The International Axion Observatory (IAXO): case, status and plans. Input to the European Strategy for Particle Physics

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Abstract

The International Axion Observatory (IAXO) is a next-generation axion helioscope that will search for solar axions with unprecedented sensitivity. IAXO has a unique position in the international landscape of axion experiments, with sensitivity to a region of the axion parameter space that no other experiment can access. In particular, it will explore QCD axion models in the meV to eV mass range, encompassing models hinted by astrophysics, and potentially also axion dark matter models. IAXO relies on proven solutions and technologies, as well as on the 15-year-long experience with CAST. An intermediate demonstration prototype, BabyIAXO, will further mitigate risk and produce first physics. BabyIAXO is under review now at DESY and will be built and operated in the coming few years, while preparing the ground for IAXO. The scale of IAXO surpasses the traditionally small size of axion experiments and thus requires consideration in the context of the European Strategy.

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1 Introduction

Although axions have been experimentally searched for since shortly after their proposal in the 70s, it is only in recent years that this field is experiencing a strong increase of interest in the world-wide community. A plethora of new detection concepts are being proposed and many of them are being actively explored in small experimental setups. But also former detection strategies are getting consolidated and they naturally lead to the need of larger facilities, of a scale generally not found in the axion community. One of these efforts is the International Axion Observatory (IAXO). The international context of the experiment is provided in other documents to the European Strategy for Particle Physics (ESPP) update process, in particular the one produced by the Physics Beyond Colliders Study Group at CERN [1], as well as the European "axion community" input document to the ESPP [2]. Here we focus on IAXO, its physics case, as well as its status and future plans.

2 Physics case and context

A very motivated category of extensions of the Standard Model (SM) predicts particles that could lie hidden at the *low energy frontier* (i.e., very light particles), of which the axion is the prototype. Axions naturally appear in models that include the Peccei-Quinn (PQ) mechanism [3–6], that offers the most promising solution to one of the most serious problems of the Standard Model to date: the *strong-charge-parity (-CP) problem*, or why the strong interactions do not seem to violate the CP symmetry (while according to quantum-chromodynamics they are expected to). Very light and very lightly coupled axion-like particles (ALP) generically emerge in extensions of the SM with spontaneous symmetry breaking of new symmetries at higher energies [7]. Notably, string theory is known to predict many such ALP fields, including the axion itself [8].

Being very light particles, axions and ALPs could affect stellar evolution in a way similar to neutrinos, and play important roles in diverse cosmological scenarios. Most relevantly, these particles constitute excellent cold Dark Matter (DM) candidates. Despite their low mass, non-relativistic axions can be produced in the early Universe by non-thermal mechanisms like vacuum-realignment and the decay of topological defects of the axion field [9, 10]. The computation of the relic axion density Ω_a for a given axion model (and thus the "prediction" of the needed axion mass to obtain the observed DM density) is rather uncertain, both cosmological and computational-wise. As a result, we remain with a fairly large range of masses to search for the DM axion. Typically a mass range of about $10^{-6} - 10^{-3}$ eV is quoted as the comologically preferred one, although masses outside this range are also possible (i.e. they may provide a value for Ω_a similar to the measured total dark matter density). In particular, values above 10^{-3} eV and up to 0.1 eV are preferred in models with long-lived topological defects [11]. These models are appealing because they bring the DM window up to the astrophysically motivated region. Indeed, a few-meV axion is the only part of the ALP parameter space in which motivations from theory (strong CP), cosmology (DM) and astrophysics overlap. IAXO will be uniquely sensitive to this region. In addition, if the axions make up only a subdominant part of DM, the right axion mass moves always to higher values with an approximate factor $m_a \sim \Omega_a^{-1}$.

More generic ALPs can also be the DM in a wider range of parameters [12]. Independently of the DM issue, they have been invoked in different cosmological scenarios. They could constitute extra relativistic degrees of freedom in the early Universe [13] (i.e. Dark Radiation, whose presence could be –slightly– favoured by recent CMB observations [14]). These dark radiation axions/ALPs can feature a coupling to photons which is likely to be in the IAXO range and can thus be observed independently by IAXO for most values of the relevant parameters [15, 16]. In addition, recent models (dubbed "ALP miracle") in which the ALP is identified with the inflaton while, at the same time, composing the DM, have produced rather well-defined predictions that could be testable by IAXO [17, 18]. Finally, particular realizations of ALP fields (e.g. chamaleon or galileon theories) may constitute viable particle interpretations of Dark Energy.

