

Axion lines from nuclear de-excitations in galactic stellar populations

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We show that mono-energetic axions are produced in abundance through nuclear de-excitations in nearby galaxies such as M87, which is the central galaxy of the Virgo cluster, and the starburst galaxy M82. If the axion couples to both nucleons and photons and is ultralight, then monochromatic hard x-ray signatures are induced by the subsequent axion-to-photon conversion in the magnetic fields permeating these systems. We search for evidence of such signals using NuSTAR data, focusing specifically on the ^{57}Fe de-excitation line at 14.4 keV, and we catalog other potentially relevant nuclear lines. We find no evidence for axions from M87 or M82 and set stringent constraints on the combined axion-nucleon and axion-photon coupling at the level of $|g_{ann} \times g_{\gamma\gamma}| \lesssim 1.1 \times 10^{-22} \text{ GeV}^{-1}$ in the limit $m_a \lesssim 10^{-10} \text{ eV}$ at 95% confidence.

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I. INTRODUCTION

Axions may solve the strong-CP problem and provide a viable candidate for dark matter (DM) [1–7]. Further, they are generically predicted in string theory, where they arise as the zero modes of higher-dimensional gauge fields upon compactification [8–12]. Axions may be classified into the quantum chromodynamics (QCD) axion, whose mass arises predominantly from QCD contributions, and axion-like particles, whose masses are unrelated to QCD. Ultralight axion masses, well below, e.g., 10^{-10} eV , are natural and indeed expected in string theory constructions since in these cases the mass contributions must be non-local and are exponentially suppressed by instanton actions (see, e.g., [13–17] for explicit constructions). While ultralight axions do not interact with QCD (but see [18]), they are expected to have interactions with quantum electrodynamics (QED) and Standard Model (SM) fermions, including quarks (see [19–22] for reviews). Below the QCD confinement scale the axion-quark interactions induce derivative couplings of the axions to nucleons. As we show in this work, this allows axions to be produced in abundance through nuclear de-excitations in hot, massive

stars found in nearby galaxies. In the case of ultralight axions, the mono-energetic axions may then convert efficiently to monochromatic x-rays in the magnetic fields in these systems. We search for these x-rays using NuSTAR data as in [23,24], which searched for axion-induced hard x-ray signatures in these same galaxies but focused on emission from Primakoff and electron Compton and bremsstrahlung processes. Unlike in those works, however, the axion-induced signals that we search for here are mono-energetic at known energies. The detection of such a line would thus be a smoking-gun signature of axions.

It is well established in the context of the Sun that axions may be emitted from the de-excitations of thermally excited nuclear excited states. The excitation energies of typical nuclei tend to be around $\mathcal{O}(\text{MeV})$. Therefore, such emission processes have excitation probabilities that are highly Boltzmann suppressed under normal stellar conditions. However, there exist certain nuclei with low-lying nuclear energy levels in the $\mathcal{O}(10) \text{ keV}$ range. Among the nuclei with low-lying nuclear energy levels, ^{57}Fe , with a transition energy of $E^* = 14.4 \text{ keV}$, is perhaps the most well studied [25–37]. Yet even this excited state is Boltzmann suppressed at the level of $\sim 10^{-5}$ in the Sun, which has a core temperature of $\sim 1 \text{ keV}$. On the other hand, we show in this work that accounting for axion production in stellar populations allows us to probe stars with much higher core temperatures, for which the 14.4 keV ^{57}Fe axion line is not Boltzmann suppressed at all. Our search is similar to that performed in [37], which searched for the ^{57}Fe axion

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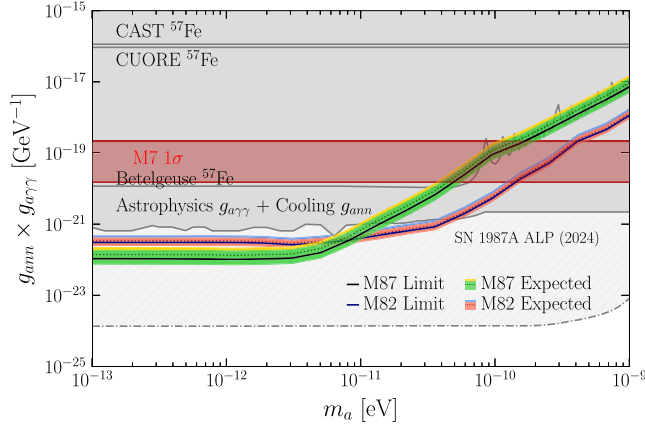


FIG. 1. The 95% upper limits (bolded) on the combined axion-nucleon and axion-photon couplings $g_{ann} \times g_{\gamma\gamma}$ from our two most stringent searches for ultralight axions produced from nuclear isotope de-excitations in galactic stellar populations. The axions convert to x-rays in the magnetic fields permeating the host galaxies, and we search for these x-rays using NuSTAR data. We also illustrate the $1\sigma/2\sigma$ containment intervals for the expected 95% upper limits on $g_{ann} \times g_{\gamma\gamma}$ under the null hypothesis. Our illustrated constraints come from the ^{57}Fe searches in M87 and M82, assuming $g_{ann} = g_{app}$ [see (8)]. Our results disfavor the axion interpretation of the previously observed M7 x-ray excess from nearby neutron stars [43,44] for low mass axions.

line with NuSTAR data toward the nearby supergiant Betelgeuse, though this work achieves superior sensitivity by summing over full stellar populations.

In addition to ^{57}Fe , previous studies have also explored axion emission and nuclear line searches involving a myriad of other isotopes, each with their own unique line energies, abundances, and other properties, for example, ^{83}Kr [38], ^{23}Na [25,39], ^{125}Te [40], ^{139}La [41], and ^{65}Cu [42]. We show in this work that ^{61}Ni and ^{73}Ge lines at 67.4 keV and 68.8 keV, respectively, are the next most luminous emission lines in axions relative to the ^{57}Fe line, though the ^{57}Fe line dominates in typical stellar populations.

The 14.4 keV ^{57}Fe line has been searched for using the CERN Axion Solar Telescope (CAST) [29], where the solar axions are converted to x-rays in the strong magnetic fields in the CAST experiment (see also [31] for a related search using the CUORE detector). The upper limit from this search constrains $|g_{ann}^{\text{eff}} \times g_{\gamma\gamma}| \lesssim 10^{-16} \text{ GeV}^{-1}$, where $g_{\gamma\gamma}$ is the axion-photon coupling, and g_{ann}^{eff} is an effective axion-nucleon coupling (see Fig. 1); these couplings are defined more precisely later in this work. We improve upon this bound by approximately six orders of magnitude for axion masses less than roughly 10^{-10} eV .

Strong constraints also exist independently on the axion-photon and axion-nucleon couplings for low-mass axions; these may be combined to constrain $|g_{ann} \times g_{\gamma\gamma}|$, as illustrated in Fig. 1. In particular, constraints at the level

of $|g_{\gamma\gamma}| \lesssim 7.8 \times 10^{-13} \text{ GeV}^{-1}$ for $m_a \lesssim 10^{-10} \text{ eV}$ at 95% confidence arise from searching for x-ray signatures with the same NuSTAR data considered in this work toward the nearby active galaxy M82, accounting for axion production in the stellar population in the galaxy through the Primakoff effect and then conversion of axions-to-photons in the magnetic field of the galaxy through inverse Primakoff [23]. Searches for axion-induced spectral modulation in Chandra x-ray data taken toward NGC 1275 are comparable [45] (see also [46–48]). Above $m_a \gtrsim 10^{-10} \text{ eV}$ constraints from the nonobservation of gamma-rays following SN1987A become prominent [49–53], as are the constraints from axion searches in magnetic white dwarfs (MWD), in particular from axion-induced polarization [54] (see also [55–57]). Two different classes of constraints exist on the axion-nucleon couplings that are nearly degenerate in magnitude. Strong constraints exist at the level of $|g_{ann}| \lesssim 1.3 \times 10^{-9}$ and $|g_{app}| \lesssim 1.5 \times 10^{-9}$ for the axion-neutron and axion-proton couplings, respectively, from neutron star (NS) cooling [58]. Similar constraints arise by considering axion production in the proto-NS formed after SN1987A; more strongly-coupled axions would have over-cooled the neutron star and modified the observed neutrino burst [59–64]. On the other hand, the most stringent constraints on the axion-nucleon times axion-photon parameter space can be inferred from the nonobservation of axion-induced gamma-rays from SN 1987A [53]. There, Solar Maximum Mission (SMM) observations were used to search for strong axion signals from the Primakoff effect and nucleon bremsstrahlung in the proto-neutron star, which then convert to gamma-rays from Galactic and stellar magnetic fields. Given various assumptions about the exact nature of the supernova emission, we show the benchmark constraint from [53] as the hatched region in Fig. 1.

II. NUCLEAR LINE SEARCHES

In stellar environments, a finite axion-nucleon coupling opens a novel channel for axion production through nuclear isotope de-excitations. The key idea is that if the temperature of the star becomes comparable to the nuclear transition energy, the nucleus can become thermally excited, and its subsequent de-excitation can result in axion emission. The emitted axion is monochromatic, with an energy corresponding to the transition energy of the specific nucleus. Before describing the calculations of these transition rates, we briefly review the axion effective field theory (EFT) in order to set the notation used throughout the rest of this work (see [19–22] for in-depth reviews).

At energy scales below the electroweak symmetry breaking scale but above the QCD confinement scale we may parametrize the relevant interactions of the axion EFT by

$$\mathcal{L} \supset \frac{1}{2f_a} \sum_q C_{aq} \partial^\mu a \bar{q} \gamma_\mu \gamma^5 q - \frac{1}{4} C_{a\gamma\gamma} \frac{e^2}{8\pi^2 f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad (1)$$

where f_a is the axion decay constant that sets the energy scale of the ultraviolet (UV) completion, a is the axion field, and in the first term, C_{aq} is a dimensionless Wilson coefficient, and the q stands for the light quarks with masses below the energy scale of the EFT. In the second term e is the electric charge, $C_{a\gamma\gamma}$ is the dimensionless axion-photon coupling, and F is the quantum electrodynamics (QED) field strength. The second term in (1) may be written as $\mathcal{L} \supset a g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B}$, with $g_{a\gamma\gamma} \equiv C_{a\gamma\gamma} e^2 / (8\pi^2 f_a)$ being the dimension-full axion-photon coupling and $\mathbf{E}$ ($\mathbf{B}$) being the electric (magnetic) field. Below the QCD confinement scale, the second term in (1) is unchanged, but the first must be matched to axion interactions with nucleons and pions, though only the axion-nucleon interactions are relevant here. In particular, we may write

$$\mathcal{L} \subset \frac{1}{2f_a} \sum_N C_{aNN} \partial^\mu a \bar{N} \gamma_\mu \gamma^5 N, \quad (2)$$

with $N = n, p$ for neutrons and protons and [65] as

$$\begin{aligned} C_{ann} &\approx 0.88 C_{auu} - 0.39 C_{add}, \\ C_{app} &\approx 0.88 C_{add} - 0.39 C_{auu}, \end{aligned} \quad (3)$$

with subdominant contributions from C_{ass} . From the coefficients above, we may define the dimensionless axion-nucleon couplings as

$$g_{ann} \equiv \frac{C_{ann} m_N}{f_a}, \quad g_{app} \equiv \frac{C_{app} m_N}{f_a}, \quad (4)$$

with m_N the nucleon mass.

