Letter of Interest Snowmass 2021: The International Axion Observatory (IAXO) and BabyIAXO: Next Generation Helioscope Search for Axion and ALP Dark Matter

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I. Introduction

Over 80 years ago, dark matter (DM) was postulated, but its very nature remains one of the fundamental questions in physics. Axions [1] and weakly-interacting massive particles (WIMPs) are the leading candidates foňon-baryonic dark matter, which is expected to account for about 25% of the energy density of the Universe. In an era with no WIMP detection at the Large Hadron Collider or in ton-scale direct detection experiments, QCD axions and other axion-like particles (ALPs [2]) provide a promising alternative approach to understanding dark matter. Since axions were initially introduced as an extension to the Standard Model of particle physics to solve a long-standing problem in quantum chromodynamics (QCD) [3], they are very appealing candidates rather than an ad hoc solutions to the DM problem.

Helioscopes [4] are a type of dark matter experiment searching for axions produced in the core of the Sun via the Primakoff effect [5]. The International Axion Observatory (IAXO [6], [7]) is a next-generation axion helioscope aiming at a sensitivity to the axion-photon coupling 1 - 1.5 orders of magnitude beyond the CERN Axion Solar Telescope (CAST, e.g. Ref. [8]), which is the current most sensitive axion helioscope. IAXO will challenge the stringent bounds from supernova SN1987A and test the axion interpretation of stellar hints [9]-[11]. Beyond standard QCD axions, this new experiment will also search for a large variety of ALPs and other novel excitations at the low-energy frontier of elementary particle physics. BabyIAXO [12] is envisioned as an intermediate-scale version of IAXO with a two-pronged goal: it will function as a risk-reduction stage to verify all IAXO technologies at a realistic scale and will simultaneously deliver significant science results by increasing the experimental sensitivity to the axion-photon coupling down to a few 10×11 GeV^{-1}. This Letter of Interest describes the proposed IAXO experiment as well as BabyIAXO, which is currently entering its final design and early construction phase.

II. The BabyIAXO and IAXO Experiments

Helioscopes convert solar axions into x-ray photons via the inverse Primakoff effect by using a strong magnetic field.

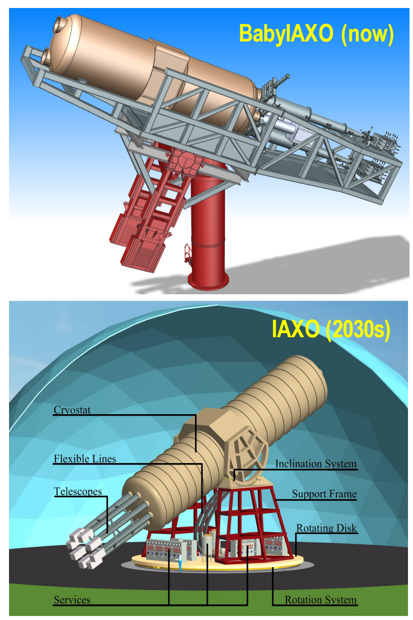

Fig. 1. Schematic experimental setup for BabyIAXO (top) and IAXO (bottom). The main difference is that the intermediate-stage experiment BabyIAXO will feature two $60 - 70$ cm diameter bores of a 10 m long magnet, while IAXO will have 8 coils of 20 m length with the same cross-sectional area.

While a strong magnet is a key component, sensitivity can be further boosted by implementing focusing devices that enable the use of small-area, low-background x-ray detectors and allow for simultaneous acquisition of data and background on different locations of the detector. BabyIAXO (see Fig. 1, top) will feature a smaller-scale magnet than IAXO but will be equipped with optics and detectors very similar to those of the the final IAXO. Beside verifying the generally mature technologies, this BabyIAXO will provide the opportunity to implement improvements to all subcomponents that might enable IAXO to go beyond its proposed baseline performance (which would then be dubbed IAXO+). In pursuit of the goal of improving detection techniques and delivering significant science results, BabyIAXO will feature a double-bore, 10-m racetrack-coil magnet with an average (peak) magnetic field

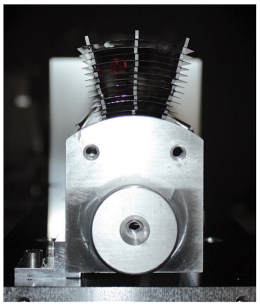

Fig. 2. IAXO segmented-glass pathfinder x-ray optic, based on NuSTAR technology [15].

