# Tracking Optimal Axion-Sensitivie Resonant Modes in ADMX

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In ADMX operations, the $TM_{010}$ mode is best coupled to our antennas as it provides the largest form factor. As the form factor is proportional to the power signal, tracking the $TM_{010}$ mode ensures the use of the optimal axion-sensitive resonant modes. In this report, I will discuss the method to tracking the optimal axion-sensitive resonant modes in ADMX to ensure maxmized power signals.

## I. INTRODUCTION

For the past few decades, the general consensus for finding out what makes up approximately 27% of the mysterious side of the universe was determined as a non-trivial task.

The most popular dark matter candidate was the theoretical weakly interacting massive particle (WIMP). WIMPs were considered a favorable candidate for a long time, both having a sensible mass for particles that interact via the weak force that coincide with the amount of dark matter we see in the universe today, as well as filling in the theorized particle in the speculative theory of supersymmetry. However, ultra sensitive terrestrial WIMP detectors have swept a range of parameter space in the theorized WIMP mass range with no signs of its existence despite the years of searching. Thus, to sum up the current state of the WIMP search as said in a review of the WIMP dark matter candidate published in 2010: the moment of truth has come for WIMPs: either we will discover them in the next five to ten years, or we will witness their inevitable decline." ref. [1]. Ergo, the null results of the WIMP search has brought to attention the search for non-WIMP dark matter candidates.

Enter: Axions. The axion particle, first theorized as a solution to the strong charge-parity problem of quantum chromodynamics (QCD), has been established as a prominent cold dark matter (CDM) candidate. If we could prove the existence of such particles, this would constitute an insight into the observed astrophysical phenomena we attribute to dark matter as well as provide an explanation for the lack of observable CP-violation in the strong force. The Axion Dark Matter eXperiment (ADMX) at the University of Washington has been the leading contributor to the search for CDM axions in the past two decades, with a proposed new plan soon to be implemented to sweep over a larger axion mass range than previously done before.

## II. BACKGROUND

### A. Motivation for Axion

In 1977, theorists Roberto Peccei and Helen Quinn proposed a solution to the well known strong CP problem. In the standard model, CP (charge-parity) symmetry is a formal symmtery of any theory in which laws of physics do not distinguish between matter and antimatter. However, in the theory of quantum chromodynamics, (QCD), the mathematical form of the theory, or the QCD lagrangian, suggests that there should be in fact a violation of this symmetry in strong interactions. Yet, no violation of the CP-symmetry has been observed in experiments involving only the strong interaction.

Peccei & Quinn provided a solution to this problem by the introduction of a light pseudoscalar particle. The properties of this particle depend on the magnitude v, where v is the vacuum expectation value such that $<\phi>=v$ (the expectation value is evaluated in the minimum-energy state with no particle excitations)[2]. This parameter value v, spontaneously breaks the $U_{PQ}(1)$ quasisymmetry– making this particle a pseudo-Nambu-Goldstone boson. Frank Wilczek named this new particle as the axion, $a$ ,after a type of detergent, because it cleaned up a profound physical problem[2].

While the axion's existence arise from the Peccei-Quinn solution to the Strong CP problem, axions are also established to be an attractive CDM candidate. Axions are cold, non-baryonic particles that are extremely weakly coupled to normal matter, and are dominated by gravitational forces. The mass of the axion arises from the spontaneous breaking of the PQ symmetry by instaton effects, given by

$$m_a \approx 6\mu eV \frac{10^{12}GeV}{f_a} \tag{1}$$

where $f_a$ is the axion decay constant and is proportional to the vacuum expectation value which breaks PQ symmetry[3].

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While the exact mass of the axion is unknown, astrophysical observations and particle physics experiments have placed constraints on the axion's mass range. The lower bound is provided by the observations of SN1987A, in which the duration of the neutrino bursts observed from the supernova explosion provided the lower bound on the decay constant, such that $f_a \geq 10^9$ GeV. The upper bound is provided by the constraint from the cosmic energy density. If $f_a \geq 10^{12}$ GeV, the axion energy density would be too large, causing the universe to be overclosed[3]. From these constraints, the elusive mass range of the axion particle will be found in the $\mu$eV to meV mass range.

This range is the Goldilock's zone for the axion mass, such that the particles would be weakly coupled to normal matter and radiation, deeming them "invisible axions."

