Superconducting Quantum Coherent Circuits
introduction, challenges, and near-term applications

John Mark Kreikebaum

Quantum Nanoelectronics Laboratory, University of California, Berkeley
Lawrence Berkeley National Laboratory

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Outline

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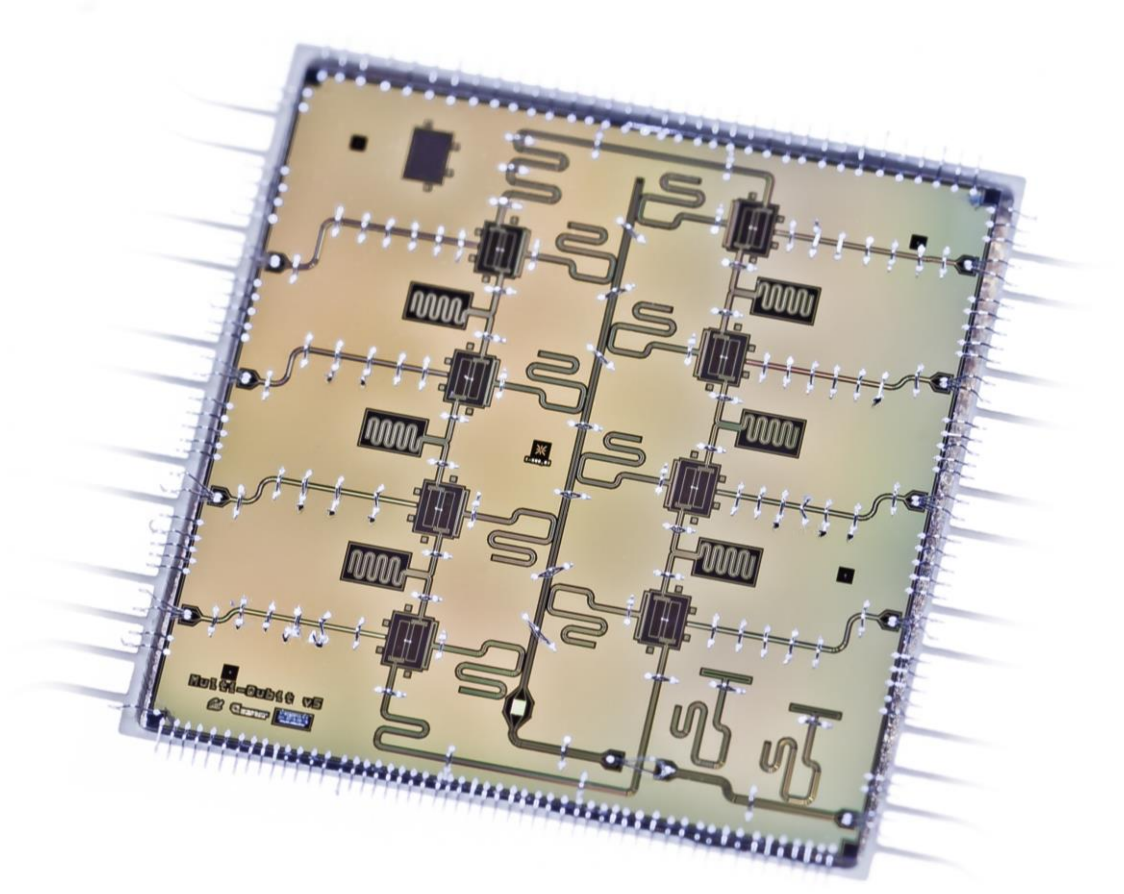
- Intro to quantum coherent circuits
- Challenges
  - Coherence
  - Fabrication precision
- Applications
  - Single microwave photon detection



Berkeley 8-qubit quantum processor
Fab: JMK
E&M design: K. O'Brien

Revolutions in Quantum Theory

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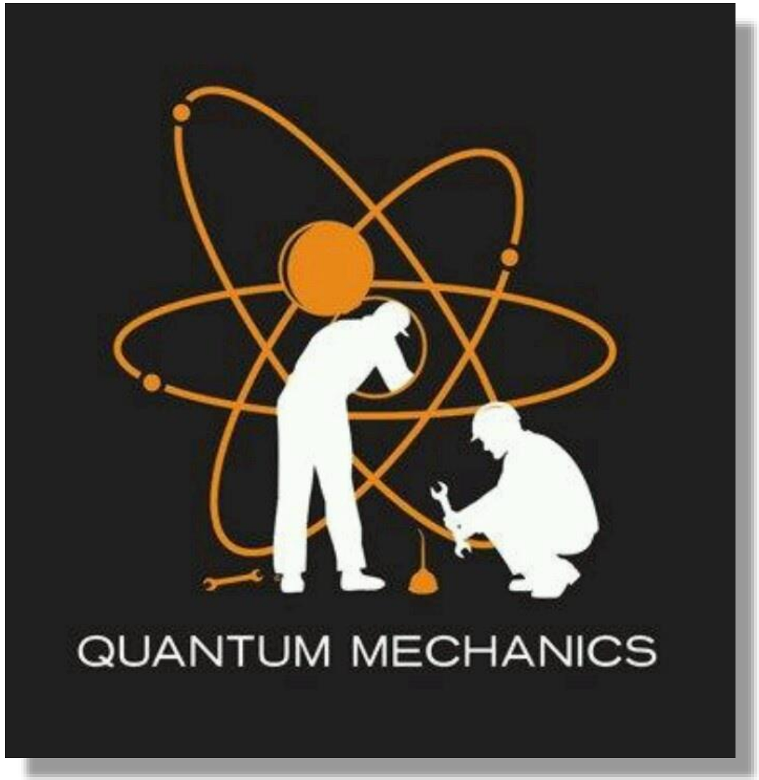

The First Quantum Revolution

The world is granular…

Spooky action at a distance?

Limits to entanglement ?

The Second Quantum Revolution

The world can be entangled on demand…

What algorithms can be run on quantum computers?

Parallel Processing with Entanglement

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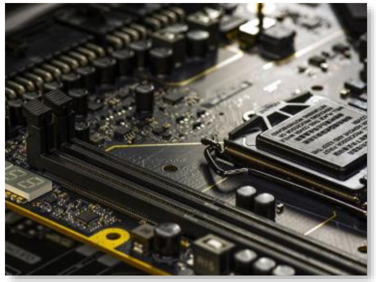
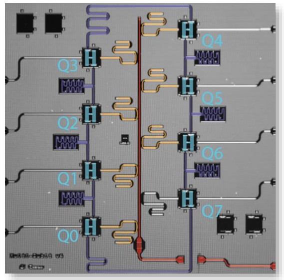
N quantum bits *entangle* to form 2^N states! (compare to 2N for classical bits)

World's fastest supercomputer: Summit at ORNL

200 petaflops ≈ 2^{57} flops





Computer

1 bit: 0 or 1

2 bits: 00, 01, 10, **or** 11

Quantum computer

1 qubit: $\alpha_1|0\rangle + \beta_1|1\rangle$

2 qubits: $\alpha_1\alpha_2|00\rangle + \alpha_1\beta_2|01\rangle + \alpha_2\beta_1|10\rangle + \beta_1\beta_2|11\rangle$

Quantum advantage: All states can be evaluated in parallel

The Eve of Quantum Supremacy

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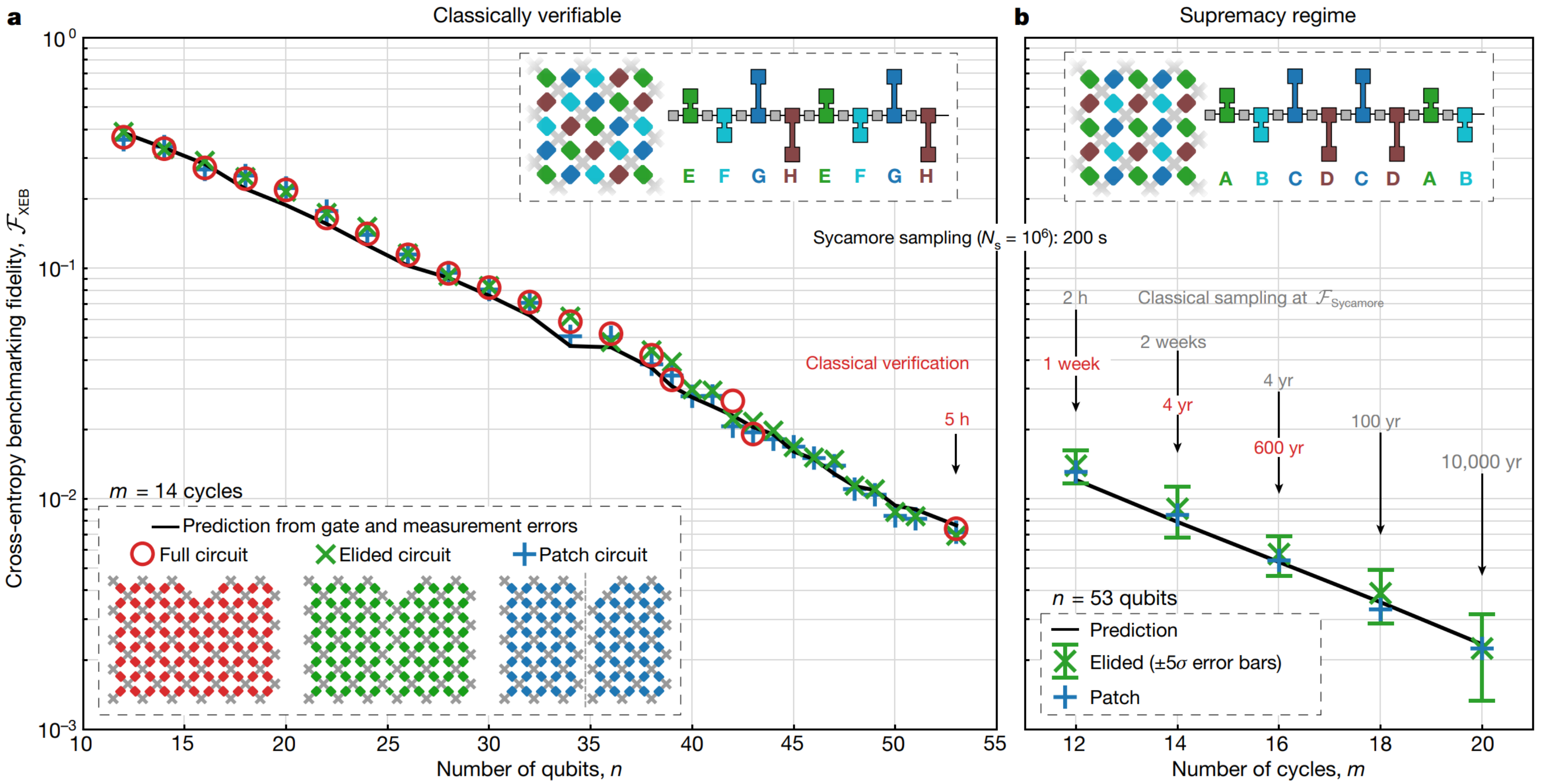
In 200 seconds with 53 qubits, Google performed a task that they estimate a would take supercomputer 10,000 years to complete.



