Search for Axionic and Dark Photon Dark Matter w/ Superconducting RF Cavities

Keston Smith

Supervisor – Raphael Cervantes

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Axions and Dark Photons as Candidates for Dark Matter

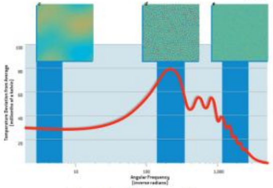
Dark Matter

- Dark matter is observed to be translucent, and weakly interacting with visible matter.
- Various phenomena cannot be explained by visible matter.
  - Gravitation Lensing (Einstein rings)
  - Galactic Rotation Curves
  - Cosmic Microwave Background
  - Bullet Cluster

Gravitational Lensing

Credit: *NASA*

Cosmic Microwave Background

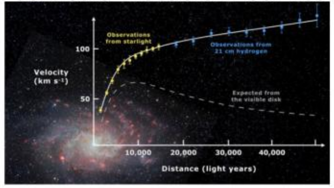


Credit: *Wayne Hu*

Bullet Cluster

Credit: *NASA*

Galactic Rotation Curves

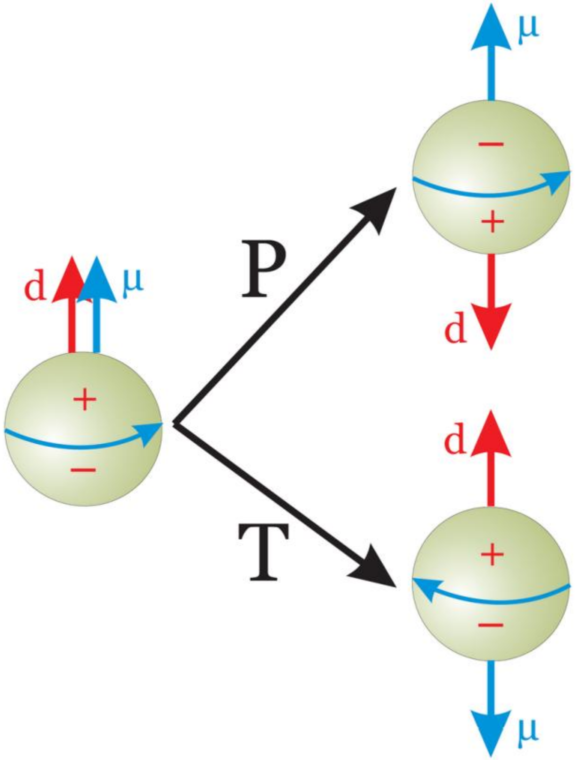


Credit: *Mario de Leo*

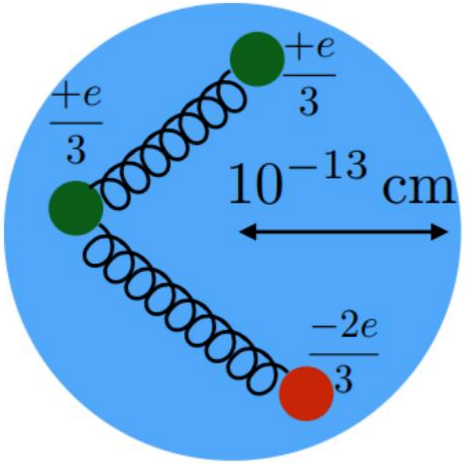
Axions/Dark Photons

- Axions and dark photons (DP) are a subset wave-like of dark matter candidates. That is the DeBroglie wavelength, λ_{DB}, of each candidate exceeds the length of interatomic separation.
- Axions were invented as a solution to the Strong CP problem that obey anomalous $U(1)$ gauge symmetries, DP is a vector boson with an Abelian $U(1)$ symmetry.

Axions and Dark Photons as Candidates for Dark Matter



Parity & Time symmetry violation



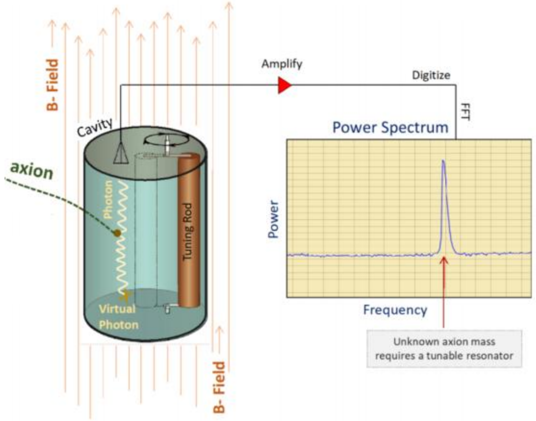
Neutron

- Electric dipole moments (EDM) violate CPT symmetries, so CP is also in violation.
- CP is somehow conserved in strong interactions; no configuration exist such that a EDM in a neutron is observed.

