

Detecting light axions from supernovae in nearby galaxies

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(Received 11 December 2025; accepted 14 August 2026; published 11 September 2026)

Axionlike particles (ALPs) coupled to nucleons can be efficiently produced in core-collapse supernovae (SNe) and then, if they couple to photons, convert into gamma rays in cosmic magnetic fields, generating short gamma-ray bursts. Though ALPs from a Galactic SN would induce an intense and easily detectable gamma-ray signal, such events are exceedingly rare. In contrast, a few SNe per year are expected in nearby galaxies within $\sim \mathcal{O}(10)$ Mpc, where strong magnetic fields can enable more efficient ALP-photon conversions than in the Milky Way, offering a promising extragalactic target. This circumstance motivates full-sky gamma-ray monitoring, ideally combined with decihertz gravitational-wave detectors to enable time-triggered searches from nearby galaxies. We show that, under realistic conditions, a decade of coverage could reach sensitivities to the product of the ALP-proton and ALP-photon couplings $g_{ap} \times g_{a\gamma} \gtrsim 10^{-24} \text{ GeV}^{-1}$ for ALP masses $m_a \lesssim 10^{-9} \text{ eV}$. This sensitivity would allow one to probe a large, currently unexplored region of the parameter space below the long-standing SN 1987A bound.

DOI: [10.1103/6xp9-gcqx](https://doi.org/10.1103/6xp9-gcqx)

I. INTRODUCTION

Axionlike particles (ALPs) emerge in several extensions of the Standard Model of particle physics [1–7]. From a top-down perspective, string theory predicts the presence of an “axiverse” with the QCD axion [8–11] and several ultralight ALPs [12–14]. From a bottom-up perspective, ALPs offer an interesting physics case in relation to dark matter [15–19] and several astrophysical puzzles [20–23]. In this context, stars provide ideal environments for ALP production due to their hot, dense plasmas [24,25] (see Refs. [7,26,27] for recent reviews). The Sun, being the closest star to Earth, has been extensively studied using “helioscope” experiments [28–30] and x-ray detectors [31]. Nevertheless, other stellar systems offer competitive discovery potential [27]. Remarkably, following the detection

of neutrinos from supernova SN 1987A [32–36], it was proposed that ALPs could be copiously produced in the supernova (SN) core alongside neutrinos [37,38]. In particular, a substantial ALP flux can be generated via interactions with nucleons in the hot and dense SN core [37,39–41]. If also coupled with photons, a fraction of these ALPs could convert into gamma rays in the Milky Way magnetic field, yielding a short gamma-ray burst coincident with the neutrino signal. The absence of such a signal in the Gamma-Ray Spectrometer aboard the Solar Maximum Mission led to stringent constraints on the product of the ALP-proton and ALP-photon couplings [42–47], excluding $g_{ap} \times g_{a\gamma} \gtrsim 3.6 \times 10^{-24} \text{ GeV}^{-1}$ for $m_a \lesssim 10^{-10} \text{ eV}$ (see the gray band in Fig. 1).

The observation of a future Galactic core-collapse supernova (CCSN) would enable tests of substantially smaller ALP couplings [52–54]. For example, if the *Fermi* Large Area Telescope (LAT) were to observe such a SN event, it could probe down to $g_{ap} \times g_{a\gamma} \gtrsim 3.7 \times 10^{-26} \text{ GeV}^{-1}$ for ultralight ALPs with $m_a \ll 10^{-9} \text{ eV}$ (see the dashed black curve in Fig. 1). In addition, including ALP-photon conversions in the strong magnetic field of the progenitor star may even grant access to the canonical QCD axion parameter space [46,47,55]. Though all this sounds extremely promising, Galactic SNe are rare events, occurring at a rate of only about two per century [56]. A different

