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Proceeding Paper

Axion Searches with IAXO and BabyIAXO †

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‡ The IAXO Collaboration is provided in Appendix A.

Abstract

Of the three major axion search experimental strategies, light-shining-through-wall experiments, haloscopes, and helioscopes, this paper focuses on the latter. IAXO, the International AXion Observatory, will be a next-generation helioscope following in the footsteps of previous experiments like SUMICO and CAST. Helioscopes aim to detect axions produced in the Sun, utilizing a magnetic field to couple them to X-ray photons. BabyIAXO represents a near-term step toward IAXO, designed to test custom components while delivering competitive results in axion searches. The experimental components are currently under development and construction. Further research into the applications of BabyIAXO beyond baseline axion searches is being conducted.

Keywords: axion; helioscope; IAXO

1. Introduction

There are three different major experiment types for the search for axions that were published by Sikivie in 1983 [1]. These remain today as light-shining-through-wall experiments, haloscopes, and helioscopes. While the former utilizes lab-produced axions and haloscopes search for relic axions from dark matter halos, helioscopes focus on the Sun as an axion source.

IAXO, the International AXion Observatory, is a proposed helioscope experiment with a functioning intermediate state called BabyIAXO [2,3]. In the axion model parameter space, helioscopes are able to cover a broad range of axion masses, as can be seen in Figure 1.

Here, the limit of the previous helioscope experiment CAST, the CERN Axion Solar Telescope, is shown, as well as the predicted parameter spaces for IAXO and BabyIAXO. The light-shining-through-wall experiment, ALPS II, which is currently under operation at DESY, is also shown. IAXO and BabyIAXO are predicted to reach the QCD axion model parameter space, including KSVZ and DFSZ axion models, marked in yellow [4]. KSVZ axions are produced in the Sun through the Primakoff effect. In contrast, DFSZ axions also couple to electrons, allowing for additional production channels through ABC processes (atomic recombination, bremsstrahlung, and Compton scattering). The energy spectra of the different fluxes coming from the Sun can be seen in Figure 2. This means that while being able to follow the Sun, IAXO and BabyIAXO also have to be sensitive to axions in the range of 1–10 keV.

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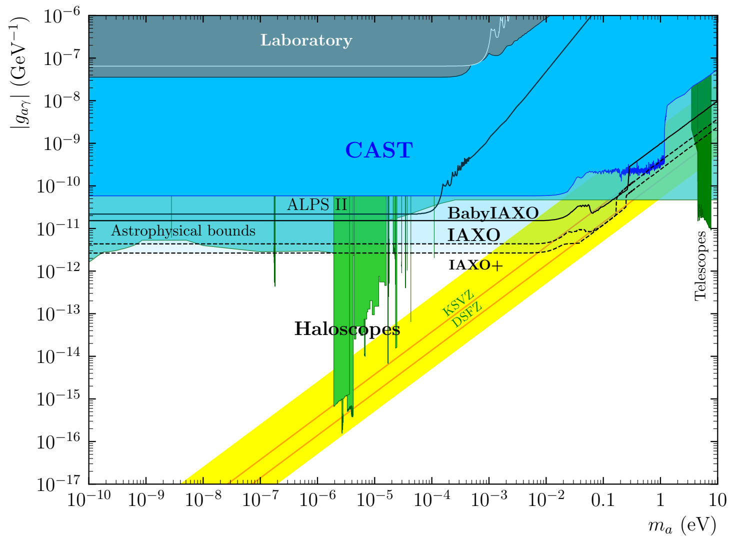


Figure 1. Exclusion plot of different axion search experiments [5]. The yellow band highlights the QCD axion model parameter space [4]. For comparison, the current astrophysical bounds are also shown [6].

