Towards superconducting quantum computing

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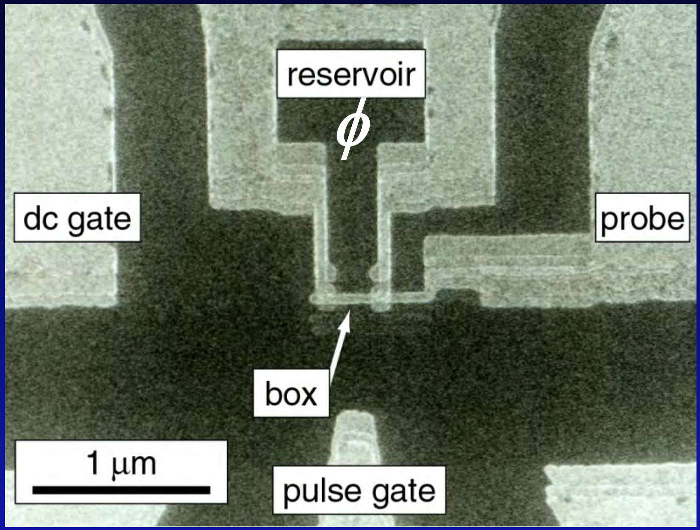
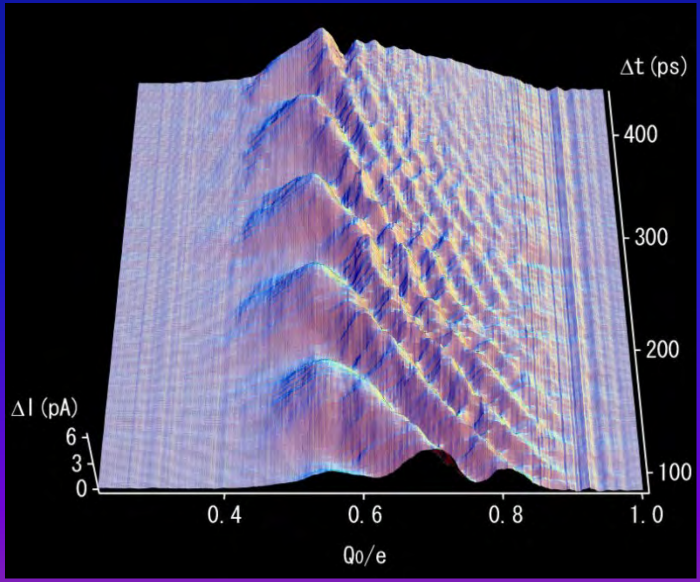
Superconducting quantum bits

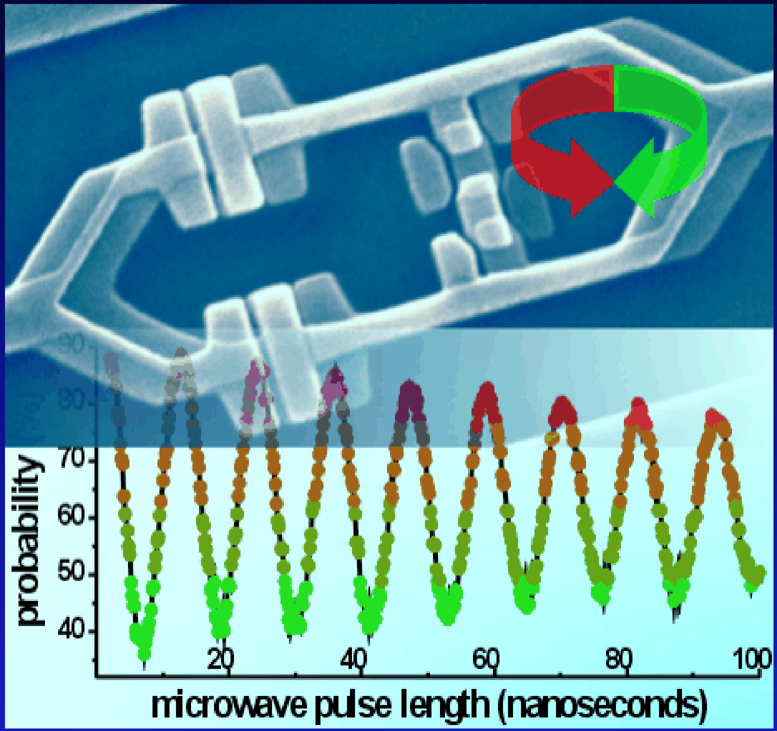
Charge qubit





YN, Pashkin, Tsai, Nature (1999)

Flux qubit



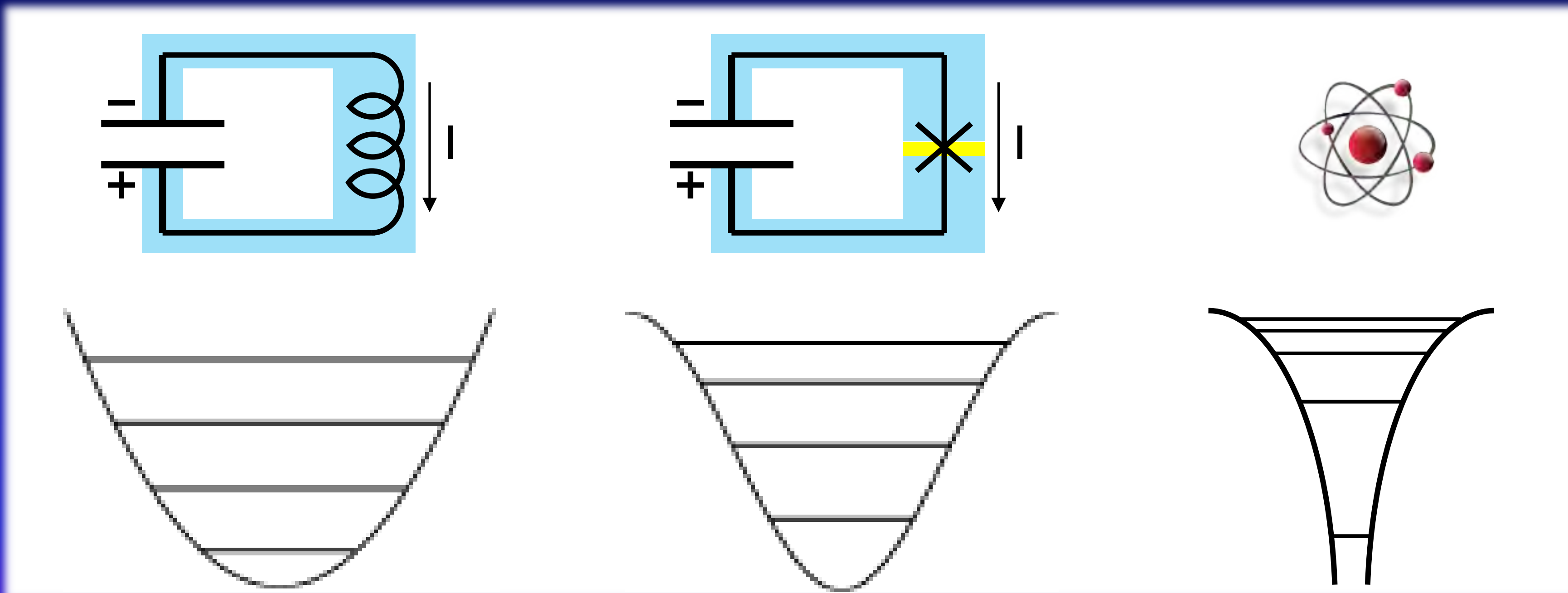
Chiorescu, YN, Harmans, Mooij, Science (2003)

Artificial two-level system in circuits

Coherent control of macroscopic system

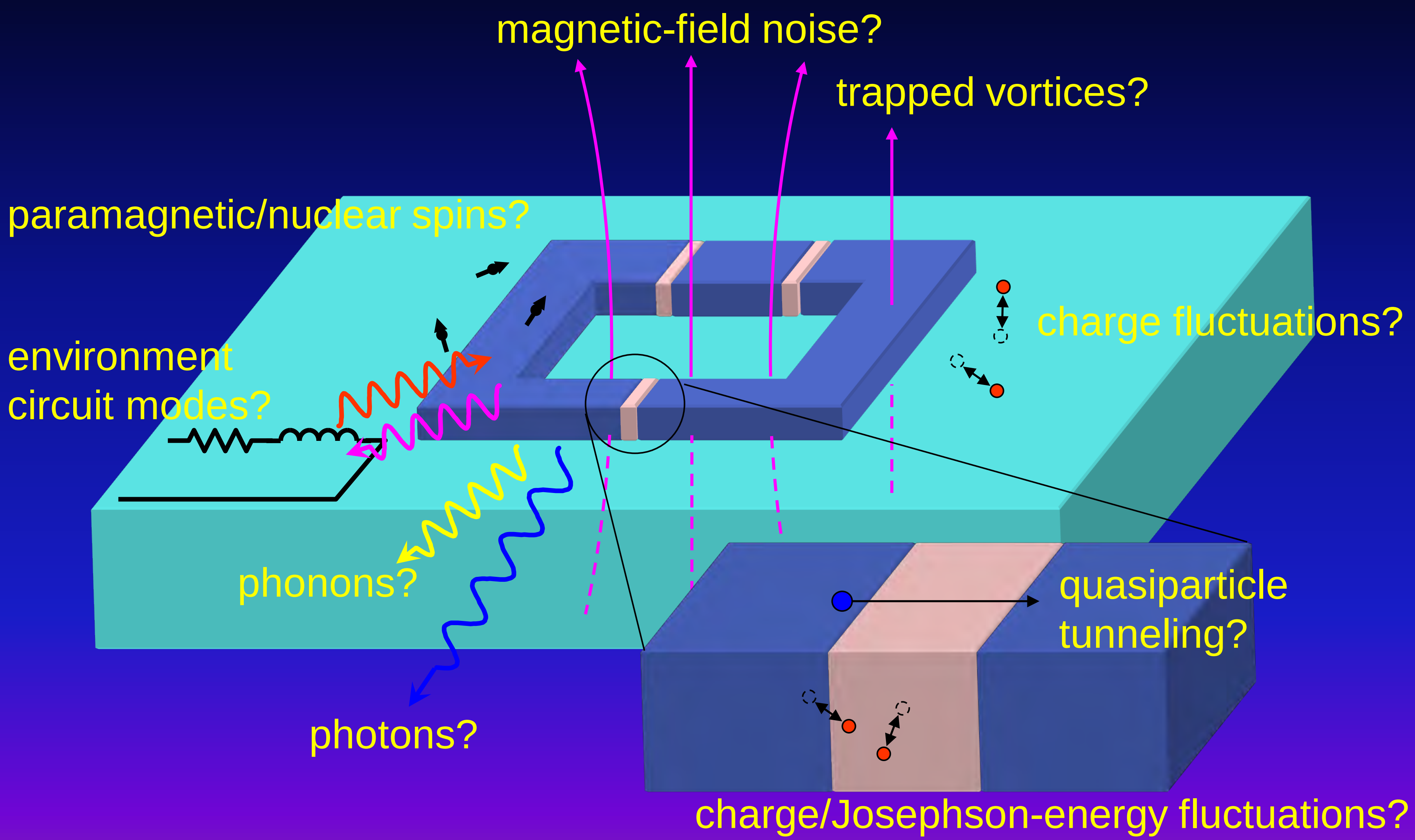
Superconducting qubit – nonlinear resonator

