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X-ray observations and their applications to the physics of axions (or other WISPs)

J. Ruz[a,b,*]

[a]*Fakultät für Physik. Technische Universität Dortmund,*
Dortmund, D-44221, Germany

[b]*Centro de Astropartículas y Física de Altas Energías. University of Zaragoza.*
Zaragoza, 50009, Spain

E-mail: `Jaime.Ruz@tu-dortmund.de`

Axion helioscopes search for solar axions by exploiting their conversion into X-ray photons within strong magnetic fields via the Primakoff effect. The Sun provides an intense and well-characterized axion source, as axions can be produced in its core through photon–plasma interactions. By aligning powerful magnets with the solar direction and employing low-background X-ray detectors, helioscopes aim to detect these converted photons as a direct experimental signature of axion–photon coupling.

In addition to this laboratory approach, axion from thermal photons in the solar core may reconvert into X-rays within the magnetic fields of the solar atmosphere, producing a faint, spatially extended, and spectrally distinct X-ray signal that could be detectable by dedicated satellite missions.

Axion production mechanisms are also enabled in other stellar environments. Nearby red supergiants such as Betelgeuse represent particularly promising targets: their hot cores can generate substantial ALP fluxes that reconvert into X-rays within Galactic magnetic fields, while the absence of stable coronae reduces conventional X-ray backgrounds. Dedicated NuSTAR observations of Betelgeuse have already placed competitive limits on the couplings $g_{a\gamma}$, g_{ae}, and g_{aN}, improving upon CAST constraints and approaching the sensitivities expected for next-generation experiments such as ALPS-II and BabyIAXO. Complementary searches in nearby systems, including the Alpha Centauri binary, M82 and M87 further explore scenarios involving gravitationally trapped ALPs decaying into monochromatic X-rays, providing robust, multi-channel constraints on axion and ALP interactions across diverse astrophysical sources.

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[*]Speaker

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1. Introduction

Axions, light pseudo-scalar boson particles, arising from the Peccei–Quinn (PQ) mechanism [1–3] are a compelling solution to the strong CP problem and are one of the candidates to cold dark matter [4]. More generally, many extensions of the SM predict axion-like particles (ALPs) [5], which, like axions, couple weakly to photons through $\mathcal{L}_{a\gamma} = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$, enabling photon–axion conversion in electromagnetic fields [4, 6].

The Sun provides a natural laboratory for exploring such particles. In its core, thermal photons can convert into axions via the Primakoff process [7], producing an intense flux that may reconvert into X-rays in the presence of strong magnetic fields [4] (see Fig. 1). To detect these signals, dedicated axion helioscopes have been developed. The first, in Tokyo in the 1990s [8], was later succeeded by the CERN Axion Solar Telescope (CAST) [9], one of the most sensitive axion searches to date. Its successor, the International Axion Observatory (IAXO) [10], aims to further improve sensitivity using a large-scale magnet, advanced optics, and next-generation detectors.

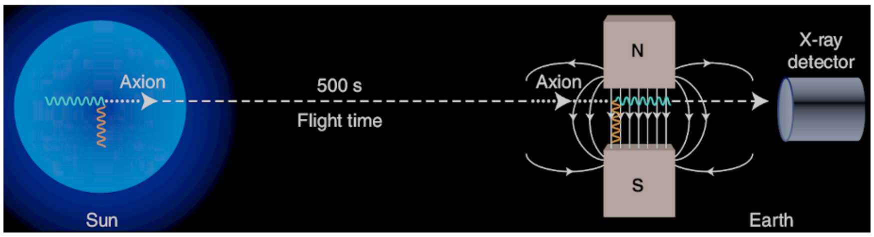

Figure 1: The Primakoff effect occurring in the hot solar core via the $a - \gamma\gamma$ vertex. On Earth, the inverse process in an external magnetic field that converts the 'invisible' axion into an observable photon [11].

