Interfacing Superconducting Qubits with Cryogenic Digital Circuits

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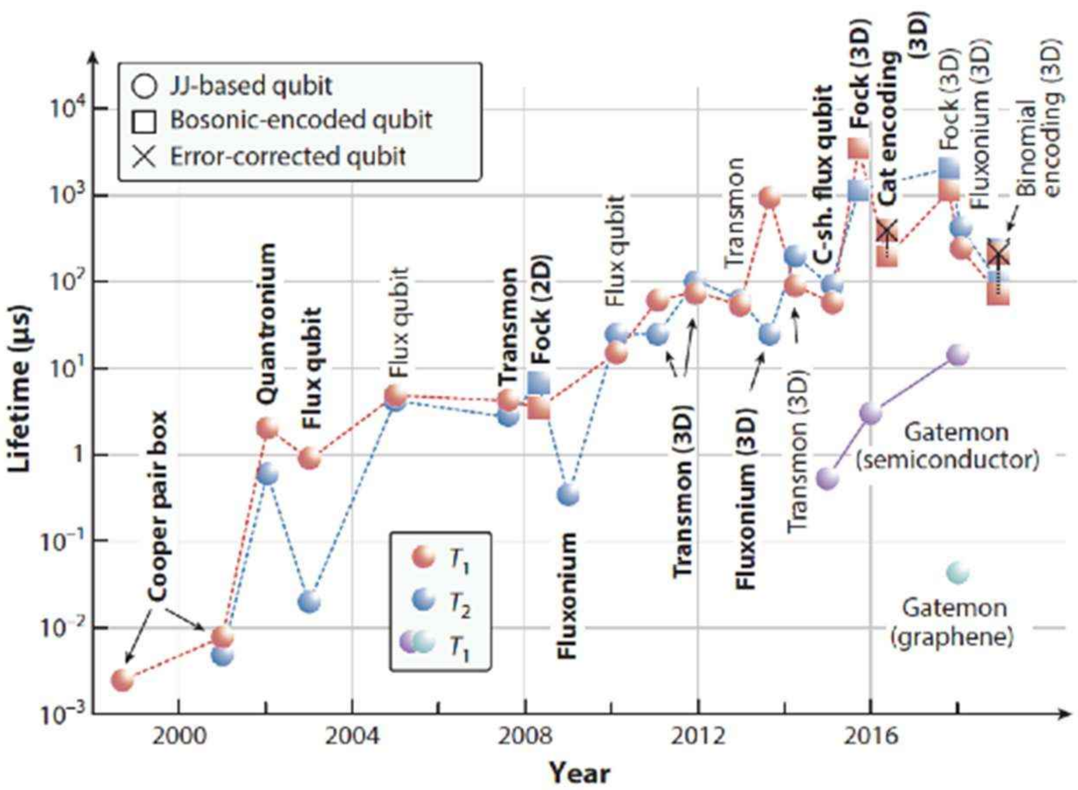
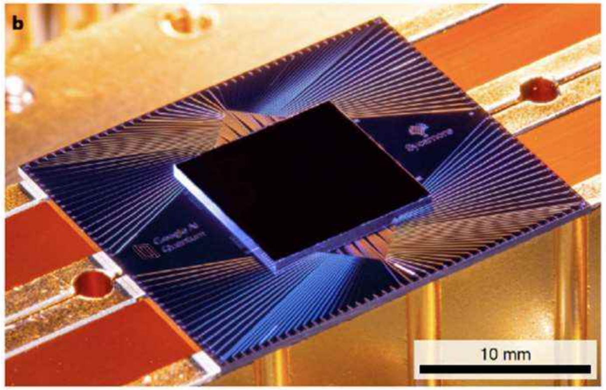
Superconducting Qubits



*Kjaergaard et al., Ann. Rev. CM Phy (2019)

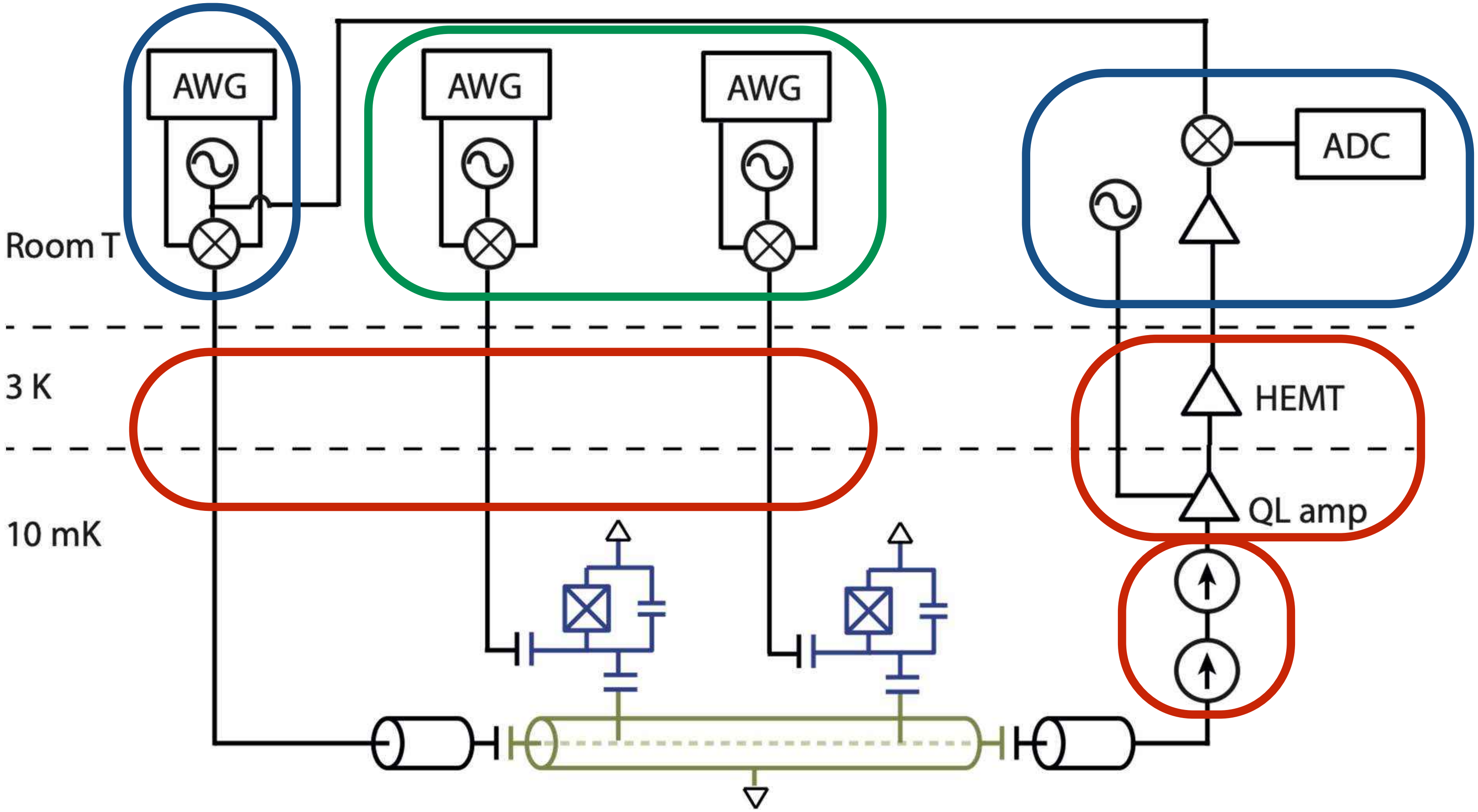
- Noisy intermediate scale quantum (NISQ) era
- Initial steps towards quantum error correction



*Arute et al., Nature (2019)

- Challenges with scaling to larger systems…

Conventional microwave-based qubit control and readout



★ Works well…, but significant hardware overhead

Single-qubit gate fidelities > 99.9%

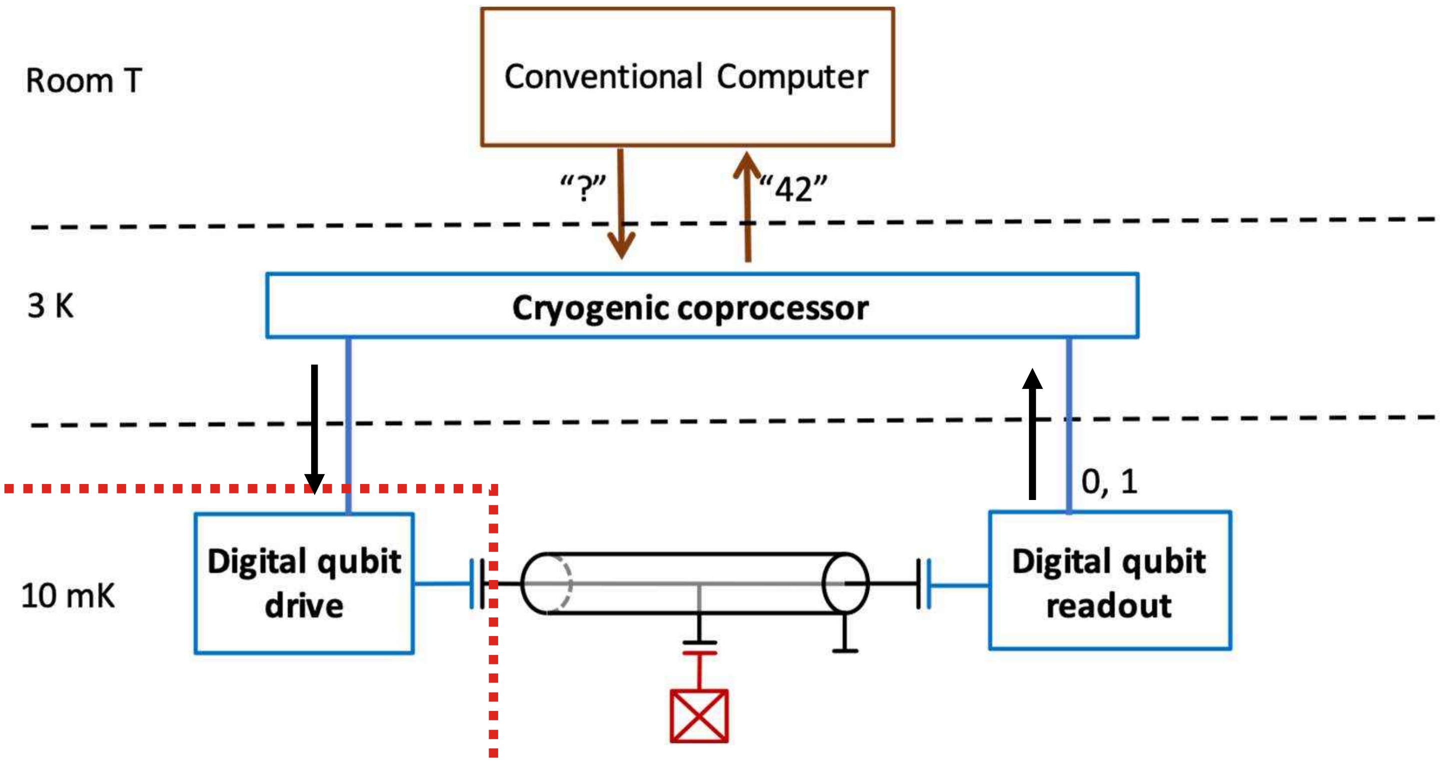
Single-shot readout fidelities > 99% in under 500 ns

**R. Barends et al., Nature (2014)*
**S. Sheldon et al. PRA (2016)*

**T. Walter et al., PR Applied (2017)*

Reducing room-temperature hardware overhead

*McDermott *et al.*, Quant. Sci. Tech. 3, 024004 (2018)



Cryogenic control of qubit state based on classical superconducting digital logic

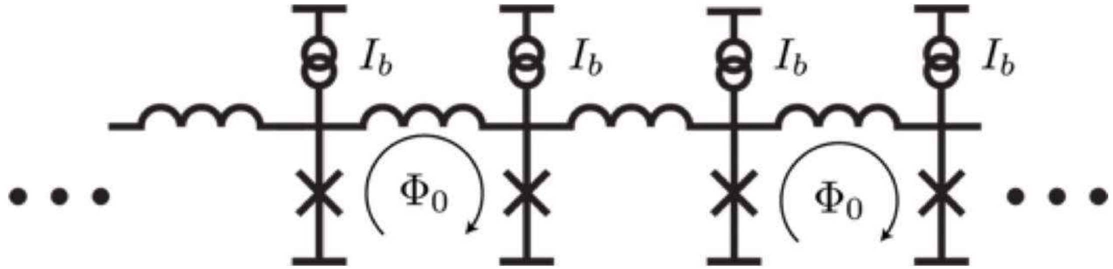
Digital readout of qubit state based on microwave photon counting

