Axion-Like Particles and Their Cosmological Consequences

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Keywords: Axion-Like Particles, Cosmology, Dark Matter, Particle Physics, Beyond Standard Model Physics.

Abstract: Axion-like particles (ALPs) are hypothetical particles that have garnered significant attention in both particle physics and cosmology due to their potential roles in addressing unresolved issues such as the strong CP problem, dark matter, and dark energy. This paper provides a comprehensive overview of ALPs, starting with their theoretical foundations and production mechanisms in the early universe. The paper will explore their interactions with standard model (SM) particles and their influence on cosmological phenomena, including Big Bang nucleosynthesis, the cosmic microwave background, and structure formation. Furthermore, the paper will examine the viability of ALPs as dark matter candidates and their potential contributions to the dynamics of dark energy. Current experimental efforts, including direct detection methods like haloscopes and helioscopes, along with indirect detection strategies through astrophysical observations, are reviewed. The challenges and open questions in ALP research are discussed, highlighting the need for future theoretical and experimental advancements to unveil the mysteries surrounding these elusive particles.

1 INTRODUCTION

As research into axions, a theoretical particle introduced to address the strong CP problem in quantum chromodynamics (QCD), progressed, it became clear that a broader class of particles, now known as axion-like particles (ALPs), could arise from a variety of theoretical models beyond the original scope of the QCD axion. These models often emerge from extensions of the Standard Model, including string theory and other high-energy frameworks that propose additional dimensions or symmetries. Unlike the QCD axion, ALPs are not strictly bound to the strong CP problem, and their properties—such as mass and coupling constants—can vary widely depending on the specific model. This flexibility makes ALPs a versatile tool for exploring new physics beyond the Standard Model, particularly in areas where existing theories fall short.

ALPs and axion have been extensively studied as promising candidates for dark matter. Their weak interactions with other standard model particles and their potential to account for different astrophysical and cosmological observations make them a significant focus in contemporary physics research.

One of the most intriguing aspects of ALPs is their potential role as dark matter candidates. Dark matter is a foundational element of modern cosmology, making up close to one third of the universe's mass-energy content (much larger than that of baryons), yet it remains elusive, interacting primarily through gravity. Traditional dark matter candidates, like weakly interacting massive particles (WIMPs), have not yet been detected, prompting researchers to explore alternatives, including ALPs. ALPs are particularly interesting because their weak interactions with Standard Model particles allow them to avoid many of the constraints that have excluded other dark matter candidates. Additionally, their ability to form cold dark matter, depending on the production mechanisms involved, aligns well with observations of large-scale cosmic structures.

Beyond their role as dark matter, ALPs may also influence cosmic evolution. The interactions between ALPs and particles like photons and nucleons could affect key events in the early universe, such as Big Bang nucleosynthesis (BBN) and the buildup of the cosmic microwave background (CMB). For instance, ALPs might alter the photon-to-baryon ratio, thereby impacting the synthesis of light elements and the

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Yu, Z.
Axion-Like Particles and Their Cosmological Consequences.
DOI: 10.5220/0013075800004601

In *Proceedings of the 1st International Conference on Innovations in Applied Mathematics, Physics and Astronomy (IAMPA 2024)*, pages 321-329
ISBN: 978-989-758-722-1

variation of temperature observed in the CMB. While these effects may be subtle, they are significant enough to make the study of ALPs an important avenue for testing cosmological models and understanding early universe conditions.

Furthermore, ALPs are also being considered as potential drivers of dark energy, an enigmatic force driving the universe's accelerated expansion. In certain theoretical models, ALPs are considered scalar fields with characteristics that enable them to imitate the behavior of a cosmological constant or various types of dynamic dark energy. These models suggest that ALPs could contribute to a slowly varying energy density that drives cosmic acceleration, offering a potential explanation for observations that challenge the standard ΛCDM model. Including ALPs in dark energy theories not only broadens our understanding of the universe's expansion history but also introduces new observational signatures that could be detected through high-precision cosmological surveys.

