Dispersive measurement of a phase qubit using a tunable cavity

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February 7, 2013

Introduction - DiVincenzo criteria

Gated quantum processing requires:

1. Scalable physical system with well characterized qubits
2. Ability to initialize qubits to a simple fiducial state (*i.e.* $|000...\rangle$)
3. Decoherence time $\gg$ than gate operation time
4. Set of "universal" quantum gates
5. Qubit-specific measurement capability

David P. DiVincenzo, **The Physical Implementation of Quantum Computation** *Fortschritte der Physik* **48** 771 2000

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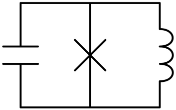
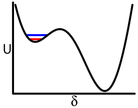
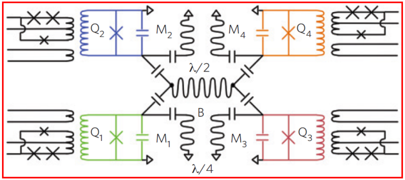
Introduction - Implementations

phase qubit

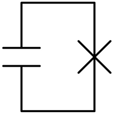


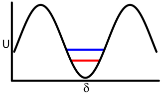


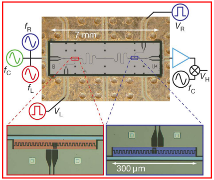


tunneling measurement

transmon



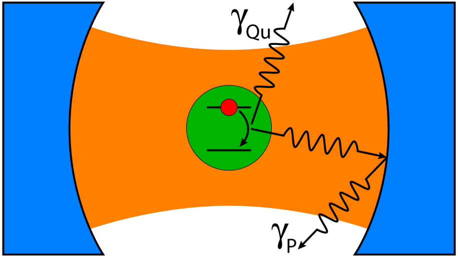


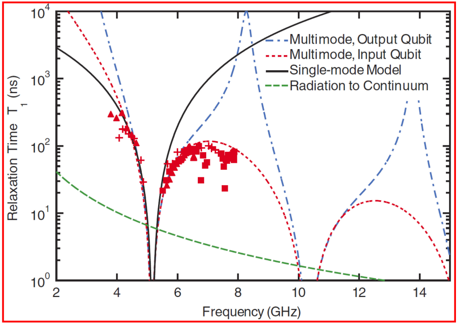


dispersive measurement

E. Lucero, **Computing prime factors with a Josephson phase qubit quantum processor** *Nature Physics* **8** 719 2012
L. DiCarlo et al, **Demonstration of two-qubit algorithms with a superconducting quantum processor** *Nature* **460** 240 2009

Introduction - Purcell effect



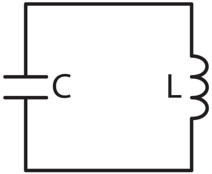


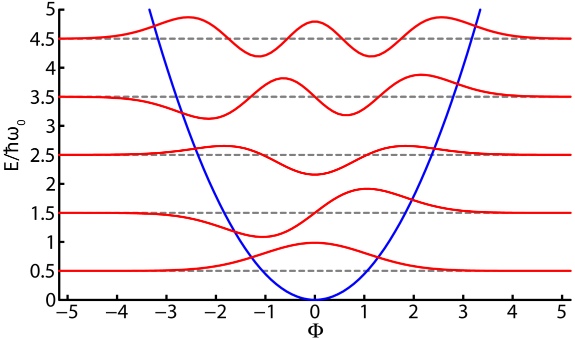
A. A. Houck et al, **Controlling the Spontaneous Emission of a Superconducting Transmon Qubit** *Physical Review Letters* **101** 080502 2008

Outline

- Introduction
- Tunneling and dispersive measurement schemes
- Device design and fabrication
- Tunneling measurements
- Dispersive measurements
- The Purcell effect
- Conclusions

Quantum harmonic oscillator

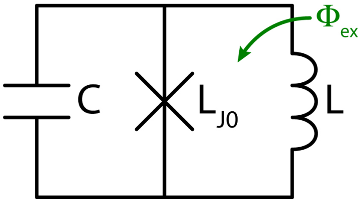




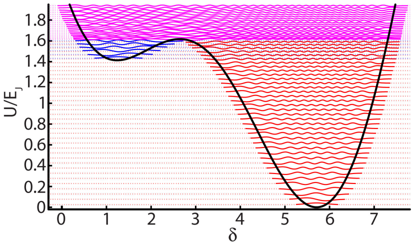
$$H = \frac{1}{2} L I_L^2 + \frac{1}{2} C V_C^2 \;\rightarrow\; \hat{H} = \hbar\omega_0 \left(a^\dagger a + 1/2 \right)$$

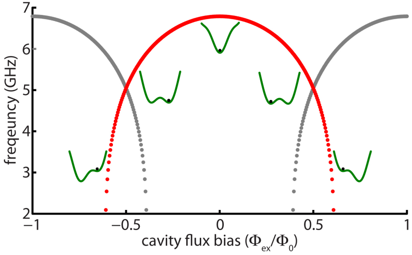
$$\omega_0 / 2\pi \approx 2 - 10 GHz,\; T \approx 40 mK,\; k_B T \ll \hbar\omega_0$$

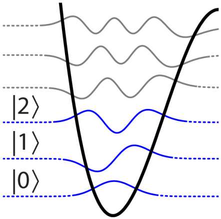
The phase qubit



$L/L_{J0} > 1.0$

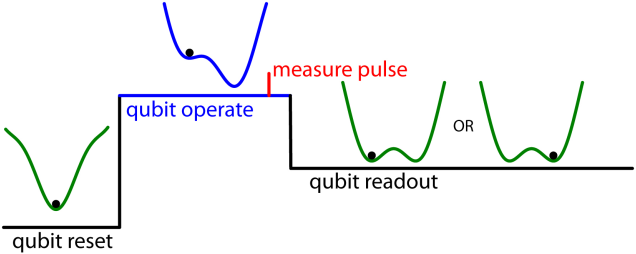


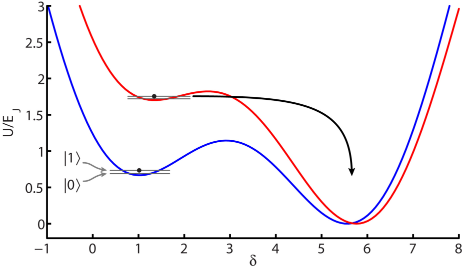




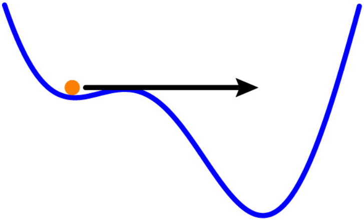
$$\alpha_r = \frac{E_{12} - E_{01}}{E_{01}}$$

