超伝導量子コンピュータの研究開発

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RIKEN Center for Quantum Computing

RIKEN QUANTUM COMPUTING

Since April 2021

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Hidehiro Yonezawa (Photon)
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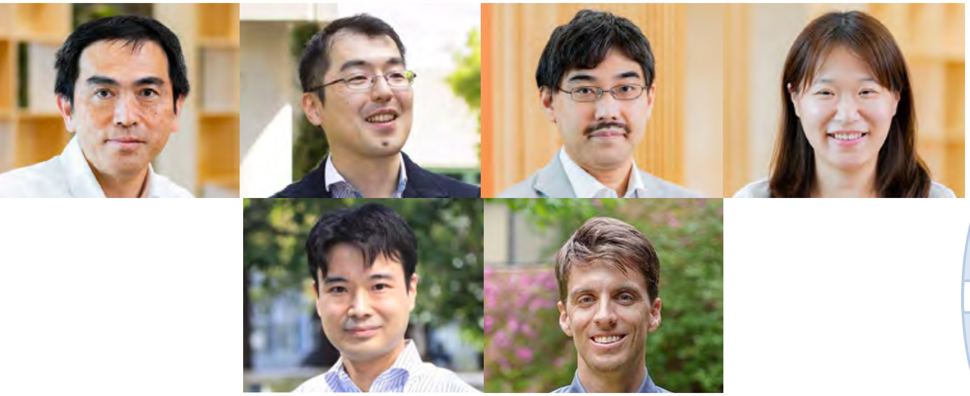
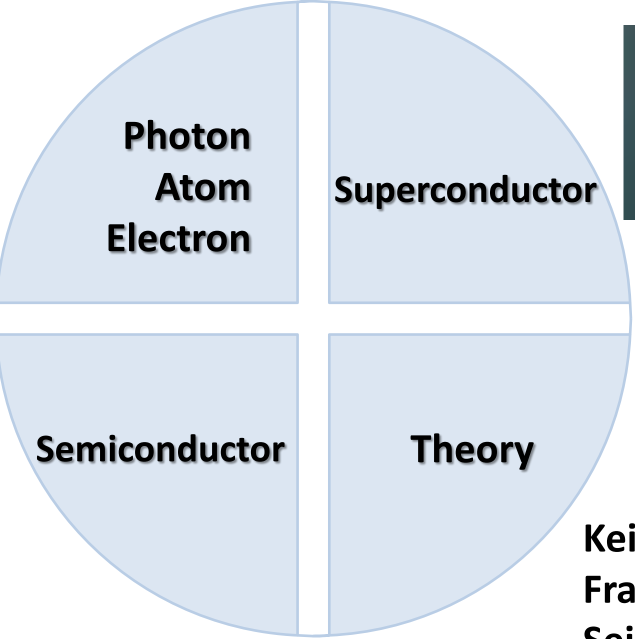
Takao Aoki (Cavity QED)
Sylvain de Léséleuc (Cold atom)
Erika Kawakami (Floating electron)



Atsushi Noguchi (Hybrid system)

Yasunobu Nakamura (Director)
Jaw-Shen Tsai
Eisuke Abe
Yutaka Tabuchi



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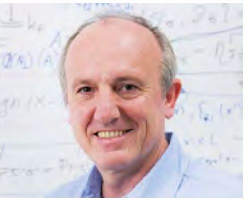
(Deputy Director of RQC-FUJITSU Collaboration Center)

FUJITSU

Seigo Tarucha

Daniel Loss



Keisuke Fujii
Franco Nori
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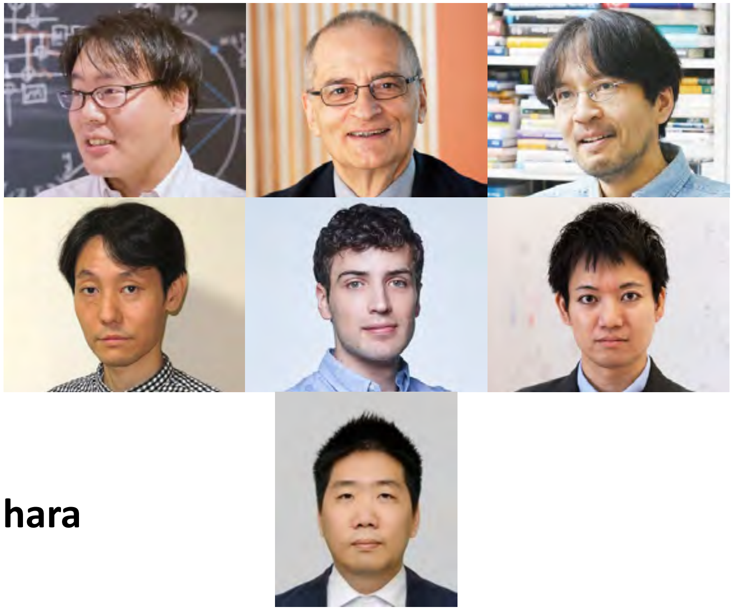
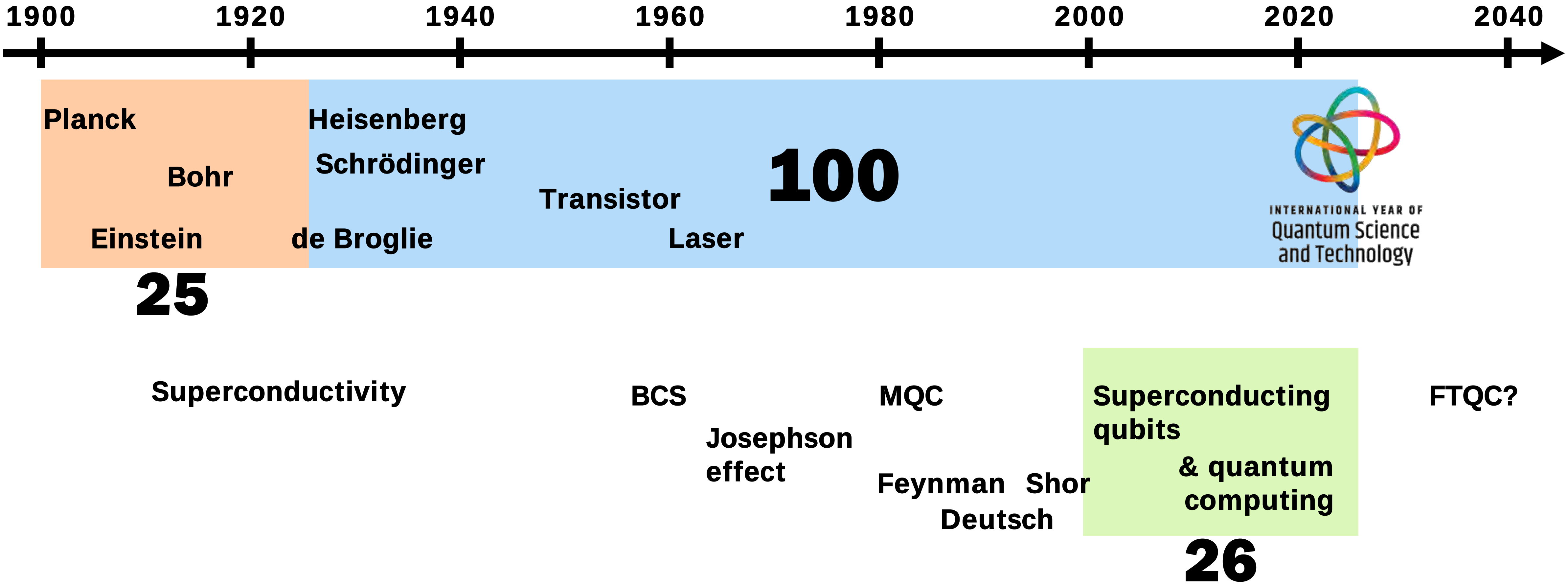
Tomotaka Kuwahara



100+ years of quantum mechanics



Planck

Bohr

Einstein

25

Heisenberg

Schrödinger

de Broglie

Transistor

Laser

100

INTERNATIONAL YEAR OF
Quantum Science
and Technology

Superconductivity

BCS

Josephson effect

MQC

Feynman Shor

Deutsch

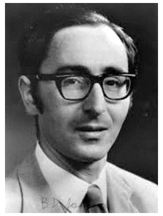
Superconducting qubits
& quantum computing

26

FTQC?

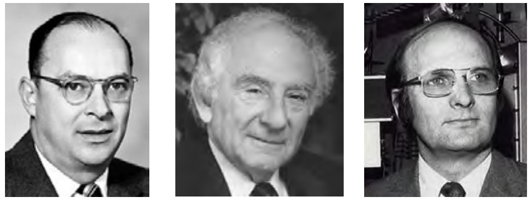
History of superconducting quantum circuits

SQUID



Josephson effect

BCS theory



1911 Superconductivity

Josephson computer

SFQ logic

Macroscopic quantum coherence

Macroscopic quantum tunneling

Energy-level quantization

Single electron charging

Mesoscopic superconductivity

Quantum information

Superconducting qubit

Circuit QED

Dissipation engineering

Waveguide QED

Microwave quantum optics

Hybrid system

NISQ

Surface code

qLDPC code

FTQC?

Bosonic mode encoding

Quantum annealing machine

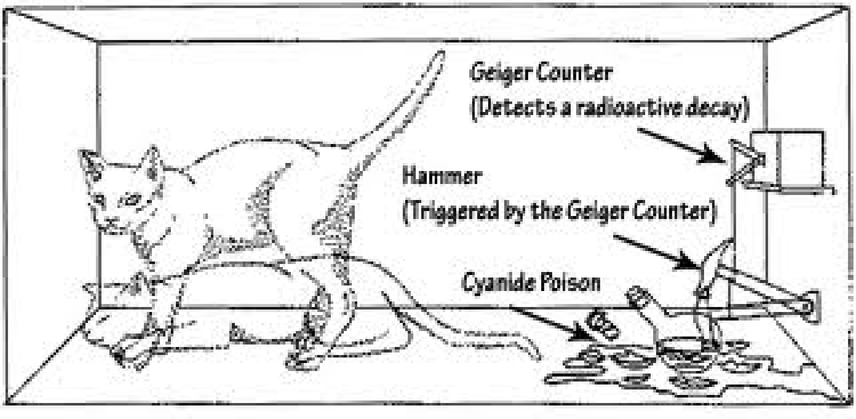
Quantum simulator

Quantum computer

???

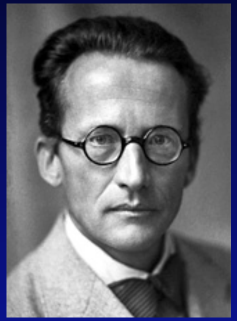
Superposition in macroscopic systems

Schrödinger's paradox



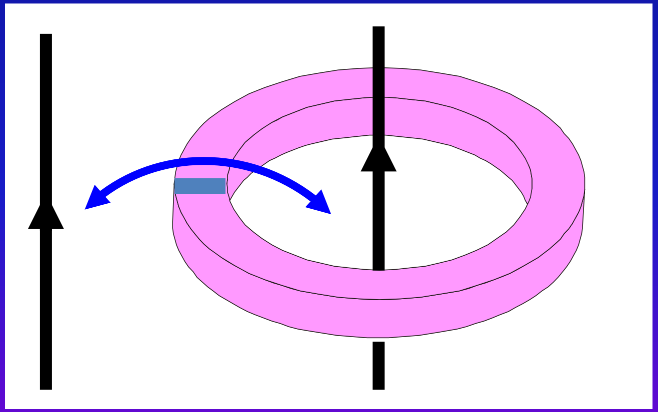
Macro-realism vs. Quantum mechanics

Dead and Alive



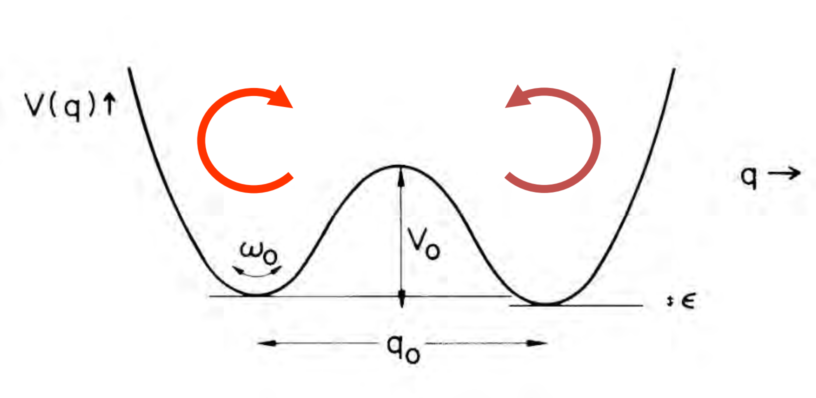
E. Schrödinger 1935

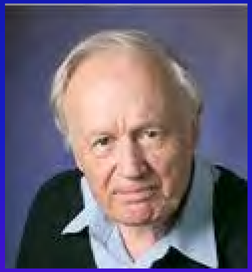
Macroscopic quantum coherence



Flux quantum
Φ_0

Superconducting
loop





A. J. Leggett 1980

Josephson effect

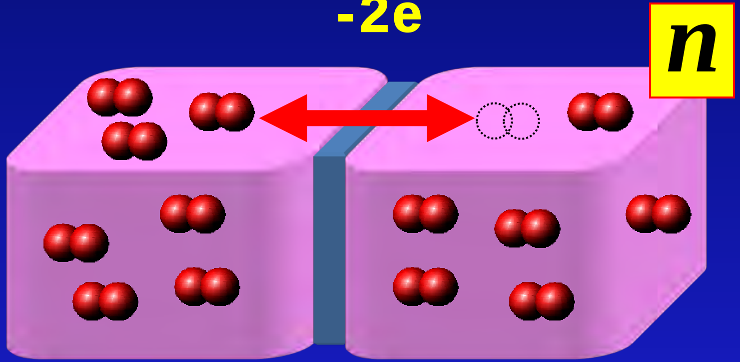
B. D. Josephson 1962

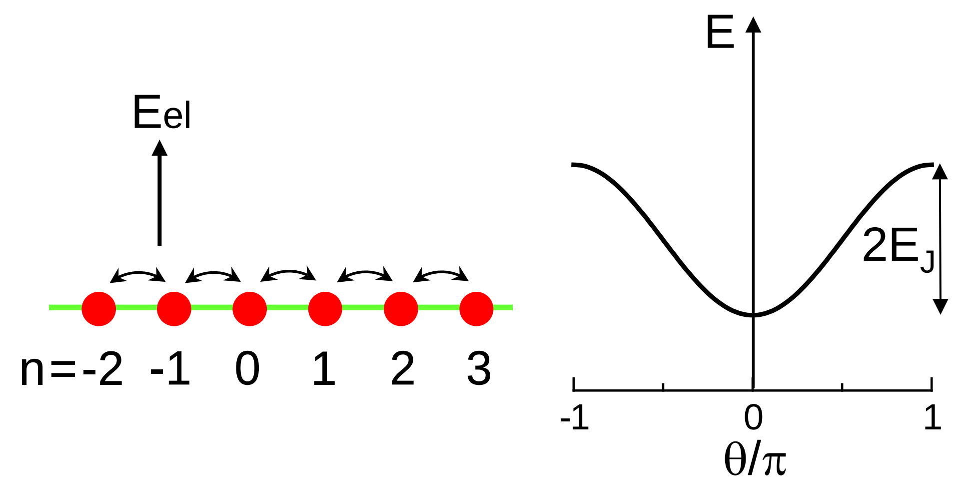
Number $n \Leftrightarrow$ Phase θ

$$[n, \theta] = -i$$

Cooper-pair tunneling

-2e





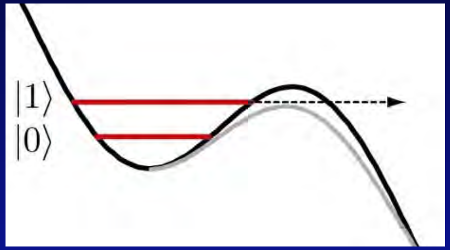
$$H = -\frac{E_J}{2}\sum_n \{|n\rangle\langle n+1| + |n+1\rangle\langle n|\} = -\int_0^{2\pi} d\theta \, E_J \cos\theta |\theta\rangle\langle\theta|$$