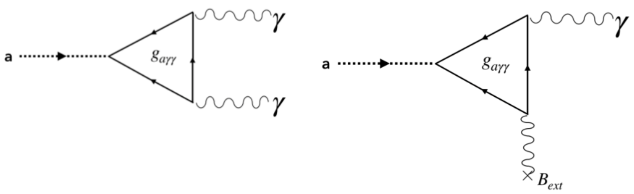

FIG. 1. (left) Primakoff Effect in a vacuum. (right) Inverse primakoff effect, adapted from [3]

Axions are so light that any decays into almost all standard model particles are considered "kinematically forbidden", in which the lifetime of the invisible axion is dominated by its decay into two photons. This is called the Primakoff Effect in a vacuum, and an inverse Primakoff Effect in a static magnetic field; the static magnetic field can be thought of as a sea of non-energetic photons, or virtual photons, such that when the axion field interacts with the sea of photons, the axion decays into a single photon. The axion-photon interaction is dictated by the Lagrangian

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a E \tag{2}$$

where $a$ is the axion field, and $E$ and $B$ are the electric and magnetic fields of the two propagating photons, respectively. The coupling constant, $g_{a\gamma\gamma}$ , is proportional to the mass of the axion by

$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{2_a} \tag{3}$$

here, $\alpha$ is the fine structure constant and $g_\gamma$ being the the model-dependent constant of order [3].

From the limits of $f_a$ and the equations above, it can be inferred that the axion coupling to electromagnetism is extremely weak, with the coupling to hardonic matter being even weaker. Futhermore, the lifetime of CDM axions within the elusive mass range is found to vastly greater than the age of the universe (for $m_a = 1\mu eV, \tau_{1/2}1054$s)[3].

## B. The Search for Axions

Due to the dark matter axions having long decay times and significantly weak interactions with both electromagnetism and hadronic matter, they were previously thought to be considered "invisible" and characteristically difficult to be observed. Sikivie proposed an axion detection scheme, based on the Primakoff effect, which used a microwave cavity permeated by a strong magnetic field to resonantly increase the number of photons produced by the decay. This experimental setup was known as an axion haloscope.

## C. Axion Dark Matter eXperiment (ADMX)

The Axion Dark Matter eXperiment (ADMX) is the largest and most sensitive axion haloscope experiment currently in operation. The experimental setup consists of a long cylindrical copper-plated microwave cavity embedded in a large superconducting solenoid with a 0.5 diameter bore. This solenoid generates a homogenous magnetic field ~ 7.6 T which stimulates axion to photon conversion such that dark-matter axions passing through the cavity can resonantly convert into detectable microwave photons[4].

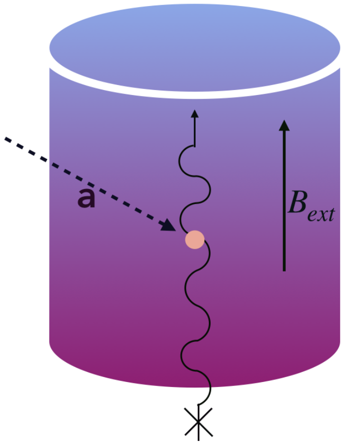

FIG. 2. A simplified schematic of axion haloscope experiment depicting a strong static magnetic field mediating the decay.(adaptation from [5])

The axion signal frequency is linearly related to the axion mass. Thus, based on the mass constraints, the axion signal is most likely to be found between 1-100GHz in an axion haloscope detector. The predicted coupling between axions and photons is model dependent; in general, axions with dominant hadronic couplings as in the Kim-Shifman-Vainshtein-Zakharov (KSVZ) model are predicted to have an axion-photon coupling roughly 2.7 times larger than that of the Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) model [4]. The geometry of the cavity is changed by the means of two copper-plated tuning rods that run coaxial within the length of the cavity interior. These 0.013m rods are attached to rotating armatures that allow the rods to be moved from the walls of the cavity to the proximity of the center of the cavity in small increments. The change of the geometry of the cavity from the change of rod positions allow for a range of frequency space to be scanned. The form factor

$$C_{mnp} = \frac{\left|\int_V dV E_{mnp}(x,t) \cdot B(x)_{ext}\right|^2}{V B_{ext}^2 \int_V dV \epsilon_r E_{mnp}^2} \qquad (4)$$