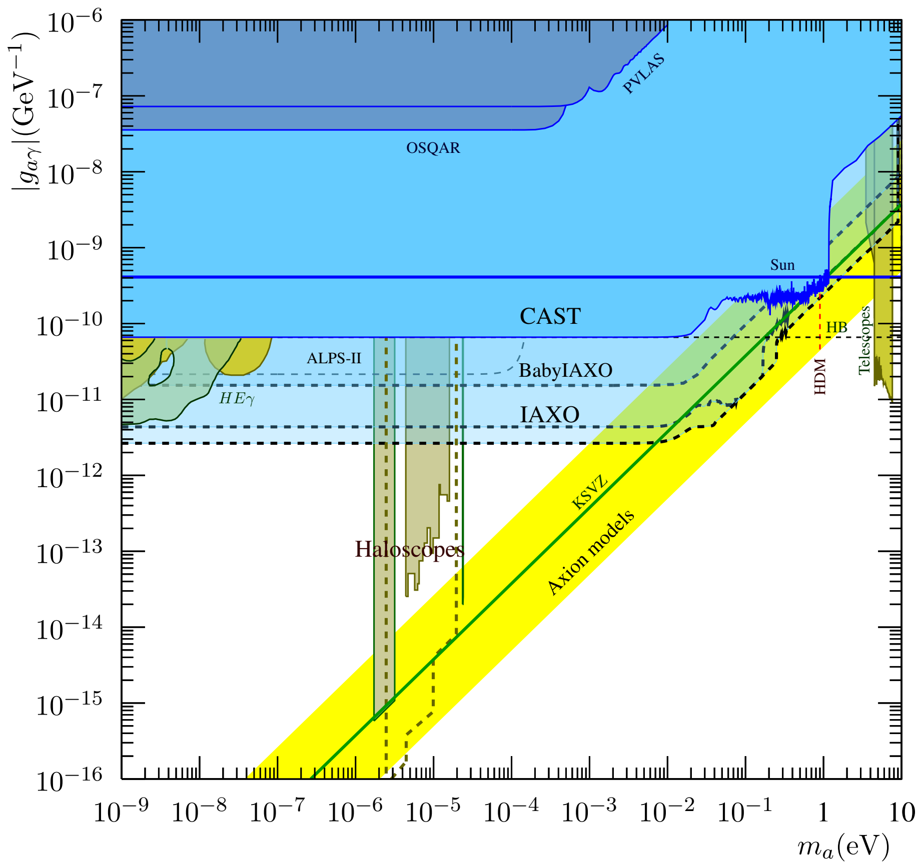

Fig. 1: Sensitivity plot of IAXO and BabyIAXO in the primary $g_{a\gamma}$ - m_a parameter space, compared with the QCD axion (yellow) band [37] and other current (solid) and future (dashed) experimental and observational limits (we refer to [38] for details on those limits). The yellow band represent the standard QCD axion models and the green line the benchmark KSVZ model.

Astrophysics has been exhaustively used to constrain the properties of axions and ALPs [19]. Despite more than 35 years of efforts, astrophysical constraints, however, still leave a relatively large window for the existence of axions (in brief, the axion-photon coupling $g_{a\gamma}$ must be lower than $\sim 10^{-10}$ GeV^{-1} and the axion mass m_a lower than $\sim$ 1 eV). Intriguingly, some astrophysical observations actually seem to hint at the presence of an axion or ALP. On one hand, the Universe seems to appear too transparent to very high-energy photons [20–24], something that has promtped several authors [20, 21, 25–34] to suggest explanations involving photon-ALP oscillations triggered by cosmic magnetic fields. For this solution to work the required ALP mass must be $m_a \lesssim 10$ neV and its coupling to photons $g_{a\gamma} \sim 10^{-11}$ GeV^{-1}. Of course, more standard explanations or systematic effects cannot be ruled out at the moment. In any case, the ALP solution to this anomaly will be fully tested by IAXO. On the other hand, an excessive cooling rate is measured in many stars at different evolutionary stages: red giants, supergiants, helium core burning stars, white dwarfs, and neutron stars. Collectively observations are in $> 3\sigma$ tension with stellar models, suggesting a new energy loss mechanism could be at work. Interestingly, a QCD axion of few-meV would provide a perfect fit [35,36]. Most of the parameter space invoked by these hints will be at reach of IAXO. In particular, a few meV axion is currently only realistically testable by IAXO, as shown in Figures 1 and 2.