LC resonator | **Superconducting qubit = Artificial atom ~mm** | **Atom ~Å**

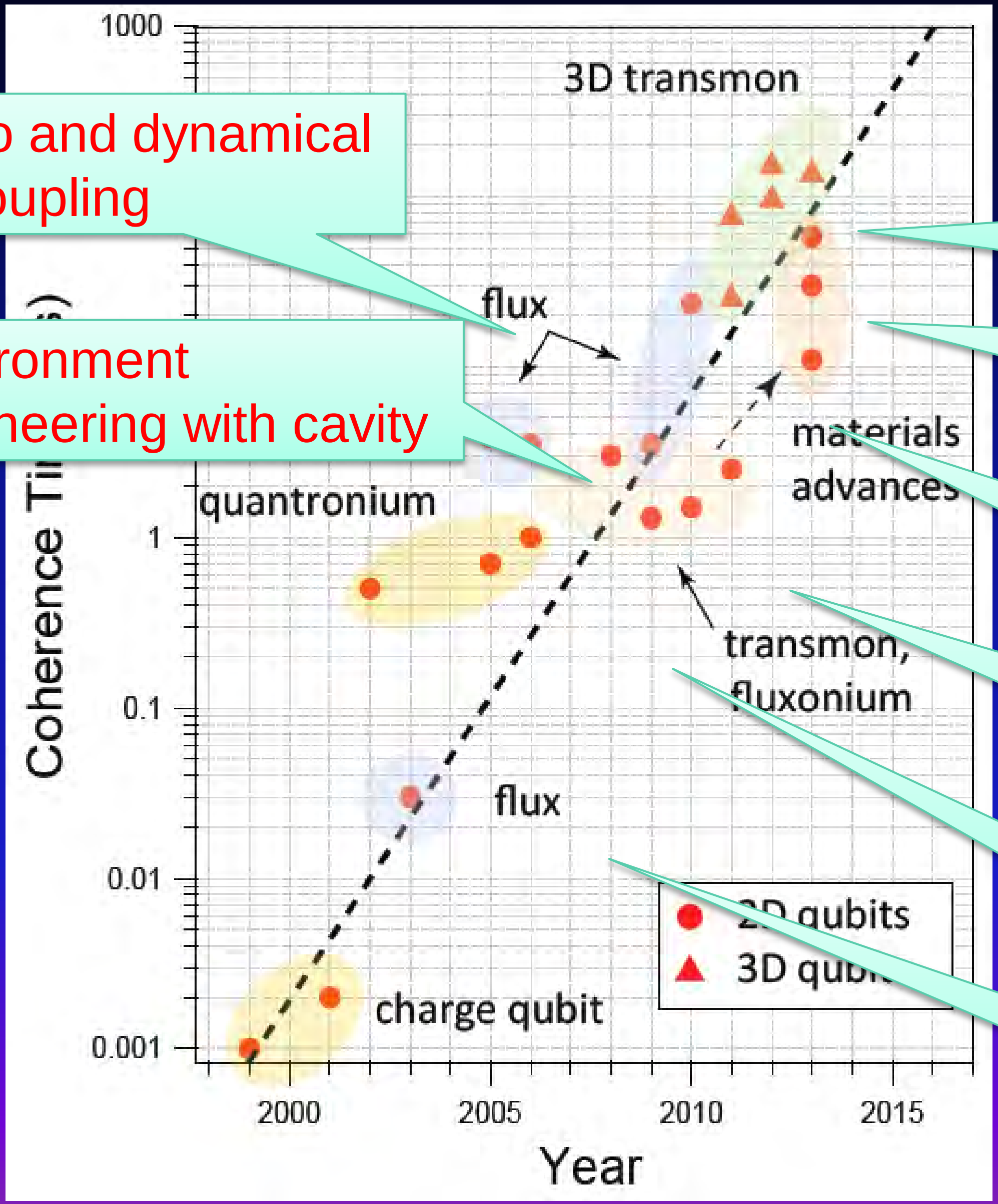


- **Superconductivity ⇒ low-loss**
- **Josephson effect ⇒ Strong nonlinearity**
- **Macroscopic size ⇒ Strong coupling**

Possible decoherence sources



Coherence time of superconducting qubits



Low-energy qubit

Echo and dynamical decoupling

Non-equilibrium quasiparticle engineering

High-frequency noise shielding

Environment engineering with cavity

Diluted surface/interface effect

Improved surface/interface/dielectric

Energy-level engineering

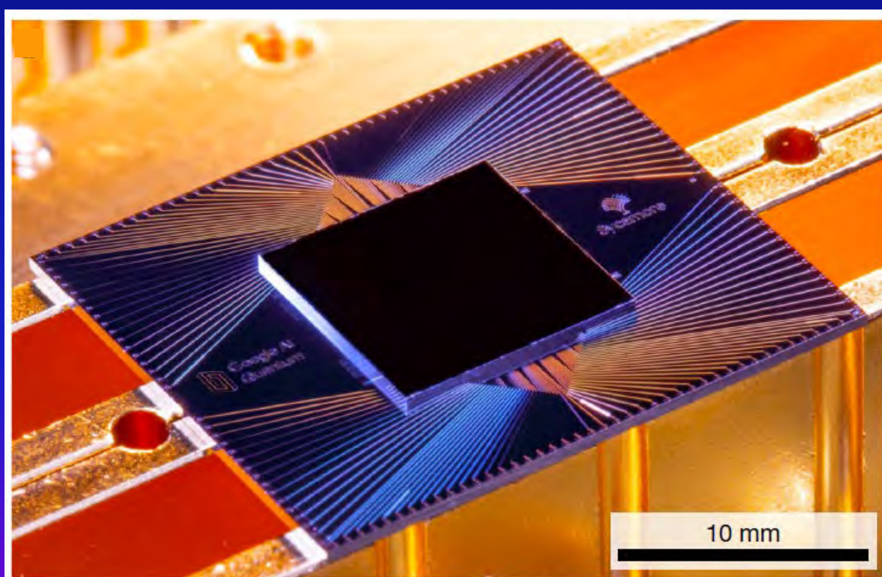
Decoupling from charge noise

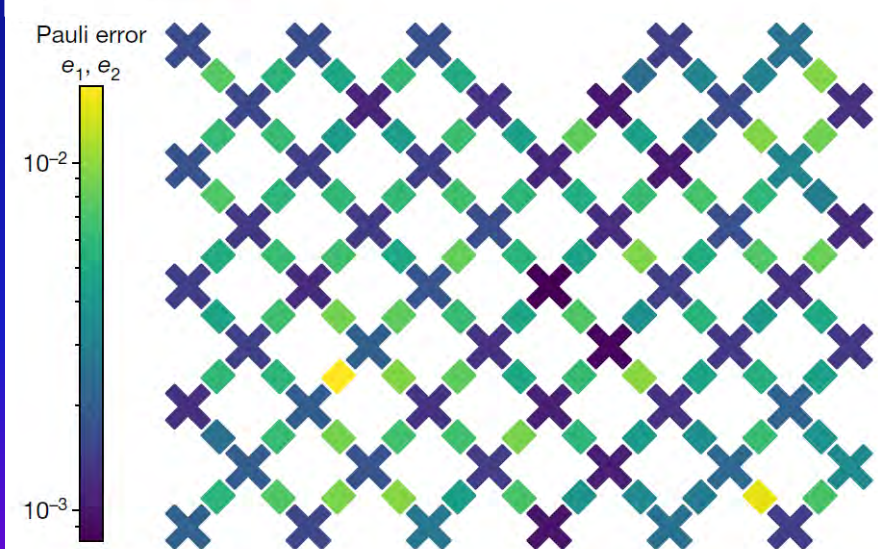
W. D. Oliver and P. Welander, MRS BULLETIN 38, 816 (2013) MIT-LL

Quantum supremacy using a programmable superconducting processor

- **Tunable-frequency qubits**
- **Tunable coupling**
  - **Fast two-qubit gate ~ 12 ns**
  - **Suppression of residual coupling**
- **Flip-chip bonding**

Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%



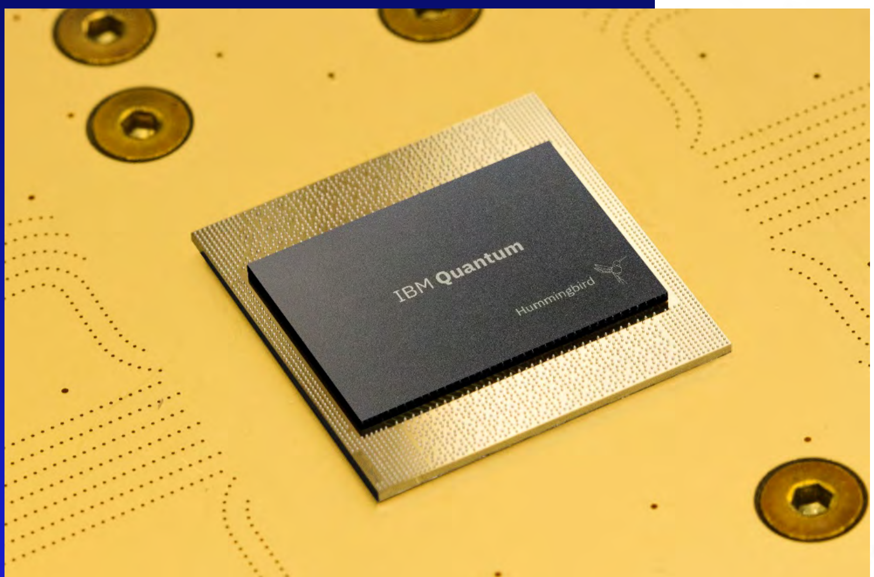


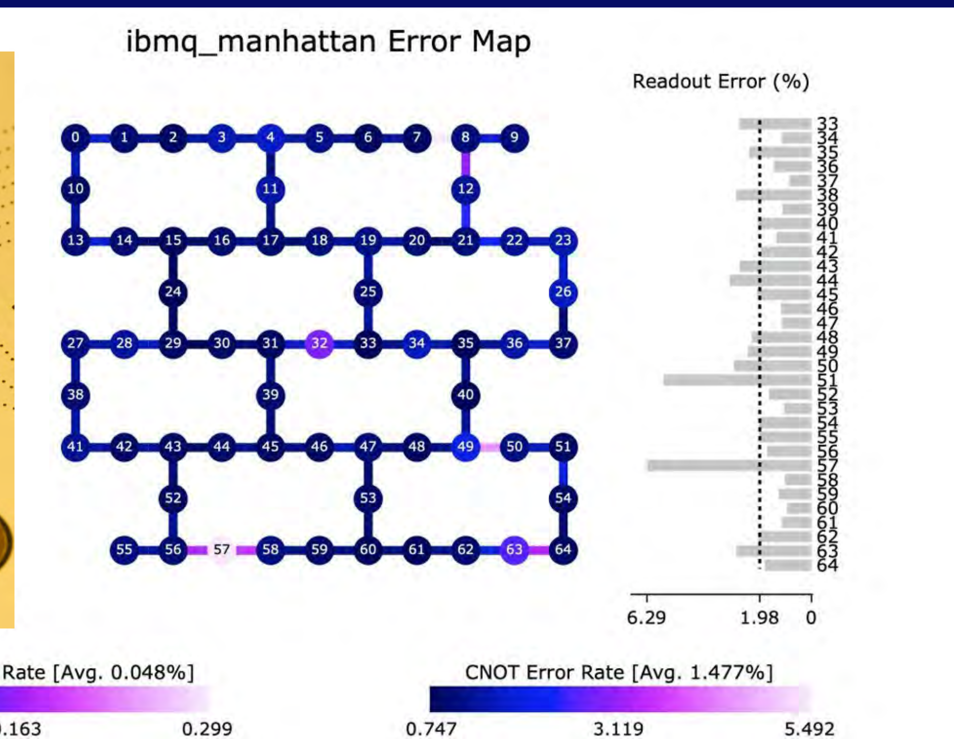
Google AI Quantum
Nature 574, 505 (2019)

