Supernova Axions Convert to Gamma Rays in Magnetic Fields of Progenitor Stars

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It has long been established that axions could have been produced within the nascent proto-neutron star formed following the type II supernova SN1987A, escaped the star due to their weak interactions, and then converted to gamma rays in the Galactic magnetic fields; the nonobservation of a gamma-ray flash coincident with the neutrino burst leads to strong constraints on the axion-photon coupling for axion masses $m_a \lesssim 10^{-10}$ eV. In this Letter, we use SN1987A to constrain higher mass axions, all the way to $m_a \sim 10^{-3}$ eV, by accounting for axion production from the Primakoff process, nucleon bremsstrahlung, and pion conversion along with axion-photon conversion on the still-intact magnetic fields of the progenitor star. Moreover, we show that gamma-ray observations of the next Galactic supernova, leveraging the magnetic fields of the progenitor star, could detect quantum chromodynamics axions for masses above roughly 50 μeV, depending on the supernova. We propose a new full-sky gamma-ray satellite constellation that we call the GALactic AXion Instrument for Supernova (GALAXIS) to search for such future signals along with related signals from extragalactic neutron star mergers.

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Supernova (SN) 1987A (SN1987A) was a type II SN that exploded in February 1987, producing roughly two dozen neutrino events that were detected at the Kamiokande II, IMB, and Baksan neutrino detectors over a time interval of around 10 s [1–3]. The SN took place in the Large Magellanic Cloud at a distance of approximately 51.4 kpc from Earth. SN1987A provides some of the most stringent and well-established constraints on a class of hypothetical ultralight pseudoscalar particles known as axions [4–10]. These constraints have been made all the more robust recently by the tentative discovery of the neutron star (NS) formed after SN1987A, helping establish that the SN formed a NS and not a black hole [11,12]. In this Letter, we point out for the first time a novel constraint from SN1987A that has promising implications for future SNs; axions produced within the proto-NS (PNS) can convert to observable gamma rays in the stellar magnetic field of the progenitor star.

Axions may address a number of outstanding problems in nature such as the strong- CP problem [13–16] (i.e., the lack of a neutron electric dipole moment) and the measured dark matter abundance in the Universe [17–19]. Moreover, axions are now understood to arise generically in string theory compactifications [20–25]. String theory motivates the picture of the "axiverse," where the quantum chromodynamics (QCD) axion that solves the strong- CP problem is accompanied by a number of axionlike particles, which interact through higher dimensional operators with the rest of the standard model but not with QCD. The QCD axions receive a mass contribution from QCD of the order $m_a^{\mathrm{QCD}} \approx 5.70\ \mu\mathrm{eV}(10^{12}\ \mathrm{GeV}/f_a)$, with f_a the axion decay constant. The axion field a has an interaction with photons $\mathcal{L} = g_{a\gamma\gamma} a \mathbf{E}\cdot\mathbf{B}$, with $\mathbf{E}$ ($\mathbf{B}$) the electric (magnetic) field, which is parametrized by the coupling constant $g_{a\gamma\gamma} \equiv C_{a\gamma\gamma}\alpha_{\mathrm{EM}}/(2\pi f_a)$, with α_{EM} the fine-structure constant and $C_{a\gamma\gamma}$ a coefficient of order unity that depends on the ultraviolet (UV) completion. For the QCD axion we thus expect $g_{a\gamma\gamma} \propto m_a$, as illustrated by the gold band in Fig. 1; axionlike particles are motivated throughout the $g_{a\gamma\gamma}$-m_a plane.

There are two classes of well-established constraints on the interaction strengths of light axions ($m_a \lesssim$ eV) with the standard model from SN1987A: (i) axion production in the PNS core can modify the thermal evolution of the PNS, modifying the predicted luminosity evolution of neutrinos [5,36–48]; and (ii) ultralight axions that escape the PNS core could later convert to gamma rays in Galactic magnetic fields [4,6–10] (see also [49,50] for prospects for future SNs). The latter probe is supported by the nonobservations of gamma rays coincident with the neutrino burst by the Solar Maximum Mission (SMM) [51], which happened to be looking in the direction of SN1987A when the explosion took place. In this Letter, we propose a third probe of axions from SN1987A, future SNs, and even NS-NS mergers that relies on axion-photon conversion in the stellar magnetic fields of the progenitor star. This third

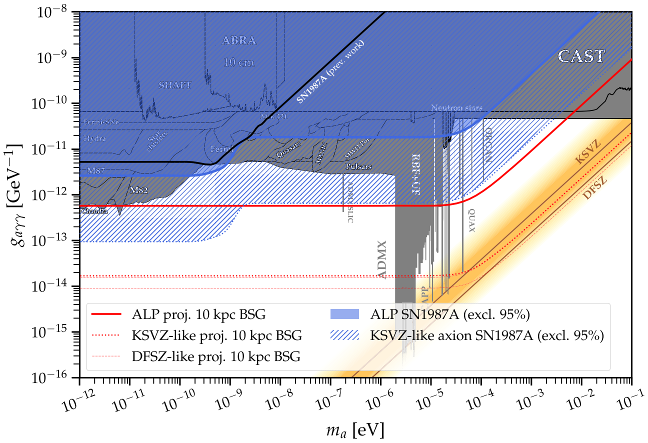

FIG. 1. Existing constraints (notably [26–33] and [34,35] for reviews) on the axion-photon coupling $g_{a\gamma\gamma}$ as a function of the axion mass m_a are shaded in gray, with the previously leading constraint from the nonobservation of axion-induced gamma rays from SN1987A highlighted [8,9]. We point out in this Letter that the axions could convert to gamma rays in the stellar magnetic field of the progenitor star, extending the upper limit on $g_{a\gamma\gamma}$ to higher masses as indicated in shaded blue. We take the surface field strength of the progenitor to be 100 G to be conservative ($\sim$1 kG is favored). Note that the KSVZ-like axion model assumes the couplings to photons and hadrons are related as in the KSVZ QCD-axion model; the axionlike particle (ALP) model assumes loop-induced hadronic couplings (see text). The nonobservation of gamma rays from the next Galactic SN (assumed to be at $d = 10$ kpc) with the proposed GALAXIS full-sky gamma-ray telescope network (modeled as being equivalent to the on-axis Fermi-LAT instrument response with full-sky coverage) could cover vast regions of QCD axion parameter space (red), depending on the properties of the progenitor star (BSG shown here, assuming a typical 1 kG surface field strength) and the axion.

probe allows us to test an intermediate axion mass range, extending up to $m_a \sim 10^{-1}$ eV, as indicated in Fig. 1.

In addition to considering SN1987A, we perform projections for the next Galactic SN and demonstrate that if an instrument such as the Fermi Large Area Telescope (LAT) were to observe such an event the nonobservation of coincident gamma rays could rule out or detect QCD axions above roughly 50 μeV, depending on the precise properties of the SN, by accounting for axion-to-photon conversion on the progenitor's magnetic fields. On the other hand, its limited field of view (FOV) means that Fermi-LAT only has around a one in five chance of fortuitously looking at the right place at the right time to catch the next Galactic SN. Given that the Galactic SN rate is around one per 100 years, we thus find ourselves unprepared to take advantage of this rare event for axion physics. To address this shortfall we propose a network of space-based gamma-ray telescopes in the hundreds of MeV range to search for gamma-ray flashes from Galactic SNs and similar nearby extragalactic events, such as NS-NS mergers; we refer to this network as the GALactic AXion Instrument for Supernova (GALAXIS).

