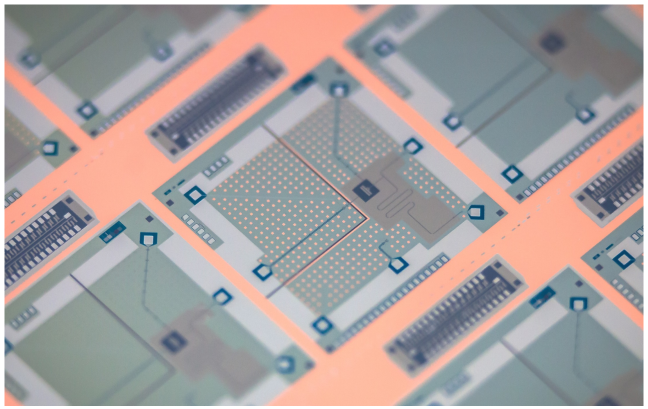
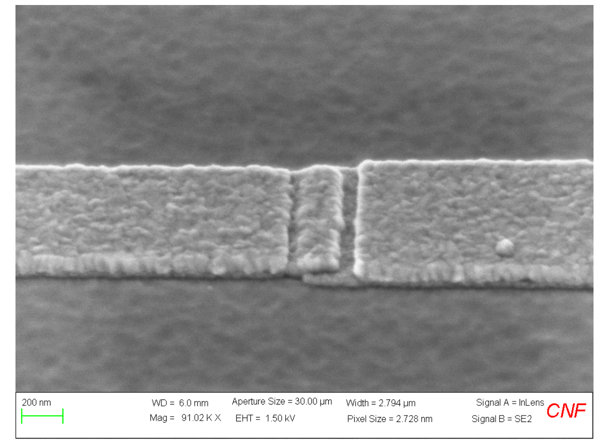
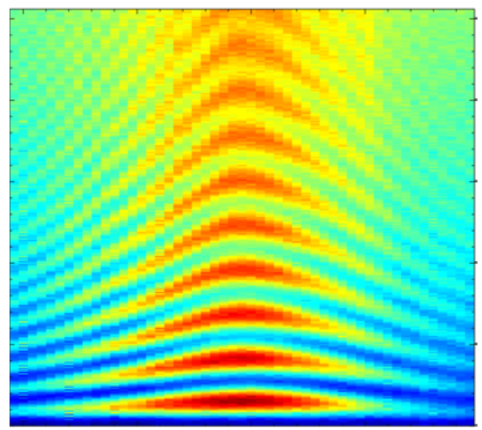
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Invited presentation Wk2EOr3A-04 given at the virtual ASC 2020, November 4, 2020.

Cryogenic Control of Coherent Quantum Systems



Britton L. T. Plourde
Syracuse University





Applied Superconductivity Conference
November 4, 2020

Acknowledgments

A. Ballard, K. Dodge, C. Howington, M. Hutchings, V. Iaia, J. Ku, T. McBroom, J. Nelson
Syracuse University

M. Beck, E. Leonard, V. Liu, A. Opremcak, U. Patel, I. Pechenezhskiy, M. Vavilov, R. McDermott
University of Wisconsin, Madison

L. Govia, P. Liebermann, E. Pritchett, F. Wilhelm
Saarland University

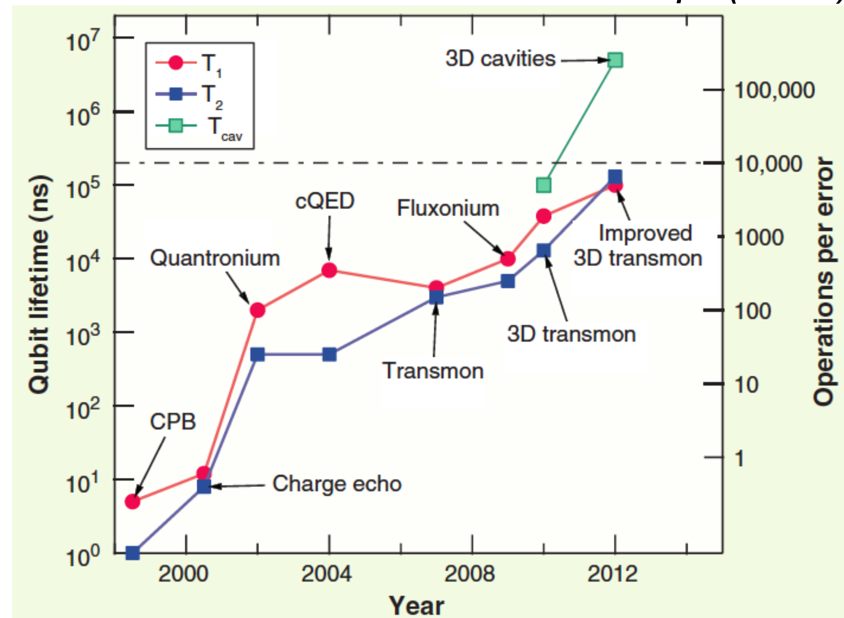
T. Ohki, *Raytheon BBN Technologies*

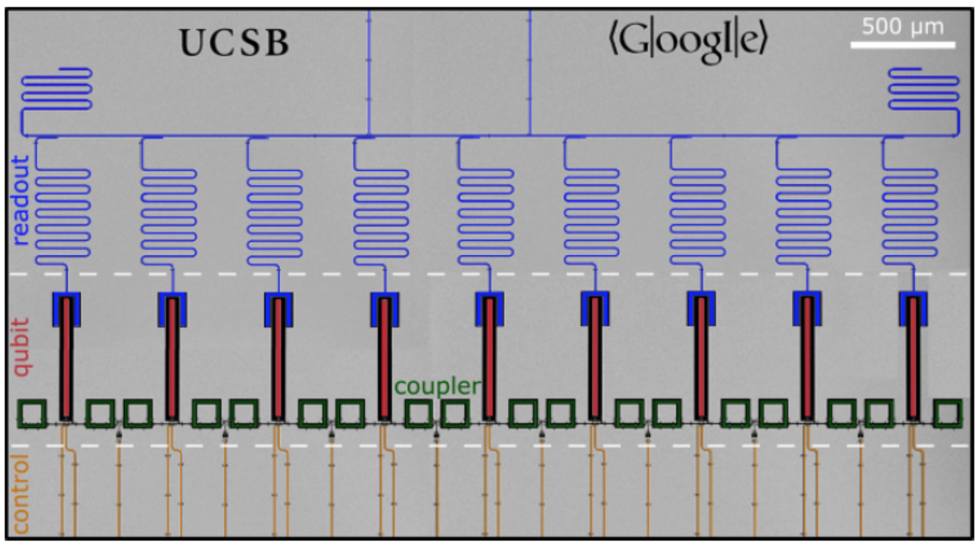
O. Mukhanov *Hypres (SeeQC)*

Superconducting qubits

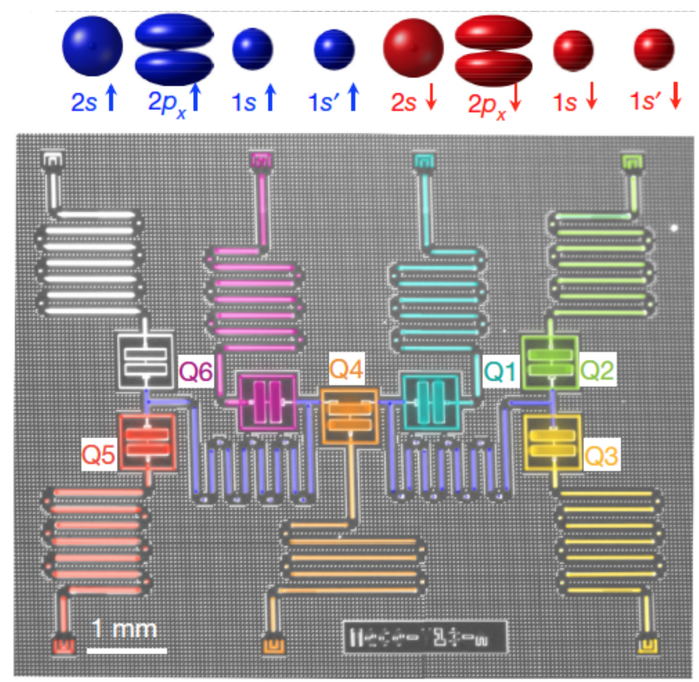
- 10^5 improvement in qubit performance
- Promising architecture for quantum information processors

*Devoret & Schoelkopf (2013)





*C. Neill et al., Science (2018)



IBM

*A. Kandala et al., Nature (2017)

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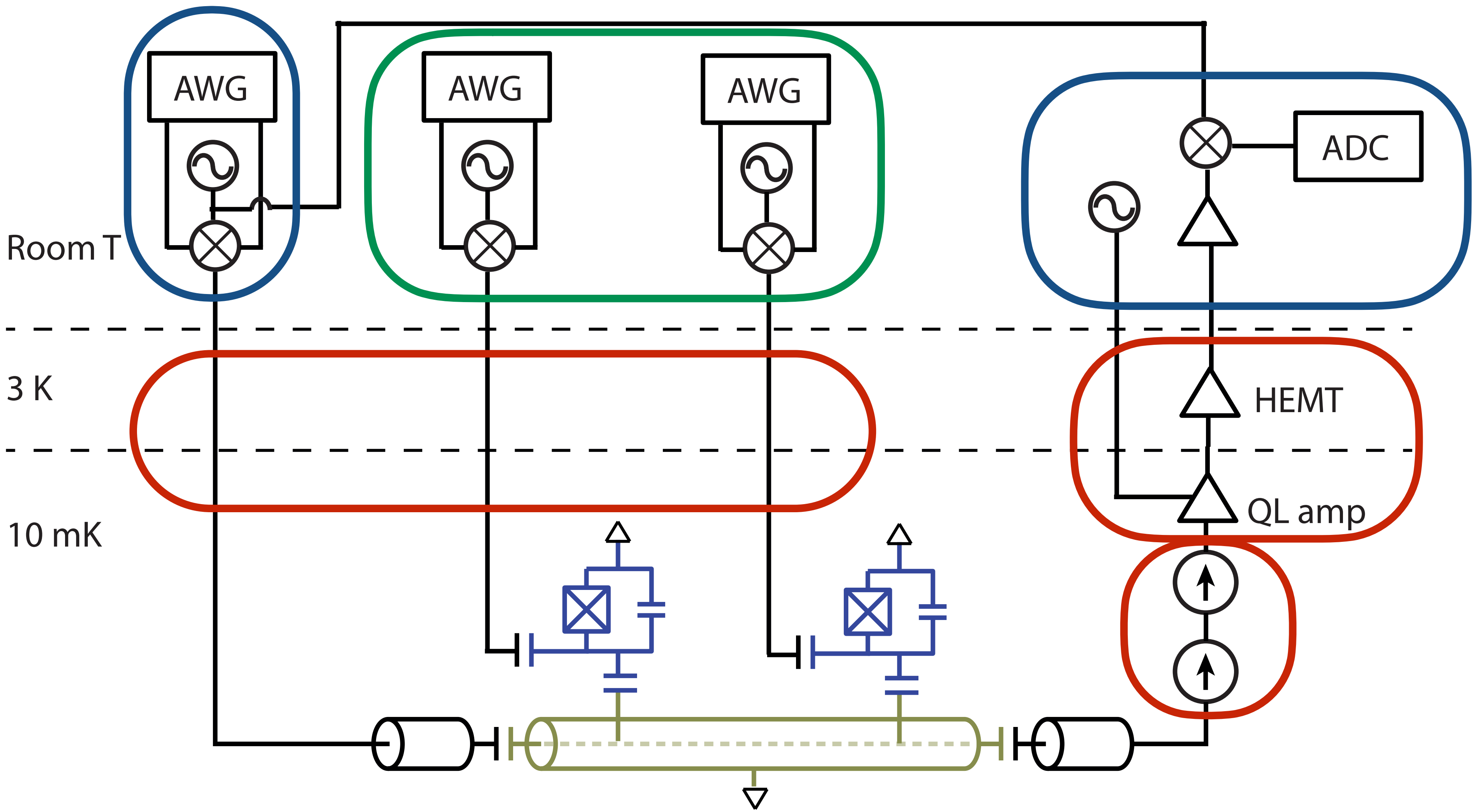
Microwave-based qubit control and readout



