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NuSTAR Bounds on Radiatively Decaying Particles from M82

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Axions and other putative feebly interacting particles with a mass of tens to several hundreds of keVs can be produced in stellar cores with a Lorentz boost factor $E_a/m_a \lesssim 10$. Thus, starburst galaxies such as M82 are efficient factories of slow axions. Their decay $a \to \gamma\gamma$ would produce a large flux of x-ray photons, peaking around 100 keV and spread around the Galaxy by an angle that can be relatively large. We use observations of the Nuclear Spectroscopic Telescope Array mission to show that the absence of these features can constrain 30–500 keV axion masses into uncharted regions for axion-photon coupling of $g_{a\gamma} \sim 10^{-10}$–$10^{-12}$ GeV^{-1}. Our argument can be applied to other heavy feebly interacting particles and astrophysical sources that are hot enough to produce them, yet cold enough to avoid large boost factors which slow down the decay.

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Introduction—Axions, sterile neutrinos, and other hypothetical feebly interacting particles (FIPs) with a mass in the keV–GeV range have increasingly been in the spotlight in recent years [1–25]. While the most stringent bounds on lighter FIPs often rest on stellar cooling arguments (see, e.g., [26–28]), as they would affect the standard evolution of stars, the existence of heavier FIPs is constrained by the null observation of the daughter particles produced by their decay. One representative case of such FIPs is an axion with a two-photon coupling $\mathcal{L}_{a\gamma\gamma} = g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$. Here we use natural units $\hbar = c = 1$, so that $g_{a\gamma}$ has dimension $(\text{energy})^{-1}$. Barring cosmological bounds (which depend on different parameters, such as the reheating temperature value [29–31]), strong constraints for axion masses m_a between the eV and the MeV scale come from the observed cooling of horizontal-branch stars [32,33], from the possible decay of axions produced by main sequence stars [34], and of axions gravitationally trapped around the Sun ("solar basin") [35,36].

At heavier masses, above the MeV range, the best probe is offered by the remnant of core-collapse supernovae (SNe), an extremely hot ($T \simeq 30$ MeV) and dense ($\rho \simeq 10^{14}$ g/cm^3) protoneutron star [26]. Axions as heavy as $\mathcal{O}(1\ \text{GeV})$ could have been copiously produced in SN1987A through Primakoff effect and coalescence. The photons produced by their subsequent decay $a \to \gamma\gamma$ would have shown up in x-ray and gamma-ray observations of SN1987A realized with the Solar Maximum Mission [3,7,10] and the Pioneer Venus Observatory [18]. Other constraints from astrophysical transients also get weaker for smaller masses, e.g., the bounds from low-energy SNe [11], and from the electromagnetic signal of the GW170817 event [37,38]. The general lesson is that the most constraining bounds are obtained for axions light enough to be produced, and heavy enough that the Lorentz boost does not impede their decay.

Here, we point out that this lesson can be extended to lower masses $m_a \lesssim 1$ MeV by looking at sources hot enough to produce the axion, but with temperatures much smaller than the remnant of core-collapse SNe, so their Lorentz boost is smaller. Starburst galaxies (SBGs) meet exactly this requirement due to their intense star-forming activity and their large number of stars reaching temperatures up to several tens of keV. This is quite visible in Fig. 1, showing the temperature and density profile for a typical star in the mass range that dominates the aggregated emission from the SBG.

Perhaps the most well-known SBG is M82, also known as the Cigar Galaxy. We show here that the axions produced in the stellar cores within the SBG should decay on their way to Earth and produce a photon flux peaking around a

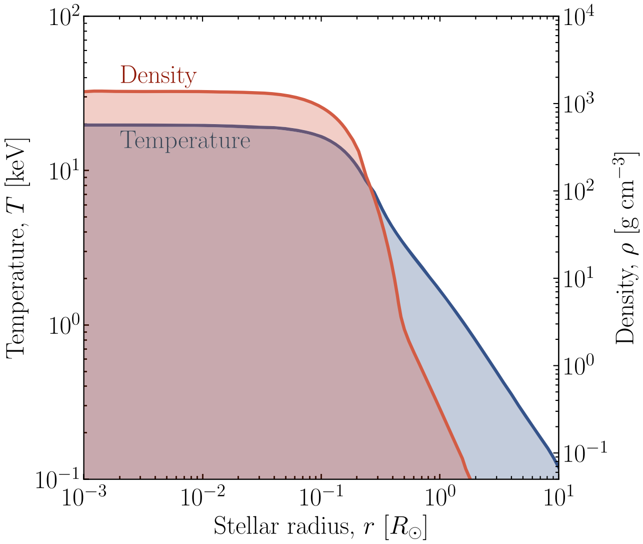

FIG. 1. Temperature and density profile for a star with an initial mass of $20M_\odot$ at an age ~8.7 Myr, as a function of stellar radius in units of the solar radius $R_\odot$. Such stars dominate the emission of axions from M82, since lighter stars attain smaller temperatures, while heavier stars are much less numerous.

