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Latest results and prospects of the CERN Axion Solar Telescope

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Abstract. The CERN Axion Solar Telescope (CAST) experiment searches for axions from the Sun converted into few keV photons via the inverse Primakoff effect in the high magnetic field of a superconducting Large Hadron Collider (LHC) decommissioned test magnet. After results obtained with vacuum in the magnet pipes (phase I of the experiment) as well as with ⁴He the collaboration is now immersed in the data taking with ³He, to be finished in 2011. The status of the experiment will be presented, including a preliminary exclusion plot of the first ³He data. CAST is currently sensitive to realistic QCD axion models at the sub-eV scale, and with axion-photon couplings down to the $\sim 2 \times 10^{-10} \text{ GeV}^{-1}$, compatible with solar life limits. Future plans include revisiting vacuum and ⁴He configurations with improved sensitivity, as well as possible additional search for non-standard signals from chamaleons, paraphotons or other WISPs. For the longer term, we study the feasibility of an altogether improved version of the axion helioscope concept, with a jump in sensitivity of about one order of magnitude in $g_{a\gamma}$ beyond CAST.

1. Introduction

Axions are light pseudoscalar particles that arise in theories in which the Peccei-Quinn U(1) symmetry has been introduced to solve the strong CP problem [1]. They could have been produced in early stages of the Universe being attractive candidates to the cold Dark Matter (and in some particular scenarios to the hot Dark Matter) that could compose up to $\sim 1/3$ of the ingredients of the Universe.

The axion-photon coupling $g_{a\gamma}$, unlike other axion couplings[2], is automatically present in every QCD axion model, and allows for the conversion of axions into photons (and viceversa) in the presence of electromagnetic fields, being the base of almost every axion detection strategy.

A combination of astrophysical and nuclear physics constraints restricts the allowed range for axion mass and couplings[3, 4, 5]. Pure cosmological arguments lead to a conservative, relatively model-independent allowed mass range of $10^{-6} \text{ eV} \lesssim m_a \lesssim 1 \text{ eV}$, the upper limit being recently set [6], by requiring thermal production of axions to be compatible with last CMB data. The coupling $g_{a\gamma}$ can be constrained independently by astrophysical observations, namely $g_{a\gamma} \lesssim 10^{-9} \text{ GeV}^{-1}$ based on the solar standard model and helioseismological observations [7], or the so-called *globular cluster* limit of $g_{a\gamma} \lesssim 10^{-10} \text{ GeV}^{-1}$ [8, 9].

Although the PQ scenario just described is probably the best motivated theoretical foundation for an axion, a phenomenologically similar scenario of a scalar or pseudoscalar particle coupled to the photon arises also in other proposed extensions of the Standard Model³¹. This broader class of models are generically referred to as axion-like particles or, referring to a even wider class of particles, WISPs, weakly interacting slim particle. In these cases, the axion-like particle is just viewed as a (pudo)scalar of mass m_a and coupling to two photons $g_{a\gamma}$, where m_a and $g_{a\gamma}$ are now two independent parameters, without further reference to the underlying theory. Therefore, every experiment (or observational consideration) based only on the property of the axions coupling to the photons could also be generalized to any axion-like particle. In particular, axion helioscope experiments are also sensitive to axion-like particles. Limits are

³¹ Examples of such extensions are extra dimensions (Kaluza-Klein) theories [10, 11, 12], quintessential dark energy models [13] or superstring theories [14] among others

expressed in a phenomenological ($g_{a\gamma} - m_a$) parameter space of the axion-like particles, with the area corresponding to the QCD axions singled out (yellow band in Fig. 1). However, one must be cautious and not forget that some of the limits mentioned before are set using specific properties of the QCD axions (other than the coupling to the photons) and therefore do not hold for any axion-like particle.

Axions could be produced at early stages of the Universe by the so-called misalignment (or realignment) effect[2], plus in some cases also from decay of primordial topological defects like axion strings or walls. These relic axions could be a substantial part of the cold dark matter (CDM) if $m_a \sim 10^{-6} - 10^{-3}$ eV, and could be detected by microwave cavities as originally proposed in[15]. Such technique is followed by experiments like the Axion Dark Matter Experiment (ADMX)[16, 17], which is actively scanning the low axion mass range mentioned above. Axions could also be copiously produced in the core of the stars by means of the Primakoff conversion of the blackbody photons in the fluctuating electric field of the plasma. Solar axions have energies of 1–10 keV, and could be detected by looking for x-rays of those energies coming from their conversion in a strong laboratory magnetic field. This *helioscope* concept[15, 18], was first experimentally applied in [19] and later on by the Tokyo helioscope [20], before CAST.

