

Probing the axion-nucleon coupling with supergiant stars

Francisco R. Candón^{1,2}, Pablo Casaseca², Maurizio Giannotti², Mathieu Kaltschmidt²,
Jaime Ruz^{1,2} and Julia K. Vogel^{1,2}

¹*Fakultät für Physik, TU Dortmund, Otto-Hahn-Straße 4a, Dortmund D-44221, Germany*

²*CAPA and Departamento de Física Teórica, Universidad de Zaragoza,
C. Pedro Cerbuna 12, 50009 Zaragoza, Spain*



(Received 20 May 2025; accepted 5 December 2025; published 29 December 2025)

A finite axion-nucleon coupling enables the production of axions in stellar environments via the thermal excitation and subsequent deexcitation of the ^{57}Fe isotope. Given its low-lying excited state at 14.4 keV, ^{57}Fe can be efficiently excited in the hot cores of supergiant stars, possibly leading to axion emission. The conversion of these axions into photons in the Galactic magnetic field results in a characteristic 14.4 keV line, potentially detectable by hard x-ray telescopes such as NASA's Nuclear Spectroscopic Telescope Array (NuSTAR). In this work, we present the first constraints on axion-nucleon couplings derived from NuSTAR observations of Betelgeuse and discuss the potential insights that could be gained from detecting this line in other nearby supergiants. Our results establish significantly more stringent bounds than those obtained from solar observations, setting a limit of $|g_{a\gamma}g_{aN}^{\text{eff}}| < (1.2\text{--}2.7) \times 10^{-20} \text{ GeV}^{-1}$ for $m_a \lesssim 10^{-10} \text{ eV}$.

DOI: [10.1103/xv5c-j2rv](https://doi.org/10.1103/xv5c-j2rv)

I. INTRODUCTION

The QCD axion, often known just as axion, is a hypothetical pseudoscalar particle that emerges as an unavoidable consequence of the Peccei-Quinn solution of the strong CP problem in QCD [1–4]. In addition to the QCD axion, many extensions of the Standard Model (SM), particularly those inspired by string theory, predict the existence of axionlike particles (ALPs), which share similar properties but are not necessarily tied to the strong CP problem [5–12]. These particles are well-motivated candidates for new physics and can be probed through their weak interactions with SM particles.¹

¹Throughout this paper, we use the terms “axion” and ALP interchangeably. However, our analysis focuses on generic ALPs rather than QCD axions. This choice is motivated by the ultralight masses required for efficient photon-ALP conversion in the Galactic magnetic field (see, e.g., Refs. [13,14]). Benchmark QCD axion models predict extremely small couplings at these masses [15], placing them outside the reach of our study. As our discussion focus on ALPs, we ignore any specific relation between the mass and the different couplings. Nevertheless, specific theoretical frameworks—such as the clockwork mechanism discussed in Ref. [16]—can yield viable combinations of photon and nucleon couplings even within QCD axion models.

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

A key feature of axions and ALPs is their coupling to photons, nucleons, and electrons, leading to a variety of potential experimental signatures. While most studies focus on the axion-photon interaction, due to its direct detectability in laboratory experiments and astrophysical observations [15,17–22], the coupling to nucleons remains an important but challenging target. In QCD axion models, the nucleon coupling gets a contribution from the axion-gluon interaction, and its measurement could provide critical information about the axion's underlying theory [15,23]. However, direct experimental probes of this interaction are scarce, and most constraints arise from astrophysical and cosmological considerations [24–39].

A promising venue to probe the axion-nucleon interaction is through nuclear transitions in astrophysical environments. As pseudoscalar particles, axions can be emitted in magnetic dipole (M1) nuclear transitions, a possibility already mentioned in the original axion proposal [1] and later developed, particularly in Ref. [40]. One of the most studied cases is the 14.4 keV transition of ^{57}Fe , which occurs when its first excited state decays to the ground state. Axions produced in this process can convert into x-ray photons in the presence of a Galactic or laboratory magnetic field via the Primakoff effect. This mechanism has been extensively studied in the Sun, where ^{57}Fe is relatively abundant, leading to constraints from dedicated axion searches such as CAST [41], CUORE [42], and XENON1T [43]. However, the Sun, with a core temperature of $\approx 1 \text{ keV}$, is not an optimal environment for

axion searches via nuclear transitions. Supergiant stars, with core temperatures significantly higher than those of main-sequence (MS) stars like the Sun, offer a compelling alternative. In fact, the axion emission rate in nuclear deexcitations depends steeply on the temperature, making hotter stellar environments much more efficient sources. A particularly interesting case is the red supergiant Betelgeuse, located in the constellation of Orion at approximately 200 pc from Earth. This target is especially promising because observational data from the hard x-ray telescope aboard the Nuclear Spectroscopic Telescope Array (NuSTAR) already exists [13], providing an opportunity to search for an axion-induced 14.4 keV line. Since this signature would appear as a monochromatic feature rather than a broad continuum, it offers a key observational advantage, as it is easier to distinguish from astrophysical backgrounds. Furthermore, its detection could provide crucial insights into stellar properties. In particular, if the line could be resolved in future observations, it could offer a new probe of the core temperature as well as information on the rotational dynamics of the core, a quantity otherwise difficult to measure directly.

In this work, we present the first experimental axion search from ^{57}Fe nuclear decay in a star other than the Sun. While our analysis does not find any significant evidence for nonstandard physics, it allows us to set the strongest experimental bound on the axion-nucleon coupling for axion masses below $\sim 10^{-10}$ eV. The results, shown in Fig. 1, demonstrate that our constraints are orders

of magnitude stronger than those obtained from previous experimental searches. Similar studies with other nearby supergiants are possible and thus future observations could further improve these bounds.

II. AXION FLUX FROM NUCLEAR TRANSITIONS IN SUPERGIANTS

The axion production in stellar environments has been extensively studied and reviewed in the last decades [22,47–52]. This production is mediated by the axion interaction with SM fields, described by the Lagrangian

$$\mathcal{L}_{\text{int}} = -\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \sum_i g_{af}a\bar{f}\gamma_5 f, \quad (1)$$

where F is the electromagnetic field strength, $\tilde{F}$ its dual, and f the fermion fields.

Axions produced in nuclear fusion and decay processes typically carry energies on the order of $\sim \text{MeV}$. For instance, the $p + d \rightarrow {}^3\text{He} + a$ reaction, which generates an axion flux at 5.5 MeV, has been experimentally investigated by Borexino [53], CAST [54], and more recently analyzed using SNO data [55]. The potential for detecting such axions in next-generation experiments has also been explored in [56,57]. However, the flux of axions from these reactions in the Sun is typically low, with an estimated rate of $d\dot{N}/dA \approx 10^{10}(g_{aN}^3)^2/(\text{cm}^2 \text{ s})$ [54]. In contrast, axions produced via nuclear deexcitations, such as the 14.4 keV transition of ^{57}Fe , offer significant advantages in environments where the temperature exceeds the excitation energy. At temperatures above ~ 14.4 keV, a substantial fraction of ^{57}Fe nuclei populate their first excited state, greatly enhancing the axion production rate. This condition is naturally met in supergiant stars, whose core temperatures reach 20 keV or higher, making them particularly efficient axion sources.

The axion emission rate per unit mass of stellar matter can be expressed as

$$\dot{\mathcal{N}}_a = \mathcal{N}\omega_1(T)\frac{1}{\tau_0}\frac{1}{1+\alpha}\frac{\Gamma_a}{\Gamma_\gamma}, \quad (2)$$

where $\mathcal{N}$ is the ^{57}Fe number density per solar mass, ω_1 the occupation number of the first excited state

$$\omega_1(T) = \frac{(2J_1 + 1)e^{-E^*/T}}{(2J_0 + 1) + (2J_1 + 1)e^{-E^*/T}}, \quad (3)$$

$\tau_0 = 141$ ns the lifetime of the excited state, $\alpha = 8.56$ the internal conversion coefficient (see, e.g., Refs. [46,58,59]), $E^* = 14.4$ keV the excitation energy, T the local temperature, and J_0 and J_1 the angular momenta of the ground and excited states, respectively. Finally, the ratio Γ_a/Γ_γ represents the branching fraction for axion emission relative to