$C_{mnp}$, is the axion-photon conversion efficiency[3]. It is essentially the overlap between the microwave electric field and the static external magnetic field. Given an empty cavity geometry and direction of the B(x) field, only the electric field distribution of the $TM_{0n0}$ modes result in nonzero form factors. The cavity's antenna's are coupled to the $TM_{010}$ mode. If the $TM_{010}$ cavity resonant mode radio frequency (rf)overlaps with the frequency of photons from dark matter axion conversion, power is expected to develop in the cavity in excess of thermal noise:

$$\begin{aligned} P_{axion} = \ & 1.9 \times 10^{-22} W (\tfrac{V}{1361})(\tfrac{B}{6.8T})^2(\tfrac{C}{0.4})(\tfrac{g_\gamma}{0.97})^2 \\ & \times(\tfrac{\rho_a}{0.45 GeV cm^{-3}})(\tfrac{f}{650 MHz})(\tfrac{Q}{50{,}000}) \end{aligned} \qquad (5)$$

V is the cavity volume, B is the static magnetic field, $g_\alpha$ is the model-dependent axion-photon coupling with a value of 0.97 and 0.36 for the KSVZ and DFSZ benchmark models, respectively, $\rho_a$ axion dark matter density at Earths location, f is the frequency of the photons from axion conversion, and Q is the loaded cavity quality factor[3].

Power in the $TM_{010}$ mode of the cavity is extracted with a critically coupled antenna, passed through an ADMX cryogenics chain and amplified by a voltage-tunable microstrip SQUID (superconducting quantum interference device) amplifier JPA (josephson parametric amplifier) located in a magnetic field-free region.

## III. MODE MAPS

Tracking the optimal-mode for ADMX operations, the $TM_{010}$ mode, is paramount to ensuring that a detecable axion signal is not missed. One can track this optimal mode by creating a mode map illustrating the cavity spectrum as a function of the rod angle $\theta$. The lowest-frequency TM modes are the $TM_{0n0}$ modes, where n is the number of nodes along $\hat{z}$. The frequencies of these modes decrease steeply with increasing radial distance of the tuning rod from cavity center (increasing $\theta$). TE modes do not couple to the antenna, and thus only become visible in the mode map near mode crossings perpendicularly intersect with TM modes. The TE mode frequencies are largely insensitive to the position of the tuning rod. These mode maps are constructed by a considerable number of wide scans taken over a run.

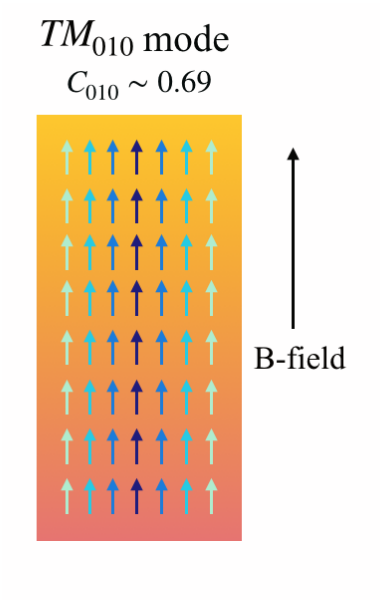

FIG. 3. Depiction of the electric field in cavity produced by microwave photon in alignment with the external static magnetic field (adapted from G. Carosi [6])

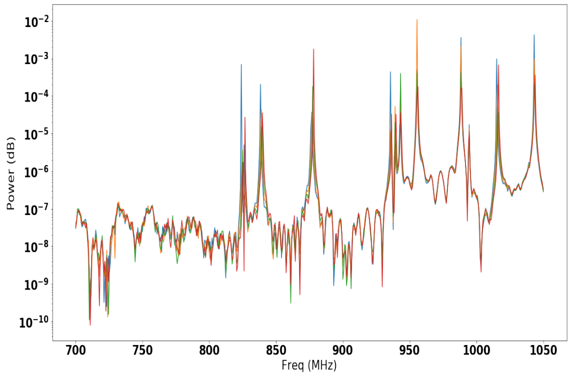

FIG. 4. Wide scans of warm data

These wide scans are then plotted against the radial rod position and frequency. The mode maps constructed were the preliminary runs for Run 1C, in both the cold and warm cavity conditions. When the TE and TM mode's frequencies are degenerate theres a mode crossing in which the two modes intersect and the resonant peak can disappear. The longer the cavity, the more TE modes there are in the tuning range. Both mode maps