★ Works well…, but significant hardware overhead

Single-qubit gate fidelities > 99.9%

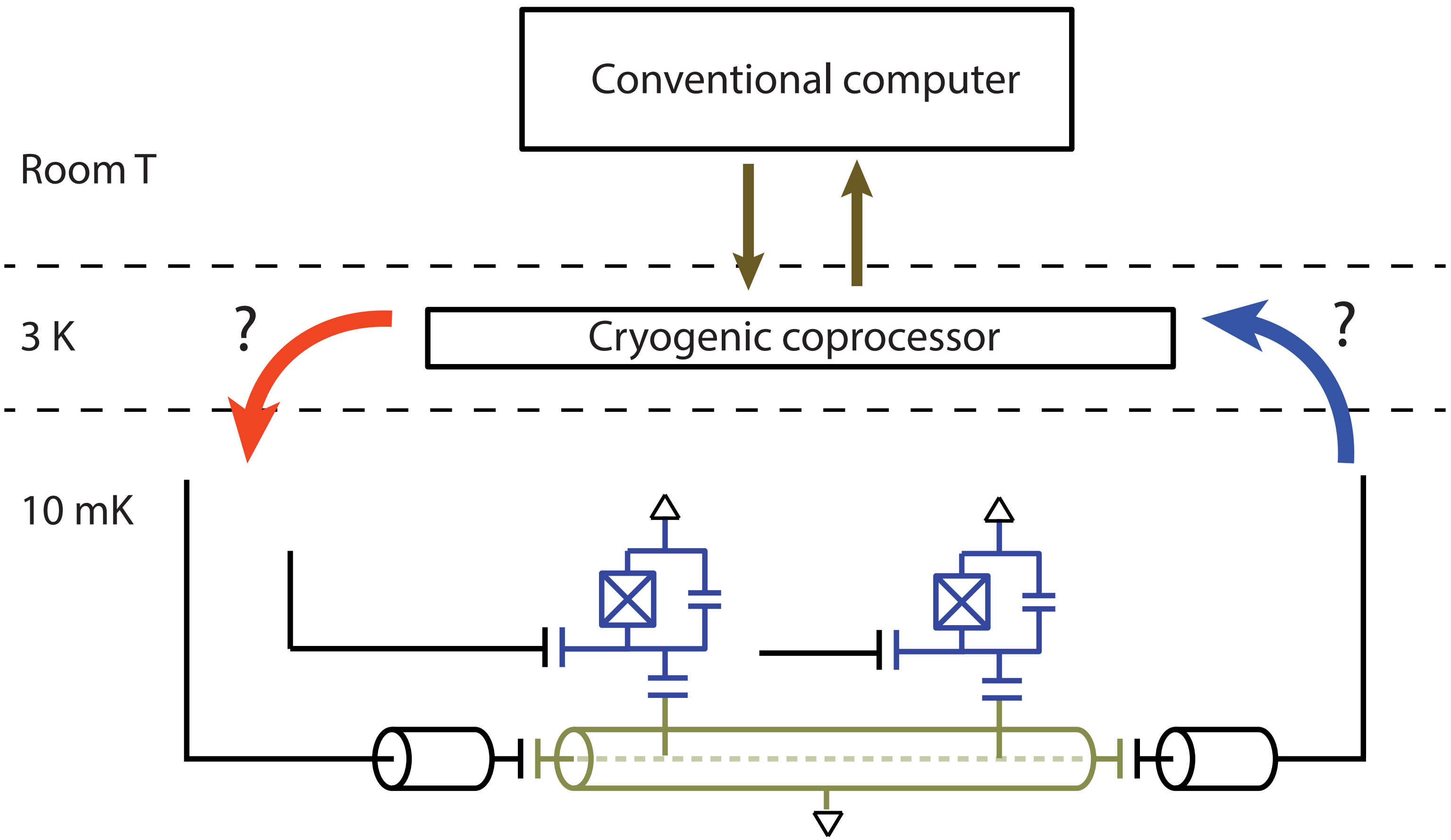
**R. Barends et al., Nature (2014)*
**S. Sheldon et al. PRA (2016)*

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

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

Reducing room-temperature hardware overhead

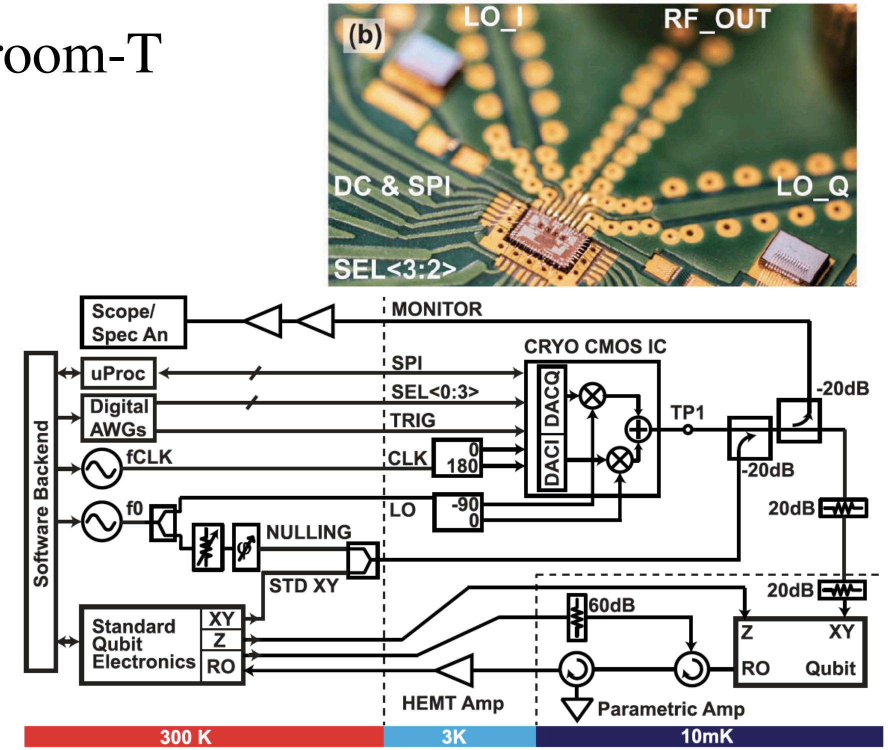
- Can we move some of the room-temperature control and readout hardware into the cryogenic environment?
- How can we implement cryogenic control and readout of qubits?



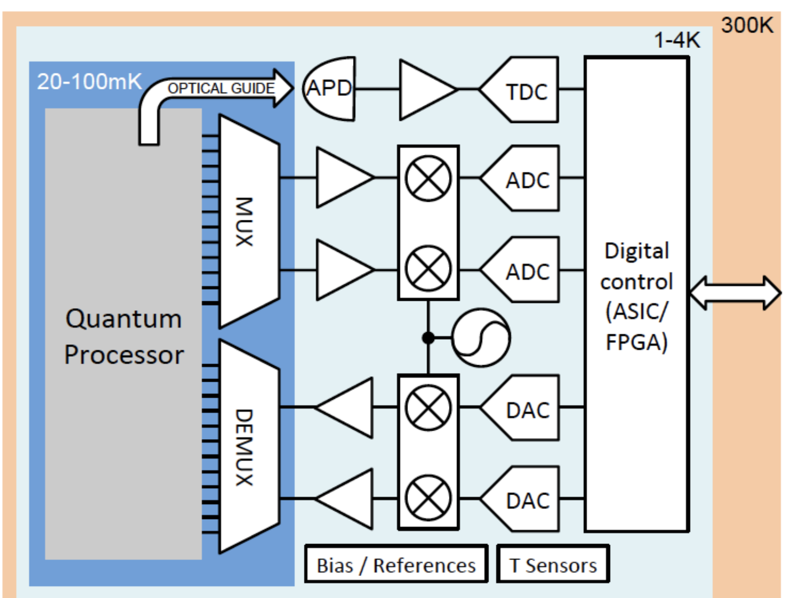
Cryogenic CMOS and Microwave Control

- One approach: miniaturize some of the room-T hardware and move to the 3 K level

- CMOS-based IQ modulator running at 3 K for generating microwave pulses for qubit gates



*J. Bardin et al., IEEE J. Solid State Circuits (2019)



*E. Charbon et al., IEDM (2016)

- Besides superconducting qubits, consider integrating semiconductor-based spin quantum dot qubits with cryo CMOS control and readout

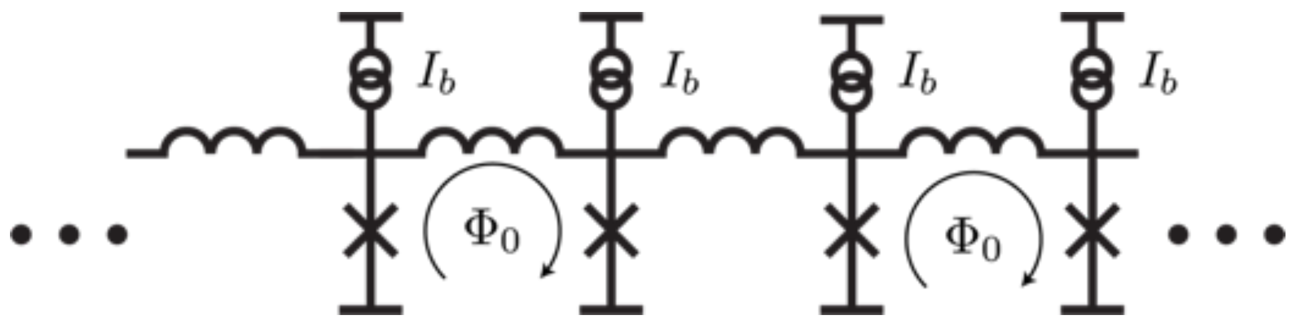
- also, Intel, Microsoft…

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



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

- Low power consumption; high speed logic

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

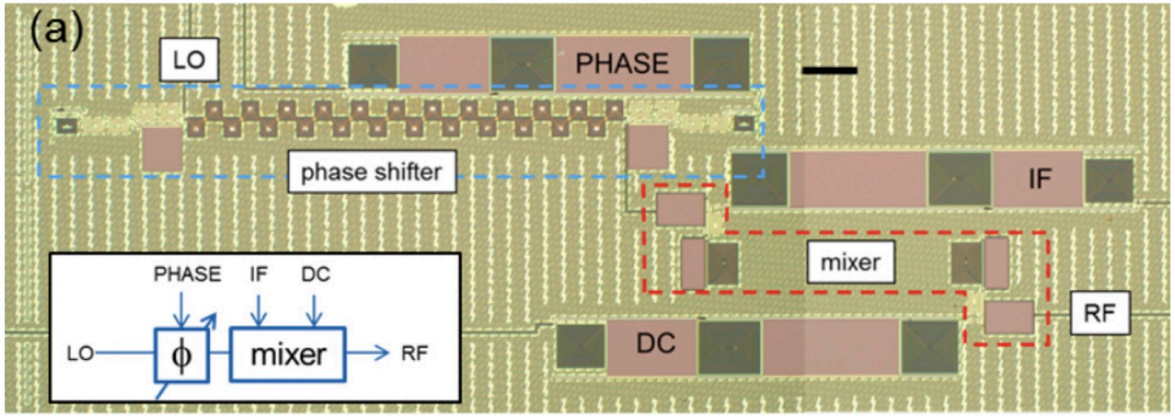
- Recent intensive effort to implement SFQ-based large-scale processor — IARPA C3 program

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

*Manheimer, *IEEE Trans. Appl. Supercon. 2015*

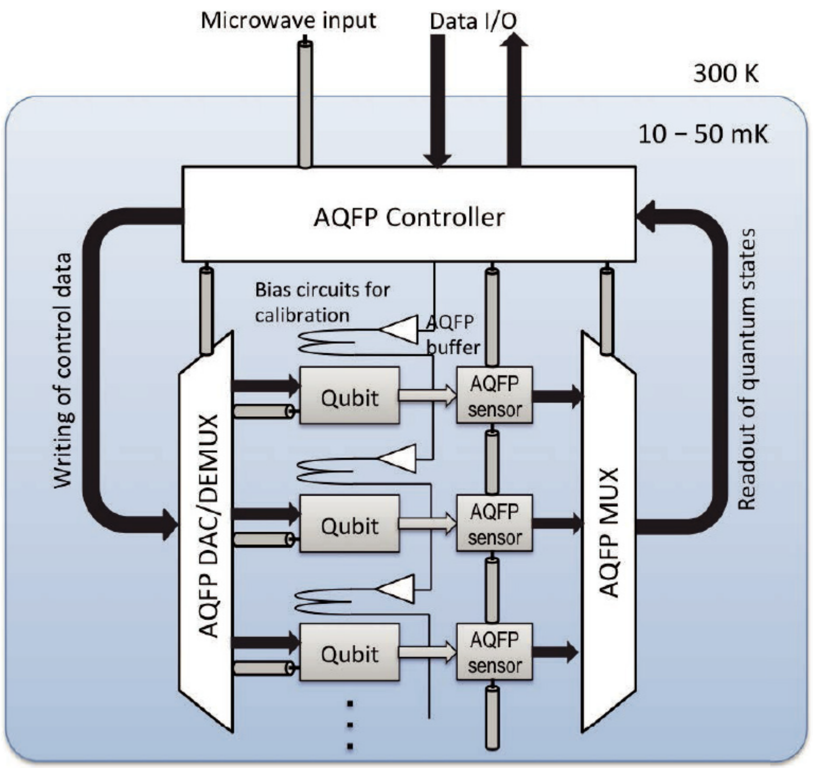
Superconducting control circuitry for qubits