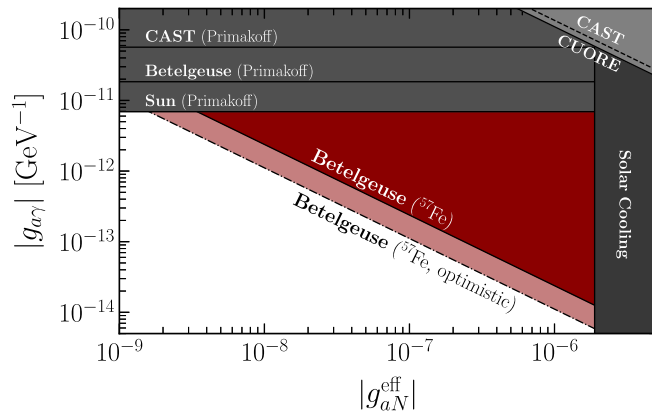


FIG. 1. Exclusion limits from the Bayesian unbinned likelihood analysis at 95% confidence level (CL), in the case of massless axions compared to previous ^{57}Fe studies. Our conservative results ($B_T = 1.4 \mu\text{G}$) are displayed in dark red and a more optimistic bound, using $B_T = 3.0 \mu\text{G}$, in a lighter red. Shown are the latest bounds on the axion-photon coupling $|g_{a\gamma}|$ from CAST [44] (dashed) and results from the Nuclear Spectroscopic Telescope Array (NuSTAR) observations of Betelgeuse [13] and the Sun [45] are gray, the solar cooling bound on the effective axion-nucleon coupling $|g_{aN}^{\text{eff}}|$ [46] in darker gray and results of searches for the 14.4 keV line of ^{57}Fe similar to this work from CAST [41] (dashed) and CUORE [42] in a lighter gray.

photon emission. In the case of ^{57}Fe deexcitation,

$$\frac{\Gamma_a}{\Gamma_\gamma} = 2.32(0.16g_{ap} + 1.16g_{an})^2. \quad (4)$$

From the form of Eq. (4), it is convenient to define the effective nucleon coupling as [46]

$$g_{aN}^{\text{eff}} = 0.16g_{ap} + 1.16g_{an}, \quad (5)$$

which is the coupling combination that controls the axion emission rate in this transition.

For all practical purposes, the axion emission from the deexcitation of ^{57}Fe appears as a spectral line for NuSTAR. The line can be modeled by a Gaussian distribution centered at $E^* = 14.4$ keV and with a total width σ_{tot} . The largest contribution to the line width is the thermal spread [46],

$$\sigma_{\text{th}}(T) = E^* \sqrt{T/m_{\text{Fe}}}, \quad (6)$$

with T the local temperature and m_{Fe} the mass of the ^{57}Fe nucleus. For the typical temperatures expected in the core of a supergiant star such as Betelgeuse during the post-MS evolutionary stages, the thermal width is expected to be $\sigma_{\text{th}}(T) \sim \mathcal{O}(10 \text{ eV})$, and can vary by a factor of a few over the course of the stellar evolution. This is substantially narrower than the instrument resolution at the relevant energies. The width is further broadened by the rotation of the core. To obtain a rough estimate of this contribution, we can start from Betelgeuse's equatorial velocity v_{eq} . Reference [60] reports $v_{\text{eq}} \sin \theta \approx 5.47 \text{ km/s}$, where θ is the inclination angle between the rotation axis and the line of sight. This yields $\sigma_{\text{rot}} \approx 0.193 \text{ eV}$, a value that remains negligible compared to thermal broadening, even when accounting for recent studies suggesting that core rotation in red-giant stars could be up to ten times faster than the observed equatorial velocity [61].

If future detectors were to be able to resolve this width, they could provide valuable insights into the core rotation—a parameter otherwise inaccessible to direct measurements. Nonetheless, since current instrumentation cannot detect this effect, we disregard its impact in the subsequent analysis.

The expected differential axion flux at a distance d from the source can be computed by integrating the Gaussian emission profile $\mathcal{G}(E, \sigma)$ over the stellar model,

$$\frac{dN_a(E)}{dE} = \frac{1}{4\pi d^2} \int_0^{R_{\text{star}}} \mathcal{N}_a(r) \mathcal{G}(E, \sigma(r)) \rho(r) 4\pi r^2 dr.$$

For our numerical estimates, we used a stellar model for a supergiant of $20M_\odot$ and solar metallicity, constructed using the MESA stellar evolution code [62–67]. Specifically, we extended the 20Mpre_ms_to_core_collapseMESA setup to include

a significantly larger nuclear reaction network, with a total of 206 isotopes, in order to properly account for all possible interactions that could affect the abundance of ^{57}Fe throughout the evolution. As the precise evolutionary stage of Betelgeuse is unknown, and s -process reactions can, in principle, affect the abundance of ^{57}Fe , we adopt a representative stellar model for our numerical results, corresponding to the onset of core carbon burning, after the ^{57}Fe abundance and therefore also the axion flux has stabilized. In any case, the resulting bounds depend very weakly on the exact evolutionary stage. This contrasts with the case of continuum emission processes, such as the Primakoff and ABC mechanisms studied in Refs. [13,68], which exhibit a stronger sensitivity to variations in the core conditions—particularly the core temperature.

In our case, the core temperature during the post-He-burning evolution remains always above the excitation energy of the ^{57}Fe nuclear level (cf. the left panel of Fig. 5). As a result, the Boltzmann factor that governs the population of the excited state saturates, leading to a very mild dependence of the emission rate on temperature. Further details on the construction of our reference stellar model are provided in Appendix A.

The axions produced in the core of Betelgeuse can convert into hard x-ray photons in the Galactic magnetic field (GMF), providing an observational signature. The conversion probability in the regular magnetic field² is given by [68],

$$P_{a\gamma} = 8.7 \times 10^{-6} g_{11}^2 \left(\frac{B_T}{1 \mu\text{G}} \right)^2 \left(\frac{d}{197 \text{ pc}} \right)^2 \frac{\sin^2(qd)}{(qd)^2}, \quad (7)$$

where $g_{11} = (g_{a\gamma}/10^{11} \text{ GeV}^{-1})$ is a normalized axion-photon coupling, and q is the momentum transfer term

$$qd \simeq \left[77 \left(\frac{m_a}{10^{-10} \text{ eV}} \right)^2 - 0.14 \left(\frac{n_e}{0.013 \text{ cm}^{-3}} \right) \right] \times \left(\frac{d}{197 \text{ pc}} \right) \left(\frac{E}{1 \text{ keV}} \right)^{-1}. \quad (8)$$

Here, m_a is the axion mass, n_e the electron number density [70], and E the axion energy. Throughout this study, we assume a constant transverse magnetic field of $B_T = 1.4 \mu\text{G}$ [71], though we present also the results for the more optimistic scenario of $B_T = 3.0 \mu\text{G}$ [72]. The exact value of the magnetic field remains the main source of uncertainty in this work, as the final signal scales $\sim B_T^2$,

²We focus only on the regular component of the magnetic field in the main text, as it is by far the most relevant and leads to a conservative result. Our numerical study of the effects of the turbulent component of the GMF, following Ref. [69], gives a standard deviation of $\mathcal{O}(10\%)$ for the conversion probability, with no significant impact on the expected spectral shape of the signal. Details can be found in Appendix B.

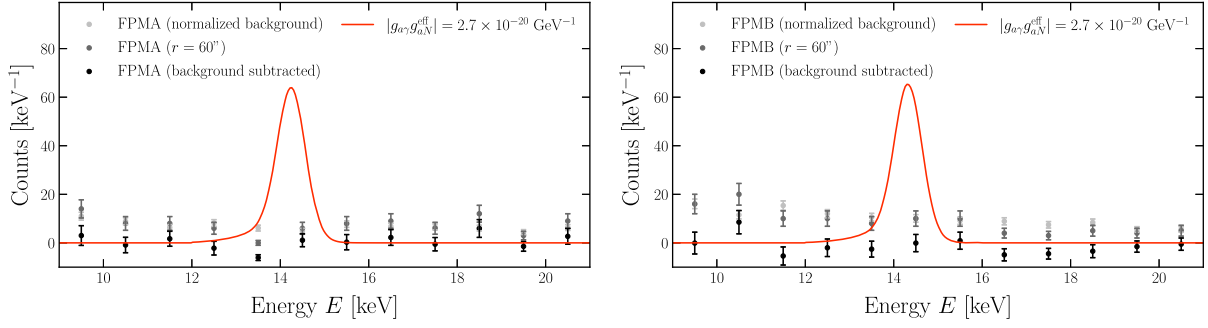


FIG. 2. Expected axion signal in the two modules FPMA (*left*) and FPMB (*right*). Shown is the signal for an effectively massless axion ($m_a \lesssim 10^{-10}$ eV) assuming the maximally allowed value for the combination of the couplings (at 95% CL) $|g_{a\gamma}g_{aN}^{\text{eff}}| = 2.7 \times 10^{-20} \text{ GeV}^{-1}$. The spectra are binned in 1 keV increments and shown in the 9–21 keV range for visualization purposes, while the analysis was conducted on the full energy range using unbinned data.

yielding $P_{a\gamma} = (1.5\text{--}9.2) \times 10^{-5}$ for the parameters used in this work. This range includes the effects of a turbulent component of the magnetic field $B_{\text{rms,turb.}}^2 \approx (1 \mu\text{G})^2$ with a correlation length of $\mathcal{O}(10 \text{ pc})$, see Appendix B for details. Finally, notice that our results are conservative as we are neglecting the contribution of the local magnetic field of Betelgeuse.³

III. NuSTAR DATA ANALYSIS AND RESULTS

For our work, we have analyzed the only available NuSTAR observation of Betelgeuse, carried out on August 23, 2019 (ObsID 30501012002). Below, we present our data analysis and the main results obtained. Further details can be found in Appendix C.

