

# High Resolution Cavity Searches for Axions

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## 1 Introduction

There is a wide body of astrophysical and cosmological evidence that indicates that most of the matter in the universe is not the ordinary matter we interact with day to day, but instead some strange, undiscovered, non-luminous type of matter. [1] The nature of this unaccounted for matter, known as dark matter, is a major outstanding problem that brings together astronomy, cosmology and particle physics. The axion, a hypothetical particle originally proposed to resolve the Strong CP problem in QCD, is a strong candidate to account for a substantial portion of this strange dark matter.

The axion is a dark matter candidate because it interacts very weakly with ordinary matter, and there is a plausible model for the production of cold (non-relativistic) axions at a phase transition in the early universe. The size of the axion contribution to the energy density depends strongly on the mass of the axion, which is a free parameter in QCD. A combination of cosmological constraints, results from particle accelerators and observations of stars and super novae have been able to weakly bound the axion mass  $m_a$  between  $1 \mu\text{eV} < m_a < 10^3 \mu\text{eV}$ . [1, 2]

There are a number of different types of experiments underway that hope to detect axions through their weak coupling to the electromagnetic field. [2] In this paper I will focus on the Axion Dark Matter eXperiment (ADMX), which uses a microwave cavity detector to search for axions in the halo of dark matter that permeates our galaxy. This experiment has not detected the axion, but it has been able to place limits on the contribution of axions to the halo density and the coupling strength between axions and photons for a mass range  $1.8\mu\text{eV} \leq m_a \leq 3.4\mu\text{eV}$ . With proposed improvements to increase sensitivity and cover a large mass range, this experiment could

either discover axions or exclude them as a dark matter candidate within the near future.

## 2 Dark Matter and Galactic Halos

The first evidence for non-luminous, or dark, matter came from observations of the rotation rates of galaxies. From images of the luminous matter in galaxies and Kepler's law  $GM(r) = v^2 r$  ( $M(r)$  is the total mass contained within a radius  $r$ ), we would expect the rotational velocity to decrease with distance from the center of galaxy. However, as can be seen in figure 1, the velocity remains roughly constant. This trend continues outside the luminous edge of the galaxy, indicating that most of the matter associated with a galaxy is actually dark matter. The observed rotation curves for numerous galaxies indicate that each galaxy is permeated by a diffuse 'halo' of non-relativistic, or cold, dark matter, contributing between 3 to 10 times the mass associated with luminous matter. [1, 3] The density of the dark matter halo for our galaxy is measured to be about  $9 \times 10^{-25} \text{g cm}^{-3} = 0.4 \text{ GeV cm}^{-3}$ . [4]

The existence of dark matter is further supported by numerous other observations, such as the structure of the peaks in CMB power spectrum and observations of Type 1a supernovae. [5] Though some of this missing matter could potentially be normal, baryonic matter that is just too dim to see, big bang nucleosynthesis limits the amount of normal, baryonic matter in the universe. It is generally agreed that about 25% of the material in the universe is cold, non-baryonic dark matter while only 5% is ordinary matter.

## 3 QCD Axions

### 3.1 The Strong CP Problem

The axion was originally proposed to resolve a puzzle in the Standard Model of particle physics. Quantum Chromodynamics (QCD) contains a parameter  $\bar{\theta}$  that in principle should be able to take on any value between 0 and  $2\pi$ . However, experimental bounds on the neutron dipole moment bound  $|\bar{\theta}| < 10^{-10}$ , an unnaturally small number. [2] Small numbers like this are typically thought to be associated with a weakly broken symmetry, and indeed  $\bar{\theta} = 0$  would correspond to CP invariance. However, the standard model is