The ongoing search for ALPs extends across multiple experimental and observational frontiers. Direct detection efforts, such as those conducted by haloscopes and helioscopes, aim to observe ALPs interacting with strong magnetic fields or being produced in astrophysical environments like the Sun. Indirect searches focus on astrophysical phenomena, such as the cooling rates of stars, gamma-ray observations, and the polarization of the CMB, which could reveal the presence of ALPs through their interactions with other particles. Despite the challenges associated with detecting such weakly interacting particles, advances in technology and experimental techniques continue to expand the limits of possibility, moving us nearer to the potential discovery of these elusive particles.

This paper aims to delve into the cosmological consequences of ALPs by first providing a thorough introduction to their theoretical foundations and production mechanisms. The paper will then explore their possible roles in dark matter, dark energy, and the formation of cosmic structures. By reviewing current theoretical models, experimental efforts, and observational evidence, the paper aim to highlight the significant challenges and open questions that remain in the field. Ultimately, this paper seeks to provide a comprehensive overview of how ALPs could reshape our comprehension of the universe and the fundamental forces that regulate it. As the paper move forward, the study of ALPs promises to be a key area of research with significant consequences for both particle physics and cosmology.

2 THEORETICAL FRAMEWORKS OF AXION-LIKE PARTICLES

2.1 Origin and Properties of ALPs

The Peccei-Quinn (PQ) mechanism, introduced in the late 1970s, was suggested as a solution to the strong CP problem, which explains why QCD appears not to violate CP symmetry as one would anticipate. CP symmetry involves the combination of charge (C) conjugation and parity (P) symmetries.

The strong CP problem arises because the QCD Lagrangian includes a term that could potentially break CP symmetry, yet experimental results have shown that such a violation is extremely rare.

The Peccei-Quinn mechanism introduces a new global U(1) symmetry, called Peccei-Quinn (PQ) symmetry, which is spontaneously broken, resulting in the appearance of a new pseudoscalar particle known as the axion.

The axion field can dynamically eliminate the CP-violating term, effectively setting $\theta_{QCD} = 0$, thus resolving the strong CP problem.

2.2 ALPs in Particle Physics Models

Axion-like particles (ALPs) are theoretical entities resembling axions, but they aren't necessarily linked to solving the strong CP problem. Unlike the QCD axion, ALPs can have a wide range of masses and coupling constants. Their mass tends to be considerably smaller than that of standard model particles, and they can arise through various mechanisms, such as explicit PQ symmetry breaking.

ALPs have very weak interactions with standard model particles, meaning their effects on gravity are notable, making them strong dark matter candidates. The interaction strengths between ALPs and standard model particles are typically described by coupling constants, which influence their interactions with photons, fermions, and gluons. These interactions are typically modeled using effective Lagrangians.

In string theory, ALPs can naturally arise as pseudo-Nambu-Goldstone bosons due to the spontaneous breaking of global symmetries. These particles may stem from higher-dimensional gauge symmetries that become apparent after compactification. Within various string theory scenarios, ALPs can exhibit a wide array of masses and coupling constants, offering a fertile ground for theoretical physics exploration.

Beyond string theory, ALPs also feature in other beyond the Standard Model (BSM) theories. These include models that extend the Higgs sector, grand unified theories (GUTs), and other standard model extensions aimed at addressing the hierarchy problem, dark matter, and baryogenesis.

3 PRODUCTION MECHANISMS OF ALPS IN THE EARLY UNIVERSE

3.1 Thermal Production mechanisms

3.1.1 ALP Thermal Production in Early Universe

In the early universe, axion-like particles (ALPs) can be thermally produced through various interactions. The production typically involves scattering and decay processes that occur at high temperatures, often before or during the epoch of BBN. The rate that ALP produces depends on their coupling to photons, electrons, nucleons and other standard model particles.

Moreover, ALPs decouple when their interaction rate becomes slower than the rate of cosmic expansion. (Carenza et al., 2021). However, in low-reheating cosmological scenarios, where the reheating temperature can be significantly lower (even down to a few MeV), the expansion rate of the universe is quicker than predicted by the standard model. This accelerated expansion causes the ALPs to decouple earlier at higher temperatures, leading to a suppression in their thermal relic abundance. Consequently, this scenario allows for the possibility of heavier ALPs, as the cosmological mass bounds are relaxed in such low-reheating environments.

3.1.2 Impact of ALP Interactions with Photons, Electrons, and Nucleons

The interactions between ALPs and standard model particles such as photons, electrons, and nucleons play a crucial role in shaping the thermal evolution of ALPs and the overall history of the universe.