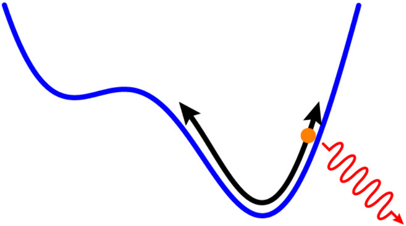
Phase qubit tunneling measurement



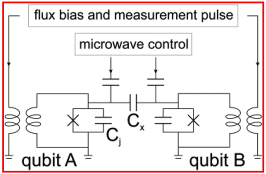


Tunneling measurement ringdown

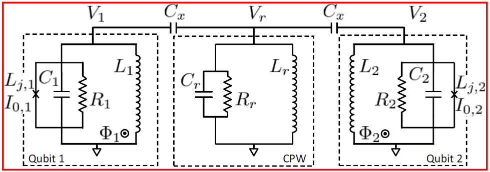




2005



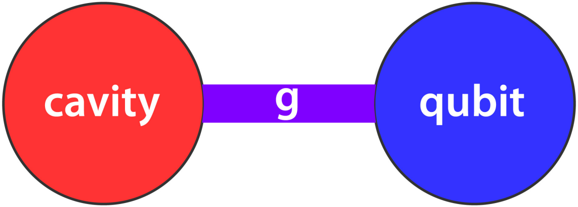
2010



R. McDermott et al, **Simultaneous State Measurement of Coupled Josephson Phase Qubits** *Science* **307** 1299 2005

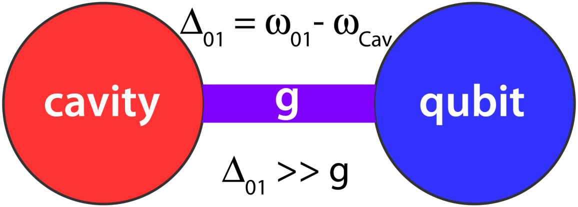
F. Altomare et al, **Measurement crosstalk between two phase qubits coupled by a coplanar waveguide** *Physical Review B* **82** 094510 2010

Jaynes-Cummings Hamiltonian



$$H_{JC} = \underbrace{\frac{1}{2}\hbar\omega_{Qu}\sigma_z}_{H_{Qu}} + \underbrace{\hbar\omega_{Cav}\left(a^\dagger a + \frac{1}{2}\right)}_{H_{Cav}} + \underbrace{\hbar g\left(a^\dagger\sigma^- + a\sigma^+\right)}_{H_{int}}$$

Jaynes-Cummings Hamiltonian



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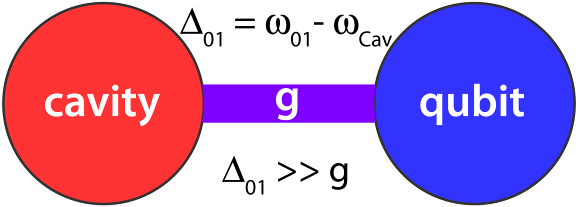
$$H_{JC} \approx \hbar\left[\omega_{Cav} + \frac{g^2}{\Delta_{01}}\sigma_z\right]a^\dagger a + \frac{\hbar}{2}\left[\omega_{Qu} + \frac{g^2}{\Delta_{01}}\right]\sigma_z$$

Jaynes-Cummings Hamiltonian



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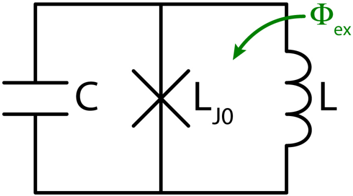
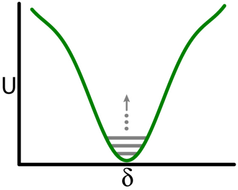
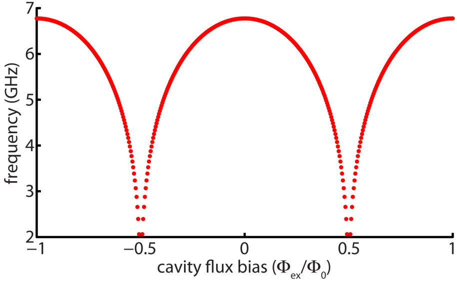
$$\widetilde{\omega_{Cav}} = \omega_{Cav} \pm \frac{g^2}{\Delta_{01}}$$

The tunable cavity

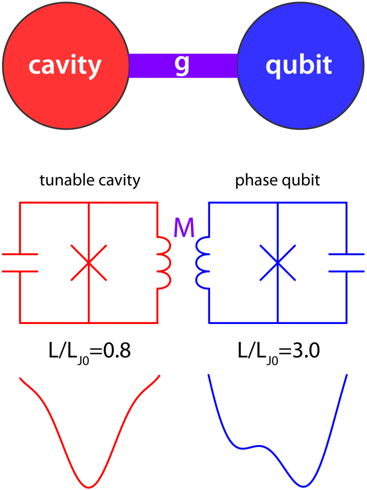




$$L/L_{J0} < 1.0$$



The device



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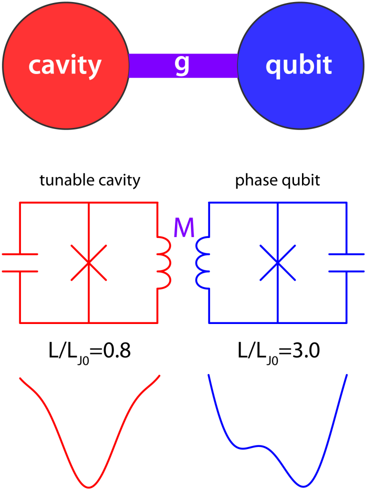
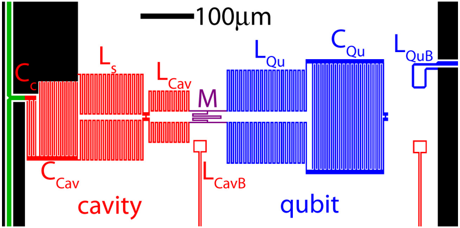
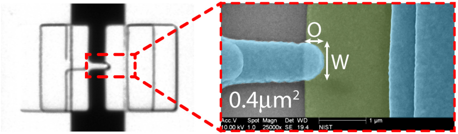
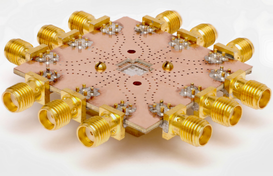

