Axions: An Overview of the Theoretical and Experimental in the Search for Dark Matter

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The axion has been proposed as a candidate for dark matter and a solution to the Strong Charge-Parity (CP) problem in quantum chromodynamics (QCD). Here, we examine the theoretical basis for axions, a hypothetical particle with a small mass and no electric charge, and discuss alternative dark matter candidates, including WIMPs and sterile neutrinos. We also highlight experimental efforts to detect them and constrain their parameter space including instruments such as helioscopes and haloscopes, and astrophysical observations of abnormal cooling in white dwarfs and neutron stars. Despite the lack of direct detection, much progress has been made in the last two decades. Experiments like ADMX have placed stringent limits on axion mass and the axion-photon coupling constant, while emerging projects such as DMRadio and MADMAX propose to explore new areas of its potential parameter space. This review evaluates the current state of axion research, summarizing the theoretical argument for its existence, experimental progress to limit its parameters, and its potential role in resolving the Strong CP problem and the nature of dark matter.

Introduction

The axion is a hypothetical particle with very small mass and no electric charge. It is thought to interact with baryonic matter and the electromagnetic field mostly through (a) its gravitational effects, as demonstrated by the curvature of spacetime around it, and (b) the Primakoff effect whereby particles are converted into photons in the presence of a strong electromagnetic field, as discussed further in Section 2. However, these interactions are extremely weak due to the axion's hypothesized small mass and lack of electric charge. As a result, this particle remains hypothetical and has not yet been concretely detected, although experiments have limited the characteristics associated with the axion such as its mass and electron-photon coupling constant. Scientific efforts to detect this particle continue as it is a plausible candidate to resolve two long-standing areas of scientific debate. The first is the Strong Charge-Parity (CP) problem in quantum chromodynamics (QCD), the study of strong force interactions between quarks, and the second is the composition of dark matter. The primary goal of this review is to summarize the current state of axion research, including both theoretical predictions and experimental progress, and to discuss current understanding of its potential role in dark matter. The Strong CP problem arises because QCD theoretically allows for CP violation, defined as a lack of symmetry under the simultaneous inversion of charge and spatial coordinates[1,2]. Unique physics should be observed, such as an electric dipole field in the neutron[3]. However, no effects like a dipole field in the neutron have been observed thus far, meaning that it is either not there, or it is much weaker than in theory. This is the Strong CP problem: the fact that physicists have not yet detected any evidence of CP violation, yet theory predicts it.

The Peccei-Quinn mechanism, proposed in 1977 to address the Strong CP problem, was the first theoretical framework to require an axion[1]. Specifically, Peccei and Quinn proposed a dynamical field term in the Lagrangian of QCD in which axions were the particle created by excitation in this field[4,5]. As discussed in more detail in Section 2, the axion is thought to be key to resolving the Strong CP problem because it emerges as a consequence of promoting the θ-term in the Strong Force Lagrangian to a dynamical scalar field, whose oscillations naturally drive the CP-violating θ-term towards a minimum.. While the axion was originally proposed to solve the Strong CP problem, its characteristics have also made it a viable candidate in the search to explain dark matter. The axion's weak interaction strength with baryonic matter and the electromagnetic field, as well as its small but non-zero mass, mean it would be largely undetectable through regular means. Additionally, axion density evolution models predict conditions much like dark matter density conditions, allowing for clustering similar to dark matter galactic halo structures. Due to its elusive nature, highly sensitive experiments must be performed to constrain the particle's potential limits and have the hope of observing the axion directly. Instruments such as helioscopes and haloscopes are among the most common experiments; both use strong electromagnets to detect axions coming from the sun and galactic halo respectively. Further attempts to observe the axion have been made in the lab: laser interferometry in the form of "light-shining-through-the-wall" experiments (photon-axion conversion via superconducting dipole magnets resulting in possible detections by photon detectors) are among the most common in this field. In addition, astrophysical cooling models may provide further supporting evidence towards axion existence. Certain white dwarfs and neutron stars exhibit abnormal cooling rates, therefore inferring an additional cooling mechanism which has been hypothesized to be axion emission. The axion has the potential to address two mysteries in physics, the strong CP problem and the nature of dark matter. This review examines the role of the axion with respect to these two problems, evaluating theoretical frameworks in Section 2, astronomical evidence in Section 3, experimental efforts in Section 4, and discussions and conclusions in Section 5. By synthesizing current research, we aim to provide insight into the plausibility of the existence of the axion particle and next steps for the field as a whole.

