Snowmass2021 - Letter of Interest

Frequency Multiplexed Dark Matter Axion Searches

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
■ (IF1) Quantum Sensors
■ (IF9) Cross Cutting and Systems Integration

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Collaboration (optional): ADMX

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Abstract: (maximum 200 words)

One of the most sensitive techniques to search for dark matter axions is the microwave cavity haloscope in which a resonant cavity immersed in a strong magnetic field boosts the axion-to-photon coupling to detectable levels. Experimental efforts, such as ADMX, are exploring using multiple, frequency matched cavities to maximize the scan rate by taking advantage of the phase coherence of the axion signal. Nevertheless, there are practical limitations to this scan strategy as one scales to 10s or 100s of cavities. Here we would like to explore an alternative scheme in which multiple superconducting cavities with separate frequency bands can be tuned using non-mechanical methods and potentially read out with single-photon counting technology. [1]

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The most sensitive dark matter axion searches rely on a microwave cavity immersed in a strong magnetic field to resonantly convert dark matter axions to detectable microwaves when the cavity is tuned to the same frequency (or mass) as the axion[1,2]. The mass is a free parameter that is expected to be between 1 μeV-1 meV (240 MHz – 240 GHz). Current operating haloscopes such as ADMX and HAYSTAC are limited to $<$ 10 GHz (40 μeV) due to the dramatic slowdown in scan speed from the rising quantum noise contribution of the first stage superconducting amplifiers. Compounding this is the dramatic loss in volume and quality factor of copper cavities as they are scaled for higher frequencies.

We plan to address these issues with current haloscope technology in three ways. First, by building off of recent demonstrations of NbTi[3] and YBCO[4] superconducting films, we have begun a program to explore superconducting cavities whose high quality factors can be maintained in a high magnetic field. Though the currently funded effort for ADMX is focused on developing the 2-4 GHz multicavity system, we would like to extend these techniques to higher frequencies and determine the ultimate limits and trade-offs in film quality for superconducting deposition on small sets of 3D cavities. This includes exploring optimization of the deposition parameters with a focus on scalability to large sets of cavities. We will fabricate small 3D cavities with a thin superconducting coating parallel to the magnetic field optimized for magnetic field resilience. While this research is targeted at improving haloscope designs, it should be noted that high magnetic field operation is attractive for the QIS community as well. Flux tunable transmon qubits require magnetic fields, and there are a number of qubit technologies where operations in high magnetic fields would be useful[5].

Secondly, we will investigate frequency tuning of cavities by non-mechanical methods, thereby alleviating a source of heating and noise, allowing realistic scaling of the system to 10s or 100s of individual cavities. By creating an array of cavities, each with their own complementary frequency span, we can lower the required tuning range for each individual cavity, thereby generating a frequency comb to search for axion-to-photon conversions. Currently the ADMX 2-4 GHz baseline design is for a multicavity array in which all the cavities are coherently combined, either using cold power combiners or by amplifying the signal from each cavity and digitally combining them. In the simplest scenarios this leads to a $\sqrt{N}$ improvement in the Signal-to-Noise ratio and an N improvement in the scan rate for N cavities. However, this does not account for the losses and increase in complexity which is likely to be prohibitive for greater than 10s of cavities. By going to a frequency multiplexed approach in which each cavity is its own experimental search over a narrow frequency range one can greatly simplify the system at the expense of taking advantage of the large-scale coherent axion signal. There is freedom in shifting to this design concept though that is worth exploring. For example, most of the single or multiple cavity systems have needed a macroscopic metal or dielectric tuning element in order to change the boundary conditions enough to explore sufficiently large frequency (mass) ranges. In addition, in order to minimize the number of avoided mode crossings (in which the tunable cavity mode that couples to the axion interacts with a stationary TE or TEM mode) most axion haloscopes keep their aspect ratio short (L/R $<$ 5 - 10). By removing the mechanical tuner, we can eliminate that requirement which allows us to make cavities with aspect ratios up to factors of 50. The limitations coming from how close one can make the TM_{011} modes (no axion coupling) from the TM_{010} mode (which couples to the axion).