Superconducting digital logic

- Classical superconducting digital logic — Single Flux Quantum (SFQ)

*Likharev and Semenov, *IEEE Trans. Appl. Supercon. 1991*

- Logical 1 (0) = presence (absence) of propagating fluxon



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

$$\Phi_0 \approx 2\mathrm{mV} \times \mathrm{ps}$$

- Low power consumption; high speed logic

$$V(t) = \frac{\Phi_0}{2\pi}\frac{\partial \delta}{\partial t}$$

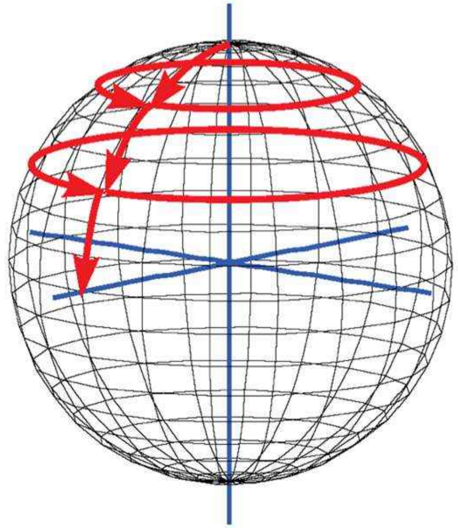
On-chip digital control of qubits

- SFQ circuitry on same chip as qubits or flip-chip coupling

- Capacitively couple resonant train of narrow SFQ pulses to drive qubit rotations without microwaves

- Important to mitigate heating/quasiparticles produced on-chip from operation of SFQ circuitry

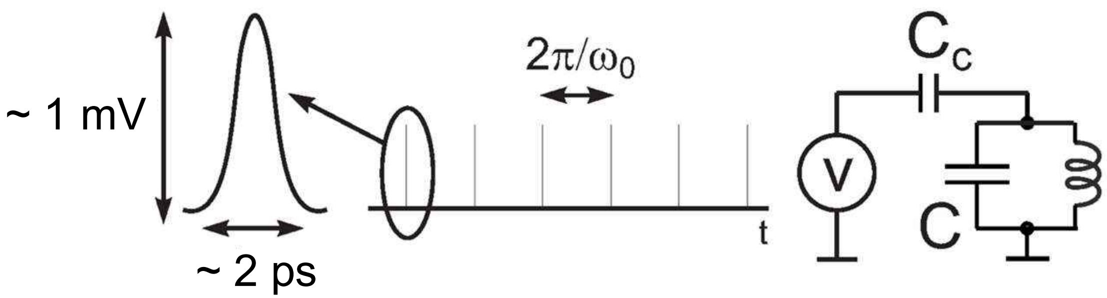
*McDermott and Vavilov, *Phys. Rev. Applied 2014*



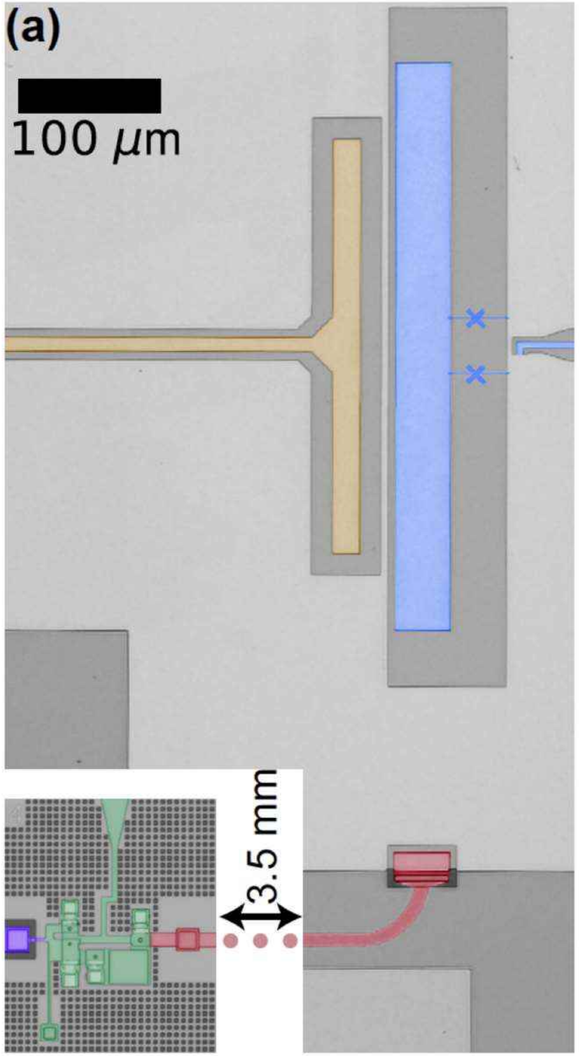
$$\delta\theta = C_c \Phi_0 \sqrt{\frac{2\omega_{01}}{\hbar C}}$$

π rotation with ~100 pulses

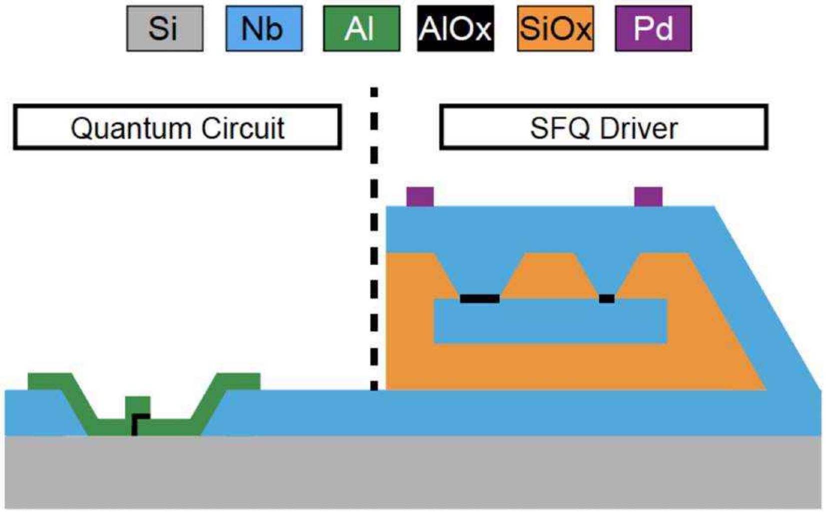
~14 ns for 7 GHz qubit



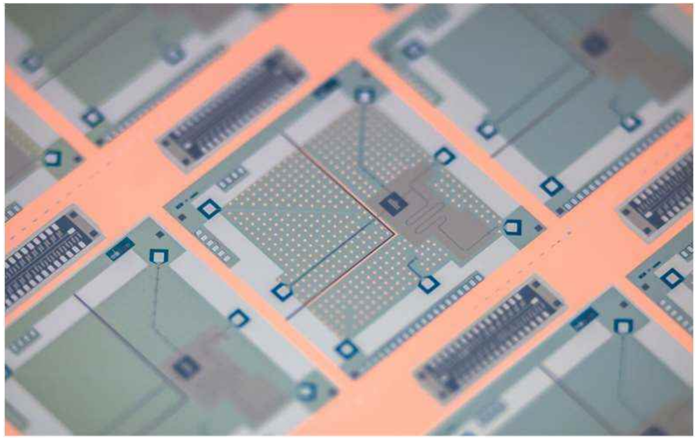
Implementation of SFQ driver and qubits

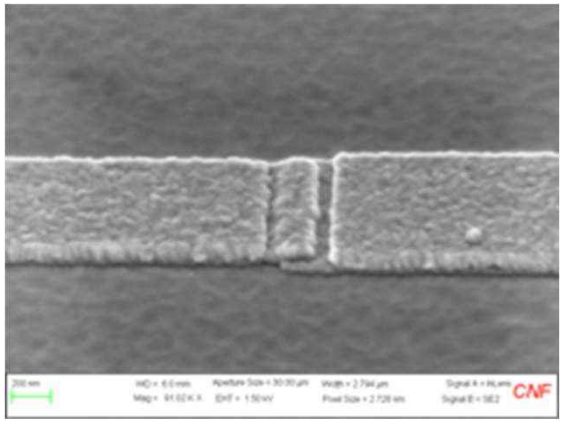


- Collaborative hybrid fabrication
- High-Jc Nb/AlOx/Nb junctions from Wisconsin
- Low-Jc Al/AlOx/Al junctions from Syracuse



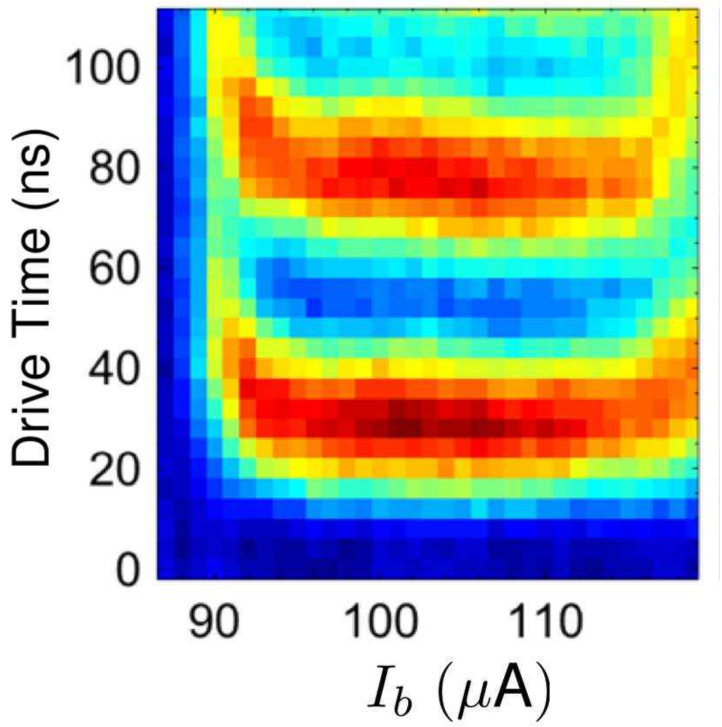
*Leonard *et al.*, Phys. Rev. Applied 11, 014009 (2019)

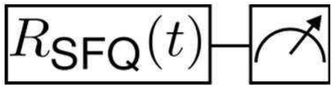


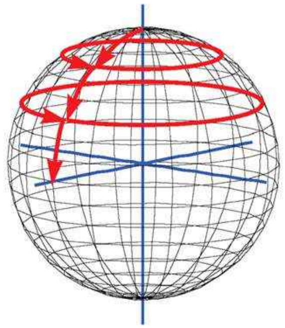


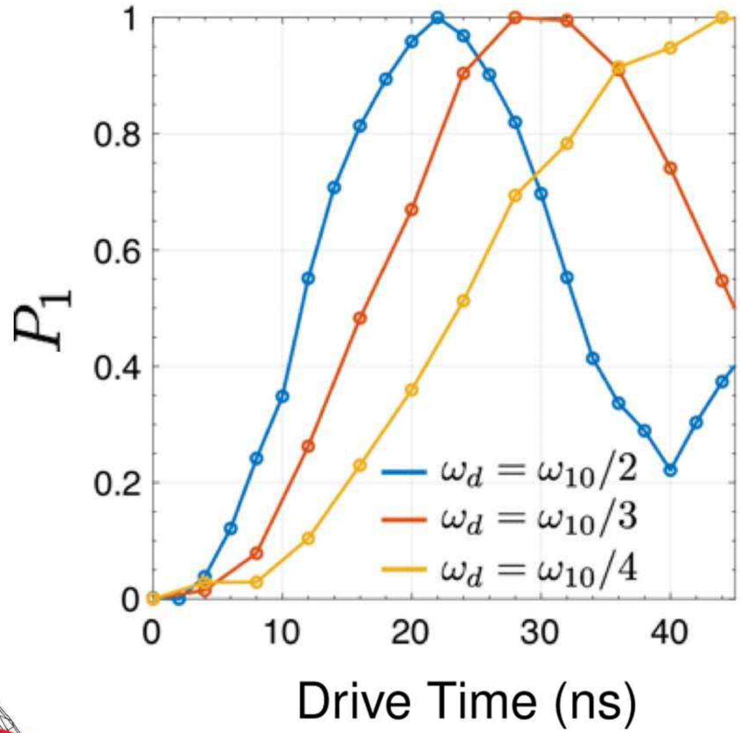
Qubit Rabi oscillations with SFQ pulses

- Bias qubit at upper sweet spot: $\omega_{10}/2\pi = 4.958\,\mathrm{GHz}$
- Send microwave pulses to trigger input of SFQ driver