2. Expected X-ray signals from solar axion physics

Accurate models of the solar axion flux are well established [12, 13], with the Primakoff process remaining the dominant production channel for hadronic (KSVZ-type) axions (see Fig. 2). Beyond

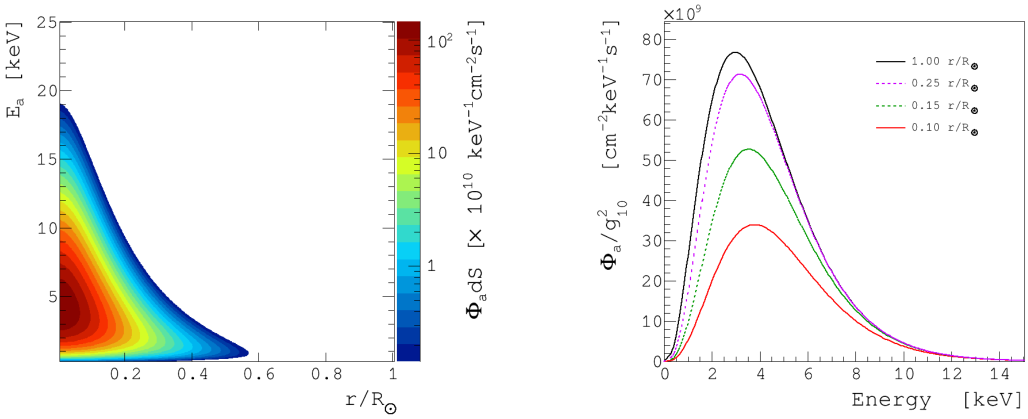

Figure 2: Left: Solar axion surface luminosity as a function of energy and solar radius r. **Right:** Differential axion spectra for different r values. Figures adapted from [14].

the Primakoff process, additional hadronic and non-hadronic axion emission channels contribute to the solar flux. In hadronic models, the M1 transition of ^{57}Fe proceeds via the axion–nucleon coupling, producing a monoenergetic axion line (14.4 keV) [15]. In non-hadronic (DFSZ-type) scenarios, axions can couple to electrons, giving rise to additional emission via bremsstrahlung, Compton scattering, and atomic transitions [16].

A new helioscope approach [17] has recently studied potential X-ray signatures from solar axions in X-ray satellite missions. This new method takes into account the possibility of core-produce axions to convert into X-rays in the extensive magnetic fields of the solar atmosphere. Fig. 3 presents the expected photon flux originating from the inner solar region, $r < 0.1\,R_\odot$, to be detected by an Earth-orbiting satellite. For $m_a \gtrsim 10^{-6}$ eV, despite the conversion probability being satisfied, absorption and scattering by free electrons and atomic species (H, He) in the solar atmosphere suppress the photon signal before it can reach Earth.

3. Latest X-ray Observations of the Sun

The CERN Axion Solar Telescope (CAST) has conducted the longest and most sensitive helioscope search for solar axions, operating at CERN from 2003 to 2021 using a 9 T, 10 m superconducting dipole magnet to convert axions into X-rays via the inverse Primakoff effect [9]. The magnet tracked the Sun, with X-rays detected by low-background detectors at its ends. CAST evolved from an initial vacuum phase [9, 14] to "gas phases" using ^{4}He [18, 19] and ^{3}He [20, 21], restoring coherence and extending sensitivity up to ~ 1.17 eV. In its final stage, it returned to vacuum operation with improved detectors, including the IAXO pathfinder line [22], which combined Micromegas detectors with a focusing X-ray telescope based on NuSTAR technology [23], demonstrating key concepts for the future International Axion Observatory (IAXO) [10].