Two methods will be investigated to tune the cavity systems. In the first method, we will use liquid helium to fill the cavities and change their dielectric constant. This has been used in previous haloscopes to avoid mode-crossings by moving the resonant frequency of the system by of order 3% (corresponding to 1/2 the dielectric permittivity of LHe)[6]. More recently this approach has been demonstrated in optimization of qubit systems[7] using superfluid helium. In the second method, we will investigate employing high kinetic inductance superconductor coatings. These coatings can change their inductance when DC currents are applied, thereby electrically changing the resonant frequency of the cavity. This technique had initially be demonstrated in planar resonator systems[8] which demonstrated tuning of around 4% at 4.5 GHz. It has also been shown that high kinetic inductance allows rapid adjustment of the inductive coupling of a resonant cavity[9]. We propose to extend the application of this concept to 3D resonators. The key will be to maximize the kinetic inductance of the superconducting cavities by exploring novel techniques such as by patterning a meander on the walls of a dielectric surface and using superconducting material with exceptionally high natural kinetic inductance. Materials such as NbTiN, TiN and even Ti64 have demonstrated exceptionally high kinetic inductance[10]. Assuming a DC tunability of $\sim$8% in the kinetic inductance, we expect a frequency tuning of $\sim$1 MHz at 10 GHz.

It should be noted that in order to achieve the 8% tuning, large current densities approaching the critical current need to be achieved. We will explore different methods of reaching this goal including decreasing the critical current by making the superconductors thinner (which will have the added benefit of increase the kinetic inductance fraction) and increasing the current density by coating the cavity with a superconducting cage rather than a continuous surface (see figure 1).

The final key to this technique is the development of photon counting technology that is scalable to a large (>100) set of cavities. Our initial plan is to develop Josephson photomultiplier (JPM) photon counters[11] to circumvent the standard quantum detection limit. The counters will be based on a microwave-frequency analog of the avalanche photodiode and are scalable so that each cavity can be deployed with is own JPM. This would allow for each cavity system to effectively be it's own experiment. The design concept for such an experiment can be seen in figure 2.

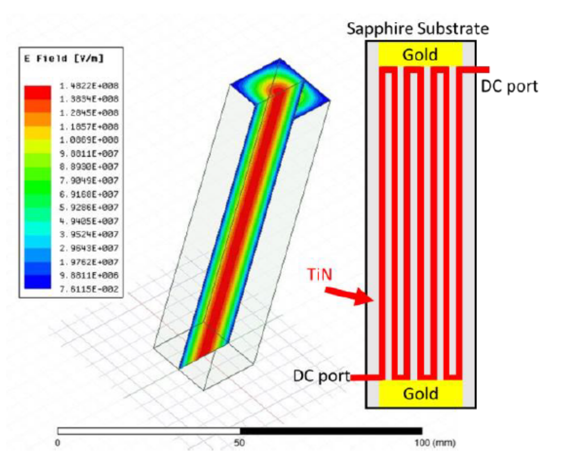

Figure 1: A simulation and example layout of a meander to allow a current to adjust the kinetic inductance of a microwave cavity, thereby changing the resonant frequency. Several Sapphire substrates can be used to enclose a cavity in a superconducting cage that makes up the resonance mode.

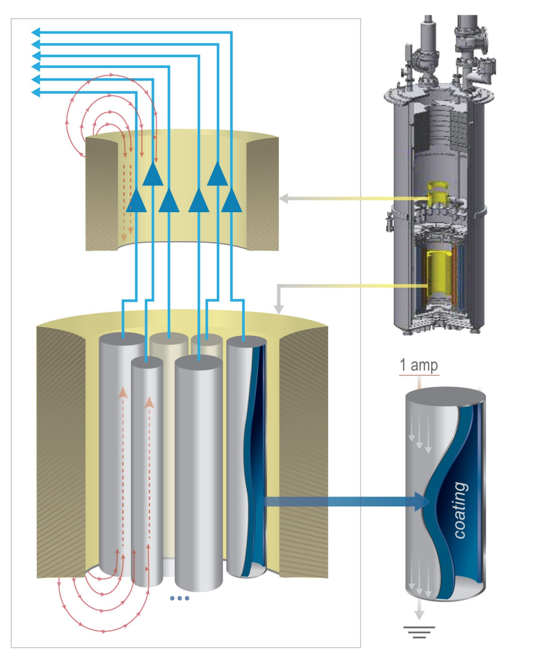

Figure 2: A preliminary detector concept that would employ multiple cavity structures of various radius that can be tuning in parallel.

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