hundred keV, and with a characteristic angular distribution that can be either narrowly centered around M82, or widened up to even several arcminutes around the source due to the delayed decay of the mildly relativistic axions. Therefore, we can use the observations of M82 from the Nuclear Spectroscopic Telescope Array (NuSTAR) telescope [39], primarily in the energy range of E_γ between 30–70 keV, to constrain the magnitude of this flux. By this strategy, we obtain the bounds shown in Fig. 2, which exclude a new window of the parameter space as large as one order of magnitude in coupling.

Stellar population and axion production—Axions interacting with photons can be produced in stars via two processes. For $m_a \lesssim T$, the only relevant mechanism is the Primakoff effect $\gamma + Ze \to Ze + a$ [11,41–45], in which thermal photons are converted into axions in the electrostatic field of charged particles. For larger masses, the photon coalescence $\gamma\gamma \to a$ [11,44,45] becomes important.

To compute the axion emission spectra from M82, we evaluate the axion production from individual stars, and then determine the aggregated signal from the stellar population of the Galaxy through the star formation history (SFH) and the initial mass function (IMF), describing the stellar distribution according to their age and mass, respectively. As further discussed in Supplemental Material (SM) [46], we compute the axion spectra from individual stars using radial profiles computed through the one-dimensional stellar evolution code Modules for Experiments in Stellar Astrophysics (MESA) [63,64] (release r23.05.1). The dominant contribution to axion emission in M82 comes from high-mass stars (with mass $M \gtrsim 20M_\odot$) [65], so we employ a grid of models between 20 and $80M_\odot$ spaced by $10M_\odot$, evolved using the default MESA suite and in-list for high-mass stars [66], from pre-main sequence to the onset of core collapse, providing us

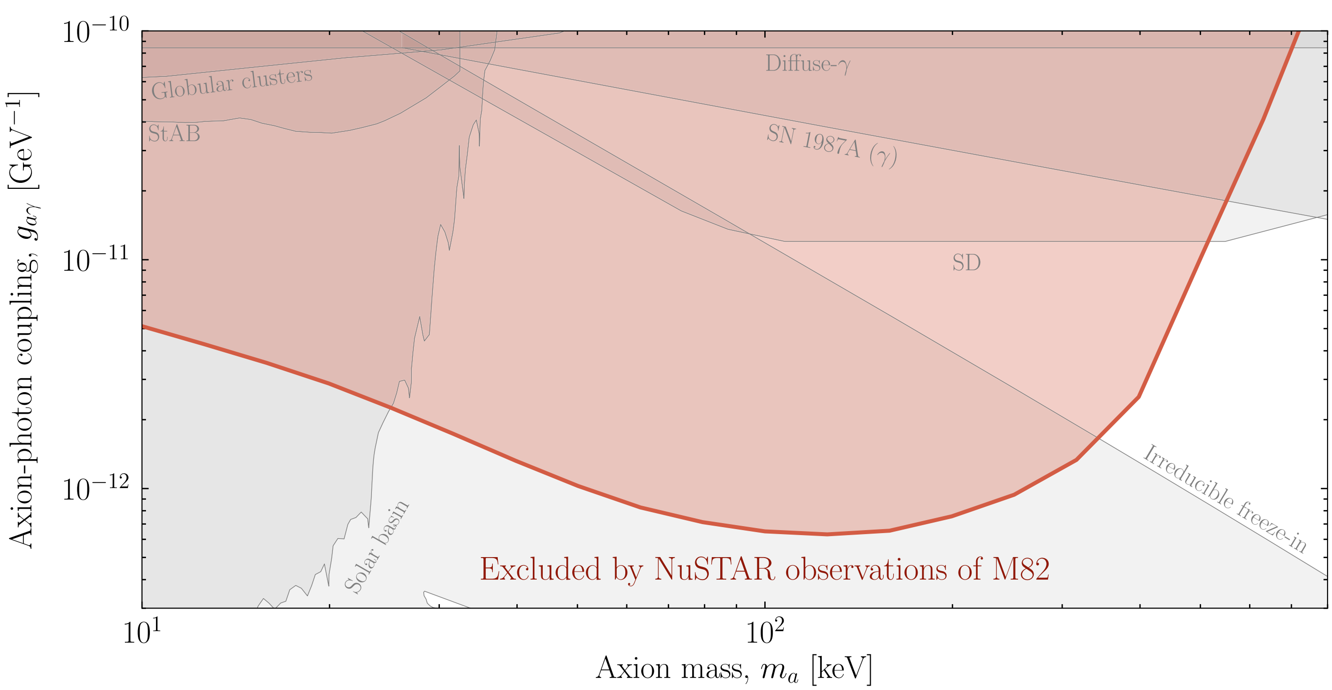

FIG. 2. Novel bounds on axions produced in M82 and decaying to photons. We show previous bounds from the literature [7,10,31,33,34,36], all extracted from Ref. [40], in gray. We also show the bounds from spectral distortions (SDs) taken from Ref. [31]; see main text for a discussion of these bounds.