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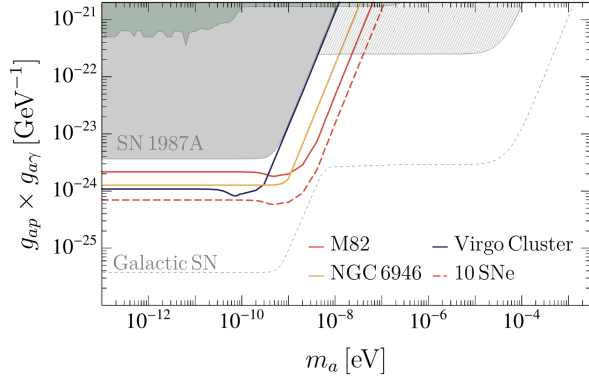


FIG. 1. Sensitivities at 95% CL in the $g_{ap} \times g_{\gamma}$ vs m_a plane for future extragalactic SN occurring in M82 (red line), NGC 6946 (yellow line), or Virgo Cluster (black line) for a *Fermi*-LAT-like gamma-ray detector, assuming an observation time window of $\Delta t = 10$ s enabled by the core-collapse time trigger provided by decihertz GW interferometers. The dashed red curve illustrates the stacked sensitivity from ten SNe in an environment similar to M82. The gray band displays the constraint from the non-observation of gamma rays from SN 1987A for ALPs converting in the Milky Way, while the hatched region would be probed by conversions in the SN 1987A progenitor magnetosphere assuming a 100 G surface field [46], but no measurements of such a field are available [47]. For comparison, we also show the sensitivity to a future Galactic SN at a distance of $d = 10$ kpc (dashed black curve) by assuming the same magnetic field models used for the SN 1987A limit. Finally, we show in green the dominant astrophysical bounds in this mass range [48–51].

approach consists in the observation of individual extragalactic SNe, producing ALPs that convert in gamma rays within the Milky Way magnetic field. This idea was first explored in Ref. [57], which investigated the sensitivity of *Fermi*-LAT to extragalactic events, at a distance $d \lesssim 270$ Mpc. However, unlike Galactic SNe, the core-collapse time cannot be precisely determined, because neutrino bursts from such distances are undetectable with current and near-future underground experiments [58]. In the absence of a neutrino trigger, the explosion time must be inferred from the optical light curves [59]. This substantially enlarges the observational time window during which ALP-induced gamma rays may appear, transforming an otherwise background-free search into a background-dominated one. Additionally, the limited field of view of *Fermi*-LAT may prevent coverage at the relevant core-collapse time (see Ref. [60] for a discussion of how the probability that *Fermi*-LAT observes at least one SN at the time of collapse scales with the sample size). For this reason, extragalactic SNe have remained largely off the radar. The aim of this article is to show that this picture can change dramatically if forthcoming experimental proposals are realized. Furthermore, nearby galaxies may host magnetic environments in which the probabilities of ALP-photon conversion are enhanced by 2–3 orders of magnitude relative to the Milky Way [50,61,62]. With the proper

experimental setup, extragalactic SNe could become a genuinely transformative tool, allowing us to probe ALP parameter space far beyond current limits (see Fig. 1).

The paper is structured as follows. In Sec. II, we evaluate the rate of extragalactic SNe and discuss the prerequisites to exploit these sources. In Sec. III, we discuss ALP production from *NN* bremsstrahlung. Section IV presents the typical conversion probabilities in host galaxies. In Sec. V, we show the obtained sensitivities. Finally, in Sec. VI, we summarize our results and draw our conclusions.

