Detecting Axion Dark Matter with Superconducting Qubits

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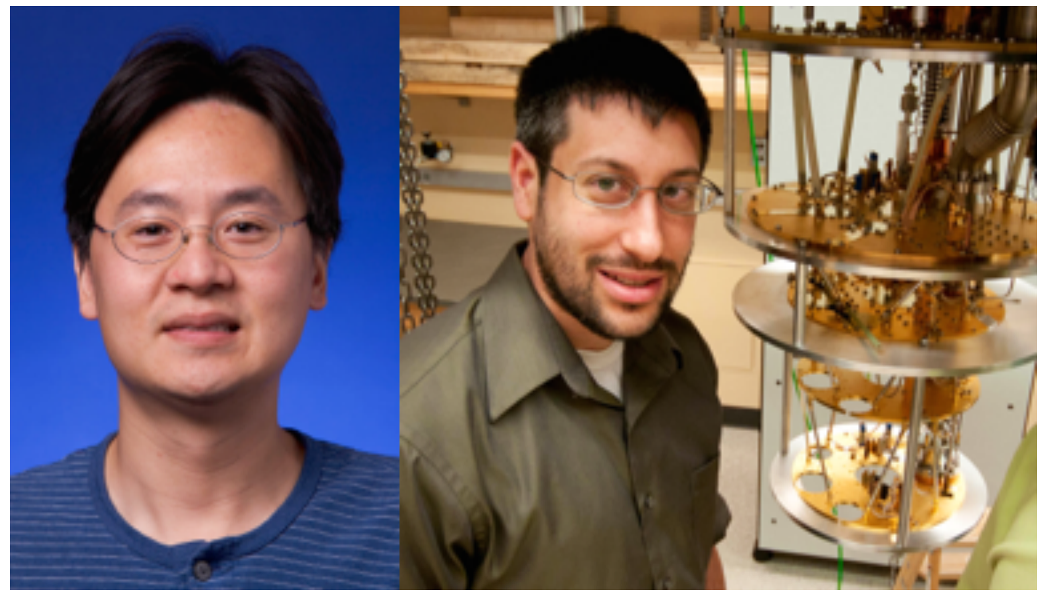
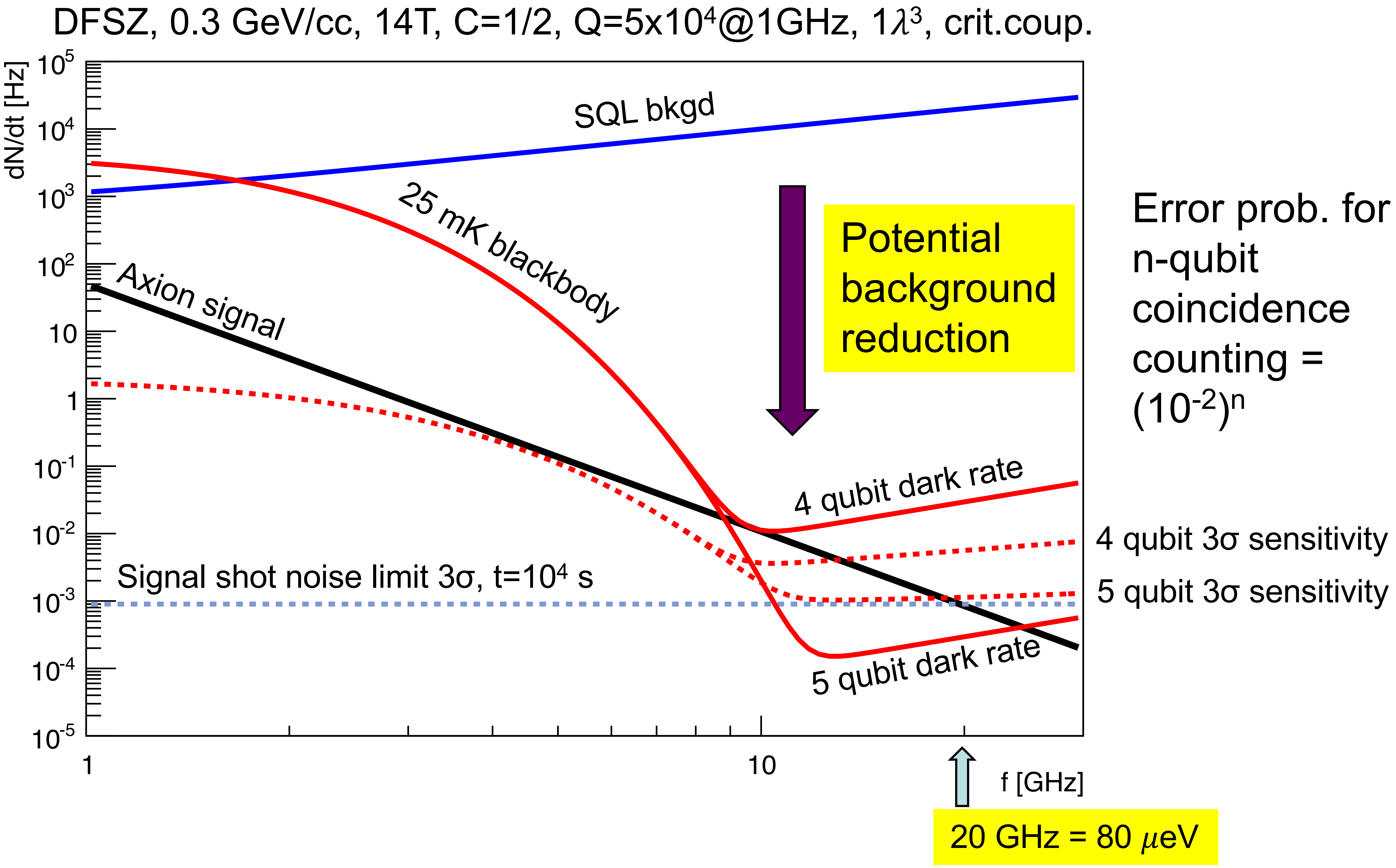


Outline of Talk

- Moving from phase preserving measurement to photon counting
- Designing a single photon counter
- Experimental protocol to determine cavity photon occupation
- Overcoming background sources and dark rates in new detection scheme

Photon Rates of Signal and Backgrounds

- Signal Rate decreases with cavity volume. <<1 photon per cavity measurement
- Quantum limited noise from linear amplifier = 1 photon/ measurement

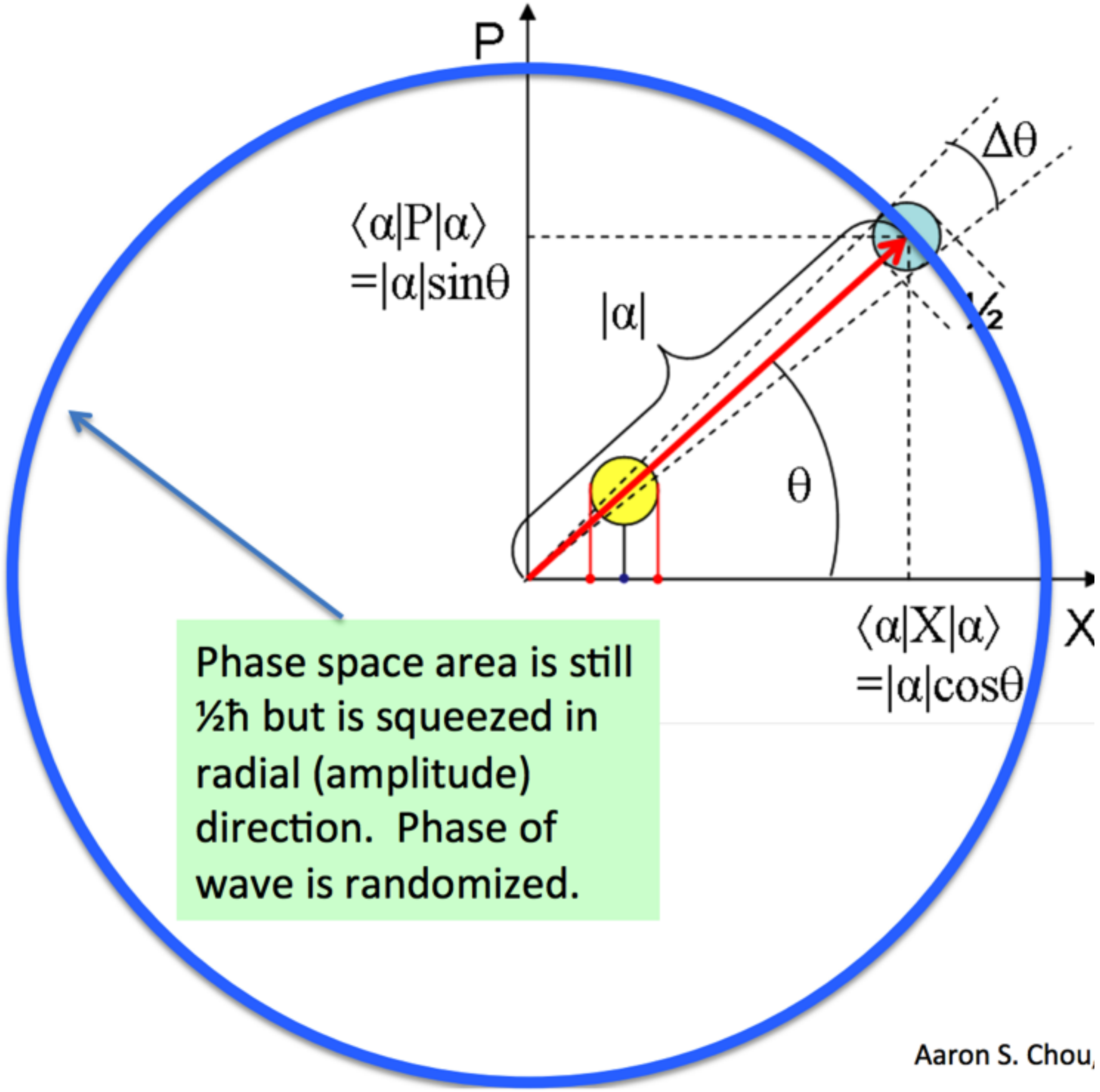


Error prob. for n-qubit coincidence counting = $(10^{-2})^n$

How to Bridge the Gap between Signal and Background

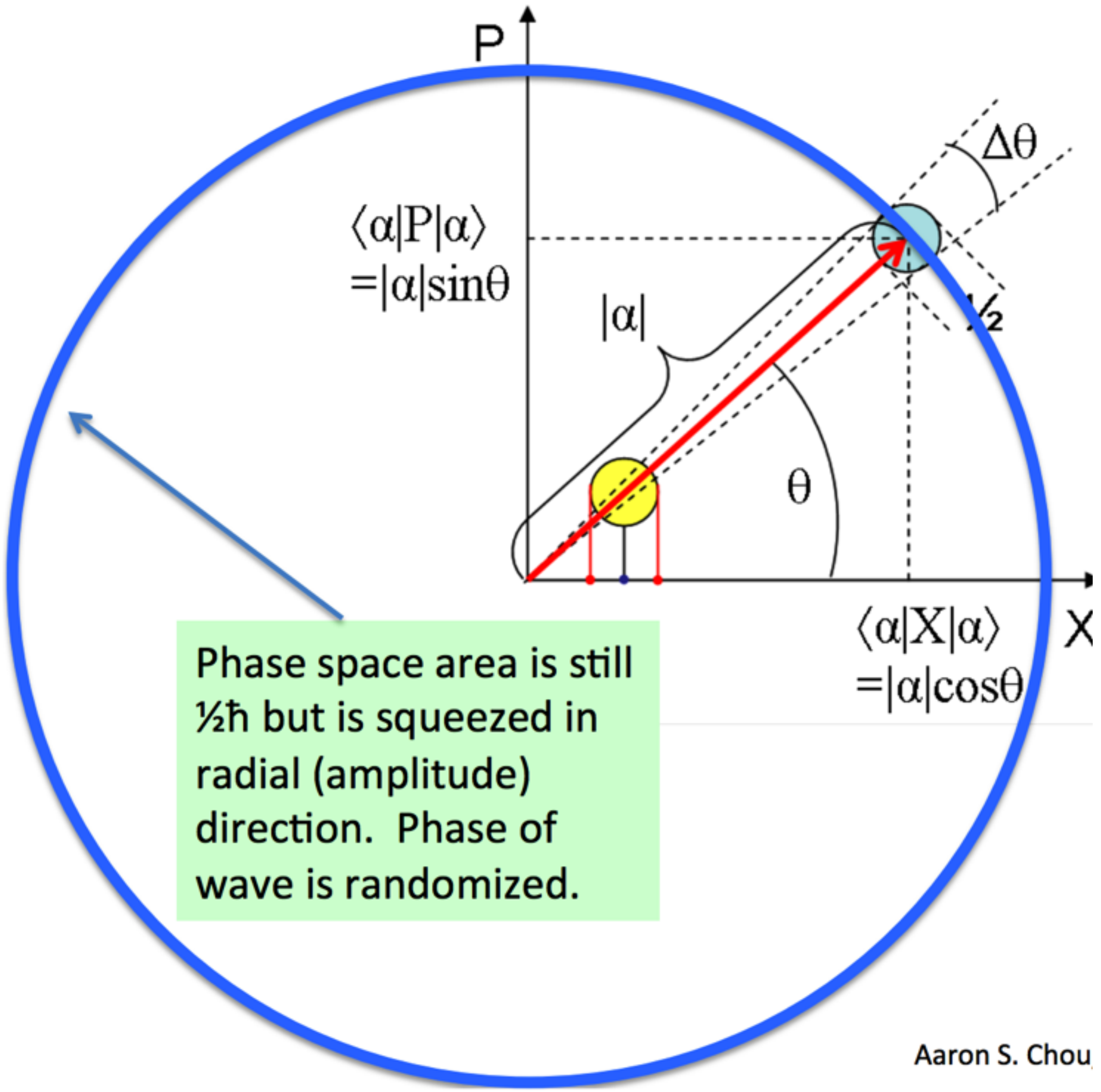
- Signal Rate decreases with cavity volume. <<1 photon per cavity measurement

- **Quantum limited noise from linear amplifier = 1 photon/measurement**



Advantages and Challenges of Counting

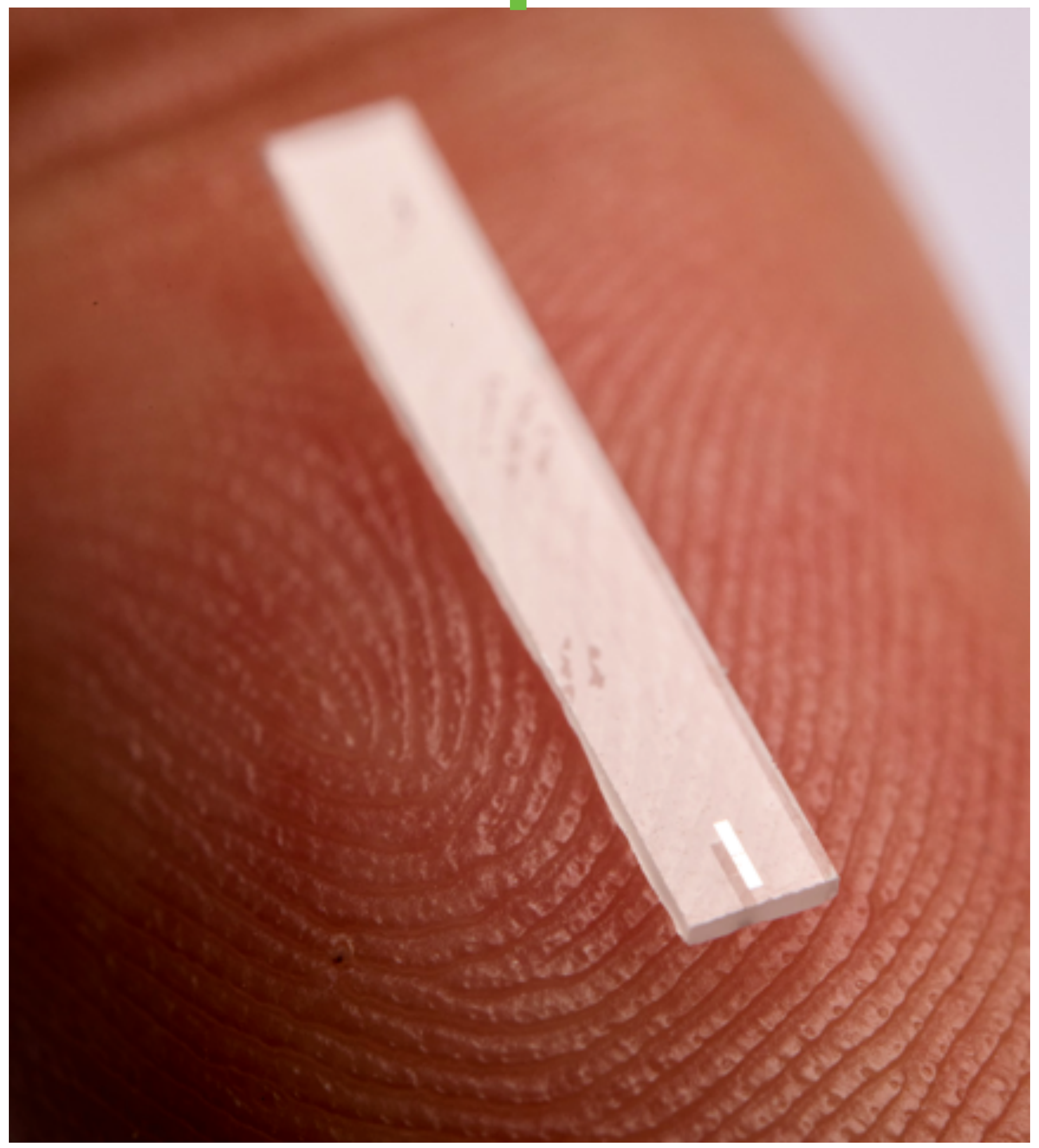
- Circumvent quantum limited phase preserving amplifier
- False positives dominate background
  - cavity thermal occupation
  - detector dark rate