We make a number of improvements in modeling axion-induced gamma-ray signals from PNSs. For axionlike particles that couple only to electroweak gauge bosons in the UV, we show that their infrared (IR) renormalization group induced couplings to quarks typically dominate the axion production rate within the PNS. Two classes of production mechanisms are important for this result: (i) axion production from nucleon bremsstrahlung, and (ii) axion production from pion conversion. (See Refs. [52–56] for previous discussions of pion-induced axions in SNs.) The QCD axion has tree-level couplings to nucleons and pions, and accounting for these interactions is crucial in projecting the sensitivity of proposed future SN observations to QCD axions. Additionally, we make use of a suite of cutting-edge SN simulations [57] that are spherically symmetric but include PNS convection, muons and muon neutrinos, general relativity, and neutrino transport [58,59].

Axion luminosity from a PNS—The effective field theories for the QCD axion and for axionlike particles contain the interactions $\mathcal{L} \supset (g_{aqq}/2m_q)(\partial^\mu a)\bar{q}\gamma_\mu\gamma_5 q$, where $g_{aqq} = C_{aqq} m_q/f_a$, with C_{aqq} a UV-dependent coefficient and m_q the quark masses for quark fields q. There are additional interactions involving leptons, but they are not relevant for this work. The QCD axion additionally has the coupling $\mathcal{L} \supset (g^2/32\pi^2 f_a) a G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}$, which involves the QCD field strength $G^a_{\mu\nu}$ and the strong coupling constant g.

Below the scale of the QCD phase transition it is more instructive to talk about the axion couplings to hadrons than to quarks. Moreover, the axion and π^0 undergo a mass mixing for the QCD axion, which provides an IR contribution to $C_{a\gamma\gamma}$. The axion-nucleon couplings are of the same form as the axion-quark couplings but with coefficients C_{app} and C_{ann} for the proton and neutron, respectively. The axion-pion-nucleon interaction may be computed in heavy baryon chiral perturbation theory [60,61] and reads

$$\mathcal{L}_{a\pi N} = i\frac{\partial_\mu a}{2f_a} C_{a\pi N}(\pi^+\bar{p}\gamma^\mu n - \pi^-\bar{n}\gamma^\mu p), \qquad (1)$$

with $C_{a\pi N} = (C_{app} - C_{ann})/\sqrt{2}g_A$, where $g_A \approx 1.28$ is the axial-vector coupling constant.

The QCD axion necessarily has tree-level couplings to hadrons because of the axion-gluon coupling. In Kim-Shifman-Vainshtein-Zakharov (KSVZ) type models [62,63], where the axion does not couple at tree-level to fermions in the UV, $C_{app} \approx -0.47$, $C_{ann} \approx -0.02$, and $C_{a\pi N} \approx -0.27$. In Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) type models [64,65] where there are UV couplings of the axion to fermions, with $\tan\beta$ the ratio of up-type to down-type vacuum expectation values of the two Higgs doublets in those models, the axion-matter couplings can be further enhanced; see the Supplemental Material (SM) [66].

Axionlike particles may or may not have UV contributions to the axion-quark and hence axion-nucleon couplings. On the other hand, even if all $C_{aqq} = 0$ at the Peccei-Quinn scale f_a, these operators are generated under the renormalization group flow, leading to nonzero values for C_{app}, C_{ann}, and $C_{a\pi N}$ in the IR [92]. The precise IR values for these loop-induced coefficients depends on how the axion couples to $SU(2)_L$ and $U(1)_Y$ gauge bosons; as we discuss further in the SM, a generic expectation for the loop-induced coefficients is $C_{app}/C_{a\gamma\gamma} \approx C_{ann}/C_{a\gamma\gamma} \approx 10^{-4}$ and $C_{a\pi N}/C_{a\gamma\gamma} \approx 10^{-5}$. We adopt these choices to be conservative, since this assumes no additional UV contributions, when discussing axionlike particle models. Note that the limit from white dwarfs in Ref. [93] in Fig. 1 also used loop-induced couplings—in that case to electrons; on the other hand, the other upper limits shown in Fig. 1 are not enhanced or otherwise affected by assuming loop-induced couplings to matter.

Hot PNSs have thermal populations of photons, nucleons, and pions. These populations may produce axions through the Primakoff process (for photons), bremsstrahlung (for nucleons), and through pion-to-axion conversion off of nucleons, either through the four-point interaction or through intermediate nucleon or Δ resonances [46,56,94].

We improve the calculation of the axion luminosity relative to previous works on gamma-ray signals from SN1987A (e.g., [8,53]) by making use of more modern SN simulations. In particular, we use the SN simulations presented in Ref. [57], whose radial profiles are accessed through the Garching Core-Collapse Supernova archive [95]. (See also the recent SN simulations in [96].) These are spherically symmetrical (1D) models that include PNS convection [97], the presence of muons and muon-neutrinos, general relativity, and neutrino transport [58,59,98].

To assess the impact of the astrophysical uncertainties related to the mass of NS1987A formed by SN1987A, we consider three different simulations: SFHo-18.6, SFHo-18.8, and SFHo-20.0. Model SFHo-18.6, which is our fiducial model, assumes an $18.6M_{\odot}$ progenitor and has a NS mass of $1.553M_{\odot}$, well within the range expected for NS 1987A (e.g., [11]). Model SFHo-18.8 assumes an $18.8M_{\odot}$ progenitor, and the remnant NS mass is $1.351M_{\odot}$, at the lower edge of the expected range, while in model SFHo-20.0 the progenitor star has a mass of $20M_{\odot}$ and the NS mass is $1.947M_{\odot}$, near the upper edge of the expected range. The SFHo equation of state that is implemented in these simulations is fully compatible with all current constraints from nuclear theory and experiment [99–101] and astrophysics, including pulsar mass measurements [102–104] and the radius constraints deduced from gravitational-wave and Neutron Star Interior Composition Explorer (NICER) measurements [105–107].

The simulations cover the first ∼10 s after bounce, with the explosion triggered at $t \sim 0.16$ s. The data are provided in intervals of 0.025 s for $0\ \mathrm{s} < t < 0.5\ \mathrm{s}$, in intervals of 0.25 s for $0.5\ \mathrm{s} < t < 3\ \mathrm{s}$, in intervals of 0.5 s for $3\ \mathrm{s} < t < 6\ \mathrm{s}$, and in intervals of 1 s until the end of the simulation. The radially dependent temperature peaks around 40 MeV at ∼1 s after the explosion and maintains a temperature ≳5 MeV until 10 s after.

