Searching for Axion/Dark Photon Conversion Signals in Superconducting Radiofrequency Cavities

Keston Smith
Department of Physics, University of Alabama at Birmingham-SIST Intern

Dark matter seems to have an autonomous presence through out the universe, but we have yet to discover the particle(s) that is responsible for the unusual observations in astrophysical data. Axions and dark photons (DP) are two convincing dark matter candidates due to their theoretical interactions with ordinary matter and overall characteristics. Both particles weakly interact with the standard model (SM) photon; residual photons of the interaction can be detected within the local dark matter halo using tunable resonant cavities coupled to low-noise electronics, this is known as a haloscope. The following work consist of simulating and analyzing averaged power spectra of a 1.3 GHz superconducting radio frequency (SRF) resonant cavity at 100mk. Analysis was performed for arbitrary signal strengths SNR ≤ 5.5; this useful for monitoring the sensitivity in exclusion limits for the axion and dark photon coupling parameter are monitored for increasing signal strengths.

I. INTRODUCTION

We know dark matter to be the most abundant form of matter as it makes up 84.4% of the universe and contribute 26.4% to its energy density. Investigating such a thing could be fruitful as it may contain the answer to many important questions in physics. To observe dark matter instead of its *effects*, is a non-trivial task due to its weak interactions with normal matter; several DM models are centered around this aspect, namely the Lambda Cold Dark matter which characterizes dark as a non-luminous, weakly interacting, non-relativistic. A plurality of theoretical particles agree with this model such as axions, axion-like particles(ALP), dark photons.

This work focuses on the detection of axions and dark photon dark matter using superconducting RF cavities, namely simulation and analysis of its power spectrum. The SRF cavity in question operate at frequencies $\mathcal{O}(10^9)$ which corresponds to a axion/dark photon masses, $\sim 10^{-6}$eV. SRF cavities posses very large quality factors (Q_0) which should should in principle be more sensitive to dark matter interactions than regular conducting cavities.

Axion/Dark Photon-Photon conversion

Axions and dark photons are known to be wave-like dark matter candidates, which means the DeBroglie Wavelength is much larger than inter-atomic separation. Axions provide a natural solution to anomalous CP conservation in QCD interactions; θ_{QCD} in QCD lagragian is CP violating when it is non-vanishing. The PQ mechanism suggest that the $\theta-$term is not a fixed value, but a psuedo-scalar field that be belong to an anomalous $U(1)_A$ symmetry group[1]. Particles with electric and magnetic dipole moments violate discrete symmetries such as parity (P) and time (T) symmetries, they also violate CPT as a consequence. Neutrons are 1/2 spin fermions with a non-vanishing magnetic dipole moment that contain up and down quarks bounded by gluon, up and down charges must cancel for neutrons; following, this logic neutrons should have an observable EDM. Since we do not observe neutron EDM θ_{QCD} must be very small[1]. Axions couple to SM photons via Primakoff effect; converted photons are sourced by photons from an external magnetic field and virialized axions which is captured by the interaction term in the Lagrangian density for EM/axion dynamics

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F^{\mu\nu}} \tag{1}$$

where $g_{a\gamma\gamma}$ is the axion/photon coupling constant. Axions alter the source terms of Maxwell's Equations([2],[3]) in the following way:

$$\vec{\nabla} \cdot \vec{E} = -g_{a\gamma\gamma} \vec{B} \cdot \vec{\nabla} a \tag{2}$$

$$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} - g_{a\gamma\gamma} \left(\vec{E} \times \vec{\nabla} a - \vec{B} \frac{\partial a}{\partial t} \right) \tag{3}$$

Dark photons couple to photons via the interaction term

$$\mathcal{L}_{d\gamma} = \frac{1}{2} \chi F_1^{\mu\nu} F_{2\mu\nu} \tag{4}$$

where $F_1^{\mu\nu}$ is electromagnetic field strength tensor and is the dark photon field strength tensor$F_{2\mu\nu}$, χ is the dark photon/photon kinetic mixing angle. Source terms in Maxwell's Equations are modified in a similar way as the axion.

Superconducting RF Cavities

SRF cavities are essential for the technology needed to do accelerator science in the high energy regime; they're engineered to efficiently store electromagnetic energy, this attribute is especially desirable for accumulating photons to generate high gradient electric fields in high-β particle accelerator[4].

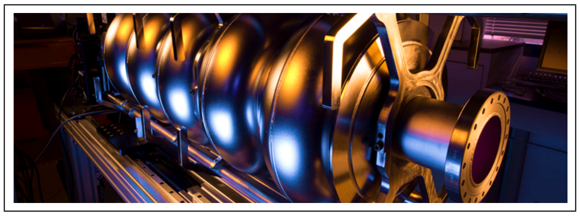


FIG. 1: Multi-cell high-β elliptical SRF cavity.