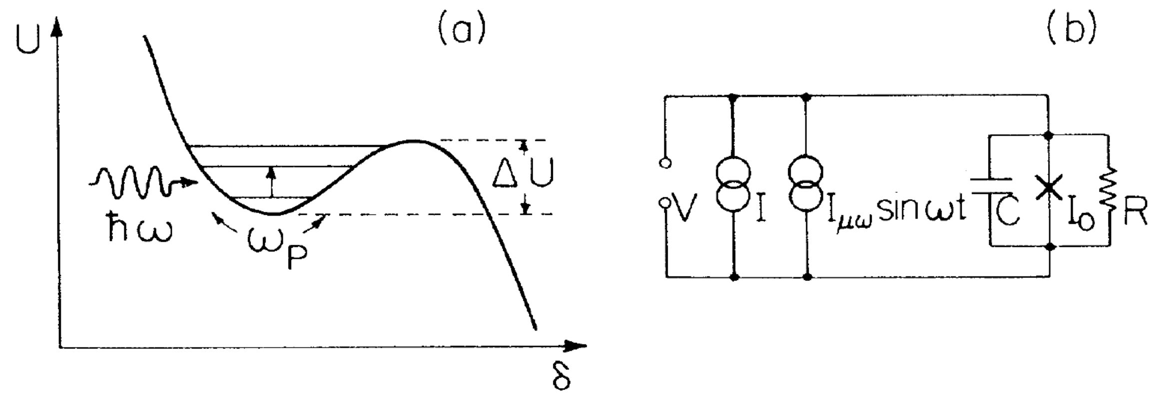
1D tight-binding model $\Rightarrow$ Bloch band

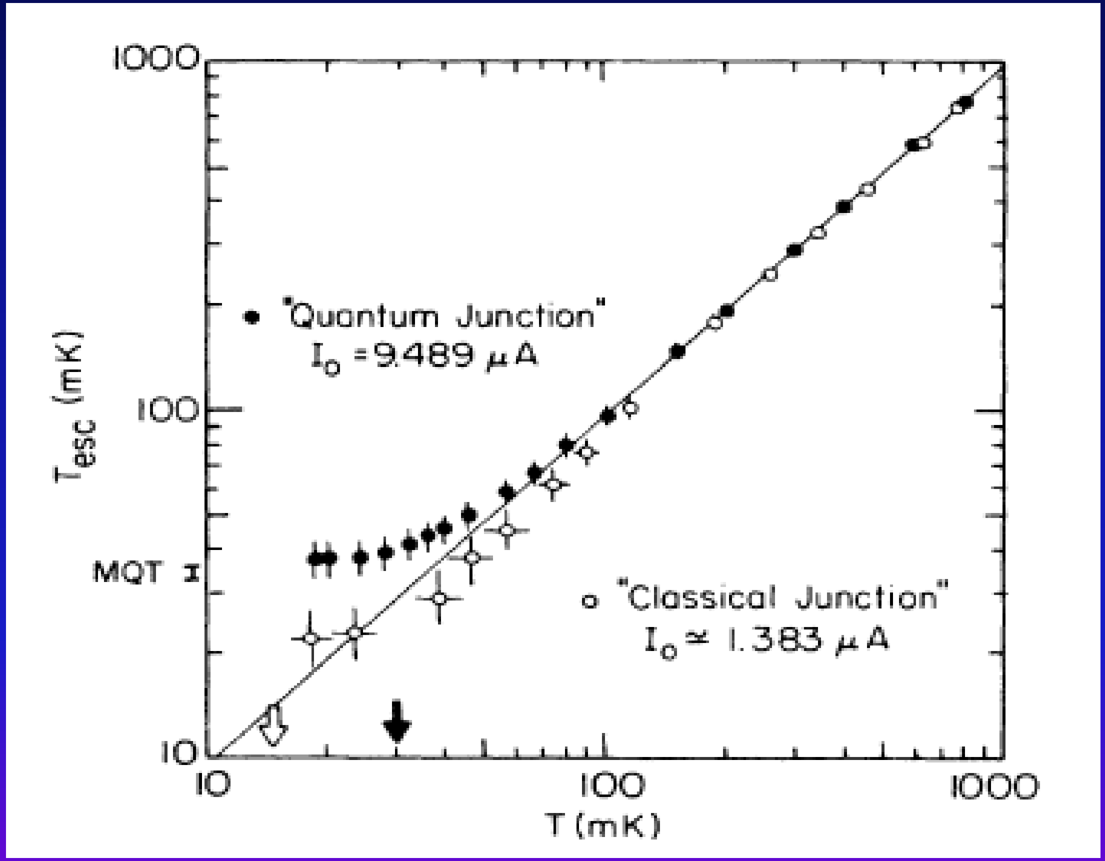
$$|\theta\rangle = \sum_n e^{in\theta}|n\rangle$$

Macroscopic quantum tunneling

Saturation of escape rate at low temperature



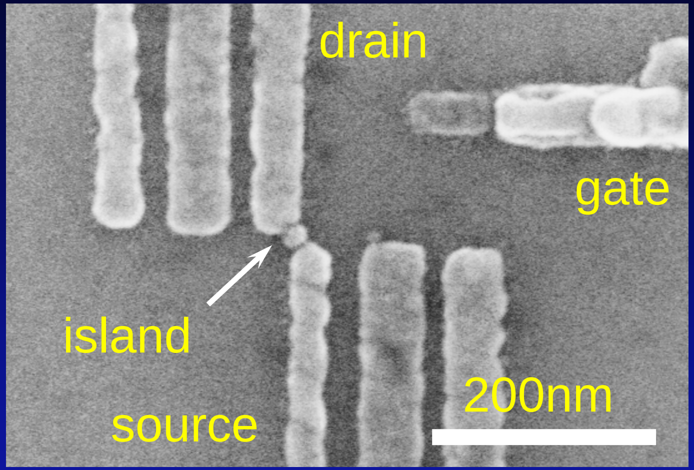


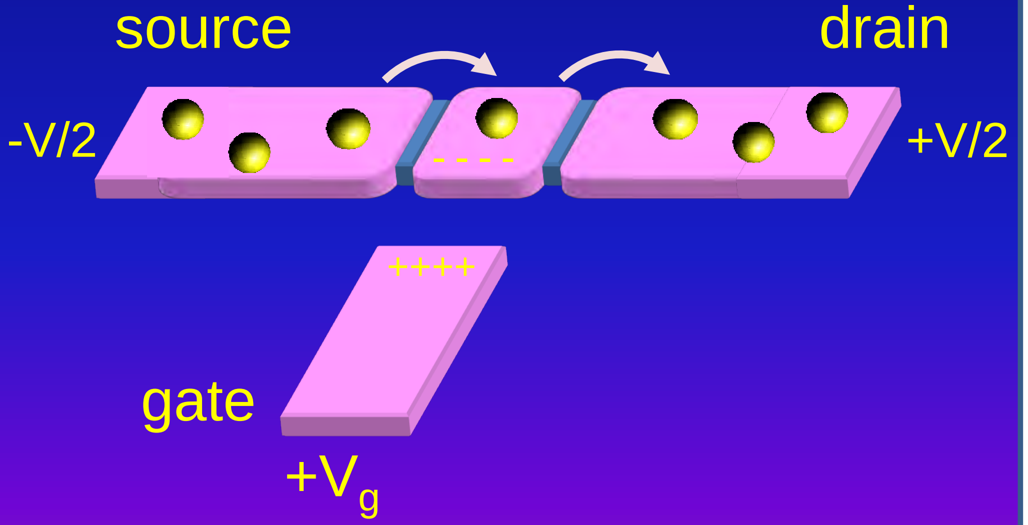


J. M. Martinis, M. H. Devoret, and J. Clarke. PRB 35, 4682 (1987).
R.F. Voss and R.A. Webb (IBM), PRL 47, 265 (1981); D.B. Schwarz et al. (SUNY), PRL 55, 1547 (1985).

Single-electron devices

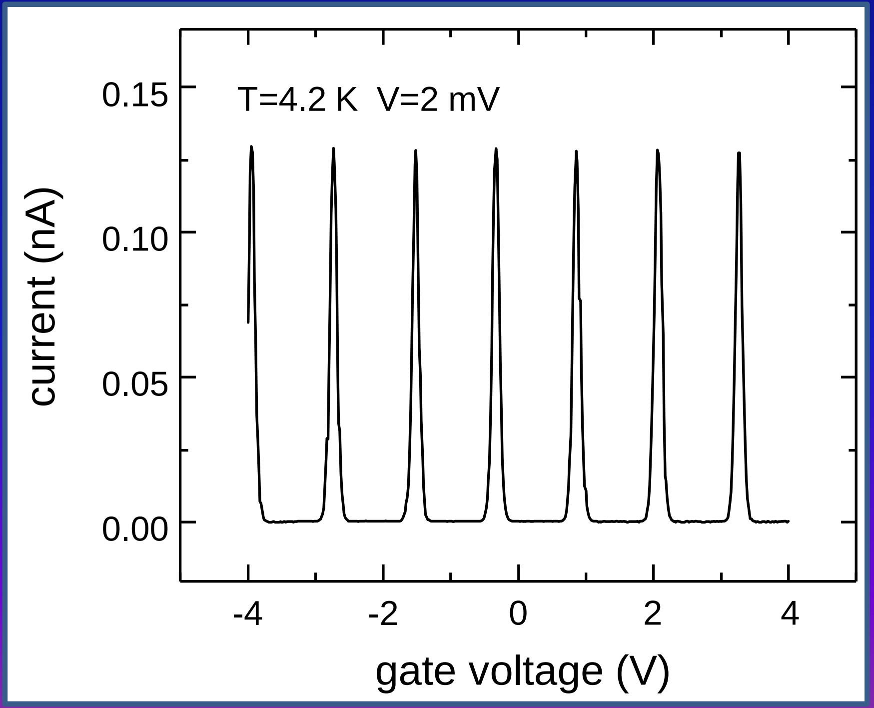
1990's



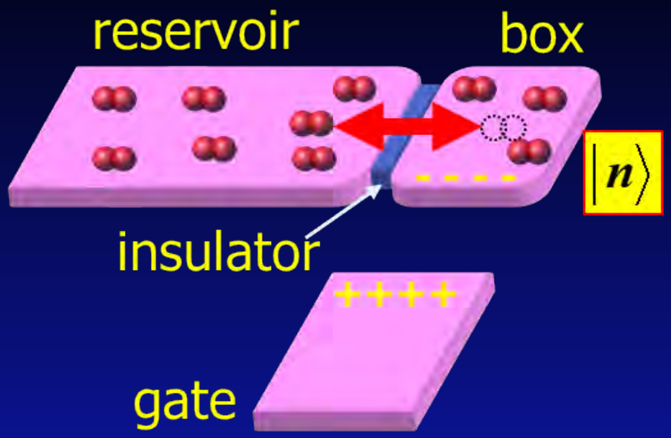


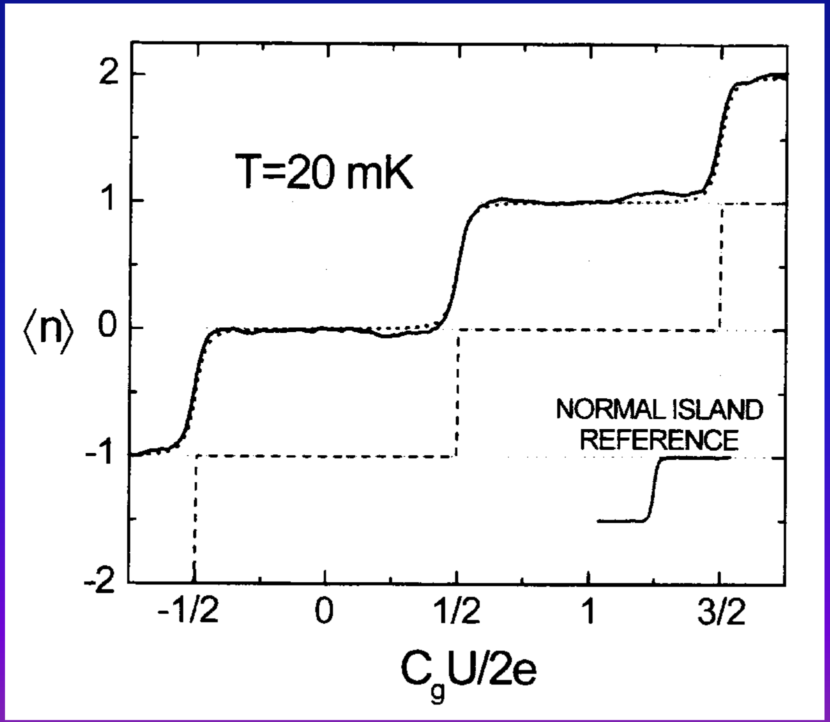
$$E_C \equiv \frac{e^2}{2C_\Sigma} \sim 11.5\,\mathrm{meV}$$

