PROCEEDINGS OF SCIENCE

CAST and more than CAST; A Dark Sector Probe for 20+ Years

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This paper is a review of the CERN Axion Solar Telescope (CAST) experiment. We summarize the CAST experimental results, give highlights on the history of CAST and discuss its evolution into various different probes in the dark sector beyond its initial goals with a timeline. The results, achievements and challenges throughout the lifetime of CAST are presented.

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1. From the CAST proposal to the CAST Experiment

CAST, the "CERN Axion Solar Telescope" experiment, initially named as the "Solar Axion Telescopic ANtenna" was proposed to CERN in 1999 [1] based on the conceptual design detailed in a 1998 NIM-A paper [2], and, was approved in 2000. The aim of the experiment was to search for the axion, which is theoretically predicted to wash out the so-called strong CP problem, and which, at the same time, is a very promising non-baryonic dark matter (DM) candidate. CAST could also discover or exclude other hypothetical (axion-like) celestial particles with similar couplings for energies above few keV.

The experiment relied on the Sun as the nearest source of axions in the 1-15 keV energy range, where, the axion is expected to be copiously produced via the Primakoff effect in the scattering of the thermal photons off the nuclei. The detection mechanism on the other hand, relied on the inverse Primakoff effect for the hypothetic solar axions to convert into real photons in the ~9T magnetic field of a ~10 meters long straight twin aperture superconducting magnet, and required high efficiency and ultralow-background x-ray detectors to detect the photons coming from the converted axions with masses up to the eV-scale. The magnet was an LHC test dipole magnet designed to operate at at ~1.8 K with ~12 kA and recycled to be the backbone of this axion helioscope a la Sikivie (see [2] and references therein).

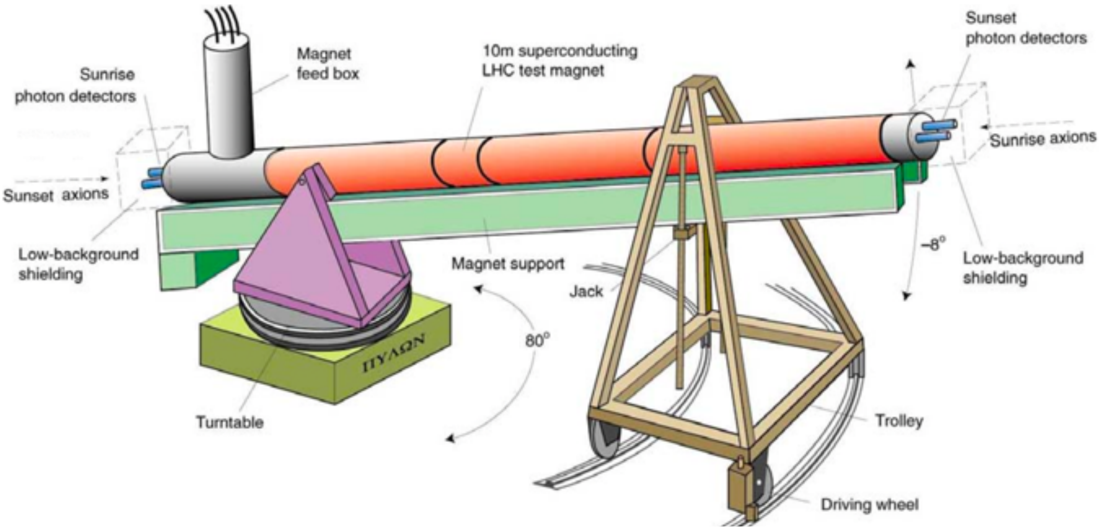

Figure 1: Drawing of the CAST magnet and the movement system.

The magnet axis had to be aligned with the Sun for a period as long as possible, using an active tracking system (figure 1). Only during alignment, a hypothetical axion signal would be expected as unique signature, where, photons from the converted axions would be emitted in the direction of the incoming axion. The photon would carry the axion's original energy and momentum, and, be detected by the detectors at the end of the magnet pipe lines.

The construction and commissioning of CAST took about two years and was completed by 2003. CAST's magnet was mounted on a platform that could move $\pm8^0$ vertically and $\pm40^0$ horizontally. X-ray detectors were mounted on either end to observe the Sun ~3 hours per day including sunrise and sunset; rest of the day was devoted to background measurements and, through the Earth's motion, observations of a large portion of the sky. Figure 2 shows the experimental hall before and after the construction.

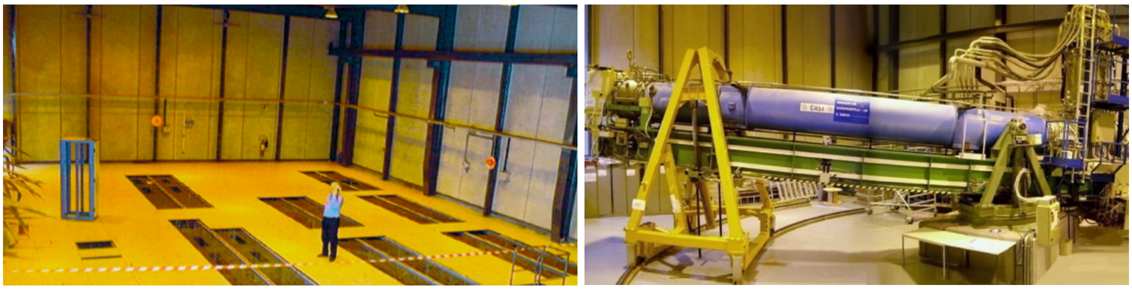

Figure 2: CAST experimental hall in 2001 (left) and in 2003 (right).