9 × 6 – 1 = 53 qubits

Fixed-frequency qubits

- **Long coherent time ~ 100 μs**
- **Cross-resonant gate ~ 150 ns F～99.2％ (max)**
- **65 qubits on cloud service**



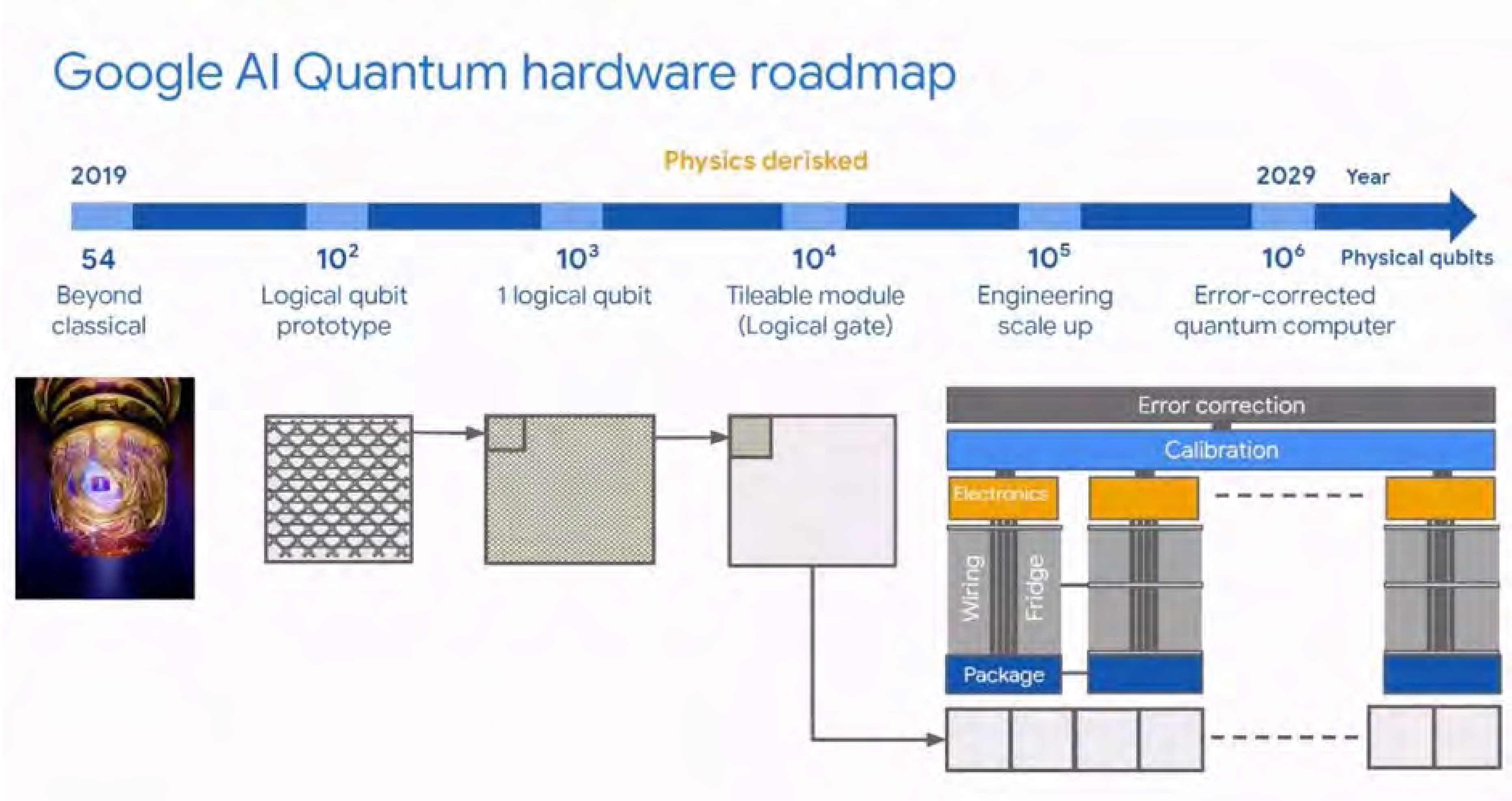


Best CR gate: F～99.7％ A. Kandala et al. arXiv:2011.07050

https://techcrunch.com/wp-content/uploads/2020/09/IBM-Quantum-Hummingbird.jpg

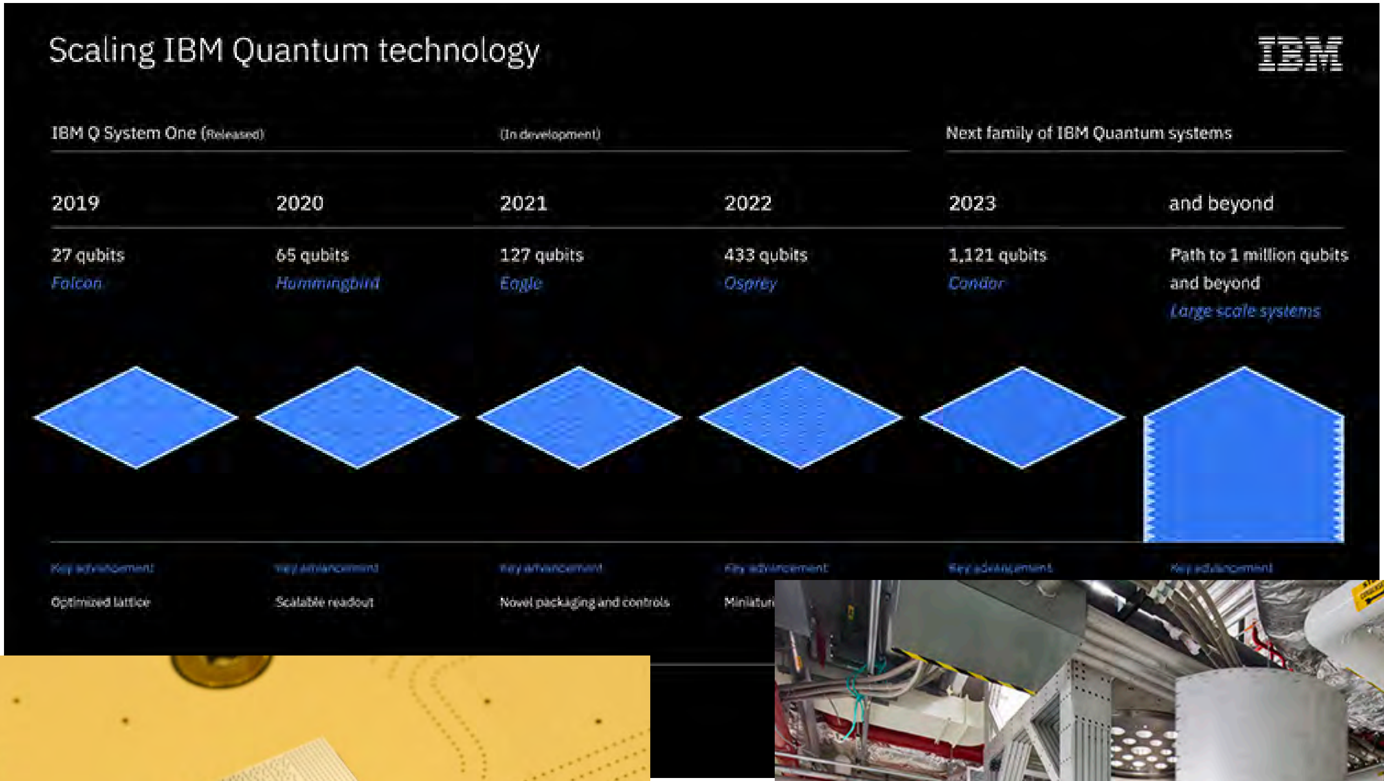
https://pbs.twimg.com/media/Eg2STiZWkAIPRDX.jpg

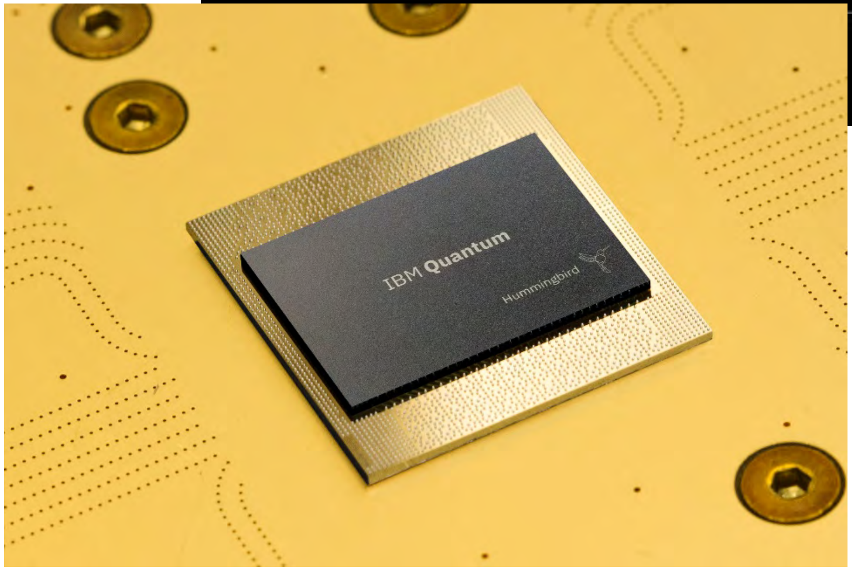
Google roadmap

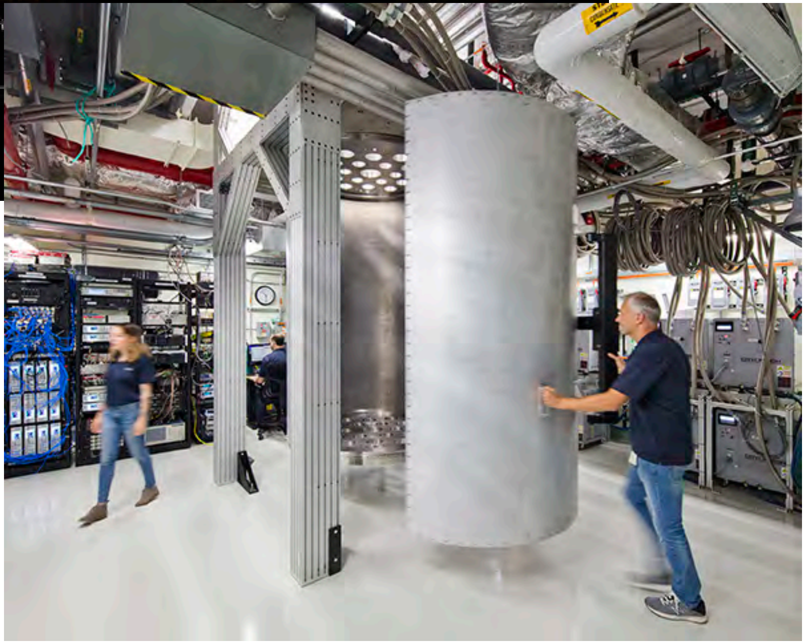


https://www.cnet.com/news/quantum-computer-makers-like-their-odds-for-big-progress-soon/

