Detecting Axion Dark Matter with Superconducting Qubits

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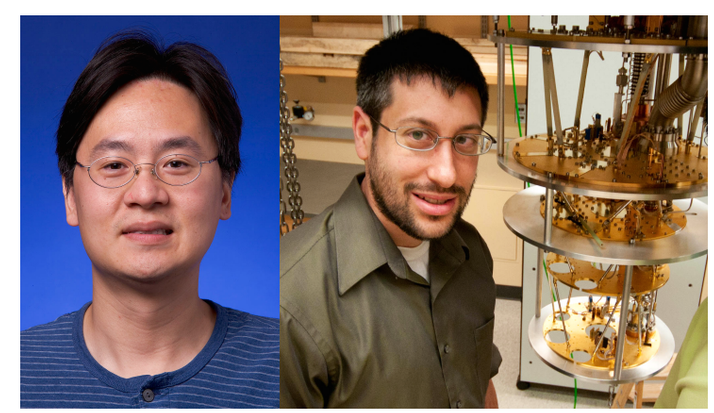
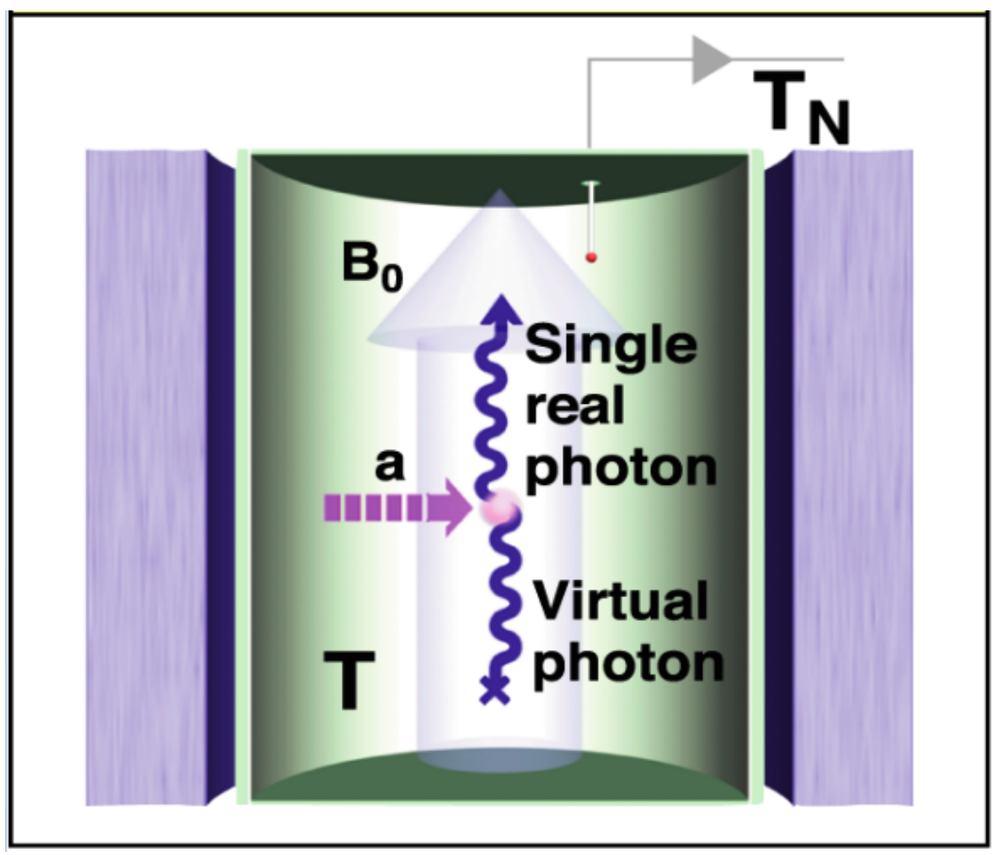


Axion Dark Matter

- Broken U1 symmetry introduced to solve Strong CP problem (Peccei & Quinn)
- Boson from symmetry breaking may be Dark Matter
- Behaves as a coherent wave over distances larger than experiment (~100m)

