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# Hunting the Axion

Igor G. Irastorza

Departamento de Física Teórica,

Área de Física Atómica, Molecular y Nuclear.

Universidad de Zaragoza, 50009 Zaragoza

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## Abstract

Probably the most important challenge of Particle Physics for the coming century is to understand the fundamental nature of the Dark Universe. More than 95% of the Universe is composed by two components, Dark Matter and Dark Energy, for which Cosmology provides growing evidence, but of which we lack a proper fundamental (Particle Physics) interpretation. The recent discovery of the Higgs boson at CERN seems to complete a very successful chapter of Particle Physics, which embodies the current understanding of the known particles and their interactions in the so-called Standard Model. However, a number of theoretical considerations point to the necessity of Physics beyond the Standard Model. With no experimental indication of such Physics in accelerators (whose data is on the contrary outstandingly well explained with just the Standard Model), is the existence of Dark Matter (and to some extent Dark Energy) viewed as the most powerful observational motivation for the study of extensions of the Standard Model. Some of these extensions predict extremely light and neutral particles that interact very weakly with standard model particles. The *axion* is the most popular and the prototype of this class of particles. Motivated by theory, but maybe also by some intriguing astrophysical observations, they at the same time constitute perfect Dark Matter candidates. Highly complementary to the exploration of the high energy frontier at the Large Hadron Collider (LHC) at CERN, the searches for axions at the low energy frontier are recently attracting an increasing attention. In this article I will review the motivation of the axion hypothesis, and the reason for the current interest, the status of the experimental techniques of these searches and their prospects to eventually detect the axion in the near future. I will finally focus on a recent initiative, the International Axion Observatory (IAXO), the most ambitious project to test the existence of axions. IAXO will be built on the experience acquired so far in the field and will highly surpass current experimental sensitivity to venture deep into uncharted axion parameter space. If the axion exists, IAXO will have good chances of discovering it. It could be the next breakthrough discovery in our race to understand the Universe, and how it works at its most fundamental level.

## Contents

## 1 Introduction

The currently accepted picture of the Universe shows that the conventional baryonic matter (planets, stars, galaxies, interstellar dust and gas, etc.) comprises only less than 5% of the total matter-energy of the Universe. The remaining majority –the dark side of the Universe– is made of Dark Energy (DE) 68.3% and Dark Matter (DM) 26.8%[1]. DE is commonly seen as a sort of vacuum energy that would be responsible for the accelerated expansion of the Universe, however whether and how we can understand it at the fundamental level (e.g. as a quantum field) is still totally unclear. On the other hand, DM seems to be composed by a kind of matter that is invisible, collision-less, and whose existence is now clearly evidenced through its gravitational effects. The particle nature of DM however is currently a mystery, and its determination is one of the hottest issues in modern fundamental physics.

From the particle physics perspective, DM particles must have mass, be electrically neutral and interact very weakly with the rest of matter. They have to provide a viable mechanism for being produced in sufficient quantities in the early Universe. Within the Standard Model (SM) of particle physics, the neutrinos have been long ago considered as possible DM candidates, however, they fail to reproduce the large scale structure of the Universe, and their contribution must be restricted to a very small fraction of relativistic (hot) DM. One has, therefore, to resort to extensions of the SM in order to find a candidate that can solve the puzzle. The problem of DM is thus linked to the very interesting topic of physics beyond the SM. Although there are numerous ways to postulate DM candidates in beyond-SM theories, the attention is focused on SM extensions that are well motivated *per se* (i.e. they are proposed to solve one of the theoretical shortcomings of the SM) and in addition provide a good DM candidate. A very popular example, attracting most of the experimental attention, are the Weakly Interacting Massive Particles (WIMPs) that appear in supersymmetric extensions of the SM.

Other extensions of the SM predict particles that could lie hidden at the low energy frontier, and could also be good candidates for the DM. The axion appearing as part of the Peccei-Quinn mechanism solving the strong CP problem is the prototype of this kind of particles. The fact that Supersymmetry has not yet been observed at the Large Hadron Collider (LHC) at CERN and that no clear signal of WIMPs has appeared in Dark Matter experiments (despite an enormous advance in sensitivity of these experiments in the last decade) has increased the community's interest for searching for axions. However axions are independently and powerfully motivated, and a Dark Matter composed by both WIMPs and axions is perfectly viable implying that they should not be considered as alternative and exclusive solutions to the same problem.

The search for axions has been a relatively minor, but continuously growing, field of experimental particle physics since the axion hypothesis was first proposed in the late 70's. Recently the field is going through a transition. In this article I will briefly review the theoretical motivation for axions, the latest advances in our understanding of their role in Cosmology and some astrophysical scenarios. I will review the status of the experimental searches for axions and finally I will focus on the International Axion Observatory (IAXO), a recent initiative of larger scale that any previous axion experiment, that aims to explore a large fraction of the still allowed parameter space for the axion.

## 2 The strong CP problem and axions

The recent discovery of the Higgs boson would complete the experimental confirmation of the particle content of the very successful Standard Model (SM) of particle physics. However, it is known that the SM is incomplete, as it does not explain some basic features of our Universe, like e.g. the nature of DM and DE, or the matter-antimatter unbalance, and does not provide satisfactory explanations for a number of features of the SM itself. One of the latter is the so-called *strong-CP problem*, or why the strong interactions seem not to violate the charge-parity (CP) symmetry [2]. Indeed, the lagrangian of Quantum Chromodynamics (QCD) includes a CP-violating term:

$$\mathcal{L}_{\bar{\theta}} = \bar{\theta}\frac{\alpha_s}{8\pi}G^{\mu\nu a}\tilde{G}_{\mu\nu a} \tag{1}$$

where $G$ is the gluon field and $\tilde{G}$ its dual, and $\alpha_s$ the strong coupling constant.

One of the experimental consequences of the term $\mathcal{L}_{\bar{\theta}}$ would be the existence of electric dipole moments (EDMs) for protons and neutrons. The non-observation of the neutron EDM [3] puts a very strong limit on the magnitude of the $\bar{\theta}$ parameter in (1) of about $|\bar{\theta}| \lesssim 10^{-10}$. But the problem is more than the unexplained smallness of an arbitrary SM parameter. The $\bar{\theta}$-angle is actually the sum of two contributions, which are in principle unrelated. The first is the angle characterizing the QCD vacuum and the second is the common phase of the matrix of SM quarks –coming from the Higgs Yukawa couplings which are known to violate CP sizeably. Thus, the smallness of $\bar{\theta}$ requires that two completely unrelated terms of the SM (from two different sectors) cancel each other with a precision of at least $10^{-10}$. The strong CP problem constitutes a very serious fine-tuning issue that remains unexplained in the SM.

The most convincing solution of the strong CP problem is the Peccei-Quinn (PQ) mechanism, proposed in 1977 [4, 5]. It introduces a new U(1) global symmetry (the PQ symmetry) that is spontaneously broken at a high scale $f_a$. This implies the existence of a new field $a$ which appears as the pseudo-Nambu-Goldstone boson of the new symmetry. The term $\mathcal{L}_{\bar{\theta}}$ ends up absorbed in a new term of the type $G^{\mu\nu}\tilde{G}_{\mu\nu}a/f_a$ where $a$ is now a dynamical variable, which can relax to a CP-conserving minimum. This solves the fine-tuning problem dynamically, for any value of $f_a$. The main observational consequence of the PQ mechanism, as was first pointed out by Weinberg and Wilczek [6, 7], is that the quantum excitations of this field –albeit very weakly coupled– are potentially observable as new particles: axions.

The PQ mechanism fixes some of the properties of the axion [8, 9] like, e.g., its mass $m_a$, acquired via mixing with the pseudoscalar mesons,

$$m_a \simeq \frac{m_\pi f_\pi}{f + a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6\,\mathrm{meV} \frac{10^9\,\mathrm{GeV}}{f_a} \tag{2}$$

where $m_\pi = 135$ MeV is the pion mass, $f_\pi \approx 92$ MeV the pion decay constant and $m_{u,d}$ the light quark masses. This same mixing makes the axions interact with hadrons and photons. All the axion couplings are suppressed by the PQ symmetry scale $f_a$, which is not determined by theory.

More concrete axion properties depend on the specific implementation of the PQ symmetry in the SM. Originally $f_a$ was identified with the weak scale, but accelerator data quickly ruled out this possibility constraining it to be higher than about $10^5$ GeV. If the fermions of the SM do not have PQ charge, axions do not couple with them at tree level. These are called "hadronic axions", of which the KSVZ [10, 11] model is an often quoted example. Other models, like the DSFZ [12, 13], feature tree-level coupling with SM fermions, e.g., the axion electron coupling $g_{ae}$.

The property of axions most relevant for experiment is the axion-two-photon coupling $g_{a\gamma}$

$$\mathcal{L}_{a\gamma} \equiv -\frac{g_{a\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a\,, \tag{3}$$

where $F$ is the electromagnetic field-strength tensor and $\tilde{F}$ its dual, while $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields. The coupling $g_{a\gamma}$ can be expressed as

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} C_\gamma \quad ; \quad C_\gamma \equiv \frac{E}{N} - \frac{2}{3} \frac{4m_d + m_u}{m_d + m_u} \simeq \frac{E}{N} - 1.92 \tag{4}$$

where the loop factor $\alpha/2\pi f_a$ reflects the fact that this is a coupling generated from the electromagnetic anomaly. $C_\gamma$ is a coefficient of order 1 with two contributions: a model-independent one due to the axion mixing with pseudoscalar mesons and a model dependent one $E/N$ which arises if the PQ symmetry is not only colour-anomalous but also has a non-zero electromagnetic anomaly ($E$ and $N$ are the electromagnetic and colour anomalies of the PQ symmetry). In general, a broad range of values for $E/N$ is possible, depending on the axion model (e.g. for DFSZ $E/N = 8/3$ and $C_\gamma \simeq 0.75$, whereas for KSVZ $E/N = 0$ and $C_\gamma \simeq -1.92$, if the new heavy quarks are taken without electric charge).

