Axion Dark Matter Detection using Superconducting Qubits

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What are Axions?

Axions are particles predicted to exist as a consequence of the Peccei-Quinn solution to the strong-CP problem and could account for all of the dark matter in our universe.

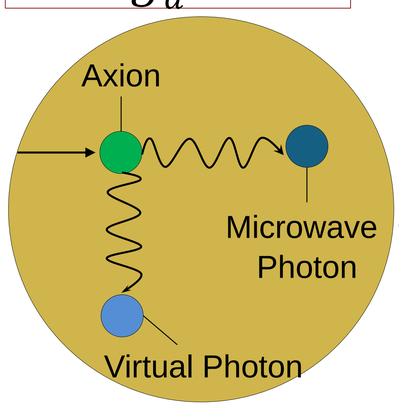
Properties of Axion

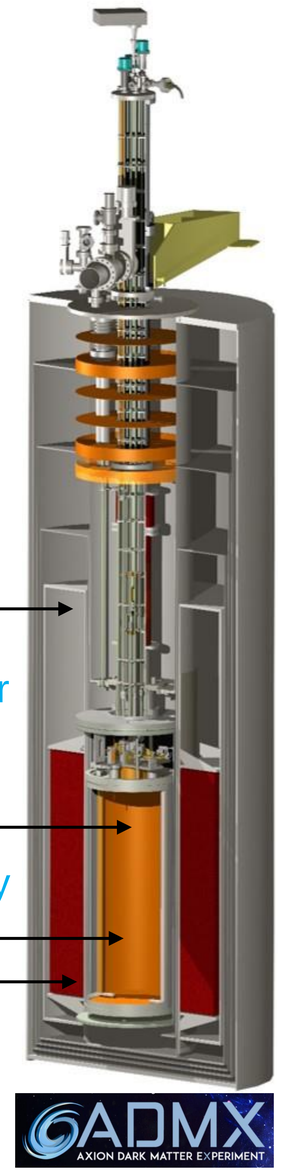
- Coherent wave over the length of baseball field
- Very weak electromagnetic interaction with matter
- Mass is proportional to the frequency

Axion Haloscope

A cold radio receiver is immersed in a strong static magnetic field. The ambient dark matter axion field produces a volume-filling current density oscillating at frequency $f = \frac{\varepsilon}{\hbar}$, where ε is the total energy consisting mostly of the axion rest mass with a small kinetic energy addition.

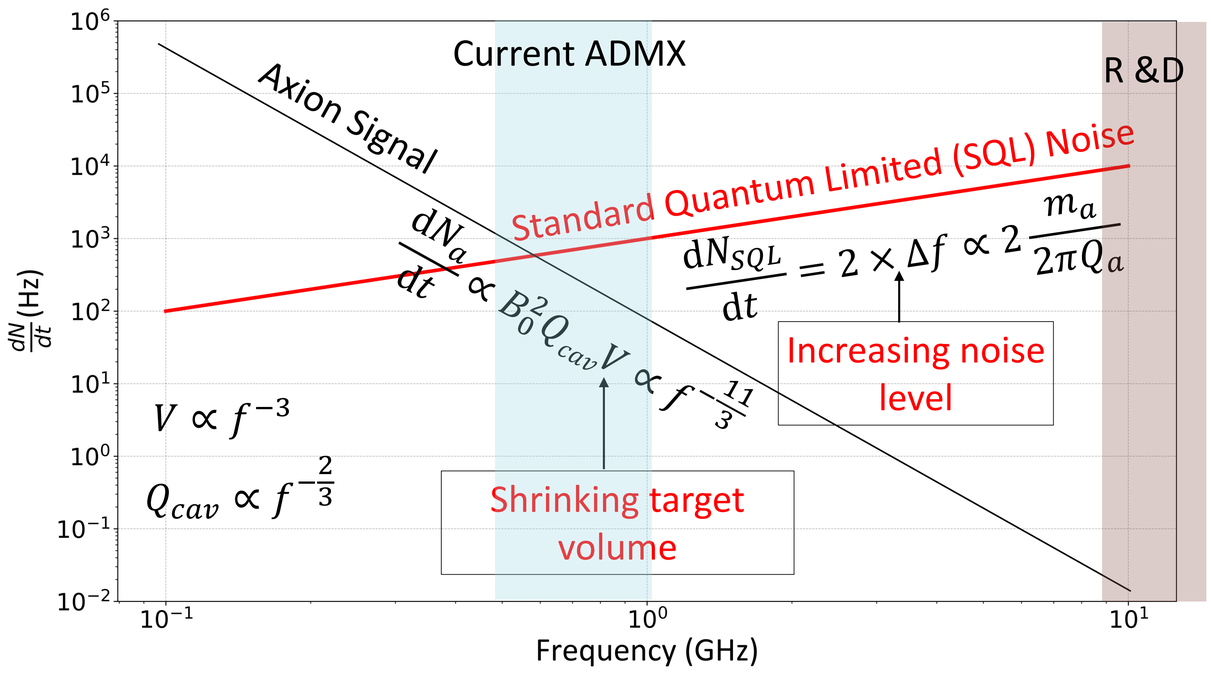
$$\mathcal{L} \propto g_a a \vec{E} \cdot \vec{B}$$