We now turn to the calculation of the axion emissivity for magnetic dipole (M1) transitions in nuclear isotopes. The axion emission rate per unit mass may be parametrized as [25,29]

$$\dot{\mathcal{N}}_a = \mathcal{N} \omega_* \frac{1}{\tau_m} \frac{1}{1 + \alpha} \frac{\Gamma_a}{\Gamma_\gamma} \quad (5)$$

where $\mathcal{N}$ denotes the number of the isotope of interest per unit mass, ω_* denotes the probability that the excited state responsible for the axion emission is excited (i.e., the excited state occupation fraction), τ_m is the total mean lifetime of the excited state, α is the internal conversion coefficient, and Γ_a/Γ_γ is the ratio of the axion decay rate to the photon decay rate. This ratio may be parametrized as follows [25]:

$$\frac{\Gamma_a}{\Gamma_\gamma} = \left(\frac{k_a}{k_\gamma} \right)^3 \frac{1}{2\pi\alpha_{\text{EM}}} \frac{1}{1 + \delta^2} \left[\frac{g_{app}(\frac{\beta+1}{2}) + g_{ann}(\frac{\beta-1}{2})}{(\mu_0 - 0.5)\beta + \mu_1 - \eta} \right]^2. \quad (6)$$

In the above equation, $\alpha_{\text{EM}} = 1/137$ is the fine structure constant, and δ is the electric quadrupole (E2) to M1 mixing ratio. Additionally, $\mu_0 = (\mu_p + \mu_n)/\mu_N \approx 0.88$ and $\mu_1 = (\mu_p - \mu_n)/\mu_N \approx 4.706$ [66] are the isoscalar and isovector nucleon magnetic moments, with μ_p (μ_n) denoting the magnetic moment of the proton (neutron) and μ_N the nuclear magneton. The coefficients β and η are nuclear-structure dependent ratios and are calculated from the nuclear shell model formalism [25]. Lastly, $k_a = \sqrt{E_\gamma^2 - m_a^2}$ and $k_\gamma = E_\gamma$ denote the momenta of the outgoing axions and photons, respectively, for the two decay channels. For ultralight axions, which are the focus in this paper, k_a/k_γ becomes unity.

For ^{57}Fe , with a de-excitation energy of $E^* \approx 14.4$ keV, the various nuclear factors are taken to be $\delta \approx 0.002$, $\beta \approx -1.19$, and $\eta \approx 0.8$ [25]. This leads to

$$\frac{\Gamma_a}{\Gamma_\gamma} \approx 1.83 (g_{ann}^{\text{eff}})^2, \quad (7)$$

where we define

$$\begin{aligned} g_{ann}^{\text{eff}} &\equiv g_{ann} - \left(\frac{\beta + 1}{2} \right) (g_{app} + g_{ann}) \\ &\approx g_{ann} + 0.095 (g_{app} + g_{ann}). \end{aligned} \quad (8)$$

The total mean lifetime of the excited state is assumed to be $\tau_m \approx 141.8$ ns, with the internal conversion coefficient $\alpha \approx 8.56$ [67]. The occupation fraction at temperature T for the first excited state is

$$\omega_* = \frac{(2J_1 + 1)e^{-E_*/T}}{(2J_0 + 1) + (2J_1 + 1)e^{-E_*/T}}, \quad (9)$$

where $J_0 = 1/2$ is the angular momentum of the ground state, and $J_1 = 3/2$ is the angular momenta of the first excited state [67].

The parameters β and η are uncertain in that they depend on nonunique choices of the nuclear shell model calculation, such as the effective interaction Hamiltonian and the effective diagonalization scheme. References [34,35] use different schemes than those we adopt above, yielding $\beta \approx -1.3065$, and $\eta \approx 1.2054$. With this choice of parameters, one computes $\Gamma_a/\Gamma_\gamma \approx 2.42 (g_{ann}^{\text{eff}})^2$, where the effective axion-nucleon coupling is given by $g_{ann}^{\text{eff}} \approx 0.15 g_{app} + 1.15 g_{ann}$ [34,35]. We choose not to adopt this parameter set in our analysis and instead use (7) (i.e., as in Ref. [25]) because it leads to more conservative results. Still, this computational uncertainty should be kept in mind

when interpreting our results, and we cannot rule out the possibility that Γ_a/Γ_γ is, in reality, even lower than we assume.

While ^{57}Fe provides the most sensitive probe of axions in our work, we also conduct a search for other potentially promising isotopes with low-lying energy transition energies E^* accessible via the NuSTAR hard x-ray telescope (i.e., $E^* \lesssim 85$ keV). In particular, we find that ^{61}Ni and ^{73}Ge , which have E^* around 67.4 keV and 68.7 keV, respectively, are competitive with ^{57}Fe in terms of axion production in particular stellar environments. We detail these findings later in this work, with details described in Appendix B.

Given a stellar model, which we discuss shortly, the axion-induced line emission rate at energy E^* in units of, e.g., erg/s, which we call L_a , is found by integrating over the stellar interior,

$$L_a = 4\pi E^* \int_0^R dr r^2 \rho(r) \dot{\mathcal{N}}_a(T(r)), \quad (10)$$

where we make explicit the radial dependence of the stellar temperature. We note that the axion emission spectral shape is not precisely monochromatic at E^* but is broadened by a number of effects, ranging from the finite lifetime of the excited state to the finite temperature of the stellar plasma. In reality, however, quantum and Doppler broadening are negligible compared to the broadening by the finite energy resolution of the NuSTAR telescope (see also [37]).

Following the procedure in [23,24], each star in the stellar population of interest is described by a state from dedicated simulations in the Modules for Experiments in Stellar Astrophysics (MESA) code package [68,69], which is designed to evolve stars over time, given inputs such as stellar mass and metallicity. MESA then returns radial profiles for the star at a stellar age, providing, e.g., the star's temperature and density, as well as its ion and electron number densities, which allows us to calculate (10) above. On the other hand, the abundances $\mathcal{N}$ of the rare isotopes considered in our work, such as ^{57}Fe , ^{61}Ni , and ^{73}Ge , are primarily informed by the initial metallicity of our galactic population models. These abundances are taken to be mostly solar,¹ as described more below. This simplification is justified, as we estimate that the existing primordial abundance of these isotopes make up the dominant contribution to a star's isotope abundance, given that these heavy, evolved isotopes are not substantially produced in stellar interiors for most of the stars' lives (see [36] which verifies this point, but also [37] for another approach). Note

¹We note that for the exceptional case of M82, there is evidence that specific heavy elements such as Fe likely have subsolar abundances [70,71]. To account for this, we take the average in [70] and set the fiducial abundances to be ≈ 0.38 times solar. See Fig. 17 in Appendix A for an illustration.

that we still attempt to include the production of these isotopes from stellar evolution, roughly estimated by, e.g., taking the ^{56}Fe abundances outputted by MESA and scaling them to ^{57}Fe abundances through solar abundance ratios (and analogously for other isotopes). While we reiterate that this is only a rough estimate, a more precise treatment (e.g., similar to [37]) would suggest that the relevant s-process nucleosynthesis reactions would only produce slightly more heavy elements like ^{57}Fe toward the latest periods of a star's life, which would overall have a minimal impact on large population studies such as the ones considered in this work.

III. STELLAR POPULATIONS

Following and extending the ultralight axion searches in [23,24], here we choose four different galactic targets to analyze: M82, M87, M31, and the Milky Way Galactic Center (GC). For each of these targets, we calculate the summed axion luminosity at energy E^* from the de-excitation transitions described in the previous section. M82, an archetypal starburst galaxy host to a myriad of young, hot, massive stars, has been shown to be particularly promising in the context of axion searches [23,24,72]. On the other hand, M87 and M31 provide complementary targets with generally older but larger stellar populations. M87 has the advantage of having significantly stronger magnetic fields ideal for axion-to-photon conversion by nature of being embedded in the Virgo cluster, while M31 is the closest galaxy to our own, around ~ 785 kpc away. We additionally adopt a simplified model of the Milky Way GC as a point of comparison to these extragalactic targets, which has the advantage of proximity.

Our stellar population modeling for M82 and M87 is identical to that presented in [23], while the model for M31 is detailed in [24]. Briefly, we detail the salient features of these models here. For M82, following [23] we take as our fiducial model a stellar population of $N_{\text{tot}} \approx 10^{10}$ stars drawn from a modified Salpeter initial mass function (IMF), a “two-burst” star formation history (SFH) across $\sim 10^7$ years, and an initial metallicity of $Z = 0.02$. For M87, following [23] we adopt a canonical Salpeter IMF, an exponential τ SFH model, $N_{\text{tot}} \approx 10^{12}$ stars, and $Z \approx 0.02$. Our model for M31 is similar to that of M87 with slightly differing N_{tot} and τ (see [24]). We also estimate the stellar population of the GC in this work, assuming a similar population as M31 but with a fraction of the number of stars determined by the estimated mass of the GC central bulge population [73]. Systematic uncertainties on quantities such as the IMF, SFH, N_{tot} , and metallicity are explored in [23,24]; briefly, they involve varying the IMF cutoff, SFH burst and/or decay parameters, total numbers of stars inferred from mass estimates, and metallicity variations, all in accordance with observational uncertainties (see [23,24]). Stars from these stellar population models are

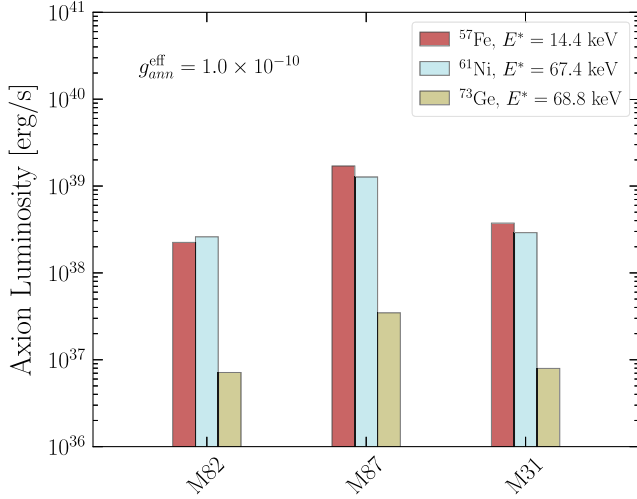


FIG. 2. Comparison of the total axion luminosity from the indicated nuclear transitions across our M82, M87, and M31 stellar populations. We note that since our GC model is similar to that of M31, with corresponding luminosities ~ 5 orders of magnitude smaller, we do not illustrate it here. Note that these luminosities are constructed with the indicated effective axion-nucleon coupling. This figure shows that the ^{57}Fe and ^{61}Ni de-excitations are the most significant sources of axions.

drawn from corresponding evolved MESA simulations in stellar mass and age, which are then used to construct our total, summed axion signal in combination with the formalism for nuclear-transition-induced axions discussed earlier.