Harmonic Oscillator + Two Level System

$$\mathcal{H} = \omega_c a^\dagger a + \omega_q \sigma_z + 2\chi a^\dagger a \sigma_z$$

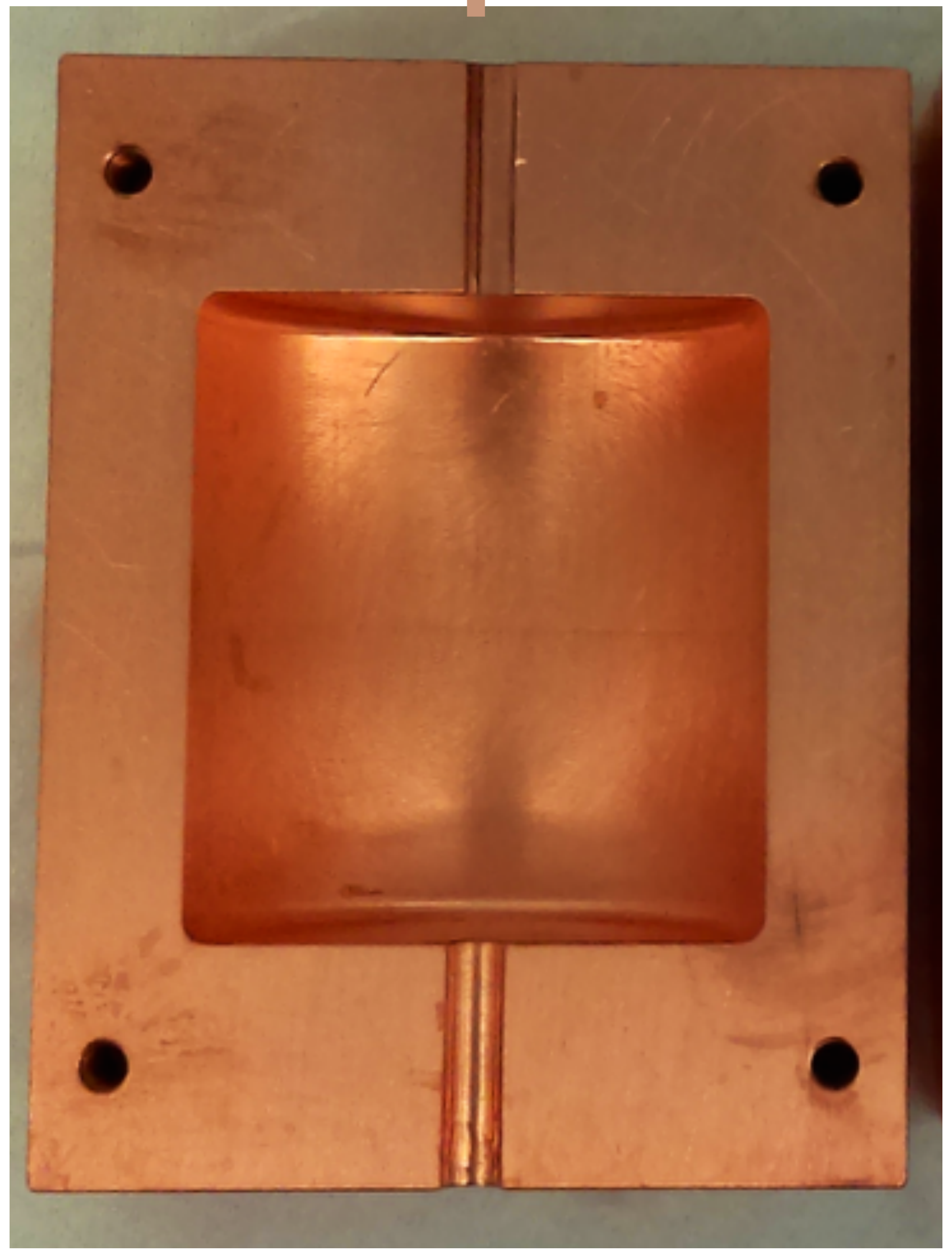


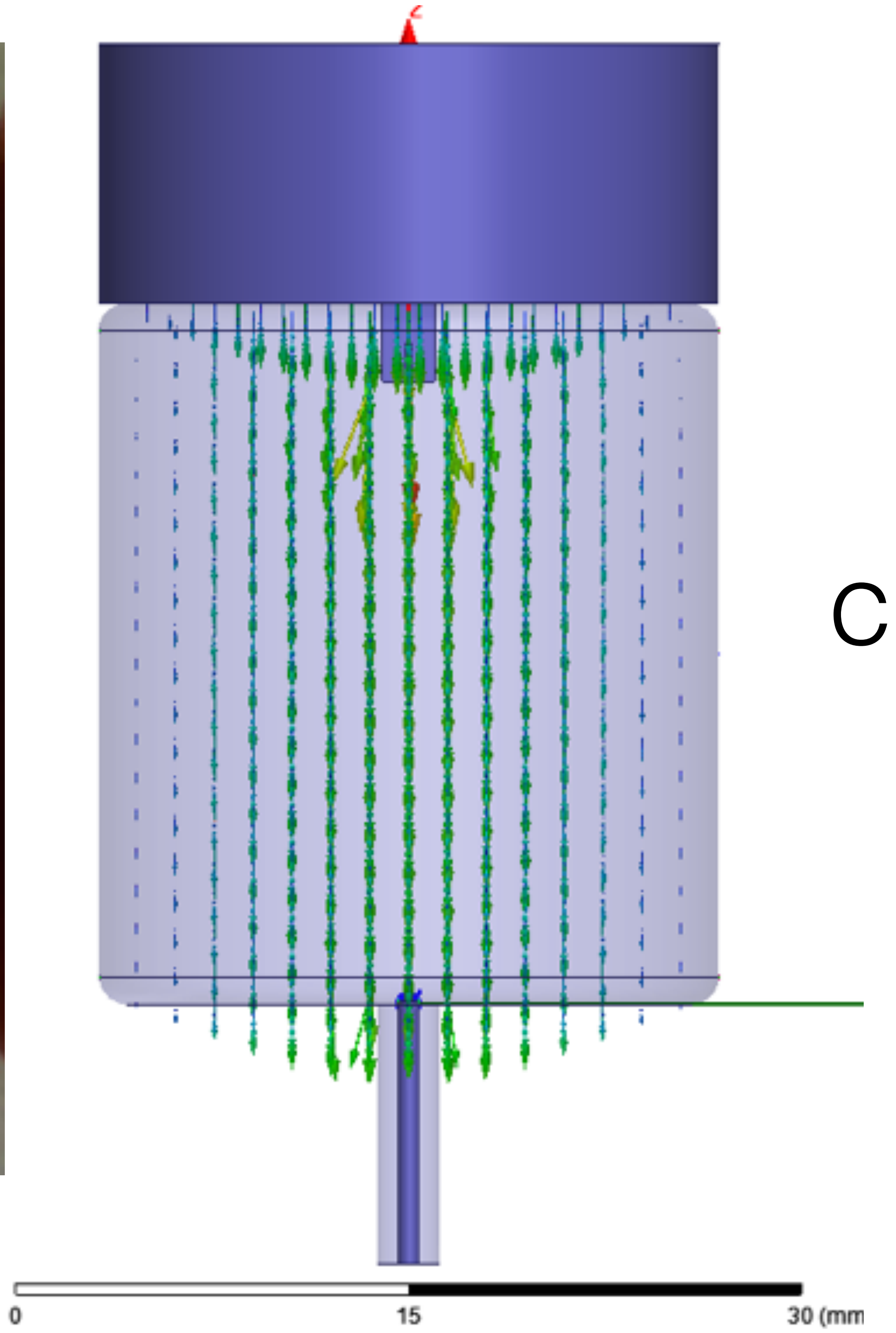


Microwave Cavity Designed to Maximize Axion Conversion

$$\mathcal{H} = \omega_c a^\dagger a + \omega_q \sigma_z + 2\chi a^\dagger a \sigma_z$$

$$\mathcal{L} \sim g a \mathbf{E} \cdot \mathbf{B}$$

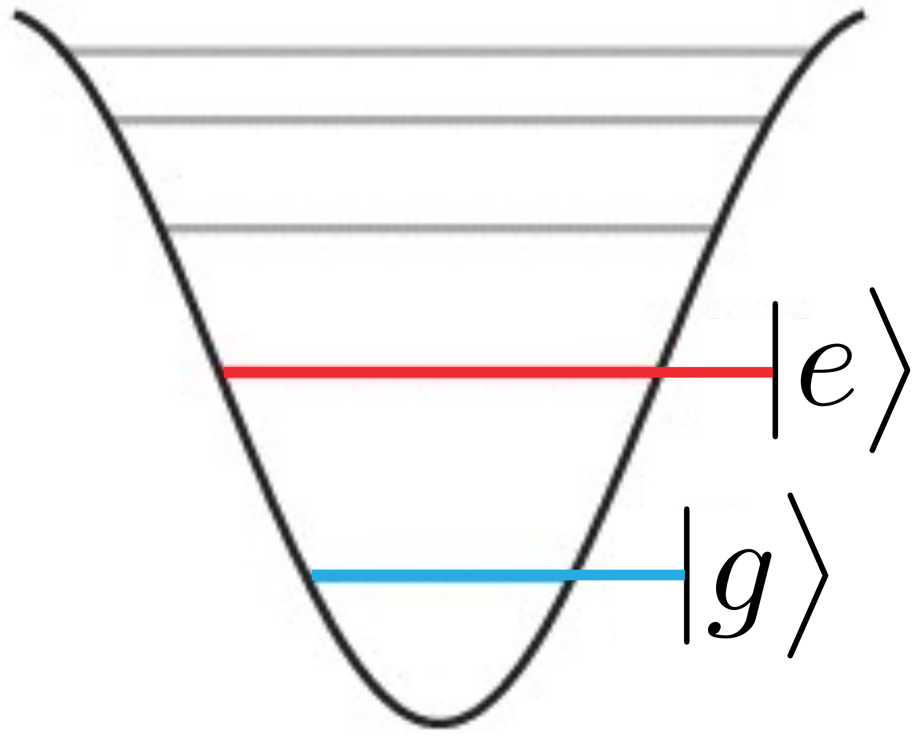




Maximize overlap between cavity mode E and external B

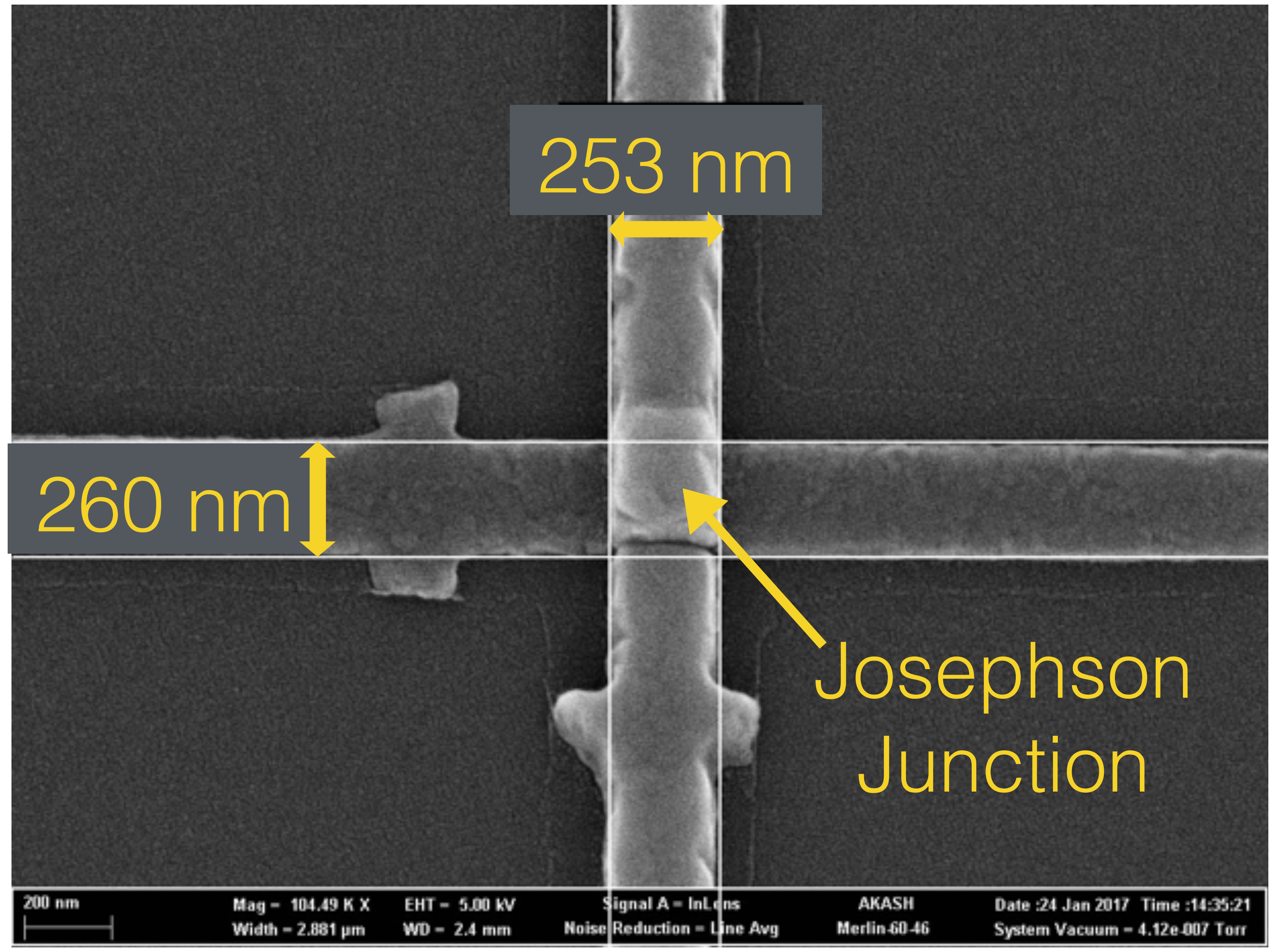
Superconducting Qubit Functions as Two-Level System

$$\mathcal{H} = \omega_c a^\dagger a + \omega_q \sigma_z + 2\chi a^\dagger a \sigma_z$$



$$\omega_q = E_1 - E_0$$

Harmonic Oscillator (LC) +
nonlinearity (Josephson Junction)



