The Use of Dielectrics for Enhanced Axion-Photon Coupling in RF-Cavity Dark Matter Searches

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Abstract

Axions provide a solution for the dark matter problem in astrophysics, as well as the strong CP problem. Searches for their detection with axion haloscopes take advantage of axion-photon coupling and use a resonant microwave cavity that can be tuned to a range of frequencies. Past haloscopes have been limited to low-frequency axion couplings; this project offers proof-of-concept for an expandable cavity design that utilizes dielectrics to allow high-frequency searches, and shows promise for a higher sensitivity in the 3-5 GHz range than previous designs.

1 Introduction

1.1 The Axion

1.1.1 Motivation: Strong CP Problem

The axion exists as a theoretical particles that is a solution to the strong CP problem. CP (charge parity) symmetry is the combination of charge symmetry and parity symmetry, and generally means that processes should behave the same when time is moving forwards as well as when time is moving backwards. According to the Lagrangian for quantum chromodynamics (QCD):

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$

CP symmetry *should* be broken by a nonzero θ, and yet this violation has never been empirically observed. This is the strong CP problem.

A popular solution to this problem is known as the Peccei-Quinn mechanism, which introduces the idea that θ is not a constant but represented by a changing field that gives it a very small value, and explains why it has never been measured (Peccei et al. 1977). This new field gives birth to a new particle: the axion.

1.1.2 Axion Mass

The mass of the axion is not predicted by any theory. This would prove problematic in attempts to find it, but fortunately the properties of the axion allows one to narrow this down to a finite range. The axion would interact gravitationally and electromagnetically, though the latter's interaction would be extremely weak. The following astrophysical observations coupled with these properties provide limits on the mass.

First, the axion would be able to escape a star much more quickly than a photon, which, through constant scattering by the dense plasma, takes on the order of a million years to travel from a star's core to the photosphere. A particle that interacts as weakly as the axion would escape the star much more quickly, and in the process carry away energy more rapidly. This causes the star to contract, heat, and increase its luminosity, resulting in a shortened lifetime. An axion of higher mass would carry away more energy, and therefore the observed lifetimes of stars would set an upper limit on the axion mass, however an even more stringent limit comes from the length of neutrino bursts that occur during type II supernovae. This burst is partly driven by the residual heat of the inner core, and the increased cooling from axions would shorten the duration. Therefore, the recorded lengths of neutrino bursts (particularly from SN1987A) further set an upper limit on the axion mass of $m_{axion} \leq 10^{-3}\ eV$ (Turner 1990).

With many ALPs searches, success is not necessarily measured in an axion signal but in a sensitivity that sets a limit lower than previous searches on the axion coupling strength; the coupling strength is another property of the particle, describing the efficacy with which it couples to photons, whose value is unknown. Searches aim to "box in" the region hiding the particle using more and more stringent limits on the coupling strength and the mass, as shown in Figure 1.

With the frequencies of the resonant modes identified and checked for an ALP signal, the failure to measure one indicates that the coupling strength is weaker than that required to reveal the signal above the noise, and sets a new limit.

1.1.3 Dark Matter and its Relevance

If the axion were to exist, and if its mass were within a certain desirable range, models show that it would account for the dark matter problem in astrophysics.

The dark matter problem is that galaxies and galaxy clusters do not interact gravitationally as we expect based on our knowledge of orbital dynamics. One of the more famous example of this is found in galaxy rotation curves (Rubin 1970). Much like our solar system, a galaxy appears to have