Axion-Photon Conversion

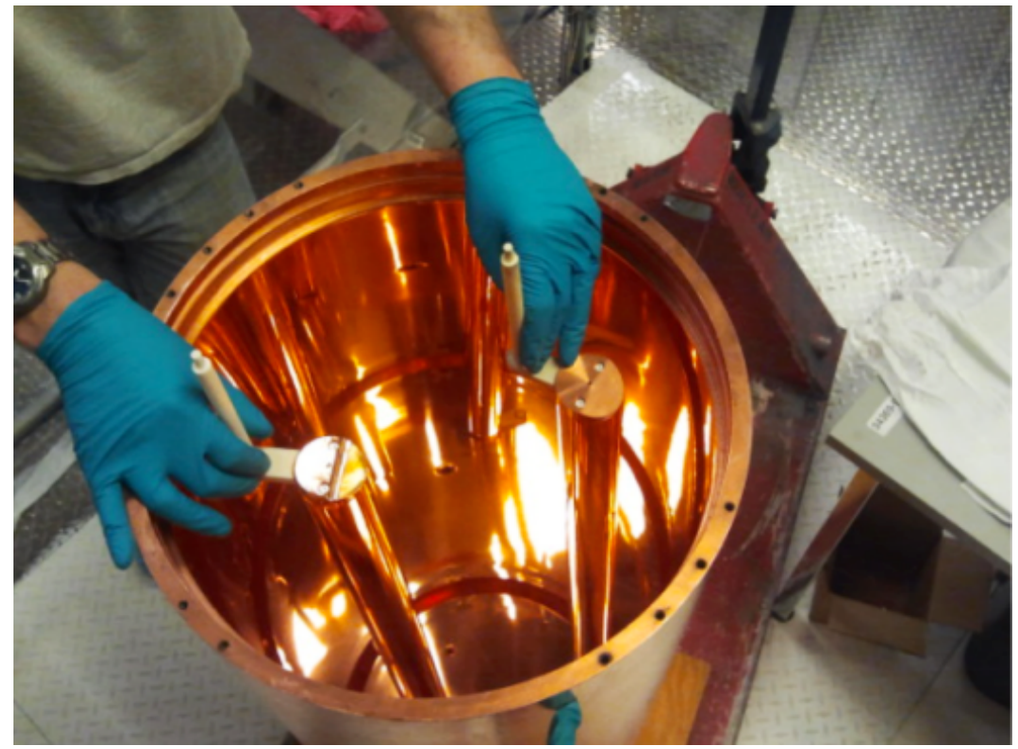


$$\mathcal{L} \sim ga\mathbf{E}\cdot\mathbf{B}$$

$$\sim g\frac{\partial a(t)}{\partial t}\mathbf{B_0}(x)\cdot\mathbf{A}$$

$$\sim \mathbf{J_a}\cdot\mathbf{A}$$

Microwave Receiver

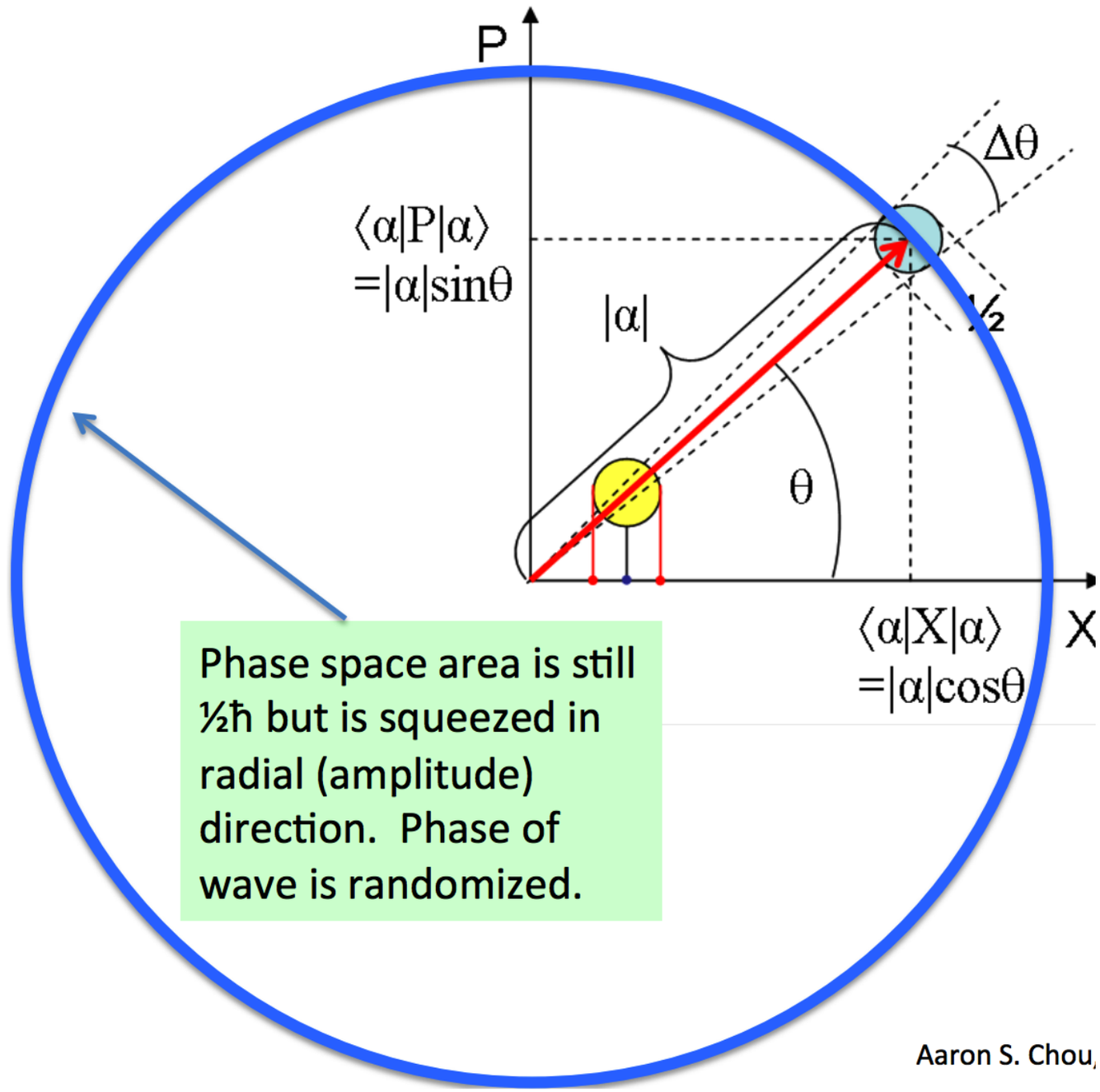


Use axion induced current to drive cavity

$$f \sim m_a$$

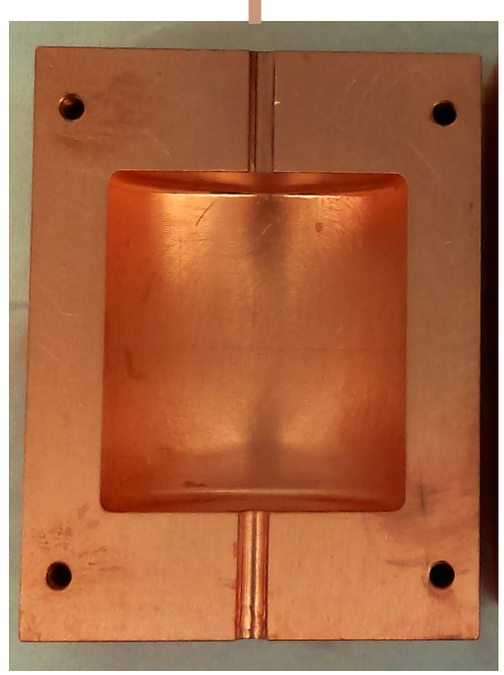
Currently operating ~1GHz, R&D ~10GHz

Single Photon Counting



Harmonic Oscillator + Two Level System

$$\mathcal{H} = \omega_c a^\dagger a + \omega_q \sigma_z + 2\frac{g^2}{\Delta} a^\dagger a \sigma_z$$



g: cavity-qubit coupling

$\Delta = \omega_q - \omega_c$ detuning

$\chi = \frac{g^2}{\Delta}$ Stark Shift

Experimental Procedure

Axion induced current pumps cavity with photon

Cavity occupation shifts qubit transition

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

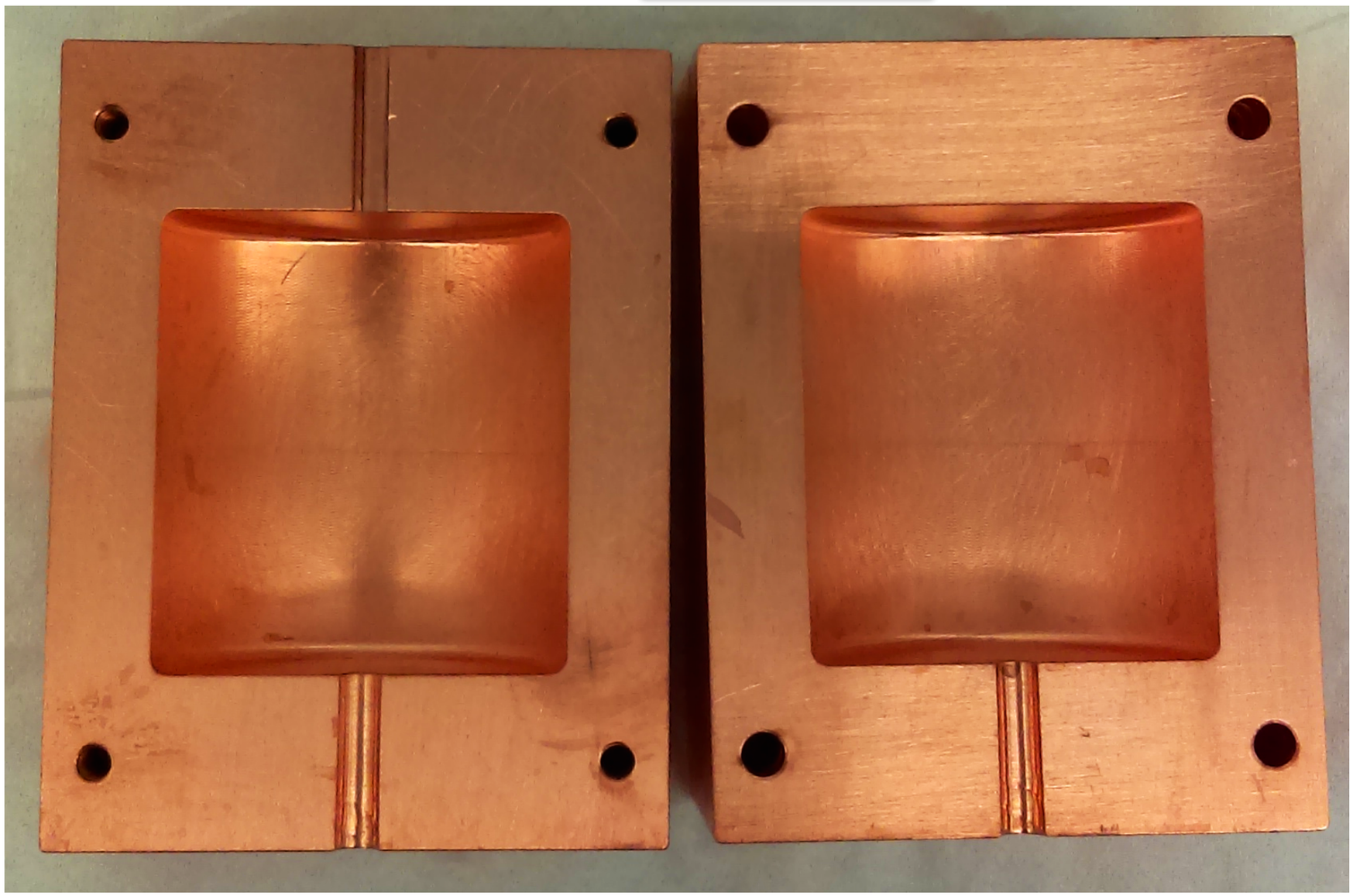
Excite qubit at shifted frequency

Measure flipped qubit by monitoring cavity line shift

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

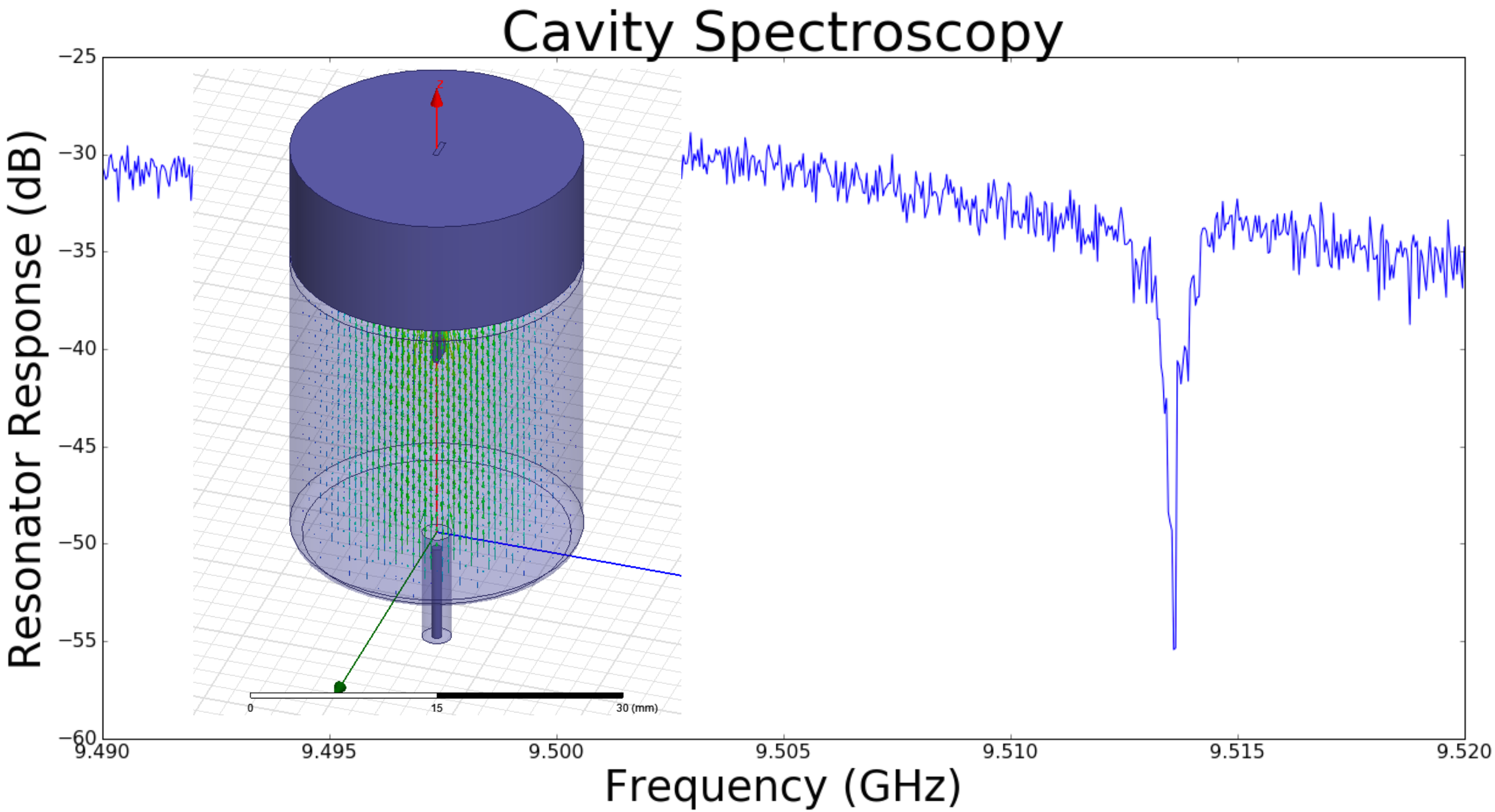
Cavity Design

$$\mathcal{H} = \omega_c a^\dagger a$$



10mm

Cavity Mode


Cavity Spectroscopy
Resonator Response (dB)
−25
−30
−35
−40
−45
−50
−55
−60
9.490
9.495
9.500
9.505
9.510
9.515
9.520
Frequency (GHz)
z
0
15
30 (mm)

