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# An update on the Axion Helioscopes front: current activities at CAST and the IAXO project.

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## Abstract

Although they have not yet been detected, axions and axion-like particles (ALPs) continue to maintain the interest (even increasingly so) of the rare-event searches community as viable candidates for the Dark Matter of the Universe but also as a solution for several other puzzles of astrophysics. Their property of coupling to photons has inspired different experimental methods for their detection, one of which is the helioscope technique. The CERN Axion Solar Telescope (CAST) is the most sensitive helioscope built up to date and has recently published part of the latest data taken with the magnet bores gradually filled with $^3$He, probing the mass range up to 1.17 eV. The International AXion Observatory (IAXO) is being proposed as a facility where different axion studies can be performed, with the primary goal to study axions coming from the Sun. Designed to maximize sensitivity, it will improve the levels reached by CAST by almost 5 orders of magnitude in signal detection, that is more than one order of magnitude in terms of $g_{a\gamma}$. Here we will summarize the most important aspects of the helioscopes, and focus mainly on IAXO, based on the recent papers [1, 2].

*Keywords:* axions, dark matter, x-ray detectors, micromegas detectors, x-ray focusing devices, magnet development, CAST, IAXO

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## 1. Introduction

The discovery that the Universe has a very intense Dark Side has supposed a revolution: 68% of the matter-energy budget is in the form of Dark Energy, 27% is in the form of Dark Matter (DM) and only 5% is ordinary matter [3]. There is still a lot of speculation on the nature of Dark Energy, however more is known about the Dark Matter particle. The most sought-after option are the Weakly Interacting Massive Particles (WIMP), while the other favourable candidate are the axions.

Axions arise as a consequence of a spontaneous breaking of a global symmetry proposed to solve the strong-CP problem [4, 5, 6] and since then have been evoked in several occasions as solutions for other problems, one of which is the DM, as they can have been copiously produced in the early Universe. They would have a very small mass, interact only weakly with ordinary matter, and have been restricted due to accelerator experiments as well as astrophysical observations.

## 2. Axion helioscopes

### 2.1. Axion detection

The generic property of axions mostly exploited in the experimental efforts to detect them, is their coupling to photons, with a coupling constant $g_{a\gamma}$. This property allows the photon-to-axion conversion in the presence of an electromagnetic field, also known as the Primakoff effect and is present in practically all the models. Although the standard or QCD axions lie on a narrow band in the $m_a$, $g_{a\gamma}$ parameter space, other Axion-Like Particles (ALPs) with a similar production mechanism may exist; these could populate any part of the phase-space. While trying to reach sensitivities that would allow to enter the QCD axion band, all of the experiments would be sensitive to a good part of the ALPs parameter space.

The experiments of the light-shining-through-a-wall type, are trying to detect axions and axion-like particles created in the same laboratory frame. Haloscopes are using microwave cavities to look for QCD axions that would constitute the DM of the halo of our galaxy; helioscopes are employing magnetic fields to convert the axions streaming out of the Sun to detectable x-ray photons.

The Primakoff effect will be in action in the core of stars, where there is a high density of photons and intense electromagnetic fields, which would make the Sun a factory of axion production. The helioscope technique [7] is based on the inverse Primakoff effect, which would allow solar axions streaming from the Sun to be reconverted into photons in the presence of a transverse electromagnetic field in a laboratory.

The pioneering helioscope was the Rochester-Brookhaven-Florida experiment [8, 9] and afterwards SUMICO [10, 11, 12] improved the results. CAST has been the third helioscope built and so far the most sensitive one. The IAXO project plans to improve the sensitivity of CAST in the future. The principle of an enhanced helioscope is explained in Fig. 1(left).

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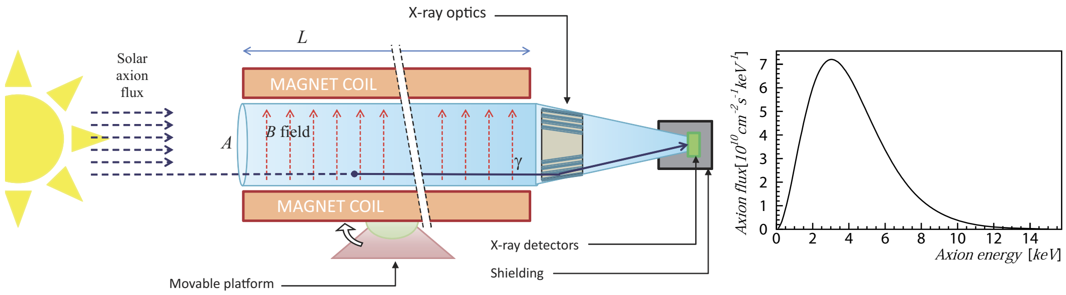

Figure 1: Left: Schematic of an enhanced axion helioscope: solar axions travelling through an intense transverse magnetic field with an axion-sensitive area A, are converted into x-rays. With the help of x-ray focusing devices, these are concentrated onto a spot on low background detectors (figure from [2]). Right: The solar axion flux as expected at the Earth. A value of $1 \times 10^{-10}$ GeV$^{-1}$ for $g_{a\gamma}$ is assumed.