Because the axion-photon interaction is generic and because photons offer many experimental options, most axion search strategies are based on this interaction. Axions mix with photons in the presence of external magnetic fields, leading to axion-photon oscillations [14, 15], similar to the well known neutrino oscillations, and to changes in the polarization state of photons propagating in a magnetic field [15, 16]. The $a\gamma\gamma$ coupling also leads to the Primakoff conversion of plasma photons into axions within stellar cores, the main axion emission channel of the Sun. The Primakoff conversion is also behind the detection principle of axion helioscopes, haloscopes [14] as well as LSW experiments, as discussed later on. The results of these searches are therefore represented in the parameter space ($g_{a\gamma}$,$m_a$) that is shown in Fig. 1. Because $g_{a\gamma}$ and $m_a$ are linked for a specific axion model (both are inversely proportional to $f_a$), an axion model is represented by a straight diagonal line in such plot (the green line in Fig. 1 correspond to the KSVZ model). The overall spread of axion models resulting from the possible values of $E/N$ in (4) is represented by the width of the yellow band of Fig. 1.

In some particular implementations of the PQ mechanism, the axion may couple to leptons at tree level. This is most importantly the case of models in which the SM is embedded in a Grand Unified Theory, where colour and electroweak interactions are unified in a larger non-abelian symmetry. The coupling to electrons can be written in two forms, equivalent for our purposes,

$$\mathcal{L}_{ae} = C_{ae}\frac{\partial_\mu a}{f_a}\bar{\psi}_e\gamma^\mu\gamma^5\psi_e \leftrightarrow g_{ae}a\bar{\psi}_e\gamma^5\psi_e \tag{5}$$

where $C_{ae}$ is a coefficient of order 1 given by specifics of the model. The equivalent Yukawa coupling is $g_{ae} = C_{ae}m_e/f_a$ where $m_e$ is the electron mass. For instance in the DSFZ model [12, 13] $C_{ae} = \frac{1}{3}\cos^2\beta$ where $\tan\beta$ is the ratio of the v.e.vs of the two Higgses present in the theory. When $C_{ae}$ is zero at tree-level, a non-zero value is generated by radiative corrections, but being loop-suppressed is typically irrelevant. When the axion couples to electrons with $C_{ae} \sim \mathcal{O}(1)$, this coupling drives the most efficient axion-production reactions in stars like the Sun, low-mass red giants and white dwarf stars.

### *2.1 Main constraints on the axion properties*

Since it was first proposed, the axion has been thoroughly studied for its implications in astrophysics, cosmology and particle physics. The most relevant limits on its properties have been drawn from astrophysical considerations [29]. The emission of axions from the Sun is nowadays best constrained from the increase they imply in the solar neutrino flux with respect to the standard one without axions [30]. The axion flux originated from the Primakoff effect constrains the coupling $g_{a\gamma} \lesssim 0.7 \times 10^{-9}$ GeV$^{-1}$ while the axio-Bremsstrahlung in electron collisions (and other reactions involving electrons) constrains

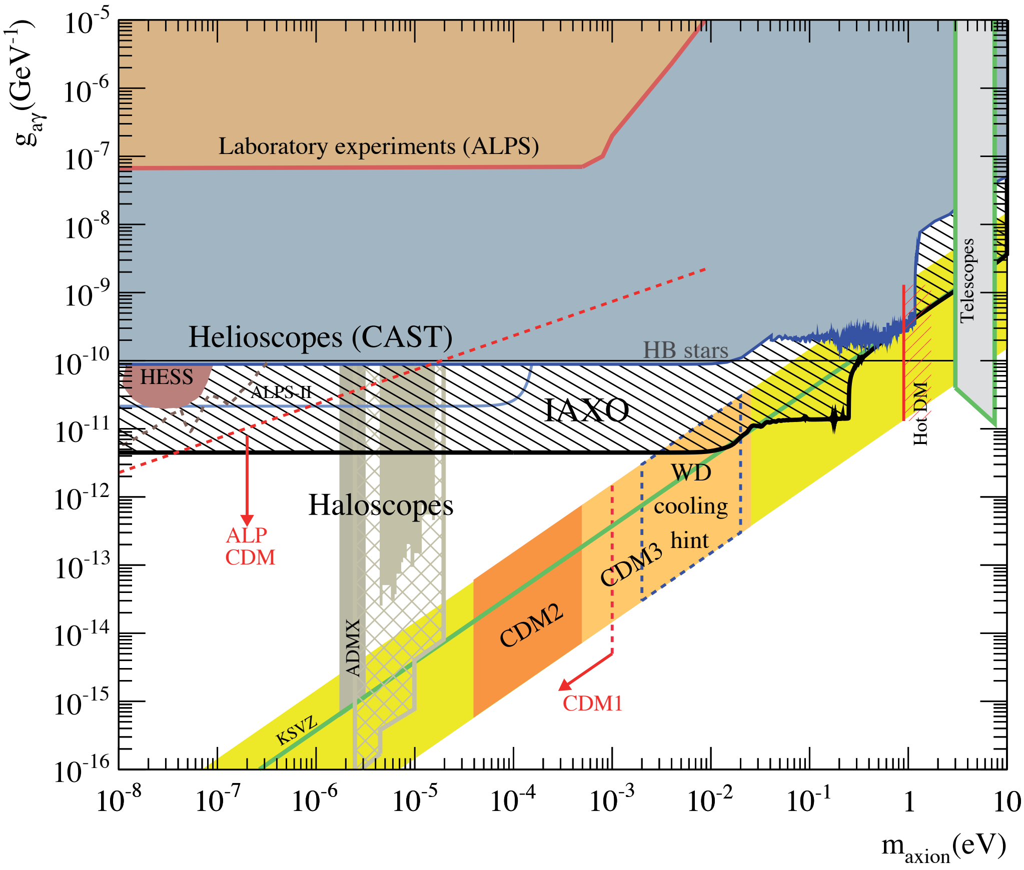

Figure 1.— Comprehensive axion/ALP parameter space, highlighting the three main front lines of direct detection experiments: LSW experiments (ALPS [17]), helioscopes and haloscopes. The blue line corresponds to the current helioscope limits, dominated by CAST [18, 19, 20, 21] for practically all axion masses. Also shown are the constraints from horizontal branch (HB) stars, and hot dark matter (HDM) and the ones from searches of decay lines in telescopes [22, 23, 24]. The yellow "axion band" is defined roughly by $m_a f_a \sim m_\pi f_\pi$ with a somewhat arbitrary width representing the range of realistic axion models. The green line refers to the KSVZ model. The orange parts of the band correspond to cosmologically interesting axion models: models in the "classical axion window" possibly composing the totality of DM (labelled "CDM2") or a fraction of it ("CDM3"). The anthropic window ("CDM1") corresponds to a range unbound on the left and up to ~1 meV. For more generic ALPs, practically all the allowed space up to the red dash line may contain valid ALP CDM models [25]. The region of axion masses invoked in the WD cooling anomaly is shown by the blue dash line. The region at low $m_a$ above the dashed grey line is the one invoked in the context of the transparency of the universe [26] (note that it extends to masses lower than the ones in the plot), while the solid brown region is excluded by HESS data [27]. The labeled hatched region represents the expected sensitivity of IAXO in the baseline helioscope configuration as explained in the text. Also future prospects of ADMX (hatched brown region) and ALPS-II [28] (light blue line) are shown.

$g_{ae} < 2.5\times10^{-11}$. The population of low-mass horizontal-branch (HB) stars and red-giants (RG) in globular clusters gets decreased and increased respectively when axions are freely emitted from their interiors. Fitting the observed population to numerical simulations one derives the limits $g_{a\gamma} \lesssim 10^{-10}$ GeV$^{-1}$ (mostly from the impact on HBs) [29, 31] and $g_{ae} < 4.7 \times 10^{-13}$ at 95% C.L. (from the tip of the RG branch in the cluster M5) [32]. A more recent and detailed revision of this result lowers the bound to $g_{a\gamma} \lesssim 0.66 \times 10^{-10}$ GeV$^{-1}$ [33]. However, at the same time, the data seem to slightly prefer some level of axion emission. Recently, it has been argued that the Primakoff flux of axions from $g_{a\gamma} > 0.8 \times 10^{-10}$ GeV$^{-1}$ will shorten so much the helium-burning phase (so called blue loop) of *massive stars* that Cepheids could not be observed [34], and thus it is excluded. Observations and theory of white dwarf cooling fit to the extent that they can exclude values of the electron coupling $g_{ae} > 3 \times 10^{-13}$ [35, 36, 37, 38]. However, some observable such as the luminosity function and the period decrease of the variable ZZ Ceti star G117-B15A seem to prefer some slight extra cooling.

Due to their coupling of protons and nucleons, axions can be efficiently emitted from the core of a Type-II supernova shortening the neutrino pulse. From the observation of the ∼10 s duration neutrino burst of SN1987A, which fits the expectations without extra axion cooling, one can derive the limit to the axion-proton Yukawa-like coupling $g_{ap} \lesssim 10^{-9}$ [39]. In general one has $g_{ap} = C_{ap} m_p / f_a$. For hadronic axions $C_{ap} \sim 0.4$ and thus $f_a > 4.8 \times 10^8$ GeV or, equivalently, $m_a < 16$ meV. For DFSZ axions $C_{ap}$ tends to be smaller and the constraints weaker, but not much because then the axion-neutron coupling becomes relevant. Similar bounds for $f_a \gtrsim 10^9$ GeV arise from neutron star cooling [40, 41]. These limits remain fairly rough estimates, due to the uncertainty in the axion emission rate, supernova modeling and the observations.

Other astrophysical, cosmological and experimental bounds, some of them commented on later, further constrain the allowed axion parameter space. However, not only have these bounds not rejected the axion, but the motivation for the existence of axions, beyond the strong CP problem, has grown on several fronts. The axion is a candidate for the dark matter of the Universe, and several tantalizing hints in astrophysics could be the result of axion-like particles at play. More recent theoretical advances are defining a more generic category of light fundamental particles, the weakly interacting slim particles (WISPs), of which the axion is the most outstanding prototype, appearing in other well-motivated extensions of the SM, like string theory. After 35 years, the axion not only remains associated with the the most compelling solution to the strong CP problem, but it is recognized as one of the best motivated experimental portals to physics beyond the SM.