Originally, the CAST proposal consisted of two phases with a total running time of three years. In the first phase, where the magnets pipes were in vacuum, the goal was to reach a sensitivity to axion-photon coupling down to $g_{a\gamma\gamma} \lesssim 5.10^{-11}$ GeV^{-1} for $m_a \lesssim 0.02$ eV. The restriction on the axion mass is due to the coherence condition which requires the axion and photon fields to be in phase. In order to extend the coherence to higher axion masses, the magnet pipes would have to be filled by gas in the second phase of the experiment; using ^{4}He up to some pressure and ^{3}He further up. At each pressure setting of the gas, the photons would be provided an effective mass, hence, the coherence condition would be recovered for a narrow mass range of the axions extending a limit reach of $g_{a\gamma\gamma} \lesssim 10^{-10}$ GeV^{-1} for axion masses up to $m_a \lesssim 1$ eV.

2. CAST data taking and results

During the lifetime of CAST, the operation of the experiment was performed in several phases with different conditions of the magnet pipes and with different detector configurations and/or detection mechanisms. We summarize below, the various data taking campaigns and their outcomes that extended to a context beyond the original proposal.

2.1 Phase I - Vacuum running (2003-2004)

During 2003 and 2004, the experiment operated with vacuum inside the magnet bores and explored the axion mass range up to 0.02 eV. CAST's X-ray detectors included gas-filled and solid state options [3]. The aperture of the LHC magnet's beam pipes being around five times the predicted solar axion source size, the X-ray detectors had to be correspondingly large, implying a high level of noise. To overcome this problem, using X-ray lenses to focus the converted X-rays emerging parallel from the 50 mm magnet aperture to a sub-millimeter spot was considered; this would introduce a vast signal-to-noise improvement.

CAST was able to track the sun for about 1.5 h during sunrise and 1.5 h during sunset. First data taking of the vacuum running was achieved in May 2003 and the continuous data taking started by July 10th, 2003 with the following detectors installed: Time Projection Chamber (TPC) covering both bores on the sunset side; Micro-Mesh Gaseous Structure (Micromegas) covering one bore on the sunrise side; Charge Coupled Device (CCD) chip coupled to an X-Ray Telescope (XRT) covering the other bore on the sunrise side. Analysis of the 2003 data [4] showed no signal above background implying an upper limit to the axion-photon coupling $g_{a\gamma\gamma} < 1.16\times10^{-10}$ GeV^{-1} at 95% C.L. for $m_a < 0.02$ eV (figure 3-left). The analysis of the full 2003-2004 vacuum running data [5] also lacked any signal and improved the axion-photon coupling constant limit as $g_{a\gamma\gamma} < 8.8 \times 10^{-11}$ GeV^{-1} at 95% C.L. (figure 3-right) which super-seeded the astrophysical limit derived from energy-loss arguments on horizontal branch stars

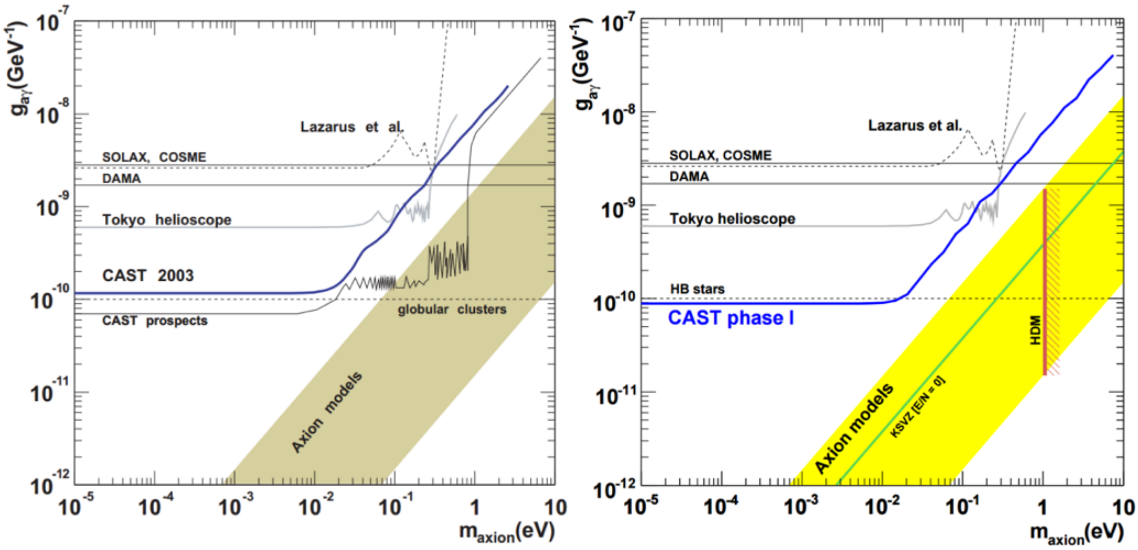

Figure 3: First results from 2003 vacuum running data (left) [4] and improved limit from full 2003-2004 vacuum running data (right) [5].

2.1.1 Other results from Phase I: M1 nuclear transition of ^{57}Fe

A search for the 14.4 keV solar axions and/or axion-like particles (ALPs), that could be emitted in the M1 nuclear transition of ^{57}Fe, was performed using the data acquired with the TPC over a period of ~5.5 months in 2004 [6]. We were able to explore the low mass region up to 0.03 eV, as a contrast to other experiments sensitive to these couplings putting constraints in the ~10^2-10^6 eV axion mass range. Having studied the cluster properties, the topology and the two-dimensional position reconstruction capability of the TPC, we applied a set of cuts to single out 14.4 keV photon events that could indicate the conversion of ^{57}Fe solar axions inside the bores of the magnet.