For instance, the interaction of ALPs with photons (resonant photon-ALP conversion) could influence the cosmic microwave background (CMB) by modifying photon distribution, leading to distortions in the black-body spectrum of the CMB, causing a reduction in the number of photons, and, consequently, an apparent decrease in the CMB temperature in the direction of the affected galaxy clusters.

ALPs coupled to nucleons can be efficiently produced in the core of supernovae through the nucleon-nucleon bremsstrahlung process. This mechanism is significant because it allows for the prolific production of ALPs in the supernova core, where large densities and high temperatures are present. The produced ALPs can escape the supernova, contributing to a large flux of ALPs.

3.2 Non-Thermal Production Mechanisms of ALPs

3.2.1 Misalignment Mechanism

The misalignment mechanism is a non-thermal process through which axions are produced in the early universe. This happens when the axion field starts off "misaligned" from the minimum of its potential, rather than starting at the minimum. This misalignment continues because, in the early universe, the Hubble expansion rate is much higher than the axion field's mass. As the universe continues to expand and cool, the Hubble parameter decreases, eventually enabling the axion field to eventually oscillate around the minimum of its potential. The oscillations resemble cold dark matter, with the axion's energy density depending on the initial angle of misalignment (axion field's initial displacement) and the axion mass.

For axion-like particles (ALPs), energy density generated by the misalignment mechanism is influenced by factors like the initial misalignment angle, the ALP mass, and the PQ scale. This mechanism is particularly intriguing because it does not depend on thermal processes and can produce a cold dark matter component that is independent of the universe's thermal history.

3.2.2 Decay of Topological Defects

Topological defects, which include structures like cosmic strings and domain walls, arise when the universe undergoes symmetry-breaking phase transitions. These defects are particularly important because their decay can lead to the production of ALPs, which contribute to the cold dark matter density in space.

As PQ symmetry break at high energies, Cosmic strings form as line-like defects where the axion field winds around a vacuum expectation value. As the universe continues to cool and experiences additional phase transitions, especially the QCD phase transition, these strings may become connected to domain walls if the domain wall number exceeds one (Chang, S., 1998). The resulting ALPs are often relativistic and could contribute to the dark radiation or act as a warm dark matter component depending on their mass and coupling constants.

Domain walls, formed by two-dimensional defects when the PQ symmetry breaking leads to discrete degeneracies in the vacuum state, are causing series result in cosmology because they can dictate the energy density of the cosmos, leading to conflicts with observed cosmological data (Saikawa, 2017). However, if these walls decay before they dominate, they are able to produce a large amount of ALPs. The ALPs produced this way is typically linked to the scale of PQ symmetry breaking.

The decay of these topological defects is affected by several aspects, such as the coupling between ALPs and other particle fields, the dynamics of the defects themselves, and the presence of any external fields that might interact with the defects.

4 ALPS AND COSMIC EVOLUTION

4.1 Influence on Big Bang Nucleosynthesis (BBN)

BBN, which involves the formation of light elements such as hydrogen, helium, and lithium within the first few minutes after the Big Bang, is extremely sensitive to the conditions present in the early universe. Key factors include the density of baryons, the rate of cosmic expansion, and interactions between particles. Axion-Like Particles (ALPs), which are hypothetical particles, could interact with Standard Model particles such as photons, nucleons, and leptons, potentially affecting these crucial conditions.

One of the primary ways ALPs can affect BBN is through their interactions with photons or nucleons. For instance, if ALPs are produced in sufficient quantities, have the potential to modify the baryon-to-photon ratio (η) as well as the effective number of relativistic degrees of freedom (N_{eff}), which could impact the expansion rate of the universe, subsequently affecting the production of light elements like deuterium (^{2}H) and helium-4 (^{4}He). The combined observations from BBN and the CMB place tight limits on the parameter space of ALPs, particularly ruling out regions where ALPs would lead to significant deviations in light element abundances (Millea et al., 2015).

4.2 Indication From Cosmic Microwave Background

The CMB is the remnant radiation from the Big Bang, offering a glimpse into the universe roughly 380,000 years after the Big Bang. The CMB carries imprints of the physics of the early universe, including potential interactions between ALPs and photons. As a fundamental observable of cosmology, the CMB serves as a critical tool for probing the early universe and any new physics, such as the existence of ALPs.