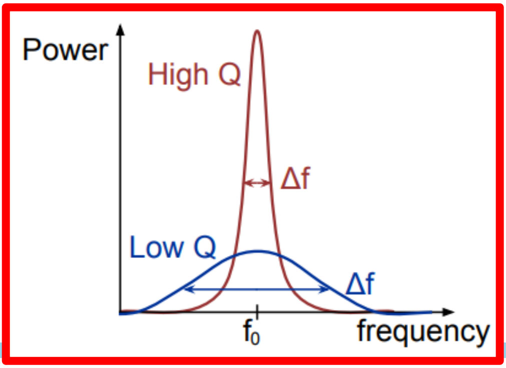
Detection/Superconducting RF Cavities

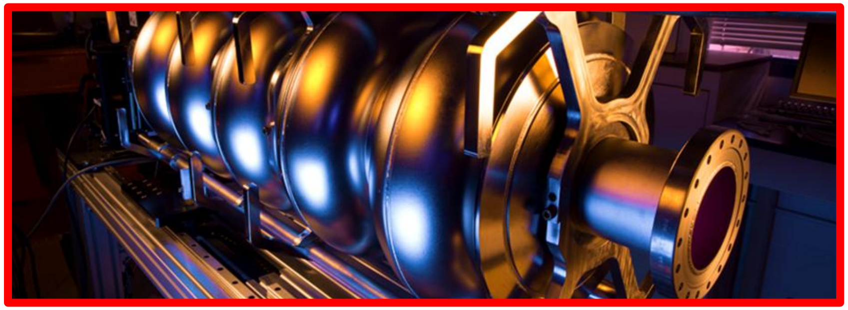
$\mathcal{L}_{int} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$ → Axion/photon(s) interaction

$\mathcal{L}_{int} = \frac{1}{2} \chi F_1^{\mu\nu} F_{2\mu\nu}$ → Dark photon/photon interaction



- Axions weakly couple to SM photons through Primakoff scattering whereas dark photons couple through kinetic mixing.
- The axion and dark photon can be detected in the local dark matter halo using tunable resonant cavities, this is known as a haloscope.
- High quality factor cavity resonators are sensitive to photon conversion signal since they only operate at frequencies near the resonance frequency.
  - A search involves recording a power spectrum at different resonant frequencies of the cavity.
  - The cavity’s oscillating electric field is coupled to the converted photon once it is tuned to the mass of an axion or dark photon.
  - Superconducting RF (SRF) cavities are efficient oscillators which ensure maximum signal to noise efficiency (SNR) when coupled to converted photons.



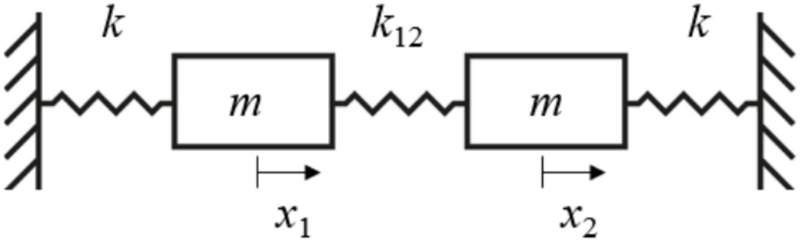


Detection/Superconducting RF Cavities

- The cavity resonantly enhance the converted photon signal once tuned to the mass of an axion or dark photon.
- This condition can be thought of as a system of coupled oscillators where the eigenfrequencies correspond to the axion/dark photon mass.