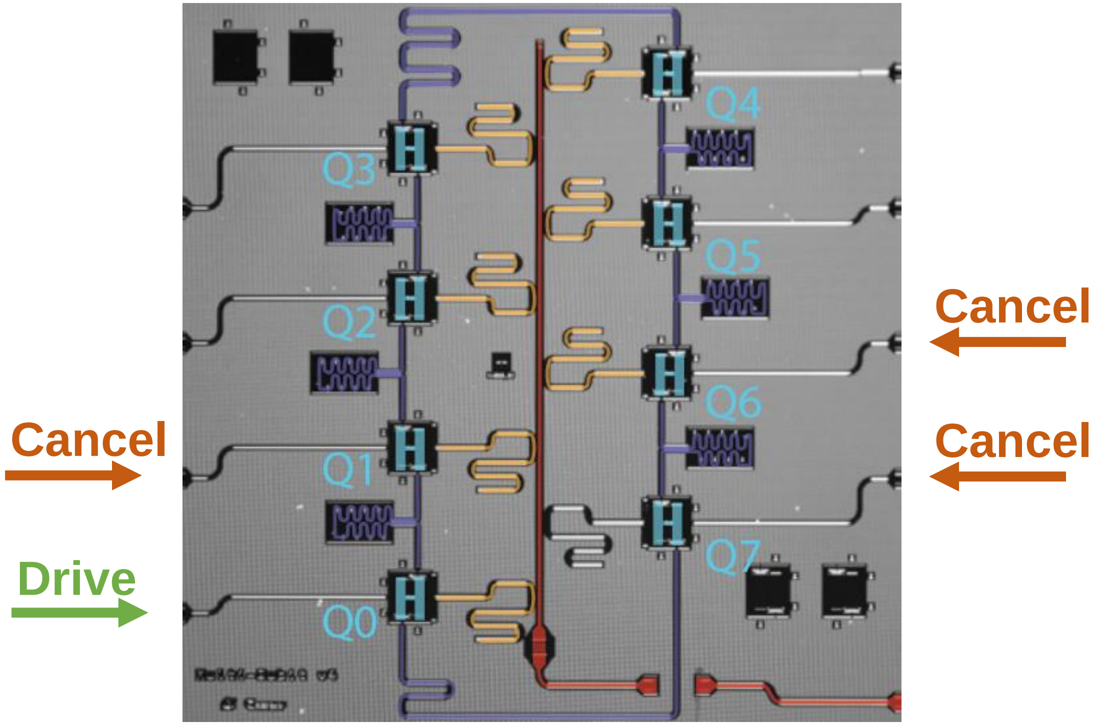
Google

"Quantum supremacy using a programmable superconducting processor" F. Arute, et al., *Nature* **574**, 505-510 (2019)

Ingredients for Ideal QPUs

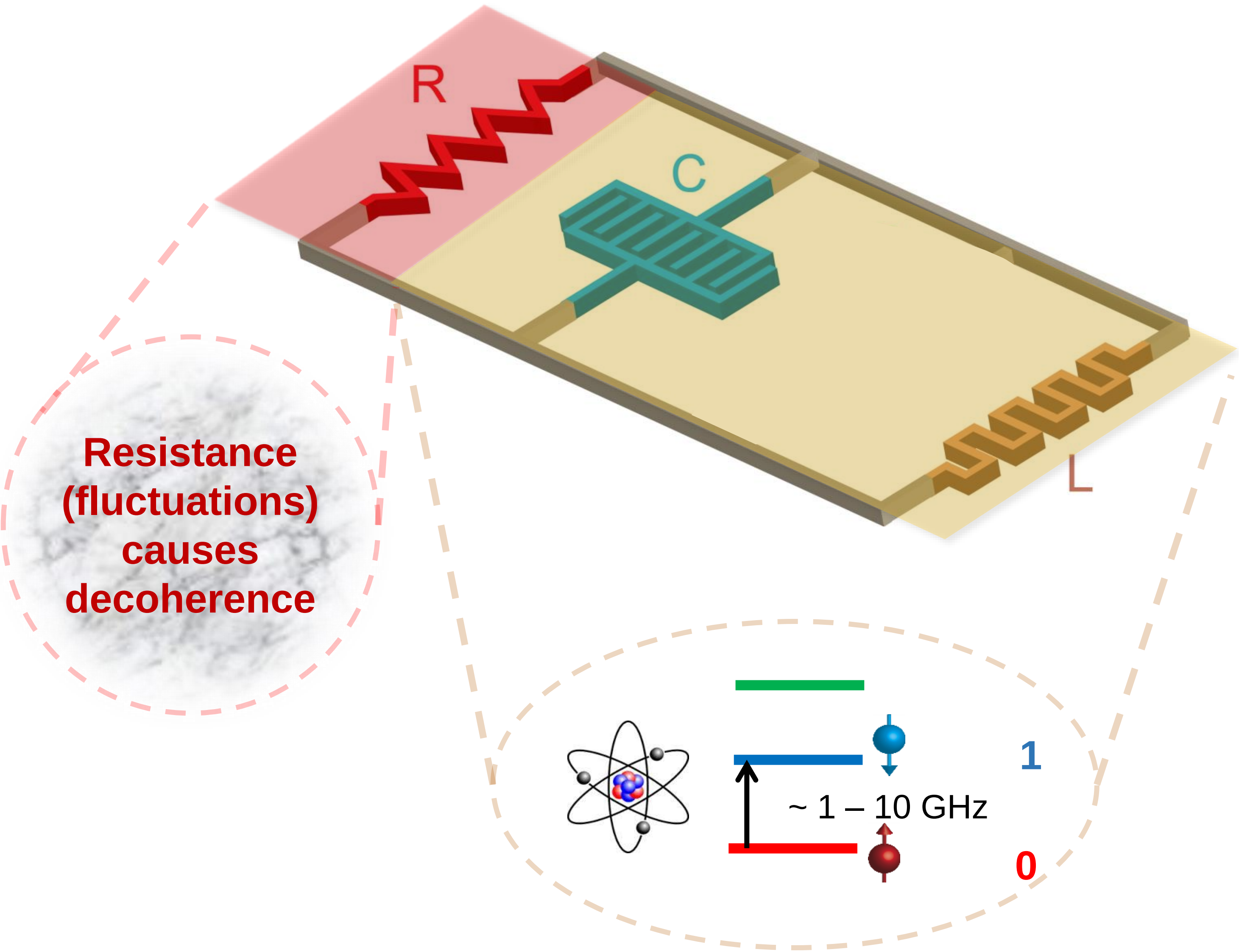
- Eliminate spurious interactions
  - coherence vs control
- Correct for errors
  - physical vs logical qubits
- Perform operations with 100% fidelity
- No sacrifice of quality for quantity
- Cooled to ground state
  - $\overline{n}_1$ = 10^{-12} for 5.6 GHz mode @ 10 mK

Suppression of spurious interactions

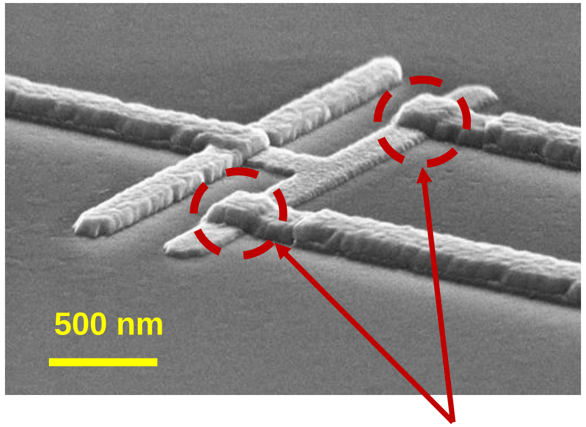


M.S. Blok, V. V. Ramasesh

A Qubit is Just a Nonlinear Oscillator



- Classical harmonic oscillator: all energies (currents) are allowed
- Quantum harmonic oscillator: only certain energies (currents) are allowed
- Tunnel junction → Nonlinear, isolate **0**, **1**



Al/AlOx/Al Josephson tunnel junctions

Introducing Nonlinearity

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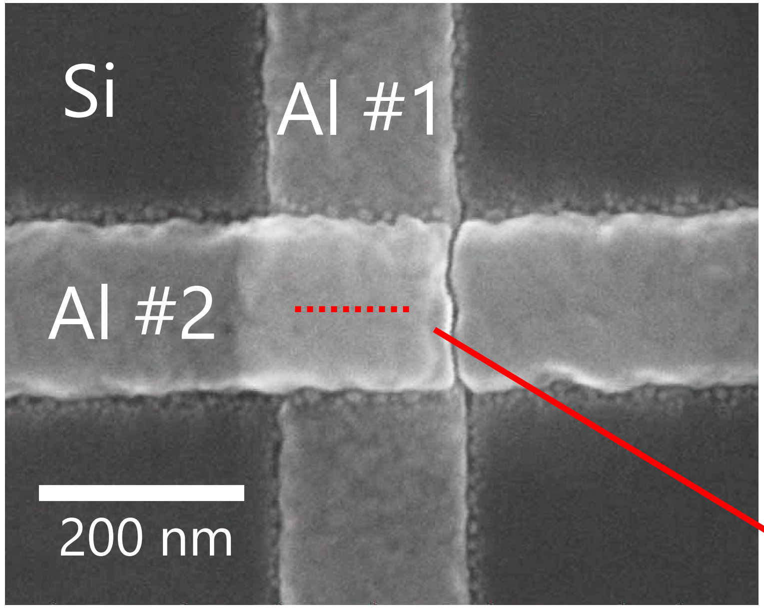
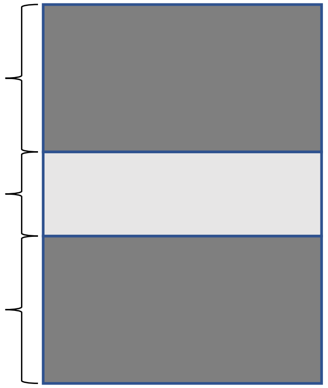
Josephson junctions



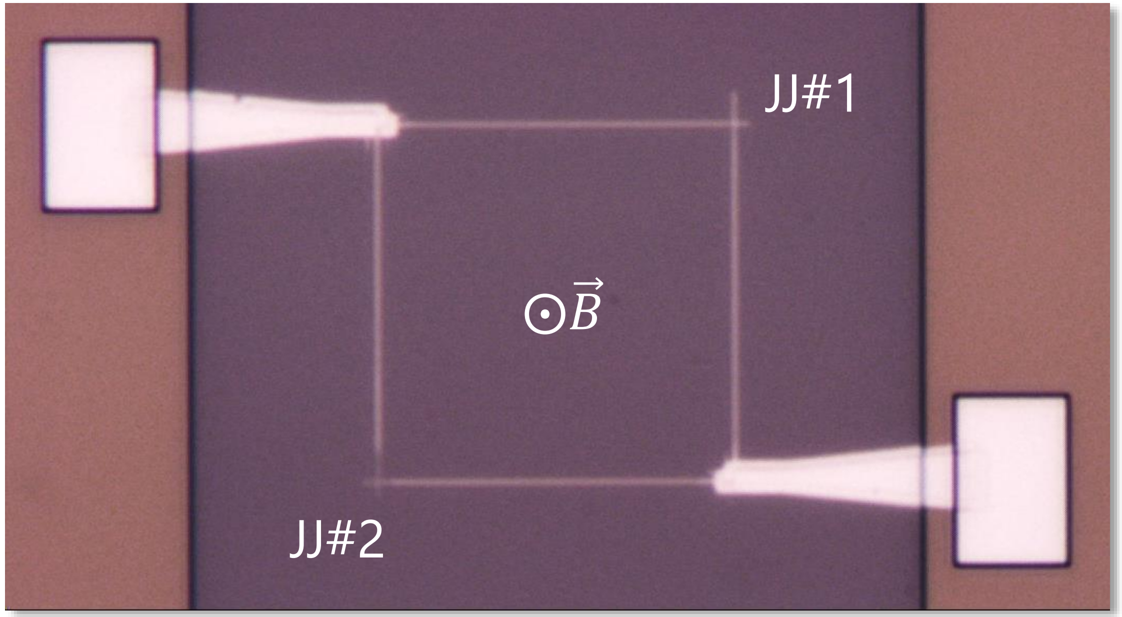
Cross section



Using AC and DC Josephson relations:

$$L_J = \frac{\Phi_0}{I_0 \cos \delta}$$

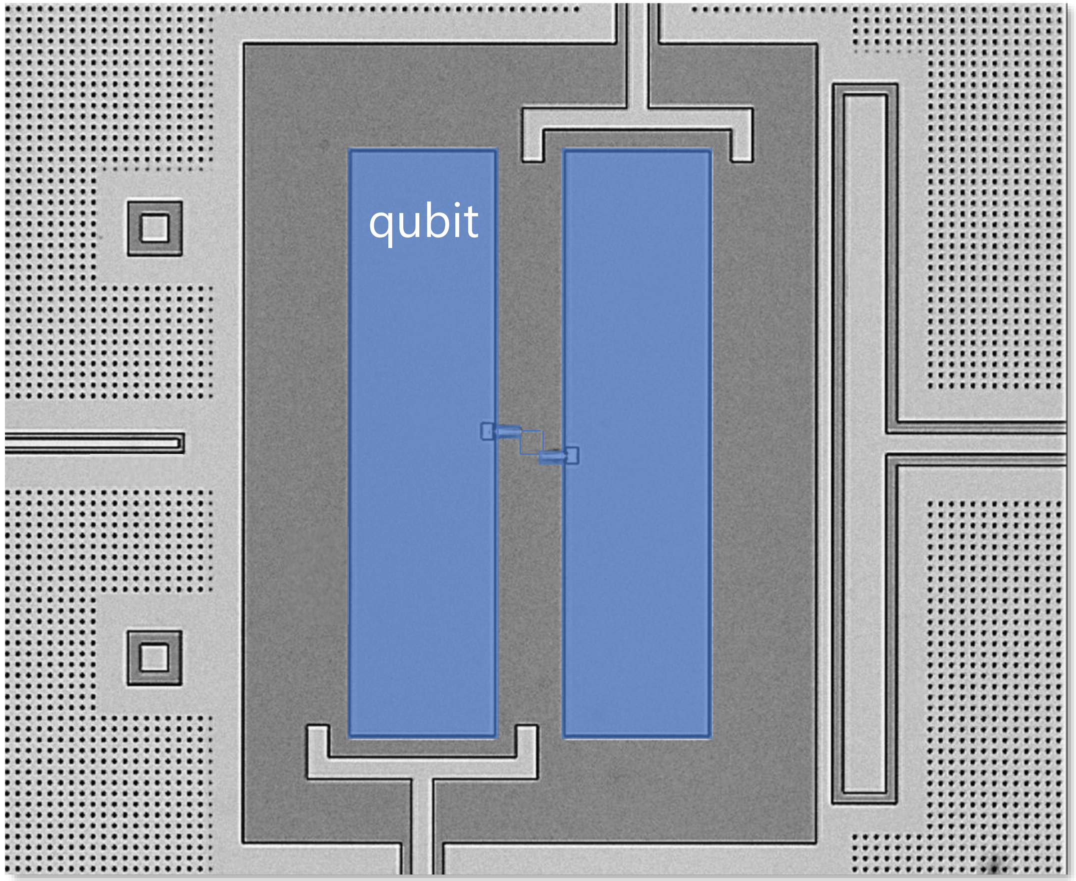
Superconducting Quantum Interference Device (SQUID)



Two JJ's in parallel give tunable inductance

$$L_J = \frac{\Phi_0}{2I_0 \cos\left(\frac{\pi\Phi}{\Phi_0}\right) \cos \delta}$$

Transmons



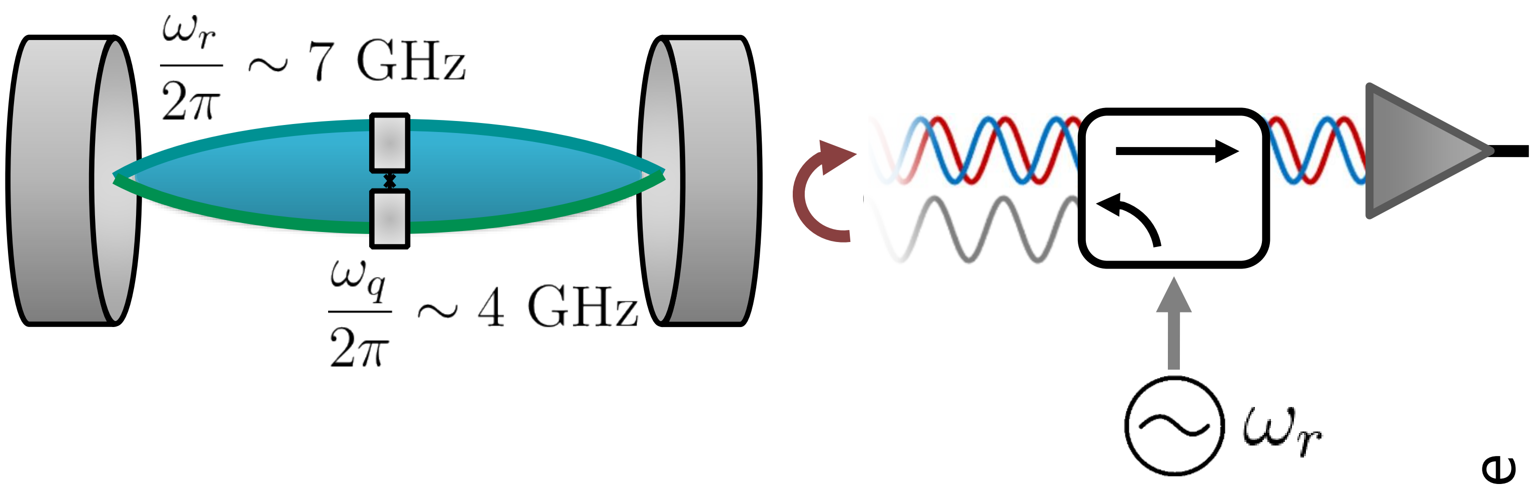
Coupling to neighboring qubits

Capacitively shunted charge qubit

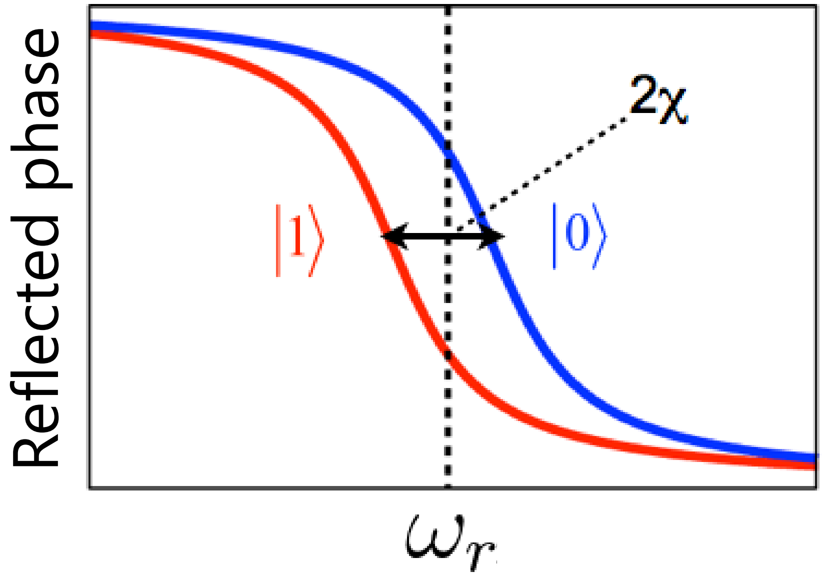
- **Exponentially suppressed sensitivity to charge noise**
- Planar or 3D implementation
- Control/decay can be 1D
- Tunable couplings
- Tunable transition frequencies

$$\omega_{01} \approx \frac{1}{\sqrt{L_J C}}$$

Dispersive Qubit Measurement



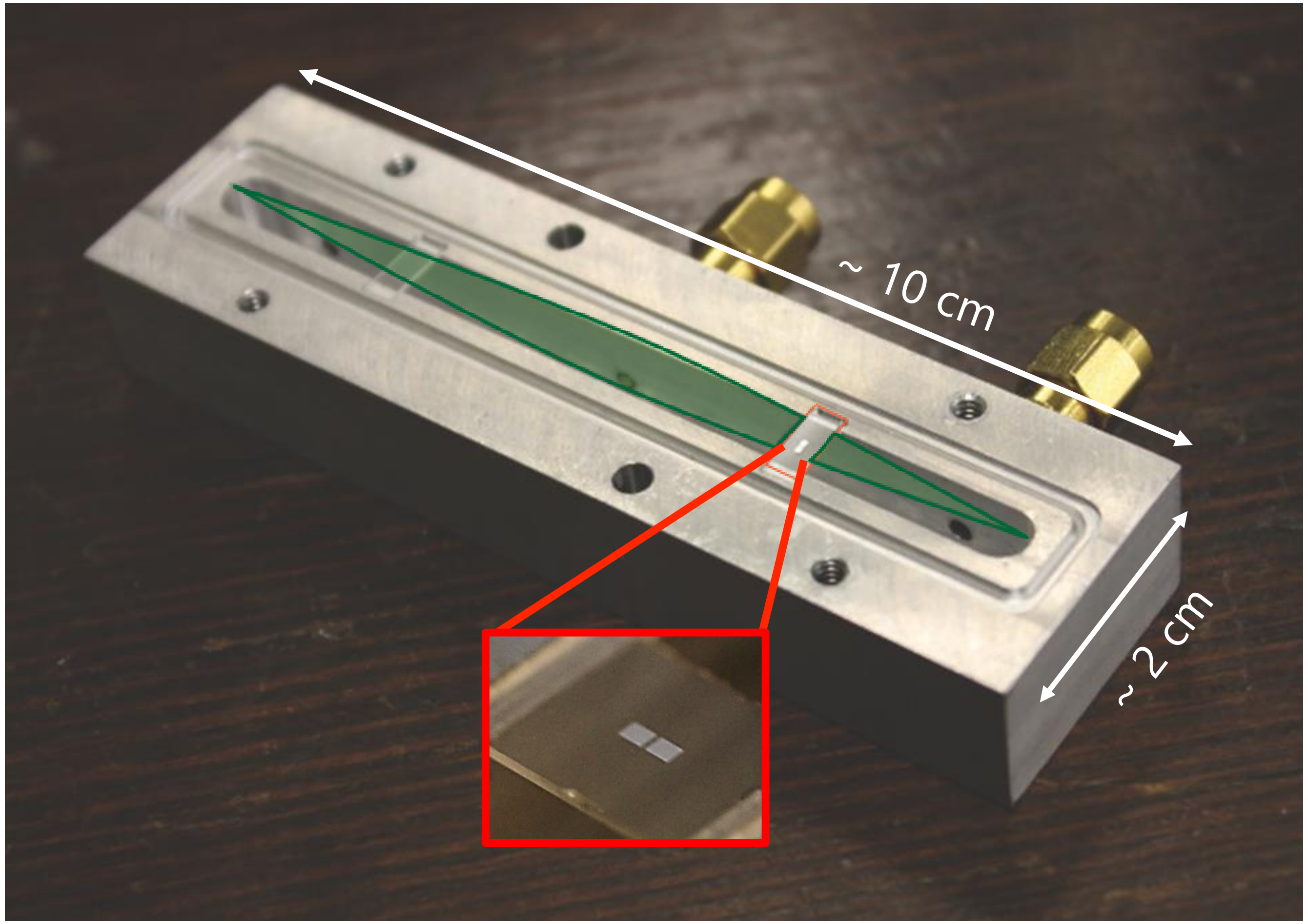
$$H_{disp} = \frac{1}{2}\hbar\omega_q\sigma_z + \hbar\boxed{(\omega_r + \chi\sigma_z)}(a^\dagger a + \frac{1}{2})$$