with stellar profiles at different ages, depending on the initial stellar mass. For instance, we show in Fig. 1 the temperature (blue) and the density (red) as a function of the stellar radius for an initial $20M_\odot$ star at an age ~8.7 Myr. We describe the stellar population in M82 using the SFH and the IMF adopted in Ref. [65]. The SFH is a "two-burst" model described by $R_0 e^{(t_{\rm burst}-t)/t_{\rm sc}}$ for $t < t_{\rm burst}$, with the normalization constant R_0 different for the two bursts and $t_{\rm sc} = 1.0$ Myr the characteristic decay timescale [67]. The old burst is characterized by $t_{\rm burst} = 9.0$ Myr and $R_0 = 31M_\odot/{\rm yr}$, while the younger one by $t_{\rm burst} = 4.1$ Myr and $R_0 = 18M_\odot/{\rm yr}$ [67]. On the other hand, we assume the IMF for M82 to be $\propto M^{-2.35}$ at high mass and flat below $\sim 3M_\odot$, with a cutoff at $100M_\odot$ [67]. Thus, the total axion production spectrum is

$$\frac{d\dot{N}_a}{dE_a} = N_{\rm tot} \int dM_s dt_s {\rm IMF}(M_s){\rm SFH}(t_s) \frac{d\dot{N}_a^s}{dE_a}, \qquad (1)$$

where $N_{\rm tot} = 1.8 \times 10^{10}$ [65] is the total number of stars in M82 estimated using luminosity observations [68] and color-mass-to-light ratio relations for disk galaxies from [69], and $d\dot{N}_a^s/dE_a$ is the production spectrum from the single star with age t_s and initial mass M_s. The determination of the axion production from each star is based on standard emission rates, as detailed in SM [46]. For the couplings we are interested in, the axion feedback on the stellar evolution is negligible since the axion luminosity is well below the stellar one. After integrating over the stellar population, we find that the dominant contribution to the axion production in M82 comes from stars with initial mass $20M_\odot$, and that the photon coalescence is the main production process for $m_a \gtrsim 30$ keV.

Photon spectrum—The decay of axions leads to the production of photons of comparable energies. When the decay is sufficiently slow, the decay length can become comparable with the distance between M82 and the Earth; in this case, photons can reach Earth even from directions away from M82. In the SM [46], we deduce the differential flux $d\Phi_\gamma/dE_\gamma d\beta$ of these photons in energy E_γ and angle from the source β to be

$$\frac{d\Phi_\gamma}{dE_\gamma d\beta} = \int_{E_{a,\rm min}}^{+\infty} \frac{2dE_a \cos\beta}{p_a} \frac{d\dot{N}_a/dE_a}{4\pi r} \Theta(\cos\beta - \cos\theta) \times \exp\left[-\frac{\Gamma_a m_a r \sin\beta}{p_a \sin\theta}\right] \frac{\Gamma_a m_a}{p_a \sin\theta}. \qquad (2)$$

Here, $\Gamma_a = g_{a\gamma}^2 m_a^3/64\pi$ is the rest-frame decay rate of an axion with mass m_a, E_a, and p_a are the axion energy and momentum, so that the velocity is $v_a = p_a/E_a$, Θ denotes the Heaviside theta, $r = 3.8$ Mpc is the distance between M82 and the Earth, and θ is the angle between the axion and photon direction at the moment of decay, with

$$\cos\theta = \frac{1}{v_a}\left[1 - \frac{E_a}{2E_\gamma}(1 - v_a^2)\right]. \qquad (3)$$

Equation (2) already includes a projection factor $\cos\beta$ for the photons impacting on a unit area of the detector, although for the small angles considered here it is irrelevant. We can clearly identify two extreme regimes: if $\Gamma m_a r/p_a \sin\theta \gg 1$, the flux is strongly suppressed at large angles. The axions are decaying very rapidly and the photon flux peaks close to the central source. On the other hand, if $\Gamma m_a r/p_a \sin\theta \lesssim 1$, the exponential suppression becomes irrelevant, and the photon flux becomes mostly independent of β for $\beta \ll 1$. Notice that this is still much more peaked toward small angles β than an isotropic flux, for which we would have $d\Phi_\gamma/dE_\gamma d\beta \propto \sin\beta$, but is spread over a wider angular range than the usual point source predictions. Thus, the best region for constraints is close to the center, but not exactly at the center where the standard astrophysical signal from M82 is largest. This motivates us to perform an angular and spectral analysis to draw our constraints.