Theoretical Frameworks for Axion Existence

The Strong CP Problem

The Strong CP problem stems from the fact that QCD allows for charge-parity violations yet, from all observations involving only strong interactions, charge conjugation and parity transformations seems to have preserved symmetry[2,6]. There is currently no concretely known reason as to why CP symmetry is conserved in QCD. Adding to this, QCD has a complicated vacuum structure which has an infinite amount of lowest energy states, allowing the vacuum to simultaneously occupy all states at once3.This complicated structure gives rise to a CP-violating term in the Lagrangian for QCD, the θ-term:

$$\theta \frac{g_s^2}{32\pi^2} G_b^{-\mu\nu} G_{b\mu\nu} \tag{1}$$

where g_s is the strong coupling constant, $G_{b\mu\nu}$ is the gluon field strength tensor, and $G_{b\mu\nu}$ its dual. A non-zero value for θ breaks CP symmetry, introducing CP-violating effects in strong interactions such as a neutron electric dipole moment[3]. However, upon experimentation[3], CP-symmetry appears to be conserved, which would imply θ should be 0. As there is no mathematical reason as to why, this method is fine tuning which should generally be avoided. To solve this issue, Peccei and Quinn give θ a promotion, theorizing it should be characterized as a dynamical scalar field[1]. They do this by introducing a new U(1) global symmetry called the Peccei-Quinn symmetry which is then spontaneously broken at a scale f_a . By extension, Wilczek & Weinberg (1978) realized that this new field could be quantized[4,5]. If θ is classified as a quantum field, θ would fall and oscillate around the minima of the effective potential due to instanton "tunneling" events between QCD vacua[6,7,8]. This concept is called the misalignment mechanism. The oscillations characterized by this mechanism generate a population of cold axions with differing abundances depending on the mass of said axion (axion mass being inversely proportional to f_a)[6]. This mechanism could allow for a density of cold dark axions that align with predictions of dark matter abundance as discussed later in this section. The axion conveniently solves both of these problems; however, the specifics of axion models and parameters vary, making researchers unsure about axion behavior.

Theoretical Axion Models

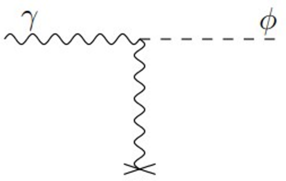
Axion parameters depend heavily on the theoretical model used to define these axions. Each model has different properties, thus making detection parameters dependent on the model. The two primary theoretical models researchers consider to be most reasonable are the Kim-Shifman-Vainshtein-Zakharov (KSVZ) model, and the Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) model[9,10]. Both the KSVZ and DFSZ models involve a global U(1) PQ symmetry broken by a complex scalar field θ. However, the KSVZ model differs from the DFSZ model in that it introduces a new heavy quark doublet with PQ charge Q (acquiring its mass through a Yukawa term: Yukawa interaction - coupling between the Higgs field and massless quarks), which transforms under PQ symmetry[9]. In this model, the only fermions that carry a PQ charge are the heavy quarks, thus, there are no couplings between the Standard Model (SM) fermions and the axion. Conversely, in the DFSZ model, axions couple directly to SM fermions through two new PQ charged Higgs doublets (Hu and Hd) that give mass to SM fermions through Yukawa terms[10].

In summary, the primary difference between the KSVZ and DFSZ models lies in the elementary particles they require (a new heavy quark doublet with PQ charge Q for the KSVZ model and two new PQ charged Higgs doublets for the DFSZ model) and the implications of these particles for detection thresholds. As a result, these two models make for different parameter windows, thus making experimental searches harder as differing parameter space must be covered depending on the model assumed. This difference in parameters may cast doubt upon the existence of axions due to the somewhat ambiguous nature of the particle. However, there is astrophysical evidence for axions that could compensate for this uncertainty.

ASTROPHYSICAL EVIDENCE FOR AXION EXISTENCE

White dwarfs

Stellar cooling anomalies (SCAs) are among the most compelling indirect evidence for the existence of axions. SCAs refers to the discrepancy between cooling rate models for stellar bodies versus the observed cooling rates. Observed cooling



rates for certain types of stars are faster than astrophysical models would predict, suggesting an additional energy-loss mechanism might be involved. Axion emission is one possible explanation for this energy-loss mechanism, as axions could be produced in the cores of some stellar bodies via the Primakoff effect. The Primakoff effect is the process by which photons interact with the electromagnetic field via the strong force, producing axions[6]. In this process, a photon travels through a dense medium, such as a stellar core, where it interacts with the strong electromagnetic field of a charged particle. In this encounter, the photon is stripped of its energy and momentum, allowing it to convert into an axion while conserving energy and momentum.

$$\gamma + Z \rightarrow a + Z \tag{2}$$

This Primakoff effect could explain the more rapid cooling of certain stellar bodies, contrary to model's predictions. One such stellar body is G117-B15A, a well-studied pulsating white dwarf in the constellation Leo Minor. G117-B15A's variability was found to be due to non-radial gravity wave pulsations[11]. Thus, the timescale for period change should be directly proportional to its cooling timescale (π). G117-B15A has a period of 215.2s and a $4\sigma\pi$ measurement of $(4.27 \pm 0.80)10-15ss^{-1}$[12]. However, the observed rate of change is more than three times larger than the value expected given the standard theory of white dwarf evolution where cooling is regulated only by the release of gravothermal energy $(1.25 \pm 0.09)10^{-15}ss^{-1}$[12]. This difference means that G117-B15A is cooling more rapidly than stellar evolution models predict. This discrepancy suggests an additional energy-loss mechanism such as axion emission.