In Fig. 2, we illustrate a comparison of the total axion luminosity from our three strongest targets: M82, M87, M31, and the three main nuclear isotopes we consider in our work. We see that at the level of the raw axion emission, the three galaxies are roughly comparable, although M87, due to its larger number of stars, has the highest axion luminosity across all three isotopes. Additionally, we note that among the three galaxies, M82 has the highest ratio of ^{61}Ni to ^{57}Fe emission, which comes from its starburst nature and larger fraction of massive stars with higher core temperatures. This benefits ^{61}Ni line emission slightly more than ^{57}Fe . Finally, we note that, of course, Fig. 2 only represents the axion emission from each galaxy; other aspects of the signal model, such as the conversion probabilities and distances, are also integral to the final photon spectrum for which we search.

IV. SEARCHING FOR ULTRALIGHT AXIONS

If axions are ultralight, they can efficiently convert to x-ray photons in the magnetic fields of our galactic targets. This idea was first fully explored in [23], where, as a summary, full-scale galactic models of magnetic fields and free-electron densities were chosen from ensembles of candidate galaxies in the IllustrisTNG TNG50 and

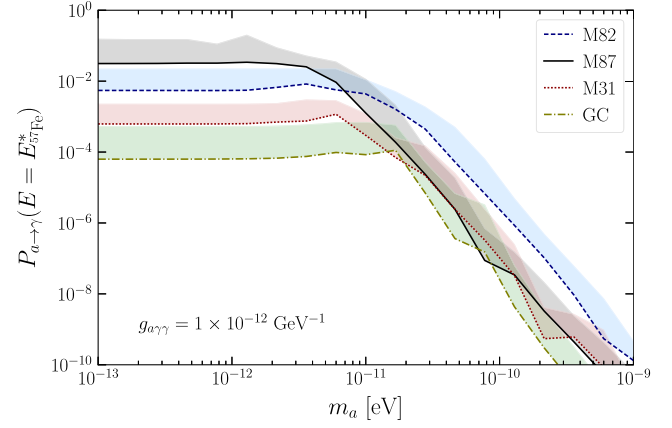


FIG. 3. Illustration of the axion-to-photon conversion probabilities across the four galactic targets considered in this work. Here, we show the conversion probabilities as a function of axion mass m_a , evaluated at the ^{57}Fe line, i.e., $E^* = 14.4$ keV. For M82, M87, and M31, whose conversion probabilities are calculated from IllustrisTNG models (see main text and [23]), we show our fiducial conversion probabilities (bold lines) as well as the 1σ containment bands for the conversion probabilities across our galaxy candidates and orientations. For the Milky Way GC, we calculate conversion probabilities from parametric magnetic field models (see main text) and show the resulting containment bands with the adopted probabilities given as the bold dash dotted line.

TNG300 simulations [74,75]. These analogue galaxies were filtered to have similar properties to the galaxies of interest, including star formation rate, stellar mass, and disk morphology. The associated magnetic field and free-electron density models allow for the calculation of the probability of an axion-to-photon conversion, $P_{a \rightarrow \gamma}$, given an axion mass m_a (see, e.g., [23]).

In this work, we follow the same setup [23] for modeling axion-to-photon conversion and refer to that work for further details, although we give a brief summary here. After selection of the analogue galaxy candidates in the simulations and randomly choosing orientations for a given galaxy, we draw stellar positions from the simulated baryonic distributions, and axion-to-photon conversion probabilities are calculated along the line-of-sight from those points. These conversion probabilities, derived from the ensemble of galaxy candidates and orientations, are then used to compute the upper limits on the axion couplings. Following [23], our choice of a fiducial model is the conservative one that minimizes the expected sensitivity (i.e., yields the weakest low-mass limit at 1σ containment). In Fig. 3, we give an illustration of our axion-to-photon conversion probabilities as a function of m_a , across our galaxy targets, evaluated at the ^{57}Fe line energy. We also show the 1σ containment bands on these probabilities, derived from our usage of IllustrisTNG galactic magnetic field models of M82, M87, and M31. For the GC, we calculate conversion probabilities for the eight parametric galactic magnetic field models in [76] as well as the

older model in [77], and we also assume the ne2001 free-electron density model [78]. To account for uncertainties in the GC magnetic field modeling, we choose the weakest (in terms of conversion probability) of the parametric models detailed in [76,77] as our fiducial model, which is illustrated, along with the uncertainty bands, in Fig. 3. Note that for the case of the IllustrisTNG-based models, we show the uncertainty bands over the full ensemble of analogue galaxies and orientations, with details for how these analogues are chosen given in [23,24].

We emphasize an overall remark here that by construction our choices for the adopted fiducial conversion probabilities are meant to be conservative, as can be seen in Fig. 3. This is especially important since the magnetic field uncertainties dominate the uncertainties in our overall analysis, exactly analogous to the situations in [23] and [24] (we defer further discussion of the astrophysical population uncertainties to those works, as they are identical). Taking the more conservative side of the magnetic field modeling, as well as other previously discussed choices in our analysis such as the more conservative set of nuclear factors in our axion production calculation, gives us confidence that our final results are reasonably robust to systematic uncertainties. For example, taking instead the median conversion probabilities instead of our fiducial, lower 1σ values for M82, M87, M31, and the GC would result in our low- m_a upper limits on $g_{ann}^{\text{eff}} \times g_{\gamma\gamma}$ being 1.4, 1.5, 1.4, and 1.7 times stronger, respectively, than our fiducial limits.

Proceeding forward, these conversion probabilities are finally combined with our axion luminosity signal to construct the expected axion-induced photon spectrum at Earth for a given galaxy distance d ,

$$\Phi = L_a \times P_{a \rightarrow \gamma}(m_a, E^*) \times \frac{1}{4\pi d^2}. \quad (11)$$

Above, we explicitly emphasize the energy and axion mass dependence of the conversion probability. In particular, the axion conversion probability becomes suppressed when, roughly, the axion and photon become out of phase over the coherence length of the magnetic fields, which roughly translates to $\delta k L \sim \frac{m_a^2}{2E^*} \text{kpc} > 1$, with δk being the momentum mismatch between the axion and photon and $L \sim \text{kpc}$ the typical galactic magnetic field coherence length. (Note that in practice we exactly solve the axion-photon mixing equations at the relevant E^* and m_a .) We forward model this monochromatic flux through the NuSTAR detector to find a line-like signal that is spectrally broadened at the level of $\sim 10\%$.

We search for the resulting axion-induced spectra using NuSTAR data toward the appropriate targets, following the procedures and analyses developed in [23,24], with the crucial difference being that the signal considered here is not spectrally broad but is instead a narrow line at a known

energy E^* . First, we compile archival NuSTAR data for M82, M87, M31, and the GC for each of the two NuSTAR Focal Plane Modules (FPM). Our archival data for M82 and M87 are detailed in [23], while that for M31 is detailed in [24] and that for the GC is listed in Table II in Appendix A. We reduce the data using HEASoft version 6.28 [79], ultimately deriving counts spectra for source (ON) and background (OFF) regions, as defined in [23,24], as well as the redistribution matrix files (RMFs) and auxiliary response files (ARFs) used for forward modeling the axion signal. Unlike the methods in [23,24], we keep the counts spectra in bins defined by the native NuSTAR energy resolution channels (with bin widths ~ 40 eV) since we are searching for a narrow spectral feature.

The forward-modeled axion signal is computed by

$$\mu_{S,i}^{\text{tot}}(\theta_S) = \sum_e t^e \int dE' \text{RMF}_i^e(E') \text{ARF}^e(E') S(E' | \theta_S), \quad (12)$$

where we sum over the different exposures with exposure times t^e . The physical axion spectrum S has units of [cts/cm²/s/keV] and has support only in a single input energy bin, with signal parameters $\theta_S = \{m_a, g_{ann}^{\text{eff}} \times g_{\gamma\gamma}\}$. The quantity $\mu_{S,i}^{\text{tot}}$ reflects the expected signal counts for signal S in energy bin i . We combine the signal model with a power-law background model with two nuisance parameters $\theta_B = \{\alpha, \beta\}$ for the normalization and spectral index to describe the data under the null hypothesis.

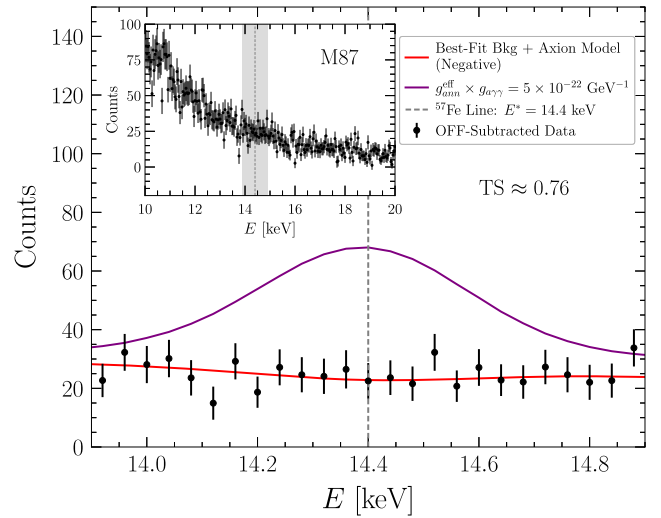


FIG. 4. Illustration of the data analysis performed for the ^{57}Fe line over the stellar population of M87. The inset shows the broader region around the $E^* = 14.4$ keV line, with the main plot showing the best-fit axion signal and background model (red), compared against the OFF-subtracted NuSTAR data in the analysis energy range around the expected line emission. Also shown is a large example axion-induced signal (purple) with the indicated couplings. The signals shown here are taken in the low m_a limit.

TABLE I. The resulting discovery of TS's for a two-sided test, 95% upper limits (U.L.) and best fits (B.F.) for $g_{ann}^{\text{eff}} \times g_{\gamma\gamma}$ from our search for nuclear de-excitation-induced axions over our selected galaxy targets and nuclear isotopes. The upper limits and best fits are quoted for the massless axion limit, and the (–) symbol indicates a negative best fit. Finding no significant evidence for axions, our most stringent constraints come from ^{57}Fe searches in M82 and M87.

