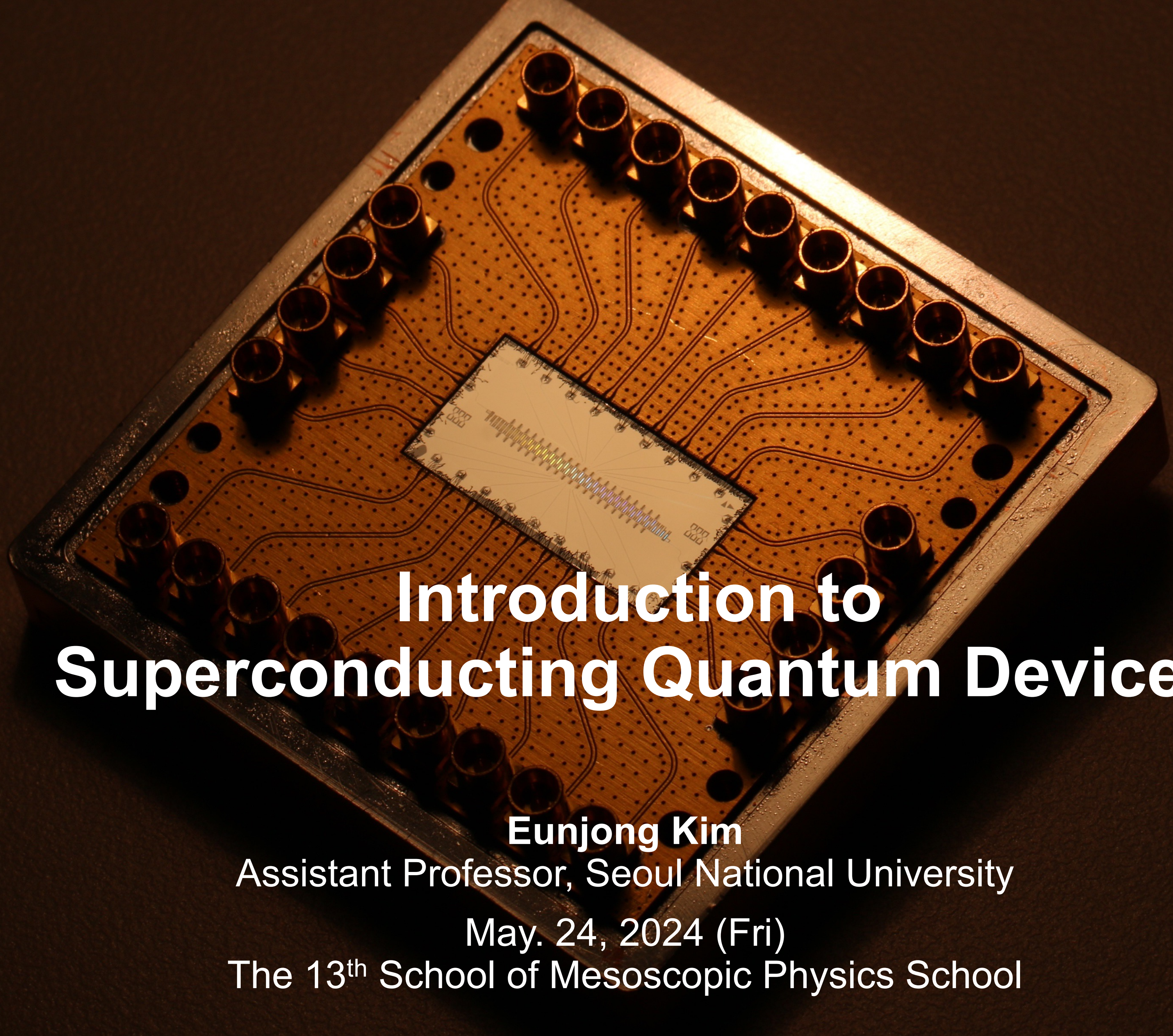
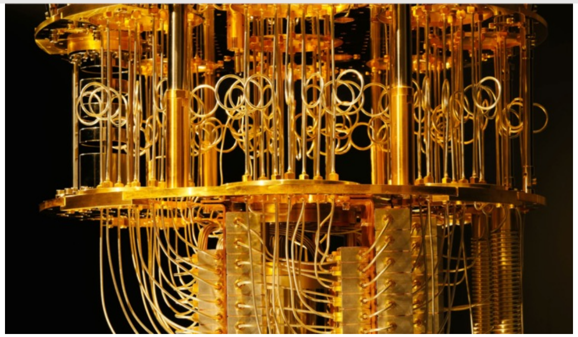


Introduction to Superconducting Quantum Devices

Eunjong Kim
Assistant Professor, Seoul National University

May. 24, 2024 (Fri)
The 13th School of Mesoscopic Physics School

Useful References



- P. Krantz et al., "*A quantum engineer's guide to superconducting qubits*," Appl. Phys. Rev. **6**, 021318 (2019)
- A. Blais et al., "*Circuit quantum electrodynamics*," Rev. Mod. Phys. **93**, 025005 (2021)
- S. E. Rasmussen et al., "*Superconducting Circuit Companion—an Introduction with Worked Examples*," PRX Quantum **2**, 042204 (2021).
- S. Girvin, "*Circuit QED: superconducting qubits coupled to microwave photons*," Lecture Notes from Les Houches Summer School in Theoretical Physics, Session XCVI (2011).

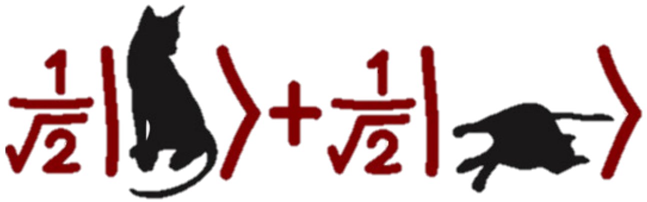
Also, you can ask questions at any time

eunjongkim (at) snu.ac.kr

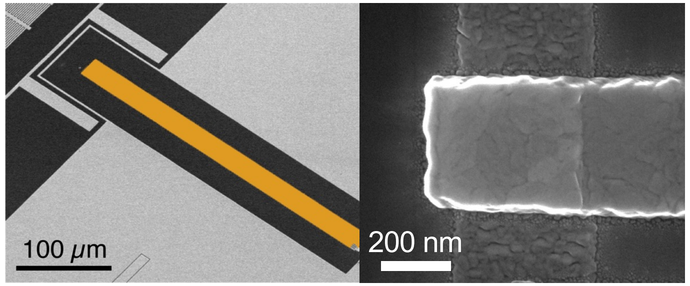
Lab Info

Content

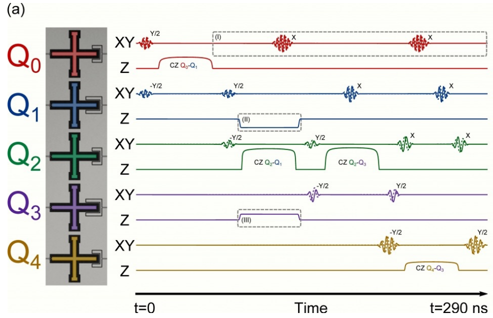
Motivation: Quantum Computation



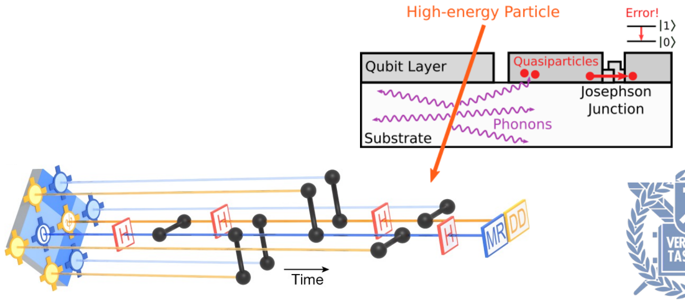
Superconducting Qubits & Circuit QED



Control & Readout of Superconducting Qubits

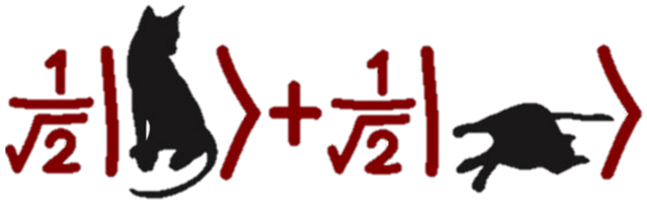


Challenges, Current Research Topics



Content

Motivation: Quantum Computation



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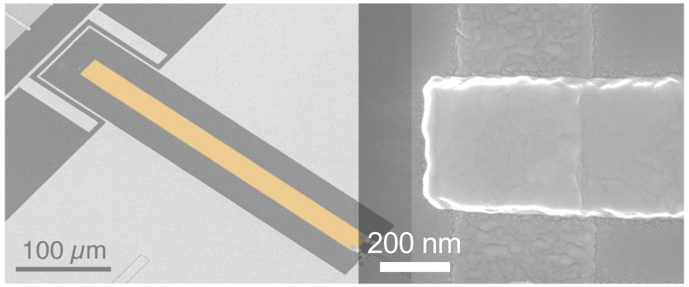

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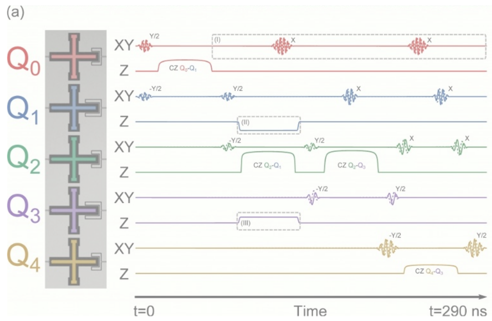
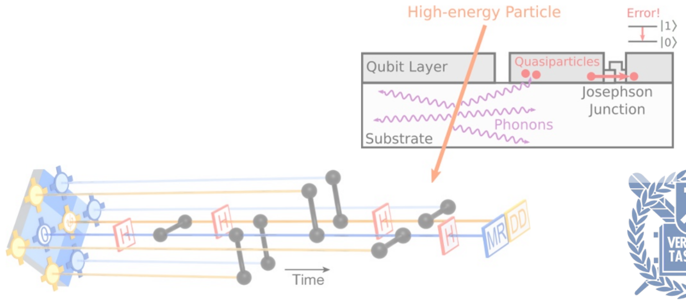
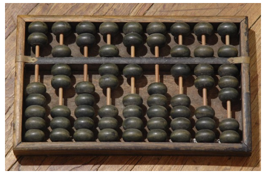


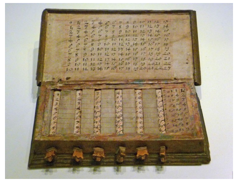
Challenges, Current Research Topics

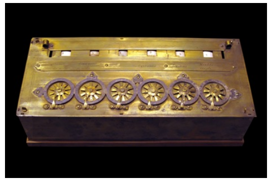


The History of Computing Hardware

Analog Calculators


Abacus (3000 BC)


Napier's Bones (1617)


Pascaline (1642)

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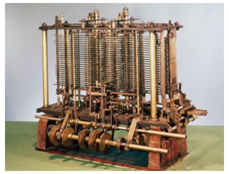
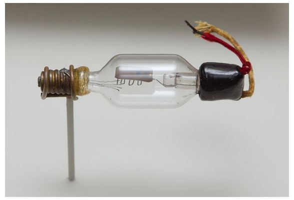
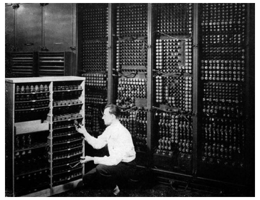
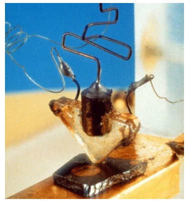

Analytical Engine (1833)

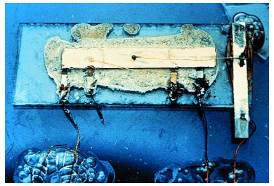
Digital Electronic Computer

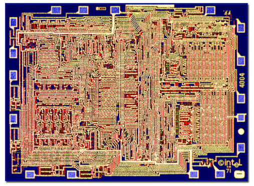

Vacuum Tube (1906)

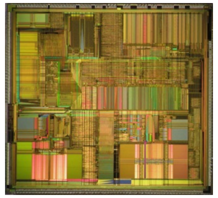

ENIAC (1946)

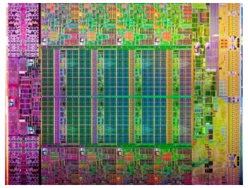

Transistor (1947)


TX-0 (1956)

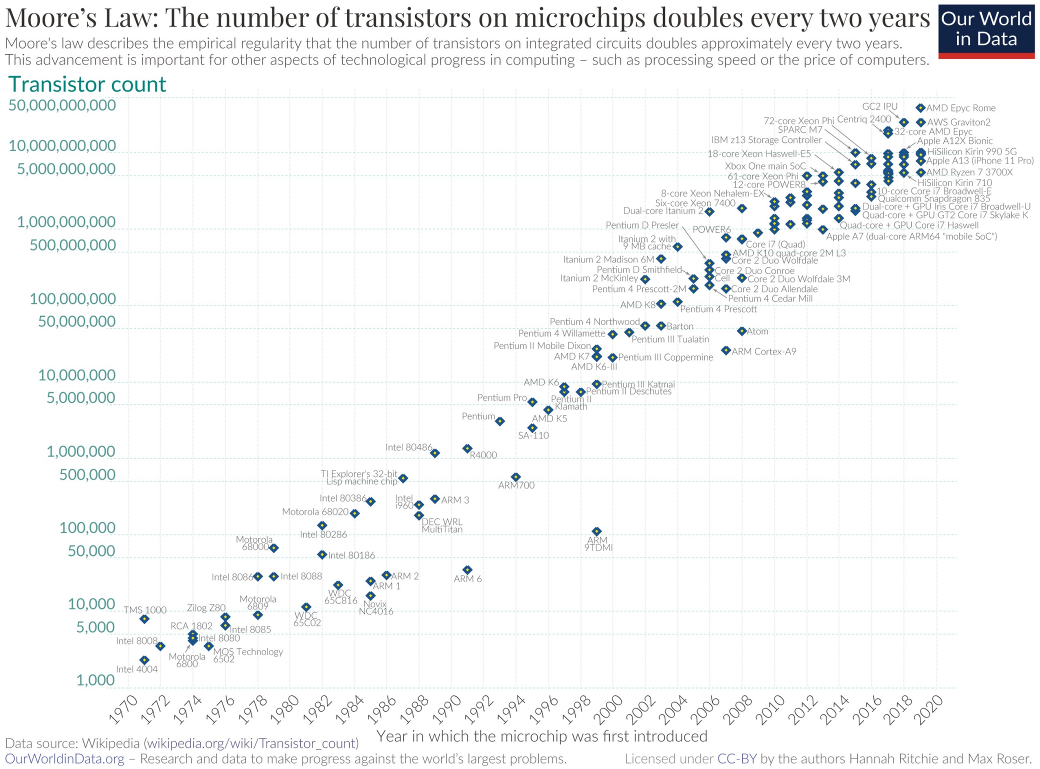

Integrated Circuit (1958)


2K transistors i4004 (1971)


5.5M transistors Pentium Pro (1995)


18 cores 5.5B transistors Xeon Haswell (2014)

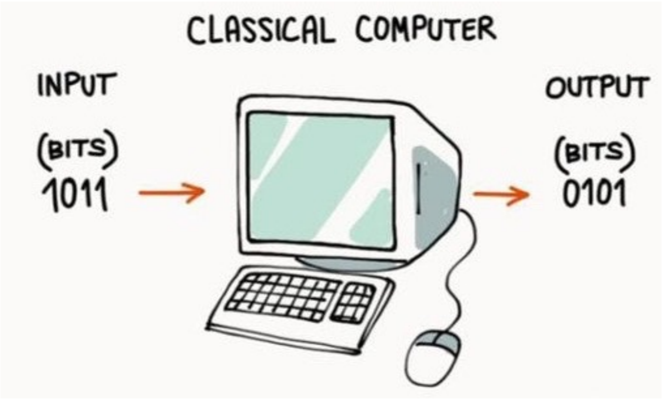
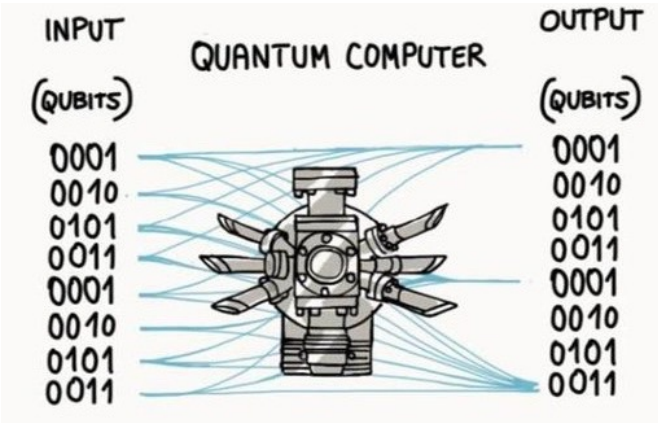
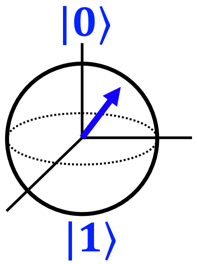
. . .



new computing device: advancement of society

What comes next?

Classical vs Quantum Computing

	Classical Computer	Quantum Computer
		
Fundamental Logic Element	"**Bit**" : classical bit (transistor, spin in magnetic memory, …)	"**Qubit**" : quantum bit (coherent two-level system)
State	**0 "or" 1** 	 **$\|0\rangle$ "and" $\|1\rangle$**  **Quantum Superposition** $\|\psi\rangle = \alpha\|0\rangle + \beta\|1\rangle$
Measurement	• ***Discrete*** states • Deterministic measurement Ex: Set as 1, Measure as 1	• ***Superposition*** states • Probabilistic measurement Ex: If $\|\alpha\| = \|\beta\|$, 50% $\|0\rangle$, 50% $\|1\rangle$

Example: Prime Factorization

Prime Factorization: Given an integer *N*, find a set of prime numbers *p*, *q* that satisfy *N* = *p* * *q*

1807082088687
4048059516561
6440590556627
8102516769401
3491701270214
5005666254024
4048387341127
5908123033717
8188796656318
2013214880557

= ? × ?

Example: Prime Factorization

Prime Factorization: Given an integer *N*, find a set of prime numbers *p*, *q* that satisfy *N* = *p* * *q*

1807082088687 4048059516561 6440590556627 8102516769401 3491701270214 5005666254024 4048387341127 5908123033717 8188796656318 2013214880557	=	3968599945959 7454290161126 1628837860675 7644911281006 4832555157243	×	4553449864673 5972188403686 8972744088643 5630126320506 9600999044599

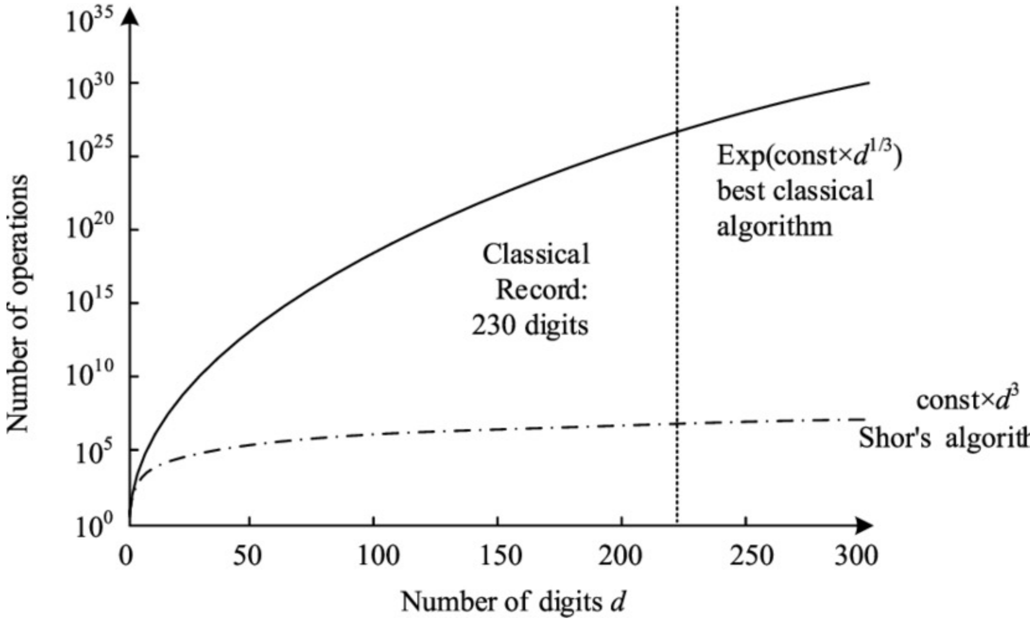
- Given *p* and *q*, it is very easy to calculate *N* = *p* * *q*. The reverse is very hard.
- Basis for many cryptographic protocols today

Classically Hard Can Be Quantum Easy

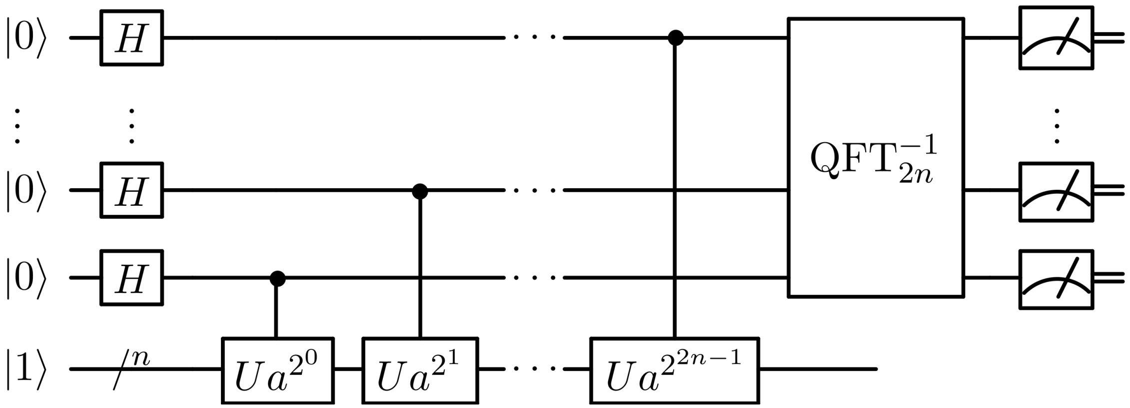
Prime Factorization: Given an integer *N*, find a set of prime numbers *p*, *q* that satisfy *N* = *p* * *q*

- Best known classical algorithm: classically hard
  Number Field Sieve $O\left(e^{1.9(\log N)^{1/3}(\log\log N)^{2/3}}\right)$

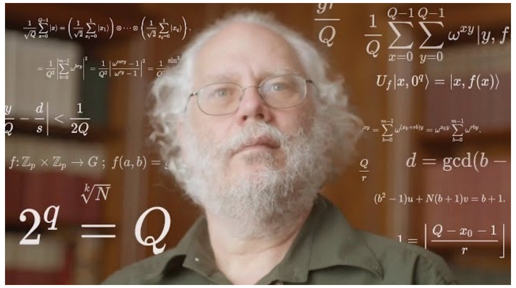
  (log N = # of bits)



- Quantum algorithm: quantum easy
  Shor's Algorithm $O\left((\log N)^2(\log\log N)(\log\log\log N)\right)$



The boundary between "hard" and "easy" seems to be different in a quantum world than in a classical world.

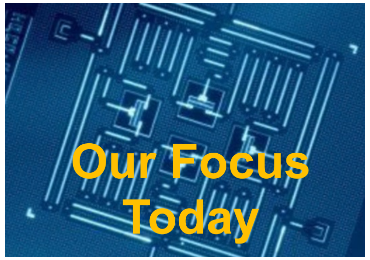


Peter Shor (MIT)

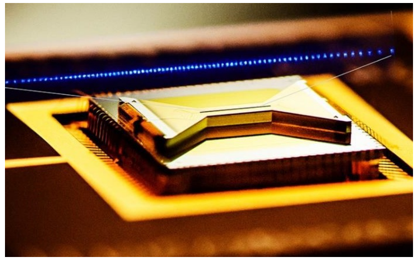
Quantum Information Science Today

Quantum Hardware

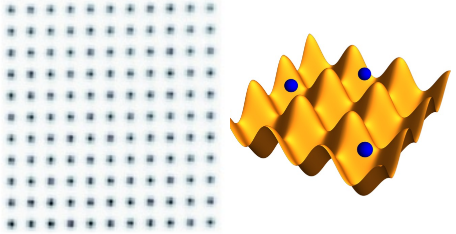
Superconducting qubits



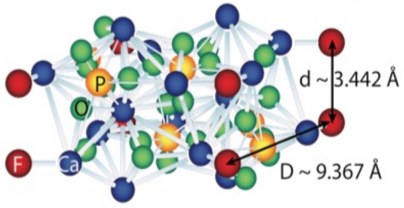
Trapped ions



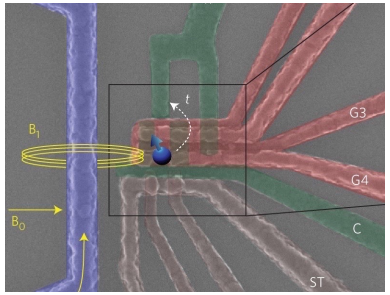
Neutral atoms



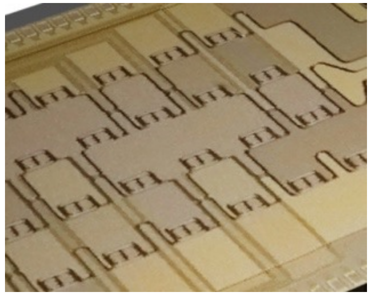
Solid-state spins



Quantum dots



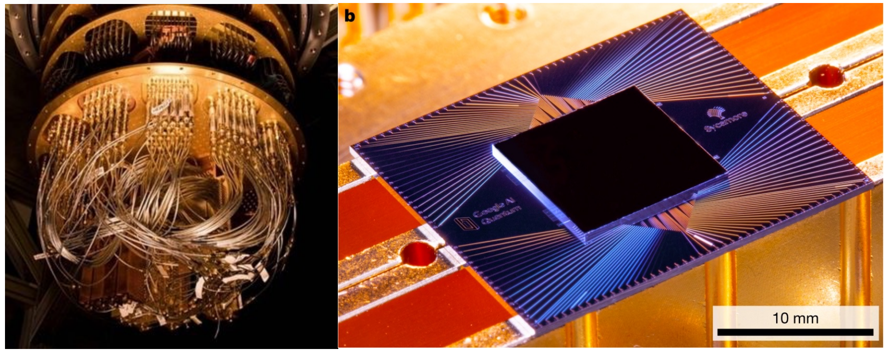
Photons



New Era of Quantum Information

Quantum Industry

IBM, Google AI, Microsoft, aws, Alibaba Group 阿里巴巴集团, IONQ, rigetti, D-Wave, XANADU, Silicon Quantum Computing, QuEra, PsiQuantum



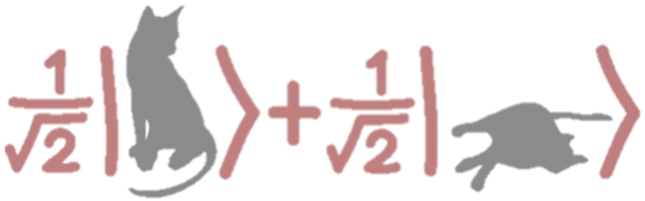
Google (2019)

USTC (2020)