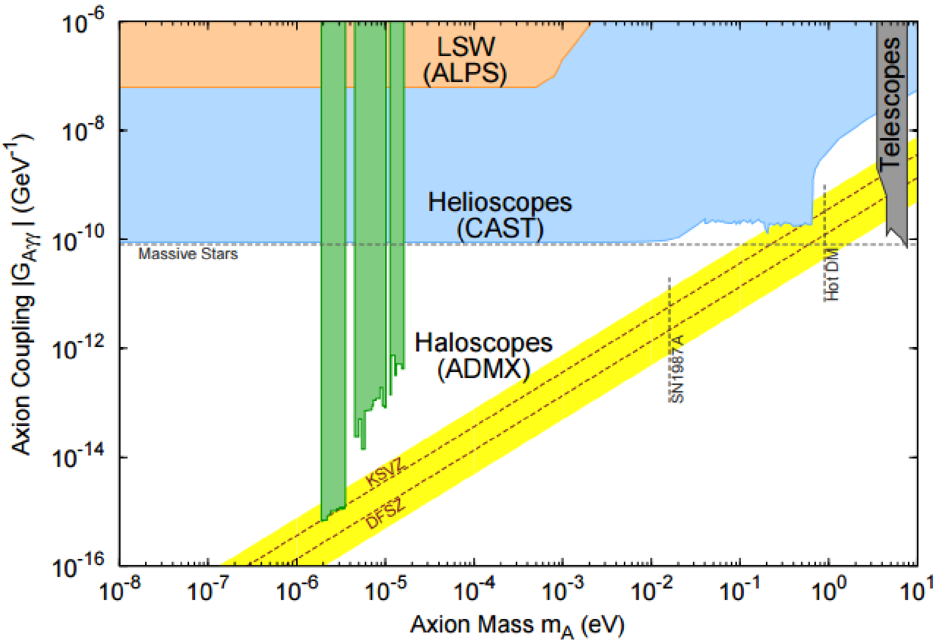

Figure 1: Searches systematically narrow the parameter region hiding the axion.

most of its mass concentrated at the center. Because orbital velocity is given by:

$$v_{orbital} \approx \sqrt{\frac{GM_{enclosed}}{r}}$$

we expect the velocity to fall off as $\frac{1}{\sqrt{r}}$, as moving out further does not enclose any more mass within the orbit. This is true of our solar system, but Doppler shift measurements of galaxies gives the surprising result of a relatively flat rotation curve (see Figure 2). This indicates that as one moves out in radius, one is enclosing more mass within the orbit at a linear rate. This unseen mass, this “dark matter”, is a great mystery to astrophysicists.

Many theories exists for the composition of dark matter: Weakly Interacting Massive Particles, Massive Compact Halo Objects (such as stellar-mass black holes or brown dwarfs), or supersymmetric particles to name a few. Axions or an axion-like particles (ALPs) produced in the early universe, should they exist within a particular mass range, would also explain this phenomenon.

The weak coupling to the electromagnetic force indicates that an axion-photon interaction would be very rare under natural conditions (in fact, a decay of an axion into two photons would take much longer than the age of

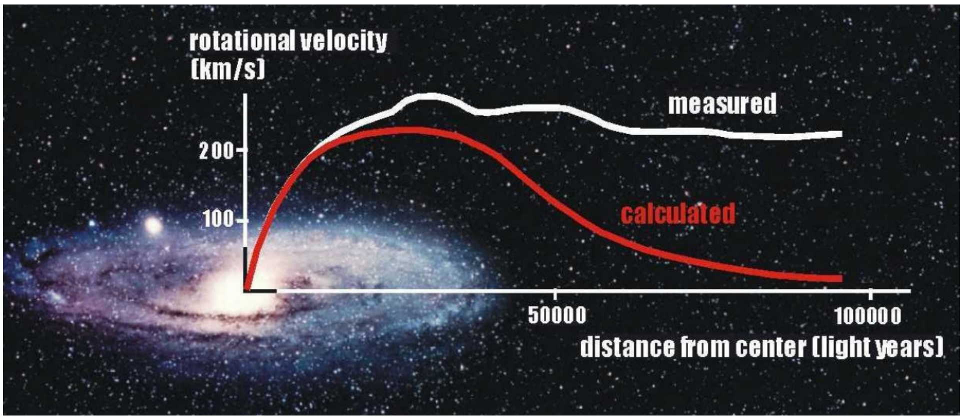

Figure 2: The unexpected rotation curve of observed galaxies.

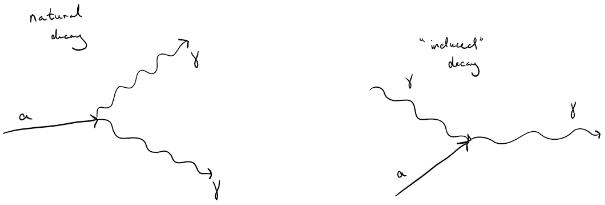

Figure 3: An external photon will induce the axion decay into another photon.

the universe to occur), and therefore it is still viable to be a dark matter candidate.