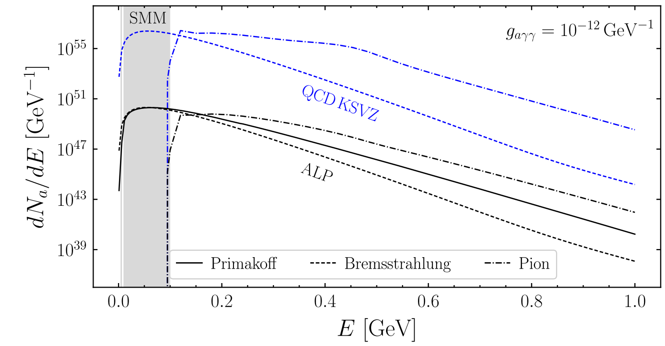

FIG. 2. The differential axion spectra integrated over the first 10 s after the SN for our fiducial SN1987A simulation SFHo-18.6 [57], corresponding to the formation of a $1.553M_{\odot}$ NS. We separate the spectra into contributions from the Primakoff production, bremsstrahlung from nucleons, and processes involving pions. The ALP curves assume no UV contributions to the axion-quark couplings, with the couplings generated in the IR under the renormalization group flow, while the curve labeled "QCD KSVZ" uses the relations $C_{ann}/C_{a\gamma\gamma} \simeq 0.01$, $C_{app}/C_{a\gamma\gamma} \simeq 0.24$, and $C_{a\pi N}/C_{a\gamma\gamma} \simeq 0.13$ appropriate for a KSVZ-type QCD axion. By construction the Primakoff curve is common to both models.

We compute the axion luminosities in each time slice of the simulation using the radial profiles of the temperature and the chemical potentials. In Fig. 2 we illustrate the differential axion spectra dN_a/dE integrated over the 10 s simulation (our fiducial model) for two different theory assumptions for the axion. Both cases have $g_{a\gamma\gamma} = 10^{-12}\ \mathrm{GeV}^{-1}$, but that labeled "ALP" has no tree-level coupling to quarks and only the loop-induced couplings described previously. The second case, labeled "QCD KSVZ," has $C_{ann}/C_{a\gamma\gamma} \simeq 0.01$, $C_{app}/C_{a\gamma\gamma} \simeq 0.24$, and $C_{a\pi N}/C_{a\gamma\gamma} \simeq 0.13$, which are the ratios expected in the KSVZ QCD axion model. (See also the "light" QCD axion models proposed in [108,109].) For each scenario we show the contributions to the luminosity from Primakoff production, nucleon bremsstrahlung involving nucleons only, and processes involving pions. Interestingly, even in the axionlike particle scenario with no tree-level fermion couplings the contribution to the luminosity from hadrons is comparable to the Primakoff production. We also indicate the energy range of the SMM telescope that observed SN1987A; the majority of the pion-induced emission is outside of SMM's energy range.

Axion-photon conversion—We consider, for the first time, the conversion of axions-to-photons on the stellar magnetic fields surrounding the progenitor star for the SN. First, it is instructive to make a rough estimate of the Galactic versus stellar conversion probabilities, with the low-axion-mass approximation $P_{a\to\gamma} \sim g_{a\gamma\gamma}^2 B^2 L^2$, with B

the astrophysical magnetic field strength and L the length of the magnetic field domain. Typical values for Galactic magnetic fields are $B \sim \mu\text{G}$ and $L \sim 1$ kpc, yielding $P_{a\to\gamma} \sim 10^{-5}(g_{a\gamma\gamma}/10^{-12}\ \text{GeV})^2$. On the other hand, the progenitor of the SN1987A was a blue supergiant (BSG), with a surface magnetic field strength $B_0 \sim$ kG [110] and a radius $r_0 \approx 45 \pm 15 R_\odot$ [111]. (We fix $r_0 = 45 R_\odot$ as this is a subdominant source of uncertainty relative to the surface magnetic field strength.) Given that $\mu\text{G} \times \text{kpc} \sim \text{kG} \times (45 R_\odot)$, we estimate that the axion-to-photon conversion probability on the stellar magnetic fields should be comparable to that on the Galactic fields. On the other hand, the estimates above are only valid in the low mass limit; in particular, they are valid when $m_a^2/(2E) \times L \ll 1$, where E is the energy of the axion. Taking $E \sim 100$ MeV, we thus estimate that the axion-conversion probability becomes degraded for $m_a \gtrsim 2 \times 10^{-11}$ eV ($m_a \gtrsim 5 \times 10^{-5}$ eV) for conversion on the Galactic (stellar) magnetic fields.

Core-collapse supernovas form PNSs when the collapsing core reaches nuclear densities; the formation of the PNS causes the in-falling matter to bounce outward, forming a rapidly expanding shock wave that blows apart the star. The outward propagating shock wave travels slower than the speed of light. In contrast, the axions propagate outward faster, nearly at the speed of light. Thus, the axions leave the star well ahead of the shock wave. They encounter the still-pristine magnetic fields of the progenitor star because the change in the magnetic field induced by the bounce propagates relatively slowly out from the stellar core at the Alfvén velocity (see, e.g., [112]).

There was no direct measurement of the magnetic field strength of the SN1987A precursor star Sk −69 202, but there is indirect evidence from combining radio and x-ray data in the decades following the SN with models for the expanding SN remnant that the precursor star had a surface field strength $B_0 \sim 3$ kG [110,113]. This field strength is in line with the ~kG level magnetic field strengths expected for BSGs [114], especially considering that Sk −69 202 likely formed from a merger of two smaller stars [115,116]. BSGs like Sk −69 202 have surface field strengths in the range ~100 G to 10 kG [117], and below we use this range of field strengths when bracketing the uncertainties in the axion-induced gamma-ray signal. In particular, we estimate from population synthesis data that less than ~3% of BSGs like SK −69 202 have dipole field strengths less than 100 G [118], such that 100 G may be considered a robust lower bound on the dipole field strength.

We model the magnetic field of the progenitor star as a dipole field, in which case B falls as $1/r^3$ away from the stellar surface. On the other hand, we note that this is a conservative choice, as the rotation of the progenitor star and its stellar wind may have led to a Parker Spiral type field [110,119], as in the case of the Sun, for which B falls more slowly, with $1/r$ and $1/r^2$ components, away from the surface. We assume for simplicity that the axions travel radially outward at the midplane, such that at every point exterior to the star the magnetic field is perpendicular to the axion trajectory. The axion-photon mixing equations are described in detail in the SM, including the nonlinear Euler-Heisenberg term in the effective Lagrangian for electromagnetism (see, e.g., [120]), which reduces the conversion probabilities given the large axion energies and high field strengths. Note that we neglect the effects of the photon plasma frequency in the medium exterior to the star, since for this to be important the free electron density would need to exceed $n_e \sim 10^{10}\ \text{cm}^{-3}$, which is not expected.