cavity
g
qubit
tunable cavity
phase qubit
M
L/L_J0=0.8
L/L_J0=3.0

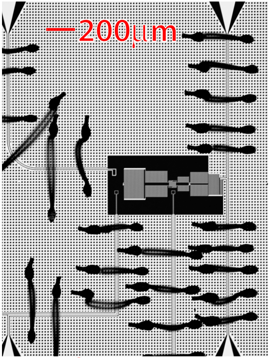

100µm
C_c
L_s
L_Cav
M
L_Qu
C_Qu
L_QuB
C_Cav
L_CavB
cavity
qubit


O
W
0.4µm²

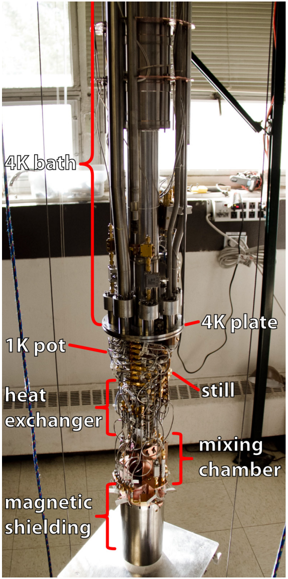
Dilution refrigerator mounting

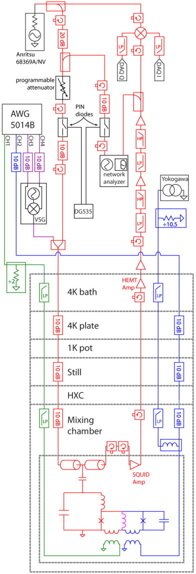


qubit bias port 1

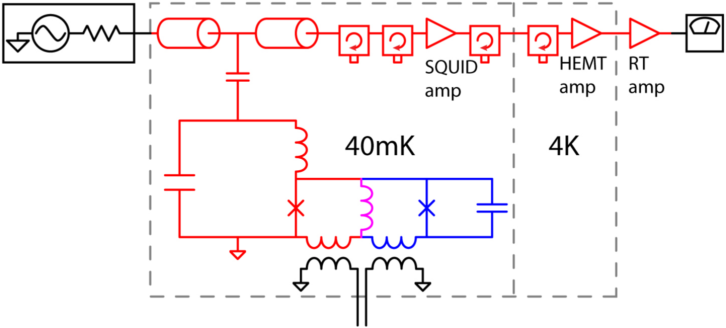


cavity bias port 2



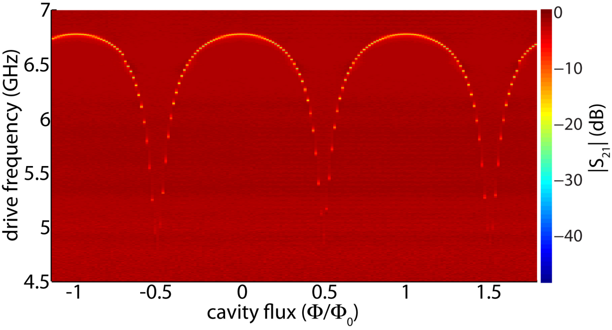


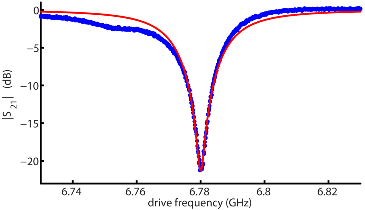
Microwave chain



Amplifier	f (GHz)	G (dB)	T_N (K)
SQUID	6.6 – 6.9	≈ 17	≈ 1
HEMT	4 – 12	≈ 38	≈ 4
RT	0.7 – 18	≈ 26	≈ 250

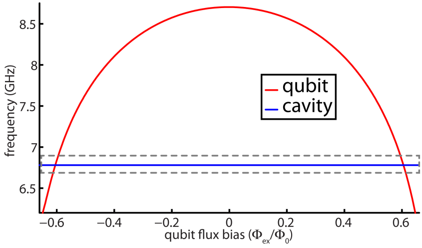
Tunable cavity characterization

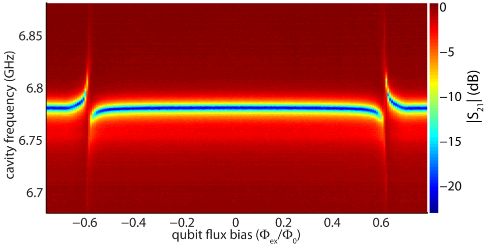


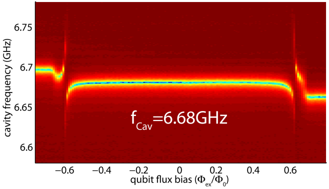


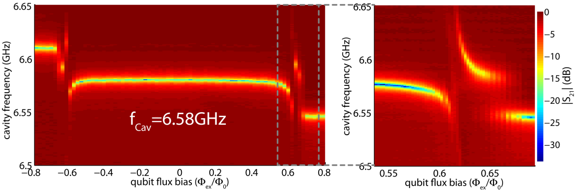
$$f_{max} = 6.78\,GHz$$
$$Q_{Cav} = 280$$
$$T_{Cav} = \frac{Q_{Cav}}{\omega_{Cav}} = 6.5\,ns$$
$$Q_{int} = 8970$$
$$Q_{ext} = 290$$

