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Research Article

Helioscopic Frontiers in Axion Physics: Theoretical Foundations, Astrophysical Motivation, and the Experimental Evolution toward the International Axion Observatory

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Abstract

The axion remains one of the most compelling hypothetical particles in modern fundamental physics, motivated originally as a solution to the strong charge–parity problem in quantum chromodynamics and subsequently emerging as a prime candidate for physics beyond the Standard Model and for non-baryonic dark matter. Over the past four decades, the theoretical axion parameter space has been reshaped by advances in particle theory, cosmology, and astrophysics, while experimental efforts have diversified into haloscopes, helioscopes, laboratory searches, and astrophysical probes. Among these, axion helioscopes occupy a unique position by directly targeting solar axions produced in the core of the Sun through well-understood plasma processes. This article presents a comprehensive and theoretically grounded examination of the development of axion helioscope science, tracing its evolution from early conceptual proposals to the current international effort embodied by the International Axion Observatory and its intermediate stage, BabyIAXO. By synthesizing insights from axion theory, solar physics, detector technology, X-ray astronomy, and large-scale instrumentation, this work elaborates on the scientific rationale, methodological frameworks, and experimental strategies that define the helioscope approach. Particular attention is given to the redefinition of the axion parameter window, the role of astrophysical constraints, the technological lineage from pioneering experiments to next-generation facilities, and the integration of precision X-ray optics and ultra-low background detectors. Through extensive theoretical elaboration and critical discussion, this article clarifies how IAXO represents not merely an incremental improvement, but a qualitative leap in sensitivity and discovery potential. The broader implications for particle physics, astrophysics, and cosmology are examined, alongside remaining challenges and future directions for axion research in the coming decades.

Keywords: Axion physics, solar axions, axion helioscopes, International Axion Observatory, BabyIAXO, astrophysical constraints

INTRODUCTION

The search for axions occupies a central position in contemporary efforts to understand the deep structure of fundamental interactions and the composition of the Universe. Originally introduced in the late 1970s as a theoretical remedy to the strong charge–parity problem in quantum chromodynamics, axions have since transcended their initial motivation and become a focal point for interdisciplinary research spanning particle physics, cosmology, and astrophysics. The strong charge–parity problem arises from the apparent absence of observable charge–parity violation in the strong interaction sector, despite the theoretical allowance for such violation within the Standard Model. The axion mechanism elegantly resolves this inconsistency by dynamically relaxing the relevant parameter to zero, thereby restoring symmetry without fine-tuning.

What renders axions particularly compelling is that their theoretical properties naturally align with several outstanding puzzles in modern physics. Depending on their mass and coupling strengths, axions and axion-like particles may constitute a significant fraction, or even the entirety, of the dark matter content of the Universe. Furthermore, axions are expected to be produced in stellar interiors, supernovae, and the early Universe, making them accessible to indirect detection through astrophysical observations as well as direct laboratory experiments. This dual identity as both a particle physics solution and an astrophysical messenger has driven a remarkably diverse experimental program.

Within this broad experimental landscape, axion helioscopes represent a conceptually simple yet technically demanding approach. The basic idea, first articulated in the early 1980s, is to exploit the Sun as a powerful axion source and to convert these axions back into detectable photons within a strong laboratory magnetic field. The pioneering proposal by Sikivie established the foundational principles of this technique, demonstrating that axion–photon conversion in a transverse magnetic field could provide a realistic detection pathway for solar axions (Sikivie, 1983). Since then, helioscope experiments have undergone several generations of refinement, each pushing the sensitivity frontier closer to theoretically motivated regions of parameter space.

Despite decades of progress, a substantial portion of the axion parameter space remains unexplored. Recent theoretical work has emphasized that earlier assumptions regarding axion masses and couplings may have been overly restrictive, leading to a redefinition of the so-called axion window (Di Luzio et al., 2017). Concurrently, advances in astrophysical modeling have sharpened constraints derived from stellar evolution, white dwarf cooling, and supernova observations, while also highlighting the complementary role of direct experimental searches (Carenza et al., 2025). These developments have reinforced the scientific urgency of next-generation helioscopes capable of achieving orders-of-magnitude improvements in sensitivity.

The International Axion Observatory emerges in this context as a flagship project designed to fully exploit the helioscope concept. Building upon the lessons learned from earlier experiments and incorporating state-of-the-art technologies in magnet design, X-ray optics, and low-background detectors, IAXO aims to probe axion–photon couplings deep into theoretically and astrophysically motivated regimes (Armengaud et al., 2014; IAXO Collaboration, 2025). The intermediate BabyIAXO stage serves both as a technological demonstrator and as a scientifically productive experiment in its own right, ensuring continuity and risk mitigation in the path toward the full observatory (Abeln et al., 2021).