The NuSTAR Observatory [75], the first high-energy focusing x-ray telescope in space, operates within the 3–79 keV energy range, which makes it well suited for investigating the expected axion-induced ^{57}Fe deexcitation signal at 14.4 keV. NuSTAR consists of two co-aligned telescope modules, each equipped with independent optics and focal-plane module (FPM) Cadmium-Zinc-Tellurium (CdZnTe) detectors, designated as FPMA and FPMB. Each module provides a field of view of approximately $13' \times 13'$ and achieves an angular resolution of $58''$ half-power diameter for point sources near the optical axis. These grazing-incidence optics efficiently direct x-rays onto the focal-plane detectors, ensuring high sensitivity and resolution for the purposes of our study.

Data from both detectors were processed using the HEASoft software (version 6.34) [76] together with the

NuSTARDAS package (version 2.1.4). The total cleaned exposures were found to be 49.16 ks for FPMA and 48.83 ks for FPMB. A circular source region with a radius of $60''$ was selected, centered on the J2000 coordinates of Betelgeuse: RA = $88^\circ 47' 34.8''$, Dec = $+07^\circ 24' 25.4''$. Following the approach used in [13,68], the background spectrum is obtained from a polygonal region separated $120''$ from the center of the source and located in the same CdZnTe chip that encompasses the source (see Appendix C 1). The x-ray spectra observed by FPMA and FPMB in both the source and background regions are displayed in Fig. 2.

The expected counts coming from the initial axion signal at NuSTAR FPMs, for a given set of nuisance parameters $\theta = \{g_{a\gamma}, g_{aN}, m_a\}$, are computed by forward modeling the photon signal from axion decay through the instrument response files and exposure times of each module (see Appendix C for a detailed explanation). In Fig. 2, the expected signal is shown for both detector modules, FPMA and FPMB.

For each module $i = \{A, B\}$, the total observed counts $N_{\text{obs},i}$ and total background counts $N_{\text{bkg},i}$ are then combined in an unbinned likelihood. In order to obtain an upper limit on the coupling product, we introduce the unbinned likelihood function

$$\mathcal{L} = \prod_{i=\{A,B\}} \mathcal{L}_i \times \prod_{i=\{A,B\}} \mathcal{G}(\delta_{\text{bkg}}^i \sigma_{\text{bkg}}^i), \quad (9)$$

and the individual likelihood, e.g., $\mathcal{L}_i$, is computed as

$$\mathcal{L}_i = \text{Poisson}(N_{\text{obs},i} | N_{\text{exp},i}) \times \prod_{j=1}^{N_{\text{obs},i}} \left[\frac{N_{\text{ax},i} P_{\text{ax}}(E'_j)}{N_{\text{exp},i}} + \frac{N_{\text{bkg},i} (1 + \delta_{\text{bkg}}^i) P_{\text{bkg}}(E'_j)}{N_{\text{exp},i}} \right] \quad (10)$$

where the first term is the usual Poisson distribution,

³Although the existence of the magnetic field of Betelgeuse is established (see, e.g., Ref. [73]), both its strength and structure remain highly uncertain, with indications of temporal variability and complex spatial morphology. Including this component would mainly affect the high-mass region of the ALP parameter space (see Ref. [74]), while our conclusions at low masses are dominated by the well-characterized Galactic field. We therefore adopted the conservative choice of excluding the local field.

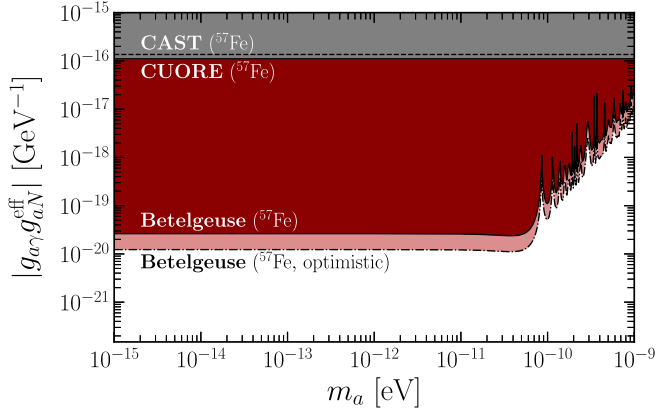


FIG. 3. Exclusion limits from the Bayesian unbinned likelihood analysis at 95% CL for massive axions. Shown are bounds from searches for the 14.4 keV line of ^{57}Fe by CAST [41] and CUORE [42].

$$\text{Poisson}(N_{\text{obs},i}|N_{\text{exp},i}) = \frac{N_{\text{exp},i}^{N_{\text{obs},i}} e^{-N_{\text{exp},i}}}{N_{\text{obs},i}!}. \quad (11)$$

Here, the expected number of events for an axion signal is given by $N_{\text{exp},i} = N_{\text{ax},i} + N_{\text{bkg},i}(1 + \delta_{\text{bkg},i}^i)$. Here, $N_{\text{ax},i}$ represents the number of axion signal events calculated via forward modeling of the photon signal resulting from axion decay. The energy-dependent axion signal probability density function, $P_{\text{ax}}(E_j)$, is defined for a specified axion mass m_a , photon coupling $g_{a\gamma}$, and transverse magnetic field B_T . In the corresponding product, it is evaluated at the energy E_j that corresponds to the j th count. For both FPMA and FPMB, the fractional systematic uncertainty of the background, $\sigma_{\text{bkg},i}$, is set to 10%, with independent Gaussian fluctuations [68]. Since the background normalization uncertainty is treated as a nuisance parameter, $\delta_{\text{bkg},i}^i$ is marginalized over the interval $\delta_{\text{bkg},i}^i \in [-1, +\infty)$. With a flat prior on the parameter vector θ , Bayes' theorem yields the posterior probability

$$P(\theta) = \frac{\mathcal{L}(\theta)}{\int \mathcal{L}(\theta') d\theta'}, \quad (12)$$

and the 95% credibility upper limit on the coupling product is determined by solving

$$\int_0^{(g_{a\gamma}^2 g_{aN}^2)_{95\%}} P(g_{a\gamma}^2 g_{aN}^2) d(g_{a\gamma}^2 g_{aN}^2) = 0.95. \quad (13)$$

For the case of a massless axion, this yields

$$|g_{a\gamma} g_{aN}^{\text{eff}}| \leq (1.2 - 2.7) \times 10^{-20} \text{ GeV}^{-1}, \quad (14)$$

at 95% CL. This result is valid for masses up to $m_a \lesssim 10^{-10}$ eV, when the axion-photon conversion loses

coherence. The results for the massive case are displayed in Fig. 3.

IV. DISCUSSION

In this work, we have presented the first search for axion-nucleon interactions via nuclear deexcitations in a supergiant star, using NuSTAR observations of Betelgeuse. Exploiting the elevated core temperature of this evolved star, we have shown that the 14.4 keV transition of ^{57}Fe offers a promising probe of the axion-induced monochromatic x-ray signature. Our analysis, based on a forward-modeled Bayesian likelihood approach, reveals no significant excess at the expected energy but leads to the strongest direct bounds on the coupling product $|g_{a\gamma} g_{aN}^{\text{eff}}|$ for $m_a \lesssim 10^{-10}$ eV, reaching values below $2.7 \times 10^{-20} \text{ GeV}^{-1}$.

These results establish supergiant stars as a powerful new laboratory for axion searches, complementing solar-based and terrestrial efforts. The expected stability of the ^{57}Fe -induced signal across stellar evolutionary phases and the narrow, linelike nature of the x-ray signature make this channel especially attractive. Unlike continuum processes such as Primakoff or Compton production [13,68], which scale strongly with temperature and stellar evolutionary stage, the axion emission from ^{57}Fe saturates rapidly once the temperature exceeds 14.4 keV. As a result, this process constitutes a more robust probe across different evolutionary phases of the star. The main source of uncertainty is thus reduced to the strength of the Galactic magnetic field, while the specific evolutionary stage plays a less significant role than in the case of continuum processes.