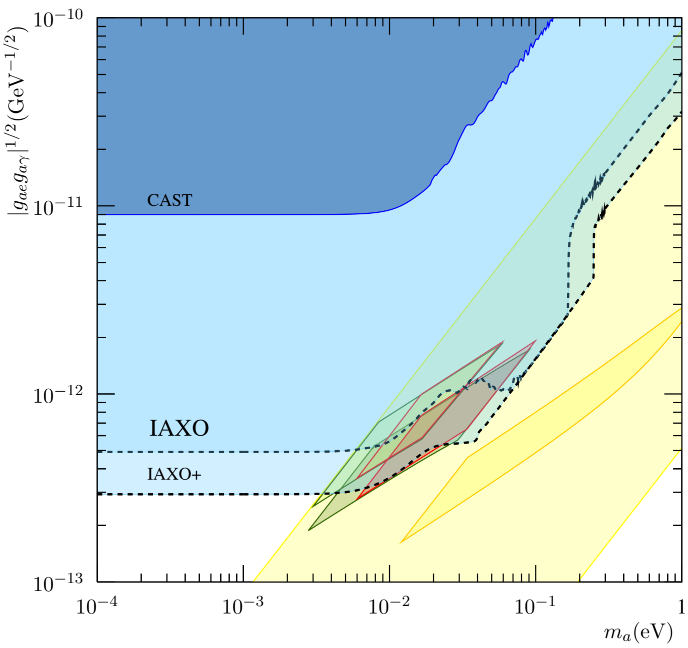

Fig. 2: Sensitivity plot of IAXO to solar axions produced via the axion-electron coupling g_{ae} (also called BCA axions [39]), in the $(|g_{ae}g_{a\gamma}|^{1/2} - m_a)$ parameter space. The yellow band correspond to the QCD axion models and the diamond-shaped color regions correspond to particular QCD axion models that are able to fit the all anomalous stellar cooling observations, following [35].

The main axion detection strategies make use of strong laboratory magnetic fields to trigger their conversion into detectable photons [38]. In principle axions can be searched for purely at the laboratory, e.g. by light-shining-through-wall configurations. However, at present the tiny conversion factors involved preclude sensitivities to QCD axion models. Natural sources of axions are therefore needed. If axions compose most of our galactic DM halo, they could produce detectable signals in appropriately designed detectors. The *axion haloscope* [40] is the most famous technique to search for DM axions. It has been proven to be able to reach sensitivity to relevant QCD models in the mass ballpark of 1–10 μeV, and there are ongoing searches with discovery potential here, e.g. by ADMX. Outside this range, the technique still requires significant developments. A number of initiatives to extend the axion haloscope technique, or to test altogether novel detection concepts, have recently been appearing to target DM axions in different mass points. As a result, a diverse and vibrant landscape of experimental efforts is emerging, most of them still relying on relatively small R&D setups.

Axion helioscopes looking for axions emitted by the Sun represent a particular category of experiments. It is the only approach that combines relative immunity to model assumptions (solar axion emission is a generic prediction of most axion models) plus a competitive sensitivity to axion parameters largely complementary to those accessible with other detection techniques. The current state-of-the-art is represented by the CERN Axion Solar Telescope (CAST). Its latest results, shown in Figure 1, are comparable with the best astrophysical limits on the axion-photon coupling ($g_{a\gamma}$) for a wide axion mass (m_a) range. IAXO aims at going substantially beyond CAST sensitivity and therefore deeply entering into unexplored regions. As shown in Figure 1, the region of ALP parameter space searchable by IAXO is largely complementary to the one accessible to haloscopes, and features a different set of assumptions. In particular, helioscopes do not rely on the axion being the DM. Thanks to the 15-year-long CAST efforts, the helioscope frontier is technologically mature, and going beyond the state-of-the-art requires to scale up and push the experimental parameters of the helioscope concept as much as possible. The experimental challenge is to coalesce the efforts of the experimental community into a single large-scale next-generation axion helioscope. This is the goal of IAXO.