The purpose of this article is to provide an exhaustive, publication-ready analysis of axion helioscope science as embodied by IAXO and BabyIAXO. Rather than offering a concise review, this work engages in extensive theoretical elaboration, critically examining the underlying physics, methodological choices, and broader implications of the helioscope program. By integrating insights from the provided references and situating them within a coherent conceptual framework, the article seeks to clarify both the current state and the future trajectory of axion helioscope research.

METHODOLOGY

The methodological framework underpinning axion helioscope experiments is rooted in the interplay between theoretical particle physics, solar modeling, magnet technology, and X-ray detection. Unlike collider-based searches, which rely on particle production in high-energy interactions, helioscopes adopt a source–detector paradigm in which the Sun acts as a natural axion generator and the laboratory apparatus functions as a converter and sensor. This methodology entails several interconnected components, each of which must be optimized to maximize sensitivity.

At the theoretical level, the expected solar axion flux is derived from well-established processes occurring in the solar core. The dominant production mechanism for axions coupled to photons is the Primakoff effect, wherein thermal photons interacting with the electromagnetic fields of charged particles convert into axions. The rate of this process depends sensitively on the axion–photon coupling strength and on solar plasma conditions, which are constrained by helioseismology and solar neutrino measurements. This theoretical predictability constitutes a major strength of helioscope searches, as it allows experimental results to be interpreted with minimal astrophysical ambiguity.

The experimental realization of axion–photon conversion relies on the inverse Primakoff effect, whereby axions traversing a strong magnetic field can reconvert into photons. The probability of this conversion increases with the strength and length of the magnetic field, motivating the use of large-aperture, high-field superconducting magnets. Early helioscopes repurposed existing accelerator magnets, but this approach imposed inherent limitations on geometry and scalability. The IAXO concept departs from this paradigm by proposing a magnet specifically optimized for axion detection, featuring multiple bores arranged in a toroidal configuration to maximize the effective conversion volume (Armengaud et al., 2014).

Another crucial methodological element is the management of axion mass effects. For sufficiently light axions, coherence between the axion and photon fields is maintained over the length of the magnet, maximizing conversion probability. As the axion mass increases, this coherence is lost unless a refractive medium is introduced to match the photon effective mass to that of the axion. The use of buffer gases, such as helium, allows helioscopes to scan a range of axion masses by tuning the gas density. This technique was demonstrated in earlier experiments and remains integral to the methodological design of IAXO and BabyIAXO (Inoue et al., 2002).

Detection of the converted photons presents its own methodological challenges. Solar axions are expected to produce X-ray photons with energies in the keV range, corresponding to the thermal spectrum of the solar core. To efficiently collect and focus these photons, helioscopes employ grazing-incidence X-ray optics inspired by astronomical observatories. The adaptation of such optics to a ground-based particle physics experiment represents a methodological innovation, drawing on the heritage of space missions such as XMM-Newton and NuSTAR (Jansen et al., 2001; Harrison et al., 2013). By focusing the signal onto a small detector area, X-ray optics dramatically improve the signal-to-background ratio.

Low-background detection constitutes the final methodological pillar. Given the extremely low expected event rates, even minute sources of background radiation can obscure a genuine axion signal. The development of ultra-low background detectors, including Micromegas and metallic magnetic calorimeters, has been a major focus of the helioscope community. These detectors combine excellent energy resolution with sophisticated shielding and background discrimination techniques, enabling unprecedented sensitivity (Unger et al., 2021).

Data acquisition and analysis methodologies have also evolved to meet the demands of next-generation helioscopes. The integration of flexible software frameworks allows for detailed simulation, calibration, and statistical interpretation of experimental data. Open-source platforms facilitate transparency, reproducibility, and collaboration across institutions, reinforcing the methodological robustness of the helioscope program (REST-for-Physics, 2025).

RESULTS

The results anticipated and already partially demonstrated by the helioscope program can be understood in terms of progressive improvements in sensitivity, coverage of parameter space, and robustness of experimental constraints. While BabyIAXO and IAXO are ongoing or planned experiments rather than completed ones, their projected performance constitutes a central result in its own right, reflecting decades of cumulative methodological refinement.

One of the most significant outcomes of the helioscope approach is the establishment of increasingly stringent upper limits on the axion–photon coupling. Earlier experiments demonstrated the feasibility of solar axion detection and set pioneering bounds that excluded portions of parameter space previously unconstrained by laboratory experiments. These results, while limited in sensitivity, provided critical proof of principle and informed subsequent designs (Irastorza et al., 2011).

The conceptual design studies of IAXO and BabyIAXO have produced detailed sensitivity projections that indicate a transformative leap in discovery potential. By combining a purpose-built magnet with large aperture, advanced X-ray optics, and ultra-low background detectors, IAXO is expected to improve sensitivity to the axion–photon coupling by more than an order of magnitude compared to previous helioscopes. This improvement translates into the ability to probe axion models consistent with astrophysical hints and theoretical expectations, including those suggested by stellar cooling anomalies (Carenza et al., 2025).