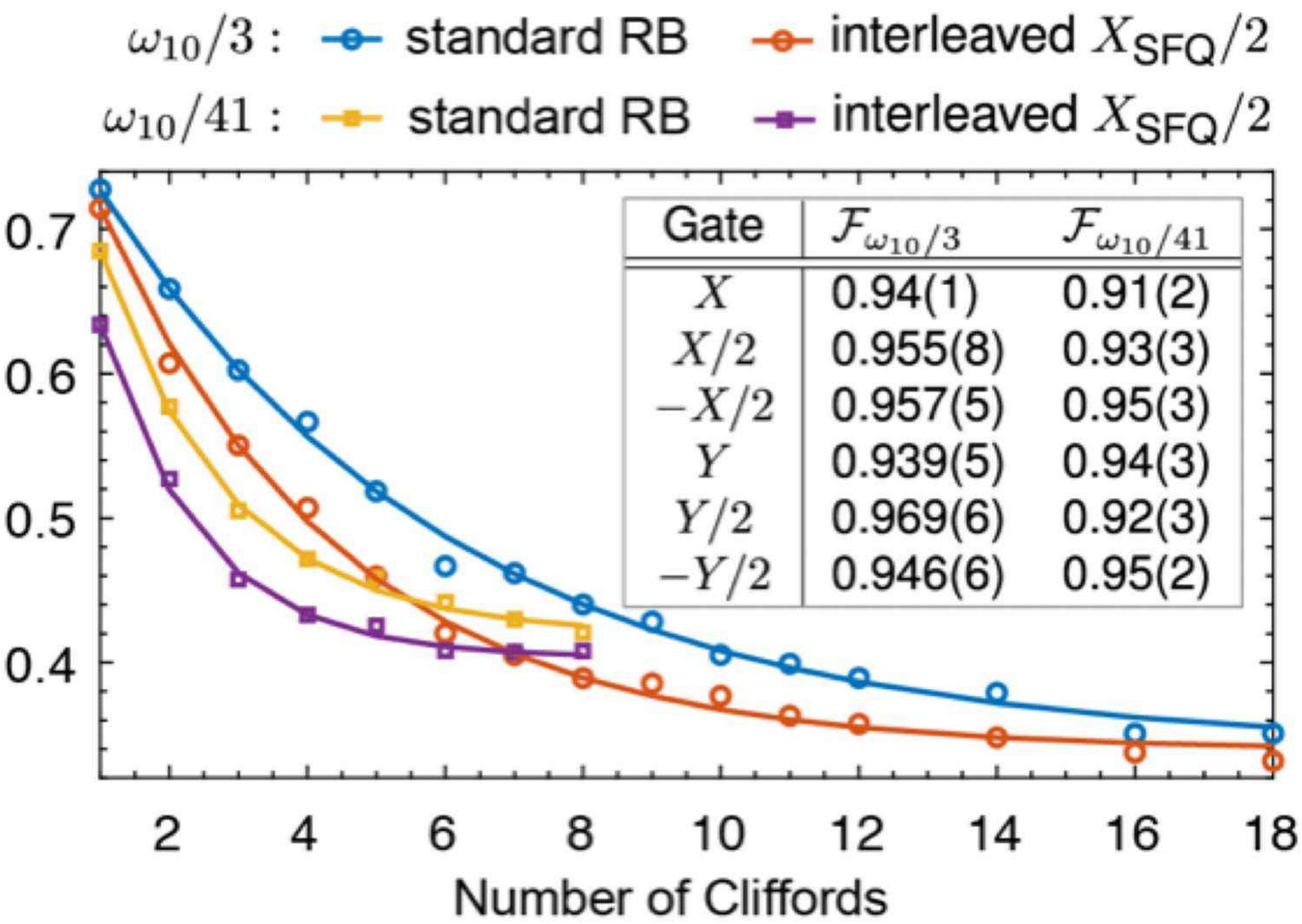




Drive SFQ circuit on subharmonic to avoid direct drive of qubit

Leonard *et al.*, Phys. Rev. Applied 11, 014009 (2019)

Characterizing fidelity of SFQ-based gates

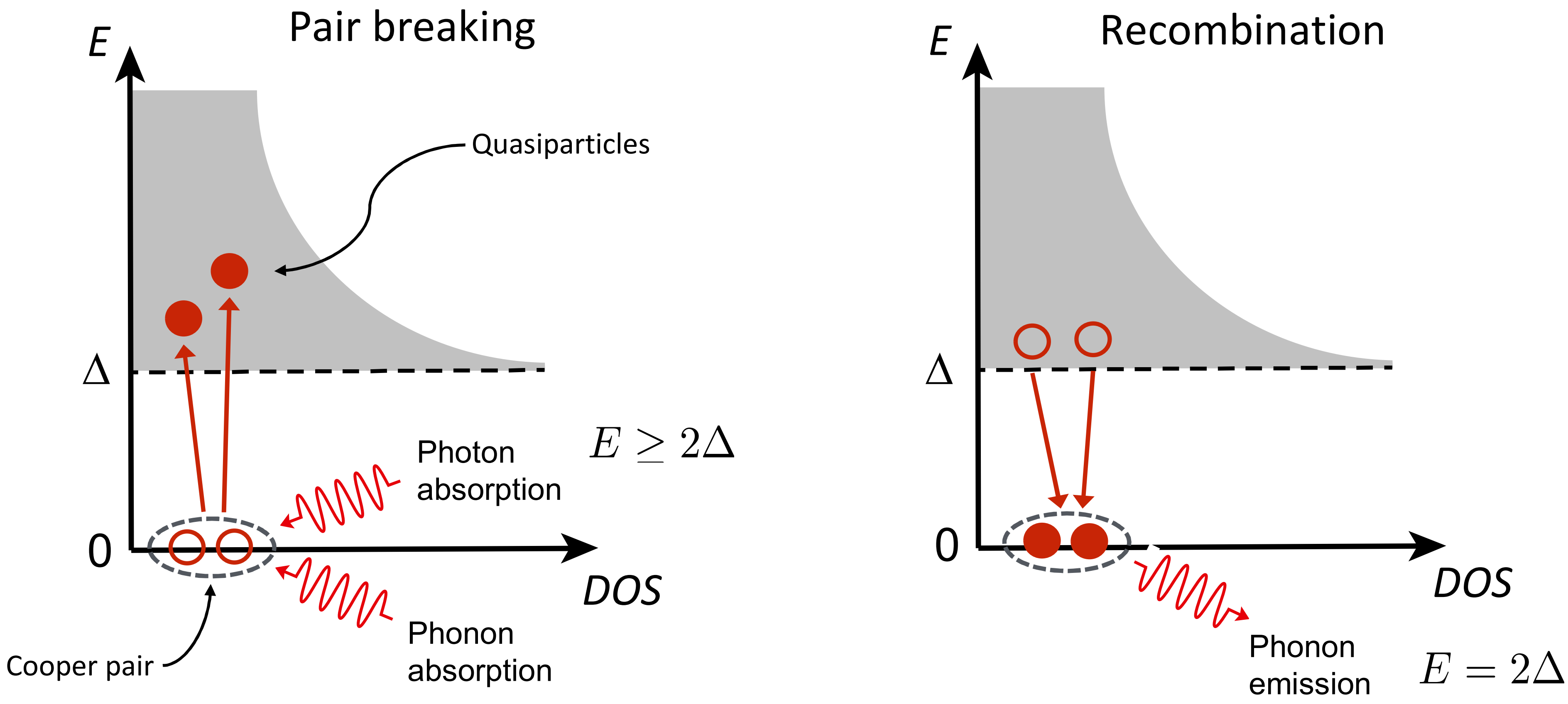


Gate	$\mathcal{F}_{\omega_{10}/3}$	$\mathcal{F}_{\omega_{10}/41}$
X	0.94(1)	0.91(2)
$X/2$	0.955(8)	0.93(3)
$-X/2$	0.957(5)	0.95(3)
Y	0.939(5)	0.94(3)
$Y/2$	0.969(6)	0.92(3)
$-Y/2$	0.946(6)	0.95(2)

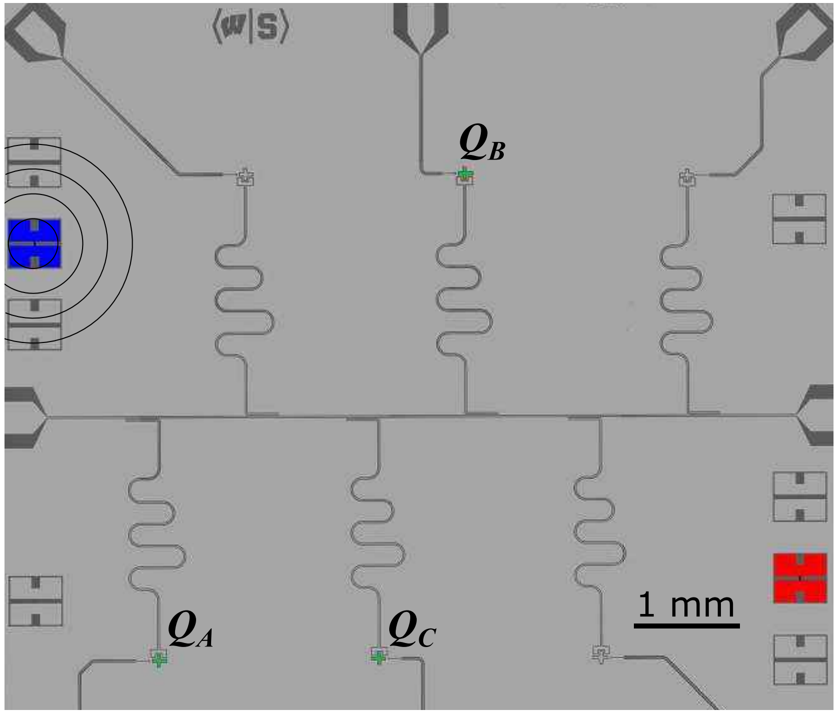
*Leonard *et al.*, Phys. Rev. Applied 11, 014009 (2019)

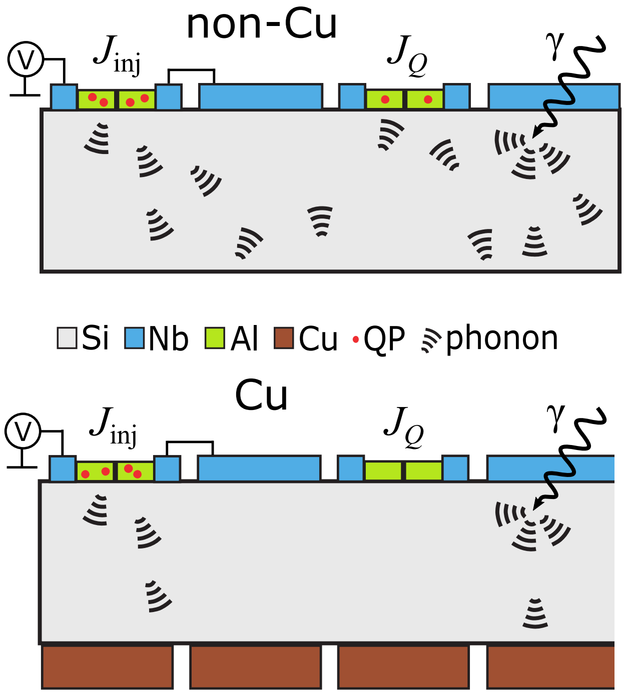
- Gate errors ~5%
- Limited by on-chip quasiparticle generation