## 3 The axion as a dark matter candidate

As mentioned in the introduction, the particle DM requires new fields beyond the SM. A popular example is the "weakly interacting massive particle" (WIMP) typically appearing in supersymmetric extensions of the SM, and actively searched for in underground experiments. However, for the time being there is no hint of supersymmetry at the LHC and also no clear signature for WIMPs in direct-detection experiments whose sensitivity to the WIMP-nucleon cross-section has advanced by an amazing four orders of magnitude over the last decade.

It has been known since the early 80s that the PQ mechanism provides a very compelling scenario for relic axion production. As shown below, axions are just as attractive a solution to the DM problem as WIMPs. Like the latter, they appear in extensions of the SM that are independently motivated and also provide a valid DM candidate (i.e. they are not conceived *ad hoc* for that purpose). Moreover, the possibility of a mixed WIMP-axion DM is not only not excluded, but theoretically appealing [42, 43]. Conventionally, both axion and WIMP cold DM are thought to behave identically at cosmological and astrophysical scales, so there is no hint from cosmology to prefer one or the other (or both). However, although still speculative, some potentially discriminating signatures have been proposed. It has been recently suggested [44] that cold axions form a Bose-Einstein condensate, and this would produce a peculiar structure in DM galactic halos (caustic rings) for which some observational evidence seems to exist [45]. This fact would be applicable to any WISP cold DM population, but not to WIMPs.

Relic axions can be produced thermally by collisions of particles in the primordial plasma, just like WIMPs. However, being quite light particles, this axion population contributes –like neutrinos– to the hot DM component. This production mechanism is more important for larger $m_a$. Cosmological observations constraining the amount of hot DM, can be translated into an upper bound on the axion mass of $m_a \lesssim 0.9$ eV [46, 47].

Most interesting from the cosmological point of view is the non-thermal production of axions: the *vacuum-realignment* mechanism and the decay of topological defects (axion strings and domain-walls), both producing non-relativistic axions and therefore contributing to the cold DM [48, 49].

In the very early universe, when the temperature drops below $\sim f_a$, i.e. at the PQ phase transition, the axion field appears in the theory and sets its initial value differently in different causally-connected regions. Later, at the QCD phase transition, the axion potential rises and only then does the axion acquire its mass $m_a$. Then the axion field relaxes to its CP conserving minimum, around which it oscillates with decreasing amplitude (thus solving the strong CP problem dynamically). These oscillations represent a population of non-relativistic axions, with a density that depends on the unknown initial value of the field before the start of the oscillations (initial misalignment angle $\theta_0 \equiv a_0/f_a \in (-\pi, \pi)$). Moreover, because $a/f_a$ is an angle variable, discrete domains, differing in $2\pi$ naturally form after QCD transition and at their borders topological defects, i.e., strings and walls, form too. These defects soon decay radiating a large amount of non-relativistic axions which add up to the realignment population. While the realignment population density is relatively easily calculable (although dependent on the value of $\theta_0$), the population from the decay of topological defects suffers from significant uncertainties.

In general, two main cosmological scenarios can be considered, depending on whether inflation happens after (*pre-inflation* scenario) or before (*post-inflation* scenario) the PQ phase transition (or if the PQ symmetry is restored by reheating after inflation). In the pre-inflation case, the axion field is homogenized by inflation, the value of $\theta_0$ is thus unique in all the observable Universe, and the topological defects are diluted away. In that case the axion cold DM density is easily determined, as *only* the realignment mechanism contributes to it. Expressed as the ratio of axion DM to the observed value $\Omega_{\rm DM,obs}h^2 = 0.111(6)$ is [50, 51]

$$\frac{\Omega_a}{\Omega_{\rm DM,obs}} \sim \theta_0^2 F \left(\frac{f_a}{5\times 10^{11}\,{\rm GeV}}\right)^{1.184} \simeq \theta_0^2 F \left(\frac{12\,\mu{\rm eV}}{m_a}\right)^{1.184} . \tag{6}$$

where $F = F(\theta_0, f_a)$ is a correction factor accounting for anharmonicities, the delay of the oscillations when $\theta_0$ is large and any effects of non-standard cosmologies (the above expression is computed assuming radiation domination during the QCD phase transition).

Contrary to thermal production, this mechanism leads to larger relic axion density for lower $m_a$. For typical values of $\theta_0 \sim \mathcal{O}(1)$, $m_a$ should exceed $\sim$10 $\mu$eV to have a relic axion density not exceeding the known CDM density. Much smaller masses could still give the correct amount of DM if by some means $\theta_0$ is accidentally small, something that could be justified for instance by anthropic reasons [52]. Axion masses up to $m_a \sim$ meV can still give the adequate relic density for large $\theta_0$.

In the post-inflation scenario, the value of $\theta_0$ is randomly distributed in different causally-connected parts of the universe at the time of the PQ phase transition. One then has to average the above result for $\theta_0 \in (-\pi, \pi)$ and obtain a robust estimate of the DM contribution due to vacuum-realignment:

$$\frac{\Omega_{a,\rm VR}}{\Omega_{\rm DM,obs}} \sim \left(\frac{40\,\mu{\rm eV}}{m_a}\right)^{1.184} . \tag{7}$$

However, in this case the contribution of axion strings and domain-wall decays to axion DM must be taken into account, but its computation is rather uncertain and a matter of a longstanding debate. Some authors argue that the contribution is of the same order as $\Omega_{a,\rm VR}$ [53], while others [49, 54] find it considerably larger:

$$\frac{\Omega_{a,\text{string+wall}}}{\Omega_{\text{DM,obs}}} \sim \left(\frac{400\,\mu\text{eV}}{m_a}\right)^{1.184} \tag{8}$$

In any case, axions could easily account for the totality of cold DM needed by current cosmological models. A prediction of the axion mass leading to this situation is not possible with precision due to the above uncertainties, but it is clear that this can happen for a wide range of feasible axion models well beyond current limits. The "classic axion window" [49], $m_a \sim 10^{-5} - 10^{-3}$ eV, associated with the post-inflation scenario above, is often quoted as the preferred $m_a$ range for axion cold DM, although much lower masses are still possible in the fine-tuned models of the pre-inflation scenario, sometimes also called "anthropic axion window" [55, 56].

Recently, the BICEP2 experiment announced the detection of primordial gravitational waves in the CMB [57]. If true, this would point to a very high energy scale for inflation. If PQ transition had happened before that scale, the axion field would have imprinted isocurvature perturbations in the CMB which are not observed. The BICEP2 observation and interpretation have been questioned and independent experimental confirmation is needed. If confirmed, the pre-inflation scenario for the axion DM would be ruled out, and the mass of the axion would be constrained to values above $\sim 10^{-5}$ eV. QCD axions with masses above the classic window can still solve the DM problem if non-standard cosmological scenarios are invoked [58], or they can be a subdominant DM component. Mixed axion-WIMP DM is a possibility that may even be theoretically appealing [42, 43]. Moreover, axions are not the only WISPs allowing for a solution to the dark matter question. The nonthermal production mechanisms attributed to axions are indeed generic to bosonic WISPs such as axion-like particles or hidden photons (see next section). As recently shown [25], a wide range of $g_{a\gamma} - m_a$ space can generically contain models with adequate DM density.

To summarize, axions are as attractive a solution to the DM problem as WIMPs. In the current situation, with no hint from supersymmetry at the LHC and without a clear signature in WIMP direct-detection experiments, the hypothesis of axion DM stands out as increasingly interesting and deserves serious attention. The cosmological implications of the axion are well founded and represent a powerful motivation to push experimental searches well beyond current limits.

## 4 Other axion-like particles (ALPs)

Although the axion is the best motivated and most studied prototype, a whole category of particles called axion-like particles (ALPs) or, more generically, weakly interacting sub-eV particles, WISPs, are often invoked in several scenarios, both theoretically and observationally motivated, at the low energy frontier of particle physics [59]. Not necessarily related to the axion, ALPs share part of its phenomenology, and therefore would be searchable by similar experiments. ALPs are light (pseudo)scalar particles that weakly couple to two photons, but not to two gluons like the axion [60, 61]. As such, the ALPs parameters $g_{a\gamma}$ and $m_a$ are now to be viewed as completely independent, and the full parameter space of Fig. 1 is potentially populated by ALPs (not constrained to the yellow band as the axion models are).

ALPs can appear in extensions of the SM as pseudo Nambu-Goldstone bosons of new symmetries broken at high energy. Moreover, it is now known that string theory also predicts a rich spectrum of ALPs (including the axion itself) [62, 63, 64]. Remarkably, the region of the ALP parameter space at reach for future experiments is theoretically favoured as they correspond to string scales contributing to the natural explanation of several hierarchy problems in the SM. It is intriguing that the possible detection of ALPs could become key to the much sought experimental test of string theory.

Beyond ALPs, other important examples of WISPs are hidden photons and minicharged particles [65, 66, 67]. They appear in extensions of the SM including hidden sectors, i.e., sectors that interact with SM particles through the interchange of very heavy particles (e.g., a hidden sector is commonly employed for supersymmetry breaking). Hidden photons have kinetic mixing with normal photons, and therefore show a phenomenology similar to axion-photon oscillations (but this time without the external magnetic field), leading to the dissapearance and regeneration of photons as they propagate in vacuum [66]. Minicharged particles are particles with fractional electric charge, arising naturally in theories with hidden sectors.

As previously mentioned, under some circumstances, WISPs can also provide the right DM density. The nonthermal production mechanisms described in the previous sections are indeed generic to other bosonic WISPs such as ALPs or hidden photons. This WISPy DM has recently been studied [25], and in both cases a wide range of parameter space (in the case of ALPs $g_{a\gamma}$–$m_a$ space) can generically contain models with adequate DM density, part of it at reach of current or future experiments.

It is remarkable that light scalars are also invoked in attempts to find a particle physics interpretation of Dark Energy, the so-called “quintessence” fields. This possibility is very much constrained from the non observation of new long-range forces, unless more sophisticated mechanisms are implemented, mechanisms that lead sometimes to ALP phenomenology [68]. More recently, fields with an environment-dependent mass or couplings, chameleons [69] or galileons, are being studied in this same context. Despite the early stage of development of these concepts, the possibility that detection techniques originally conceived to search for axions or ALPs could evolve into the first particle physics experiments directly testing Dark Energy is truly exciting.