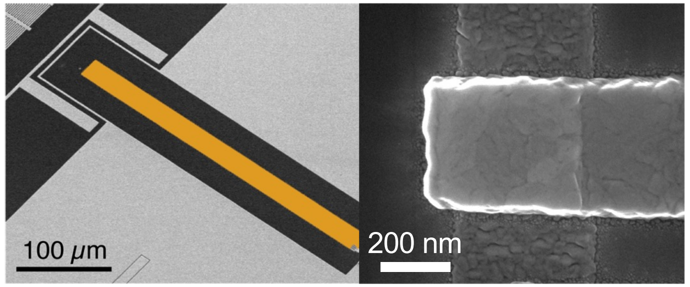
Quantum Advantage

Content

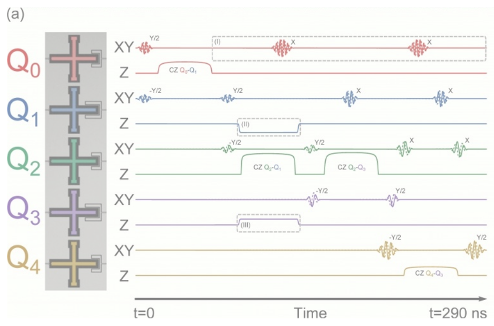
Motivation: Quantum Computation



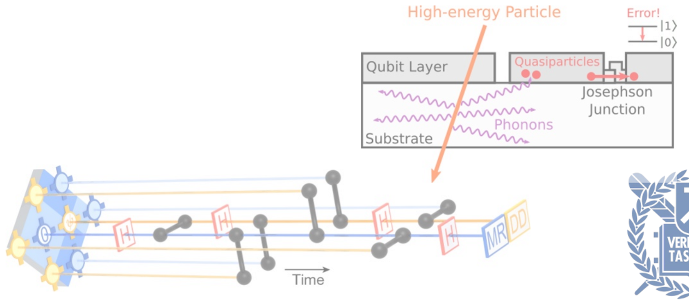
Superconducting Qubits & Circuit QED



Control & Readout of Superconducting Qubits



Challenges, Current Research Topics



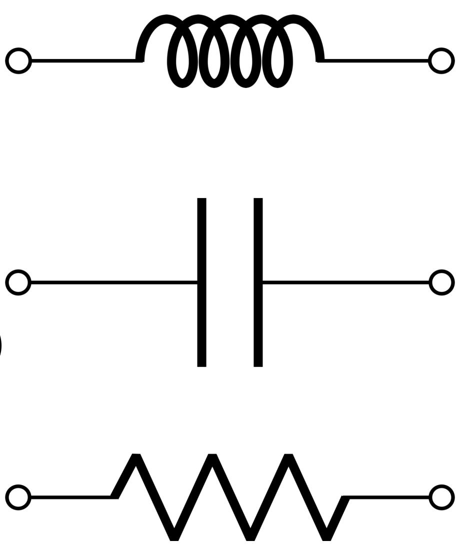
Classical vs Quantum Electrical Circuit

Classical Electrical Circuits

L
(inductor)

C
(Capacitor)

R
(Resistor)

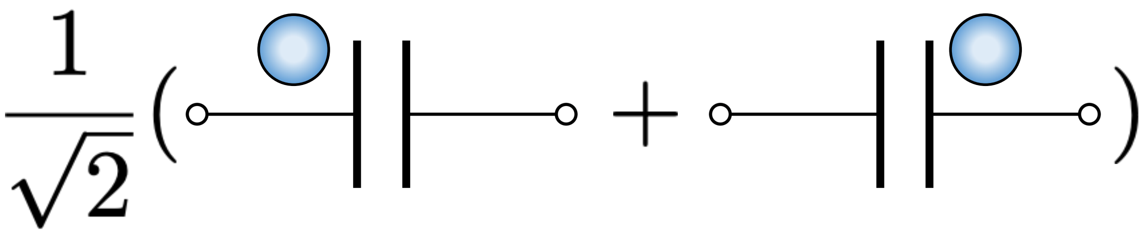


Basis of modern information and
communication technology

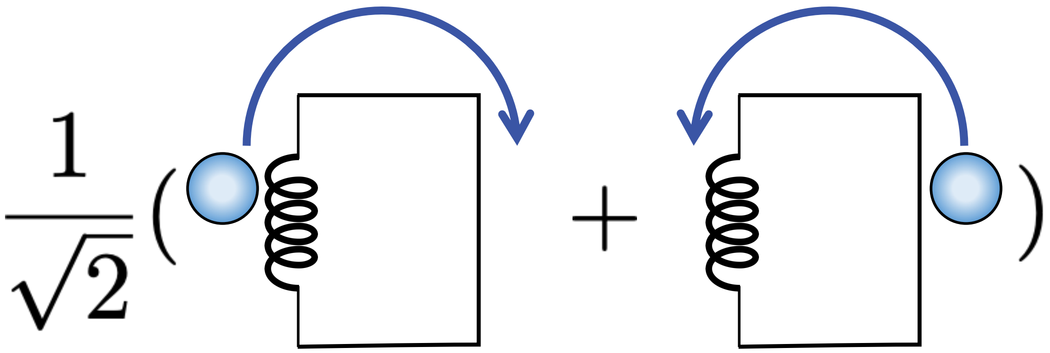
- classical physics
- no superposition principle
- no quantization of fields

Quantum Electrical Circuits

charge (Q) on a capacitor:



current or magnetic flux (Φ) in an inductor:



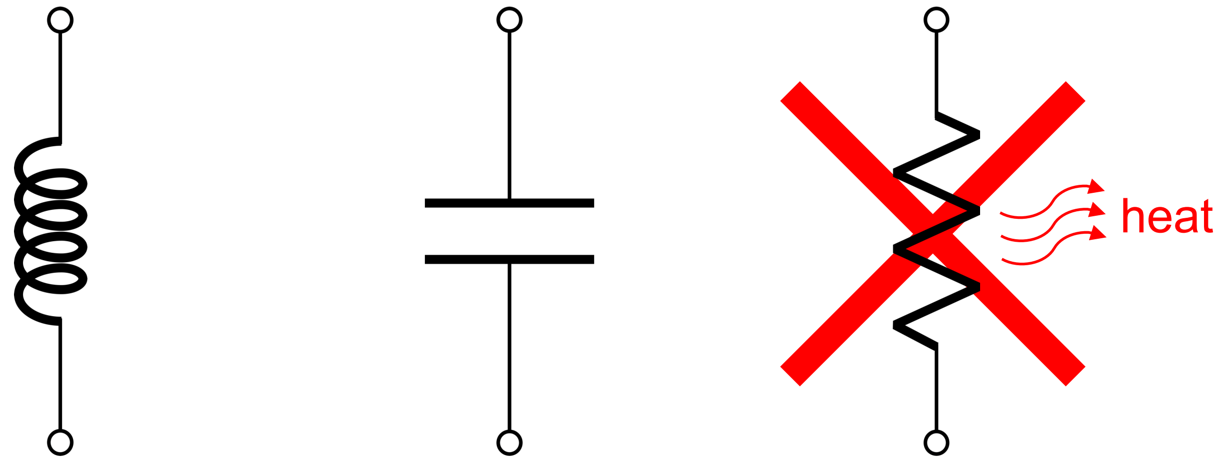
Superconducting Quantum Circuits

Can Electrical Circuits behave Quantum Mechanically ?

Requirement:
R = 0

Circuit Elements:

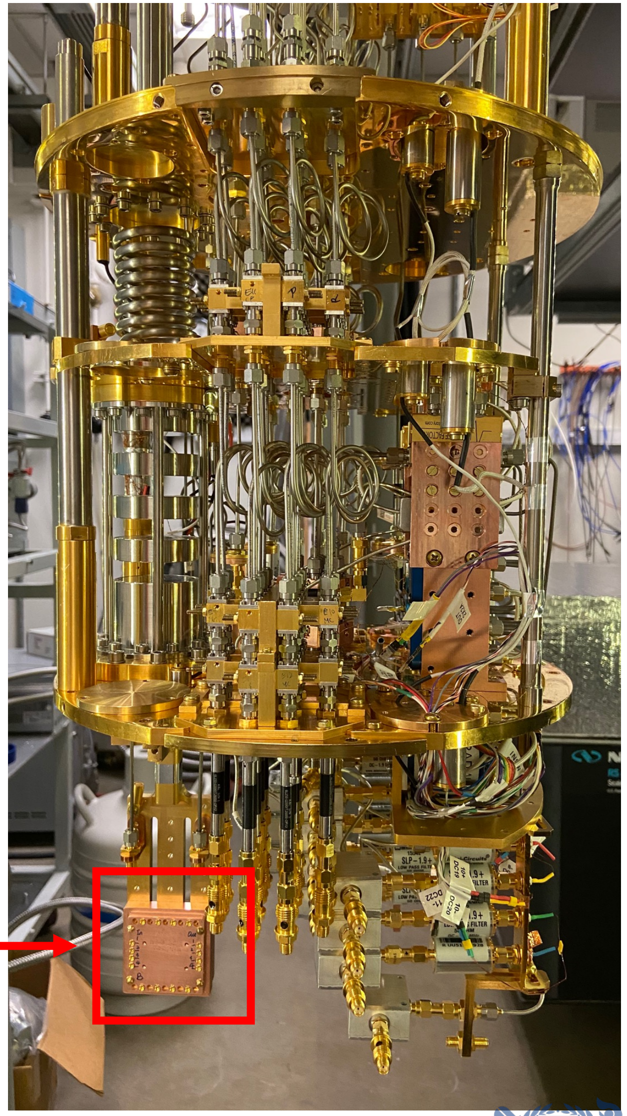
Non-Energy-Preserving



L (inductor)   C (Capacitor)   R (Resistor)

Operating Frequencies 3 – 9 GHz

Sample < 10 mK

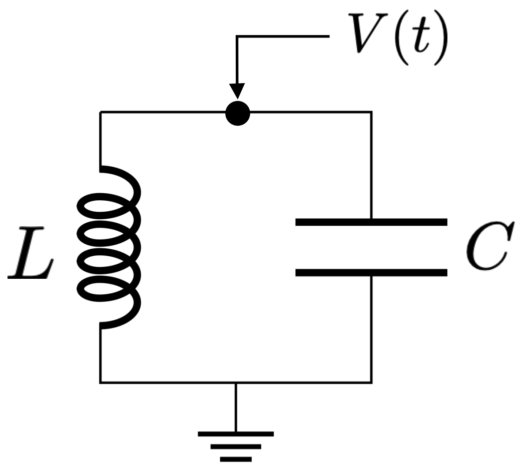


Dilution Refrigerator "DF2"
(Painter Lab @ Caltech)

Superconducting electrical circuits at temperature $T \ll hf / k_B$
(zero resistance)

Linear Quantum Circuit: LC Resonator

LC Resonator



Our canonical coordinate:

Node Flux $\Phi(t) = \int_{-\infty}^{t} V(t')dt'$

Capacitive Energy $E_C = \frac{1}{2}CV^2 = \frac{1}{2}C\dot{\Phi}^2$

Inductive Energy $E_L = \frac{1}{2}LI^2 = \frac{\Phi^2}{2L}$

$V = L\frac{dI}{dt}$

Lagrangian $\mathcal{L} = E_C(\dot{\Phi}) - E_L(\Phi) = \frac{1}{2}C\dot{\Phi}^2 - \frac{\Phi^2}{2L}$

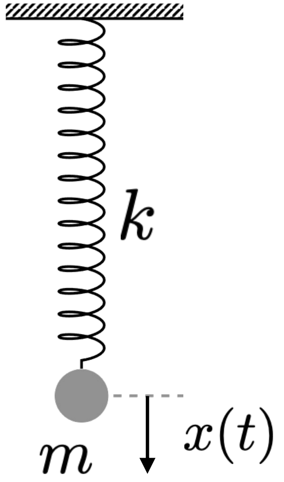
conj. variable $Q = \frac{\partial \mathcal{L}}{\partial \dot{\Phi}} = C\dot{\Phi}$ (charge)

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

Harmonic Oscillator

Mass on a spring

$x(t)$ Position



$T = \frac{1}{2}m\dot{x}^2$ Kinetic Energy

$U = \frac{1}{2}kx^2$ Potential Energy

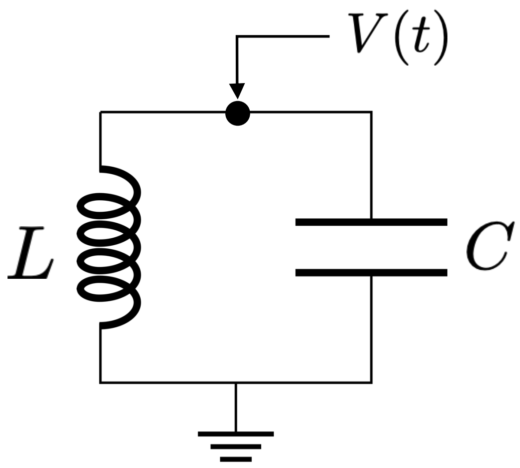
$\mathcal{L} = \frac{1}{2}m\dot{x}^2 - \frac{1}{2}kx^2$

$p = \frac{\partial \mathcal{L}}{\partial \dot{x}} = m\dot{x}$ (momentum)

$H = \frac{p^2}{2m} + \frac{1}{2}kx^2$

Linear Quantum Circuit: LC Resonator

LC Resonator



Our canonical coordinate:

Node Flux $\Phi(t) = \int_{-\infty}^{t} V(t')dt'$

$$Q = \frac{\partial \mathcal{L}}{\partial \dot{\Phi}} = C\dot{\Phi} \quad \text{(charge)}$$

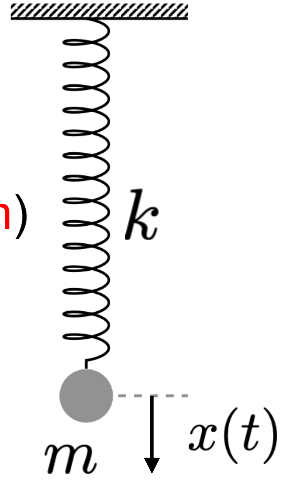
$$H = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

Mass on a spring

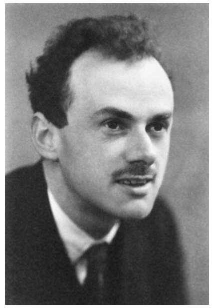
$x(t)$ Position

$$p = \frac{\partial \mathcal{L}}{\partial \dot{x}} = m\dot{x} \quad \text{(momentum)}$$

$$H = \frac{p^2}{2m} + \frac{1}{2}kx^2$$



Hamiltonian Theory of Classical Mechanics → Quantum Theory



Paul Dirac

Classical Poisson Brackets $\{A, B\}$ → Commutator b/w Observables $\frac{1}{i\hbar}[\hat{A}, \hat{B}]$

$$\{\Phi, Q\} = 1 \qquad [\hat{\Phi}, \hat{Q}] = i\hbar$$

uncertainty principle

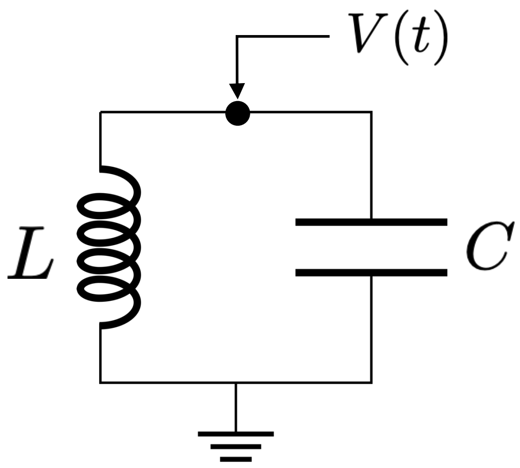
$$\Delta\Phi\Delta Q \geq \frac{\hbar}{2}$$

flux and charge satisfy the canonical commutation relation !

Now, we are good to talk about "quantum" electrical circuits

Quantum LC Resonator

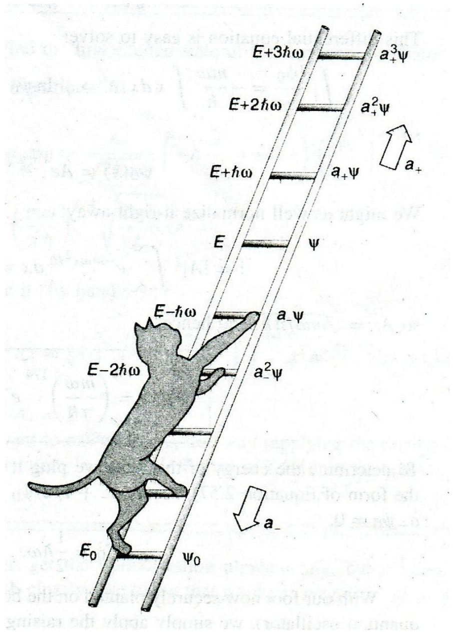
LC Resonator

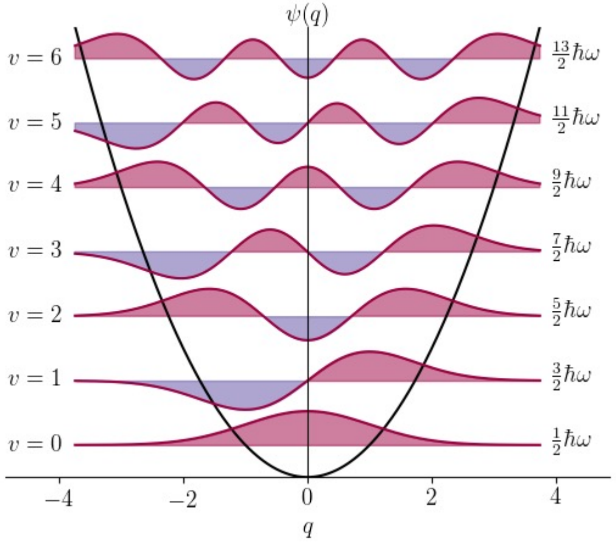


$$[\hat{\Phi}, \hat{Q}] = i\hbar$$

$$\hat{H} = \frac{\hat{\Phi}^2}{2L} + \frac{\hat{Q}^2}{2C} = \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right)$$

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

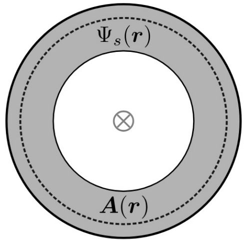




The LC resonator becomes a quantum harmonic oscillator

magnetic flux quantum

$$\Phi_0 = \frac{h}{2e}$$



Cooper-pair number $\hat{N} = -\frac{\hat{Q}}{2e}$

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

$$\hat{H} = 4E_C\hat{N}^2 + \frac{1}{2}E_L\hat{\varphi}^2$$

Number-phase uncertainty

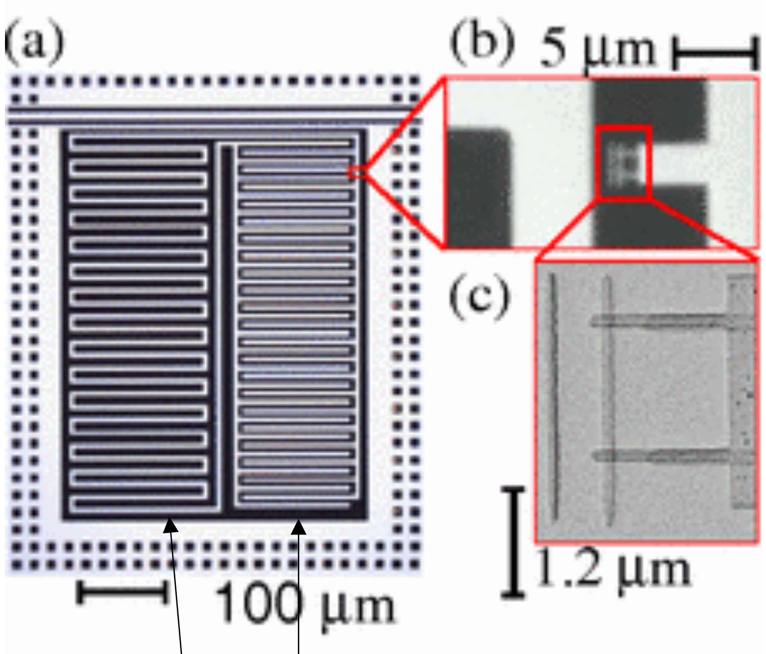
$$\text{“}[\hat{N}, \hat{\varphi}] = i\text{”}$$

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

$E_L = \frac{1}{L}\left(\frac{\Phi_0}{2\pi}\right)^2$ inductive E

Variations of Superconducting Resonators

Lumped-element Resonator:

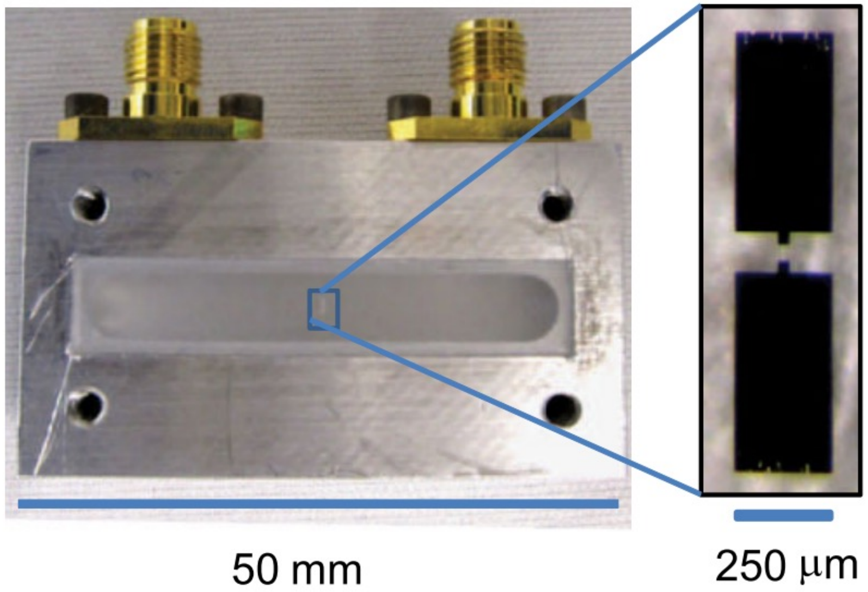


Z. Kim et al., PRL 106, 120501 (2011)

meander inductor

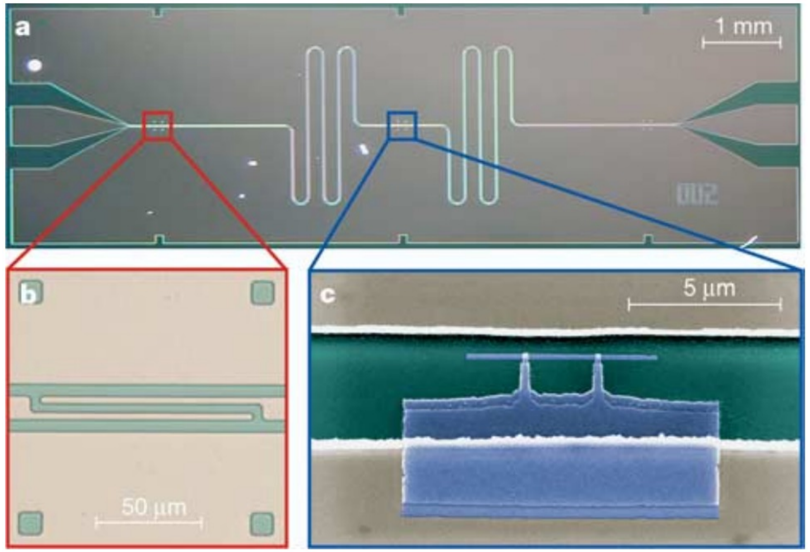
interdigitated capacitor

3D Cavity:

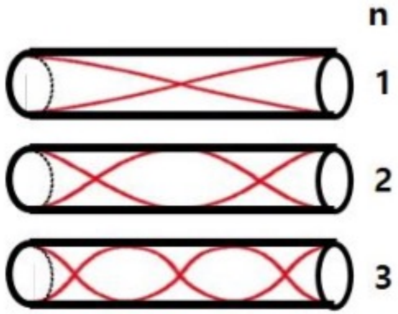


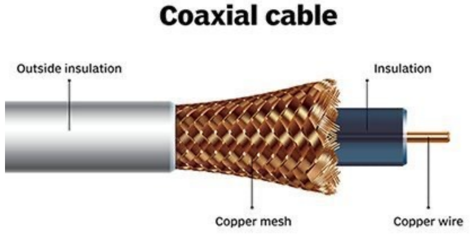
H. Paik et al., PRL 107, 240501 (2011)

Planar transmission-line resonator



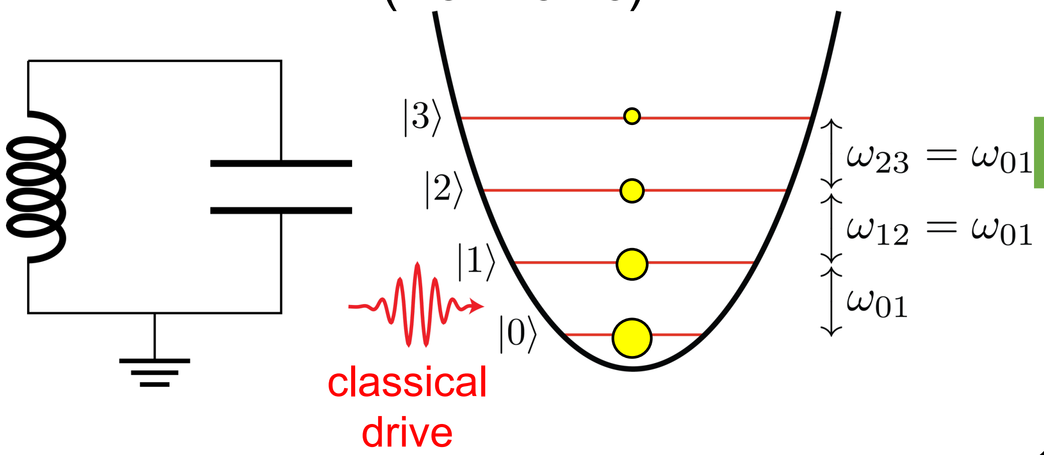
A. Wallraff et al., Nature 431, 162 (2004)

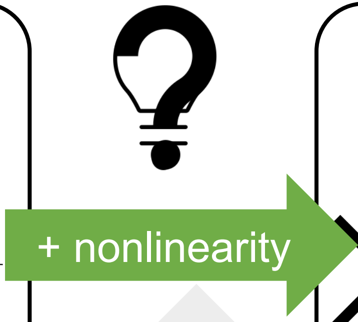




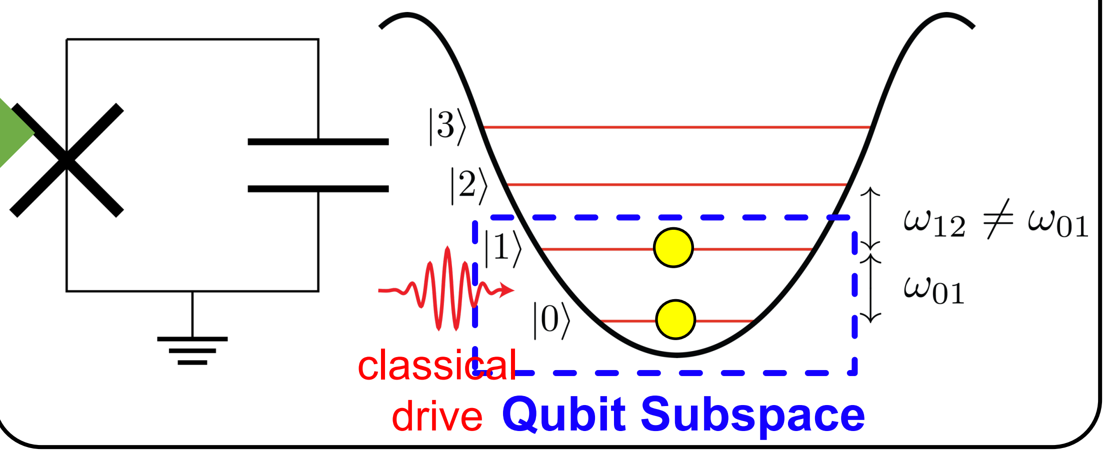
One missing circuit element: JJ

LC Resonator (Harmonic)





