Hunting Dark Matter Axions with CAST

Marios Maroudas and Kaan Ozbozduman

1 Introduction

One of the most fundamental problems of Modern Physics is that of the composition of Dark Matter (DM) which accounts for approximately 85% of the total matter content in the universe. One of the most promising particle candidates for DM are the axions. They are hypothetical elementary particles that were initially postulated in 1978 resulting from the Peccei–Quinn mechanism [1] which was introduced as a solution to the strong CP problem of the Standard Model. Axions, which got their name after a detergent, if they exist they must have a very small mass and must interact very feebly with normal matter. At the same time, they can sufficiently be produced during the Big Bang making them ideal candidates for cold DM.

CERN's Axion Solar Telescope (CAST) started searching for axions coming from our Sun in 2003. The detection principle is based on the inverse Primakoff effect, where, in the presence of a strong magnetic or electric field, the axion can convert into a photon. Cutting-edge limits on the axion-photon coupling were then set by CAST during its operation. As seen in Fig. 1, the latest upper limit on the axion-photon coupling for axion masses bellow 0.02 eV is 0.66×10^{-10} GeV^{-1} [2].

In 2019, following a suggestion from 2012 [3] CAST was transformed from an axion helioscope looking for solar axions to an axion haloscope looking for DM axions in the μeV mass region. This was based on the Sikivie haloscope technique [4], where, in the presence of a strong magnetic field, axions from the galactic halo convert into photons if the resulting photons are detected inside a high-quality

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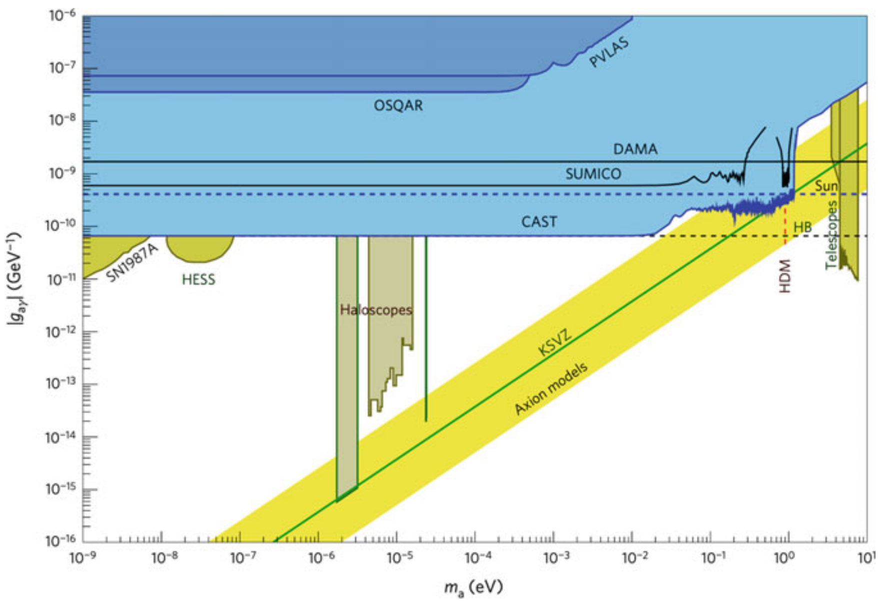

Fig. 1 The solar axion exclusion plot set by CAST while pointing at the Sun [2]

microwave cavity resonating to the corresponding frequency defined by the unknown axion rest mass. The microwave signal is then extracted through an antenna which is critically coupled to the cavity. Since the axion mass is unknown, haloscopes should be tuneable in order to be able to change the cavity's resonant frequency and thus scan a wide range of axion masses.

The CAST superconducting dipole magnet provides the strong external magnetic field of 8.8 T and has a twin-bore geometry into which rectangular cavities are fitted. The probability of a DM axion to be converted into a real photon inside a microwave cavity, increases with the square of the magnetic field (B^2), the quality factor of the cavity (Q) which is the ratio of the cavity stored energy to its power loss per cycle, the volume of the cavity (V) and the geometry factor (C) which is determined by the direction of the external magnetic field and the cavity mode used:

$$P_{\text{axion}} \approx g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 Q V C \tag{1}$$

where ρ_a is the local mass density of DM axions, m_a the mass of the axion and $g_{a\gamma\gamma}$ the axion-photon coupling.