1.2 Axion Detectors

1.2.1 The Axion Haloscope

As mentioned above, the axion will naturally decay into photons given a sufficient amount of time. Because photons are easy to detect, many axion searches take advantage of this to infer the existence of the particle. These variants of axion detectors are referred to as axion haloscopes. The age of the universe is a somewhat impractical amount of time to run an experiment, so axion haloscopes will stimulate this decay using virtual photons provided by an $\vec{E}/\vec{B}$ field (see Figure 3). $\vec{B}$ fields are favored because it is much easier to store energy within them.

An axion haloscope will therefore be a cavity immersed in a strong $\vec{B}$ field that searches for these converted photons in the form of excess power at the predicted frequencies of axion coupling. The excess power from axions is predicted to be extremely weak; a haloscope will want to maximize it in

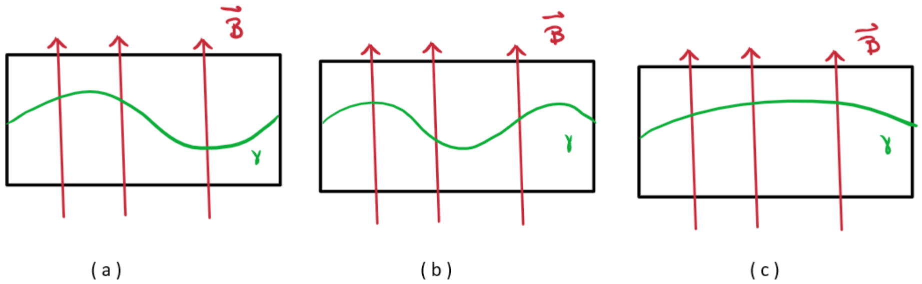

Figure 4: We can see that the quantity $\int \vec{E} \cdot \vec{B}$ is zero for cavity a, and that while it is nonzero for cavity b, it is cavity c that has the maximum value.

the following ways.

Many techniques to lower noise are implemented, but one of the best ways to ensure higher power is to create a cavity whose shape supports resonant modes that correspond with your desired frequency. The resonant modes refer to waves that can fit an integer amount of wavelengths inside the cavity. Power at these frequencies is less readily absorbed by the cavity and so power picked up by the antenna is maximized.

Theory predicts that the axion-photon coupling strength is proportional to the quantity $\vec{E} \cdot \vec{B}$. The form factor for an axion haloscope is a defined quantity that represents a measure of the axion-photon coupling; a higher form factor will result in a higher power for the axion signal. This form factor is proportional to $\int \vec{E} \cdot \vec{B}$. In an axion haloscope, $\vec{E}$ represents the field of a given mode and $\vec{B}$ represents the external magnetic field. Thus, it is essential to construct a cavity that maximizes this quantity.

Finally, a simple yet crucial way to maximize power is to have a cavity with a large volume, so more axions may be contained within it.

1.2.2 Previous Designs

Axion haloscopes are limited to low-frequency axion wavelengths due to the need to maximize the quantity $\int \vec{E} \cdot \vec{B}$. Figure 4 shows that in order to do this, the cavity must be tuned to a half-integer wavelength of the desired axion mode. Because the cavity must have a sufficient volume, high frequency-tuned cavities would be too small..

2 Experiment

2.1 Apparatus

The cavity built for this experiment, nicknamed "Electric Tiger" for the striped appearance, is an expandable haloscope design that uses dielectrics