Quasiparticle dynamics in superconducting circuits

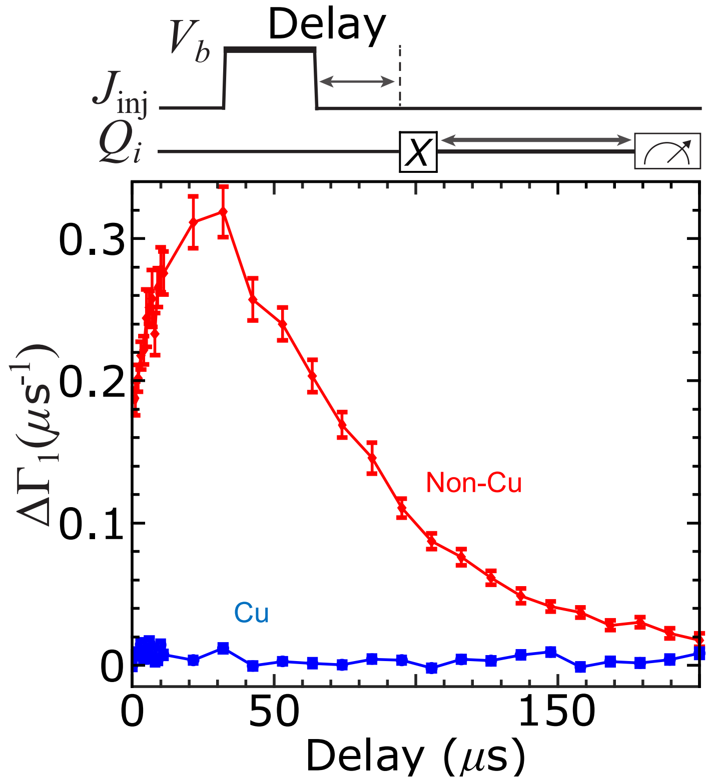


Controlled study of phonon-mediated QP poisoning





$$\Delta\Gamma_1 = \frac{1}{T_1} - \frac{1}{T_1^b}$$



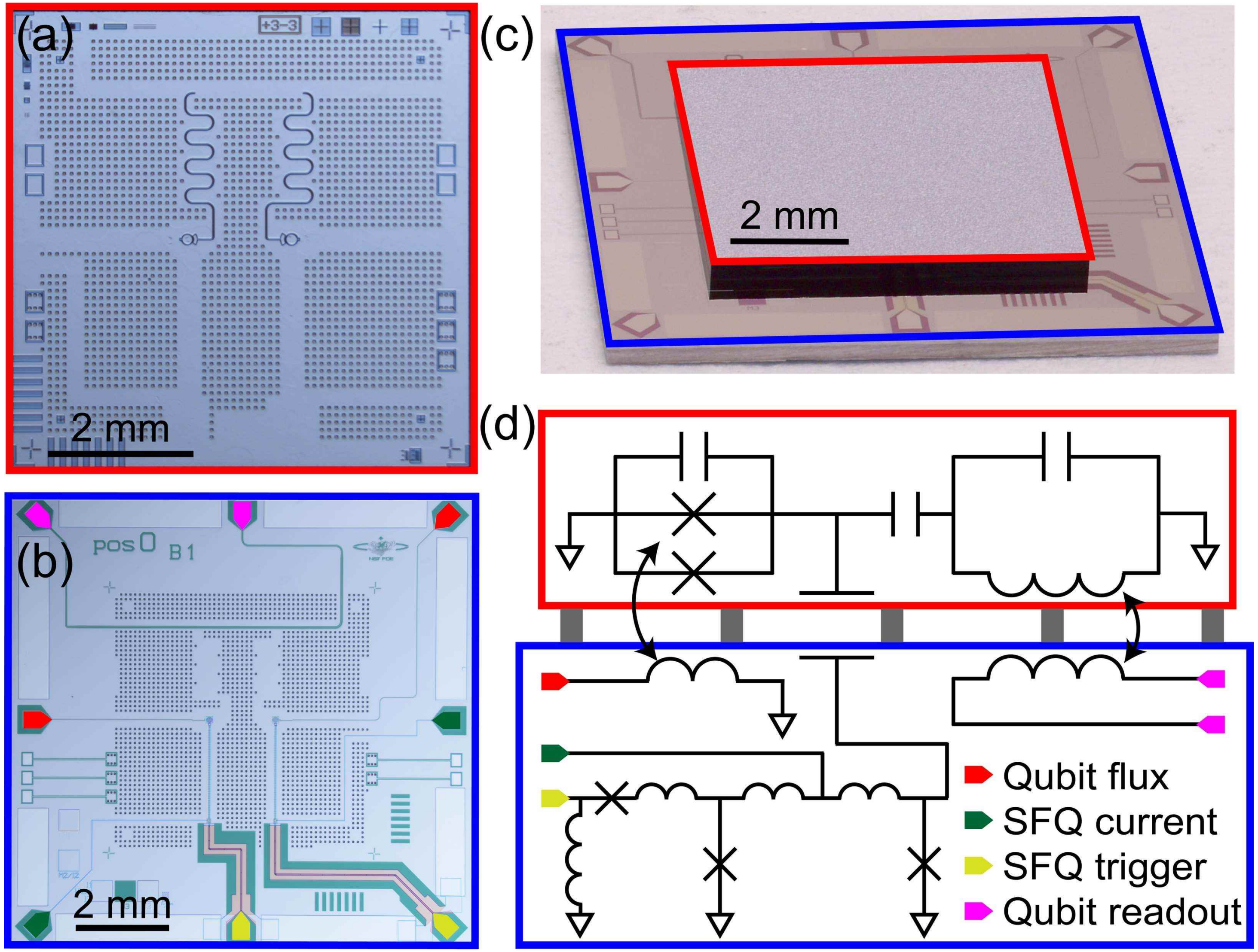
Iaia, Ku *et al*., Nature Comm. 13, 6425 (2022)

Patel *et al*., PRB 96, 220501 (R) (2017)

Mitigating phonon-mediated quasiparticle poisoning

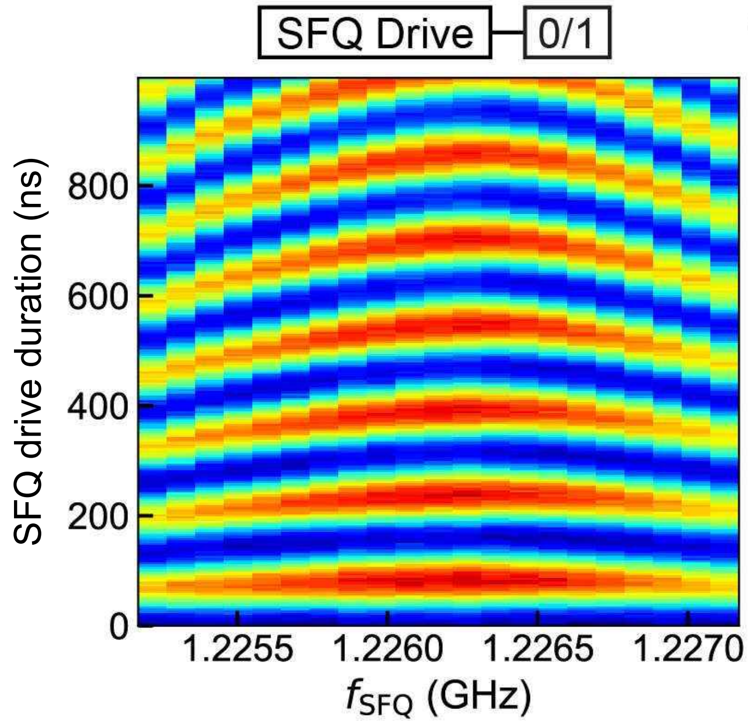
- Multi-chip module (MCM) with indium bump bonds
- Qubits & readout cavities on one chip
- SFQ elements, bias lines, and microwave feedline on separate chip

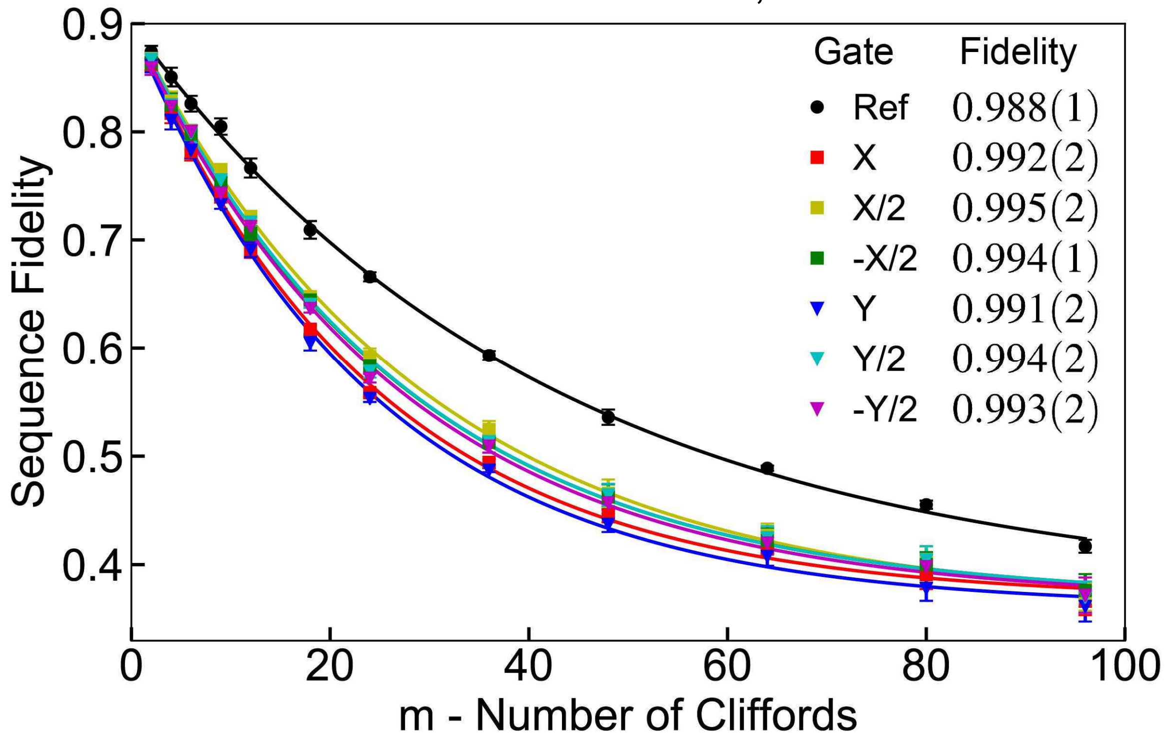
*Liu *et al.*, arXiv: 2301.05696



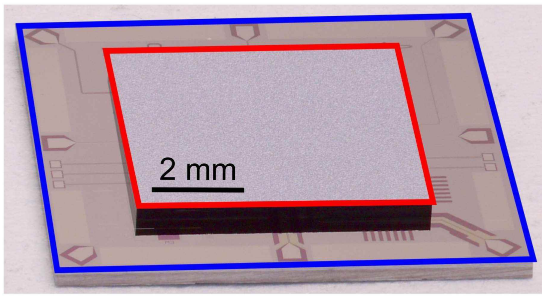
Characterizing fidelity of SFQ-based gates in MCM

Liu *et al.*, arXiv: 2301.05696

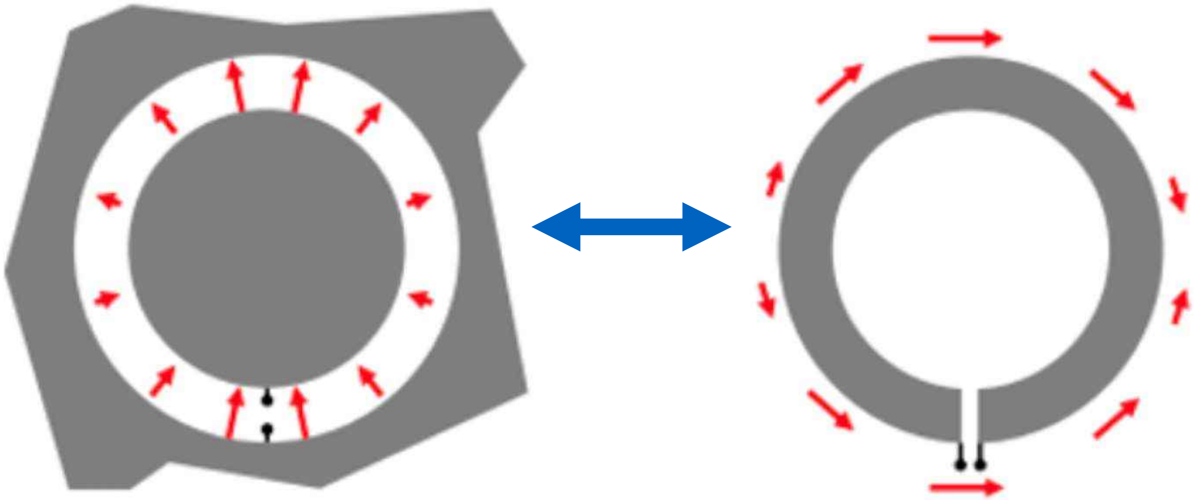




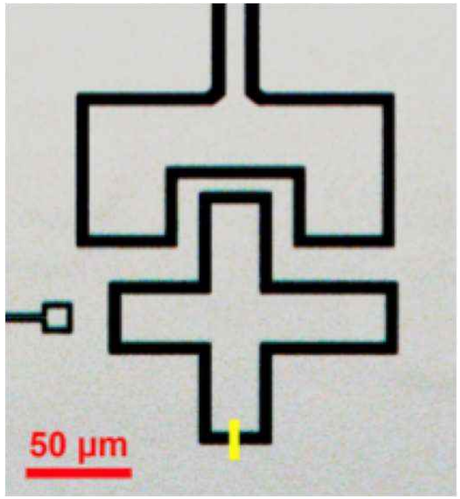
- Previous monolithic SFQ-qubit devices had gate errors ~5%
- Now, nearly one order of magnitude better with MCM, ~0.5%
- Still limited by quasiparticle poisoning…