The conventional search for DM axions has been so far based on the assumed isotropic halo distribution of our galaxy with the local DM density ρ_a usually assumed to have an average value of 0.45 GeV/cm^3 [5, 6]. However, this could be the reason why axions have not been detected so far. As we will see also in Sect. 2, considering axion DM streams [7] propagating near the ecliptic plane of our solar system and

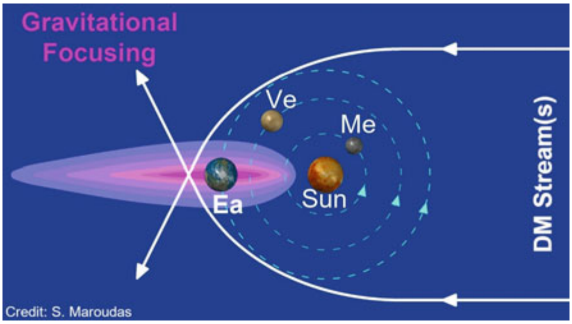

Fig. 2 Schematic view of the flow of a slow-moving DM stream being gravitationally focused by the Sun towards the Earth resulting in flux enhancements of several orders of magnitude (© Marios Maroudas 2022. All rights reserved)

towards an Earth bound DM axion detector like CAST-CAPP, large flux enhancements can take place due to gravitational focusing effects by the solar system bodies including the Sun itself (see Fig. 2) [8, 9].

To take advantage of such burst-like axion flux enhancements due to temporally occurring stream alignments with the Earth, two criteria must be fulfilled:

1. The covered frequency range must be as wide as possible since the axion mass is unknown.
2. The scanning time must be as short as possible in order to take advantage also of short-lasting alignments towards the Earth between the stream and the intervening solar system body.

2 Methodology

In 2019 two different microwave cavity detectors were installed inside each one of the two bores of CAST's dipole magnet, CAST-RADES and CAST-CAPP (see Fig. 3), making CAST the only experiment at CERN searching directly for DM. The CAST-RADES sub-detector consists of a 1 m long cavity comprised of alternating irises searching for DM axions around 34.67 μeV [10]. On the other hand, the CAST-CAPP sub-detector, on which we focus here, consists of four rectangular stainless steel cavities, each with a volume of 224 cm^3, and the ability to be tuned in a quite wide range of axion rest mass of about 660 MHz.

As shown in Fig. 4, CAST-CAPP is a unique axion detector containing a delicate fast-tuning mechanism inside each cavity, consisting of two parallel sapphire strips which are displaced by a piezoelectric motor through a locomotive mechanism providing a tuning resolution of less than 100 Hz in stable conditions. The sapphire strips are symmetrically placed parallel to the cavity longitudinal sides moving simultaneously towards the centre. The maximum scanning speed reached with CAST-CAPP is 10 MHz/min with the coverage of the full frequency range taking about 1 h. Thus, if the axion rest mass is within this range, CAST-CAPP can search also for streaming

Fig. 3 The CAST experiment with a close up photo of the twin bores where CAST-RADES and CAST-CAPP microwave cavities are installed (CAST credits)

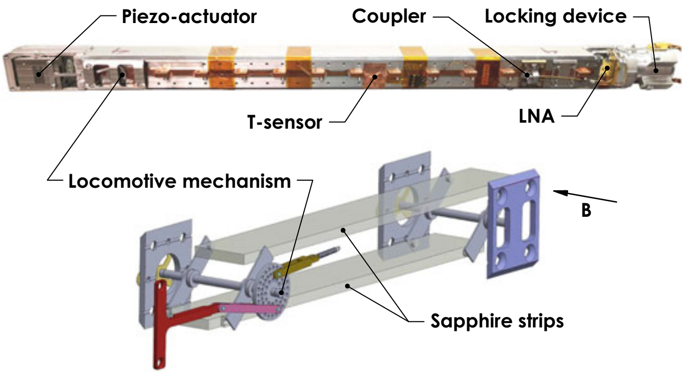

Fig. 4 The CAST-CAPP cavity assembly (top) and its tuning mechanism with the two sapphire strips (bottom) (CAST credits)

DM axions with enhanced sensitivity due to higher axion densities by up to several orders of magnitude.

Smaller cavities are required in order to reach higher axion masses. However, as follows from Eq. 1, the detection sensitivity increases with the cavity volume. To mitigate this issue, CAST-CAPP is using four identical cavities together with the phase-matching technique to increase the effective volume. This technique, which is introduced for the very first time in axion research, improves linearly the signal-to-noise ratio with the number of cavities [11]. To achieve this, a coherent combination of the simultaneous power outputs from the four frequency-matched cavities has to be performed in data-taking conditions.