SMM data analysis from SN1987A—We compute the mass-dependent upper limits on $g_{a\gamma\gamma}$ from the nonobservation of excess gamma rays from SN1987A with the SMM. We use the SMM data and instrument response approximations presented in [9] (see the SM). We find no evidence for axions, consistent with previous works, with the 95% upper limits illustrated in Fig. 1. The limit shaded in blue labeled "ALP SN1987A" accounts both for the conversion in the Galactic magnetic field, with the fields modeled using the updated Galactic model [121] (for each mass and energy point we use the lowest conversion probability among all models described in Ref. [121]), and for axion-to-photon conversion in the stellar magnetic field of the progenitor (dominating the sensitivity for m_a above $\sim 10^{-9}$ eV). We account for Primakoff production and hadronic processes, with our fiducial loop-level couplings to hadrons. Only accounting for Primakoff emission weakens the limit at low m_a from $|g_{a\gamma\gamma}| \lesssim 2.6 \times 10^{-12}\ \text{GeV}^{-1}$ to $|g_{a\gamma\gamma}| \lesssim 3.1 \times 10^{-12}\ \text{GeV}^{-1}$. On the other hand, changing to the older Galactic magnetic field model in Ref. [122], matching that used in previous works [8,9], weakens the low-mass axion limit to $|g_{a\gamma\gamma}| \lesssim 3.4 \times 10^{-12}\ \text{GeV}^{-1}$. Using the magnetic field model in [122] and only accounting for Primakoff emission, as in Refs. [8,9], we find a nearly identical upper limit to that in [9] at $m_a = 0$ eV (<10% difference), suggesting that the differences in SN simulations are subleading.

Our upper limits in Fig. 1 take a stellar surface field strength of 100 G to be conservative, even though higher field strengths are favored. Our axionlike particle limit (labeled "ALP SN1987A") excludes new parameter space for $m_a \gtrsim 10\ \mu\text{eV}$. The upper limit labeled "KSVZ-like axion SN1987A" assumes that the ratios of $C_{app}/C_{a\gamma\gamma}$, $C_{ann}/C_{a\gamma\gamma}$, and $C_{a\pi N}/C_{a\gamma\gamma}$ are as expected in the KSVZ QCD axion model. This upper limit is around an order of magnitude away in terms of $g_{a\gamma\gamma}$ from probing the KSVZ QCD axion model for $m_a \gtrsim 10^{-4}$ eV, strongly motivating future observations with increased sensitivity.

Our axionlike particle upper limit in Fig. 1 excludes much of the parameter space that will be probed by the ALPS II light-shining-through-walls experiment [123–125]; taking a more realistic but less conservative surface magnetic fields strength of $B_0 = 1$ kG, we exclude the full parameter space to be probed by ALPS II (see the SM).

Note that our results are strictly speaking only valid for, roughly, $|g_{a\gamma\gamma}| \lesssim 10^{-8}\ \mathrm{GeV}^{-1}$ ($m_a \lesssim 10^{-2}$ eV) for the axionlike particle model (the KSVZ QCD axion), as for larger couplings we estimate that the axion luminosity 1 s postbounce exceeds the neutrino luminosity. The axion model at larger couplings is disfavored [4,10], and modeling this scenario would require including the backreaction of the axion emission in the SN simulations.

GALAXIS: Galactic Axion Instrument for Supernova—If a Galactic SN went off today, we estimate using the FERMITOOLS [126] that the chance Fermi-LAT would be looking at the correct place at the correct time to catch the ∼10 s axion-induced burst is only around ∼20%, accounting for the finite FOV of the instrument and downtime during its orbit. On the other hand, if the next SN went off directly above Fermi (at its zenith), the estimated 95% upper limits on $g_{a\gamma\gamma}$ we would be able to obtain are illustrated in Fig. 1. We use the FERMITOOLS to obtain the instrument response with the `P8R3_TRANSIENT020_V2` event class; we estimate ∼0 background events over the ∼10 s duration of the SN. The effective area at zenith at $E = 200$ MeV is $\sim 0.72\ \mathrm{m}^2$. We illustrate the expected 95% upper limits under the null hypothesis for the axionlike particle scenario, the KSVZ-like axion, and a DFSZ-like scenario, scanning over $\tan\beta$. (We show the strongest and weakest limits across the range of $\tan\beta$; see the SM for details.) We make these projections using our fiducial SFHo-18.6 SN simulation, and we assume a distance of 10 kpc to the next Galactic SN. We only account for axion-photon conversion on the stellar magnetic fields of the progenitor star, assuming a 1 kG surface magnetic field for a BSG SN that is otherwise the same as SN1987A. (The axions could also convert to photons on the Galactic magnetic field, enhancing the low-mass sensitivity.) In the SM we discusses red supergiant SNs, which are more prevalent and as we show have comparable sensitivity.

Without new instrumentation the opportunity to probe QCD axions using gamma-ray observations of the next Galactic SN will almost certainly be lost, since the event will likely have no advanced warning (but see Ref. [127]) and not be within the FOV of the Fermi-LAT. The proposed Advanced Particle-astrophysics Telescope (APT) [128,129] may have an increased FOV relative to the Fermi-LAT, though it will likely also not be 4π. We thus propose a full-sky gamma-ray telescope network, which we call the GALactic AXion Instrument for Supernova (GALAXIS) (see Fig. 3).

The idea behind GALAXIS is to establish a full-sky constellation of gamma-ray satellites to provide continuous 4π coverage of the gamma-ray sky between ∼100 MeV and ∼1 GeV. (See also the recent work [130] that made a related proposal.) The network would consist of multiple (e.g., ∼5 or more) gamma-ray telescopes on different orbital trajectories, such that any future SN would be in

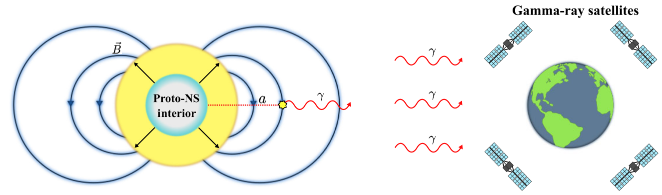

FIG. 3. The GALAXIS gamma-ray satellite constellation proposed in this Letter to search for axion-induced gamma-ray signatures from core-collapse SNs and NS-NS mergers. The axions are generated in the hot PNS cores and then convert to gamma rays on the stellar magnetic fields of the progenitor stars. Such an instrument with a Fermi-LAT-level effective area could potentially probe QCD axions for any $m_a \gtrsim 50$ μeV, depending on the properties of the event.

view of at least one telescope in the network. Such an instrument would complement the multiple gamma-ray telescope constellations in planning stages at energies below ∼10 MeV (see Ref. [131] and references therein). We leave a full technical investigation to future work. In Fig. 1 we simply assume for the projections that the GALAXIS instrument response is identical to that of the on-axis Fermi-LAT (see the SM). The main improvements with the future projections relative to the SN1987A constraints come from the distance to the SN, the large effective area and improved background rate of GALAXIS (i.e., Fermi-LAT) relative to the SMM, and the inclusion of higher-energy photons above ∼100 MeV that allow for probing pion-induced axions. GALAXIS may reach sensitivity to the QCD axion, making it competitive with upcoming efforts to target QCD axions such as IAXO [132], MADMAX [133], and ALPHA [134].