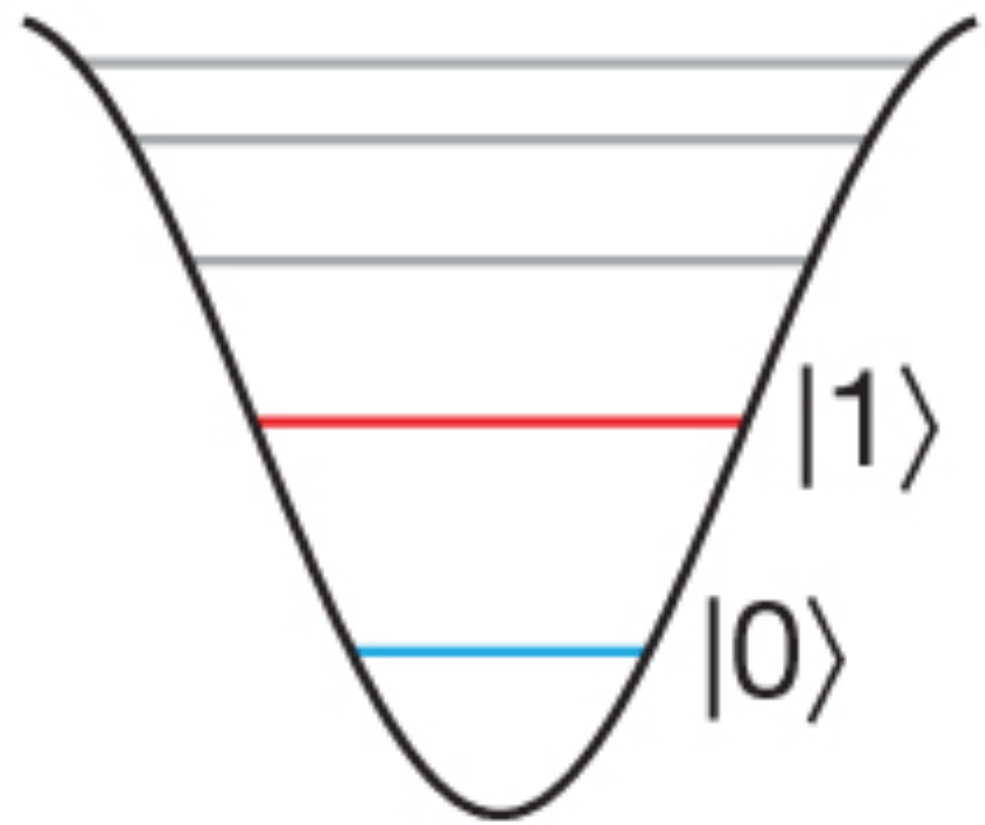
Custom Atom

$$\mathcal{H} = \omega_q \sigma_z$$

Design your own

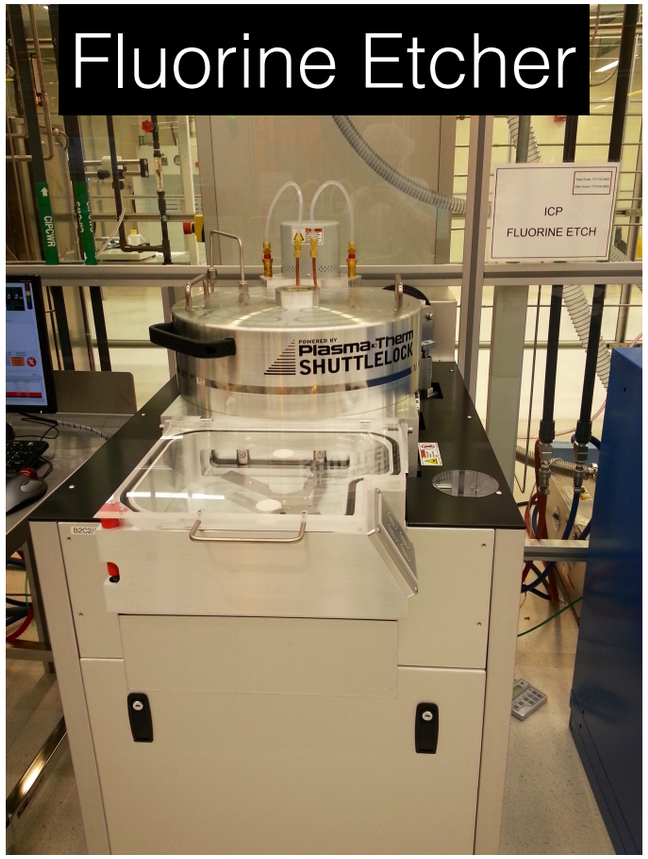
- Frequency
- Dipole Moment

Harmonic Oscillator (LC) + nonlinearity (Josephson Junction)