Corsico et al. (2012) took this into account when computing white dwarf cooling sequences, incorporating axion emission according to the axion emission rates of Nakagawa et al. (1988). Using an ma range of 0 to 30 meV, Corsico et al. (2012) found that the cooling timescale is strongly influenced by increasing axion masses and the cooling in G117-B15A is consistent with axions of $massm_a cos^2\beta \sim 17.4meV$. Corsico et al. (2012) further note that other stars, such as DAV star R548, exhibit similar changes in their pulsation periods[12]. Similar cooling anomalies have been observed (although disputed) in red giants and neutron stars[13], providing further support for the axion cooling mechanism. This not only demonstrates that G117-B15A is most likely not an anomaly, but also provides a future pathway for study of these stars using the methods described in Corsico et al. (2012).

Neutron Stars

The case for anomalous cooling in neutron stars (NSs) largely stems from a neutron star at the center of supernova Cassiopeia A (Cas A). Over a decade, X-ray telescope Chandra analyzed surface temperature (T_s) data, reporting an anomalous steady decrease in Ts of about 2.4%-3.3% depending on absorbing hydrogen column density[13]. Under normal standard cooling scenarios, over 10 years, NS Cas A should have a Ts decline of 0.2-0.3%[13]. Although there are other non-standard cooling scenarios that have been proposed (such as softened pion modes, quarks, and more), the existence of these softened pions or quarks does not depend on temperature, making the declining rate in surface temperature constant since the birth of the NS. However, if this rate were to be constant, the current temperature would be much lower than measured. Therefore, it can be reasonably assumed that the cooling was initially slow but later accelerated. This acceleration could be explained by neutron superfluidity in the core which would cause a huge neutrino flux. However, theoretical simulations have shown that this process is perhaps slightly not efficient enough to explain the rapid temperature drop featured in NS Cas A[14, 15]. To investigate the potential contribution of axions to the observed cooling, Leinson et. al simulated a cooling scenario that incorporated axion emission as well as neutron cooling. The results roughly reproduced the cooling scenario observed in NS Cas A, depending largely on the axion decay constant[15]. The steepness of the cooling curve is related directly to the axion decay constant (assuming axion emission). Therefore through the 99% confidence interval obtained by observational data, the axion decay constant can be restricted to $f_{aKSVZ} > 310^7 GeV \text{and} f_{aDFSZ} > 4.510^8 GeV$[15]. However, it should be noted that other authors[14] describe the rapid cooling of NS Cas A as a systematic artifact. Regardless, neutron star cooling offers weak evidence for the axion, and could further restrict axion parameters given the existence of the additional cooling mechanism. However, indirect evidence for axions goes beyond just stellar phenomena; many researchers believe that there is a link between axions and the elementary dark matter particle.

Dark Matter

Dark matter is a hypothetical form of matter that is implied via observed gravitational effects on baryonic matter and radiation that do not align with general relativity. Dark matter is "dark" because it appears to only interact with the electromagnetic field and baryonic matter through gravity, and has not otherwise been observed. The current dominating hypothesis for the composition of dark matter is that it is constructed of some undiscovered subatomic particle such as the axion. The term "dark matter" was first coined in 1906 by Henri Poincaré in a response to Lord Kelvin's 1884 work in which he postulated that there must be a "thousand million stars, perhaps a great majority of them, [are] dark bodies."[16] Zwicky (1933) suggested the existence of this elusive form of matter again, after observing the movement of outer galaxies in the Coma Cluster and finding that the motion was different from predictions, given the number of galaxies and brightness of the Coma Cluster[7]. Specifically, Zwicky estimated the cluster contained about 400 times more mass than estimations based on the number of galaxies and brightness as a result of this observation. Although Zwicky's calculations turned out to be more than an order of magnitude off (mainly due to a rough value of the Hubble constant at the time), he still correctly postulated that much of the Coma Cluster's mass was hidden from view. A significant breakthrough came in the 1970s when Vera Rubin and Kent Ford used a new spectrograph to measure the velocity curve of spiral galaxies[17]. Rubin and Ford wished to know if luminous mass (the mass calculated from visible stars) is relatively equal to dynamic mass (mass deduced from its gravitational influence). Theoretically, the maximum rotational velocity is supposed to be found a few kilo-parsecs (kps) from the center of a galaxy, with rotational velocity past that point following a Keplerian decrease. Therefore, in theory, the stars in the outer parts of the galactic disk move more slowly than those closer to the nucleus. However, Rubin and Ford observed that stars at the periphery of the Andromeda Galaxy rotated faster than in theory. In fact, past a certain distance from the center, the velocity remained relatively constant. This discovery, as illustrated by the difference between the red and blue curves in Figure 1, implied a different galactic mass distribution and a larger mass-to-light ratio than previously thought.