Finally, evidence for axions could also be produced altogether in the laboratory, by means of strong light sources combined with strong magnetic fields[21]. Although the sensitivity of laboratory experiments is still far from that of ADMX or CAST, they do not rely on any assumption on astrophysical sources of the axions. Like CAST, but unlike ADMX, they are also sensitive to axion-like particles.

2. Status of CAST and latest results

The CAST experiment is making use of a decommissioned LHC test magnet that provides a magnetic field of 9 Tesla along its two parallel pipes of 2×14.5 cm² area and 10 m length, increasing the corresponding axion-photon conversion probability by a factor 100 with respect to the previous best implementation of the helioscope concept[22]. The magnet is able to track the Sun by about 3 hours per day, half in the morning and half in the evening. At its two ends x-ray detectors are placed, at the "sunrise" side, a Micromegas detector[23] and a CCD[24], and at the "sunset" side two additional Micromegas detectors, installed in 2007 replacing the former TPC[25]. All of the detector setups are conceived following low background techniques (shielding, radiopure materials). The CCD is coupled to a focusing X-ray device (X-ray telescope)[24] that enhances its signal-to-background ratio by two orders of magnitude. Both the CCD and the X-ray telescope are prototypes developed for X-ray astronomy.

The experiment already released its phase I results from data taken in 2003 and 2004 with vacuum in the magnet bores[22, 26]. No signal above background was observed, implying an upper limit to the axion-photon coupling $g_{a\gamma} < 8.8 \times 10^{-11}$ GeV⁻¹ at 95% CL for the low mass (coherence) region $m_a \lesssim 0.02$ eV (Fig. 1). Since 2006 the experiment runs its second phase, which makes use of a buffer gas inside the magnet bores to recover the coherence of the conversion for specific axion masses matching the effective photon mass defined by the buffer gas density. The pressure of the gas is changed in discrete small steps to scan the parameter space above $m_a \sim 0.02$ eV. The ⁴He Run taken in 2006[27], allowed to scan axion masses up to 0.39 eV, for axion-photon couplings down to about 2.2×10^{-10} GeV⁻¹, entering into the QCD axion model band, as shown in Fig. 1. Due to gas condensation, in order to go to higher pressures, the experiment switched to ³He as buffer gas in 2007. The experiment is currently immersed in the ³He Run since beginning of 2008. It should last until mid 2011 and should allow us to explore up to 1.2 eV in axion mass approximately, overlapping with the CMB upper limit on the axion mass discussed above.

At the moment of writing this paper, the experiment has explored a region of axion masses up to about $m_a \sim 1$ eV. The first part of these data, taken in 2008, and covering approximately

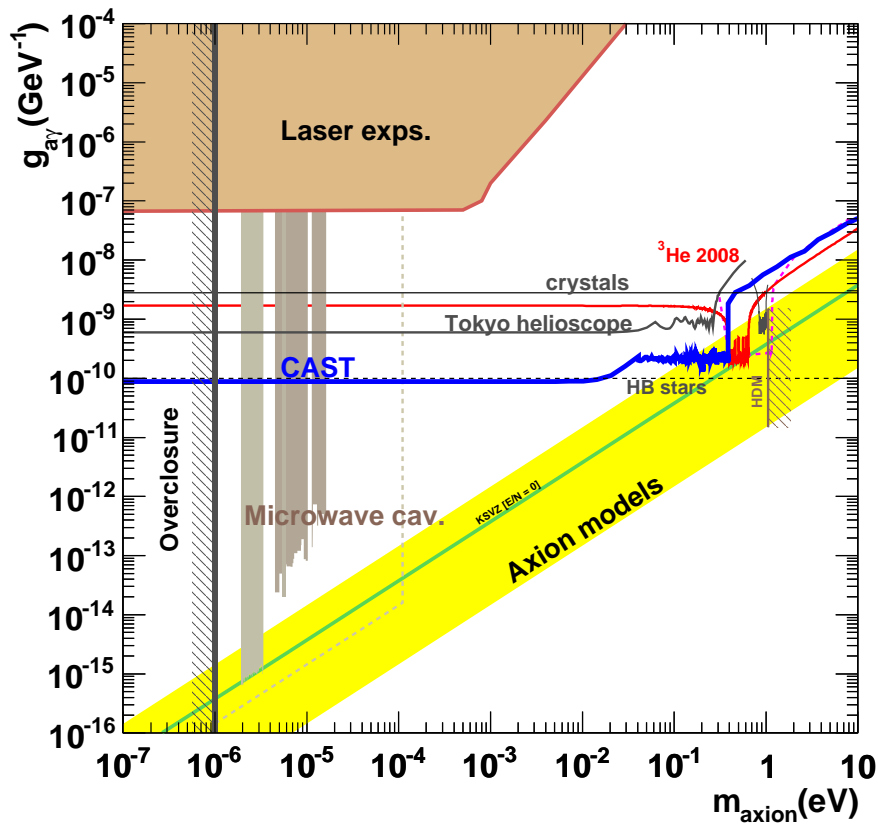


Figure 1. 95% CL exclusion line obtained from the previously published CAST data [22, 26] (blue line) and the preliminary analysis of the first 2008 ^3He data (red line, including only data from the 3 Micromegas detectors). Limits from other experiments or observations are included for comparison, such as the Tokyo helioscope and the cosmological upper limit on the axion mentioned in the text. The yellow area indicates the region of theoretical preference for axion models.