In its final operational phase (2019–2021), CAST and the IAXO pathfinder line improved upon the 2017 data by increasing exposure and optimizing detector performance. The Micromegas detectors were filled with a xenon-based gas mixture, providing enhanced stopping power and energy resolution, and offering valuable technical insights for the future Xe-based detectors of IAXO. No excess counts were observed, leading to the most stringent CAST bound to date on the solar axion–photon coupling [24]. Complementing ground-based helioscopes, the Nuclear

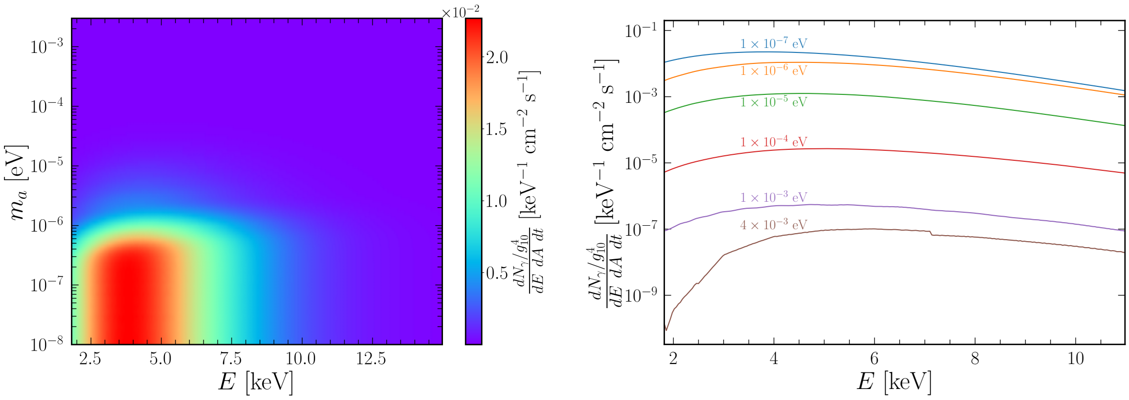

Figure 3: Left: Photons reaching the NuSTAR satellite from Primakoff conversion in the solar atmosphere ($g_{10} = g_{a\gamma}/10^{-10}\,\mathrm{GeV}^{-1}$). **Right:** X-ray spectra for different axion masses. Figures adapted from [17].

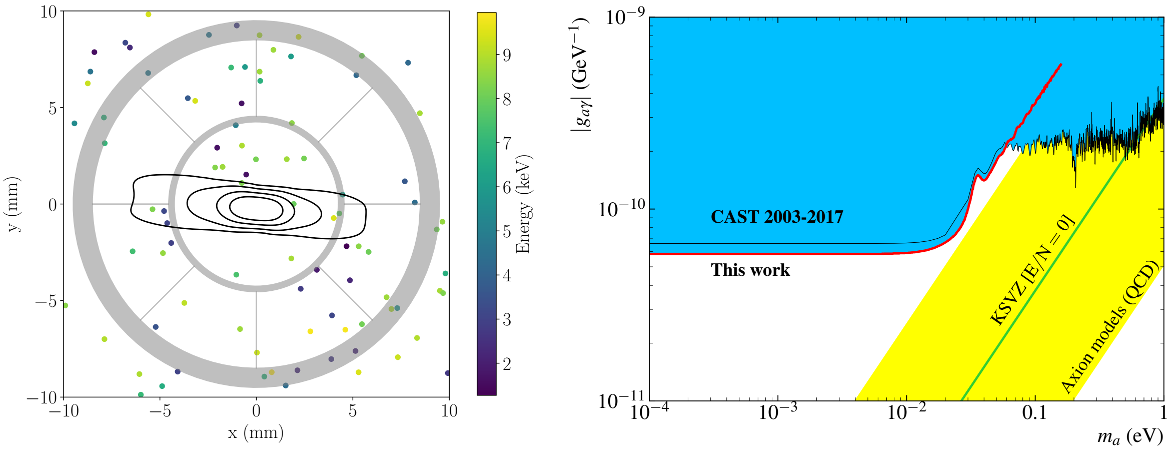

Figure 4: Left: Hitmap of detected events during solar-tracking runs. Contours represent 68%, 85%, 95%, and 99% axion signal-encircling regions. **Right:** CAST new exclusion limit (red), improving upon previous constraints (black). Figures adapted from [24].