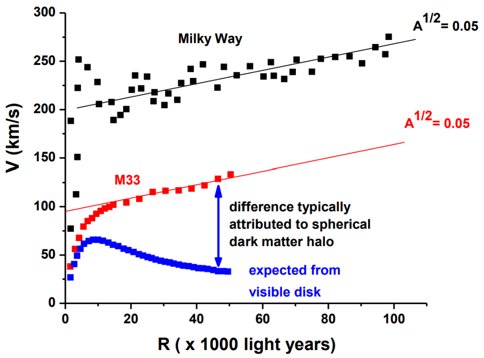


Fig. 1 Smolyaninov, Igor. (2020). Oscillating Cosmological Force Modifies Newtonian Dynamics. Galaxies. 8. 45. 10.3390/galaxies8020045.

FIG 1. This figure compares the observed rotation curve (red) with the computed rotation curve (blue) for the spiral galaxy M33, as well as the observed rotation curve of the Milky Way (in black). The difference between the predicted and observed curves indicates the presence of dark matter.

Further observations of gravitational lensing and the anisotropies in the cosmic microwave background provided more evidence for dark matter. Today, dark matter is theorized to play a decisive role in the evolution of many large-scale cosmic structures, making up 27% of the total mass-energy density of our universe (according to the ΛCDM model). If axions are the dark matter elementary particle, they would have to exist in great abundance to account for 27% of the total mass-energy density. For this to happen, there must be a sufficient explanation for dark matter field evolution.

The Case for Axions as Dark Matter

There are two separate theories for axion dark matter (DM) field evolution and its subsequent density distribution: the pre-inflationary scenario and the post-inflationary scenario. These scenarios depend on when the PQ phase transition occurred, either before or after Thot (peak temperature in the Big Bang). The pre-inflationary scenario ($T_{PQ} > T_{hot}$) scenario occurs when PQ symmetry is broken and never restored in inflation, as well as when there is a homogeneous initial misalignment angle (θ_i). A homogeneous θ_i occurs when the misalignment angle of the axion field, θ, is uniform across the entire universe. For this to happen, inflation must correct any preexisting inhomogeneities to a large enough scale to where the universe is effectively homogeneous. In this scenario, the evolution of the axion field and thus, DM density depends primarily on just two values, the initial value of the axion field, $\theta(t_{hot})$ and m_a. This is calculated through a wave equation where the expansion of the universe acts as a friction term, therefore damping oscillations. In the post- inflationary scenario ($T_{PQ} < T_{hot}$) scenario, PQ symmetry breaks after cosmic inflation, and the universe is inhomogeneous at small scales at the time of PQ symmetry breaking, leading to differing initial misalignment angles in different regions. This scenario results in a more complex and inhomogeneous density distribution of axions, as axion density depends on θ_i and θ_i would vary in different regions of the universe[16]. Furthermore, in this scenario, axion production results from the decay of topological defects (axion configurations between different axion field values), which may then decay into axion DM. As a consequence of the inhomogeneous density distribution, axion "mini clusters" form as illustrated in Figure 2 through n-body simulation. These mini clusters provide new avenues for astrophysical detection, while at the same time increasing theoretical uncertainty for density distributions.

Apart from mini clusters, populations of CDM axions could be produced through the aforementioned two scenarios. In these scenarios, ultralight axions (ULA) of $m \sim 10^{-22} eV/c^2$ could

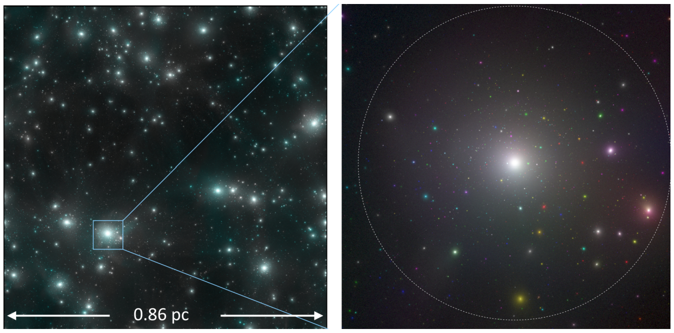


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Fig. 2 N-body simulations of nonlinear density perturbations after QCD phase transition showing axion miniclusters.

be a dark matter scalar field that aligns with the correct relic density without fine tuning[18]. Furthermore, it is hypothesized that these ULAs would form a Bose-Einstein condensate (BEC), therefore possibly accounting for a significant fraction of dark matter[19]. Both scenarios involve a substantial change when the universe’s expansion rate decreases to below the frequency of axion oscillations (t_{dyn}). When this happens, the axion field transitions to a dynamical state from the previous static state, as illustrated in Figure 3. This boundary marks the transition between relativistic and non-relativistic axions, thus the boundary at which DM axions are produced. Axion production lasts as long as the energy density stored up from the phase transition is converted into field oscillations, i.e. axion particles. The time at which axion production ceases is defined as t_{cold}; from t_{cold} onward, axion number density is diluted in a large comoving volume. This allows axion clustering, possibly forming DM mini structures and DM halos.