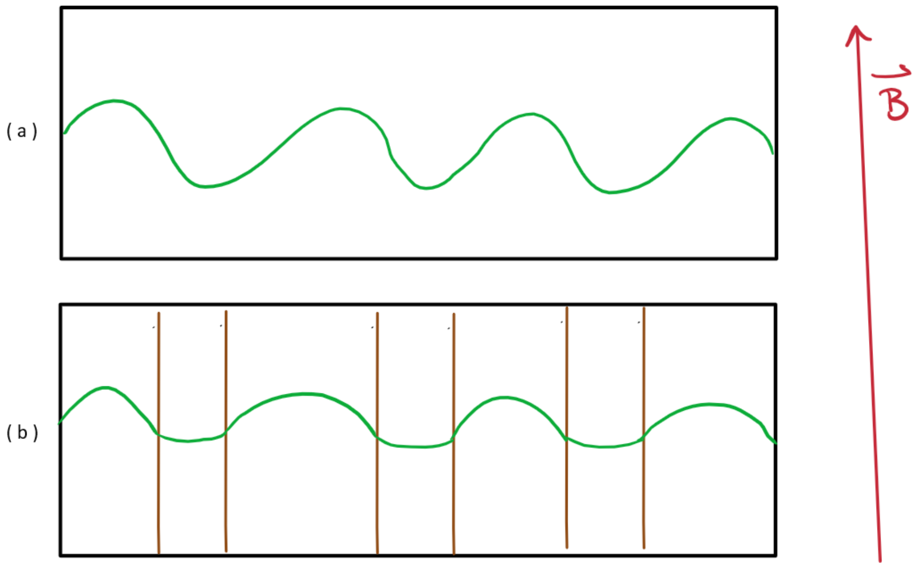

Figure 5: Note that the addition of a dielectric at the trough of the wave allows for $\int \vec{E} \cdot \vec{B}$ to be much higher in cavity b than in cavity a.

to be capable of tuning to higher frequency axions without sacrificing cavity volume. Its design is described below.

2.1.1 Dielectric Structure

To be receptive to high frequency axion signals without sacrificing volume, a haloscope would need to contain multi-wavelength signals without diminishing the quantity $\int \vec{E} \cdot \vec{B}$. Electric Tiger uses evenly spaced dielectrics in the form of 3 1-cm thick nylon blocks to accomplish this. The dielectrics diminish the electric field within them (see Figure 5), and have been arranged strategically to correspond to the troughs of the wave to enhance coupling to the modes in the 3-5 GHz range.

2.1.2 Resonant Cavity

The haloscope cavity must be shaped so that the desired frequency mode is a resonant frequency. The axion frequency is not yet known, so it is essential to design a haloscope with a cavity that can tune its resonant modes to avoid building billions of differently sized cavities. Electric Tiger utilizes an expandable cavity design that can be finely tuned by a stepper motor to change its resonant mode structure (see Figure 6). Using this, it can tune to use the dielectrics to be receptive to an axion frequency range of

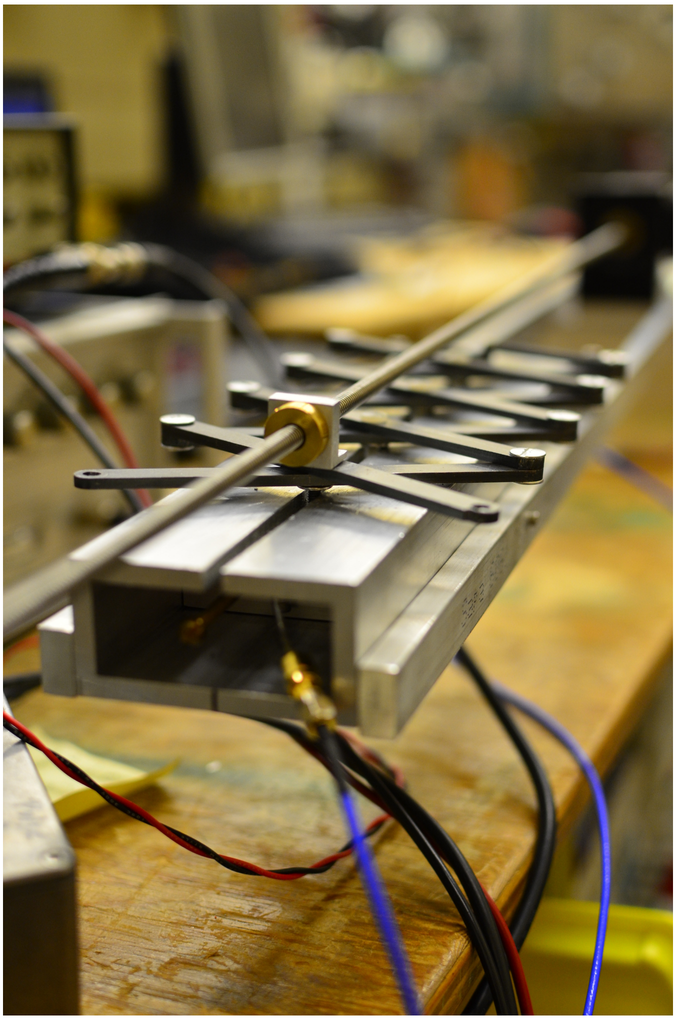

Figure 6: The expandable cavity of Electric Tiger.

approximately 3 to 5 GHz.