from 0.40 to 0.65 eV is almost fully analysed. They show no positive signal for axions and a preliminary exclusion plot (including for the moment only data from the 3 Micromegas detectors) is shown in Fig. 1. It extends previous CAST limit further into the QCD axion models band, and in particular now it traverses the benchmark model line (green line of Fig. 1), corresponding to a particular type of axions (KSVZ with $E/N = 0$ [28, 29]) for the mentioned axion masses. Everyday a new thin slice of untouched parameter space is being explored. Due to the sharp coherence effect, and to the fact that the parameter space to which we are sensitive now is populated by realistic QCD axion models and not excluded by previous experiments, a clear positive signal in CAST may appear at any moment.

The collaboration has performed by-product analysis of the data taken, to look for non-standard axion scenarios to which CAST would also be sensitive. Using data from the TPC in the CAST phase I, a search for 14 keV axions coming from M1 transitions in the Sun has been recently released[30]. In addition, data taken with a calorimeter during the phase I, were used to search for high energy (MeV) lines from high energy axion conversion[31]. Moreover, data has been taken with a visible detector coupled to one end of the CAST magnet, in search for axions with wavelengths in the "visible" range, possibly produced in the surface magnetic field

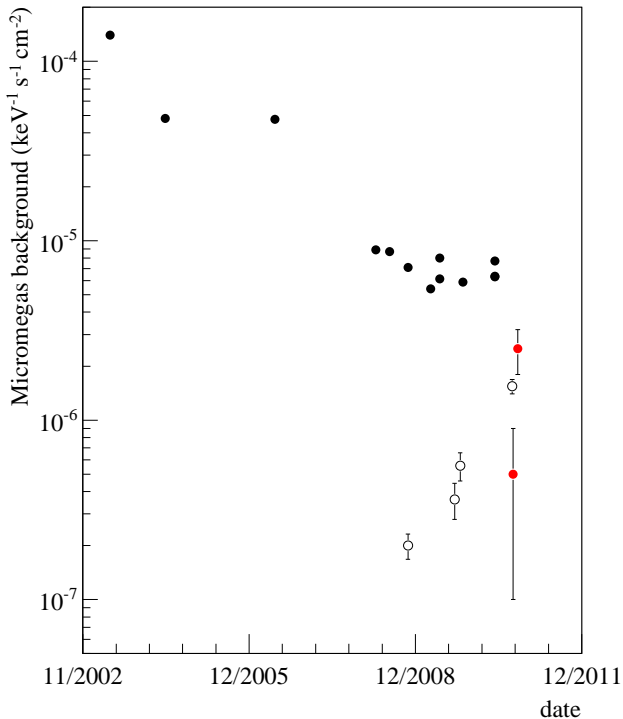


Figure 2. Background levels of Micromegas detectors over the years. Black points represents nominal values in CAST data taking campaigns. Open points correspond to ultralow background periods in CAST and the red points to data taken in special shielding conditions in the Canfranc underground laboratory.

of the Sun. A preliminary result was presented in [32], but more extended data taking is going on without interfering with the standard program of CAST thanks to a thin mirror foil that is transparent to x-rays but reflects visible photons into a dedicated setup.

Once the current ${}^3\text{He}$ phase finishes, the collaboration plans to revisit previous vacuum and ${}^4\text{He}$ configurations with improved sensitivity. This is possible thanks to the currently available detector's lower background levels. Micromegas detectors in CAST have gone through intense development over the years. By means of better shielding, cleaner detector materials, improved offline data treatment, and following the state-of-the-art *microbulk* fabrication technique, current Micromegas' backgrounds are now about a factor 20 lower than at the beginning of the experiment (see Fig. 2). A brief review of these efforts and prospects has been given by F. J. Iguaz at this conference.