Spectroscopic Telescope Array (NuSTAR) has recently opened a new observational channel for solar axion searches [17]. The observation occurred during solar minimum, suppressing contamination from active regions and flares. No significant excess was detected, and the resulting non-observation led to the most restrictive limits on $g_{a\gamma}$ obtained from a helioscope to date, surpassing CAST in certain mass ranges (see Fig. 5).

4. Stellar ALP Production and X-ray Observational Constraints from Betelgeuse

Nearby red supergiants are ideal laboratories for axion searches [25]. Stars such as Betelgeuse and Antares are particularly promising candidates: their hot cores can generate substantial axion fluxes that may reconvert into photons within the Galactic magnetic field, producing potential X-ray

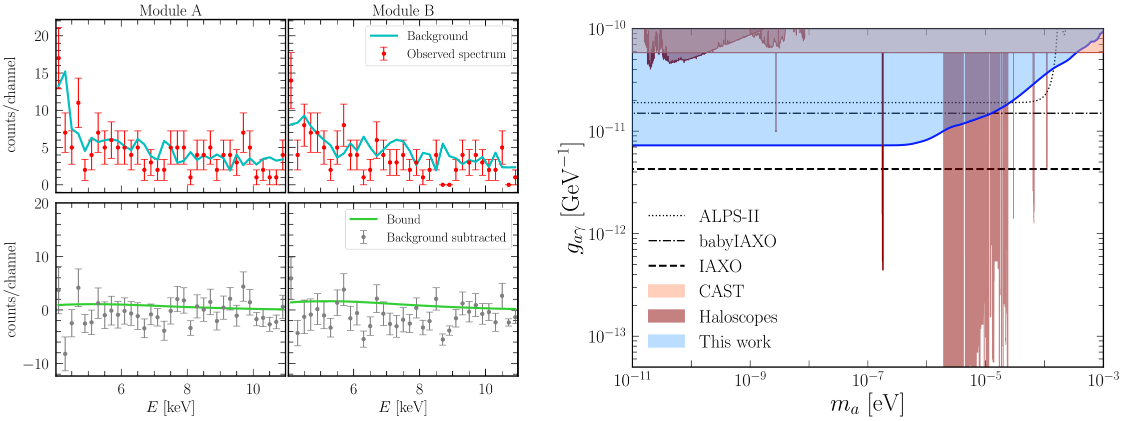

Figure 5: Left: NuSTAR observed spectra for modules A and . The background-subtracted spectrum (bottom) shows the expected axion spectral shape (green) at 95% CL. **Right:** NuSTAR 95% C.L. exclusion on the axion–photon coupling $g_{a\gamma}$ (blue), compared to previous constraints. Figures adapted from [17].

signals [26]. This strategy can be extended to other supergiants and clusters of hot, young stars, with nearby objects benefiting from relatively well-constrained local magnetic fields. Dedicated NuSTAR observations of Betelgeuse have been employed to set limits on the $g_{a\gamma}$, g_{ae}, and g_{aN} couplings. These limits improve upon those from CAST by a factor of a few and are comparable to the sensitivities projected for next-generation laboratory experiments such as ALPS-II [27] and BabyIAXO [10], while remaining competitive with bounds derived from SN 1987A observations [28]. The agreement among independent astrophysical limits, each based on distinct stellar modeling assumptions, reinforces the robustness of these constraints.