- JJ-based vector modulator for generating microwave pulses for qubit gates
- Minimal on-chip power dissipation, potential for integrating near qubits



*O. Naaman et al., J. Appl. Phys. (2017)

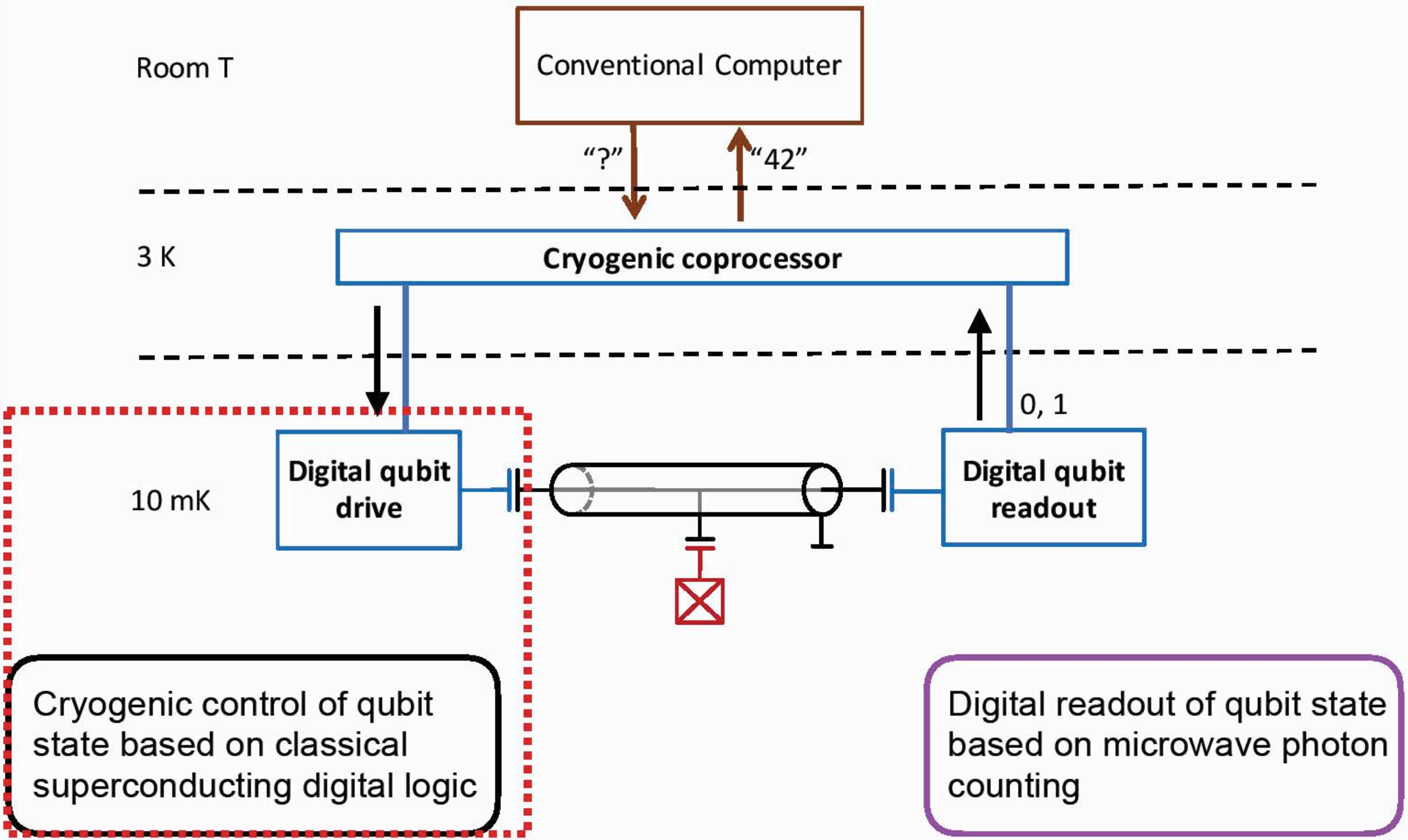
- AQFP for integrated qubit control and readout at mK stage
- MUX and DEMUX of dc and microwave signals for qubit control/ readout
- Potential for low power dissipation of AQFP circuitry



*N. Yoshikawa, IEICE Trans. Electron. (2019)

Reducing room-temperature hardware overhead

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



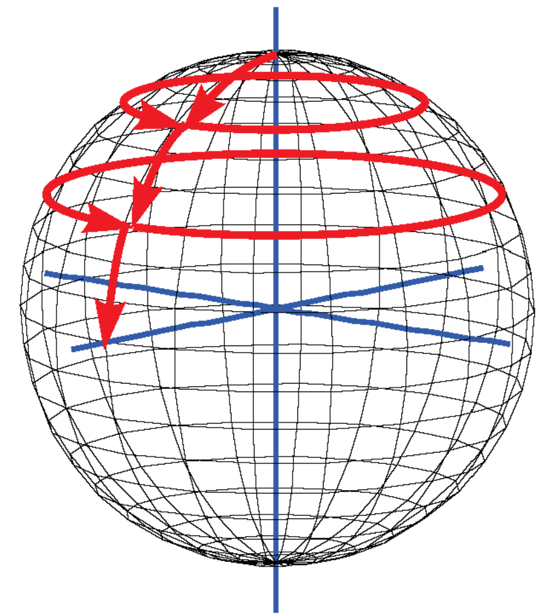
On-chip digital control of qubits

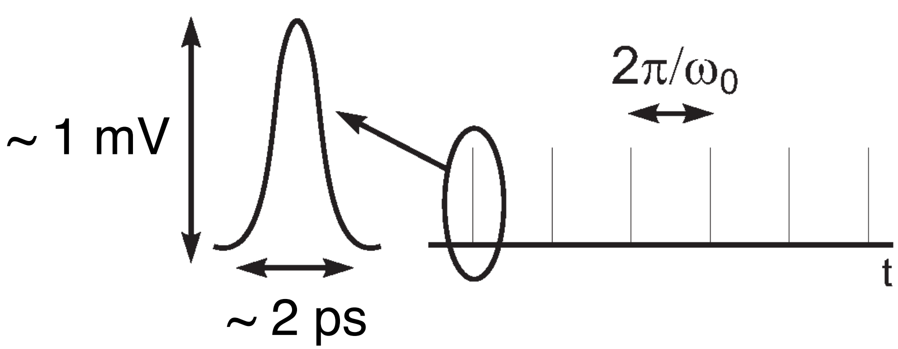
- SFQ circuitry on same chip as qubits or flip-chip coupling

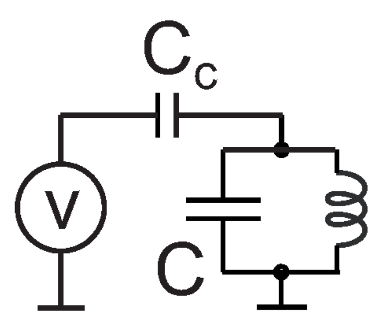
- Capacitively couple resonant train of narrow SFQ pulses to drive qubit rotations without microwaves

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

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







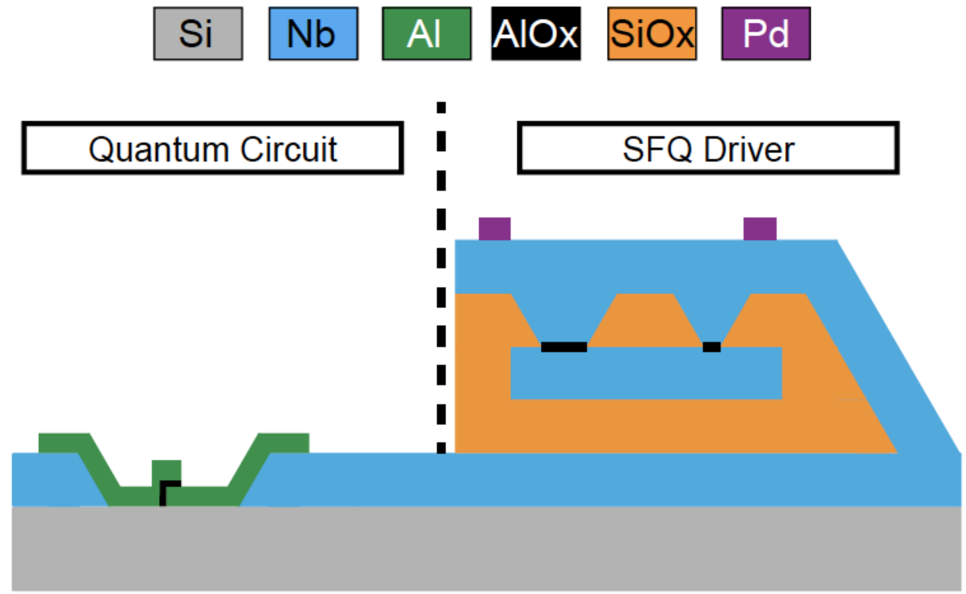
$$\delta\theta = C_c \Phi_0 \sqrt{\frac{2\omega_{01}}{\hbar C}}$$