SQMS division at Fermilab will utilize the long coherence time of photons to extend the lifetime of quantum states to build multiqubit quantum processors. Low surface resistance grant SRF cavities a significant advantage in power efficiency, so it suffers far less rf losses than traditional cavity resonators. SRF cavities are treated in state of the art clean rooms to decrease the chance of degrading quality of the oscillating field. The efficiency of a cavity is measured by the number of oscillations completed before the loss of EM radiation to the walls of the cavity[5]. Quantitatively speaking that is,

$$Q_0 = \frac{f_0}{\Delta f} \tag{5}$$

where f_0 is the resonant frequency at which the response of the cavity is at a maximum and Δf is the full frequency range at which the response is at least half its maximum power. The ratio of the two conveniently quantify the efficiency of a given oscillator. It can easily be seen that in the limit $\Delta f \ll f_0$, Q_0 is very large; it follows that SRF cavities with quality factors $Q_0 \leq 10^{10}$ must respond to a small range of frequencies which guarantee that a large fraction of injected rf power is stored. Photon storage is particularly useful for dark matter/photon couplings. SRF cavities at GHz frequencies correspond to axion/DP mass in the μeV regime.

II. SIMULATED SPECTRA ANALYSIS

The following simulations are generated using the NumPy module in python. Frequency bins corresponds to a SRF cavity with $\Delta f \approx 100$Hz and a loaded quality factor set to $Q_L = 3.07 \times 10^9$. Resonance frequency is set to the central frequency of the data set. Individual bins are sampled from a χ^2 distribution with two degrees of freedom. The system gain is simulated by the equation

$$\frac{1}{2}(0.1\sin^2(15/N)e^{-2f/N} + 1) \tag{6}$$

when N is the the number of bin and f is the frequency bin where power is intended to be simulated at. An averaged power spectrum is constructed from 1000 sub-spectra at 100mK is generated.

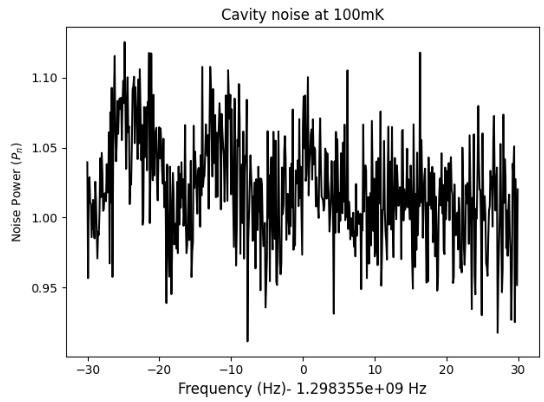


FIG. 2: Simulated power spectrum of 1.3GHz superconducting RF cavity. Each frequency bin is constructed using the average power of 1000 sub-spectra at the equivalent frequency bin.

A signal is then injected at the cavity resonance frequency which is an imitation of a resonantly enhanced photon signal for when the eigenmode frequency is equal to the mass of dark matter. Axion/DP signal power on resonance is

$$P_{a/DP} \propto Q_L L(f, f_0, Q_L) \tag{7}$$

Q_L is the loaded quality factor and $L(f, f_0, Q_L)$ is the axion/DP lineshape. Cavity noise power is given by $P_n = k_B bT$ where b is the frequency bin width. A synthetic signal can be generated by the equation

$$P_{synthetic} = \text{SNR} \times \frac{\mathcal{F}(f)}{\mathcal{F}_{max}(f)\sigma_p P_n} \tag{8}$$

I have defined axion/DP lineshape $\mathcal{F}(f) \equiv L(f, f_0, Q_L)$, σ_p is the standard deviation in the noise power.

The mean of the averaged spectrum converge to the mean or a normal distribution by the Central Limit Theorem. Large scale variation is removed by renormalizing the raw spectrum to the mean; a Savitzky Golay (SG) filter is used to remove any variation beyond the expected gaussian fluctuations. This filter is then divided out such that the mean is now one, then each bin is subtracted by one which result in a flat spectrum

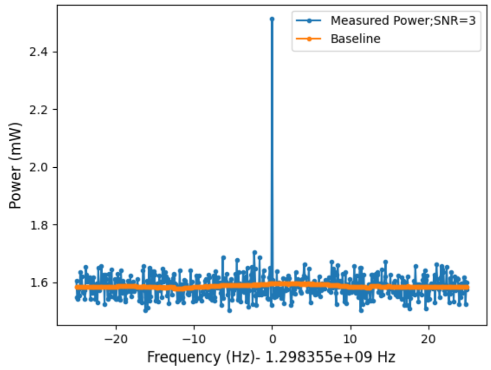


FIG. 3: Renormalized power spectrum, the orange line indicate the applied SG filter.

fluctuating about zero. The result of the latter manipulation is reffered to as the processed spectrum. This type of procedure is invited by the fact that the signal width is a lot smaller that the spectral width[6]. A histogram of the power

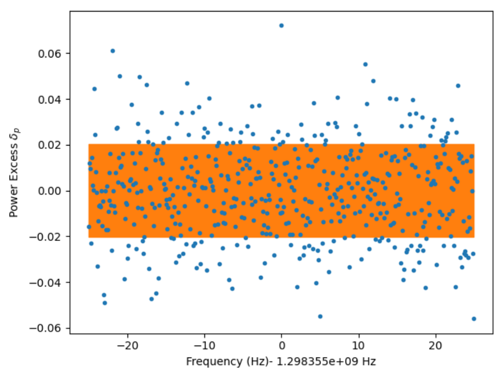


FIG. 4: Processed spectrum, a coherent photon signal will now be detected as a power excess over the gaussian noise

excess is then created which show that the power spectrum is $\sim \mathcal{N}(0,1)$ in the absence of dark matter. The mean μ_a undergo a slight increase after signal injection.