II. ALPS FROM EXTRAGALACTIC SNE: WHAT IS NEEDED?

To clarify the physics case for ALP searches from extragalactic SNe, in Fig. 2 we plot the number of observed CCSN rates up to a distance $d = 20$ Mpc reported in the Transient Name Server [63] for the period 2008–2025, corresponding to the lifetime of *Fermi*-LAT. The detailed list of core-collapse SNe with their distances is reported in Sec. A in Supplemental Material [64]. From such a plot, one infers that roughly seven core-collapse SNe per year occurred within this volume. Therefore, extending the SN horizon to nearby galaxies dramatically increases the number of potential events, removing the dependence on the rare occurrence of a Galactic SN. Based on these results, in this article, we show that, to turn extragalactic CCSNe into powerful ALP laboratories, two key experimental capabilities are required: (a) a full-sky, continuously operating constellation of gamma-ray detectors and (b) an external time trigger that determines the SN core-collapse time with sufficient accuracy. These are not speculative or serendipitous conditions—they represent clear, achievable technological objectives whose realization would decisively enable extragalactic ALP astrophysics. The first objective, condition (a), is well within reach. Concepts such as the GALAXIS mission [46] already outline a satellite constellation with *Fermi*-LAT-like sensitivity and genuine full-sky coverage. Although primarily

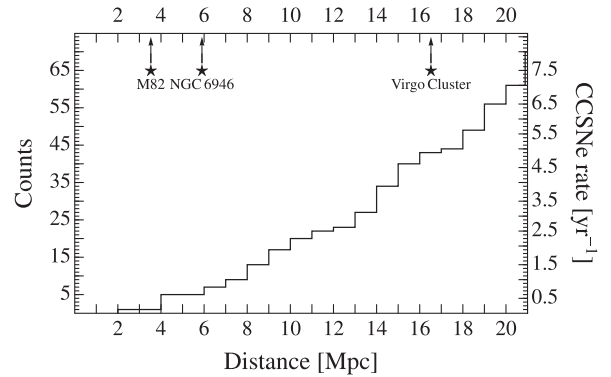


FIG. 2. Cumulative number of observed core-collapse supernovae in the period 2008–2025 (left vertical axis) from nearby galaxies in function of the distance. On the right vertical axis is also indicated the inferred SN rate per year.

designed for Galactic SNe, we show below that its physics reach extends naturally to extragalactic distances when combined with requirement (b).

This latter prerequisite is equally realistic. While large underground neutrino detectors are intrinsically limited to probing SNe within a few megaparsecs [58], current optical surveys, which aim to discover SNe up to tens of megaparsecs, may determine the core-collapse time with an accuracy of $\Delta t = 1$ d [65,66]. Furthermore, future optical surveys may reach $\Delta t = 1$ h [59]. Indeed, by modeling the early light curve of the SN, Ref. [67] determined the core-collapse time of real SNe within an accuracy of better than a few hours. Finally, next-generation decihertz gravitational-wave (GW) observatories (DECIGO and BBO) [68–70] are expected to detect the supernova gravitational *neutrino-memory* signal out to tens of megaparsecs [58,71], providing the optimal explosion-time trigger needed for ALP searches. The memory develops 0.1 s from the onset of neutrino emission, making it an ideal timing marker. Building on these possibilities, we show that the presence of an accurate external trigger with low-latency alert dissemination may open new regions of ALP parameter space beyond those excluded by SN 1987A observations for nearby ($d \lesssim 20$ Mpc) extragalactic SNe.

III. ALP PRODUCTION IN SN CORE

The production of ALPs in the SN core has been extensively studied over the past decades [24,37,40,47,72–75]. A particularly efficient production channel is nucleon-nucleon (NN) bremsstrahlung [40], mediated by the ALP-nucleon interaction described by the Lagrangian $\mathcal{L}_{aN} = (2m_N)^{-1} \partial_\mu a \sum_{N=p,n} g_{aN} \bar{N} \gamma^\mu \gamma_5 N$, where a is the ALP field, m_N is the nucleon mass, and g_{aN} is the ALP coupling to nucleon species, with $N = p, n$ for protons and neutrons, respectively. In the following, for simplicity, we assume ALPs coupling only to protons. In this work, we calculate the SN ALP fluxes using as benchmark the 1D spherical symmetric GARCHING group’s SN model SFHo-s18.8 provided in Ref. [76] and based on the neutrino-hydrodynamics code PROMETHEUS-VERTEX [77]. Notably, the NN bremsstrahlung produces an ALP thermal spectrum with average energy $E_a \simeq 70$ MeV. The emissivity can be further enhanced if a sizable population of thermal pions is present in the SN core, enabling additional ALP production through pionic Compton-like (πN) processes [41]. Because of the uncertainties in this process, we neglect it in the following discussion. See Sec. B in Supplemental Material [64] for more details on the SN ALP emissivity.