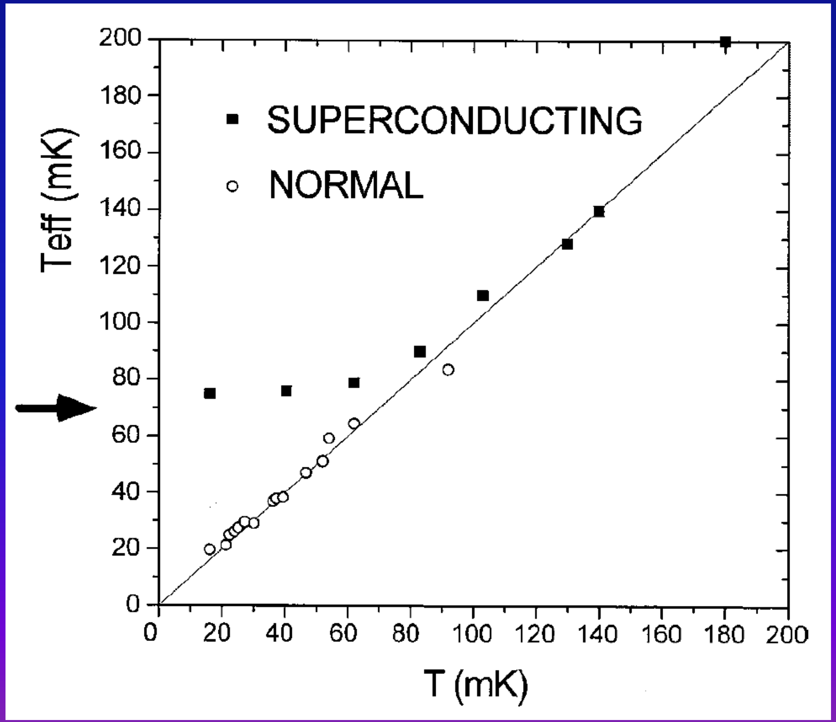
$$E_C/k_B \sim 130\,\mathrm{K}$$



Superposition of charge-number states in Cooper-pair box

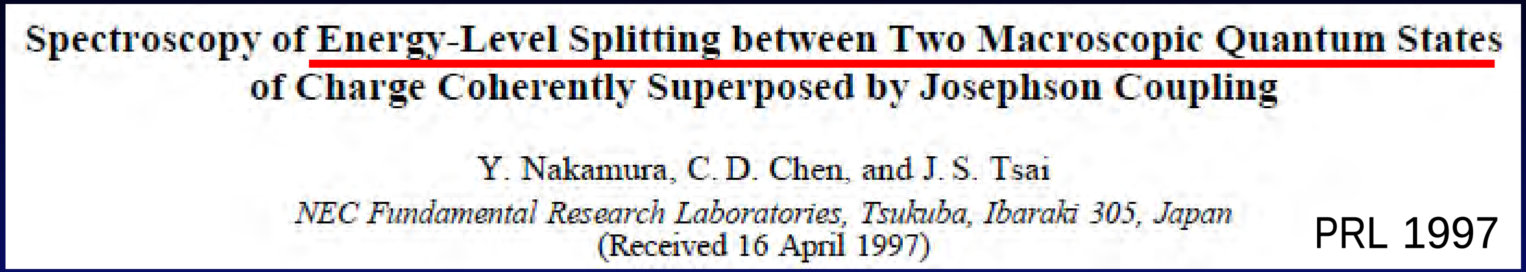






V. Bouchiat et al. Phys. Scr. T76, 165 (1998) Saclay

Superposition of charge-number states in Cooper-pair box



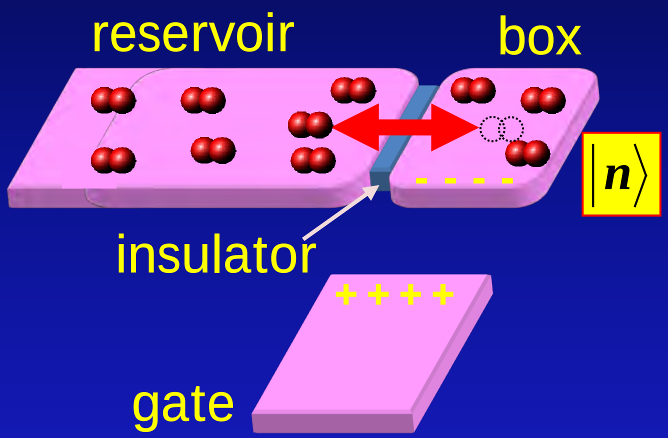
Spectroscopy of Energy-Level Splitting between Two Macroscopic Quantum States of Charge Coherently Superposed by Josephson Coupling

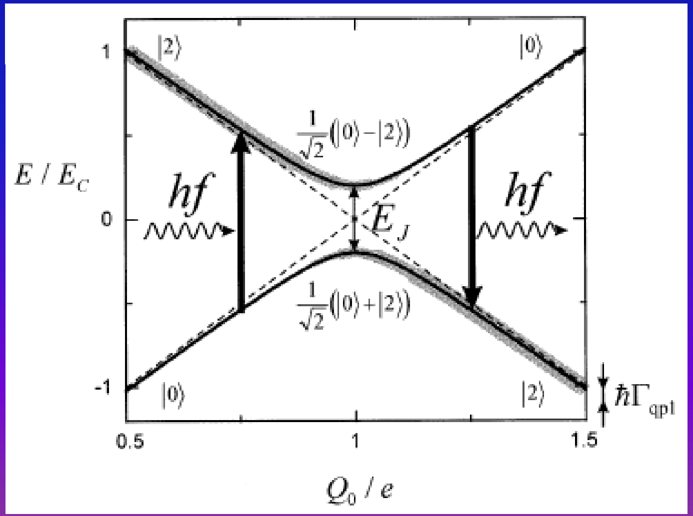
Y. Nakamura, C. D. Chen, and J. S. Tsai

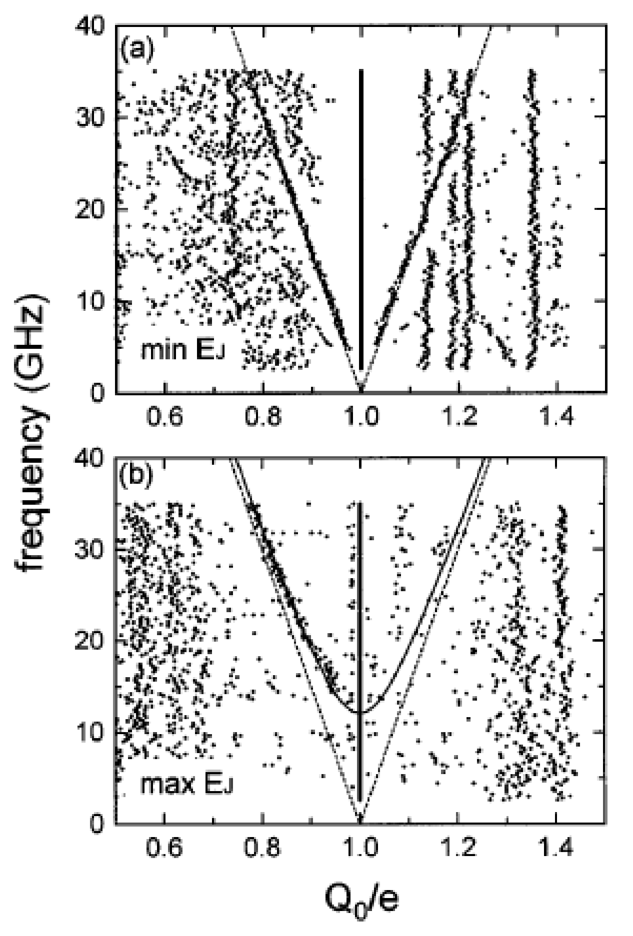
NEC Fundamental Research Laboratories, Tsukuba, Ibaraki 305, Japan

(Received 16 April 1997)

PRL 1997

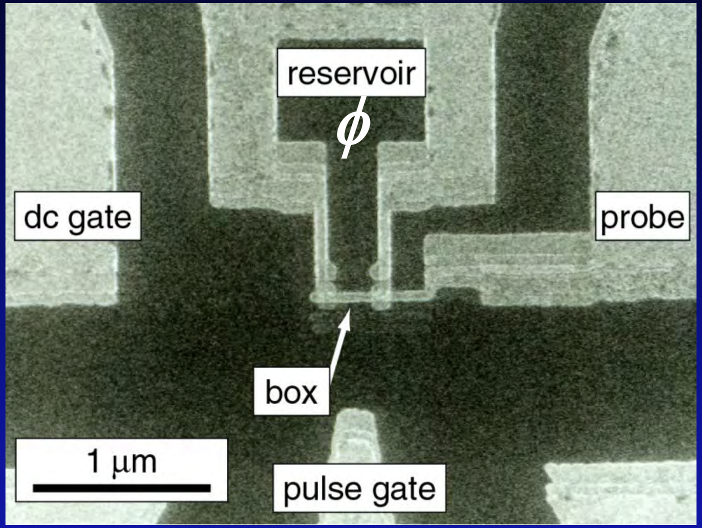


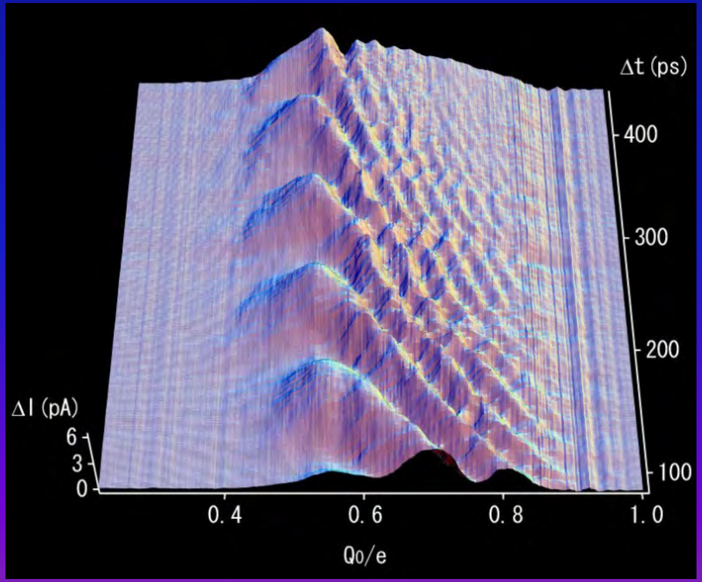




Superconducting quantum bits

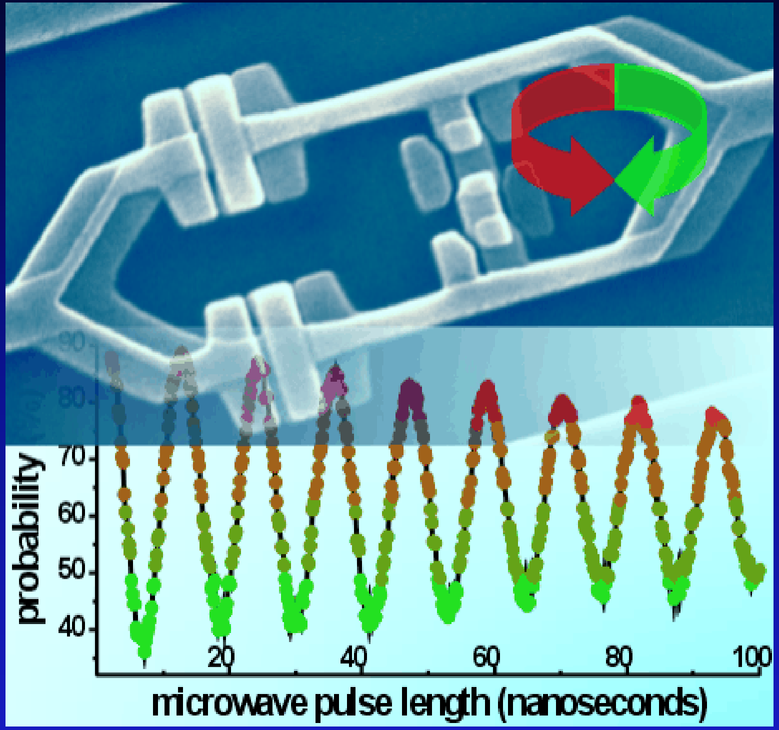
Charge qubit





YN, Pashkin, Tsai, Nature (1999); YN, Nature Electronics 8, 92 (2025).

Flux qubit



Chiorescu, YN, Harmans, Mooij, Science (2003)

Artificial two-level system in circuits

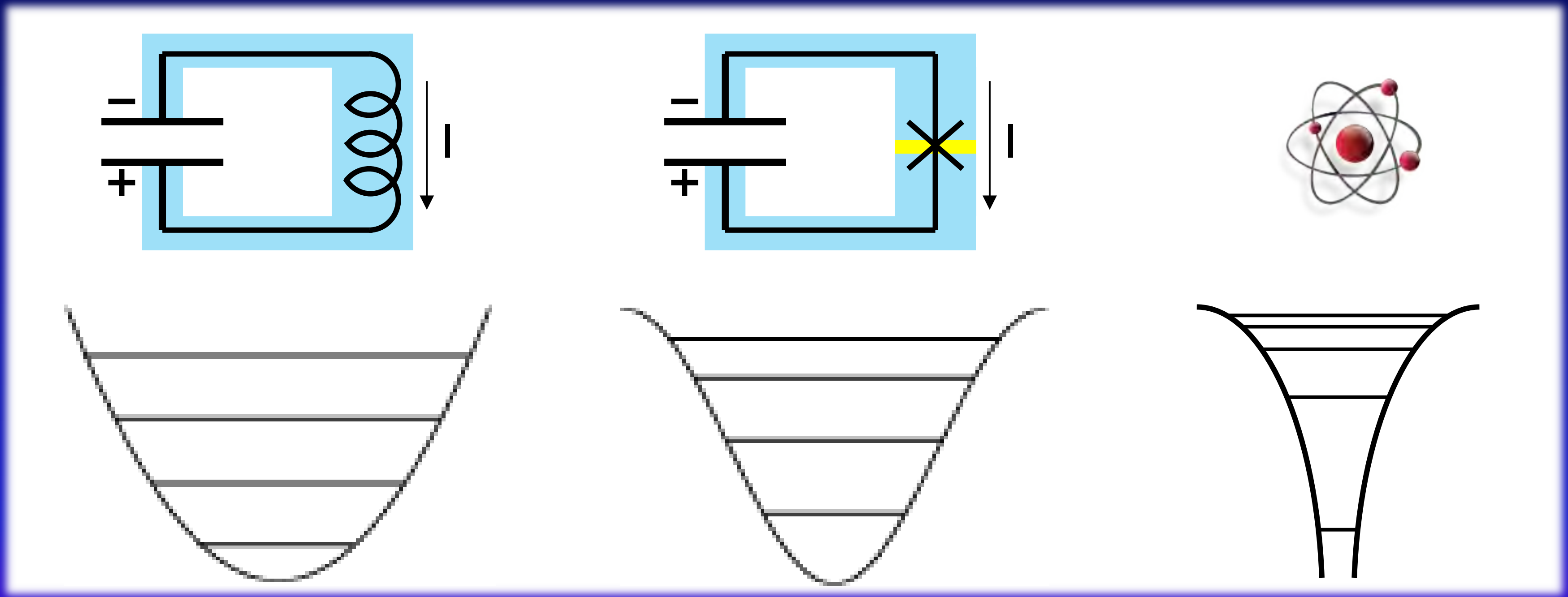
Coherent control of macroscopic system

Superconducting qubit – nonlinear resonator

LC resonator

Superconducting qubit
= Artificial atom
~mm

Atom
~Å



- **Superconductivity ⇒ low-loss**
- **Josephson effect ⇒ Strong nonlinearity**
- **Macroscopic size ⇒ Strong coupling**

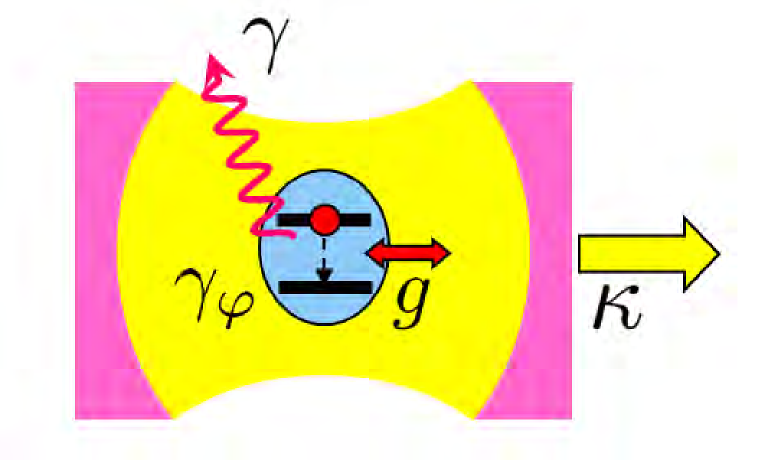
Circuit QED: cavity QED and waveguide QED