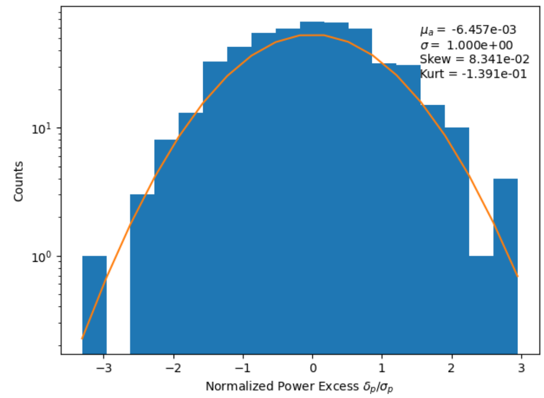


FIG. 5: Histogram of power excess with out conversion signal.

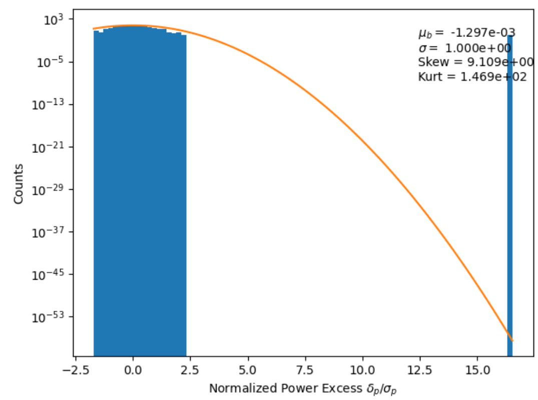
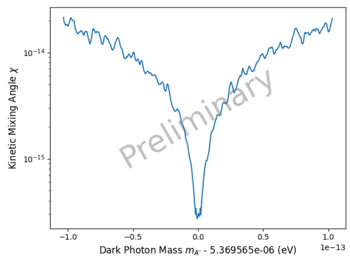


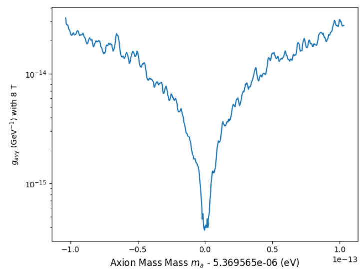
FIG. 6: Histogram with conversion signal.

III. EXCLUSION LIMIT SENSITIVITY

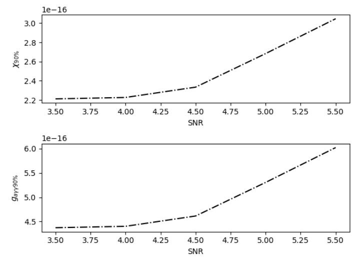
Exclusion limits can be placed on axion/DP coupling parameters using the inverse cumulative distribution function; limit are devirved for increasing signal strengths up to SNR $\leq$ 5.5 for each respective coupling parameter. Sensitivity to the lower limit interactions is lost at about SNR $= 4$; below this threshold the analysis is sensitive the axion/DP coupling parameter $\sim \mathcal{O}(10^{-16})$



(a) Excluded $g_{a\gamma\gamma}$ axion/photon coupling constant.



(b) Excluded kinetic mixing angle χ.



(c) Excluded coupling parameters for increasing signal strength.

FIG. 7: Exlusion limits on axion/DP coupling parameter space.

REFERENCES

[1] B. M. Brubaker, *First results from the HAYSTAC axion search*, Ph.D. thesis, Yale University (2017).

[2] C. Gao and R. Harnik, Journal of High Energy Physics **2021**, 1 (2021).

[3] F. P. Huang and H.-S. Lee, International Journal of Modern Physics A **34**, 1950012 (2019).

[4] B. Aune, R. Bandelmann, D. Bloess, B. Bonin, A. Bosotti, M. Champion, C. Crawford, G. Deppe, B. Dwersteg, D. Edwards, *et al.*, Physical Review special topics-accelerators and beams **3**, 092001 (2000).

[5] H. Padamsee, arXiv preprint arXiv:1501.07129 (2015).

[6] R. Cervantes, G. Carosi, C. Hanretty, S. Kimes, B. LaRoque, G. Leum, P. Mohapatra, N. Oblath, R. Ottens, Y. Park, *et al.*, arXiv preprint arXiv:2204.09475 (2022).