Qubit-Cavity System

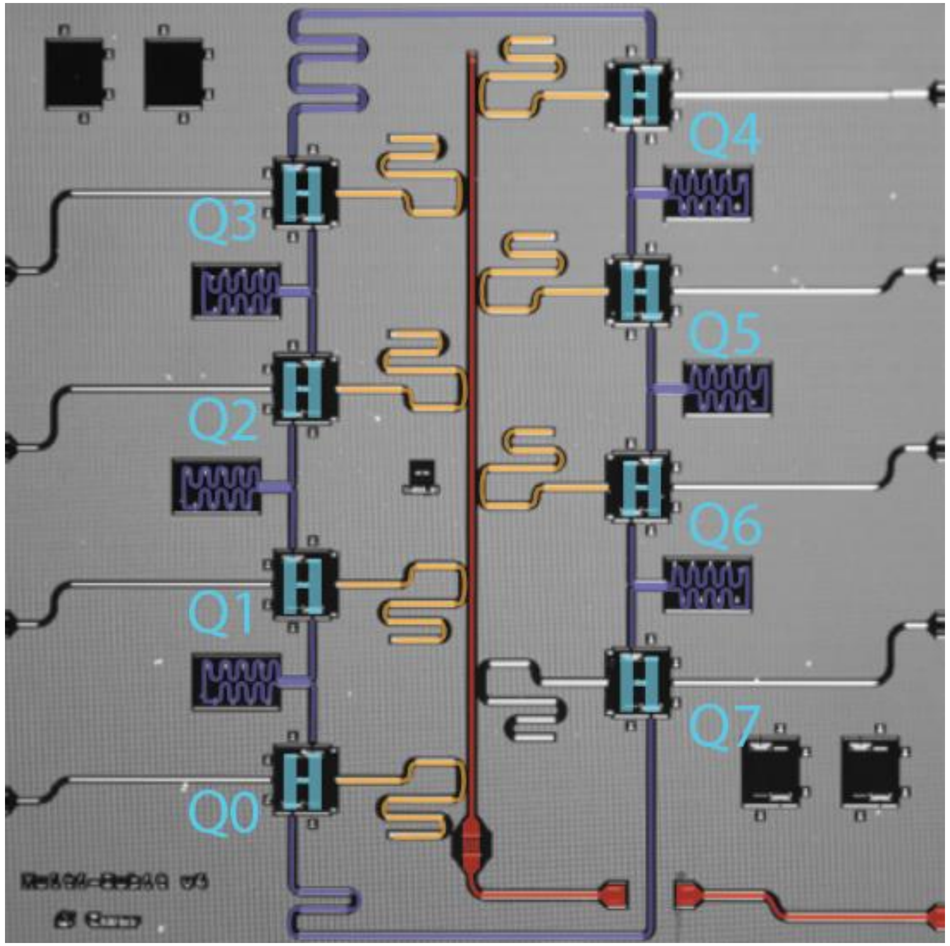
3D architecture

T_1 ~ 30-300 μs



2D architecture

T_1 ~ 30-150 μs



1 x 1 cm

Cooling to the Ground State

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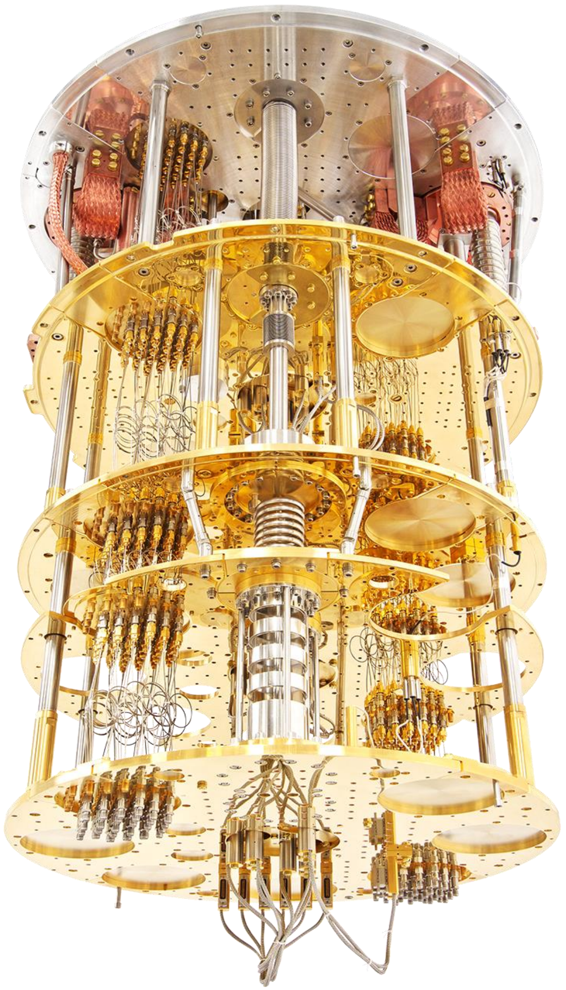
BluFors XLD1000



1m

Commercially available $^{3}\mathrm{He}/^{4}\mathrm{He}$ dilution refrigerator

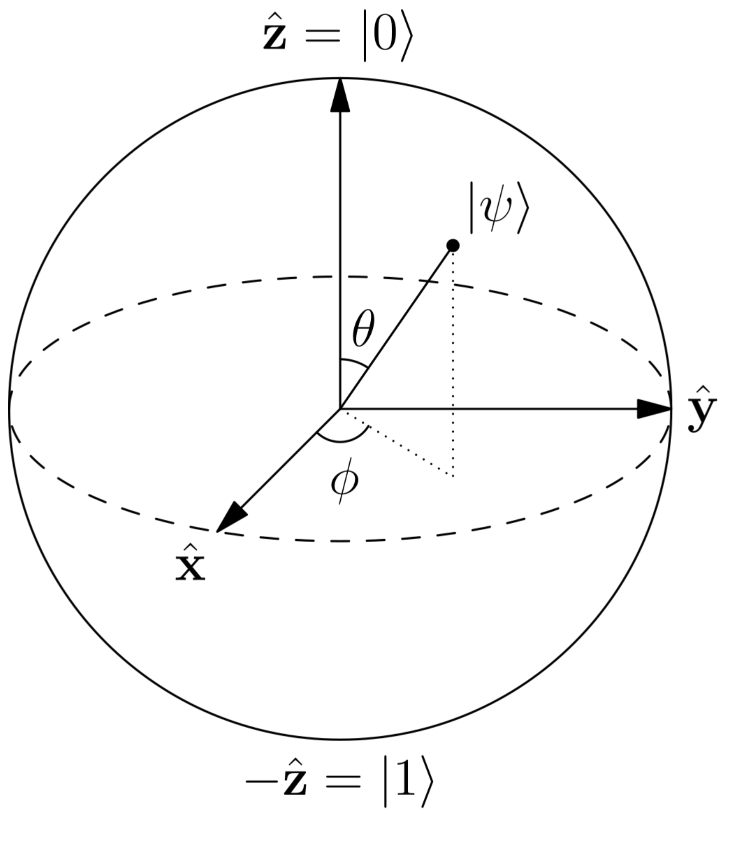
1000 μw cooling power @100 mK

Ability to cool down sample with ~1000 coax

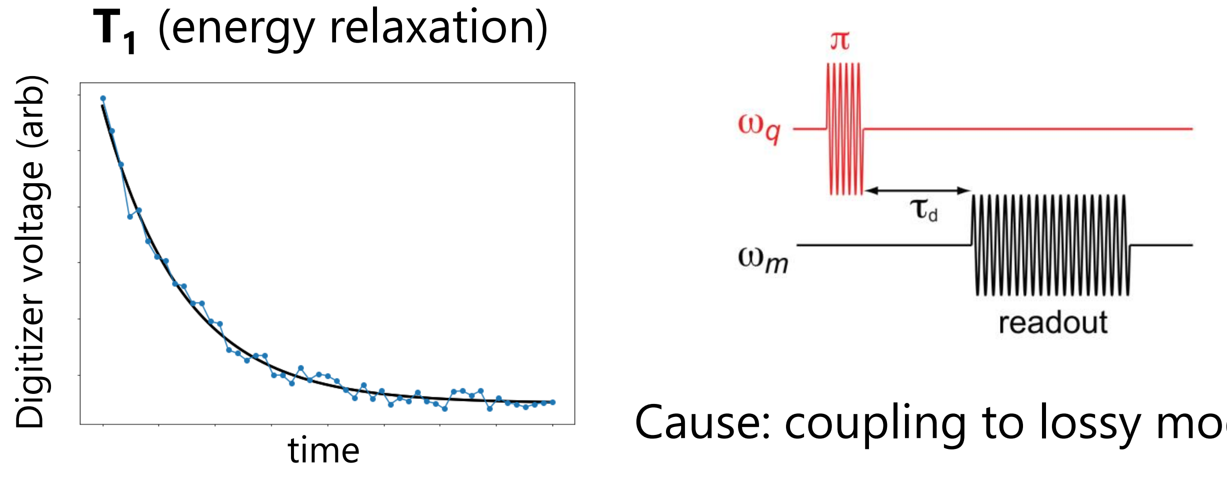
T_{base} = 8 mK

Effective qubit temperature: T_{eff} = 68 mK → P_g = 98%

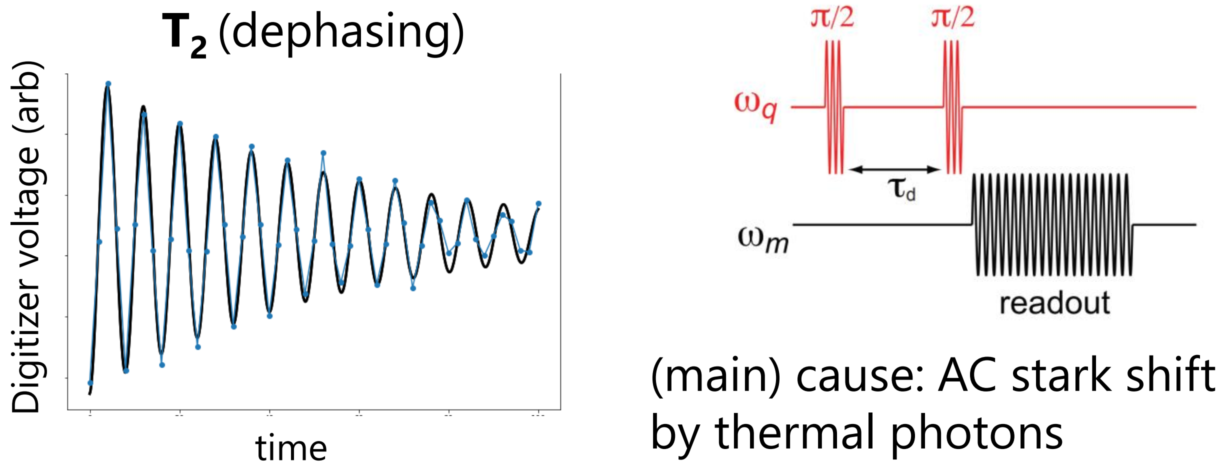
Coherence: T_1, T_2



Bloch sphere representation of qubit



Cause: coupling to lossy modes



(main) cause: AC stark shift by thermal photons

Recall: photons follow Poisson statistics so mean = variance

Wafer-scale Production of SC Devices

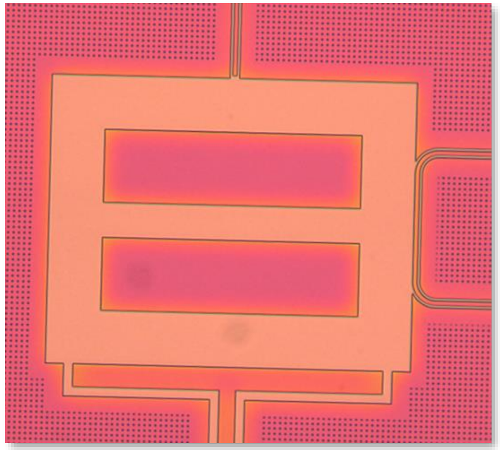
3 days design → device

64 1x1 cm dies

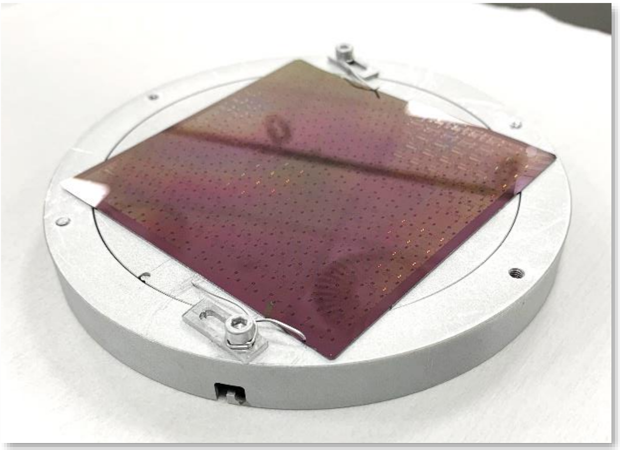
Main challenges:

- Coherence
- Frequency uncertainty

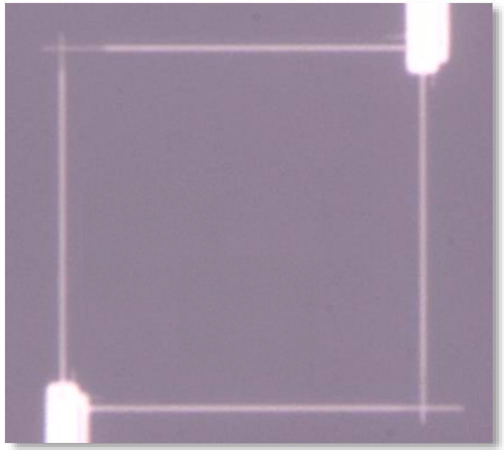
6″ intrinsic Si



Pattern Nb



Add nonlinear elements



Inspect and improve

Dedicated Superconducting Foundry

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Class 100 deposition and analysis lab

Sputter and evaporate: SCs, insulators
Measure, inspect (SEM, AFM), package

Class 10 lithography lab

100 keV e-beam lithography
+/- 0.05 C temperature stability
Chemical bay for resist processing