π rotation with ~100 pulses

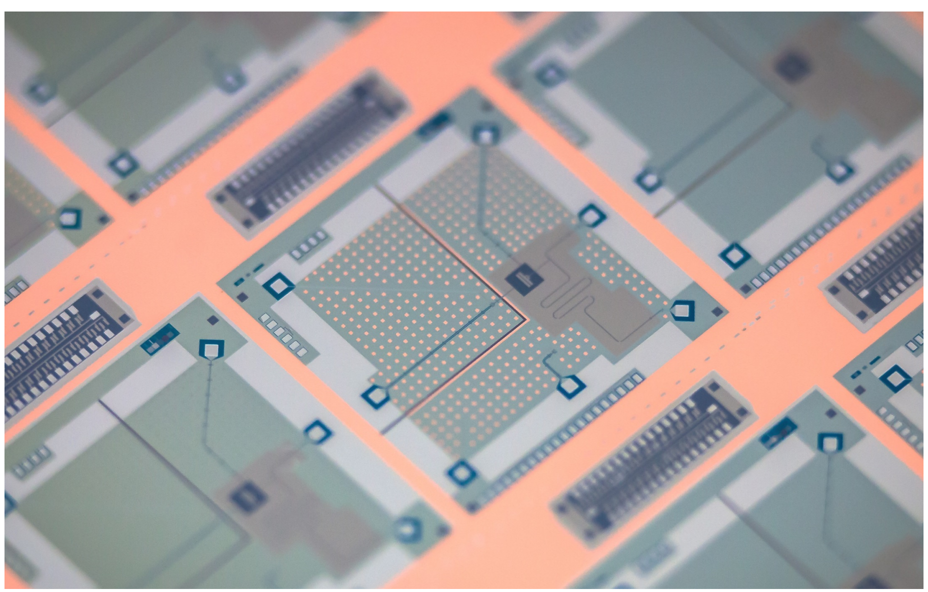
~14 ns for 7 GHz qubit

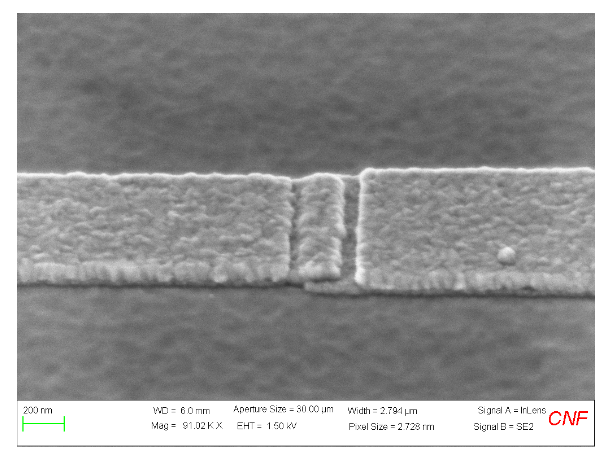
Implementation of SFQ driver and qubits

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

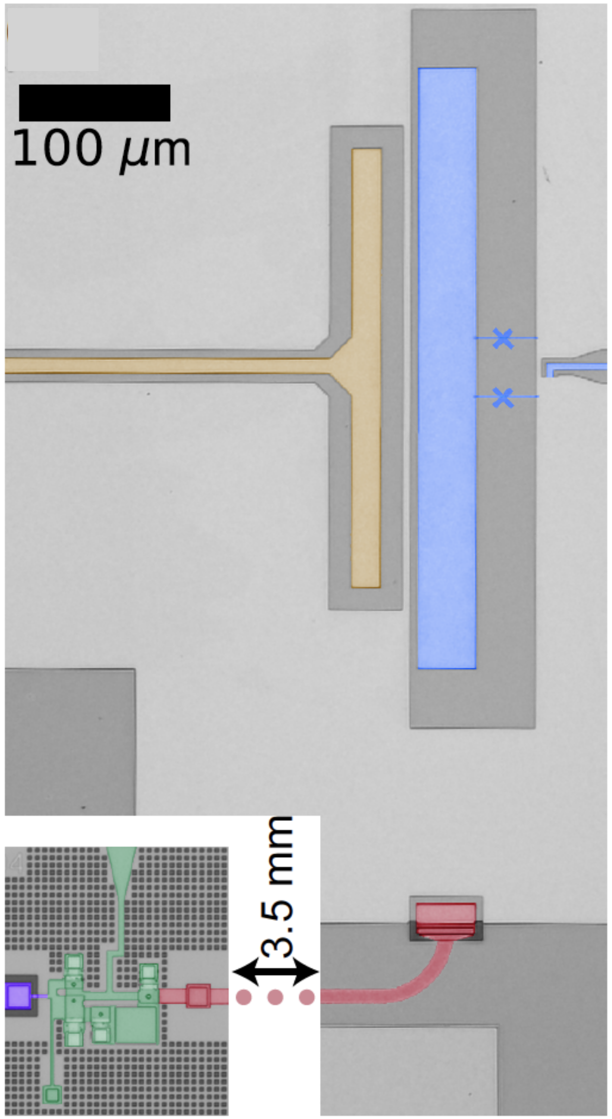


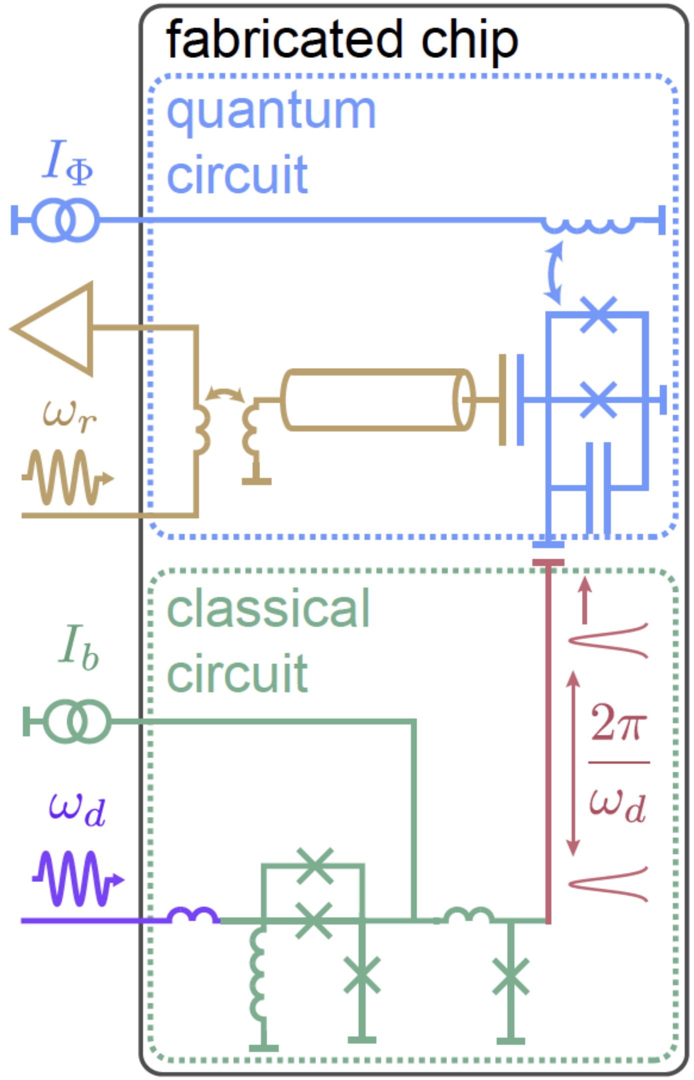
*Leonard *et al.*, Phys. Rev. Applied 11, 014009 (2019)



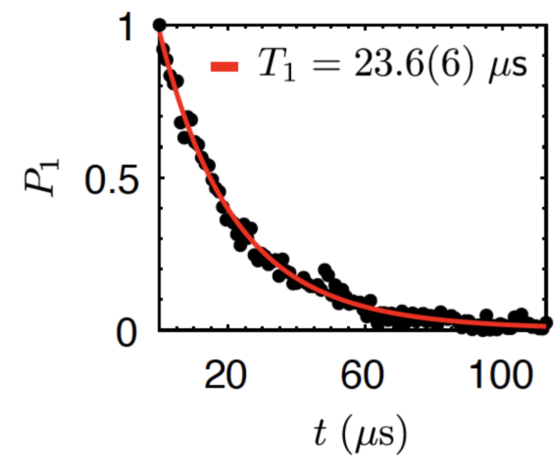


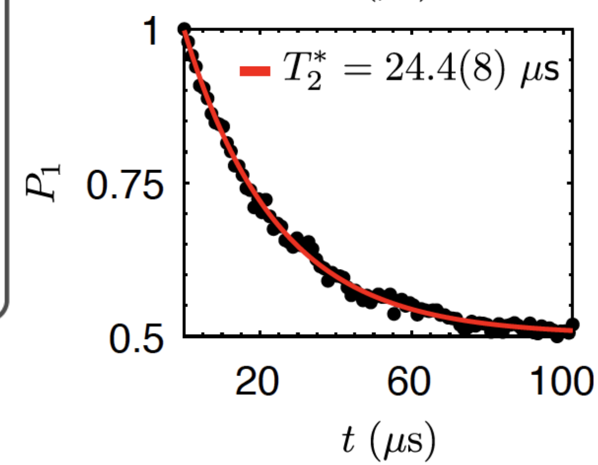
Layout of SFQ driver and qubit





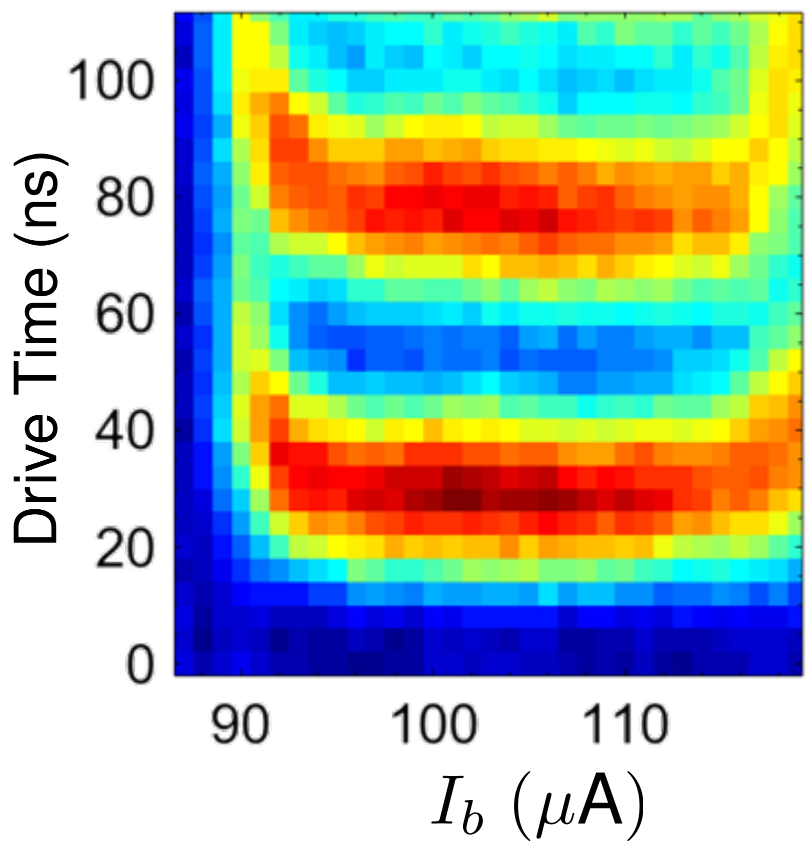
- Conventional heterodyne qubit readout
- Decent coherence

