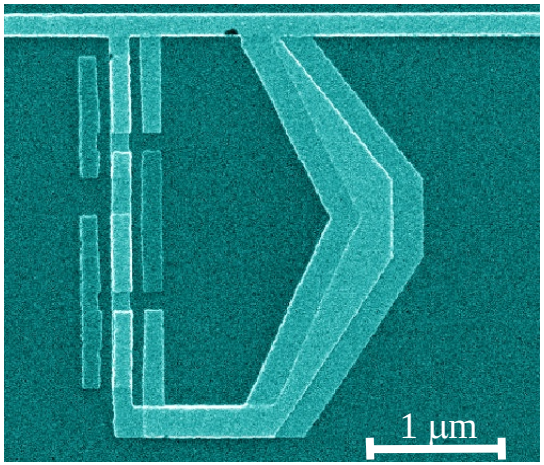
кубит изготовлен в Германии

спектр кубита





МИСиС

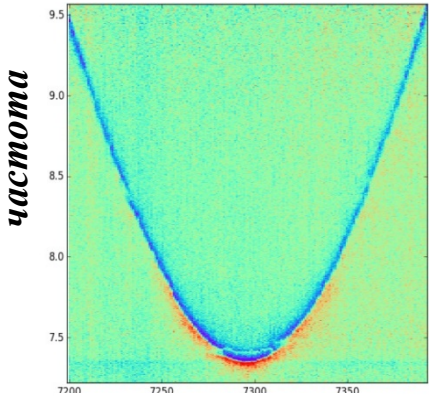


МФТИ

ИФТТ РАН
ISSP RAS

май 2015 г.
первый кубит, изготовленный в России

RQC
Russian Quantum Center



Практические задачи для квантовых компьютеров

Универсальные квантовые компьютеры

факторизация (алгоритм Шора)
поиск в базе данных (алгоритм Гровера и др.)
квантовая химия
расчет новых материалов
...

Адиабатические компьютеры, устройства квантового отжига

задачи оптимизации
машинное обучение (combinatorial optimization problems)
искусственный интеллект
...

Аналоговые квантовые компьютеры (симуляторы)

моделирование квантовых систем
фотосинтез и лекарства
квантовый "Лего“
...