Materials Improvements

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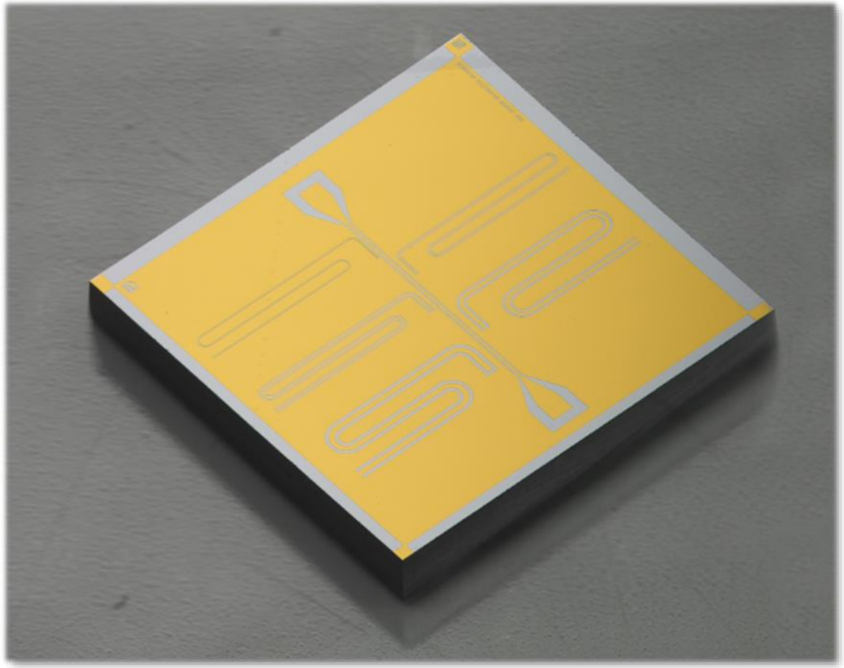
Use CPW resonators as a proxy to identify and rectify sources of loss



Current UCB process:

$$Q_i(\overline{n} = 1) = 3 \times 10^6$$

Four Pronged Attack to Reach Resonator Q ~ 10M

Modeling

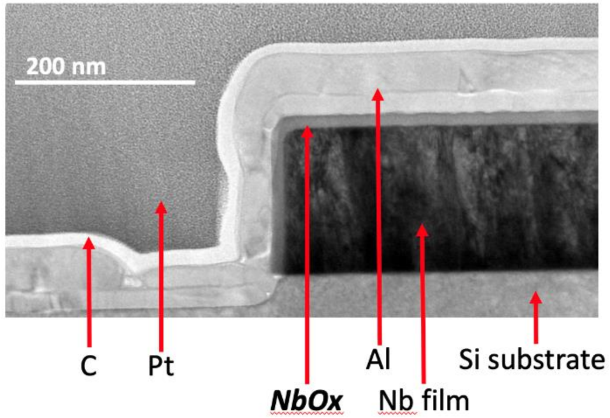
Imaging

Measurements

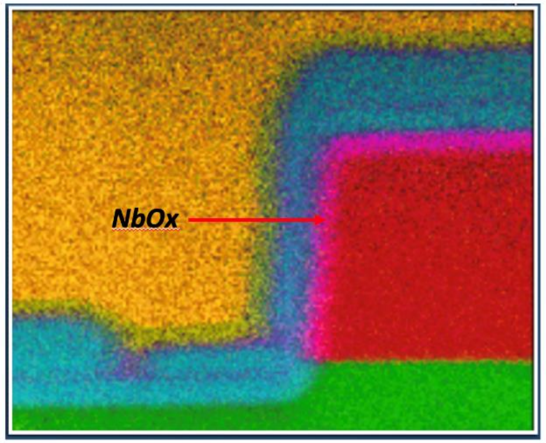
Surface treatments

MOLECULAR FOUNDRY

TEM cross section

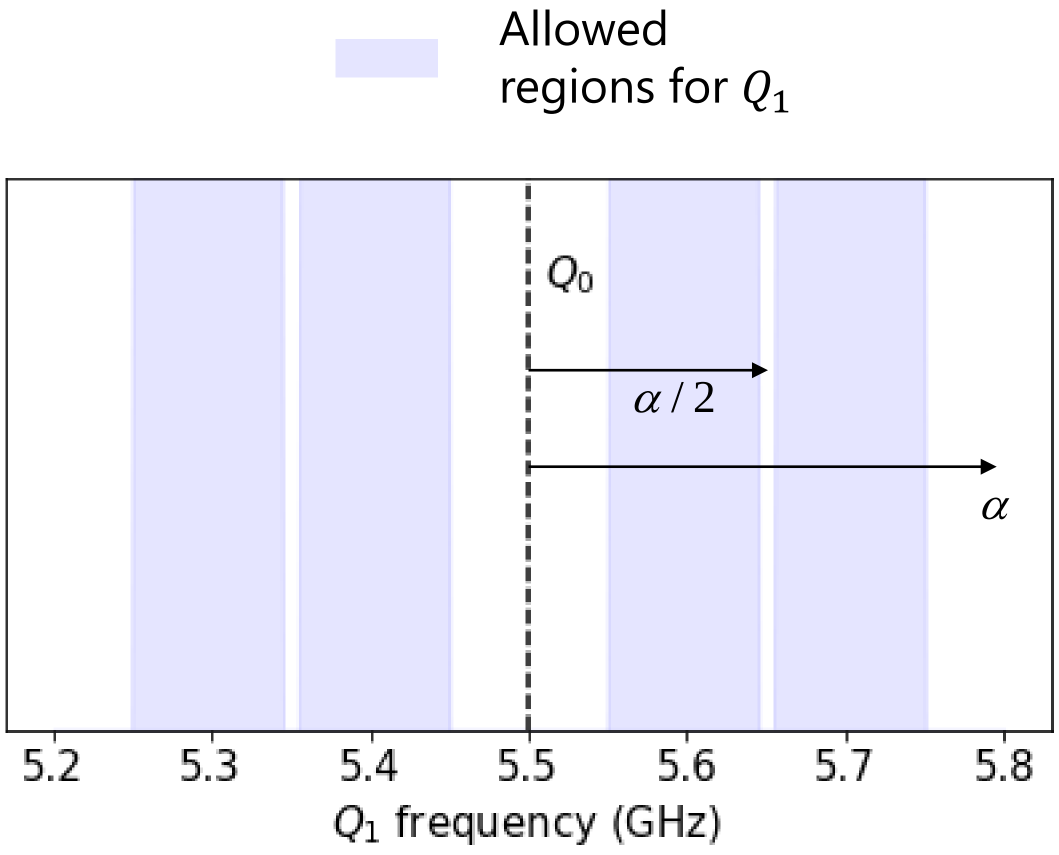


X-ray EDS chemical mapping



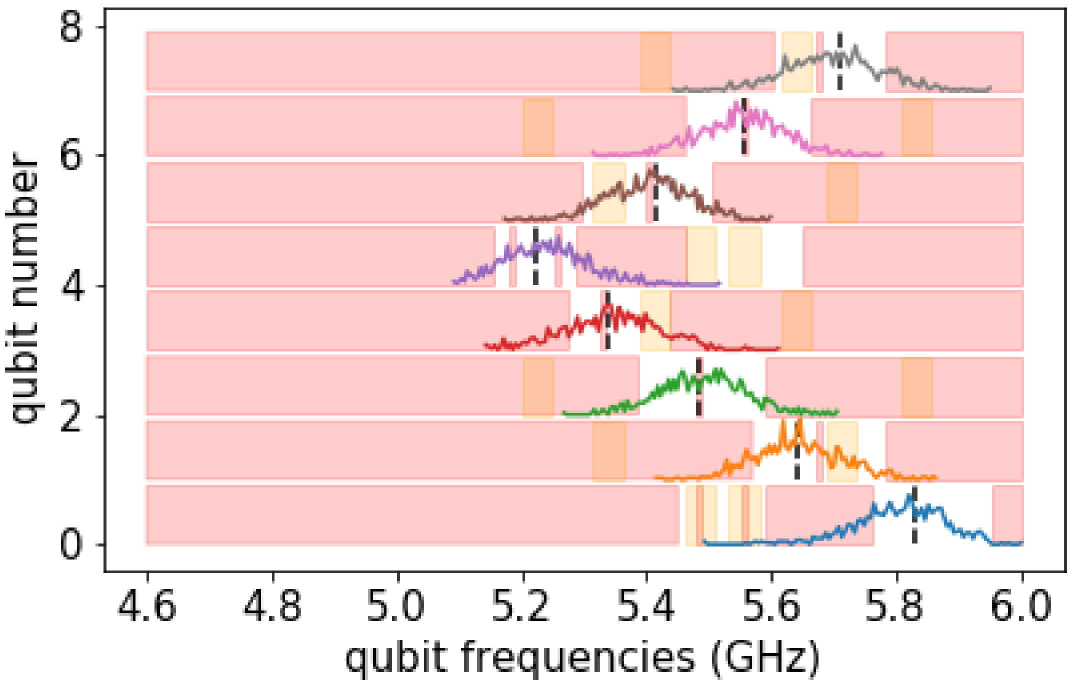
significant oxide present at Nb surfaces.

Qubit Frequency Constraints



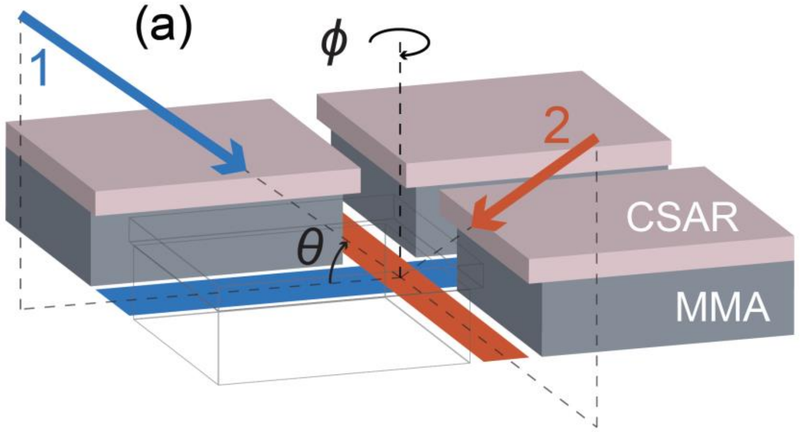
Simulated

σ=100 MHz. yield = 0.9%

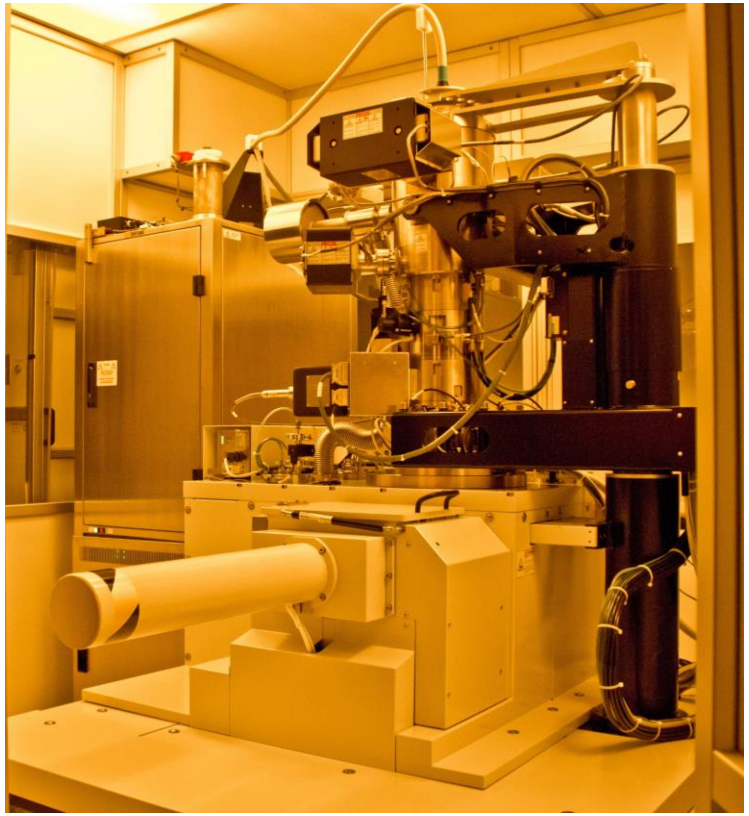


Based in part on work by IBM: J. Hertzberg et al. "Frequency precision in fixed-frequency transmon qubits, and implications for scalable fault-tolerant quantum computing circuits." APS March 2018. http://meetings.aps.org/Meeting/MAR18/Session/A33.3