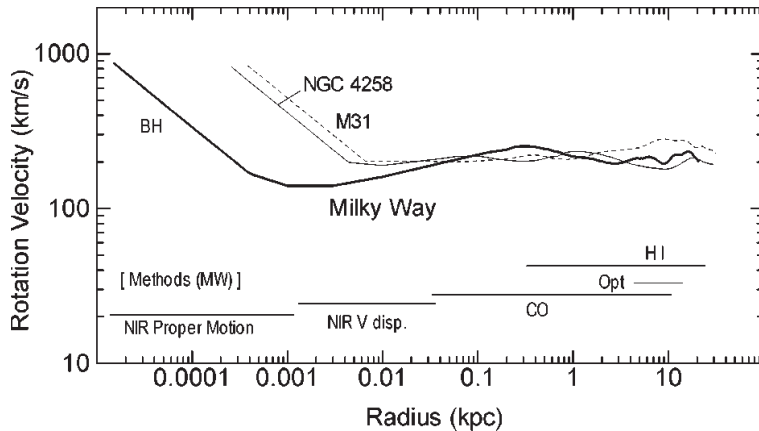


Figure 1: Logarithmic rotation curves of the Milky Way (thick line), NGC 4258 (thin line), and M31 (dashed line). Taken from [3]

not CP invariant due to the weak interaction, so the question of why  $\bar{\theta}$  is still so small remains and is known as the "Strong CP Problem".

A solution to this problem was proposed by Peccei and Quinn, who added an additional scalar field  $a(x)$  to the standard model lagrangian in such a way that the theory has a new global  $U(1)$  symmetry. [6, 2] This symmetry, known as Peccei-Quinn (PQ) symmetry, is spontaneously broken by the color anomaly. There will naturally be pseudo-Nambu-Goldstone bosons associated with this broken symmetry, which were named 'axions' by Wilczek. [7, 8] This scalar field solves the CP problem by making  $\bar{\theta}$  a dynamic variable that depends on the axion field  $a(x)$ . The QCD vacuum energy depends on  $\bar{\theta}$ , and is minimized by  $\bar{\theta} = 0$ , so a small measured value for  $\bar{\theta}$  is no longer unnatural. [9]

### 3.2 Properties of the Axion

There are two dominant axion models, know as the Kim, Shifman, Vainshten and Zakharov (KSVZ) model and the Dine, Fischler, Srednicki and Zhitnitsky (DFSZ). In the KSVZ model the axion only directly couples to quarks, while in the DFSZ model the axion can directly couple to leptons as well. The coupling to the electromagnetic field arises indirectly, from an axion splitting into two quarks, which then exchange a third quark and emit

two photons. This leads to an effective coupling of the form

$$\mathcal{L}_{a\gamma\gamma} = -g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \mathbf{E} \cdot \mathbf{B} \quad (1)$$

where  $g_\gamma$  a constant of order one and depends on the details of the axion model (0.36 for DFSZ, -0.97 for KSVZ). This effective interaction is very weak, making the axions non-luminous, and hence a possible dark matter candidate.

Axion models contains one free parameter,  $f_a$ , the energy scale at which the Peccei-Quinn symmetry is broken. Though originally thought be on the order of the weak interaction, there is no real restriction on  $f_a$ . [2] The axion mass is

$$m_a \simeq 6 \text{ eV} \frac{10^6 \text{ GeV}}{f_a} \quad (2)$$

Since  $f_a$  is theoretically unrestricted, so is  $m_a$ . Accelerator experiments were able to exclude heavy axions and bound the axion mass below  $10^5$  eV. Since the axion is weakly interacting, it would play a large role in stellar cooling. Observation of the lifetimes of red giants exclude the 100 keV to eV range, while the duration of the neutrino pulse from supernova 1987A exclude eV to meV range. The lower bound on the axion mass is  $10^{-6}$  eV, and arises from the condition the axion not over-close the universe. [2] We will explore this limit in more detail in the next section.

## 4 Axions and Cosmology

### 4.1 Production in the Early Universe

In order for the axion to be a suitable dark matter candidate, in addition to being non-luminous, it must also be abundant in sufficient quantities. This will depend on the number of axions produced in the early universe, which ends up depending on the mass of the axion.