To complete our analysis, we now relate our bound to the very strong astrophysical bounds derived from the cooling of supernova (SN) 1987A [34,35], as well as from observations on the cooling of neutron stars [77]. Both arguments provide the approximate bound $g_{aN} \lesssim 10^{-9}$, where with g_{aN} we indicate a generic axion-nucleon coupling [22]. Let us take the SN bound in Ref. [34] as our concrete example. Using the methods discussed in Refs. [46,56], we see that $g_{aN}^{\text{SN}} = 10^{-9}$ corresponds to our $g_{aN}^{\text{eff}} = 0.9 \times 10^{-9}$. If we fix the axion-nucleon coupling to this value and translate our result into a bound on the photon coupling, we find $g_{a\gamma} \lesssim 1.1 \times 10^{-11} \text{ GeV}^{-1}$, which is slightly stronger than the current CAST limit and lies within the region targeted by future helioscope experiments [78–80]. We finally notice that the region explored in this work is in tension with the bound derived from the nonobservation of a gamma ray flux associated to the SN 1987A event, by the Solar Maximum Mission [81,82]. In particular, Ref. [83] provides the bound $g_{a\gamma} < 3.4 \times 10^{-15} \text{ GeV}^{-1}$ for $m_a \lesssim 0.1$ neV, in the case of $g_{aN}^{\text{SN}} = 10^{-9}$, with g_{aN}^{SN} the effective coupling entering in the axion bremsstrahlung production in SN [34,37,38]. Using $g_{aN}^{\text{eff}} = 0.9 \times 10^{-9}$, we see that the bound extracted in Ref. [83] translates to $|g_{a\gamma} g_{aN}^{\text{eff}}| \lesssim 3 \times 10^{-24} \text{ GeV}^{-1}$ for $m_a \lesssim 10^{-10}$ eV. We have

not reported this bound in our figures as it was not a direct measurement.⁴

Future observations of additional nearby supergiants, together with advancements in x-ray instrumentation and improved modeling of the Galactic magnetic field, hold strong potential to further tighten current constraints—or even lead to the first detection of an axion signal from stellar nuclear transitions. Moreover, as first shown in Refs. [84–86], entire galaxies can act as competitive axion sources. In particular, starburst galaxies such as M82, with their high abundance of supergiant stars, offer promising laboratories to test the axion-nucleon coupling via ^{57}Fe decay. Preliminary studies indicate that the analysis of NuSTAR observations of M82 could yield an even more stringent bound on $|g_{a\gamma}g_{aN}^{\text{eff}}|$ than the one derived here. A detailed study along these lines is left for future work.

Data analysis was performed using the NuSTAR Data Analysis Software, which was jointly developed by the ASI Science Data Center in Italy and the California Institute of Technology in the United States.

ACKNOWLEDGMENTS

We warmly thank Diego Guadagnoli, Guiseppe Lucente, and Edoardo Vitagliano for helpful comments on the draft. F. R. C. and M. K. acknowledge insightful discussions with Igor Irastorza about statistics. This article is based upon work from COST Action COSMIC WISPerS (CA21106). F. R. C. is supported by the Universidad de Zaragoza under the “Programa Investigo” (Programa Investigo-095-28), as part of the Plan de Recuperación, Transformación y Resiliencia, funded by the European Union-NextGenerationEU. The work of M. G. and M. K. is supported by the Grant No. PGC2022-126078NB-C21 funded by MCIN/AEI/ 10.13039/501100011033 and “ERDF A way of making Europe.” M. G. and M. K. further acknowledge the Grants No. DGA-FSE 2023-E21-23R and No. DGA-FSE 2020-E21-17R (Gobierno de Aragón (Aragon Government) and the European Union—Next Generation EU Recovery and Resilience), respectively. Both are funded by the Aragon Government and the European Union—Next Generation EU Recovery and Resilience program on “Astrofísica y Física de Altas Energías” CEFCA-CAPA-ITAINNOVA. M. G. acknowledges funding from the European Union’s Horizon 2020 research and innovation program under the European Research Council (ERC) Grant Agreement No. ERC-2017-AdG788781 (IAXO+). M. K. is further supported by the Government of Aragón, Spain, with a PhD fellowship as specified in ORDEN CUS/702/2022.

⁴In fact, as explicitly discussed in Ref. [81], the telescope was not even pointing at the SN location at the time of the explosion.

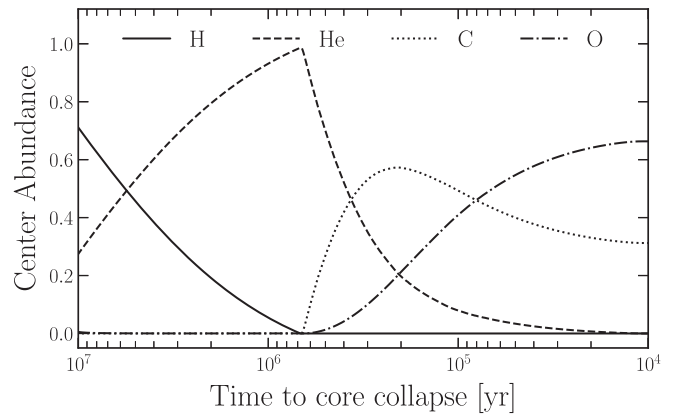


FIG. 4. Central abundances of hydrogen, helium, carbon, and oxygen for the supergiant star as a function of time. Tracking the abundances allows one to identify the key stages of the stellar evolution, like the onset of helium and carbon burning in the stellar core.

DATA AVAILABILITY

The data that support the findings of this article are openly available [87].

APPENDIX A: MESA SIMULATION DETAILS

Our numerical stellar model, representing a $20M_{\odot}$ star with metallicity $Z = 0.02$, was produced with MESA v.24.08.1, a publicly available one-dimensional stellar evolution code, which solves the equations of stellar structure and returns stellar profiles throughout the stellar evolutionary stages [62–67]. In order to account for the several processes that might impact the abundance of ^{57}Fe , we extended the nuclear reaction network significantly, including a total of 206 isotopes.⁵ Our final models are quite similar to the ones used in Refs. [13,68], which we used as a reference for the stellar properties, except for the much larger nuclear network.

In Fig. 4, we show the time evolution of the central abundances in our $20M_{\odot}$ supergiant star model. The ignition of helium in the core, occurring about 0.7 Myr before core collapse, is evident as the helium abundance begins to decrease while carbon and oxygen abundances increase. This marks the transition to the red giant phase. As it is well known, throughout the stellar evolution, heavier and heavier elements are ignited in the core, up to the formation of an inert iron core, which, being unable to release energy through fusion, triggers gravitational collapse and signals the end of its life. The core temperature of the star increases steadily during the post-core-helium-burning phase, as shown in the right panel of Fig. 5, and remains consistently above the ^{57}Fe excitation energy of 14.4 keV, marked as a

⁵This network is provided in the MESA framework as the file “MESA_206.NET,” and is primarily used in presupernova models.

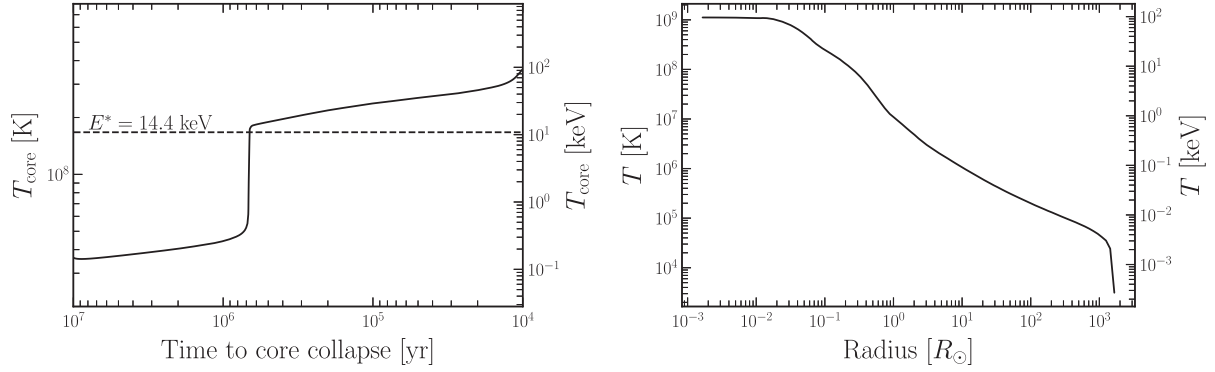


FIG. 5. *Left*: stellar core temperature as a function of time to core collapse for our simulation. *Right*: radial temperature profile of our benchmark $20M_{\odot}$ stellar model, taken at a time when the carbon burning phase is about to finish.

dashed line. As discussed in the text, the temperature dependence of the deexcitation rate—which rises steeply for $T < E^*$ —becomes very weak above the excitation temperature, as the Boltzmann exponential saturates. This represents a substantial difference between our process and other continuous mechanisms, such as the ABC and Primakoff processes studied in Refs. [13,68].

In the right panel of Fig. 5, we show the radial temperature profile at a single time step for our $20M_{\odot}$ supergiant star. Specifically, the selected time step is chosen to avoid major evolutionary transition periods, when the axion flux has stabilized to its post-He ignition value.

Apart from temperature, the abundance of ^{57}Fe is another key parameter influencing the axion deexcitation rate. We find that after the star enters the red giant regime, the ^{57}Fe abundance remains approximately constant, with a notable exception: Right at the ignition of He burning, we observe an increased neutron density that sources ^{57}Fe via neutron capture (i.e., s processes such as $^{56}\text{Fe} + n \rightarrow ^{57}\text{Fe} + \gamma$) or neutron-proton exchange (e.g., $^{57}\text{Co} + n \rightarrow ^{57}\text{Fe} + p$). Subsequently, the increase in the abundance is countered by reactions such as $^{57}\text{Fe} + n \rightarrow ^{58}\text{Fe} + \gamma$, leading to a relaxation of the abundance to roughly the value from right at the beginning of He burning. This value is stable from the onset of carbon burning until just before core collapse, which justifies the choice of any profile from early He burning or after the onset of C-burning for a conservative estimate of the axion flux.