Cavity spectroscopy

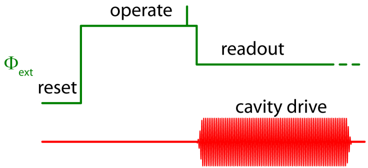


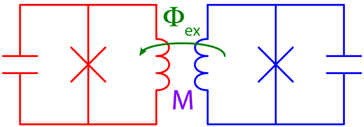


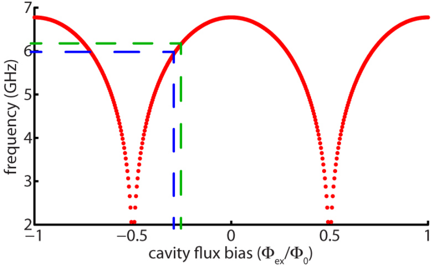


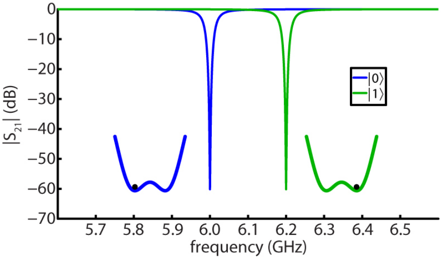


Flux readout with microwaves



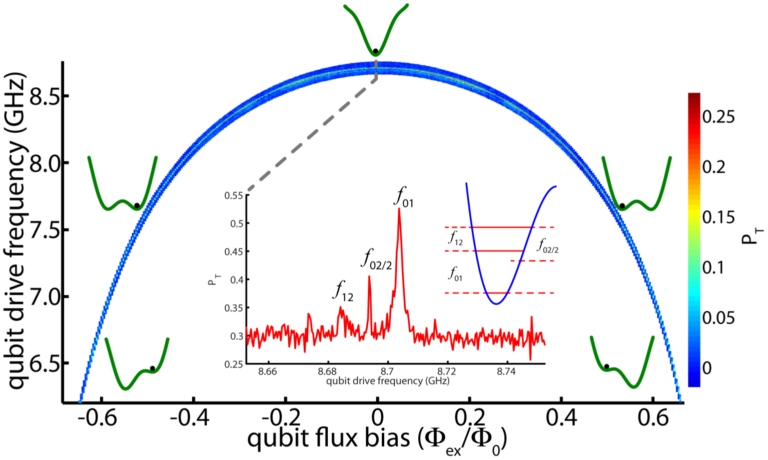




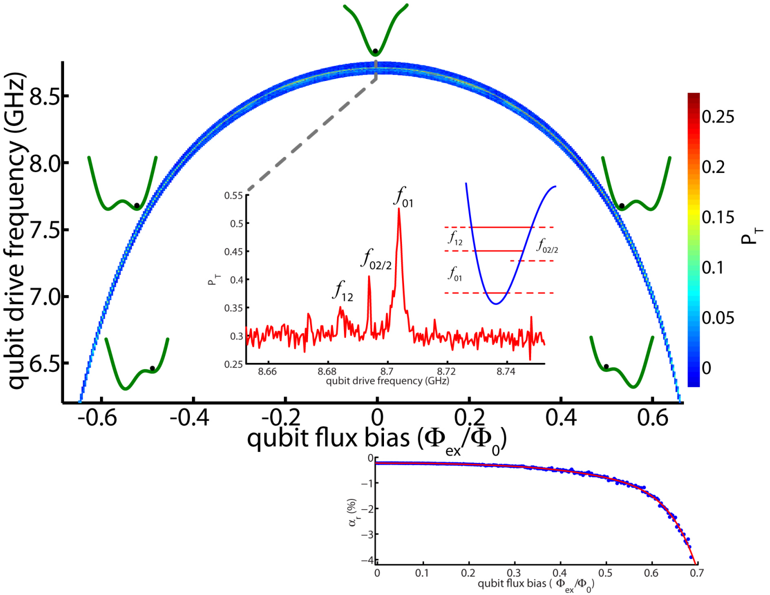


T. Wirth et al, **Microwave readout scheme for a Josephson phase qubit** *Applied Physics Letters* **97** 262508 2010
Y. Chen et al, **Multiplexed dispersive readout of superconducting phase qubits** *Applied Physics Letters* **101** 182601 2012
U. Patel et al, **Coherent Josephson phase qubit with a single crystal silicon capacitor** *arXiv.org* cond-mat.supr-con:1210.1545v1 2012