As Fig. 1(right) shows, the expected signal is in the energy range of 1–10 keV. The operation of a helioscope consists in following the Sun as long as technically possible, in axion sensitive conditions, and taking background data when there is no alignment with the Sun. The sought-after signal would be the excess of photons in the expected energy range that the x-ray detectors will register when tracking the Sun, compared to the background gathered during the rest of the time. The number of excess photons expected depends on the very weak $g_{a\gamma}$ coupling constant, which is a measure of a helioscope's sensitivity. According to the following expression [13]

$$g_{a\gamma}^4 \sim B^2 L^2 A\, \epsilon_d b^{-1/2}\, \epsilon_o a^{-1/2}\, \epsilon_t^{1/2} t^{1/2}, \tag{1}$$

four are the main parameters to take into account when designing a helioscope: a) time: the total time of data-taking of the experiment $t$ and $\epsilon_t$, the fraction of time the magnet tracks the Sun; b) magnet: the length $L$ and the strength $B$ of the provided magnetic field as well as the axion-sensitive area $A$; c) low-background x-ray detectors: the background level $b$ and their detection efficiencies $\epsilon_d$ and d) x-ray focusing optics: their efficiency $\epsilon_o$ and total focusing area $a$. The focusing devices are an addition to the classical helioscope experiment, and were implemented for the first time in the third generation axion helioscope, the CAST experiment.

## 3. The CERN Axion Solar Telescope (CAST)

The CERN Axion Solar Telescope (CAST) presented an important improvement in the sensitivity of the helioscope technique, based on two major innovations; focusing optics and low background techniques for the detectors. CAST is the first helioscope to use an x-ray telescope, comprising of an x-ray focusing device coupled to a Charged Coupled Device (CCD) camera, recycled from the ABRIXAS and XMM-Newton space missions. The addition of the telescope improved the signal-to-noise ratio of the system and therefore the sensitivity of the experiment. On the magnet front, CAST recycled a decommissioned LHC prototype magnet, which reaches 9 T over a length of 10 m. The magnet has two bores and has been equipped with up to four detectors; the x-ray telescope mentioned above, and three Micromegas detectors was the latest configuration. The total axion-sensitive area achieved in this way is $\sim$ 30 cm$^2$. The whole system is sitting on a movable platform controlled by a tracking system, pointing it to the centre of the Sun during 1.5 h twice a day, at sunrise and at sunset.

Since 2003, when CAST started operating, data have been taken in different experimental conditions which gradually extended the axion mass sensitivity of the experiment: from keeping the magnet bores under vacuum ($m_{\rm a} \lesssim 0.02$ eV) [14, 15] to gradually filling them with $^4$He ($m_{\rm a} \lesssim 0.39$ eV) [16] and later on with $^3$He. The first part of the $^3$He data covered the mass range up to $m_{\rm a}$ $\sim$0.64 eV [17] and in 2011 masses up to $m_{\rm a}$ $\sim$1.17 eV were reached. A part of these data has been analyzed and has shown no excess of signal over background, leading to an upper bound of the axion-to-photon constant of $g_{a\gamma} < 3.3 \times 10^{-10}$ GeV$^{-1}$ for the mass range between 0.64 eV and 1.17 eV [18]. CAST has provided the most stringent limits on the axion-to-photon coupling constant over a large part of the axion masses and has covered -for the first time- part of the QCD-favoured band for masses above $\sim$0.15 eV, as can be seen in Fig. 2.