Using these two novel techniques of fast-frequency tuning and phase-matching, during searches for conventional DM axions, CAST-CAPP became sensitive also to transient events such as axion streams [7] and cosmologically motivated axion mini-clusters [8, 12, 13]. These can give rise to temporally enhanced flux densities (ρ_a)

by several orders of magnitude, in particular when combined with the gravitational lensing effects by the solar system as seen in Fig. 2 [14, 15]. In the ideal case, the flux enhancement due to the gravitational focusing of the Sun can be as high as $\sim 10^{11}$ whereas from the intrinsic Earth mass distribution the enhancement can be up to $\sim 10^{9}$ [16]. Apparently, the faster the scanning the shorter the axion bursts that can be utilized, making the fast-tuning mechanism of CAST-CAPP an indispensable component.

3 Results

From 09/2019 to 06/2021 CAST-CAPP has taken about 172 d of data with both single and phase-matched cavities in data taking conditions with $B = 8.8$ T. The scanned frequency range extended from 4.77 to 5.43 GHz covering a parameter phase space of ∼660 MHz. This corresponds to axion masses between 19.74 and 22.47 μeV. At the same time background data were taken with $B = 0$ T for about 16 d to exclude possible axion candidates.

Several quality checks were also applied in these data to ensure that undesired effects such as mechanical vibrations are removed from the from further consideration in the analysis. The applied criteria resulted in rejecting about 4.4% of the recorded data.

The performed data analysis was based on widely-accepted methods [6, 17, 18], but was adjusted to the specific experimental conditions of CAST-CAPP. The derived

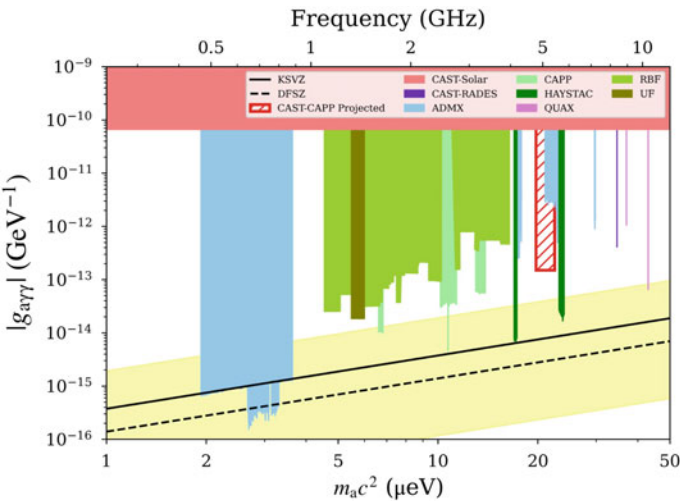

Fig. 5 CAST-CAPP projected exclusion limit on the axion-photon coupling as a function of axion mass compared to other axion search results [2, 17–27]

results showed no galactic DM axion candidate signal above the predefined 5σ level. Therefore, as seen in Fig. 5 new limits on the axion-photon coupling as a function of the axion mass were set, with the achieved performance being competitive with other state-of-the-art DM axion detectors. These results have been submitted for publication and are under consideration.

At the same time, an independent analysis is pending for the next few months, which will allow to search for transients due to aforementioned axion streams or mini clusters. The preliminary results also showed no significant axion lines. However, this novel analysis procedure has to be optimized and therefore it could give a surprise!

4 Conclusions

CAST has been searching for axions for about 22 years. It has progressively set stronger and stronger limits on the solar axion interaction strength, becoming a point of reference in axion research. CAST never stopped evolving throughout the years upgrading its instrumentation and improving its sensitivity for axions, axion-like particles and chameleons [2, 28–31], becoming recently also a DM axion antenna using microwave cavities. The recent competitive results of CAST-RADES [19] and CAST-CAPP were able to set world-class limits on the galactic DM axion-photon conversion and laid the foundations for a search of short-lasting transient events by making use of the two newly developed techniques of fast scanning and phase-matching.

Even though the axion has still eluded CAST efforts, the huge experience gained over the years together with the new technologies and experimental approaches that were introduced will help define the future axion searches with next-generation helioscopes and haloscopes.

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