All these families of models compose together a growing field of theoretical research.

It is now acknowledged that, complementary to the conventional research performed at colliders of increasing energy (the high energy frontier), new physics can be hidden at very low energies too (the intensity frontier) for which different experimental tools, based rather on high precision and high source intensity, are required.

## 5 Astrophysical hints for axions and ALPs

The existence of axions or ALPs may have important consequences for some astrophysical phenomena. Since the early days of axions, well understood stellar physics has been used to constrain axion couplings [29] and derive limits, the most relevant of which have been presented previously. More intriguing are the cases where unexplained astrophysical observations may indicate the effects of an ALP. These situations must be treated with caution because usually an alternative explanation using standard physics or an uncontrolled systematic effect cannot be ruled out. At the same time, such models can further strengthen the physics case for exploring favored regions of parameter space, when other motivations already exist. Two such cases can be considered specially relevant: the excessive transparency of the intergalactic medium to very high energy (VHE) photons, and the anomalous cooling rate of white dwarfs.

VHE photons (i.e., with energies $\gtrsim$ 100 GeV) have a non-negligible probability to interact via $e^+e^-$ pair production with the background photons permeating the Universe – the extragalactic background light (EBL) – when long intergalactic distances are involved. That is, the Universe should be opaque to distant VHE emitters like active galactic nuclei (AGN). EBL density is measured by its imprint in blazar spectra by both HESS[70] and Fermi [71], and found in agreement with models. However, several independent observations seem to indicate that the degree of transparency of the Universe at VHE is too high, even for the lowest density EBL models developed [72, 73]. Current imaging atmospheric Cherenkov telescopes (both HESS [74] and MAGIC [75, 76]) have reported the observation of VHE photons with arrival directions clearly correlated with AGNs, some of them as distant as a $\sim$Gpc, with spectra that require either a too low density EBL, or anomalously hard spectra at origin. Alternatively, these photons could be secondaries produced in electromagnetic cascades [77], but this is in conflict with the sometimes fast time-variability of these sources [26]. Independent additional evidence might come from the observation of ultra high energy cosmic rays (UHECR) of energies $E > 10^{18}$ GeV correlated with very distant blazars [78, 79].

These observations could be easily explained by scenarios invoking photon-ALP oscillations triggered by intervening cosmic magnetic fields. These fields can be the intergalactic magnetic field, or the local magnetic fields at origin (at the AGN itself, or in the case of objects belonging to galactic clusters, the cluster magnetic field) and in the Milky Way.

Thus, the ALP component can travel unimpeded through the intergalactic medium, and as a result the effective mean free path of the photon increases. Several authors have invoked one of these scenarios [80, 81, 82, 83, 84, 85, 73, 26] to account for the unexplained observations. For some of these cases, approximate required ALP parameters $g_{a\gamma}$ and $m_a$ are drawn. Interestingly, most of them coincide roughly in requiring very small ALP mass $m_a \lesssim 10^{-(10-7)}$ eV (to maintain coherence over sufficiently large magnetic lengths) and a $g_{a\gamma}$ coupling in the ballpark of $g_{a\gamma} \sim 10^{-12}$–$10^{-10}$ GeV$^{-1}$. A more definite region -shown in Fig. 1- is extracted in [26] from a large sample of VHE gamma-ray spectra. Note that it extends to lower $m_a$ values than the ones shown on the plot. Although these parameters are far from the standard QCD axions, as more generic ALP models they lie just beyond the best current experimental limits on $g_{a\gamma}$ from CAST (see next section). As commented later on (and shown in Fig. 1) most of this region could be explored by IAXO.

The random character of astrophysical magnetic fields produces a particular scattering of the photon arrival probability that complicates the test of the ALP hypothesis [86]. In turn, this randomness can be used to constraints the ALP parameters, as it should imprint irregularities in high-energy source spectra [87]. This effect is used by the HESS collaboration with blazar observations to exclude couplings of the order of a few $10^{-11}$ GeV$^{-1}$ for masses of $10^{-8} - 10^{-7}$ eV (1), as shown in Fig. 1. The same method is used with X-ray data from the Hydra galaxy cluster [88] constraining $g_{a\gamma} < 8 \times 10^{-12}$ GeV$^{-1}$ for ALP masses $< 10^{-11}$ eV. Still in the X-ray band, some luminosity relations of active galactic nuclei were recently shown to have precisely this particular scatter [89] although this claim is still controversial [90]. Finally, photon-ALP mixing is polarization dependent, a fact that could explain long-distance correlations of quasar polarization [91] and offers further testing opportunities [92]. This possibility is nonetheless challenged by the absence of significant circular polarisation [93].

A different astrophysical scenario for which axion-related hypothesis have been invoked are the interior of white dwarf (WD) stars. The evolution of these objects follows just a gravothermal process of cooling, therefore their luminosity function (number of stars per luminosity interval) is predicted with accuracy by stellar models. The presence of extra cooling via axion emission speeds up the cooling thus suppressing the luminosity function at certain values of the WD luminosity. This is most relevant for non-hadronic axions with coupling to electrons $g_{ae}$, because axio-bremstrahlung would be very efficient in WDs. These arguments constrain $g_{ae} < 3 \times 10^{-13}$ [35] and they have been cross-checked and improved over the years [36, 37, 38, 94]. However, recent works are based on such a well populated luminosity function and well-studied WD cooling models that are able to claim that a small amount of axion energy loss is actually favored by data [36, 37]. This claim corresponds to $g_{ae} \sim 1 - 2 \times 10^{-13}$. Further evidence for extra cooling in WDs comes from independent observations. The period decrease of certain pulsating WDs provides a direct measurement of their cooling and thus can be used to assess the necessity of non-standard cooling mechanisms. Two pulsating WDs have been studied and shown a preference for axion cooling: the ZZ Ceti star G117-B15A [95] and R548 [96]. Both fit better the expectations for $g_{ae} \simeq 5^{+1.2}_{-1.6} \times 10^{-13}$ and $g_{ae} \simeq 5^{+1.7}_{-4.9} \times 10^{-13}$, respectively ($2\sigma$ intervals quoted). Given the scatter of the preferred values of $g_{ae}$, the tension with other limits and the possibility of unaccounted systematics or forgotten standard effects it is certainly premature to conclude the existence of axion energy loss in WDs. However, it is intriguing that all theses observables seem to improve with some extra cooling, which could be attributed to axions (or any pseudoscalar with coupling to electrons) with $g_{ae} \sim 1-5 \times 10^{-13}$.

These $g_{ae}$ values imply axion decay constants in the range $f_a \in (2{-}5) \times C_{ae} 10^9$ GeV, corresponding to an axion mass $m_a \in (1{-}4)$ meV$/C_{ae}$. For DSFZ axions $C_{ae} < 1/3$ and this value corresponds to axion masses $m_a > 3$ meV (see "WD cooling hint" in Fig. 1). As shown later, IAXO may reach sensitivity to these models through the direct observation of solar axions from $g_{ae}$-reactions. Finally, generic ALPs appearing in field and string theory extensions of the SM can just, as DFSZ axions, feature a coupling of electrons and photons. In this context, the WD favored region is sometimes expressed as a $g_{a\gamma}$ range [97] of typically $g_{a\gamma}^{\rm ALP} \sim (C_\gamma^{\rm ALP}/C_e^{\rm ALP}) 2 \times 10^{-13}$ GeV$^{-1}$, where the model dependence $C_\gamma^{\rm ALP}/C_e^{\rm ALP}$ can be significant.

Once more, although alternative explanations for these observations cannot be ruled out, it is intriguing that they together point to relatively well defined axion parameters, that are compatible with feasible QCD axion parameters, and that are not excluded by previous bounds. Moreover, axions at the meV scale are very close to the DM favoured window (see previous section), have interesting phenomenological implications [98] and constitute a region especially difficult to explore experimentally. As shown later, IAXO constitutes probably the only realistic experimental technique able to explore (part of) these models.

## 6 Searches for axions

In spite of their weak interactions, axions could be directly detected in a number of realistic experimental scenarios. Three main categories of experimental approaches can be distinguished depending on the source of axions employed: *haloscopes* look for the relic axions potentially composing our dark matter galactic halo, *helioscopes* look for axions potentially emitted at the core of the sun, and *light-shining-through-wall* (LSW) experiments look for axion-related phenomena generated entirely in the laboratory. All three strategies invoke the generic axion-photon interaction, and thus rely on the use of powerful magnetic fields to trigger the conversion of the axions into photons that can be subsequently detected.

Haloscopes [14] use high-Q microwave cavities inside a magnetic field to detect photons from the conversion of relic axions. Being non relativistic, these axions convert into monochromatic photons of energy equal to $m_a$. For a cavity resonant frequency matching $m_a$, the conversion is substantially enhanced. The cavity must therefore be tunable and the data taking is performed by scanning very thin $m_a$-slices of parameter space. The experimental implementation of this idea was pioneered in Brookhaven [99, 100], and later on continued by the CARRACK [101] and ADMX collaborations. As shown in Fig. 1, only ADMX [102, 103], have reached sensitivities in $g_{a\gamma}$ enough to probe QCD axion models for $m_a$ in the $2-3$ $\mu$eV range, under the assumption that axions are the main cold DM component. ADMX is carrying out an active program [104] to improve the background noise of the present experiment, as well as to extend the sensitivity to higher masses (the ADMX-HF setup). In the light of the considerations exposed above, it turns out that current haloscope efforts are focused in the low mass part of the region motivated by cosmology. To apply the haloscope technique to higher axion masses is problematic for a number of reasons. First of all, given that the cavity must resonate at the axion mass, higher masses imply the use of smaller cavities, and therefore lower expected signals. Moreover, smaller cavities usually have poorer quality factors, and the noise figure of the microwave sensors usually increase with frequency. New ideas are recently being put forward to overcome these problems and access the very motivated region of $m_a \sim 10^{-5} - 10^{-3}$ eV. Not exhaustively, they invoke the use of long thin cavities [105, 106] (waveguides or tubes), resonators with a specific dielectric or wire structure to make them resonate to higher frequencies, active resonators, among others[1]. A significant departure from the original haloscope idea is the dish antenna concept [107, 108], proposing to use a spherical dish in a magnetic field to convert the DM axions into photons and and focus them into a single spot. This concept trades off the resonant enhancement of cavities for the potentially large area of a dish antenna.