Spurious Antenna Modes of Superconducting Qubits



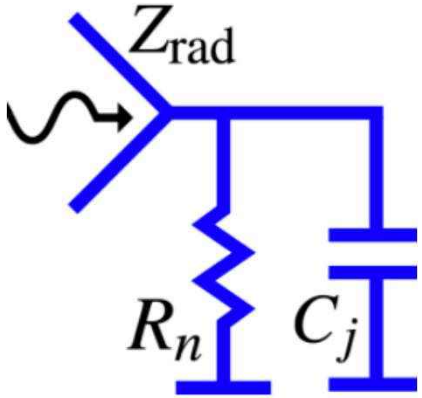
Babinet's Principle



Coupling efficiency:

$$e_c = 1 - |\Gamma|^2$$

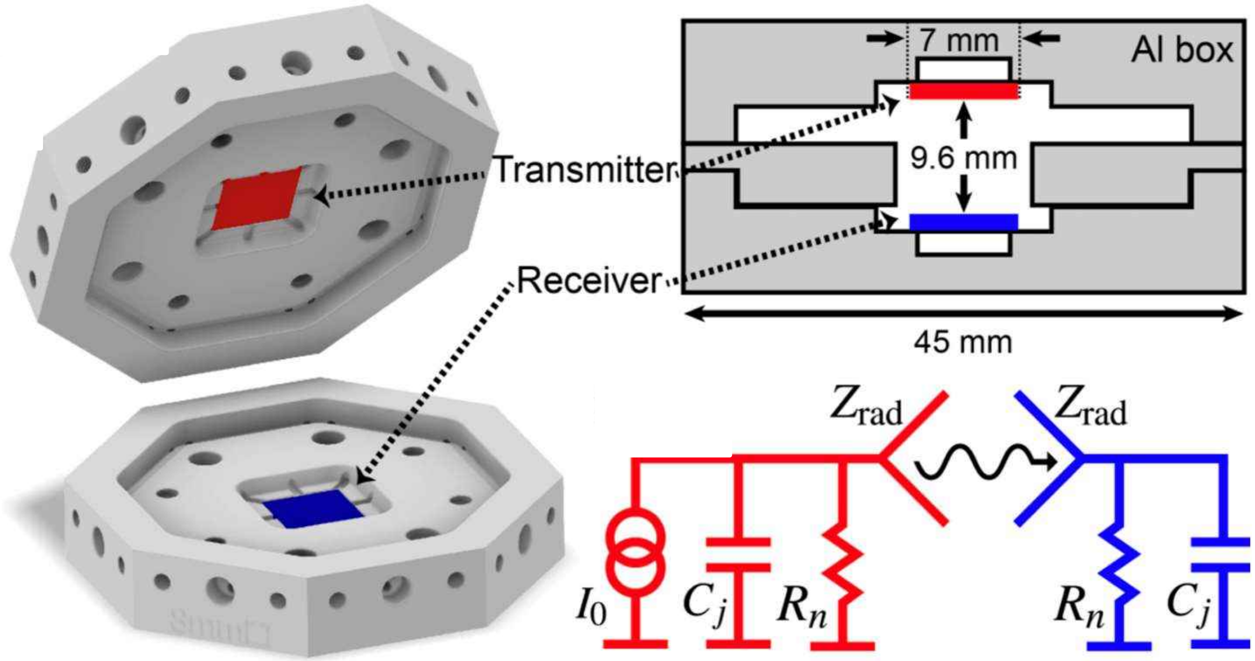
$$\Gamma = \frac{Z_{\rm rad} - Z_J^*}{Z_{\rm rad} + Z_J^*}$$

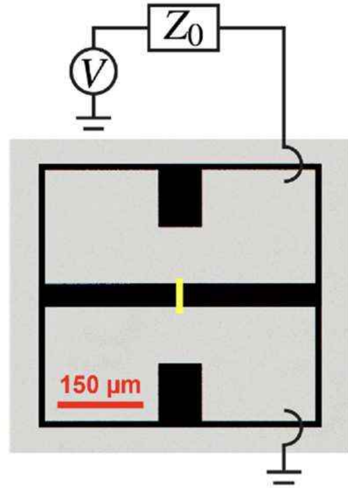


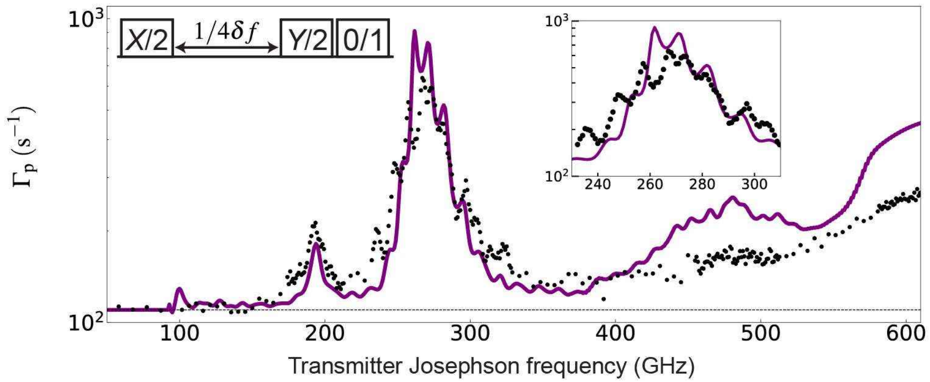
Rafferty *et al*., arXiv:2103.06803

Houzet *et al*., Phys. Rev. Lett. 2019

Measuring Photon-mediated Quasiparticle Poisoning







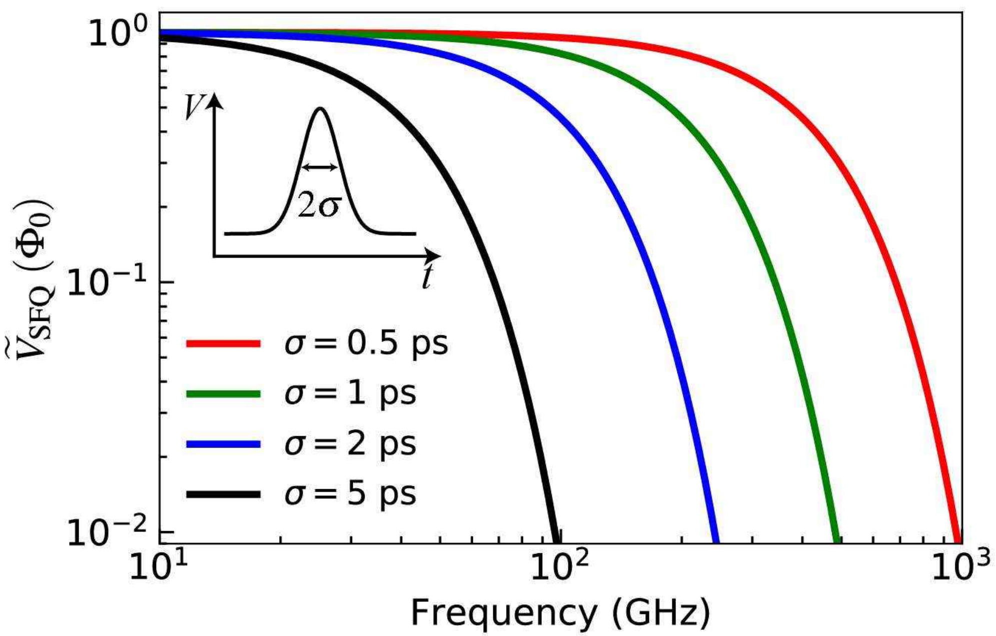
Josephson oscillations from voltage-biased junction

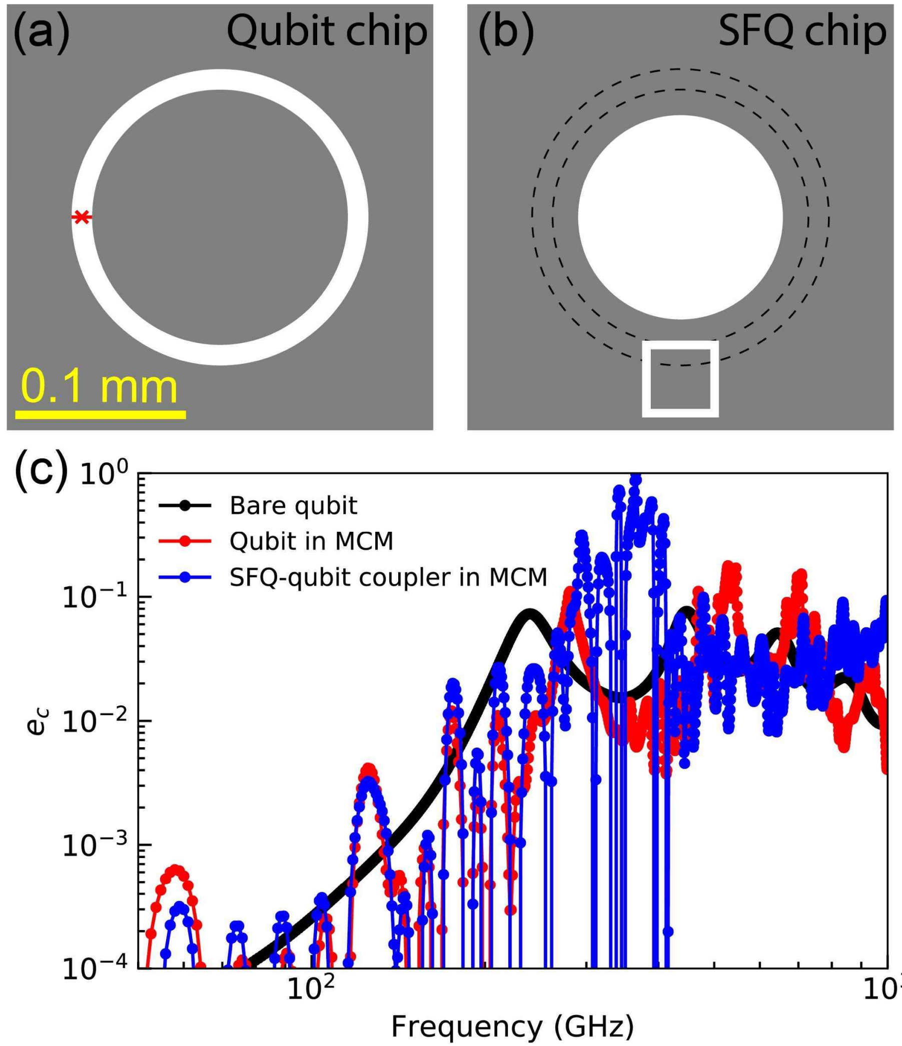
$$f = V/\Phi_0 \rightarrow 484\,\mathrm{GHz/mV}$$

Liu *et al.*, arXiv:2203.06577

SFQ-based qubit control: next steps

- More compact qubits with higher antenna resonance frequency
- SFQ elements with lower bandwidth pulses