Customize transition frequency

Designing Qubit-Cavity Interaction

$$\mathcal{H} = \omega_c a^\dagger a + \omega_q \sigma_z + 2\chi a^\dagger a \sigma_z$$

$$\chi = \frac{g^2}{\Delta(\Delta + \alpha)}\alpha$$

Designing Qubit-Cavity Interaction

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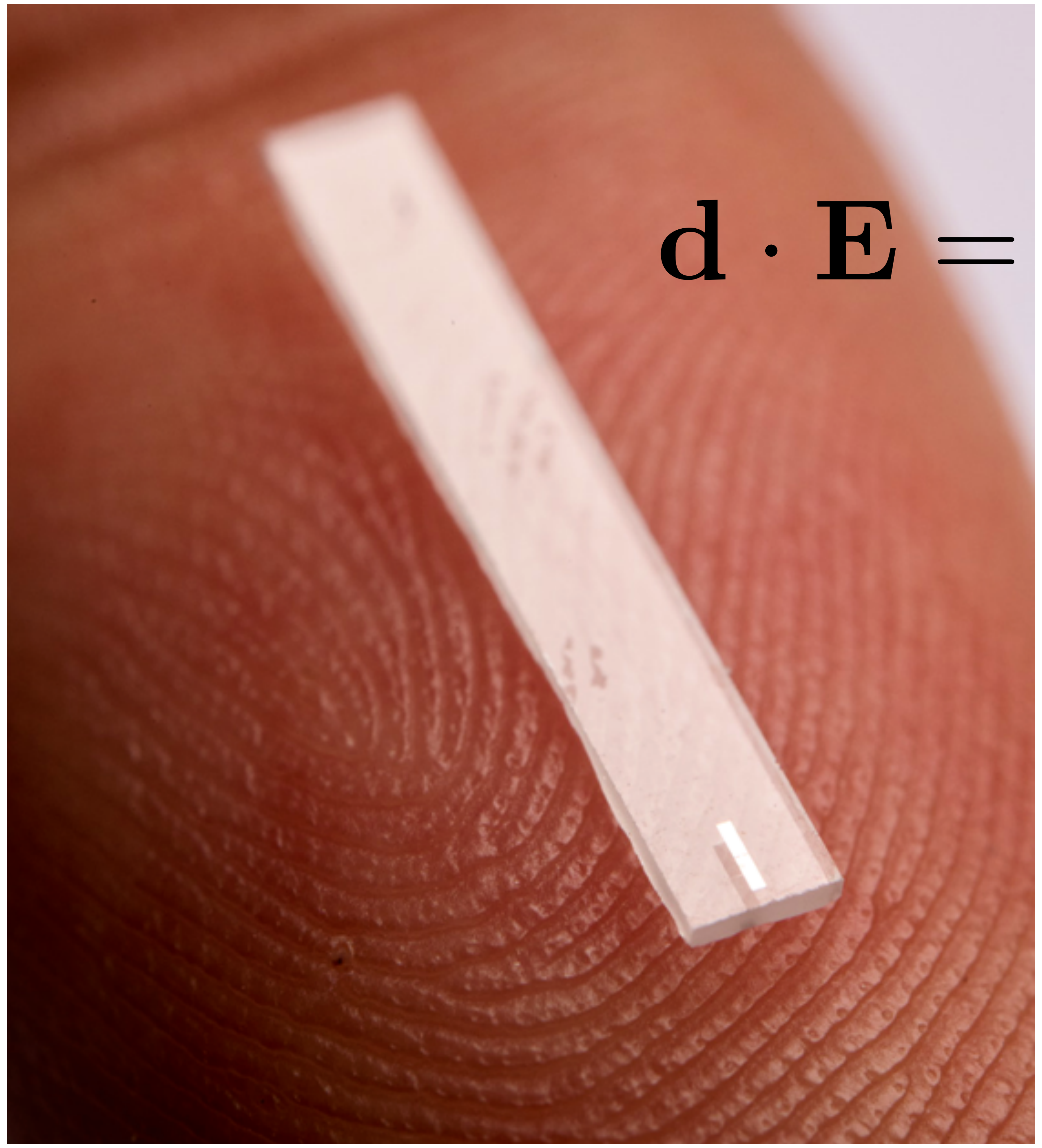

$$\mathbf{d} \cdot \mathbf{E} = q\Delta s \sqrt{\frac{\hbar\omega}{V}}$$

$$\chi = \frac{g^2}{\Delta(\Delta + \alpha)}\alpha$$

Designing Qubit-Cavity Interaction

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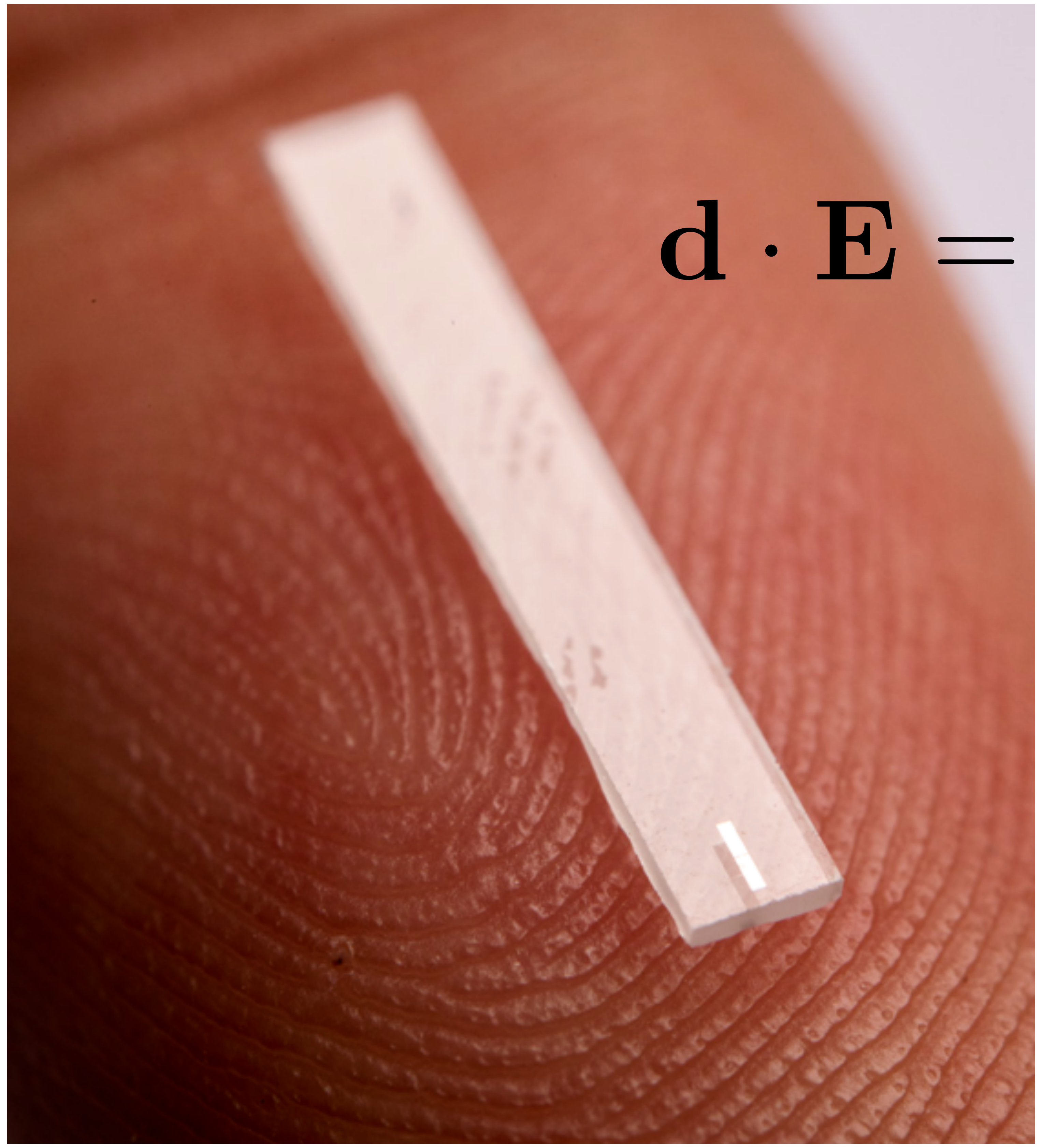

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$$\Delta = \omega_q - \omega_c$$

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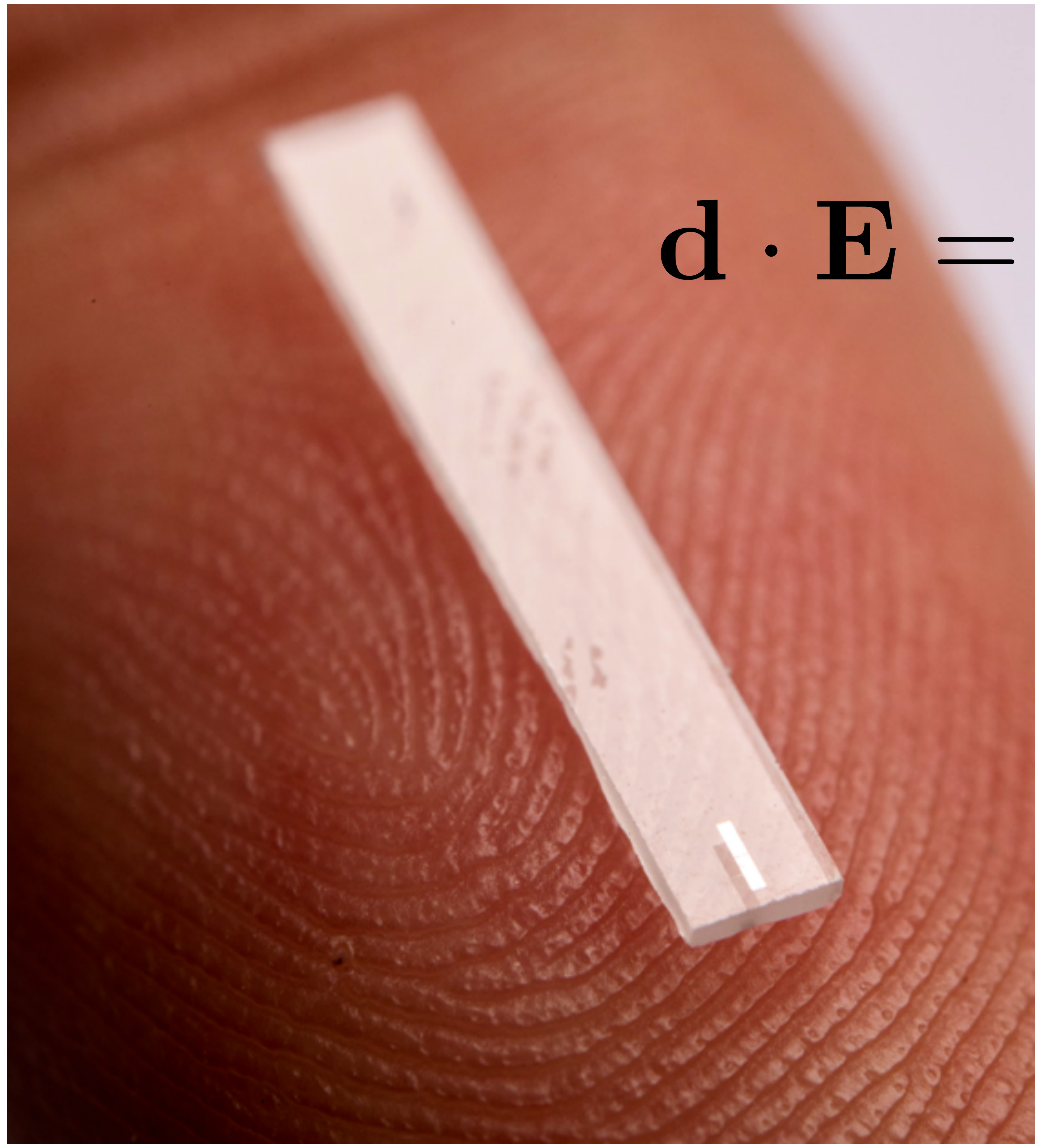

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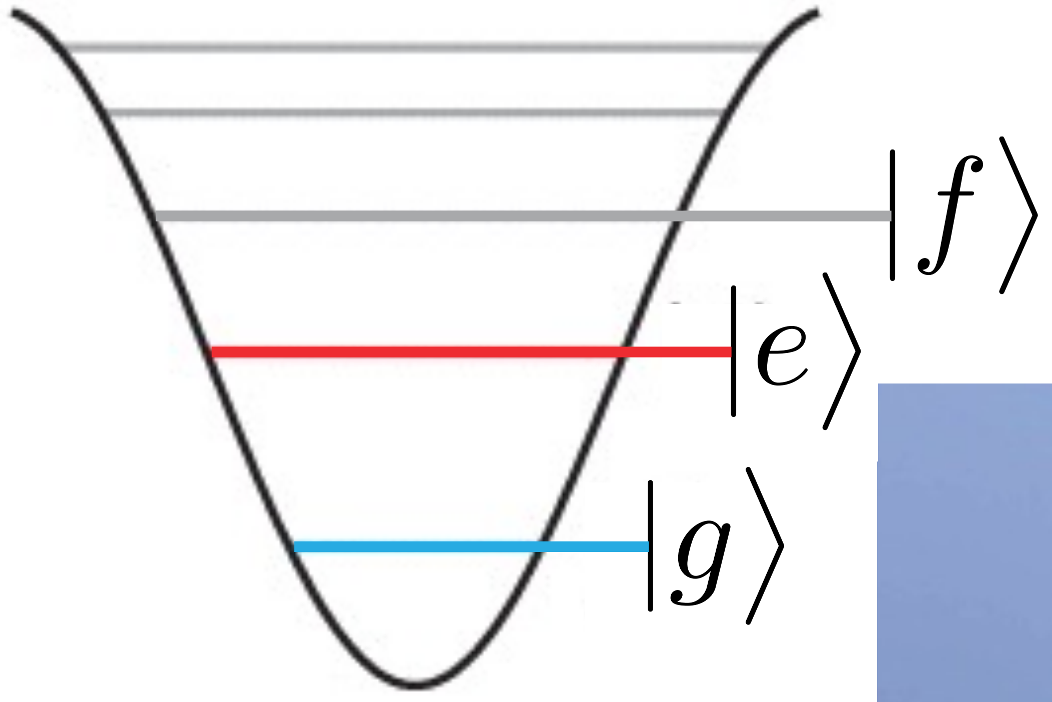
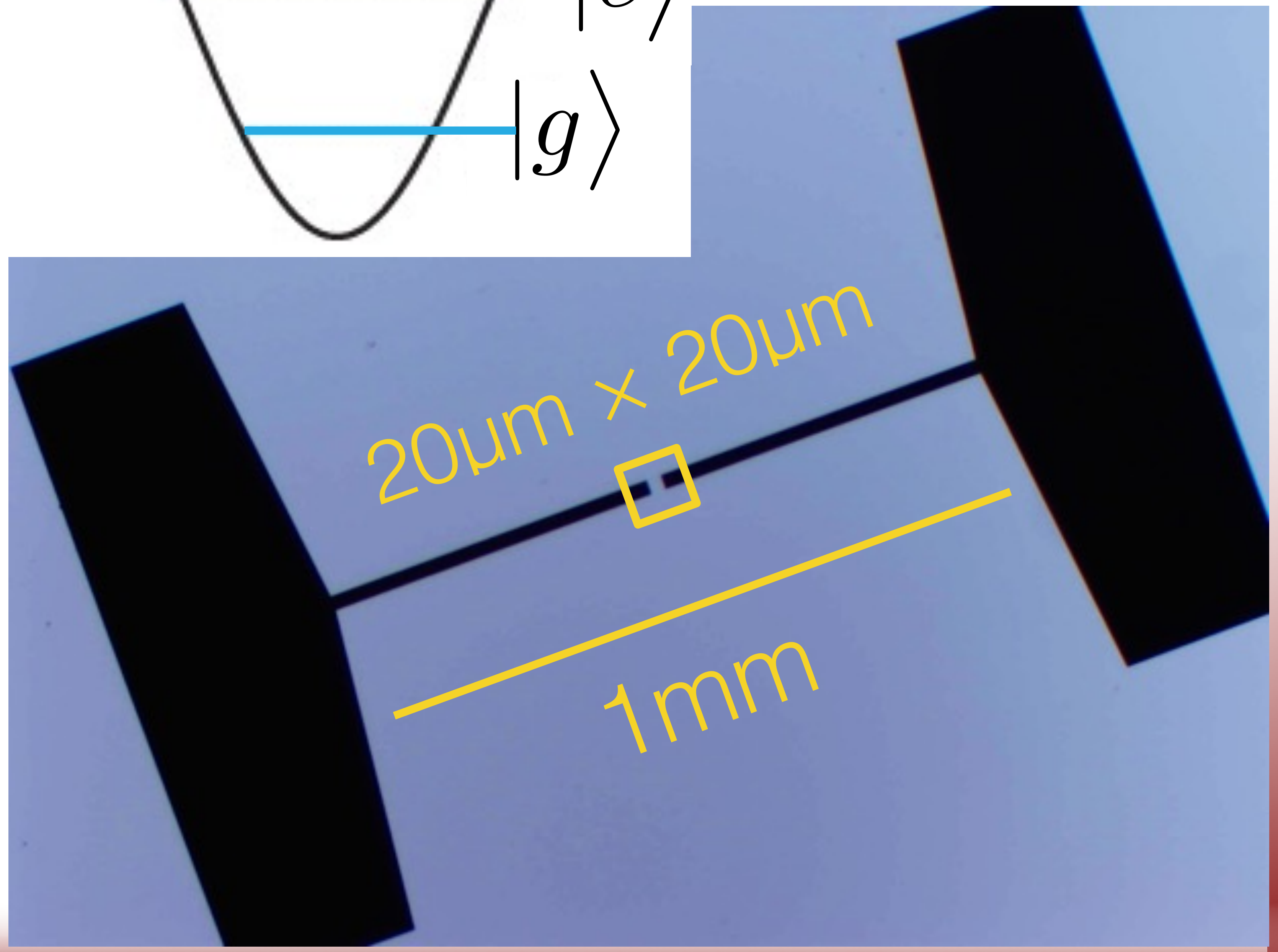
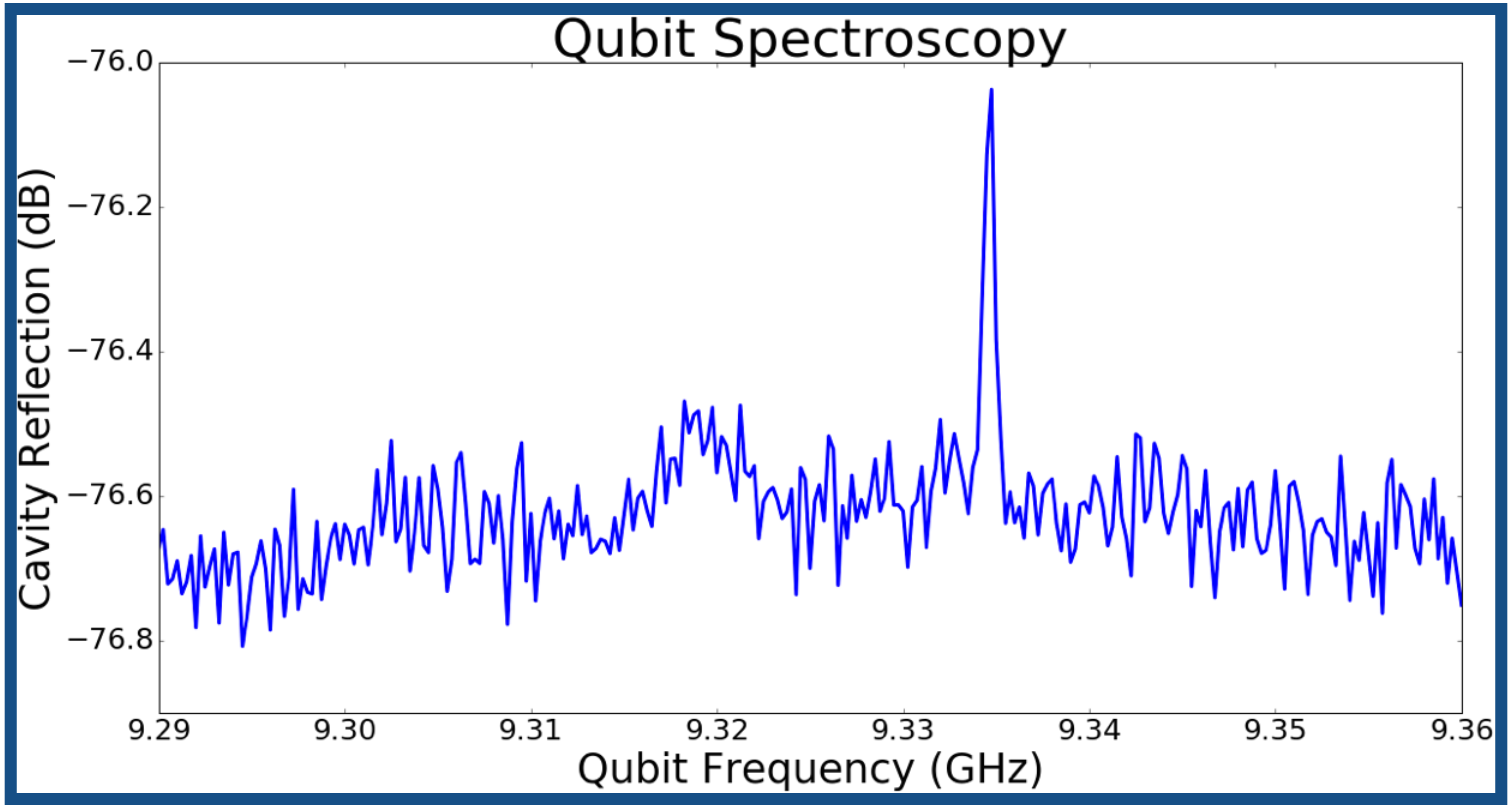