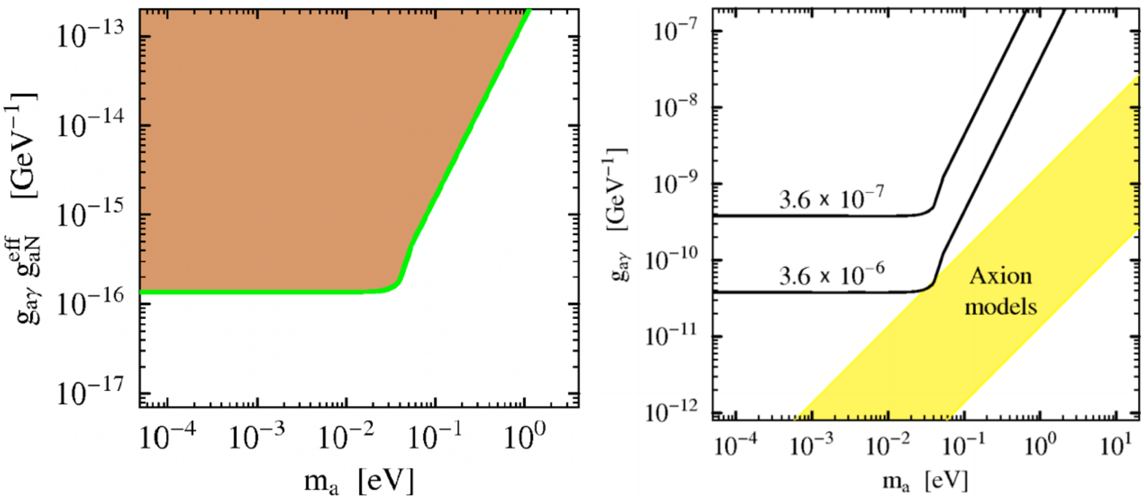

Figure 4: 95% CL. exclusion plots for the product $g_{a\gamma}g_{aN}$ (left) and for $g_{a\gamma}$ (right) from the search of ^{57}Fe solar axions [6]. Dependance of the limits on variations of g_{aN} from 3.6 x 10^{-6} to 3.6 x 10^{-7} due to ^{57}Fe solar axion luminosity and detection sensitivity are shown separately (right).

No excess of 14.4 keV X-rays was found when the magnet was pointing to the Sun, hence, we were able to set model-independent constraints on the coupling constants of pseudoscalar particles that couple to two photons and to a nucleon at 95% C.L. as $g_{a\gamma}g_{aN} < 1.36 \times 10^{-16}$ GeV^{-1} for $m_a < 0.03$ eV (figure 4).

2.1.2 Other results from Phase I: ^{7}Li and D(p,γ) ^{3}He nuclear decays

A search for high-energy axion emission signals from ^{7}Li (0.478 MeV) and D(p,γ) ^{3}He (5.5 MeV) nuclear transitions was performed for 6 months in 2004 [7]. To detect photons coming from conversion of these axions in the CAST magnet, we used a low-background high-energy photon calorimeter that was mounted on the sunset side after the Micromegas detector. This was the first such search for high-energy pseudoscalar bosons with couplings to nucleons conducted using a helioscope approach. No excess signal above background was found (figure 5).

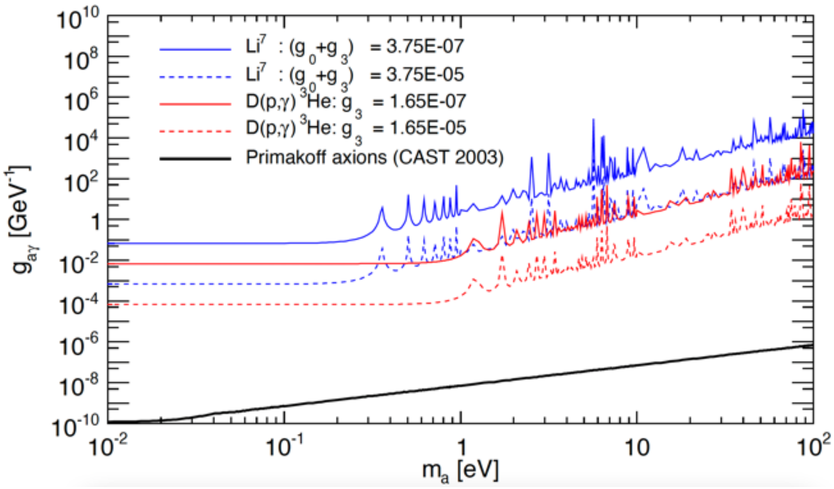

Figure 5: Limits obtained on the axion-photon coupling versus axion rest mass for 478 keV axions from ^{7}Li decay and 5.5MeV axions from proton-deuteron fusion for two values of the nuclear couplings [7].

2.1.3 Other results from Phase I: axion-electron coupling

The Sun could be producing a strong axion flux by bremsstrahlung, Compton scattering, and axio-recombination (the "BCA processes) when non-hadronic axion models are considered. Based on a new calculation of this flux, including for the first time axio-recombination, we derived limits on the axion-electron Yukawa coupling g_{ae} and axion-photon interaction strength g_{ag} using Phase-I data [8]. The sensitivity of CAST to non-hadronic axions allowed us to set a bound on the product of both coupling constants for $m_a \leq 10$ meV as $g_{a\gamma}g_{ae} < 8.1 \times 10^{-23}$ GeV^{-1} at 95% CL (figure 6).