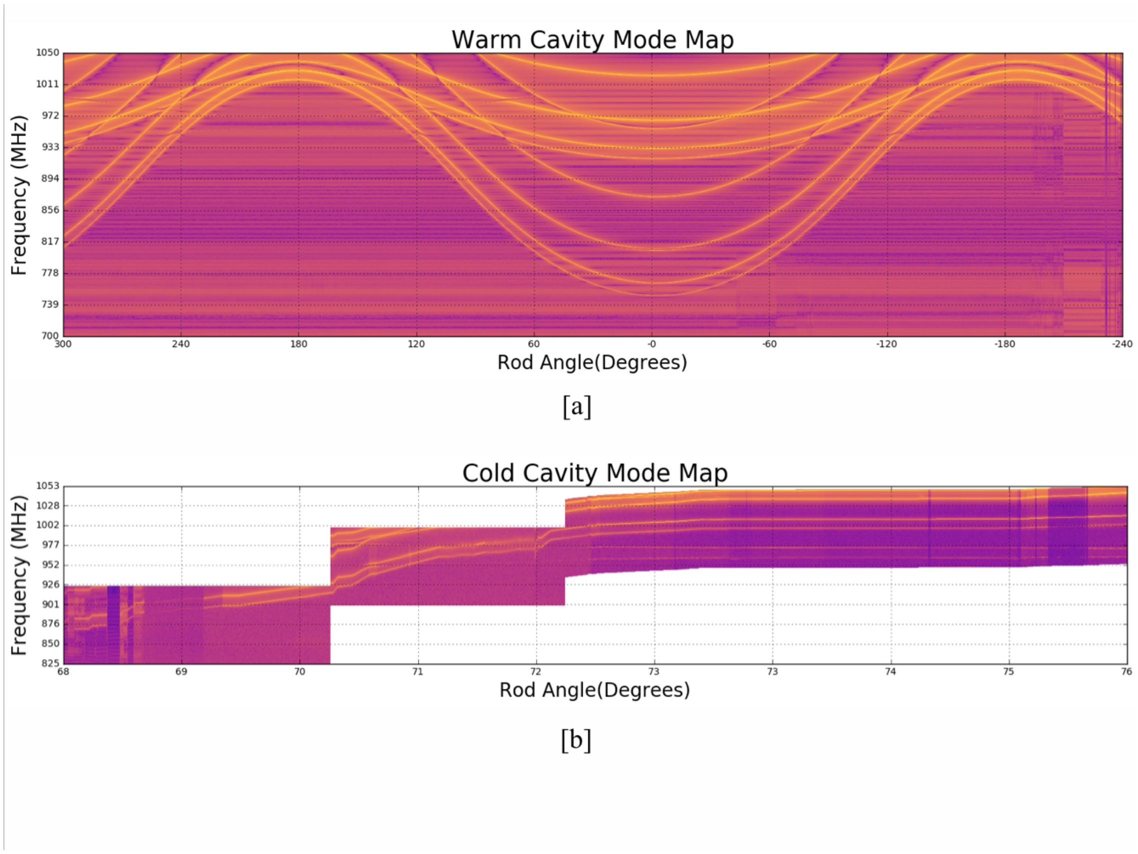

FIG. 5. [a] Measured warm cavity mode map. Gain (dB) is the color. The lowest-frequency mode is the $TM_{010}$ mode. The points at which the TM modes intersect with TE modes (horizontal modes) are mode crossings. [b] Measured cold cavity mode map. Again, the lowest-frequency mode is the $TM_{010}$ mode.

produced were used for symmetric rod movements.

## IV. DISCUSSION

As the exact mass of the axion remains unknown, the use of a tunable resonantor is principal to sweeping over the proposed mass range for the theoretical particle. The power signal of the microwave photon's frequency is most distinct when near or at the cavity's resonant frequency, thus tracking the $TM_{010}$ proves as a non-trivial task to ensure optimized power sensitivity if we are to detect the axion particle. Previously, there was no streamline process for tracking the $TM_{010}$ mode, now we have a reliable means of making mode maps for all future scans. This allows all future ADMX operations the ability to track the optimal axion-sensitive resonant mode in the cavity and can be used for both symmetric and asymmetric rod mode maps.

In the future, these mode maps can be compared to predicted simulations to validate optimal axion-sensitive resonant modes in future ADMX operations.

## V. ACKNOWLEDGEMENTS

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