However, there are more fundamental reasons as to why axions are considered one of the most probable dark matter candidates. DM’s most fundamental property is its weak interaction strength with baryonic matter; axions also have this characteristic, interacting minimally, primarily through gravity - therefore contributing to observed gravitational effects and the overall mass density. This lines up perfectly with the necessary requirements for an elementary dark matter particle, only adding to the support for an axion-like dark matter particle. While axions are one of the most prominent candidates for dark matter, though, other hypothetical particles have been theorized to explain the decades-old inquiry. The next section describes the primary two alternatives, weakly interacting massive particles (WIMPs) and sterile neutrinos.

The Case for Alternative Dark Matter Candidates

WIMPs are described as elementary particles that interact via gravity and other forces weaker than the weak nuclear force. Many WIMP candidates are theorized to have been produced thermally in the early universe, similar to the particles displayed in the standard model, and to interact only through gravity and the weak nuclear force. This means that WIMPS are weakly interacting with electromagnetic radiation, making them effectively “dark” therefore, fulfilling the criteria to become a dark matter candidate[20, 21]. Also, because WIMPS are characterized as non-relative, it is theorized that they would be unable to overcome mutual gravitational effects, allowing them to clump together, forming associations much like theoretical models for dark matter clusters and halo structures[21]. Sterile neutrinos, also referred to as inert neutrinos, are hypothetical particles that interact via gravity. Unlike their competitors, the only other interaction they are proposed to have with the Standard Model is through mixing with active neutrinos. The term "sterile"distinguishes them from active neutrinos, referring to their isospin (a quantum number used to specify the electrically charged part of the weak interaction) charge of $\pm\frac{1}{2}$, their tendency to engage in weak interactions, their right-handed chirality (where spin and direction of motion are aligned), and their different behavior compared to the left-handed chirality of active neutrinos.[22].

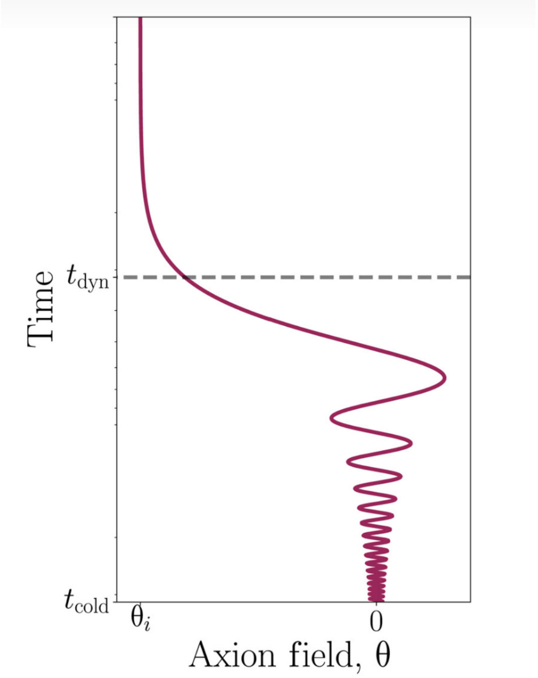


Fig. 3 The boundary t_{dyn} marks the transition between relativistic and non-relativistic axions, thus the boundary at which DM axions are produced.

Experimental results indicate that all observed and produced neutrinos have left-handed helicities (spin projection onto the momentum direction), or spin that is not parallel to momentum, meaning that all antineutrinos have a right-handed spin[23]. Only certain helicities and chiralities are permitted in the standard model of particle interactions. Specifically, left-handed helicity and chirality are allowed for neutrinos, and right-handed helicity and chirality are allowed for antineutrinos.

Particles that contradict the Standard Model are typically excluded from formulas. However, recent discoveries, like neutrino oscillation, imply that neutrinos have mass, which challenges the Standard Model[22]. This discovery explains the right-handed helicity of neutrinos and the left-handed helicity of antineutrinos, proposing that a particle with left-handed chirality can develop a right-handed component as it travels. This contradicts the assumption that chirality remains unchanged regardless of the particle's speed and mass in every inertial frame of reference, leading to two interpretations for neutrinos: Dirac particles and Majorana particles. If neutrinos (including sterile neutrinos) are Dirac particles, they have distinct antiparticles, with a right-handed sterile neutrino corresponding to a left-handed antineutrino. These particles could have small mass and be largely stable over cosmological timescales, potentially produced in the early universe through a mechanism such as non-thermal production[20]. If neutrinos are Majorana particles, they are their own antiparticles. This allows a sterile neutrino to potentially annihilate or decay in ways that Dirac particles cannot, leaving detectable signatures such as X-rays or other particles which could provide indirect evidence of dark matter[23].