APPENDIX B: IMPACT OF THE TURBULENT COMPONENT OF THE GALACTIC MAGNETIC FIELD

The results shown in the main text (including in the figures) consider only the regular component of the magnetic field. However, as extensively discussed in Ref. [69], radio observations of synchrotron emission and polarization reveal the presence of an additional small-scale component of the magnetic field, superimposed on the regular one. This turbulent (or random) component has a

comparable field strength of $\mathcal{O}(1) \mu\text{G}$ but a much shorter correlation length of $\mathcal{O}(10\text{--}100)$ pc than the regular field. The analysis in Ref. [69] showed that this turbulent component can have a non-negligible impact on the ALP-photon oscillation probability, making a dedicated study necessary for each specific case. Employing the methodology of Ref. [69], we studied the impact of additional different *random* Gaussian fields on our results for the characteristic 14.4 keV line of ^{57}Fe . One such realization of a Gaussian random field with $B_{\text{rms,turb.}}^2 = (1 \mu\text{G})^2$ and $\ell_{\text{corr}} = 10$ pc as computed using the gammaALPSs code [88] is displayed in Fig. 6. Here, the power spectrum of the turbulent field follows a power law, $M(k) \sim k^q$, with spectral index $q = -11/3$, known as Kolmogorov spectrum, and is normalized with respect to $B_{\text{rms,turb.}}^2$. The Fourier transform of the correlation function of the transversal component of the B field, B_T , which is the relevant one for the conversion process, is given by

$$\tilde{\epsilon}_{\perp}(k) = \frac{\pi B_{\text{rms,turb.}}^2}{4} F_q(k; k_L, k_H), \quad (\text{B1})$$

where the functional form of $F_q(k; k_L, k_H)$ is explicitly derived in the Appendix of Ref. [89].

We estimated the effects of the turbulent component of the magnetic field by simulating 20 realizations of *random* Gaussian fields and comparing the resulting mean and standard deviation to the result, which includes only the regular field. Figure 7 shows our findings, with the dashed lines corresponding to the regular magnetic field alone and the colored bands representing the impact of the random component. As expected, the effects of the turbulent magnetic field are practically limited to the larger mass case. In fact, while the ALP-photon oscillations are coherent, the oscillation probability scales approximately as $(LB)^2$, with L the correlation length and B the strength of the magnetic field component, and thus the regular component dominates. However, at higher ALP mass, when the oscillations induced by the regular magnetic

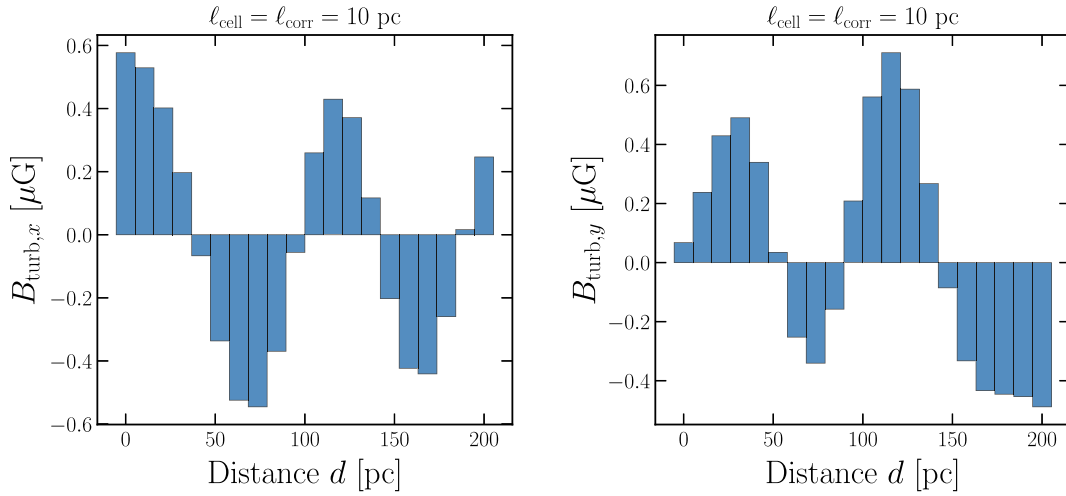


FIG. 6. Visualization of an example realization of a turbulent component of the GMF with $B_{\text{rms,turb.}}^2 = (1.0 \mu\text{G})^2$ and $\ell_{\text{corr}} = 10$ pc, as computed with the gammaALPSs code [88].

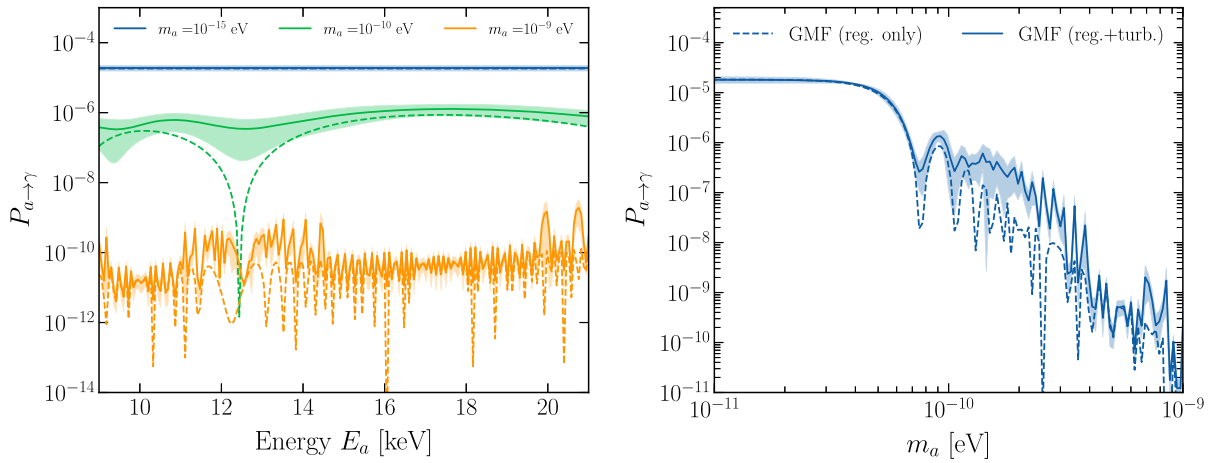


FIG. 7. *Left*: axion-photon conversion spectrum $P_{a\rightarrow\gamma}(E_a)$ in the relevant energy range for the expected signal at NuSTAR, cf. Fig. 2, with $g_{a\gamma} = 10^{-11} \text{ GeV}^{-1}$ and $B_{T,\text{reg.}} = 1.4 \mu\text{G}$. *Right*: mass-dependent axion-photon conversion probability $P_{a\rightarrow\gamma}$ for a fixed axion energy of $E_a = 14.4 \text{ keV}$, $g_{a\gamma} = 10^{-11} \text{ GeV}^{-1}$ and $B_{T,\text{reg.}} = 1.4 \mu\text{G}$. In both plots we show the regular-only GMF case, as used for the main part of the work, as a dashed line and the mean and standard deviation of a series of 20 random realizations including a turbulent component of the GMF of $B_{\text{rms,turb.}}^2 = (1.0 \mu\text{G})^2$ similar to the example shown in Fig. 6, as a solid line with a shaded band.

field lose coherence, the effect of the turbulent field becomes more relevant, as the shorter correlation length raises the threshold mass at which coherence is lost [cf. Eq. (8)].

APPENDIX C: DATA REDUCTION AND NuSTAR ANALYSIS

NuSTAR [75] is the first space-based focusing telescope capable of extending energy sensitivity into the hard x-ray regime, observing within the 3–79 keV range. Launched into a near-equatorial low-Earth orbit in 2012, NuSTAR is equipped with two detection assemblies; focal plane modules A and B (FPMA/FPMB). Each module includes

a telescope structure based on a segmented-glass design, featuring 133 nested shells coated with reflective multilayers. These layers consist of Pt/C for the inner shells and W/Si for the outer shells. The telescope employs a conical approximation of a Wolter-I geometry, optimized for grazing-incidence reflection. The focal plane detectors for each module consist of a 2×2 array of CdZnTe semiconductor chips. Each chip contains 32×32 pixels, resulting in a total of 4096 pixels per detector. Each pixel measures $0.6 \text{ mm} \times 0.6 \text{ mm}$, providing a FOV of approximately $12'$ in both x and y directions at 3 keV. At higher energies ($>10 \text{ keV}$), the FOV is typically reduced to between $6'$ and $10'$. The observatory achieves an angular resolution, determined mainly by its optics, of $18''$ full