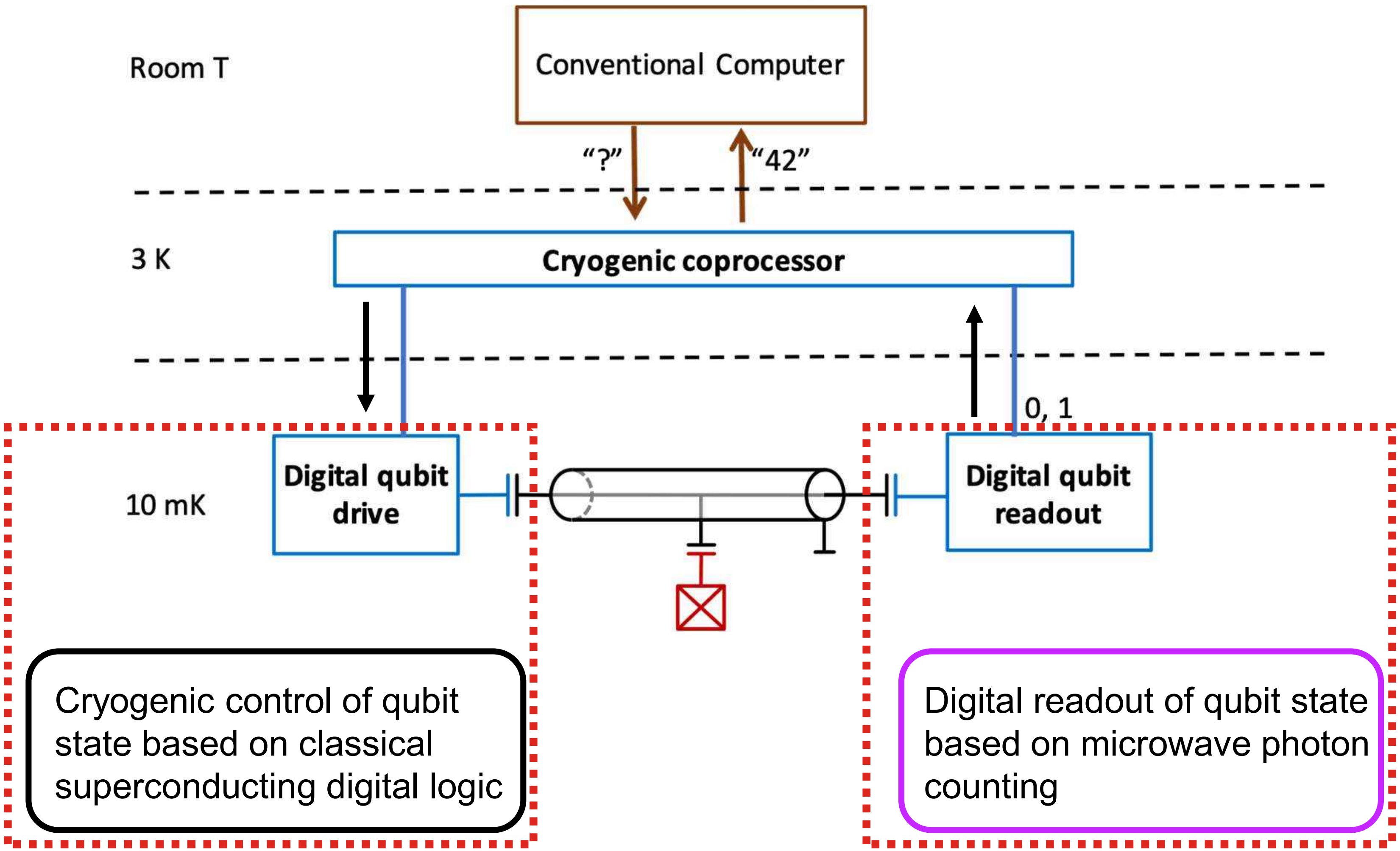




Liu *et al.*, arXiv: 2301.05696

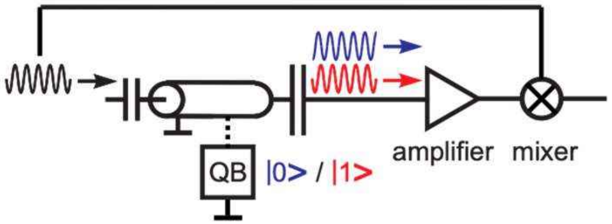
Reducing room-temperature hardware overhead

*McDermott *et al.*, Quant. Sci. Tech. 3, 024004 (2018)

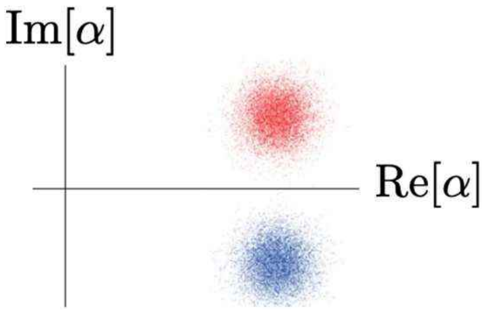


Alternative approaches to dispersive readout in cQED

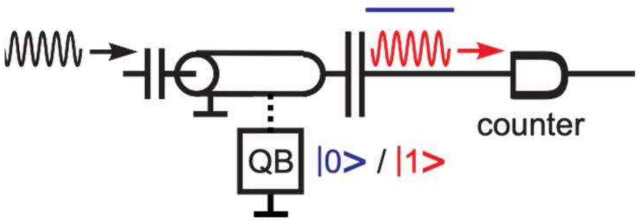
…by Amplification:



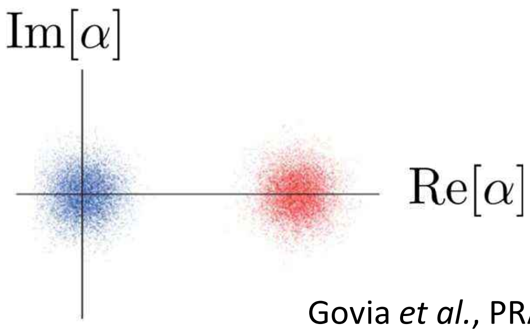
Coherent state discrimination



…by Photon Counting:



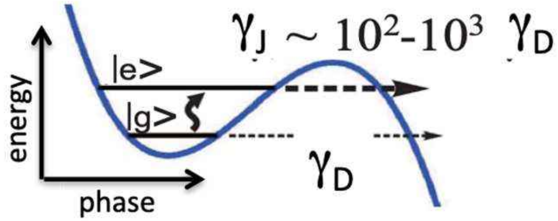
Intensity discrimination



Govia *et al.*, PRA **90**, 062307 (2014)
Govia *et al.*, PRA **92**, 022335 (2015)

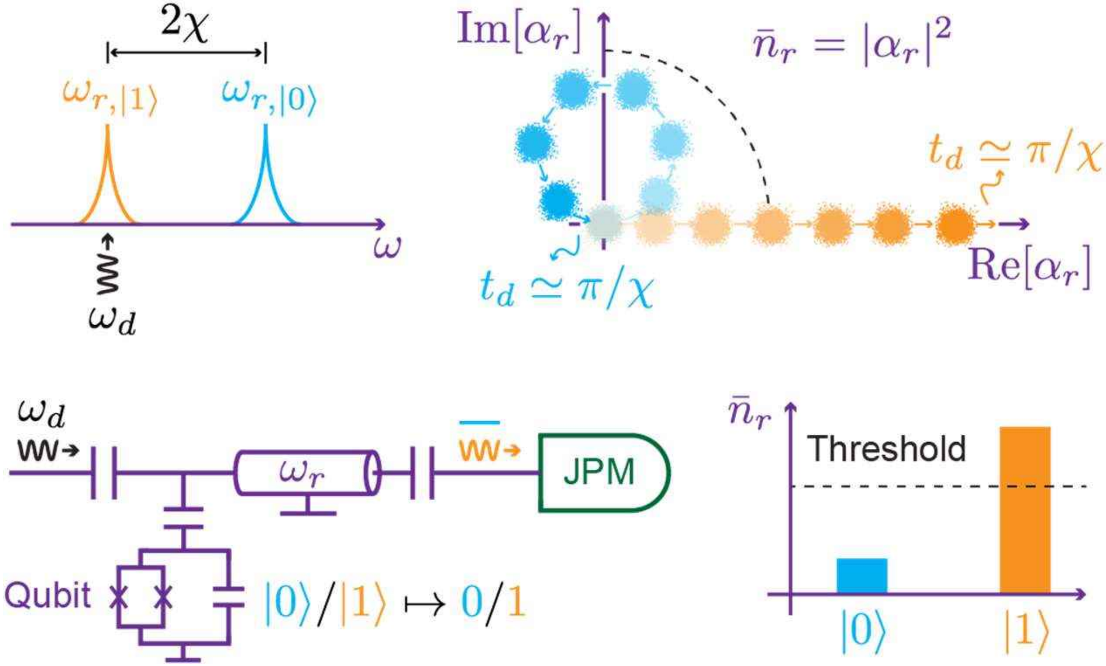
Josephson Photomultiplier (JPM)

Chen *et al.*, PRL **107**, 217401 (2011)

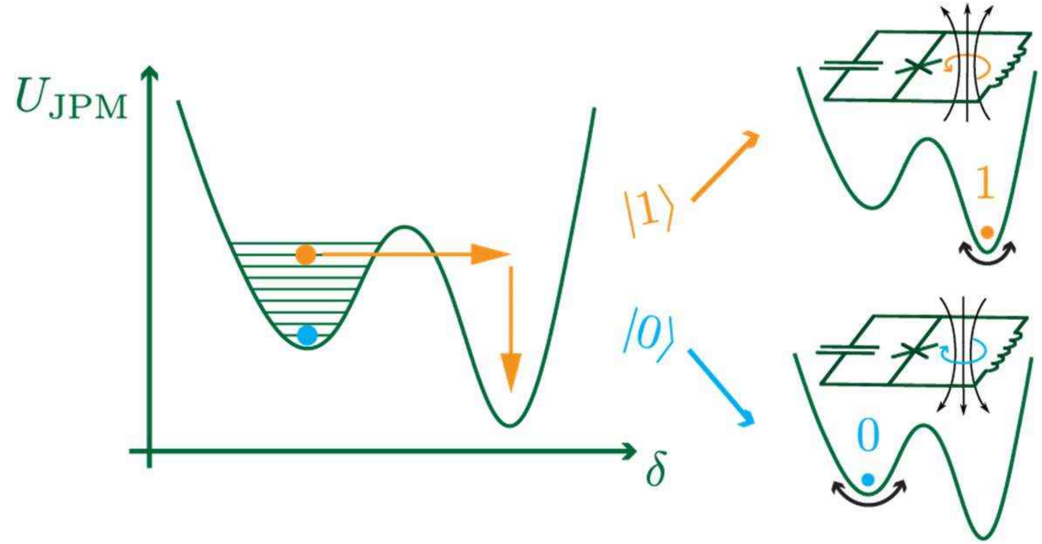


Tunneling events produce easily-measured, unambiguous “clicks”

Digital readout of qubit with Josephson Photomultiplier



1) Map qubit state onto cavity photon occupation



2) Use JPM as threshold detector of cavity photon occupation

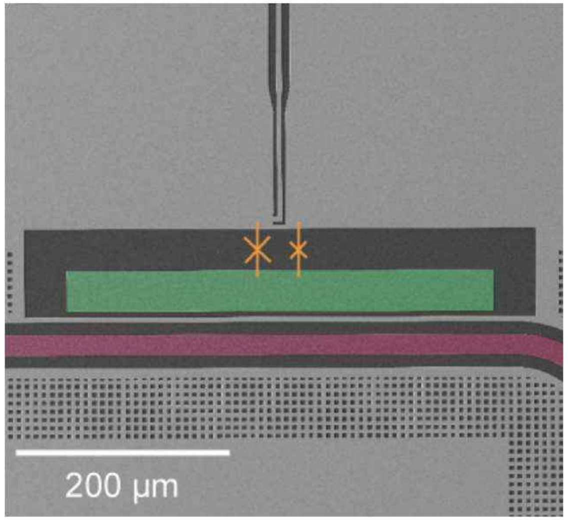
*Opremcak *et al.*, Science 361, 1239 (2018)

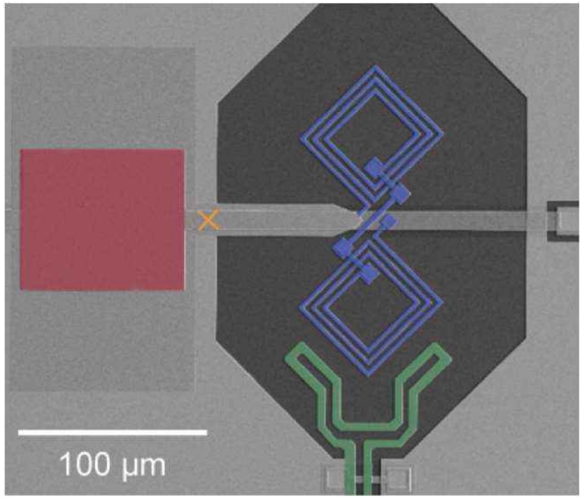
*Opremcak *et al.*, PRX 11, 011027 (2021)