While a strong theoretical argument has been made for the role of axions, WIMPs, and sterile neutrinos as dark matter candidates, none have been directly detected. WIMPs are predicted by models such as Supersymmetry, and their properties align with some of the characteristics expected of dark matter. Sterile neutrinos could explain both dark matter and the observed left-handed helicities of active neutrinos. They could be indirectly detected through X-ray emissions from particle decay or annihilation. Axions were originally proposed as a possible solution to the Strong CP problem in quantum chromodynamics (QCD), and are now also considered to be a promising candidate for dark matter due to their small mass and weak interactions. A further advantage of axions is that, if they exist, they should be detectable through a variety of experimental methods, including helioscopes and haloscopes that search for axion-photon interactions. The next section discusses these experimental methods in detail.

Axion Detection Experiments

Solar helioscopes

Solar helioscopes use strong magnetic fields to detect axions potentially produced inside the Sun. The principle behind this is similar to the Primakoff effect but in reverse, so it's often referred to as the inverse Primakoff effect. In this process, axions produced inside the sun via the Primakoff effect are then exposed to a strong magnetic field where the axions are effectively converted into photons. Solar helioscopes exploit this effect by utilizing a strong magnet, typically a dipole magnet, to facilitate this axion conversion. This conversion to photon means that these once-axions are now detectable through photon detectors. This is the essence of a solar helioscope, making once-undetectable axions detectable through the use of strong magnets.

A key source of error and uncertainty in helioscope observations is the signal-to-noise ratio. This is being addressed through improvements in X-Ray optics and detection, stronger magnets and lower temperatures as discussed in CAST Collaboration[24]. Such improvements are the focus of new initiatives such as the International Axion Observatory's next generation helioscope that is projected to have a 10^4 improvement in signal-to-noise ratio[25]. The ma and the axion-photon coupling constant ($g_{a\gamma}$, the strength of the force exerted in axion-photon coupling) are important characteristics in axion detectability. One of the currently most advanced helioscopes focusing on narrowing the possible range of these variable is the CERN Axion Solar Telescope (CAST)[26]. CAST has been dominating the frontier of solar axion detection experiments for the past 20 years. Although CAST has not directly detected axions, it has helped place strong constraints on search parameters, narrowing the window for axion existence. This makes future searches easier as there is less ground to cover. Over the last two decades, CAST has set a number of restraints on $g_{a\gamma}$ as summarized in Section 5, Table 1.

Haloscopes

Haloscopes, similar to helioscopes, detect potential dark matter axions using the Primakoff effect. They employ a resonant cavity to enhance photon detectability after axion-photon conversion[27]. A resonant cavity supports standing electromagnetic waves at specific frequencies ν determined by its shape, size, and boundary conditions as given by:

$$\nu_{lmn} = \frac{c}{2}\sqrt{\left(\frac{l}{L_x}\right)^2 + \left(\frac{m}{L_y}\right)^2 + \left(\frac{n}{L_z}\right)^2} \tag{3}$$

where L_x , L_y , and L_z are the side lengths in a rectangular cavity and l, m, and n are the mode indices (describe specific standing wave patterns that are supported by the resonance cavity). When the axion-converted photon (ACP) frequency matches that of the resonance mode frequencies of the cavity, ACPs resonate inside the cavity. Thus, different structured resonance cavities correspond to different ACP frequencies f as defined by:

$$f = \frac{mc^2}{h} \tag{4}$$

where c is the speed of light and h the Planck constant (assuming negligible kinetic energy compared to rest mass which corresponds to dark-matter (DM) axions with velocity $\sim 10^{-3}c$). This equation means that a haloscope resonant cavity can be specifically tailored to axions of corresponding masses via tuning mechanisms[28].

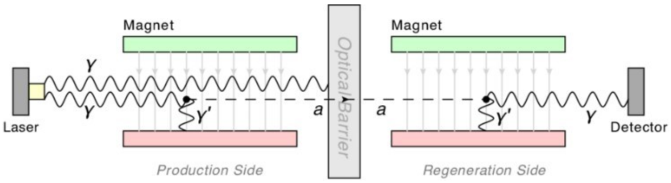
ACP signals are very weak; therefore ultra-low-noise amplifiers such as Josephson Parametric Amplifiers (relying on two or more superconductors coupled by a weak link) are often used to amplify the weak axion-induced photon signal while adding minimal noise. Thermal noise can be further reduced by operating in a cryogenic environment, often around a few Kelvin[29].