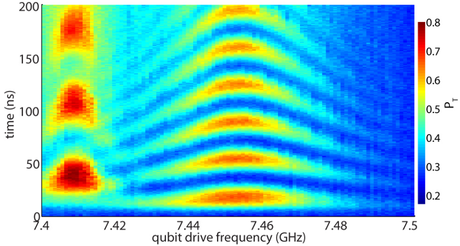
Qubit spectroscopy

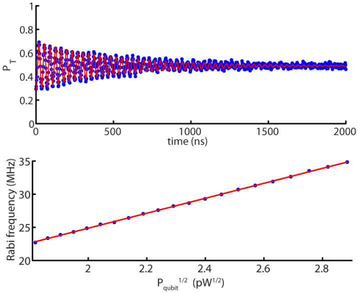


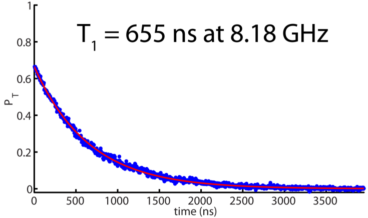
Qubit spectroscopy

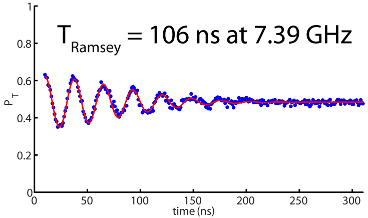


Qubit characterization

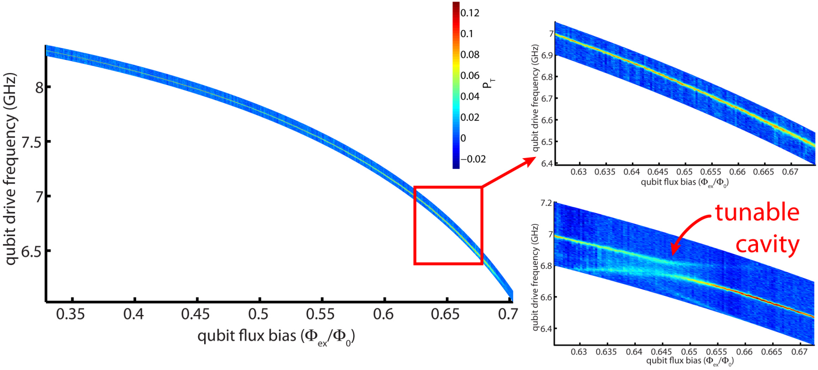






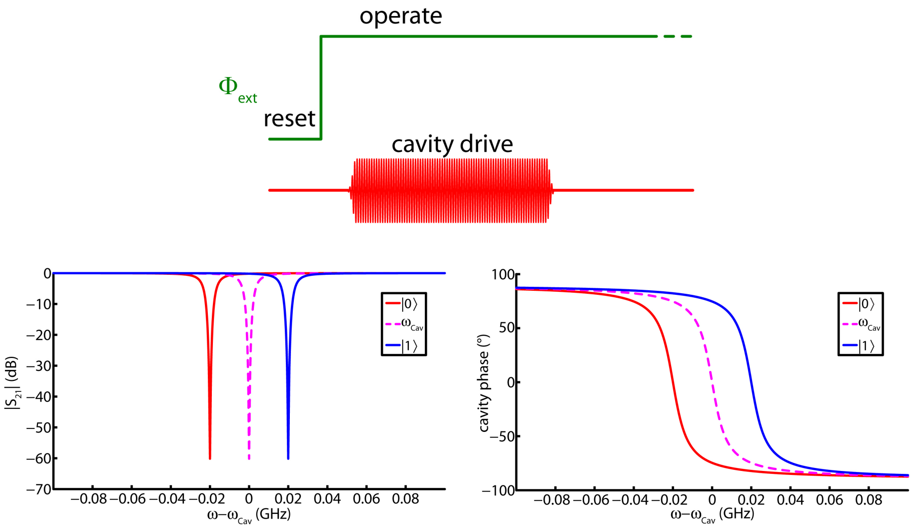


Qubit-cavity spectroscopy

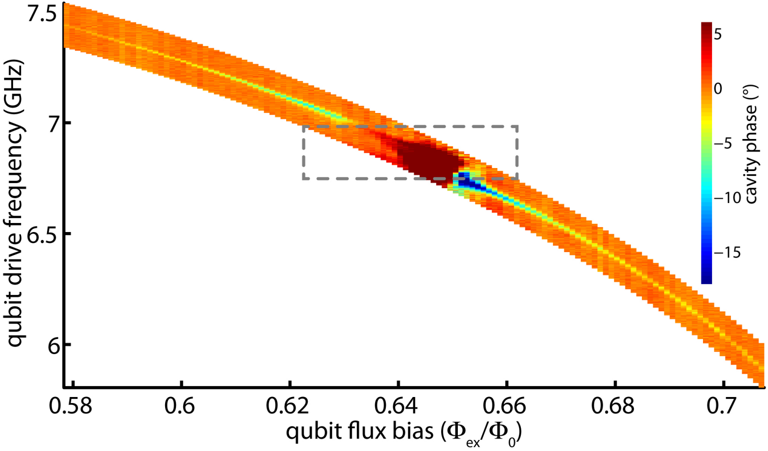


$$g/2\pi = 40MHz$$

Dispersive measurement

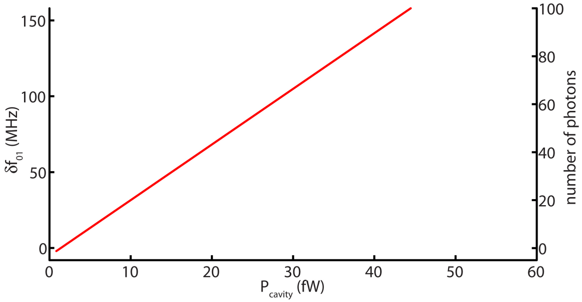


Dispersive qubit spectroscopy



$$\delta\omega = \pm\frac{g^2}{\Delta_{01}}$$

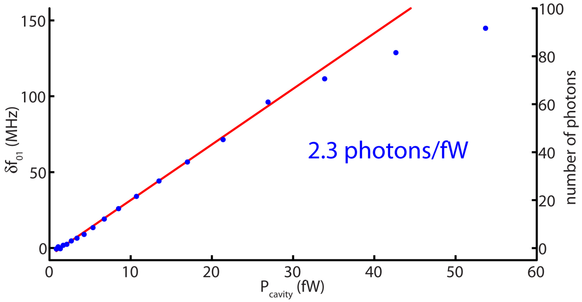
The AC Stark shift, $\Delta_{01} \gg g$



$$H \approx \hbar\omega_{Cav}\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar}{2}\left[\omega_{Qu} + 2\frac{g^2}{\Delta_{01}}a^\dagger a + \frac{g^2}{\Delta_{01}}\right]\sigma_z$$

$$\widetilde{\omega_{Qu}} = \omega_{Qu} + \underbrace{2n\frac{g^2}{\Delta_{01}}}_{AC\ \ Stark} + \underbrace{\frac{g^2}{\Delta_{01}}}_{Lamb}, \quad \Delta_{01} = \omega_{01} - \omega_{Cav}$$