Figure 3 collects the spectral and angular distribution of the produced radiation for increasing axion-photon coupling $g_{a\gamma}$ and a fixed $m_a = 316$ keV; we denote by $\mathcal{F}_\gamma = \int \Phi_\gamma E_\gamma dE_\gamma$ the photon energy flux. The central benchmark

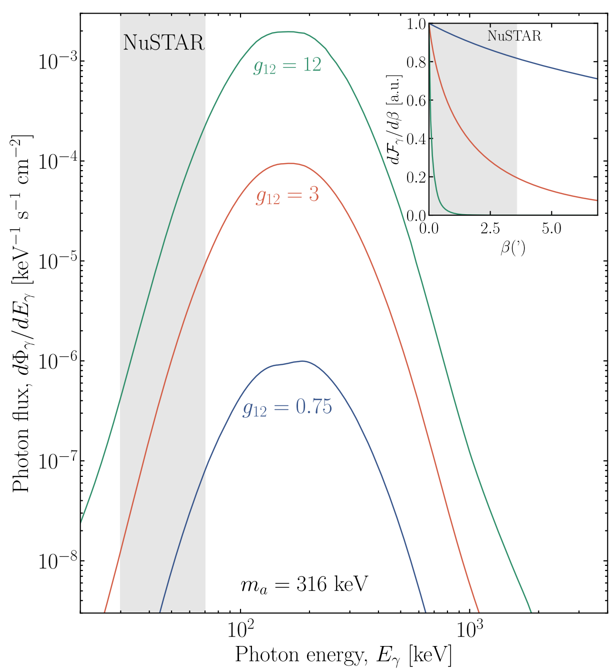

FIG. 3. Energy (main plot) and angular (inset) distribution of the photons from axion decay. The angular and energy range used in the analysis of the NuSTAR observations is highlighted in gray. The energy distribution $d\Phi_\gamma/dE_\gamma$ is integrated over photons within the angular range used in the analysis; similarly, the angular distribution of the integrated energy flux $d\mathcal{F}_\gamma/d\beta$ is integrated over photons between 30 and 70 keV.

coupling choice corresponds to the constraint we obtain and it is shown in Fig. 2. Around this value of coupling, the photons from axion decay have two unique features compared to the standard M82 signal: they are spread over a range of a few arcminutes (comparable with the angular range we use for our analysis), while still being visibly nonisotropic, and they peak at energies of 100 keV, while in the standard case hot thermal photons from stellar cores with comparable energies of course cannot reach us.

NuSTAR data and results—We analyze and process 26 observations of M82, totaling ∼1.96 Ms of exposure time, obtained from archival data of the NuSTAR Observatory [39]. NuSTAR, the first high-energy focusing x-ray telescope in space, operates within the 3–79 keV energy range, making it highly suitable for probing an axion signal from the stars of M82. It consists of two identical coaligned instrument lines, each equipped with independent optics and focal-plane module (FPM) detectors, referred to as FPMA and FPMB. Each telescope subtends a field of view of approximately $13' \times 13'$, with an angular resolution of about $60''$ half-power diameter for a point source located near the optical axis. These grazing-incidence telescope modules enable NuSTAR to focus x-rays efficiently onto its focal plane detectors, providing high sensitivity and resolution for our analysis. Data from both detectors were reduced using HEASoft software version 6.34 [70] and NuSTARDAS version 2.1.4. We defined a circular source region with a radius of $60''$ centered at the coordinates of M82 (in right ascension (RA) and declination (Dec), epoch = J2000): $\mathrm{RA} = 09^{\mathrm{h}}55^{\mathrm{min}}52.43^{\mathrm{s}}$, $\mathrm{DEC} = +69°40'46.9''$. Additionally, we define eight concentric annular regions ranging from $60''$ to $237''$, with an equidistant separation of $22''$ (see SM [46]). Spectra are extracted from each annular region, allowing us to investigate the angular distribution of photons. We do not perform any background subtraction, as the signal is anticipated to encompass the entire field of view, but we later include an isotropic background as a free fit parameter. As detailed in SM [46], we have also explored alternative background treatments (such as using an OFF region and incorporating a power-law component), which result in slightly stronger constraints, thereby confirming the conservative nature of our primary approach. We stack and regroup the data into 5-keV wide energy bins, focusing on a fiducial energy range of 30–70 keV. We do not consider energies below 30 keV to mitigate potential effects of insufficiently accurate modeling of low-energy astrophysical x-ray emission from the Galaxy, following the approach outlined in [65]. To compute the expected axion decay signal counts at the NuSTAR FPMs for a given set of nuisance parameters $\boldsymbol{\theta} = \{g_{a\gamma}, m_a\}$, we forward-model the photon signal from axion decay through the instrument response files and exposure times of each observation. This process is performed for each energy bin i, angular bin α, observation, and module. We then sum over all observations and both modules to obtain the total expected counts $N^a_{i,\alpha}(\boldsymbol{\theta})$.