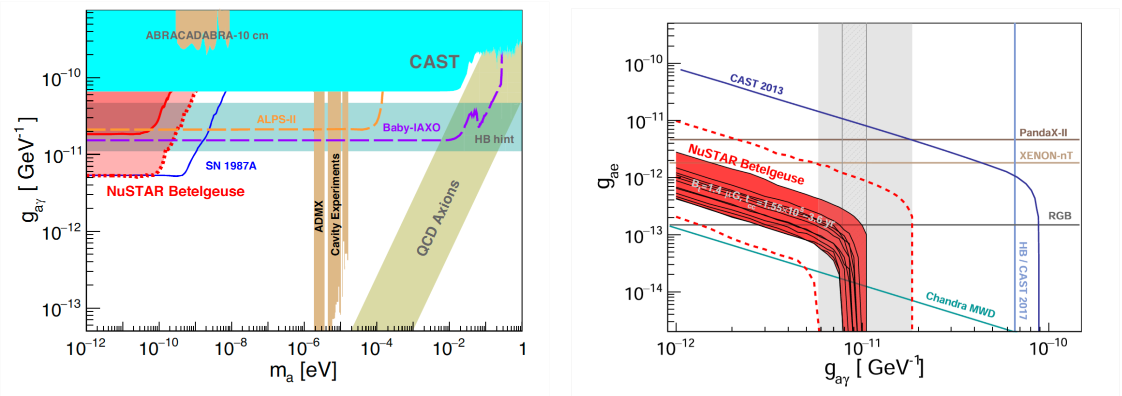

Figure 6: Constraints on axion couplings from NuSTAR observations of Betelgeuse. **Left:** 95% C.L. upper limits on the axion–photon coupling $g_{a\gamma}$ [26]. **Right:** 95% C.L. limits on the axion–electron coupling $g_{ae} - g_{a\gamma}$ for $m_a \lesssim 3.5 \times 10^{-11}$ eV [29].

Recently, the ^{57}Fe axion emission channel has been investigated for Betelgeuse using NuSTAR [30], yielding the most stringent experimental constraints to date on the axion–nucleon coupling for axion masses below $\sim 10^{-10}$ eV (see Fig. 7).

5. X-ray Searches for Axions from M82/M87 and Alpha-Centauri

The NuSTAR telescope has increasingly been employed in astrophysical searches for axions, extending its application beyond the Sun to other stellar systems and galaxies. In particular, high-energy axions are expected to be produced in the cores of hot, massive stars—primarily red supergiants (RSGs) and O-type stars—in galaxies such as M82 or in the central region of the M87

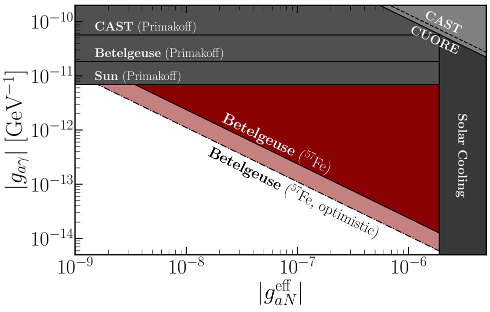

Figure 7: Betelgeuse $g_{a\gamma} - g_{aN}^{eff}$ (95% CL) exclusion limits compared to previous ^{57}Fe searches [30].

galaxy of the Virgo Cluster. These axions could then convert into X-rays in the strong magnetic fields present in these environments, providing a potential observational signature [31].