ALPs can interact with photons through resonant conversion processes, particularly in the presence of magnetic fields within galaxy clusters. These interactions can lead to observable polarized distortions in the CMB, such as changes in the anisotropy spectrum or polarization patterns, which would manifest differently from other well-known CMB signals like those caused by gravitational lensing. The presence of ALPs could also result in additional temperature fluctuations at high multipoles, distinct from the standard CMB spectrum. These temperature fluctuations, if detected, would offer further evidence supporting the existence of ALPs, highlighting the importance of high-resolution CMB observations.

Moreover, spectral distortions in the CMB, which can arise from processes such as energy injection or non-thermal effects, could also provide indirect evidence for ALPs. These distortions are highly sensitive to the thermal history of the universe and any new particles or interactions that could alter this history. As such, analyzing spectral distortions allows cosmologists to explore the thermal processes in the early universe, where ALPs could play a significant role.

Future CMB experiments with improved capabilities are expected to significantly tighten these constraints, offering a more comprehensive picture of ALPs' impact on the universe.

4.3 Role in Structure Formation

Axion-like particles (ALPs) also plays a crucial role in the formation of cosmic structures such as galaxies, clusters, and large-scale filaments in the universe. Unlike traditional cold dark matter (CDM), ALPs can have different properties, exhibiting wave-like effects on certain scales where these effects dominate over self-gravity and a smaller mass or interactions with other particles, which can lead to distinct signatures in structure formation.

ALPs can form a form of dark matter that is slightly warmer than CDM, sometimes referred to as "fuzzy dark matter" (Shen et al., 2023) or "ultralight dark matter." The quantum mechanical effects due to the small mass of ALPs can cause a reduction in the formation of structures at smaller scales.

This suppression occurs because the de Broglie wavelength of ALPs, which is inversely proportional to their mass, can become comparable to or larger than the size of small-scale structures, leading to a phenomenon known as "quantum pressure" or "wave-like behavior". This effect can prevent the formation of scale of diminutive structures. For example, dwarf galaxies, which would be abundant in a purely CDM scenario. Moreover, such suppression is related to the quantum pressure that counteracts gravitational collapse on small scales, resulting in a cutoff in the linear matter power spectrum.

Moreover, ALP dark matter can influence the formation of cosmic structures by affecting the collapse of dark matter halos, the building blocks of galaxies and larger structures. In scenarios involving fuzzy dark matter, halos can form solitonic cores — dense, stable regions at the centers of dark matter halos. These cores are surrounded by more diffuse outer regions, creating a unique structure that can be contrasted with predictions from standard denser CDM models.

5 ALPS AND DARK MATTER

5.1 ALPs as Dark Matter Candidates

Just like what the previous section 2 passage indicate, ALPs are considered strong contenders for dark matter due to their distinct properties, including weak interactions with standard model particles and the potential to make up a significant portion, or even all, of dark matter.

ALPs as a weak coupling dark matter can arise in various theoretical frameworks, including string theory and other beyond the Standard Model (BSM) scenarios. Depending on their mass and coupling constants, ALPs can manifest as cold dark matter, similar to the canonical WIMP (Weakly Interacting Massive Particle) models. ALPs are also being regards as the substance of "Fuzzy dark matter" models, where they have ultralight masses, suppress small-scale structures due to quantum mechanical effects, providing a potential answer to some of the small-scale issues encountered with CDM.

The characteristics of ALPs as potential dark matter contenders are constrained by various astrophysical observations and experimental searches. Astrophysical observations, such as the CMB, can serve to limit or define the characteristics of ALPs.

Overall, while ALPs remain a reasonable contender for dark matter, their exact role depends on further observational and experimental evidence, which will help to narrow down the range of allowed properties and clarify their contribution to the composition of dark matter present in the universe.

5.2 Direct and Indirect Detection Methods

5.2.1 Laboratory Searches for ALPs

Haloscopes and helioscopes are two of the primary laboratory-based techniques used to look for ALPs.