IBMQ scaling







https://techcrunch.com/wp-content/uploads/2020/09/IBM-Quantum-Hummingbird.jpg

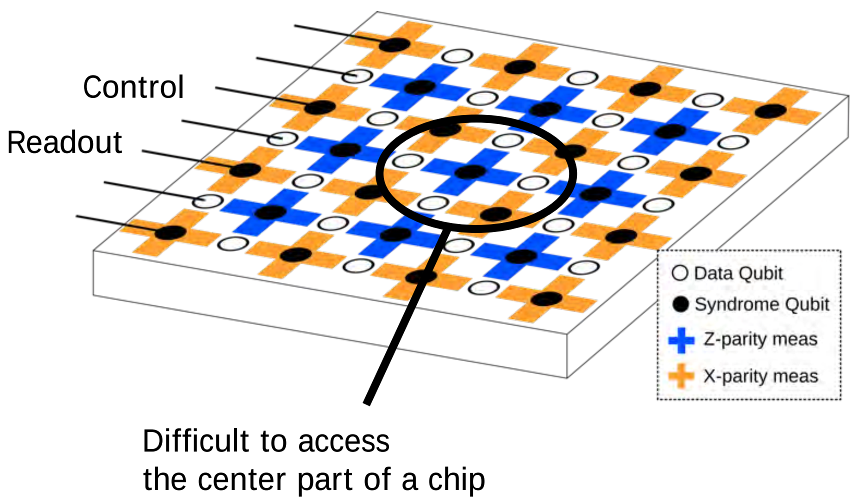
https://www.ibm.com/blogs/research/2020/09/ibm-quantum-roadmap/

Packaging for superconducting quantum computer chips

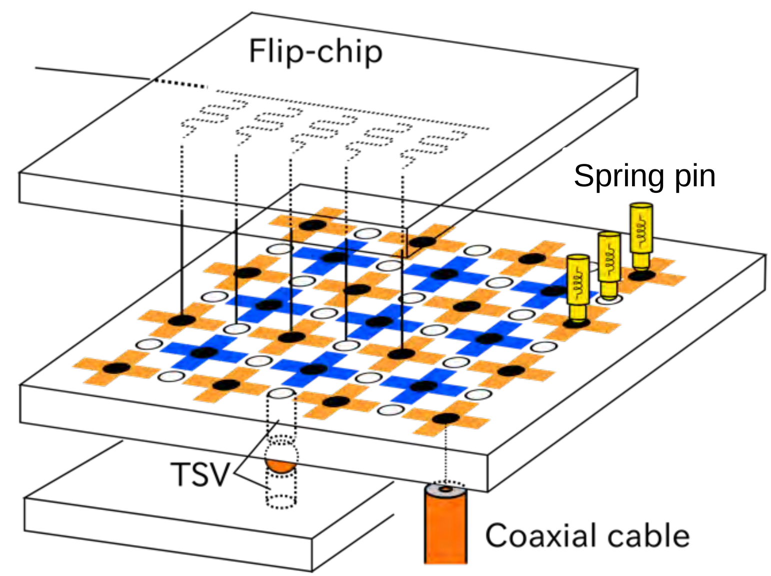
Demands:

- 2D (or 3D) integration of qubits
- High-density wiring with scalability
- High-density I/O connectors
- High-frequency wiring <~ 10 GHz
- Low crosstalk, no parasitic mode
- Low dissipation
- (Superconducting contact)
- Heat anchoring to ~10 mK
- “Light-tight” radiation shielding
- Non-magnetic, non-radioactive, (cosmic-ray proof)

Wiring issues for scaling-up



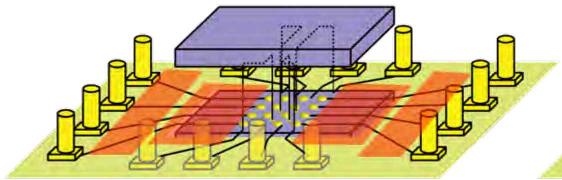
3D wiring to a qubit chip



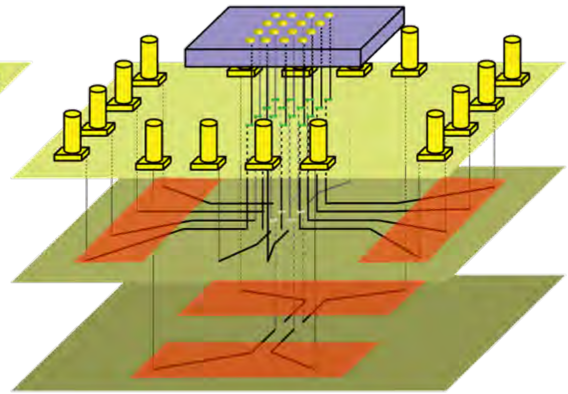
S. Tamate et al. APS March meeting 2021

Scalability of wiring

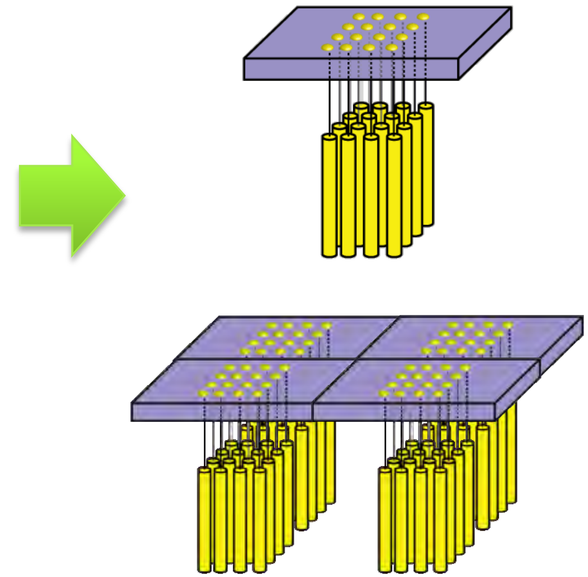
Flip-chip bonding



TSV + Multi-layer PCB



TSV + Vertical coax cable



N: number of qubits

: $O(\sqrt{N})$ wiring density

	Flip-chip bonding	TSV + Multi-layer PCB	TSV + Vertical coax
On-chip density	$O(\sqrt{N})$	$O(1)$	$O(1)$
On-PCB density	$O(\sqrt{N})$	$O(\sqrt{N})$	N.A.