A different type of relic axion search strategy has been recently proposed (the so-called CASPEr experiment [109]), aiming at detecting the precession of nuclear spin in a material sample that, in the presence of an electric field, should appear by virtue of the time varying nuclear moment induced by the interaction with the background axion DM. Using precision magnetometry this effect should be detectable if the axion has very low masses $m_a \lesssim 10^{-9}$ eV (potentially improvable to $m_a \lesssim 10^{-6}$ eV).

Helioscopes [14] look for axions emitted by the Sun, and therefore do not rely on the assumption of axions being the DM. Axion emission by the solar core is a robust prediction involving well known solar physics and the Primakoff conversion of plasma

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[1] For a display of recent ideas see talks at the last Patras Workshop on Axions, WIMPs and WISPs. `http://axion-wimp2014.desy.de/`

photons into axions. Solar axions have ∼keV energies and in strong laboratory magnetic fields can convert back into detectable x-ray photons. Contrary to haloscopes, the signal in helioscopes is independent on the axion mass up to relatively large values (e.g. 0.02 eV for CAST). Using the technique of the buffer gas [110] the sensitivity can be further extended to masses up to ∼eV [19, 20, 21]. The technique of the axion helioscope was first experimentally applied in Brookhaven [111] and later on by the SUMICO helioscope at Tokyo University [112, 113]. Currently, the same basic concept is being used by the CERN Axion Solar Telescope (CAST experiment) [114, 115, 19, 20, 21] with some original additions that provide a considerable step forward in sensitivity. Its latest results, shown in Fig. 1, have surpassed the astrophysical limit $g_{a\gamma} \sim 10^{-10}$ GeV$^{-1}$ in a wide $m_a$ range. This means that for the highest mass values, close to the ∼1 eV, the sensitivity allows tests of some QCD axion models. Together with haloscopes, helioscopes are the only experimental technique with sensitivity to explore realistic QCD axion models. These two techniques are complementary, exploring the lower- (with haloscopes) and the higher-mass (with helioscopes) regions of the axion phase space not yet searched nor excluded. An advantage of helioscopes is that there is a clear scaling strategy to substantially push the present sensitivity frontline to lower values of $g_{a\gamma}$ and $m_a$, a strategy that is implemented in the IAXO proposal, in which I focus below.

It is worth mentioning that a similar helioscope-like scheme can be invoked in solid crystalline detectors, and used to detect solar axions. In this case, the local conversion into photons is triggered by the periodic electromagnetic field of the crystal [116, 117, 118], giving rise to very characteristic Bragg patterns that have been searched for as by-products of a number of underground WIMP experiments [119, 120, 121, 122, 123]. However, the prospects of this technique have proven limited [124, 125] and do not compete with dedicated helioscope experiments.

LSW [126] experiments use high intensity light sources (e.g., lasers) and strong magnetic fields to produce ALPs in the laboratory. These ALPs can reconvert back into detectable photons after an opaque wall. This technique therefore does not rely on any astrophysical or cosmological assumption for the ALPs. A number of experiments have already used this technique to search for ALPs, with a sensitivity, however, still a few orders of magnitude behind helioscopes (see the ALPS limit in Fig. 1 from [17]). The prospects for future scaled-up setups [127], in particular ALPS-II [128], could surpass current helioscope limits for low $m_a$ values and reach some unexplored ALP parameter space, although in any case, still without enough sensitivity to reach the QCD axion band.

All the searches mentioned up to now rely solely on the axion-photon phenomenology and therefore can be represented in the ALP parameter space of Fig. 1. Other small scale searches have been performed with a less generic scope, sometimes as by-products of other experiments. They are relevant for specific subsets of axion or WISP models. For example, axions have been searched for via more specific phenomenology (e.g. through the axioelectric effect [129, 130, 131, 132], or axion-emitting nuclear transitions [133, 134, 135, 136, 137, 138], among others). Specific non-axion WISPs have been (or are being) searched for in dedicated setups (e.g. hidden photons [139, 140]) or as by-products of axion and ALPs searches (e.g. chameleons [141]) or WIMP searches (e.g. [142]). For an updated review of all initiatives going on, I refer to the community documents prepared in recent roadmapping events, both in US [97, 143] and Europe [144, 145].

Below I will focus on the helioscope frontier. I will argue that the decade-long operation of CAST has not only led to one of the most competitive set of bounds on the axion and ALPs, but also to the establishment of a relevant community and the specific operational experience required to design a scaled-up version (forth generation) of the axion helioscope concept. IAXO is based on these ideas and aims to substantially push the helioscope envelope well into unexplored regions of the axion and ALP parameter space motivated by the arguments detailed in the previous section.

### *6.1 Solar axions and the axion helioscope frontier*

Axions can be produced in the solar interior by a number of reactions. The most relevant channel is the Primakoff conversion of plasma photons into axions in the Coulomb field of charged particles via the generic $a\gamma\gamma$ vertex. The Primakoff solar axion flux, shown on the left of Fig. 2 peaks at 4.2 keV and exponentially decreases for higher energies. This spectral shape is a robust prediction depending only on well known solar physics, while the only unknown axion parameter is $g_{a\gamma}$ and enters the flux as an overall multiplicative factor $\propto g_{a\gamma}^2$. For the particular case of non-hadronic axions having tree-level interactions with electrons, other productions channels (e.g., brehmstrahlung, compton or axion recombination) should be taken into account, as their contribution can be greater than that of the Primakoff mechanism. The calculation of these channels have been recently updated [146] and the corresponding solar spectrum is shown on the right of Fig. 2. However, the usual procedure in helioscopes considers only the Primakoff component because: 1) it maintains the broadest generality and covers a larger fraction of ALPs and 2) astrophysical limits on $g_{ae}$ are quite restrictive and largely disfavour the values that could be reached by helioscopes looking at the non-hadronic solar axion flux. With IAXO, it will be possible for the first time to supersede even astrophysical limits on $g_{ae}$, opening the possibility to probe an interesting set of models of non-hadronic axions.

By means again of the $a\gamma\gamma$ vertex, solar axions can be efficiently converted back into photons in the presence of an electromagnetic field. The energy of the reconverted photon is equal to the incoming axion, so a flux of detectable x-rays of few keV energies is expected. The probability that an axion going through the transverse magnetic field $B$

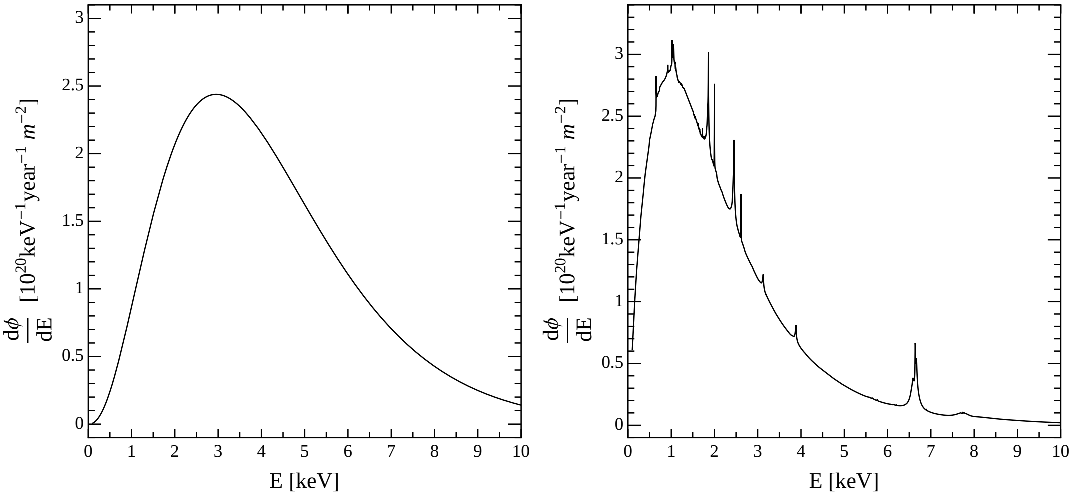

Figure 2.— Solar axion flux spectra at Earth by different production mechanisms. On the left, the most generic situation in which only the Primakoff conversion of plasma photons into axions is assumed. On the right the spectrum originating from processes involving electrons, bremsstrahlung, Compton and axio-recombination [146, 147]. The illustrative values of the coupling constants chosen are $g_{a\gamma} = 10^{-12}$ GeV$^{-1}$ and $g_{ae} = 10^{-13}$. Plots from [148].

over a length $L$ will convert to a photon is given by [14, 115, 18]:

$$P_{a\gamma} = 2.6 \times 10^{-17} \left(\frac{B}{10\ \mathrm{T}}\right)^2 \left(\frac{L}{10\ \mathrm{m}}\right)^2 \left(g_{a\gamma} \times 10^{10}\ \mathrm{GeV}\right)^2 \mathcal{F}$$

where the form factor $\mathcal{F}$ accounts for the coherence of the process:

$$\mathcal{F} = \frac{2(1-\cos qL)}{(qL)^2} \tag{9}$$

and $q$ is the momentum transfer. The fact that the axion is not massless, puts the axion and photon waves out of phase after a certain length. The coherence is preserved ($\mathcal{F} \simeq 1$) as long as $qL \ll 1$, which for solar axion energies and a magnet length of $\sim$10 m happens at axion masses up to $\sim 10^{-2}$ eV, while for higher masses $\mathcal{F}$ begins to decrease, and so does the sensitivity of the experiment. To mitigate the loss of coherence, a buffer gas can be introduced into the magnet beam pipes [110, 19] to impart an effective mass to the photons $m_\gamma = \omega_\mathrm{p}$ (where $\omega_\mathrm{p}$ is the plasma frequency of the gas, $\omega_\mathrm{p}^2 = 4\pi\alpha n_e/m_e$). For axion masses that match the photon mass, $q = 0$ and the coherence is restored. By changing the pressure of the gas inside the pipe in a controlled manner, the photon mass can be systematically increased and the sensitivity of the experiment can be extended to higher axion masses.