Discussion—In this Letter we focus on axion-induced gamma-ray signals from nearby PNSs formed after core-collapse SNs due to axion-photon conversion in the stellar magnetic fields of the progenitor stars. However, there are a number of related axion-induced gamma-ray signals that may proceed similarly and be detectable with the proposed GALAXIS gamma-ray observatory. For example, in cases where the compact remnant of the core-collapse SN is a black hole (as suggested could be the case for SN1987A in [135], though this is now disfavored [11,12]), a hot, massive PNS remnant forms prior to collapse. It would be interesting to study the axion-induced gamma-ray signal from such a short-lived remnant with dedicated simulations. Similarly, NS-NS mergers can lead to stable NSs or hypermassive remnants that collapse to black holes; in either case, exceedingly hot PNSs form within the first tens of ms, with temperatures that can exceed those in core-collapse SNs. As we show in the SM, nearby NS-NS mergers (within ∼50 Mpc of Earth) are promising targets for gamma-ray axion searches (see also [136–138]). Given the compact sizes of the NSs, these objects can potentially probe higher axion masses and may even reach QCD axion sensitivity near ∼1 meV (see the SM). NS-NS mergers, along with SNs within the local group and nearby galaxy clusters, can be expected on a near yearly basis, meaning that the proposed GALAXIS instrument would have frequent opportunities for axion science.

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[1] K. Hirata *et al.* (Kamiokande-II Collaboration), Observation of a neutrino burst from the supernova SN 1987a, Phys. Rev. Lett. **58**, 1490 (1987).

[2] R.M. Bionta *et al.*, Observation of a neutrino burst in coincidence with supernova SN 1987a in the large magellanic cloud, Phys. Rev. Lett. **58**, 1494 (1987).

[3] E. N. Alekseev, L. N. Alekseeva, V. I. Volchenko, and I. V. Krivosheina, Possible detection of a neutrino signal on 23 February 1987 at the baksan underground scintillation telescope of the institute of nuclear research, JETP Lett. **45**, 589 (1987), http://jetpletters.ru/ps/1245/article_18825.shtml.

[4] G. G. Raffelt, *Stars as laboratories for fundamental physics: The astrophysics of neutrinos, axions, and other weakly interacting particles* (1996), https://press.uchicago.edu/ucp/books/book/chicago/S/bo3683609.html.

[5] Georg G. Raffelt, Astrophysical methods to constrain axions and other novel particle phenomena, Phys. Rep. **198**, 1 (1990).

[6] Jack W. Brockway, Eric D. Carlson, and Georg G. Raffelt, SN1987A gamma-ray limits on the conversion of pseudoscalars, Phys. Lett. B **383**, 439 (1996).

[7] J. A. Grifols, E. Masso, and R. Toldra, Gamma-rays from SN1987A due to pseudoscalar conversion, Phys. Rev. Lett. **77**, 2372 (1996).

[8] Alexandre Payez, Carmelo Evoli, Tobias Fischer, Maurizio Giannotti, Alessandro Mirizzi, and Andreas Ringwald, Revisiting the SN1987A gamma-ray limit on ultralight axion-like particles, J. Cosmol. Astropart. Phys. 02 (2015) 006.

[9] Sebastian Hoof and Lena Schulz, Updated constraints on axion-like particles from temporal information in supernova SN1987A gamma-ray data, J. Cosmol. Astropart. Phys. 03 (2023) 054.

[10] Andrea Caputo and Georg Raffelt, Astrophysical axion bounds: The 2024 Edition, Proc. Sci., 454 (**2024**) 041 [arXiv:2401.13728].

[11] Dany Page, Mikhail V. Beznogov, Iván Garibay, James M. Lattimer, Madappa Prakash, and Hans-Thomas Janka, NS 1987A in SN 1987A, Astrophys. J. **898**, 125 (2020).

[12] C. Fransson *et al.*, Emission lines due to ionizing radiation from a compact object in the remnant of Supernova 1987A, Science **383**, 898 (2024).

[13] R. D. Peccei and Helen R. Quinn, *CP* conservation in the presence of instantons, Phys. Rev. Lett. **38**, 1440 (1977).

[14] R. D. Peccei and Helen R. Quinn, Constraints imposed by *CP* conservation in the presence of instantons, Phys. Rev. D **16**, 1791 (1977).

[15] Steven Weinberg, A new light boson?, Phys. Rev. Lett. **40**, 223 (1978).

[16] Frank Wilczek, Problem of strong *P* and *T* invariance in the presence of instantons, Phys. Rev. Lett. **40**, 279 (1978).

[17] John Preskill, Mark B. Wise, and Frank Wilczek, Cosmology of the invisible axion, Phys. Lett. **120B**, 127 (1983).

[18] L. F. Abbott and P. Sikivie, A cosmological bound on the invisible axion, Phys. Lett. **120B**, 133 (1983).

[19] Michael Dine and Willy Fischler, The not so harmless axion, Phys. Lett. **120B**, 137 (1983).

[20] Peter Svrcek and Edward Witten, Axions in string theory, J. High Energy Phys. 06 (2006) 051.

[21] Asimina Arvanitaki, Savas Dimopoulos, Sergei Dubovsky, Nemanja Kaloper, and John March-Russell, String axiverse, Phys. Rev. D **81**, 123530 (2010).

[22] Michele Cicoli, Mark Goodsell, and Andreas Ringwald, The type IIB string axiverse and its low-energy phenomenology, J. High Energy Phys. 10 (2012) 146.

[23] Mehmet Demirtas, Cody Long, Liam McAllister, and Mike Stillman, The Kreuzer-Skarke axiverse, J. High Energy Phys. 04 (2020) 138.

[24] James Halverson, Cody Long, Brent Nelson, and Gustavo Salinas, Towards string theory expectations for photon couplings to axionlike particles, Phys. Rev. D **100**, 106010 (2019).

[25] Mehmet Demirtas, Naomi Gendler, Cody Long, Liam McAllister, and Jakob Moritz, PQ axiverse, J. High Energy Phys. 06 (2023) 092.

[26] Christopher S. Reynolds, M. C. David Marsh, Helen R. Russell, Andrew C. Fabian, Robyn Smith, Francesco Tombesi, and Sylvain Veilleux, Astrophysical limits on very light axion-like particles from Chandra grating spectroscopy of NGC 1275, Astrophys. J. **890**, 59 (2020).

[27] Christopher Dessert, Joshua W. Foster, and Benjamin R. Safdi, X-ray searches for axions from super star clusters, Phys. Rev. Lett. **125**, 261102 (2020).

[28] Júlia Sisk Reynés, James H. Matthews, Christopher S. Reynolds, Helen R. Russell, Robyn N. Smith, and M. C. David 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).

[29] Dion Noordhuis, Anirudh Prabhu, Samuel J. Witte, Alexander Y. Chen, Fábio Cruz, and Christoph Weniger, Novel constraints on axions produced in pulsar polar-cap cascades, Phys. Rev. Lett. **131**, 111004 (2023).