Isotope	Energy [keV]	Target	Discovery TS	$g_{ann}^{\text{eff}} \times g_{\gamma\gamma}$ [GeV $^{-1}$] 95% U.L.	$g_{ann}^{\text{eff}} \times g_{\gamma\gamma}$ [GeV $^{-1}$] B.F.
^{57}Fe	14.4	M82	0.03	4.0×10^{-22}	7.6×10^{-23}
		M87	0.76	1.4×10^{-22}	(–)
		M31	0.30	5.6×10^{-22}	(–)
		GC	0.17	1.2×10^{-21}	(–)
^{61}Ni	67.4	M82	1.5	1.2×10^{-21}	7.9×10^{-22}
		M87	1.9	1.0×10^{-21}	6.8×10^{-22}
		M31	1.9	4.2×10^{-21}	3.0×10^{-21}
		GC	0.68	2.3×10^{-21}	(–)
^{73}Ge	68.8	M82	0.18	4.7×10^{-21}	(–)
		M87	2.5	5.3×10^{-21}	3.5×10^{-21}
		M31	0.06	1.9×10^{-20}	5.3×10^{-21}
		GC	1.4	1.1×10^{-20}	(–)

This combined signal and astrophysical background is then compared to the NuSTAR OFF-subtracted counts data using a Gaussian likelihood. We profile over the background nuisance parameters using standard frequentist techniques [21,80,81] to obtain, given a fixed m_a , quantities such as the best-fit signal, the 95% upper limit on our signal parameters $g_{ann}^{\text{eff}} \times g_{\gamma\gamma}$, as well as the 1σ and 2σ expectations for the 95% upper limits under the null hypothesis.

Note that in performing the analyses, we select data within $\pm 3\sigma$ of the line energy E^* , with σ defined as the approximate standard deviation of the NuSTAR energy resolution at central energy E^* . For ^{57}Fe (^{61}Ni) (^{73}Ge), we find $\sigma \approx 0.19$ keV ($\sigma \approx 0.29$ keV) ($\sigma \approx 0.29$ keV). We also note that our analysis energy ranges do not coincide with known NuSTAR instrumental lines [82].

In Fig. 4, we illustrate the best-fit signal model and background over our OFF-subtracted NuSTAR data for our most stringent constraint, the search for ^{57}Fe from M87. The signal shows up as a narrow bump in the spectra around the de-excitation energy $E^* = 14.4$ keV. More illustrations, i.e., those for a selection of our other targets, can be found in Appendix A.

Ultimately, we find no evidence for axions in our targets and for the nuclear isotope de-excitation energies considered (see Table I). Interpreting our results first under the fiducial assumption of $g_{ann} = g_{app}$, we show our two most stringent 95% upper limits and their $1/2\sigma$ containment intervals on $g_{ann} \times g_{\gamma\gamma}$ under the null hypothesis in Fig. 1 (a more complete illustration of our results can be found in Appendix A). Our most stringent constraints come from ^{57}Fe searches from M87 and M82, where we constrain $|g_{ann} \times g_{\gamma\gamma}| \lesssim 1.1 \times 10^{-22}$ GeV $^{-1}$ and $|g_{ann} \times g_{\gamma\gamma}| \lesssim$

3.1×10^{-22} GeV $^{-1}$, respectively, with the significance of axion discovery being 0.87σ and 0.17σ , respectively. We also derive slightly less competitive constraints from the ^{57}Fe search in M31 and the GC, as well as the ^{61}Ni searches from M82 and M87 (see Appendix A).

V. DISCUSSION

In this work, we derive stringent constraints on $|g_{ann}^{\text{eff}} \times g_{\gamma\gamma}|$ for ultralight axions with masses $m_a \lesssim 10^{-10}$ eV, where g_{ann}^{eff} is approximately equal to g_{ann} but includes a small admixture of g_{app} . Axions coupled to nucleons through g_{ann}^{eff} may be emitted efficiently from nuclear de-excitations in massive, hot stars with core temperatures near the excitation energies E^* . Our strongest constraints come from considering the ^{57}Fe transition, though ^{61}Ni and ^{73}Ge are competitive. We consider axions emitted from nearby stellar populations in the Milky Way, M31, M82, and M87. While the emission rates are not sensitive to m_a for $m_a \lesssim$ keV, the efficient conversion of these axions to x-rays in the magnetic fields permeating these galaxies requires ultralight axion masses. We search for the converted hard x-rays using data from NuSTAR toward these targets. Our strongest constraints arise from M87 partially due to the efficient axion-to-photon conversion rates in the Virgo cluster that hosts M87.

As we show in Fig. 1, our results disfavor the axion interpretation of the M7 neutron star x-ray excess [44] for axion masses below roughly 10^{-10} eV by over two orders of magnitude in $|g_{ann} \times g_{\gamma\gamma}|$. In that figure, we show the 1σ best-fit parameter space to explain the excess high-energy x-rays observed toward the nearby M7 neutron stars by the Chandra and XMM-Newton telescopes [43]. These x-ray

excesses could be explained by axions produced within the cores of these neutron stars through nuclear bremsstrahlung and then subsequently the axions converting to x-rays in the neutron star magnetic fields. However, our work shows that if the M7 excess is indeed arising from axions, the axion mass must be above roughly 10^{-10} eV.

While this work requires the axion to couple to both nucleons and photons, it is worth contextualizing our results with those of searches that are only sensitive to the axion-photon coupling. In Fig. 7, we show our results in the $|g_{a\gamma\gamma}| - m_a$ plane under two different assumptions for the dimensionless EFT coefficients $C_{ann}/C_{a\gamma\gamma}$. Under the assumption $C_{ann} = C_{a\gamma\gamma}$, which would be expected in, e.g., DFSZ type UV completions [20], our results surpass in sensitivity those of all prior searches for $g_{a\gamma\gamma}$ alone at low masses. Thus, in classes of models where axions couple strongly to quarks, our search is the most sensitive to date. On the other hand, in models such as KSVZ where the axion has no tree-level coupling to quarks and the axion-quark couplings are loop induced (see Appendix C), our constraints are subleading relative to existing searches for $g_{a\gamma\gamma}$ alone.

In this work, we show that axions are produced in abundance through nuclear de-excitations in nearby galaxies. It would be interesting to try to use this aspect of our analysis, independent of the axion-to-photon conversion phenomena which is crucial to this work but requires low axion masses, to probe higher mass axions. For example, heavier axions could decay in-flight (see, e.g., [72,83]) or more strongly coupled axions could lead to such large energy losses in parts of the stellar population that the back-reaction of the axions on the stellar population modeling would be important. We leave such studies to future work.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: ADDITIONAL FIGURES AND TABLES

In this section, we illustrate additional figures and a table closely related to those presented in the main text. In Fig. 5, we illustrate the 95% upper limits on $g_{ann} \times g_{a\gamma\gamma}$ resulting from our complete searches across our four selected galactic targets and our three selected nuclear isotopes. In Fig. 6, we illustrate our ^{57}Fe constraints cast

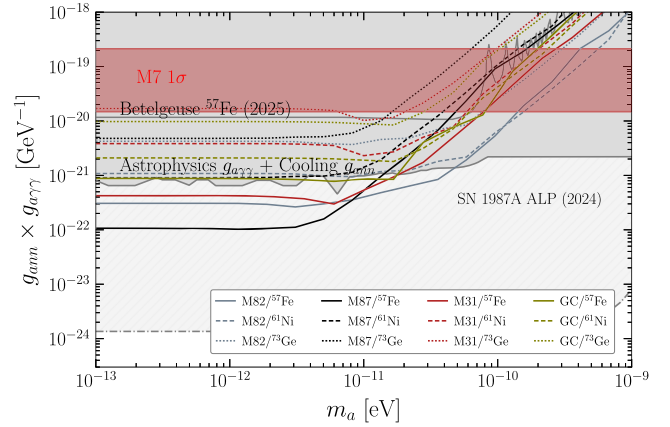


FIG. 5. The 95% upper limits on the combined axion-nucleon axion-photon coupling $g_{ann} \times g_{a\gamma\gamma}$ from our search for ultralight axions produced from nuclear isotope de-excitation across our four selected galactic targets and our three selected nuclear isotopes. In gray, we illustrate existing astrophysical constraints, with more details in the main text (the red band indicates the 1σ signal for axions found in [44]).

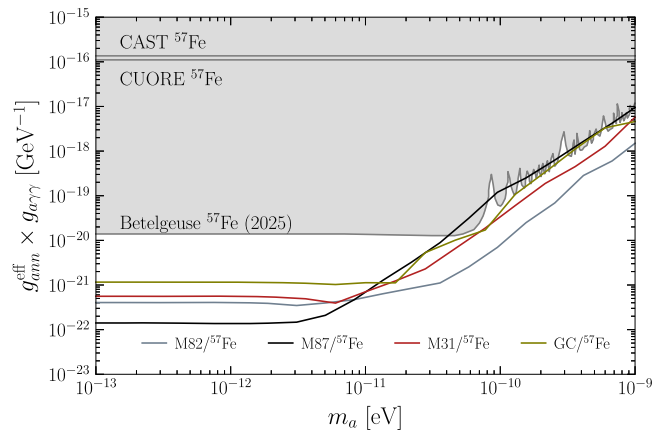


FIG. 6. Similar to Fig. 5, although only illustrating constraints which directly probe $g_{ann}^{\text{eff}} \times g_{a\gamma\gamma}$, which include [29,37,84] [rescaled using our Γ_a/Γ_γ coefficient in (7)]. We show only our analogous constraints for ^{57}Fe over our galactic targets and display all results in terms of $g_{ann}^{\text{eff}} \times g_{a\gamma\gamma}$.

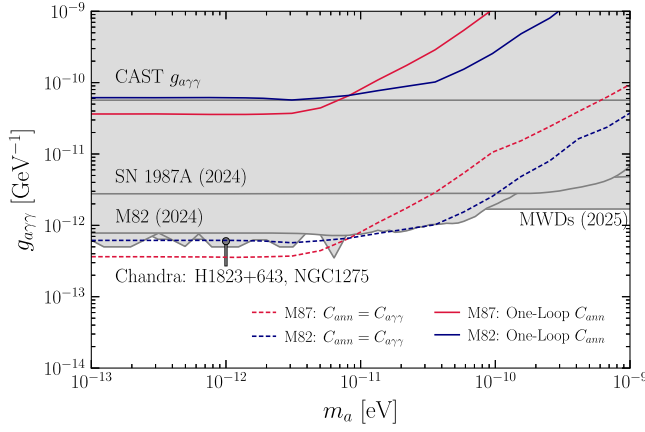


FIG. 7. The 95% upper limits from Fig. 1 translated to limits on $g_{a\gamma\gamma}$ alone under the assumptions of a tree-level axion-nucleon coupling where $C_{ann} = C_{a\gamma\gamma}$, as well as a one-loop induced axion-nucleon coupling where $C_{ann} \sim 10^{-4} C_{a\gamma\gamma}$ (see Appendix C for details). Existing limits taken from [85].

as limits on the effective nucleon coupling $g_{ann}^{\text{eff}} \times g_{a\gamma\gamma}$, compared to other direct constraints on $g_{ann}^{\text{eff}} \times g_{a\gamma\gamma}$. Here, we also rescale the constraint from [37] to our Γ_a/Γ_γ coefficient in (7). Figure 8 is the constraint from Fig. 1 recast as constraints on the $g_{a\gamma\gamma} - g_{ann}$ parameter space for $g_{ann} = g_{app}$ and massless axions. Figures 9–11 are illustrations similar to Fig. 4, where we show our data analyses searching for axions from ^{57}Fe and ^{61}Ni de-excitation lines across our two most powerful targets, M82 and M87. Also, for these two targets and for ^{57}Fe (the strongest constraints in this work), we illustrate in