Axion production through vacuum realignment can be understood in terms of a simple scalar field theory. [10, 2, 1] PQ symmetry breaking occurs at temperature  $T \sim f_a$ , when a complex scalar field  $\Psi = f_a e^{i\bar{\theta}}$  acquires a non-zero expectation value. Around this temperature we have a typical 'mexican hat' potential

$$V(\Psi) = \lambda(|\Psi|^2 - f_a^2)^2 \quad T \sim f_a \quad (3)$$

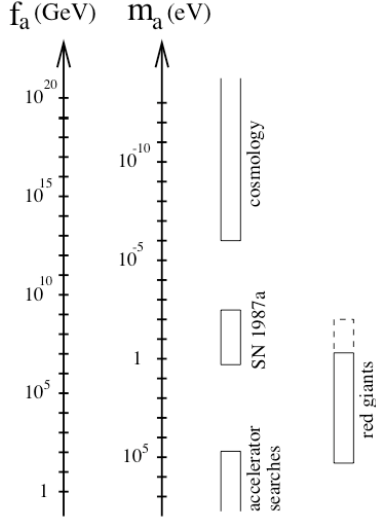


Figure 2: Excluded axion mass and PQ Symmetry breaking scale. Taken from [2]

This potential is independent of  $\bar{\theta}$ , and the axion is the mass-less Nambu-Goldstone associated with this  $U(1)$  symmetry. When the temperature cools to QCD scale,  $T \sim \Lambda_{QCD}$ , this symmetry is broken by tipping the potential so that there is a unique vacuum at  $\bar{\theta} = 0$ . This tipping turns on the axion potential, which we can approximate as  $V(a) \simeq \frac{1}{2}m_a^2 a^2$ . If we assume  $a$  is homogeneous on the horizon scale, the equation of motion for  $a$  would then be

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0 \quad (4)$$

At a time  $t_1 \sim m_a(t_1)^{-1}$  the axion field would begin to oscillate. At this time the energy density of the field would be  $\rho_a \sim \frac{1}{2}m_a(t_1)^2 a(t_1)^2 \sim \frac{1}{2}m_a(t_1)^2 f_a^2$ . The number density at this time is given by  $n_a(t_1) \sim m_a(t_1) f_a^2$ . The ratio of axion number density to entropy density is assumed to be constant, so the energy density today is given by

$$\rho_a = \frac{n_a(t_1)}{s(t_1)} s_0 m_a \sim \frac{m_a(T_1) f_a^2}{s(T_1)} s_0 m_a \quad (5)$$

where the temperature is  $T_1$  at time  $t_1$ . The ratio of the axion density to the

critical density  $\rho_c = 3H/8\pi G$  works out to be [2]

$$\Omega_a \simeq 0.5 \left( \frac{6 \mu\text{eV}}{m_a} \right)^{7/6} \quad (6)$$

We see that an axion mass below the  $\mu\text{eV}$  range,  $\Omega_a > 1$  and the axion would over-close the universe. If  $m_a \sim \mu\text{eV}$  then  $\Omega_a \sim 0.25$  and we would have found most of our missing matter, while if  $m_a$  is higher than it is not the dominant component of dark matter and we would have to look elsewhere. However, vacuum realignment is not the only way to produce axions in the early universe.

Since we have a complex scalar field, this theory contains axion strings as topological defects. If inflation is occurred, and the reheating temperature is lower than the PQ symmetry breaking temperature, then these defects would annihilate during inflation and the strings would be "inflated" away. However, if the PQ symmetry is broken after inflation ended, then these strings would remain and radiate axions until the axion mass turned on. There is still debate about the contribution from axion string decay. Some simulations predict that the contribution from strings is approximately 10 times the contribution from vacuum realignment, while other simulations indicate that it is of the same order. [2] There are numerous other ways to alter  $\Omega_a$ , such as an abrupt change in  $m_a$  at a QCD phase transition, or allowing for a time dependent  $f_a$ . These other possibilities make the bound  $m_a > 10^{-6}$  very weak.

In these models for axion production, the axions that are produced are non-relativistic from the start and were never in thermal equilibrium with the rest of the universe, making them a clear candidate for cold dark matter.