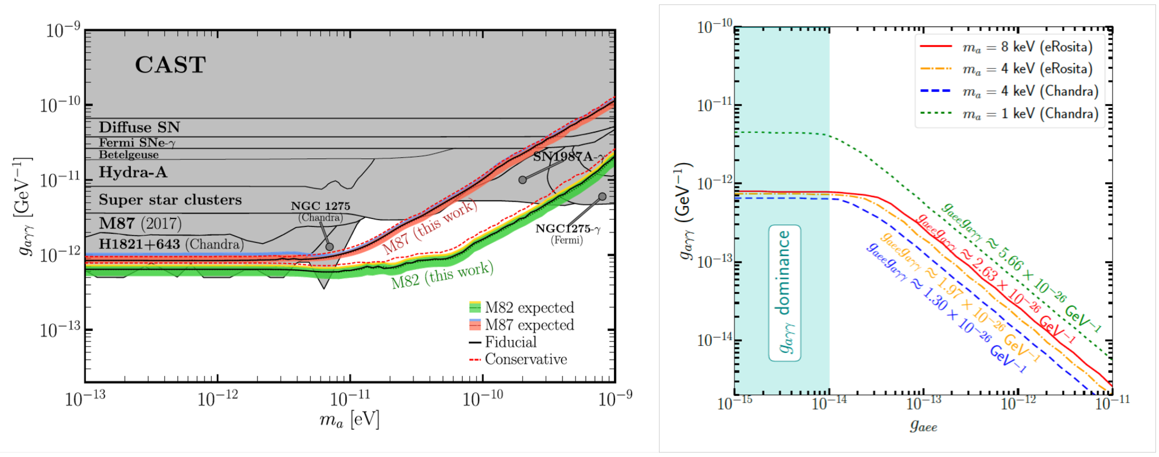

Figure 8: Left: M82 and M87 constraints on $g_{a\gamma}$ (95% CL) from *NuSTAR* [31]. **Right:** Upper limits on $g_{a\gamma} - g_{ae}$ (95% CL) from the Alpha Centauri X-ray observations with *Chandra* and *eROSITA* [32].

In addition, nearby stellar systems offer complementary opportunities to probe low-energy axions. For example, the Alpha Centauri binary system, our closest stellar neighbor consisting of Alpha Centauri A and B, could gravitationally trap low-energy axion-like particles (ALPs), which would eventually decay into two photons. Sensitive X-ray observatories such as *Chandra* and *eROSITA* can search for these decay signals as monochromatic X-ray lines. Dedicated searches in the energy range of 0.2–10 keV have so far yielded null results, allowing us to set the most stringent experimental limits on ALP interactions to date [32].

6. Results and Conclusions

The combined analysis of solar, stellar, and extragalactic X-ray datasets provides the most comprehensive limits to date on axion and ALP couplings to photons, electrons, and nucleons across a broad mass range. Solar searches using CAST set a limit of $g_{a\gamma} \lesssim 6.6{\times}10^{-11}$ GeV^{-1} (95% CL) for $m_a \lesssim 0.02$ eV [24], while the IAXO pathfinder validated next-generation helioscope technologies; complementary NuSTAR observations of the solar core improved this to $g_{a\gamma} \lesssim 7.3 \times 10^{-12}$ GeV^{-1} for $m_a \lesssim 4 \times 10^{-7}$ eV [17], representing the strongest X-ray helioscope bounds to date. Beyond the Sun, NuSTAR studies of Betelgeuse constrained $g_{a\gamma}$, g_{ae}, and provided the most stringent limits so far on g_{aN}, with sensitivities comparable to BabyIAXO projections, while extragalactic observations of M82 and M87 further limited ultralight axions. Additional analyses with Chandra and eROSITA of Alpha Centauri found no decay-line signals, tightening bounds on both photon and electron couplings, collectively demonstrating the strong synergy between laboratory and astrophysical approaches in precision X-ray searches for axions.

7. Acknowledgments

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References

[1] R. D. Peccei and H. R. Quinn. Cp conservation in the presence of instantons. *Phys. Rev. Lett.*, 38:1440, 1977.

[2] S. Weinberg. A new light boson? *Phys. Rev. Lett.*, 40:223, 1978.

[3] F. Wilczek. Problem of strong p and t invariance in the presence of instantons. *Phys. Rev. Lett.*, 40:279, 1978.

[4] P. Sikivie. Experimental tests of the invisible axion. *Phys. Rev. Lett.*, 51:1415, 1983.

[5] J. Jaeckel and A. Ringwald. The low-energy frontier of particle physics. *Ann. Rev. Nucl. Part. Sci.*, 60:405, 2010.

[6] G. G. Raffelt and L. Stodolsky. Mixing of the photon with low mass particles. *Phys. Rev. D*, 37:1237, 1988.

[7] G. G. Raffelt. Astrophysical axion bounds diminished by screening effects. *Phys. Rev. D*, 33:897, 1986.

[8] S. Moriyama et al. Direct search for solar axions by using strong magnetic field and x-ray detectors. *Phys. Lett. B*, 434:147, 1998.