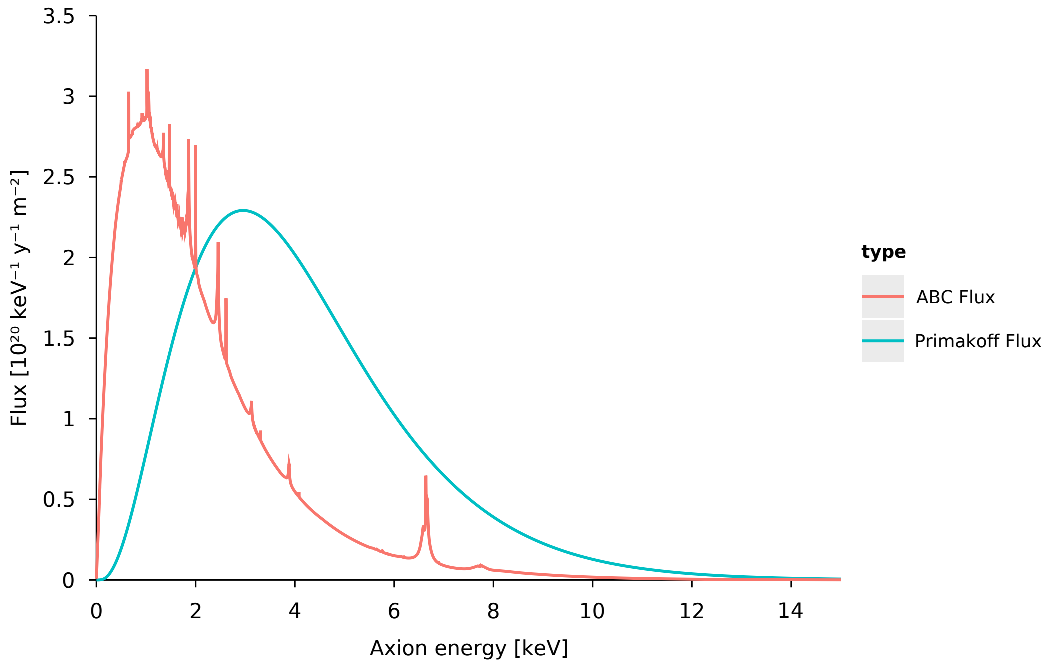


Figure 2. Solar axion energy spectrum for different production mechanisms. The coupling strengths used here are $g_{a\gamma} = 10^{-11}$ GeV^{-1} and $g_{ae} = 10^{-13}$.

To detect these axions, helioscopes utilize axion–photon coupling in a transversal magnetic field. The resulting photons inherit the directions and energies of the axions. This means that the components mounted to the magnet should be X-ray-detecting. Usually, this consists of an X-ray-focusing optic, for example, a Wolter I type and an X-ray detector. The figure of merit of a helioscope is therefore usually described as [7]

$$FoM = B^2L^2A \cdot \epsilon_O \alpha^{-1/2} \cdot \epsilon_d b^{-1/2} \cdot \epsilon_t^{-1/2} t^{1/2} \quad (1)$$

Here, the first part is in reference to the magnetic field B with its length L and A as the cross-section of the magnet bore. The second term contains the optics' focusing efficiency ϵ_O and α as the area of the focused signal. The third term refers to the detector with ϵ_d as the detection efficiency and b as its background. The last term is influenced by the fraction of time that the sun is being tracked by the experiment ϵ_t and the total time of operation t.

2. Materials and Methods

IAXO has been proposed as a next-generation helioscope in 2013 and will consist of a 25 m long superconducting magnet with eight bores for eight setups [2]. This magnet and the attached setups of optics and detectors will be movable to follow the Sun for 12 h a day. The whole length of the experiment will be 40 m, and the *FoM* is aimed to be 10,000 times higher than CAST. A model of the experiment can be seen in Figure 3.

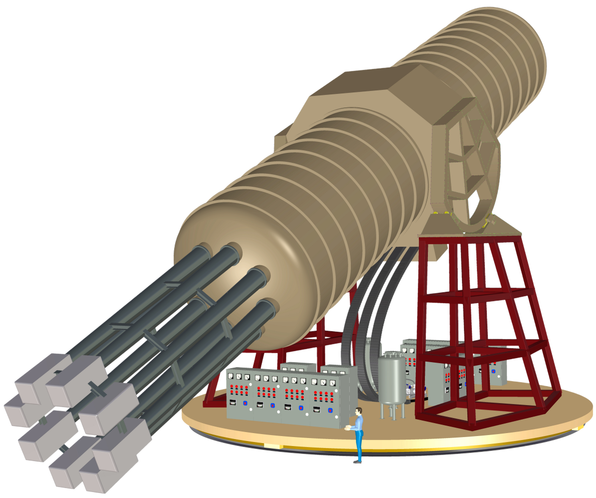


Figure 3. A model of IAXO as described in [2].