The AC Stark shift, $\Delta_{01} \gg g$



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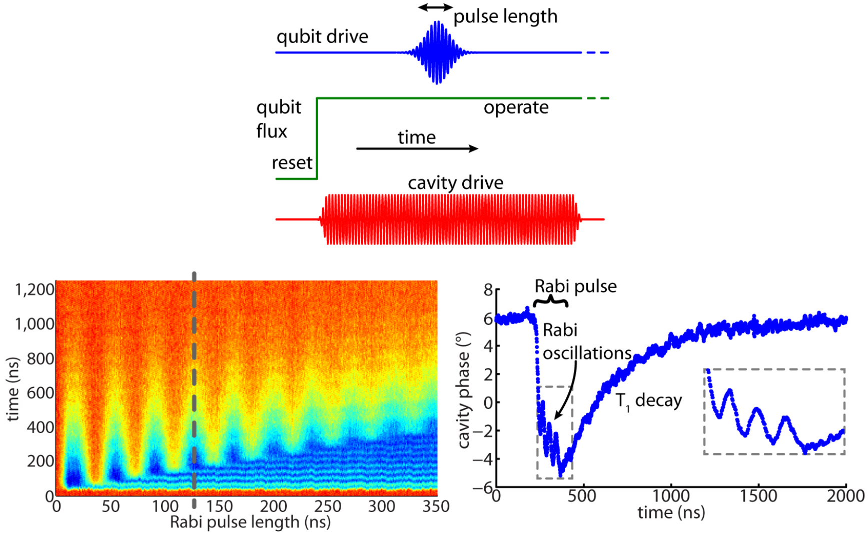
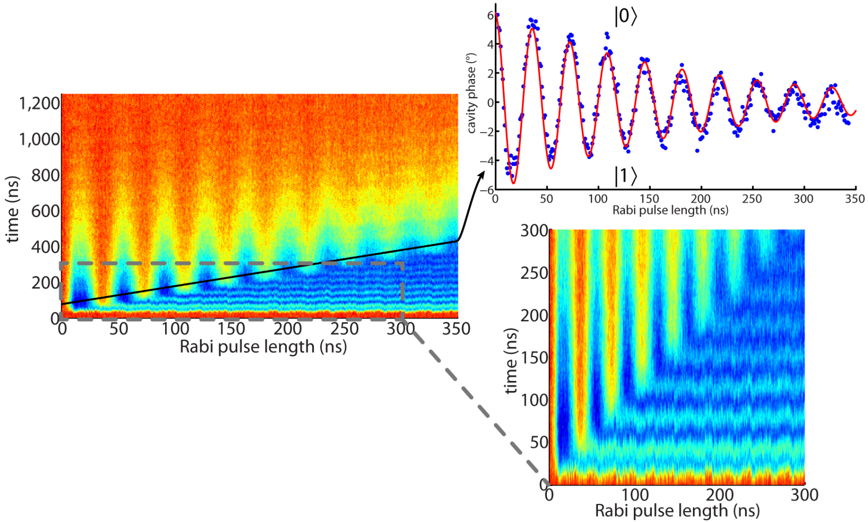
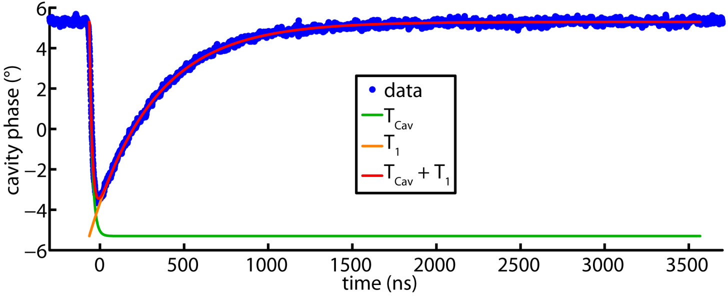
Rabi oscillations



Rabi oscillations



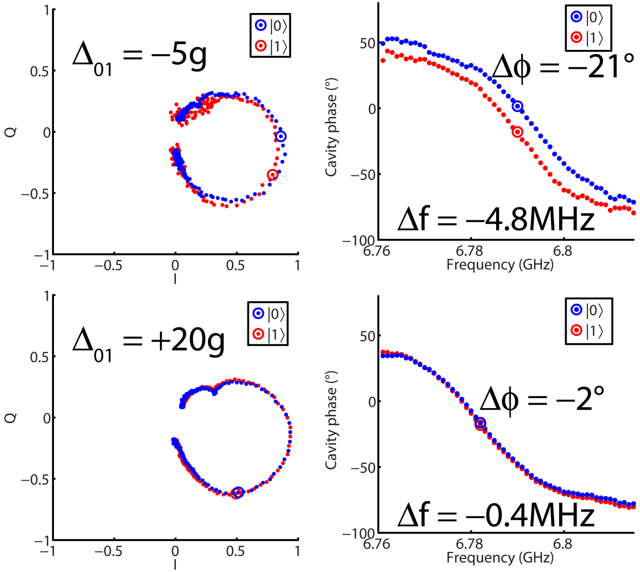
T_1 data



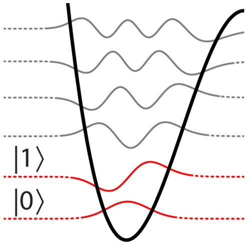
$$f_{01} = 7.18GHz,\ f_{Cav} = 6.78GHz\ (\Delta_{01} = +10g)$$

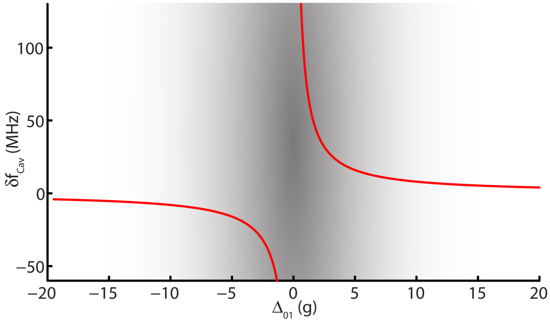
$$T_1 = 380ns\ (620ns \text{ with } f_{Cav} = 4.9GHz),\ T_{Cav} = 17ns$$

State discrimination



The dispersive shift, $\Delta_{01} \gg g$

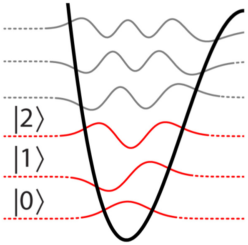


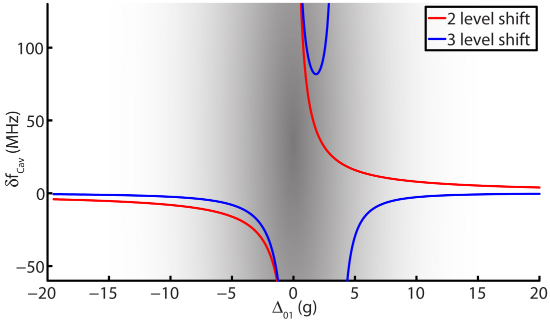


$$H_{JC} \approx \hbar \left[\omega_{Cav} + \frac{g^2}{\Delta_{01}} \sigma_z \right] a^\dagger a + \frac{\hbar}{2} \left[\omega_{Qu} + \frac{g^2}{\Delta_{01}} \right] \sigma_z$$