2.2 Procedure

To test the efficacy of this cavity design, Electric Tiger was placed in a 1.45 T field and scanned over an axion frequency range of 4.1 - 4.3 GHz (corresponding to $\approx$ 0.19558 - 0.18288 m cavity length). A mode-tracking program is implemented to follow the resonant modes across this range. This tracking program starts by injecting power into the cavity and measuring the power that is reflected back into the antenna. Low reflected power at a frequency indicates a resonant mode; power is not readily absorbed into the cavity at these frequencies. Figure 7 shows a reflection map that illustrates visually illustrates how the mode changes with cavity length, as well as Electric

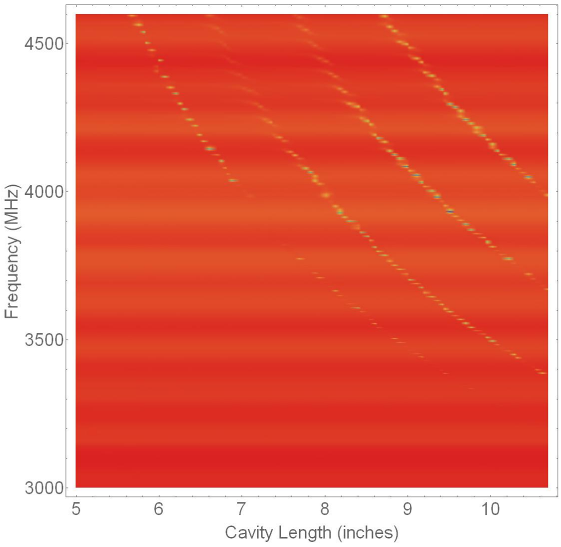

Figure 7: This reflection map illustrates power vs frequency vs cavity length. The lighter regions indicate less power, revealing the frequency of the resonant mode. The clearly defined trails compared to the transmission mode map (see below) are the reason that Electric Tiger uses reflection to track the modes.

Tiger's ability to successfully track them.

With the location of the mode found, the tracking program measures transmitted power to measure the quality factor Q of the mode. Figure 8 shows a mode map of transmitted power for comparison.

For each cavity configuration, power is integrated at the frequency of the target mode to build up a power spectrum and reduce noise. The experiment was run at room temperature, and the amplifiers used for this test added 32.5 K to the system. The average Q for identified modes was $\approx$ 100.

3 Results

Electric Tiger is currently taking data. The projected sensitivity for this search is to an axion coupling strength of $1.107 \times 10^{-10}\ GeV^{-1}$, and is expected to reach $6.228 \times 10^{-11}\ GeV^{-1}$ with planned upgrades that employ a digitizer to increase efficiency, allowing for more stringent limits for operation per unit time. As seen in Figure 10, this limit is more sensitive in our frequency range than that set by both ALPS (Any Light Particle Search), which uses a 5.3T field, and the cryogenic CAST (CERN Axion Solar Telescope) experiment.

Given this, the Electric Tiger cavity design is promising for axion searches,

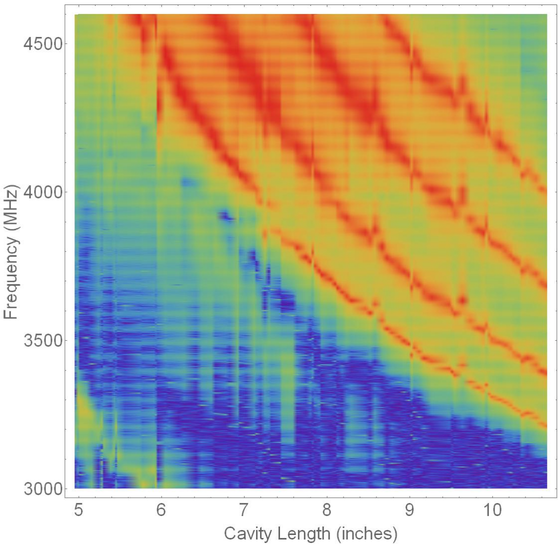

Figure 8: The mode map of transmitted power.