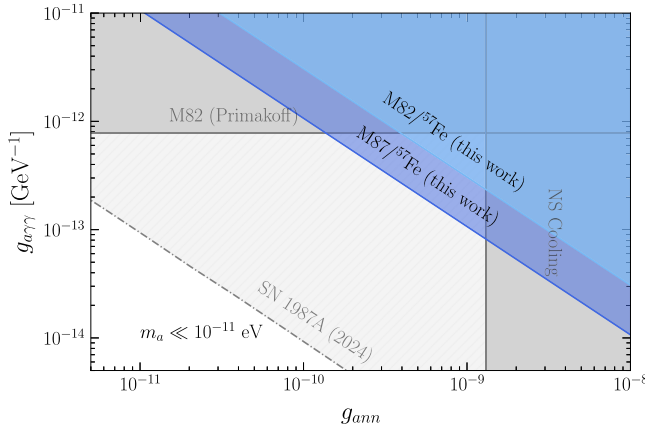


FIG. 8. Illustration of our limits from Fig. 1 recast as constraints on the $g_{a\gamma\gamma} - g_{ann}$ parameter space (for $g_{ann} = g_{app}$) in the massless axion limit. We illustrate the leading constraint in this limit on $g_{a\gamma\gamma}$ from the Primakoff production of axions from M82 [23], the leading constraint on g_{ann} from neutron star cooling [58], and the constraint on both of these parameters from the nonobservation of axion-induced gamma-rays in SN 1987A [53].

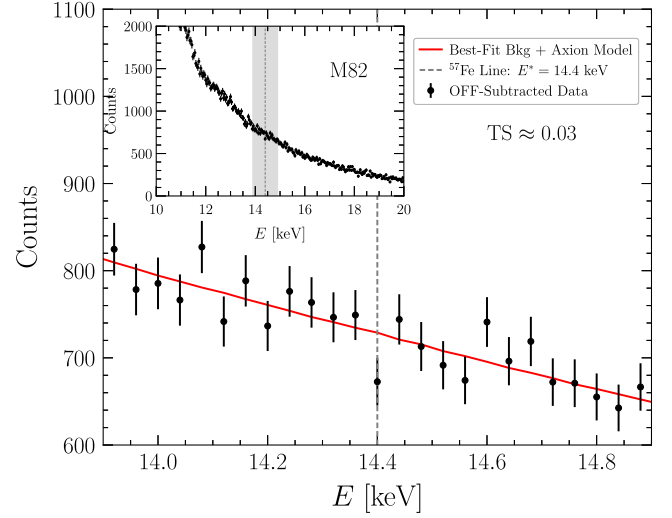


FIG. 9. Same for Fig. 4 but for M82, with the search for ^{57}Fe . Again, the inset shows the broader region around the $E^* = 14.4$ keV line, with the main plot showing the best-fit axion signal and background model, compared against the OFF-subtracted NuSTAR data in the 3σ region around the expected line emission.

Fig. 12 the explicit ON data, OFF data, and OFF-subtracted data used in our analyses.

Additionally, we also illustrate in Fig. 13 the distributions of the core temperatures of the stars comprising the stellar populations of M82 and M87. This gives one a general idea of the accessible energies available for the types of nuclear transition line searches discussed in this work. In Fig. 14, we illustrate the axion luminosity emitted by an example $20M_\odot$ star throughout various representative stages of its lifetime.

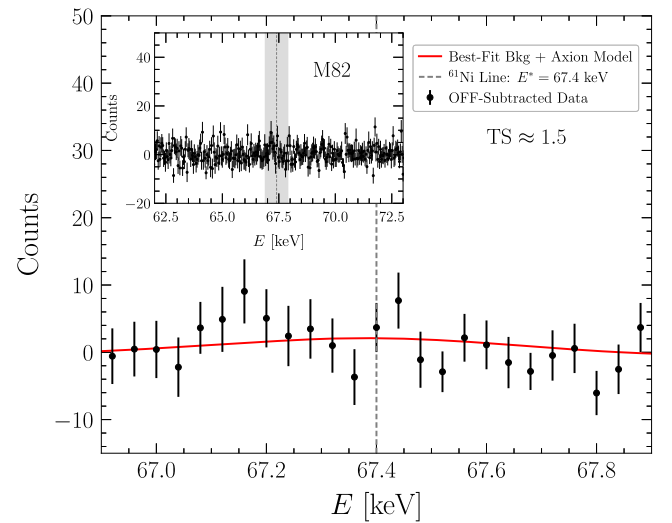


FIG. 10. Same for Fig. 4 but for M82, with the search for ^{61}Ni . The inset shows the broader region around the $E^* = 67.4$ keV line.

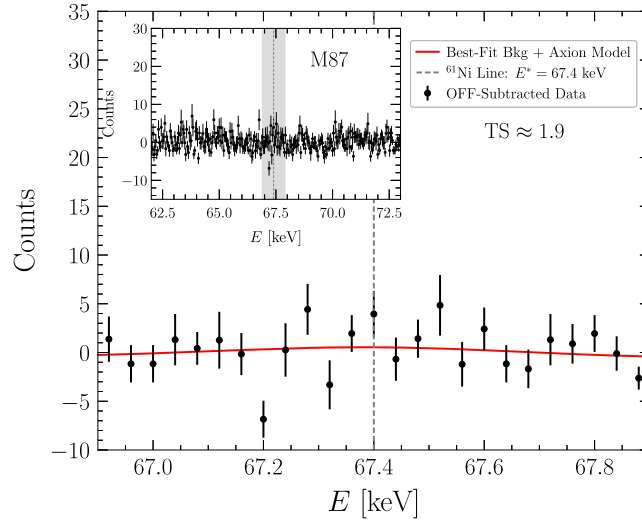
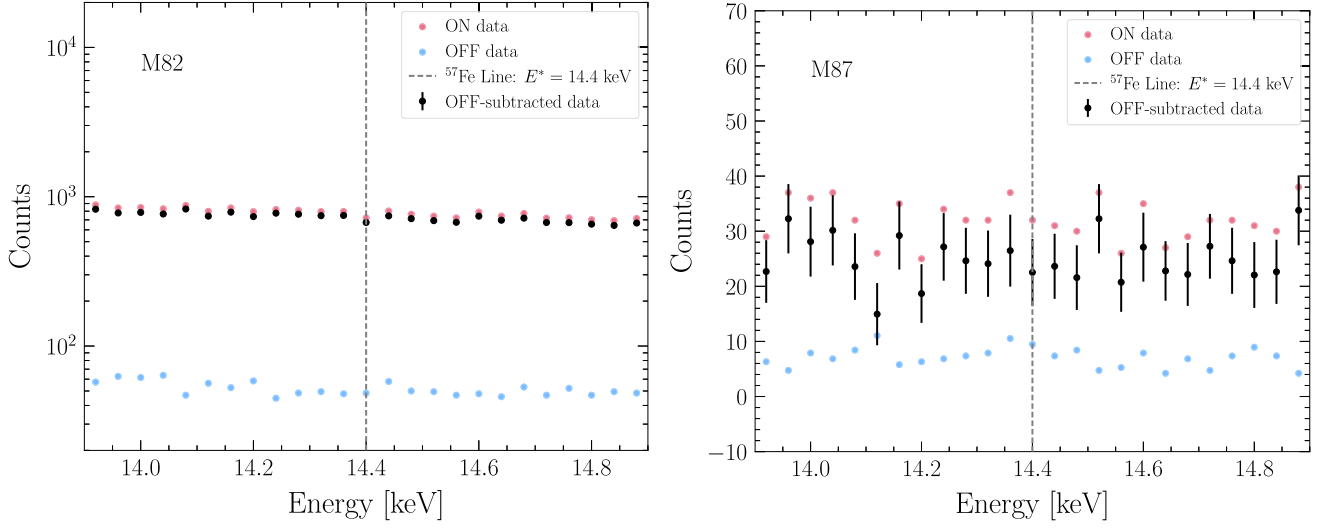
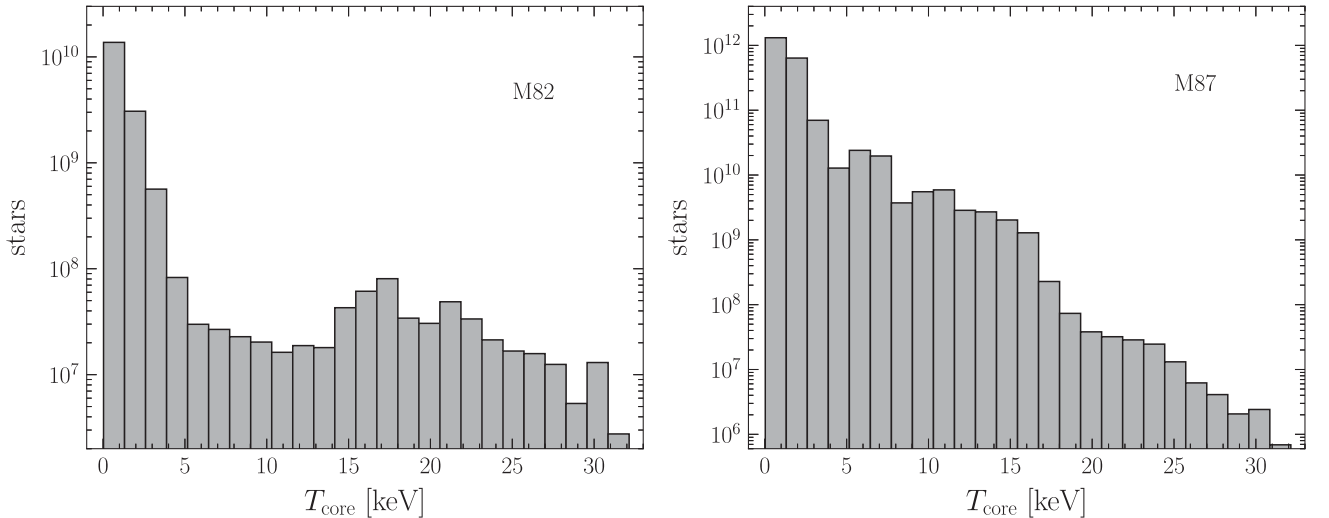
FIG. 11. Same for Fig. 4 but for M87, with the search for ^{61}Ni .FIG. 12. (Left) Illustration of the ON data, the OFF data, and the OFF-subtracted data for our analysis of the ^{57}Fe line search in M82, with 68% Poisson uncertainties shown for the OFF-subtracted data. (Right) As in the left panel but for M87. We see in both cases that the overall high number of counts per bin justifies the use of Gaussian errors in our analyses.