$$\widetilde{\omega_{Cav}} = \omega_{Cav} \pm \frac{g^2}{\Delta_{01}}$$

The three level dispersive shift, $\Delta_{01} \gg g$





$$\widetilde{\omega_{Cav}} = \omega_{Cav} \pm \left(\frac{g^2}{\Delta_{01}} - \frac{g^2}{\Delta_{12}} \right)$$

$$\Delta_{12} = \omega_{12} - \omega_{Cav}$$

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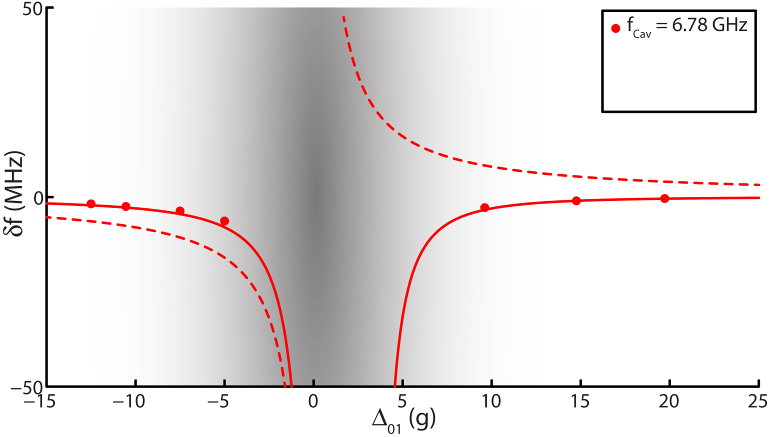
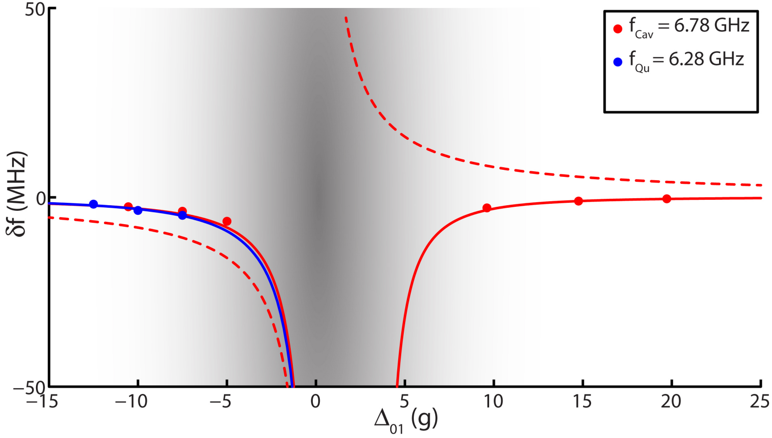
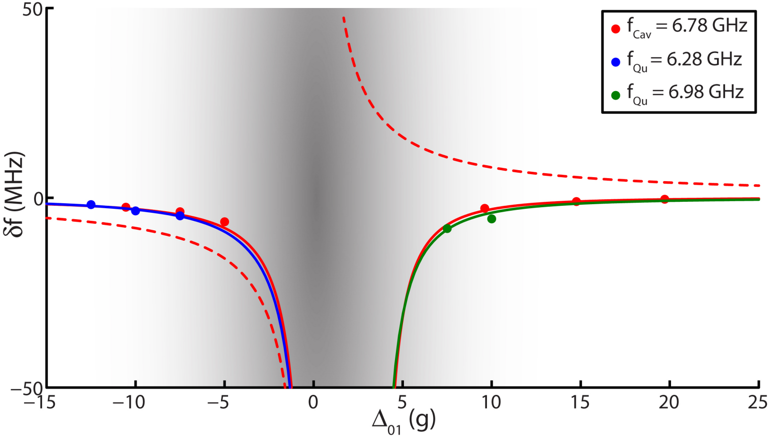
Dispersive shifts



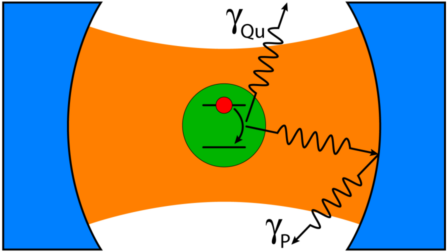
Dispersive shifts

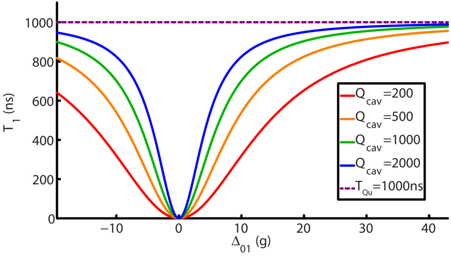


Dispersive shifts



The Purcell effect





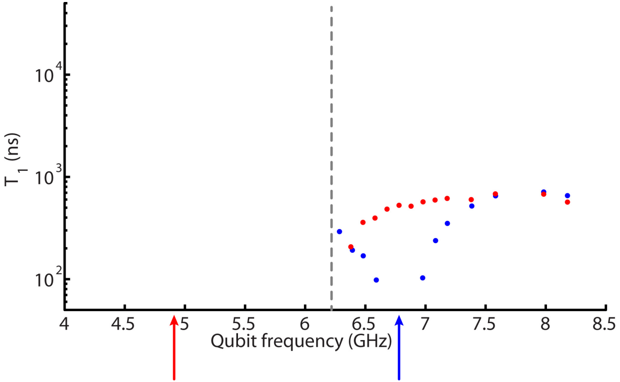
$$T_1 = \frac{1}{\gamma_P + \gamma_{Qu}}$$

$$\gamma_P = \kappa \left|\langle f|a|i\rangle\right|^2 = \frac{\omega_{Cav}}{Q_{Cav}} \frac{g^2}{\Delta_{01}^2}$$