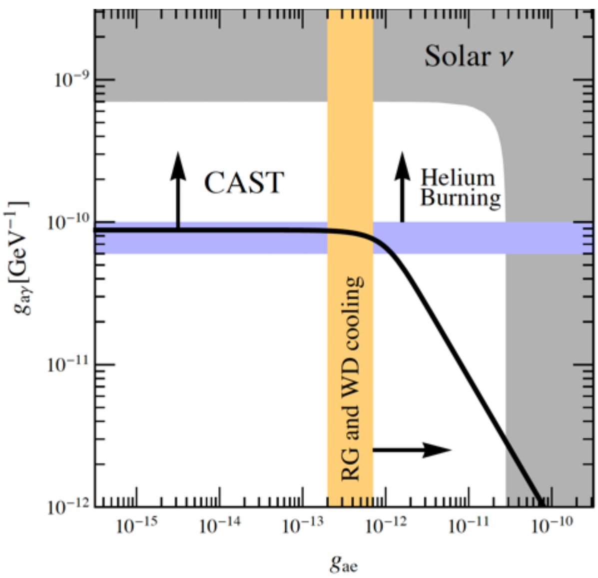

Figure 6: Constraints on g_{ae} and $g_{a\gamma}$ for $m_a \leq 10$ meV [8].

2.2 Phase II - Gas filled running (2005-2012)

In order to extend CAST sensitivity to higher axion masses as explained in section 1, magnet bores were filled with gas in Phase II using ^{4}He and ^{3}He at different data taking campaigns.

2.2.1 ^{4}He running (2005-2007)

From 2005 to 2007 the magnet bores were filled with ^{4}He at pressure steps of 0.08 mbar at 1.8K (figure 7). With 160 different pressure settings, the range of axion masses up to 0.39 eV was scanned.

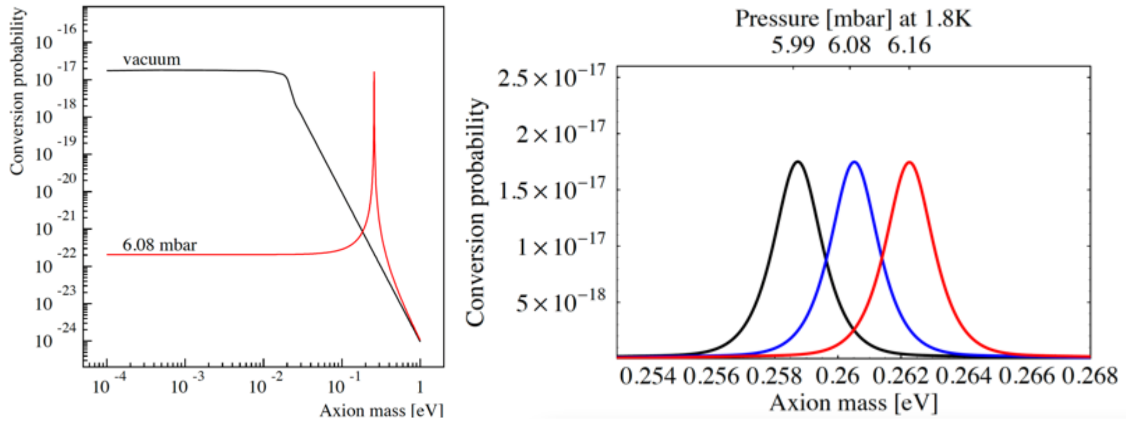

Figure 7: Conversion probability of a pressure setting compared to vacuum (left) and to adjacent settings (right) [9].

The detector configuration was the same as in Phase I, but with improvements on electronic noise of TPC, upgrades of vacuum system for XRT+CCD and new Micromegas with reduced detector background. New upper limits on the axion-photon coupling constant [9] were achieved (figure 8). The measurement time at each pressure setting was only a few hours, resulting in large statistical fluctuations of the exclusion limit. For the first time, the limit entered the QCD axion model band in the eV range.

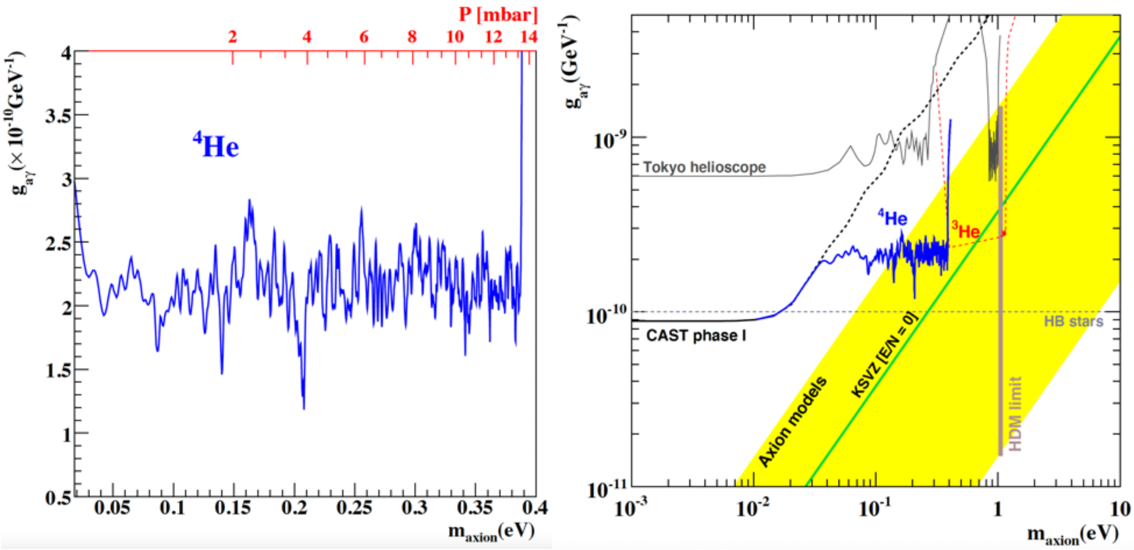

Figure 8: Axion masses scanned in this ^{4}He running (left) and overall exclusion of CAST with vacuum and ^{4}He running (right) [9].