In order to obtain the bounds from M82, we model the signal as the superposition of the axion decay component $N^a_{i,\alpha}(\boldsymbol{\theta})$ in each angular and energy bin, and an isotropic background. We model the latter with a completely free energy spectrum, so we treat the fluxes in each of the eight energy bins as nuisance parameters, and the count rate $N^{\mathrm{bg}}_{i,\alpha}(\boldsymbol{\theta})$ in each angular bin is proportional to the solid angle of the bin. We do not include here an energy-dependent component for the astrophysical signal in the central bin, which is often modeled as a power law; this is conservative, because such a signal acts as a background for astrophysical searches. More importantly, as further discussed in SM [46], we have explicitly verified that our constraints are only marginally increased by subtracting off the background using an OFF region and modeling the photon signal from the central M82 source with a power law. This can be explained by taking into account that for the values of the coupling we are probing the main contribution to the axion signal comes from an ON region of radius $\lesssim 2'$ and, for the largest masses we are interested in [$m_a \gtrsim O(100)$ keV], constraints are dominated by the high-energy bins in the ON region, where the astrophysical background becomes smaller. The observed counts in each bin are denoted by $N^{\mathrm{obs}}_{i\alpha}$. To obtain our bounds, we introduce a log-likelihood Λ

$$\Lambda(g_{a\gamma}, m_a) = \max_{\boldsymbol{\theta}} \sum_{i,\alpha} \left[N^{\mathrm{obs}}_{i\alpha} \log\left(N^a_{i\alpha} + N^{\mathrm{bg}}_{i\alpha}\right) - N^a_{i\alpha} - N^{\mathrm{bg}}_{i\alpha} \right]. \tag{4}$$

We now define a test statistic (TS) following the prescriptions of Ref. [71] as $\mathrm{TS} = -2(\Lambda - \max_{g_{a\gamma}} \Lambda)$ if $g_{a\gamma}$ is above the best-fit value that maximizes Λ, and $\mathrm{TS} = 0$ otherwise. With this definition, the TS follows a half-chi-squared distribution with one degree of freedom, and the upper bounds on $g_{a\gamma}$ can be obtained by the threshold condition $\mathrm{TS} = 2.7$.

Discussion and outlook—Our bounds, shown in Fig. 2, are more than an order of magnitude stronger than other astrophysical bounds in the mass range of 30–300 keV. Part of the excluded region is already ruled out by arguments based on the freeze-in of the axions in the early Universe; this is a cosmological observable highly complementary to the astrophysical one introduced here. An additional cosmological observable that can rule out parameter space of interest to us is the spectral distortion of the cosmic microwave background induced by axions decaying to photons in the early Universe. Here, we report these bounds as shown in Ref. [31], which have been indirectly obtained from Ref. [30]. Our arguments rule out a previously uncharted region of parameter space which, at masses of several hundreds of keV, supersedes the previous bounds by nearly an order of magnitude.

NuSTAR provides an excellent instrument for the signature we identified, due to its angular resolution that allows us to probe the angular distribution over angles close to a few arcminutes from the source. Notice also that the constrained couplings lead to a decay length larger than ~Mpc; that means that extragalactic sources are best suited for this kind of search. On the other hand, Fig. 3 also shows that the energy window probed by NuSTAR is not directly centered on the peak of the photon spectrum. Therefore, measurements at higher photon energies in the hundreds of keV range, corresponding to the range of, e.g., INTEGRAL, could offer some advantage and complementarity to the strategy followed here. This is especially true since a tiny portion of the axions, produced with nonrelativistic velocities below the escape velocity of their progenitor star, might remain trapped around the star and form a "basin" similar to the solar basin. These axions, being at rest, would produce photons in the hundreds of keV region. We will consider the potential of these complementary signatures in a future work.

We should also distinguish our new observable from the recent proposal of Ref. [72], which considers a scenario in which axions are produced in the stellar cores through electron and photon couplings within Alpha Centauri, remain gravitationally trapped, and subsequently decay nearly at rest into photons. In our case, the temperatures of the stars dominating axion production are much higher, so our bounds reach up to much larger axion masses.

Notice that in this work we assume a minimal axion coupling to photons only. Obviously, for a specific UV-complete model, couplings to other species could be present as well. We focus here on the introduction of a novel observable whose relevance is general; the specifics of a given model only affect the details, but not the core, of our approach. For example, an additional coupling to electrons could enhance the axion emissivity from stellar cores, leading to strong constraints on the combined parameter space; this would only enlarge the parameter space without providing new insight. On the other hand, for a given UV-complete model, our approach can easily be extended to include the correct production processes.