FIG. 13. (Left) The distribution of stellar core temperatures across our stellar population for M82. This illustration gives a broad idea of the available energies one has access to in the context of the search for nuclear line transitions discussed in this work. (Right) The same but for M87.

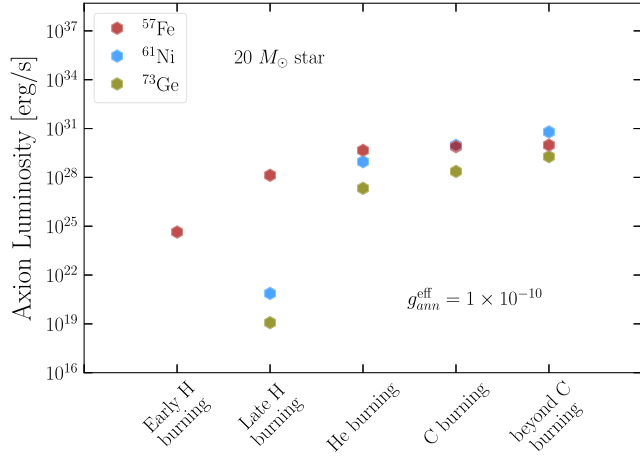


FIG. 14. Illustration of the total axion luminosity emitted from a $20 M_{\odot}$ star throughout various representative points in its lifetime. We show the luminosities for our three main isotopes at the indicated axion-nucleon coupling. We note that the axion luminosities are primarily due to primordial elemental abundances, given that heavy elements are not substantially produced in stellar interiors for the vast majority of a star's life (see main text).

In Fig. 15 we show the total axion luminosity emitted from the M87 stellar population by the burning core element, along with stellar numbers. In Fig. 16, also for M87, we show the total axion luminosities and stellar numbers across our main stellar subtype populations. In Fig. 17, we illustrate the effect on axion luminosity from various choices for Fe abundances in M82 (which is likely to be subsolar, see main text). Finally, Table II

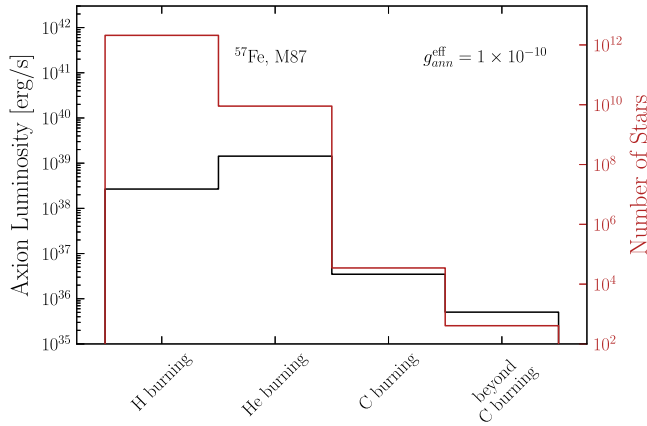


FIG. 15. Illustration of the total axion luminosities (black) and the stellar numbers (red) across our stellar population in M87 distributed according to the main fusing element in the stellar core for the ^{57}Fe transition and with the indicated axion-nucleon coupling. Across our population, for our axion searches we are primarily sensitive to He core-burning stars. While there is evidence for a factor of a few enhancement in produced heavy elements such as ^{57}Fe , mostly during the C burning stages and beyond [37]. This would only have a minor effect on our overall population signal.

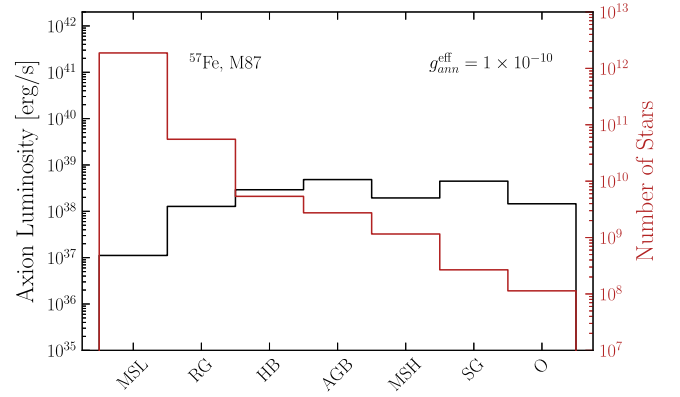


FIG. 16. Illustration of the total axion luminosities (black) and stellar numbers (red) across our main stellar subtype populations for the ^{57}Fe transition in M87 at the indicated axion-nucleon coupling. The phases include main sequence for low-mass/high-mass stars (MSL, MSH), red giant (RG), horizontal branch (HB), asymptotic giant branch (AGB), supergiants (SG), and O-type (O) stars.

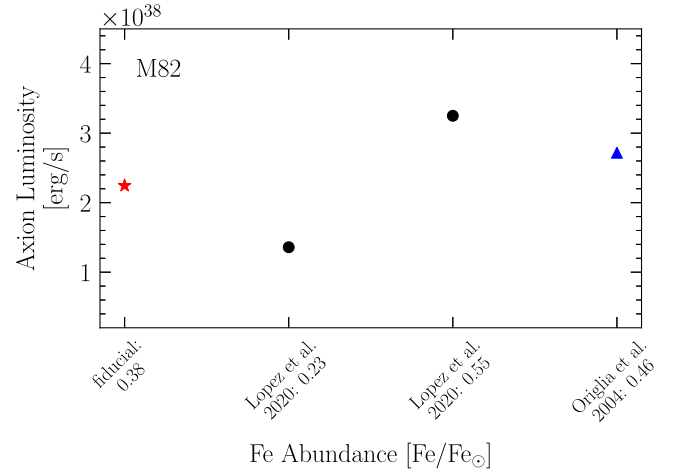


FIG. 17. Illustration of the various choices of Fe abundances possible for M82 and their resulting axion luminosities. Shown are the minimum and maximum measured abundances from [86] (Lopez *et al.*), as well as the stellar Fe abundance quoted in [71] (Origlia *et al.*). The fiducial abundance adopted is taken from the average of the abundances found in [86].

TABLE II. Observation IDs and exposure time (in [ks]) of the archival NuSTAR data used in our GC analysis, in which the target is chosen to be the center-most region of the galactic bulge, and the observations are away from known bright x-ray transients.

ObsID	t_{exp} [ks]
30001002001	154.2
30001002003	77.1
30001002004	49.6
Total	280.9

lists the NuSTAR observations used in our analysis of the GC, which are chosen to correspond to the most central region of the bulge while also keeping away from known bright X-ray transients.

APPENDIX B: NUCLEAR TRANSITION CALCULATIONS AND ISOTOPES

In this section, we summarize a survey and comparison of a variety of isotopes besides the ones highlighted in the main text. These additional isotopes with stable nuclear ground states, while not further explored in this work, could be potentially interesting for other related ideas exploring axion production from nuclear de-excitation (e.g., such as any search which might only be sensitive to one of g_{ann} or g_{app} separately). We leave any such ideas for future work.

First, in Table III, we list, in order of increasing excitation energy E^* , various selected isotopes whose de-excitation energies could in principle be probed by x-ray axion searches within the range of a hard x-ray telescope such as NuSTAR (i.e., with $E^* \lesssim 85$ keV). We list parameters relevant to axion emission [see (5), (6)], such as the angular momenta of the ground and excited states (J_0 and J_1 , respectively), the total mean lifetime

τ_m , the internal conversion coefficient α , the δ mixing ratio, as well as solar abundances of each isotope and their unpaired nucleons. We note that the precise determination of the nuclear factors β and η for each nuclei in general should come from detailed calculations of nuclear shell models, which is beyond the scope of this work. However, one can adopt rough approximations of these factors given in [87], which estimates that a nuclei with an unpaired neutron should have values close to $\beta = -1$ and $\eta = 0.5$, whereas a nuclei with an unpaired proton would instead have $\beta = 1$ and $\eta = 0.5$. For this reason we include the unpaired nucleon for each isotope as the final column of Table III. We note that while these are only rough estimates, they still serve as useful guidelines for computing branching ratios, i.e., (7), in the absence of precise nuclear shell model calculations, which would be of great interest for future work.

The isotopes in Table III were estimated to be the strongest in terms of axion emission, relevant for either high-mass or low-mass stars, and we compare these isotopes in both stellar cases in Figs. 18 and 19, respectively. For the case of a solar-like low-mass star, i.e., Fig. 19, it is clear that ^{57}Fe is indeed the strongest isotope for axion de-excitation production by a large margin,

TABLE III. A survey of isotopes potentially interesting for nuclear de-excitation axion line searches with NuSTAR ($E_* \lesssim 85$ keV)). Nuclear parameter inputs are taken from [67], solar abundances are taken from [88], and further details, including parameter definitions, are in the main text.

Isotope	E_* (keV)	J_0	J_1	τ_m (ns)	α	δ	Solar abundance ($M_\odot^{-1}$)	Unpaired nucleon (p/n)
^{169}Tm	8.4	1/2	3/2	5.9	263	0.033	1.4×10^{45}	p
^{83}Kr	9.4	9/2	7/2	226.2	17.09	0.013	2.0×10^{47}	n
^{187}Os	9.7	1/2	3/2	3.43	280	0.04	2.9×10^{44}	n
^{119}Sn	23.9	1/2	3/2	26	5.06	0.003	1.0×10^{46}	n
^{201}Hg	26.3	3/2	5/2	0.91	72.9	0.012	1.6×10^{45}	n
^{125}Te	35.5	1/2	3/2	2.14	13.69	0.031	1.1×10^{46}	n
^{121}Sb	37.1	5/2	7/2	5	10.88	0.06	6.9×10^{45}	p
^{129}Xe	39.6	1/2	3/2	1.4	12.03	-0.027	5.1×10^{46}	n
^{183}W	46.5	1/2	3/2	0.27	8.4	-0.084	6.9×10^{44}	n
^{157}Gd	54.5	3/2	5/2	0.19	12.1	0.19	1.8×10^{45}	n
^{127}I	57.6	5/2	7/2	2.81	3.72	-0.083	5.4×10^{46}	p
^{159}Tb	58	3/2	5/2	0.08	10.73	0.119	2.1×10^{45}	p
^{155}Gd	60	3/2	5/2	0.28	9.14	-0.198	1.7×10^{45}	n
^{171}Yb	66.7	1/2	3/2	1.14	12.6	0.684	1.2×10^{45}	n
^{61}Ni	67.4	3/2	5/2	7.7	0.137	0.008	1.9×10^{49}	n
^{73}Ge	68.7	9/2	7/2	2.57	0.238	0.074	3.1×10^{47}	n
^{193}Ir	73	3/2	1/2	8.79	6.1	-0.558	3.5×10^{46}	p
^{197}Au	77.3	3/2	1/2	2.76	4.36	-0.368	6.6×10^{45}	p
^{173}Yb	78.6	5/2	7/2	0.07	7.01	-0.224	1.4×10^{45}	n
^{167}Er	79.3	7/2	9/2	0.17	5.7	-0.32	2.0×10^{45}	n
^{131}Xe	80.2	3/2	1/2	0.69	1.57	0.1	4.0×10^{46}	n
^{133}Cs	81	7/2	5/2	9.06	1.7	0.158	1.2×10^{46}	p
^{191}Ir	82.4	3/2	1/2	5.92	10.54	-0.871	8.0×10^{45}	p
^{153}Eu	83.4	5/2	7/2	1.14	3.76	0.81	5.1×10^{45}	p