$$(\mathbf{V} - \lambda_k \mathbf{T})\vec{\mathbf{a}}_k = 0$$

$$\omega_k = \sqrt{\lambda_k} \implies f_k = \frac{\sqrt{\lambda_k}}{2\pi}$$



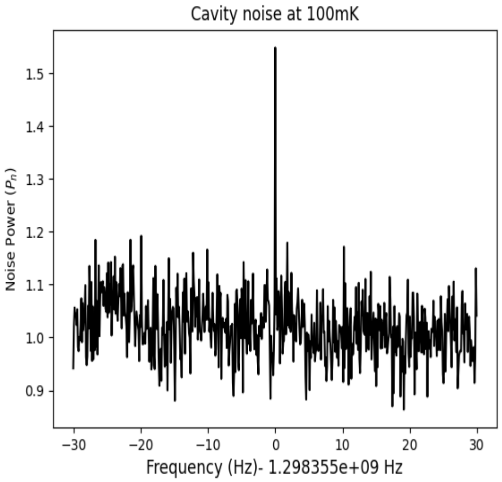
Simulating Averaged Power Spectrum

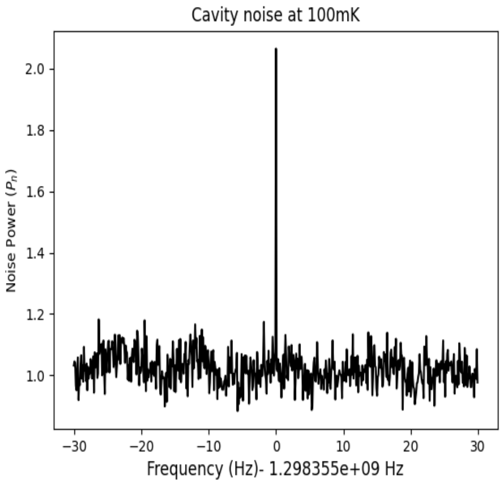
- Average power spectra are simulated for a 1.3GHz SRF cavity with a Q value $\sim\mathcal{O}(10^9)$ at 100mK. Frequency bins are sampled from a χ^2 distribution with two degrees of freedom.
- The power sample in the resonance frequency bin, f_0, is replaced synthetic signal of arbitrary strength.

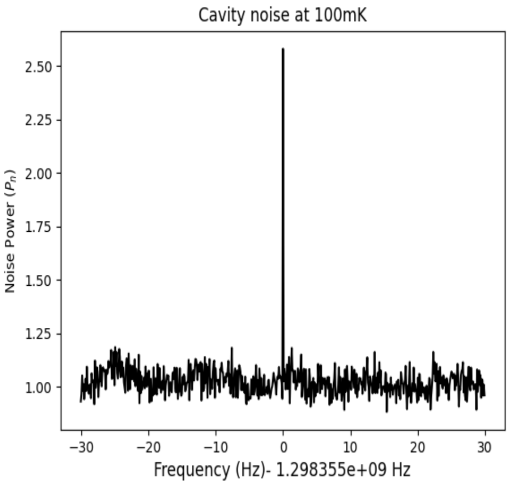
$$\mathrm{SNR} = P_S/\sigma_{P_n}$$

$$\Longrightarrow \mathrm{SNR} = (P_S/P_n)\sqrt{b\Delta t}$$

$$P_{synthetic} = \mathrm{SNR} \times \frac{\mathcal{F}(f)}{max\mathcal{F}(f)\sigma_P P_n}$$