To summarize, we have found that the cores of heavy stars within SBGs are by far the most powerful astrophysical probe of axion production in the tens-to-hundreds of keV mass range. Cosmological observables offer orthogonal probes, but our new argument can still exclude regions of parameter space that were previously allowed. By the same token, we expect other FIPs with radiative decay channels, such as sterile neutrinos, to also be probed by similar arguments. In this way, we have extended the observability of radiatively decaying FIPs to a new class of astrophysical sources.

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Data availability—The data supporting this study's findings are available within the article.

[1] J. H. Chang, R. Essig, and S. D. McDermott, Revisiting supernova 1987A constraints on dark photons, J. High Energy Phys. 01 (2017) 107.

[2] E. Hardy and R. Lasenby, Stellar cooling bounds on new light particles: Plasma mixing effects, J. High Energy Phys. 02 (2017) 033.

[3] J. Jaeckel, P. C. Malta, and J. Redondo, Decay photons from the axionlike particles burst of type II supernovae, Phys. Rev. D **98**, 055032 (2018).

[4] J. H. Chang, R. Essig, and S. D. McDermott, Supernova 1987A constraints on Sub-GeV dark sectors, millicharged particles, the QCD axion, and an axion-like particle, J. High Energy Phys. 09 (2018) 051.

[5] W. DeRocco, P. W. Graham, D. Kasen, G. Marques-Tavares, and S. Rajendran, Observable signatures of dark photons from supernovae, J. High Energy Phys. 02 (2019) 171.

[6] D. Croon, G. Elor, R. K. Leane, and S. D. McDermott, Supernova muons: New constraints on Z' bosons, axions and ALPs, J. High Energy Phys. 01 (2021) 107.

[7] 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.

[8] J. M. Camalich, J. Terol-Calvo, L. Tolos, and R. Ziegler, Supernova constraints on dark flavored sectors, Phys. Rev. D **103**, L121301 (2021).

[9] A. Caputo, P. Carenza, G. Lucente, E. Vitagliano, M. Giannotti, K. Kotake, T. Kuroda, and A. Mirizzi, Axionlike particles from hypernovae, Phys. Rev. Lett. **127**, 181102 (2021).

[10] A. Caputo, G. Raffelt, and E. Vitagliano, Muonic boson limits: Supernova redux, Phys. Rev. D **105**, 035022 (2022).

[11] A. Caputo, H.-T. Janka, G. Raffelt, and E. Vitagliano, Low-energy supernovae severely constrain radiative particle decays, Phys. Rev. Lett. **128**, 221103 (2022).

[12] R. Z. Ferreira, M. C. D. Marsh, and E. Müller, Strong supernovae bounds on ALPs from quantum loops, J. Cosmol. Astropart. Phys. 11 (2022) 057.

[13] A. Caputo, G. Raffelt, and E. Vitagliano, Radiative transfer in stars by feebly interacting bosons, J. Cosmol. Astropart. Phys. 08 (2022) 045.

[14] D. F. G. Fiorillo, G. G. Raffelt, and E. Vitagliano, Strong supernova 1987A constraints on bosons decaying to neutrinos, Phys. Rev. Lett. **131**, 021001 (2023).

[15] P. Carenza, G. Lucente, L. Mastrototaro, A. Mirizzi, and P. D. Serpico, Comprehensive constraints on heavy sterile neutrinos from core-collapse supernovae, Phys. Rev. D **109**, 063010 (2024).

[16] C. A. Manzari, J. Martin Camalich, J. Spinner, and R. Ziegler, Supernova limits on muonic dark forces, Phys. Rev. D **108**, 103020 (2023).

[17] 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).

[18] M. Diamond, D. F. G. Fiorillo, G. Marques-Tavares, and E. Vitagliano, Axion-sourced fireballs from supernovae, Phys. Rev. D **107**, 103029 (2023); **108**, 049902(E) (2023).

[19] K. Akita, S. H. Im, M. Masud, and S. Yun, Limits on heavy neutral leptons, Z' bosons and Majorons from high-energy supernova neutrinos, J. High Energy Phys. 07 (2024) 057.

[20] E. Müller, P. Carenza, C. Eckner, and A. Goobar, Constraining MeV-scale axionlike particles with Fermi-LAT observations of SN 2023ixf, Phys. Rev. D **109**, 023018 (2024).

[21] D. F. G. Fiorillo, G. G. Raffelt, and E. Vitagliano, Supernova emission of secretly interacting neutrino fluid: Theoretical foundations, Phys. Rev. D **109**, 023017 (2024).