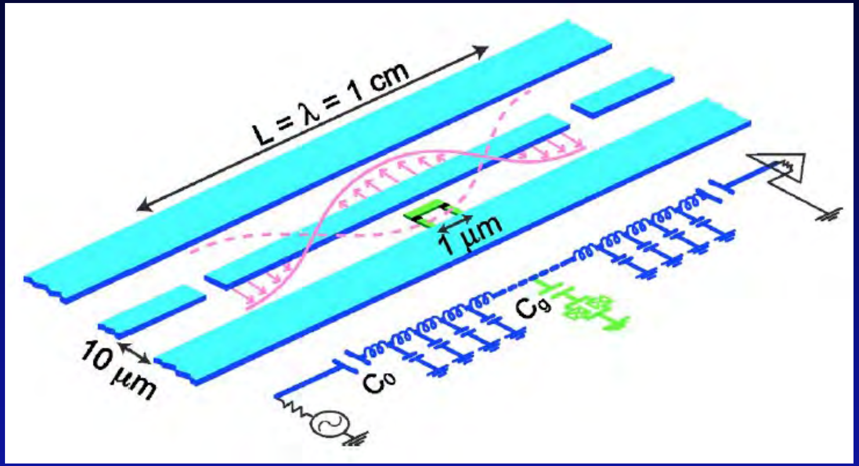
Cavity QED

Atom + 0D mode (discrete)

Strong coupling

$$g \gg \kappa, \gamma, \gamma_\varphi$$





A. Blais et al. PRA 69, 062320 (2004); A. Wallraff et al. Nature 431, 163 (2004), Yale

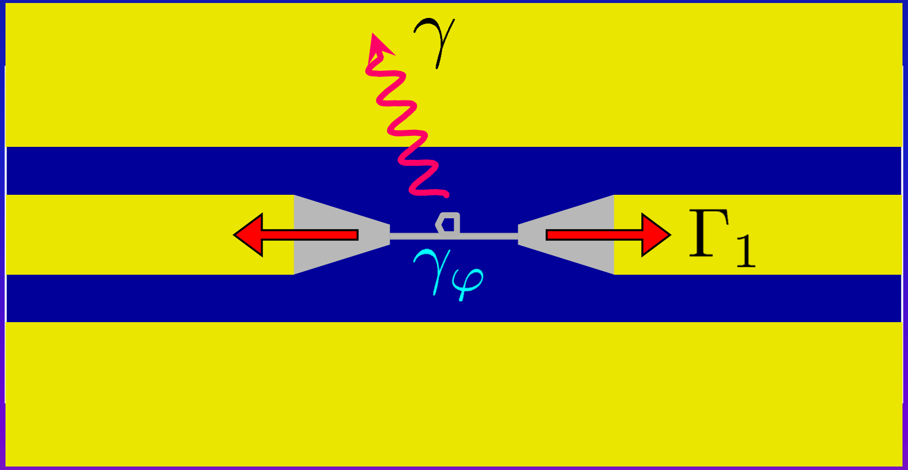
Waveguide QED

Atom + 1D mode (continuum)

Mode matching, interference

"Strong coupling"

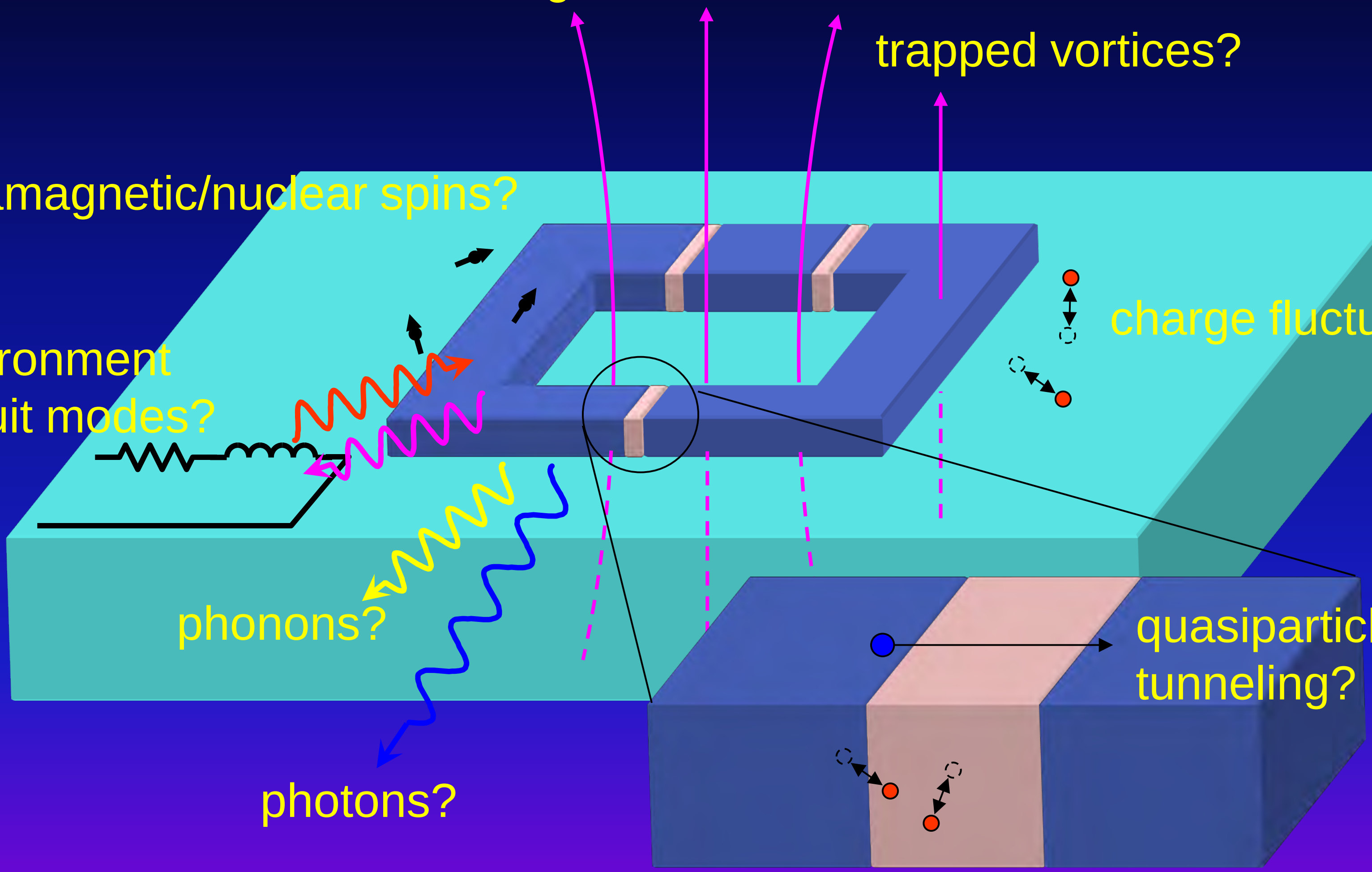
$$\Gamma_1 \gg \gamma, \gamma_\varphi$$



Microwave quantum optics

O. Astafiev et al. Science 327, 840 (2010)

Possible decoherence sources



magnetic-field noise?

trapped vortices?

paramagnetic/nuclear spins?

charge fluctuations?

environment circuit modes?

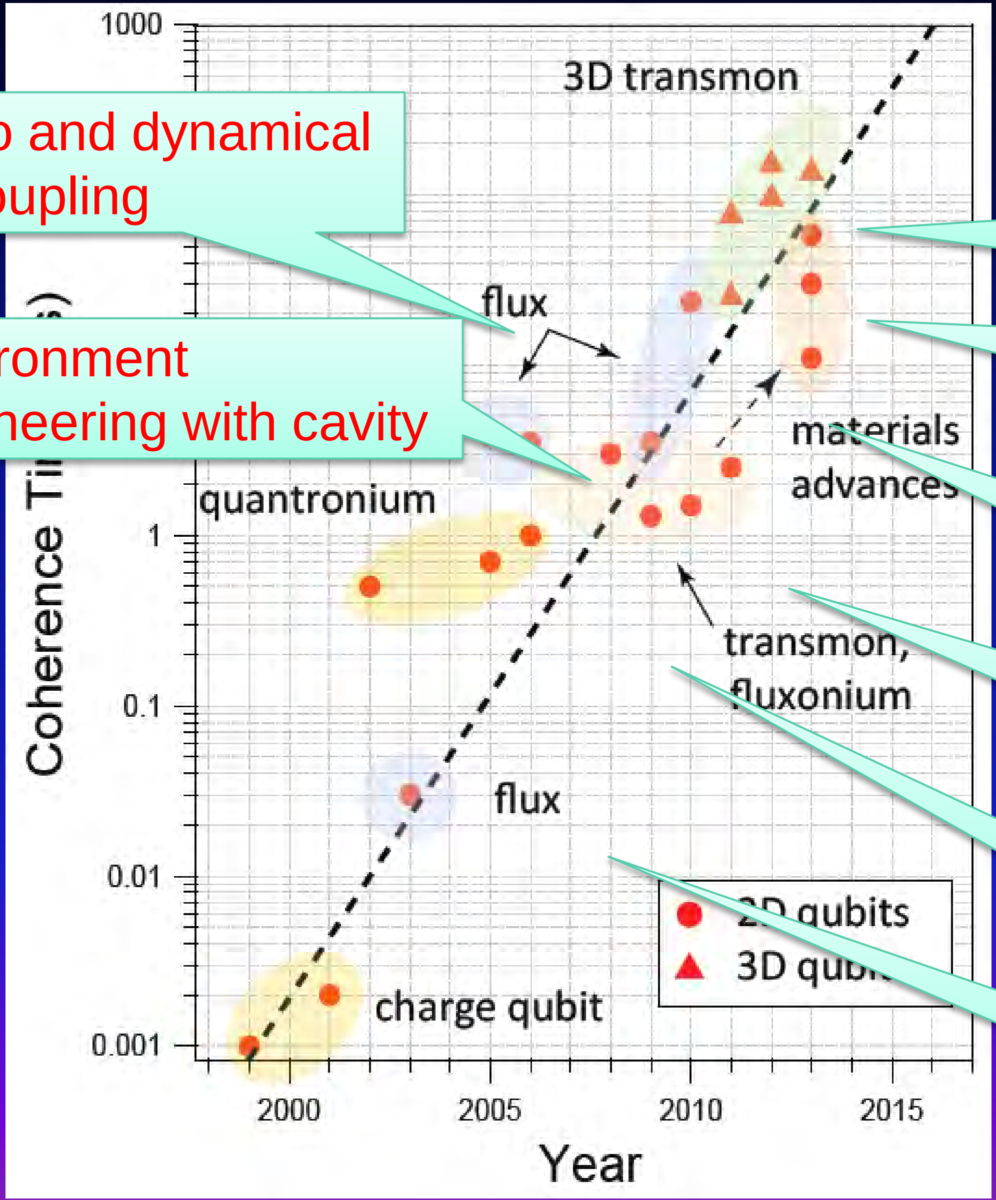
phonons?

quasiparticle tunneling?

photons?

charge/Josephson-energy fluctuations?