As a proof of concept for IAXO, BabyIAXO has been proposed to be built at DESY [3]. This experiment will be able to test components like the drive system and magnet and detection systems for IAXO while also producing relevant results in axion searches. It will have two bores for two setups in a 10 m long magnet, which will be mounted on a movable platform. A model of this can be seen in Figure 4.

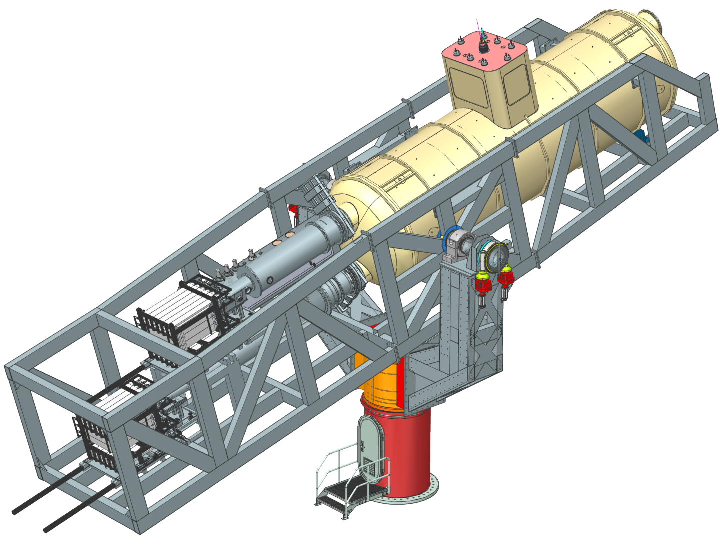


Figure 4. A model of BabyIAXO.

The drive system will make it possible for the magnet to be focused on the Sun for 12 h a day. This, among other things, results in an *FoM* about 100 times higher than CAST.

To confirm the setup, BabyIAXO has been extensively simulated. A ray tracer was written, including all of the experimental components and the axion production in the Sun as a source [8]. This Monte Carlo-based method can be used to compare different signal efficiencies and optimize the setup as well as consider gravitational effects.

3. Results

Currently, the components of BabyIAXO are under construction or in development. Parts of the structure and drive system, containing components of the CTA/MST prototype, have been delivered to the Hera South Hall at DESY.

The magnet will be a cryogenic system developed by CERN and DESY based on an aluminium-stabilised Rutherford cable. The cable will be arranged in two parallel racetrack coils to ensure a quasi-homogeneous magnetic field with a peak of 3.2 T in the bores. The setup can be seen in Figure 5. Parts of this cable are currently being tested.

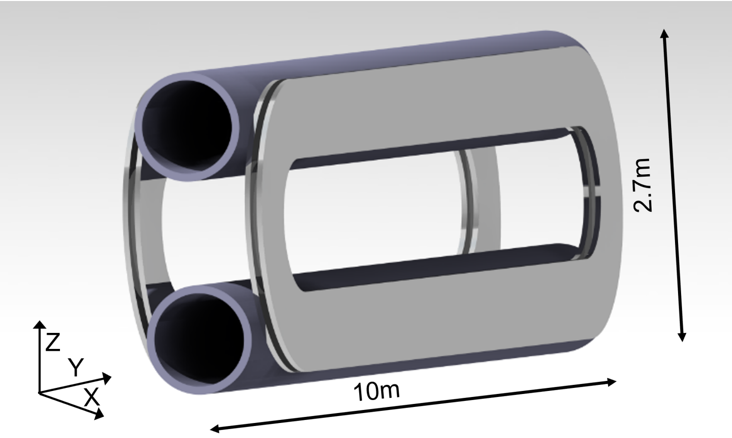


Figure 5. A schematic view of the bores and the racetrack coils.

Since there will be two bores, there will be two lines with an X-ray optic each. One of the optics is a flight module from the XMM-Newton space mission [9], and the other will involve custom optic testing for a possible configuration for IAXO. Both of them are Wolter I-type optics consisting of stacks of mirrors, where the X-rays get reflected at very shallow angles. The XMM optic's mirrors are gold-coated nickel shells that are supported by a spider structure in the front. The optic has been unpacked for the first time after 20 years, as can be seen in Figure 6, and it is ready to be tested at the PANTER test facility.