Superconducting Qubit (Anharmonic)



Cannot use classical drive to address individual levels (i.e. no quantum-level control)

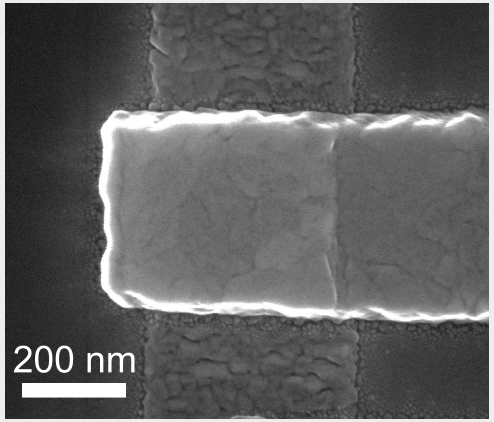
Josephson Equations:

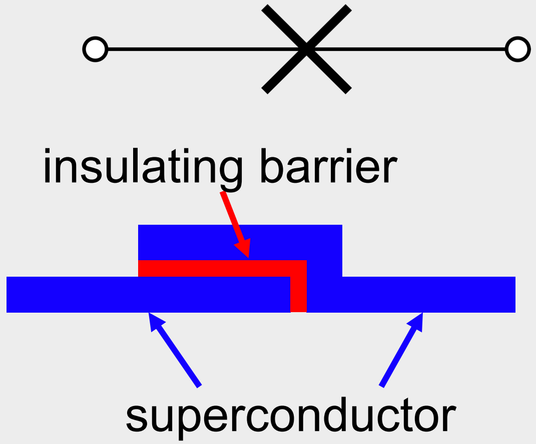
$$\frac{\partial \varphi}{\partial t} = \frac{2\pi}{\Phi_0} V(t) \qquad I(t) = I_c \sin\varphi$$

"Josephson Energy"

$$U_J = -E_J \cos\hat{\varphi} \qquad E_J = \frac{I_c \Phi_0}{2\pi} = \frac{h\Delta}{8e^2 R_n}$$

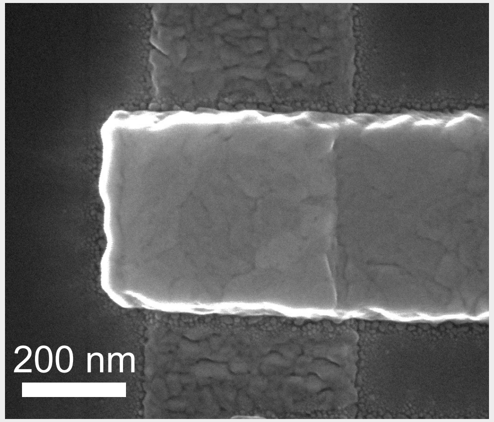
Josephson Junction: non-dissipative & non-linear

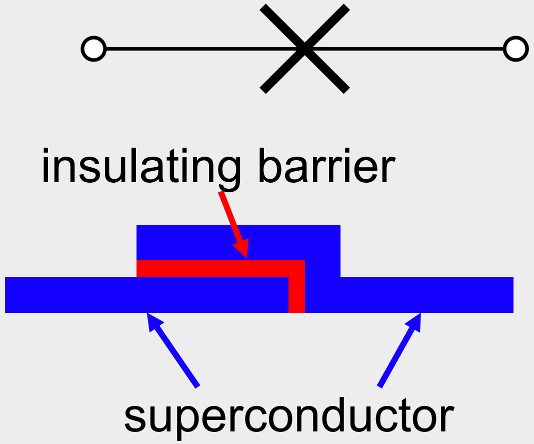




Josephson Tunnel Junctions

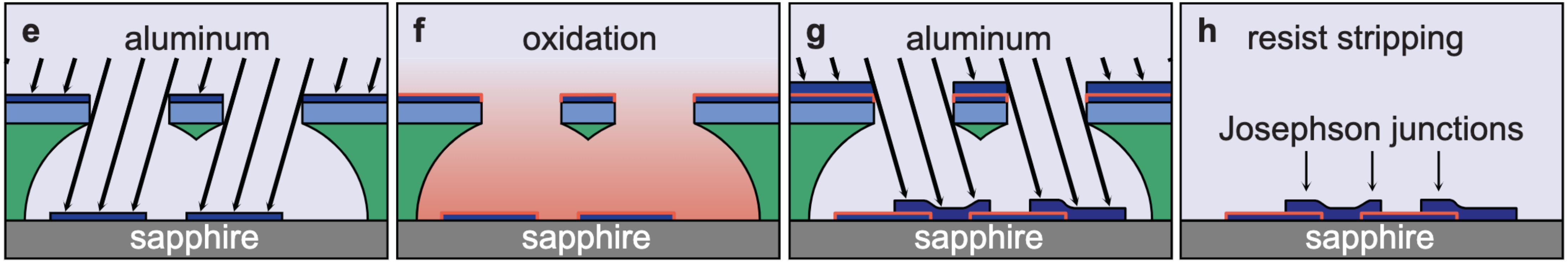
Josephson Junction: non-dissipative & non-linear





- superconductors: Nb, Al
- insulating barrier: AlO_x

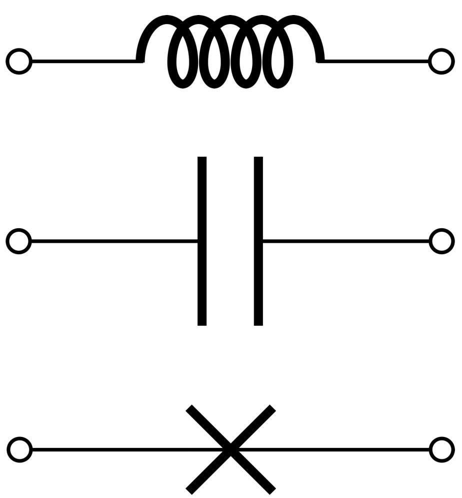
Fabrication: Shadow evaporation technique



Very good fabrication yield. typically a few % error in E_J (disorder)

Engineering Superconducting Quantum Circuits

Relevant Energies

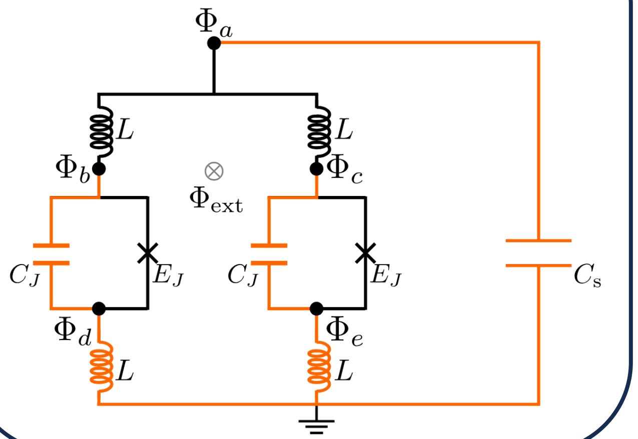


L: $E_L = \frac{1}{L}\left(\frac{\Phi_0}{2\pi}\right)^2$ Inductive Energy

C: $E_C = \frac{e^2}{2C}$ Charging Energy

JJ: $E_J = \frac{I_c \Phi_0}{2\pi}$ Josephson Energy

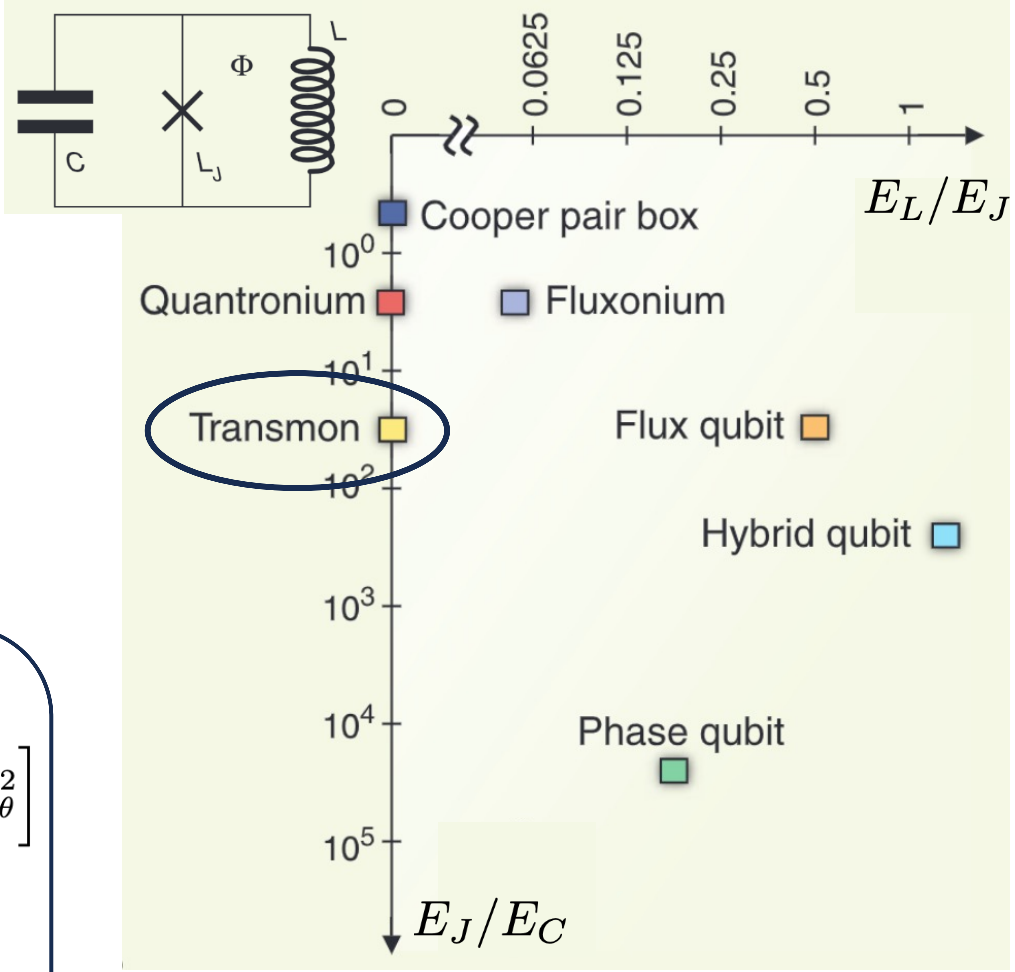
Design your circuit



Design your Hamiltonian

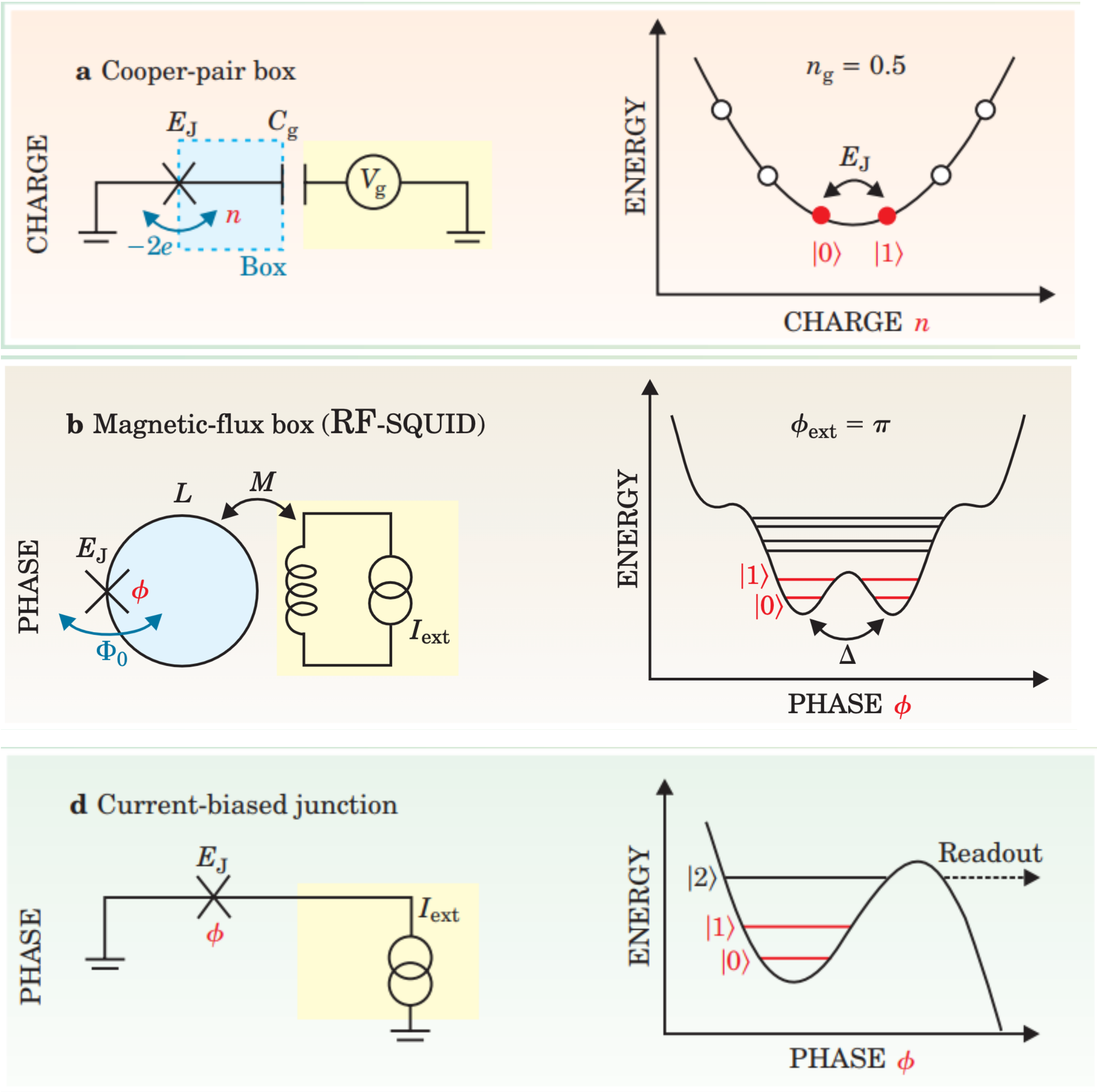
$$\mathcal{H} = 4E_{C_J}\left[4q_\phi^2 + (q_\chi - q_\theta)^2 + 2\frac{C_J}{C_s}q_\theta^2\right]$$
$$- 2E_J \cos(\chi)\cos\left(\frac{\phi}{2}\right)$$
$$+ \frac{E_L}{2}\left[\frac{1}{4}(\phi - \phi_{\mathrm{ext}})^2 + \theta^2\right]$$

"Periodic Table of Superconducting Qubits"



Science **339**, 1169 (2013)

1st Generation SC Qubits (early 2000s)



	Regime	Qubit States
Charge Qubit: A box for a Cooper pairs controlled by external voltage	$\frac{E_J}{E_C} \sim 0.1$	Superposition of Cooper pair number states $\|0\rangle, \|1\rangle$
Flux Qubit: A loop controlled by an external magnetic field	$\frac{E_J}{E_C} \sim 10$	Superposition of Persistent current states $\|\circlearrowleft\rangle, \|\circlearrowright\rangle$
Phase Qubit: A Josephson junction biased by a current	$\frac{E_J}{E_C} \sim 10^6$	Quantized levels in a phase potential well

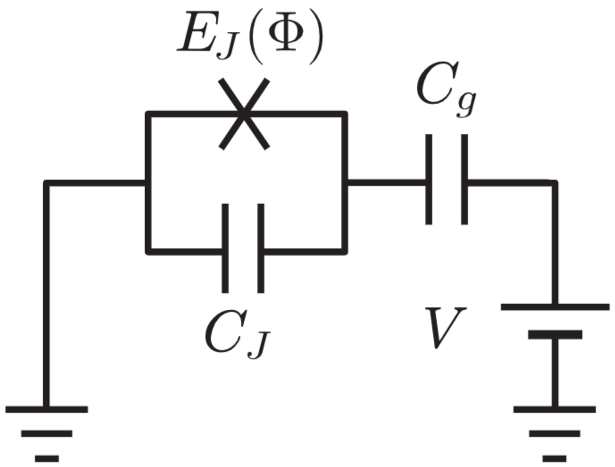
Phys. Today **58**, 42-47 (2005)

Modern SC Qubit: Transmon Qubit

transmon: "Transmission line shunted plasmon oscillation circuit"

(same circuit diagram as the charge qubit)

$$E_C = \frac{e^2}{2(C_g + C_J)}$$



$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos\hat{\varphi}.$$

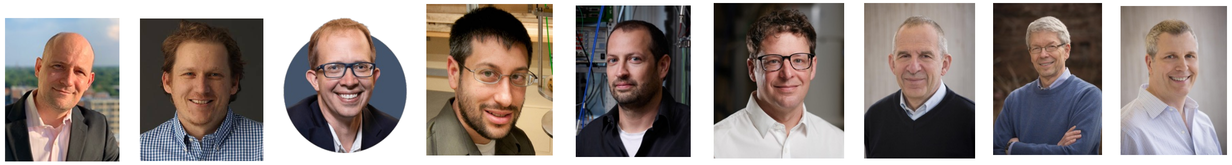
fluctuation of n_g: charge noise

Difference:

charge qubit regime: $E_J < E_C$

vs.

transmon qubit regime: $E_J \gg E_C$



Jens Koch | Jay Gambetta | Andrew Houck | David Schuster | Johannes Majer | Alexandre Blais | Michel Devoret | Steve Girvin | Robert Schoelkopf

Proposal:
(cited > 3000 times!)

PHYSICAL REVIEW A **76**, 042319 (2007)

Charge-insensitive qubit design derived from the Cooper pair box

Jens Koch,[1] Terri M. Yu,[1] Jay Gambetta,[1] A. A. Houck,[1] D. I. Schuster,[1] J. Majer,[1] Alexandre Blais,[2] M. H. Devoret,[1] S. M. Girvin,[1] and R. J. Schoelkopf[1]
[1]*Departments of Physics and Applied Physics, Yale University, New Haven, Connecticut 06520, USA*
[2]*Département de Physique et Regroupement Québécois sur les Matériaux de Pointe, Université de Sherbrooke, Sherbrooke, Québec, Canada J1K 2R1*
(Received 22 May 2007; published 12 October 2007)

Short dephasing times pose one of the main challenges in realizing a quantum computer. Different approaches have been devised to cure this problem for superconducting qubits, a prime example being the operation of such devices at optimal working points, so-called "sweet spots." This latter approach led to significant improvement of T_2 times in Cooper pair box qubits [D. Vion *et al.*, Science **296**, 886 (2002)]. Here, we introduce a new type of superconducting qubit called the "transmon." Unlike the charge qubit, the transmon is designed to operate in a regime of significantly increased ratio of Josephson energy and charging energy E_J/E_C. The transmon benefits from the fact that its charge dispersion decreases exponentially with E_J/E_C, while its loss in anharmonicity is described by a weak power law. As a result, we predict a drastic reduction in sensitivity to charge noise relative to the Cooper pair box and an increase in the qubit-photon coupling, while maintaining sufficient anharmonicity for selective qubit control. Our detailed analysis of the full system shows that this gain is not compromised by increased noise in other known channels.

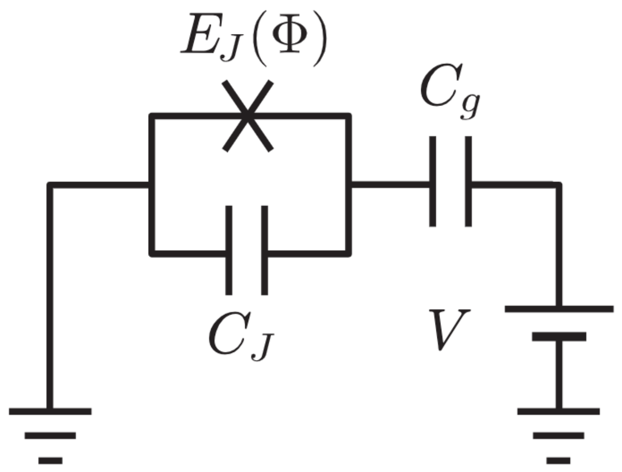
DOI: 10.1103/PhysRevA.76.042319 PACS number(s): 03.67.Lx, 74.50.+r, 32.80.−t

small E_C
⇒ small sensitivity of E to n_g
⇒ charge-noise insensitive!

Transmon Qubit: Idea

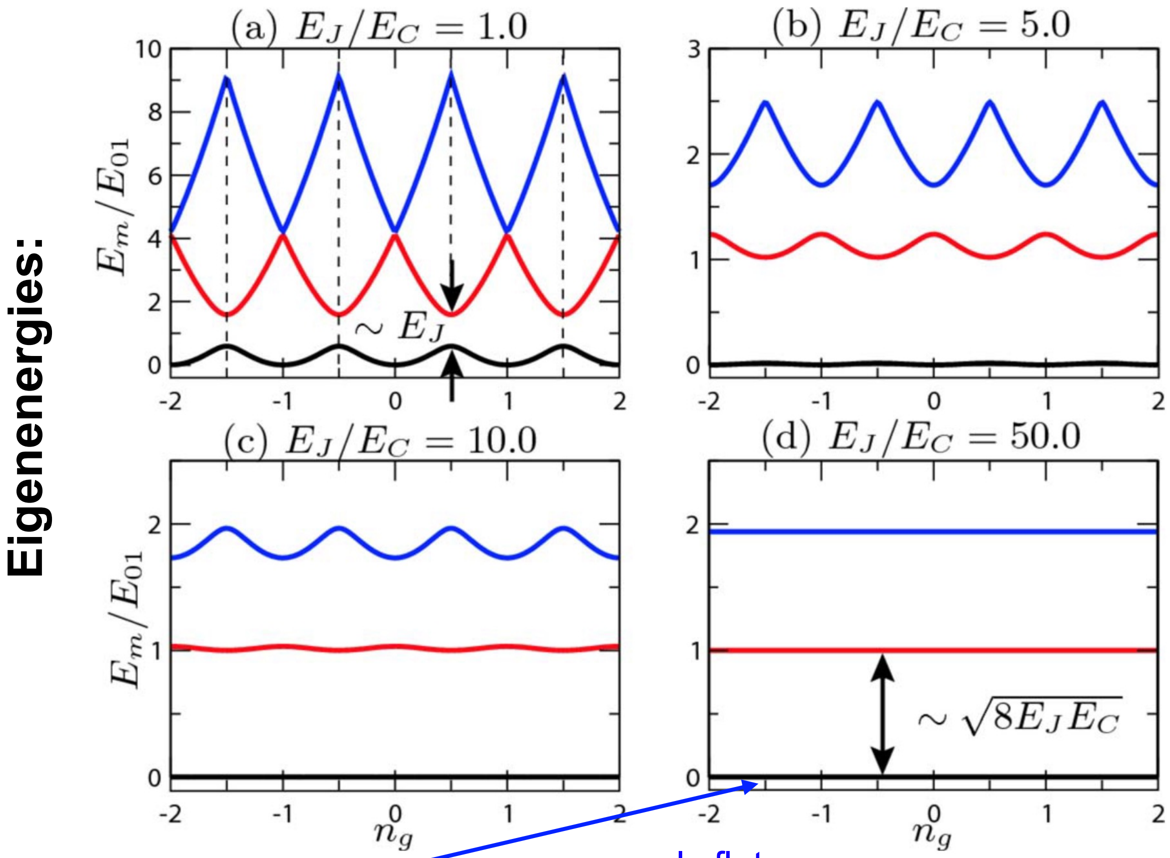
(same circuit diagram as the charge qubit)

$$E_C = \frac{e^2}{2(C_g + C_J)}$$



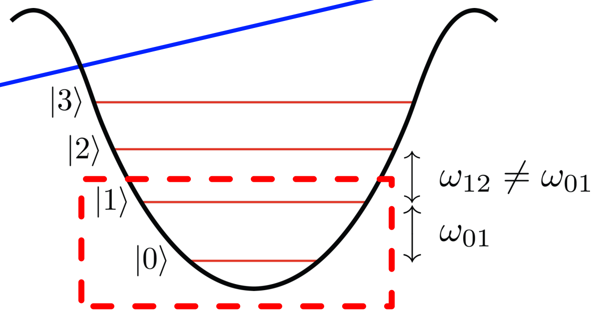
$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos \hat{\varphi}.$$

fluctuation of n_g: charge noise



Key Idea 1:
Charge dispersion reduces exponentially in E_J/E_C
⇒ nearly full protection against the charge noise

Problem: reduction of anharmonicity = $|E_{12} - E_{01}|$
(crucial element for qubit operation)

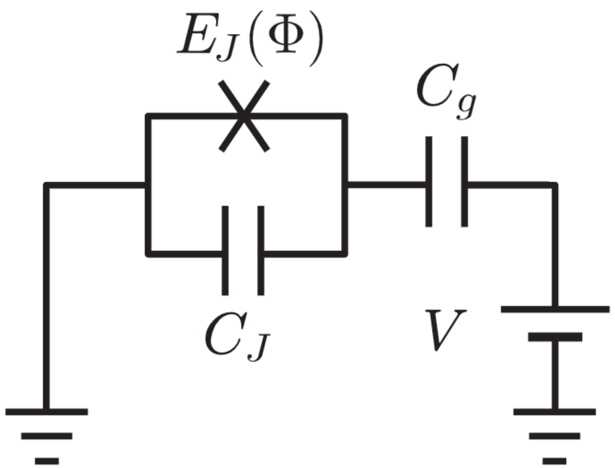


J. Koch et al., Phys. Rev. A **76**, 042319 (2007)

Transmon Qubit: Idea

(same circuit diagram as the charge qubit)

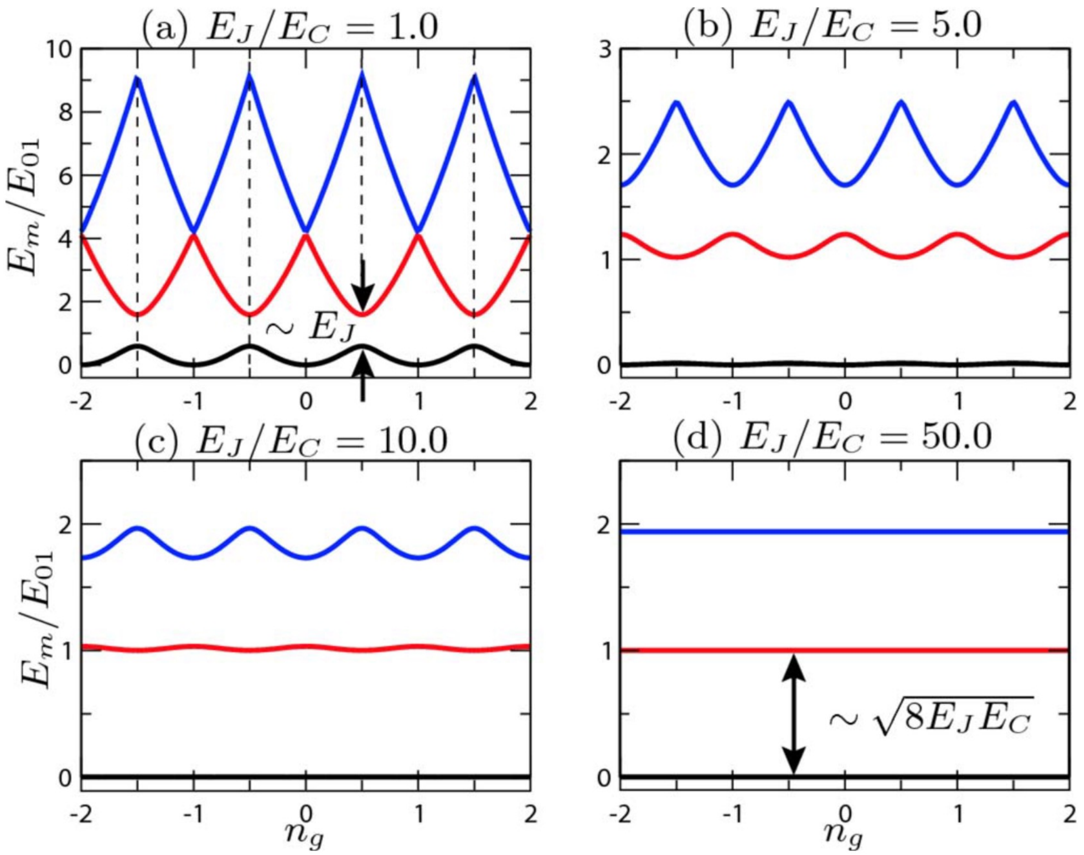
$$E_C = \frac{e^2}{2(C_g + C_J)}$$



$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos \hat{\varphi}.$$

fluctuation of n_g: charge noise

Eigenenergies:



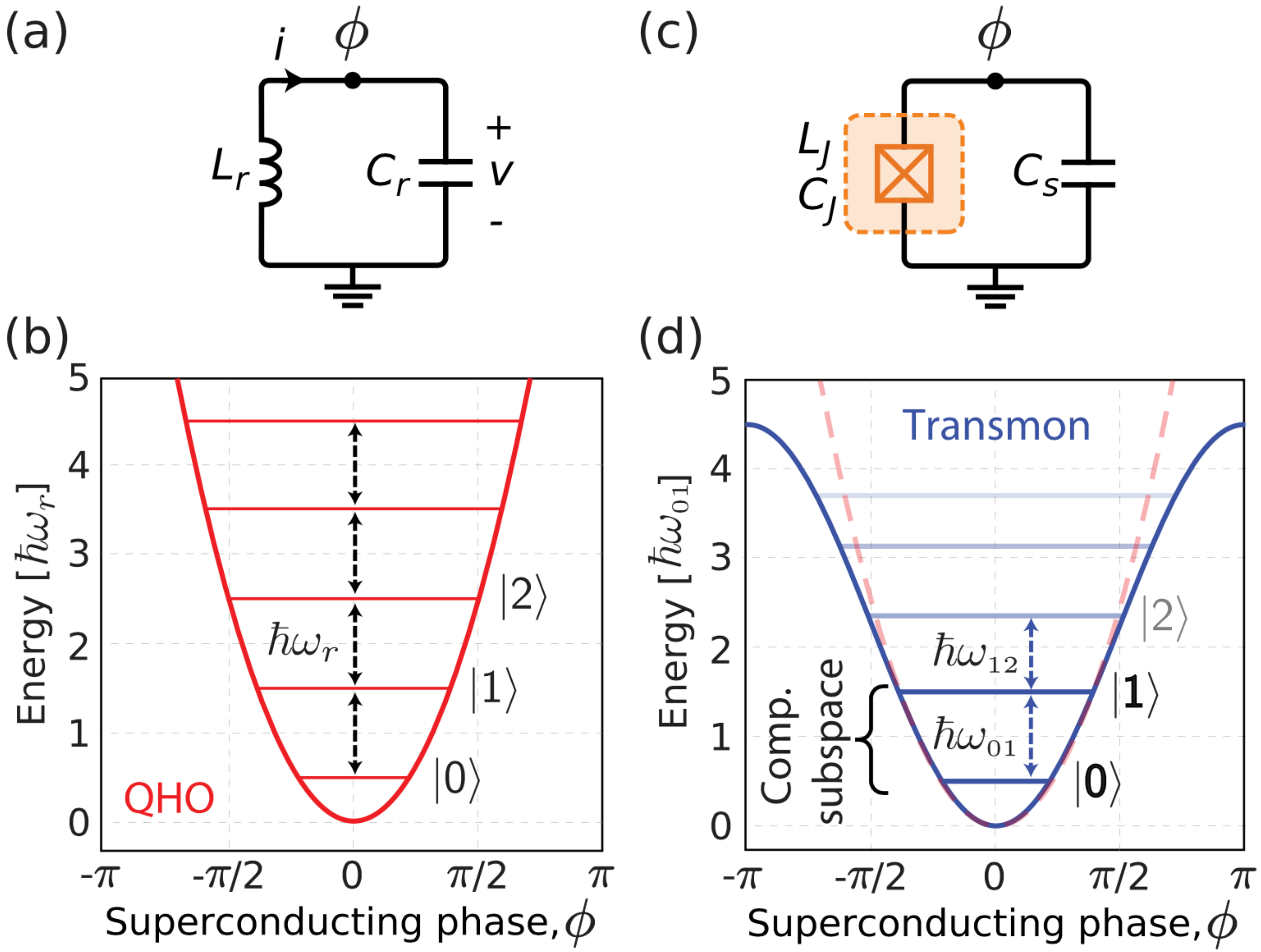
Key Idea 1:
Charge dispersion reduces exponentially in E_J/E_C
⇒ nearly full protection against the charge noise

Problem: reduction of anharmonicity = $|E_{12} - E_{01}|$
(crucial element for qubit operation)

Key Idea 2:
Anharmonicity only decreases algebraically, with a slow power law in E_J/E_C
⇒ only a small sacrifice in the two-level approximation

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

Transmon Qubit: Summary



Transmon: Weakly anharmonic oscillator

$$\hat{H} = \omega \hat{b}^\dagger \hat{b} + \frac{\alpha}{2} \hat{b}^\dagger \hat{b} (\hat{b}^\dagger \hat{b} - 1)$$

ω : qubit frequency (~ 2π × 6 GHz)

α : anharmonicity (~ −2π × 200 MHz)

$$\omega_{01} = \omega$$
$$\omega_{12} = \omega + \alpha$$

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

3D transmon qubit (2011)

3D superconducting microwave cavity:
Low-loss, well-controlled electromagnetic environment for the qubit

Hanhee Paik

40501 (2011) Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 9 DECEMBER 2011

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

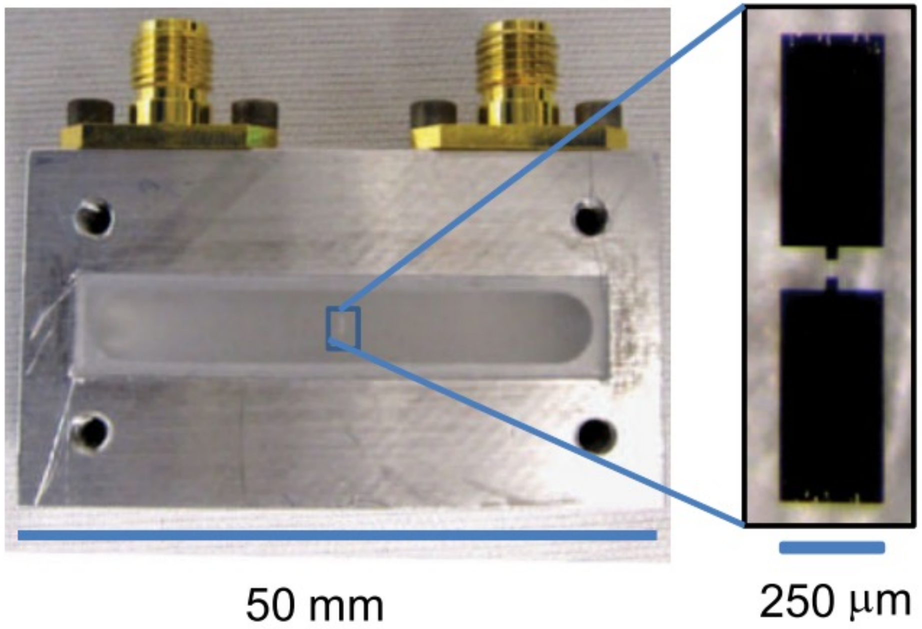
Hanhee Paik,[1] D. I. Schuster,[1,2] Lev S. Bishop,[1,3] G. Kirchmair,[1] G. Catelani,[1] A. P. Sears,[1] B. R. Johnson,[1,4] M. J. Reagor,[1] L. Frunzio,[1] L. I. Glazman,[1] S. M. Girvin,[1] M. H. Devoret,[1] and R. J. Schoelkopf[1]

[1]*Department of Physics and Applied Physics, Yale University, New Haven, Connecticut 06520, USA*
[2]*Department of Physics and James Franck Institute, University of Chicago, Chicago, Illinois 60637, USA*
[3]*Joint Quantum Institute and Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[4]*Raytheon BBN Technologies, Cambridge, Massachusetts 02138, USA*

(Received 3 July 2011; revised manuscript received 15 September 2011; published 5 December 2011)

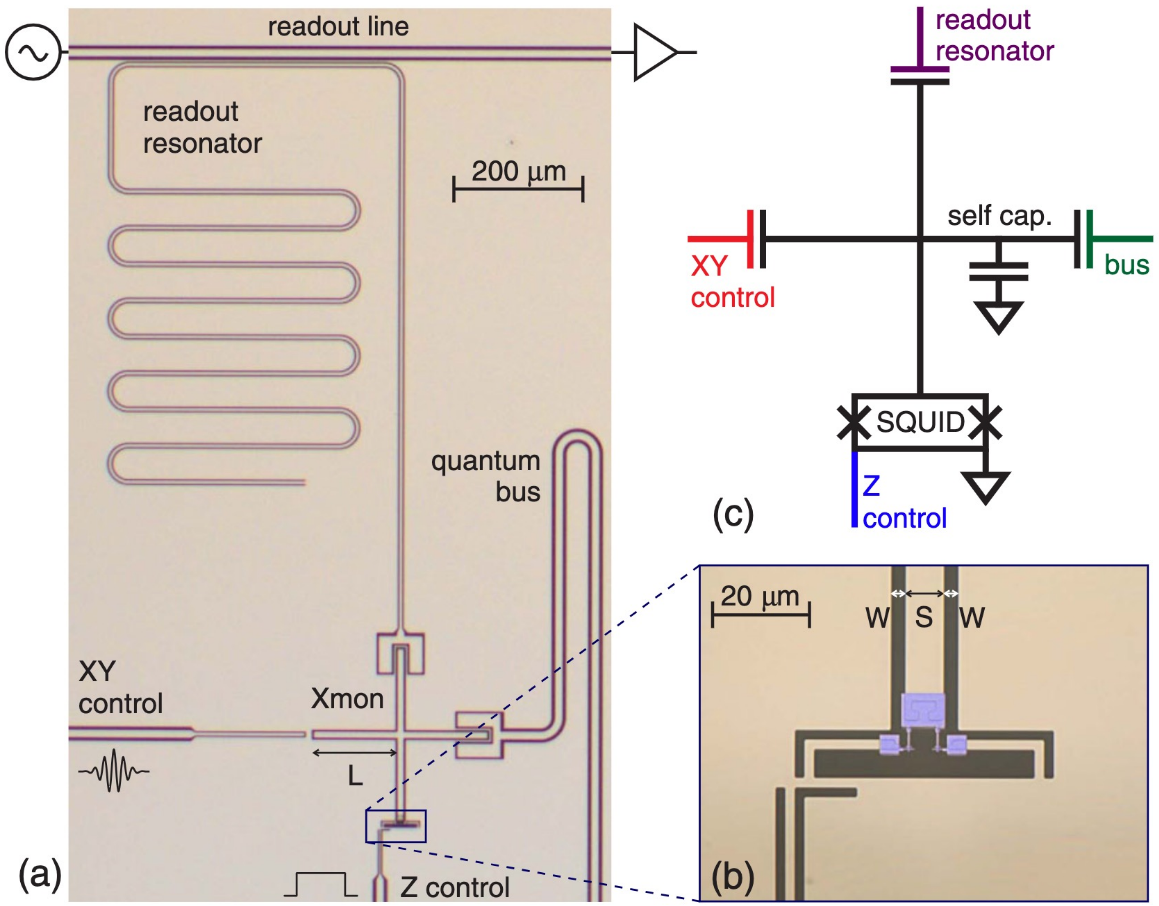
Superconducting quantum circuits based on Josephson junctions have made rapid progress in demonstrating quantum behavior and scalability. However, the future prospects ultimately depend upon the intrinsic coherence of Josephson junctions, and whether superconducting qubits can be adequately isolated from their environment. We introduce a new architecture for superconducting quantum circuits employing a three-dimensional resonator that suppresses qubit decoherence while maintaining sufficient coupling to the control signal. With the new architecture, we demonstrate that Josephson junction qubits are highly coherent, with $T_2 \sim 10$ to $20\ \mu s$ without the use of spin echo, and highly stable, showing no evidence for $1/f$ critical current noise. These results suggest that the overall quality of Josephson junctions in these qubits will allow error rates of a few 10^{-4}, approaching the error correction threshold.

DOI: 10.1103/PhysRevLett.107.240501 PACS numbers: 03.67.Lx, 42.50.Pq, 85.25.−j



- Much longer coherence time observed: $T_1 \sim 60\ \mu s$, $T_2 \sim 20\ \mu s$ (order of magnitude improvement!)
- Demystified Josephson junction voodoos (People believed JJ would ultimately limit the coherence time to ~ few 10 μs)

Xmon qubit (2013)



Andrew Cleland

John Martinis

PRL **111,** 080502 (2013) PHYSICAL REVIEW LETTERS week ending 23 AUGUST 2013

Coherent Josephson Qubit Suitable for Scalable Quantum Integrated Circuits

R. Barends, J. Kelly, A. Megrant, D. Sank, E. Jeffrey, Y. Chen, Y. Yin,* B. Chiaro, J. Mutus, C. Neill, P. O'Malley, P. Roushan, J. Wenner, T. C. White, A. N. Cleland, and John M. Martinis

Department of Physics, University of California, Santa Barbara, California 93106, USA

(Received 5 April 2013; published 22 August 2013)

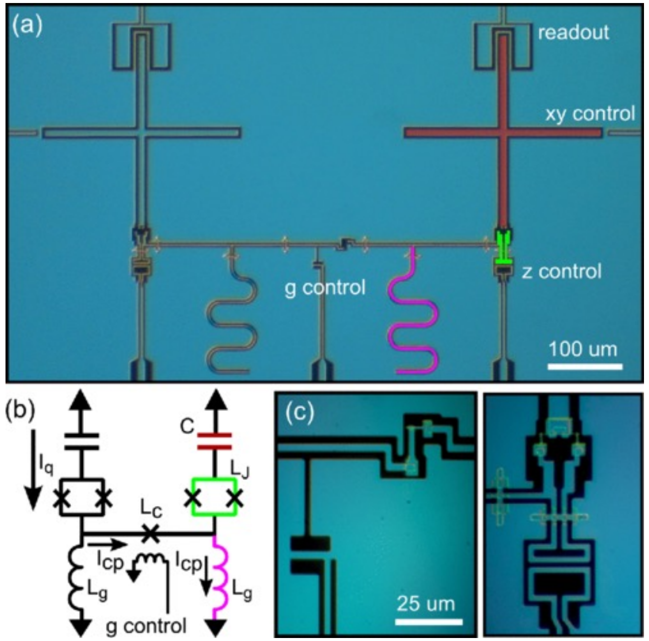
We demonstrate a planar, tunable superconducting qubit with energy relaxation times up to 44 μs. This is achieved by using a geometry designed to both minimize radiative loss and reduce coupling to materials-related defects. At these levels of coherence, we find a fine structure in the qubit energy lifetime as a function of frequency, indicating the presence of a sparse population of incoherent, weakly coupled two-level defects. We elucidate this defect physics by experimentally varying the geometry and by a model analysis. Our "Xmon" qubit combines facile fabrication, straightforward connectivity, fast control, and long coherence, opening a viable route to constructing a chip-based quantum computer.

DOI: 10.1103/PhysRevLett.111.080502 PACS numbers: 03.67.Lx, 03.65.Yz, 85.25.Cp

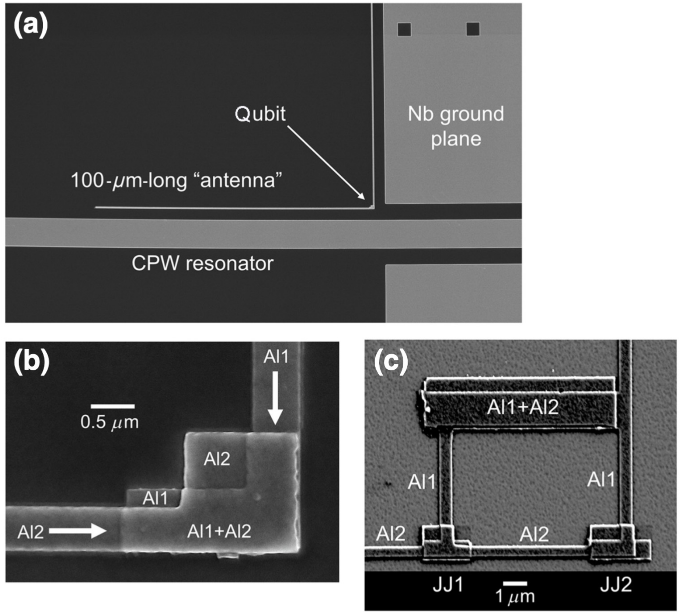
- modification of transmon geometry to a "grounded" cross-shaped circuit
- Each control method (XY, Z, RO, 2Q gate) established using the "arm" of Xmon
- moderate, reproducible coherence times on a planar circuit T_1 > 40 μs, T_2 ~ 20 μs

Design basis of modern superconducting quantum processors

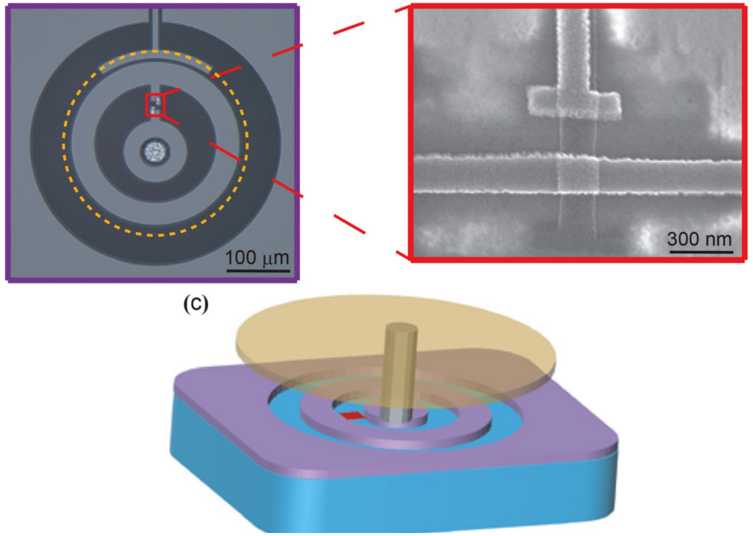
Lots of –mon qubit (variants of transmons)



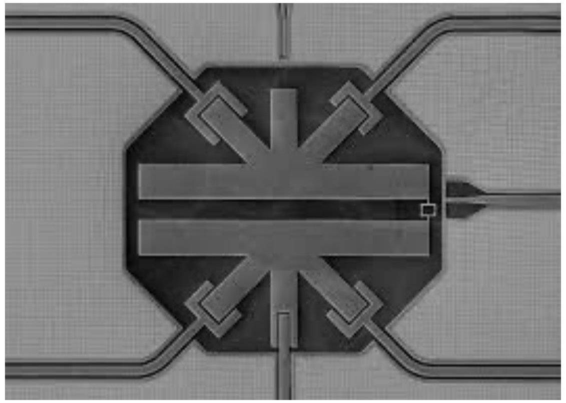
Gmon (UCSB, Google)



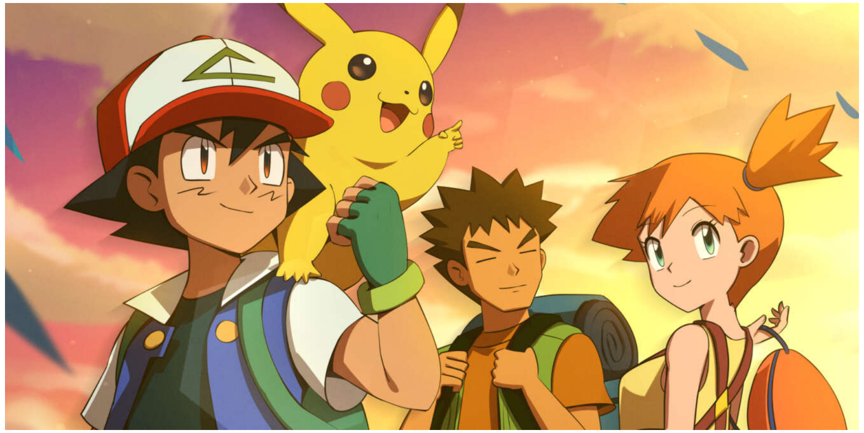
Mergemon (IBM)



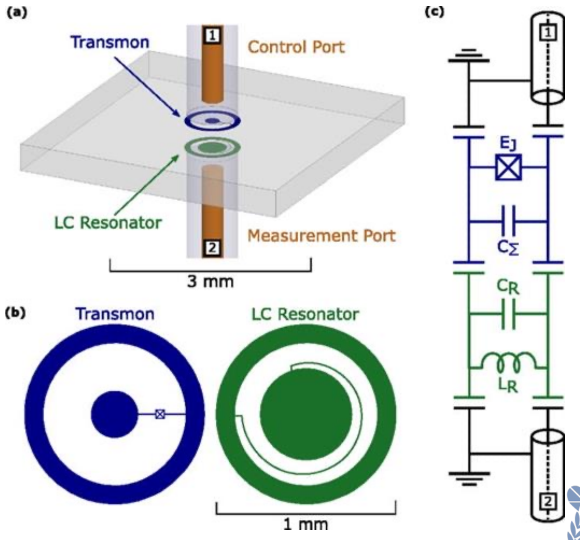
Flipmon (BAQIS, China)



Starmon (intel, TU Delft)



What is your next qubit? 😂



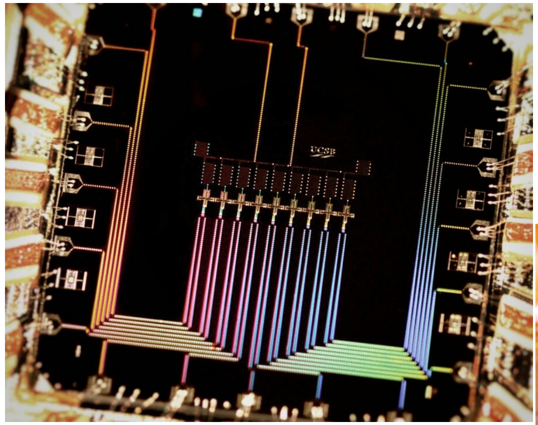
Coaxmon (Oxford U)

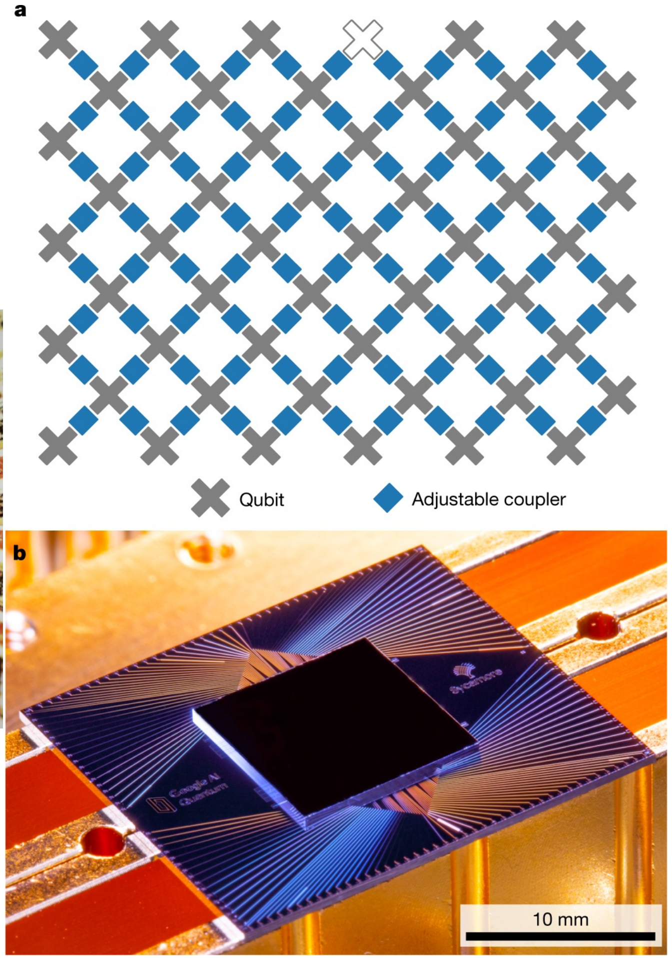
Transmon qubit today: in quantum processors