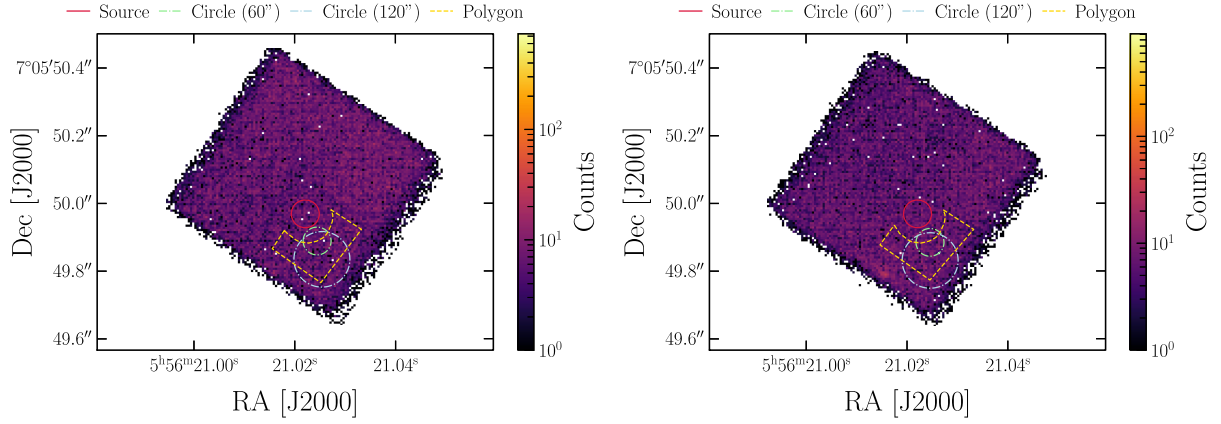


FIG. 8. Field of view (FOV) of the Betelgeuse observation for module A (*top*) and B (*bottom*). The 60'' source region is displayed in a red solid line. On the other hand, the background regions considered in Appendix C 1 are displayed as dashed lines. The polygon region, yellow dashed, is the background region used in the final analysis.

width at half maximum (FWHM) and a half-power diameter of about 60''. Designed specifically for high performance in the hard x-ray spectrum, NuSTAR delivers an energy resolution with a FWHM of 0.4 keV at 10 keV and 0.9 keV at 68 keV.

The Betelgeuse observation examined in this research was retrieved from NASA's HEASARC data archive. To process the NuSTAR observation, we employed the NuSTARDAS software suite (version 2.1.4), which is part of the HEASoft package (version 6.34) [76]. The workflow begins with reprocessing the raw data from the archival files using the NUPIPELINE task provided by NuSTARDAS, with the flags SAAMODE=OPTIMIZED and TENTACLE=YES to remove intervals exhibiting elevated instrument backgrounds, typically occurring when the telescope passes through the south Atlantic anomaly. As explained in the main text and shown in Fig. 8, the source region is defined as a 60'' circular region centered at Betelgeuse's coordinates. The background region is chosen to be a polygon separated 120'' from the source center and in the same CdZnTe detector chip as the source. For an extended discussion on the background region optimization, confer Appendix C 1.

Next, NUPRODUCTS, with the previously mentioned regions, is used to subtract the source and normalized background spectra. Then, we employ HEASoft's XSPEC tool [90] version 12.14.1 to read the spectra and export the data into ASCII format.

On the other hand, the predicted differential photon flux from axion decay is forward modeled by incorporating the response files corresponding to both optics and detector, to determine the expected counts in the NuSTAR detector. The effective area of the telescope is taken into account by the ancillary response files (ARFs) and the detector energy response by the response matrix files (RMFs). Thus, our axion-induced expected counts for each energy bin j and each module $i = \{A, B\}$ can be computed via

$$N_{\text{ax},i}^j(m_a, g_{a\gamma}, g_{aN}) = \Delta t_i \int \text{RMF}^i(E_j, E) \text{ARF}^i(E) \times \frac{dN_a(m_a, g_{aN})}{dE} P_{a \rightarrow \gamma}(E, g_{a\gamma}) dE, \quad (\text{C1})$$

where Δt_i corresponds to the exposure time of the module i .

1. Background region optimization

In order to accurately account for the spatial variation of the background components—primarily the unfocused cosmic x-ray background and the x-rays arising from fluorescence/activation of the instrument structure—across the detector arrays, we selected various background regions following the methodology of [13]. Given that the detector background intensity is known to vary between chips, while remaining largely constant within each chip [91], we compared the background spectra from three distinct regions on a given chip: a 60'' region near the source, a 120'' region, and a polygonal region, each located at least 120'' away from the source.

To reinforce the selection of the polygonal background region, we calculated and compared the signal-to-noise ratio (SNR), defined as $\text{SNR} = \sum \text{Counts} / (\sum \text{Errors}^2)^{1/2}$, for each region and compared the corresponding background spectra on the same detector chip; see Fig. 8 for a visual

TABLE I. SNR values for the three background estimation regions in both Module A and Module B. The polygon region exhibits the highest SNR, making it the most reliable choice for background estimation.

Region	SNR (A)	SNR (B)
Polygon	47.00	50.01
60'' Circle	23.30	25.08
120'' Circle	45.50	49.10

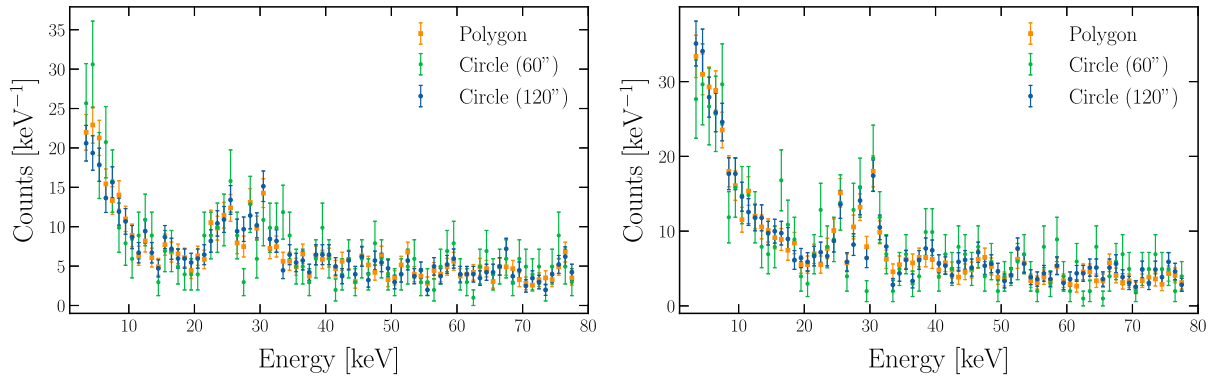


FIG. 9. X-ray spectra in the 3–79 keV energy range from FPMA (*left*) and FPMB (*right*) in different background regions after the normalization, the polygonal region in orange; the spectrum from the 60'' circle region in green and the spectrum from the 120'' circle region in blue. The data is binned in 1 keV increments and multiplied by the exposure time (49.160 ks for FPMA and 48.830 ks for FPMB).

representation. The SNR values for each region are reported in Table I, and the background spectra are shown in Fig. 9.

Although all regions exhibit similar background characteristics, the polygonal region yields the highest SNR.

This indicates that the polygonal region provides a cleaner and more reliable background estimate with reduced noise contamination, thereby ensuring more precise background subtraction across both modules.

-
- [1] S. Weinberg, A new light boson?, *Phys. Rev. Lett.* **40**, 223 (1978).
 - [2] F. Wilczek, Problem of strong P and T invariance in the presence of instantons, *Phys. Rev. Lett.* **40**, 279 (1978).
 - [3] R. D. Peccei and H. R. Quinn, CP conservation in the presence of instantons, *Phys. Rev. Lett.* **38**, 1440 (1977).
 - [4] R. D. Peccei and H. R. Quinn, Constraints imposed by CP conservation in the presence of instantons, *Phys. Rev. D* **16**, 1791 (1977).
 - [5] E. Witten, Some properties of $O(32)$ superstrings, *Phys. Lett.* **149B**, 351 (1984).
 - [6] J. P. Conlon, The QCD axion and moduli stabilisation, *J. High Energy Phys.* **05** (2006) 078.
 - [7] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, String axiverse, *Phys. Rev. D* **81**, 123530 (2010).
 - [8] B. S. Acharya, K. Bobkov, and P. Kumar, An M theory solution to the strong CP problem and constraints on the axiverse, *J. High Energy Phys.* **11** (2010) 105.
 - [9] T. Higaki and T. Kobayashi, Note on moduli stabilization, supersymmetry breaking and axiverse, *Phys. Rev. D* **84**, 045021 (2011).
 - [10] M. Cicoli, M. Goodsell, and A. Ringwald, The type IIB string axiverse and its low-energy phenomenology, *J. High Energy Phys.* **10** (2012) 146.
 - [11] M. Demirtas, C. Long, L. McAllister, and M. Stillman, The Kreuzer-Skarke axiverse, *J. High Energy Phys.* **04** (2020) 138.
 - [12] V. M. Mehta, M. Demirtas, C. Long, D. J. E. Marsh, L. McAllister, and M. J. Stott, Superradiance in string theory, *J. Cosmol. Astropart. Phys.* **07** (2021) 033.
 - [13] M. Xiao, K. M. Perez, M. Giannotti, O. Straniero, A. Mirizzi, B. W. Grefenstette, B. M. Roach, and M. Nynka, Constraints on axionlike particles from a hard x-ray observation of betelgeuse, *Phys. Rev. Lett.* **126**, 031101 (2021).
 - [14] C. Dessert, J. W. Foster, and B. R. Safdi, X-ray searches for axions from super star clusters, *Phys. Rev. Lett.* **125**, 261102 (2020).
 - [15] L. Di Luzio, M. Giannotti, E. Nardi, and L. Visinelli, The landscape of QCD axion models, *Phys. Rep.* **870**, 1 (2020).
 - [16] L. Darmé, L. Di Luzio, M. Giannotti, and E. Nardi, Selective enhancement of the QCD axion couplings, *Phys. Rev. D* **103**, 015034 (2021).
 - [17] I. G. Irastorza and J. Redondo, New experimental approaches in the search for axion-like particles, *Prog. Part. Nucl. Phys.* **102**, 89 (2018).
 - [18] P. Di Vecchia, M. Giannotti, M. Lattanzi, and A. Lindner, Round table on axions and axion-like particles, *Proc. Sci. Confinement 2018* (2019) 034 [arXiv:1902.06567].
 - [19] P. Agrawal *et al.*, Feebly-interacting particles: FIPs 2020 workshop report, *Eur. Phys. J. C* **81**, 1015 (2021).
 - [20] P. Sikivie, Invisible axion search methods, *Rev. Mod. Phys.* **93**, 015004 (2021).
 - [21] M. Giannotti, Status and perspectives on axion searches, *Proc. Sci., COSMICWISPers2024* (2025) 033 [arXiv:2412.08733].