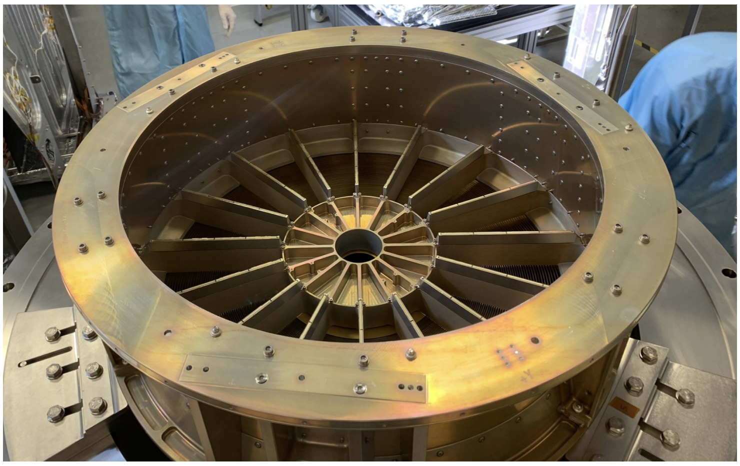


Figure 6. Unpacking the XMM optic at PANTER. ©MPE/PANTER.

The custom optic will consist of two parts, an inner and an outer one, which can be seen in Figure 7. The inner optic will be based on a technology from NASA's NuSTAR satellite, where the mirrors are made of thermally slumped glass [10]. Here, the current glass inventory from previous experiments is being tested for reuse. The outer optic will be built using cold-slumped Willow glass, and a prototype is currently under construction at INAF.

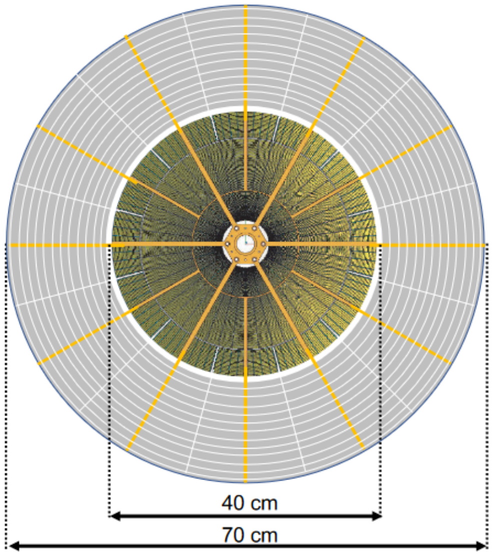


Figure 7. A schematic view of the custom optic showing the inner and the outer part [3].

As a last step of the experiment, the X-rays need to be detected. The nature of the solar axion spectrum and conversion in the magnet results in a unique combination of challenges. The detectors have to be sensitive to 1–10 keV X-rays while also reaching a background level of $<10^{-7}$counts keV^{-1}cm^{-2}s^{-1} for BabyIAXO. Several detector types have been identified as candidates and are under development.

The Micromegas detector from the University of Zaragoza and CEA Saclay is a gaseous detector with a vacuum-tight window to let the X-rays in. They then produce electrons in the gas which travel to the readout chip with a mesh on top, which can be seen in Figure 8. The detector has undergone several iterations and is now getting close to the desired background level in an underground lab.