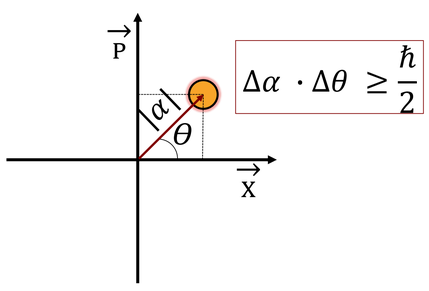


Signal Rate

As we move to higher mass axion search, the signal-to-noise ratio plummets and thus, we will have to fundamentally change our measurement scheme by counting the number of photons rather than measuring excess power in the cavity.

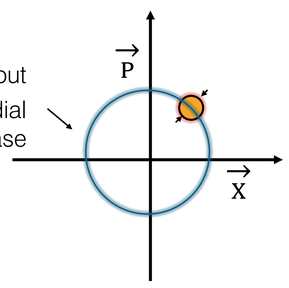


Moving from conventional phase preserving amplifiers to number counting thus, evading the quantum-back action noise.

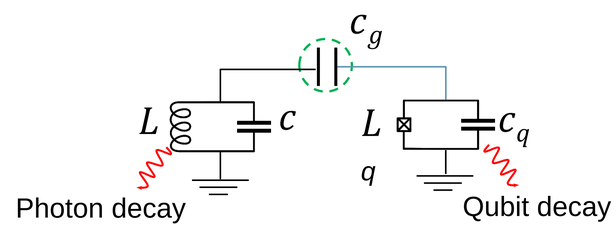


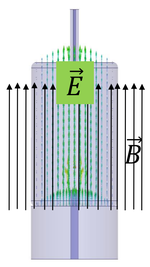
$$\Delta\alpha \cdot \Delta\theta \geq \frac{\hbar}{2}$$

Phase space area is still $\frac{\hbar}{2}$ but is **squeezed** in the radial direction (Amplitude). Phase of wave is **randomized**



Single Photon Detector



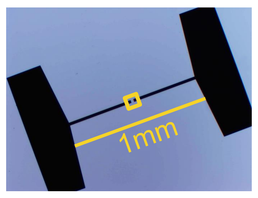


Maximum overlap between the applied magnetic field and the cavity mode (TM_{010})

$$\omega_{010} = 2\pi\, 9.56\ GHz$$

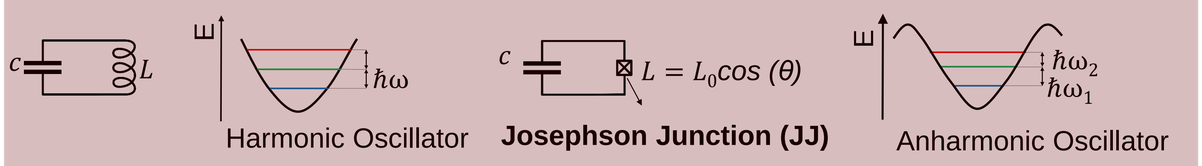
$$\hat{\mathcal{H}} = \omega_c a^\dagger a + \omega_q \frac{\sigma_z}{2} - \chi a^\dagger a \sigma_z$$