The basic layout of an axion helioscope thus requires a powerful magnet coupled to one or more x-ray detectors. When the magnet is aligned with the Sun, an excess of x-rays at the exit of the magnet is expected, over the background measured at non-alignment periods. This detection concept was first experimentally realized at Brookhaven National Laboratory (BNL) in 1992. A stationary dipole magnet with a field of $B = 2.2$ T and a length of $L = 1.8$ m was oriented towards the setting Sun [111]. The experiment derived an upper limit on $g_{a\gamma}$ (99% CL) $< 3.6 \times 10^{-9}$ GeV$^{-1}$ for $m_a < 0.03$ eV. At the University of Tokyo, a second-generation experiment was built: the SUMICO axion heliscope. Not only did this experiment implement a dynamic tracking of the Sun but it also used a more powerful magnet ($B = 4$ T, $L = 2.3$ m) than the BNL predecessor. The bore, located between the two coils of the magnet, was evacuated and higher-performance detectors were installed [149, 112, 113]. This new setup resulted in an improved upper limit in the mass range up to 0.03 eV of $g_{a\gamma}$(95% CL) $< 6.0 \times 10^{-10}$ GeV$^{-1}$. Later experimental improvements included the additional use of a buffer gas to enhance sensitivity to higher-mass axions.

A third-generation experiment, the CERN Axion Solar Telescope (CAST), began data collection in 2003. The experiment uses a Large Hadron Collider (LHC) dipole prototype magnet with a magnetic field of up to 9 T over a length of 9.3 m [114]. CAST is able to follow the Sun for several hours per day using a sophisticated elevation and azimuth drive. This CERN experiment is the first helioscope to employ x-ray focusing optics for one of its four detector lines [150], as well as low background techniques from detectors in underground laboratories [151]. During its observational program from 2003 to 2011, CAST operated first with the magnet bores in vacuum (2003–2004) to probe masses $m_a <$ 0.02 eV. No significant signal above background was observed. Thus, an upper limit on the axion-to-photon coupling of $g_{a\gamma}$ (95% CL) $< 8.8 \times 10^{-11}$ GeV$^{-1}$ was obtained [115, 18]. The experiment was then upgraded to be operated with $^4$He (2005–2006) and $^3$He gas (2008–2011) to obtain continuous, high sensitivity up to an axion mass of $m_a = 1.17$ eV. Data released up to now provide an average limit of $g_{a\gamma}$ (95% CL) $\lesssim 2.3 \times 10^{-10}$ GeV$^{-1}$, for the higher mass range of 0.02 eV $< m_a <$ 0.64 eV [19, 20] and of about $g_{a\gamma}$ (95% CL) $\lesssim 3.3 \times 10^{-10}$ GeV$^{-1}$ for 0.64 eV $< m_a <$ 1.17 eV [21], with the exact value depending on the pressure setting.

So far each subsequent generation of axion helioscopes has resulted in an improvement in sensitivity to the axion-photon coupling constant of about a factor 6 over its predecessors. CAST has been the first axion helioscope to surpass the stringent limits from astrophysics $g_{a\gamma} \lesssim 10^{-10}$ GeV$^{-1}$ over a large mass range and to probe previously unexplored ALP parameter space. As shown in Fig. 1, in the region of higher axion masses ($m_a \gtrsim 0.1$ eV), the experiment has entered the band of QCD axion models for the first time and excluded KSVZ axions of specific mass values. CAST is the largest collaboration in axion physics with $\sim$ 70 physicists from about 16 different institutions in Europe and the USA, and one of the first astroparticle experiments at CERN. CAST has demonstrated

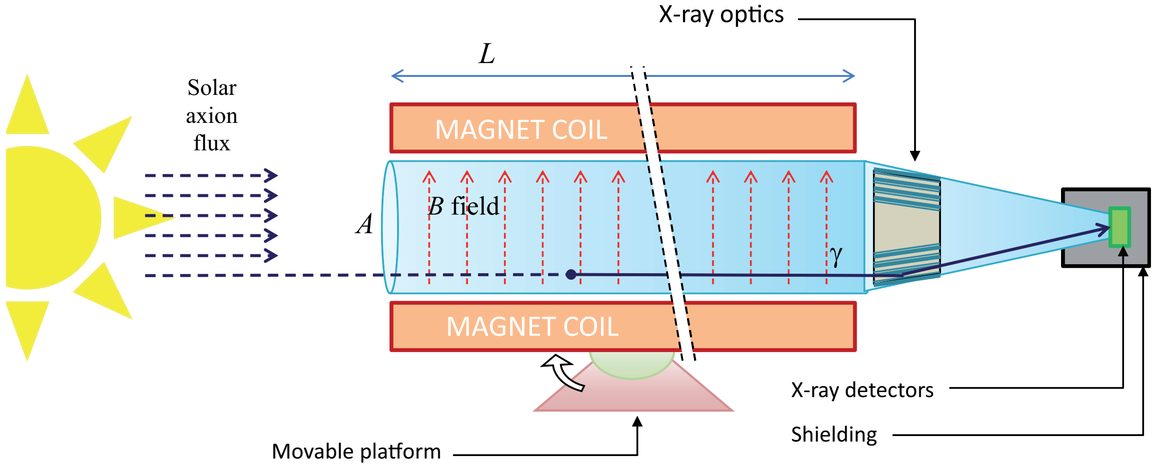

Figure 3.— Conceptual arrangement of an enhanced axion helioscope with x-ray focalization. Solar axions are converted into photons by the transverse magnetic field inside the bore of a powerful magnet. The resulting quasi-parallel beam of photons of cross sectional area $A$ is concentrated by an appropriate x-ray optics onto a small spot area $a$ in a low background detector. The envisaged design for IAXO, shown in Figure 4, includes eight such magnet bores, with their respective optics and detectors.

that the helioscope is the most technologically mature technique for axion detection and that is ready to be scaled-up in size. A further, substantial step beyond the current state-of-the-art represented by CAST is possible [152] with a new fourth-generation axion helioscope as the proposed International Axion Observatory (IAXO).

## 7 The International Axion Observatory (IAXO)

All axion helioscopes to date have made use of “recycled” magnets that were originally built for other experimental purposes. The CAST success has relied, to a large extent, on the availability of the first-class LHC test magnet. Going substantially beyond CAST sensitivity is possible only by going to a new magnet, designed and built maximizing the helioscope magnet's figure of merit $f_M = B^2\, L^2\, A$, where $B$, $L$ and $A$ are the magnet's field strength, length and cross sectional area, respectively. $f_M$ is defined proportional to the photon signal from converted axions. Improving CAST $f_M$ can only be achieved [152] by a completely different magnet configuration with a much larger magnet aperture $A$, which in the case of the CAST magnet is only $3 \times 10^{-3}$ m$^2$. However, for this figure of merit to directly translate into signal-to-noise ratio of the overall experiment, the entire cross sectional area of the magnet must be equipped with x-ray focusing optics. The layout of this *enhanced axion helioscope*, sketched in Figure 3, was proposed in [152] as the basis for IAXO.

Thus the central component of IAXO is a new superconducting magnet. Contrary

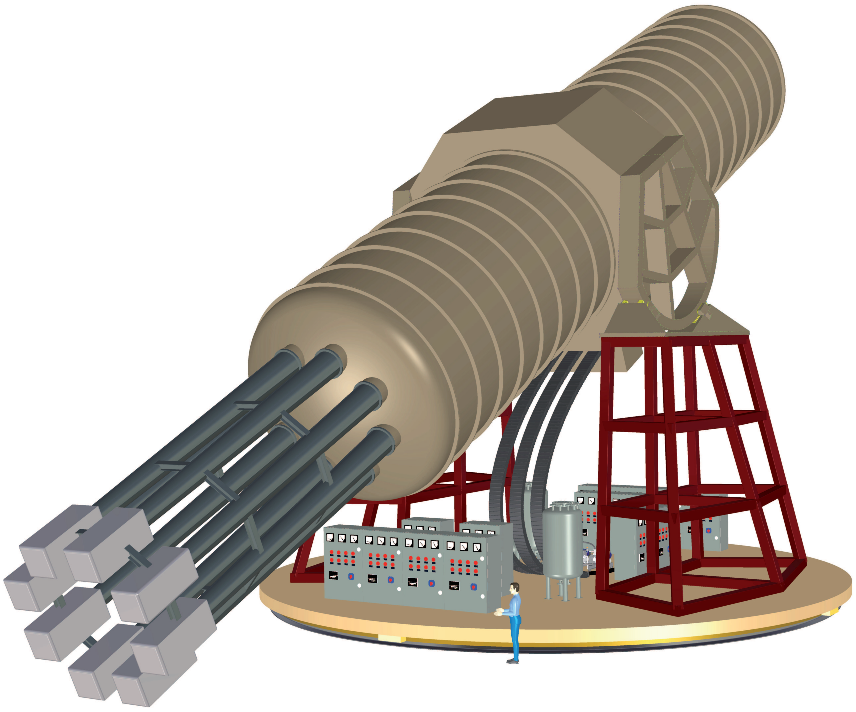

Figure 4.— Schematic view of IAXO. Shown are the cryostat, eight telescopes, the flexible lines guiding services into the magnet, cryogenics and powering services units, inclination system and the rotating platform for horizontal movement. The dimensions of the system can be appreciated by a comparison to the human figure positioned by the rotating table [156].

to previous helioscopes, IAXO's magnet will follow a toroidal configuration [153], to efficiently produce an intense magnetic field over a large volume. Dimensions are fixed by maximizing the figure of merit within realistic limits of the different technologies in play. This consideration leads to a 25 m long and 5.2 m diameter toroid assembled from 8 coils, and generating effectively 2.5 tesla in 8 bores of 600 mm diameter. This represents a 300 times better $f_M$ than CAST magnet. The toroid's stored energy is 500 MJ. The design is inspired by the ATLAS barrel and end-cap toroids[154, 155], the largest superconducting toroids built and presently in operation at CERN. The superconductor used is a NbTi/Cu based Rutherford cable co-extruded with Aluminum, a successful technology common to most modern detector magnets. Figure 1 shows the conceptual design of the overall infrastructure [156]. IAXO needs to track the Sun for the longest possible period. For the rotation around the two axes to happen, the 250 tons magnet is supported at the centre of mass by a system also used for very large telescopes. The necessary magnet services for vacuum, helium supply, current and controls are rotating along with the magnet.