[9] K. Zioutas et al. (CAST Collaboration). First results from the cern axion solar telescope (cast). *Phys. Rev. Lett.*, 94:121301, 2005.

[10] E. Armengaud et al. (IAXO Collaboration). Physics potential of the international axion observatory (iaxo). *JCAP*, 2019(06):047, 2019.

[11] K. Zioutas et al. Solar x-rays from axions: Conversion of solar axions into photons in the earth's magnetic field. *New J. Phys.*, 11:105020, 2009.

[12] G. G. Raffelt. Astrophysical axion bounds. *Lect. Notes Phys.*, 741:51, 2008.

[13] P. Carenza and J. Redondo. Updated solar axion flux from the primakoff process. *Phys. Rev. D*, 109:083005, 2024.

[14] S. Andriamonje et al. (CAST Collaboration). An improved limit on the axion,Äìphoton coupling from the cast experiment. *JCAP*, 2007(04):010, 2007.

[15] S Andriamonje et al. (CAST Collaboration). Search for solar axions from 14.4 kev ^{57}fe transitions. *Phys. Rev. Lett.*, 107:261302, 2011.

[16] K. Barth et al. (CAST Collaboration). Cast constraints on the axion-electron coupling. *JCAP*, 2013(05):010, 2013.

[17] J. Ruz et al. Nustar as an axion helioscope. *Phys. Rev. Lett.*, 135:141001, 2025.

[18] E. Arik et al. (CAST Collaboration). Probing ev-scale axions with cast. *JCAP*, 02:008, 2009.

[19] M. Arik et al. (CAST Collaboration). New solar axion search using the cern axion solar telescope with ^{4}He filling. *Phys. Rev. D*, 92:021101, 2015.

[20] S. Aune et al. (CAST Collaboration). Cast search for solar axions in the ^{3}he phase. *Phys. Rev. Lett.*, 107:261302, 2011.

[21] M. Arik et al. (CAST Collaboration). Search for solar axions by the cern axion solar telescope with ^{3}He buffer gas: Closing the hot dark matter gap. *Phys. Rev. Lett.*, 112:091302, 2014.

[22] F. Aznar et al. Micromegas detectors for the iaxo pathfinder and future axion experiments. *JINST*, 10:P11011, 2015.

[23] F. A. Harrison et al. The nuclear spectroscopic telescope array (nustar) high-energy x-ray mission. *Astrophys. J.*, 770:103, 2013.

[24] K. Altenmüller et al. (CAST Collaboration). New upper limit on the axion-photon coupling with an extended cast run with a xe-based micromegas detector. *Phys. Rev. Lett.*, 133:221005, 2024.

[25] M. Giannotti. Stellar evolution bounds on the alp-photon coupling: new results and perspectives. In *10th Patras Workshop on Axions, WIMPs and WISPs (Patras 2014)*, 2014. Contributed talk; arXiv:1409.7981.

[26] M. Xiao et al. Constraints on axion-like particles from a hard x-ray observation of betelgeuse. *Phys. Rev. Lett.*, 126(3):031101, 2021.

[27] R. Bähre et al. Any light particle search ii — technical design report. *Journal of Instrumentation*, 8(09):T09001, 2013.

[28] Michael S. A. Burrows, M. S. Turner and R. P. Brinkmann. Axions and sn 1987a. *Phys. Rev. D*, 39:1020–1028, 1989.

[29] M. Xiao et al. Betelgeuse constraints on coupling between axionlike particles and electrons. *Phys. Rev. D*, 106:123019, 2022.

[30] F. R. Candón et al. Probing the axion-nucleon coupling with supergiant stars. *arXiv:2504.21107*, 2025.

[31] O. Ning and B. R. Safdi. Leading axion–photon sensitivity with nustar observations of m82 and m87. *Phys. Rev. Lett.*, 134(17):171003, 2025.

[32] Yu-Xuan Chen et al. Searching for axion-like particles with x-ray observations of alpha centauri. *Phys. Rev. Lett.*, 134(24):241001, 2025.