[22] D. F. G. Fiorillo, G. G. Raffelt, and E. Vitagliano, Large neutrino secret interactions have a small impact on supernovae, Phys. Rev. Lett. **132**, 021002 (2024).

[23] D. F. G. Fiorillo and E. Vitagliano, Self-interacting dark sectors in supernovae can behave as a relativistic fluid, Phys. Rev. Lett. **133**, 251004 (2024).

[24] B. Telalovic, D. F. G. Fiorillo, P. Martínez-Miravé, E. Vitagliano, and M. Bustamante, The next galactic supernova can uncover mass and couplings of particles decaying to neutrinos, J. Cosmol. Astropart. Phys. 11 (2024) 011.

[25] E. Hardy, A. Sokolov, and H. Stubbs, Supernova bounds on new scalars from resonant and soft emission, arXiv:2410.17347.

[26] G. G. Raffelt, *Stars as laboratories for fundamental physics: The astrophysics of neutrinos, axions, and other weakly interacting particles* (University of Chicago Press, 1996.

[27] A. Caputo and G. Raffelt, Astrophysical axion bounds: The 2024 edition, Proc. Sci. COSMICWISPers (2024) 041 [arXiv:2401.13728].

[28] P. Carenza, M. Giannotti, J. Isern, A. Mirizzi, and O. Straniero, Axion astrophysics, Phys. Rep. **1117**, 1 (2025).

[29] P. F. Depta, M. Hufnagel, and K. Schmidt-Hoberg, Updated BBN constraints on electromagnetic decays of MeV-scale particles, J. Cosmol. Astropart. Phys. 04 (2021) 011.

[30] C. Balázs *et al.*, Cosmological constraints on decaying axion-like particles: A global analysis, J. Cosmol. Astropart. Phys. 12 (2022) 027.

[31] K. Langhoff, N. J. Outmezguine, and N. L. Rodd, Irreducible axion background, Phys. Rev. Lett. **129**, 241101 (2022).

[32] A. Ayala, I. Domínguez, M. Giannotti, A. Mirizzi, and O. Straniero, Revisiting the bound on axion-photon coupling from globular clusters, Phys. Rev. Lett. **113**, 191302 (2014).

[33] M. J. Dolan, F. J. Hiskens, and R. R. Volkas, Advancing globular cluster constraints on the axion-photon coupling, J. Cosmol. Astropart. Phys. 10 (2022) 096.

[34] N. H. Nguyen, E. H. Tanin, and M. Kamionkowski, Spectra of axions emitted from main sequence stars, J. Cosmol. Astropart. Phys. 11 (2023) 091.

[35] K. Van Tilburg, Stellar basins of gravitationally bound particles, Phys. Rev. D **104**, 023019 (2021).

[36] C. Beaufort, M. Bastero-Gil, T. Luce, and D. Santos, New solar x-ray constraints on keV axionlike particles, Phys. Rev. D **108**, L081302 (2023).

[37] M. Diamond, D. F. G. Fiorillo, G. Marques-Tavares, I. Tamborra, and E. Vitagliano, Multimessenger constraints on radiatively decaying axions from GW170817, Phys. Rev. Lett. **132**, 101004 (2024).

[38] P. S. B. Dev, J.-F. Fortin, S. P. Harris, K. Sinha, and Y. Zhang, First constraints on the photon coupling of axionlike particles from multimessenger studies of the neutron star merger GW170817, Phys. Rev. Lett. **132**, 101003 (2024).

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

[40] C. O'Hare, cajohare/axionlimits: Axionlimits, 10.5281/zenodo.3932430 (2020).

[41] D. A. Dicus, E. W. Kolb, V. L. Teplitz, and R. V. Wagoner, Astrophysical bounds on very low mass axions, Phys. Rev. D **22**, 839 (1980).

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

[43] L. Di Lella, A. Pilaftsis, G. Raffelt, and K. Zioutas, Search for solar Kaluza-Klein axions in theories of low scale quantum gravity, Phys. Rev. D **62**, 125011 (2000).

[44] P. Carenza, O. Straniero, B. Döbrich, M. Giannotti, G. Lucente, and A. Mirizzi, Constraints on the coupling with photons of heavy axion-like-particles from globular clusters, Phys. Lett. B **809**, 135709 (2020).

[45] G. Lucente, P. Carenza, T. Fischer, M. Giannotti, and A. Mirizzi, Heavy axion-like particles and core-collapse supernovae: Constraints and impact on the explosion mechanism, J. Cosmol. Astropart. Phys. 12 (2020) 008.