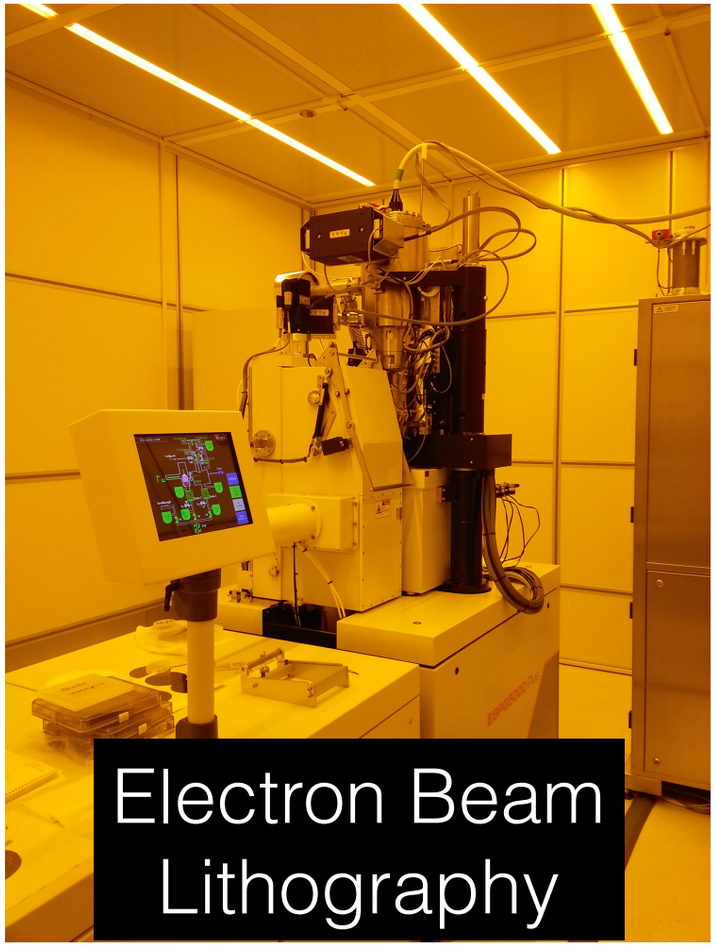
$$\omega_q = E_1 - E_0$$

Pritzker Nanofab Lab @UChicago



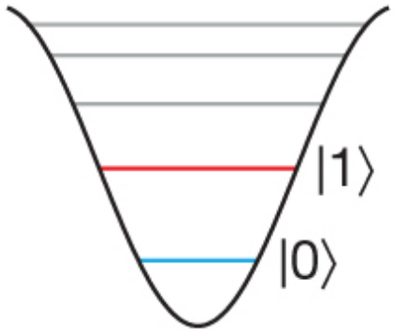
Fluorine Etcher

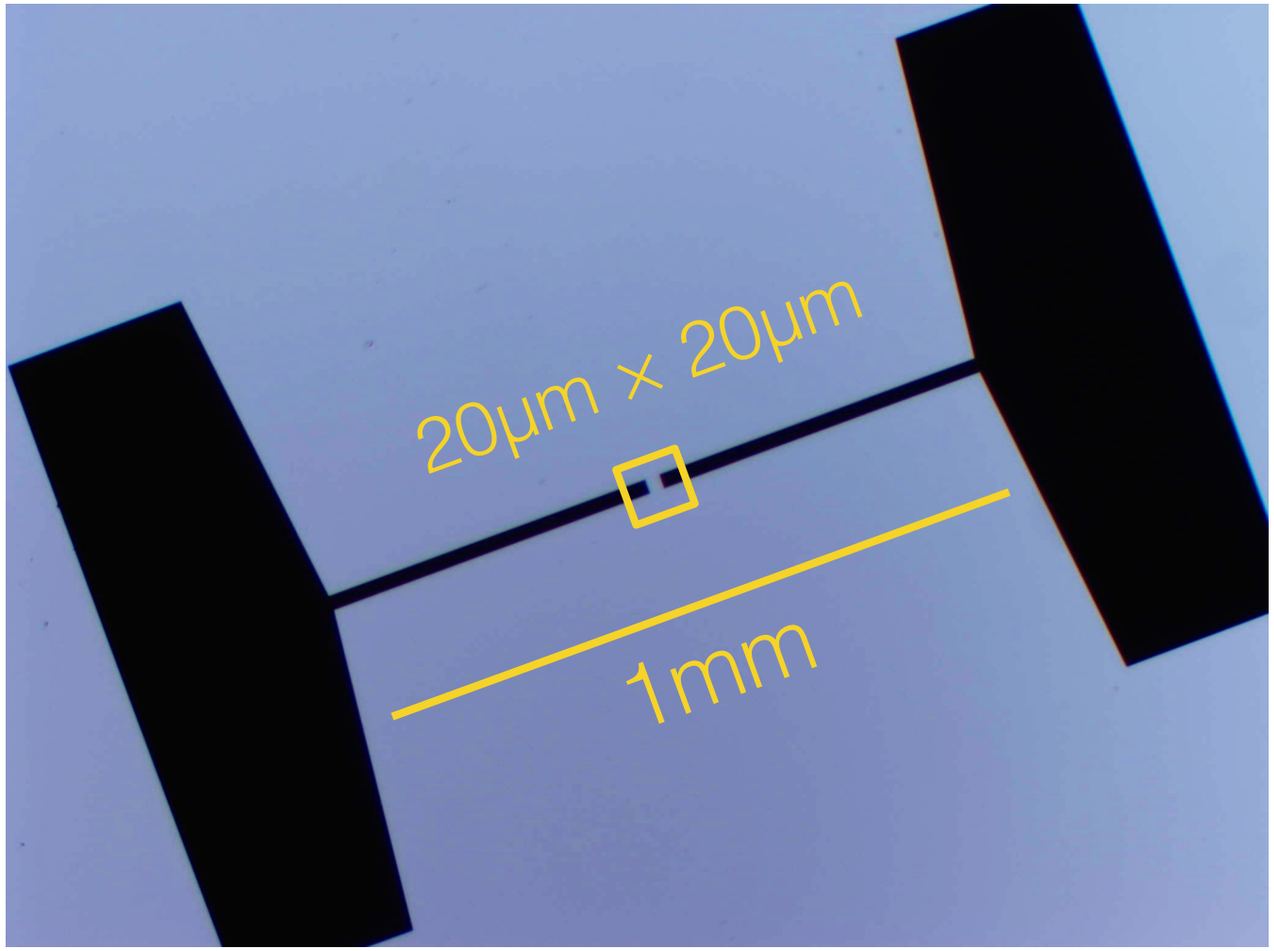
Optical Direct Writer


Electron Beam Lithography

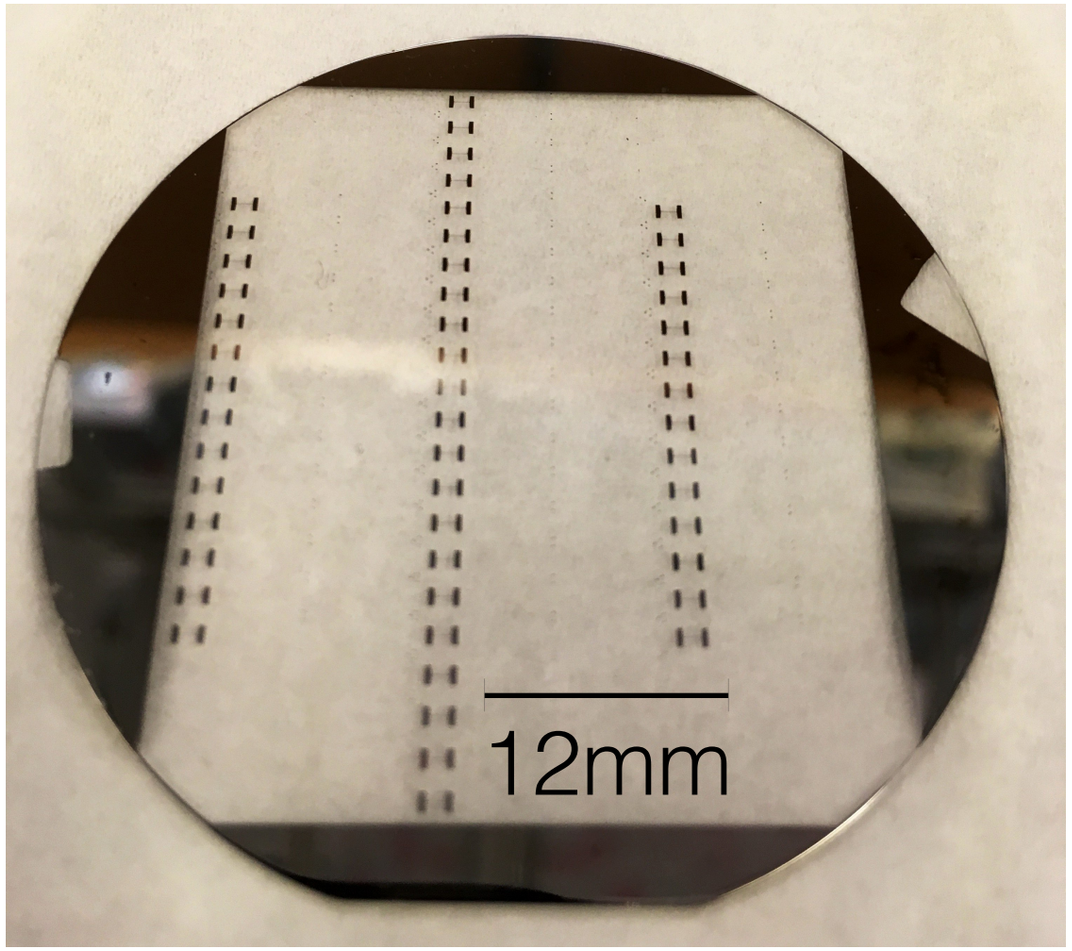
Not pictured:
-Double Angle Evap
-Thermal Evap
-Dicing Saw
-SEM
-Sputter Coater

Qubit



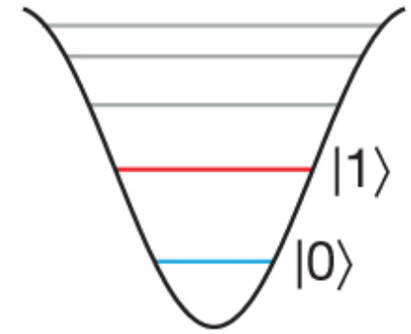


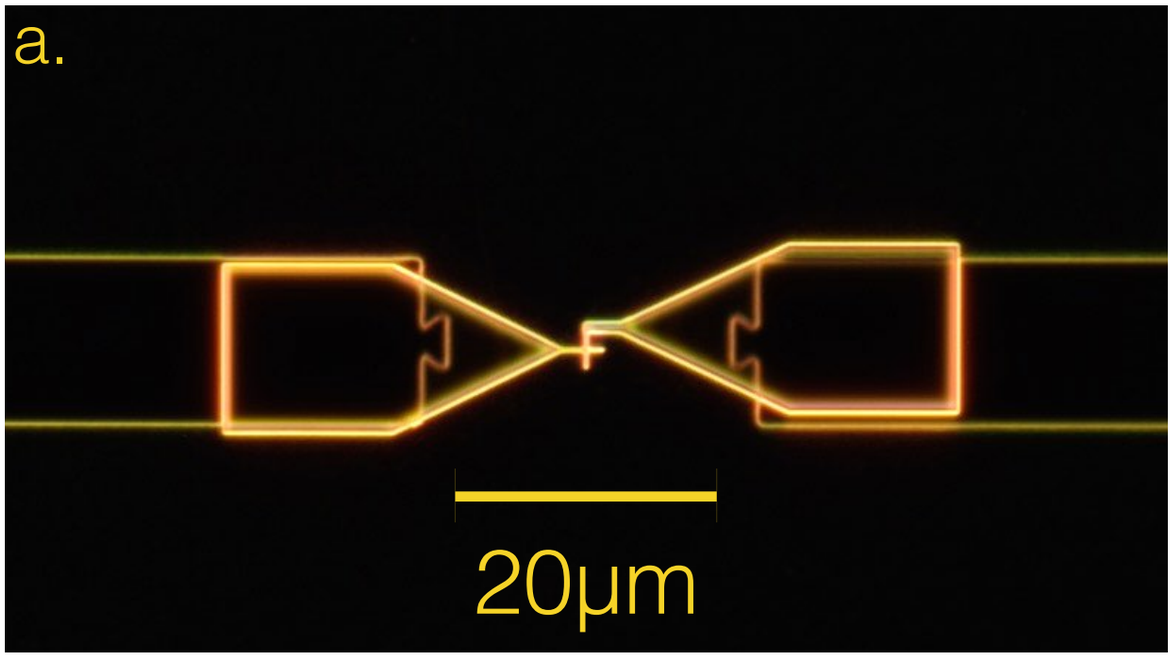
Nb optically patterned and etched to form dipole arms and capacitive pads



