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The Fermi Large Area Telescope as a Galactic Supernovae Axionscope

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In a Galactic core-collapse supernova (SN), axionlike particles (ALPs) could be emitted via the Primakoff process and eventually convert into γ rays in the magnetic field of the Milky Way. From a data-driven sensitivity estimate, we find that, for a SN exploding in our Galaxy, the *Fermi* Large Area Telescope (LAT) would be able to explore the photon-ALP coupling down to $g_{a\gamma} \simeq 2 \times 10^{-13}$ GeV^{-1} for an ALP mass $m_a \lesssim 10^{-9}$ eV. These values are out of reach of next generation laboratory experiments. In this event, the *Fermi* LAT would probe large regions of the ALP parameter space invoked to explain the anomalous transparency of the Universe to γ rays, stellar cooling anomalies, and cold dark matter. If no γ-ray emission were to be detected, *Fermi*-LAT observations would improve current bounds derived from SN 1987A by more than one order of magnitude.

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Introduction.—Axionlike particles (ALPs) are light pseudo-scalar bosons with a two-photon coupling $a\gamma\gamma$ of strength $g_{a\gamma}$ which are predicted by several extensions of the Standard Model (see [1] for a review). These particles can constitute a significant fraction or the entire cold dark matter [2–6]. In the presence of an external magnetic field, the $a\gamma\gamma$ coupling leads to photon-ALP mixing [7]. This effect is exploited to search for ALPs in light-shining-through-the-wall experiments such as ALPS [8, 9], for solar ALPs (e.g. the CAST experiment [10]) and for ALP dark matter in cavity experiments (e.g. ADMX [11]). The best experimental bound on the photon-ALP coupling is $g_{\mathrm{a}\gamma} \lesssim 8.8 \times 10^{-11}$ GeV^{-1} obtained with the CAST experiment for $m_a \lesssim 0.02$ eV [10]. ALP production in stars via the Primakoff process [12] would also cause an additional energy drain that may change the stellar lifetime, eventually beyond the limits allowed by observations (see [13] for a review). For masses $m_a \lesssim$ keV, one finds $g_{a\gamma} \lesssim 8 \times 10^{-11}$ GeV^{-1} from Cepheid stars [14], and $g_{a\gamma} \lesssim 6.6 \times 10^{-11}$ GeV^{-1} from globular clusters [15].

For ALPs with masses $m_a \lesssim 10^{-9}$ eV, the strongest bound on $g_{a\gamma}$ is derived from the absence of γ rays from SN 1987A, a core-collapse supernova (SN) that exploded in the Large Magellanic Cloud at a distance of about 50 kpc. ALPs would be copiously emitted by the SN core and part of this flux would be converted to γ rays in the Galactic magnetic field (GMF). Upper limits on the SN 1987A γ-ray flux by the Gamma-Ray Spectrometer on the Solar Maximum Mission satellite imply a bound on the coupling [16, 17]. A recent analysis with state-of-the-art models, both for the GMF and for the production of ALPs in the SN, results in $g_{a\gamma} < 5 \times 10^{-12}\,\mathrm{GeV}^{-1}$ for $m_a < 10^{-10}\,\mathrm{eV}$ [18]. This bound significantly constrains the parameter space for photon-ALP conversions in large-scale magnetic fields proposed as a mechanism to explain evidence for a reduced γ-ray absorption on the extragalactic background light [19–25] (see, however, [26, 27]) as well as most of the low-mass region where ALPs could explain observed stellar cooling anomalies [28].

The *Fermi* Large Area Telescope (LAT) is sensitive to γ rays with energies from 20 MeV to > 300 GeV and monitors the entire sky every three hours. It is therefore perfectly suited to search for the ALP-induced γ-ray burst from the next Galactic SN. Motivated by this perspective, our work aims to present a detailed evaluation of the *Fermi*-LAT sensitivity to the photon-ALP coupling from a SN event.