IV. ALP-PHOTON CONVERSIONS IN HOST GALAXIES

Generically, ALPs can also couple to photons through the Lagrangian term [78,79] $\mathcal{L}_{a\gamma} = g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$, where $g_{a\gamma}$ is the

ALP-photon coupling. In this scenario, ultralight ALPs would efficiently convert within the cosmic magnetic fields, giving rise to a gamma-ray signal observable by gamma-ray experiments operating in the MeV energy range. In Ref. [57], the conversions of ALPs from extragalactic SNe were characterized by assuming only the presence of the Milky Way magnetic field. Therefore, compared to the case of a Galactic SN at $d \sim 10$ kpc, we expect a flux penalty factor for extragalactic SNe $\mathcal{O}([10 \text{ kpc}/10 \text{ Mpc}]^2) \sim 10^{-6}$, leading to a reduction in the sensitivity to $g_{ap} \times g_{a\gamma}$ of 3 orders of magnitudes. However, the penalty associated with the much larger distances of extragalactic SNe can be substantially mitigated by the presence of strong magnetic fields in and around their host galaxies. As recently shown in Ref. [50], ALPs produced in stellar populations of nearby galaxies can undergo highly efficient conversions in these environments. A particularly striking example is the M82 starburst galaxy ($d = 3.5$ Mpc), where magnetic fields enhanced by starburst activity can reach ~ 0.1 – 1 mG [80], leading to sizable ALP-photon conversion probabilities [50,61,62].¹ Reference [50] also examined the elliptical galaxy M87 ($d = 16.9$ Mpc). The latter would benefit from its position inside the Virgo Cluster, where megaparsec-scale intracluster magnetic fields provide long conversion baselines that can compensate the inherently weaker strengths. Following Ref. [50], we model the B field and the electron density in these environments using the cosmological magnetohydrodynamical simulations from IllustrisTNG [82,83], as documented in Sec. C in Supplemental Material [64]. As an additional example, we consider a third system, the spiral galaxy NGC 6946 at $d = 5.9$ Mpc. Although relatively small ($L \sim 9$ kpc), it hosts magnetic fields of the order of $\mathcal{O}(10)$ μG [84]. Across all three environments, we compared the TNG-based predictions with existing models in the literature. The resulting conversion probabilities are consistent with, or even exceed, those derived from IllustrisTNG, demonstrating the robustness of our approach (see Sec. C in Supplemental Material [64] for further details about the computation of conversion probabilities).

In order to calculate ALP-photon conversions, we closely follow the technique described in Ref. [85], to which we address the reader for more details. For each subhalo modeling the properties of the environment, we compute the conversion probabilities across 10^4 realizations, sampled by varying 10^2 CCSN positions and 10^2 observation directions. We define our *fiducial* configuration as the one yielding the median conversion probability. This latter for $g_{a\gamma} = 10^{-12} \text{ GeV}^{-1}$ assumes values $P_{a\gamma} = 8.8 \times 10^{-4}$ for M82, $P_{a\gamma} = 6.8 \times 10^{-3}$ for NGC 6946, and $P_{a\gamma} = 7.6 \times 10^{-2}$ for Virgo Cluster, in the limit of $m_a \lesssim 10^{-9} \text{ eV}$. The observed gamma-ray flux will scale as $\Phi_\gamma \propto P_{a\gamma}/d^2$,

¹Observations of this galaxy also allow constraints on massive ALPs decaying into photons [81].