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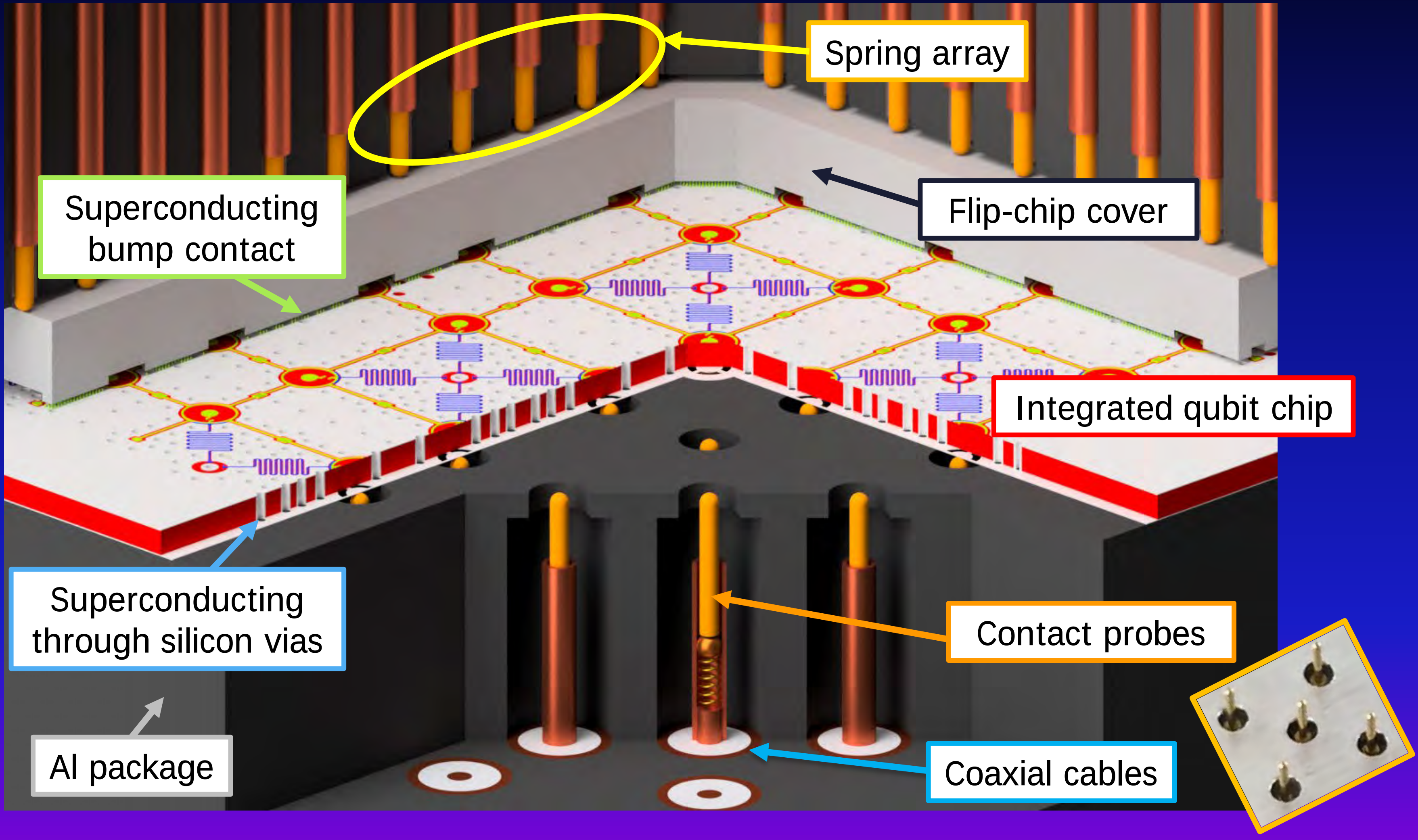
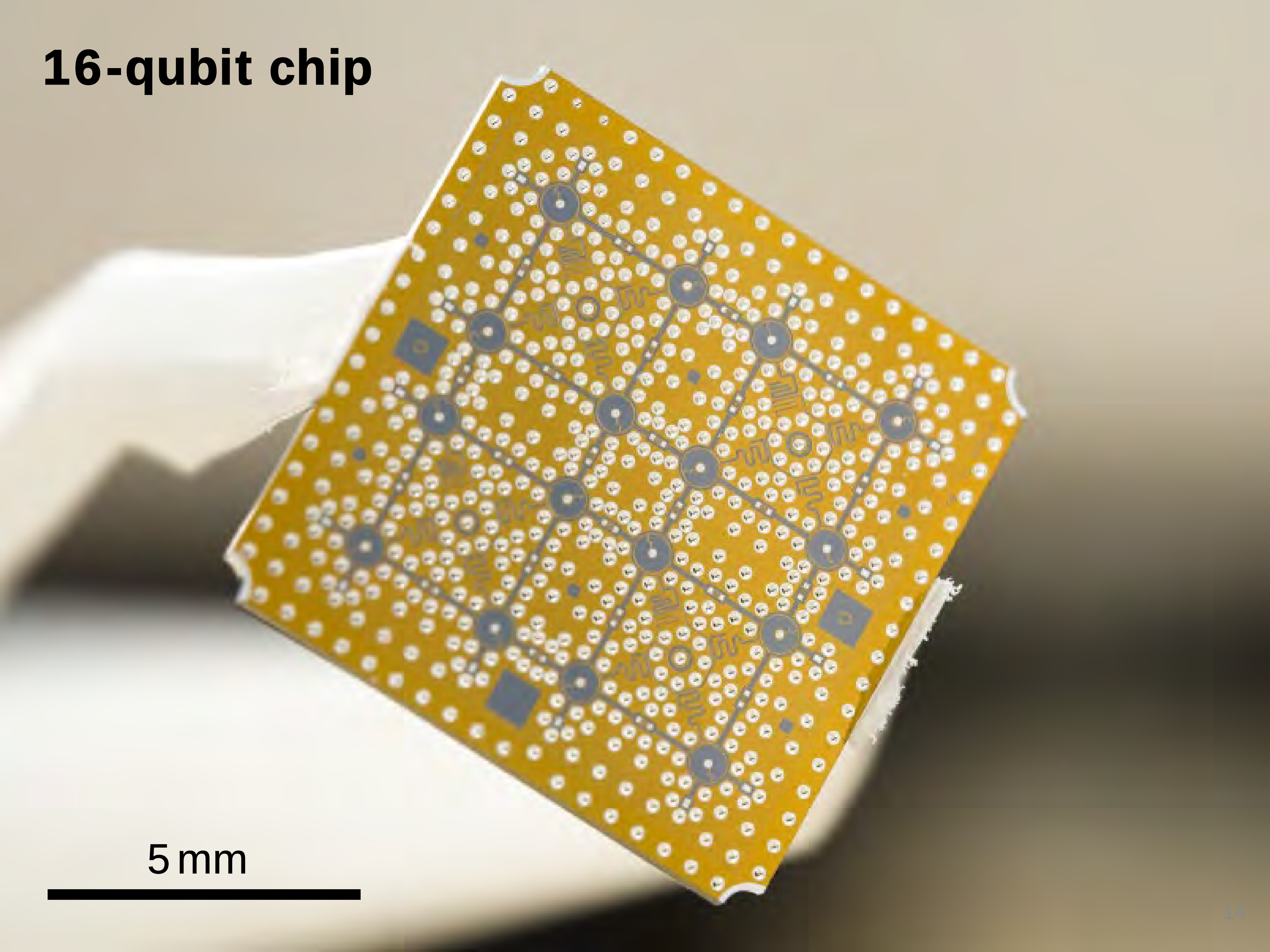
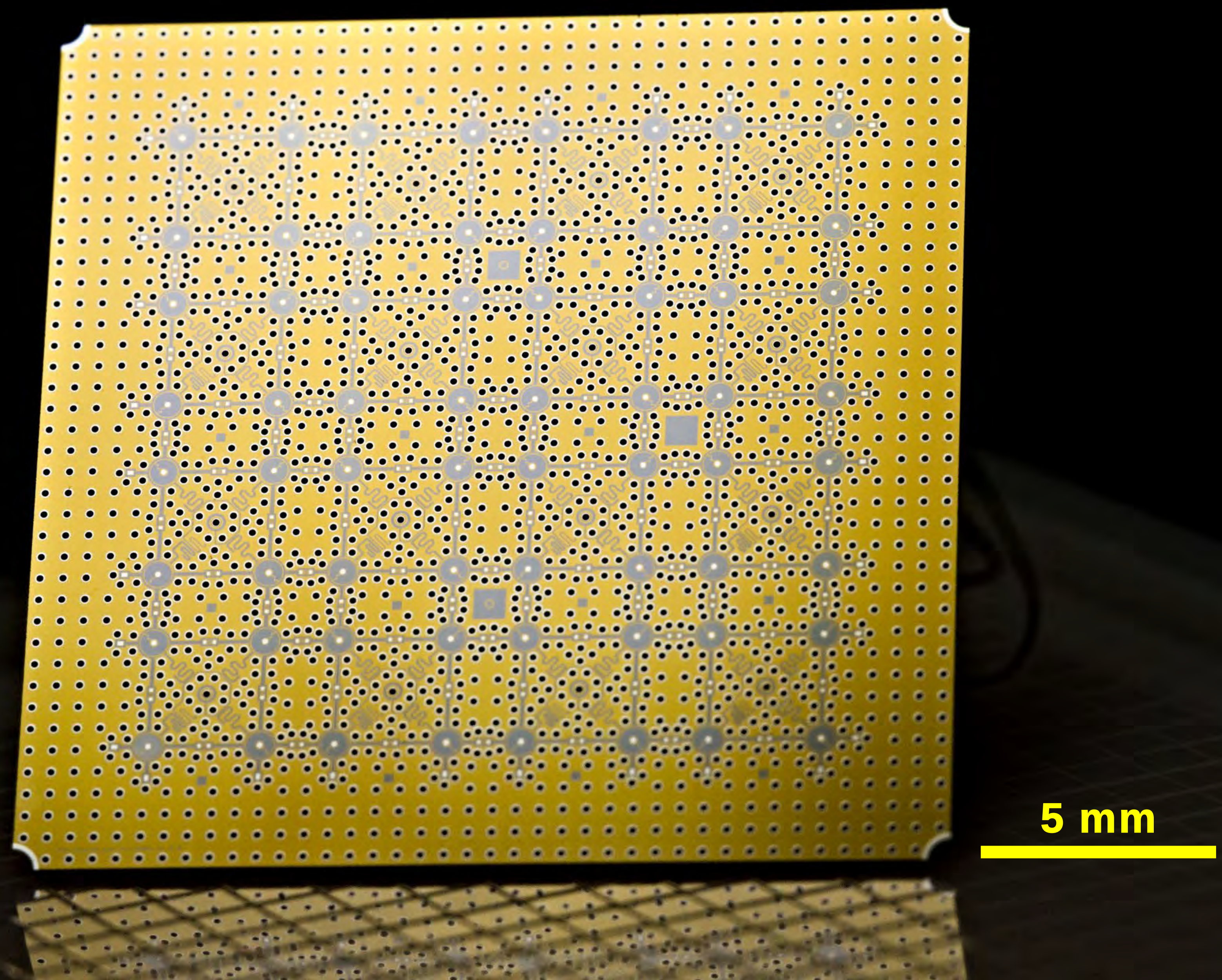
2D integration with 3D wiring



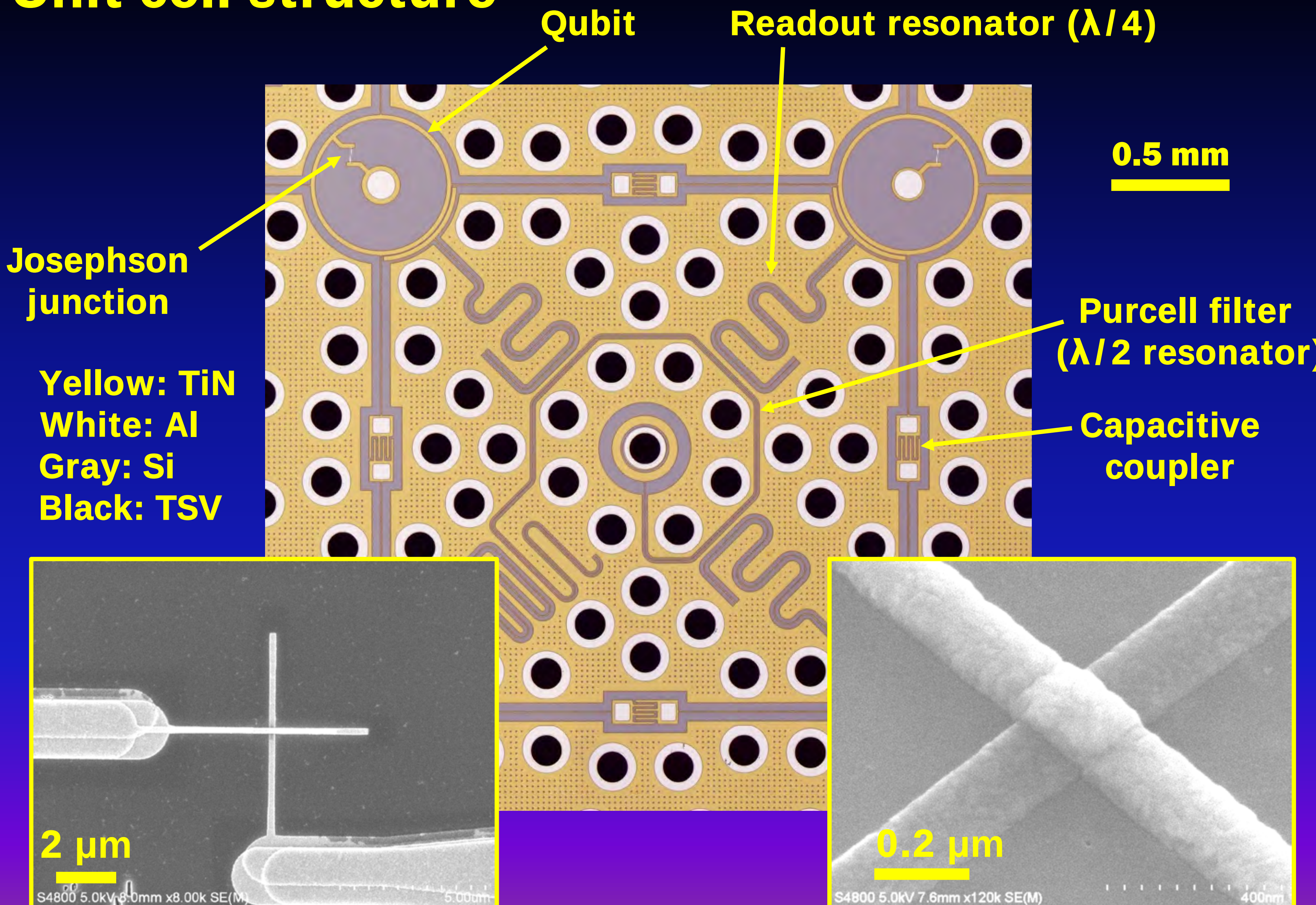
16-qubit chip



64-qubit chip



Unit cell structure



Unit cell structure ユニットセル構造

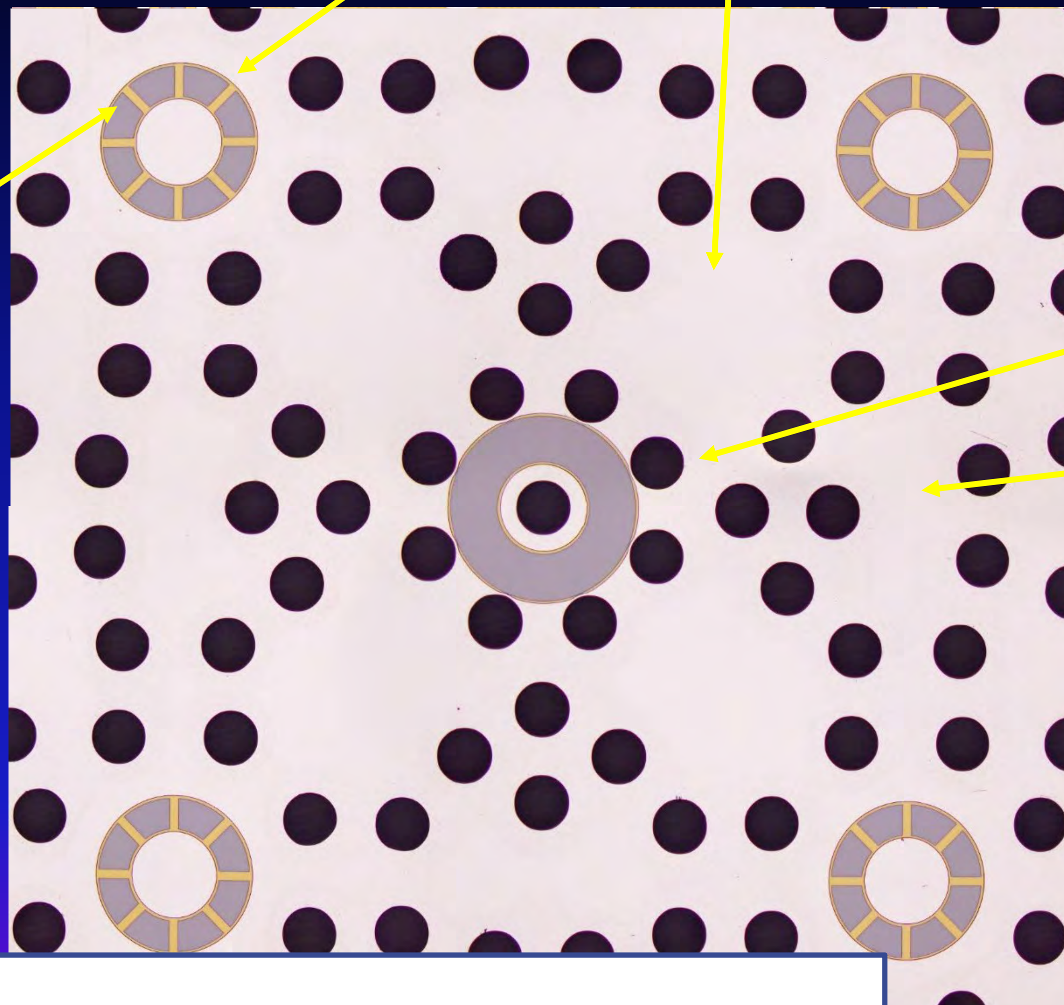
Qubit

Readout resonator (λ/4)