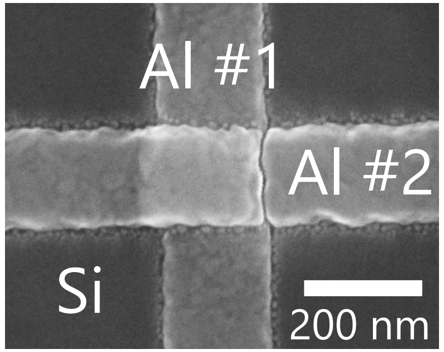
Junction Reproducibility



Junctions defined "Manhattan-style"



Exposed with Raith EBPG 5150



$$\omega_{01} \approx \frac{1}{\sqrt{L_J C}}$$

$$L_J = \frac{\Phi_0}{I_0 \cos\delta}$$

$$I_0 = J_0 * A$$

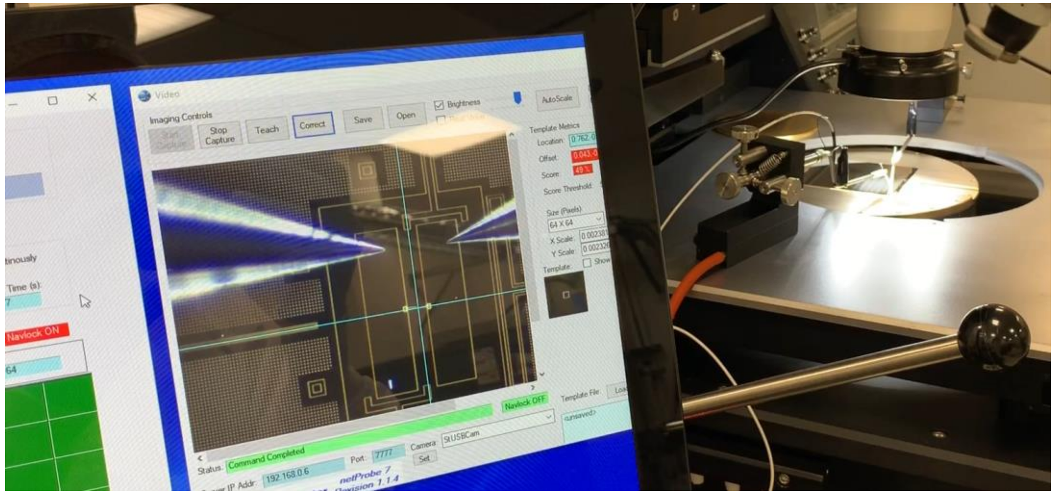
J.M. Kreikebaum, et al., *under review at SUST;* arXiv: 1909.09165

Improving Uniformity

43 wafer systematic study to:

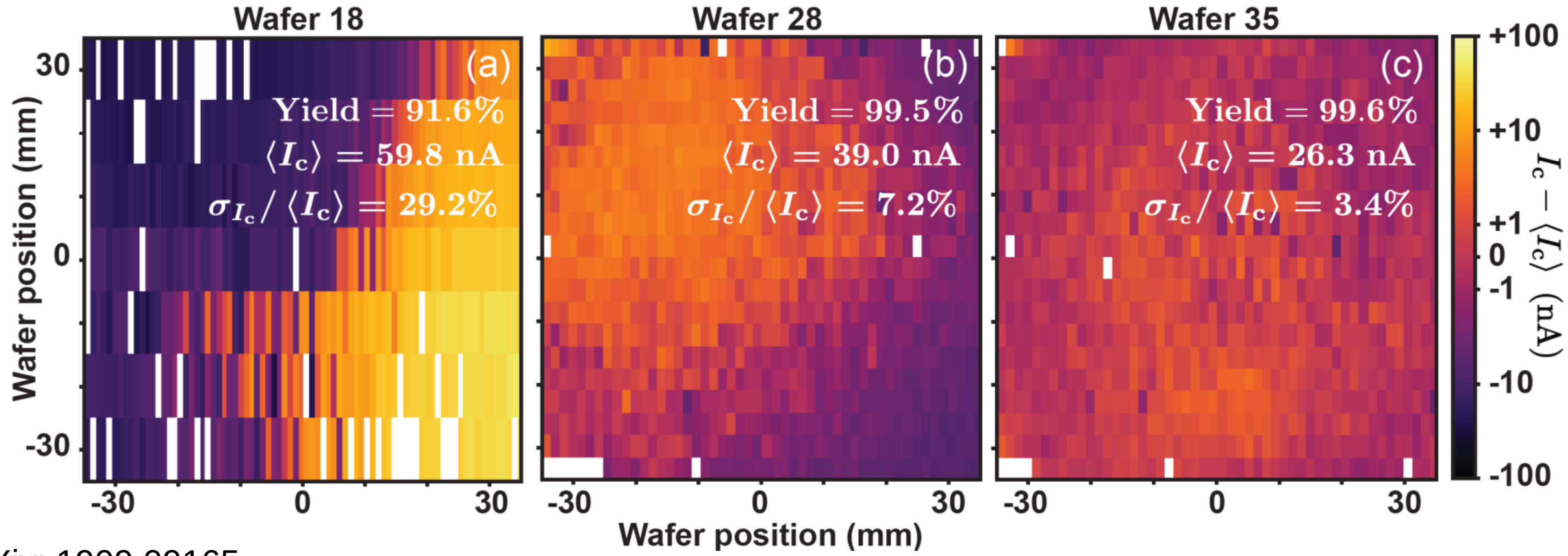
- Mitigate sources of I_c drift across ~50 cm^2
- Improve yield

Automated probing used to acquire statistics on ~100k junctions



Key improvements:

- Ultrasonic development
- O_2 plasma uniformity
- dynamic oxidation
- decreased evaporation rate



J.M. Kreikebaum, et al., *under review at SUST;* arXiv: 1909.09165

Impact on QPU Fabrication

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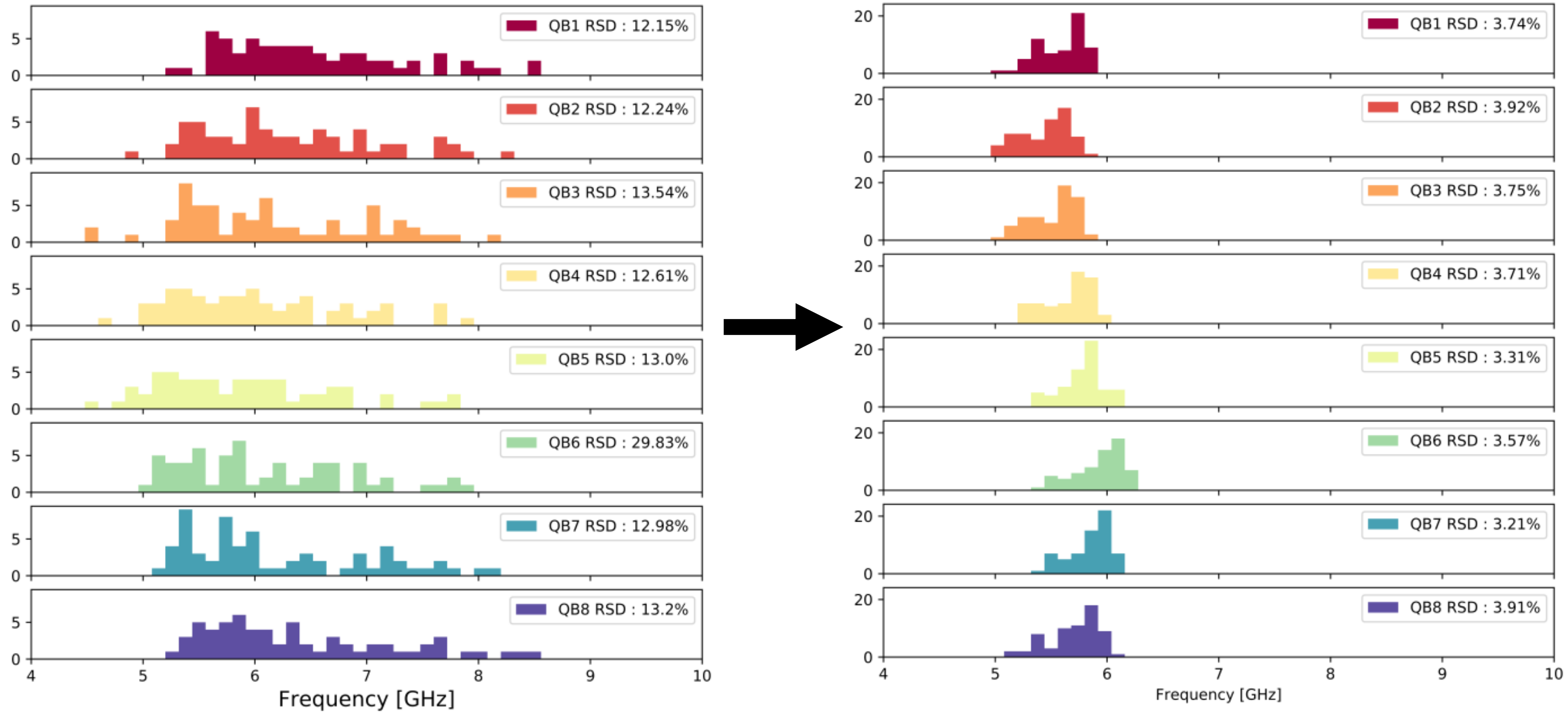
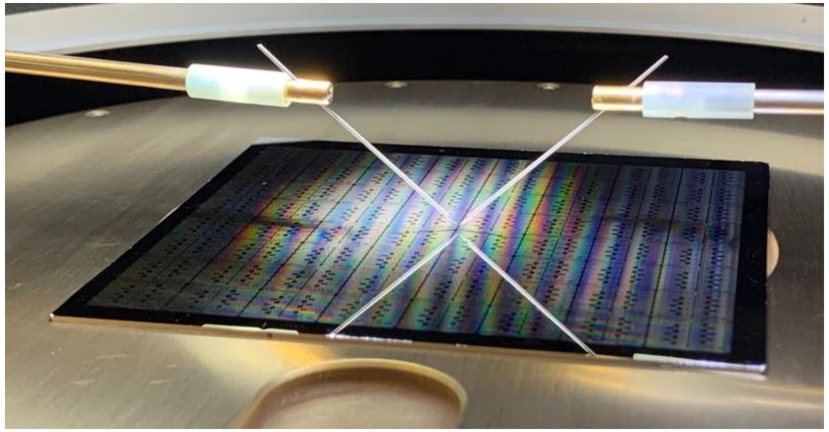
Estimated yield of an 8 qubit chip optimized for the cross resonance gate: **0.5% → 5.4%**





Recent discovery:
Remaining non-uniformity inherent to evaporator geometry (but solvable with radial based biases)