$\uparrow Q_{Cav} = \uparrow T_{Cav} \rightarrow$ slower cavity

$T_{Cav} \ll T_{Qu}$ for measurement

The Purcell effect

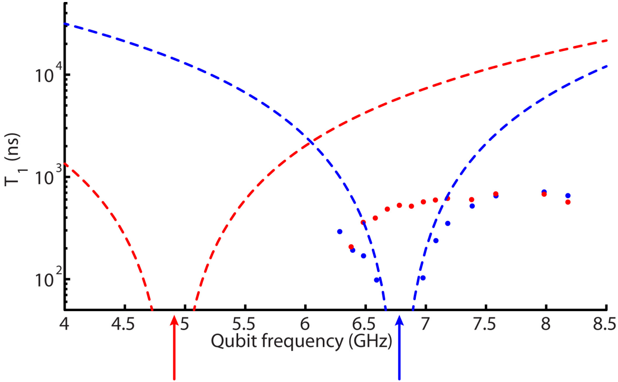


$$T_1 = \frac{1}{\gamma_P + \gamma_{Qu}}$$

$$\gamma_P = \frac{2\pi f_{Cav}}{Q_{Cav}} \frac{g^2}{\Delta_{01}^2}$$

$$\gamma_{Qu} = 1/T_{Qu}$$

The Purcell effect



$$T_1 = \frac{1}{\gamma_P + \gamma_{Qu}}$$

$$\gamma_P = \frac{2\pi f_{Cav}}{Q_{Cav}} \frac{g^2}{\Delta_{01}^2}$$

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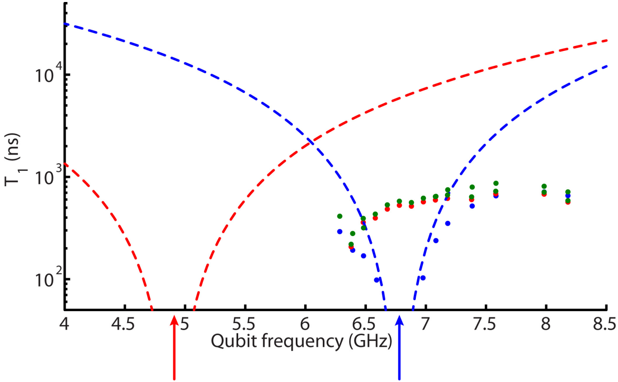
The Purcell effect



$$T_1 = \frac{1}{\gamma_P + \gamma_{Qu}}$$

$$\gamma_P = \frac{2\pi f_{Cav}}{Q_{Cav}} \frac{g^2}{\Delta_{01}^2}$$

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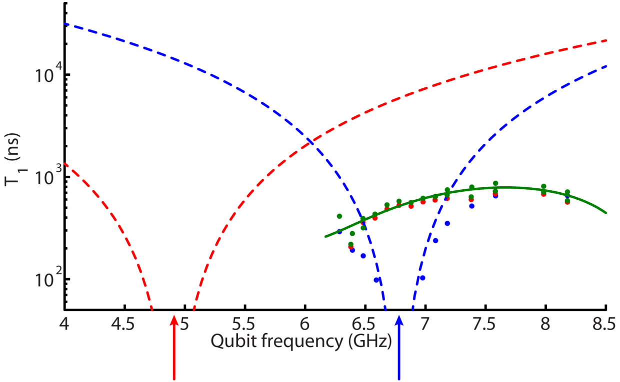
The Purcell effect

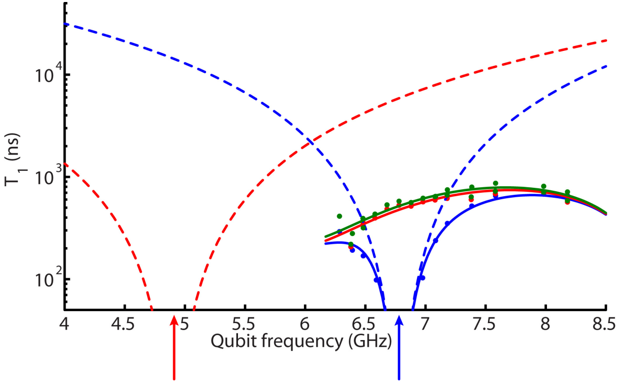


$$T_1 = \frac{1}{\gamma_P + \gamma_{Qu}}$$

$$\gamma_P = \frac{2\pi f_{Cav}}{Q_{Cav}} \frac{g^2}{\Delta_{01}^2}$$

$$\gamma_{Qu} = 1/T_{Qu}$$

The Purcell effect

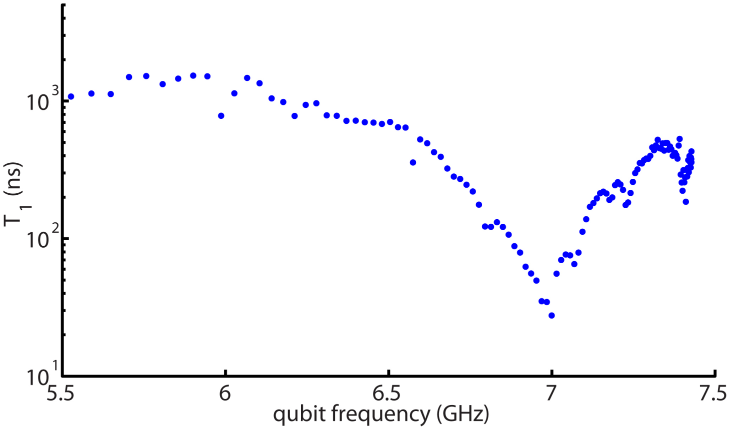


$$T_1 = \frac{1}{\gamma_P + \gamma_{Qu}}$$

$$\gamma_P = \frac{2\pi f_{Cav}}{Q_{Cav}} \frac{g^2}{\Delta_{01}^2}$$

$$\gamma_{Qu} = 1/T_{Qu}$$

New Purcell data



$f_{Cav} = 6.96$ GHz, $Q_{Cav} \approx 1500$, $T_1 \approx 1.5\ \mu$s, $g = 65$ MHz

Summary of results

- Read out results of tunneling measurement with tunable cavity
- Dispersively measured a phase qubit
- Observed and changed Purcell effect with tunable cavity

Future work

- Design improvements
- Perform bifurcation measurement, compare to tunneling measurement
- Swap cavity and qubit roles in one device; exploit tunable anharmonicity
- Multiplex multiple devices