To summarize, the physics case of IAXO can be condensed in the following few statements:

– IAXO follows the only proposed technique able to probe a large fraction of QCD axion models in the meV to eV mass band (e.g. KSVZ axions down to a few meV will be probed). **No other proposed experiment provides sensitivity in this region**. This region is the only one in which astrophysical, cosmological (DM) and theoretical (strong CP problem) motivations overlap.
– IAXO will fully probe the ALP region invoked to solve the transparency anomaly, and will largely probe the axion region invoked to solve observed stellar cooling anomalies.
– IAXO will partially explore viable QCD axion DM models, and largely explore a subset of predictive ALP models (dubbed *ALP miracle*) recently studied to simultaneously solve both DM and inflation.
– The above sensitivity goals do not depend on the hypothesis of axions being the DM, i.e. in case of non-detection, IAXO will robustly exclude the corresponding range of parameters for the axion/ALP.
– IAXO relies on detection concepts that have been tested in the CAST experiment at CERN. Risks associated with the scaling up of the different subsystems will be mitigated by the realization of BabyIAXO.
– Finally, IAXO will also constitute a generic infrastructure for axion/ALP physics with potential for additional search strategies (e.g. the option of implementing RF cavities to search for DM axions).

3 The IAXO facility

The new generation axion helioscope IAXO will enjoy sensitivity to the $g_{a\gamma}$ down to a few 10^{-12} GeV^{-1}, a factor of $\sim$20 better than the current best limit from CAST (a factor of more than $\sim 10^4$ in signal-to-noise ratio). This leap in overall sensitivity is achieved by (1) the realization of a large-scale magnet, (2) extensive use of x-ray focusing optics, (3) low background detectors and (4) enhanced tracking capabilities increasing the total exposure in axion-sensitive conditions. Figure 3 shows a view of the experiment.

The main element of IAXO is thus a new dedicated large superconducting magnet, designed to maximize the helioscope figure of merit. The IAXO magnet will be a superconducting magnet following a large multi-bore toroidal configuration, to efficiently produce an intense magnetic field over a large volume. The design is inspired by the ATLAS barrel and end-cap toroids, the largest superconducting toroids ever built and presently in operation at CERN. Indeed the experience of CERN in the design, construction and operation of large superconducting magnets is a key aspect of the project.

X-ray focusing relies on the fact that it is possible to fabricate x-ray mirrors with high reflectivity at grazing incident angles. IAXO envisions newly-built optics similar to those used onboard NASA's NuSTAR satellite mission [43], but optimized for the energies of the solar axion spectrum and adapted in size to match the evisioned IAXO dimensions. Each of the eight $\sim$60 cm diameter magnet bores will be equipped with such optics. At the focal plane of each of the telescopes, IAXO will have low-background x-ray detectors. Several detection technologies are under consideration, but the most developed types are small gaseous chambers read by pixelised microbulk Micromegas planes [44, 45]. They involve low-background techniques typically developed in underground laboratories, like radiopure detector components, appropriate shielding, and offline discrimination algorithms. Alternative or additional x-ray detection technologies are also considered, like GridPix detectors, Magnetic Metallic Calorimeters, Transition Edge Sensors, or Silicon Drift Detectors. All of them show promising prospects to outperform the baseline Micromegas detectors in aspects like energy threshold or resolution, which are of interest,

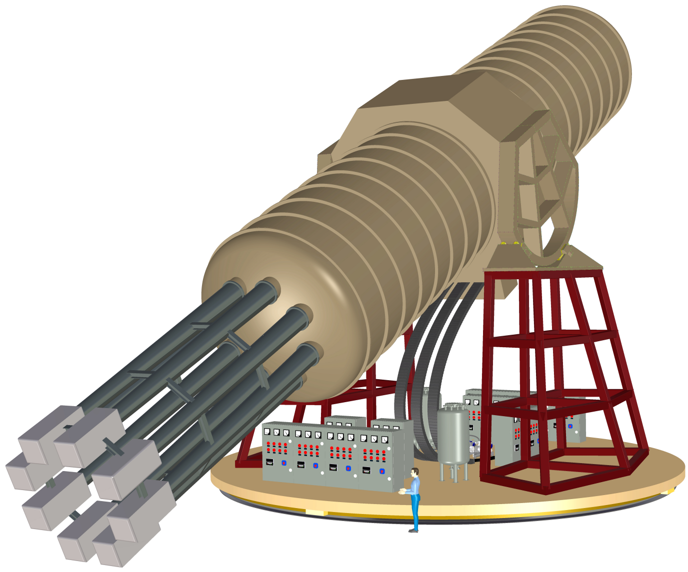

Fig. 3: Conceptual design of IAXO as defined in [41, 42].

for example, to search for solar axions via the axion-electron coupling, a process featuring both lower energies than the standard Primakoff ones, and monochromatic peaks in the spectrum.