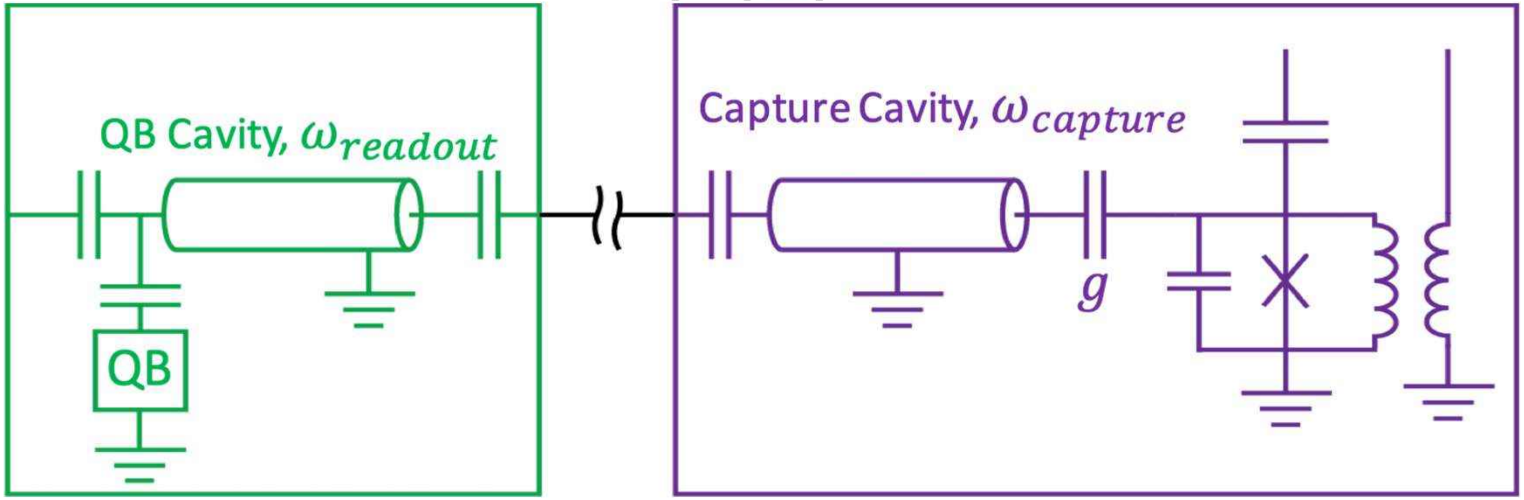
Digital readout of qubit with Josephson Photomultiplier

- Initial approach: qubit & readout cavity on separate chip from JPM

*Opremcak *et al.*, Science 361, 1239 (2018)

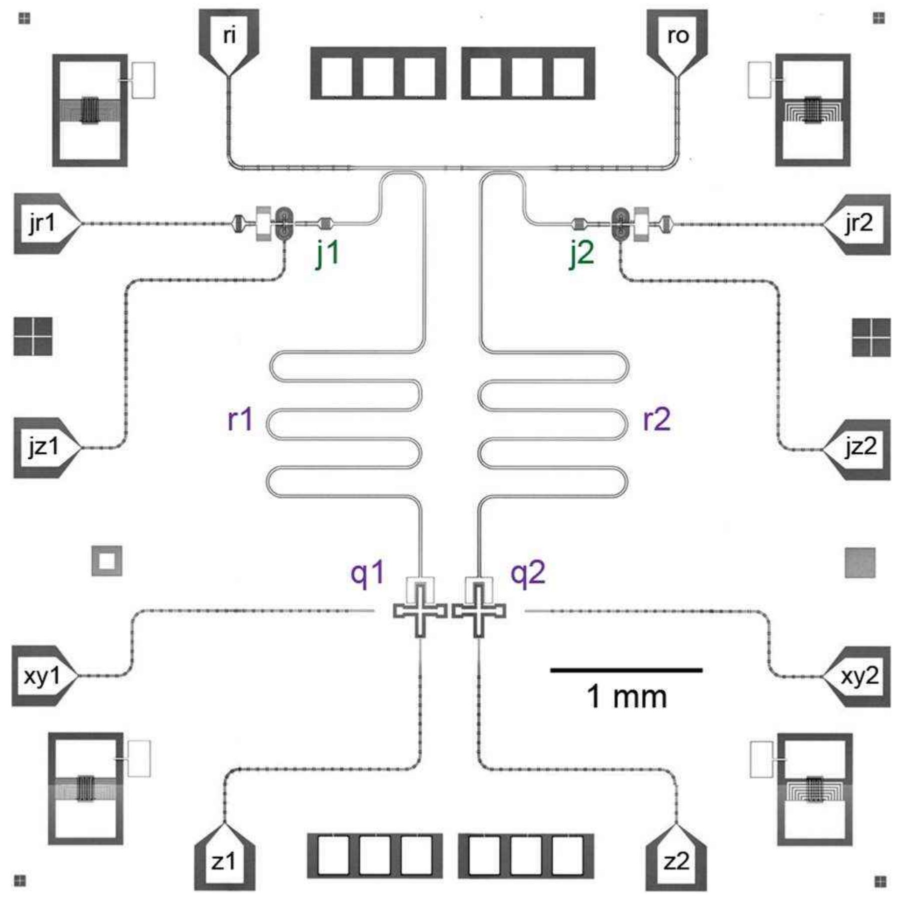


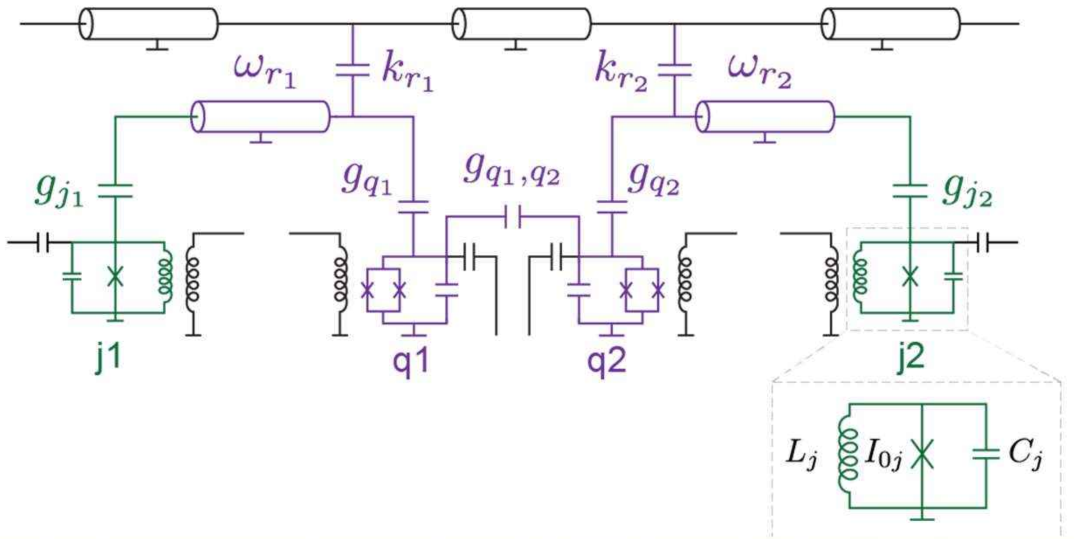


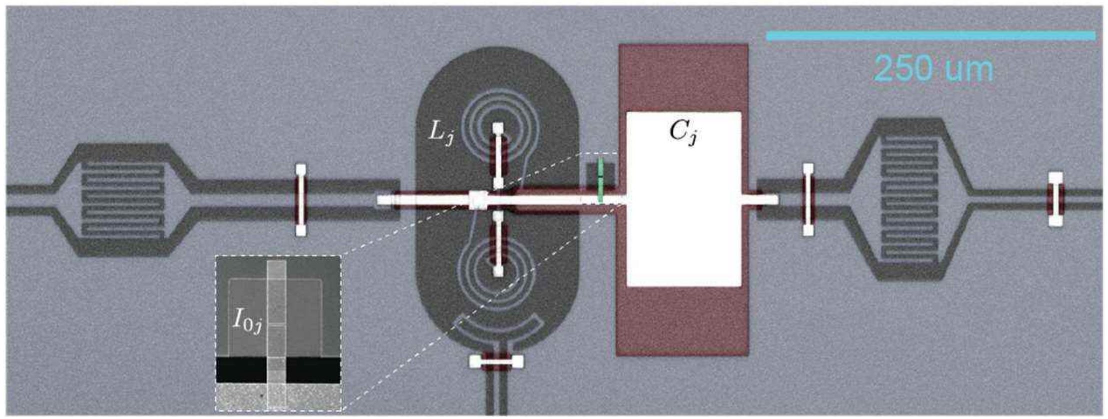


Digital readout of qubit with Josephson Photomultiplier

- Integrate qubit, readout cavity, JPM onto single chip

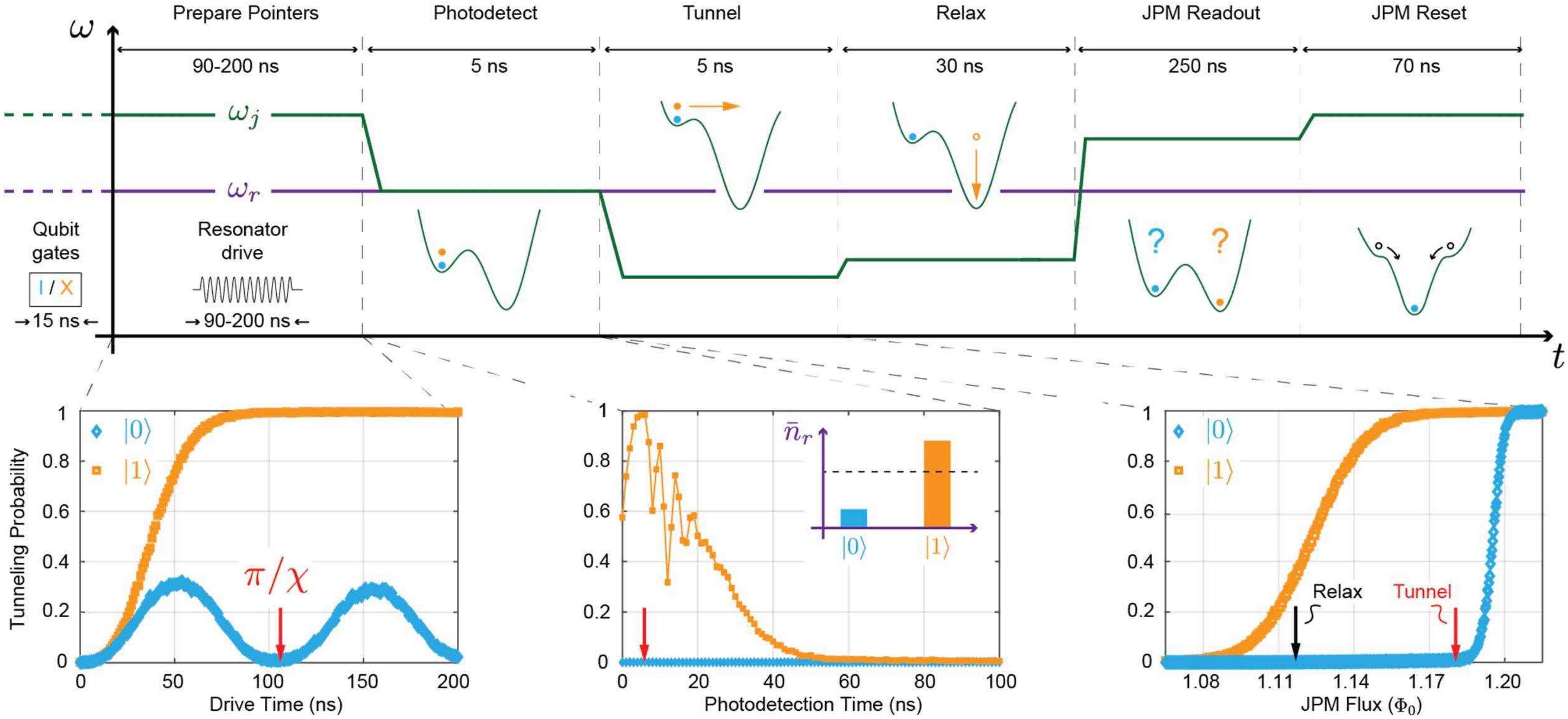




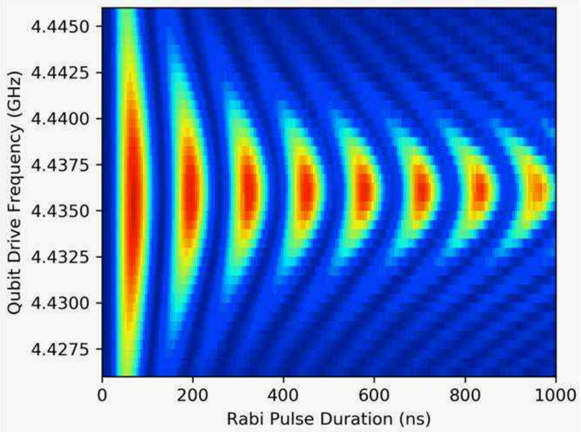


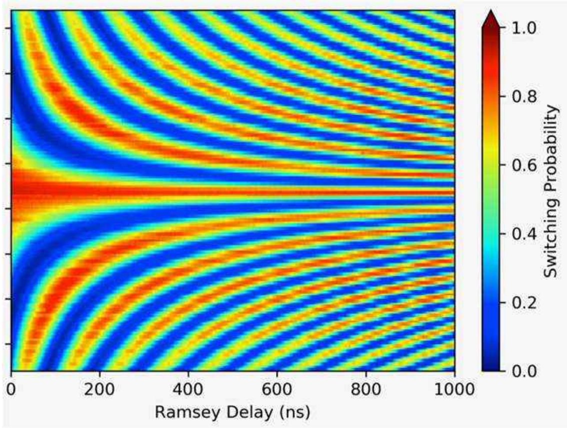
*Opremcak *et al.*, PRX 11, 011027 (2021)

