Detecting Axions with Superconducting Qubits

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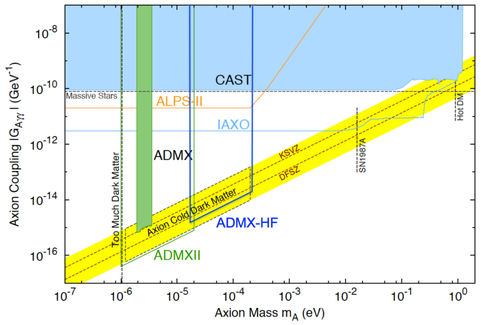
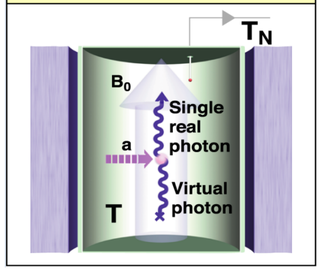
Axion Dark Matter



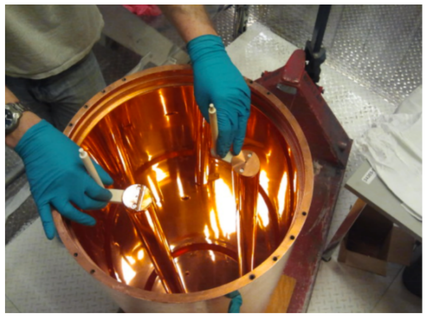
Primakoff Conversion



Axion model provides a solution to the Strong CP problem and accounts for the observed dark matter density

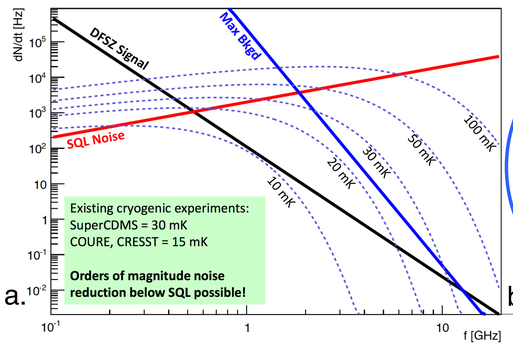
$$\mathcal{L}_{int} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B_0}$$

a.

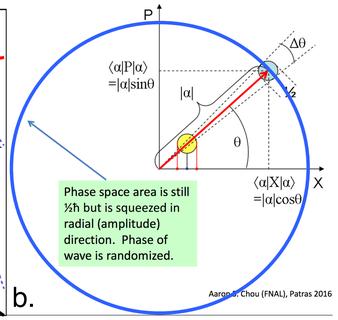


b.

a. Cryogenic axion scattering cavity lifted from superconducting magnet **b.** High Q copper cavity, tuning rods shift mode frequency enabling scanning for axion mass



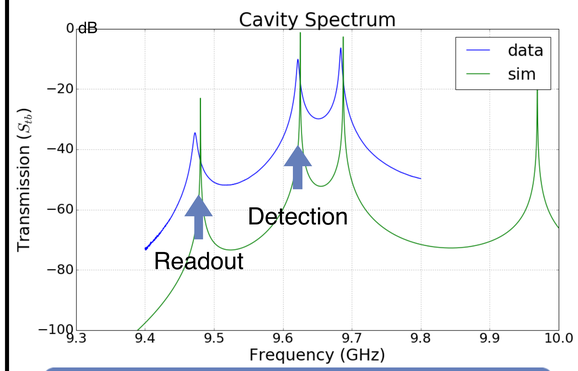
a.

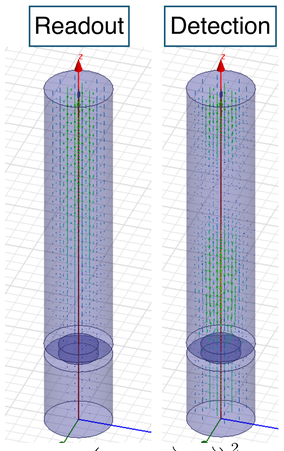


b.

a. Photon rate for axion signal (black), standard quantum limit (red), thermal noise (dashed). Past ~2 GHz, zero point noise from a linear amplifier is no longer tolerable **b.** By measuring only field amplitude (photon counting), sensitivity below the SQL can be achieved.