implying $\Phi_{\gamma}^{\text{M82}} : \Phi_{\gamma}^{\text{NGC 6946}} : \Phi_{\gamma}^{\text{M87}} = 1 : 2.7 : 4.0$. Therefore, despite the differences in the input parameters, one expects a similar sensitivity to $g_{ap} \times g_{a\gamma}$ as shown in Fig. 1. Furthermore, we highlight that typical values of the conversion probability in the Milky Way are $P_{a\gamma} \sim \mathcal{O}(10^{-5})$ for $g_{a\gamma} = 10^{-12} \text{ GeV}^{-1}$ and so negligible with respect to the values reached in all the considered environments. Indeed, accounting for conversions only in the Milky Way, for a SN exploding in M82 we would find a sensitivity to $g_{ap} \times g_{a\gamma} \sim 1.3 \times 10^{-23} \text{ GeV}^{-1}$, which is above the existing bound from SN 1987A. We also observe that the effect of a potentially strong magnetic field in the progenitor of the SN, as considered in [46,47,55], would extend the sensitivity to larger masses but in a region of the parameter space already excluded by other astrophysical constraints. Therefore, for simplicity, we neglect also this effect.

V. SENSITIVITIES IN $g_{ap} \times g_{a\gamma}$

With these results in hand, we are ready to derive the sensitivity to the product of ALP-nucleon and ALP-photon couplings $g_{ap} \times g_{a\gamma}$. Since the three nearby galaxies introduced before are expected to give a similar sensitivity in the low-mass ALP range ($m_a \lesssim 10^{-9} \text{ eV}$), for definiteness we focus on M82. We assume to have a gamma-ray detector like the proposed project GALAXIS [46] with the same performances of *Fermi*-LAT, guaranteeing full-sky coverage (see Sec. D in Supplemental Material [64]). In Fig. 3, we show the 95% confidence level (CL) sensitivity [86] to $g_{ap} \times g_{a\gamma}$ in the case of low-mass ALPs assuming different observation-time windows, determined by the accuracy in the determination of the SN core-collapse time. In low-background regime, the statistical analysis follows the Feldman-Cousins prescription [87].

As a first case, we consider an accuracy of $\Delta t = 1 \text{ d}$ (dashed curve) determined by the extrapolation of the observed light curve from optical surveys [65,66]. In such a large observational time window, the gamma-ray detector is expected to accumulate a significant number of background events [$N_{\text{bkg}} \sim \mathcal{O}(100)$]. Therefore, the statistical analysis points out that if a SN explodes in M82, we will be sensitive to $g_{ap} \times g_{a\gamma} \gtrsim 4.5 \times 10^{-24} \text{ GeV}^{-1}$ at 95% CL, which is a factor of 1.25 above the SN 1987A bound. In this case, the significant improvement expected with respect to the results of Ref. [57] is due to enhancement of the conversions in the magnetic environment of the host galaxy with respect to the Milky Way, as shown in Sec. F in Supplemental Material [64].

In order to further improve the sensitivities, it is crucial to reduce the background shortening the uncertainty on the determination of the SN core-collapse time. Let us first assume that future optical surveys might be able to reach $\Delta t = 1 \text{ h}$ (dot-dashed curve), as considered in Ref. [59]. With this accuracy, we get a sensitivity of