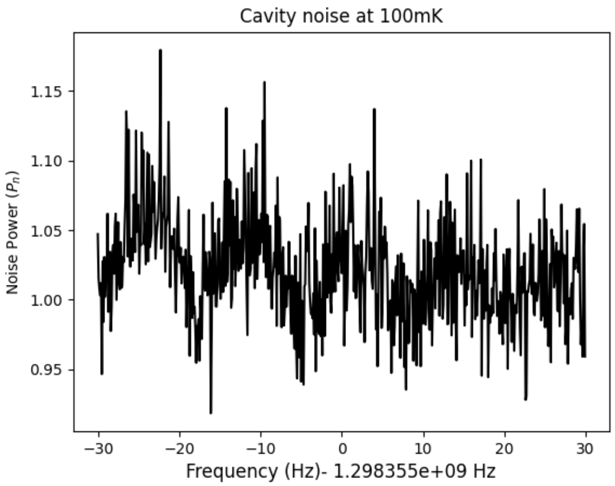


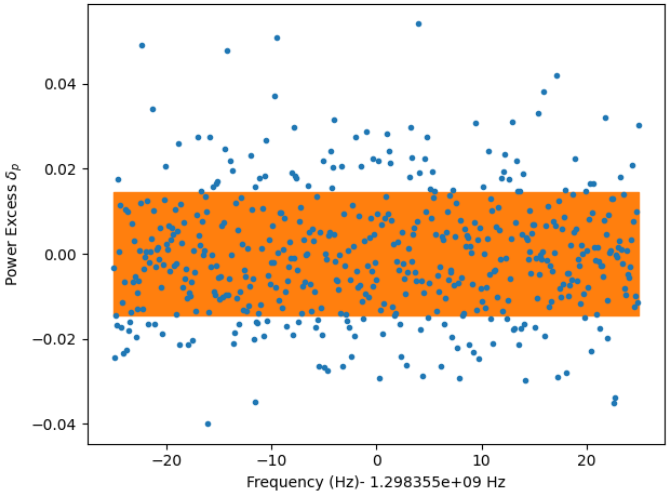




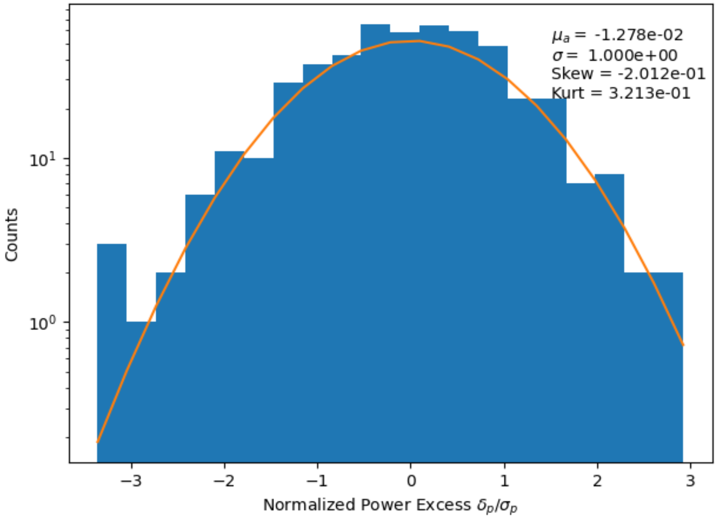
Spectral Analysis

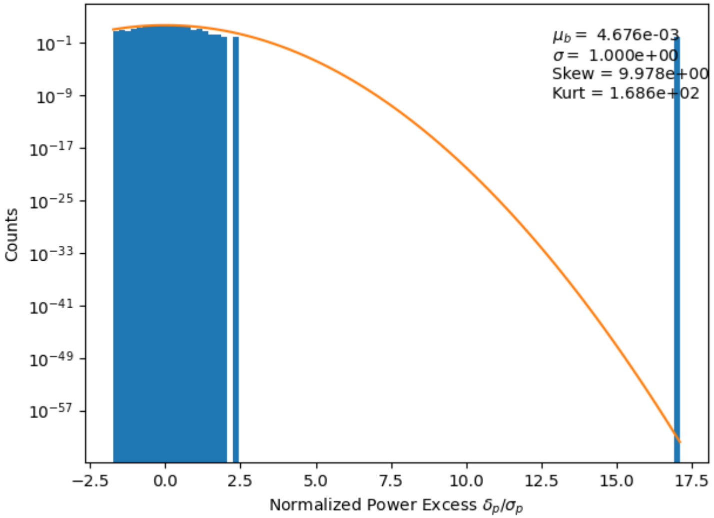
- The averaged spectrum bins are constructed from the average of 1000 sub spectra.
- Power fluctuations are approximately gaussian in accordance with the Central Limit Theorem.
- Significant variation can be removed since the signal is very narrow compared to the large-scale structure. The resulting spectrum is referred to as the processed spectrum where cavity noise is interpreted as power excess.
- Narrow signals with large power excess are a result of two coupled photons oscillating at the resonance frequency of the cavity's TM_{010} mode.