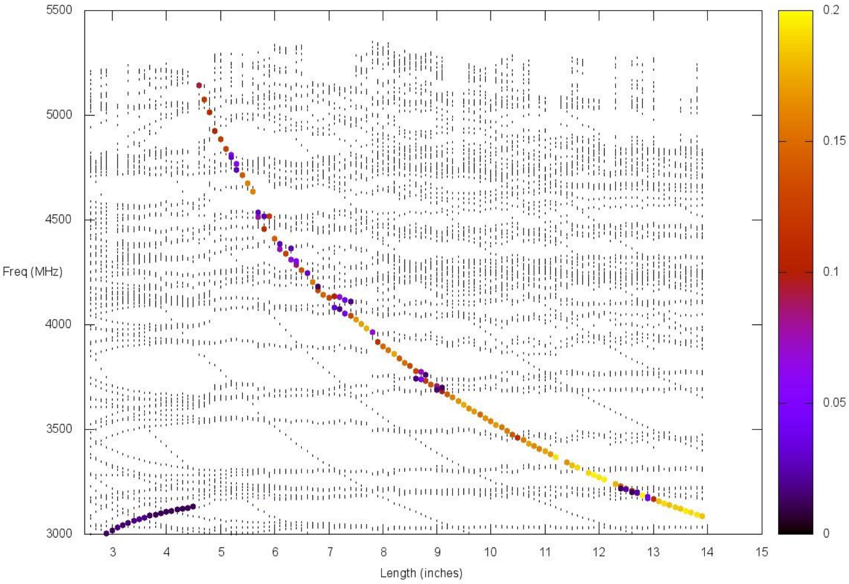

Figure 9: This predicted mode from a simulation shows how accurately Electric Tiger is able to track.

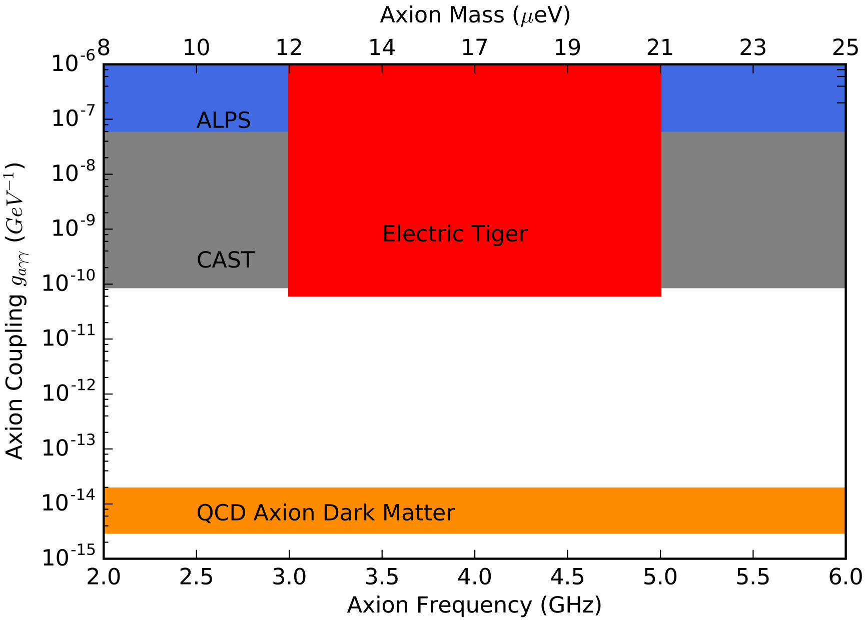

Figure 10: With minimal upgrades, Electric Tiger has the potential to surpass the sensitivity of larger detectors.

worthy of consideration for more costly upgrades in the future such as a stronger magnetic field or reduced noise through cooling systems.

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