2.2.2 Other searches during Phase II: BaRBE low energy run (2007-2008)

There could be a low energy tail of the expected energy distribution of reconverted photons peaking at 3 keV due to various processes active in the Sun. A study of this low energy tail of the CAST spectrum would be a prime example of such a search; hence, The BaRBE (Basso Rate Bassa Energia) experiment of INFN was set-up to achieve a low-background, single-photon counting system for low energy photons [10]. The observed Dark Count Rate with BaRBE was 0.4 Hz with both detectors, and no excess of photons over background was observed around the 2 eV energy range for the runs taken in between November 2007 and March 2008.

2.2.3 ^{3}He running (2009-2011)

From 2009 to 2011, CAST took data with ^{3}He inside the magnet bores and scanned the range of axion masses up to 1.18 eV. During this campaign, the TPC was replaced with two Micromegas detectors of readouts fabricated with novel bulk and microbulk techniques, and, on the sunrise end, a new shielded bulk (and later on microbulk) Micromegas replaced the unshielded one of the previous run, while the XRT+CCD remained unchanged.

The first results for the axion mass range 0.39 eV < m_a < 0.64 eV enabled CAST to become the first axion helioscope experiment that crossed the KSVZ axion line [11].

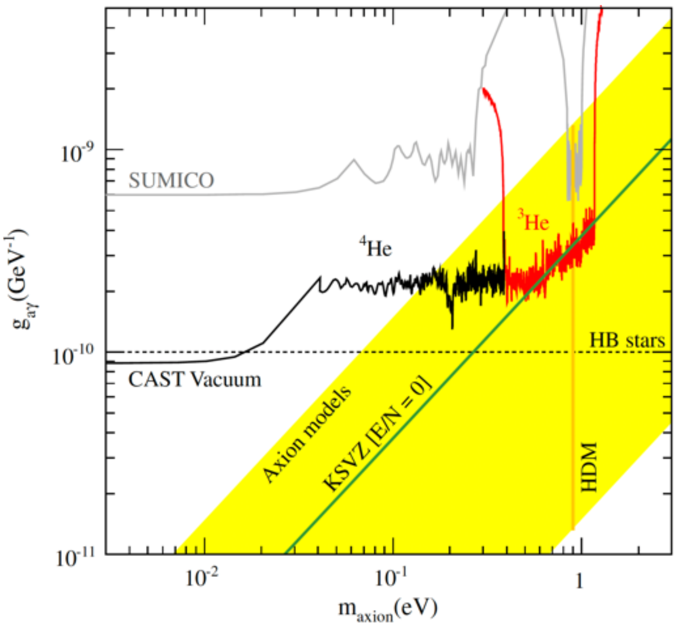

Figure 9: CAST exclusion regions in the m_a-$g_{a\gamma\gamma}$ plane achieved in vacuum, ^{4}He and ^{3}He phase (red) [12].

Then, covering the search range 0.64 eV $\lesssim m_a \lesssim$ 1.17 eV closed the gap to the cosmological hot dark matter limit and actually overlapped with it [12]. From the absence of excess X-rays when the magnet was pointing to the Sun, an upper limit on the axion-photon coupling of $g_{a\gamma\gamma} \lesssim 3.3 \times 10^{-10}$ GeV^{-1} at 95% C.L. was set, with the exact value depending on the pressure setting (figure 9).

2.2.4 Other searches during Phase II - Paraphoton search with BaRBE (2010-2012)

Hidden sector photons, or paraphotons, are massive equivalents of real photons, and an oscillation could occur between both. Hidden sector photons can be produced also in the sun and propagate freely to the Earth where they can transform into real photons within vacuum. CAST searched for solar hidden sector photons using the BaRBE detector setup at periods when the vacuum phase was revisited between 2010-2012. These measurements allowed CAST to place preliminary bounds on the coupling strength of paraphotons to real photons ("kinetic mixing") in the mass range up to 1 eV.

2.2.5 ^{4}He running revisited (2012)

In 2012, CAST has been using ^{4}He in order to revisit, with improved sensitivity and longer exposures, a narrow part at ~0.2 eV and a theoretically motivated range of axion masses around 0.4 eV. Detector configuration during this run consisted of three Micromegas detectors of the microbulk type (one in the sunrise and two in the sunset side) and XRT+CCD on the sunrise side. The detectors on the sunrise side remained unchanged since Phase II, but the Micromegas detectors on the sunset side were upgraded, improving the background levels of the detectors.

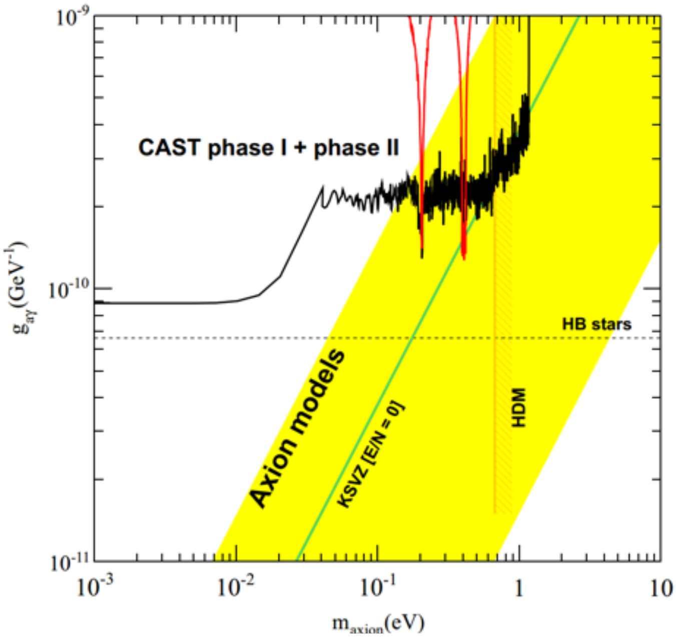

Figure 10: CAST exclusion regions in the m_a-$g_{a\gamma\gamma}$ plane. New limits near m_a = 0.2 and 0.4 eV with ^{4}He are shown in red [13].