[30] Christopher Dessert, David Dunsky, and Benjamin R. Safdi, Upper limit on the axion-photon coupling from magnetic white dwarf polarization, Phys. Rev. D **105**, 103034 (2022).
[31] Matthew J. Dolan, Frederick J. Hiskens, and Raymond R. Volkas, Advancing globular cluster constraints on the axion-photon coupling, J. Cosmol. Astropart. Phys. 10 (2022) 096.
[32] James Davies, Manuel Meyer, and Garret Cotter, Constraints on axionlike particles from a combined analysis of three flaring Fermi flat-spectrum radio quasars, Phys. Rev. D **107**, 083027 (2023).
[33] Orion Ning and Benjamin R. Safdi, Leading axion-photon sensitivity with NuSTAR observations of M82 and M87, arXiv:2404.14476.
[34] Ciaran O'HARE, cajohare/axionlimits: Axionlimits (2020).
[35] R. L. Workman and Others (Particle Data Group), Review of particle physics, Prog. Theor. Exp. Phys. **2022**, 083C01 (2022).
[36] Georg Raffelt and David Seckel, Bounds on exotic particle interactions from SN 1987a, Phys. Rev. Lett. **60**, 1793 (1988).
[37] John Ellis and K. A. Olive, Constraints on light particles from supernova SN 1987A, Phys. Lett. B **193**, 525 (1987).
[38] Michael S. Turner, Axions from SN 1987a, Phys. Rev. Lett. **60**, 1797 (1988).
[39] Ron Mayle, James R. Wilson, John Ellis, Keith Olive, David N. Schramm, and Gary Steigman, Constraints on axions from SN 1987A, Phys. Lett. B **203**, 188 (1988).
[40] Ron Mayle, James R. Wilson, John Ellis, Keith A. Olive, David N. Schramm, and Gary Steigman, Updated constraints on axions from SN1987A, in *The Big Bang and Other Explosions in Nuclear and Particle Astrophysics*, edited by D. N. Schramm (World Scientific Publishing Co. Pte. Ltd, Singapore, 1996), pp. 188–193.
[41] Ralf Peter Brinkmann and Michael S. Turner, Numerical rates for nucleon-nucleon axion bremsstrahlung, Phys. Rev. D **38**, 2338 (1988).
[42] Adam Burrows, Michael S. Turner, and R. P. Brinkmann, Axions and SN 1987a, Phys. Rev. D **39**, 1020 (1989).
[43] Hans-Thomas Janka, Wolfgang Keil, Georg Raffelt, and David Seckel, Nucleon spin fluctuations and the supernova emission of neutrinos and axions, Phys. Rev. Lett. **76**, 2621 (1996).
[44] Wolfgang Keil, Hans-Thomas Janka, David N. Schramm, Gunter Sigl, Michael S. Turner, and John R. Ellis, A fresh look at axions and SN-1987A, Phys. Rev. D **56**, 2419 (1997).
[45] Tobias Fischer, Sovan Chakraborty, Maurizio Giannotti, Alessandro Mirizzi, Alexandre Payez, and Andreas Ringwald, Probing axions with the neutrino signal from the next galactic supernova, Phys. Rev. D **94**, 085012 (2016).
[46] Pierluca Carenza, Tobias Fischer, Maurizio Giannotti, Gang Guo, Gabriel Martínez-Pinedo, and Alessandro Mirizzi, Improved axion emissivity from a supernova via nucleon-nucleon bremsstrahlung, J. Cosmol. Astropart. Phys. 10 (2019) 016; 05 (2020) E01.
[47] Alessandro Lella, Pierluca Carenza, Giampaolo Co', Giuseppe Lucente, Maurizio Giannotti, Alessandro Mirizzi, and Thomas Rauscher, Getting the most on supernova axions, Phys. Rev. D **109**, 023001 (2024).
[48] Claudio Andrea Manzari, Jorge Martin Camalich, Jonas Spinner, and Robert Ziegler, Supernova limits on muonic dark forces, Phys. Rev. D **108**, 103020 (2023).
[49] M. Meyer, M. Giannotti, A. Mirizzi, J. Conrad, and M. A. Sánchez-Conde, Fermi large area telescope as a galactic supernovae axionscope, Phys. Rev. Lett. **118**, 011103 (2017).
[50] Francesca Calore, Pierluca Carenza, Christopher Eckner, Maurizio Giannotti, Giuseppe Lucente, Alessandro Mirizzi, and Francesco Sivo, Uncovering axionlike particles in supernova gamma-ray spectra, Phys. Rev. D **109**, 043010 (2024).
[51] D. J. Forrest, E. L. Chupp, J. M. Ryan, M. L. Cherry, I. U. Gleske, C. Reppin, K. Pinkau, E. Rieger, G. Kanbach, R. L. Kinzer, G. Share, W. N. Johnson, and J. D. Kurfess, The gamma ray spectrometer for the solar maximum mission, Sol. Phys. **65**, 15 (1980).
[52] Pierluca Carenza, Bryce Fore, Maurizio Giannotti, Alessandro Mirizzi, and Sanjay Reddy, Enhanced supernova axion emission and its implications, Phys. Rev. Lett. **126**, 071102 (2021).
[53] Tobias Fischer, Pierluca Carenza, Bryce Fore, Maurizio Giannotti, Alessandro Mirizzi, and Sanjay Reddy, Observable signatures of enhanced axion emission from protoneutron stars, Phys. Rev. D **104**, 103012 (2021).
[54] Kiwoon Choi, Hee Jung Kim, Hyeonseok Seong, and Chang Sub Shin, Axion emission from supernova with axion-pion-nucleon contact interaction, J. High Energy Phys. 02 (2022) 143.
[55] Thomas Vonk, Feng-Kun Guo, and Ulf-G. Meißner, Pion axioproduction: The Δ resonance contribution, Phys. Rev. D **105**, 054029 (2022).
[56] Shu-Yu Ho, Jongkuk Kim, Pyungwon Ko, and Jae-hyeon Park, Supernova axion emissivity with $\Delta(1232)$ resonance in heavy baryon chiral perturbation theory, Phys. Rev. D **107**, 075002 (2023).
[57] Robert Bollig, William DeRocco, Peter W. Graham, and Hans-Thomas Janka, Muons in supernovae: Implications for the axion-muon coupling, Phys. Rev. Lett. **125**, 051104 (2020).
[58] Hans-Thomas Janka, Explosion mechanisms of core-collapse supernovae, Annu. Rev. Nucl. Part. Sci. **62**, 407 (2012).
[59] R. Bollig, H. Th. Janka, A. Lohs, G. Martinez-Pinedo, C. J. Horowitz, and T. Melson, Muon creation in supernova matter facilitates neutrino-driven explosions, Phys. Rev. Lett. **119**, 242702 (2017).
[60] Sanghyeon Chang and Kiwoon Choi, Hadronic axion window and the big bang nucleosynthesis, Phys. Lett. B **316**, 51 (1993).
[61] Thomas Vonk, Feng-Kun Guo, and Ulf-G. Meißner, The axion-baryon coupling in SU(3) heavy baryon chiral perturbation theory, J. High Energy Phys. 08 (2021) 024.
[62] Jihn E. Kim, Weak interaction singlet and strong *CP* invariance, Phys. Rev. Lett. **43**, 103 (1979).
[63] Mikhail A. Shifman, A. I. Vainshtein, and Valentin I. Zakharov, Can confinement ensure natural *CP* invariance of strong interactions?, Nucl. Phys. **B166**, 493 (1980).
[64] Michael Dine, Willy Fischler, and Mark Srednicki, A simple solution to the strong *CP* problem with a harmless axion, Phys. Lett. **104B**, 199 (1981).