ALP production in a supernova core.— ALPs would be produced in a stellar medium primarily through the Primakoff process [12], in which thermal photons are converted into ALPs in the electrostatic field of ions, electrons, and protons. In order to calculate the ALP production rate in a SN core via the Primakoff process we closely follow Ref. [18]. We find

$$\frac{d\dot{n}_a}{dE} = \frac{g_{a\gamma}^2 \xi^2 \, T^3 \, E^2}{8\pi^3 \left(e^{E/T} - 1\right)} \left[\left(1 + \frac{\xi^2 T^2}{E^2}\right) \ln(1 + E^2/\xi^2 T^2) - 1\right] , \quad (1)$$

where E is the photon energy, T the temperature, and $\xi^2 = \kappa^2/4T^2$ with κ the inverse Debye screening length, due to the finite range of electric field surrounding charged particles in the plasma. The total ALP production rate per unit energy is found by integrating Eq. (1) over the SN volume. We consider one-dimensional SN models with progenitor masses of 10 and 18 $M_\odot$ [29], and account for the effects of partial proton degeneracy and effective nuclear mass at high density.

Integrated over the explosion time, which is of the order of 10 s, we find that the ALP spectrum can be parametrized by a power law with exponential cutoff,

$$\frac{dN_a}{dE} = C \left(\frac{g_{a\gamma}}{10^{-11}\,\mathrm{GeV}^{-1}} \right)^2 \left(\frac{E}{E_0} \right)^{\beta} \exp\left(-\frac{(\beta+1)E}{E_0} \right) \quad (2)$$

with C, E_0, and β given in Tab. I.

Progenitor mass	C [10^{50} MeV^{-1}]	E_0 [MeV]	β
$10\,M_\odot$	5.32	94	2.12
$18\,M_\odot$	9.31	102	2.25

TABLE I. Best fitting values for the parameters in Eq. (2).

ALP–photon conversions in the Milky Way.—Given the photon-ALP couplings we are considering here, the mean free path of ALPs inside the SN is much larger than the SN radius. Hence, once produced, they can escape the star without further interactions [16] and subsequently convert into photons in the GMF.

We use the coherent component of the Jansson and Farrar model [30] (JF12 hereafter) as our GMF benchmark model, and describe the Galactic electron density as proposed in Ref. [31]. The model discussed by Pshirkov *et al.* [32] (PTKN11 in the following) gives similar results for the GMF in our regions of interest. We closely follow the technique described in Ref. [33] to solve the full beam propagation equation along a Galactic line of sight.

Once the ALP production rate and the Galactic ALP-photon conversion probability are known, we find the the differential γ-ray flux per unit energy integrated over the explosion time arriving at Earth

$$\frac{dN_\gamma}{dE} = \frac{1}{4\pi d^2} \frac{dN_a}{dE} \times P_{a\gamma}\,, \quad (3)$$

where d is the SN distance.

Sensitivity Estimate.— Current neutrino detectors are expected to measure a plenitude of neutrinos from the next Galactic SN. For instance, the Super-Kamiokande water Cherenkov detector should detect about 10^4 neutrino events from a SN at $d = 10\,\mathrm{kpc}$ (e.g., [34, 35]). The ALP-induced γ-ray signal is expected to arrive roughly simultaneously to the neutrinos and hence the neutrino signal would provide the required timing information to search for a coincident γ-ray signal (see [36] for a review).

The distribution of supernovae in the Galaxy must follow regions of star formation, notably in the spiral arms. These distributions are very broad [37] so that any distance between 2 and 20 kpc is almost equally likely. For definiteness, we estimate the sensitivity of the *Fermi* LAT to detect the burst from a Galactic SN at the position of the Galactic center (GC). We use actual data instead of simulations. This approach has the advantage that we do not rely on the modeling of the instrumental response functions (IRFs) within the simulations. Since the background rate and the photon-ALP conversion probability change with the SN position, we also consider the test cases of Betelgeuse and the possibility of an extragalactic SN in M 31 (Andromeda). We return to these sources in the Discussion.