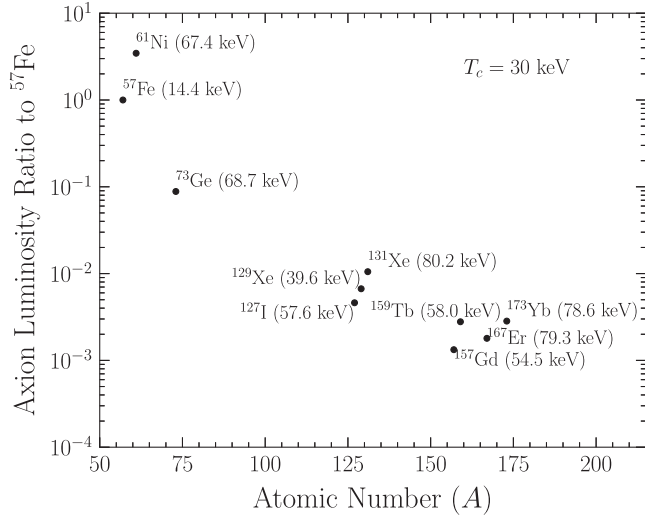


FIG. 18. Axion emission rates for various isotopes in a stellar core with a temperature of $T_c = 30$ keV normalized to the emission rate from ^{57}Fe . We note that the excitation/de-excitation energies E^* are in parentheses next to the isotope name. For visual clarity, we only select the top ten isotopes with respect to axion luminosity relative to ^{57}Fe . Here, we see that the three most prominent isotopes are ^{57}Fe , ^{61}Ni , and ^{73}Ge , and so we focus on these isotopes in the main text.

whereas in the case of a typical high-mass star, i.e., Fig. 18, ^{61}Ni is a factor of a few stronger, and ^{73}Ge is only a little over an order of magnitude weaker than ^{57}Fe . Hence, we only focus on these isotopes, with particular emphasis on ^{57}Fe , in our main text. While the numerical values of the de-excitation parameters certainly influence the total axion flux considerably, one general

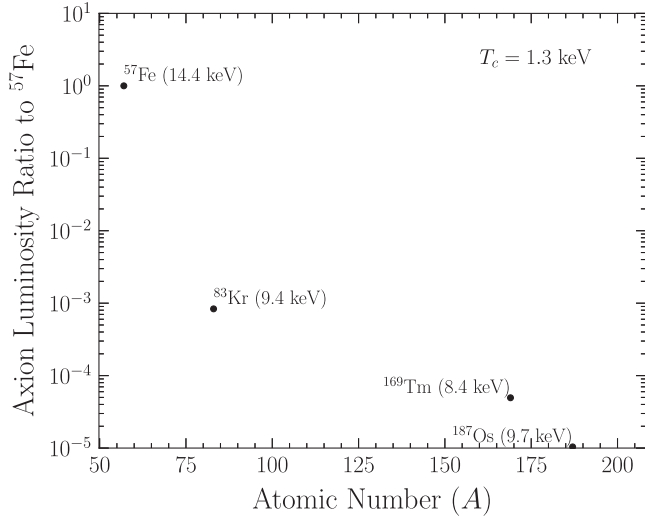


FIG. 19. Same as Fig. 18 but for a stellar core temperature of $T_c = 1.3$ keV (approximately the core-temperature of the Sun). Only isotopes with contributions above 10^{-5} relative to ^{57}Fe are shown.

reason why the other numerous isotopes in Table III are largely subdominant in axion flux is because their abundances are far too low in normal stellar matter, which is increasingly true with heavier isotopes. For all of our isotopes, as discussed in the main text, our isotope abundances are primarily informed from galactic metallicities, which we mostly take as roughly solar and hence extract from tables in [88].

We finally note that there exist potentially interesting isotopes beyond the x-ray range considered here; for example, ^{23}Na was explored in [39], and among other isotopes we separately explored, ^{55}Mn , ^{47}Ti , and ^{21}Ne (with transition energies of order $\mathcal{O}(0.1) - \mathcal{O}(1)$ MeV), they seemed to potentially have combinations of nuclear parameters and abundances, making them marginally comparable, in terms of axion flux, to the isotopes considered in our main work, although for only very narrow choices of stellar masses and lifetimes. The difficulty, furthermore, of transitions on the order of $\mathcal{O}(0.1) - \mathcal{O}(1)$ MeV lies in the reduced sensitivity and general dearth of current telescopes probing these energy ranges. This was the original reason why an isotope such as ^{57}Fe was special; it is an isotope that balances an unusually low transition energy in the $\mathcal{O}(10)$ keV range with a high enough stellar abundance. Upcoming MeV telescopes such as the COSI instrument [89] would, however, be able to efficiently search for higher energy transitions from other isotopes which could be potentially interesting for axion searches similar to those described in this work. We leave such studies for future work.

APPENDIX C: LOOP-INDUCED AXION-NUCLEON COUPLING

In this section, we additionally consider a benchmark scenario where our axion-like particles possess couplings generated under the renormalization (RG) flow [90–92]. We consider the scenario where the axion only couples to electroweak gauge bosons in the UV, in which case the couplings of axions to the nucleons relevant in this work are induced through RG running. Following the derivation in [53] and calculating the running at one-loop with a benchmark UV scale of $\Lambda = 10^9$ GeV, one finds that the axion-nucleon coupling coefficients C_{app} and C_{ann} can be derived as

$$\begin{aligned} C_{app} &\sim 3.5 \times 10^{-5} C_{aBB} + 2.1 \times 10^{-4} C_{aWW}, \\ C_{ann} &\sim -5.6 \times 10^{-6} C_{aBB} + 2.1 \times 10^{-4} C_{aWW}, \end{aligned} \quad (\text{C1})$$

which means that for a generic UV completion where we impose $C_{aWW} \sim C_{aBB}$, we find the coupling relations $C_{app}/C_{a\gamma\gamma} \sim C_{ann}/C_{a\gamma\gamma} \sim 10^{-4}$, which we adopt when recasting our original limits on $g_{ann} \times g_{a\gamma\gamma}$ to that of $g_{a\gamma\gamma}$ alone, as in Fig. 7.

- [1] R. D. Peccei and H. R. Quinn, *CP* conservation in the presence of instantons, *Phys. Rev. Lett.* **38**, 1440 (1977).
- [2] R. D. Peccei and H. R. Quinn, Constraints imposed by *CP* conservation in the presence of instantons, *Phys. Rev. D* **16**, 1791 (1977).
- [3] S. Weinberg, A new light boson?, *Phys. Rev. Lett.* **40**, 223 (1978).
- [4] F. Wilczek, Problem of strong *P* and *T* invariance in the presence of instantons, *Phys. Rev. Lett.* **40**, 279 (1978).
- [5] J. Preskill, M. B. Wise, and F. Wilczek, Cosmology of the invisible axion, *Phys. Lett.* **120B**, 127 (1983).
- [6] L. F. Abbott and P. Sikivie, A cosmological bound on the invisible axion, *Phys. Lett.* **120B**, 133 (1983).
- [7] M. Dine and W. Fischler, The not so harmless axion, *Phys. Lett.* **120B**, 137 (1983).
- [8] E. Witten, Some properties of $O(32)$ superstrings, *Phys. Lett.* **149B**, 351 (1984).
- [9] K. Choi and J. E. Kim, Harmful axions in superstring models, *Phys. Lett.* **154B**, 393 (1985); *Phys. Lett.* **156B**, 452(E) (1985).
- [10] S. M. Barr, Harmless axions in superstring theories, *Phys. Lett.* **158B**, 397 (1985).
- [11] P. Svrcek and E. Witten, Axions in string theory, *J. High Energy Phys.* **06** (2006) 051.
- [12] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, String axiverse, *Phys. Rev. D* **81**, 123530 (2010).
- [13] M. Demirtas, C. Long, L. McAllister, and M. Stillman, The Kreuzer-Skarke axiverse, *J. High Energy Phys.* **04** (2020) 138.
- [14] J. Halverson, C. Long, B. Nelson, and G. Salinas, Towards string theory expectations for photon couplings to axionlike particles, *Phys. Rev. D* **100**, 106010 (2019).
- [15] 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.
- [16] N. Gendler, D. J. E. Marsh, L. McAllister, and J. Moritz, Glimmers from the axiverse, *J. Cosmol. Astropart. Phys.* **09** (2024) 071.
- [17] J. N. Benabou, K. Fraser, M. Reig, and B. R. Safdi, String theory and grand unification suggest a sub-micron-volt QCD axion, *Phys. Rev. D* **112**, 066003 (2025).
- [18] A. Hook, Solving the hierarchy problem discretely, *Phys. Rev. Lett.* **120**, 261802 (2018).
- [19] A. Hook, TASI lectures on the strong *CP* problem and axions, *Proc. Sci. TASI2018* (2019) 004 [arXiv:1812.02669].
- [20] L. Di Luzio, M. Giannotti, E. Nardi, and L. Visinelli, The landscape of QCD axion models, *Phys. Rep.* **870**, 1 (2020).
- [21] B. R. Safdi, TASI lectures on the particle physics and astrophysics of dark matter, *Proc. Sci. TASI2022* (2024) 009 [arXiv:2303.02169].
- [22] C. A. J. O'Hare, Cosmology of axion dark matter, *Proc. Sci. COSMICWIPers* (2024) 040 [arXiv:2403.17697].
- [23] O. Ning and B. R. Safdi, Leading axion-photon sensitivity with NuSTAR observations of M82 and M87, *Phys. Rev. Lett.* **134**, 171003 (2025).
- [24] O. Ning and B. R. Safdi, Probing the axion-electron coupling with NuSTAR observations of galaxies, *Phys. Rev. D* **113**, 015021 (2026).
- [25] W. C. Haxton and K. Y. Lee, Red-giant evolution, metallicity, and new bounds on hadronic axions, *Phys. Rev. Lett.* **66**, 2557 (1991).
- [26] S. Moriyama, A proposal to search for a monochromatic component of solar axions using ^{57}Fe , *Phys. Rev. Lett.* **75**, 3222 (1995).
- [27] M. Krcmar, Z. Krecak, M. Stipcevic, A. Ljubicic, and D. A. Bradley, Search for invisible axions using ^{57}Fe , *Phys. Lett. B* **442**, 38 (1998).
- [28] T. Namba, Results of a search for monochromatic solar axions using ^{57}Fe , *Phys. Lett. B* **645**, 398 (2007).
- [29] S. Andriamonje *et al.* (CAST Collaboration), Search for 14.4-keV solar axions emitted in the M1-transition of ^{57}Fe nuclei with CAST, *J. Cosmol. Astropart. Phys.* **12** (2009) 002.
- [30] A. V. Derbin, V. N. Muratova, D. A. Semenov, and E. V. Unzhakov, New limit on the mass of 14.4-keV solar axions emitted in an M1 transition in ^{57}Fe nuclei, *Phys. At. Nucl.* **74**, 596 (2011).
- [31] F. Alessandria *et al.* (CUORE Collaboration), Search for 14.4 keV solar axions from M1 transition of ^{57}Fe with CUORE crystals, *J. Cosmol. Astropart. Phys.* **05** (2013) 007.
- [32] E. Armengaud *et al.*, Axion searches with the EDELWEISS-II experiment, *J. Cosmol. Astropart. Phys.* **11** (2013) 067.
- [33] N. Abgrall *et al.* (Majorana Collaboration), New limits on bosonic dark matter, solar axions, pauli exclusion principle violation, and electron decay from the Majorana demonstrator, *Phys. Rev. Lett.* **118**, 161801 (2017).
- [34] 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.
- [35] L. Di Luzio *et al.*, Probing the axion-nucleon coupling with the next generation of axion helioscopes, *Eur. Phys. J. C* **82**, 120 (2022).
- [36] L. Fleury, I. Caiazzo, and J. Heyl, Constraining axions with ZTF J1901 + 1458, *Phys. Rev. D* **107**, L101303 (2023).
- [37] F. R. Candón, P. Casaseca, M. Giannotti, M. Kaltschmidt, J. Ruz, and J. K. Vogel, Probing the axion-nucleon coupling with supergiant stars, *Phys. Rev. D* **112**, 123050 (2025).
- [38] Y. M. Gavriluk *et al.*, First result of the experimental search for the 9.4 keV solar axion reactions with ^{83}Kr in the copper proportional counter, *Phys. Part. Nucl.* **46**, 152 (2015).
- [39] W. C. Haxton, X. Liu, A. McCutcheon, and A. Ray, A continuous galactic line source of axions: The remarkable case of ^{23}Na , *Phys. Rev. Lett.* **135**, 222701 (2025).
- [40] A. V. Derbin, A. I. Egorov, I. A. Mitropolskii, V. N. Muratova, S. V. Bakhlanov, and L. M. Tikhonov, Search for the invisible axion emitted in the M1 transition in $^{125\text{m}}\text{Te}$, *JETP Lett.* **65**, 605 (1997).
- [41] M. Minowa, Y. Inoue, T. Asanuma, and M. Imamura, Invisible axion search in ^{139}La M1 transition, *Phys. Rev. Lett.* **71**, 4120 (1993).
- [42] F. T. Avignone III, C. Baktash, W. C. Barker, F. P. Calaprice, R. W. Dunford, W. C. Haxton, D. Kahana, R. T. Kouzes, H. S. Miley, and D. M. Moltz, Search for axions from the 1115-keV transition of ^{65}Cu , *Phys. Rev. D* **37**, 618 (1988).