Qubit Coherence

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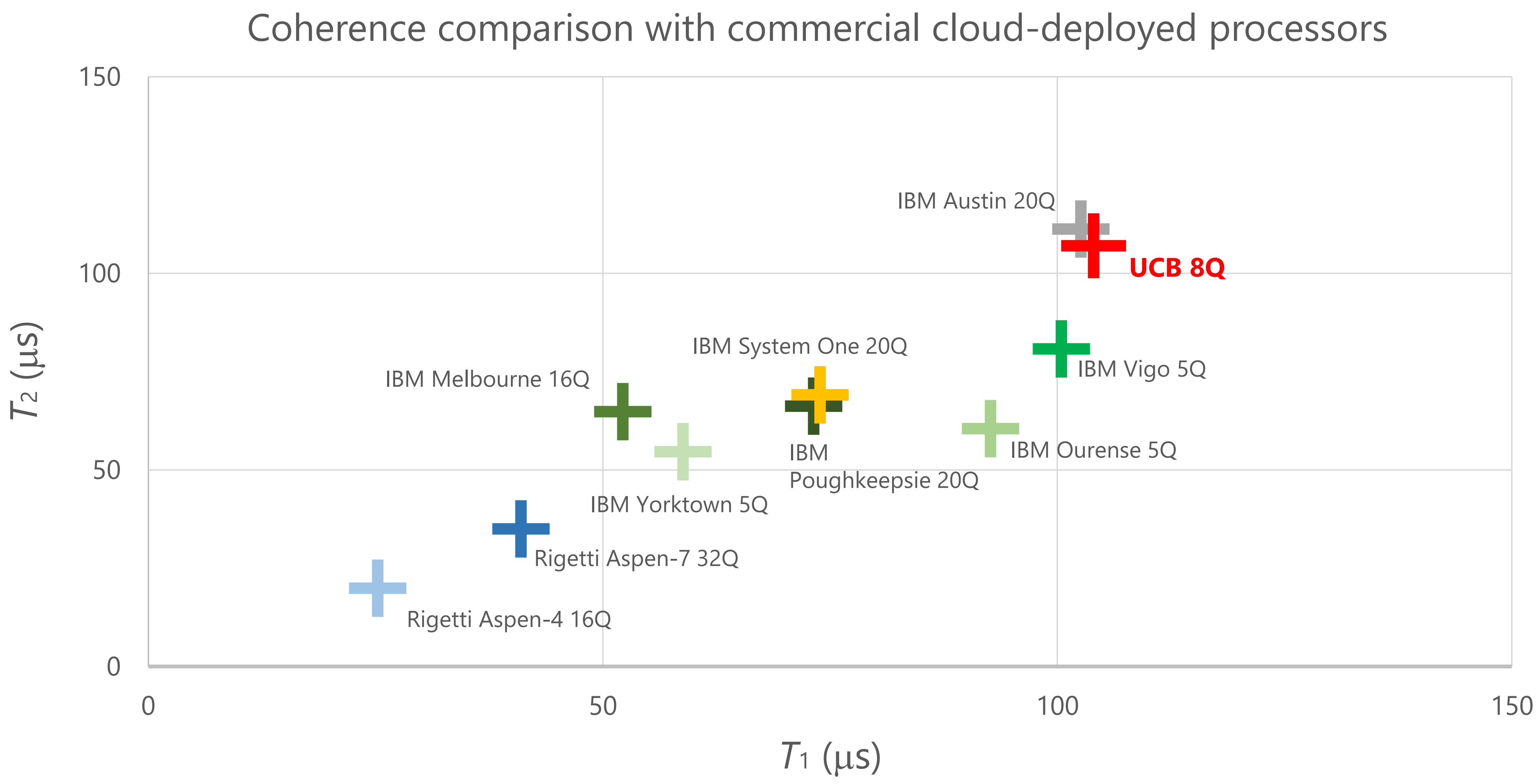

Single Microwave Photon Detection

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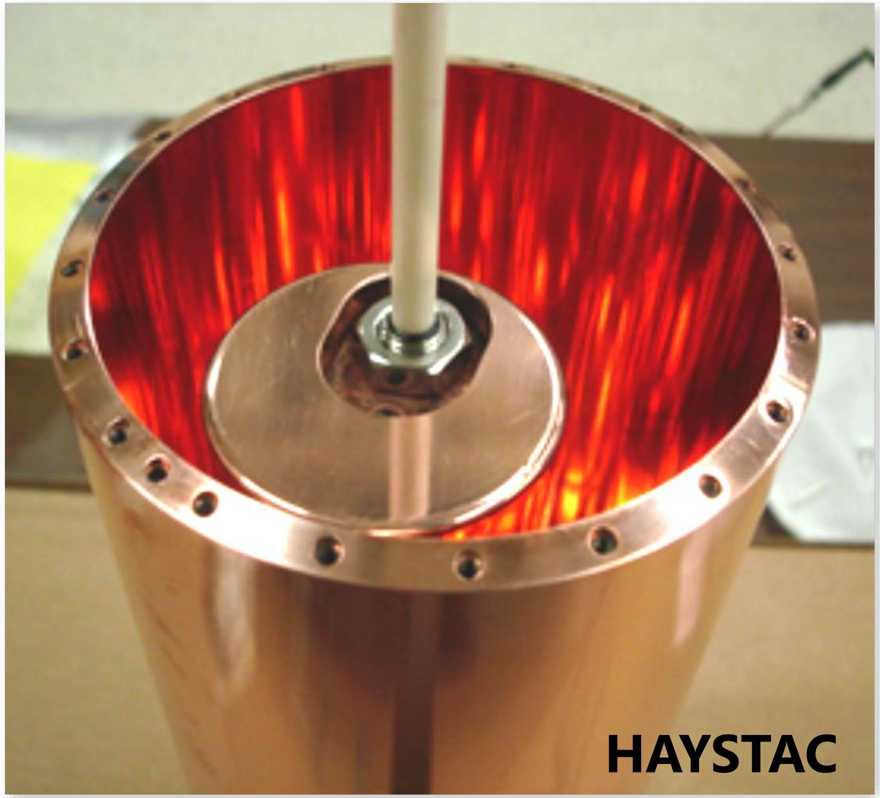
Enrich microwave quantum optics

Astronomical detectors

- **CMB**
- **Axion**[1,2]



Axion scan rates increased by up to **10^4** if JPA (not utilizing a squeezer JPA) is replaced with adequate SPD[3]

[1]Kenany, S., et al., NIMA 854 11-24 (2017)
[2]Caldwell, A. PRL 118, 091801 (2017)
[3]Zheng, H., et al., arXiv: 1607.02529

Single Photon Detection
Microwave vs Optical Photons

- $E = \hbar\omega_{mw}$

$E = \hbar\omega_{opt}$

Circuit Realization

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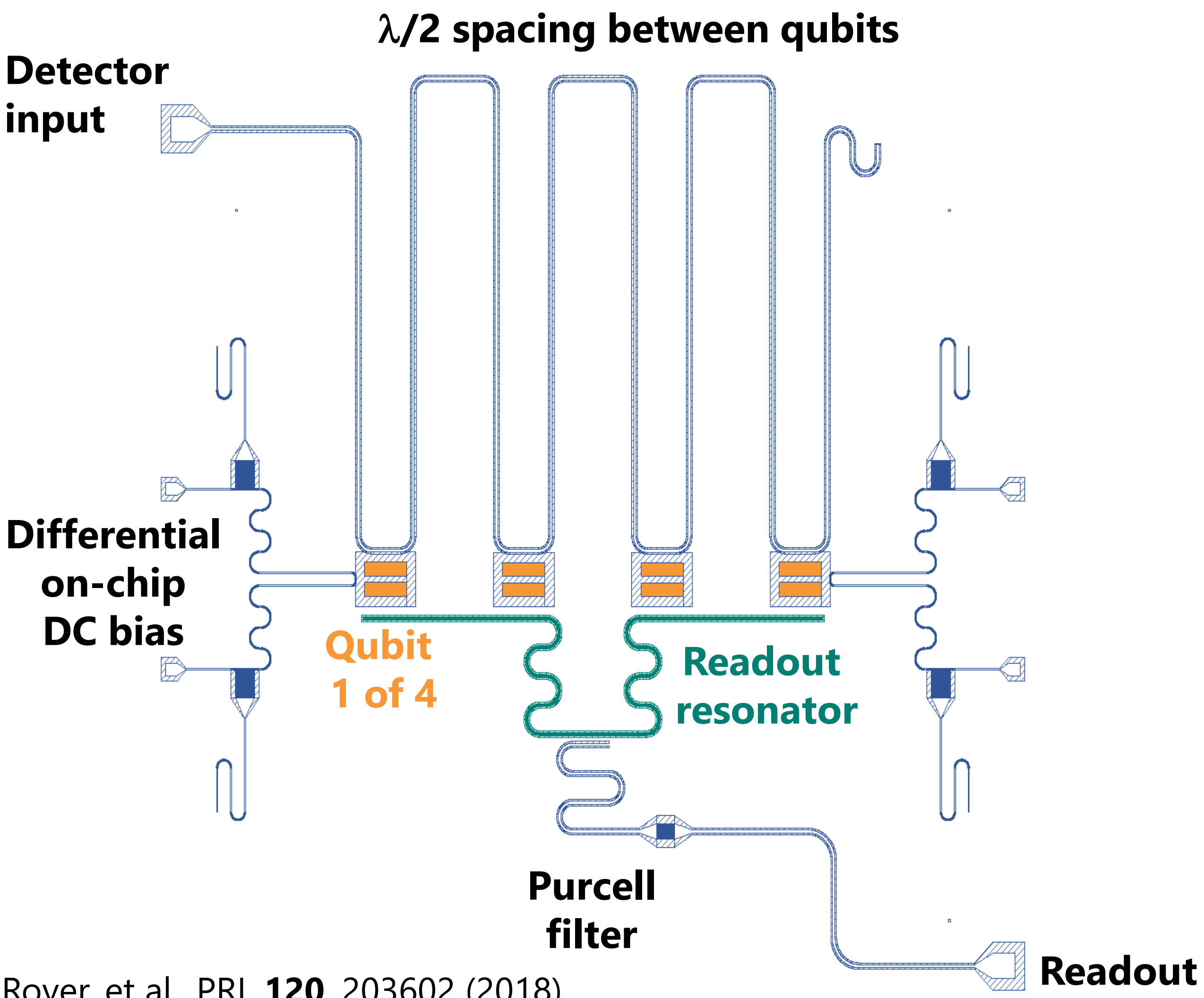
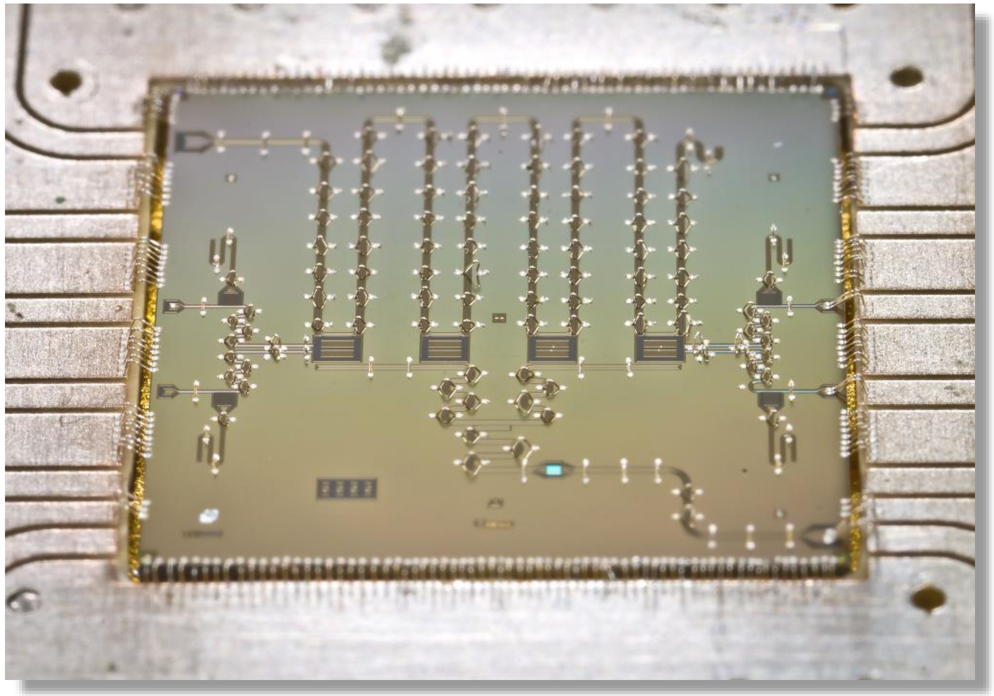
Basic principle: trap photons using waveguide QED in a mode for longer than the inverse of the absorber's linewidth