Many key experiments combine methods to further constrain axion parameters. Prominent haloscope experiments include HAYSTAC, the Center for Axion and Precision Physics Research (CAPP), and the Axion Dark Matter eXperiment (ADMX). AMDX uses a haloscope to search for cold dark matter axions in the local galactic dark matter halo, a hypothetical structure of dark matter surrounding the galactic disk[27]. ADMX uses a combination of a high strength electromagnet, a microwave resonant cavity, and the world's lowest-noise microwave receiver to be the first experiment sensitive to realistic dark-matter axion masses and coupling constants. Similar to CAST, ADMX has run a range of experiments that set upper limits on certain axion parameters such as m_a and $g_{a\gamma}$; these are summarized in Section Five, Table 1. Laser Interferometry Laser interferometry provides a somewhat simpler method of axion detection via the light-shining-through-wall (LSTW) experiment illustrated in Figure 4. In LSTW, the Primakoff and inverse Primakoff effects are both utilized to convert photons into axions, later reconstituting the axions into photons once axions pass through an opaque non-magnetic barrier. This experiment directs a coherent beam of photons from a high-power laser at a metal barrier. However, in between the photon origin and the barrier is a strong perpendicular magnetic field (often generated via superconducting dipole magnets), stripping some of the photons of their energy and momentum, thus theoretically converting it into an axion[30]. The probability for photon-to axion ($\gamma \to A$) conversion is given by:

$$P_{\gamma\leftrightarrow A} = \frac{1}{4}\left(g_{A\gamma\gamma}\right)^2 \left(\frac{2}{qL}\sin\frac{qL}{2}\right)^2 \tag{5}$$

where L is the vacuum length, B the transverse magnetic field strength, $g_{A\gamma\gamma}$ the axion-photon-photon coupling constant, and q the momentum transfer $\left\|\omega - \sqrt{\omega^2 - m_a^2}\right\|$ where ω is the photon energy.

As axions interact weakly with baryonic matter, the axion can pass through the barrier. On the other side is another strong transverse magnetic field that accomplishes the inverse of the previous operation, changing the axions back into photons (using the same probability equation), then hitting an ultra-sensitive photon detector on the other side.



High magnetic fields for fundamental physics - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/The-concept-of-the-light-shining-through-walls-experiments-The-g-photons-areassociated_fig4_323904881 [accessed 7 Jul, 2024]

Fig. 4 A diagram illustrating the light-shining-through-walls experiments. The γ photons are associated with the quasistatic magnetic field.

There are a few forms of this experiment being run worldwide, the most well-known ones being Any Light Particle Search (ALPS) and Optical Search for QED Vacuum Birefringence, Axions, and Photon Regeneration (OSQAR) in Geneva. Although neither detected axions, both have set further limits to the axion-photon coupling constant (OSQAR massless sets the limit at $g_{a\gamma\gamma} < 8.010^{-8} GeV^{-1}$)[30].

DISCUSSION AND CONCLUSIONS

Summary of Theoretical and Experimental Evidence

Theoretical evidence for axions is based on their role in resolving the Strong CP problem QCD and the fact that their small mass and weak interactions make them a plausible candidate for dark matter. Although the results of helioscope, haloscope and laser interferometry experiments to date have failed to directly detect axions, these experiments have greatly restricted the possible parameters of the axion or axion-like particles.

Table 1 provides a summary of the main experimental results to date. These findings are crucial as they narrow down the range of axion masses and coupling strengths to be investigated in future experiments.

Experiment	m_a	$g_{a\gamma}$ **limit**	**Citation**
CAST 2007	$m_a \leq .02eV$	$g_{a\gamma} \leq 8.810^{-11} GeV^{-1}$	26
CAST-RADES	$34.6771\mu eV \leq m_a \leq 34.6738$	$g_{a\gamma} \geq 410^{-13} GeV^{-1}$	31
CAST 2017	$m_a \leq .02eV$	$g_{a\gamma} < .6610^{-10} GeV^{-1}$	24
CAST-CAPP	$19.74 \leq m_a \leq 22.47\mu eV$	$g_{a\gamma} < 810^{-14} GeV^{-1}$	32
ADMX-SLIC (1)	$1.7498 \leq m_a \leq 1.751910^{-7} eV$	$g_{a\gamma} < 10^{-12} GeV^{-1}$	33
ADMX-SLIC (2)	$1.7734 \leq m_a \leq 1.773810^{-7} eV$	$g_{a\gamma} < 10^{-12} GeV^{-1}$	33
ADMX-SLIC (3)	$1.8007 \leq m_a \leq 1.801510^{-7} eV$	$g_{a\gamma} < 10^{-12} GeV^{-1}$	33
OSQAR	$m_a = 0$	$g_{a\gamma\gamma} < 8.010^{-8} GeV^{-1}$	30