We extract a random day of *Fermi*-LAT data (July 28, 2015) in the energy range between 50 MeV and 500 MeV motivated from the expected ALP spectrum. We do not consider lower energies since the effective area of the *Fermi* LAT decreases rapidly at 50 MeV. To minimize the contamination of the Earth Limb we only use events that arrive at zenith angles $< 80°$. As we are expecting a short burst of a duration of 10–20 s, we utilize events passing the `P8R2_TRANSIENT020` selection cuts which are analyzed with the corresponding `V6` IRFs.[1]

For the one day of data, we calculate good time intervals (GTIs) for which data quality cuts are fulfilled and the region of interest is not contaminated by the γ rays from the Earth Limb. The SN will be detectable with the *Fermi* LAT if it occurs at a time within one GTI, which is assumed here. We bin each GTI in time bins of 20 s, so that the entire burst would be contained in one bin. We extract the point spread function (PSF) at 50 MeV in each bin using the `gtpsf` tool included in the *Fermi Science Tools* version 10r01p01 and determine the 68 % containment radius, r_{68}, and its time average over the whole GTI, $\langle r_{68} \rangle$.[2] During one GTI, the PSF and exposure change slightly as the source moves through the field of view.

For each GTI we generate the 20 s light curve for γ-ray events that arrive within $\langle r_{68} \rangle$ from the GC. In an SN event, the time bin containing the potential signal plus background (x "ON" counts) would be tagged by the detection of the neutrino events. The remaining time bins i with counts y_i ("OFF" counts) and relative exposure ϵ_i in comparison to the ON bin can be used to estimate the expected number of background counts in the ON bin, b. For one GTI, we use all time bins for the background estimation and the exposure of the central time bin of the light curve as the ON exposure. Maximizing the standard Poisson likelihood for the OFF bins, one finds the maximum likelihood estimator $\hat{b} = \alpha y$, with $y = \sum_i y_i$ and $\alpha = (\sum_i \epsilon_i)^{-1}$. Stepping through the expected number of signal counts μ we derive the 95 % confidence interval for observed counts x using the method of Feldman and Cousins [38]. Assuming no SN signal, we set x to be equal to the smallest integer greater than or equal to $\hat{b}$,

[1] See `http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm`
[2] See `http://fermi.gsfc.nasa.gov/ssc/data/analysis/`.

i.e. $x = \lceil \hat{b} \rceil$, and calculate the 95 % upper limit on the number of expected counts, μ_{UL}, from the confidence interval. The method of setting the observed counts equal to the expected number of counts is often referred to as an "Asimov data set" [39].

In the following, we focus on one representative GTI that gives the median value for μ_{UL} for all considered GTIs. We list the values for the start time t_0, the length of the considered GTI Δt, as well as α, $\hat{b}$, and μ_{UL} in Tab. II.

	GC	Betelgeuse	M 31	SN 1987A
R.A. (°)	266.42	88.79	10.63	83.87
Dec. (°)	−28.99	7.41	41.30	−69.27
Distance (kpc)	8.5	0.197	778	51.4
t_0 (MJD)	57,231.582	57,231.284	57,231.144	54757.806
Δt (s)	1581	1519	1079	867
$\langle r_{68} \rangle$(°)	10.92	9.73	10.37	8.94
$\hat{b}$	3.32	1.11	0.94	1.05
α	0.014	0.014	0.030	0.024
μ_{UL}	6.43	5.61	4.19	5.67

TABLE II. Positions and times for the data extraction for the considered hypothetical SN. Also listed are the 68 % containment radius time-averaged over the GTI ($\langle r_{68} \rangle$), the expected background counts ($\hat{b}$), relative exposures (α), and upper limits on signal counts (μ_{UL}).