0.5 mm

Josephson junction

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



Purcell filter (λ/2 resonator)

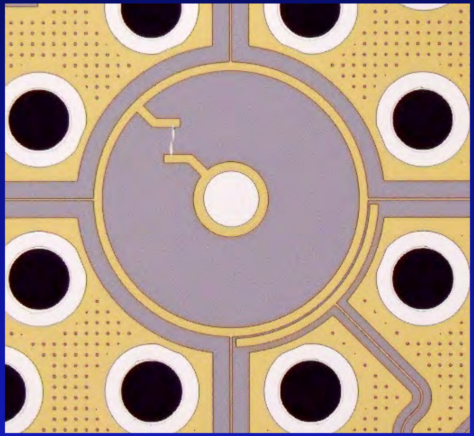
Capacitive coupler

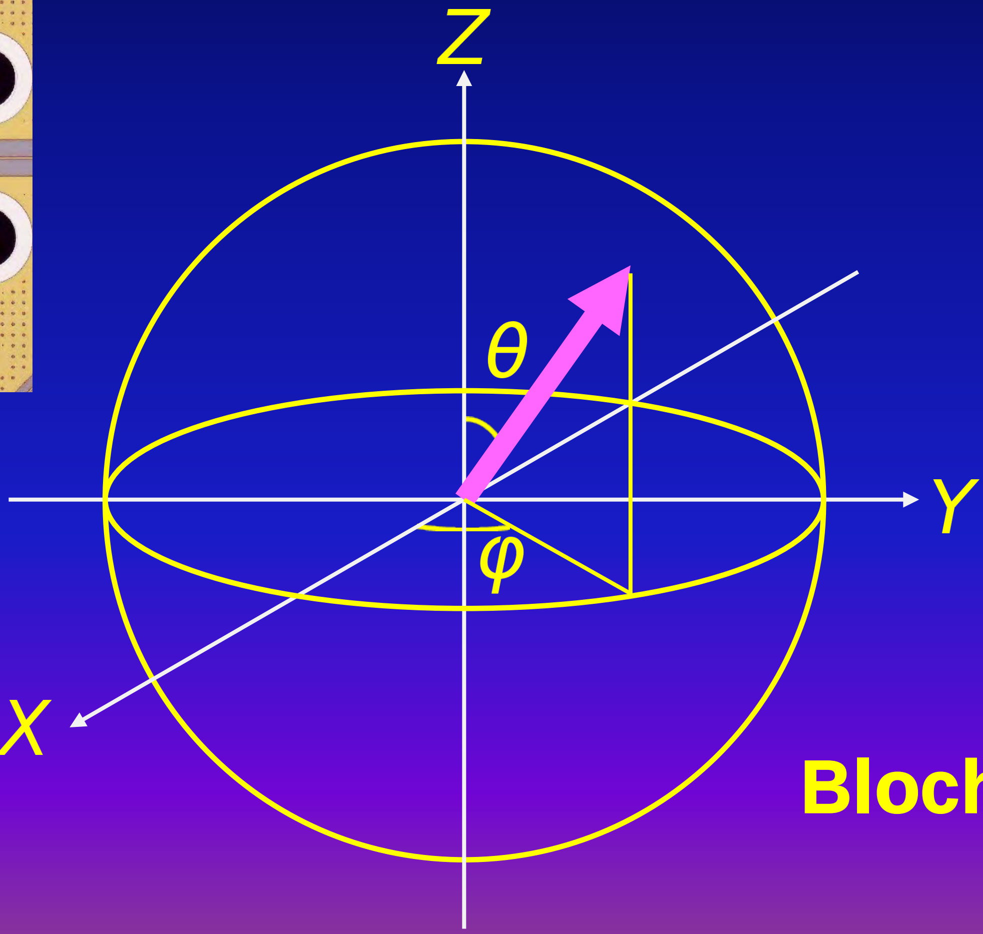
Backside

Quantum bit

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad (|\alpha|^2 + |\beta|^2 = 1)$$

$$= \cos(\theta/2)\,|0\rangle + e^{i\varphi}\sin(\theta/2)\,|1\rangle$$

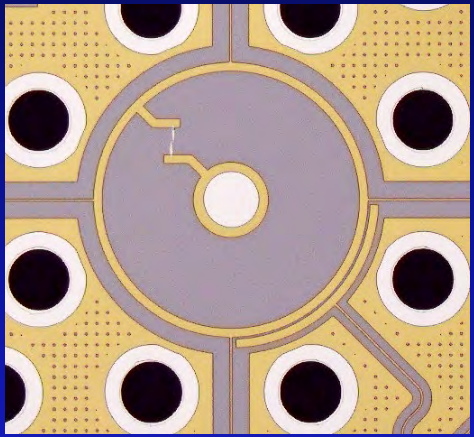


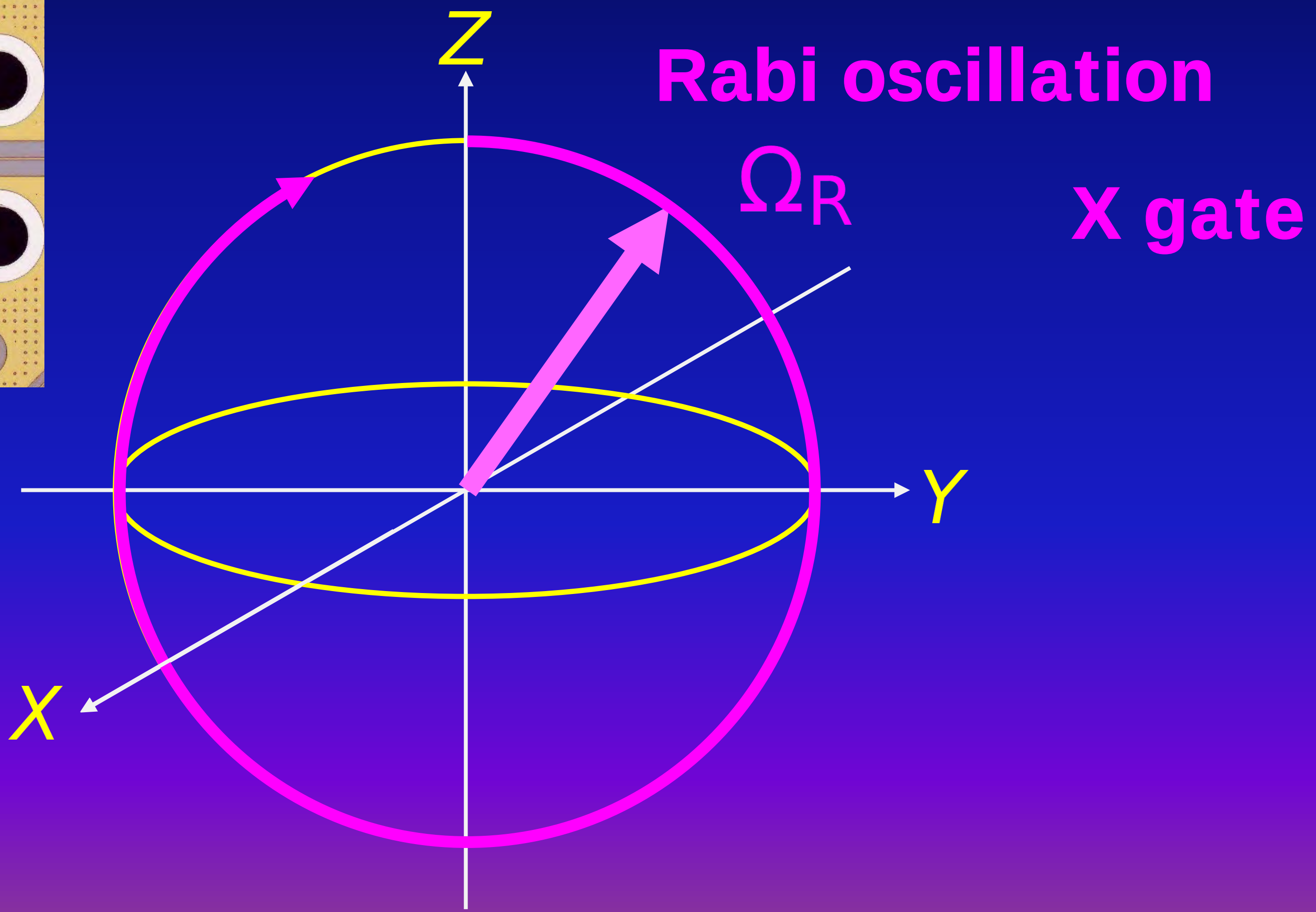


Bloch sphere

Single-qubit gate

$$\frac{H}{\hbar} = \frac{\omega_q}{2}\sigma_z + \Omega_R \cos\omega_q t\, \sigma_x$$