Coherence time of superconducting qubits



Echo and dynamical decoupling

Environment engineering with cavity

Low-energy qubit

Non-equilibrium quasiparticle engineering

High-frequency noise shielding

Diluted surface/interface effect

Improved surface/interface/dielectric

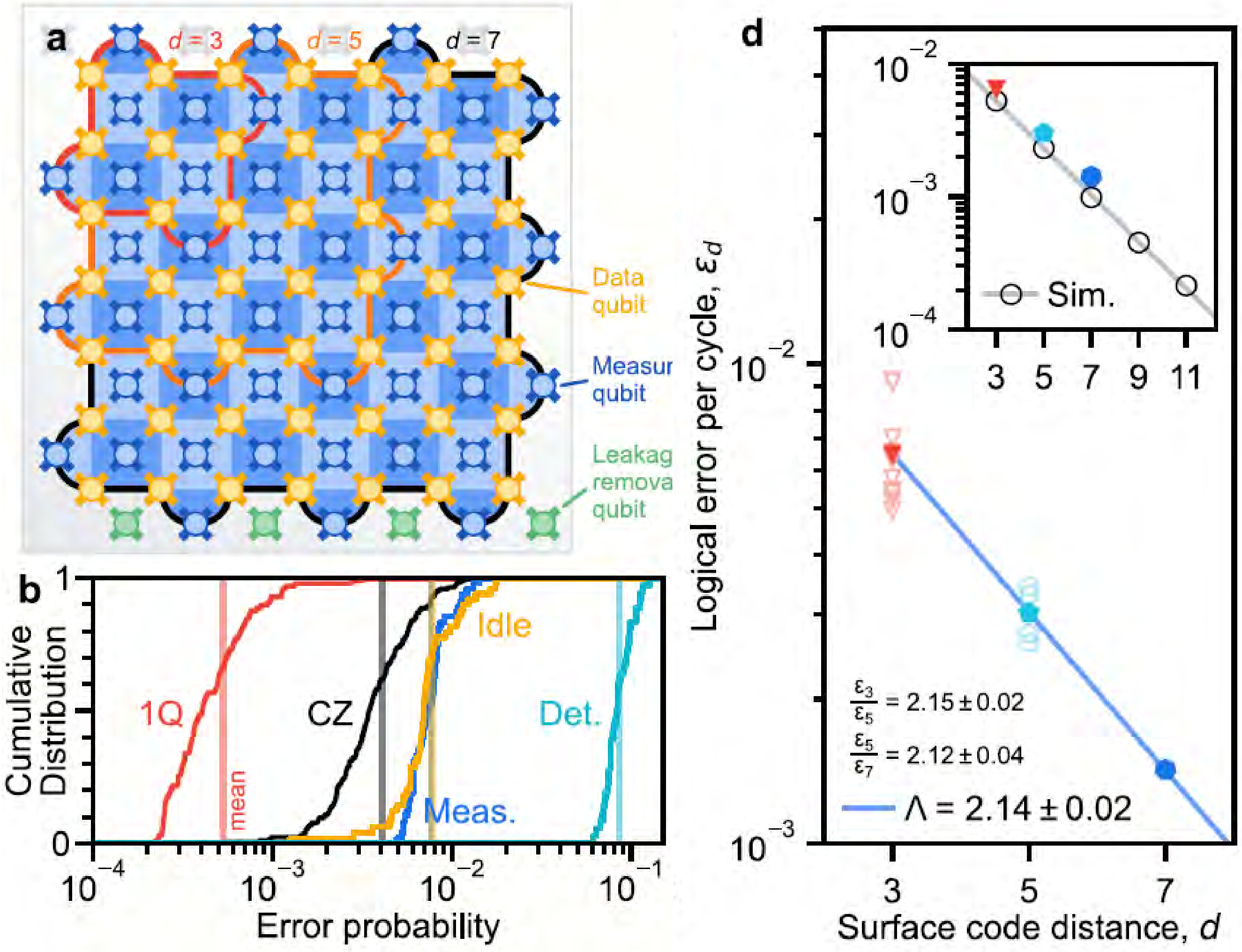
Energy-level engineering

Decoupling from charge noise

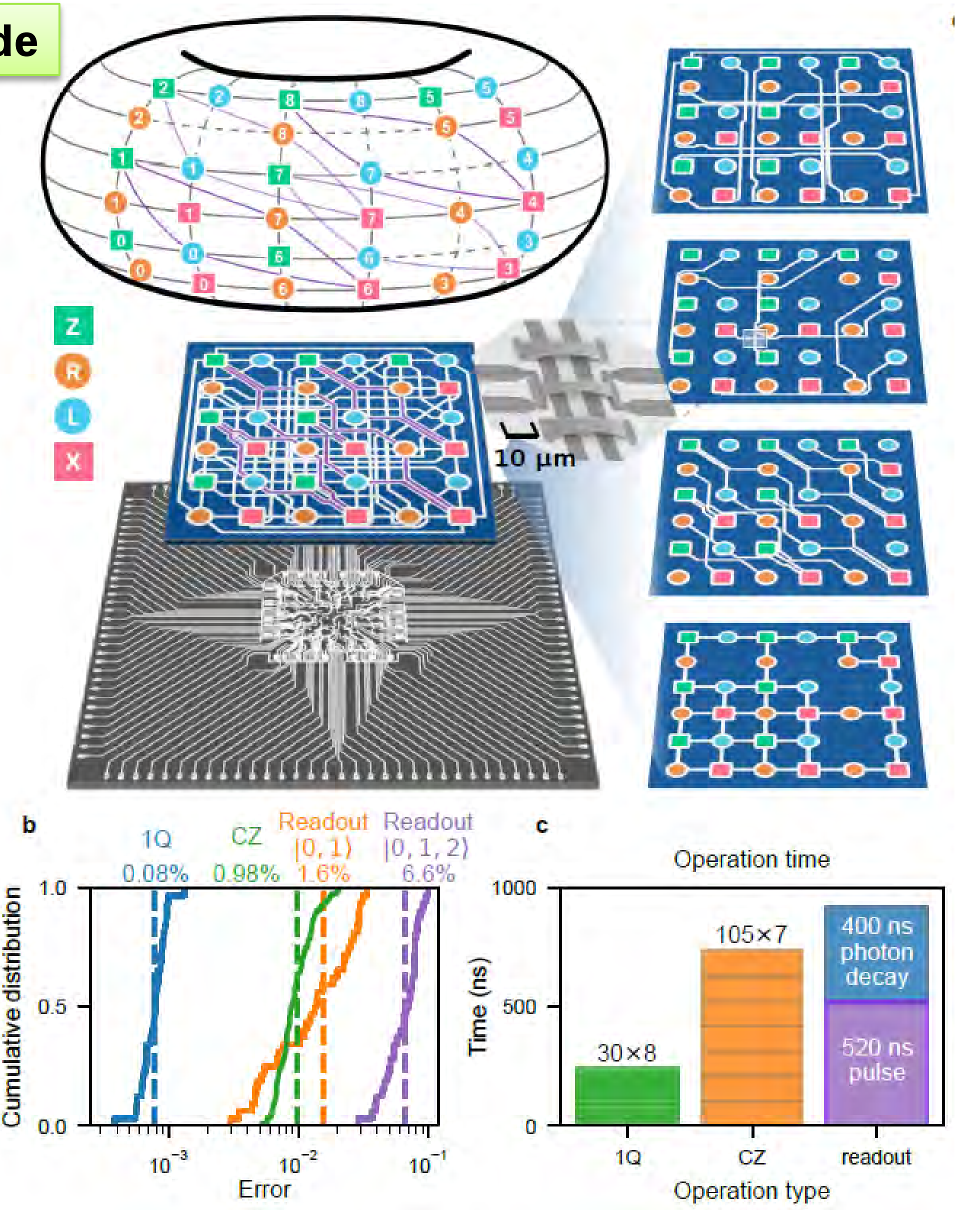
W. D. Oliver and P. Welander, MRS BULLETIN 38, 816 (2013) MIT-LL

Towards quantum error correction

Logical error suppression with surface code



qLDPC code

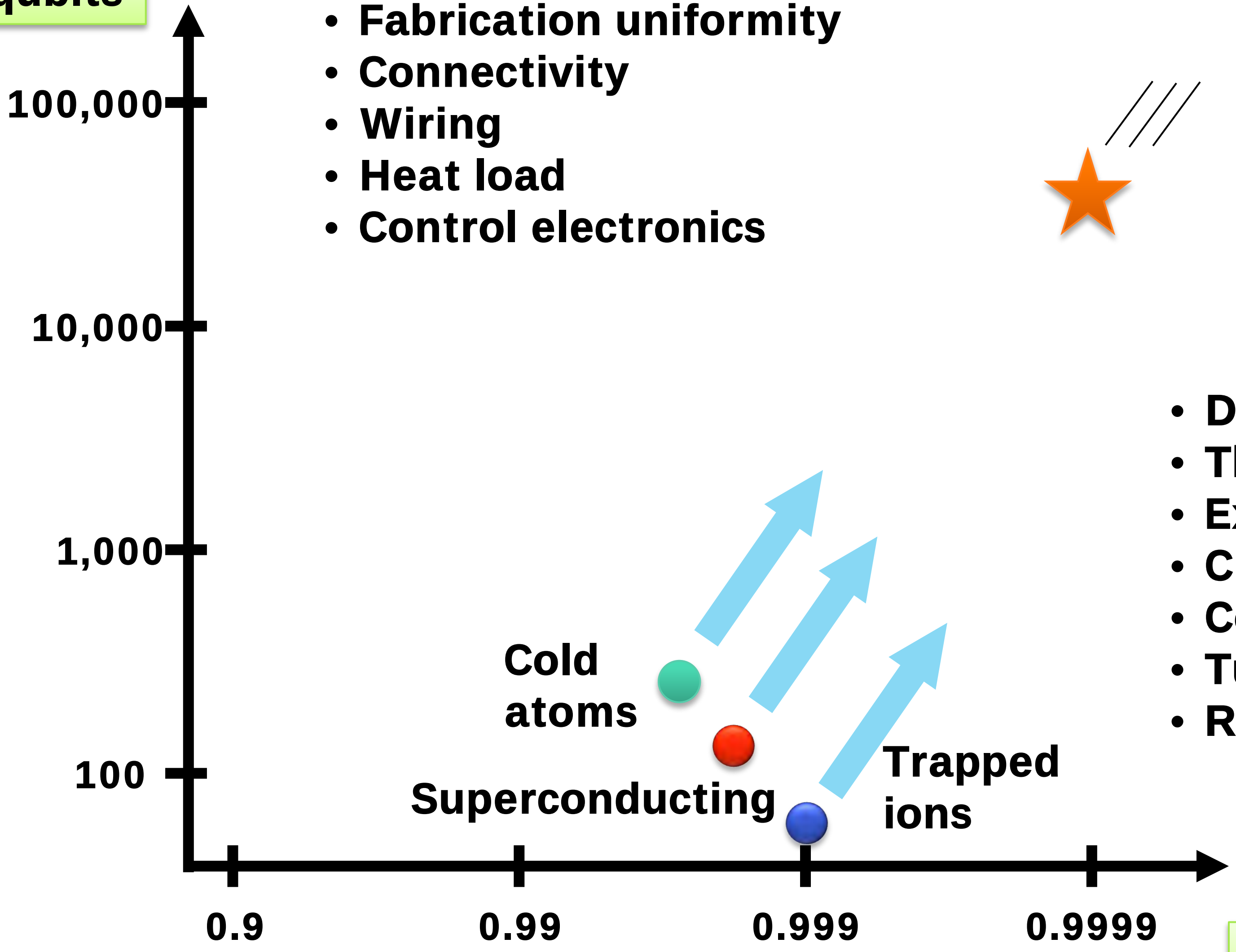


Google Quatum AI, Nature 638, 920 (2025)

K. Wang et al. arXiv:2505.09684 (Zhejiang U)

Challenges for the future

Number of physical qubits



Fidelity

- Fabrication uniformity
- Connectivity
- Wiring
- Heat load
- Control electronics

- Error correction code
- FTQC architecture
- Algorithm
- Application

- Decoherence
- Thermalization
- External noise
- Crosstalk
- Control pulse shaping
- Tunable coupling
- Readout backaction