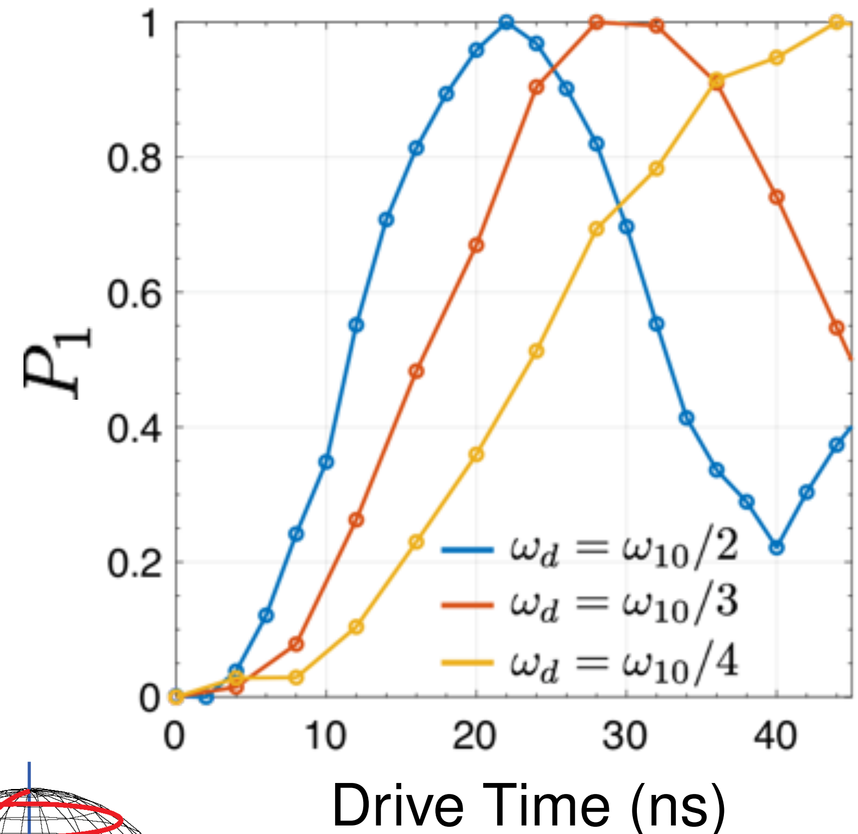


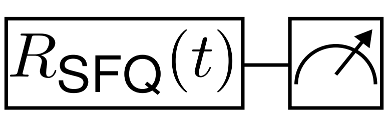


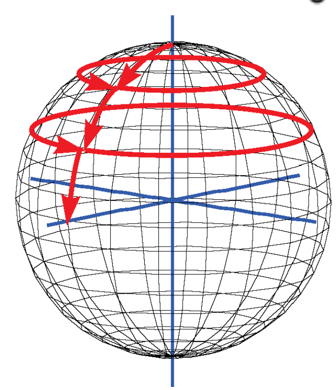
Qubit Rabi oscillations with SFQ pulses

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



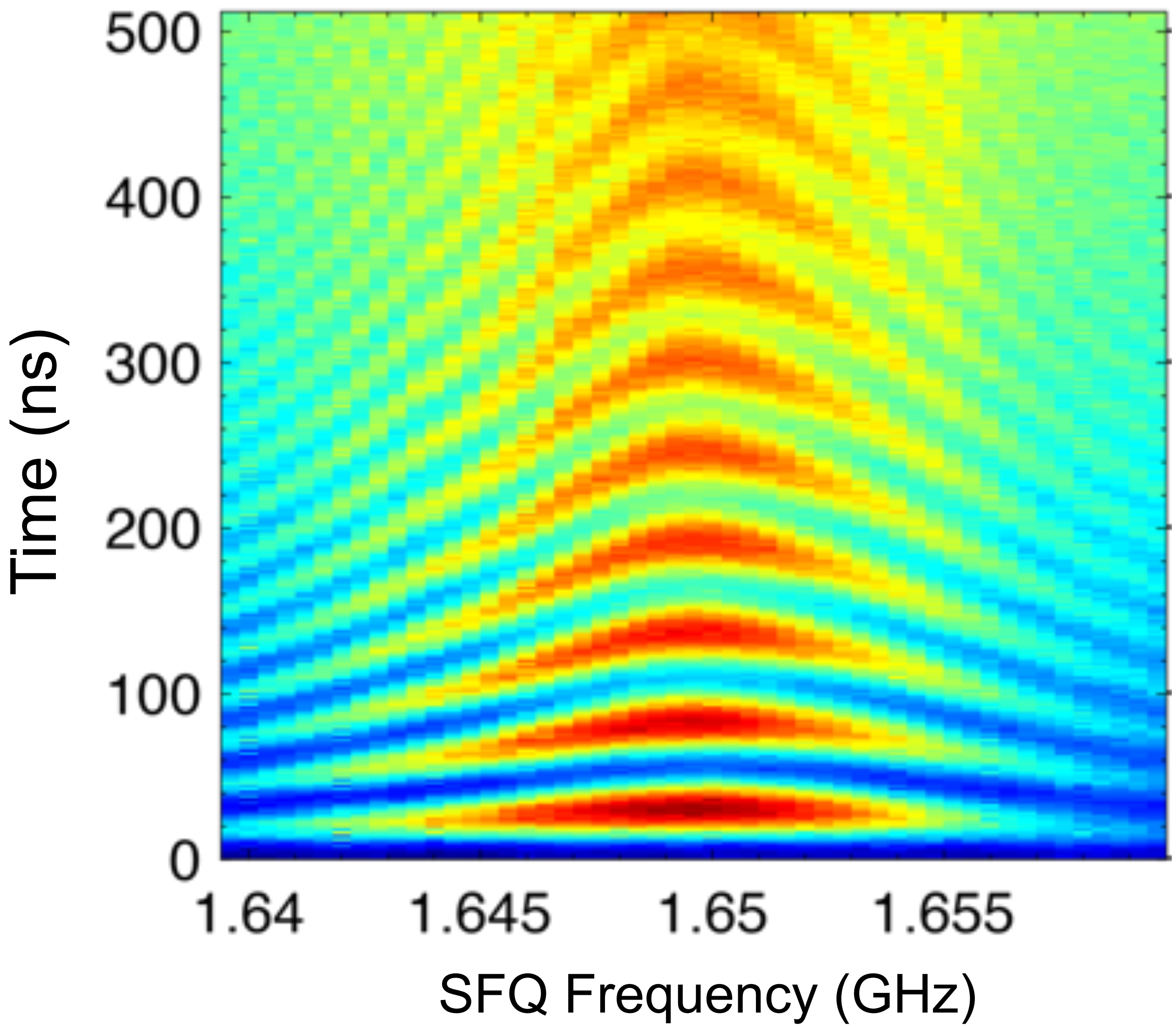


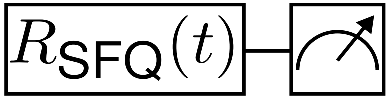




Drive SFQ circuit on subharmonic to avoid direct drive of qubit

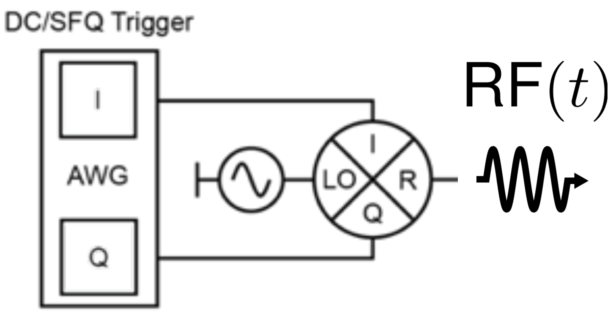
Qubit Rabi oscillations at $\omega_{10}/3$

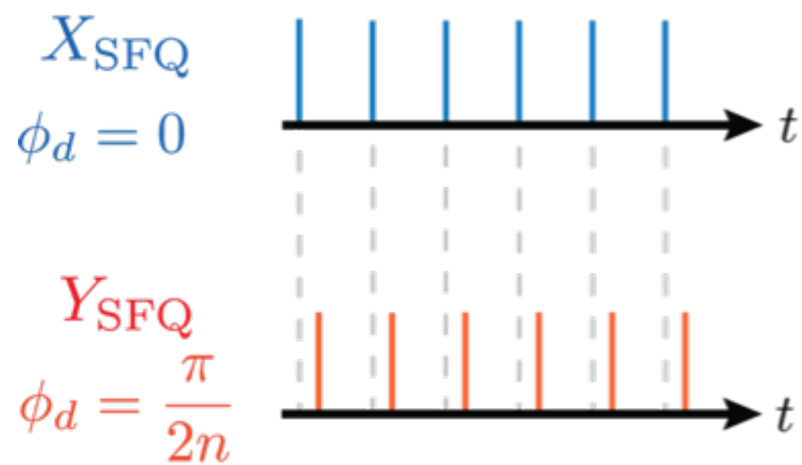


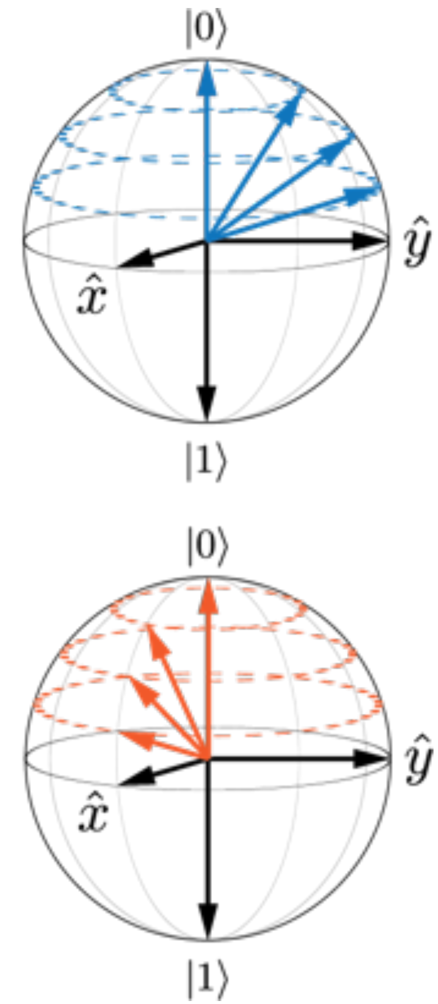


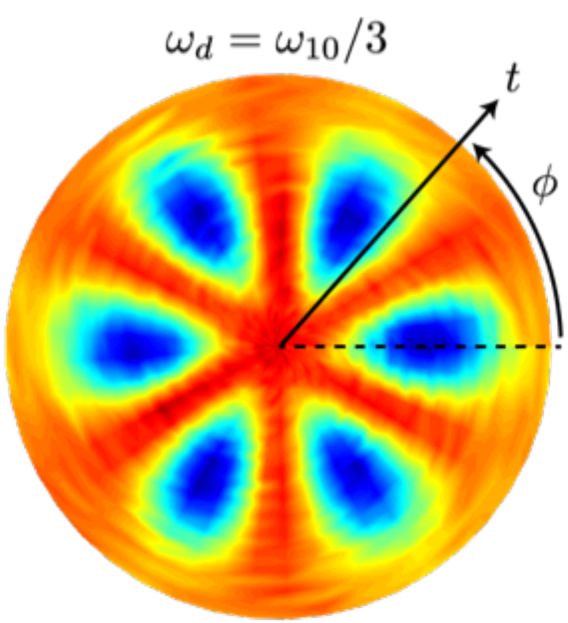
Orthogonal gates with SFQ pulses

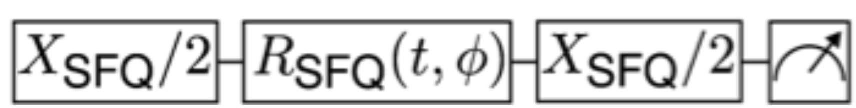
$$\mathrm{RF}(t) = \cos[\underbrace{(\omega_{\mathrm{LO}} - \omega_{\mathrm{IF}})}_{\omega_d} t + \phi_d]$$





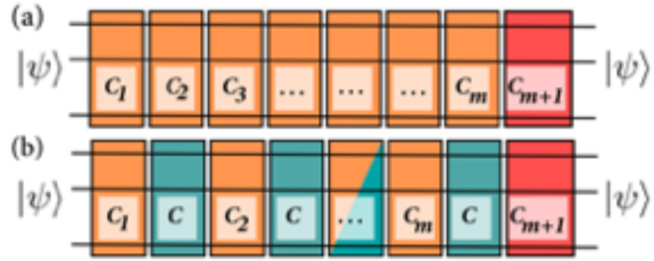




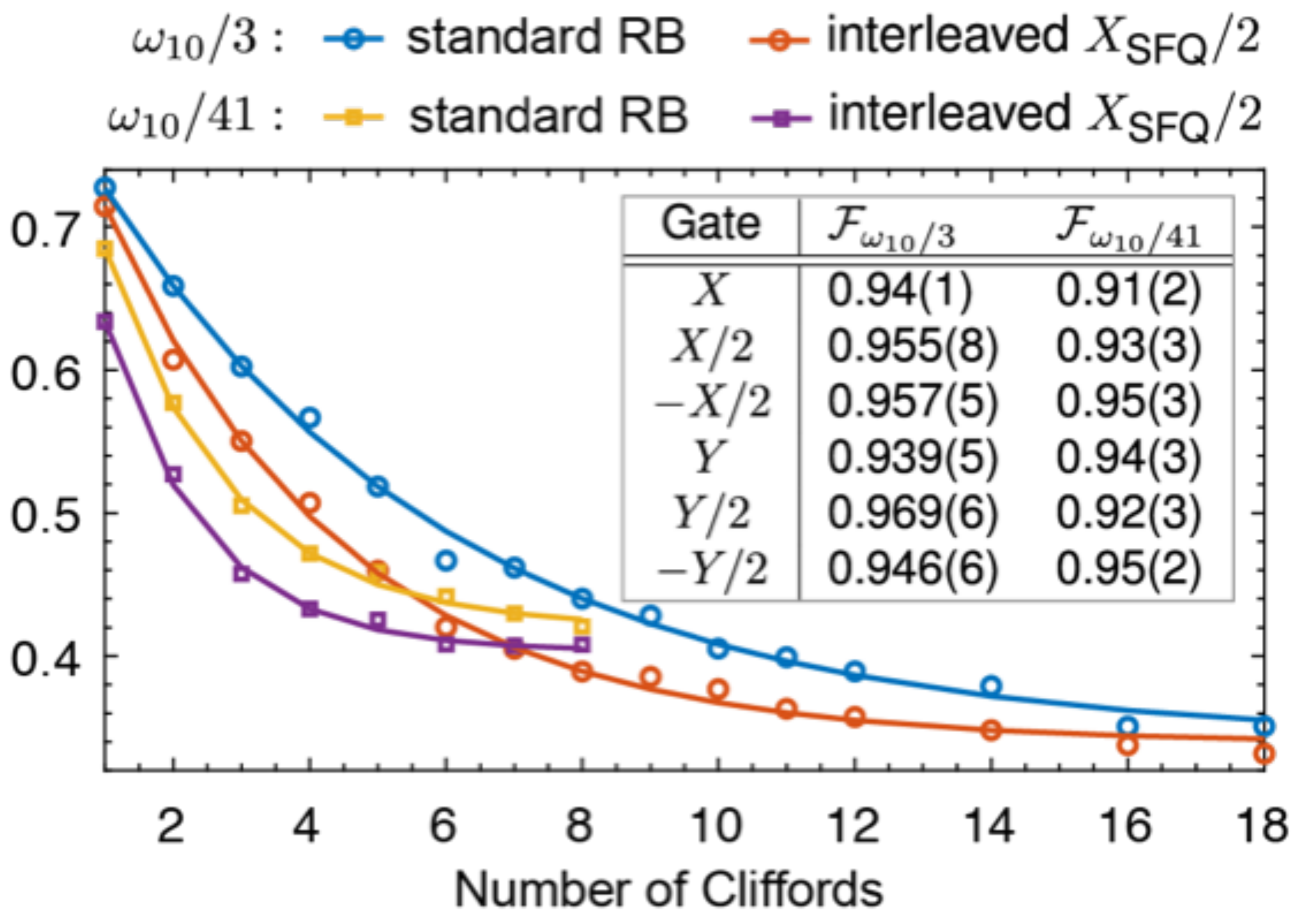


Characterizing SFQ-based gates

Randomized benchmarking



*Magesan *et al.*, PRL 109, 080505 (2012)