Qubits on wafer

Qubit

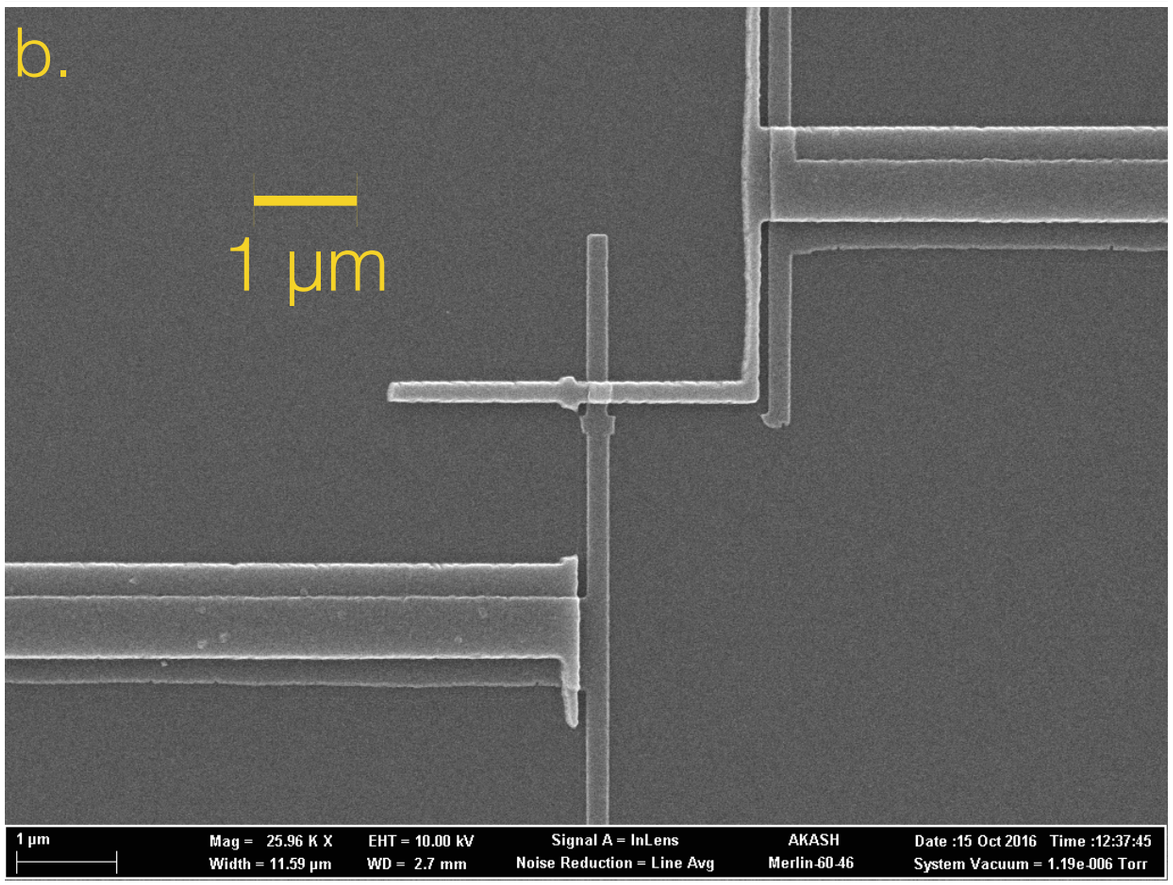


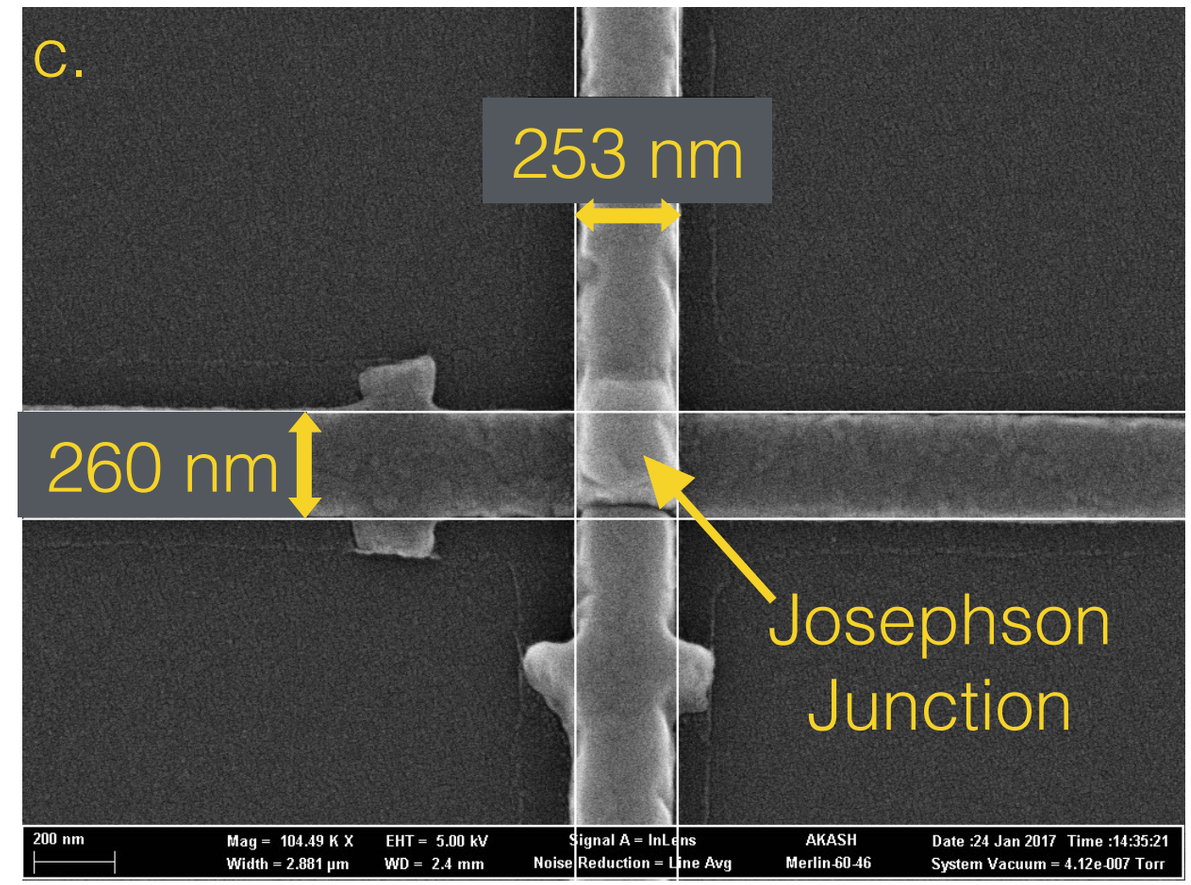


a. Electron beam junction patterning

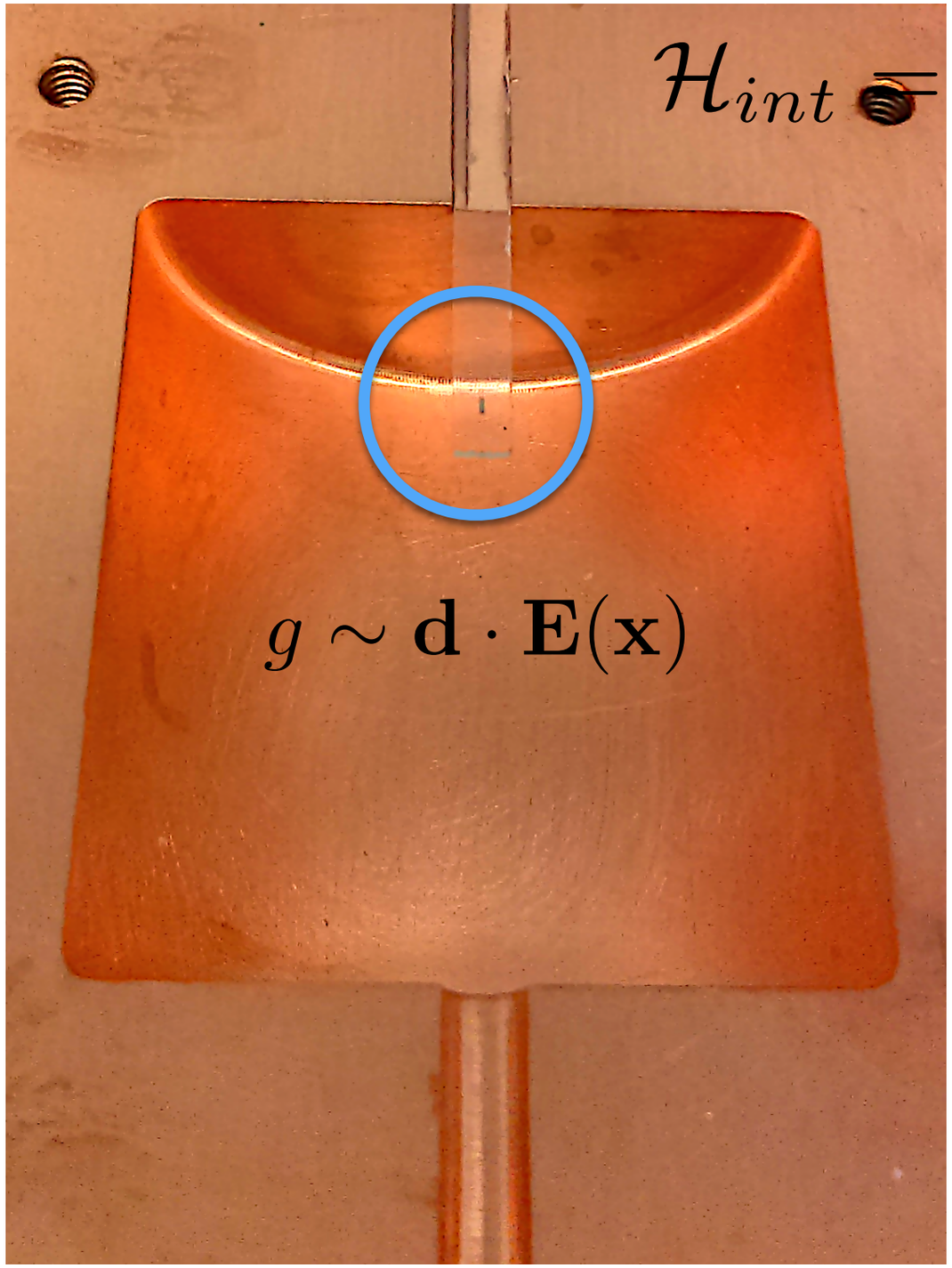
b. Scanning electron microscopy

c. Josephson Junction



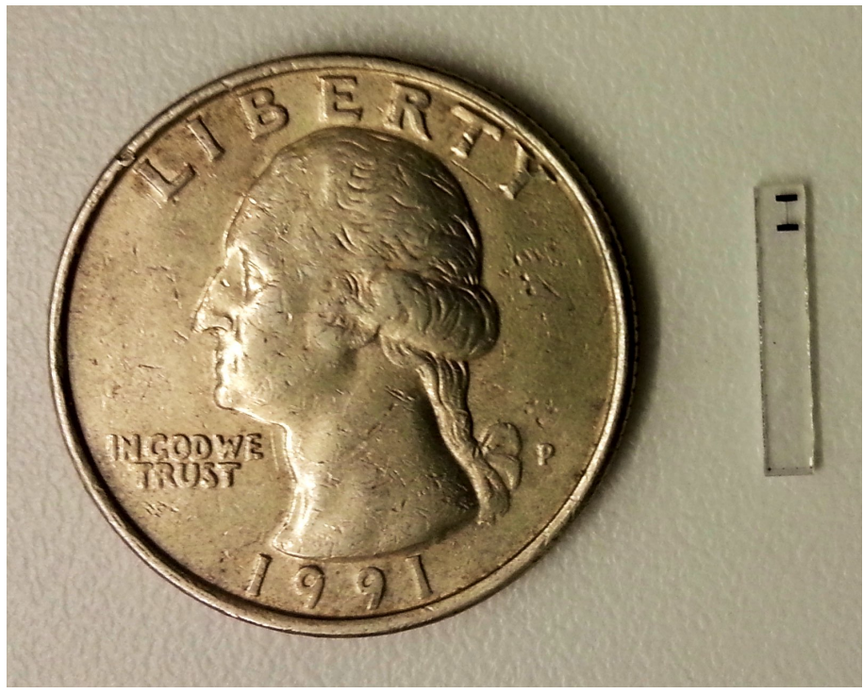


Cavity + Qubit



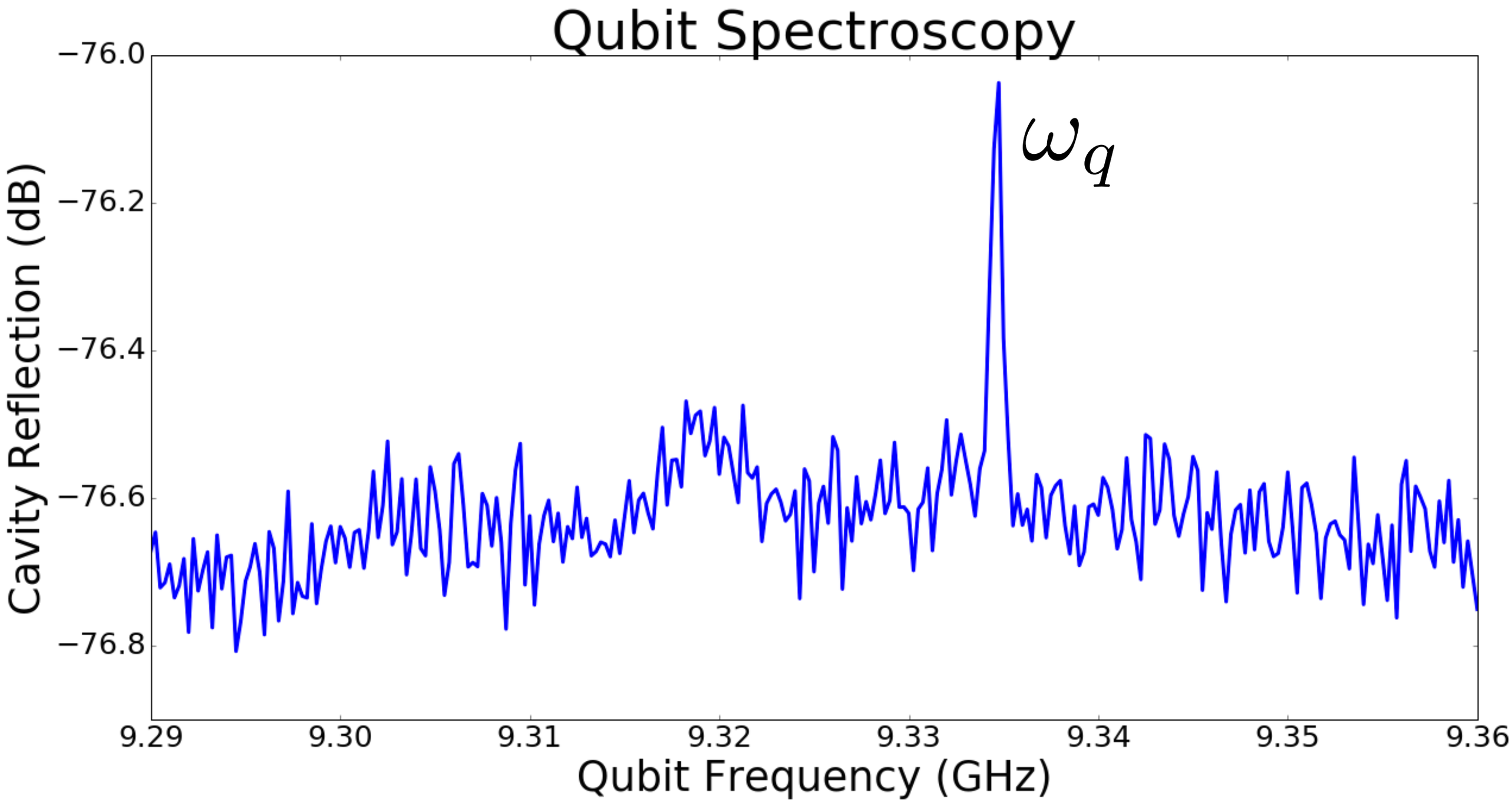
$$\mathcal{H}_{int} = 2\frac{g^2}{\Delta}a^\dagger a \sigma_z$$

$$g \sim \mathbf{d} \cdot \mathbf{E}(\mathbf{x})$$