## 5 Dark Matter Axion Detection

There are numerous searches for axions underway, all of which rely on axion to photon conversion through the  $g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \mathbf{E} \cdot \mathbf{B}$  interaction perviously mentioned. Given the wide range for the possible mass of the axion,  $10^{-3} \text{ eV} > m_a > 10^{-6} \text{ eV}$ , it is difficult for a single experiment to be sensitive to realistic axion models over this full range of possible masses. As you can see from figure 3, very few experiments can cover realistic QCD axion models in reasonable mass range. The ADMX collaboration just barely intersects the

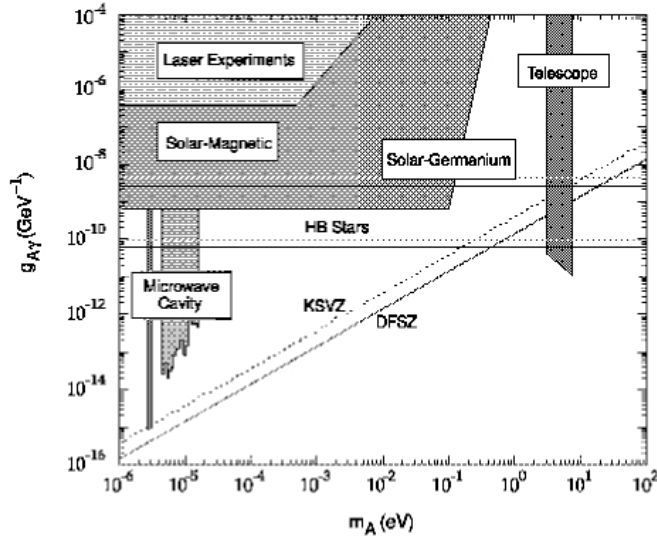


Figure 3: Axion couplings and masses covered by various axion searches. The thin line that intersects the KSVZ model in the  $\mu\text{eV}$  range is the ADMX collaboration. Taken from the ADMX website <http://www.phys.ufl.edu/axion/>

KSVZ model in the 1.9 to 3.3  $\mu\text{eV}$  range, and I will focus on the work of this collaboration for the rest of this paper.

## 5.1 Cavity Searches

This experiment uses an electromagnetic cavity permeated by a strong, static magnetic field to convert axions from the dark matter halo into real, observable photons. [5, 11, 2] The factor  $g_\gamma \frac{\alpha}{\pi} \frac{1}{f_a}$  is so small that the time for an axion to spontaneously split into two photons is longer than the age of the universe. [5] However, this conversion process can be greatly enhanced in the resonant cavity. Since the halo axions are non-relativistic, their energy approximately equal to their mass. If frequency of the cavity matches the mass of the axion, this process is resonantly enhanced. [12, 11] In the presence of a static magnetic field  $B_0$ , the coupling of the axion to a particular mode is given by

$$g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} B_0 \int_V d^3x E_\omega(\mathbf{x}, t) \quad (7)$$

where  $V$  is the volume of the cavity. Assuming a spatially uniform axion field  $a(t)$ , Maxwell's equations are modified by the additional interaction so that [12, 13]

$$(\mu\epsilon\partial_t^2 - \nabla^2)E = \frac{\alpha}{\pi} \frac{1}{f_a} B_0 \partial_t^2 a \quad (8)$$

The power from axion to photon conversion works out to be

$$P = \left(\frac{\alpha g_\gamma}{\pi f_a}\right)^2 V B_0^2 \rho_a m_a^{-1} C \min(Q, Q_a) \quad (9)$$

where  $C$  form factor which depends on the cavity geometry and the mode,  $Q$  and  $Q_a$  are quality factors for the cavity and axion signal respectively. For the lowest TM mode  $C$  0.7, and it is lower for other modes. [11, 2] To give a rough idea of the scales involved, this can be rewritten as

$$P = 10^{-26} \text{ Watt} \left(\frac{V}{500\text{liter}}\right) \left(\frac{B_0}{7\text{Tesla}}\right)^2 \left(\frac{\rho_a}{10^{-24}\text{g/cm}^3}\right) \left(\frac{m_a}{2\pi\text{GHz}}\right) (g_\gamma/4)^2 C \min(Q, Q_a) \quad (10)$$

## 5.2 The ADMX Setup

The ADMX cavity is located at Lawrence Livermore National Laboratory, it has been in operation since 1997, with a few improvements made in the past few years. I wish to dwell on the experimental details for a moment, since these details are key to determining the mass range that can be scanned and determining whether certain axion models can be excluded.