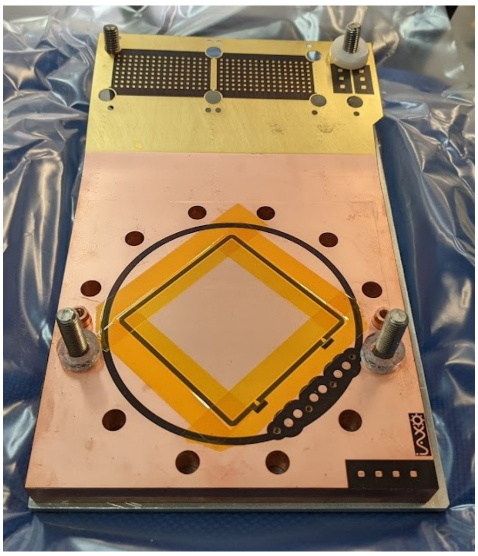
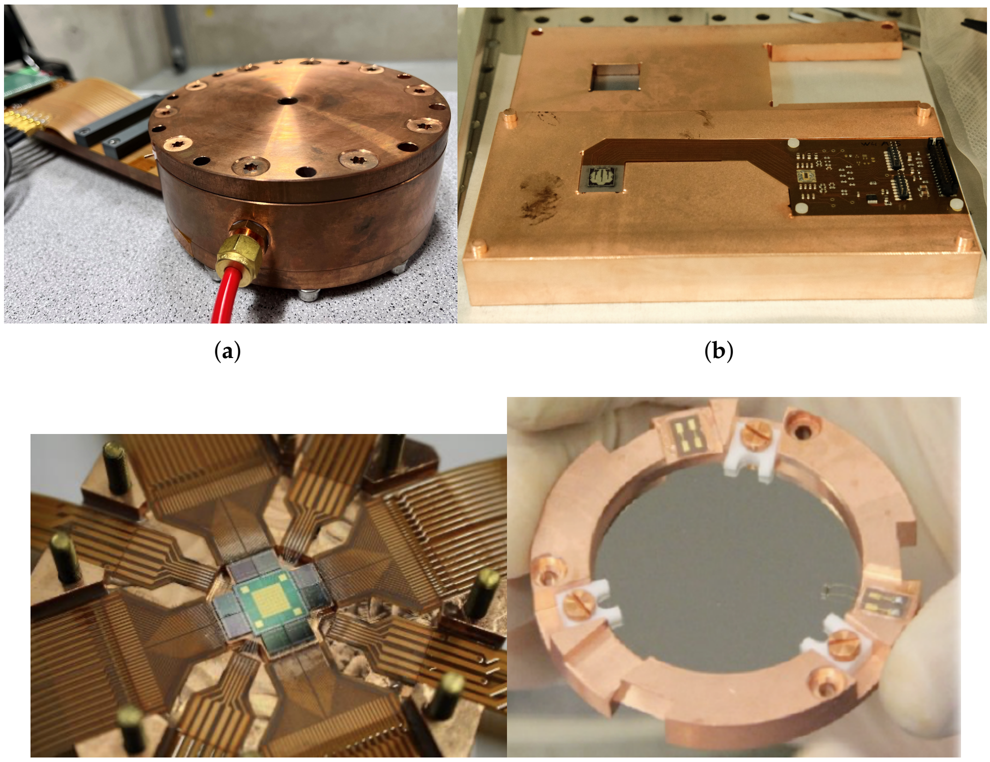


Figure 8. A Micromegas detection plane from the University of Zaragoza and CEA Saclay. ©CAPA.

Other detectors that are being considered can be sensitive to lower or higher energy X-rays, have a higher efficiency, or a higher energy resolution. These include a GridPix detector from the University of Bonn, a silicon drift detector (SDD) from MPIK and HLL, a metallic magnetic calorimeter (MMC) detector array from Heidelberg University [11], and a transition edge sensor (TES) from IJCLab. These can be seen in Figure 9. The detection setup will also include passive lead shielding and active shielding in the form of a muon veto.



(a) (b) (c) (d)

Figure 9. Different detector options for BabyIAXO. (**a**) A GridPix detector from the University of Bonn. (**b**) A silicon drift detector (SDD) from MPIK and HLL. (**c**) A metallic magnetic calorimeter (MMC) detector array from Heidelberg University. (**d**) A transition edge sensor (TES) from IJCLab.

BabyIAXO has been simulated for different applications. In addition to calculating the sensitivity to axion–photon coupling [8], a ray tracer has been used to quantify the challenges of the setup. Figure 10 shows the simulated signal distribution at the detection plane of an optimal alignment of all components. With the help of the ray tracer, the signal loss of a misaligned system was calculated to gather information about the accepted amount of misalignment and factor in gravitational effects. One of the main results is that the accepted movement of the detector side at 99% efficiency is (1.45 ± 0.32) mm downward and at the magnet side, it is (1.12 ± 0.25) mm downward, which is more than the simulated deformation differences due to gravity during operation.