No excess was observed for these revisited mass ranges and the exclusion plot was improved as shown in figure 10 [13].

2.3 Phase III - Vacuum run with upgraded detectors and Chameleon Searches (2013-2017)

Between 2013 and 2017, CAST operated in vacuum phase with various upgrades and changes its detector configuration that led to improved limits on the search for axions as well as search for Solar Chameleons that extended the reach of CAST sensitivity to the dark energy sector for the first time.

2.3.1 SSD and InGrid detectors for Solar Chameleon Search (2013-2014)

CAST used sub-keV detectors for the first time in 2013 and 2014; an SDD (Silicon Drift Detector) and an InGrid (Integrated Grid) detector. By reducing the X-ray detection energy threshold used for axions from 1 keV to 400 eV, CAST became sensitive to the converted solar chameleon spectrum which peaks around 600 eV. Not having observed any excess above background, CAST provided a 95% C.L. limit for the coupling strength of chameleons to photons of β_γ 10^{11} for $1 < \beta_m < 10^6$ (figure 11).

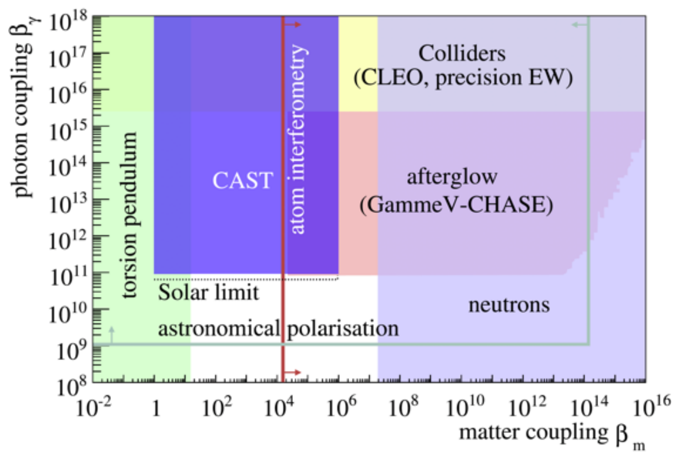

Figure 11: Chameleon exclusion region in the β_γ-β_m plane [14].

With this study [14], CAST made a first dedicated sub-keV energy search for solar chameleons based on the Primakoff effect.

2.3.2 A GridPix detector for Solar Chameleon Search (2014-2015)

A new X-ray detector, the "GridPix" detector (a combination of a Timepix ASIC and a Micromegas gas amplification stage) behind the X-ray telescope (XRT) of CAST was used to search for soft X-ray photons in the energy range from 200 eV to 10 keV from converted solar chameleons [15].

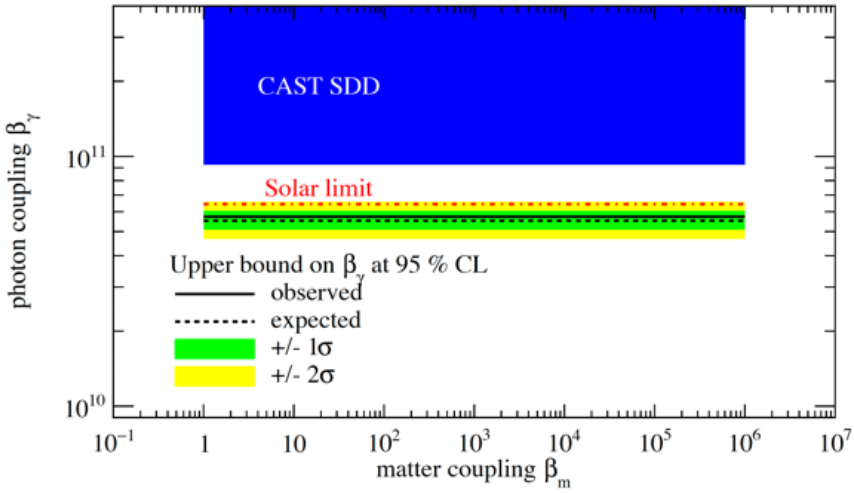

Figure 12: Chameleon exclusion region in the β_γ-β_m plane, improved by CAST [15].

No significant excess over the expected background was observed and an improved limit by a factor two on the chameleon photon coupling, $B_\gamma \lesssim 5.7 \times 10^{10}$ for $1 < B_m < 10^6$ at 95% C.L. was achieved (figure 12).

2.3.3 Improved limit on axion-γ coupling (2013-2015)

In the 2013-2015 run, thanks to low-background detectors and a new X-ray telescope, the signal-to-noise ratio was increased by about a factor of three. The data used for this analysis were taken with three detectors; two low background Micromegas detectors on the sunset side and an improved Micromegas detector situated at the focal plane of the new XRT on the sunrise side. Analyzing this data, the best limit so far on the axion–photon coupling strength of 0.66×10^{-10} GeV^{-1} at 95% CL [16] was set (figure 13).