Currently, CAST is revisiting the vacuum phase; this time with the aim, on one hand to look at the low energy part for evidence of other hypothetical particles such as chameleons, which appear in Dark Energy models or hidden photons [19], and on the other to exploit the

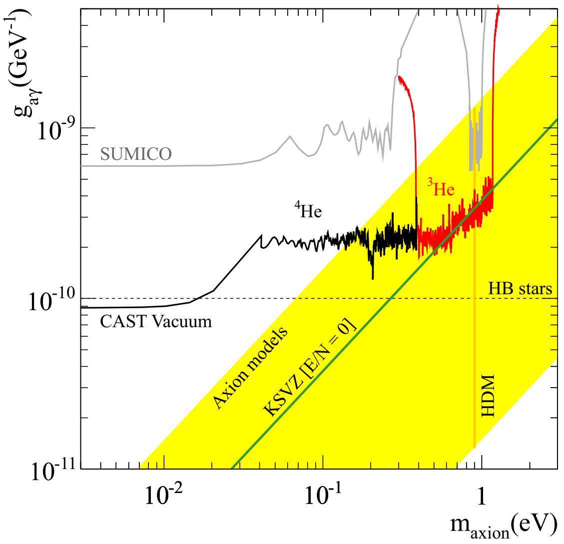

Figure 2: Expanded view of the CAST results in the vacuum,$^4$He (in black) and the $^3$He phases with the new limit (in red). The limit from SUMICO, the hot dark matter (HDM) bound and the horizontal branch (HB) stars are also shown. The yellow band denotes typical theoretical models, while the green solid line corresponds to $E/N = 0$ (KSVZ model).

unprecedented background levels reached by the Micromegas detectors of the experiment. A lot of effort has been invested on the design of an efficient layout of the detector, an appropriate shielding, as well as carefully choosing the low-radioactivity materials in the vicinity of the detectors. New Micromegas detectors of the microbulk type were installed in the experiment in 2013, reaching levels down to $1 \times 10^{-6}$ keV$^{-1}$ cm$^2$ s$^{-1}$ [20]. In the summer of 2014, a new x-ray focusing device was installed in front of one of the new Micromegas detectors and started taking data. This system is considered a pathfinder for the International AXion Observatory (IAXO).

## 4. IAXO: the International AXion Observatory

The IAXO project brings forward the idea of an enhanced axion helioscope, the ultimate generation experiment that the helioscope technique can offer [13, 1]. A schematic of the system is given in Fig. 3(left).

A magnet conceived for axion physics is one of the first issues that the project addresses; the main disadvantage that the use of accelerator magnets (like the one of CAST) presents for a helioscope is the small axion-sensitive area they provide. An axion-dedicated magnet will have to allow for bigger sensitive areas. The studies for what the state-of-the-art technology can offer for a magnet design has pointed to an ATLAS-like toroidal magnet which will measure approximately 25 m in length. It optimizes the features of the magnet in order to maximize sensitivity and comprises eight coils which provide bores with a diameter of close to 60 cm. The improvement in sensitivity considering this and the length, is enough to overcome the lower magnetic field which this magnet will offer, of the order of 2.5 T.

The observation time will also be improved by almost a factor 10 with respect to CAST, as the design foresees that the magnet follow the Sun 12 h daily. The rest of the time would be devoted to the very important background measurement and determination.

The eight bores of the magnet are going to be equipped with as many x-ray focusing optics. As mentioned already, the use of focusing devices is a feature that can significantly enhance the performance of the helioscope; they permit employing small-area x-ray detectors with an affordable shielding while keeping the sensitivity of the helioscope that the large-area openings of the magnet grant. For this important part IAXO will take advantage of existing technology as well, in order to procure such large-size focusing devices; the NuSTAR satellite mission [21] developed x-ray optics with sufficiently large throughput and small focal spot onto which to concentrate the 2800 cm$^2$ area of each bore.

The detectors to equip the magnet, identified for the baseline of the project, are microbulk Micromegas. The order $10^{-6}$ keV$^{-1}$ cm$^2$ s$^{-1}$ background levels achieved with these detectors in CAST is encouraging [20]. This result, in combination with the results of studies performed at the Canfranc Underground Laboratory using dedicated test benches, provides a strong indication that the IAXO requirement of $10^{-7}$ keV$^{-1}$ cm$^2$ s$^{-1}$ (or better) background levels can be met. Adequate shielding that will help reach these goals will be surrounding each of the IAXO detectors.

An important milestone for IAXO has been achieved with the installation of the pathfinder at CAST; a prototype of the optics developed for IAXO, coupled to a Micromegas detector surrounded by a complete shielding. The operation and data taking with this line will provide useful information and valuable experience for the future project.