[65] A. R. Zhitnitsky, On possible suppression of the axion hadron interactions. (In Russian), Sov. J. Nucl. Phys. **31**, 260 (1980).
[66] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.133.211002 for additional derivations, extended data analyses, and supporting figures, which includes Ref. [67–91].
[67] Malte Buschmann, Raymond T. Co, Christopher Dessert, and Benjamin R. Safdi, Axion emission can explain a new hard x-ray excess from nearby isolated neutron stars, Phys. Rev. Lett. **126**, 021102 (2021).
[68] Andrea Caputo, Georg Raffelt, and Edoardo Vitagliano, Muonic boson limits: Supernova redux, Phys. Rev. D **105**, 035022 (2022).
[69] Pierluca Carenza, Axion emission from supernovae: A cheatsheet, Eur. Phys. J. Plus **138**, 836 (2023).
[70] Mark Srednicki, Axion couplings to matter. 1. *CP* conserving parts, Nucl. Phys. **B260**, 689 (1985).
[71] Martin Bauer, Matthias Neubert, and Andrea Thamm, Collider probes of axion-like particles, J. High Energy Phys. 12 (2017) 044.
[72] Martin Bauer, Matthias Neubert, Sophie Renner, Marvin Schnubel, and Andrea Thamm, The low-energy effective theory of axions and ALPs, J. High Energy Phys. 04 (2021) 063.
[73] Giovanni Grilli di Cortona, Edward Hardy, Javier Pardo Vega, and Giovanni Villadoro, The QCD axion, precisely, J. High Energy Phys. 01 (2016) 034.
[74] Luca Di Luzio, Maurizio Giannotti, Enrico Nardi, and Luca Visinelli, The landscape of QCD axion models, Phys. Rep. **870**, 1 (2020).
[75] Georg Raffelt and Leo Stodolsky, Mixing of the photon with low mass particles, Phys. Rev. D **37**, 1237 (1988).
[76] W. Heisenberg and H. Euler, Consequences of Dirac theory of the positron, Z. Phys. **98**, 714 (1936).
[77] James 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.
[78] M. Aurière, J. F. Donati, R. Konstantinova-Antova, G. Perrin, P. Petit, and T. Roudier, The magnetic field of Betelgeuse: A local dynamo from giant convection cells?, Astron. Astrophys. **516**, L2 (2010).
[79] S. B. F. Dorch, Magnetic activity in late—type giant stars: Numerical MHD simulations of non-linear dynamo action in Betelgeuse, Astron. Astrophys. **423**, 1101 (2004).
[80] Jared A. Goldberg, Yan-Fei Jiang, and Lars Bildsten, Numerical simulations of convective three-dimensional red supergiant envelopes, Astrophys. J. **929**, 156 (2022).
[81] Arkady B. Migdal, E. E. Saperstein, M. A. Troitsky, and D. N. Voskresensky, Pion degrees of freedom in nuclear matter, Phys. Rep. **192**, 179 (1990).
[82] Bryce Fore and Sanjay Reddy, Pions in hot dense matter and their astrophysical implications, Phys. Rev. C **101**, 035809 (2020).
[83] Bryce Fore, Norbert Kaiser, Sanjay Reddy, and Neill C. Warrington, The mass of charged pions in neutron star matter, Phys. Rev. C **110**, 025803 (2024).
[84] Malte Buschmann, Christopher Dessert, Joshua W. Foster, Andrew J. Long, and Benjamin R. Safdi, Upper limit on the QCD axion mass from isolated neutron star cooling, Phys. Rev. Lett. **128**, 091102 (2022).
[85] Kenta Kiuchi, Sho Fujibayashi, Kota Hayashi, Koutarou Kyutoku, Yuichiro Sekiguchi, and Masaru Shibata, Self-consistent picture of the mass ejection from a one second long binary neutron star merger leaving a short-lived remnant in a general-relativistic neutrino-radiation magnetohydrodynamic simulation, Phys. Rev. Lett. **131**, 011401 (2023).
[86] Matthias Hanauske, Jan Steinheimer, Anton Motornenko, Volodymyr Vovchenko, Luke Bovard, Elias R. Most, L. Jens Papenfort, Stefan Schramm, and Horst Stöcker, Neutron star mergers: Probing the EoS of hot, dense matter by gravitational waves, Particles **2**, 44 (2019).
[87] Francesco Zappa, Sebastiano Bernuzzi, David Radice, and Albino Perego, Binary neutron star merger simulations with neutrino transport and turbulent viscosity: Impact of different schemes and grid resolution, Mon. Not. R. Astron. Soc. **520**, 1481 (2023).
[88] David Radice and Sebastiano Bernuzzi, Ab-initio general-relativistic neutrino-radiation hydrodynamics simulations of long-lived neutron star merger remnants to neutrino cooling timescales, Astrophys. J. **959**, 46 (2023).
[89] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), GWTC-1: A gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs, Phys. Rev. X **9**, 031040 (2019).
[90] Luciano Combi and Daniel M. Siegel, Jets from neutron-star merger remnants and massive blue kilonovae, Phys. Rev. Lett. **131**, 231402 (2023).
[91] Jean-François Fortin, Huai-Ke Guo, Steven P. Harris, Elijah Sheridan, and Kuver Sinha, Magnetars and axion-like particles: Probes with the hard x-ray spectrum, J. Cosmol. Astropart. Phys. 06 (2021) 036.
[92] Martin Bauer, Matthias Neubert, Sophie Renner, Marvin Schnubel, and Andrea Thamm, Flavor probes of axion-like particles, J. High Energy Phys. 09 (2022) 056.
[93] Christopher Dessert, Andrew J. Long, and Benjamin R. Safdi, No evidence for axions from chandra observation of the magnetic white dwarf RE J0317-853, Phys. Rev. Lett. **128**, 071102 (2022).
[94] Georg G. Raffelt, Astrophysical axion bounds diminished by screening effects, Phys. Rev. D **33**, 897 (1986).
[95] Garching Core-Collapse Supernova archive, https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/.
[96] Damiano F. G. Fiorillo, Malte Heinlein, Hans-Thomas Janka, Georg Raffelt, Edoardo Vitagliano, and Robert Bollig, Supernova simulations confront SN 1987A neutrinos, Phys. Rev. D **108**, 083040 (2023).
[97] Alessandro Mirizzi, Irene Tamborra, Hans-Thomas Janka, Ninetta Saviano, Kate Scholberg, Robert Bollig, Lorenz Hudepohl, and Sovan Chakraborty, Supernova neutrinos: Production, oscillations and detection, Riv. Nuovo Cimento **39**, 1 (2016).
[98] Markus Rampp and H. Thomas Janka, Radiation hydrodynamics with neutrinos: Variable Eddington factor method for core collapse supernova simulations, Astron. Astrophys. **396**, 361 (2002).

[99] Tobias Fischer, Matthias Hempel, Irina Sagert, Yudai Suwa, and Jürgen Schaffner-Bielich, Symmetry energy impact in simulations of core-collapse supernovae, Eur. Phys. J. A **50**, 46 (2014).

[100] M. Oertel, M. Hempel, T. Klähn, and S. Typel, Equations of state for supernovae and compact stars, Rev. Mod. Phys. **89**, 015007 (2017).