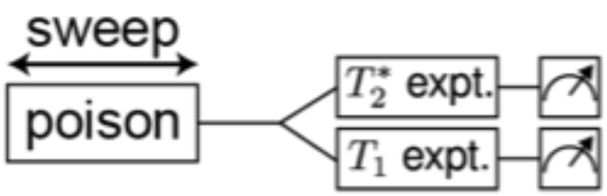


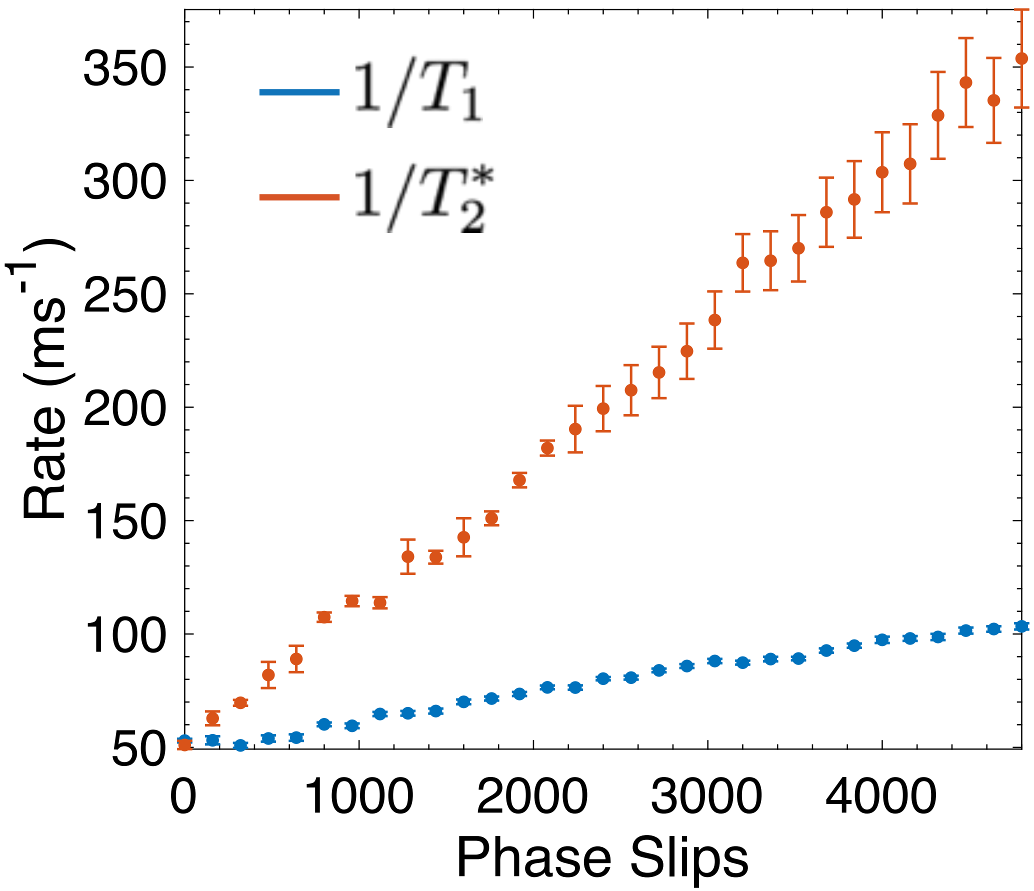
Gate	$\mathcal{F}_{\omega_{10}/3}$	$\mathcal{F}_{\omega_{10}/41}$
X	0.94(1)	0.91(2)
$X/2$	0.955(8)	0.93(3)
$-X/2$	0.957(5)	0.95(3)
Y	0.939(5)	0.94(3)
$Y/2$	0.969(6)	0.92(3)
$-Y/2$	0.946(6)	0.95(2)

Gate fidelities limited by on-chip quasiparticle generation

Quasiparticle poisoning

- Trigger SFQ driver off-resonant from qubit subharmonics
- Phase slips of SFQ junctions generate quasiparticles that poison qubit





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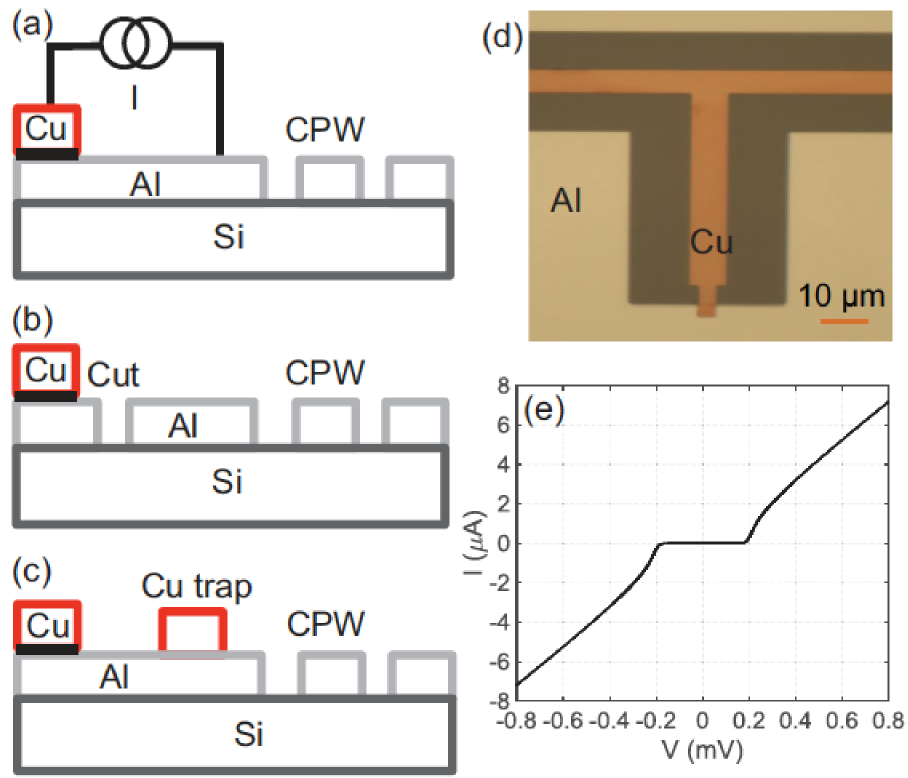
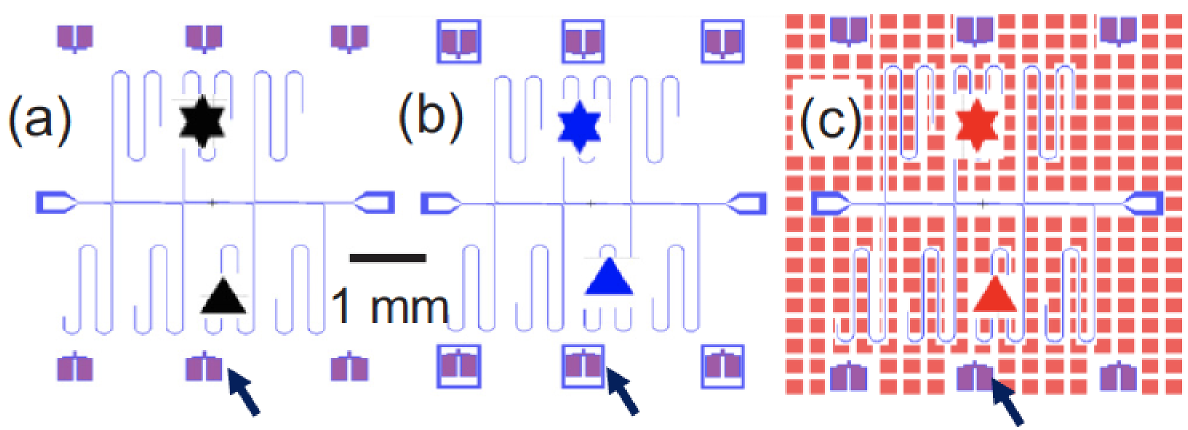
Loss due to quasiparticle injection

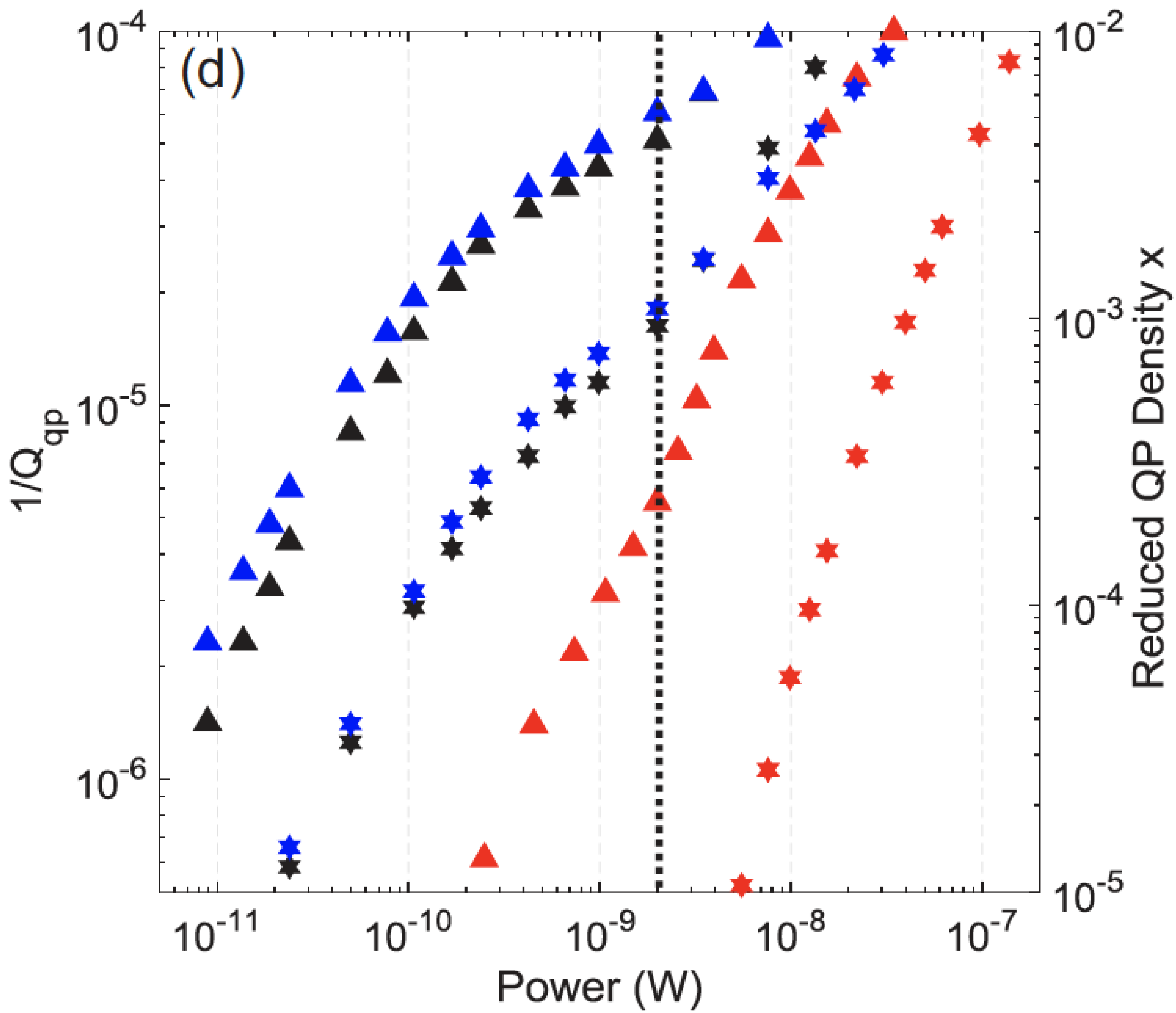
- Aluminum CPW resonators
- NIS junctions along perimeter of ground plane
- Bias junctions beyond gap to inject quasiparticles into ground plane