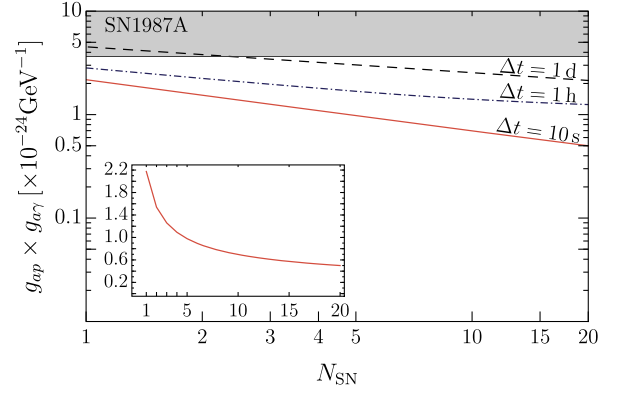


FIG. 3. Sensitivity (95% CL) to $g_{ap} \times g_{a\gamma}$ as a function of the number of observed extragalactic SNe, N_{SN} , yielding a gamma-ray flux similar to the one estimated in the case of M82. We assume different time windows to search for the ALP signal, namely, $\Delta t = 1 \text{ d}$ (dashed curve), $\Delta t = 1 \text{ h}$ (dot-dashed curve), achievable with current and future optical surveys, and $\Delta t = 10 \text{ s}$ (continuous curve), relying on an external trigger and operational conditions specified in the main text. In the inset, we show on a linear scale the sensitivity for $\Delta t = 10 \text{ s}$ scaling as $N_{\text{SN}}^{-1/2}$. The x and y axes are the same as in the main panel.

$g_{ap} \times g_{a\gamma} \gtrsim 2.8 \times 10^{-24} \text{ GeV}^{-1}$, improving by a factor of ~ 1.6 the case with $\Delta t = 1 \text{ d}$. Finally, we consider the optimistic scenario of $\Delta t = 10 \text{ s}$ (continuous curve) corresponding to the duration of the ALP burst. Achieving such a narrow observational window requires a precise determination of the burst onset, expected to be possible in the presence of a decihertz GW interferometer observing the SN neutrino memory signal. This short-window scenario relies on specific operational conditions: (a) an external trigger with $\mathcal{O}(10) \text{ s}$ timing uncertainty, (b) low latency in alert dissemination, and (c) a nearby SN ($d \lesssim 20 \text{ Mpc}$) to ensure a high signal-to-noise ratio. At these distances, the trigger is robust, as the stochastic GW background from cosmological SNe is negligible [58]. In this case, since we are in a background-free regime, we compute the 95% CL sensitivity by requiring that ~ 3 ALP-induced events are observed [87], leading to $g_{ap} \times g_{a\gamma} \gtrsim 2.3 \times 10^{-24} \text{ GeV}^{-1}$. This corresponds to an improvement over the SN 1987A bound by a factor of ~ 1.6 .

We also estimate how the sensitivity would improve if multiple extragalactic SN explosions are observed over the detector's lifetime. From the SN catalog covering the period 2008–2025 (Table A1 in Sec. A in Supplemental Material [64]), we find that seven SNe occurred during this time window in the three environments considered in this work (see Table A3 [64]). Since the expected ALP-induced signal from each of these systems is comparable to that of M82, observing seven such events is effectively equivalent to detecting seven explosions from M82 itself. Therefore, we show in Fig. 3 the resulting sensitivity enhancement as a function of the number of observed SNe N_{SN} , adopting M82 as a benchmark case. In a background-dominated situation,

corresponding to SN core-collapse time known with an accuracy of $\Delta t = 1$ d, the sensitivity to $g_{ap} \times g_{a\gamma}$ scales as $N_{\text{SN}}^{-1/4}$. For $\Delta t = 1$ h, one finds an intermediate regime between background-free and high-background scenarios.

Short coincidence windows, $\Delta t \approx 10$ s, enabled by a GW trigger, suppress the expected background and can place the search in the background-free regime. Besides the obvious advantages of a reduced background, in this limit, stacking becomes maximally efficient, with the coupling sensitivity scaling as $g_{ap}g_{a\gamma} \propto N_{\text{SN}}^{-1/2}$. Thus, reducing the time window directly accelerates the gain from multiple events. This provides strong motivation for synergies with next-generation GW detectors, which can sharply localize the burst time. As an illustration, stacking $N_{\text{SN}} = 5$ CCSNe within $d \simeq 20$ Mpc, each with an M82-like expected flux, yields a projected sensitivity of $g_{ap} \times g_{a\gamma} \simeq 9.8 \times 10^{-25} \text{ GeV}^{-1}$, an improvement of a factor of 3.7 over the SN 1987A bound. Remarkably, this corresponds to $g_{a\gamma} \gtrsim 9.8 \times 10^{-16} \text{ GeV}^{-1}$, assuming $g_{ap} \sim 10^{-9}$ (near the SN 1987A cooling limit [47,75]). Beyond ~ 10 stacked extragalactic SNe, however, the returns become marginal, as shown in the inset in Fig. 3. Consequently, even with a rate of one nearby SN per year, a decade-long monitoring program would be sufficient to either detect a signal or set a substantially stronger bound on the ALP couplings.