To detect ALPs that could comprise the dark matter halo over our galaxy, various experiments focus on the interaction between the axion field and photons in the presence of a strong magnetic field, which facilitates the conversion of ALPs into detectable photons. The most prominent haloscope experiment is ADMX (Axion Dark Matter eXperiment), which has established significant constraints on ALP masses and couplings within the microwave frequency range (Khatiwada et al., 2021).

Other methods like Helioscopes are telescopes designed to detect ALPs produced in the Sun. The best helioscope here is CAST (CERN Axion Solar Telescope), which detects potential axions generated in the Sun by observing the effect produced by their conversion into photons under a strong magnetic field (Barth et al., 2013). The experiment has progressed through several stages, employing a decommissioned LHC dipole magnet to track movement of the Sun and convert the generated axions into discernible X-ray photons via axion-photon interactions. This help narrow down the parameter space where ALPs could exist.

5.2.2 Indirect Detection through Astrophysical Signals

Indirect detection includes gamma ray observations. For gamma-ray observations, ALPs can interact with photons when exposed to external magnetic fields, which allows for photon-ALP conversions. This conversion is facilitated by the two-photon vertex interaction described in the context of ALPs, where high-energy gamma rays from astrophysical sources can convert into ALPs and vice versa when they pass through regions with strong magnetic fields (Hooper & Serpico, 2007). For example, gamma rays from distant astrophysical sources could convert into ALPs when subjected to B fields, leading to irregularities in the detected high-energy photon flux. Observatories like the Fermi Gamma-ray Space Telescope have been used to search for such signatures, providing constraints on ALP properties.

Gamma-ray telescopes, both space-based (like the GLAST satellite) and ground-based (such as HESS, MAGIC, and VERITAS), can potentially detect the signature of ALP-photon conversions by observing distortions in the gamma-ray spectra. The detection strategy involves looking for spectral features that deviate from the expected power-law behavior due to the depletion of gamma rays converted into ALPs.

Other methods include Stellar Cooling: ALPs could be produced in the cores of stars and subsequently escape, carrying away energy and affecting the cooling rates of stars (Zhang et al., 2024). Observations of white dwarfs, red giants, and other stellar remnants provide constraints on ALP couplings based on how well these stars' cooling behaviors match theoretical predictions. The faster-than-expected cooling of certain stars has been proposed as indirect evidence for ALPs, although alternative explanations also exist.

6 ALPS AND DARK ENERGY

6.1 ALPs as a Source of Dark Energy

6.1.1 Theoretical Models Linking ALPs to Dark Energy

In some theoretical models, ALPs are introduced as scalar fields with properties that allow them to influence the large-scale dynamics of the universe. These models often draw from ideas in string theory and other extensions of the Standard Model.

One of the primary mechanisms through which ALPs could contribute to dark energy is by acting as a quintessence field. In these models, ALPs possess a very light mass and a potential energy that evolves slowly over time, leading to a negative pressure that drives cosmic acceleration. The slow roll of the ALP field down its potential mimics the behavior of a cosmological constant, but with time-dependent characteristics that could be observed in the evolution of the universe's expansion rate.

6.1.2 Cosmological Implications of ALP-driven Dark Energy

Including ALPs as potential candidates for dark energy has profound implications for cosmology. A key prediction of ALP-driven dark energy models is the development of the equation of state parameter w, which characterizes the relationship between the pressure and density of dark energy. Unlike the cosmological constant, where $w = -1$, ALP models can result in a temporally evolving equation of state w. This variation could be observed through detailed studies of the CMB, large-scale structure, and supernovae.

These models also influence the growth of cosmic structures (Ruchika et al., 2023).

ALP-driven dark energy can modify the rate at which structures form and evolve, leading to observable differences in the distribution of galaxies and clusters. Additionally, the coupling between ALPs and other fields can lead to new signatures in gravitational wave observations, providing a unique way to test these models.

6.2 Observational Signatures

As ALPs are considered a source of dark energy, they could produce distinctive signatures that may be detectable through various cosmological observations.

A possible indication could arise from the gravitational signatures produced by ALPs with non-periodic potentials. These particles may undergo processes such as parametric resonance and field fragmentation, which can lead to the formation of dense halos. These halos could result in observable gravitational phenomena, covering phenomena such as astrometric lensing, the diffraction of gravitational waves from black hole mergers, and the photometric microlensing of stars with extreme magnification (Chatc**r**h**o**n et al., 2024). These phenomena could provide indirect evidence for the presence of ALPs and their contribution to cosmological processes, including dark energy.