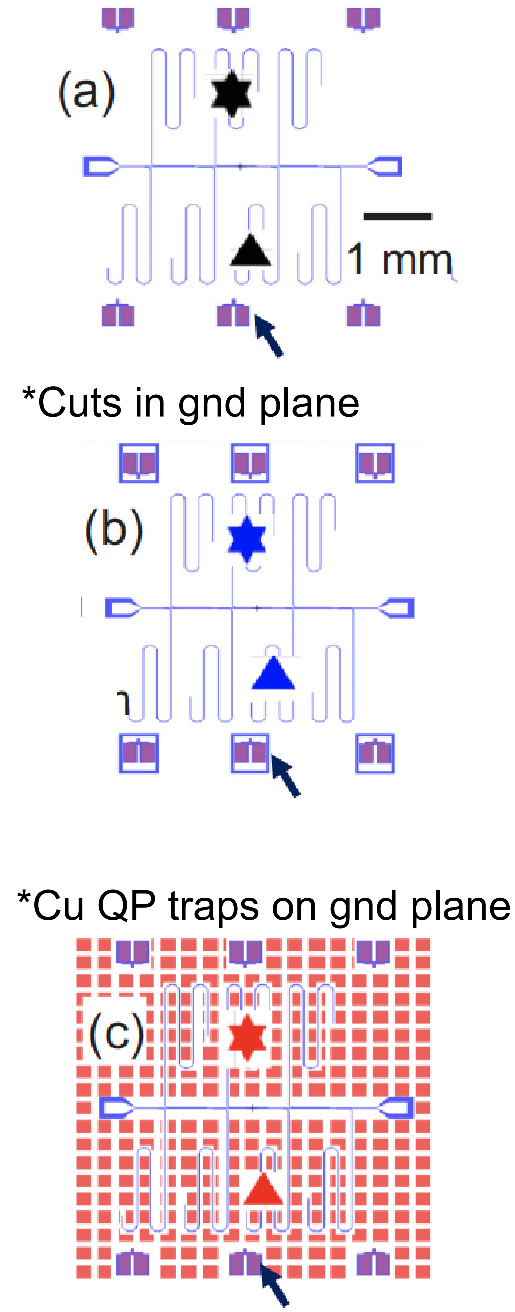




*Patel et al., *PRB 96, 220501 (R) (2017)*

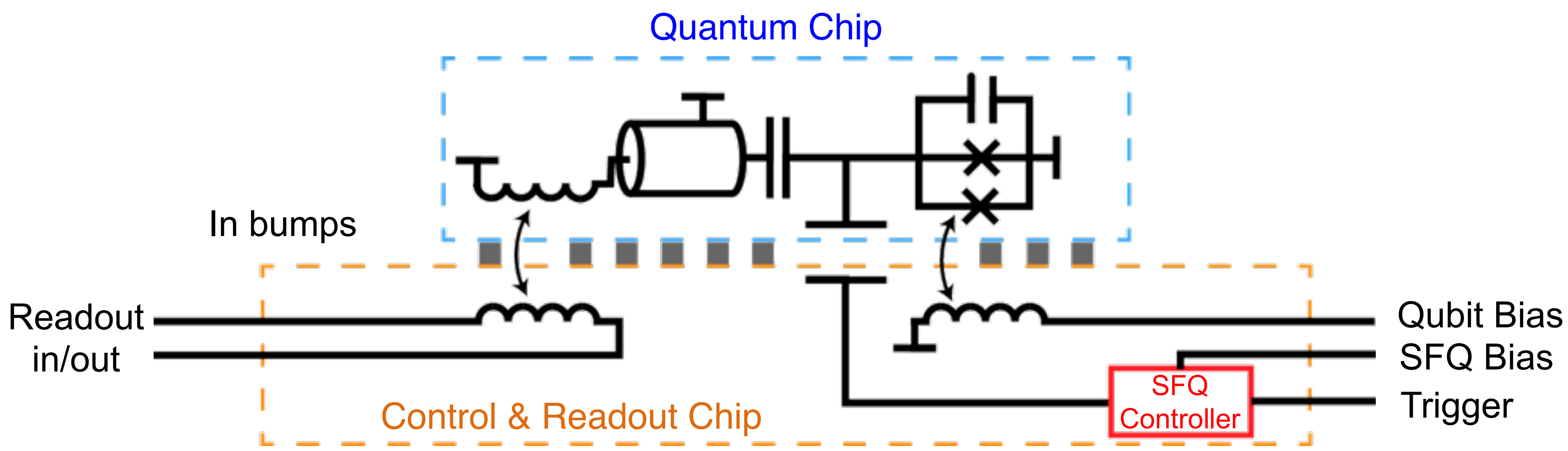
Loss due to quasiparticle injection



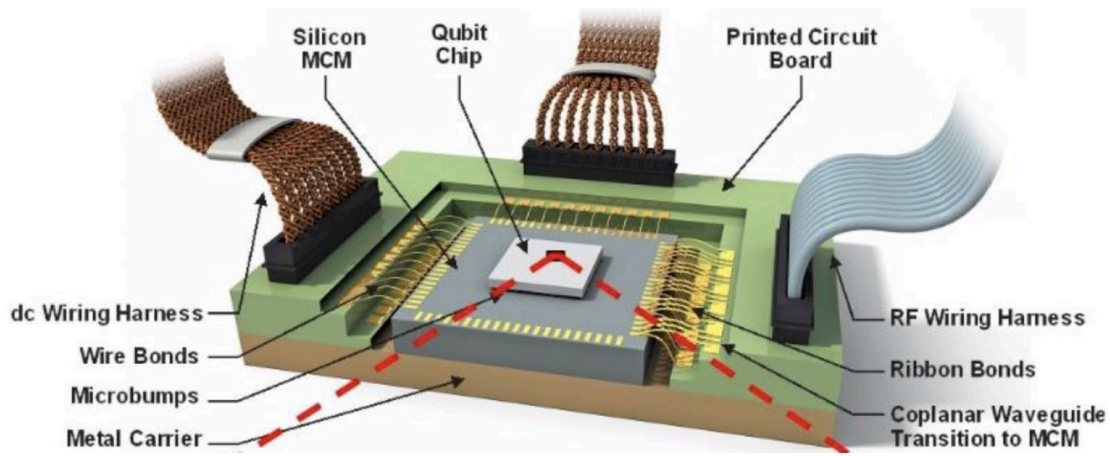


*Patel et al., *PRB 96, 220501 (R) (2017)*

Mitigating quasiparticle poisoning



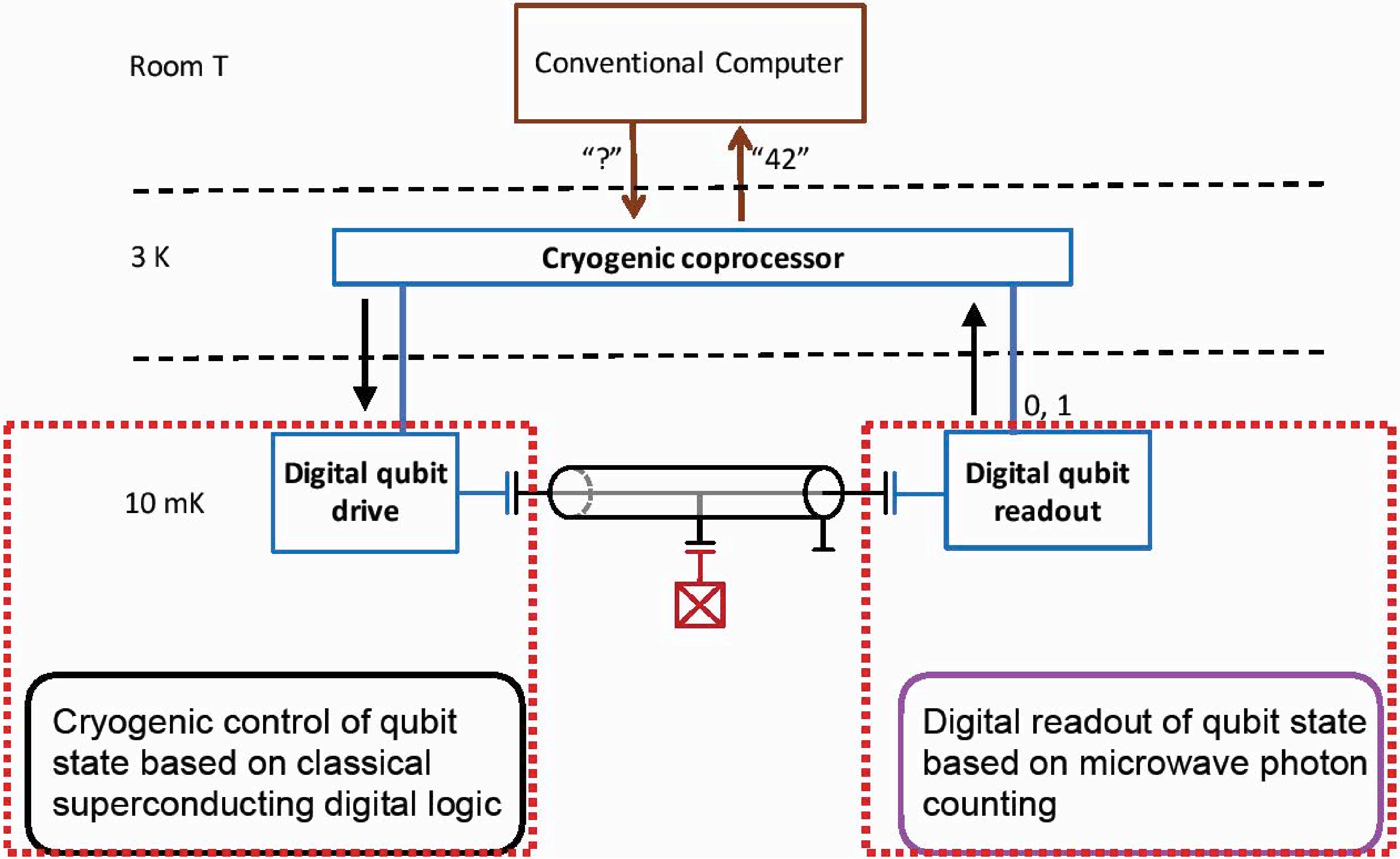
- Multi-chip module (MCM) configuration
- Separate high-coherence qubits and resonators from dissipative classical control/ readout circuitry



R. Das et al., IEEE 68th ECTC (2018)

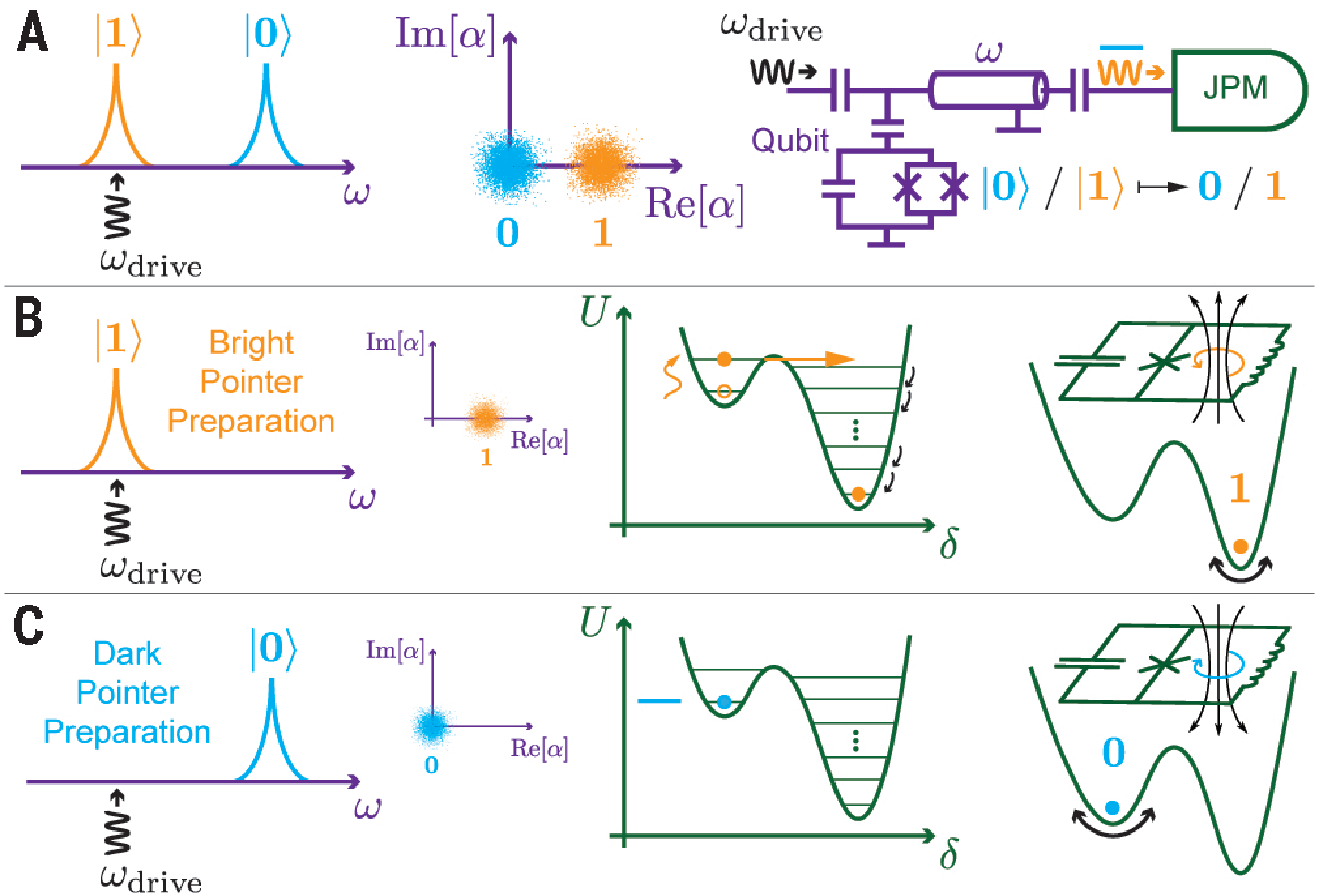
Reducing room-temperature hardware overhead