In addition to this, the mainly cosmic background has been simulated, followed up by measurements at DESY that are still ongoing.

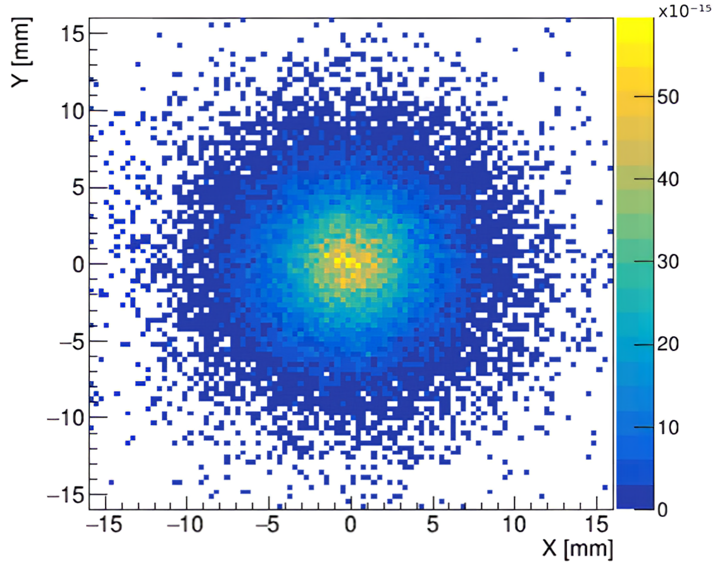


Figure 10. The simulated signal at the detection plane, ray tracing through all of the components. This simulation has been performed with the Primakoff flux, the XMM optic, and with REST for Physics v2.4.1. The source code for this can be found here: [12].

4. Discussions and Outlook

IAXO has been proposed to be built as a next-generation helioscope, with BabyIAXO as its intermediate stage. Both experiments are expected to search for axions in a relevant parameter space. The various components of BabyIAXO are in active development and have seen substantial advancements over the past few years.

Beyond the baseline use of IAXO and BabyIAXO, there are many plans and proposals for further investigations. This includes a gas phase where the magnet bores are filled with gas, which allows for the detection of heavier axions [13].

In addition to this, the sensitivity to other axion production models than the Primakoff and ABC flux can be studied. These include the detection of the 14.4 keV axion line from the de-excitation of solar ^{57}Fe nuclei [14] and the detection of the flux of axions produced in a solar magnetic field [15]. Figure 11 shows the energy spectrum of a KSVZ axion model with those effects included.

Detecting axions produced from longitudinal plasmons in a solar magnetic field would provide valuable insights into the Sun's magnetic field profile [16]. Additional post-discovery proposals include using the ABC axion flux to probe solar metallicity [17] and gaining information on the solar temperature profile [18].

Beyond solar axions, other potential sources have been considered for IAXO and BabyIAXO. These include dark matter axions by converting BabyIAXO into a haloscope using the RADES setup with integrated resonant cavities [19], as well as the detection of supernova axions using a helium–γ (He-γ) detector [20].