The sensitivity of IAXO with these characteristics, is expected to be more than one order of magnitude better than CAST (almost 5 orders of magnitude more sensitive in detectable signal) which translates to a sensitivity of $g_{a\gamma}$ down to few times $10^{-12}$ GeV$^{-1}$ for masses up to approx. 0.02 eV, in the vacuum phase. The addition of a system that will allow the extension of the sensitivity to

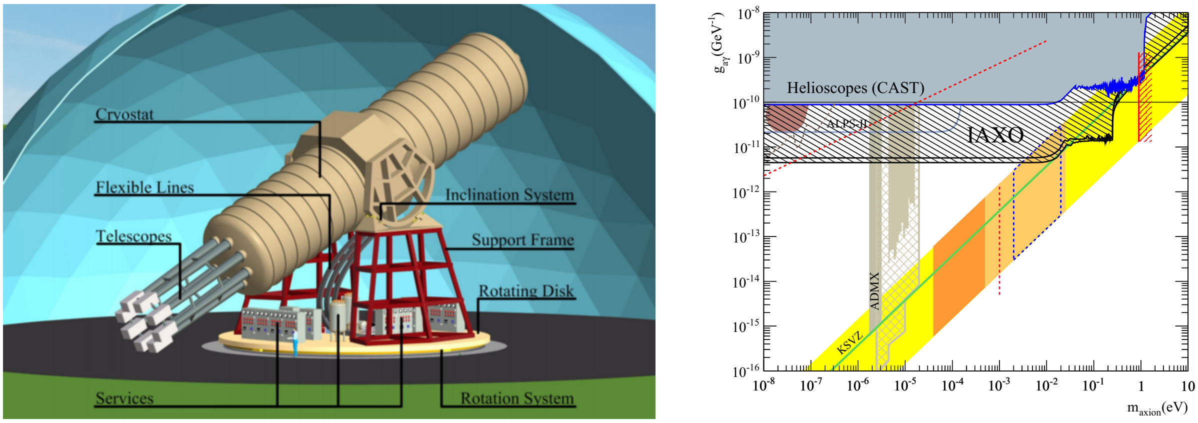

Figure 3: Left: A drawing of IAXO on its rotating platform: the cryostat containing the dipole magnet can be seen, with eight telescopes attached to it, and the shielded detectors. The human figure positioned at the feet of the structure gives an idea of the dimensions of the system. Right: The expected sensitivity of IAXO in an extended version of the $g_{a\gamma}$-$m_a$ plot. Current bounds (solid colour) and future prospects (dashed area) of other experiments (CAST, ADMX [22], ALPS-II [23]) can also be seen. The area below the red dashed line is viable ALP DM parameter space. The region at low $m_a$ above the dashed grey line is the one invoked in the context of the transparency of the universe. The region excluded by H.E.S.S. data [24] is shown in solid brown. For the sake of clarity the labels of the other bounds have been removed. For those,we refer to [2].

higher masses through the injection of a light gas could take place in a later phase. Fig. 3(right) shows how IAXO would be able to probe large parts of the phase-space in which reside not only the ‘standard’ axion but also ALPs from many interesting models and theories, such as those in which the axion is postulated as part of the DM of the Universe. At the lower axion-mass end, below $10^{-7}$ eV, IAXO would test the hypothesis of ALPs which have been proposed as an explanation to anomalies in light propagation over astronomical distances [25].

Axion helioscopes can also study the axion-to-electron coupling ($g_{ae}$), allowed in non-hadronic models, in combination with the axion-to-photon coupling, as CAST has already done [26]. Axions with $g_{ae}$ of few $\times 10^{-13}$ are proposed as an explanation of the anomalous cooling in white dwarfs from astrophysical observations [27], making these studies attractive; in fact IAXO would have enough sensitivity to directly measure the solar axions produced via this mechanism.

As a generic search facility, IAXO could also serve for studies of hidden photons, chameleons or similar. The direct search of relic axions that would have been produced in the early stages of the Universe is also being studied [28], as the design of the magnet could accommodate the necessary equipment such as microwave cavities or dish antennas.

IAXO has presented a Letter of Intent to CERN [2] and is currently working towards a Technical Design Report.

## 5. Conclusions

Axion helioscopes continue to present an attractive technique to look for axions and axion-like particles. IAXO is an ambitious project that aims at building a dedicated axion facility, that will surpass current sensitivities by more than an order of magnitude. The proposal is based on well-known technologies for the main features of the project, i.e. the magnet, the x-ray focusing devices and the low-background detectors. In the meantime, CAST, the most sensitive helioscope so far, has published part of the data from the $^3$He phase during which it entered well into the QCD-axion region at the upper masses end, setting an upper limit for the coupling constant of $g_{a\gamma} > 3.3 \times 10^{-10}$ GeV$^{-1}$ for $m_a$ between 0.64 eV and 1.17 eV. Currently the experiment is revisiting the vacuum phase with increased sensitivity and is also looking for other exotica such as chameleons. In the summer of 2014, a prototype x-ray focusing device, built with the technology to be employed for the IAXO optics, was installed and coupled to a Micromegas detector, covering an important benchmark for the IAXO project.

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