[46] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.134.171004 for explicit discussions about the axion production and decay, about the data reduction and NuSTAR analysis, and for a comparison

with bounds previously used in the literature, which includes Refs. [47–62].
[47] L. Origlia, P. Ranalli, A. Comastri, and R. Maiolino, Stellar and gaseous abundances in M82, Astrophys. J. **606**, 862 (2004).
[48] B. W. Carroll and D. A. Ostlie, *An Introduction to Modern Astrophysics* (Benjamin Cummings, 1996).
[49] L. Oberauer, C. Hagner, G. Raffelt, and E. Rieger, Supernova bounds on neutrino radiative decays, Astropart. Phys. **1**, 377 (1993).
[50] J. Blackburn, Ftools: A fits data processing and analysis software package, in *Astronomical Data Analysis Software and Systems IV* (Astronomical Society of the Pacific, San Francisco, California, 1995), Vol. 77, p. 367.
[51] K. Arnaud *et al.*, Xspec: An x-ray spectral fitting package, Astrophysics Source Code Library (1999) ascl.
[52] 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).
[53] R. Krivonos, D. Wik, B. Grefenstette, K. Madsen, K. Perez, S. Rossland, S. Sazonov, and A. Zoglauer, NuSTAR measurement of the cosmic x-ray background in the 3–20 KeV energy band, Mon. Not. R. Astron. Soc. **502**, 3966 (2021).
[54] F. Bergsma *et al.* (CHARM Collaboration), Search for axion like particle production in 400-GeV proton—copper interactions, Phys. Lett. **157B**, 458 (1985).
[55] E. M. Riordan *et al.*, A search for short lived axions in an electron beam dump experiment, Phys. Rev. Lett. **59**, 755 (1987).
[56] J. Blumlein *et al.*, Limits on neutral light scalar and pseudoscalar particles in a proton beam dump experiment, Z. Phys. C **51**, 341 (1991).
[57] D. Banerjee *et al.* (NA64 Collaboration), Search for axion-like and scalar particles with the NA64 experiment, Phys. Rev. Lett. **125**, 081801 (2020).
[58] M. J. Dolan, T. Ferber, C. Hearty, F. Kahlhoefer, and K. Schmidt-Hoberg, Revised constraints and Belle II sensitivity for visible and invisible axion-like particles, J. High Energy Phys. 12 (2017) 094; 03 (2021) 190(E).
[59] F. Capozzi, B. Dutta, G. Gurung, W. Jang, I. M. Shoemaker, A. Thompson, and J. Yu, New constraints on ALP couplings to electrons and photons from ArgoNeuT and the MiniBooNE beam dump, Phys. Rev. D **108**, 075019 (2023).
[60] N. Vinyoles, A. Serenelli, F. L. Villante, S. Basu, J. Redondo, and J. Isern, New axion and hidden photon constraints from a solar data global fit, J. Cosmol. Astropart. Phys. 10 (2015) 015.
[61] M. J. Dolan, F. J. Hiskens, and R. R. Volkas, Constraining axion-like particles using the white dwarf initial-final mass relation, J. Cosmol. Astropart. Phys. 09 (2021) 010.
[62] D. F. G. Fiorillo, M. Heinlein, H.-T. Janka, G. Raffelt, E. Vitagliano, and R. Bollig, Supernova simulations confront SN 1987A neutrinos, Phys. Rev. D **108**, 083040 (2023).
[63] B. Paxton, L. Bildsten, A. Dotter, F. Herwig, P. Lesaffre, and F. Timmes (MESA Collaboration), Modules for experiments in stellar astrophysics (MESA), Astrophys. J. Suppl. Ser. **192**, 3 (2011).
[64] B. Paxton *et al.*, Modules for experiments in stellar astrophysics (MESA): Planets, oscillations, rotation, and massive stars, Astrophys. J. Suppl. Ser. **208**, 4 (2013).
[65] O. Ning and B. R. Safdi, preceding Letter, Leading axion-photon sensitivity with NuSTAR observations of M82 and M87, Phys. Rev. Lett. **134**, 171003 (2025).
[66] See https://docs.mesastar.org/en/latest/test_suite/20M_pre_ms_to_core_collapse.html.
[67] N. M. Forster Schreiber, R. Genzel, D. Lutz, and A. Sternberg, The nature of starburst activity in M82, Astrophys. J. **599**, 193 (2003).
[68] NASA/IPAC Extragalactic Database (NED), http://ned.ipac.caltech.edu/.
[69] S. S. McGaugh and J. M. Schombert, Color-mass-to-light-ratio relations for disk galaxies, Astron. J. **148**, 77 (2014).
[70] 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.
[71] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C **71**, 1554 (2011); **73**, 2501(E) (2013).
[72] Y.-X. Chen, L. Lei, Z.-Q. Xia, Z. Wang, Y.-L. S. Tsai, and Y.-Z. Fan, Searching for axion-like particles with x-ray observations of alpha centauri, arXiv:2410.16065.