Axion Deposits Single Photon in Cavity

$$\mathcal{H} = \omega_c a^\dagger a + (\omega_q + 2\chi a^\dagger a)\sigma_z$$

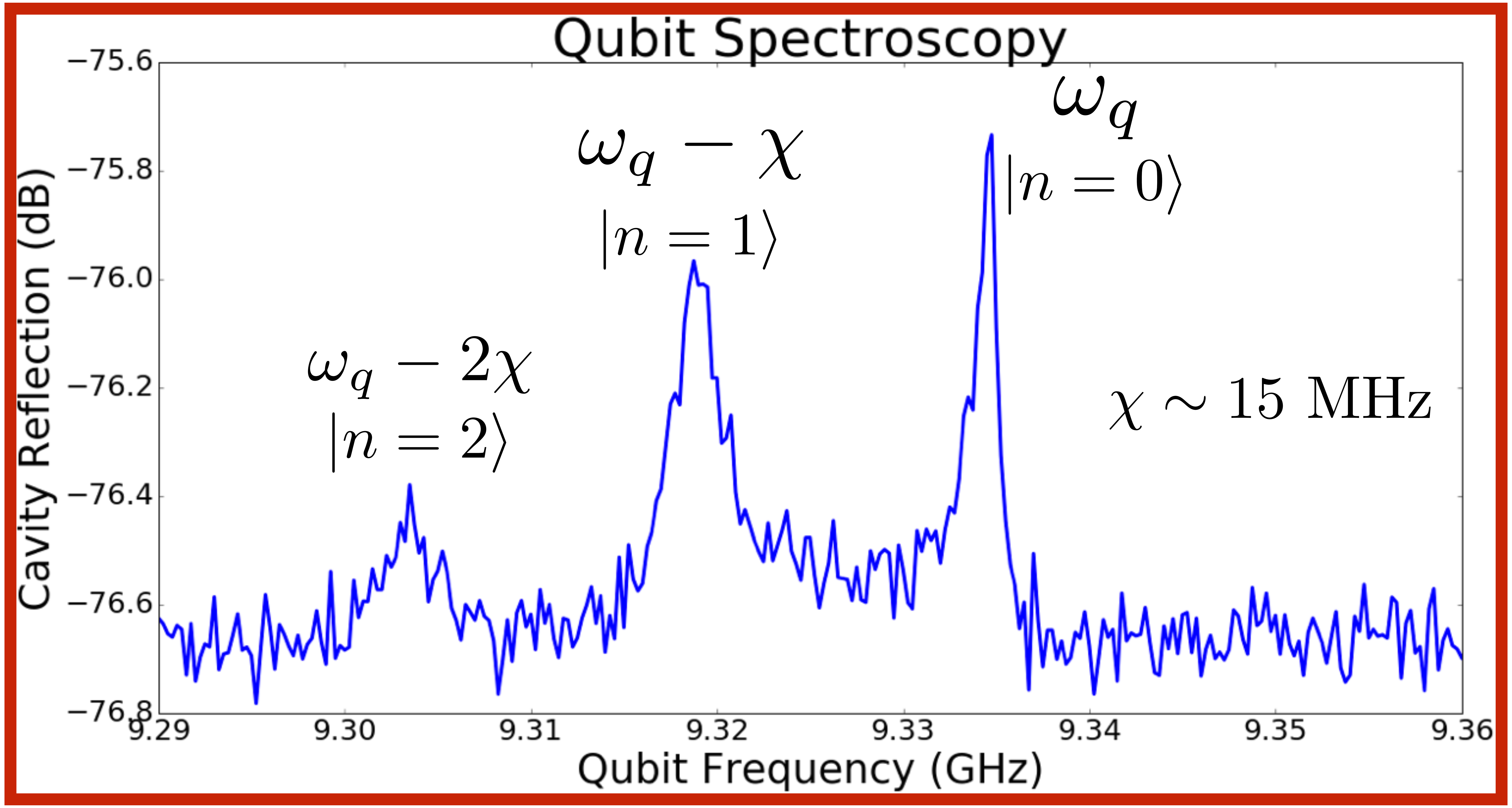
Axion induced current pumps cavity with photon



Cavity Occupation Imprinted on Qubit

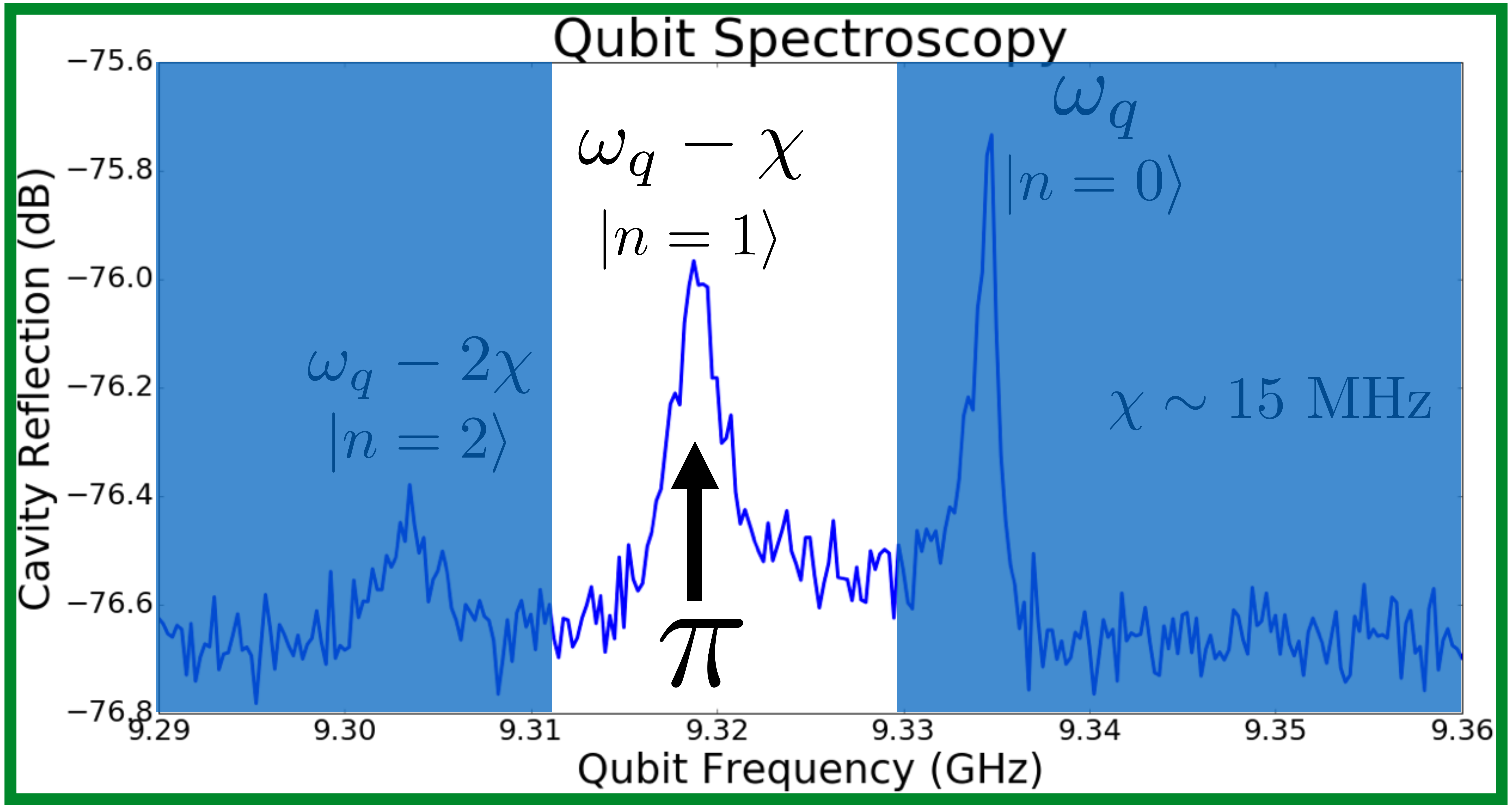
$$\mathcal{H} = \omega_c a^\dagger a + (\omega_q + 2\chi a^\dagger a)\sigma_z$$