Transmon: choice of qubit in major industry-led quantum computing efforts

Google

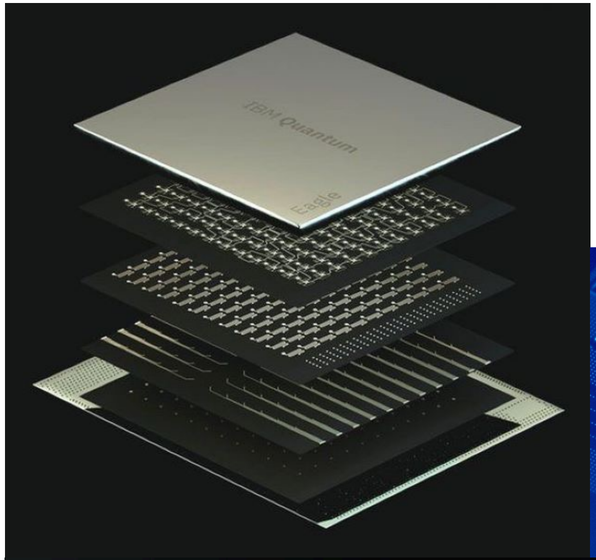
tunable-frequency
Xmons

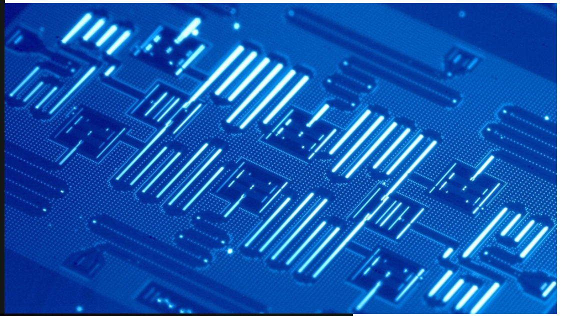


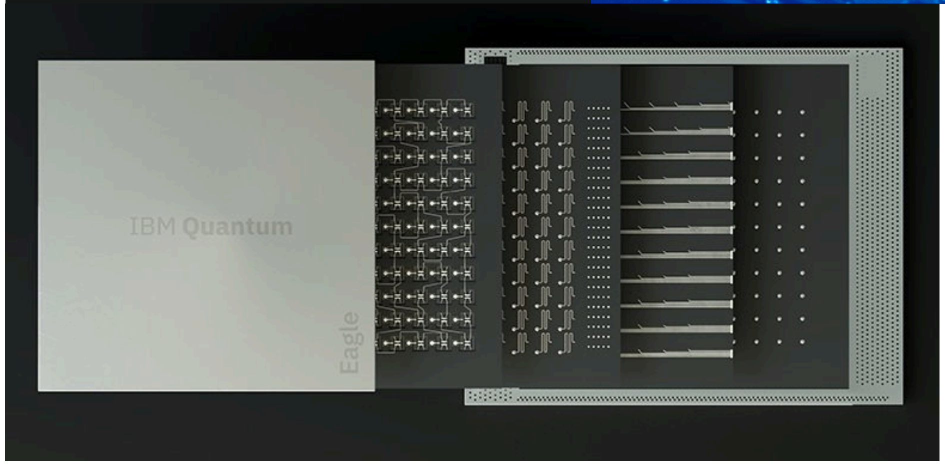


IBM

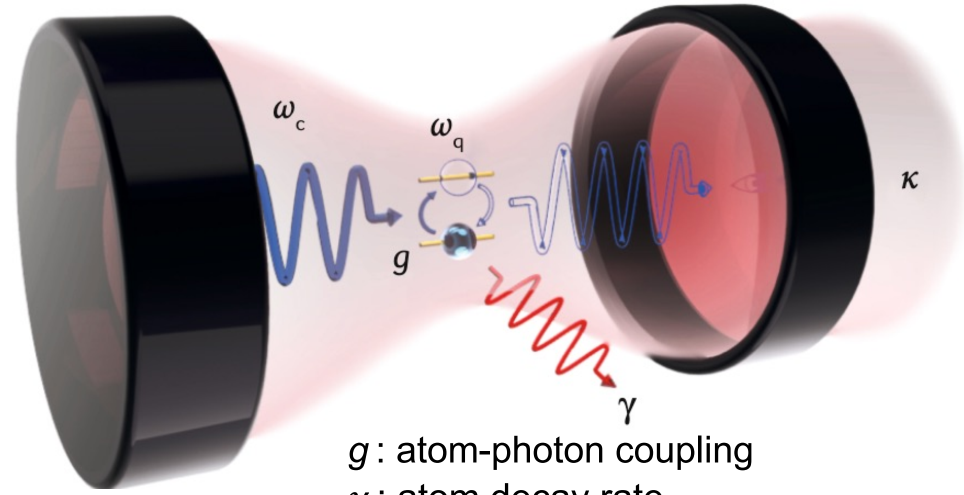
fixed-frequency
transmons







Cavity Quantum Electrodynamics (QED) with SC Circuits

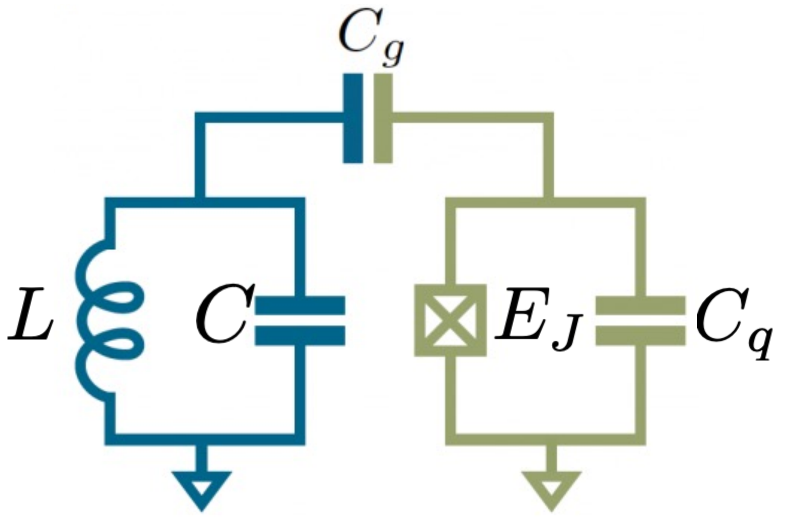


g : atom-photon coupling
γ : atom decay rate
κ : cavity decay rate

Controllable coherent interaction
of **single photons** with **individual two-level systems**

With atoms:
J. M. Raimond et al., RMP **73**, 565 (2001)
S. Haroche & J. Raimond, Exploring the Quantum (2006)
J. Ye, H. J. Kimble, H. Katori, Science 320, 1734 (2008)

With superconducting circuits: "**Circuit QED**"

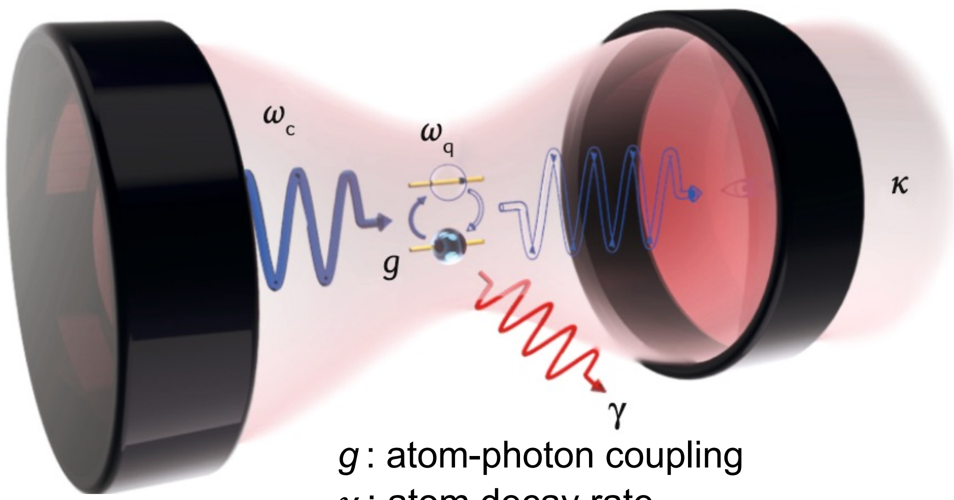


Review: A. Blais et al., RMP **93**, 025005 (2021)

How is circuit QED useful for quantum information processing?

- Isolating qubits from their electromagnetic environment
- Maintaining the addressability of qubits
- Reading out the state of qubits
- Coupling qubits to each other
- Converting stationary qubits to flying qubits

Cavity Quantum Electrodynamics (QED) with SC Circuits



g : atom-photon coupling
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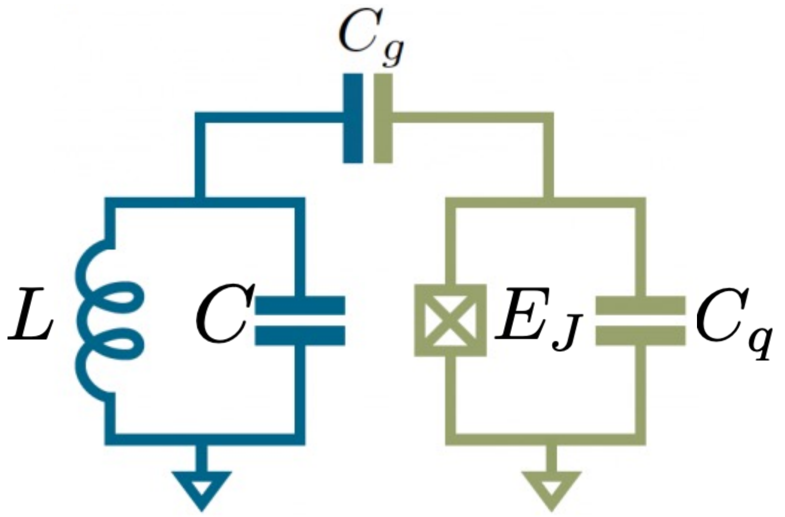
With superconducting circuits: "**Circuit QED**"



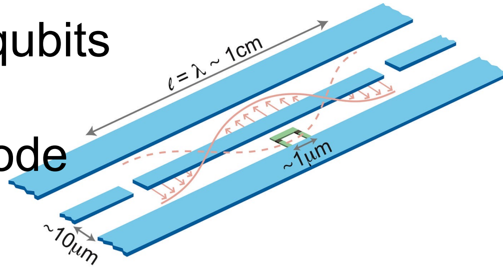
Review: A. Blais et al., RMP **93**, 025005 (2021)

Figure of Merit: Cooperativity $C = \frac{4g^2}{\kappa\gamma}$

In superconducting circuits, very easy to realize large *g* values

$$g = d\sqrt{\frac{\omega}{2\hbar\epsilon_0 V_m}}$$

- large transition dipole *d* of superconducting qubits
- sub-wavelength confinement of resonator mode (small mode volume V_m)



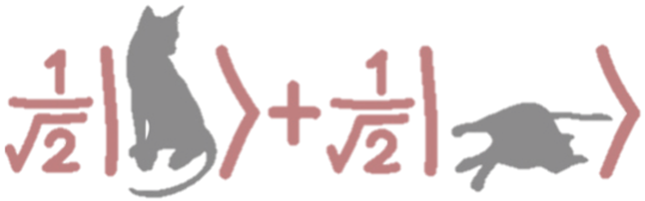
Very easy to achieve strong-coupling regime (*C* >> 1) of cavity QED

- Offers a good platform to study quantum optics

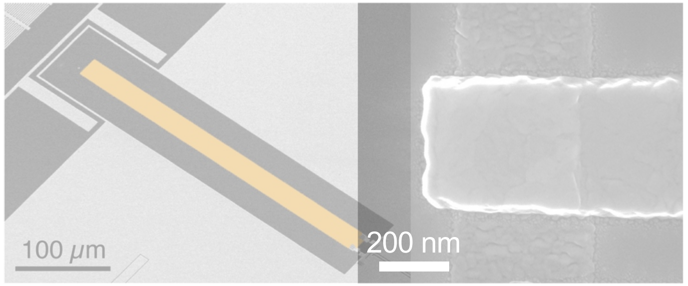
Interesting current research topics:
Ultrastrong coupling regime, Waveguide QED,
Topological Quantum Optics, Driven-Dissipative Systems…
(what we work on)

Content

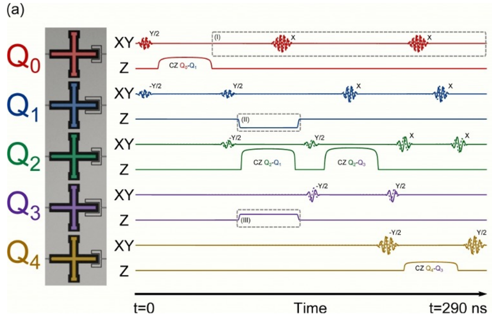
Motivation: Quantum Computation



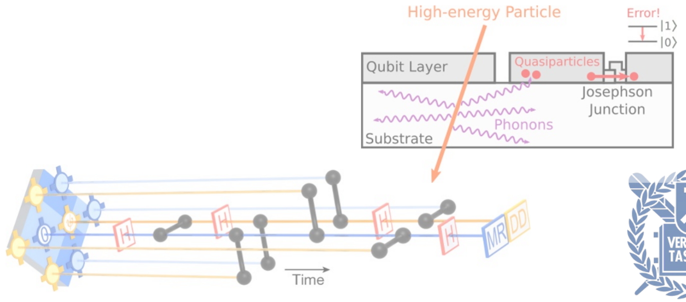
Superconducting Qubits & Circuit QED



Control & Readout of Superconducting Qubits



Challenges, Current Research Topics

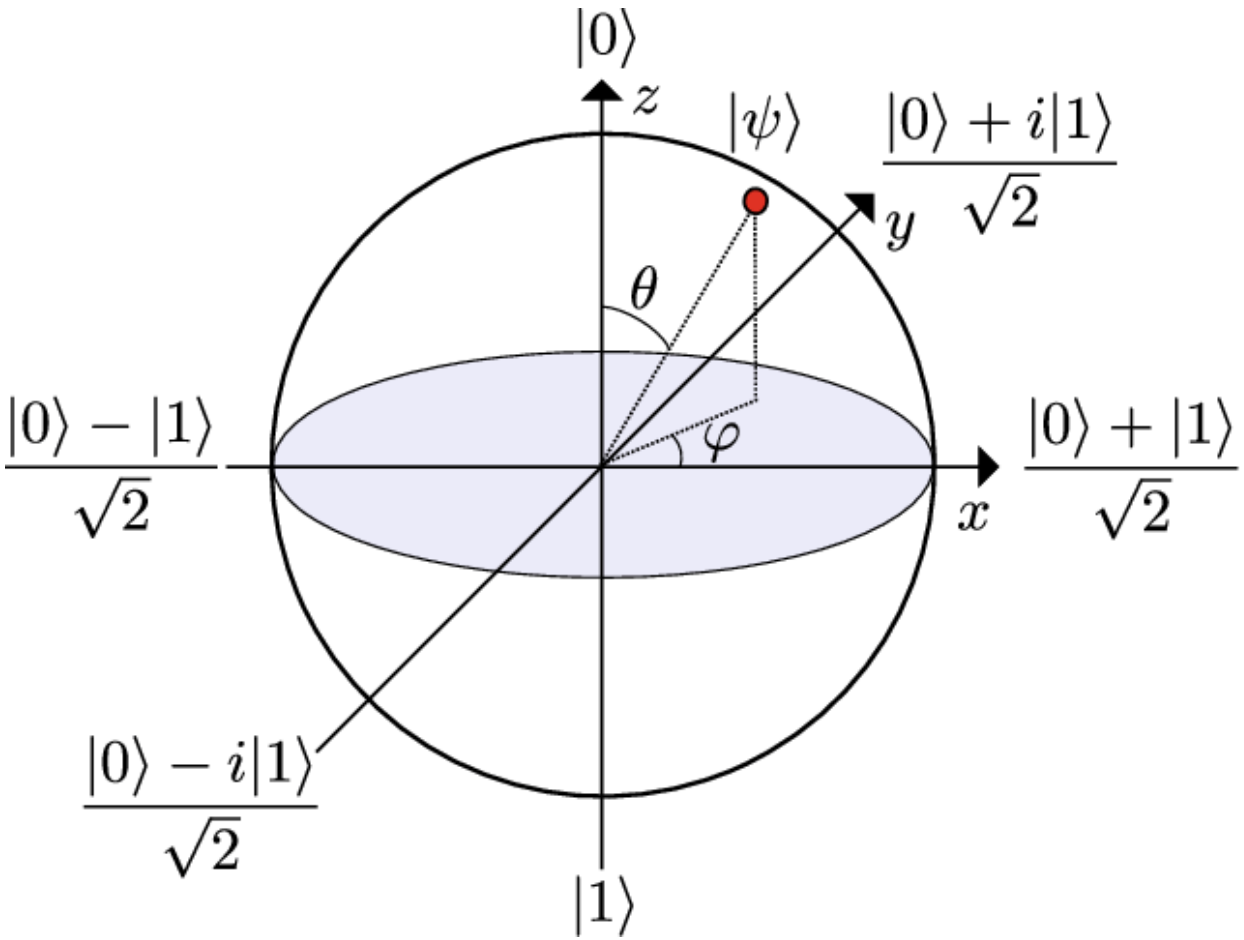


Visualizing the state of a qubit: Bloch Sphere

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$

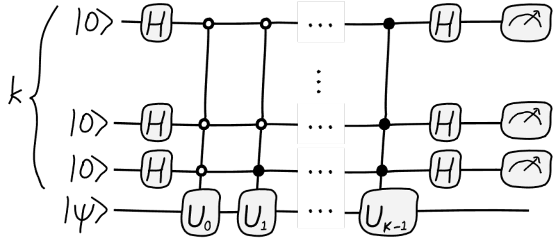
(up to a global phase factor)



"Bloch Sphere"

Given a state $|\psi\rangle$, the Bloch vector points at $\langle\boldsymbol{\sigma}\rangle = (\langle\sigma_x\rangle, \langle\sigma_y\rangle, \langle\sigma_z\rangle)$

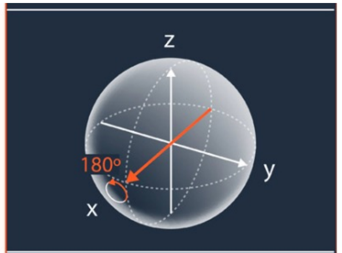
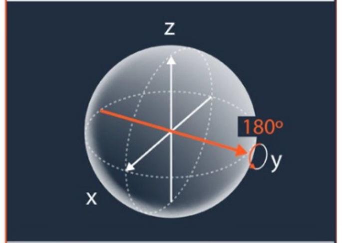
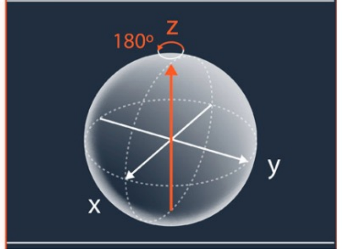
Logic Gates used in Quantum Computers



Quantum Logic: Unitary operations on quantum states

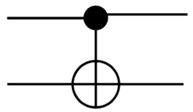
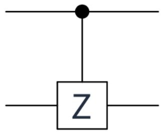
→ implemented by a set of single-qubit and two-qubit gates

- single-qubit gates: rotation on a Bloch sphere

X gate: rotates the qubit state by π radians (180º) about the x-axis.	X	$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	Input / Output $\|0\rangle$ → $\|1\rangle$ $\|1\rangle$ → $\|0\rangle$	
Y gate: rotates the qubit state by π radians (180º) about the y-axis.	Y	$Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$	Input / Output $\|0\rangle$ → $i\|1\rangle$ $\|1\rangle$ → $-i\|0\rangle$	
Z gate: rotates the qubit state by π radians (180º) about the z-axis.	Z	$Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$	Input / Output $\|0\rangle$ → $\|0\rangle$ $\|1\rangle$ → $-\|1\rangle$	

⋮

- two-qubit gate: controls entanglement

Controlled-NOT gate: apply an X-gate to the target qubit if the control qubit is in state $\|1\rangle$		$\text{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$	Input / Output $\|00\rangle$ → $\|00\rangle$ $\|01\rangle$ → $\|01\rangle$ $\|10\rangle$ → $\|11\rangle$ $\|11\rangle$ → $\|10\rangle$
Controlled-phase gate: apply a Z-gate to the target qubit if the control qubit is in state $\|1\rangle$		$\text{CPHASE (CZ)} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$	Input / Output $\|00\rangle$ → $\|00\rangle$ $\|01\rangle$ → $\|01\rangle$ $\|10\rangle$ → $\|10\rangle$ $\|11\rangle$ → $-\|11\rangle$

⋮

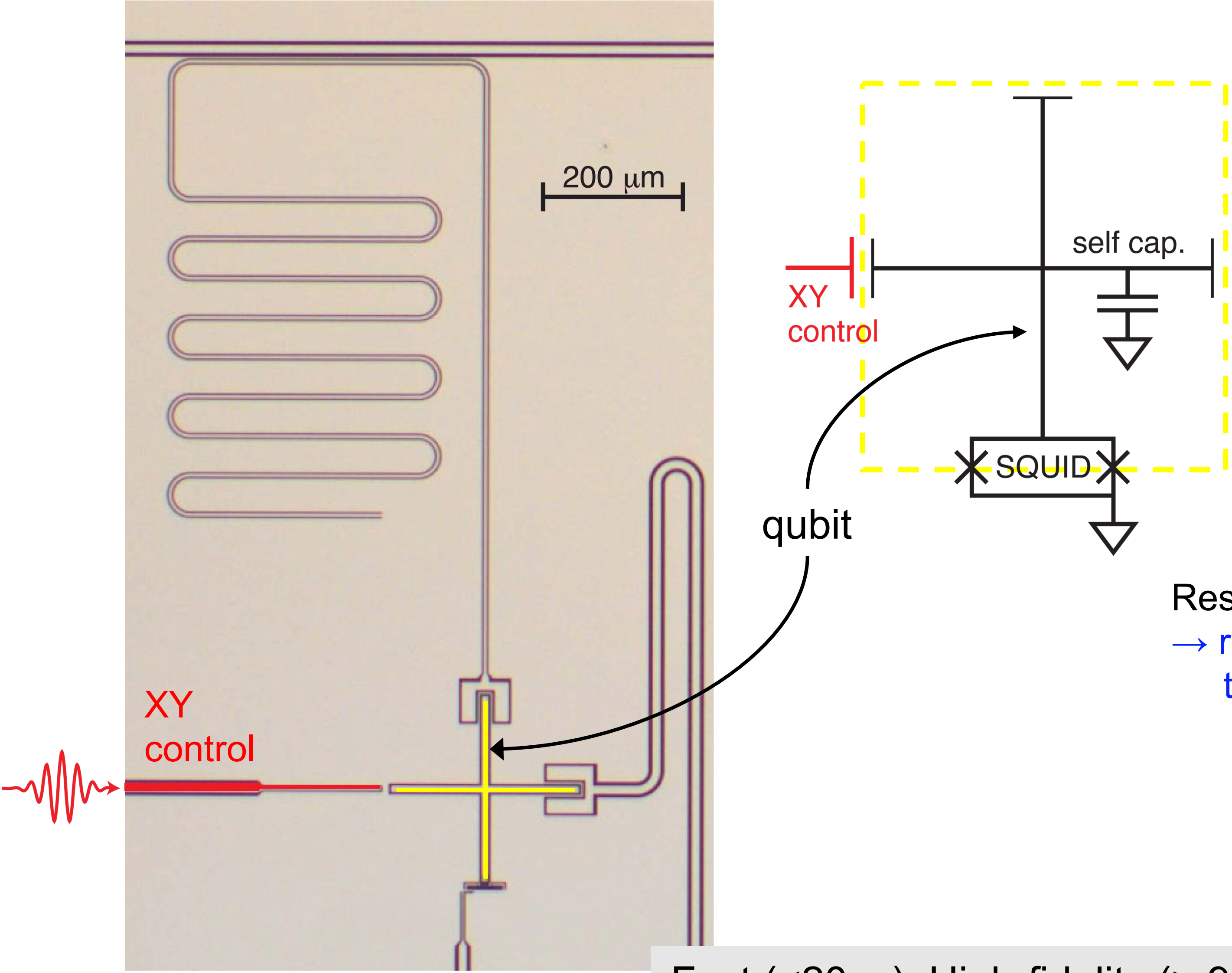
operation on the target qubit,
conditioned on the state of the control qubit

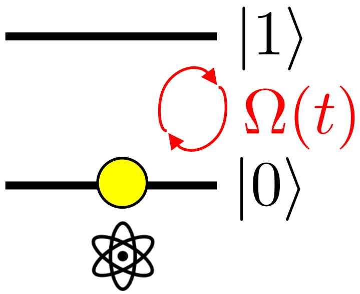
Universal Gate Set: a set of gates sufficient to implement an arbitrary quantum logic

Example: {arbitrary 1Q rotations, CNOT (or CZ)}

How do we *physically* realize such a universal gate set?

Single-Qubit Gates: XY control

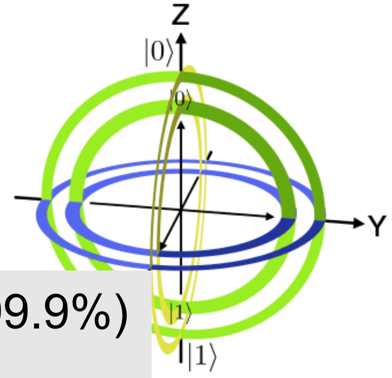




$$\hat{H} = +\frac{\Omega(t)}{2}\hat{\sigma}_x$$

✓ XY control: microwave pulse (charge drive)

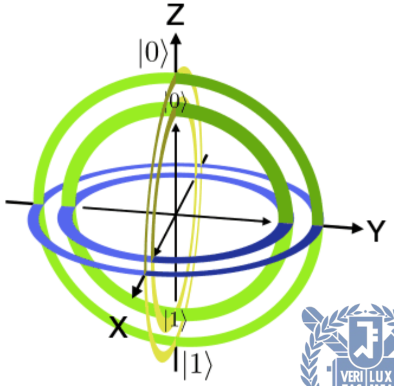
Resonant drive: induce $|0\rangle \leftrightarrow |1\rangle$ state transition (**bit-flip**)
→ rotation about an axis lying on the equator (xy-plane) of the Bloch sphere



π-rotation:

$|0\rangle \rightarrow |1\rangle$

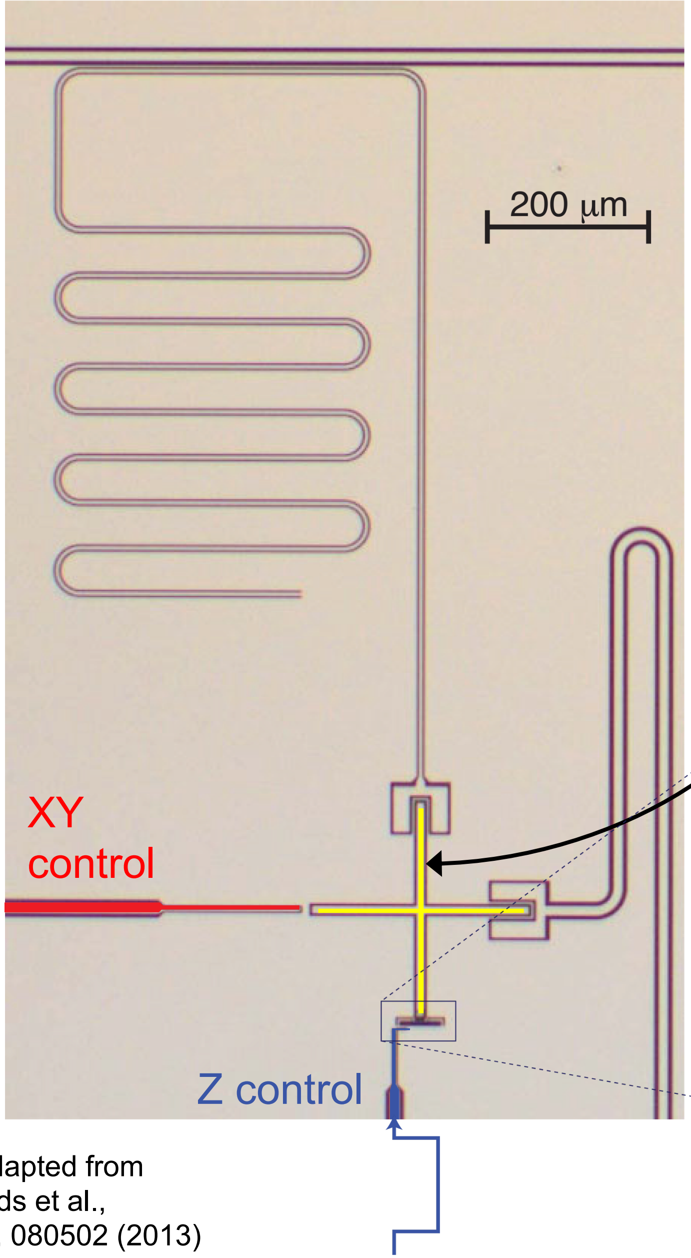
$|1\rangle \rightarrow |0\rangle$

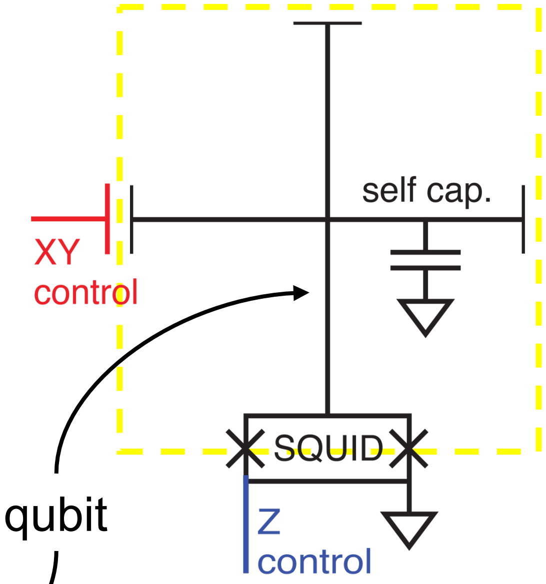


Fast (<20ns), High-fidelity (> 99.9%) XY Gates Achievable

Figure adapted from
R. Barends et al.,
PRL **111**, 080502 (2013)