- [43] C. Dessert, J. W. Foster, and B. R. Safdi, Hard X-ray excess from the magnificent seven neutron stars, *Astrophys. J.* **904**, 42 (2020).
- [44] M. Buschmann, R. T. Co, C. Dessert, and B. R. Safdi, Axion emission can explain a new hard x-ray excess from nearby isolated neutron stars, *Phys. Rev. Lett.* **126**, 021102 (2021).
- [45] C. S. Reynolds, M. C. D. Marsh, H. R. Russell, A. C. Fabian, R. Smith, F. Tombesi, and S. Veilleux, Astrophysical limits on very light axion-like particles from Chandra grating spectroscopy of NGC 1275, *Astrophys. J.* **890**, 59 (2020).
- [46] M. C. D. Marsh, H. R. Russell, A. C. Fabian, B. P. McNamara, P. Nulsen, and C. S. Reynolds, A new bound on axion-like particles, *J. Cosmol. Astropart. Phys.* **12** (2017) 036.
- [47] J. P. Conlon, F. Day, N. Jennings, S. Krippendorf, and M. Rummel, Constraints on axion-like particles from non-observation of spectral modulations for x-ray point sources, *J. Cosmol. Astropart. Phys.* **07** (2017) 005.
- [48] J. S. Reynés, J. H. Matthews, C. S. Reynolds, H. R. Russell, R. N. Smith, and M. C. D. Marsh, New constraints on light axion-like particles using Chandra transmission grating spectroscopy of the powerful cluster-hosted quasar H1821 + 643, *Mon. Not. R. Astron. Soc.* **510**, 1264 (2021).
- [49] J. W. Brockway, E. D. Carlson, and G. G. Raffelt, SN1987A gamma-ray limits on the conversion of pseudoscalars, *Phys. Lett. B* **383**, 439 (1996).
- [50] J. A. Grifols, E. Masso, and R. Toldra, Gamma-rays from SN1987A due to pseudoscalar conversion, *Phys. Rev. Lett.* **77**, 2372 (1996).
- [51] 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.
- [52] 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.
- [53] 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).
- [54] J. N. Benabou, C. Dessert, K. C. Patra, T. G. Brink, W. Zheng, A. V. Filippenko, and B. R. Safdi, Search for axions in magnetic white dwarf polarization at lick and keck observatories, [arXiv:2504.12377](https://arxiv.org/abs/2504.12377).
- [55] C. Dessert, D. Dunskey, and B. R. Safdi, Upper limit on the axion-photon coupling from magnetic white dwarf polarization, *Phys. Rev. D* **105**, 103034 (2022).
- [56] C. Dessert, A. J. Long, and B. R. Safdi, No evidence for axions from Chandra observation of the magnetic white dwarf RE J0317-853, *Phys. Rev. Lett.* **128**, 071102 (2022).
- [57] O. Ning, C. Dessert, V. Hong, and B. R. Safdi, Search for axions from magnetic white dwarfs with Chandra, *Phys. Rev. D* **111**, 103002 (2025).
- [58] 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).
- [59] A. Caputo and G. Raffelt, Astrophysical axion bounds: The 2024 edition, *Proc. Sci. COSMICWISPer* (2024) 041 [[arXiv:2401.13728](https://arxiv.org/abs/2401.13728)].
- [60] G. G. Raffelt, Astrophysical axion bounds, *Lect. Notes Phys.* **741**, 51 (2008).
- [61] T. Fischer, S. Chakraborty, M. Giannotti, A. Mirizzi, A. Payez, and A. Ringwald, Probing axions with the neutrino signal from the next galactic supernova, *Phys. Rev. D* **94**, 085012 (2016).
- [62] 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.
- [63] 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; *J. Cosmol. Astropart. Phys.* **05** (2020) E01.
- [64] P. Carenza, B. Fore, M. Giannotti, A. Mirizzi, and S. Reddy, Enhanced supernova axion emission and its implications, *Phys. Rev. Lett.* **126**, 071102 (2021).
- [65] G. Grilli di Cortona, E. Hardy, J. Pardo Vega, and G. Villadoro, The QCD axion, precisely, *J. High Energy Phys.* **01** (2016) 034.
- [66] C. Patrignani *et al.* (Particle Data Group), Review of particle physics, *Chin. Phys. C* **40**, 100001 (2016).
- [67] N. N. D. Center, Nudat 3.0 database (n.d.), Brookhaven National Laboratory, <https://www.nndc.bnl.gov/nudat3/>.
- [68] 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).
- [69] 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).
- [70] L. A. Lopez, S. Mathur, D. D. Nguyen, T. A. Thompson, and G. M. Olivier, Temperature and metallicity gradients in the hot gas outflows of M82, *Astrophys. J.* **904**, 152 (2020).
- [71] L. Origlia, P. Ranalli, A. Comastri, and R. Maiolino, Stellar and gaseous abundances in M82, *Astrophys. J.* **606**, 862 (2004).
- [72] 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).
- [73] K. Abd El Dayem *et al.* (GRAVITY Collaboration), Improving constraints on the extended mass distribution in the Galactic Center with stellar orbits, *Astron. Astrophys.* **692**, A242 (2024).
- [74] A. Pillepich *et al.*, First results from the TNG50 simulation: The evolution of stellar and gaseous discs across cosmic time, *Mon. Not. R. Astron. Soc.* **490**, 3196 (2019).
- [75] D. Nelson, A. Pillepich, V. Springel, R. Pakmor, R. Weinberger, S. Genel, P. Torrey, M. Vogelsberger, F. Marinacci, and L. Hernquist, First results from the TNG50 simulation: Galactic outflows driven by supernovae and black hole feedback, *Mon. Not. R. Astron. Soc.* **490**, 3234 (2019).
- [76] M. Unger and G. R. Farrar, The coherent magnetic field of the Milky Way, *Astrophys. J.* **970**, 95 (2024).
- [77] R. Jansson and G. R. Farrar, A new model of the galactic magnetic field, *Astrophys. J.* **757**, 14 (2012).

- [78] J. M. Cordes and T. J. W. Lazio, NE2001. 1. A new model for the galactic distribution of free electrons and its fluctuations, [arXiv:astro-ph/0207156](#).
- [79] Nasa High Energy Astrophysics Science Archive Research Center (Heasarc), HEASoft: Unified Release of FTOOLS and XANADU, record ascl:1408.004 (2014), <https://ui.adsabs.harvard.edu/abs/2014ascl.soft08004N>.
- [80] 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); *Eur. Phys. J. C* **73**, 2501(E) (2013).
- [81] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Power-constrained limits, [arXiv:1105.3166](#).
- [82] 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).
- [83] O. Ning, K. Raman, and B. R. Safdi, Cosmological neutron stars produce diffuse axion x-ray signatures, [arXiv:2512.15849](#).
- [84] 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.
- [85] C. O'HARE, cajohare/axionlimits: Axionlimits, (2020), [10.5281/zenodo.3932430](https://zenodo.org/record/3932430).
- [86] L. A. Lopez, S. Mathur, D. D. Nguyen, T. A. Thompson, and G. M. Olivier, Temperature and metallicity gradients in the hot gas outflows of M82, *Astrophys. J.* **904**, 152 (2020).
- [87] R. Massarczyk, P. H. Chu, and S. R. Elliott, Axion emission from nuclear magnetic dipole transitions, *Phys. Rev. D* **105**, 015031 (2022).
- [88] K. Lodders, Solar elemental abundances, [arXiv:1912.00844](#).
- [89] J. A. Tomsick *et al.*, The Compton spectrometer and imager, *Proc. Sci. ICRC2023* (**2023**) 745 [[arXiv:2308.12362](#)].
- [90] M. Srednicki, Axion couplings to matter. 1. *CP* conserving parts, *Nucl. Phys.* **B260**, 689 (1985).
- [91] M. Bauer, M. Neubert, and A. Thamm, Collider probes of axion-like particles, *J. High Energy Phys.* **12** (2017) 044.
- [92] M. Bauer, M. Neubert, S. Renner, M. Schnubel, and A. Thamm, The low-energy effective theory of axions and ALPs, *J. High Energy Phys.* **04** (2021) 063.