Cavity occupation shifts qubit transition



Qubit Interrogation

$$\mathcal{H} = \omega_c a^\dagger a + (\omega_q + 2\chi a^\dagger a)\sigma_z$$



Excite qubit at shifted frequency

False Positives from Backgrounds and Detector Dark Rate

Cavity Photon Population

$$4.66 \times 10^{-5} < \bar{n}_{cav} < 4.47 \times 10^{-4}$$

$$T_{cav} = 55.13^{+4.52}_{-9.01} mK$$

Residual photons in the cavity are indistinguishable from signal photons

Qubit Excited State Population

$$P_e = 0.014$$

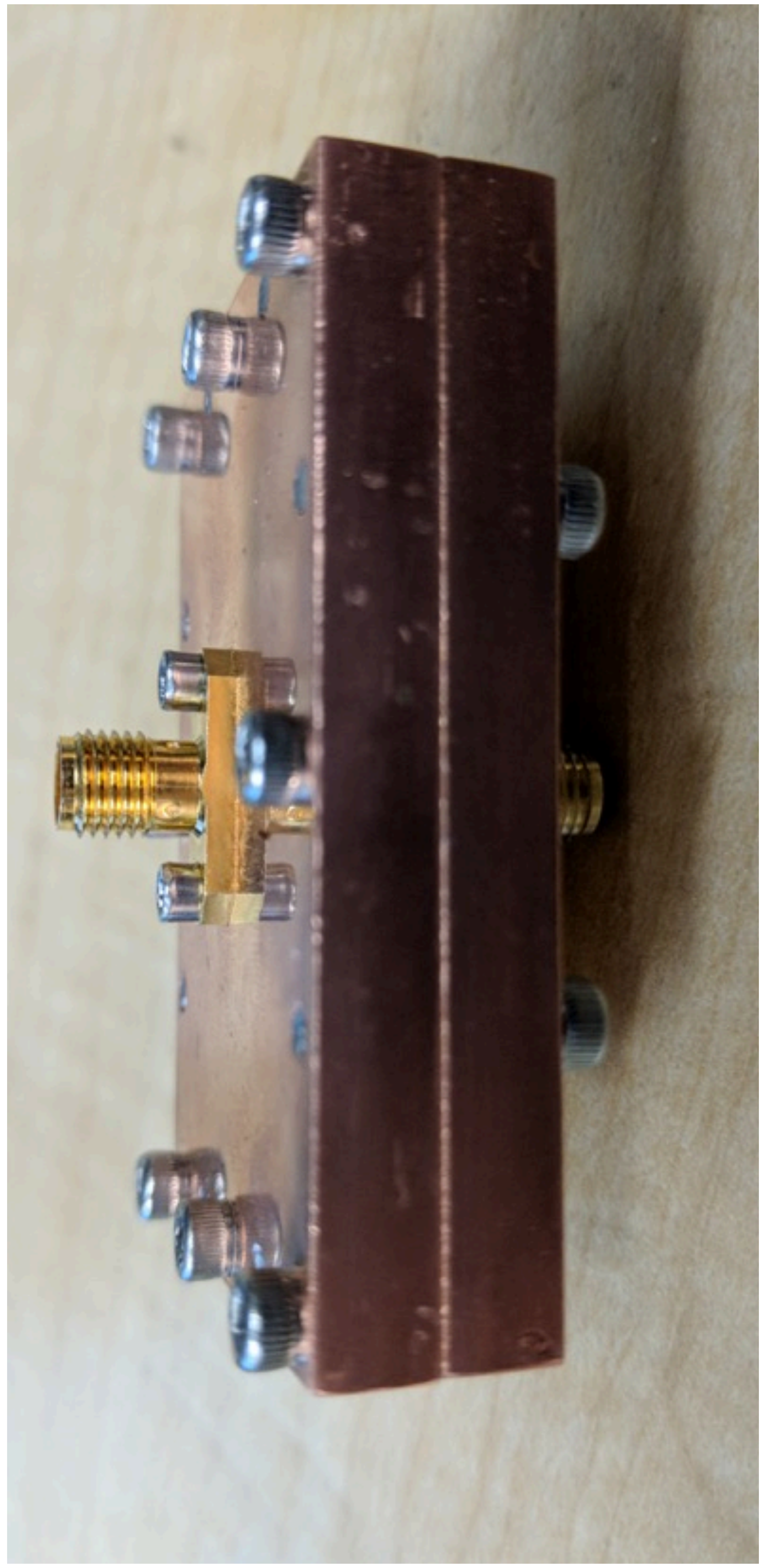
$$T_{qubit} = 82mK$$

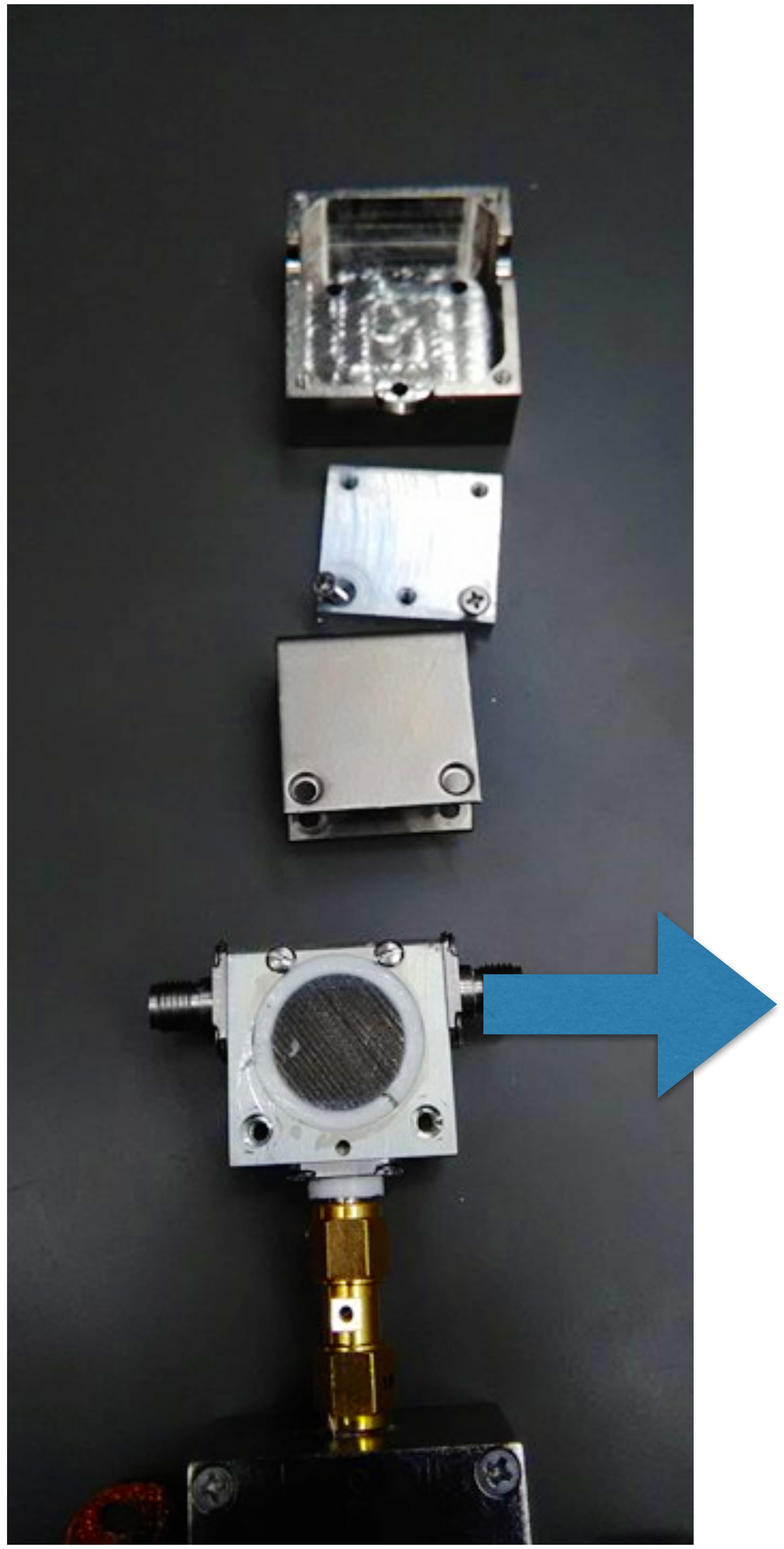
Spurious population in the qubit excited state mimics a successful qubit flip

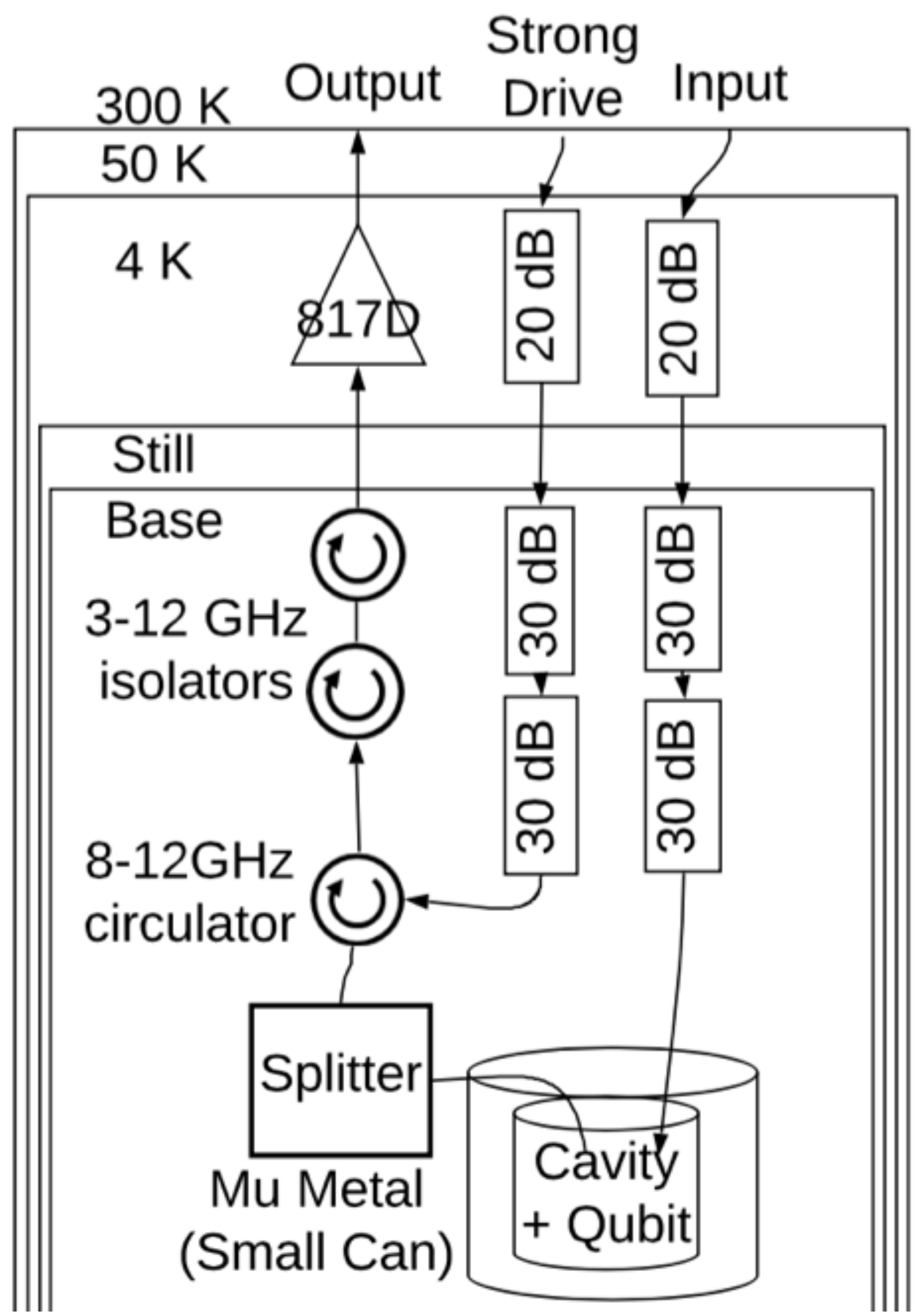
Reducing Cavity Thermal Occupation

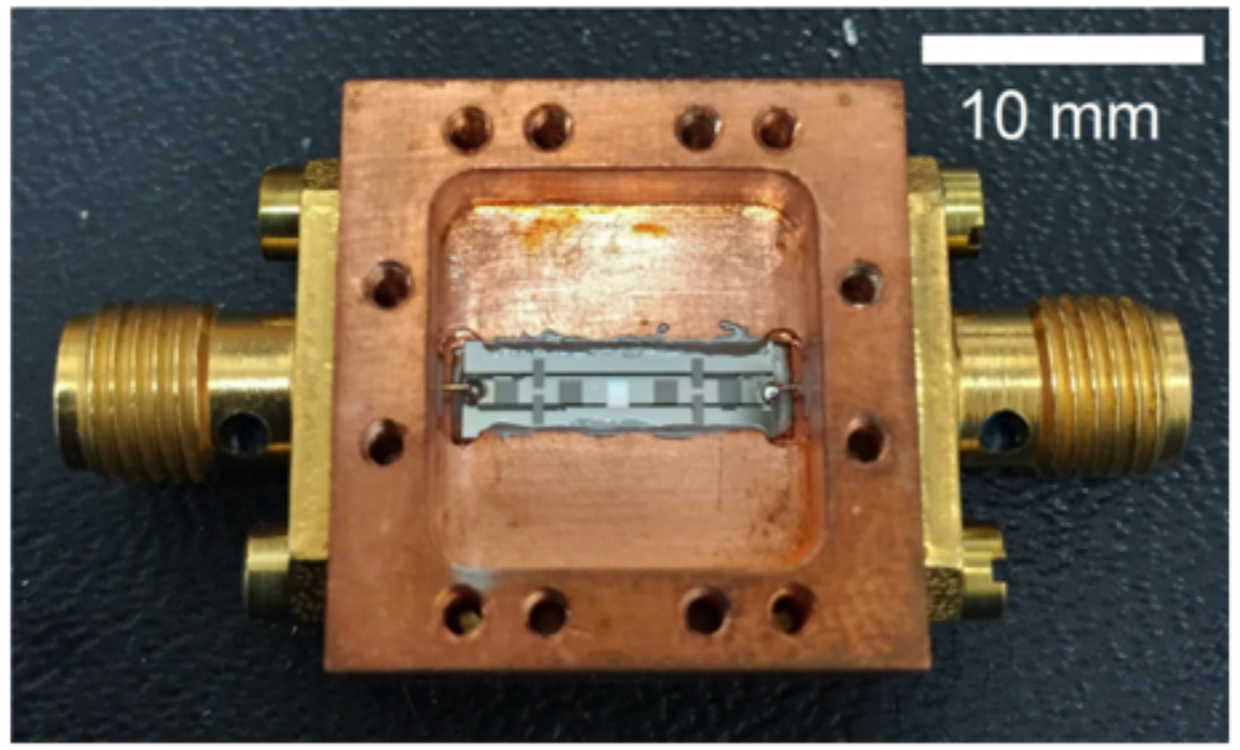
- Reduce photons from higher temperature stages with line attenuation
- Are circulators and isolators cold?
  - attenuators?

Custom atten courtesy of B. Palmer: Journal of Applied Physics 121, 224501 (2017)



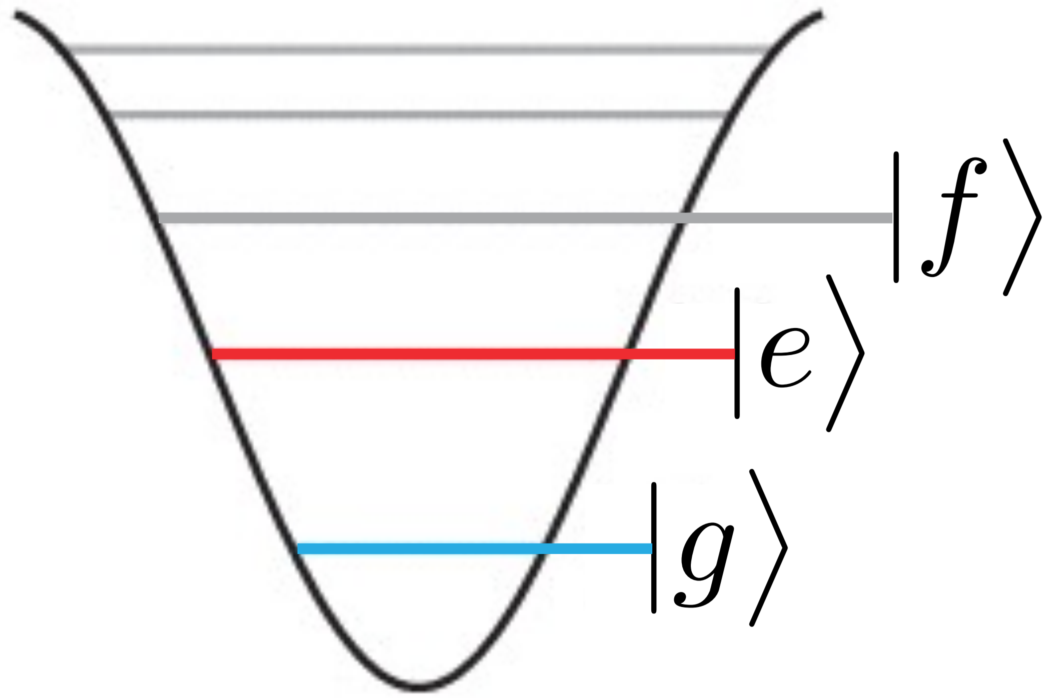






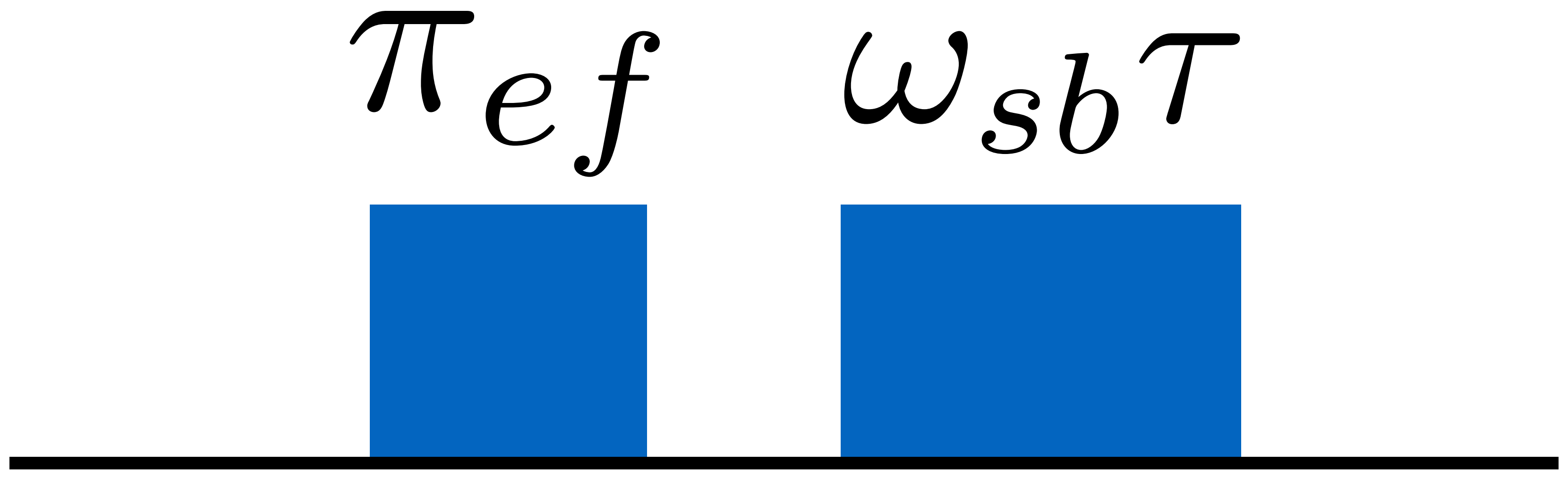
Active Cooling of Qubit Population

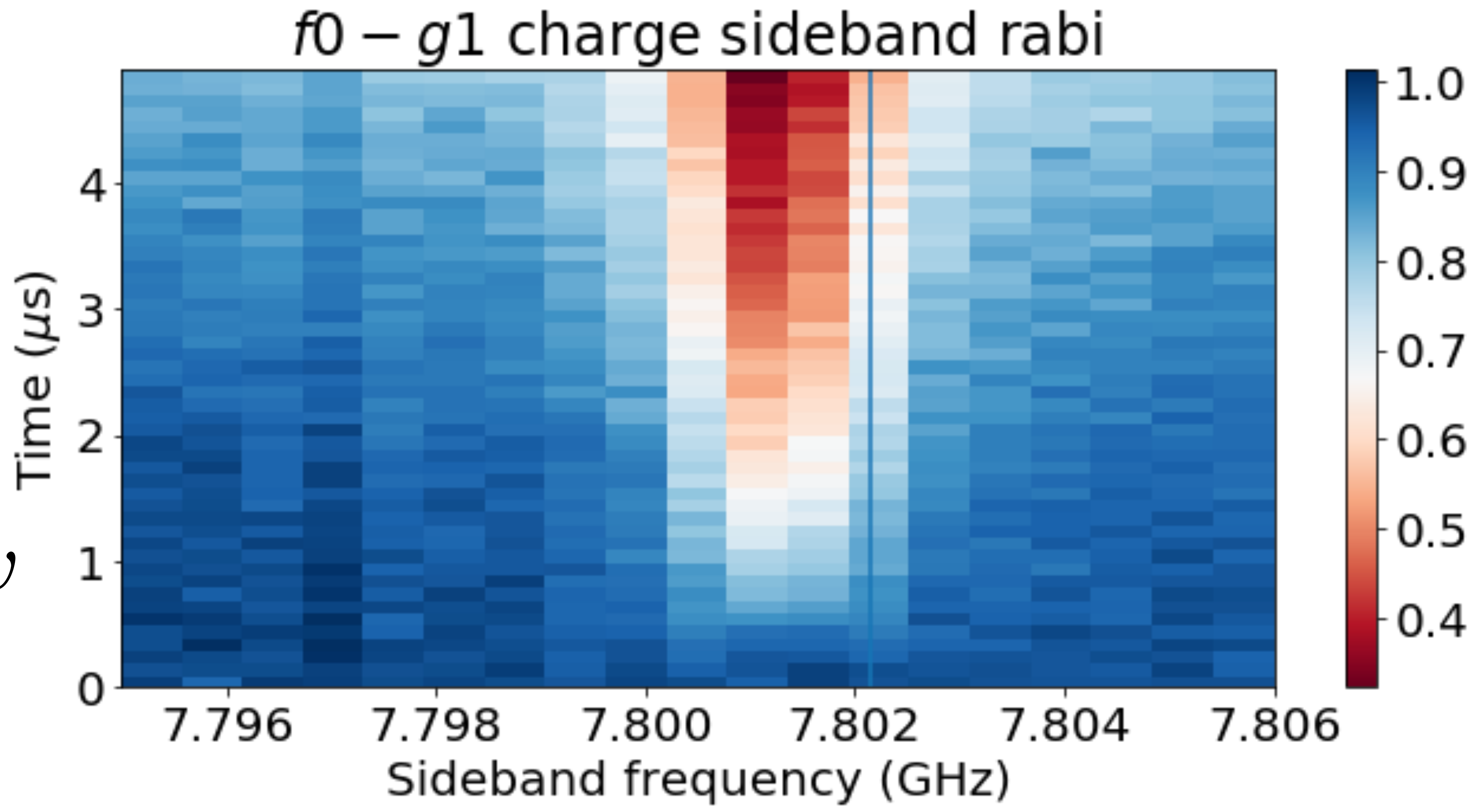
Active sideband cooling with higher **qubit** levels