Single-Qubit Gates: Z control





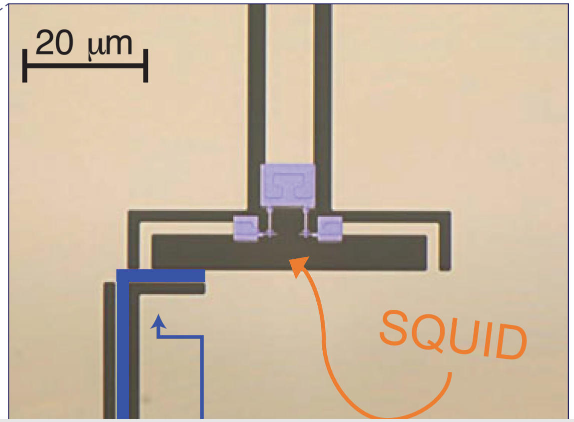
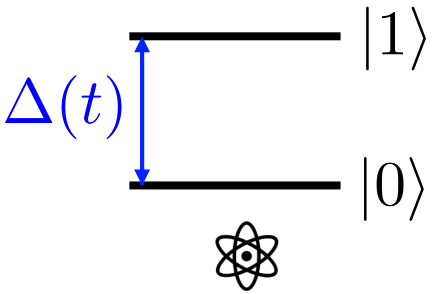


Figure adapted from
R. Barends et al.,
PRL **111**, 080502 (2013)

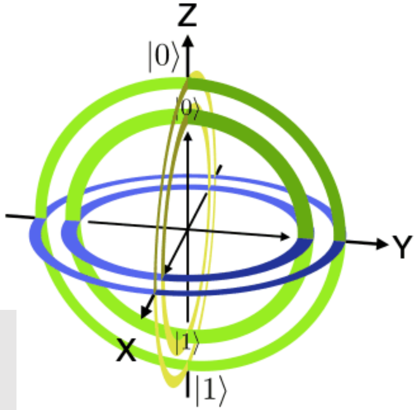
Alternatively, Virtual Z-rotation: perfect
(updating oscillator phase)



$$\hat{H} = -\frac{\Delta(t)}{2}\hat{\sigma}_z$$

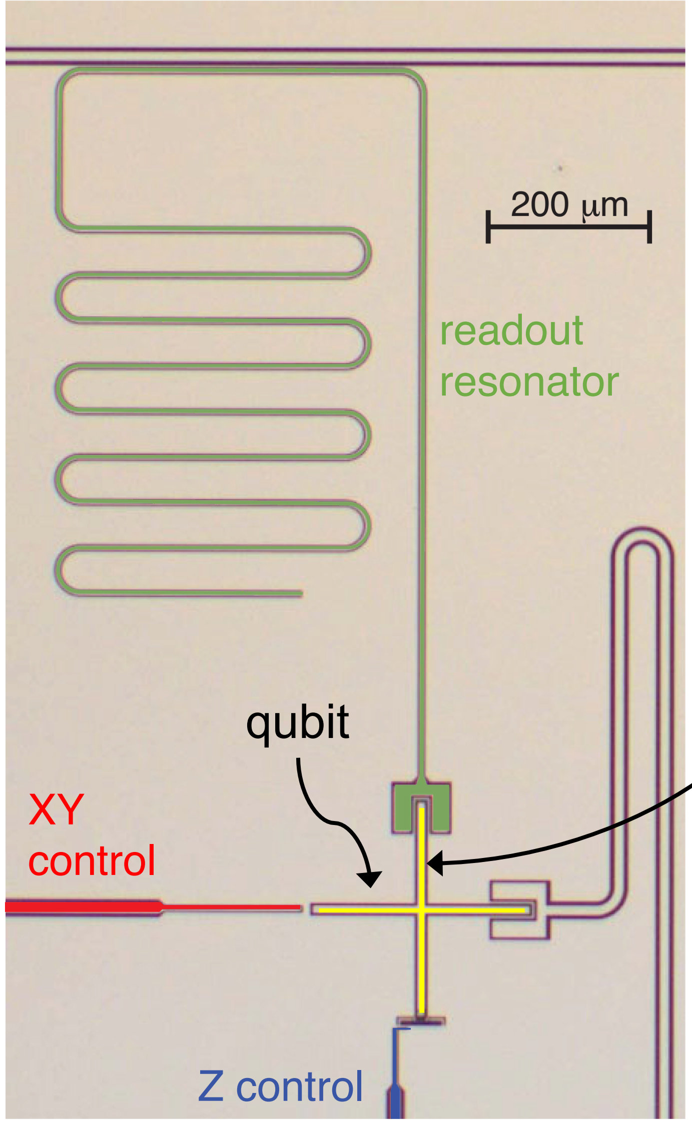
✓ Z control: square pulse (flux bias)

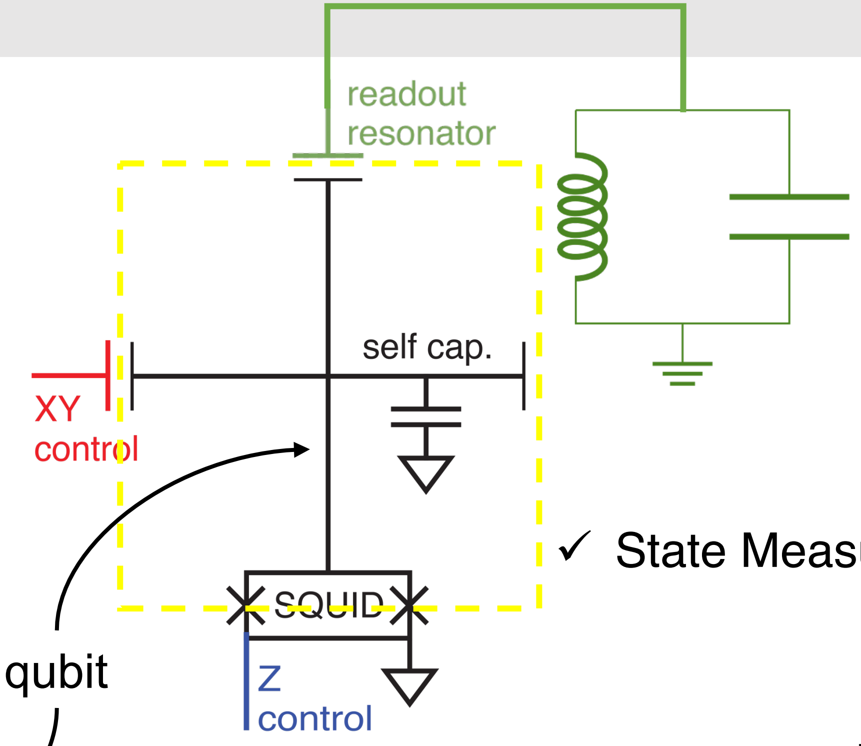
flux on SQUID: shifts qubit frequency (**phase-flip**)
→ rotation about the z-axis of the Bloch sphere

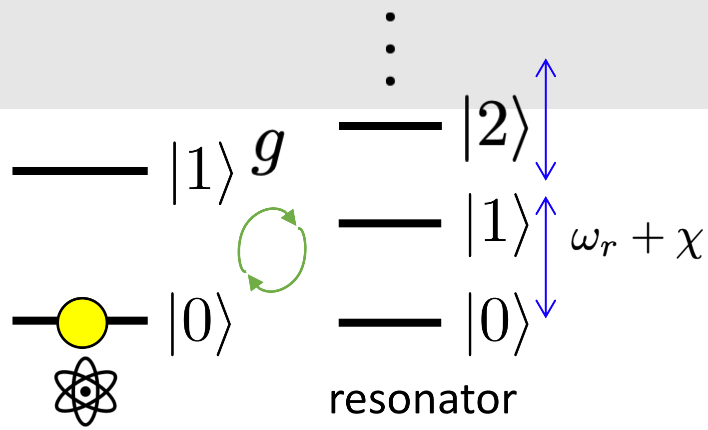


$$\frac{|0\rangle \pm |1\rangle}{\sqrt{2}} \to \frac{|0\rangle \mp |1\rangle}{\sqrt{2}}$$

Qubit Readout







$$\hat{H}_{\mathrm{disp}} = \chi\, \hat{a}^\dagger \hat{a}\, \hat{\sigma}_z$$

✓ State Measurement: by using a readout resonator

Measured Voltage Signal

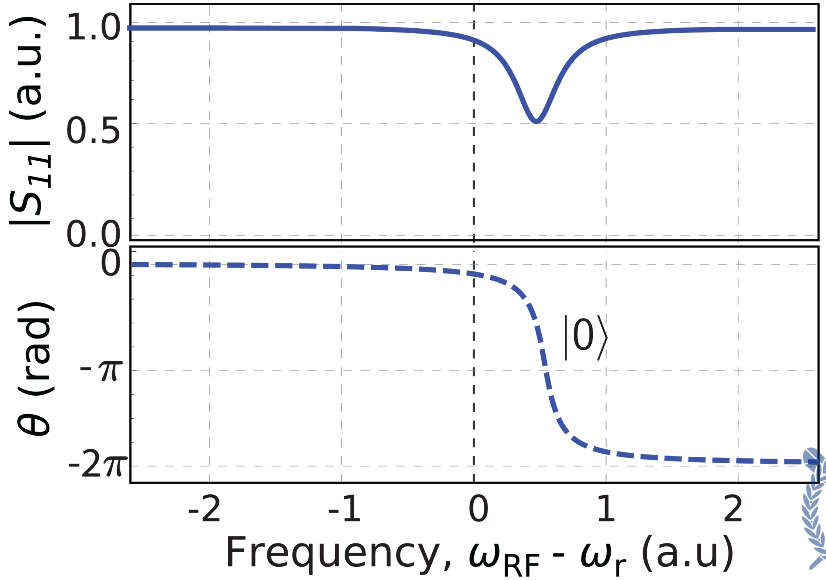
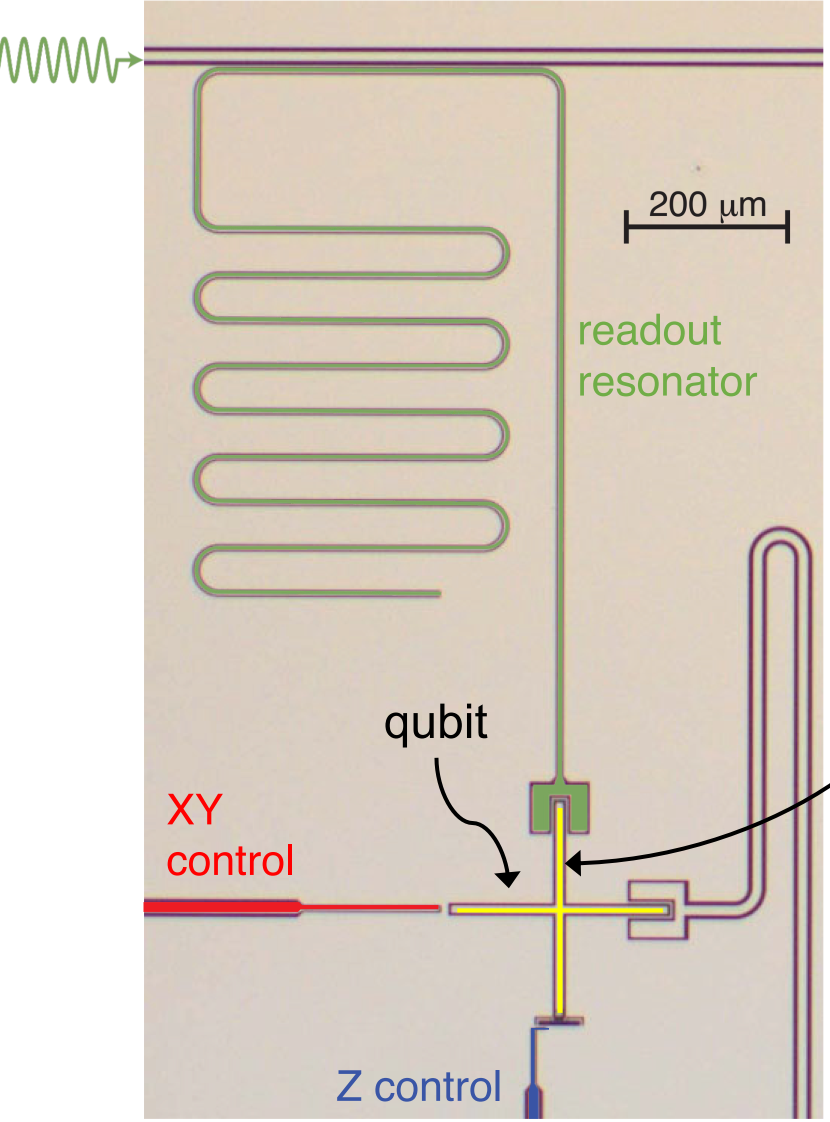
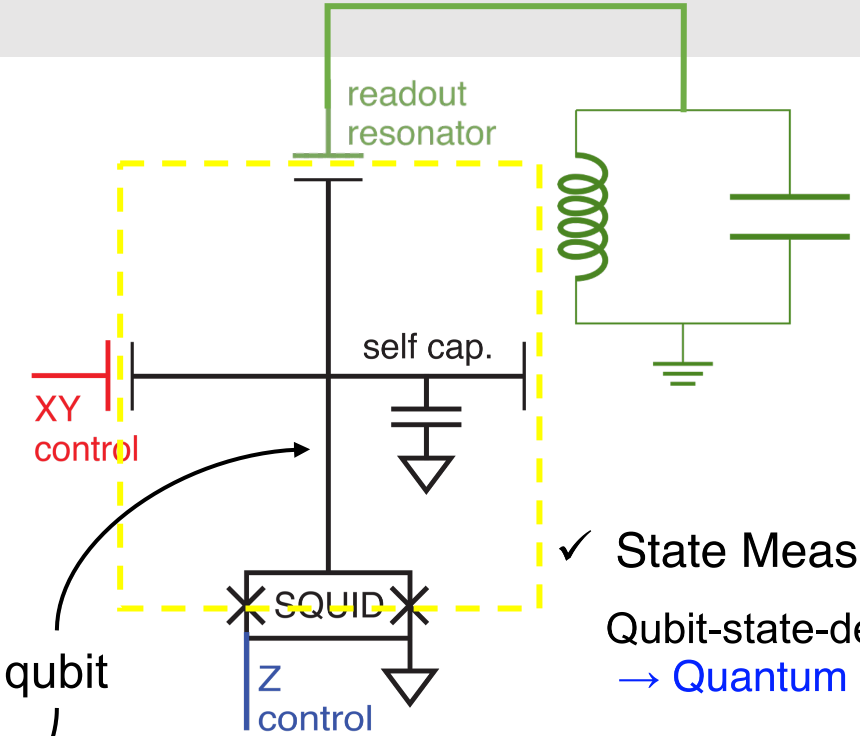
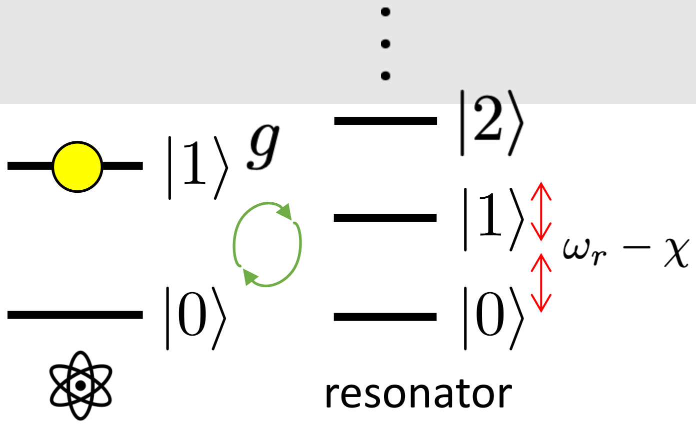


Figure adapted from
R. Barends et al.,
PRL **111**, 080502 (2013)

Qubit Readout



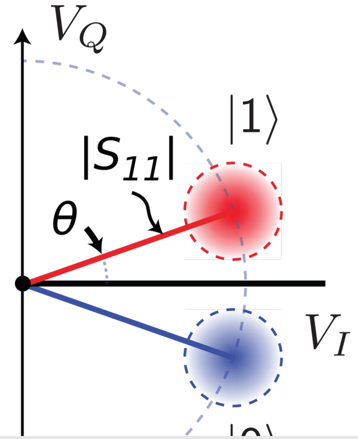




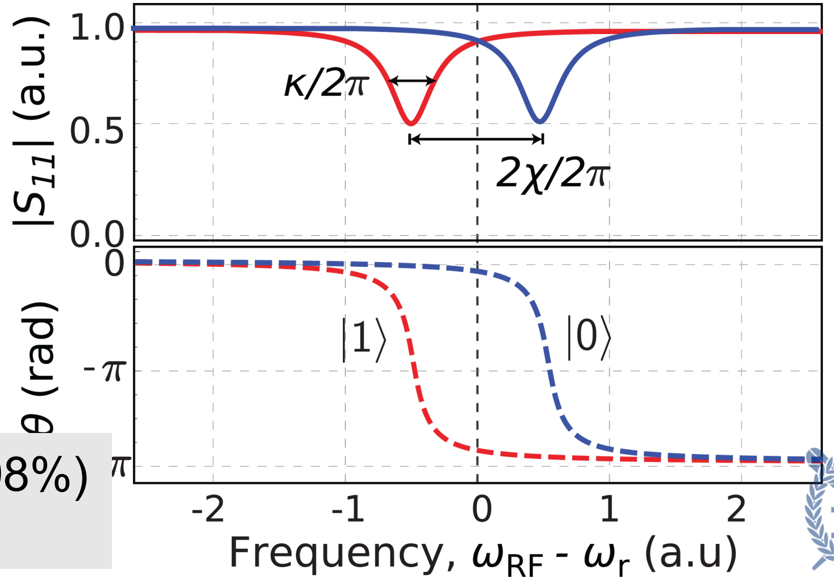
$$\hat{H}_{\text{disp}} = \chi\, \hat{a}^\dagger \hat{a}\, \hat{\sigma}_z$$

✓ State Measurement: by using a readout resonator

Qubit-state-dependent shift of resonator frequency
→ Quantum Non-Demolition (QND) Readout



Measured Voltage Signal

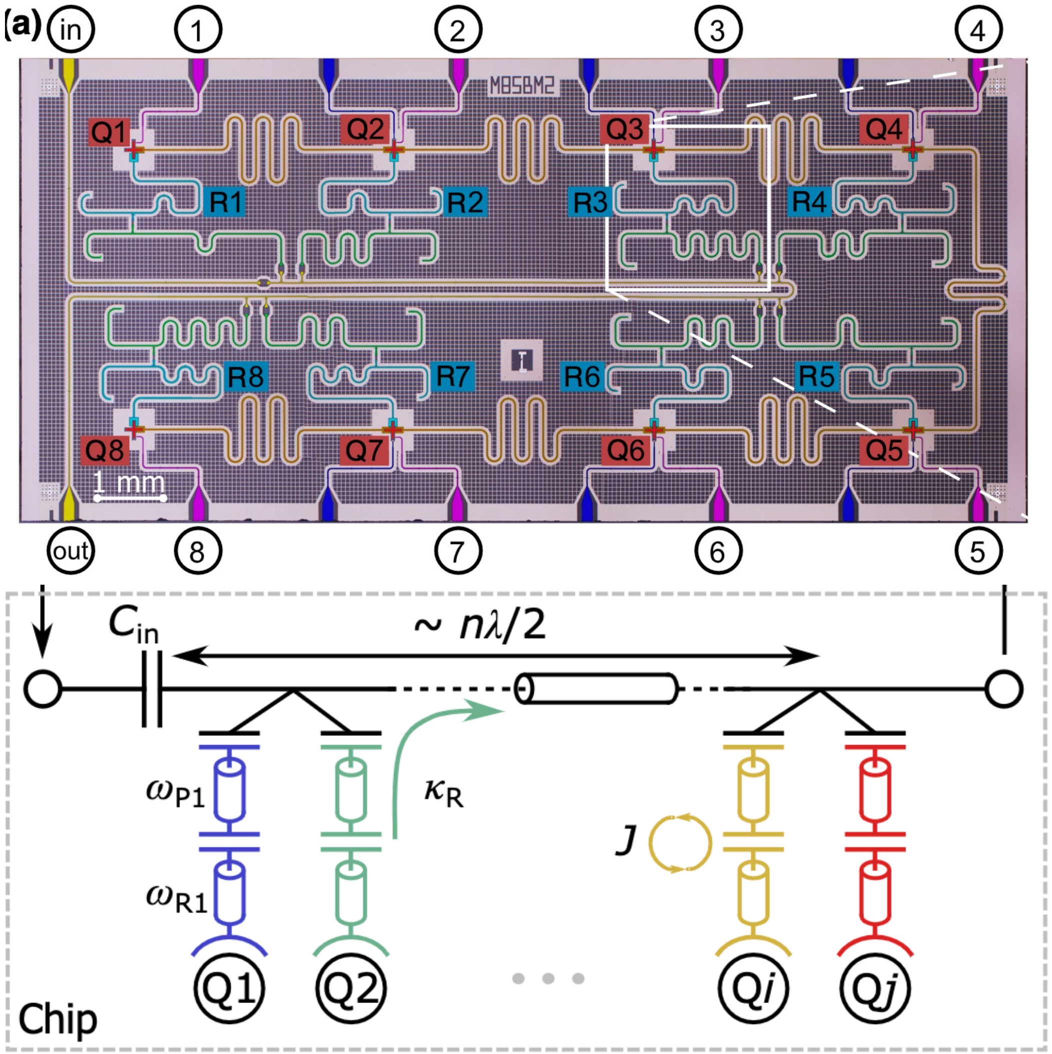


Rapid (<200ns), High-Fidelity(>98%)
QND Readout Achieveable

Figure adapted from
R. Barends et al.,
PRL **111**, 080502 (2013)

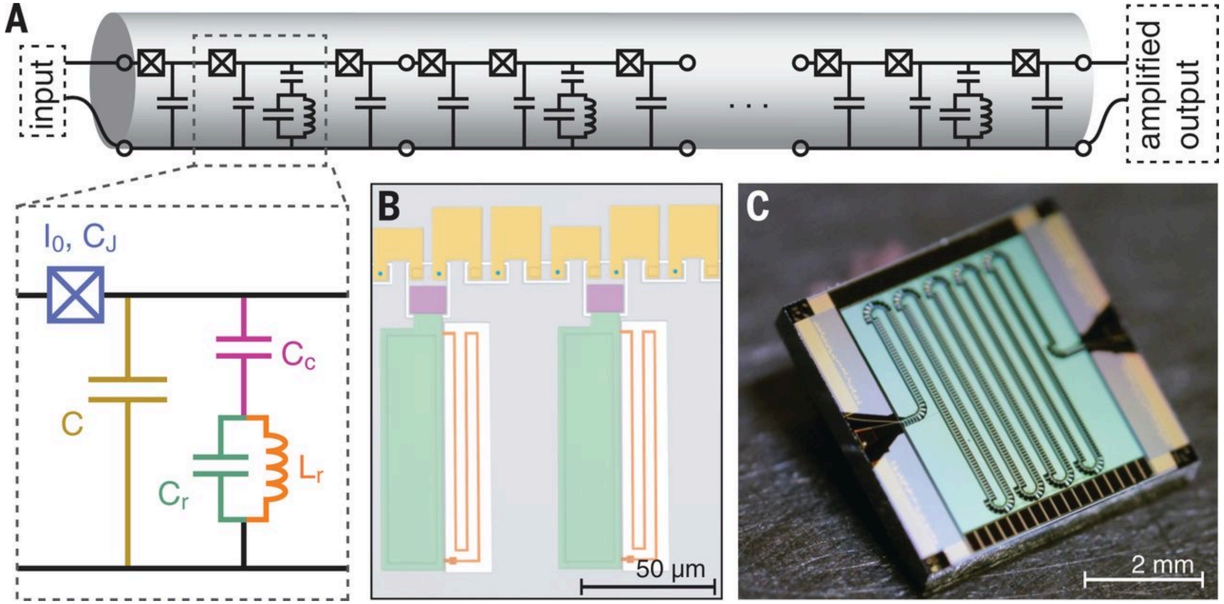
Simultaneous Readout of Multiple Qubits

Multiplexed Readout: use readout resonators at different frequencies, allocated to each qubit



PRApplied **10**, 034040 (2018)

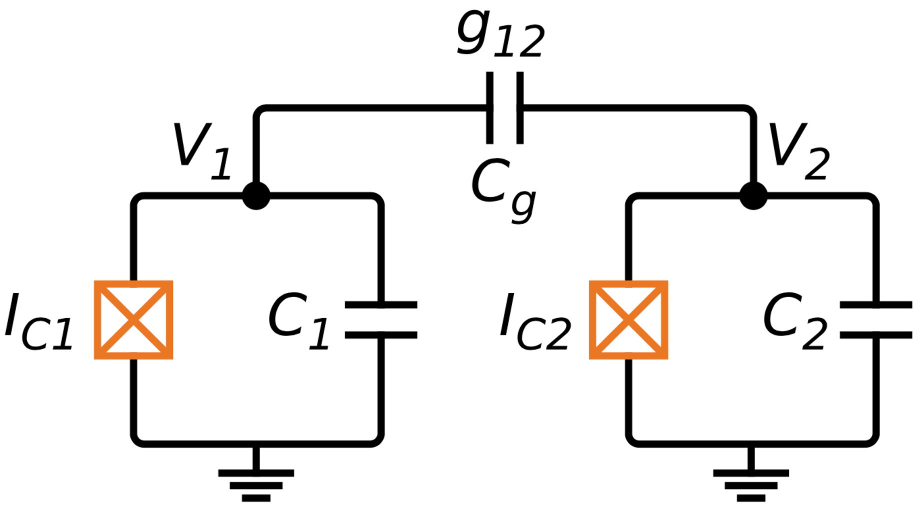
With the help of wideband Josephson parametric amp:
Josephson Travelling-Wave Parametric Amplifier (JTWPA)



Science **350**, 307-310 (2015)

- Can simultaneously readout 4-5 qubits using a single amp. chain
- Mid-Circuit Measurement Possible*

Two-Qubit Gate: Using Capacitive Coupling



Qubit-Qubit interaction from capacitive coupling

$$\hat{H} = g(\hat{\sigma}_1^+\hat{\sigma}_2^- + \hat{\sigma}_2^+\hat{\sigma}_1^-) = \frac{g}{2}(\hat{\sigma}_1^x\hat{\sigma}_2^x + \hat{\sigma}_1^y\hat{\sigma}_2^y)$$