To translate this upper limit into an expected limit on the ALP parameters, we multiply the time-integrated ALP spectrum (cf. Eq. (2)) with the photon-ALP conversion probability, integrate it over the considered energy range, and fold it with the *Fermi*-LAT IRF. The IRF is generated with the `gtrspgen` tool for every time bin of the light curve. To account for the PSF, we have to multiply this number with the fraction of counts contained within $\langle r_{68} \rangle$ (≈ 0.68 at 50 MeV). For energies above 50 MeV this fraction becomes > 0.68 as the PSF improves. However, the sensitivity is dominated by the lowest energies due to the shape of the ALP spectrum. We therefore make the assumption that this fraction is equal to 0.68 over the entire energy range. We have checked that including the full PSF has a negligible effect on the final sensitivity. We consider ALP parameters on a logarithmically spaced (24×24) grid in ALP mass and photon-ALP coupling with $-3 \leq \log_{10}(g_{11}) \leq 1$ and $-1 \leq \log_{10}(m_{\mathrm{neV}}) \leq 3$, where $g_{11} = g_{a\gamma}/10^{-11}\,\mathrm{GeV}^{-1}$ and $m_{\mathrm{neV}} = m_a/\mathrm{neV}$. For a fixed ALP mass, we find $\mu \propto g_{a\gamma}^4$, as expected since both the ALP production and the photon-ALP conversion scale as $g_{a\gamma}^2$. ALP parameters that result in $\mu \geq \mu_{\mathrm{UL}}$ can be excluded at 95 % confidence.

Discussion.—We show the expected upper limit on the ALP parameters in the left panel of Fig. 1 for two GMF models (JF12 and PTKN11) and the two progenitor masses $10\,M_\odot$ and $18\,M_\odot$. Depending on the time bin in which the SN explosion occurs, the exposure of the *Fermi* LAT varies, resulting in an uncertainty of a factor up to ~ 1.6 for each GTI. The solid lines depict the median limit values. The upturn of the limits around $m_a = 1\,\mathrm{neV}$ is due to a reduced conversion probability for high ALP masses. In the absence of a signal, regardless of the progenitor mass and the GMF, the *Fermi*-LAT observations of a Galactic SN would improve the current SN 1987A limit [18] (gray shaded region in Fig. 1) by over an order of magnitude.

The number of expected counts increases by $\sim 75\,\%$ for the highest progenitor mass considered, yet the $g_{a\gamma}^4$ dependence of μ leads only to a marginal improvement of the limits by a factor of $(1.75)^{1/4} \sim 1.15$. Hence our limits are nearly insensitive to the exact progenitor mass. We will restrict ourselves to $10\,M_\odot$ progenitors in the following. Stars with masses $< 10\,M_\odot$ might also explode as an SN, however the exact minimum value remains a topic of on-going discussion and would only minimally change our results [e.g. 40, 41].

Using the PTKN11 GMF model instead of JF12 improves the limits by almost a factor of two (73 %) at $m_{\mathrm{neV}} = 0.1$ (red solid line in the left panel of Fig. 1), making the JF12 model a conservative choice. Yet, one should note that the conversion probability depends on the sky position and distance of the SN and it is not expected that the PTKN11 would always result in better limits.

We perform the same analysis for a total of ten GTIs on the same day and for a GTI at another date ($t_0 = 55{,}153.989$ MJD) and find the change of the limits to be negligible. We furthermore test how the binning affects the limits by changing the bin size of the light curve to 30 s and 60 s, respectively. The longer integration time leads to higher background rates which result in upper limit values $\mu_{\mathrm{UL}} = 7.25$ and 8.37, respectively, against the 6.43 found in our fiducial analysis. We find decreased limits on the photon-ALP coupling by 3 % and 6 %, respectively. We conclude that the major systematic uncertainty of our analysis is related to the choice of the GMF model.

As a further example, we investigate the expected limits for a SN of the red supergiant Betelgeuse (see Tab. II). We assume the JF12 GMF model and a $10\,M_\odot$ progenitor mass which is within the mass estimate of Neilson *et al.* who find $11.6^{+5.0}_{-3.9}\,M_\odot$ [42]. The small distance of ~ 197 pc implies a low conversion probability in the GMF. This is compensated by the higher flux relative to a SN in the GC. Furthermore, the expected number of background counts $\hat{b}$ is about three times smaller for the region of interest around Betelgeuse compared to the Galactic center (cf. Tab. II). These points eventually lead to similar limits (cf. Fig. 1). Using a local measurement of the B field close to the line of sight to Betelgeuse [43] leads to a substantial improvement of the limits by a factor of 4.5, making the JF12 model again a conserva-