IAXO was designed with the requirement that no development or prototype was mandatory. However, the current plans of the collaboration involve the implementation of an intermediate stage, BabyIAXO, described in the next section. The experience with BabyIAXO will result in improved design options or parameters for the final IAXO. We use the label "IAXO+" to represent a possible enhanced FOM for IAXO, somewhat arbitrarily fixed as an improved factor of 10 with respect to the nominal set of design parameters, which would enable probing most of the astrophysically motivated models shown in Fig. 2. Both scenarios, nominal and enhanced, are represented in the sensitivity figures 1 and 2. This enhanced scenario must be understood as a desired target whose feasibility will be studied as part of the BabyIAXO phase, but the nominal IAXO scenario remains our baseline projection, well based on previous design studies [41, 42].

4 BabyIAXO and near term plans

An intermediate experimental stage called BabyIAXO is the near term goal of the collaboration. BabyIAXO will test magnet, optics and detectors at a technically representative scale for the full IAXO, and, at the same time, it will be operated and will take data as a fully-fledged helioscope experiment, with sensitivity beyond CAST and potential for discovery.

BabyIAXO will feature a 10 m long superconducting magnet following a "common coil" layout, i.e. two flat racetracks coils that resemble the unit coils of the final IAXO magnet described in the previous section. In between the coils two parallel 10 m long, 70 cm diameter bores are placed. Both bores will be equipped with detection lines (optics and detector) of similar dimensions as the final ones foreseen for IAXO. The overall experiment is shown in Figure 4.

The baseline x-ray optic for BabyIAXO is an x-ray telescope that is as close as possible in dimensions and performance to the final IAXO optic, based on the same technology, and made of multiple thermoformed substrates. In order to fabricate the BabyIAXO optic quickly and cost-efficiently, the production leverages investments of NASA's NuSTAR mission in both technology and construction. This fabrication could alternatively make use of cold glass replication [46], and in this case potentially take

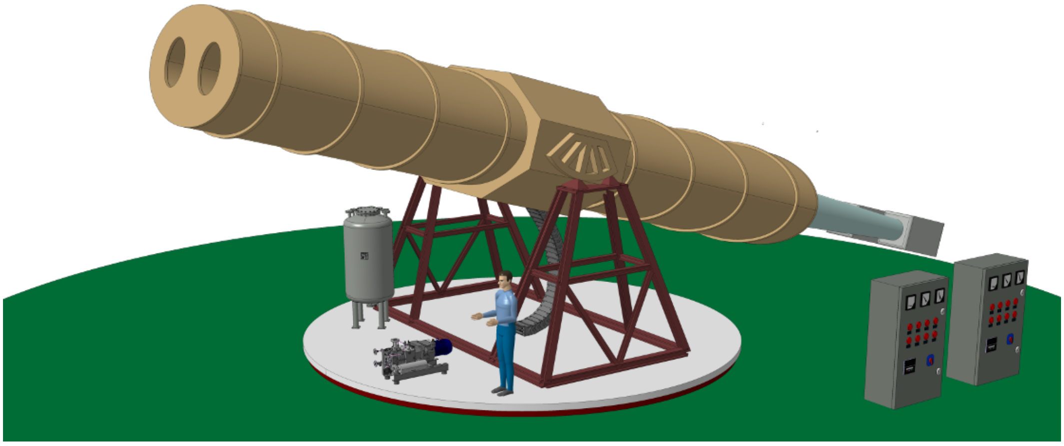

Fig. 4: BabyIAXO set-up showing the double bore design based on using baseline IAXO magnet technology. Overall system length is about 18 meter.

advantage of a purpose-designed integration machine at INAF. Additionally to one of the IAXO baseline optics, the collaboration is planning on using an existing, 70-cm diameter XMM Newton [47] flight spare telescope on the second BabyIAXO magnet bore. Two such optics exist and they are property of ESA. Although not optimized for this application, the XMM optics are very close to BabyIAXO requirements, and represent a cost-effective low-risk solution for the experiment. Initial talks with ESA about the availability of one or two of the XMM flight spare optics are ongoing.

In addition to being a technological demonstrator of all the subsystems of IAXO, BabyIAXO will enjoy a relevant physics potential in itself, and will allow the collaboration to move into "experiment" mode relatively early, and, in doing so, create intangible resources in the collaboration (working groups on analysis, software, data taking, etc.) that will be needed for IAXO. The experimental parameters expected from the above design allow BabyIAXO to probe new unexplored axion and ALP parameter space, as shown in Figure 1.