Another area for improvement will be the x-ray optics. Although CAST has proven the concept, only one of the four CAST magnet bores is equipped with optics. Each of the eight IAXO magnet bores will be equipped with x-ray focusing optics that rely on x-ray reflection on surfaces at grazing angles. By working at shallow incident angles, it is possible to make mirrors with high reflectivity. Here the challenge is not so much achieving exquisite focusing or near-unity reflectivity, but the availability of cost-effective x-ray optics of the required size. For nearly 50 years, the x-ray astronomy and astrophysics community has been building telescopes following the design principle of Hans Wolter, employing two conic-shaped mirrors to provide true-imaging optics. This class of optics allows "nesting", that is, placing concentric co-focal x-ray mirrors inside one another to achieve high throughput. The IAXO collaboration envisions using optics similar to those used on NASA's NuSTAR [157], an x-ray astrophysics satellite with two focusing telescopes that operate in the 3 - 79 keV band. The NuSTAR's optics, shown in Figure 5, consists of thousands of thermally-formed glass substrates deposited with multilayer coatings to enhance the reflectivity above 10 keV (figure 2). For IAXO, the multilayer coatings will be designed to match the solar axion spectrum [158].

At the focal plane in each of the optics, IAXO will have small gaseous chambers read by pixelised planes of Micromegas. CAST has enjoyed the sustained development of its detectors towards lower backgrounds during its lifetime. The latest generation of Micromegas detectors in CAST are achieving backgrounds below $\sim 10^{-6}$ counts keV$^{-1}$ cm$^{-2}$ s$^{-1}$ [159, 160]. This value is already a factor of more than 100 better than the background levels obtained during the first data-taking periods of CAST. Prospects for reducing this level to $10^{-7}$ counts keV$^{-1}$ cm$^{-2}$ s$^{-1}$ or even lower appear feasible after the active R&D going on, in particular that being carried out at the University of Zaragoza, under the T-REX ERC-funded project [161, 162, 163, 164]. As part of this work, a replica of the CAST Micromegas detectors is taking data in an underground test bench at the Laboratorio Subterráneo de Canfranc, already reaching a background level of $\sim 10^{-7}$ counts keV$^{-1}$ cm$^{-2}$ s$^{-1}$ [159]. These background levels are achieved by the use of radiopure detector components, appropriate shielding, and offline discrimination-algorithms on the 3D event topology in the gas registered by the pixelised readout.

The components described so far compose the baseline configuration of IAXO as an enhanced axion helioscope. Beyond this baseline, additional enhancements are being considered to explore extensions of the physics case for IAXO. For some of the additional physics cases of IAXO, lowering the theshold well below 1 keV is interesting. For this reason other types of x-ray detection technologies are also under consideration, like GridPix detectors, Transition Edge Sensors (TES) or low noise CCDs to be placed at the optics focal points. Beyond that, because a high magnetic field in a large volume is an essential component in any axion experiment, IAXO could evolve to a generic "axion facility" and host different detection techniques. The most relevant of these possibilities, at the moment actively explored, is to use microwave cavities and antennas to search for dark-matter axions. Some of the developments being carried out in the community (briefly mentioned above in section 6) could profit from the availability of the large magnetic field of IAXO, and reach sensitivity to axions in mass ranges complementary to those in previous searches.

The IAXO collaboration has recently finished the conceptual design of the experiment [156], and last year a Letter of Intent [148] was submitted to the SPS and PS experiments Committee (SPSC) of CERN. The committee acknowledged the physics goals of IAXO and recommended proceeding with the next stage, the creation of the technical design report (TDR), a necessary step before facing construction. As part of the TDR, prototyping activities are foreseen, including magnet (the construction and test of a single shorter superconducting coil), optics and detector aspects. At the same moment of preparation of this review, a “IAXO optics+detector pathfinder system” has just been assembled in CAST at CERN. It consist of a small x-ray optics (of CAST bore dimensions) coupled to a low-background Micromegas detector. This is the first time that the two techniques pioneered by CAST –x-ray focusing and low background detectors–, previously used in different lines of the experiment, are now coupled together in the same line. It is also the first time that an x-ray optics is manufactured specifically for axion physics. This system will tests the two technologies proposed for IAXO coupled together. The first data is already being taken: the experience with this system will be precious for the preparation of IAXO.

## 8 Physics potential of IAXO

The sensitivity regions in the $(g_{a\gamma}, m_a)-$plane have been computed from the standard channel of Primakoff solar axions [148]. Figure 1 shows the attainable region in the wider context of axion searches and motivated regions. Figure 6 focuses on the high mass region.

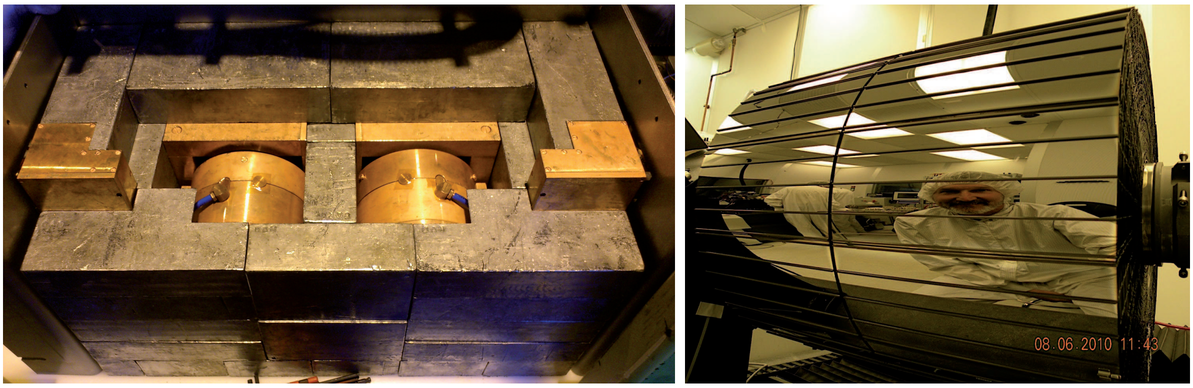

Figure 5.— Left: two lead- and copper-shielded, ultra-low background Micromegas x-ray detectors currently in use at CAST. Right: the NuSTAR x-ray telescope, with optics very similar to that proposed for IAXO.

The sensitivity is calculated assuming realistic experimental parameters (see [148] for details), and two 3-year data taking periods, the first with vacuum in the magnet bores and the second one with variable-pressure gas. The first period determines the sensitivity of IAXO for axion masses below $m_a \lesssim 0.01$ eV, while the second one above that value. The range of densities used (number of gas density steps) will determine how far in $m_a$ to go. The current sensitivity curves are calculated assuming that the gas density is continuously changed from 0 to 1 bar of $^4$He at room temperature. This program would allow IAXO to reach an axion mass of 0.25 eV. The shape of the sensitivity region in the range $m_a \sim 0.01-0.25$ eV depends on the actual distribution of the exposure time in density, which is for now assumed flat, i.e. equal time is spent at each gas density. This distribution may be redefined in the future according to the evolution of bounds on the axion mass or other eventual results/interest favouring a particular $m_a$ value or range.

As seen, IAXO will be a factor of $\sim 15-20$ more sensitive than CAST in terms of the axion-photon coupling constant $g_{a\gamma}$, which translates in about **5 orders of magnitude more sensitive** in terms of signal intensity. That is, IAXO could be sensitive to $g_{a\gamma}$ values as low as, or even surpassing,

$$g_{a\gamma} \sim 5 \times 10^{-12}\ \text{GeV}^{-1} \tag{10}$$

for a wide range of axion masses up to about 0.01 eV and around $g_{a\gamma} \sim 10^{-11}$ GeV$^{-1}$ up to about 0.25 eV.

While CAST was the first experimental search reaching, and slightly surpassing, the limit $g_{a\gamma} \lesssim 10^{-10}$ GeV $^{-1}$ in this mass range, and therefore started probing ALP parameter space allowed by astrophysics, IAXO will deeply enter into completely unexplored ALP and axion parameter space, as indicated by Fig. 1. At a minimum, IAXO will exclude a large region of the QCD axion phase space that has yet to be explored. If IAXO does discover a new pseudoscalar fundamental, it would be a groundbreaking result for particle physics.