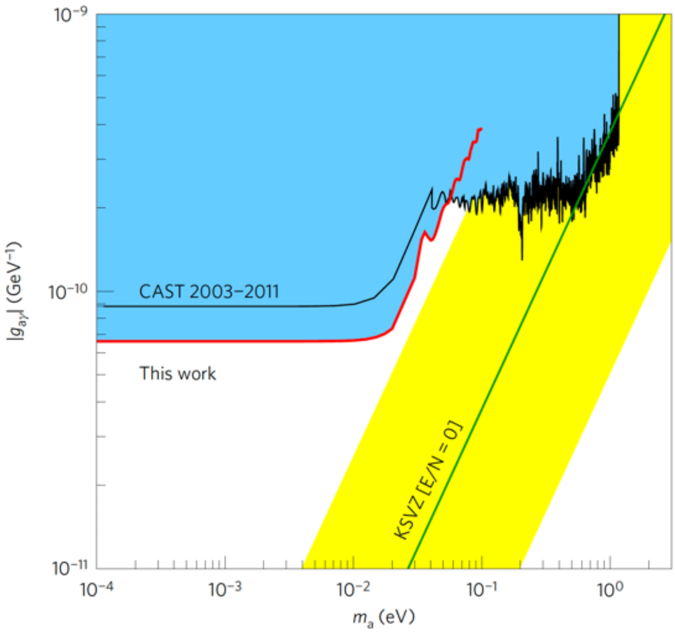

Figure 13: Improved limit on axion-γ coupling with 2013-2015 data [16].

2.3.4 KWISP detector for matter couplings of Solar Chameleons (2017)

In 2017, a first measurement with a sensitive opto-mechanical force sensor (KWISP - Kinetic WISP) designed for the direct detection of coupling of chameleons to matter was performed, benefiting also from the focusing action of the X-ray telescope installed at CAST. The results of the measurements [17] put the limit on the force acting at the membrane at 44 ± 18 pN, which, when combined with the expected chameleon flux at the detector, allowed to define an exclusion region in the β_m-β_γ plane (figure 14). The detector was sensitive for direct coupling to matter $10^4 \leq \beta_m \leq 10^8$, where the coupling to photons was bound to $\beta_\gamma \leq 10^{11}$.

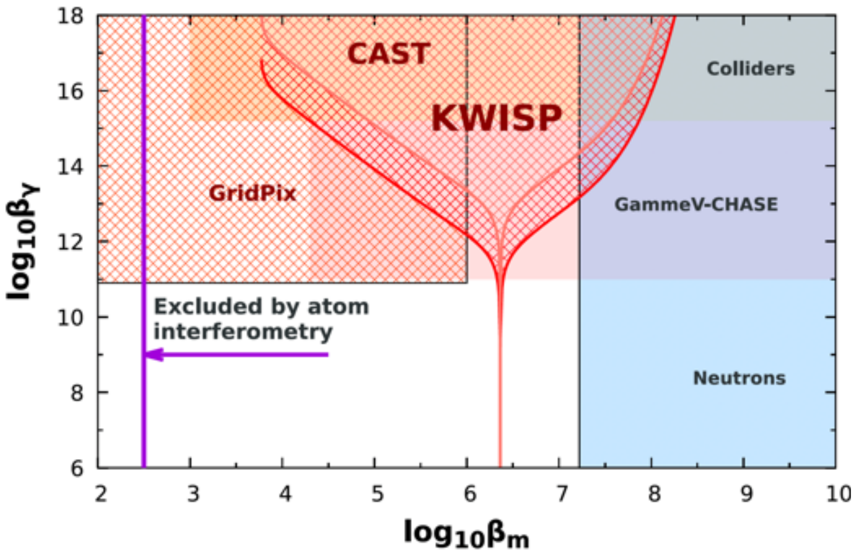

Figure 14: Exclusion limit for Chameleons at CAST are shown with hatched pattern. The KWISP measurement is illustrated in red colour. [17].

2.4 Phase IV - CAST transforming into a haloscope (2018-2022)

Initially proposed and built to run as an axion helioscope, CAST was transformed into an axion haloscope as of 2018 by inserting cavities inside the cold bores of the magnet following the Sikivie haloscope principle, where DM axions convert into photons within a resonator immersed in a magnetic field.

2.4.1 The RADES resonator (2018)

The Relic Axion Dark-Matter Exploratory Setup (RADES) installed in CAST to search for axion masses above 30 μeV. From this axion search in 2018 [18] at 34.67 μeV, an exclusion limit with 95% C.L. on the axion-photon coupling constant of $g_{a\gamma\gamma} \geq 4 \times 10^{-13}$ GeV^{-1} over a mass range of 34.6738 μeV < m_a < 34.6771 μeV was set (figure 15). This limit for a narrow frequency band improved the previous CAST limit at the corresponding axion mass by more than two orders of magnitude.

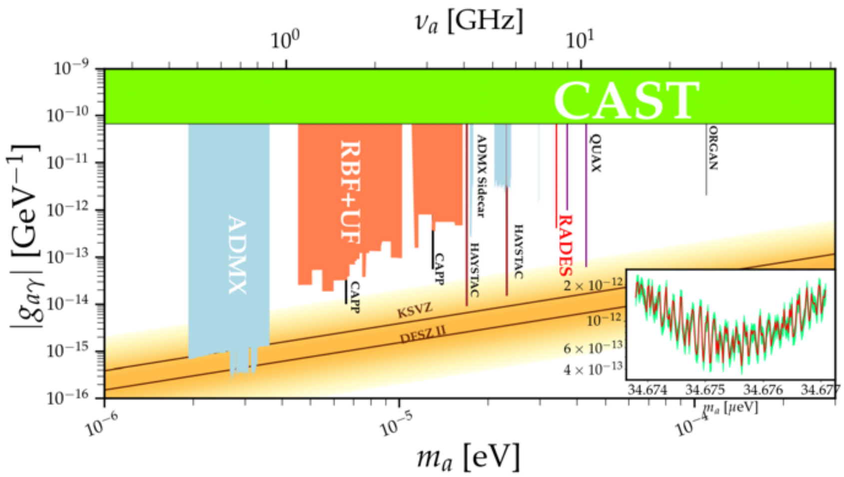

Figure 15: Axion-photon coupling vs axion mass phase-space. In dark red is the CAST-RADES axion-photon coupling exclusion limit [18].