5 Collaboration and timetable

After a few years of preparatory phase, project socialization and interaction with funding agencies, the IAXO collaboration was eventually formalized in July 2017. A collaboration agreement document (by-laws) was signed by 17 institutions from Croatia, France, Germany, Italy, Russia, Spain, South Africa, the USA, as well as CERN. The collaboration includes about $\sim$75 physicists at the moment. It is likely that this list will increase with new members in the near future. A collaboration management has already been defined and actively implemented steps towards the BabyIAXO design and construction. The experiment will likely be sited at DESY, and it is expected to be built in 2-3 years, entering into data taking in 3-4 years since start of construction.

The collaboration already nicely encompasses all the know-hows to cover BabyIAXO expertise needs, and therefore a distribution of responsibilities in the construction of the experiment already exists. The magnet of (Baby)IAXO is of a size and field strength comparable to that of large detector magnets typically built in high energy physics. For this, IAXO relies on the unique expertise of CERN in large superconducting magnets. The CERN magnet detector group has already led all the magnet design work so far for the IAXO CDR. Further CERN participation is expected in terms of, at the least, allocation of expert personnel to oversee the construction of the magnet, as well as the use of existing CERN infrastructure. This technological connection with CERN is acknowledged in the Physics Beyond Colliders process [1]. Other groups with magnet expertise in the collaboration are CEA-Irfu and INR. The groups of LLNL, MIT and INAF are experts in the development and construction of x-ray optics, in particular in the technology chosen for the IAXO optics. Detector expertise exists in many of the collaboration groups, encompassing the technologies mentioned above. Experience in general engineering, large infrastructure operation and management is present in several groups and in particular in centers like CERN or DESY. Many of the groups have experience in axion phenomenology and the connection with experiment, and more specifically experience with running the CAST experiment. Following these guidelines the collaboration board is in the process of defining a collaboration agreement (MoU) to organize the distribution of efforts and commitments among the collaborating institutes.

6 BabyIAXO and IAXO at DESY

In DESY's longer term strategy for future particle physics experiments, IAXO is a very prominent option, which would ideally complement DESY's ongoing ALPS II activities and its participation in remote accelerator based experiments. Therefore, DESY has offered to contribute already in the preparatory phase with support from its project office to structure and coordinate the international activities. In addition, options for BabyIAXO and IAXO sites on the DESY campus in Hamburg are presently being investigated in detail. BabyIAXO could be located in one of the big experimental halls of the HERA facility, which was shut down in 2007. Their infrastructure is well suited to construct and operate the prototype. In October 2018, BabyIAXO and IAXO have been presented to the DESY Physics Research Committee (PRC), a panel of external experts advising the DESY directorate on all matters related to the particle and astroparticle physics programs at DESY. The PRC has welcomed the proposal and will organize for an in-depth review of BabyIAXO in spring 2019. Depending on the result of the review, focused discussion on funding for BabyIAXO between DESY, CERN and other funding bodies can start. As IAXO will require significant international funding, further discussions to realize the large helioscope at DESY have to await the outcome of the update process of the ESPP.

7 Conclusions

Axion searches are now recognized as a very appealing portal for new physics beyond the Standard Model. IAXO has a privileged position in the world-wide landscape of axion experiments. The axion helioscope technique is the only realistic strategy to explore certain ranges of the parameter space, in particular the QCD axion models with masses between meV and eV. IAXO will test most of the astrophysically motivated regions, including some axion DM models. This potential is largely complementary to other efforts of the community, as stressed in respective community documents to the ESPP [1, 2].

As has been detailed in this document, IAXO is solidly based on previous experience in the CAST experiment, as well as on a number of well-proven solutions and technologies, most relevantly on superconducting magnet expertise present at CERN. The IAXO collaboration, formally established last year, is the largest collaboration in experimental axion research, and encompasses all the needed core know-how to carry out the IAXO program. The near term goal of the collaboration is to build and operate BabyIAXO, an intermediate stage that will serve as technological prototype and will already produce first physics results. BabyIAXO will enable the collaboration to quickly move into "science mode" and will lay the groundwork for the full IAXO. First important funding decisions have been obtained for BabyIAXO, including an ERC-AdG grant, and the project is at this moment under review to be hosted by DESY.

IAXO has the potential to become a flagship project of the international axion community. Although still relatively small compared to the large HEP facilities, the final IAXO experiment will be of an unprecedented scale for typical axion experiments. The consideration of axion searches by the European Strategy for Particle Physics, and in particular of the IAXO project, is therefore required to face the challenges of its realization in the coming decade.

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