Given the constraints of both theoretical and experimental analyses, Figure 5 illustrates how there is still a large plausible

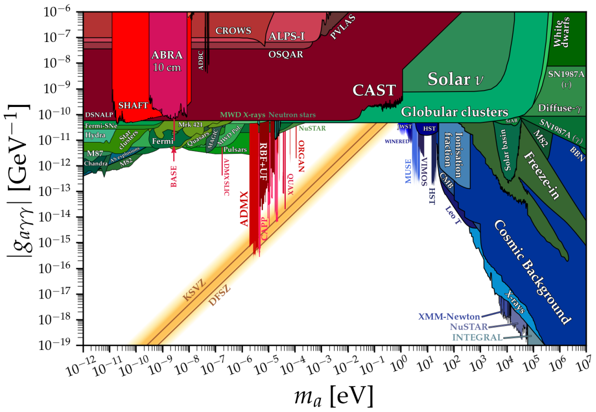


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Fig. 5 The search parameters currently covered by axion detection experiments can be best visualized within the ma and $g_{a\gamma}$ space. QCD axions would exist close to either the KSVZ or DFSZ lines in the yellow shaded area, while axion-like particles could be anywhere on the graph.

window for the existence of such particles. The yellow shaded area is where axions would exist according to theoretical models, axion-like particles could exist anywhere in this space, and the colored areas show the domain of the various experiments that have been conducted thus far.

ADMX (as indicated by the narrow vertical red areas) is the only project to have DFSZ level sensitivity, reaching into the yellow shaded area and only for a narrow range. Clearly, science has only scratched the surface of the parameter window and much work remains to be done. As axion detection technology improves, these constraints will continue to guide the search and more of the white areas in Figure 5 will become filled in until either the particle is detected or until no axions have been detected across the entirety of the plausible window, suggesting that the particle does not in fact exist.

Emerging Developments

While no direct detection has been achieved, the results summarized in Table 1 and Figure 5 have already guided the development of and provided a foundation for improving the sensitivity of upcoming experiments such as the upgraded ADMX and new projects like Dark Matter Radio (DMRadio), the Cosmic Axion Spin Precession Experiment (CASPEr) and the Magnetized Disk and Mirror Axion Experiment (MADMAX).

The DMRadio project aims to detect axions using sensitive superconducting devices including Superconducting Quantum Interference Devices (SQUIDs) and Quantum Sensors. DMRadio includes two experiments, DMRadio-50L which is the current generation of DMRadio under construction sensitive to axions with energy ~ 10 peV to ~ 10 neV and DMRadio-m3, a next generation experiment sensitive to QCD axions below 1 μeV[34]. CASPEr is an experiment that is attempting to detect very light axions, with masses less than 10-9 eV/c2[35]. CASPEr operates on the possibility that oscillating axion fields exert spin torques on polarized materials. This torque could cause a spin precession detectable via nuclear magnetic resonance techniques.

Finally, MADMAX proposes to use a stack of dielectric disks in front of a mirror to enhance potential axion-photon conversion signals[36]. It is currently in the prototype stage, with research and development still ongoing.

Conclusions and Next Steps

This review has summarized the current state of axion research, covering both theoretical predictions and experimental advancements. Axions were originally proposed as an explanation for the Strong CP problem in QCD. Despite no experimental detections of axions, over the last two decades multiple avenues of experimentation have narrowed down search parameters using various methods such as haloscopes, helioscopes, and laser interferometry (Table 1 and Figure 5). New methods informed by these results and by advances in instrumentation, particularly methods that reduce the signal to noise ratio of the observations, hold significant promise to continue to limit the parameters of this theoretical particle, or even result in a detection.

At the other end of the spatial scale, dark matter is the mystery of the modern age: directly undetected, yet clearly visible through its impact on unusual gravitational lensing and baffling spiral galaxy velocity curves. The axion provides a solution to this conundrum as well, with its small mass and weak interactions being consistent with observational evidence for dark matter. Although other dark matter candidates such as WIMPs and sterile neutrinos have been proposed, none have yet been observed.

Ongoing and future experiments are crucial for narrowing the potential range of axion parameters and potentially detecting this still theoretical particle. It is essential for science to continue exploring this space to either confirm or rule out axion theory. Upcoming projects such as DMRadio and MADMAX will employ innovative detection techniques that could either further constrain the search space or lead to a direct detection of the axion.

While significant progress has been made, much remains to be done. Sustained funding and research will be necessary to cover the yet-unexplored regions in Figure 8. Regardless of the outcome, however, each new experiment will continue to push the boundaries of detection, advancing scientific understanding of the axion's existence and true nature. Assuming that scientific support for experimentation continues and advances in instrumental capacity continue to be made, we conclude that it is only a matter of time before the axion particle is either confirmed or ruled out as a candidate for explaining both the Strong CP problem and the composition of dark matter.

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