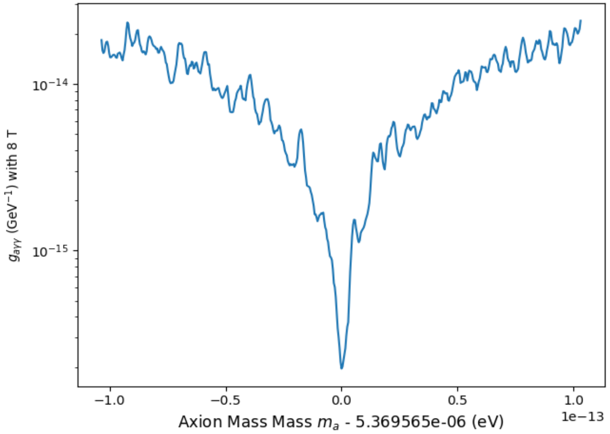


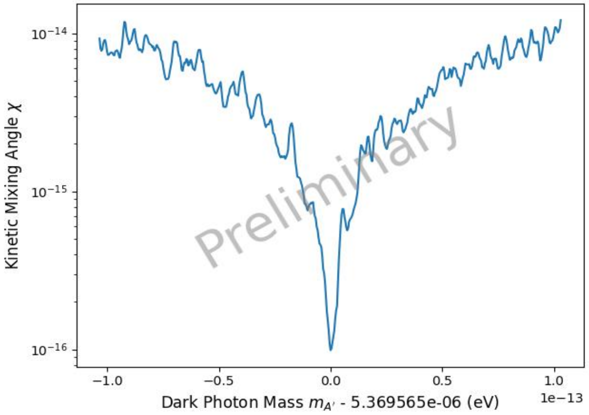
Spectral Analysis



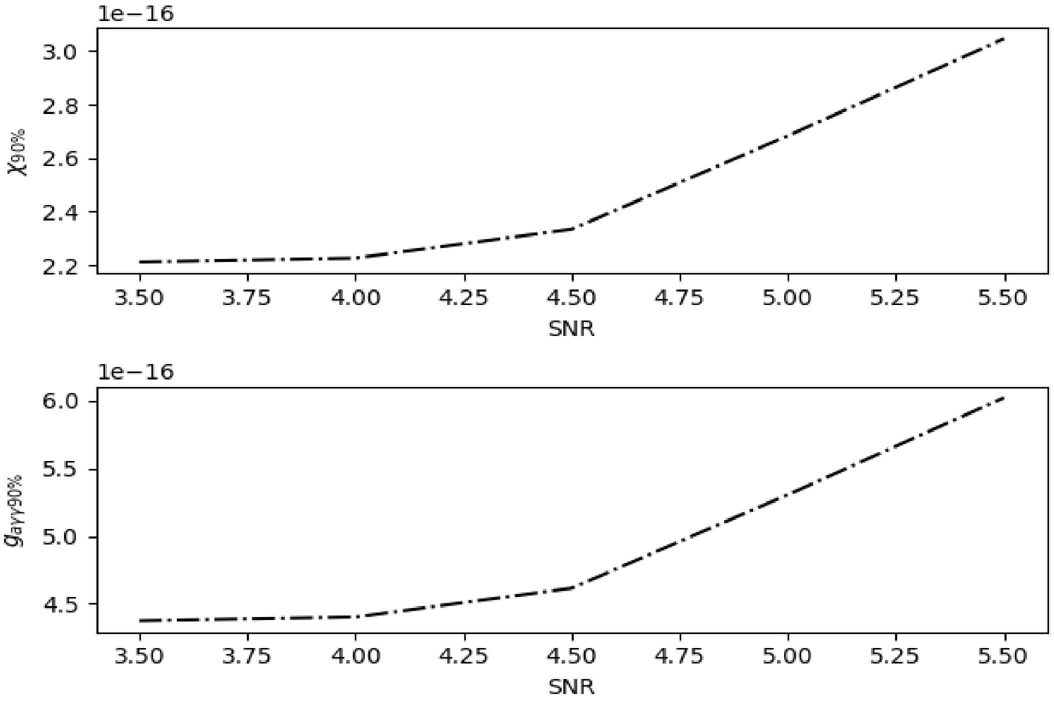


- When no signal is present, power fluctuations are $\sim\mathcal{N}(0,1)$.
- The mean has increased after signal injection $\mu_a < \mu_b$.
- Exclusion limits are placed on spectrums the result in gaussian fluctuations. Axion limits are placed with an axial magnetic field of 8T.





Spectral Analysis



- The analysis procedure is performed for increasing signal strengths $\{SNR|\, 3.5 \leq SNR \leq 5.5\}$.
- Deflection in the excluded coupling parameter for each respective particle indicates a loss in sensitivity to lower limit interactions.

Thank You!

Questions?