2.4.2 The CAST-CAPP resonators (2019-2021)

The CAST-CAPP axion haloscope, searched for axions from 2019 to 2021 [19]. The CAST-CAPP resonator was an array of four individual rectangular cavities inserted in series inside one of the two bores of CAST's superconducting dipole magnet, phase-matched to maximize the detection sensitivity.

Combining signals from individual cavities was shown to be feasible and unique in DM axion search. The successful scan of a significant mass range showed that this experiment is at the cutting-edge of cavity tunability in axion research. The fast-scanning technique when combined with the high sensitivity, permits to quickly re-tune the cavities to a frequency of interest. A total frequency range of 660 MHz, from 4.774 to 5.434 GHz corresponding to axion masses between 19.74 and 22.47 μeV was scanned. Within this search range, we excluded axion-photon couplings for galactic axions down to $g_{a\gamma\gamma} = 8 \times 10^{-14}$ GeV^{-1} at 90% C.L. (figure 16).

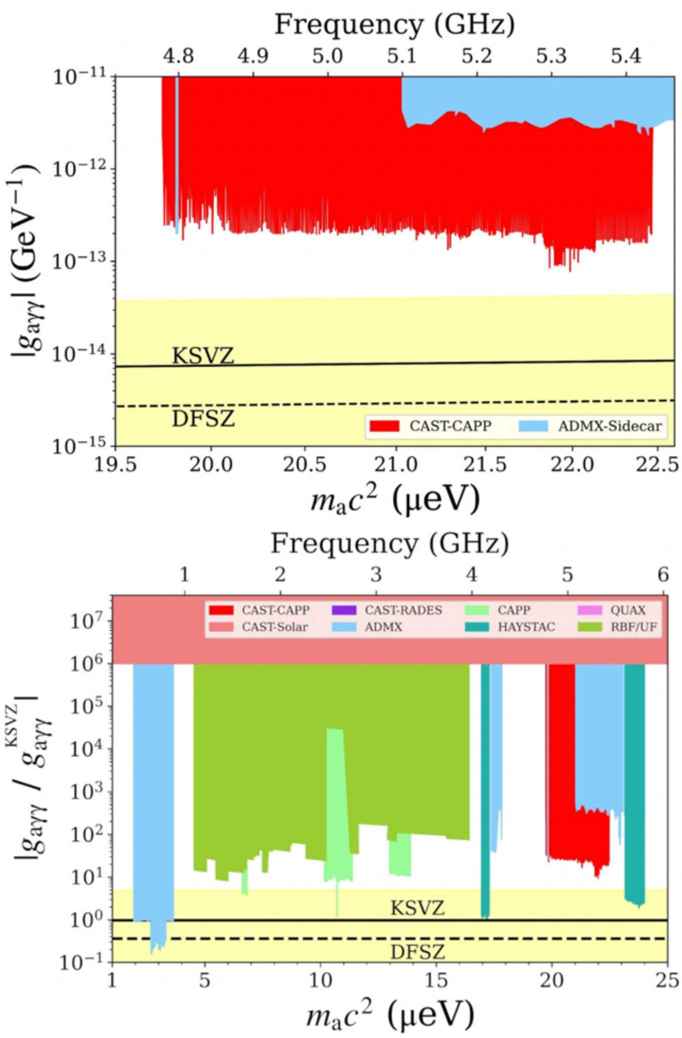

Figure 16: CAST-CAPP exclusion limit on the axion-photon coupling at 90% confidence level (left), and compared to other axion search results within the mass range 1–25 μeV (right) [19].

3. Summary and conclusions

CAST was a new departure for CERN, relying not on the laboratory's expertise in accelerators but on its know-how in X-ray detection, magnets and cryogenics. It started as an axion helioscope and transformed later into an axion haloscope as well. CAST did not only search for dark matter candidates but also became sensitive to chameleons, which extended its reach to the dark energy sector. As of 2023, CAST stopped data taking and switched to data analysis status.

CAST has been a COSMIC LISTENer of the COSMIC WISPers for 20+ years; with many opportunities, challenges, firsts and leading results. In the end, the LHC test magnet paid off much more than it was built for.

4. In memoriam

CAST's success has been the result of the hard work and commitment of each and every CASTer, the shared devotion and friendship of whom made CAST a great family. We dedicate this article in loving memory of our dear colleagues and friends who passed away during the lifetime of CAST: Angel Morales - 2004 (U. of Zaragoza, Spain), Engin Arık - 2007 (Boğaziçi U., Türkiye), Fatma Şenel Boydağ - 2007 (Doğuş U., Türkiye), Özgen Berkol Doğan - 2007 (Boğaziçi U., Türkiye), İskender Hikmet 2007 (Doğuş U., Türkiye), Julio Morales - 2009 (U. of Zaragoza, Spain), Gerhard Lutz - 2017 (MPI Garching, Germany), Biljana Lakic - 2020 (Rudjer Boskovic Inst., Croatia) and Hans Riege - 2023 (Darmstadt Technical U., Germany).

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