3. Towards a new generation axion helioscope

For the longer term, a feasibility study is ongoing towards a new generation axion helioscope, with an improved sensitivity of at least one order of magnitude in $g_{a\gamma}$ beyond CAST. There is an important motivation to extend current CAST solar axion bounds further down to at least 10^{-11} or if possible to $10^{-12} \text{ GeV}^{-1}$. This region includes, at the high mass range, a large set of plausible QCD axion models, relevant as hot dark matter candidates. At lower axion masses, this region includes the ALP parameters invoked repeatedly for the emission mechanism of several classes of astrophysical phenomena [33, 34, 35, 36, 37, 38, 39]. This region is currently not excluded by any experimental results or astrophysical limits, and moreover, they are out of reach of foreseeable improvements of the experimental techniques for direct axion detection, with the exception of an enhanced axion helioscope.

Although the study is still ongoing, preliminary considerations point to the fact that an enhanced axion helioscope, based on pursuing innovations already introduced by CAST (specifically the use of x-ray optics to increase the signal-to-noise ratio and low background x-ray detectors), coupled with the use of a new, larger cross section, toroidal magnet, could achieve a sensitivity of 1 to 1.5 orders beyond current CAST limits, and therefore surpassing $g_{a\gamma} \sim 10^{-11} \text{ GeV}^{-1}$, for a wide axion mass range of up to $\sim 0.25 \text{ eV}$. Such a tentatively accessible region is shown in Fig. 3, together with current limits and similar long-term prospects for the microwave cavity technique, resulting in largely complementary regions. Details on this preliminary results, including analysis of the three key elements of the new helioscope, magnet, optics and detectors, will be included in a publication in preparation.

4. Conclusions and prospects

The CAST experiment is currently finishing the ^3He phase of data taking. First preliminary results with ^3He have been presented, extending previous CAST limits further to higher masses (to $\sim 0.65 \text{ eV}$) and deeper into the region favored by QCD axion models. After the ^3He phase, CAST plans to revisit previous configurations with improved detectors. Farther in the future, a feasibility study for a new generation axion helioscope is ongoing. Pushing innovations introduced by CAST, like the use of x-ray optics and of low background techniques, together with a specifically designed magnet, a substantial region, of at least one order of magnitude beyond current CAST limit, could be explored.

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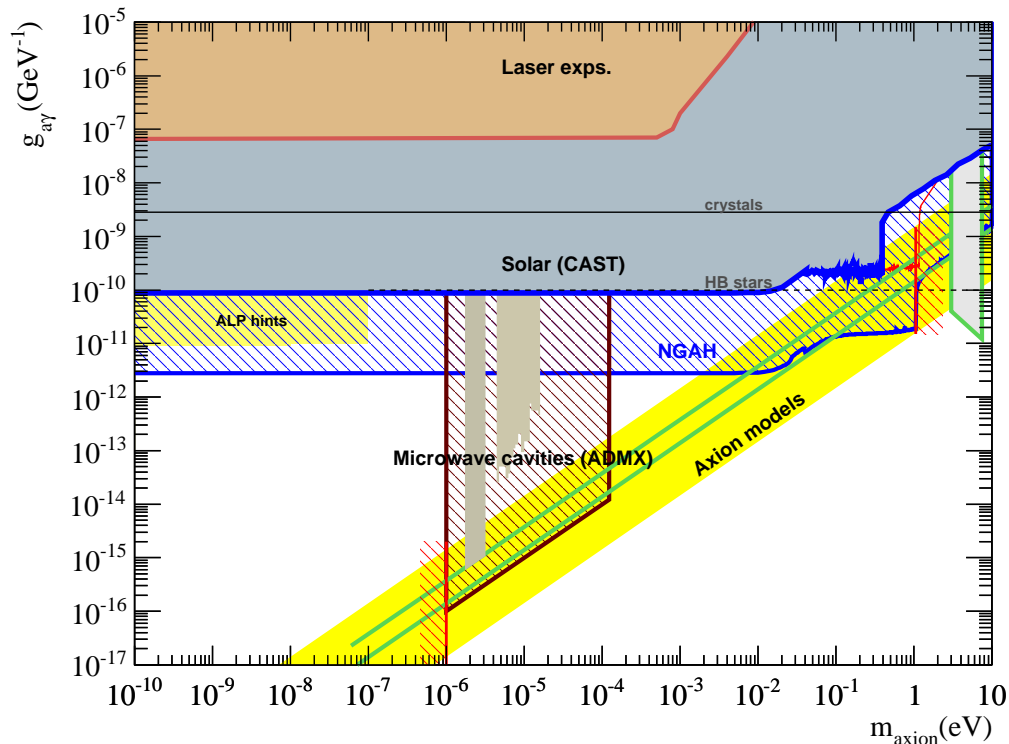


Figure 3. A comprehensive axion-like particle parameter space plot, including the regions tentatively explorable with a future new generation axion helioscope (dashed blue region) and with the microwave cavity technique (dashed brown region). Also shown is the region relevant to the astrophysical hints for ALPs (yellow rectangle in the low mass part of the plot) discussed in the text.

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