- [22] P. Carenza, M. Giannotti, J. Isern, A. Mirizzi, and O. Straniero, Axion astrophysics, *Phys. Rep.* **1117**, 1 (2025).
- [23] G. Grilli di Cortona, E. Hardy, J. Pardo Vega, and G. Villadoro, The QCD axion, precisely, *J. High Energy Phys.* **01** (2016) 034.
- [24] J. Keller and A. Sedrakian, Axions from cooling compact stars, *Nucl. Phys.* **A897**, 62 (2013).
- [25] A. Sedrakian, Axion cooling of neutron stars, *Phys. Rev. D* **93**, 065044 (2016).
- [26] K. Hamaguchi, N. Nagata, K. Yanagi, and J. Zheng, Limit on the axion decay constant from the cooling neutron star in Cassiopeia A, *Phys. Rev. D* **98**, 103015 (2018).
- [27] M. V. Beznogov, E. Rrapaj, D. Page, and S. Reddy, Constraints on axion-like particles and nucleon pairing in dense matter from the hot neutron star in HESS J1731-347, *Phys. Rev. C* **98**, 035802 (2018).
- [28] A. Sedrakian, Axion cooling of neutron stars. II. Beyond hadronic axions, *Phys. Rev. D* **99**, 043011 (2019).
- [29] L. B. Leinson, Impact of axions on the Cassiopeia a neutron star cooling, *J. Cosmol. Astropart. Phys.* **09** (2021) 001.
- [30] M. S. Turner, Axions from SN 1987a, *Phys. Rev. Lett.* **60**, 1797 (1988).
- [31] A. Burrows, M. S. Turner, and R. P. Brinkmann, Axions and SN 1987a, *Phys. Rev. D* **39**, 1020 (1989).
- [32] G. Raffelt and D. Seckel, Bounds on exotic particle interactions from SN 1987a, *Phys. Rev. Lett.* **60**, 1793 (1988).
- [33] G. G. Raffelt, Astrophysical methods to constrain axions and other novel particle phenomena, *Phys. Rep.* **198**, 1 (1990).
- [34] P. Carenza, T. Fischer, M. Giannotti, G. Guo, G. Martínez-Pinedo, and A. Mirizzi, Improved axion emissivity from a supernova via nucleon-nucleon bremsstrahlung, *J. Cosmol. Astropart. Phys.* **10** (2019) 016; **05** (2020) E01(E).
- [35] P. Carenza, B. Fore, M. Giannotti, A. Mirizzi, and S. Reddy, Enhanced supernova axion emission and its implications, *Phys. Rev. Lett.* **126**, 071102 (2021).
- [36] T. Fischer, P. Carenza, B. Fore, M. Giannotti, A. Mirizzi, and S. Reddy, Observable signatures of enhanced axion emission from protoneutron stars, *Phys. Rev. D* **104**, 103012 (2021).
- [37] A. Lella, P. Carenza, G. Lucente, M. Giannotti, and A. Mirizzi, Protoneutron stars as cosmic factories for massive axionlike particles, *Phys. Rev. D* **107**, 103017 (2023).
- [38] A. Lella, P. Carenza, G. Co', G. Lucente, M. Giannotti, A. Mirizzi, and T. Rauscher, Getting the most on supernova axions, *Phys. Rev. D* **109**, 023001 (2024).
- [39] A. Lella, F. Calore, P. Carenza, C. Eckner, M. Giannotti, G. Lucente, and A. Mirizzi, Probing protoneutron stars with gamma-ray axionscopes, *J. Cosmol. Astropart. Phys.* **11** (2024) 009.
- [40] T. W. Donnelly, S. J. Freedman, R. S. Lytel, R. D. Peccei, and M. Schwartz, Do axions exist?, *Phys. Rev. D* **18**, 1607 (1978).
- [41] S. Andriamonje *et al.* (CAST Collaboration), Search for 14.4-keV solar axions emitted in the M1-transition of Fe-57 nuclei with CAST, *J. Cosmol. Astropart. Phys.* **12** (2009) 002.
- [42] D. Li, R. J. Creswick, F. T. Avignone, and Y. Wang, Sensitivity of the CUORE detector to 14.4 keV solar axions emitted by the M1 nuclear transition of ^{57}Fe , *J. Cosmol. Astropart. Phys.* **02** (2016) 031.
- [43] E. Aprile *et al.* (XENON Collaboration), Excess electronic recoil events in XENON1T, *Phys. Rev. D* **102**, 072004 (2020).
- [44] 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).
- [45] J. Ruz *et al.*, NuSTAR as an axion helioscope, *Phys. Rev. Lett.* **135**, 141001 (2025).
- [46] L. Di Luzio *et al.*, Probing the axion–nucleon coupling with the next generation of axion helioscopes, *Eur. Phys. J. C* **82**, 120 (2022).
- [47] G. G. Raffelt, *Stars as Laboratories for Fundamental Physics: The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles* (University of Chicago Press, Chicago, 1996).
- [48] M. Giannotti, I. Irastorza, J. Redondo, and A. Ringwald, Cool WISPs for stellar cooling excesses, *J. Cosmol. Astropart. Phys.* **05** (2016) 057.
- [49] M. Giannotti, I. G. Irastorza, J. Redondo, A. Ringwald, and K. Saikawa, Stellar recipes for axion hunters, *J. Cosmol. Astropart. Phys.* **10** (2017) 010.
- [50] L. Di Luzio, M. Fedele, M. Giannotti, F. Mescia, and E. Nardi, Solar axions cannot explain the XENON1T excess, *Phys. Rev. Lett.* **125**, 131804 (2020).
- [51] L. Di Luzio, M. Fedele, M. Giannotti, F. Mescia, and E. Nardi, Stellar evolution confronts axion models, *J. Cosmol. Astropart. Phys.* **02** (2022) 035.
- [52] A. Caputo and G. Raffelt, Astrophysical axion bounds: The 2024 edition, *Proc. Sci. COSMICWISPs* (2024) 041 [arXiv:2401.13728].
- [53] G. Bellini *et al.* (Borexino Collaboration), Search for solar axions produced in $p(d, ^3\text{He})A$ reaction with Borexino detector, *Phys. Rev. D* **85**, 092003 (2012).
- [54] S. Andriamonje *et al.* (CAST Collaboration), Search for solar axion emission from ^7Li and $D(p, \gamma)^3\text{He}$ nuclear decays with the CAST γ -ray calorimeter, *J. Cosmol. Astropart. Phys.* **03** (2010) 032.
- [55] A. Bhusal, N. Houston, and T. Li, Searching for solar axions using data from the Sudbury Neutrino Observatory, *Phys. Rev. Lett.* **126**, 091601 (2021).
- [56] G. Lucente, N. Nath, F. Capozzi, M. Giannotti, and A. Mirizzi, Probing high-energy solar axion flux with a large scintillation neutrino detector, *Phys. Rev. D* **106**, 123007 (2022).
- [57] F. Arias-Aragón, M. Giannotti, G. G. di Cortona, and F. Mescia, Axion-induced pair production: A new strategy for axion detection, *Phys. Rev. D* **111**, 043021 (2025).
- [58] F. T. Avignone, R. J. Creswick, J. D. Vergados, P. Pirinen, P. C. Srivastava, and J. Suhonen, Estimating the flux of the 14.4 keV solar axions, *J. Cosmol. Astropart. Phys.* **01** (2018) 021.
- [59] T. O'Shea, M. Giannotti, I. G. Irastorza, L. M. Plasencia, J. Redondo, J. Ruz, and J. K. Vogel, Prospects on the detection of solar dark photons by the International Axion Observatory, *J. Cosmol. Astropart. Phys.* **06** (2024) 070.
- [60] Pierre Kervella, Leen Decin, Anita M. S. Richards, Graham M. Harper, Iain McDonald, Eamon O'Gorman,