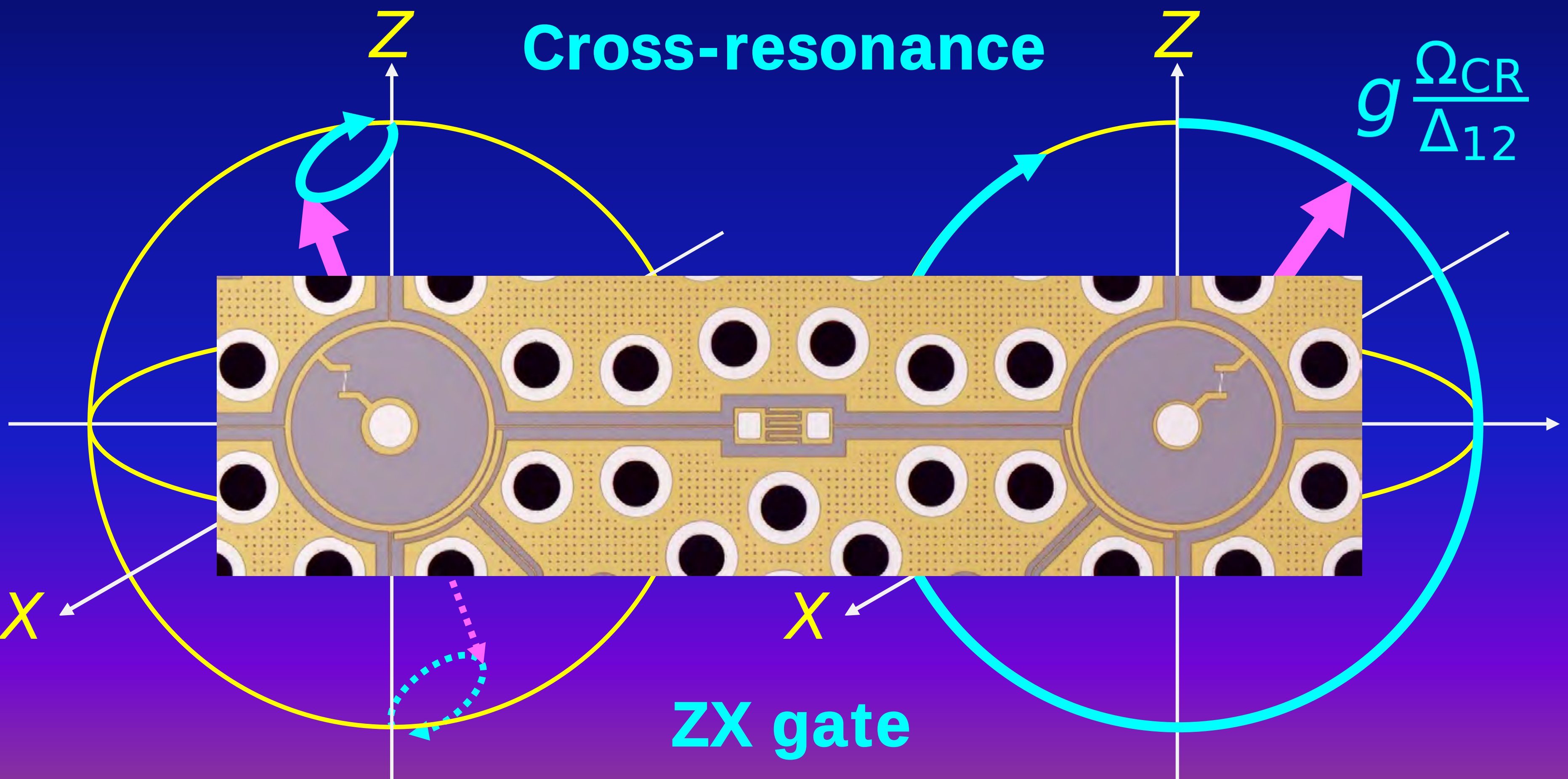


Two-qubit gate

$$\frac{H}{\hbar} = \frac{\omega_{q1}}{2}\sigma_{z1} + \frac{\omega_{q2}}{2}\sigma_{z2} + g\sigma_{x1}\sigma_{x2}$$

$$+\Omega_{CR}\cos\omega_{q2}t\,\sigma_{x1} \qquad \Delta_{12} \equiv \omega_{q1} - \omega_{q2} \gg g$$

Cross-resonance



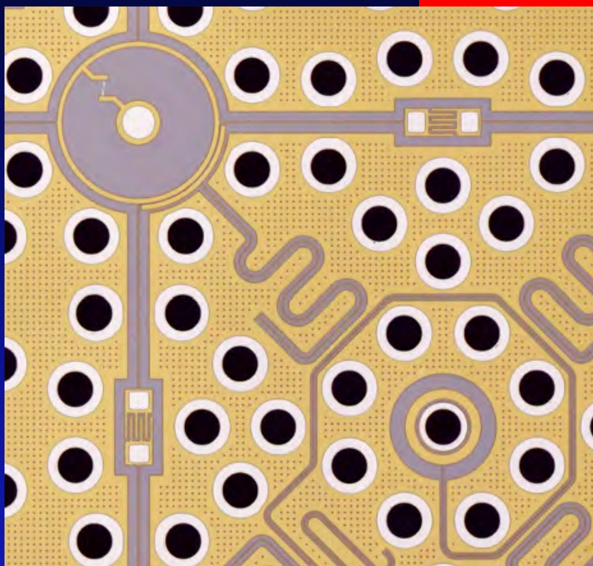
ZX gate

Qubit readout

$$H_{\mathrm{JC}} = \frac{\hbar\omega_{\mathrm{q}}}{2}\hat{\sigma}_z + \hbar\omega_{\mathrm{c}}\hat{a}^{\dagger}\hat{a} + \hbar g(\hat{\sigma}_{+}\hat{a} + \hat{\sigma}_{-}\hat{a}^{\dagger})$$

Cavity mode

Interaction



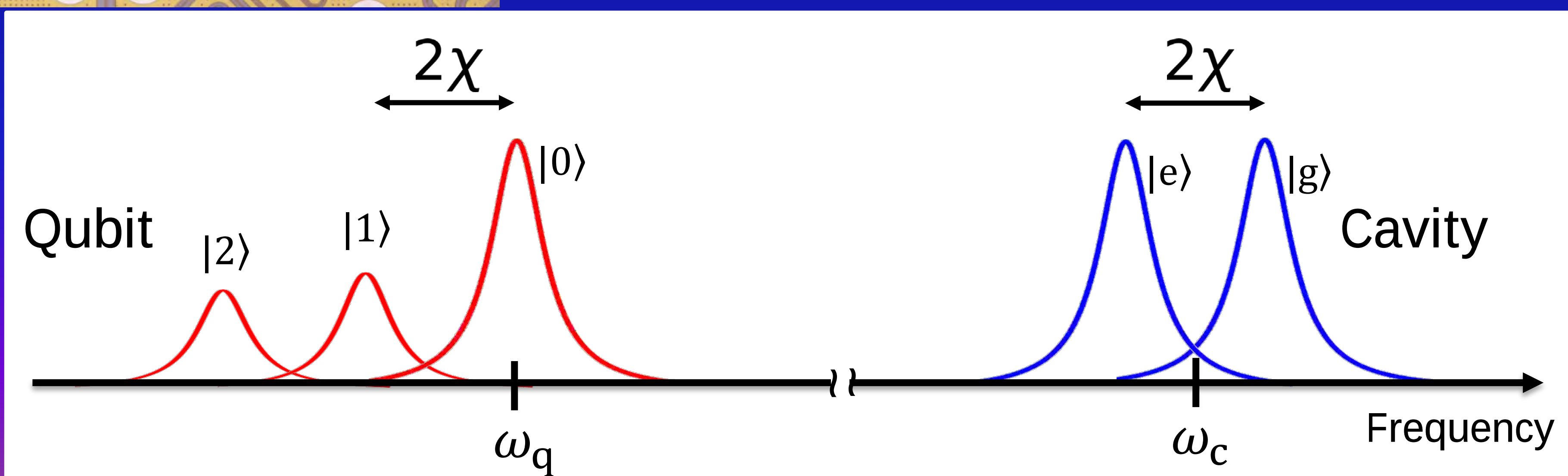
$$(\Delta \equiv \omega_{\mathrm{q}} - \omega_{\mathrm{c}},\ \ \chi = g^2/\Delta)$$

$$\frac{\hbar(\omega_{\mathrm{q}}-\chi)}{2}\hat{\sigma}_z + \hbar\omega_{\mathrm{c}}\hat{a}^{\dagger}\hat{a} - \hbar\chi\hat{a}^{\dagger}\hat{a}\hat{\sigma}_z$$