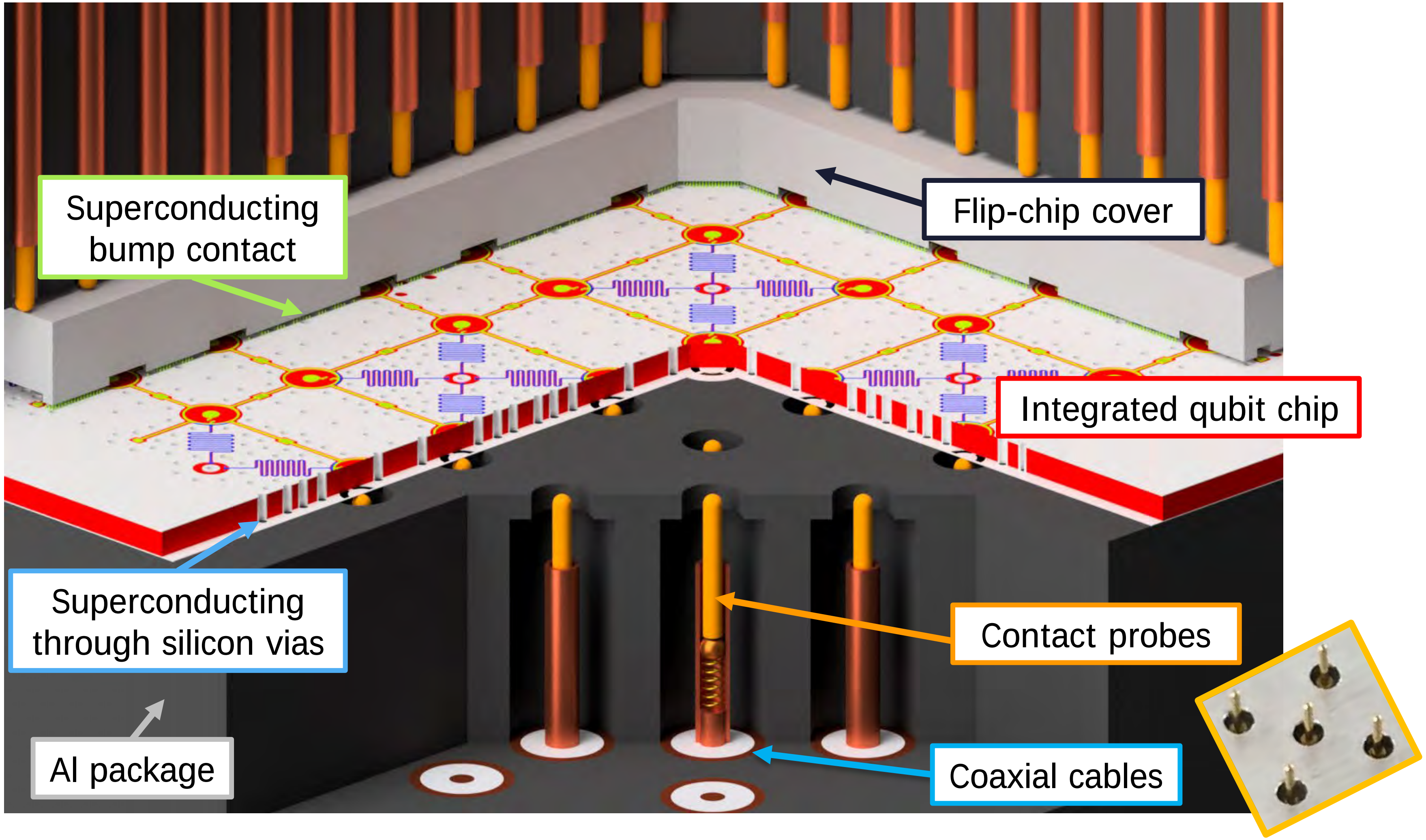
Multiple fridges

Modular units

Multi-chip modules

Necessary coherence time for 100-ns-long 2Q gate → 10 μs 100 μs 1 ms

Superconducting quantum processor unit @RQC



Superconducting bump contact

Flip-chip cover

Integrated qubit chip

Superconducting through silicon vias

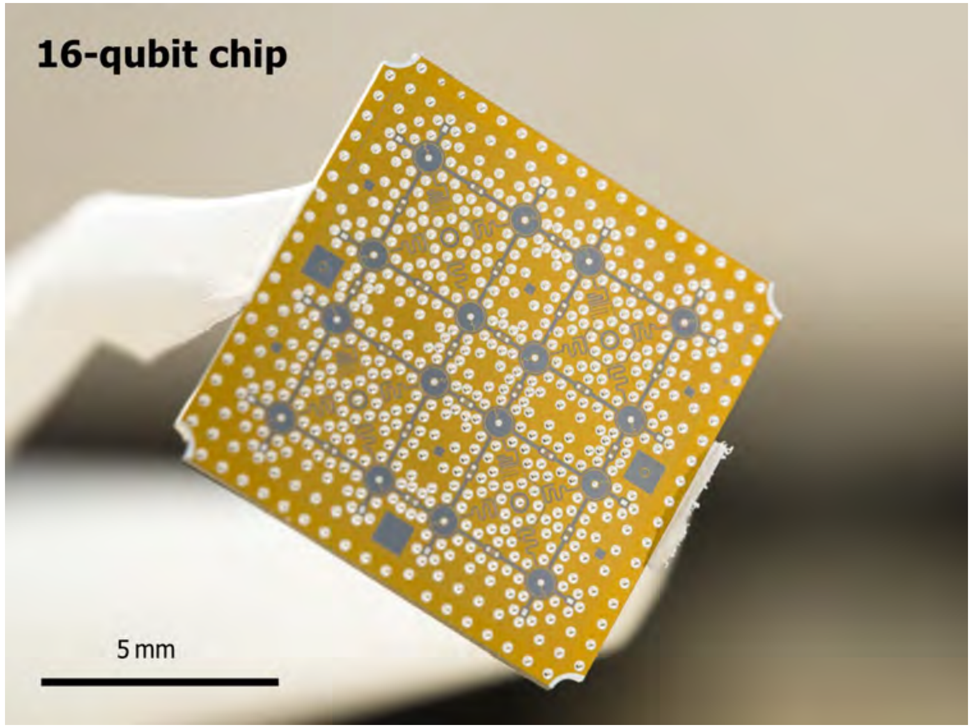
Contact probes

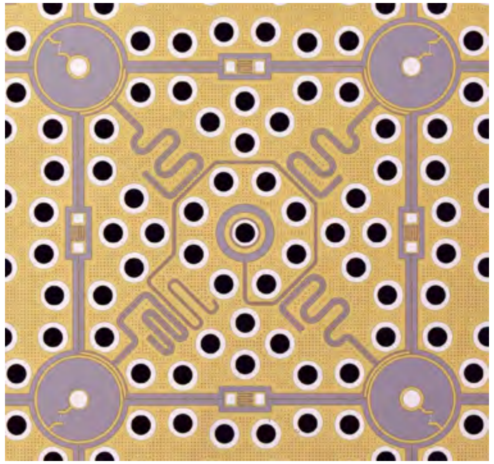
Al package

Coaxial cables

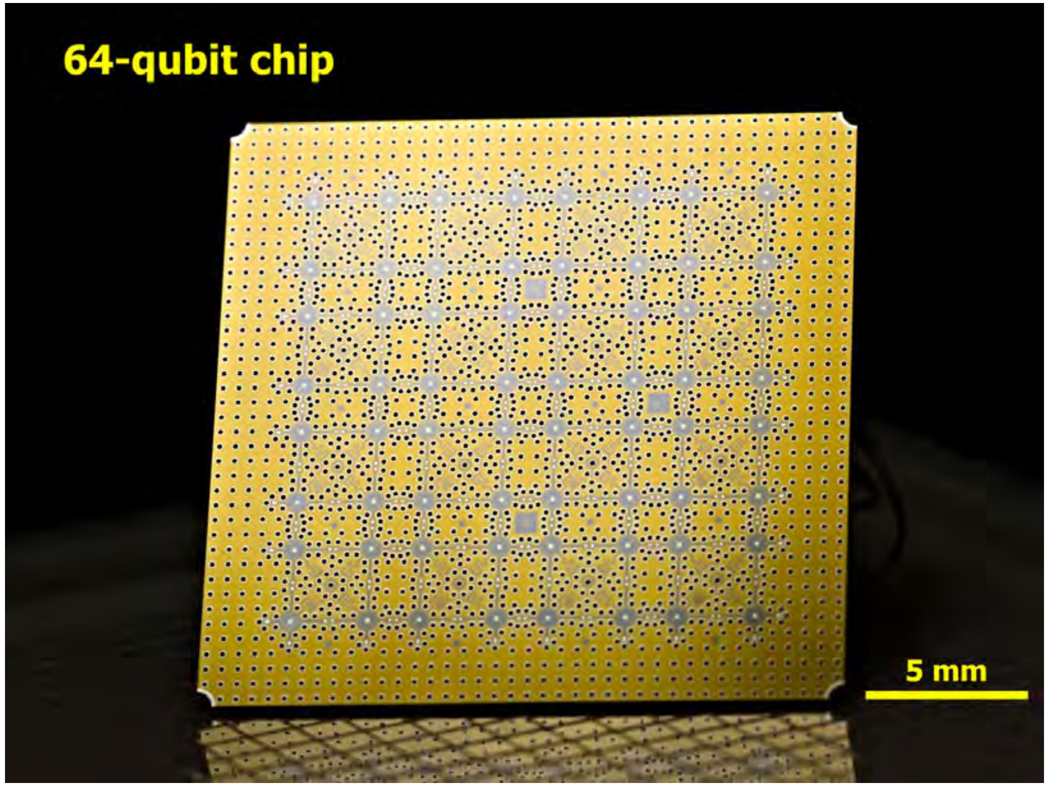
2D integration with 3D wiring

Supercondcuting qubit chip





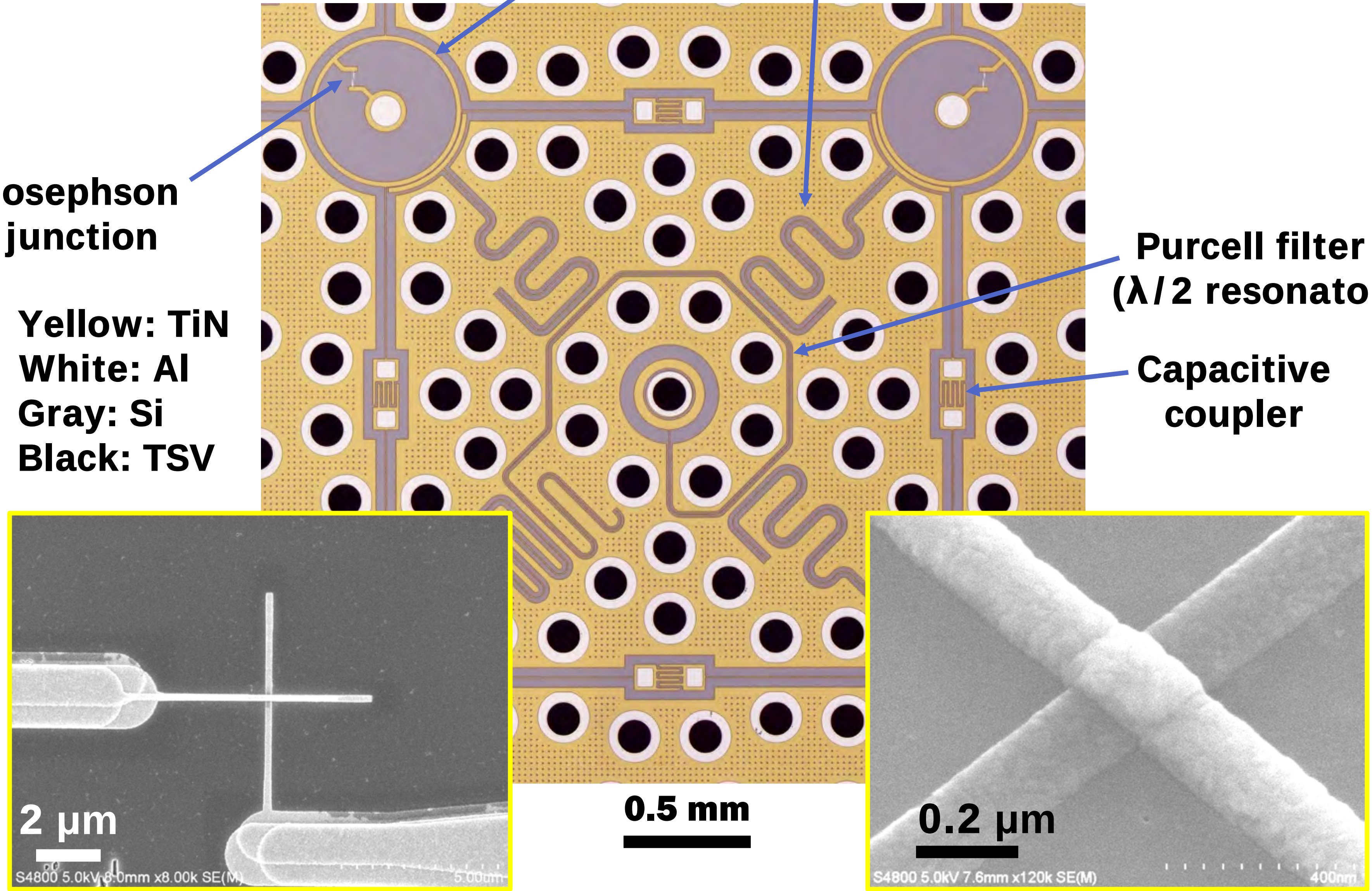
Unit-cell structure



Square lattices of fixed-frequency transmons

Nearest-neighbor capacitive coupling

Unit-cell structure



Qubit

Readout resonator (λ/4)

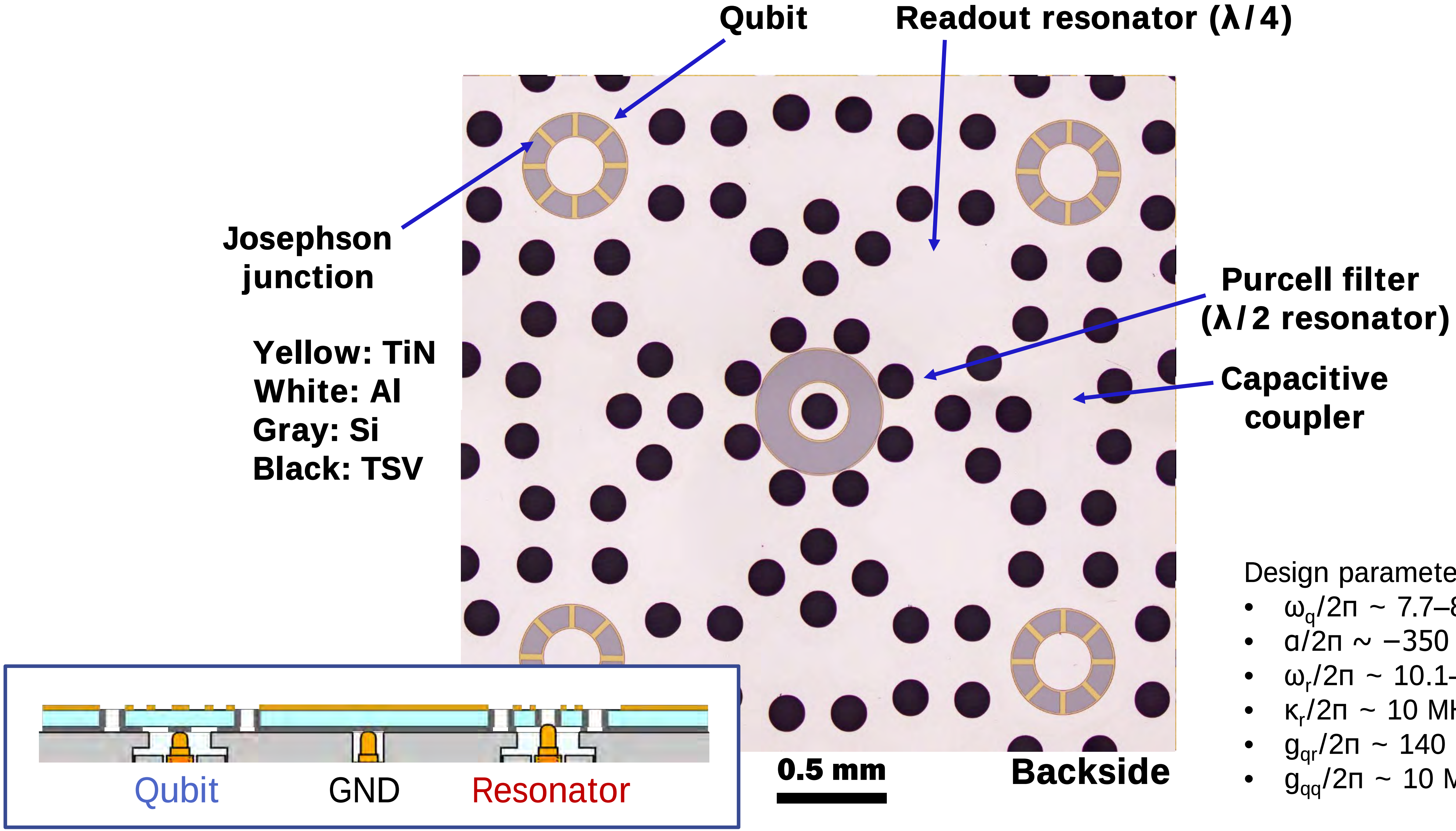
Josephson junction

Purcell filter (λ/2 resonator)

Capacitive coupler

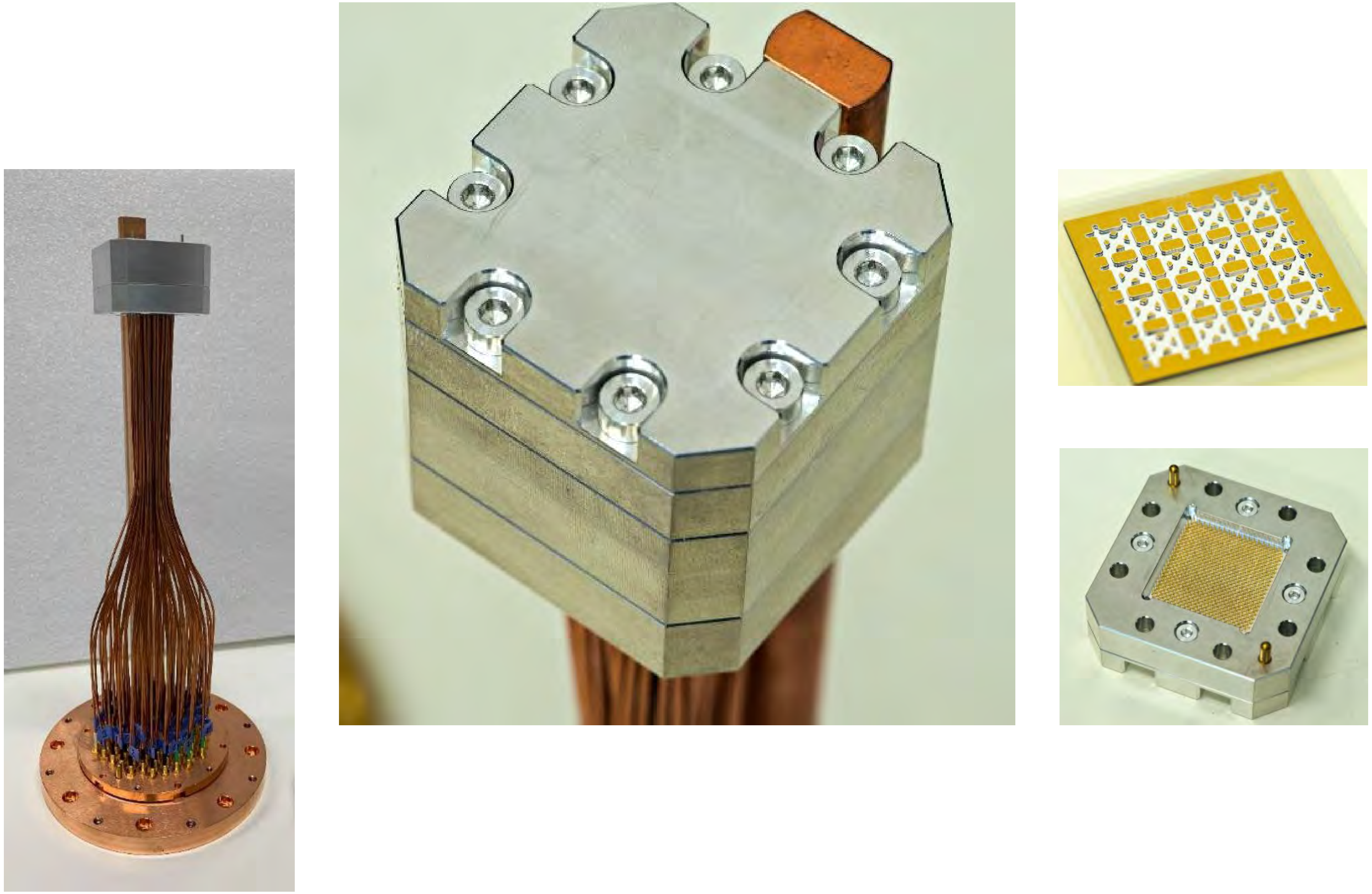
Yellow: TiN
White: Al
Gray: Si
Black: TSV

Unit-cell structure



Design parameters (example)
- $\omega_q/2\pi$ ~ 7.7–8.9 GHz (fixed)
- $\alpha/2\pi$ ~ −350 - −450 MHz
- $\omega_r/2\pi$ ~ 10.1–10.4 GHz
- $\kappa_r/2\pi$ ~ 10 MHz
- $g_{qr}/2\pi$ ~ 140 MHz
- $g_{qq}/2\pi$ ~ 10 MHz

Packaging with vertical access



Cryostat for 64Q system

Input	96 lines*
Output	16 lines
Total	112 lines (1.75 line/qubit)