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



Digital Readout of Qubit with Josephson Photomultiplier

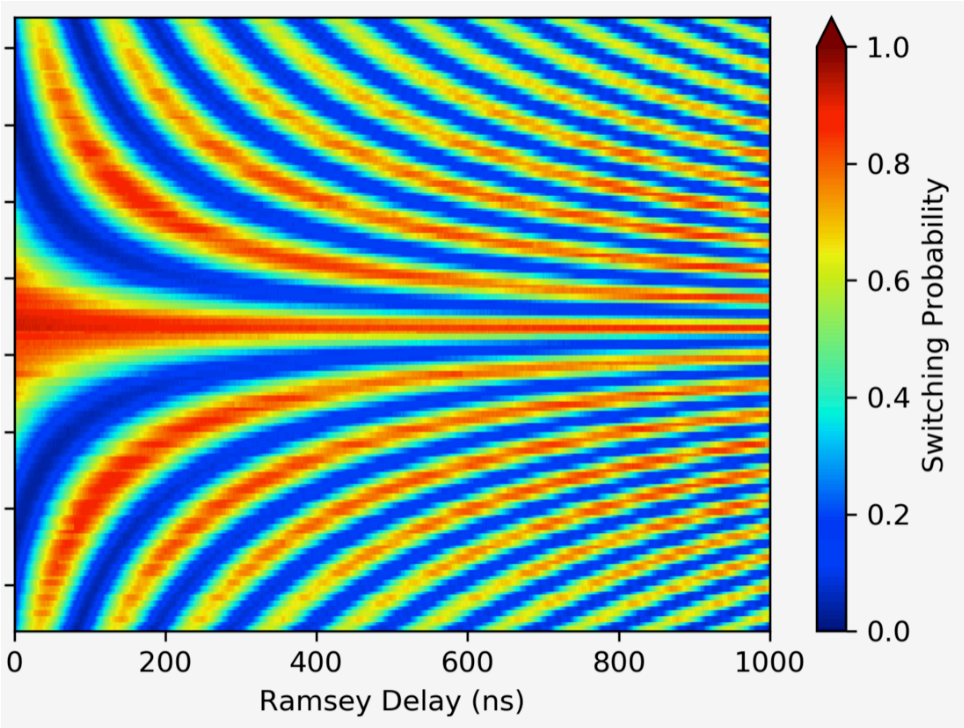
*Opremcak *et al.*, Science 361, 1239 (2018)



*Chen *et al.*, Phys. Rev. Lett. (2011)
*Govia *et al.*, Phys. Rev. A (2014)

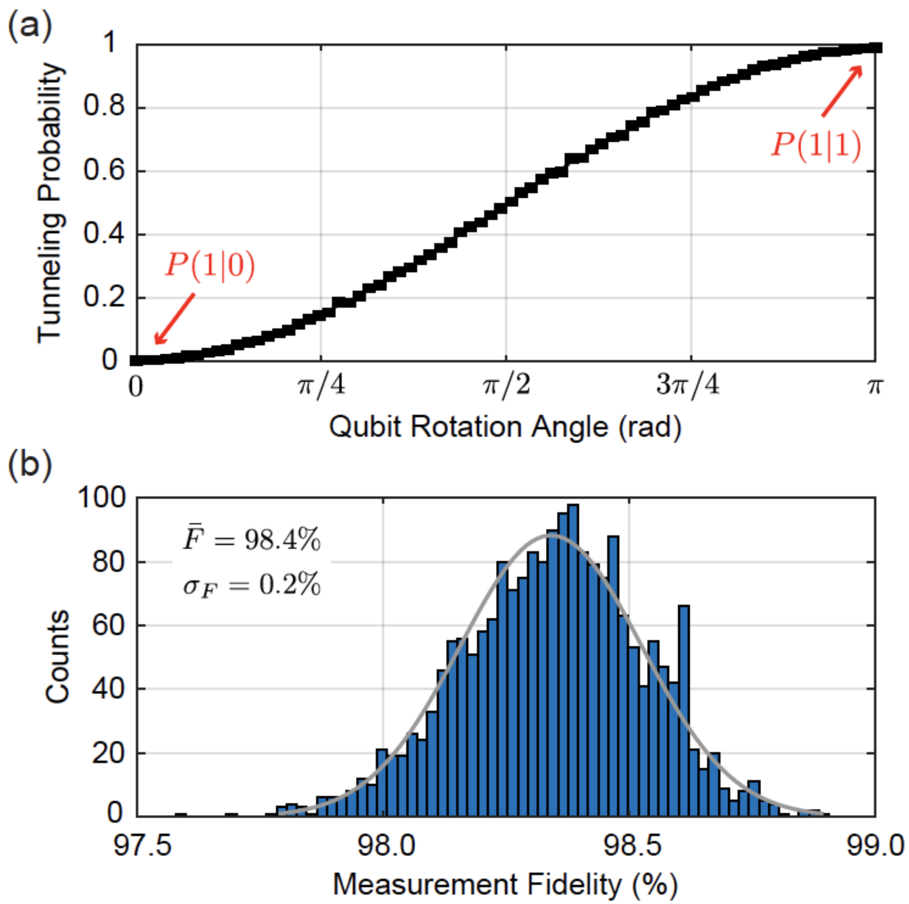
Digital Readout of Qubit with Josephson Photomultiplier

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



Raw measurement fidelity ≈ 92%

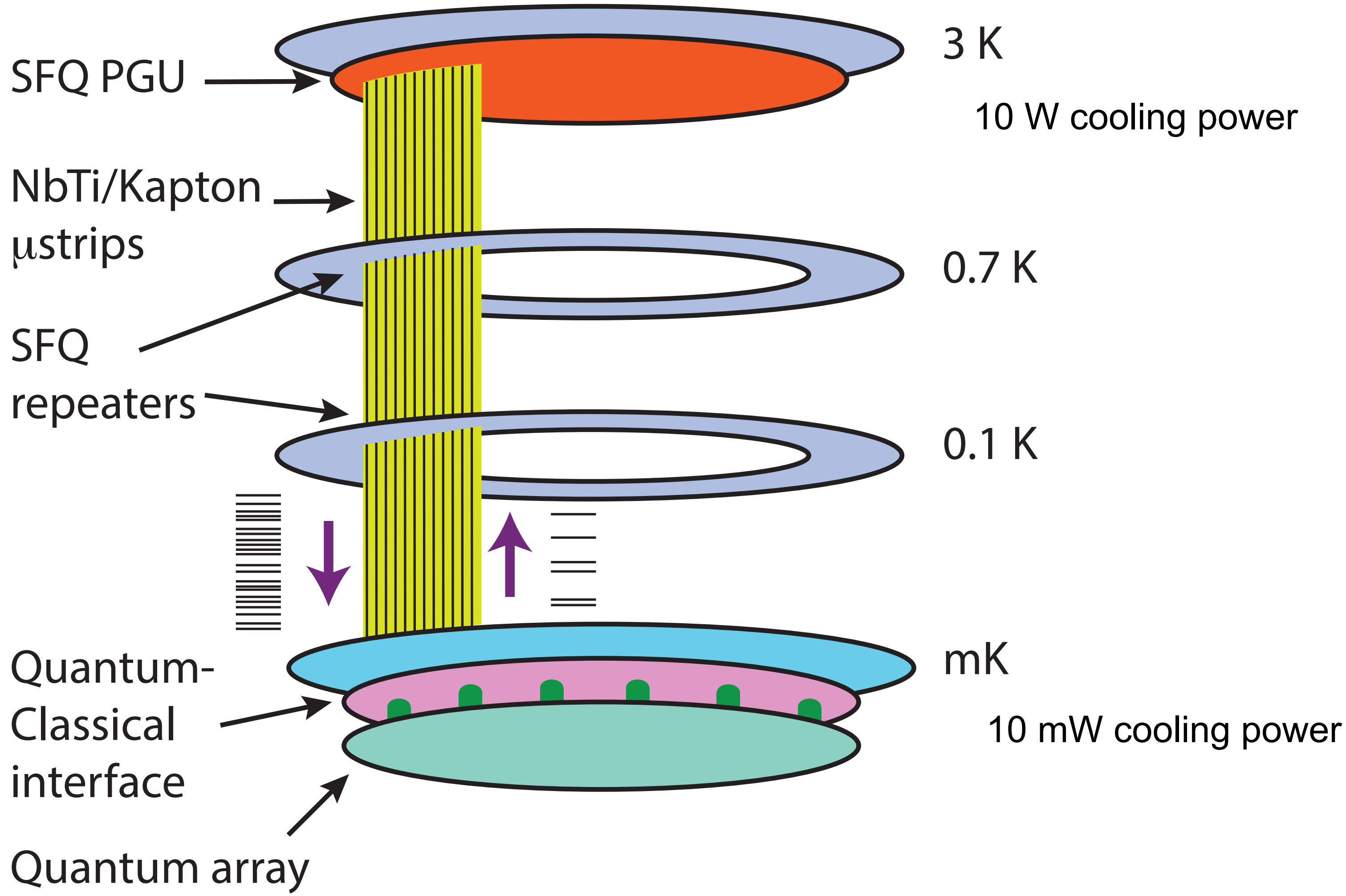
*Opremcak *et al.*, arXiv:2008.02346 (2020)



- Fast, high-fidelity qubit readout with no need for microwave isolators
- Measurement result accessible at mK; possibility of converting to SFQ signal for cryogenic processing

*Howington *et al.*, IEEE Trans. Appl. SC (2019)

Quantum-Classical Interface



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

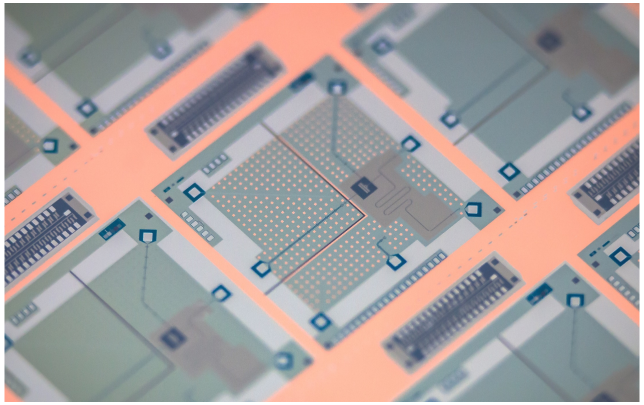
Quantum layer = qubits and readout resonators only; minimal fab processing

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

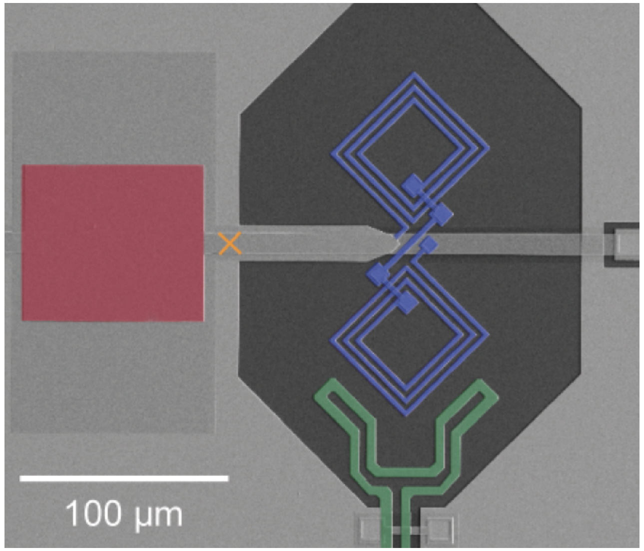
  *McDermott *et al.*, Quant. Sci. Tech. 3, 024004 (2018)



- Cryogenic control offers a pathway to overcome scaling challenges

- SFQ-based qubit control without microwave pulses

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



- Microwave photon counter JPMs for digital readout of qubit state

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