Cavity



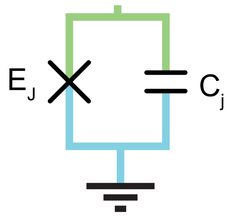


Bottom portion of cavity is inserted into magnetic field to couple axion field with detection mode: form factor $C > 0$

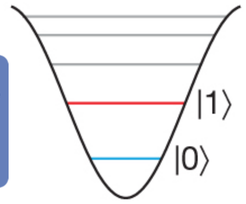
Top part of cavity designed to isolate superconducting qubit from applied magnetic field

$$C = \frac{\left(\int_V d^3x \vec{E} \cdot \vec{B_0}\right)^2}{\int_V d^3x\, |B_0|^2 \int_V d^3x\, |E|^2}$$

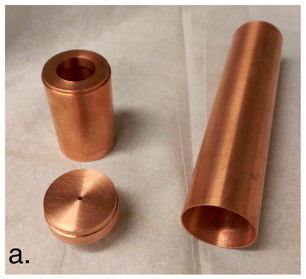
Qubit



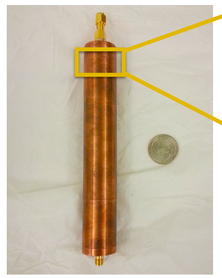
Transmon qubit: Josephson junction combined with large capacitor to make a nonlinear resonator. The ground (Q=0) and first excited (Q=1) states constitute a two level system.



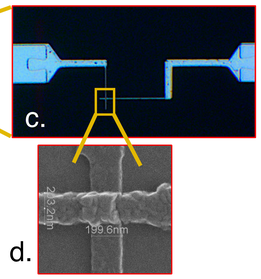
Cavity QED



a.



b.

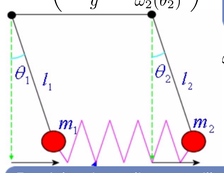


c.

d.

a. (L) Axion scattering region of cavity, (R) Waveguide coupler to qubit **b.** Assembled cavity **c.** Qubit: Josephson junction with dipole arms and capacitive pads **d.** Josephson junction

$$\mathcal{H} = \begin{pmatrix} \omega_1(\theta_1) & g \\ g & \omega_2(\theta_2) \end{pmatrix}$$



Pendulum is nonlinear oscillator

Normal mode frequencies are amplitude dependent

$$\omega_\pm = \omega_i \pm \frac{g_{ij}^2}{\omega_i(\theta_i) - \omega_j(\theta_j)}$$

Amplitude to frequency transducer

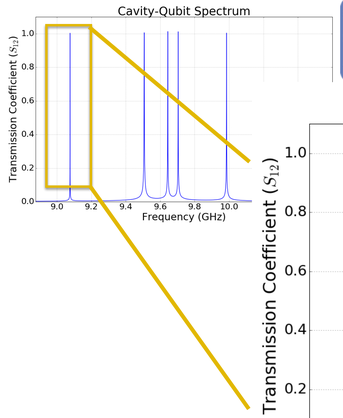
$$\mathcal{H} = \omega_c a^\dagger a + \omega_q \sigma_z + 2\frac{g^2}{\Delta} a^\dagger a \sigma_z$$

Cavity frequency

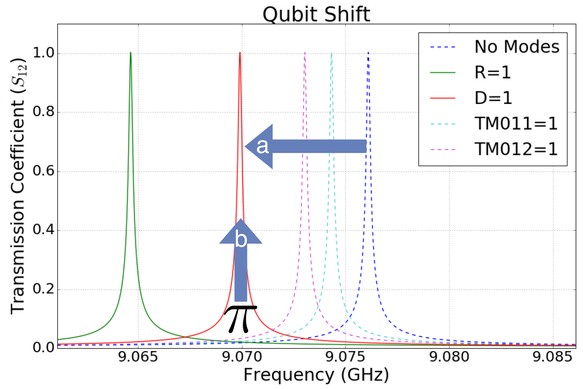
Qubit resonance

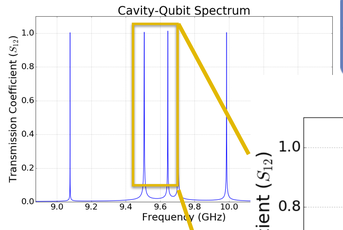
Stark Shift: Qubit (cavity) frequency shifted by an amount proportional to cavity (qubit) occupation

Measurement Protocol

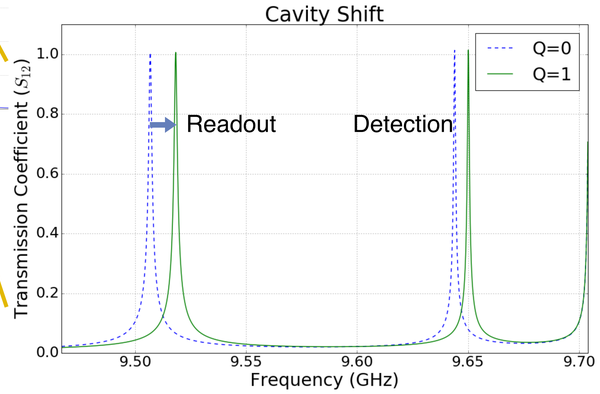


a. Qubit resonance is shifted due to axion signal driving single photon excitation in the detection mode (D=1) **b.** Apply π pulse to flip qubit to the first excited state





Excitation of qubit results in shift of readout mode frequency. The line shift can be probed with a reflection measurement.



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