- Miguel Montargès, Ward Homan, and Keiichi Ohnaka, The close circumstellar environment of betelgeuse—V. Rotation velocity and molecular envelope properties from alma, *Astron. Astrophys.* **609**, A67 (2018).
- [61] P. G. Beck *et al.*, Fast core rotation in red-giant stars as revealed by gravity-dominated mixed modes, *Nature (London)* **481**, 55 (2012).
- [62] B. Paxton, L. Bildsten, A. Dotter, F. Herwig, P. Lesaffre, and F. Timmes, Modules for Experiments in Stellar Astrophysics (MESA), *Astrophys. J. Suppl. Ser.* **192**, 3 (2011).
- [63] B. Paxton, M. Cantiello, P. Arras, L. Bildsten, E. F. Brown, A. Dotter, C. Mankovich, M. H. Montgomery, D. Stello, F. X. Timmes, and R. Townsend, Modules for Experiments in Stellar Astrophysics (MESA): Planets, oscillations, rotation, and massive stars, *Astrophys. J. Suppl. Ser.* **208**, 4 (2013).
- [64] B. Paxton, P. Marchant, J. Schwab, E. B. Bauer, L. Bildsten, M. Cantiello, L. Dessart, R. Farmer, H. Hu, N. Langer, R. H. D. Townsend, D. M. Townsley, and F. X. Timmes, Modules for Experiments in Stellar Astrophysics (MESA): Binaries, pulsations, and explosions, *Astrophys. J. Suppl. Ser.* **220**, 15 (2015).
- [65] B. Paxton, J. Schwab, E. B. Bauer, L. Bildsten, S. Blinnikov, P. Duffell, R. Farmer, J. A. Goldberg, P. Marchant, E. Sorokina, A. Thoul, R. H. D. Townsend, and F. X. Timmes, Modules for Experiments in Stellar Astrophysics (MESA): convective boundaries, element diffusion, and massive star explosions, *Astrophys. J. Suppl. Ser.* **234**, 34 (2018).
- [66] B. Paxton, R. Smolec, J. Schwab, A. Gautschi, L. Bildsten, M. Cantiello, A. Dotter, R. Farmer, J. A. Goldberg, A. S. Jermyn, S. M. Kanbur, P. Marchant, A. Thoul, R. H. D. Townsend, W. M. Wolf, M. Zhang, and F. X. Timmes, Modules for Experiments in Stellar Astrophysics (MESA): Pulsating variable stars, rotation, convective boundaries, and energy conservation, *Astrophys. J. Suppl. Ser.* **243**, 10 (2019).
- [67] A. S. Jermyn *et al.*, Modules for Experiments in Stellar Astrophysics (MESA): Time-dependent convection, energy conservation, automatic differentiation, and infrastructure, *Astrophys. J. Suppl. Ser.* **265**, 15 (2023).
- [68] M. Xiao, P. Carenza, M. Giannotti, A. Mirizzi, K. M. Perez, O. Straniero, and B. W. Grefenstette, Betelgeuse constraints on coupling between axionlike particles and electrons, *Phys. Rev. D* **106**, 123019 (2022).
- [69] P. Carenza, C. Evoli, M. Giannotti, A. Mirizzi, and D. Montanino, Turbulent axion-photon conversions in the Milky Way, *Phys. Rev. D* **104**, 023003 (2021).
- [70] J. M. Cordes and T. J. W. Lazio, Ne2001.I. A new model for the galactic distribution of free electrons and its fluctuations, *arXiv:astro-ph/0207156*.
- [71] J. Xu and J. L. Han, Magnetic fields in the solar vicinity and in the Galactic halo, *Mon. Not. R. Astron. Soc.* **486**, 4275 (2019).
- [72] L. Harvey-Smith, G. J. Madsen, and B. M. Gaensler, Magnetic fields in large-diameter HII regions revealed by the faraday rotation of compact extragalactic radio sources, *Astrophys. J.* **736**, 83 (2011).
- [73] M. Auriere, J. F. Donati, R. Konstantinova-Antova, G. Perrin, P. Petit, and T. Roudier, The magnetic field of Betelgeuse: A local dynamo from giant convection cells?, *Astron. Astrophys.* **516**, L2 (2010).
- [74] C. A. Manzari, Y. Park, B. R. Safdi, and I. Savoray, Supernova axions convert to gamma rays in magnetic fields of progenitor stars, *Phys. Rev. Lett.* **133**, 211002 (2024).
- [75] F. A. Harrison *et al.* (NuSTAR Collaboration), The Nuclear Spectroscopic Telescope Array (NuSTAR) high-energy x-ray mission, *Astrophys. J.* **770**, 103 (2013).
- [76] NASA High Energy Astrophysics Science Archive Research Center (HEASARC), HEASoft: Unified Release of FTOOLS and XANADU, 2014. Astrophysics Source Code Library, record ascl:1408.004.
- [77] M. Buschmann, C. Dessert, J. W. Foster, A. J. Long, and B. R. Safdi, Upper limit on the QCD axion mass from isolated neutron star cooling, *Phys. Rev. Lett.* **128**, 091102 (2022).
- [78] E. Armengaud *et al.* (IAXO Collaboration), Physics potential of the International Axion Observatory (IAXO), *J. Cosmol. Astropart. Phys.* **06** (2019) 047.
- [79] A. Abeln *et al.* (IAXO Collaboration), Conceptual design of BabyIAXO, the intermediate stage towards the International Axion Observatory, *J. High Energy Phys.* **05** (2021) 137.
- [80] S. Ahyoune *et al.* (IAXO Collaboration), An accurate solar axions ray-tracing response of BabyIAXO, *J. High Energy Phys.* **02** (2025) 159.
- [81] A. Payez, C. Evoli, T. Fischer, M. Giannotti, A. Mirizzi, and A. Ringwald, Revisiting the SN1987A gamma-ray limit on ultralight axion-like particles, *J. Cosmol. Astropart. Phys.* **02** (2015) 006.
- [82] S. Hoof and L. Schulz, Updated constraints on axion-like particles from temporal information in supernova SN1987A gamma-ray data, *J. Cosmol. Astropart. Phys.* **03** (2023) 054.
- [83] F. Calore, P. Carenza, M. Giannotti, J. Jaeckel, and A. Mirizzi, Bounds on axionlike particles from the diffuse supernova flux, *Phys. Rev. D* **102**, 123005 (2020).
- [84] O. Ning and B. R. Safdi, Leading axion-photon sensitivity with NuSTAR observations of M82 and M87, *Phys. Rev. Lett.* **134**, 171003 (2025).
- [85] O. Ning and B. R. Safdi, Probing the axion-electron coupling with NuSTAR Observations of Galaxies, *arXiv:2503.09682*.
- [86] F. R. Candón, D. F. G. Fiorillo, G. Lucente, E. Vitagliano, and J. K. Vogel, NuSTAR bounds on radiatively decaying particles from M82, *Phys. Rev. Lett.* **134**, 171004 (2025).
- [87] NuSTAR Mission, NuSTAR observation data for Betelgeuse (ObsID 30501012002), Observation date 2019-08-23, NASA High Energy Astrophysics Science Archive Research Center (HEASARC), NASA Goddard Space Flight Center, <https://heasarc.gsfc.nasa.gov/FTP/nustar/data/obs/05/3/30501012002/>.
- [88] M. Meyer, J. Davies, and J. Kuhlmann, gammaALPSs: An open-source Python package for computing photon-axion-like-particle oscillations in astrophysical environments, *Proc. Sci. ICRC2021* (2021) 557 [arXiv:2108.02061].
- [89] M. Meyer, D. Montanino, and J. Conrad, On detecting oscillations of gamma rays into axion-like particles in turbulent and coherent magnetic fields, *J. Cosmol. Astropart. Phys.* **09** (2014) 003.

-
- [90] K. A. Arnaud, B. Dorman, and C. Gordon, XSPEC: An X-ray spectral fitting package, Astrophysics Source Code Library, record ascl:9910.005 (1999), <https://ascl.net/9910.005>.
- [91] D. R. Wik, A. Hornstrup, S. Molendi, G. Madejski, F. A. Harrison, A. Zoglauer, B. W. Grefenstette, F. Gastaldello, K. K. Madsen, N. J. Westergaard, D. D. M. Ferreira, T. Kitaguchi, K. Pedersen, S. E. Boggs, F. E. Christensen, W. W. Craig, C. J. Hailey, D. Stern, and W. W. Zhang, NuSTAR observations of the bullet cluster: Constraints on inverse compton emission, *Astrophys. J.* **792**, 48 (2014).