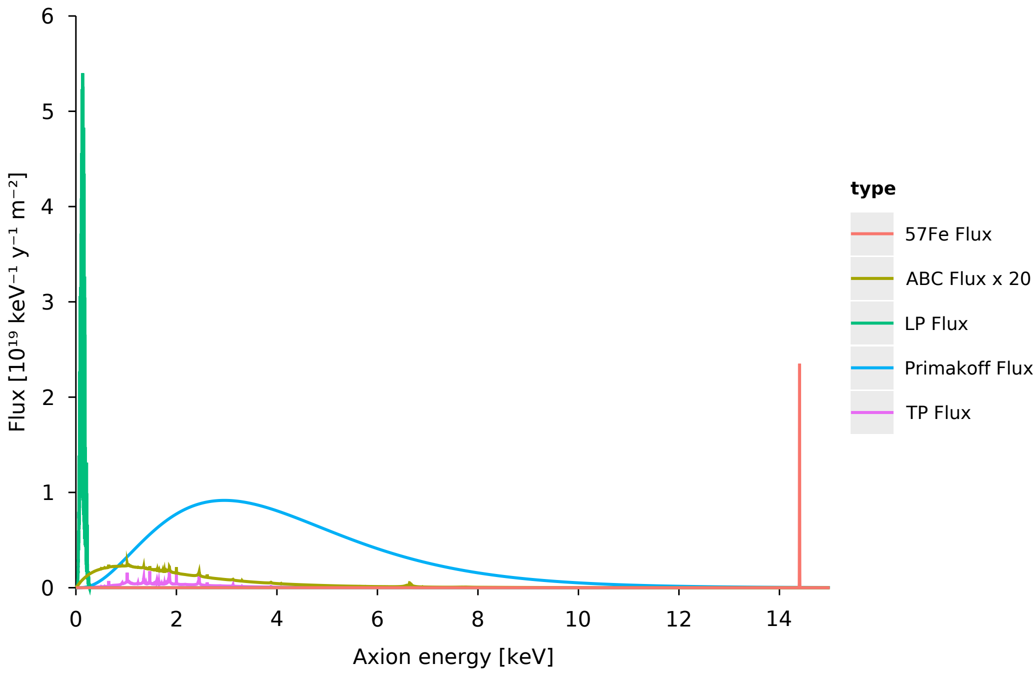


Figure 11. The simulated axion flux for KSVZ model axions including the flux from ^{57}Fe and longitudinal (LP) and transverse (TP) plasmon interactions in the solar core's magnetic field. The coupling strengths used here are $g_{a\gamma} = 2 \times 10^{-12}$ GeV^{-1}, $g_{ae} = 2 \times 10^{-15}$, and $g_{aN} = 10^{-9}$. The calculations of these can be seen in [14,15].

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Appendix A. The IAXO Collaboration

S. Ahyoune, K. Altenmüller, I. Antolín, S. Basso, P. Brun, V. Burwitz, F. R. Candón, J. F. Castel, S. Cebrián, D. Chouhan, R. Della Ceca, M. Cervera-Cortés, M. M. Civitani, C. Cogollos, E. Costa, V. Cotroneo, T. Dafní, K. Desch, M. C. Díaz-Martín, A. Díaz-Morcillo, D. Díez-Ibáñez, C. Diez Pardos, M. Dinter, B. Döbrich, A. Dudarev, A. Ezquerro, S. Fabiani, E. Ferrer-Ribas, F. Finelli, I. Fleck, J. Galán, G. Galanti, M. Galaverni, J. A. García, J. M. García-Barceló, L. Gastaldo, M. Giannotti, A. Giganon, C. Goblin, N. Goyal, Y. Gu, L. Hagge, L. Helary, D. Hengstler, D. Heuchel, S. Hoof, R. Iglesias-Marzoa, F. J. Iguaz, C. Iñiguez, I. G. Irastorza, K. Jakovčić, D. Käfer, J. Kaminski, S. Karstensen, M. Law, A. Lindner, M. Loidl, C. Loiseau, G. López-Alegre, A. Lozano-Guerrero, G. Luzón, I. Manthos, C. Margalejo, A. Marín-Franch, J. Marqués, F. Marutzky, C. Menneglier, M. Mentink, S. Mertens, J. Miralda-Escudé, H. Mirallas, F. Muleri, J. R. Navarro-Madrid, X. F. Navick, K. Nikolopoulos, A. Notari, L. Obis, A. Ortiz-de-Solórzano, T. O'Shea, J. von Oy, G. Pareschi, T. Papaevangelou, K. Perez, O. Pérez, E. Picatoste, M. J. Pivovaroff, J. Porrón, M. J. Puyuelo, A. Quintana, J. Redondo, D. Reuther, A. Ringwald, M. Rodrigues, A. Rubini, S. Rueda-Teruel, F. Rueda-Teruel, E. Ruiz-Chóliz, J. Ruz, J. Schaffran, T. Schiffer, S. Schmidt, U. Schneekloth, L. Schönfeld, M. Schott, L. Segui, U. R. Singh, P. Soffitta, D. Spiga, M. Stern, O. Straniero, F. Tavecchio, G. Vecchi, J. K. Vogel, R. Ward, A. Weltman, C. Wiesinger, R. Wolf, A. Yanes-Díaz, Y. Yu.

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