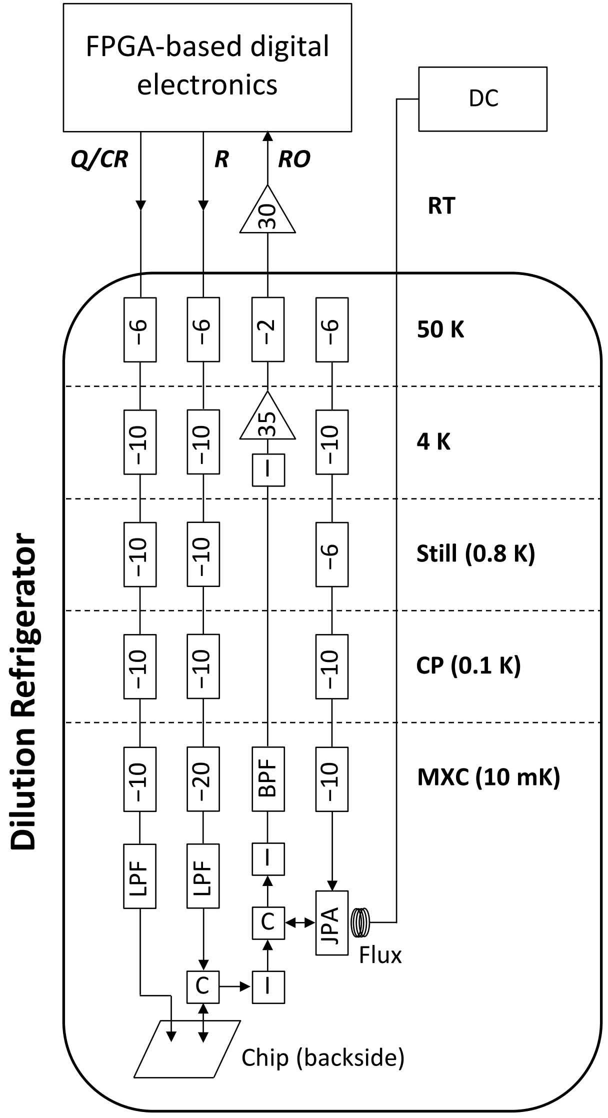
- 16 low-temperature HEMT amplifier

- 16 impedance-matched Josephson parametric amplifier (JPA)

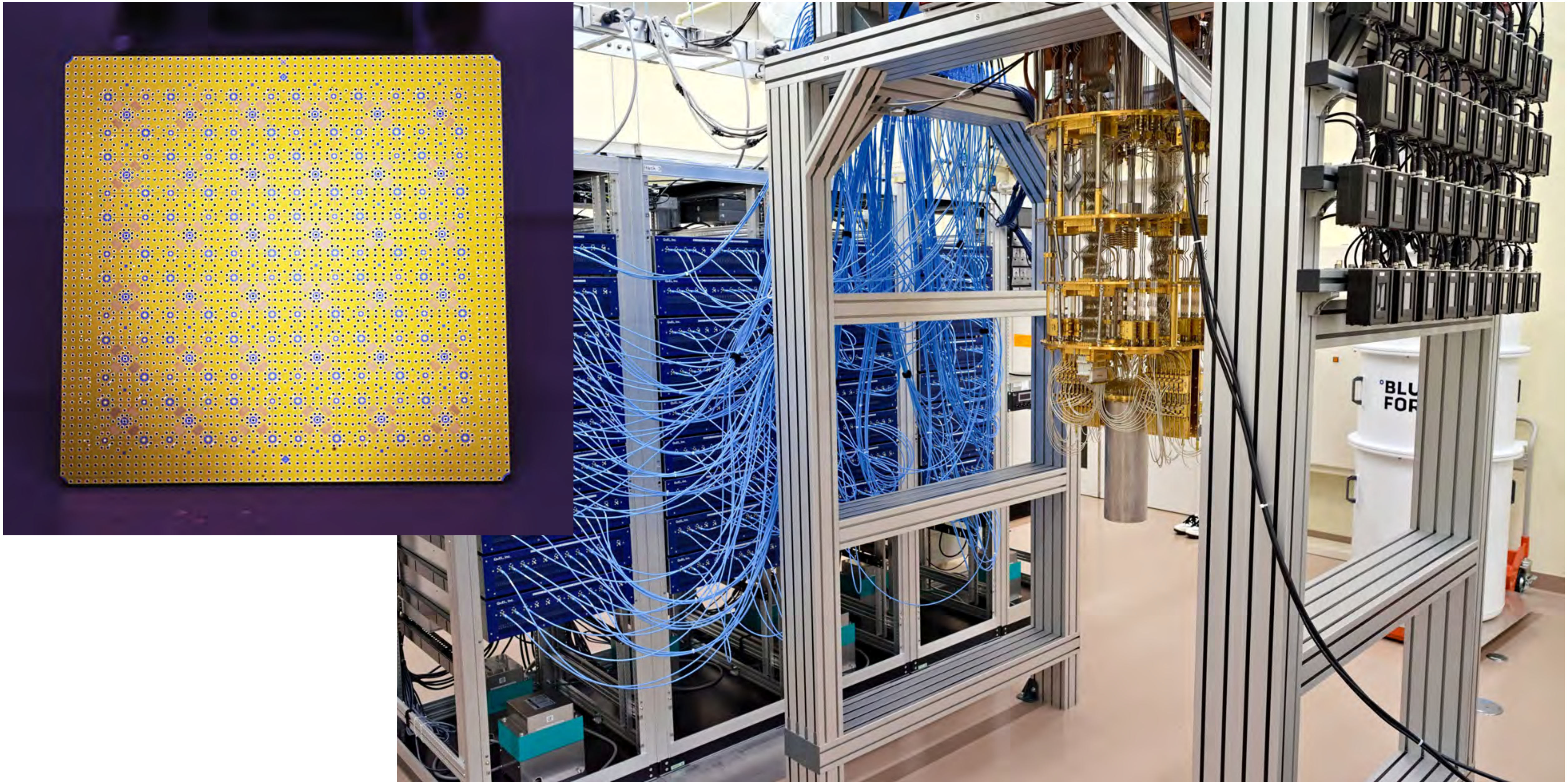
- Magnetic shield

- Radiation shield at 10 mK

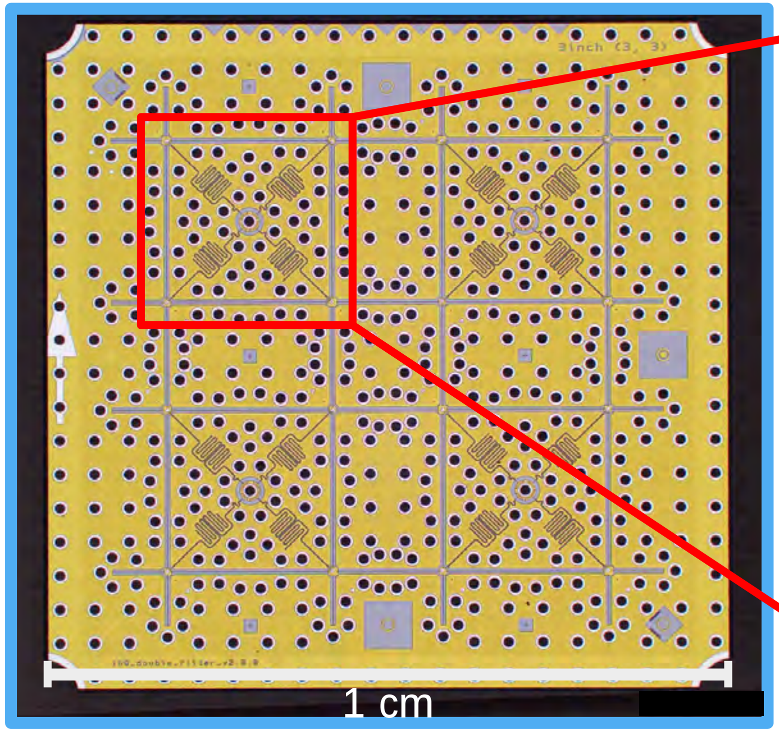
*	
Qubit control	64
Readout signal input	16
JPA pump	16



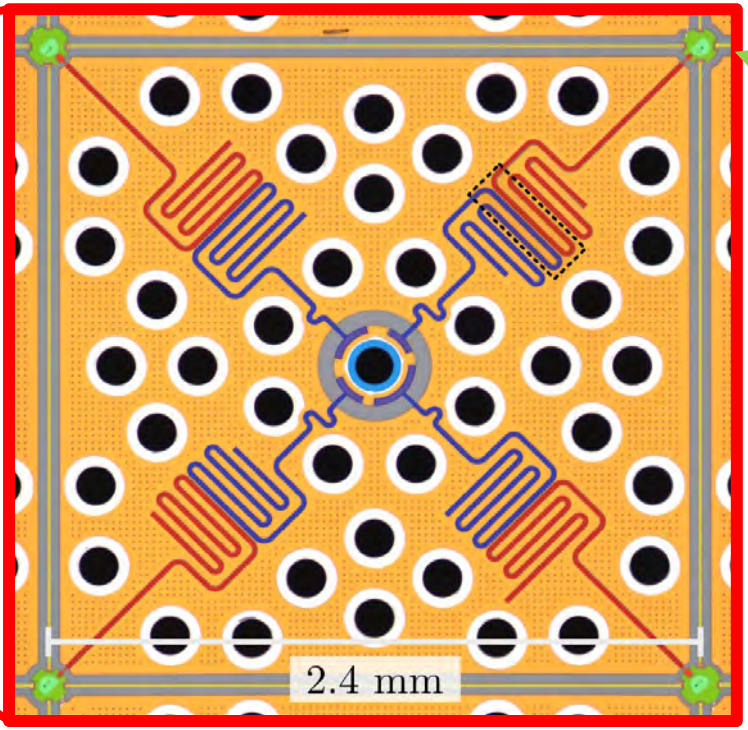
144Q system



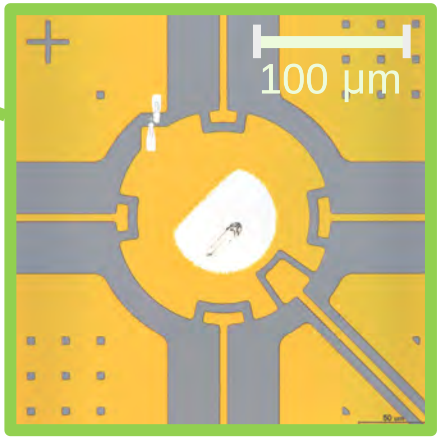
High-fidelity qubit readout on a 2D-integrated chip



16Q device



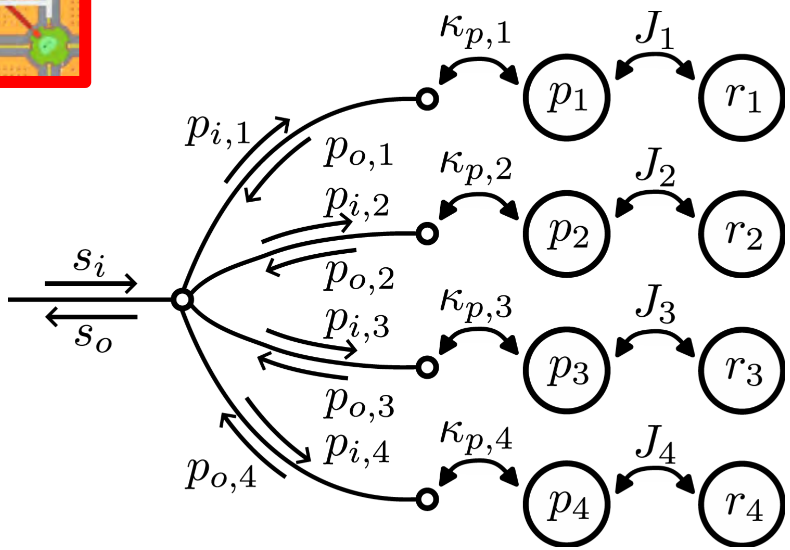
4Q unit-cell



Transmon qubit

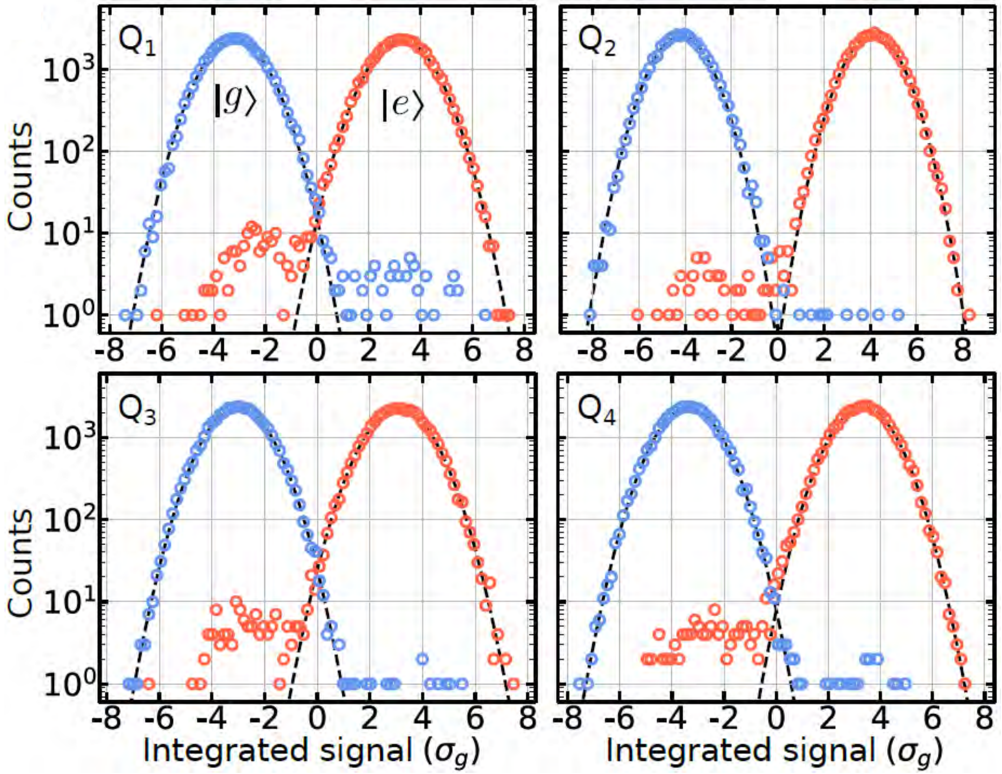
4-fold multiplexed simultaneous readout

Individual Purcell filter + Intrinsic notch filter



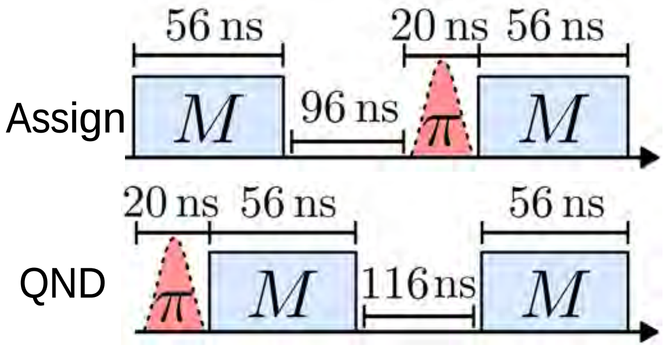
P. A. Spring et al. PRX Quantum 6, 020345 (2025)