$$|f0\rangle \rightarrow |g1\rangle$$

$$\omega_{sb} = \omega_q^{ge} + \omega_q^{ef} - \omega_{cav}$$

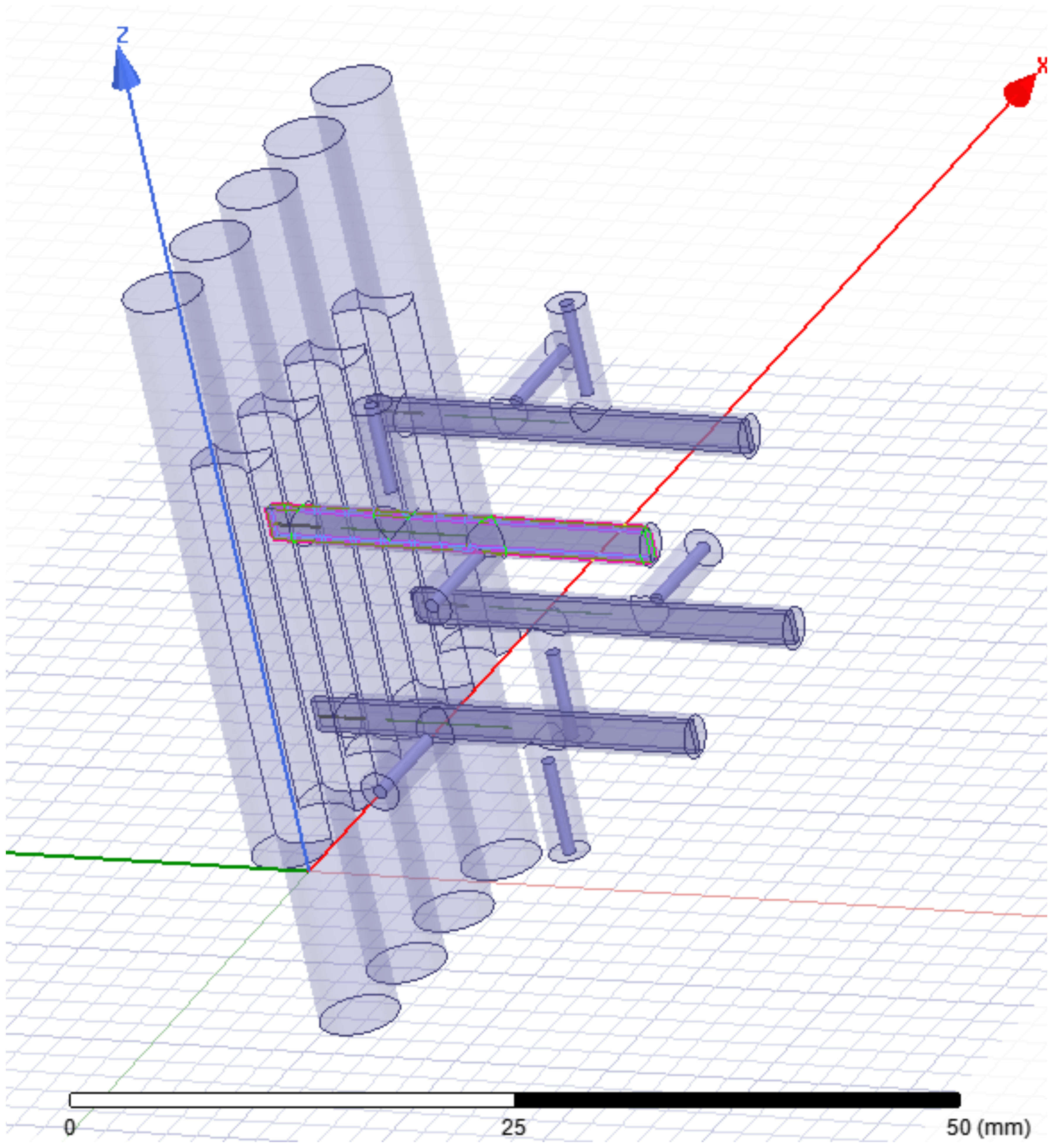


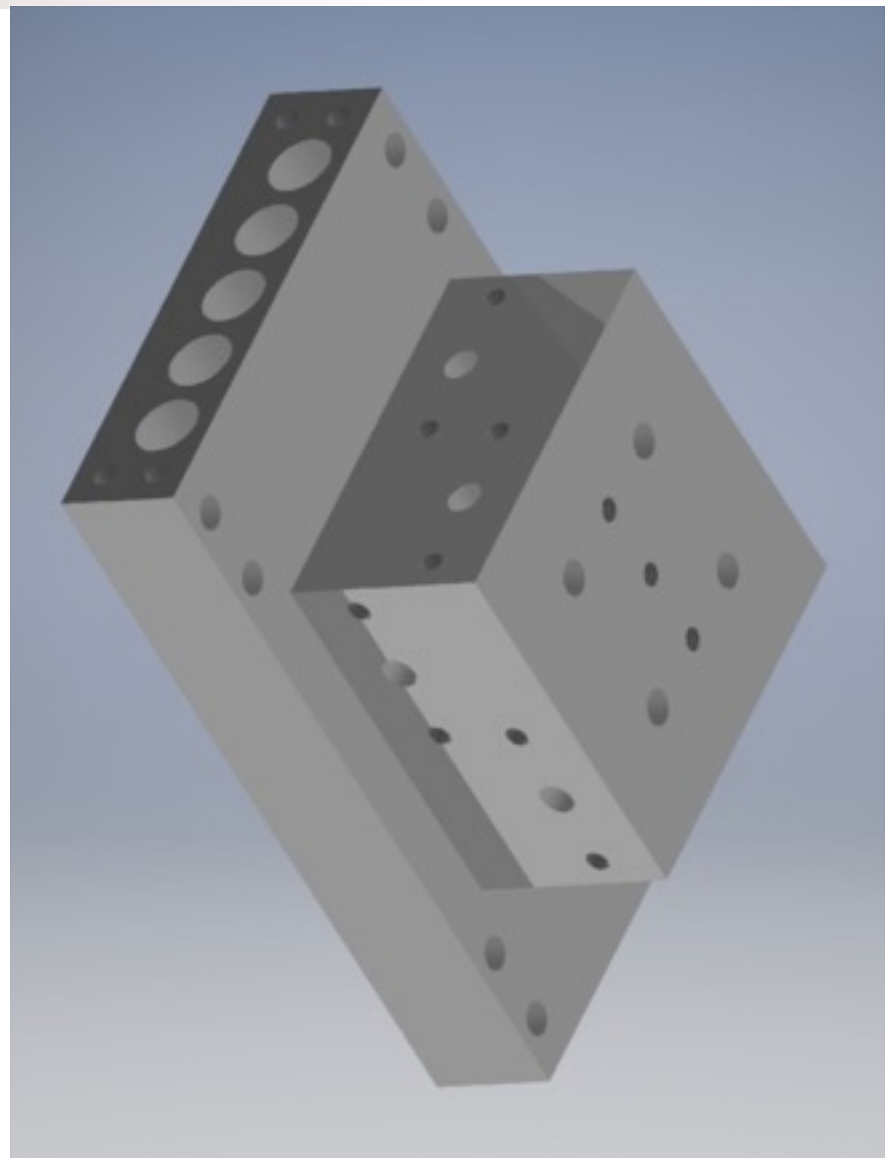


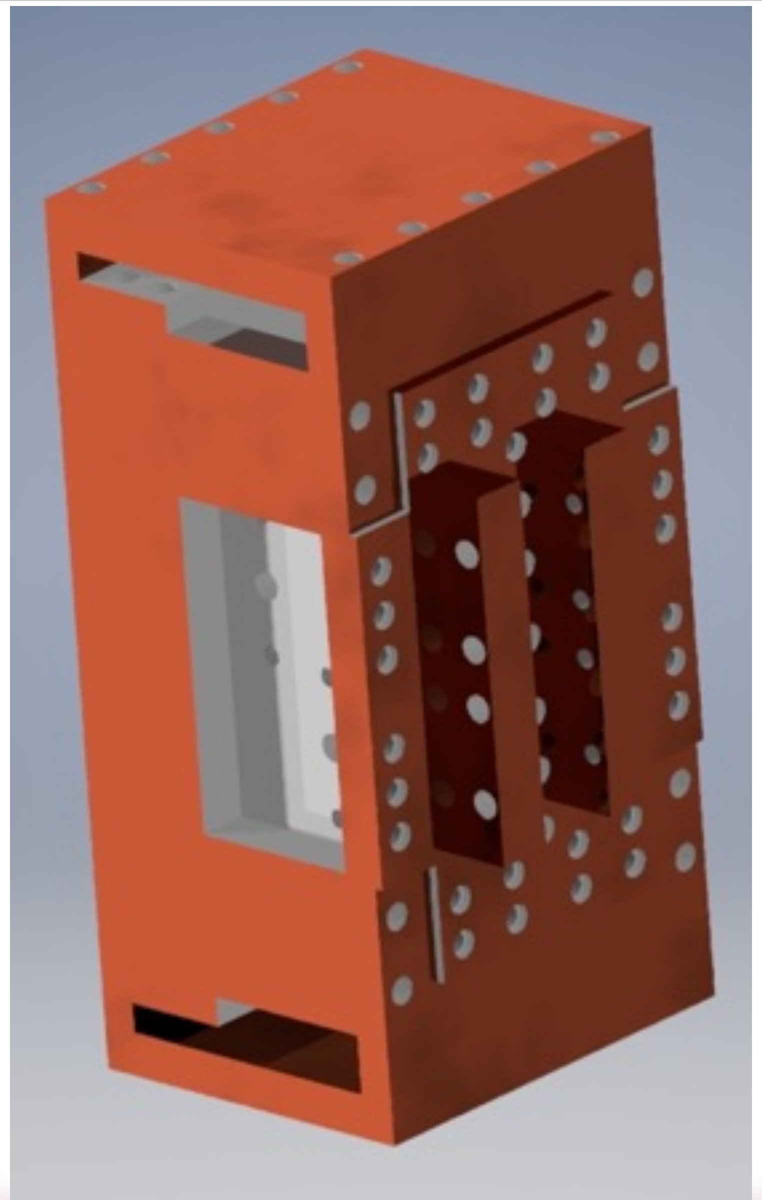
Reduce effective dark rate by combining qubit measurements

- Sample the same qubit N times
    - requires N times as much time to complete experiment
    - photon decays quickly (1us)
- **Sample N different qubits with error rate alpha**