strength of 2.5 Tesla (4.1 Tesla) within the bores of diameter $0.6 - 0.7$ m, similar to those of the full-scale IAXO. The final IAXO is expected to consist of 8 bores, each 20 m in length (Fig 1, bottom) with average and peak fields similar to BabyIAXO (2.5 Tesla and 5.1 Tesla, respectively). Eight x-ray telescopes (baseline technology: segmented-glass optics or replicated optics) and eight detectors (baseline: microbulk Micromegas) will complete the final IAXO designs. Further details on the IAXO design can be found in Ref. [7] as well as in the upcoming publication on the conceptual design of BabyIAXO [12].
In preparation for IAXO and BabyIAXO, a pathfinder system [13], [14] consisting of a prototype x-ray telescope (XRT, shown in Fig. 2) and a novel low-background Micromegas detector was designed, built, tested and installed at CAST. The XRT is based on the same slumped-glass technology developed for NASAs NuSTAR satellite mission [15] and the pathfinder enabled new benchmark limits on solar axions at CAST [16], while demonstrating that this approach works well for axion physics experiments and is highly suitable for BabyIAXO and IAXO. Other approaches to build an XRT following the Astro-H/Hitomi and XRISM technology [17] are under study along with additional suitable detector technologies testable in BabyIAXO and to be fully implemented in IAXO. More details on the IAXO detector and optics technologies can be found in dedicated Letters of Interest in the Snowmass 2021 process [18], [19].

III. IAXO Physics Reach

IAXO's primary science driver is the search for solar axions and ALPs emitted via the generic Primakoff effect for which it will improve the sensitivity with respect to CAST by more than 1 order of magnitude in sensitivity to $g_{a\gamma}$, which corresponds to a factor of $10^4 - 10^5$ in terms of signal to noise. The experiment will probe a large fraction of QCD axion models in the meV to eV mass band not accessible to any other proposed technique. In addition to exploring viable QCD axion DM models, IAXO will also probe large regions of theoretically-motivated parameter space for the "ALP miracle" models [20], in which both DM and inflation can be addressed by the same axion solution. Furthermore IAXO will also be sensitive to non-hadronic axions, i.e. axions coupling to electrons in addition to photons, and could directly measure the solar axion flux produced via BCA processes (Bremsstrahlung, Compton

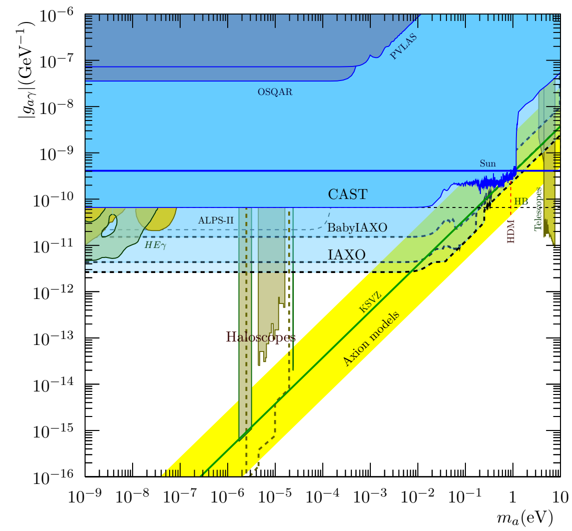

Fig. 3. Exclusion plot with current-best upper limits (CAST [16] on the axion-photon coupling constant $g_{a\gamma}$ as a function of axion mass together with sensitivity prospects for BabyIAXO, IAXO and IAXO+. The yellow band represents QCD axion models. Figure taken from [24].

scattering, and axio-recombination) for the first time with sensitivities to values of g_{ae} required to explain the anomalous cooling observed in white dwarfs. Beyond this, IAXO can also be sensitive to other, more exotic, proposed particles at the low energy frontier of particle physics, such as hidden photons [21] or chameleons [22], and is able to study the ALP region invoked to solve the transparency anomaly [23]. It is worth noting that all these questions can be addressed independent of whether axions are a subdominant DM component or all of the DM, while the experiment is largely complementary to other axion and ALP search strategies. BabyIAXO will already start shedding light on some of these aspects and improve the state-of-the-art as shown in Fig. 3. Here the best currently available upper limits on the axion-photon coupling from CAST are shown as a function of axion mass in comparison with the prospects for BabyIAXO, IAXO and IAXO+. A detailed discussion of the IAXO science potential has been recently published [24].

IV. Conclusion

BabyIAXO and IAXO are the next generation of axion helioscope and will surpass any previous heiloscope performance by more than one order of magnitude. Needless to say that the discovery of an axion would be revolutionary for particle physics, astrophysics and cosmology, but even in the absence of a signal the achieved results will be extremely useful in constraining the axion parameter space and testing various hints from astrophysics. IAXO and BabyIAXO are the first generation of axion helioscopes that will require fully custom-designed components, from the magnet, over the x-ray optics to the extremely low-background detectors. Together with axion haloscope, axion helioscopes will be able to either detect or significantly close in on the remaining axion window.

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