VI. CONCLUSIONS

Core-collapse supernovae in nearby galaxies offer a powerful and previously underutilized opportunity to explore the ALP parameter space well beyond existing limits. Their unique role stems from the fact that several nearby galaxies host magnetic environments—ranging from starburst-driven mG fields to cluster-scale intracluster structures—where ALP-photon conversion efficiencies exceed those of the Milky Way by 2–3 orders of magnitude.

In addition, a few core-collapse SNe are expected to occur every year within ~ 20 Mpc, providing a steady stream of potential ALP sources. Yet current gamma-ray facilities lack the full-sky coverage and time-tagging accuracy needed to exploit these events effectively. Our analysis shows that two realistic experimental capabilities would decisively change this situation: (i) a full-sky, continuously operating constellation of MeV gamma-ray detectors and (ii) an external trigger capable of determining the core-collapse time to within seconds, most naturally provided by next-generation decihertz GW interferometers. If these conditions are met, extragalactic SNe become a transformative ALP probe. A single explosion in a favorable host galaxy would surpass the SN 1987A constraint, and a decade-long program could explore $g_{ap} \times g_{a\gamma}$ at the level of $\sim 10^{-24} \text{ GeV}^{-1}$, reaching deep into currently inaccessible parameter space.

Extragalactic SN ALP searches would, thus, represent a major new frontier in *multimessenger astronomy*. By

combining gamma rays, optical surveys, and gravitational waves, they open a realistic pathway toward *extragalactic ALP astronomy*, in which the cumulative SN activity of the local Universe becomes a precision tool for fundamental physics.

ACKNOWLEDGMENTS

We warmly thank Christopher Eckner, Damiano F. G. Fiorillo, Orion Ning, and Edoardo Vitagliano for their helpful comments on the manuscript. This article is based on work from COST Action COSMIC WISPerS CA21106, supported by COST (European Cooperation in Science and Technology). The work of A. M., A. L., and F. L. was partially supported by the research Grant No. 2022E2J4RK “PANTHEON: Perspectives in Astroparticle and Neutrino Theory with Old and New messengers” under the program PRIN 2022 (mission 4, component 1, CUP I53D23001110006) funded by the Italian Ministero dell’Università e della Ricerca (MUR) and by the European Union–Next Generation EU. A. L. acknowledges support from Italian MUR through the FIS 2 Project No. FIS-2023-01577 (DD No. 23314 10-12-2024, CUP C53C24001460001) and by Istituto Nazionale di Fisica Nucleare (INFN) through the Theoretical Astroparticle Physics (TAsP) project. G. L. acknowledges support from the U.S. Department of Energy under Contract No. DE-AC02-76SF00515. This work is (partially) supported by ICSC–Centro Nazionale di Ricerca in High Performance Computing. M. G. acknowledges support from the Spanish Agencia Estatal de Investigación through Grant No. PID2019–108122 GB-C31, funded by MCIN/AEI/10.13039/501100011033, and from the European Union NextGenerationEU/PRTR initiative (Planes Complementarios, Programa de Astrofísica y Física de Altas Energías). M. G. also acknowledges support from Grant No. PGC2022-126078NB-C21, “Aún más allá de los modelos estándar,” funded by MCIN/AEI/10.13039/501100011033 and by the European Regional Development Fund (ERDF), “A way of making Europe”; from the European Union’s Horizon 2020 research and innovation program under European Research Council (ERC) Grant Agreement No. 788781 (IAXO+); and from Project No. CNS2025-165965, “Señales de axiones en el rango MeV desde fuentes astrofísicas hasta detectores actuales y futuros,” funded by MICIU/AEI/10.13039/501100011033.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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