Measurement sequence for JPM-based readout



Digital readout of qubit with Josephson Photomultiplier

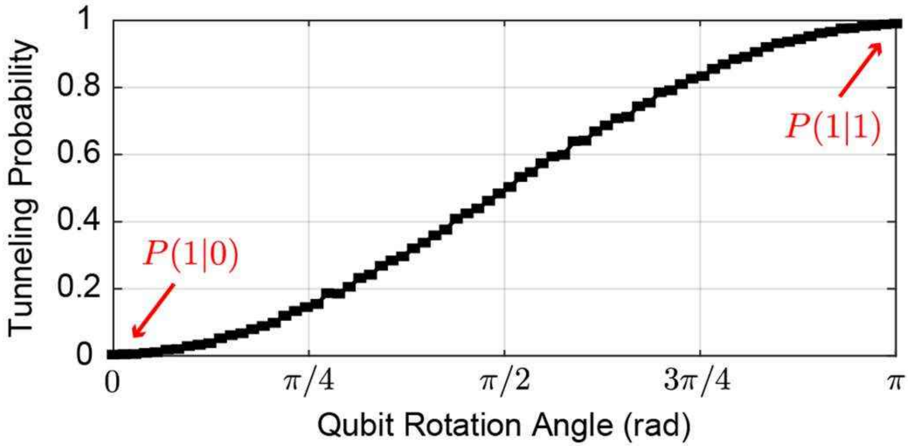


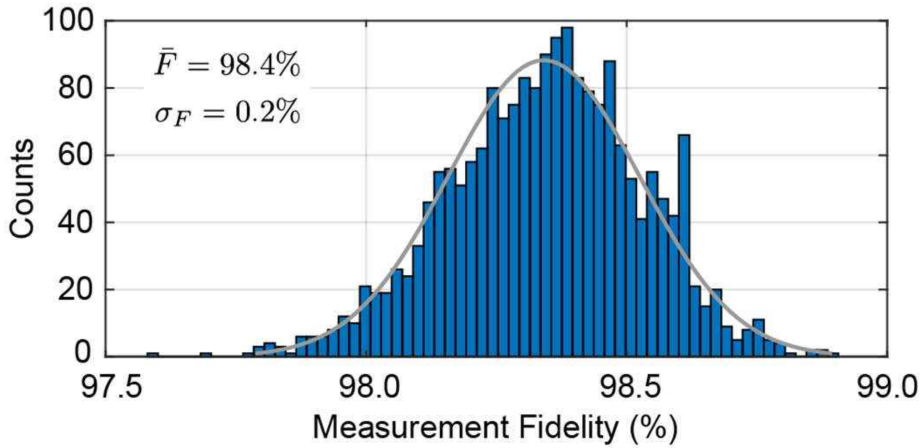


- Initial approach:

  Measurement fidelity ~ 92% in ~1.4 μs

*Opremcak *et al.*, Science 361, 1239 (2018)



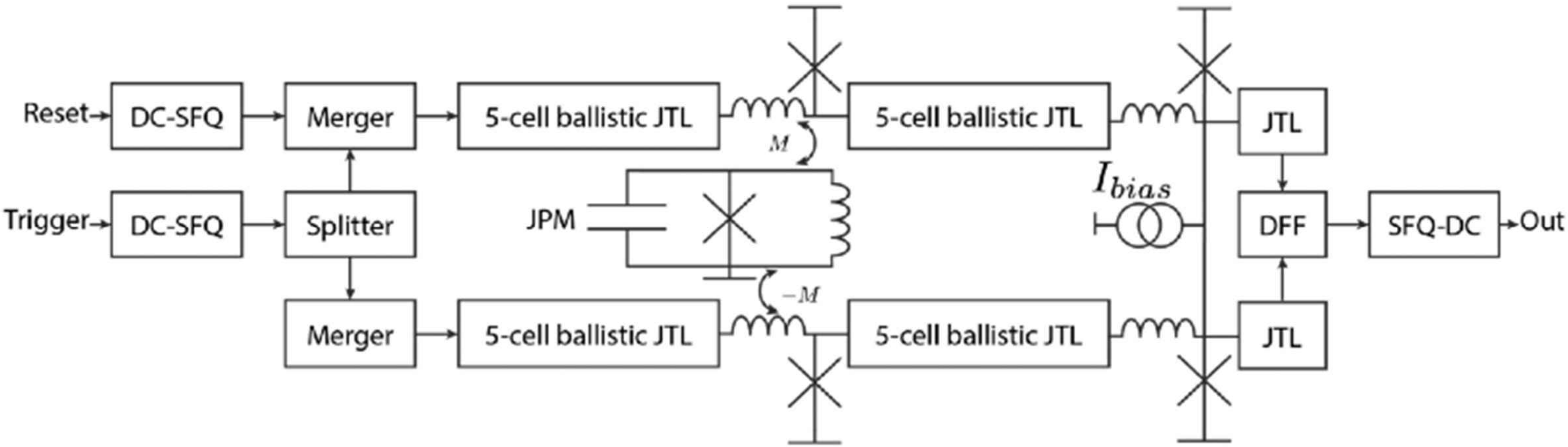


- Improved design: measurement fidelity = 98.4% in under 500 ns

*Opremcak *et al.*, PRX 11, 011027 (2021)

Interfacing JPM output with SFQ logic

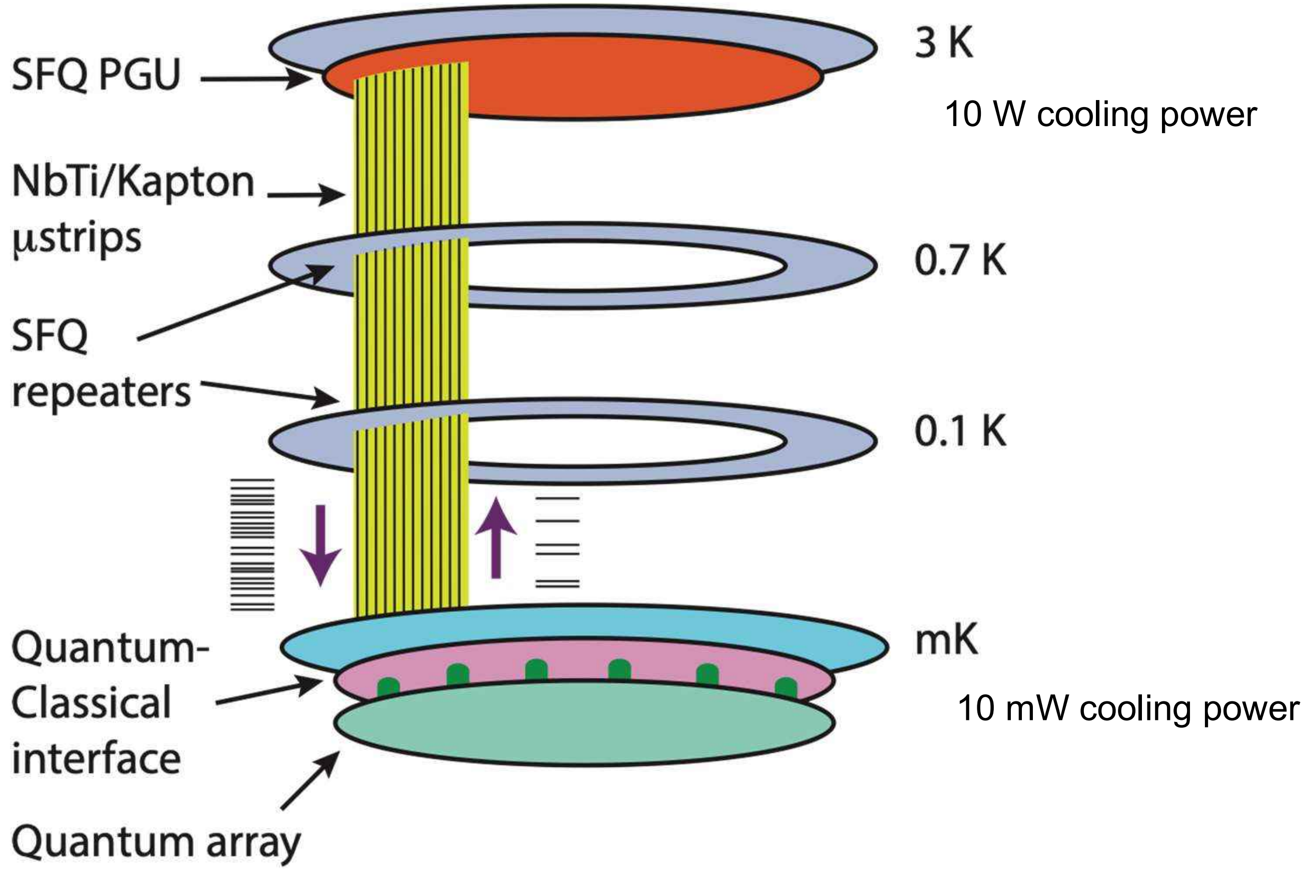
- Qubit measurement result encoded in classical circulating current states of JPM
- Inductively couple JPM loop to two Josephson Transmission Lines (JTLs)
- SFQ output from final stage depends on sense of circulating current of JPM



*Howington et al., *IEEE Trans. Appl. Supercon. 29, 1700305 (2019)*

Quantum-Classical Interface

*McDermott *et al.*, Quant. Sci. Tech. 3, 024004 (2018)



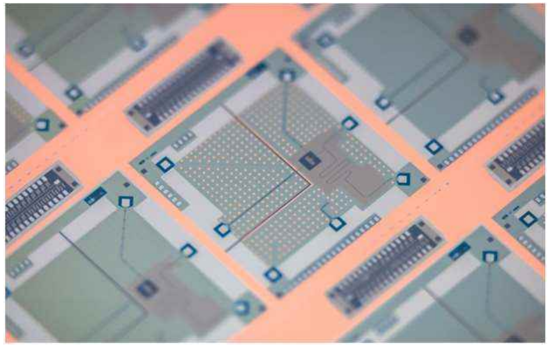
Quantum layer = qubits and readout resonators only; minimal fab processing

Quantum-Classical interface layer = SFQ drivers; JPMs and SFQ output; flux bias lines

Summary

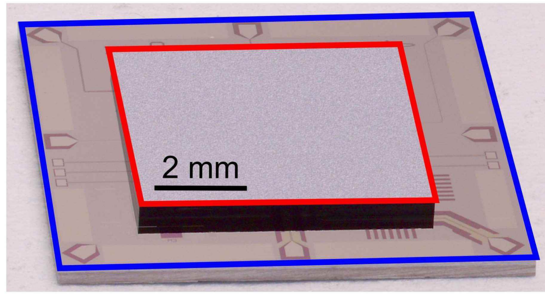
- Hardware challenges for scaling to large qubit arrays with conventional microwave-based control and readout

  McDermott *et al.*, Quant. Sci. Tech. 3, 024004 (2018)



- SFQ-based qubit control and multi-chip modules

  Liu *et al.*, arXiv: 2301.05696



- JPMs: microwave photon detectors for digital readout of qubit state

  Opremcak *et al.*, PRX 11, 011027 (2021)