(spin flip-flop interaction or spin XY model)

coupling strength determined from circuit parameters:

$$g = \frac{1}{2}\sqrt{\omega_1\omega_2}\frac{C_g}{\sqrt{(C_1+C_g)(C_2+C_g)}}$$

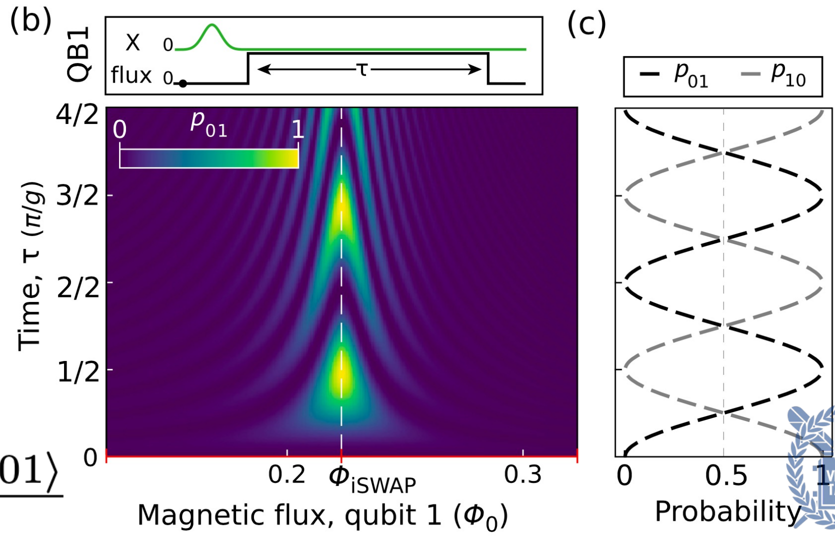
Typical values: 10-40 MHz

Unitary evolution matrix in the $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$ basis

$$U_{qq}(t) = e^{-i\frac{g}{2}(\sigma_x\sigma_x+\sigma_y\sigma_y)t} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(gt) & -i\sin(gt) & 0 \\ 0 & -i\sin(gt) & \cos(gt) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

At $t = \pi/g$, iSWAP gate: $|01\rangle \to -i|10\rangle$, $|10\rangle \to -i|01\rangle$

At $t = \pi/(2g)$, $\sqrt{\text{iSWAP}}$ gate: $|01\rangle \to \frac{|01\rangle - i|10\rangle}{2}$, $|10\rangle \to \frac{|10\rangle - i|01\rangle}{\sqrt{2}}$

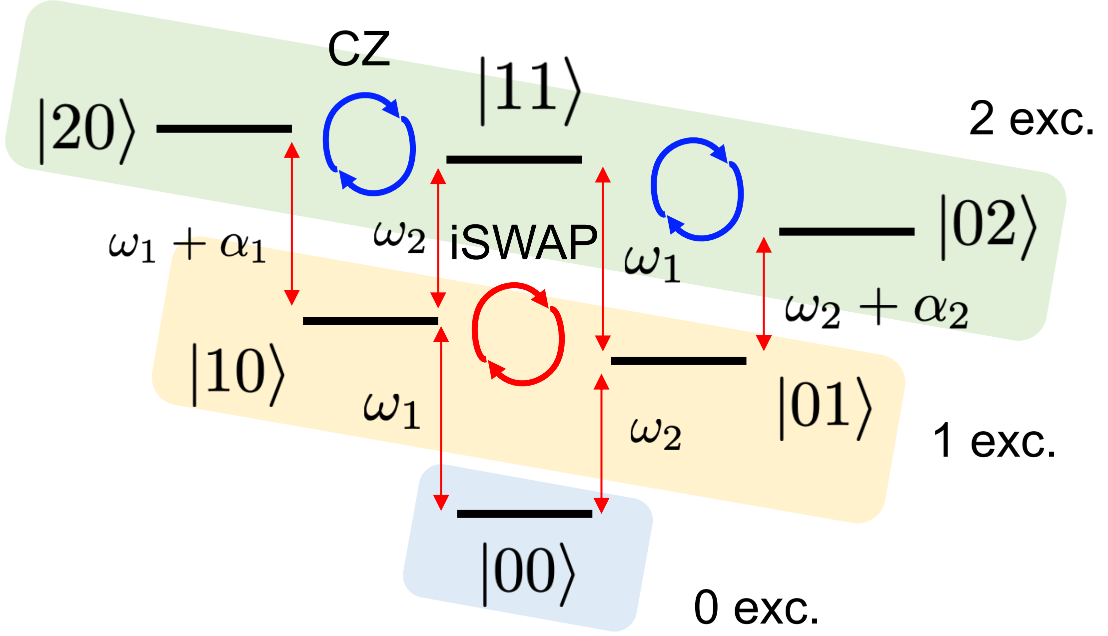


Two-Qubit Gate: CZ gate

Inclusion of higher excited levels (transmon)

$$\hat{H} = g(\hat{\sigma}_1^+\hat{\sigma}_2^- + \hat{\sigma}_2^+\hat{\sigma}_1^-) \longrightarrow \hat{H} = g(\hat{b}_1^\dagger\hat{b}_2 + \hat{b}_2^\dagger\hat{b}_1)$$

$$\hat{H} = \begin{bmatrix} E_{|00\rangle} & 0 & 0 & 0 & 0 & 0 \\ 0 & E_{|01\rangle} & g & 0 & 0 & 0 \\ 0 & g & E_{|10\rangle} & 0 & 0 & 0 \\ 0 & 0 & 0 & E_{|11\rangle} & \sqrt{2}g & \sqrt{2}g \\ 0 & 0 & 0 & \sqrt{2}g & E_{|02\rangle} & 0 \\ 0 & 0 & 0 & \sqrt{2}g & 0 & E_{|20\rangle} \end{bmatrix}$$



$|ij\rangle$: qubit 1 in state $|i\rangle$, qubit 2 in state $|j\rangle$

$|11\rangle \leftrightarrow |20\rangle$ are coupled when $\omega_1 + \alpha_1 = \omega_2$

$$|\psi(t)\rangle = \cos(\sqrt{2}gt)|11\rangle - i\sin(\sqrt{2}gt)|20\rangle$$

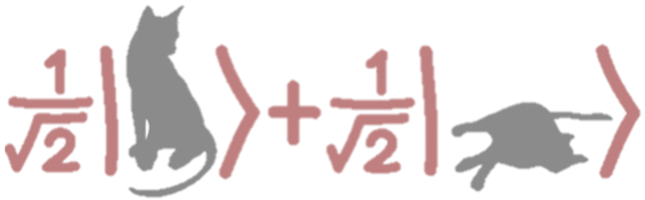
At $t_{\mathrm{CZ}} = \pi/(\sqrt{2}g)$, $|\psi(t_{\mathrm{CZ}})\rangle = -|11\rangle$

$$U_{\mathrm{CZ}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

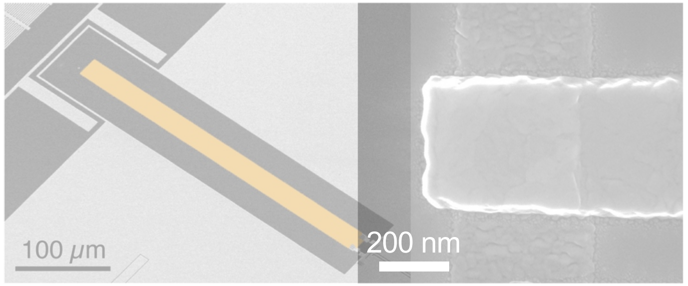
Now we have the universal gate set!

Content

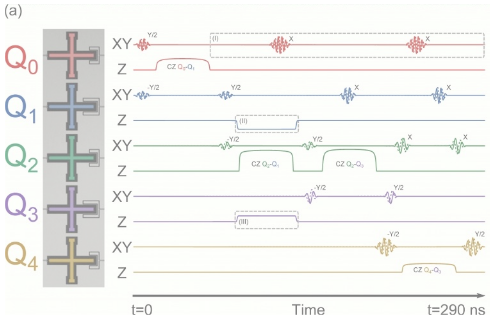
Motivation: Quantum Computation



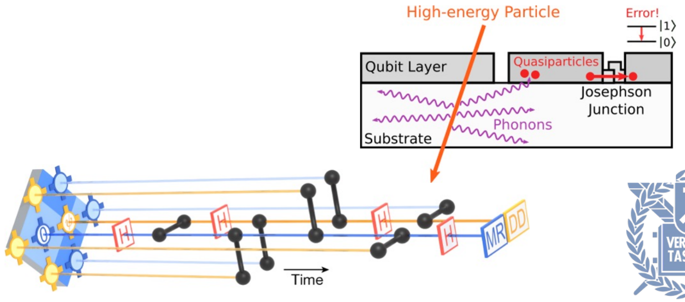
Superconducting Qubits & Circuit QED



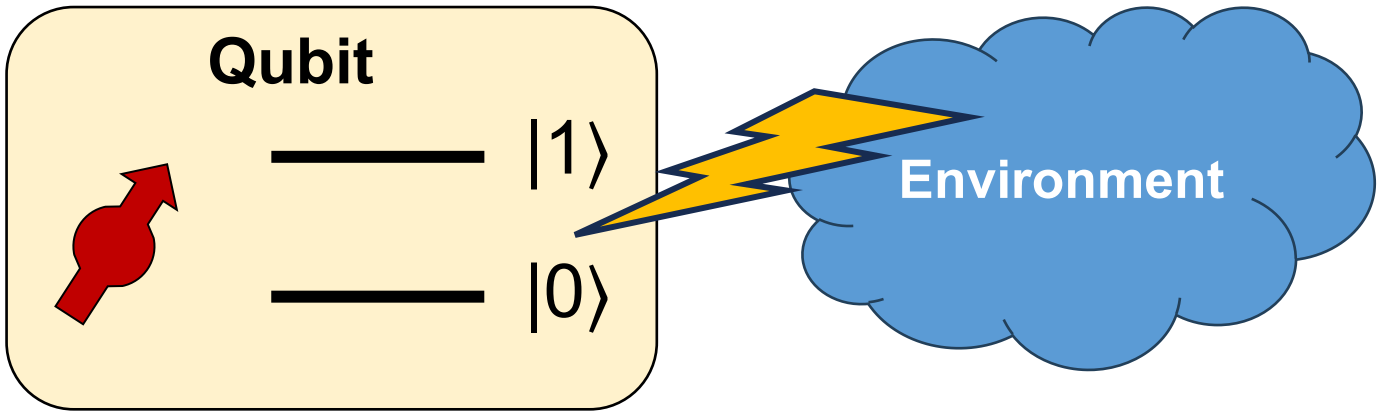
Control & Readout of Superconducting Qubits



Challenges, Current Research Topics

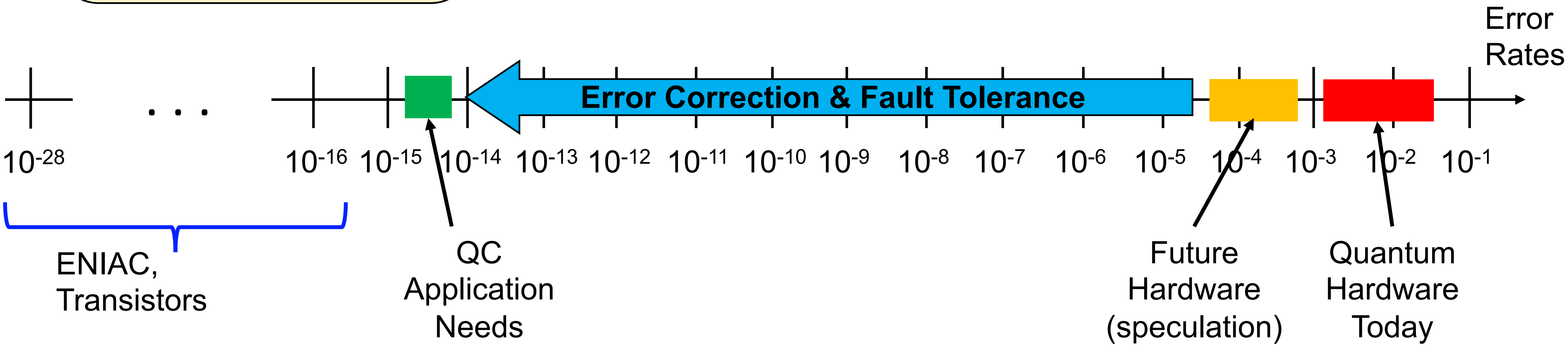


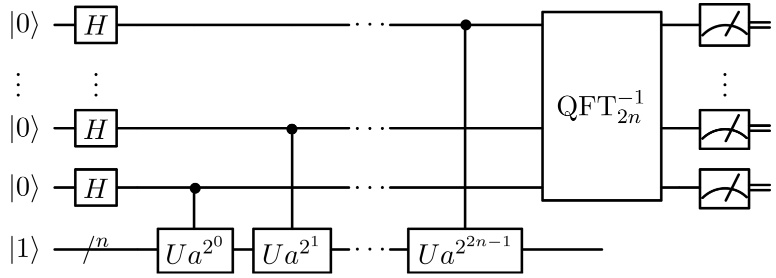
Problem: Quantum information is fragile

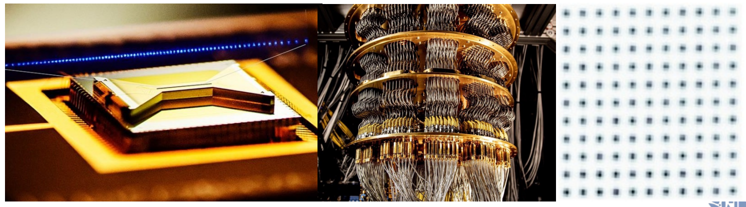


"The environment is watching"

Decoherence



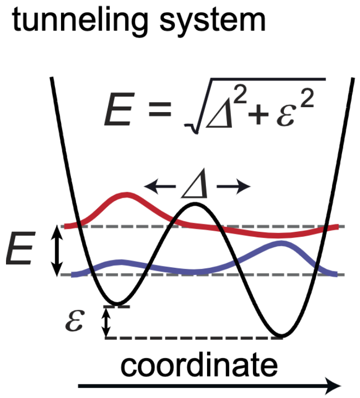


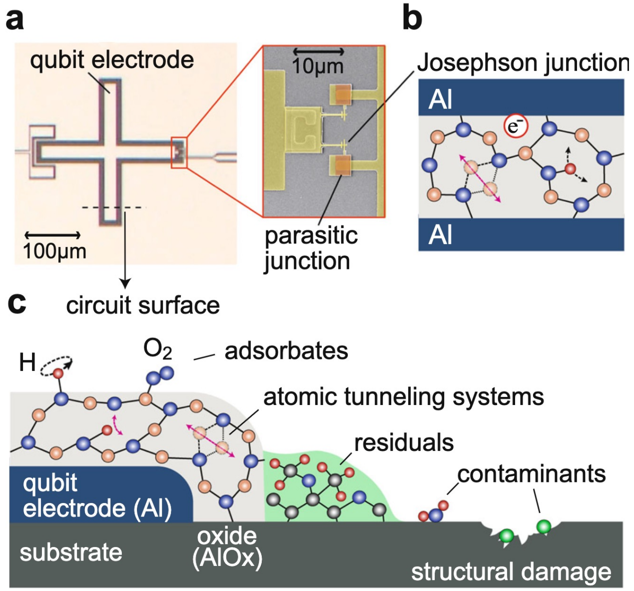


Reducing Error: Decoherence Mechanisms

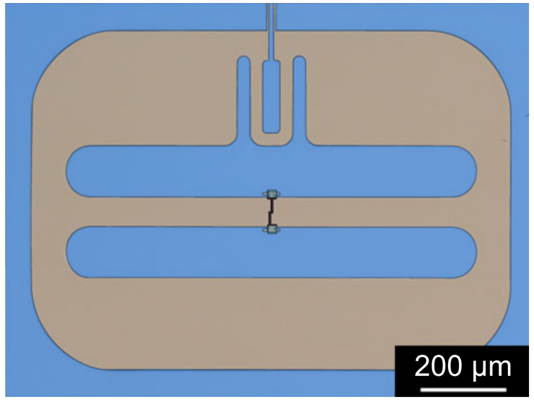
Engineering of electromagnetic environment from advanced circuit design, better fab
→ T_1 ~ 100 μs until 2019

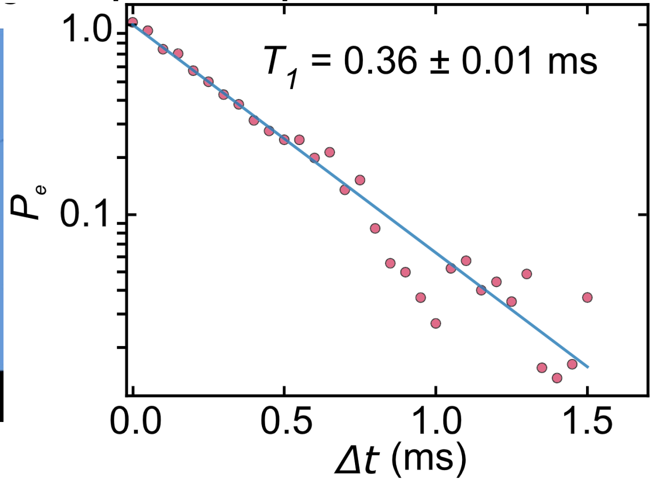
Major decoherence mechanism:
Two-Level System (TLS) defects → dielectric loss

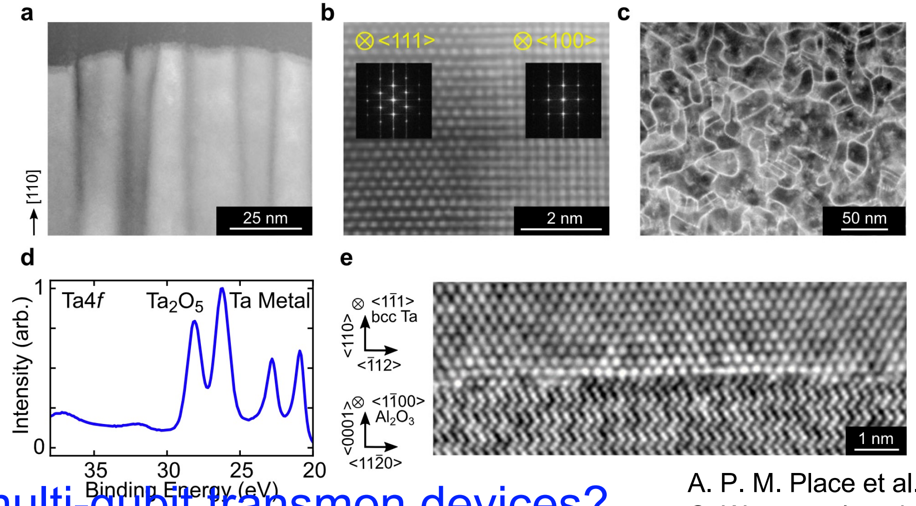




Breakthrough in the early 2020s:
use of α-Ta (T_c ~ 4.4K) for qubit capacitor







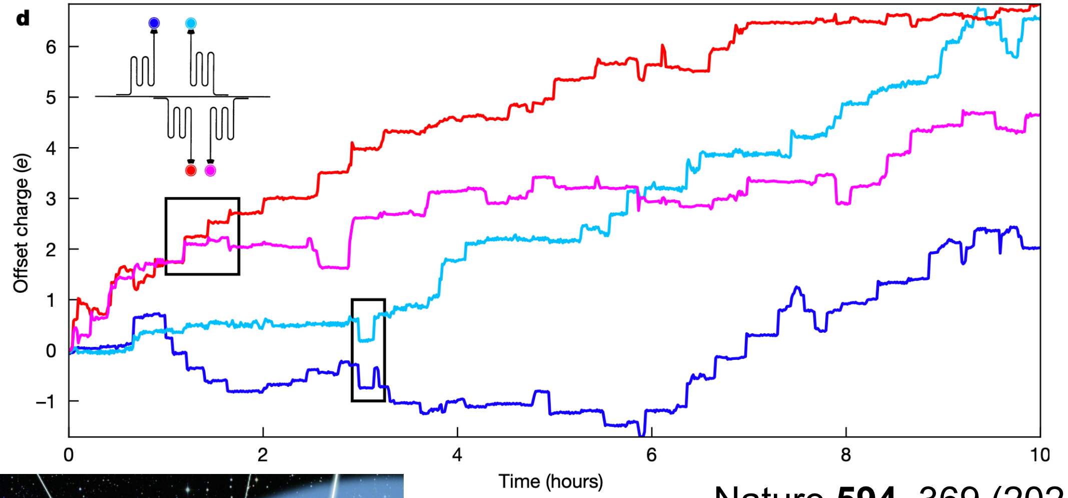
Best Lifetime:
T_1 ~ 300-500 μs

Open Question:
Is it possible to achieve millisecond coherence times in multi-qubit transmon devices?

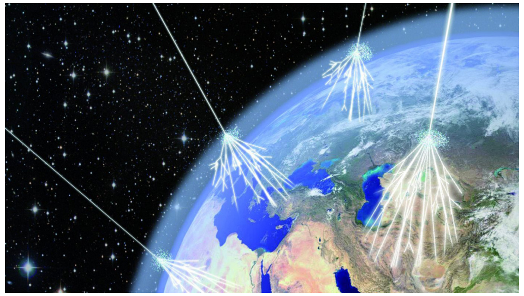
A. P. M. Place et al., Nat. Commun. **12**, 1779 (2021)
C. Wang et al., npj Quantum Inf. **8**, 3 (2022)

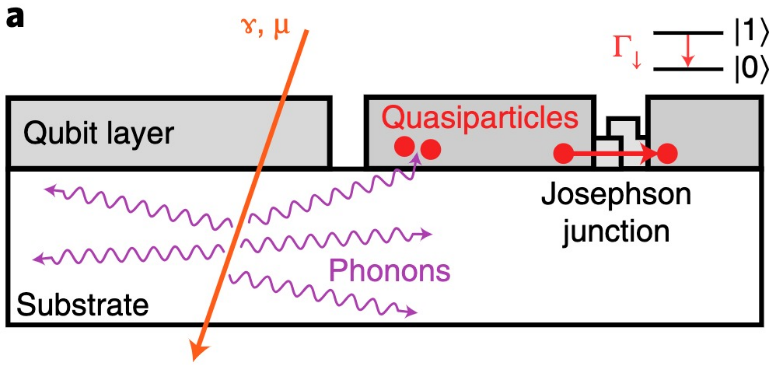
Reducing Error: Decoherence Mechanisms

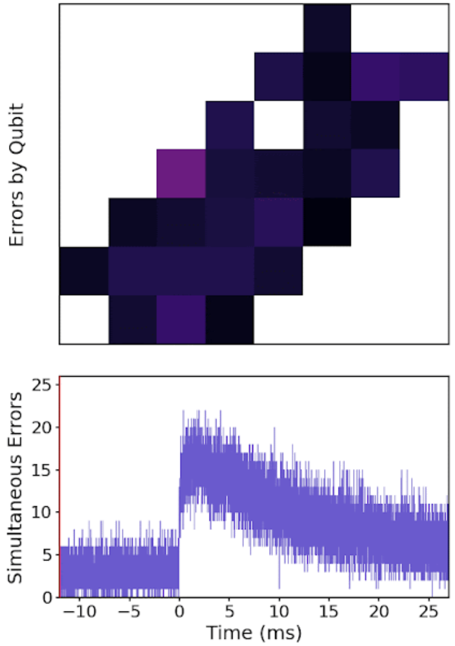
Correlated Errors: Cannot be corrected with QEC



Nature **594**, 369 (2021)







Nature Physics **18**, 107 (2022)

This event happens
once every 10s on average

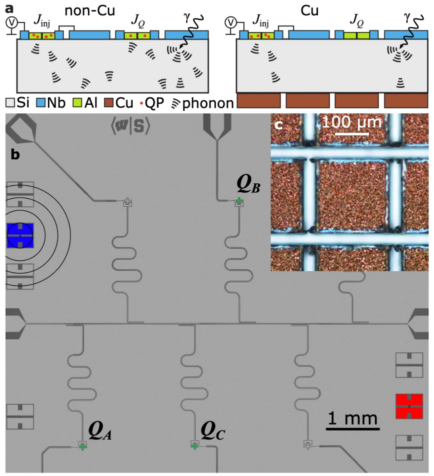
Cosmic ray (high-energy particle E ~ 100keV – 1MeV) hits the sample

→ Phonons in the bulk substrate are excited

→ Break Cooper pairs (Δ ~ 350 ueV), induces quasiparticles

→ Correlated qubit decay or parity jump

Mitigation strategy example: normal-metal reservoir

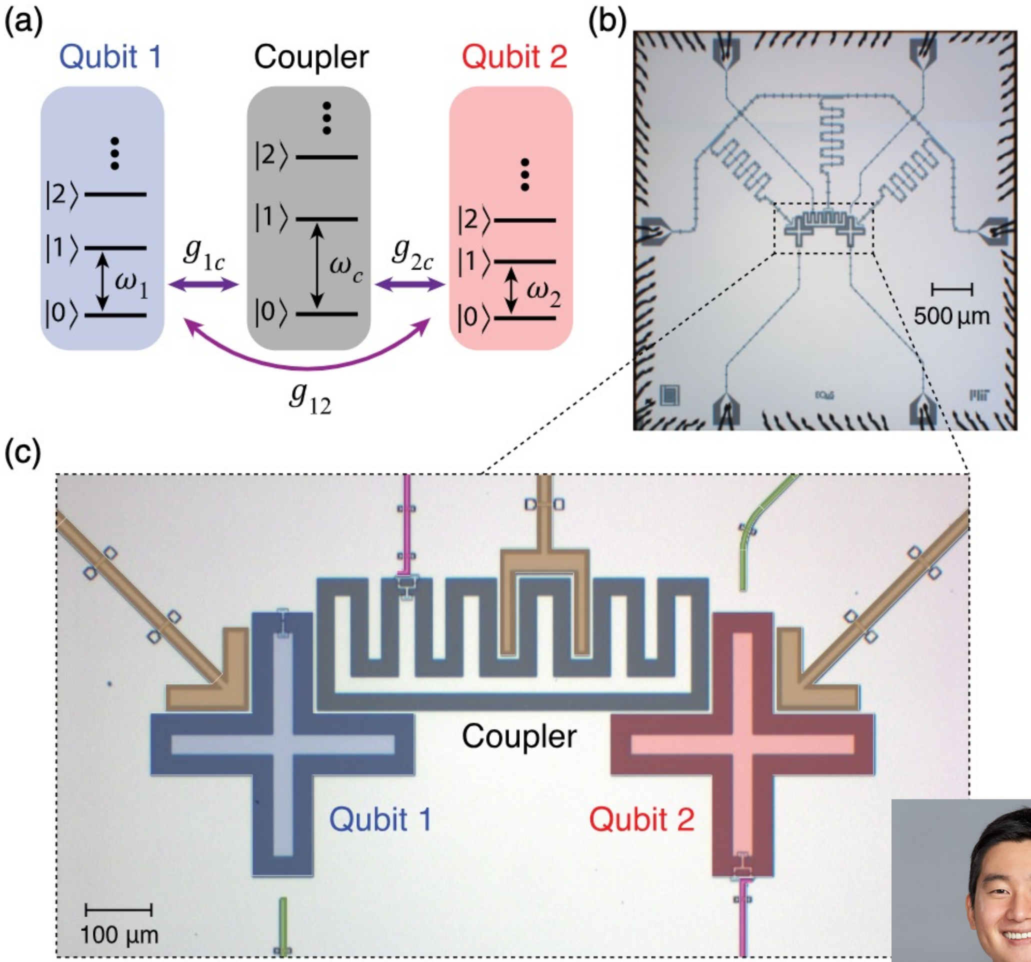


V. Iaia, J. Ku et al., Nat. Commun. **13**, 6425 (2022)

Dr. Jaseung Ku
(currently @ KRISS)

Reducing Error: High-Fidelity Gate

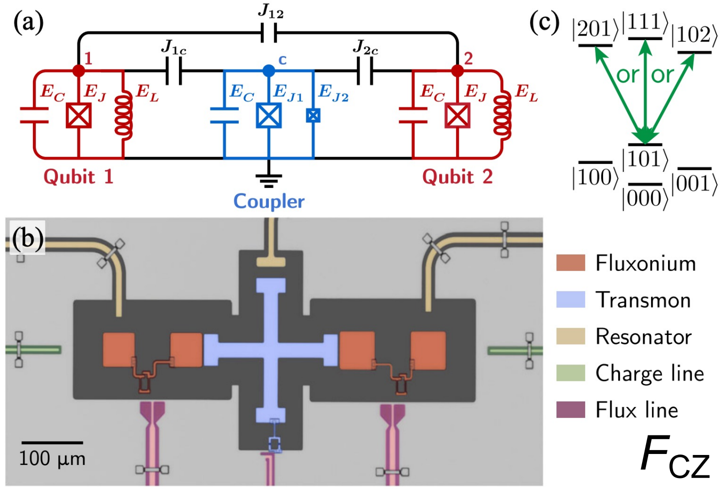
Tunable-coupling element: high on-off ratio of coupling