The microwave cavity has a volume of 189 L, and is housed in a superconducting solenoid which generates a static magnetic field of 7.8 T. It's quality factor is on the order of  $10^4$ . The typical axion velocity is of the order  $10^{-3}$ , so  $E_a = m_a + (1/2)m_a v^2 = m_a(1 + \mathcal{O}(10^{-6}))$ , which implies  $Q_a \sim 10^6$ . The resonant frequency can be adjusted from 478 - 880 MHz ( $1.9 - 3.4\mu\text{eV}$ ) by adjusting a metal tuning rod and a dielectric tuning rod. The entire setup (including cryostat vessel) is about 3.6 meters tall. if the axion mass is in the  $\mu\text{eV}$  range, then the power of the axion signal would be  $10^{-22}$  Watts. For comparison, the signal power from Pioneer 10, 11 billion kilometers away, is about  $10^{-17}$  Watts. [14] The signal is amplified by a GaAs heterostructure-field-effect transistor (HFET) amplifier, which have a noise temperature of about 2 K and a power gain of 17 dB. For each resonant frequency, ten thousand power spectra covering a 30 kHz bandwidth are averaged together. The axion signal would show up as excess power close to the resonant frequency.

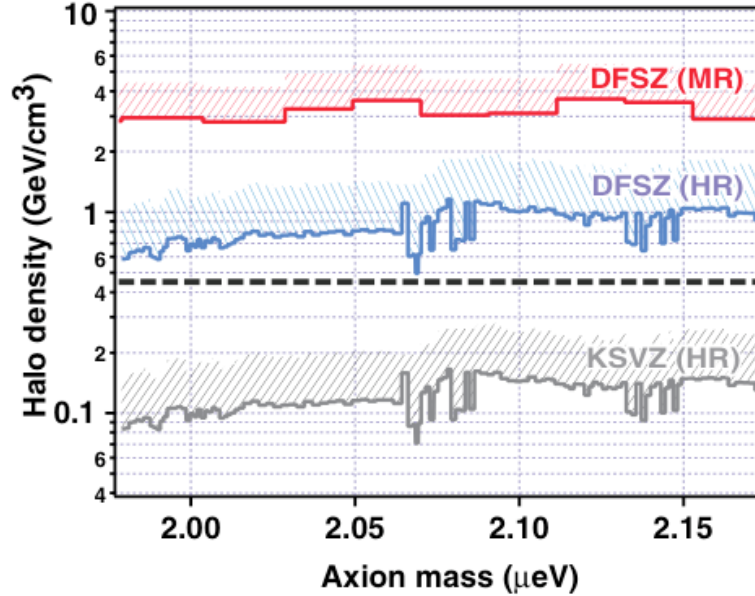


Figure 4: Upper limits on the halo density from DFSZ and KSVZ axions taken from [15]. The two curves for the DFSZ correspond to two different search channels (the old medium resolution channel (MR) and the new high resolution channel (HR)). The dotted line corresponds to dark matter halo density.

### 5.3 ADMX Results

So far, there has clear axion signal. Instead, they can only place limits on the density of axions corresponding to different axion models. Plotted in figures 4 and 5 are the 90% confidence limits on axion density for DFSZ and KSVZ models for two different mass ranges. Recall the the dark matter halo density is roughly  $0.4 \text{ GeV cm}^{-3}$ , so we can weakly exclude KSVZ axions in the  $1.9 - 3.4 \mu\text{eV}$  mass range as the dominant component of dark matter. We cannot make such a strong claim about DFSZ axions, though in the most recent results we are getting very close.