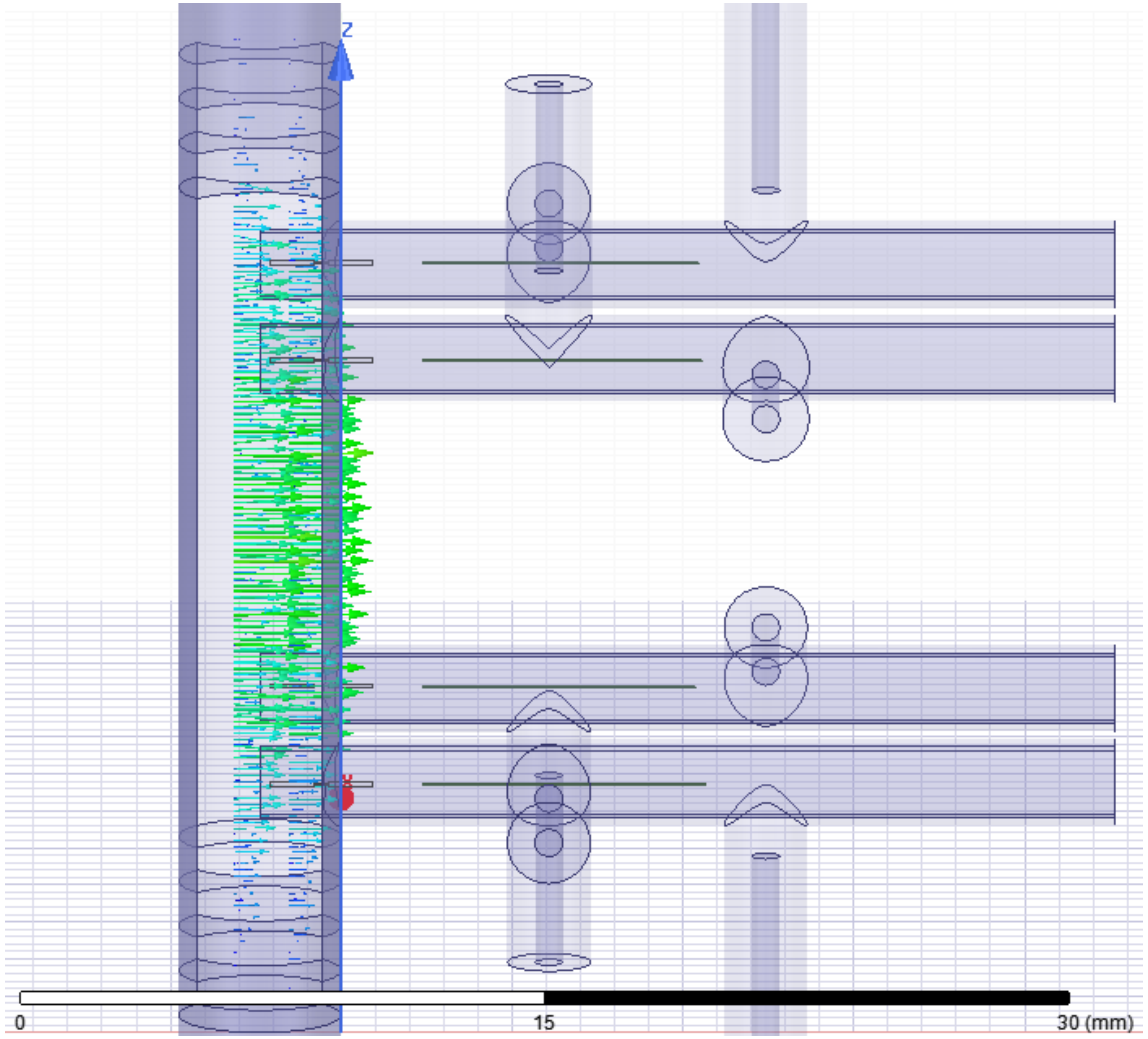
$$P_{N errors} = (\alpha)^N$$

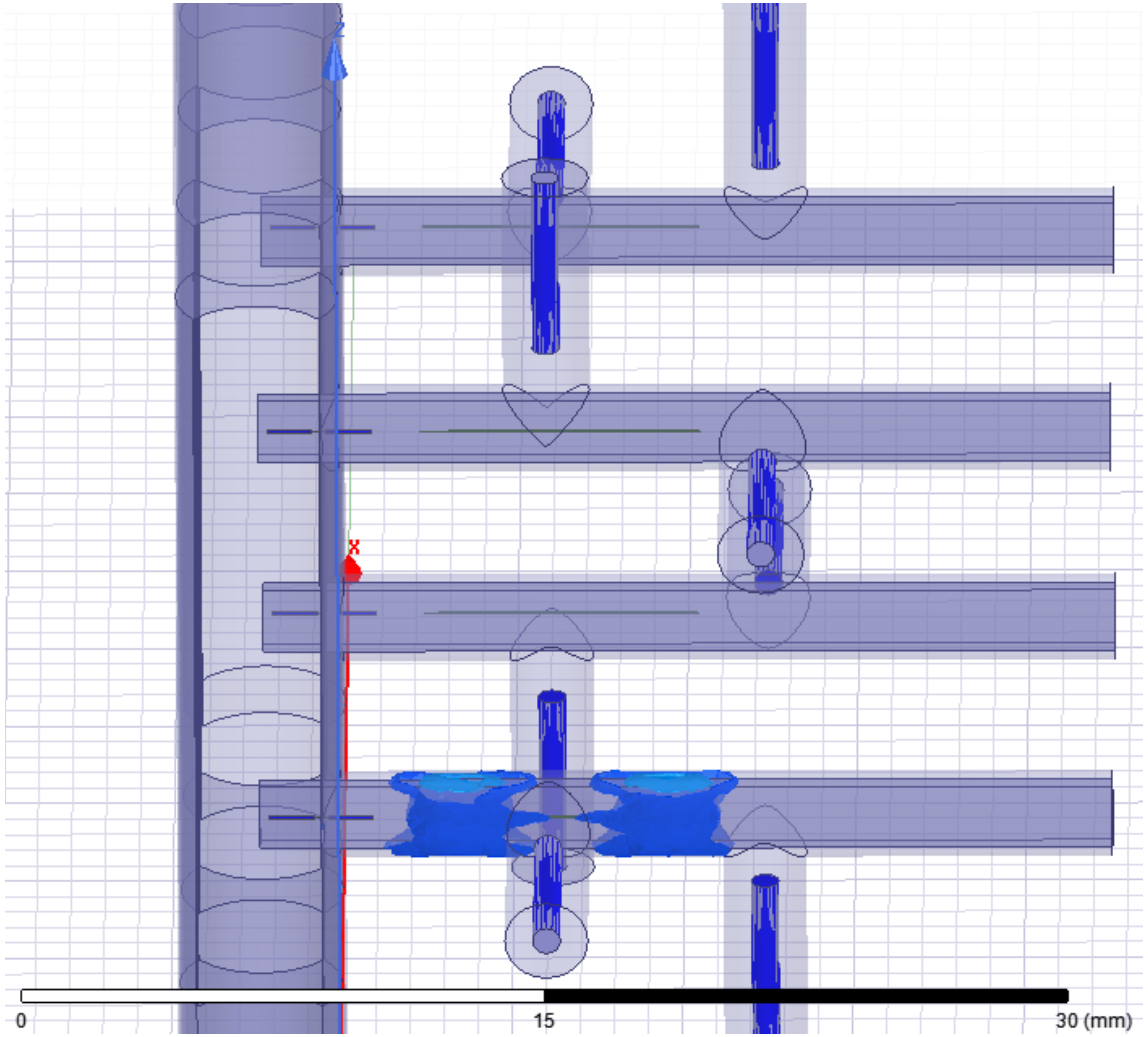






4-Qubit Cavity Design



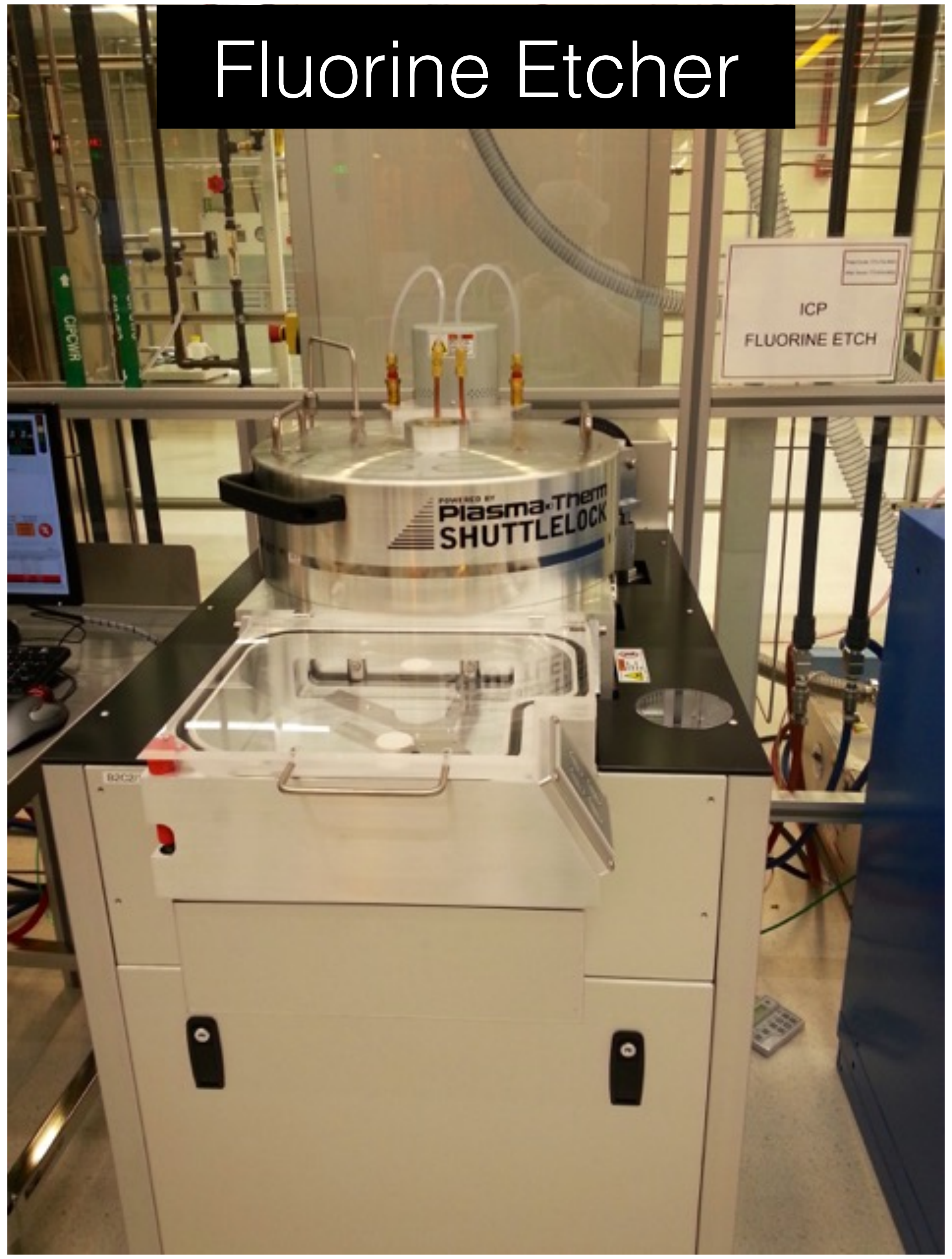


Conclusions

- Employ quantum computing techniques/devices for dark matter cosmology experiment
- Shift penalties of standard quantum limit by dispersively counting photons
- Build superconducting detectors with customizable interactions with an EM environment
- Use Qubit-Cavity interactions to store & process quantum information

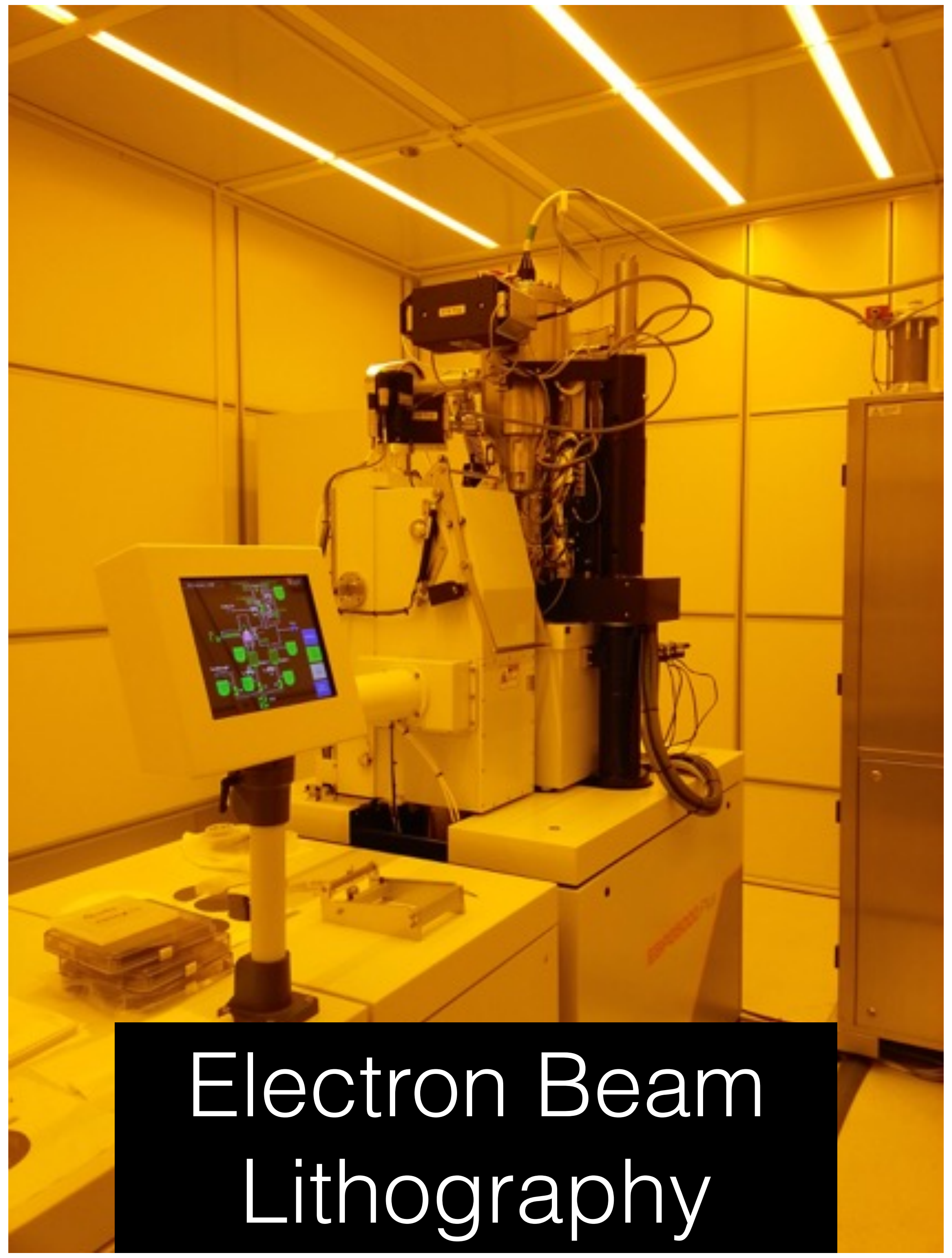
the David & Lucile Packard Foundation
Heising-Simons Foundation
Army Research Office
ADMX Axion Dark Matter Experiment
Pritzker Nanofabrication Facility
schuster.lab
The University of Chicago
Fermilab