Quantized Field | Qubit | Dispersive Coupling



χ set by:
1. Dipole arm geometry
2. Qubit location in cavity
3. Qubit-cavity frequency detuning
4. Qubit anharmonicity

Qubit



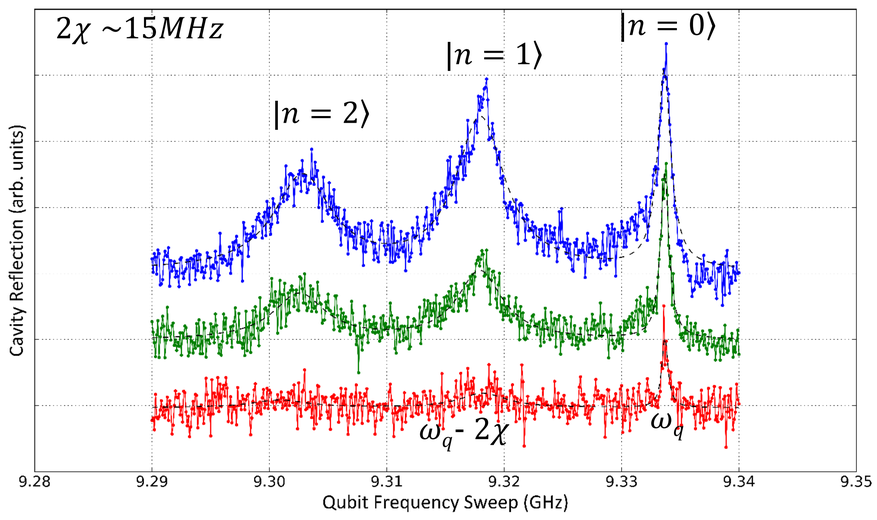
Quantum Non-demolition (QND) Measurement

Triggering a click without destroying the photon

$$\hat{\mathcal{H}} = \omega_c a^\dagger a + (\omega_q - 2\chi a^\dagger a)\frac{\sigma_z}{2} \qquad \hat{\mathcal{H}} = (\omega_c - 2\chi\frac{\sigma_z}{2})\, a^\dagger a + \omega_q \sigma_z$$

Qubit Spectroscopy:

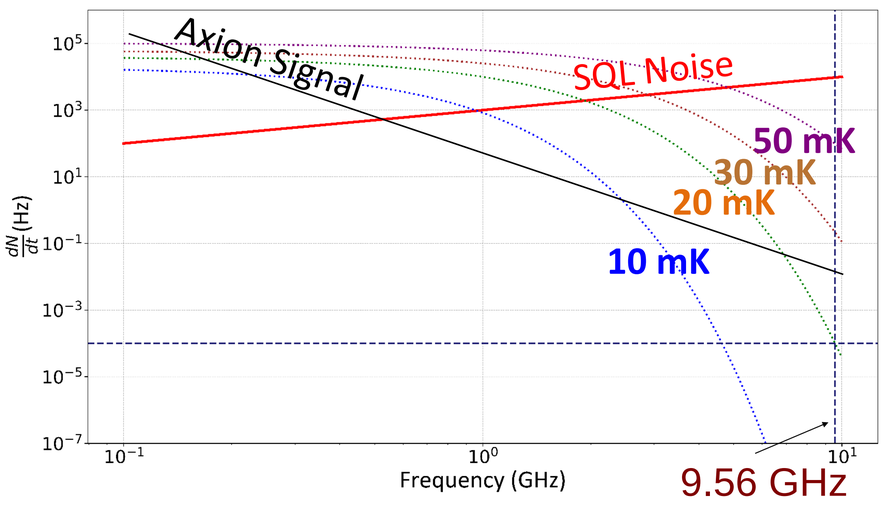
- Probe the **cavity** at constant frequency
- Drive the **qubit** at variable frequency
- Observe change in the probe field response, when drive matches the qubit transition frequency



- Achieved qubit lifetime (T1) of $\sim 60\ \mu s$ but currently limited by our cavity lifetime of only $\sim 1\ \mu s$

Challenges & Scope of Work

- Thermal photons as background
- Qubit thermal occupation as false positives
- Multiple qubits for readout
- High-Q dielectric cavities



- Measured cavity occupation of $< 0.03\%$

References
1. Schuster et AL Nature 445 (7127), 515
2. ADMX PRL 120, 151301 (2018)

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