Dipole arms + qubit location in cavity set qubit-cavity coupling

Bare Qubit


Qubit Spectroscopy
ω_q
−76.0
−76.2
−76.4
−76.6
−76.8
Cavity Reflection (dB)
9.29
9.30
9.31
9.32
9.33
9.34
9.35
9.36
Qubit Frequency (GHz)

Experimental Procedure

Axion induced current pumps cavity with photon

Cavity occupation shifts qubit transition

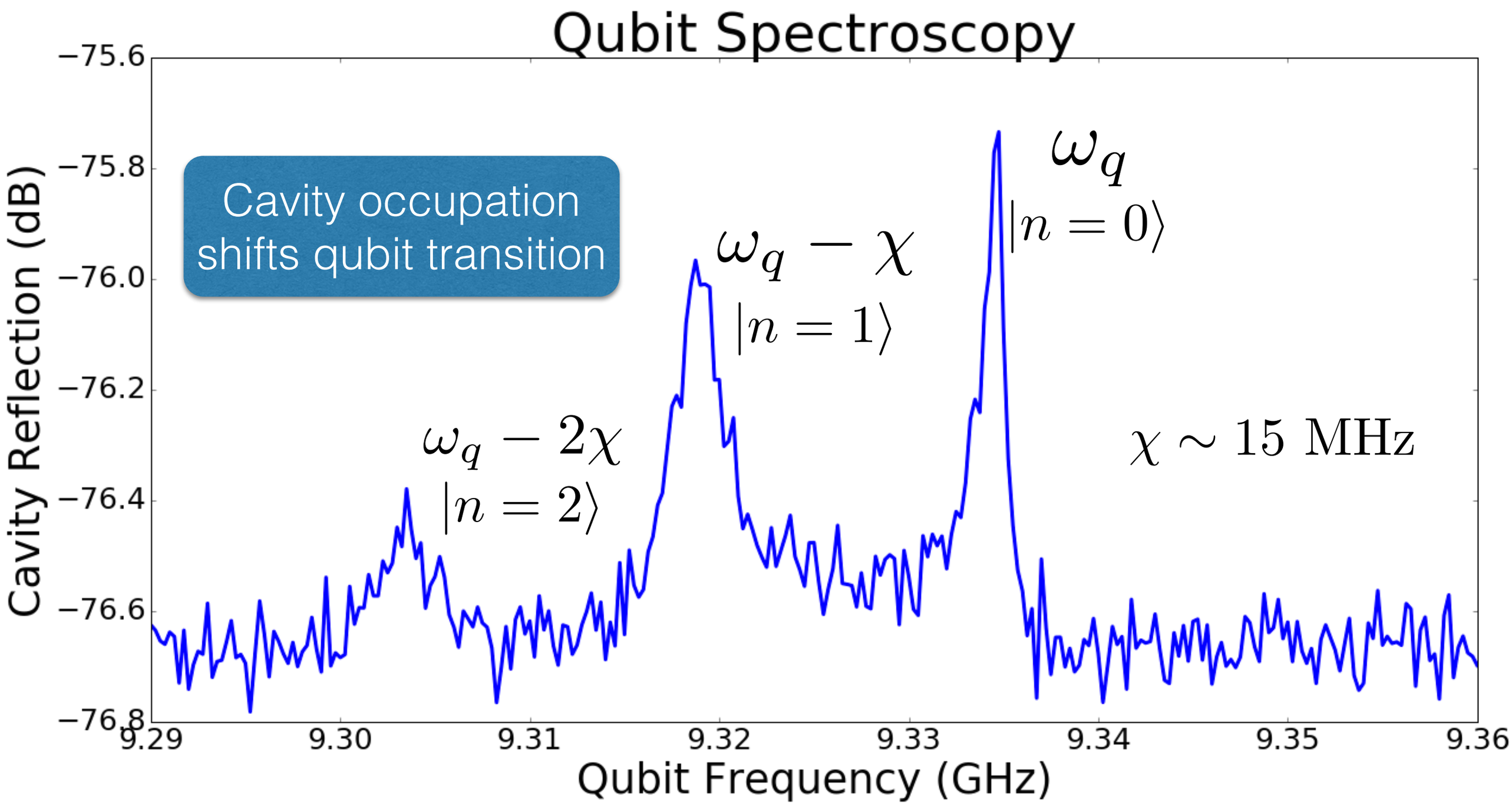
$$\mathcal{H} = \omega_c a^\dagger a + (\omega_q + 2\frac{g^2}{\Delta} a^\dagger a)\sigma_z$$