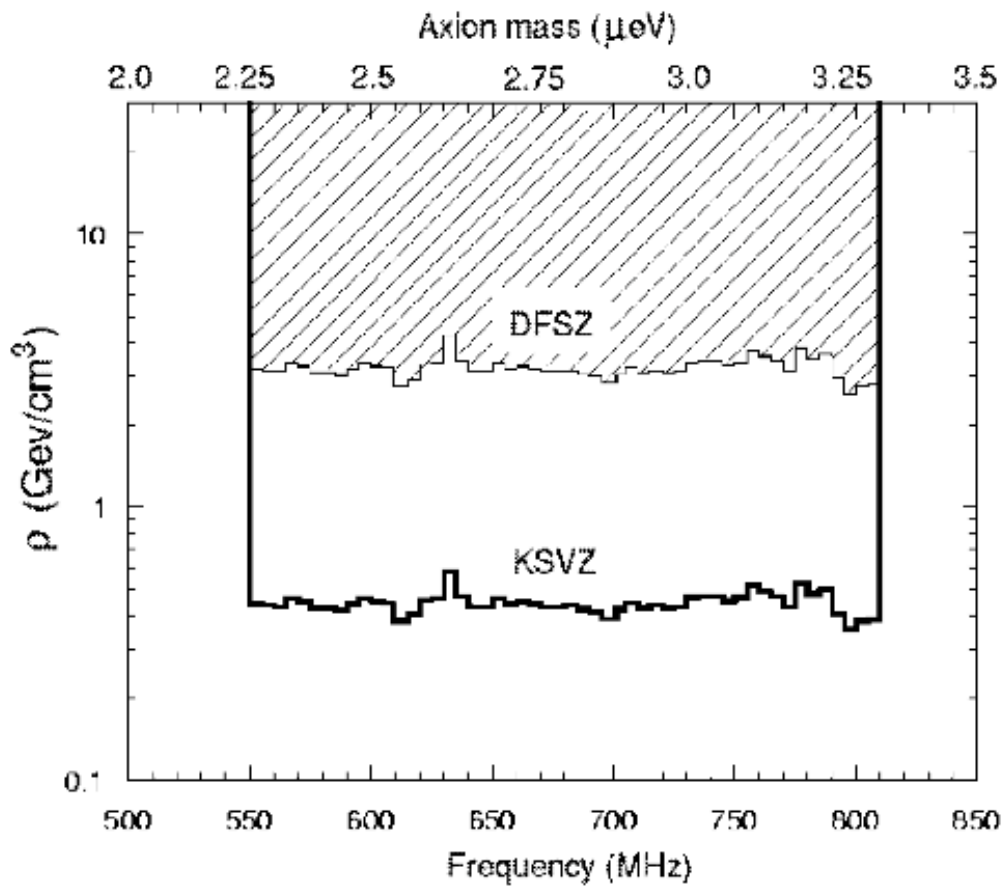


Figure 5: Upper limits on the halo density from DFSZ and KSVZ axions taken from [5] covering a slightly higher mass range.

## 6 Prospects and Conclusions

Though we have yet to detect the QCD axion, we are very close to being able to either detect it or exclude it as a viable dark matter candidate. There are a number of promising improvements proposed improve the sensitivity and range of the ADMX experiment. Though a larger cavity to scan lower frequencies (masses) would be much more expensive (since it would require both a bigger magnet and bigger refrigeration system), smaller cavities to scan higher frequencies (masses) could be put in the existing setup. Though there would be a loss in power due to the smaller volume, this could be compensated for by using multiple cavities. There is also the prospect of replacing the HFET amplifiers with Superconducting Quantum Interference Device (SQUID) amplifiers. These devices have a noise temperature around 0.05 K, and could improve the signal to noise ratio by a factor of 10, allowing the detector to be sensitive to detect QCD axions at a fraction of the local halo density. [2]

The axion is particularly compelling because of the way it brings cosmology, astrophysics and particle physics together so elegantly. It is exciting to think that we may be within striking distance of discovering a particle that would solve a major problem in Standard model and and answer a major question in cosmology at the same time.

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