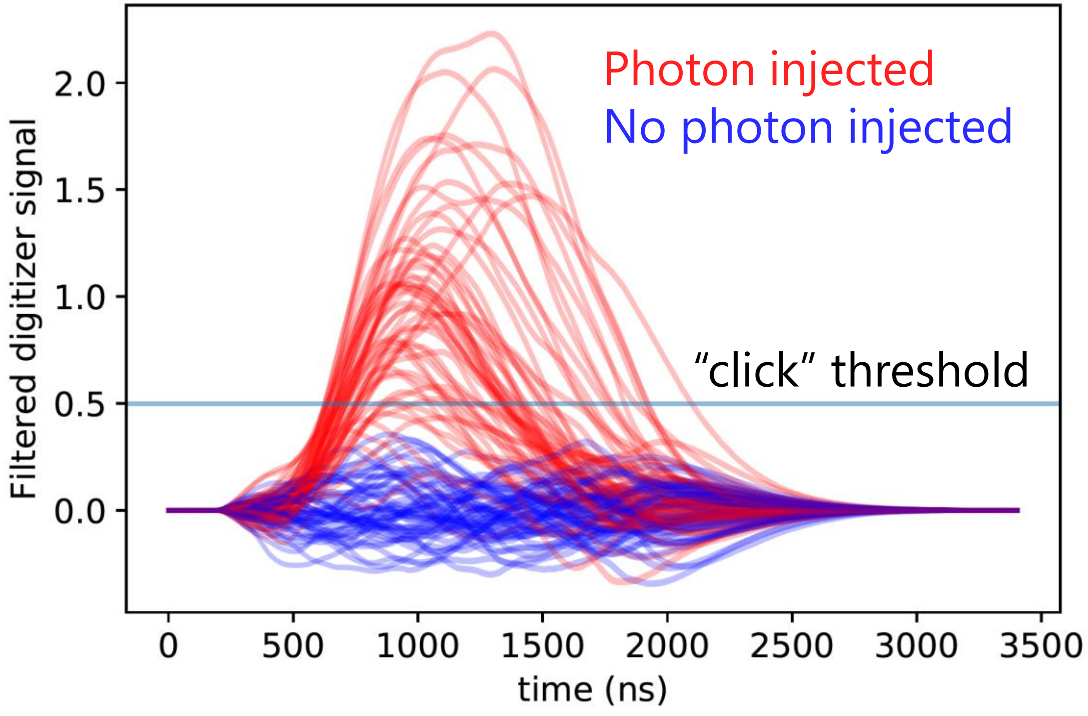


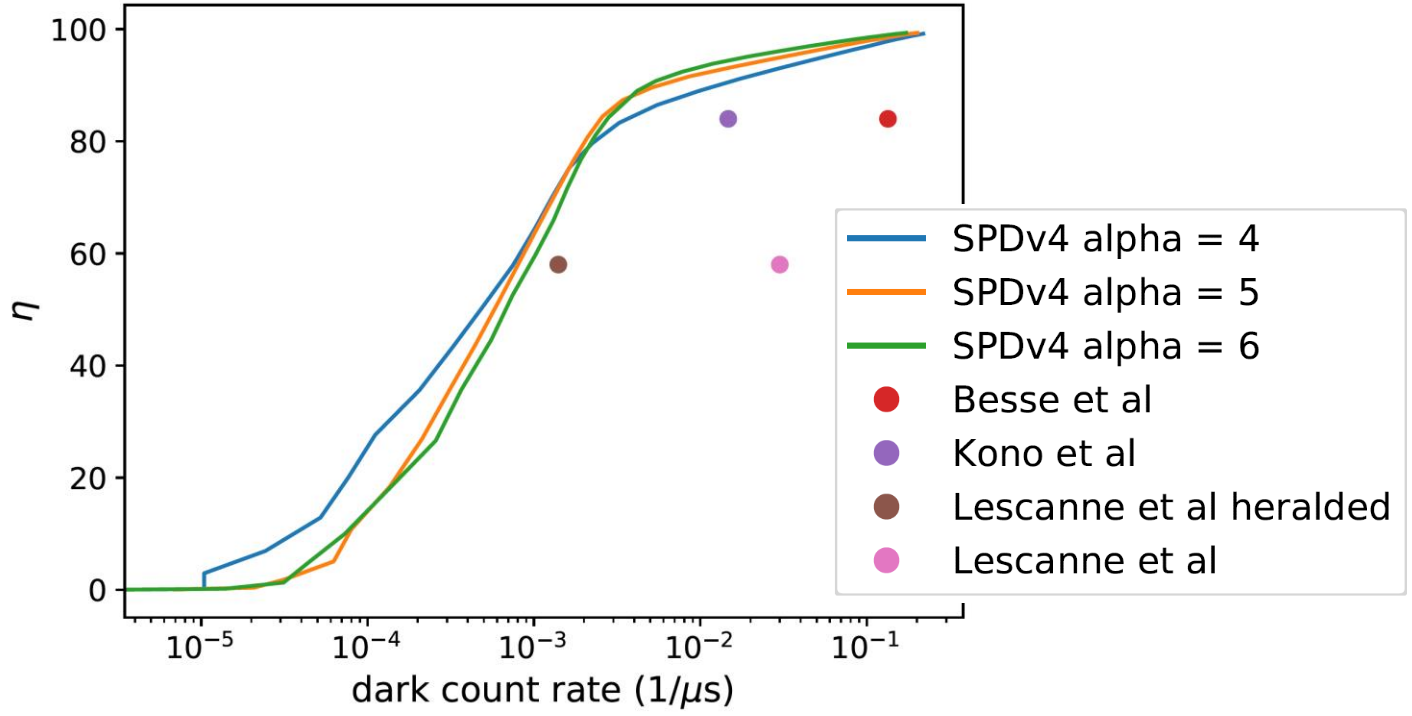


Thy: B. Royer, et al., PRL **120**, 203602 (2018)

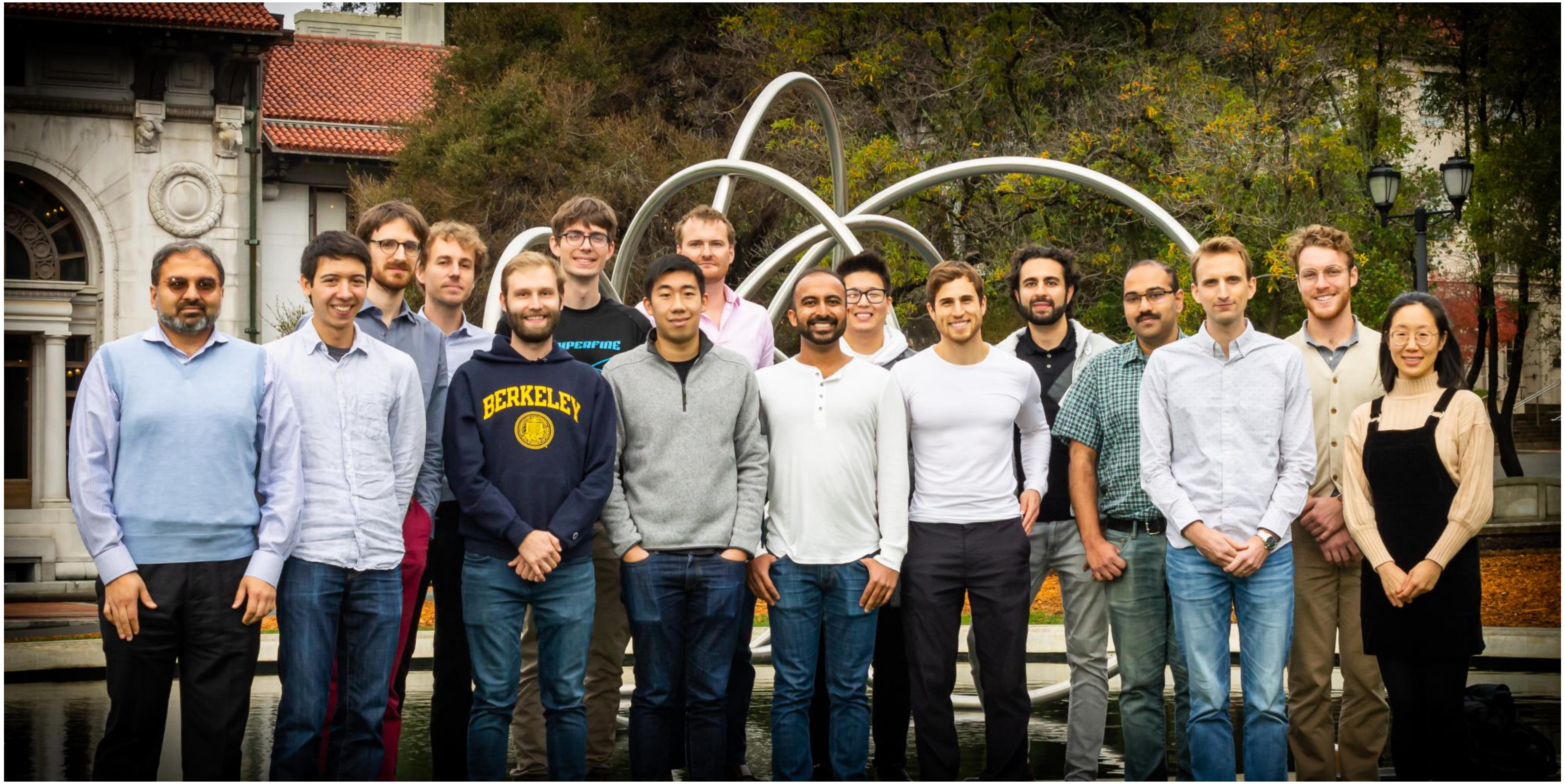
Detector Performance

Initial experimental results with a weak coherent tone source





The Team



QNL group photo 2020

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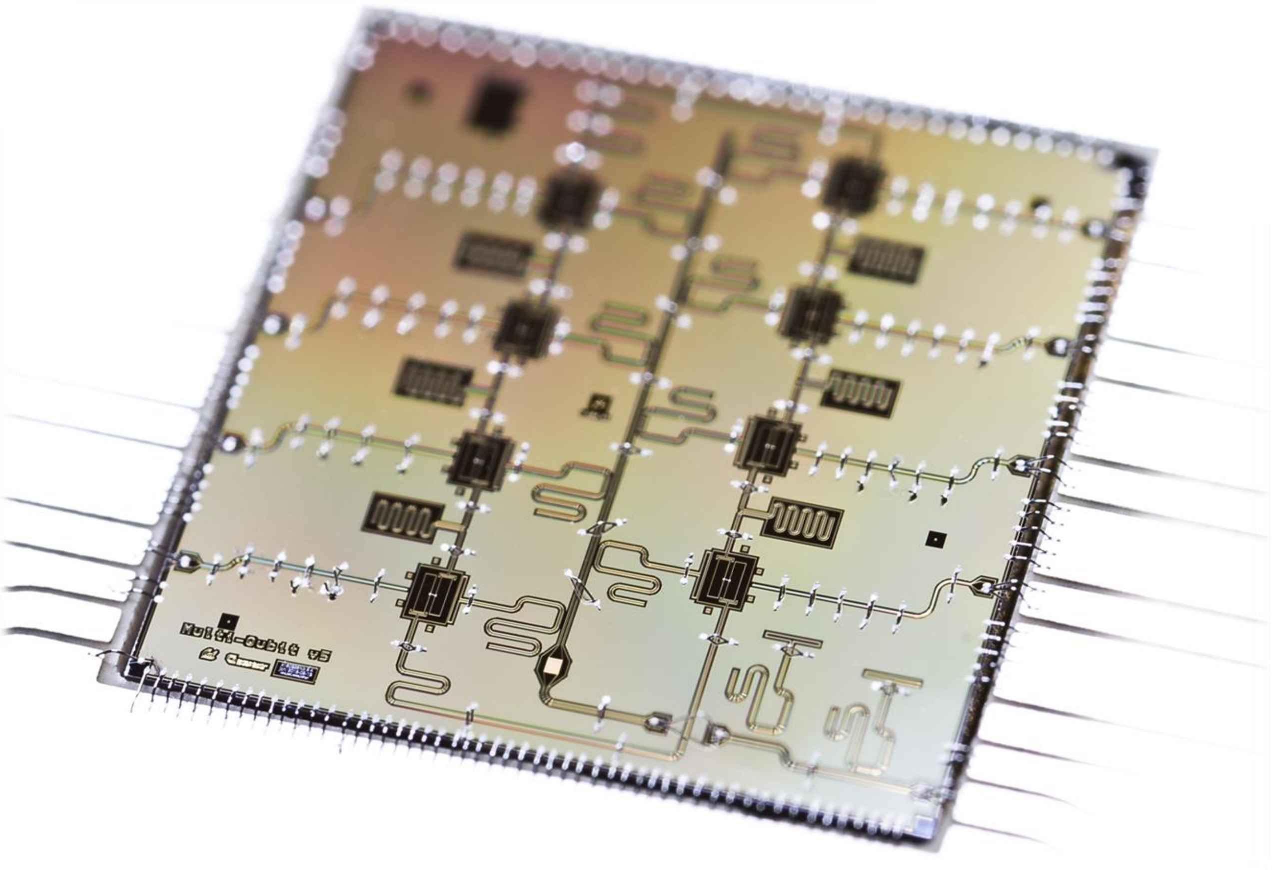
Superconducting circuits are a promising platform for universal quantum computation (and other sensors!)

But many engineering challenges remain to be solved!



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