Excite qubit at shifted frequency

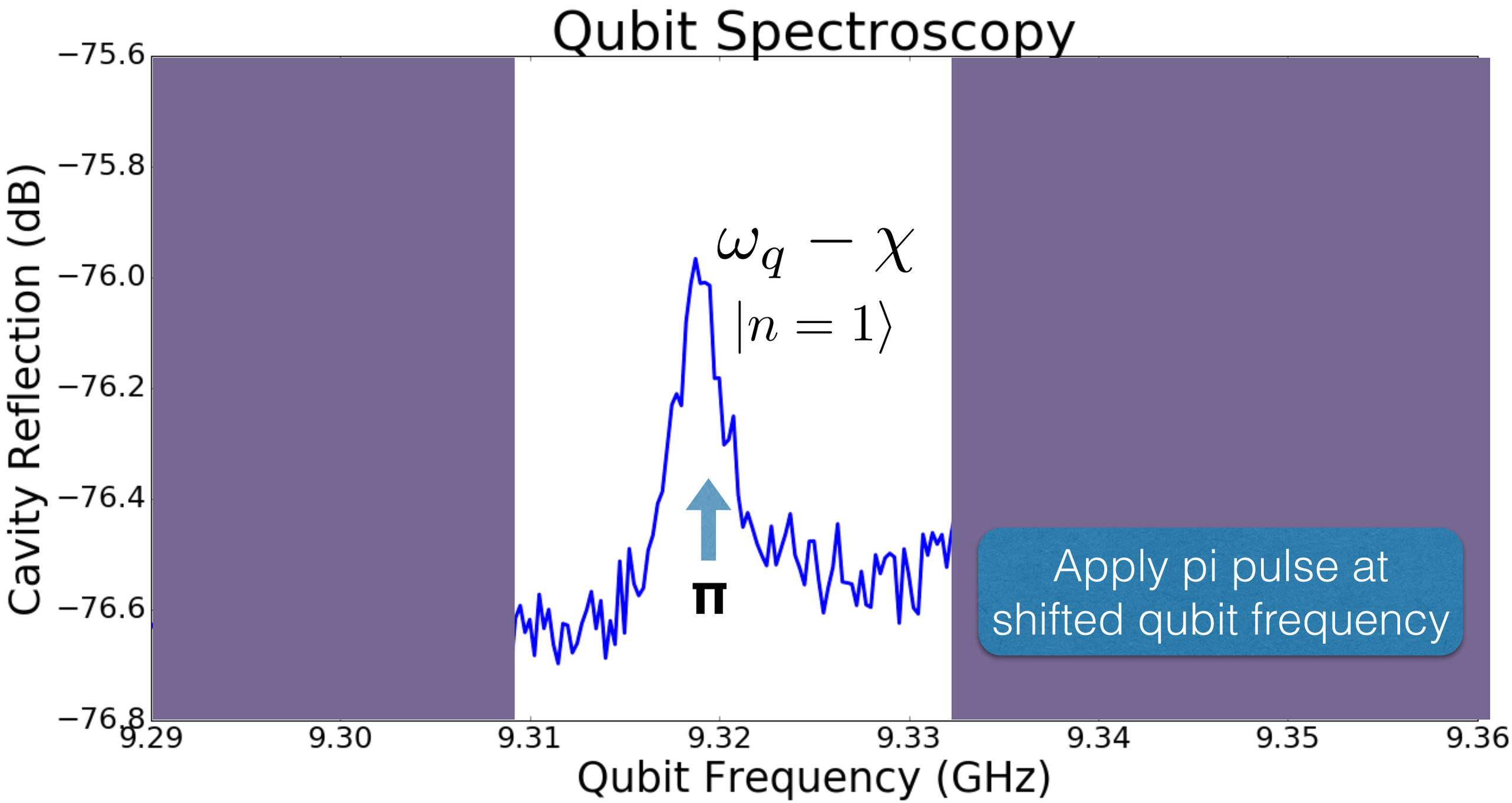
Measure flipped qubit by monitoring cavity line shift

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

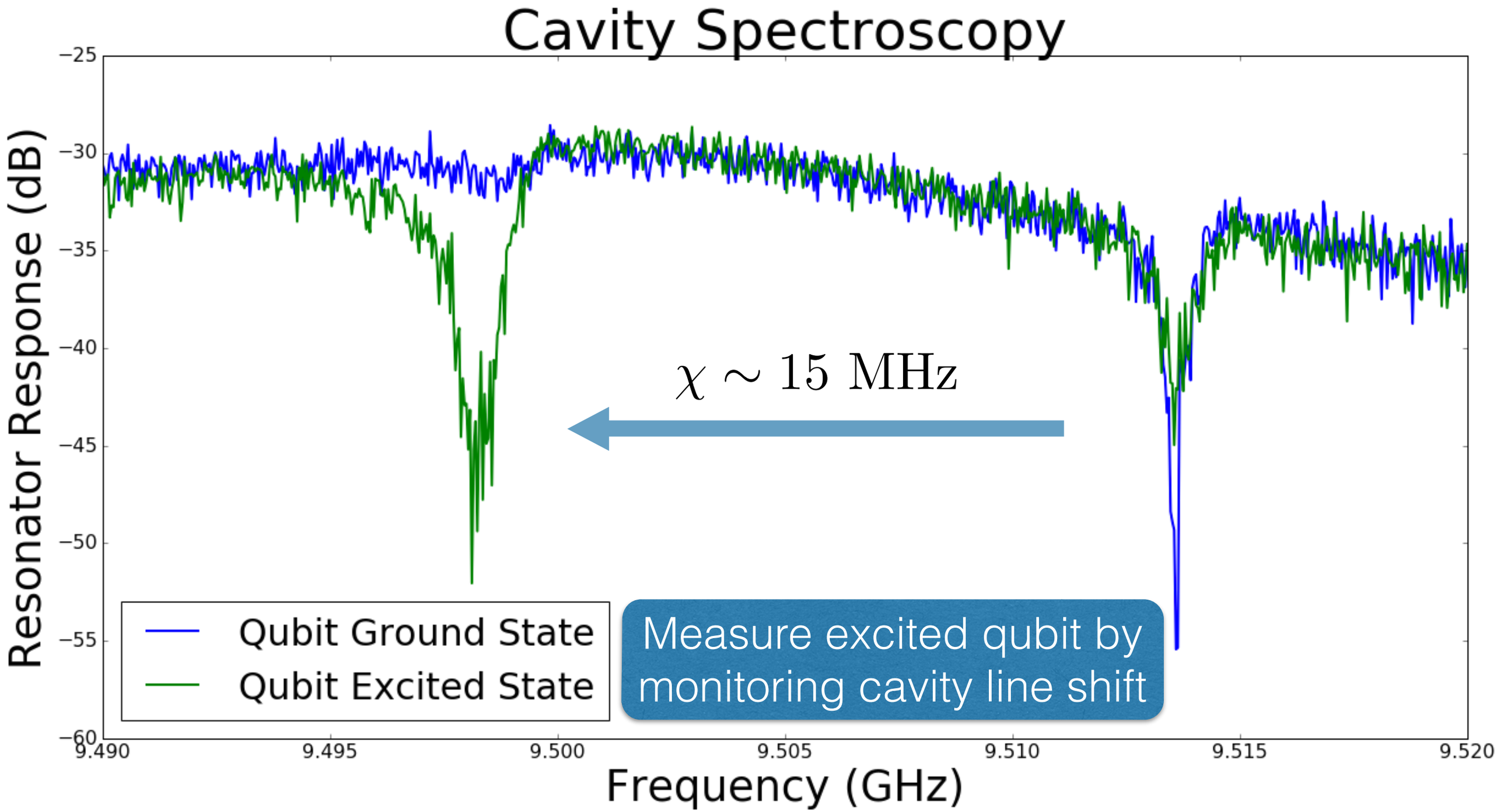
Cavity Dependent Qubit



Qubit Interrogation



Confirm Qubit Flip w/ Cavity



Conclusion

Shift penalties of standard quantum limit by counting photons rather than absorbing them

I make solid state superconducting detectors with customizable interactions with an EM environment

I employ quantum computing techniques/devices for dark matter cosmology experiment

Thank you

HEISING-SIMONS FOUNDATION

Pritzker Nanofabrication Facility

schuster.lab

THE UNIVERSITY OF CHICAGO

Fermilab

ADMX AXION DARK MATTER EXPERIMENT

SiDet tour
Friday
1:00-3:30 pm

References

[1] D.I. Schuster. *Circuit Quantum Electrodynamics*. PhD thesis, Yale University, 2007.

[2] B.R. Johnson. *Controlling Photons in Superconducting Electrical Circuits*. PhD thesis, Yale University, 2011.

[3] S. K. Lamoreaux, K. A. van Bibber, K. W. Lehnert, and G. Carosi. *Analysis of single-photon and linear amplifier detectors for microwave cavity dark matter axion searches*. Phys. Rev. D, 88:035020, Aug 2013.

[4] V Bouchiat, D Vion, P Joyez, D Esteve, and M H Devoret. *Quantum coherence with a single cooper pair*. Physica Scripta, 1998(T76):165, 1998.

[5] Jens Koch, Terri M. Yu, Jay Gambetta, A. A. Houck, D. I. Schuster, J. Majer, Alexandre Blais, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf. *Charge-insensitive qubit design derived from the cooper pair box*. Phys. Rev. A, 76:042319, Oct 2007.