High-fidelity qubit readout with dedicated Purcell filters

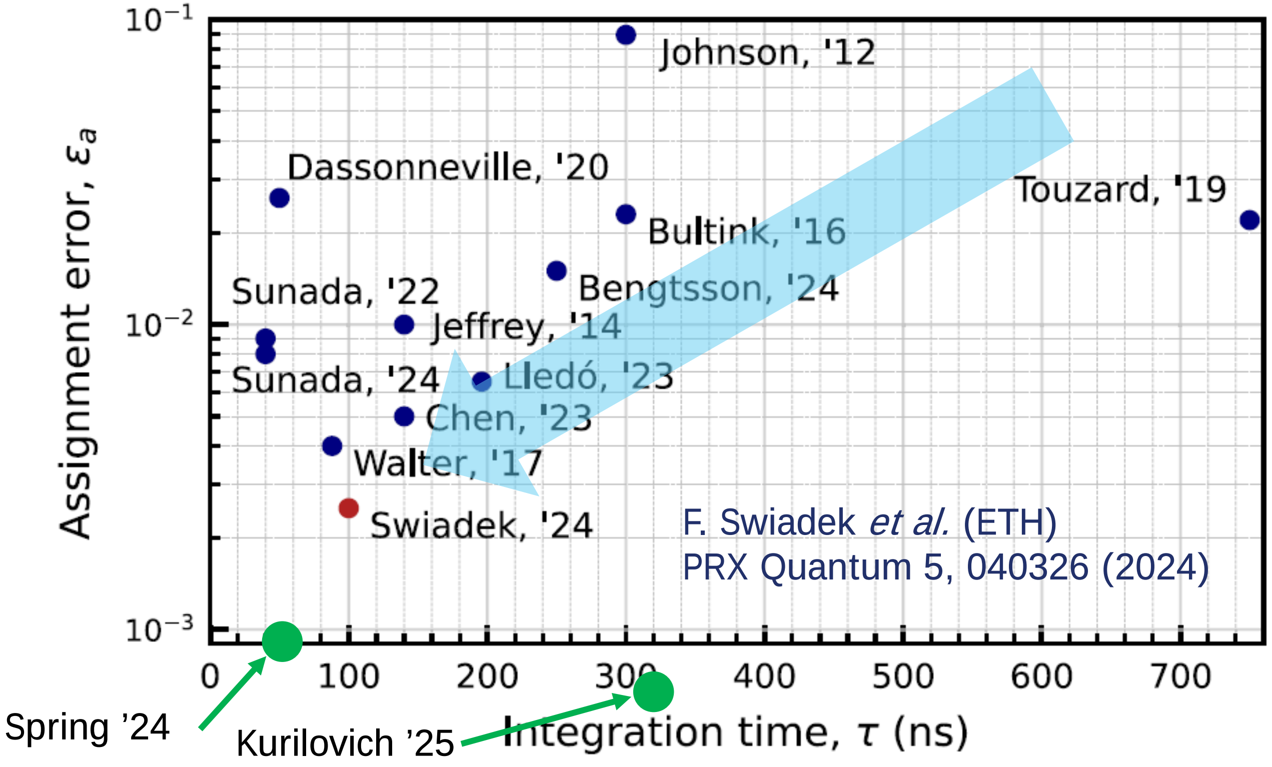


Histograms from $4\text{x}10^4$ simultaneous 56-ns measurements

Assignment & QND fidelity pulse sequences



- Fast readout in 56 ns, repeatable in every 100 ns
- Assignment fidelity 99.91%, QND fidelity 99.67%
- Leakage error ~0.01%/readout
- QND infidelity dominated by induced qubit relaxation



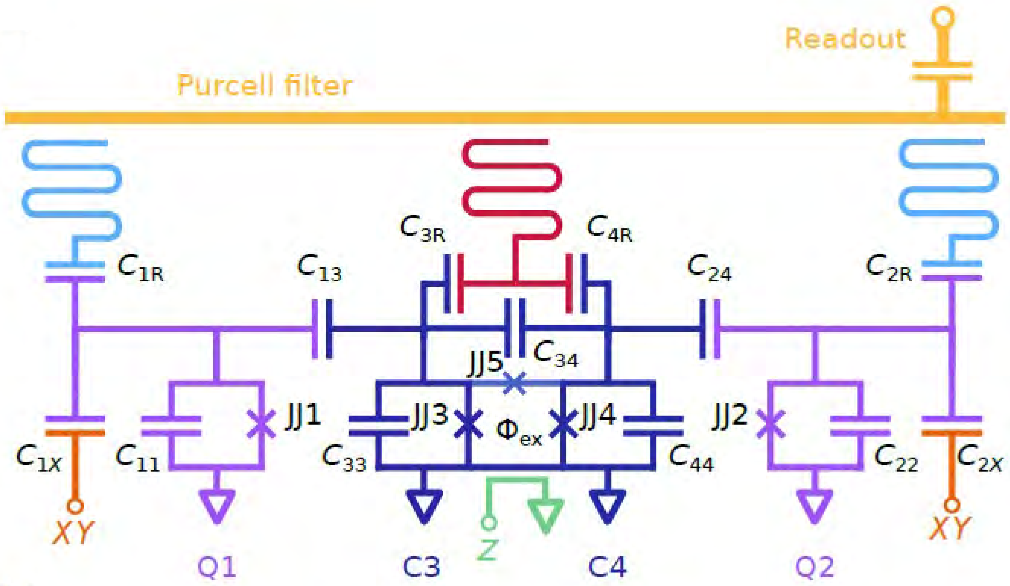
F. Swiadek *et al.* (ETH)
PRX Quantum 5, 040326 (2024)

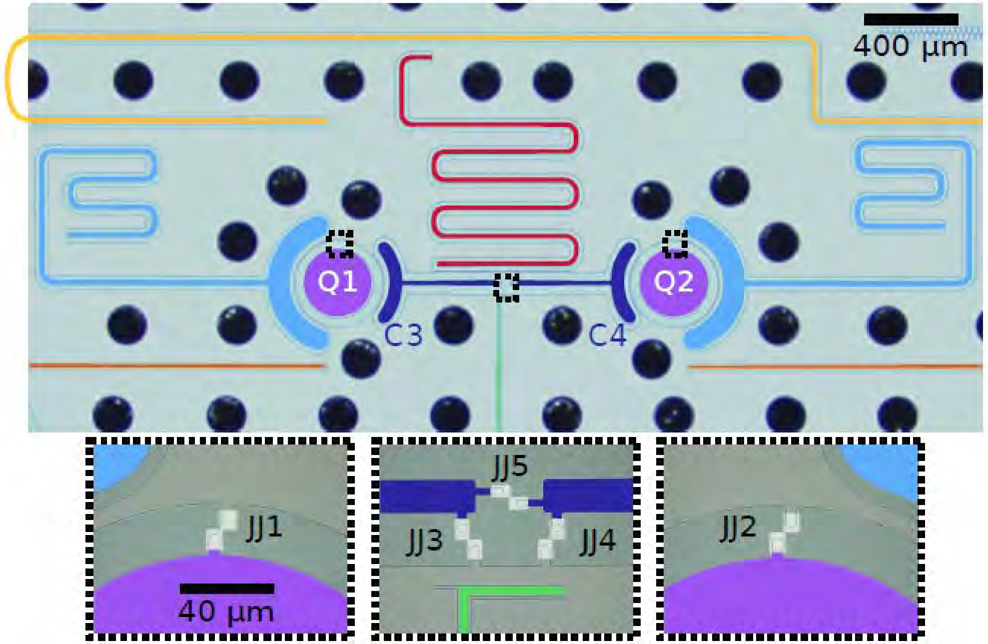
P. A. Spring et al. PRX Quantum 6, 020345 (2025)

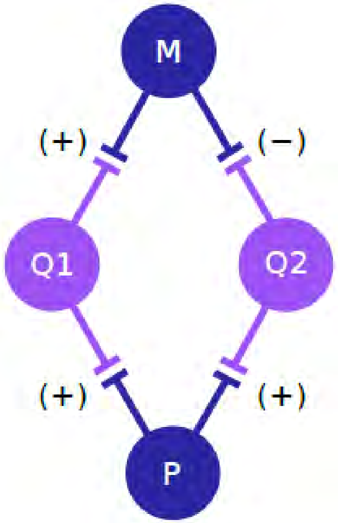
High-fidelity gate with double-transmon coupler

RIKEN QUANTUM COMPUTING

in collaboration with **TOSHIBA**





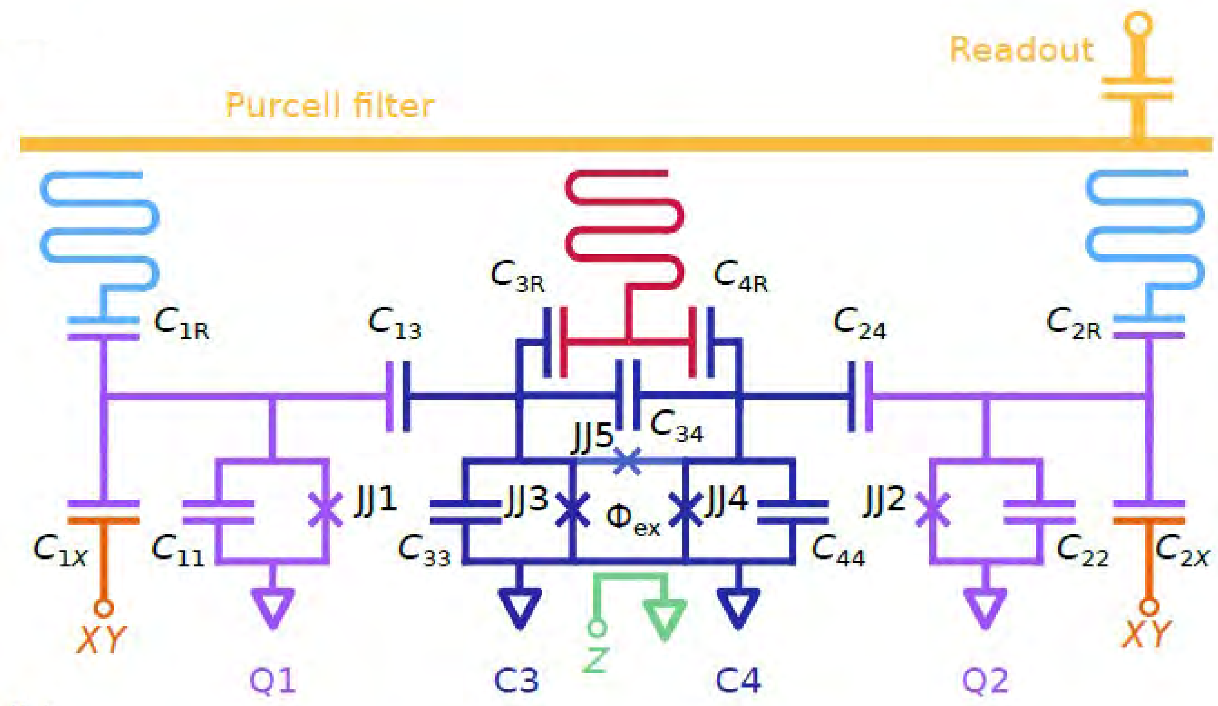


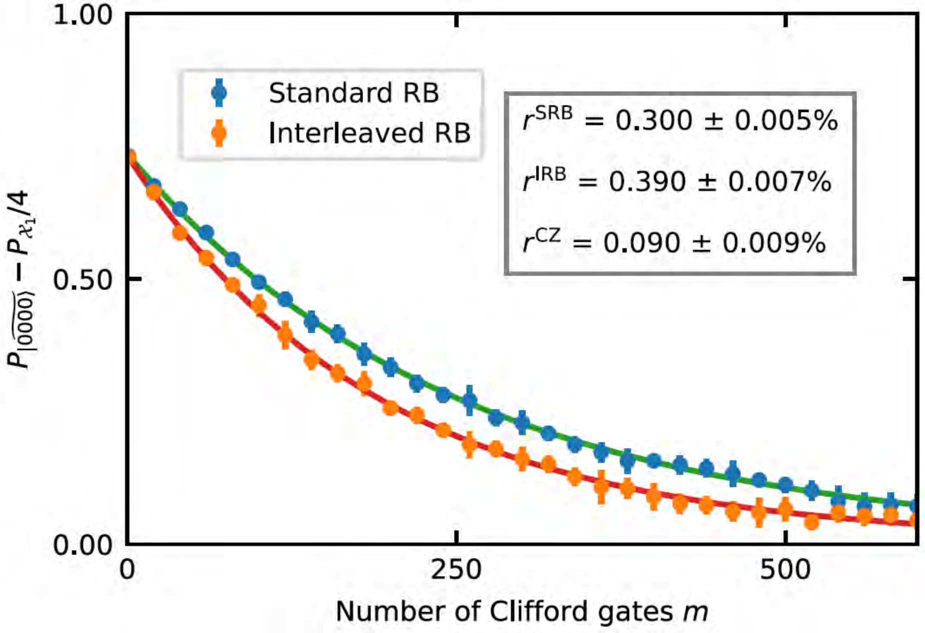
$$g_{\mathrm{eff}} = \frac{g_{1\mathrm{p}} g_{2\mathrm{p}}}{2} \left(\frac{1}{\Delta_{1\mathrm{p}}} + \frac{1}{\Delta_{2\mathrm{p}}} \right) - \frac{g_{1\mathrm{m}} g_{2\mathrm{m}}}{2} \left(\frac{1}{\Delta_{1\mathrm{m}}} + \frac{1}{\Delta_{2\mathrm{m}}} \right)$$

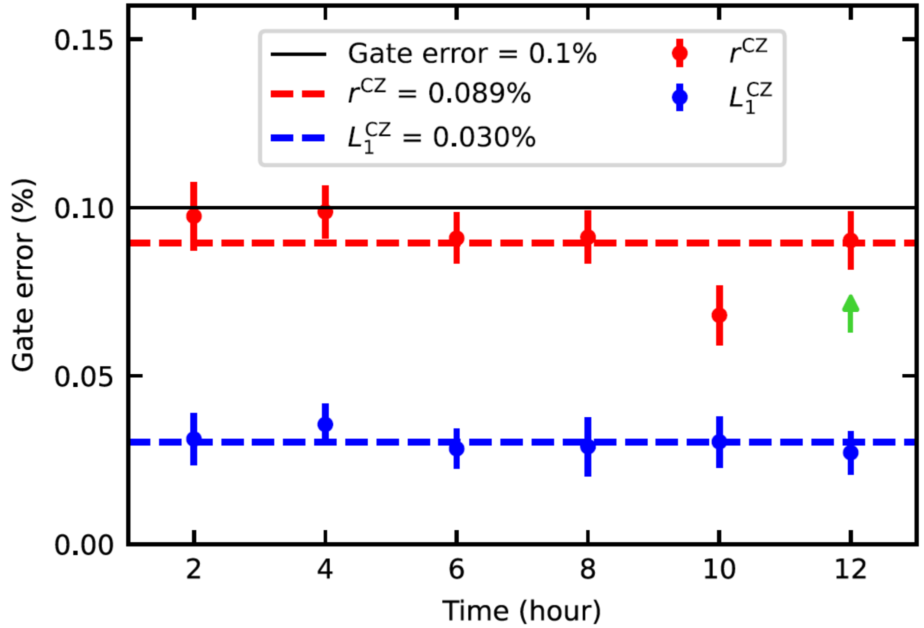
Tunable coupler consisting of double transmons and
a Josephson-junction loop
between two fixed-frequency data transmon qubits

R. Li et al. PRX 14, 041050 (2024)
(Theory) H. Goto, Phys. Rev. Appl. 18, 034038 (2022);
K. Kubo et al. Phys. Rev. Appl. 22, 024057 (2024)

High-fidelity CZ gate with double-transmon coupler







- Fast (48-ns) adiabatic flux-bias pulse for CZ gate
- CZ gate fidelity 99.90%
- Leakage error 0.03%
- Stable for 12 h

R. Li et al. PRX 14, 041050 (2024); see also Phys. Rev. Appl. 23, 064069 (2025)

Summary

Macroscopic quantum coherence

- Superposition in quantum systems with a large number of degrees of freedom

⇩

Superconducting qubits

- Artificial two-level systems in macroscopic-scale electrical circuits

⇩

Quantum computers

- Platform for precise control and measurement
  of (open) quantum systems with a large number of degrees of freedom