[101] Tobias Fischer, Niels-Uwe Bastian, David Blaschke, Mateusz Cierniak, Matthias Hempel, Thomas Klähn, Gabriel Martínez-Pinedo, William G. Newton, Gerd Röpke, and Stefan Typel, The state of matter in simulations of core-collapse supernovae—Reflections and recent developments, Pub. Astron. Soc. Aust. **34**, 67 (2017).

[102] Paul Demorest, Tim Pennucci, Scott Ransom, Mallory Roberts, and Jason Hessels, Shapiro delay measurement of a two solar mass neutron star, Nature (London) **467**, 1081 (2010).

[103] John Antoniadis *et al.*, A massive pulsar in a compact relativistic binary, Science **340**, 6131 (2013).

[104] H. T. Cromartie *et al.* (NANOGrav Collaboration), Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar, Nat. Astron. **4**, 72 (2019).

[105] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), GW170817: Measurements of neutron star radii and equation of state, Phys. Rev. Lett. **121**, 161101 (2018).

[106] Andreas Bauswein, Oliver Just, Hans-Thomas Janka, and Nikolaos Stergioulas, Neutron-star radius constraints from GW170817 and future detections, Astrophys. J. Lett. **850**, L34 (2017).

[107] Reed Essick, Ingo Tews, Philippe Landry, Sanjay Reddy, and Daniel E. Holz, Direct astrophysical tests of chiral effective field theory at supranuclear densities, Phys. Rev. C **102**, 055803 (2020).

[108] Anson Hook, Solving the hierarchy problem discretely, Phys. Rev. Lett. **120**, 261802 (2018).

[109] Luca Di Luzio, Belen Gavela, Pablo Quilez, and Andreas Ringwald, An even lighter QCD axion, J. High Energy Phys. 05 (2021) 184.

[110] S. Orlando *et al.*, 3D MHD modeling of the expanding remnant of SN 1987A. Role of magnetic field and non-thermal radio emission, Astron. Astrophys. **622**, A73 (2019).

[111] S. E. Woosley, SN 1987A: After the peak, Astrophys. J. **330**, 218 (1988).

[112] T. K. Suzuki, K. Sumiyoshi, and S. Yamada, Alfven wave-driven supernova explosion, Astrophys. J. **678**, 1200 (2008).

[113] O. Petruk, V. Beshley, S. Orlando, F. Bocchino, M. Miceli, S. Nagataki, M. Ono, S. Loru, A. Pellizzoni, and E. Egron, Polarized radio emission unveils the structure of the pre-supernova circumstellar magnetic field and the radio emission in SN1987A, Mon. Not. R. Astron. Soc. **518**, 6377 (2022).

[114] I. Petermann, N. Langer, N. Castro, and L. Fossati, Blue supergiants as descendants of magnetic main sequence stars, Astron. Astrophys. **584**, A54 (2015).

[115] H. Sana, S. E. de Mink, A. de Koter, N. Langer, C. J. Evans, M. Gieles, E. Gosset, R. G. Izzard, J. B. Le Bouquin, and F. R. N. Schneider, Binary interaction dominates the evolution of massive stars, Science **337**, 444 (2012).

[116] Thomas Morris and Philipp Podsiadlowski, The triple-ring nebula around SN 1987A: Fingerprint of a binary merger, Science **315**, 1103 (2007).

[117] J. F. Donati and J. D. Landstreet, Magnetic fields of nondegenerate stars, Annu. Rev. Astron. Astrophys. **47**, 333 (2009).

[118] L. Fossati, N. Castro, T. Morel, N. Langer, M. Briquet, T. A. Carroll, S. Hubrig, M. F. Nieva, L. M. Oskinova, N. Przybilla, F. R. N. Schneider, M. Schöller, S. Simón-Díaz, I. Ilyin, A. de Koter, A. Reisenegger, and H. Sana, B fields in OB stars (BOB): On the detection of weak magnetic fields in the two early B-type stars βCMa and ϵCMa. Possible lack of a “magnetic desert”' in massive stars, Astron. Astrophys. **574**, A20 (2015).

[119] E. N. Parker, Dynamics of the interplanetary gas and magnetic fields, Astrophys. J. **128**, 664 (1958).

[120] Benjamin R. Safdi, TASI lectures on the particle physics and astrophysics of dark matter, Proc. Sci., TASI2022, 009 (2024) [arXiv:2303.02169].

[121] Michael Unger and Glennys R. Farrar, The coherent magnetic field of the Milky Way, Astrophys. J. **970**, 95 (2024).

[122] Ronnie Jansson and Glennys R. Farrar, A new model of the galactic magnetic field, Astrophys. J. **757**, 14 (2012).

[123] Robin Bähre *et al.*, Any light particle search II—technical design report, J. Instrum. **8**, T09001 (2013).

[124] Isabella Oceano (ALPS II Collaboration), Axion and ALP search with the any light particle search II experiment at DESY, Proc. Sci., EPS-HEP2023 (**2024**) 117.

[125] Andreas Ringwald, Review on axions, arXiv:2404.09036.

[126] https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/.

[127] Shao-Feng Ge, Koichi Hamaguchi, Koichi Ichimura, Koji Ishidoshiro, Yoshiki Kanazawa, Yasuhiro Kishimoto, Natsumi Nagata, and Jiaming Zheng, Supernova-scope for the direct search of supernova axions, J. Cosmol. Astropart. Phys. 11 (2020) 059.

[128] Samer Alnussirat *et al.*, The advanced particle-astrophysics telescope: Simulation of the instrument performance for gamma-ray detection, Proc. Sci., ICRC2021 (**2021**) 590.

[129] James H. Buckley *et al.* (APT Collaboration), The advanced particle-astrophysics telescope (APT) project status, Proc. Sci., ICRC2021 (**2021**) 655.

[130] Alessandro Lella, Francesca Calore, Pierluca Carenza, Christopher Eckner, Maurizio Giannotti, Giuseppe Lucente, and Alessandro Mirizzi, Probing protoneutron stars with gamma-ray axionscopes, arXiv:2405.02395.

[131] Peter F. Bloser, David Murphy, Fabrizio Fiore, and Jeremy Perkins, CubeSats for gamma-ray astronomy, arXiv:2212.11413.

[132] E. Armengaud *et al.* (IAXO Collaboration), Physics potential of the international axion observatory (IAXO), J. Cosmol. Astropart. Phys. 06 (2019) 047.

[133] S. Beurthey *et al.*, MADMAX status report, arXiv:2003.10894.

[134] Alexander J. Millar *et al.*, Searching for dark matter with plasma haloscopes, Phys. Rev. D **107**, 055013 (2023).
[135] Nitsan Bar, Kfir Blum, and Guido D'Amico, Is there a supernova bound on axions?, Phys. Rev. D **101**, 123025 (2020).
[136] Tim Dietrich and Katy Clough, Cooling binary neutron star remnants via nucleon-nucleon-axion bremsstrahlung, Phys. Rev. D **100**, 083005 (2019).
[137] Steven P. Harris, Jean-Francois Fortin, Kuver Sinha, and Mark G. Alford, Axions in neutron star mergers, J. Cosmol. Astropart. Phys. 07 (2020) 023.
[138] P. S. Bhupal Dev, Jean-François Fortin, Steven P. Harris, Kuver Sinha, and Yongchao 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).