F. Yan et al., PRApplied **10**, 054062 (2018)
Y. Sung et al., PRX **11**, 021058 (2021)

Dr. Youngkyu Sung
(currently @ Atlantic Quantum)

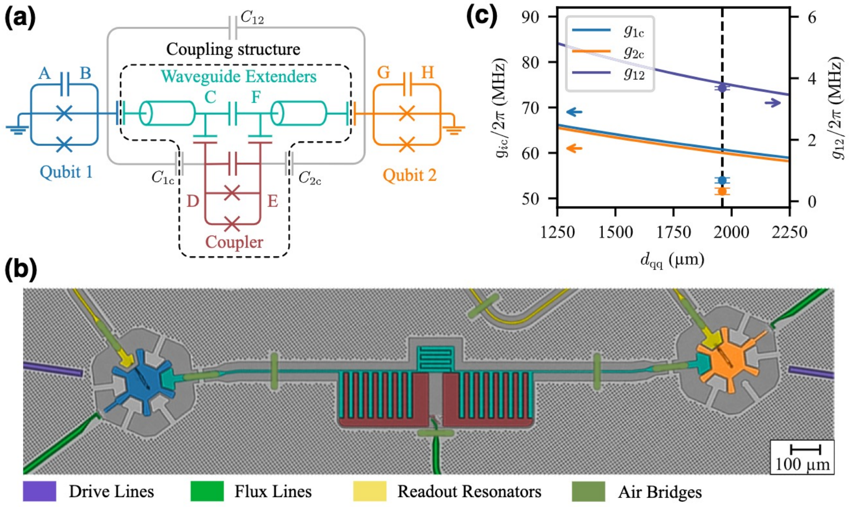
- Fluxonium-Transmon-Fluxonium Architecture



F_{CZ} > 99.9%

PRX **13**, 031035 (2023)

- Long-Distance Transmon Coupler

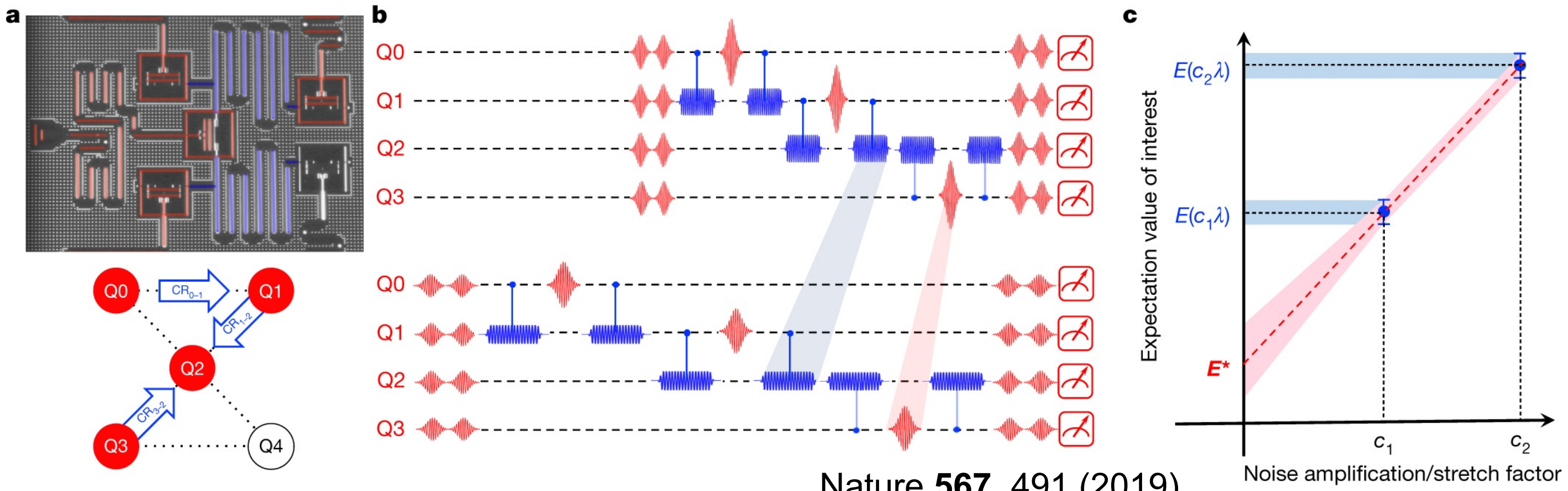


PRX Quantum **4**, 010314 (2023)

F_{CZ} > 99.8%

Surviving from Error: Quantum Error Mitigation

Zero-Noise Extrapolation (ZNE):



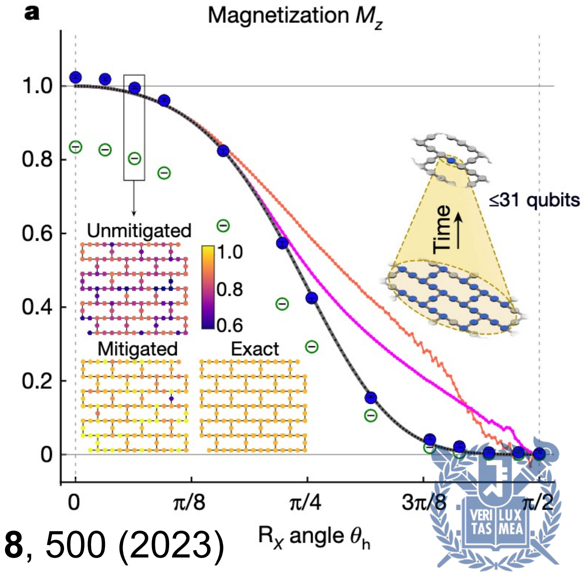
Nature **567**, 491 (2019)

Expectation value obtained from scaling the noise (e.g., can use a longer pulse with the same area)

→ Used to extrapolate the zero-noise limit of the expectation value (result that we want)

Successful execution reported in 127-qubit IBM quantum processor

→ utility of quantum computing before fault tolerance?

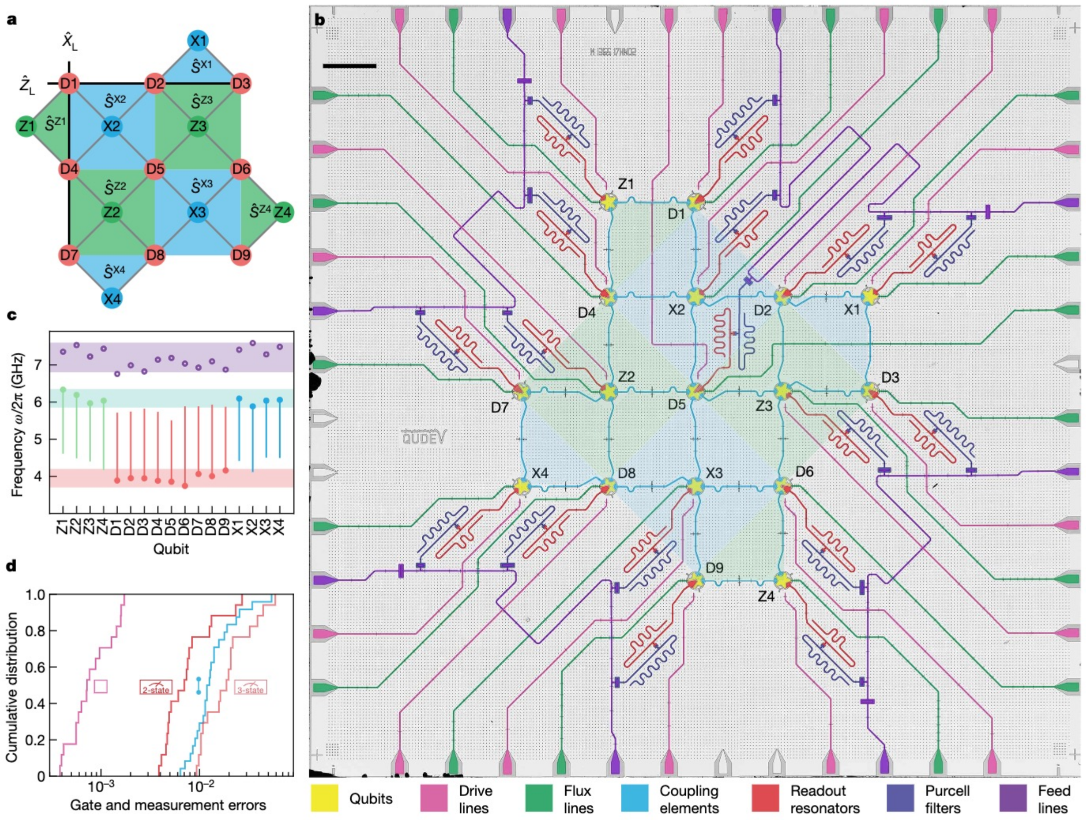


Nature **618**, 500 (2023)

See Review: RMP **95**, 045005 (2023)

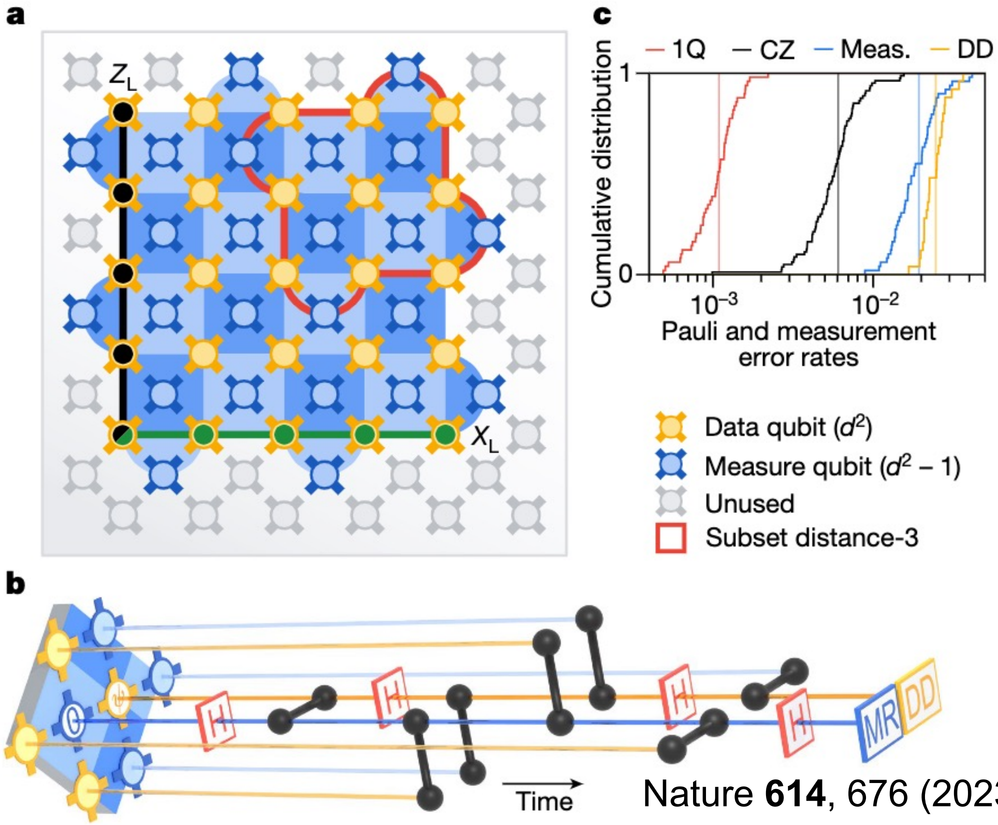
Fighting off Error: Quantum Error Correction

- Distance-3 Surface Code



Nature **605**, 669 (2022)

- Logical Error Reduction by Scaling Surface Code



Nature **614**, 676 (2023)

distance-3: (3.028 ± 0.023)% logical error per cycle

distance-5: (2.914 ± 0.016)% logical error per cycle

Challenge: massive overhead

Assuming physical error rate of 10^{-3},

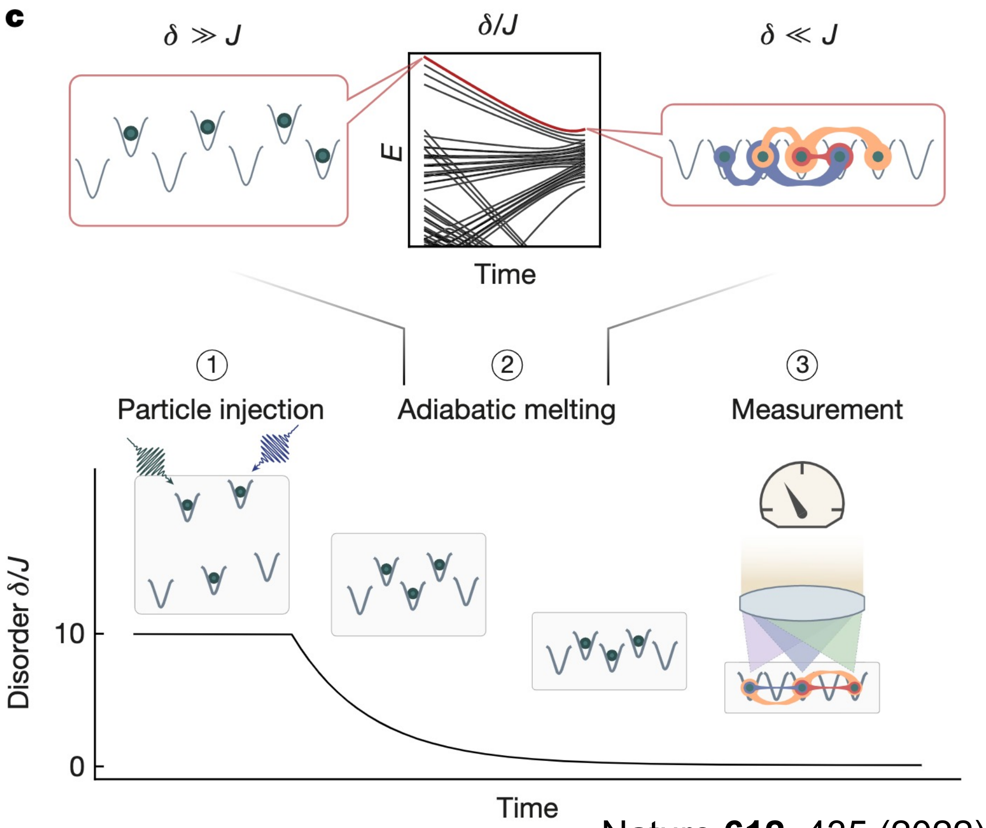
Need more than 1000 qubits per logical qubit to realize "practical" logical error rate < 10^{-12}

New Error Correction Schemes: Quantum LDPC Code → requires long-range connectivity between qubits

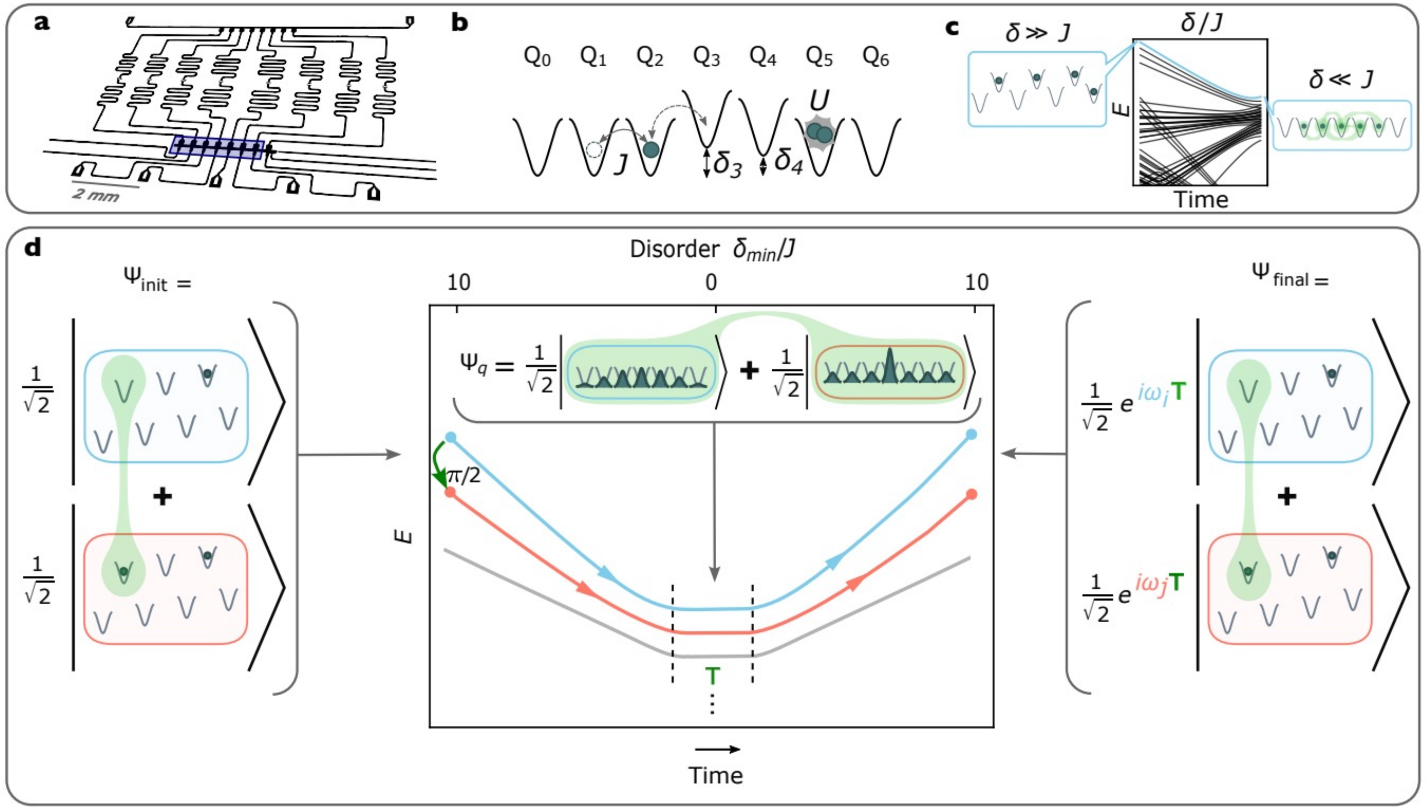
Nature **627**, 778 (2024)

Quantum Many-Body Physics

- Full individual local qubit control (XY and Z)
- Quantum non-demolition measurement + mid-circuit measurement
- Real-time feedback operation (enables fast repetition with active reset)



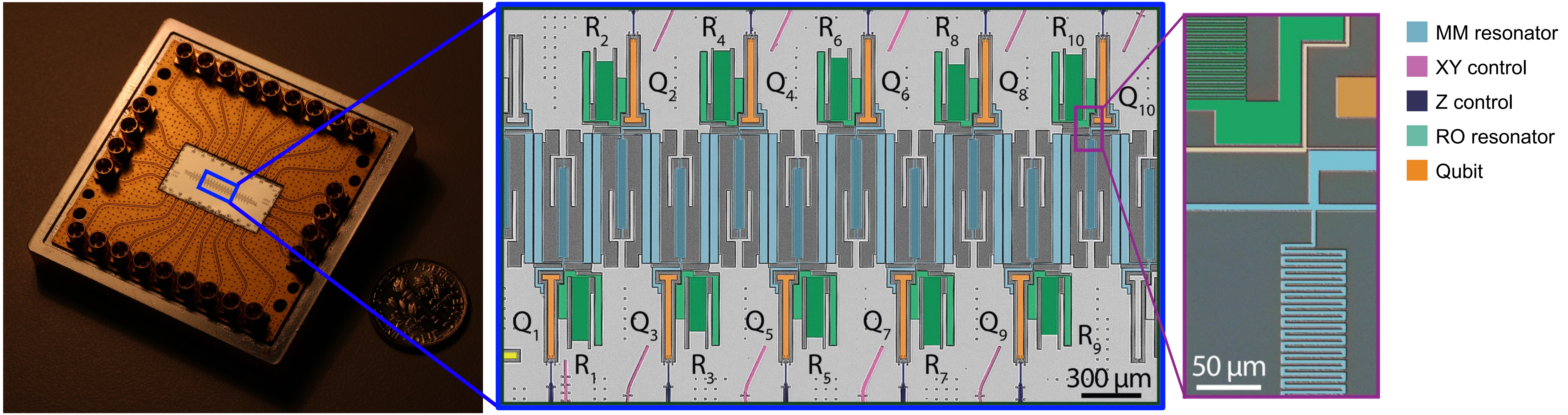
Nature **612**, 435 (2022)

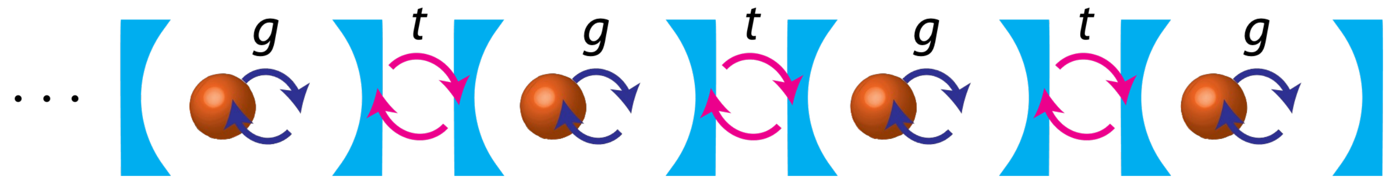


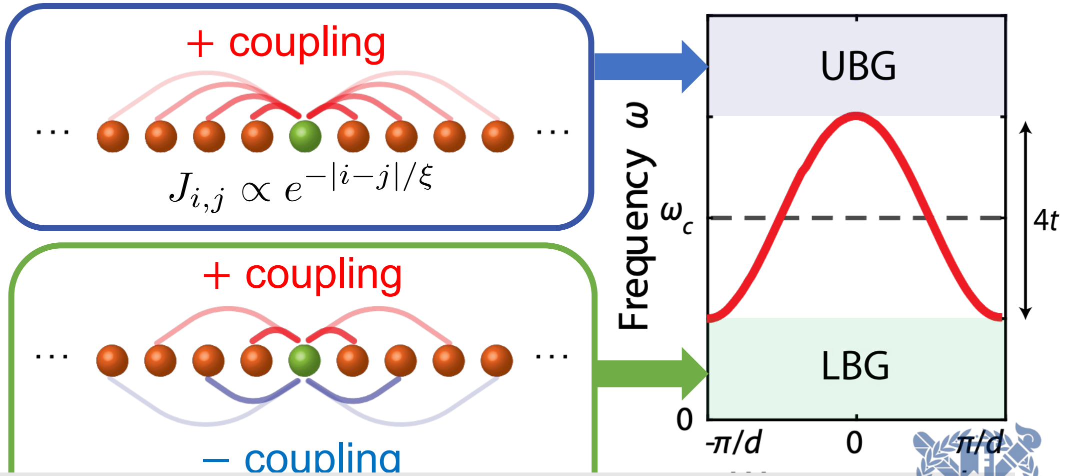
arXiv:2309.05727 (2023)

→ Playground for high-fidelity quantum simulation of many-body phenomena

Our work: Interfacing with MW Photonic Structures







Photonic-bandgap metamaterial:
a tight-binding array of microwave cavities

Superconducting qubits:
coupled to every cavity site of the metamaterial

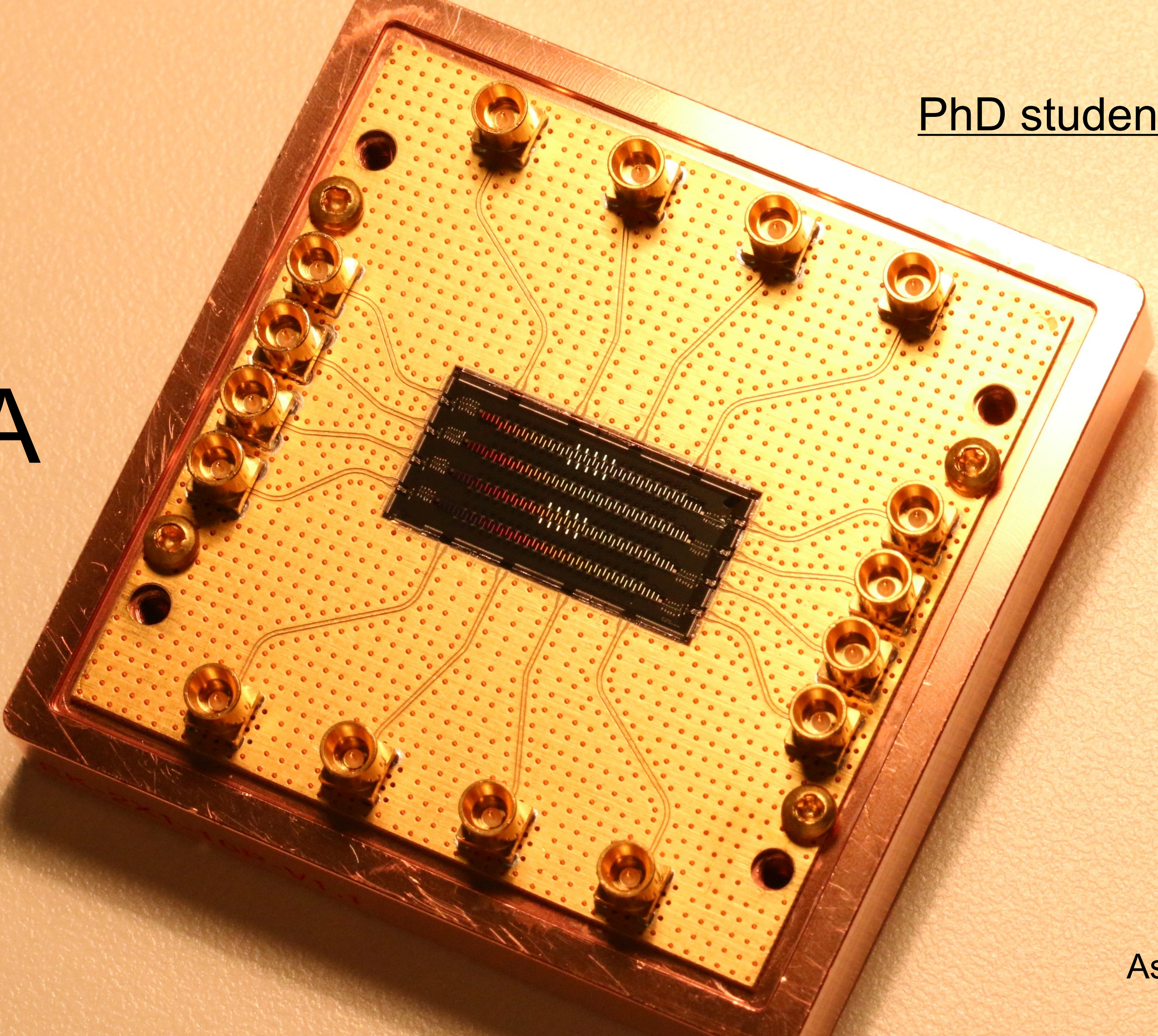
X. Zhang*, **EK*** et al. Science **379**, 278-283 (2022)

Goal: Novel Directions for Quantum Simulation with Superconducting Circuits

Looking for
PhD students & Postdocs!

Lab Info

Q & A



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