This gravitational effect could be observed by gravitational microlensing phenomenon, where an axion star and a background star align, causing the light from the star to be lensed, creating a characteristic light curve that can be detected by telescopes.

Additionally, Large-scale structure (LSS) surveys and supernovae observations are critical tools for constraining ALP-driven dark energy models (Ivanov et al., 2020). LSS surveys, which map the distribution of galaxies across vast cosmic volumes, can reveal how the growth of structures has evolved over time. Deviations from the expected clustering patterns in the ΛCDM model could indicate the presence of ALP-induced modifications to dark energy.

Supernovae, particularly Type Ia supernovae, serve as "standard candles," are essential for measuring cosmic distances. By analyzing the observed brightness of these supernovae across various redshifts, astronomers can trace the history of expansion of the cosmos. Any deviation on the expected relationship between distance and redshift could provide evidence for a varying equation of state driven by ALPs.

These constraints help narrow down the parameter space where ALPs could play a role as dark energy and provide essential tests for the validity of these models.

7 CURRENT AND FUTHER EXPERIMENTAL EFFORTS

7.1 Existing Experiments and Observations

Current effort on observation of ALPs (axion-like particles) includes ADMX and CAST that previous passage have introduced, and the more advanced generation helioscope — IAXO.

Recent findings from ADMX have further advanced the sensitivity to ALPs. The ADMX Run 1A analysis targeted a specific frequency range (645–680 MHz), which corresponds to an axion mass range of 2.66–2.81 μeV, achieving sensitivity at the DFSZ (Dine-Fischler-Srednicki-Zhitnitsky) level (Boutan et al., 2023). The experiment did not detect any signals that would suggest the presence of axions, leading to exclusion limits on axion-photon couplings at or below the DFSZ sensitivity, with a confidence level larger than nine tenth. This effectively excludes axions as the sole component of dark matter within the scanned frequency range, assuming a virialization version of galactic halo model.

Additionally, the recent extended run of CAST, which included a new Xe-based Micromegas detector, has set a updated maximum bound on the axion-photon coupling constant. The new limit here shows $g_{a\gamma} < 5.7 \times 10^{-11}\text{GeV}^{-1}$ at 95% confidence level (CAST Collaboration et al., 2024), which is the most stringent experimental limit to date for axion-photon coupling, particularly in the low-mass range (for $m_a \lesssim 0.02$ eV)

With CAST ceasing operations in 2021, these findings represent the final and most comprehensive limits from this experiment. The results from this extended run will remain the most stringent bounds on solar axions until new data from upcoming experiments, such as BabyIAXO and IAXO, become available.

The International Axion Observatory (IAXO) is a next-generation helioscope experiment designed to significantly enhance the sensitivity of CAST, achieving improvements by several orders of magnitude. It will utilize a much larger magnetic field volume and advanced X-ray optics to detect ALPs with greater precision. IAXO is anticipated to provide new insights into the ALP parameter space, potentially exploring uncharted regions that could include ALP dark matter or ALPs linked to other astrophysical phenomena (Ribas et al., 2015).

Though still in the preparatory phase, IAXO has been incorporating cutting-edge technologies that are expected to achieve unparalleled sensitivity to ALPs. The update highlights the importance of BabyIAXO in advancing axion research, particularly in the detection of solar ALPs. BabyIAXO is engineered to give a significant enhancement on probe’s sensitivity to axions compared to earlier experiments like CAST.

7.2 Future Prospects and Upcoming Experiments

Several new experiments are poised to greatly enhance the search for axion-like particles (ALPs) by investigating regions of the ALP parameter space that were previously unexplored.

These efforts aim to identify ALPs across a broad spectrum of masses and coupling strengths, utilizing both direct detection methods and astrophysical observations.

The MADMAX (Magnetized Disk and Mirror Axion Experiment) project is specifically intended to detect axions and ALPs within the mass range of several tens of micro-electronvolts (μeV). This experiment employs a dielectric haloscope, which uses a series of dielectric disks placed within a strong magnetic field to trigger the transformation of ALPs into detectable photons. This innovative setup provides a new method for probing ALP dark matter.