Fig. 6 focuses on the sensitivity for the high mass region $m_a > 1$ meV. At these masses this experiment would explore a broad range of realistic axion models that accompany the Peccei-Quinn solution of the strong CP problem. Its sensitivity would cover axion models with masses down to the few meV range, superseding the SN 1987A energy loss limits on the axion mass. Axion models in this region are of high cosmological interest. As explained in previous sections, they are favoured dark matter candidates and could compose all or part of the cold dark matter of the Universe. In non-standard cosmological scenarios, or in more generic ALP frameworks [25], the range of ALP parameters of interest as DM is enlarged and most of the region at reach by IAXO contains possible dark matter candidates. At the higher part of the range (0.1 - 1 eV) axions are good candidates

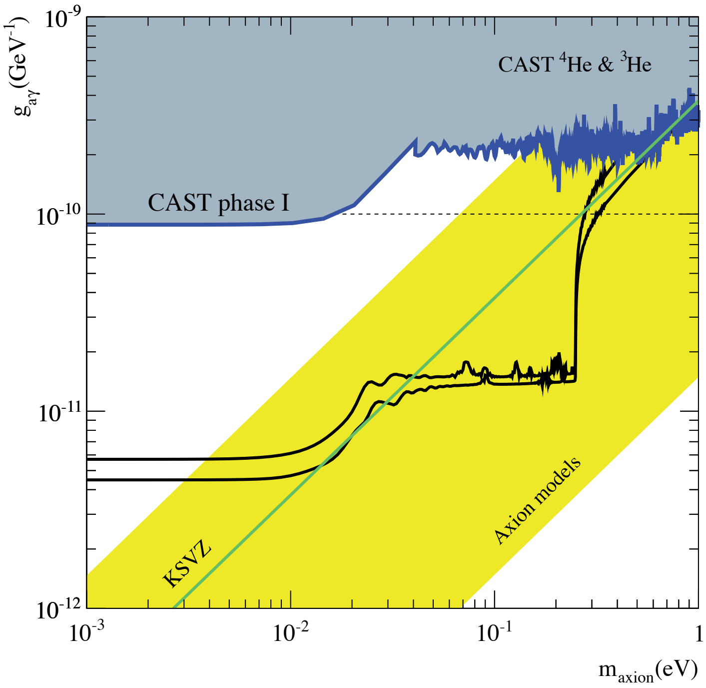

Figure 6.— Close-up of the high mass part of parameter space of Fig. 1 (1 meV $< m_a <$ 1 eV). The two lines correspond to two different set of assumptions (more or less conservative) to compute IAXO sensitivity. Plot from [148].

to the hot DM or additional *dark radiation* that is recently invoked to solve tension in cosmological parameters. At much lower masses, below $\sim 10^{-7}$ eV, the region attainable by IAXO includes ALP parameters invoked repeatedly to explain the anomalies in light propagation over astronomical distances commented in section 5. IAXO could provide a definitive test of this hypothesis.

### *8.1 Additional IAXO physics cases*

In addition to the standard helioscope result exposed above, a number of additional physics cases are being studied to extend the reach of IAXO. Particularly interesting in the sensitivity of IAXO to axions with an axion-electron coupling $g_{ae}$ as have been invoked to solve the anomalous cooling observed in white dwarfs (see above section 5). Figure 7 summarizes the expected sensitivity to axions produced by BCA reactions (see right of Figure 7) in the Sun, with couplings $g_{ae} \sim \mathcal{O}(10^{-13})$ (see [148] for details). In summary, IAXO could directly measure the solar flux of axions produced by the BCA processes, for the first time with sensitivity to values of $g_{ae}$ not previously excluded and relevant to test the hypothesis that the cooling of WD is enhanced by axion emission (via BCA procesees, the same mechanisms that IAXO would be testing in the Sun), and for values of $m_a$ for which QCD axion models can give the needed $g_{ae}$ values.

IAXO can be sensitive to models of other proposed particles at the low energy frontier of particle physics. Some examples are hidden photons or chameleons. They could also be produced in the Sun, and give specific signatures in axion helioscope data. Hidden photons emitted from the Sun have been studied in the context of specific searches [139] or as by-products of axion helioscopes like SUMICO [140] or CAST [165]. Chameleons are scalars with an environment-dependent mass that are proposed in the context of dark energy models. Recent calculations [166, 28] show that resonant production in the magnetic regions of the solar atmosphere might allow for the propagation of these chameleons into a solar helioscope where they can be regenerated into soft x-rays through the inverse Primakoff-effect. For these searches, sensitivity to energies lower than the baseline Primakoff axion spectrum (sub-keV and lower) is needed, something that IAXO could obtain by one or more of the additional equipment described in section [148].

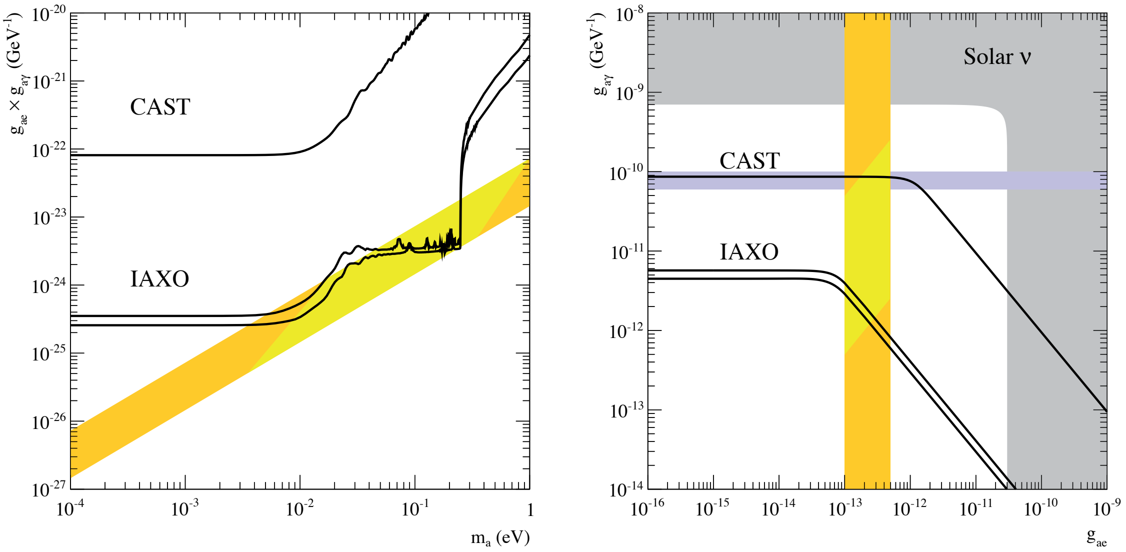

Figure 7.— Left: IAXO sensitivity line for $g_{ae}g_{a\gamma}$ as a function of $m_a$, assuming the solar emission is dominated by the BCA reactions which involve only the electron coupling $g_{ae}$. The orange band corresponds to values of $g_{ae} \sim 1 - 5 \times 10^{-13}$ and $g_{a\gamma}$ related to $m_a$ by the DSFZ model with $C_\gamma = 0.75$. The part of the band highlighted in yellow corresponds to those models for which the relation of $g_{ae}$ with $m_a$ is also considered (taking a reasonable range $\cos^2\beta$ =0.01−1). The recent limit of CAST on $g_{ae}$ is also shown. Right: IAXO sensitivity on $g_{ae}$ and $g_{a\gamma}$ for $m_a \lesssim 10$ meV. The gray region is excluded by solar neutrino measurements. The orange band corresponds to values of $g_{ae} \sim 1 - 5 \times 10^{-13}$. The part of the band highlighted in yellow corresponds to models that satisfy the model-dependent relation between $g_{a\gamma}$ and $g_{ae}$ (taking again $C_\gamma = 0.75$ and $\cos^2\beta$ =0.01−1). The recent limit of CAST on $g_{ae}$ is also shown. In the orange bands, axion emission affects white dwarf cooling and the evolution of low-mass red giants; couplings stronger than in these bands are firmly excluded. Likewise, helium-burning stars would be perceptibly affected in the blue band of the right plot and parameters above it are excluded. Plots from [148]

More intriguing would be the possibility to detect relativistic axions or ALPs from other sources in the sky, using IAXO as a true axion telescope. Although most potential astrophysical axion sources will probably be too faint to be detected by IAXO, some relic populations of ALPs could provide detectable signals. If the dark radiation that is recently invoked to relieve the tension in cosmological parameters [1] is composed by relativistic axions or ALPs (from, e.g., primordial decays of heavy fields [167]) they would still linger today as a Cosmic Axion Background with energies of $\sim \mathcal{O}(100)$ eV. With appropriate low energy detectors, the predicted fluxes could be within reach of IAXO for some ALP parameters.

Another experimental configuration of IAXO could be to equip two of the bores with microwave cavities, one of them with a strong emitter, and the second one with a low-noise receiver. This would be an analogous LSW experiment with microwaves, conceptually similar to the one performed in [168]. Given the size of the IAXO magnet bores, the operating frequency of such a configuration would be around 200 Mhz. The potential of this configuration is currently under study.

Yet the most promising option for a IAXO extension seems to be the search for the non-relativistic axions potentially composing the galactic dark matter halo. This could be accomplished by using microwave cavities (and turning IAXO into a haloscope kind of detector), or dish antennas [107, 108] inside the large IAXO magnetic volume. The size and strength of the IAXO magnet make this possibility very appealing and deserves serious consideration. Although many technical questions need to be addressed before considering this as a realistic possibilities, preliminary studies [169] point to very promising prospects. IAXO could easily convert its magnet bores into resonant cavities, and easily gain competitive sensitivity to $m_a$ around and below 1 $\mu$eV. A more challenging –but more interesting– option is to fill part of IAXO magnetic volume with a set of power-combined parallelepipedic long thin cavities, that could provide sensitivity right in the mass range around $\sim 10^{-4}$ eV, most favoured by cosmology. Finally, a setup based on the dish antenna might provide access to a wider and higher mass range. In general, there seems to be potential to extend the sensitivity of IAXO well beyond the level of the baseline configuration of Figure 1 in mass ranges complementary to previous searches.

## 9 Conclusions

After more than three decades, the axion hypothesis remains the most compelling solution to the strong CP problem, one of the most serious blemish of the Standard Model of particle physics. In addition, the issue of the nature of the dark matter of the Universe, one of the biggest mystery that modern fundamental science is facing, could also be solved by the axion. The fact that Supersymmetry does not appear at the LHC, nor do WIMPs in underground experiments, is increasing the interest in axions. In addition, recent work in theory and phenomenology is sharpening their physics case. Some intriguing astrophysical observations could already be hinting at the axion (or an axion-like particle). The experimental efforts to search for axions, still a relatively minor field, are steadily increasing. Dark matter axions at the few $\mu$eV could be detected by current haloscopes like ADMX. Pushing haloscope sensitivity to higher masses is technically very challenging and it is the object of a number of recent new ingenuous ideas. At the helioscope frontier, the situation is technically more mature, and the CAST experiment has been running for the last decade with sensitivity to axions at the sub-eV scale. CAST is the largest axion experiment, and has been the seed for the newly proposed International Axion Obvservatory (IAXO), aiming at a 5 orders of magnitude of improvement in signal-to-noise ratio over CAST. IAXO will use CERN's expertise efficiently to venture deep into unexplored axion parameter space. If the axion exists, there is a reasonable chance for it to be seen by IAXO. We may be living through the emergence of a new field in the interface of particle physics and cosmology, with potential groundbreaking consequences for both of them.

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