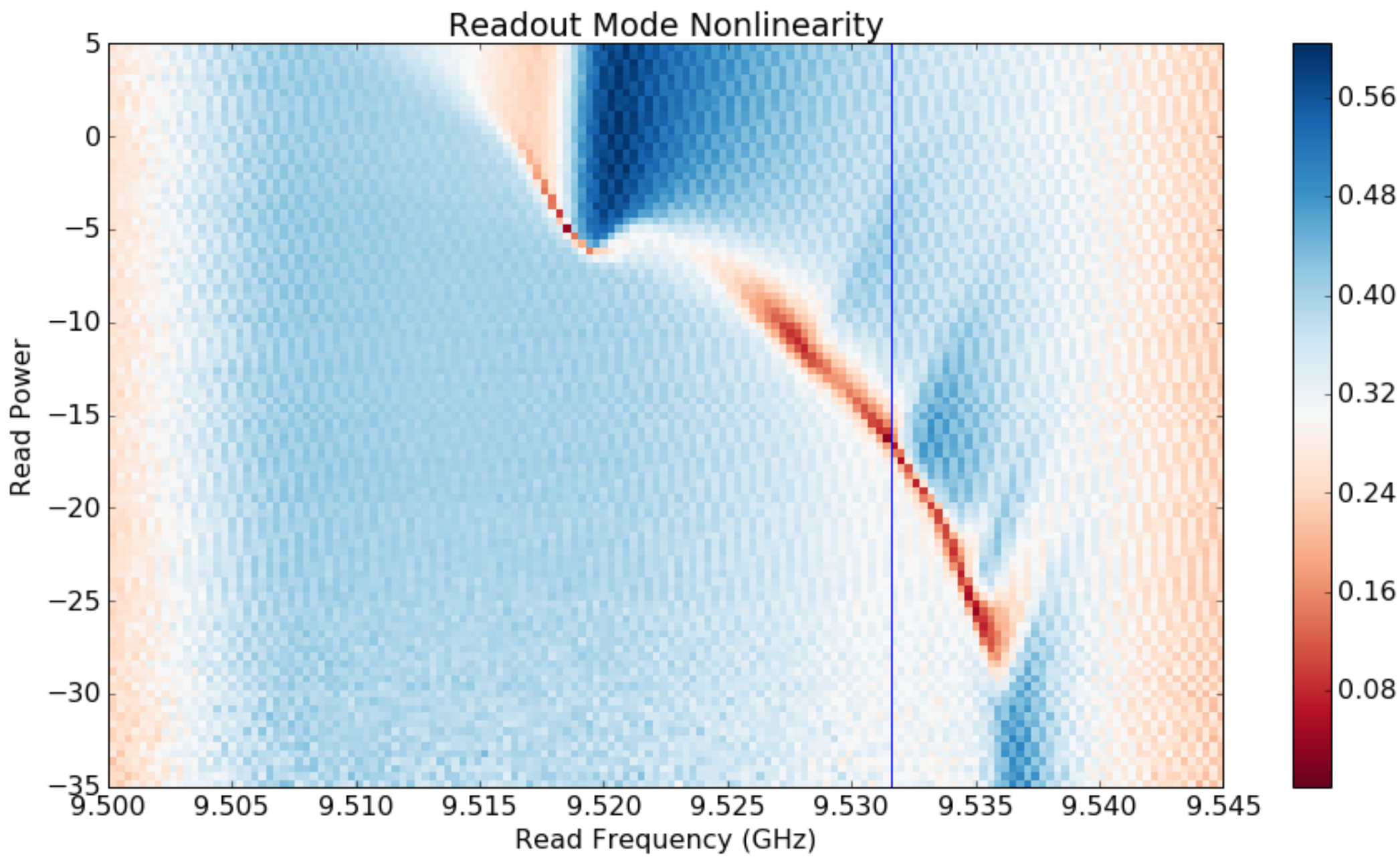
[6] Simon E. Nigg, Hanhee Paik, Brian Vlastakis, Gerhard Kirchmair, S. Shankar, Luigi Frunzio, M. H. Devoret, R. J. Schoelkopf, and S. M. Girvin. *Black-box superconducting circuit quantization*. Phys. Rev. Lett., 108:240502, Jun 2012.

[7] http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.105.173601

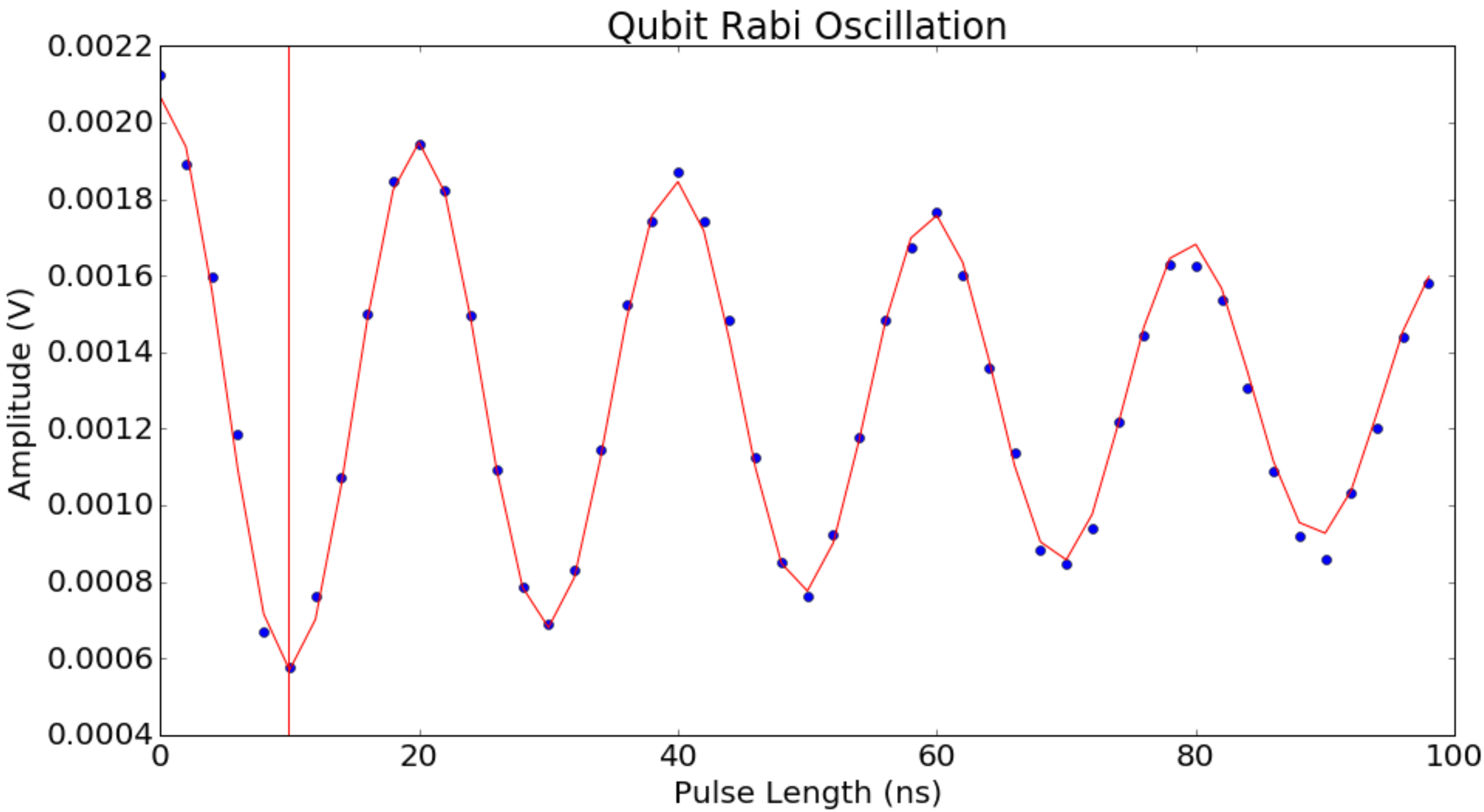
[8] https://arxiv.org/pdf/1206.1265.pdf

Cavity

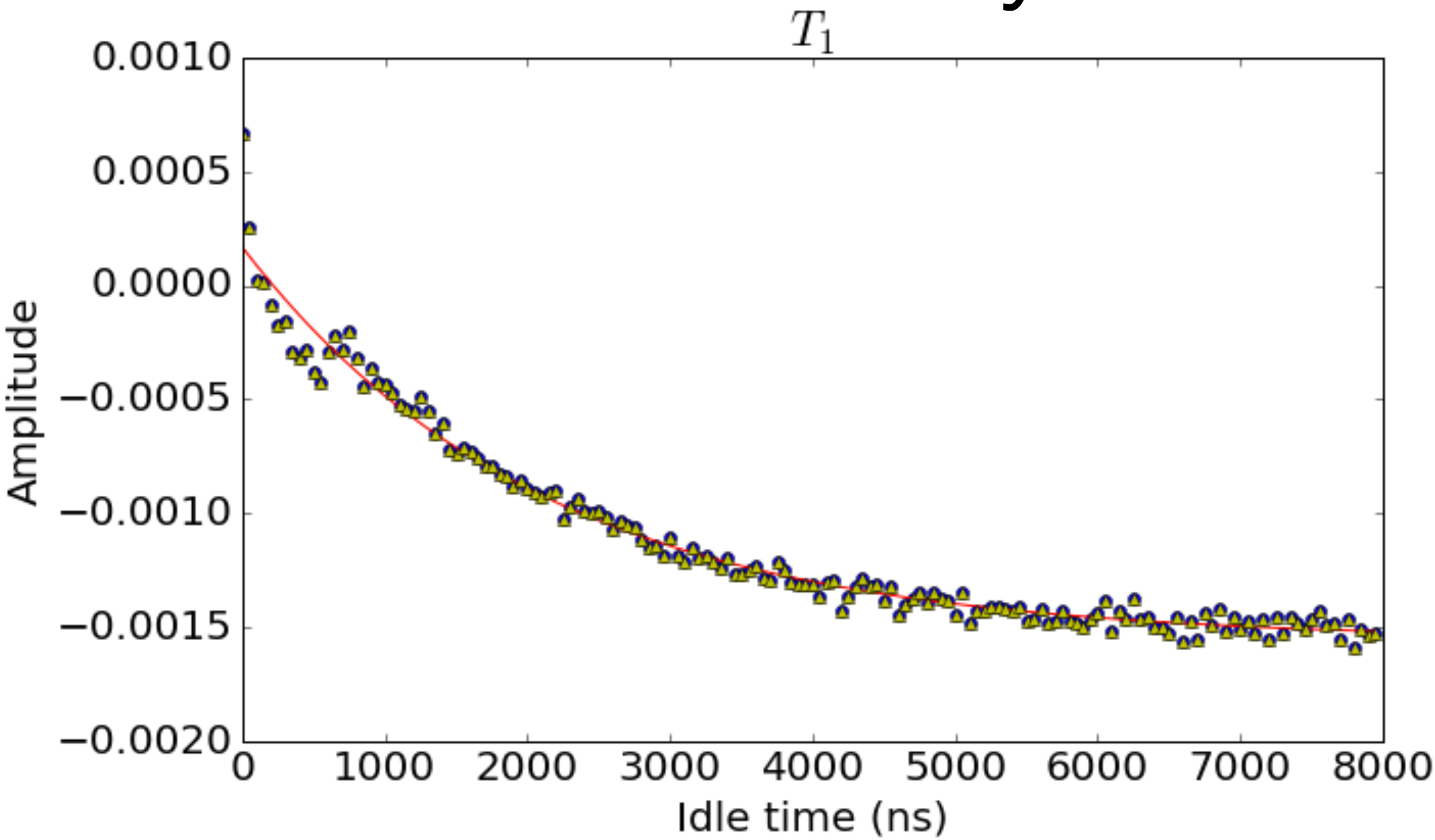
Fourth order term, Cavity nonlinearity



Qubit Rabi Oscillations



Qubit Decay


T_1
0.0010
0.0005
0.0000
−0.0005
−0.0010
−0.0015
−0.0020
Amplitude
0
1000
2000
3000
4000
5000
6000
7000
8000
Idle time (ns)