Another significant effort is the ALPS II (Any Light Particle Search II) experiment, an advanced "light-shining-through-a-wall" setup. It aims to detect ALPs and other weakly interacting particles with masses below an electronvolt (sub-eV) by using high-power lasers and strong magnetic fields to induce ALP-photon conversion, with the goal of achieving unprecedented sensitivity to these interactions. If successful, ALPS II could provide key evidence for axions or ALPs, which are viewed as promising dark matter contenders and might also address the strong CP problem.

Overall, these advancements, together with improvements to existing detectors like ADMX, are expected to expand our understanding of ALPs significantly, potentially uncovering new physics beyond the Standard Model.

8 CHALLENGES AND OPEN QUESTIONS

8.1 Theoretical Challenges in ALP Research

Axion-like particles (ALPs) present a rich field of study with a wide range of theoretical models, but these models come with significant uncertainties. One of the primary challenges is the large parameter space associated with ALPs, including their masses, couplings, and potential interactions with standard model particles.

Theories predicting ALPs often emerge from frameworks like string theory or other beyond the Standard Model (BSM) physics, leading to a multitude of possible ALP properties. These uncertainties complicate efforts to make precise predictions about ALP behaviours in various contexts, such as their potential role in dark matter, dark energy, or their interaction coupling with photons, nucleons, or other particles. Moreover, different ALP models can predict vastly different cosmological and astrophysical phenomena, making it difficult to design experiments that can comprehensively test for ALPs.

Given the broad range of possible ALP properties, there is a pressing need for more precise theoretical predictions to guide experimental searches. This requires a better understanding of the underlying physics that governs ALP interactions and how these interactions might manifest in observable phenomena. Since adding all these theoretical assumptions increase the complexity of the whole experimental system; thus, it is needed to be selected carefully for parameters within the theory. Additionally, advances in computational techniques and simulations could provide more accurate predictions of ALP behavior under different conditions, helping to narrow down the parameter space and identify the most promising regions for experimental exploration.

8.2 Observational Challenges in ALP Research

Current observational techniques for detecting axion-like particles (ALPs) face challenges, primarily due to the weak interactions that ALPs are hypothesized to have with standard model particles. This makes them incredibly difficult to detect, requiring extremely sensitive instruments and often relying on indirect methods.

The main limitation of current detectors, such as those used in haloscope experiments like ADMX, is their sensitivity. These detectors must be capable of detecting extremely faint signals generated by the conversion of ALPs into photons, a process that is expected to occur at very low rates, making distinguishing a potential ALP signal from background noise very difficult.

Advances in superconducting technologies, such as the development of quantum amplifiers, could significantly enhance the sensitivity of detectors used in haloscope experiments. These amplifiers can reduce noise levels and increase the signal-to-noise ratio, making it easier to detect faint ALP signals.

9 CONCLUSIONS

This comprehensive study of axion-like particles (ALPs) delves into their theoretical foundations, potential cosmological roles, and the current state of experimental efforts aimed at detecting these elusive particles. ALPs have emerged as versatile candidates for various cosmological phenomena, including dark matter or energy, and the formation of cosmic structures.

Weak interactions with SM particles and the broad parameter space they occupy, underlies the challenge and intrigue of ALPs, making them significant subjects for both theoretical and experimental research.

The exploration of ALPs extends well beyond the search for a single particle; it opens up new avenues for understanding the fundamental forces and particles that shape our universe.

If ALPs are detected, they could offer valuable insights into high-energy physics, thereby not only advancing our knowledge of physics beyond the SM but also providing explanations for dark matter, contributing to our current knowledge of cosmic structure formation, also influencing the evolution of dark energy.

Their potential to address significant problems in both particle physics and cosmology highlights their importance in these fields.

Ongoing research into ALPs is essential for advancing our understanding of the universe. As experimental techniques improve and new theoretical models are developed, the chances of discovering ALPs increase. Future experiments like ADMX, CAST, IAXO, MADMAX, and ALPS II, along with simulations that bridge particle physics theory and cosmological observations, will play a critical role in this pursuit. The implications of ALP research are profound, with the potential to reshape our comprehension of the universe and the fundamental principles that underlie its workings.

Given the challenges and high stakes involved, ALP research stands at an exciting frontier, promising insights that could have far-reaching consequences for both physics and cosmology.

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