BabyIAXO, as an intermediate stage, yields tangible scientific results even before the full observatory is realized. Its projected sensitivity already surpasses that of earlier helioscopes, enabling meaningful exploration of axion parameter space and serving as a platform for validating key technologies. The accurate ray-tracing simulations of solar axion signals in BabyIAXO have demonstrated that the combined system of magnet, optics, and detectors can achieve the expected performance, providing confidence in the scalability of the approach (Ahyoune et al., 2025).

Another important result lies in the integration of astronomical X-ray optics into a particle physics experiment. Drawing on the technological heritage of missions such as XMM-Newton and NuSTAR, helioscopes have adapted focusing optics to operate in a terrestrial environment. This cross-disciplinary transfer of technology has yielded demonstrable gains in background suppression and signal localization, setting a new standard for low-rate rare-event searches (Jansen et al., 2001; Harrison et al., 2013).

Beyond quantitative sensitivity metrics, the helioscope program has produced qualitative results in terms of experimental maturity and community organization. The establishment of an international collaboration with a clear long-term vision reflects the consolidation of axion helioscopes as a major research direction within particle physics. The articulation of a staged approach, culminating in IAXO, ensures continuity of expertise and sustained scientific output (IAXO Collaboration, 2025).

DISCUSSION

The implications of the helioscope program extend far beyond the immediate goal of detecting solar axions. At a fundamental level, the success or failure of experiments such as IAXO will directly inform our understanding of the strong interaction and the mechanisms underlying symmetry conservation in nature. A positive detection would constitute direct evidence for physics beyond the Standard Model, with profound consequences for particle theory, cosmology, and astrophysics. Conversely, the absence of a signal within the sensitivity reach of IAXO would impose stringent constraints on axion models, potentially ruling out entire classes of theoretical scenarios.

One of the most salient discussion points concerns the redefinition of the axion window. Traditional depictions of axion parameter space were based on assumptions that are now recognized as model-dependent and incomplete. Recent theoretical analyses have shown that viable axion models can occupy a much broader range of masses and couplings than previously thought, reinforcing the need for experimental coverage across multiple decades of parameter space (Di Luzio et al., 2017). Helioscopes are uniquely positioned in this context, as they probe couplings and masses that are difficult to access by other experimental techniques.

Astrophysical considerations further enrich the discussion. Stellar evolution provides some of the most stringent indirect constraints on axions, as excessive axion emission would alter observed stellar lifetimes and luminosities. At the same time, certain anomalies in stellar cooling data have been interpreted as potential hints of axion-like particles. Helioscope experiments offer a critical means of testing these interpretations under controlled laboratory conditions, thereby bridging the gap between astrophysical inference and direct detection (Carenza et al., 2025).

The technological challenges associated with IAXO also warrant careful discussion. The construction of a large, custom superconducting magnet represents a significant engineering endeavor, requiring coordination between physicists, engineers, and industry. Similarly, the deployment of large-area X-ray optics and the maintenance of ultra-low background conditions demand meticulous design and operation. While these challenges are substantial, the staged approach embodied by BabyIAXO mitigates risk by enabling incremental validation of key components (Abeln et al., 2021).

From a methodological perspective, helioscopes exemplify the benefits of interdisciplinary collaboration. The fusion of particle physics, solar physics, and X-ray astronomy has not only enabled technical innovations but has also fostered a more holistic understanding of axion phenomenology. This interdisciplinarity may serve as a model for future experiments targeting weakly interacting particles, where sensitivity gains increasingly depend on the integration of diverse expertise.

Looking ahead, the future scope of helioscope research extends beyond IAXO itself. Potential upgrades, complementary detection channels, and synergies with other axion searches could further enhance discovery prospects. Even in the absence of a detection, the methodological advances achieved through the helioscope program will have lasting value, informing the design of future rare-event experiments and reinforcing the empirical foundations of particle astrophysics.

CONCLUSION

Axion helioscopes represent a mature and intellectually rich approach to one of the most profound questions in modern physics: the existence and nature of new fundamental particles beyond the Standard Model. From the seminal proposal of axion detection via solar conversion to the ambitious vision of the International Axion Observatory, the helioscope program has evolved through sustained theoretical insight, technological innovation, and collaborative effort. The development of BabyIAXO and IAXO marks a decisive moment in this trajectory, promising sensitivity levels that intersect directly with theoretically and astrophysically motivated axion models.

Through extensive theoretical elaboration and critical analysis, this article has shown that IAXO is not merely an incremental experiment but a comprehensive observatory designed to explore axion physics with unprecedented depth and breadth. Its success would reshape our understanding of fundamental symmetries, stellar processes, and the composition of the Universe. Even in the absence of a discovery, the constraints imposed by IAXO will significantly refine the landscape of viable theories, guiding future research directions.

In this sense, the helioscope frontier embodies the enduring scientific principle that progress arises from the interplay of bold ideas, rigorous methodology, and sustained empirical effort. As the axion quest continues, the International Axion Observatory stands as a testament to the power of this principle and to the collective aspiration to uncover the hidden structure of reality.

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