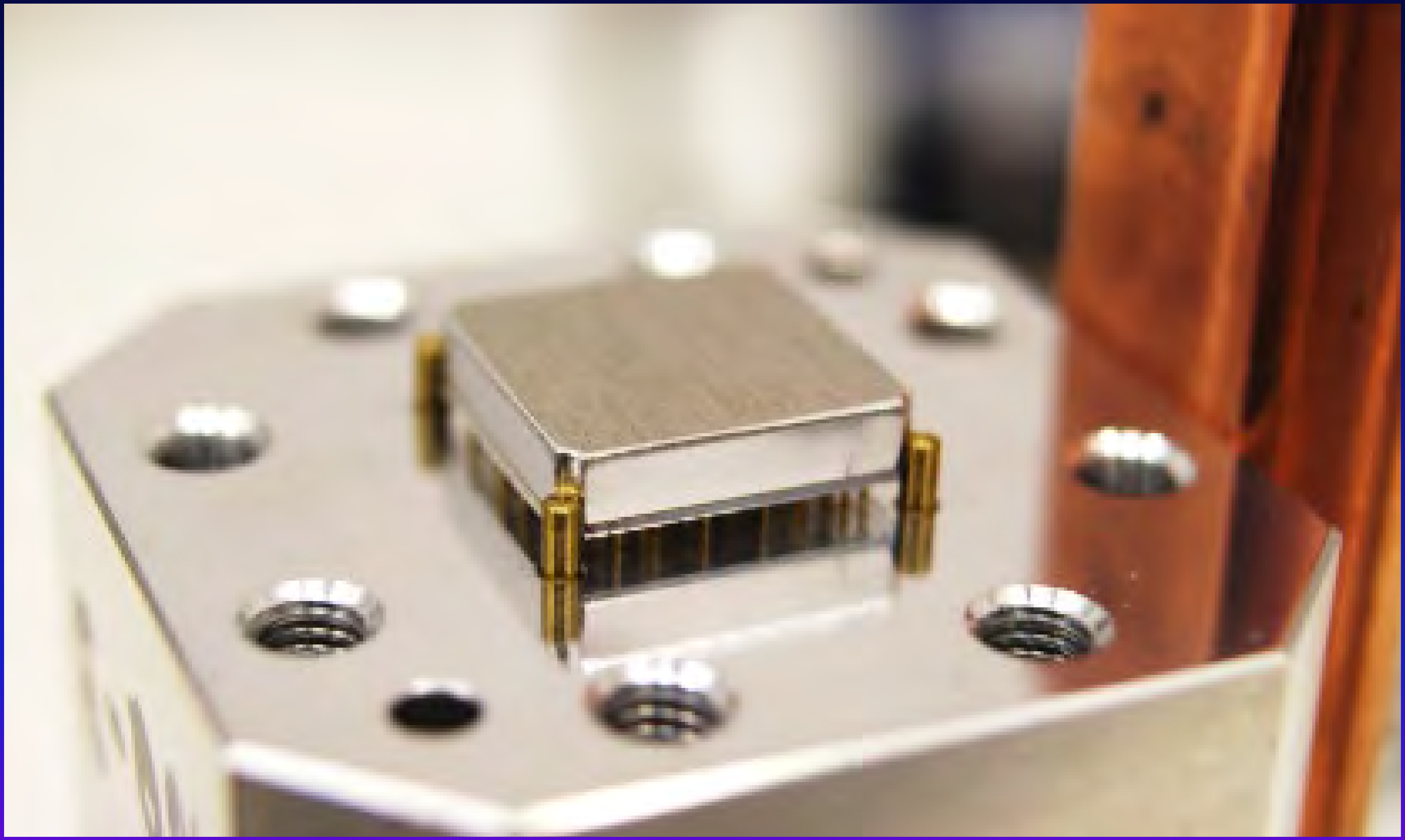
Qubit

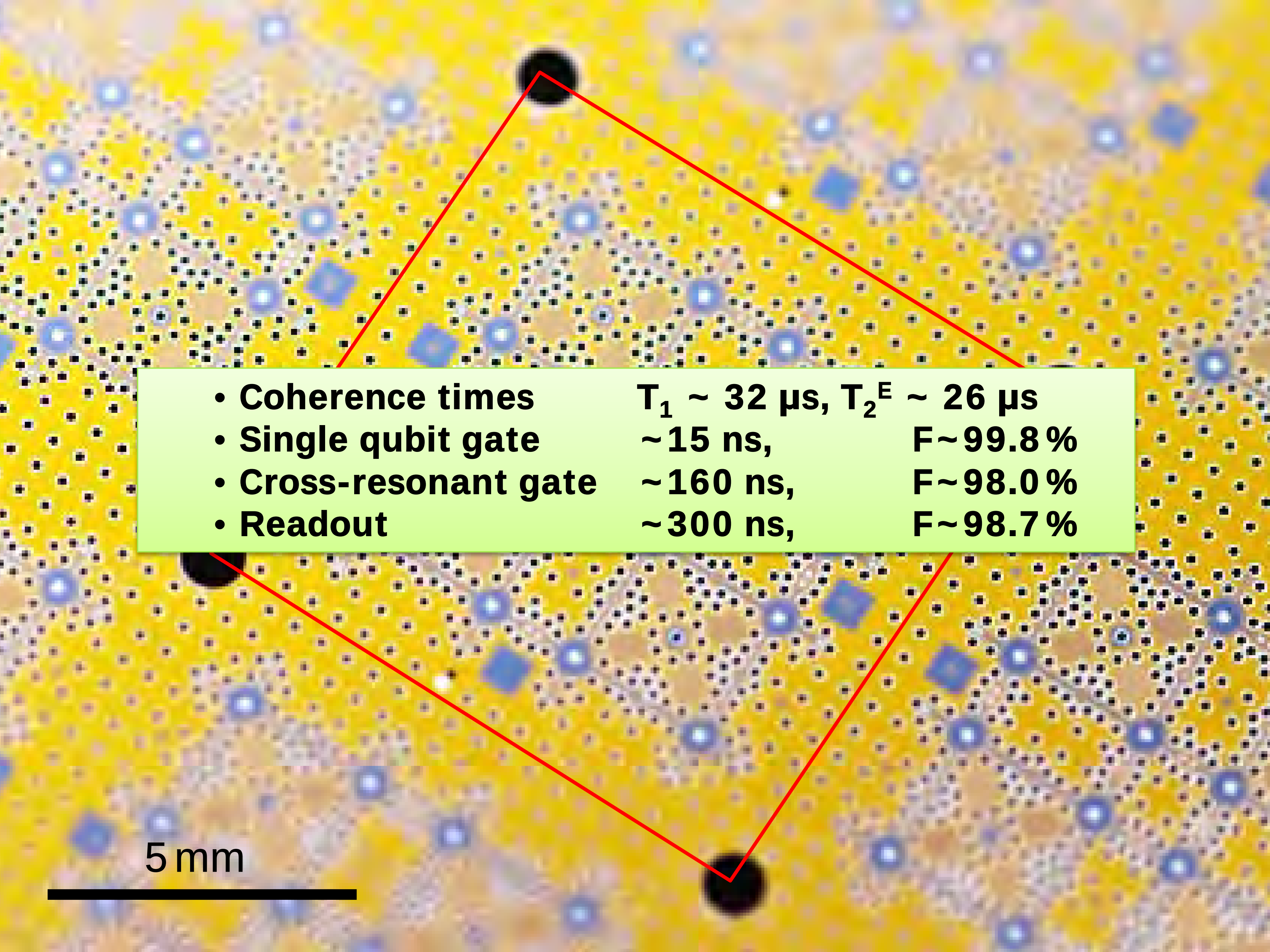
Cavity mode

Interaction

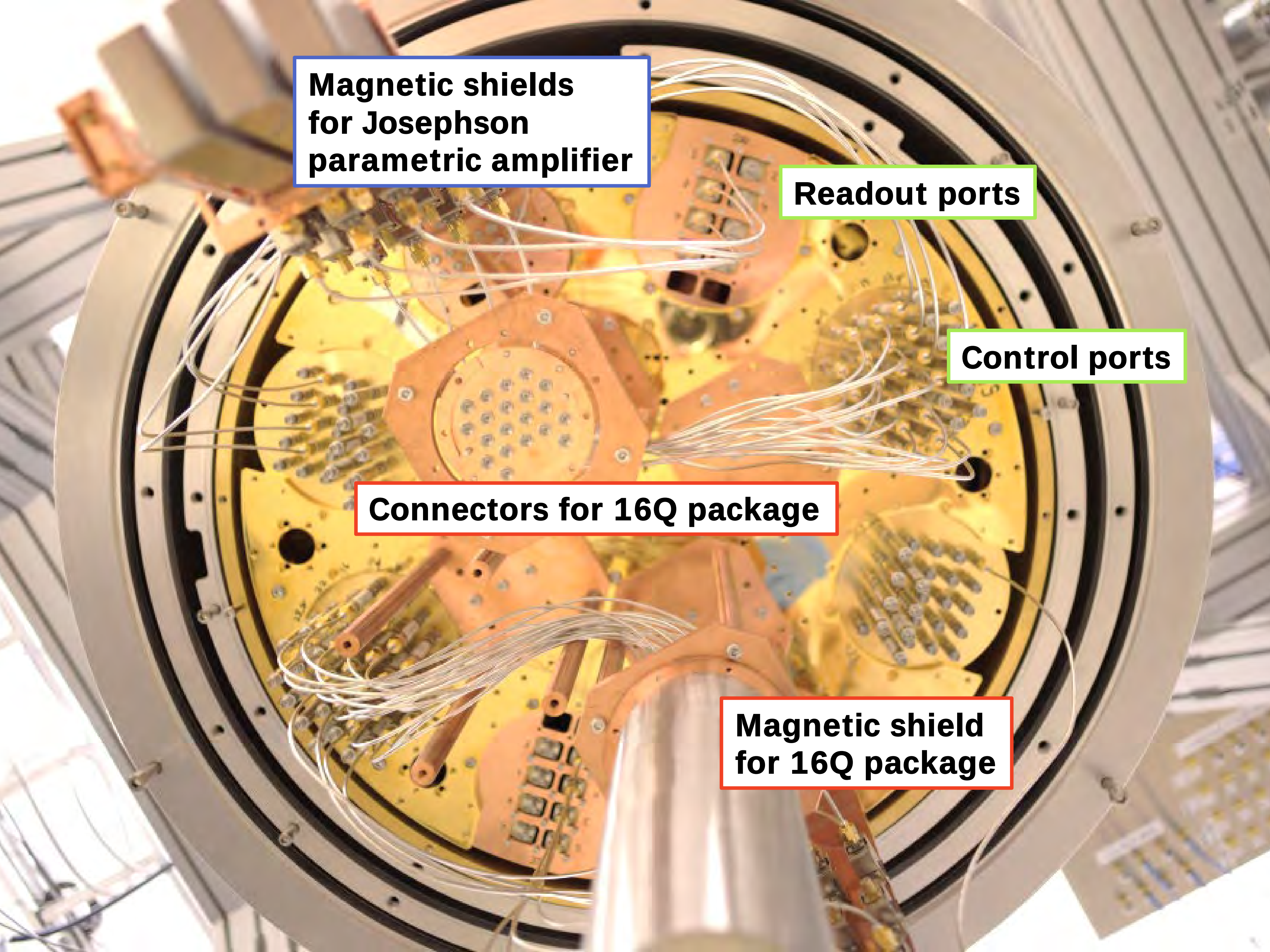


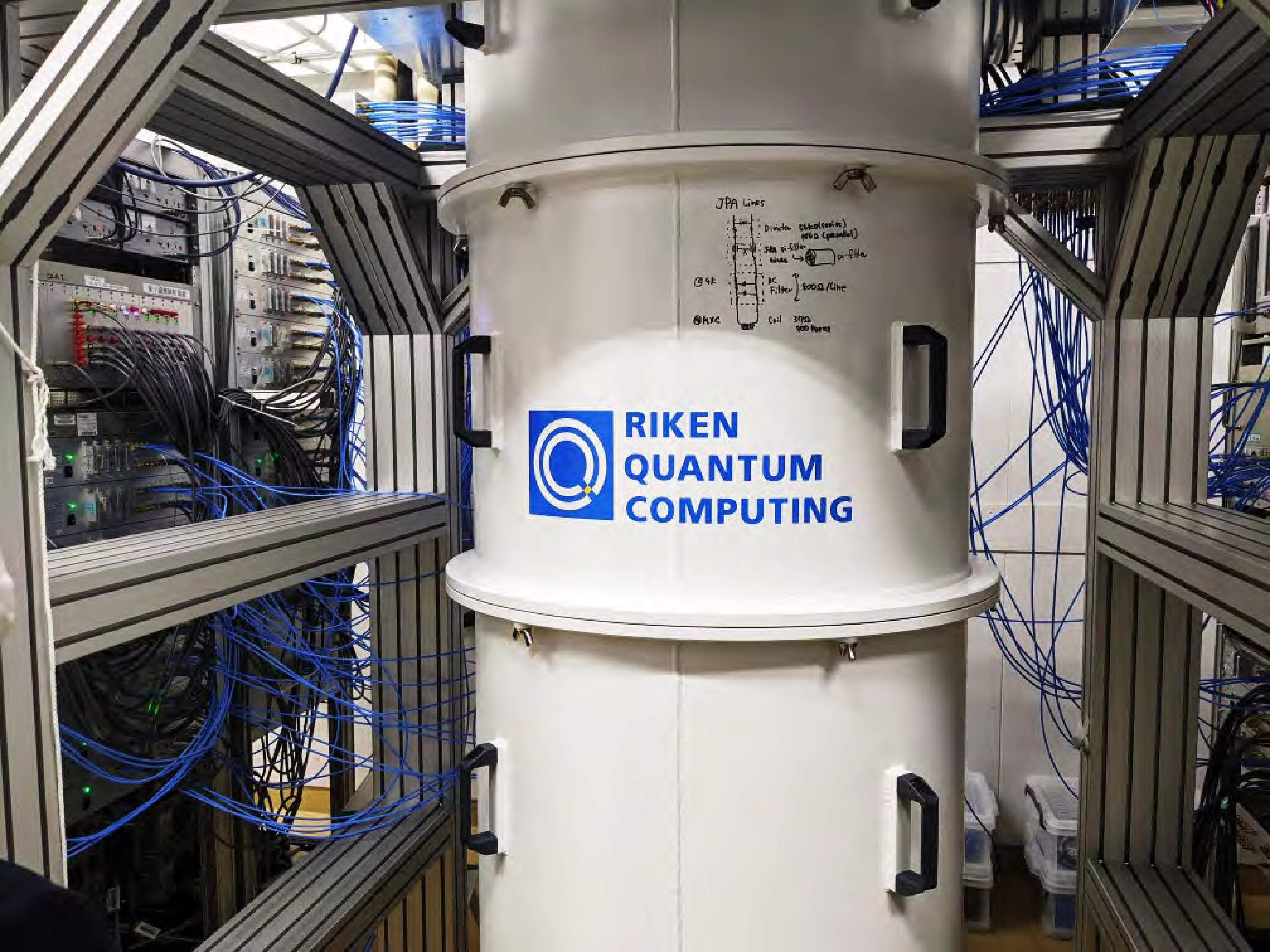
Packaging with vertical access





• Coherence times T_1 ~ 32 μs, T_2^E ~ 26 μs
• Single qubit gate ~15 ns, F~99.8 %
• Cross-resonant gate ~160 ns, F~98.0 %
• Readout ~300 ns, F~98.7 %
5 mm


Magnetic shields for Josephson parametric amplifier
Readout ports
Control ports
Connectors for 16Q package
Magnetic shield for 16Q package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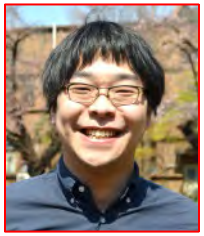
Q-LEAP Superconducting quantum computing flagship

東京大学 THE UNIVERSITY OF TOKYO


T. Sugiyama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