Qubit Fabrication



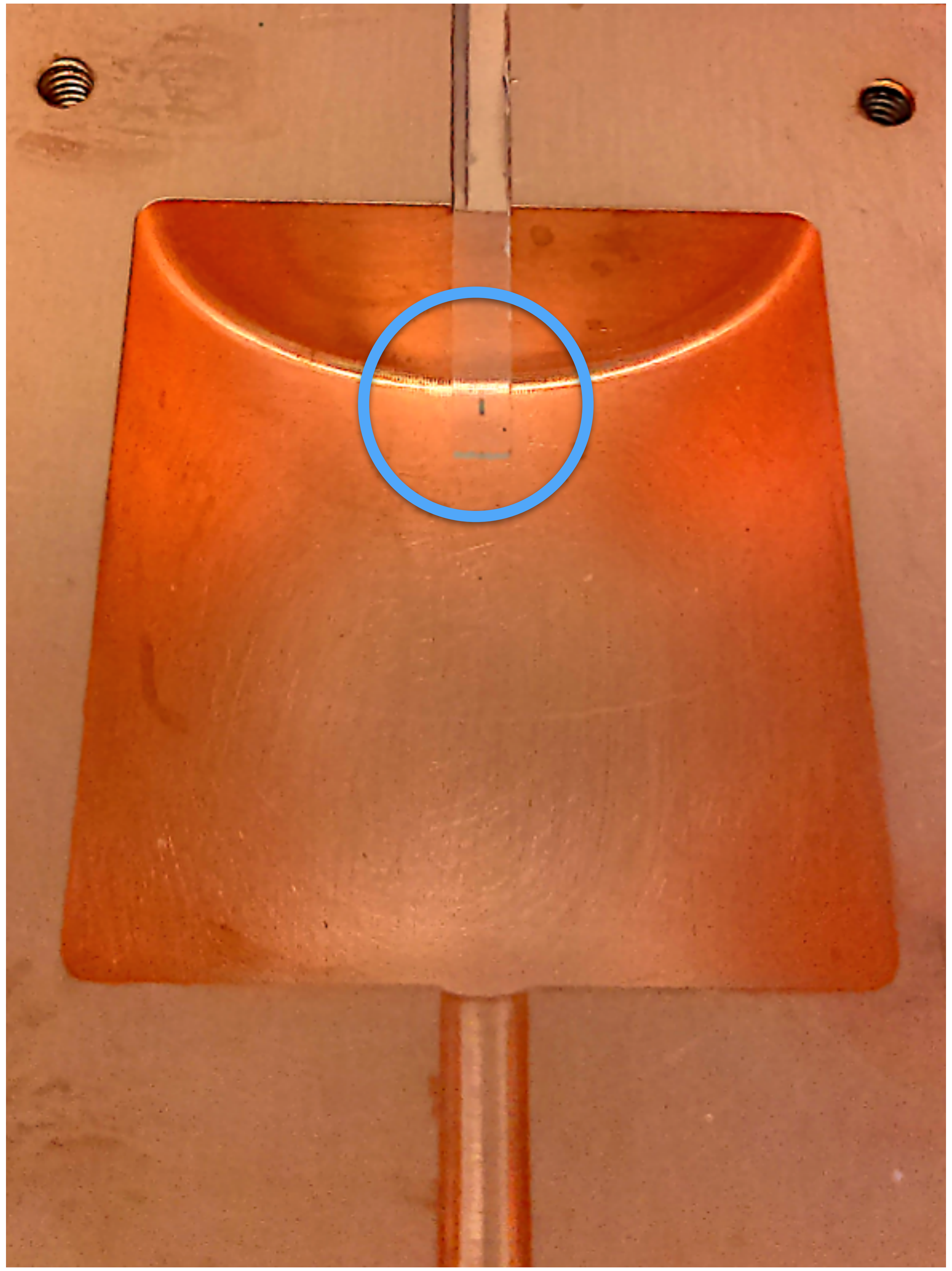
Fluorine Etcher

Optical Direct Writer

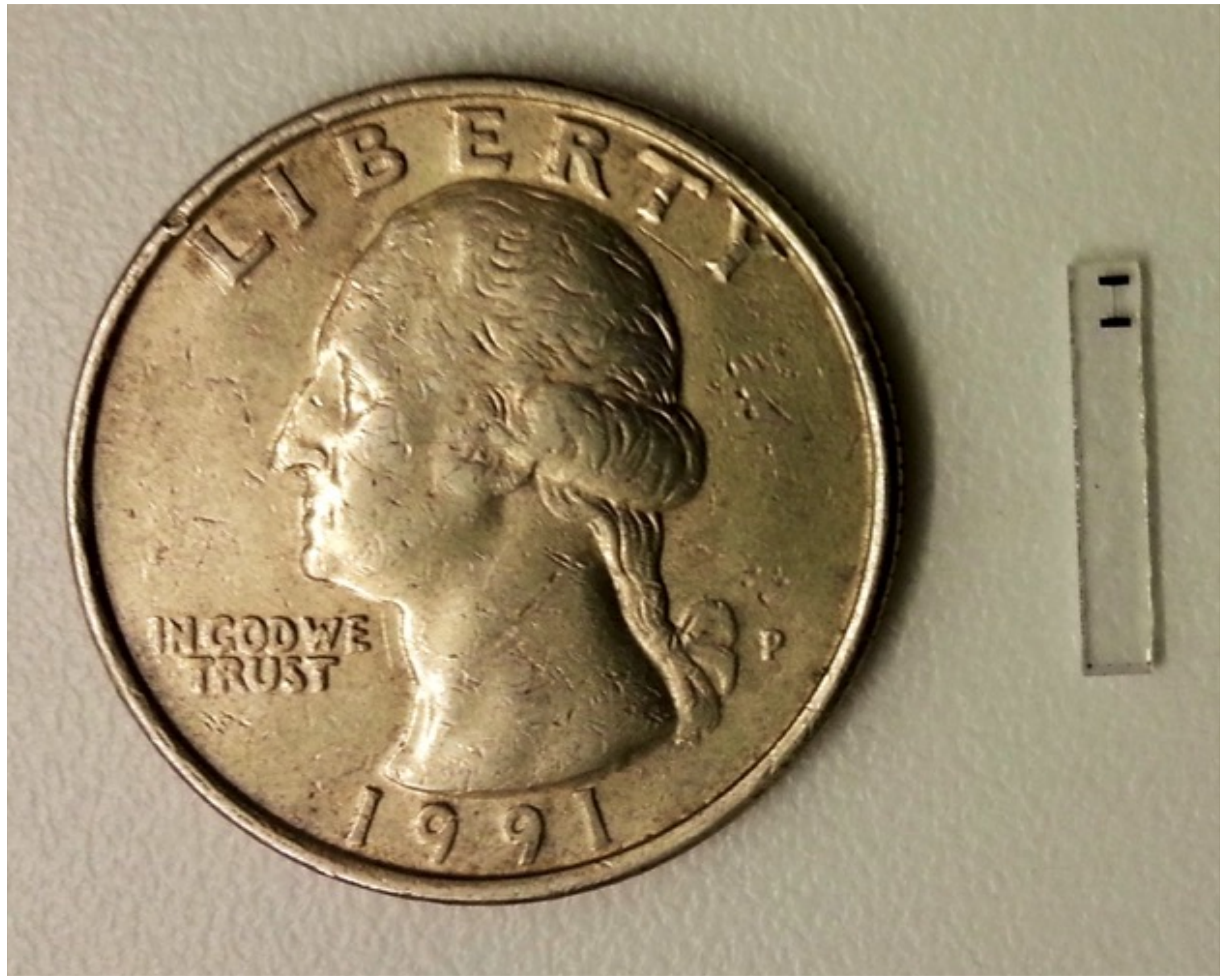

Electron Beam Lithography

Not pictured:
-Double Angle Evap
-Thermal Evap
-Dicing Saw
-SEM
-Sputter Coater

Dispersive Coupling of the Cavity and Qubit

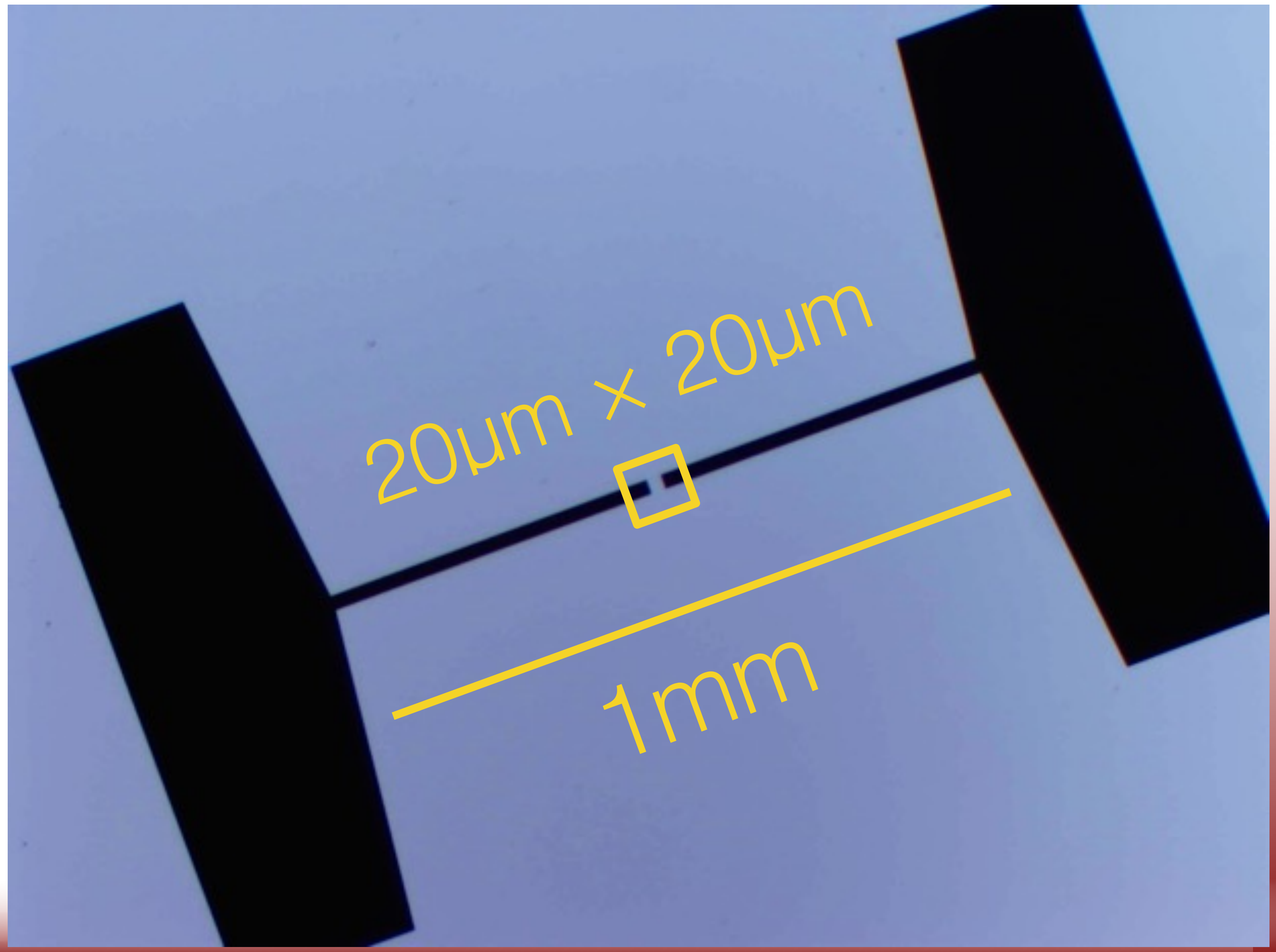


$$H_{int} = 2\chi a^\dagger a \sigma_z$$



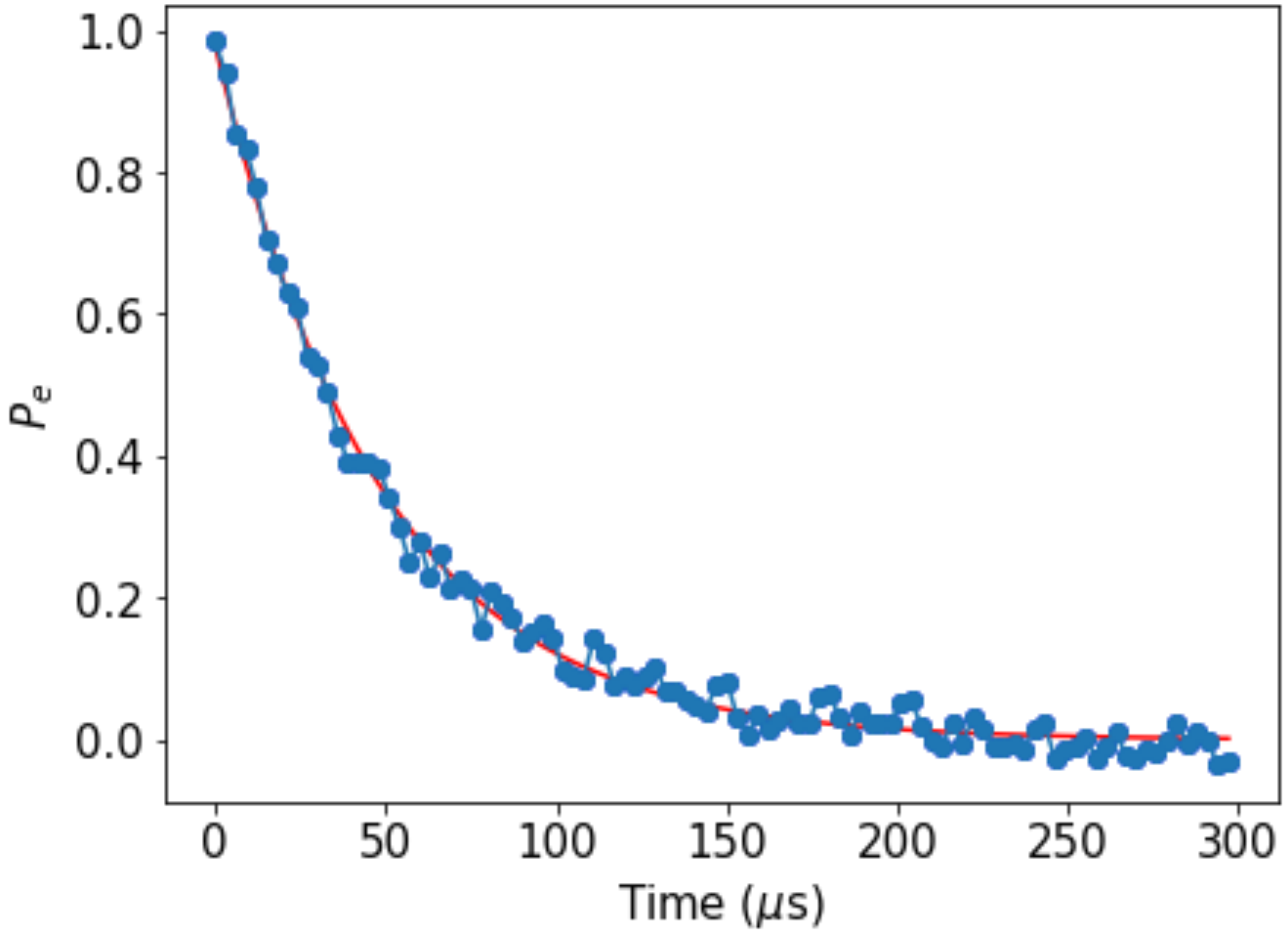
Interaction set by:

- dipole arm geometry
- qubit location in cavity
- qubit-cavity frequency detuning
- qubit anharmonicity

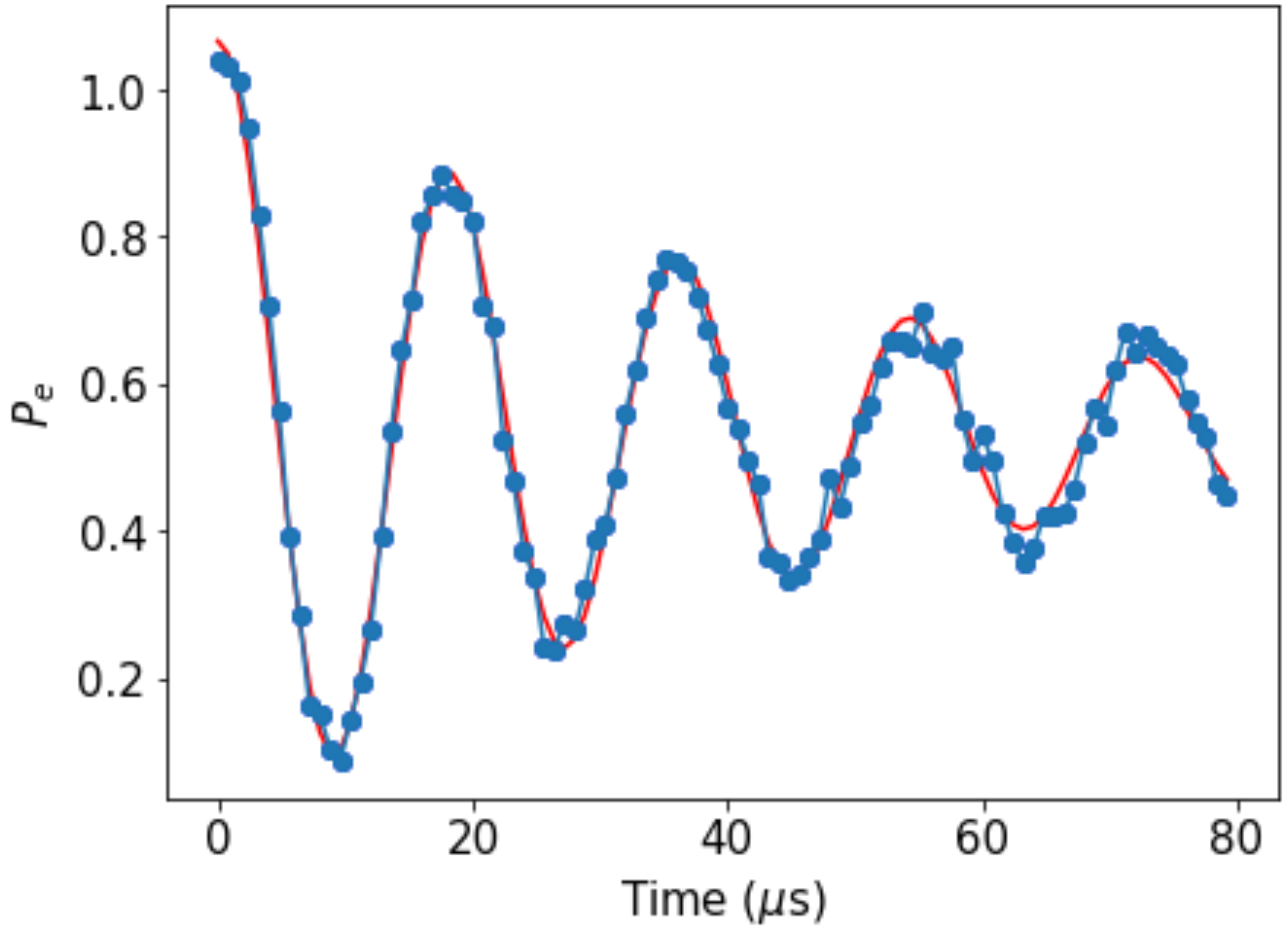


Qubit Characterization

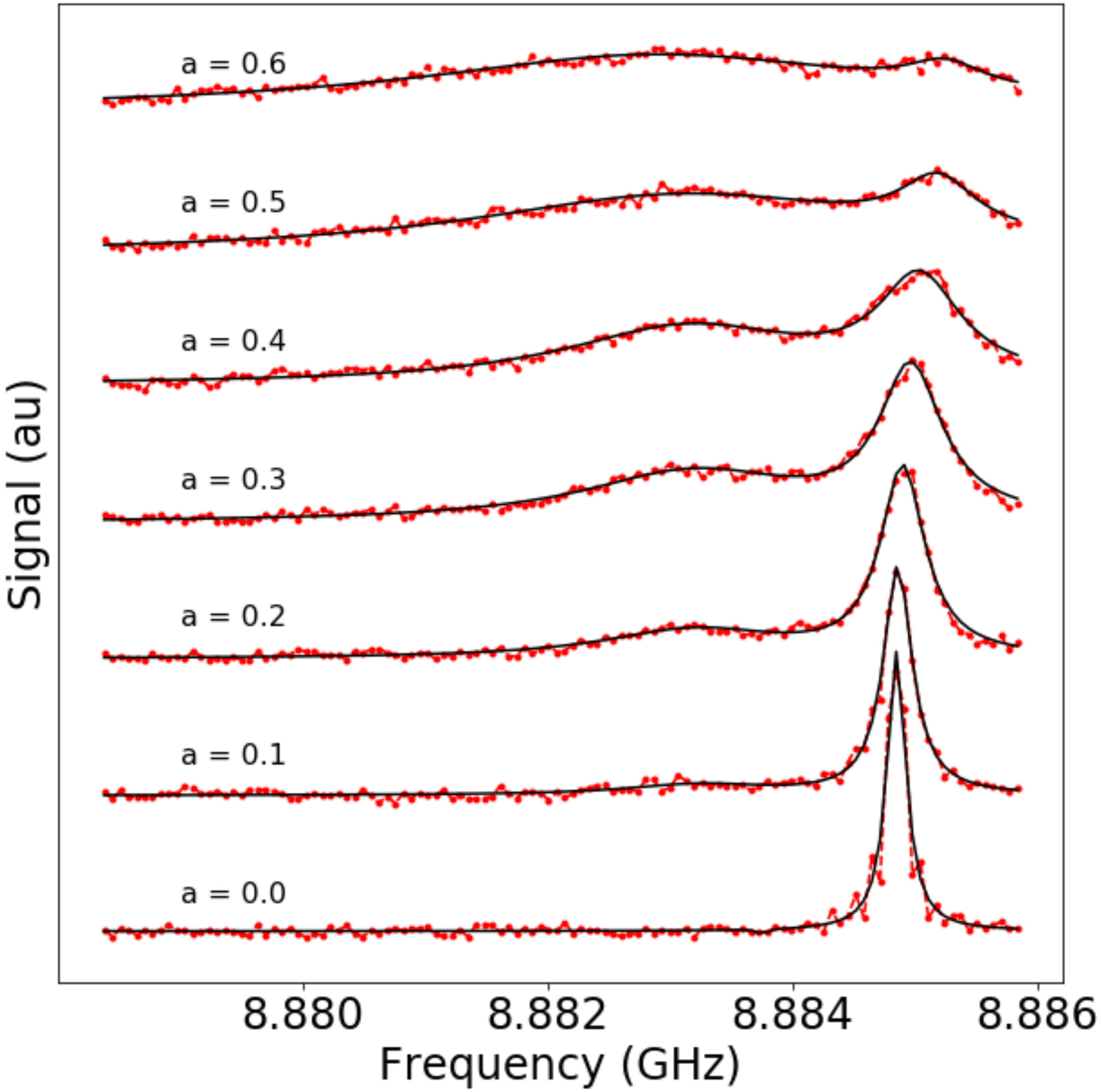
Qubit Energy Relaxation
T1 = 48us



Qubit Decoherence
Ramsey Experiment
T2 = 44.5us



Number Splitting



Dephasing with Cavity Drive