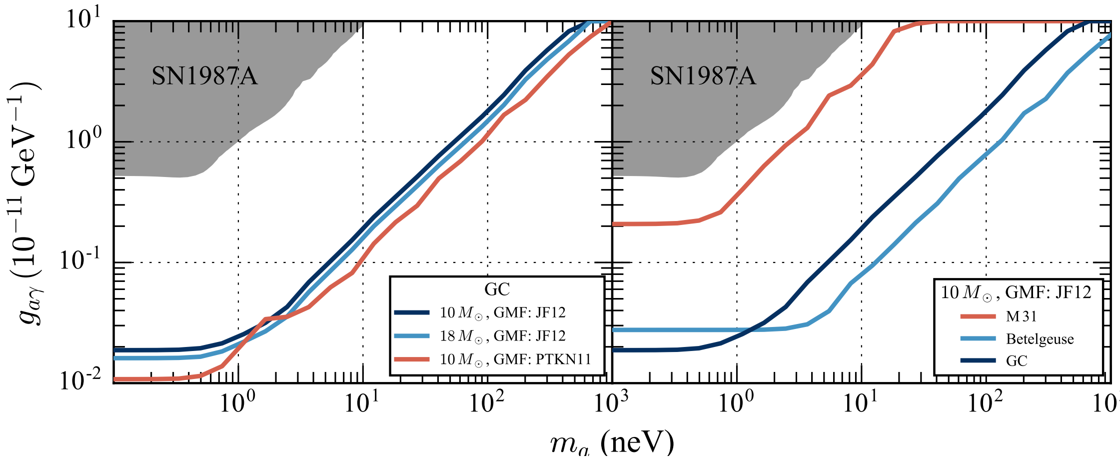

FIG. 1. Expected limits on ALP parameters from a SN explosion. The gray shaded region shows the constraints from SN 1987A. *Left*: Limits for different progenitor masses and GMF models. *Right*: Limits for different potential SN positions.

tive choice. We also calculate the expected limit for an extragalactic SN in M 31 at a distance of ~ 778 kpc. The limit would improve compared to SN 1987A constraints by a factor of ~ 2, also thanks to the low number of background counts expected in this direction. (cf. Tab. II and Fig. 1). Including the possibility of ALP-photon conversions in the magnetic field of M 31 (with a strength of $5\,\mu$G, coherent over 20 kpc [44]) improves the limits substantially by a factor of 5. However, the main challenge would be the detection of a neutrino signal from a SN in M 31. Super-Kamiokande could detect one neutrino event which could be connected to a SN if an optical counterpart was found within a day of the explosion [45]. In general, it will take the next generation of Mton class water Cerenkov neutrino detectors to reliably detect extragalactic SN with possibly 0.1 neutrino events per year and up to 100 events from a SN in M 31 [45, 46]. Until then, a source stacking over longer integration times for many extragalactic supernovae, similar to the analysis of Ref. [47], might be a possible venue. This is left for future work.

We also repeat the analysis for a position coincident with SN 1987A and find that current limits would improve by a factor of ~ 5 (dark-red dashed line in the right panel of Fig. 1).

Conclusions.—We compare the expected ALP limits from a SN of a $10\,M_\odot$ progenitor in the GC calculated with the JF12 GMF model with other limits and sensitivity projections in Fig. 2. A SN event within the lifetime of the *Fermi* LAT would allow an unprecedented exploration of the ALP parameter space for ALP masses below 100 neV, surpassing current bounds [18, 48–51] and the projected sensitivity of future dedicated laboratory searches such as ALPS II [9] and IAXO [52] for masses up to 10 neV. It would also be possible to probe portions of the so-far unconstrained parameter space where ALPs with masses $0.01 \lesssim m_{\mathrm{neV}} \lesssim 10$ could constitute the entire dark matter (black dashed line in Fig. 2 [53]). Furthermore, such an event would provide a definitive verdict on the role of ALPs in explaining hints of an anomalous transparency of the Universe to very-high-energy photons [19–25] and could indicate if low mass ALPs are responsible for the additional cooling observed in different stellar systems [28].

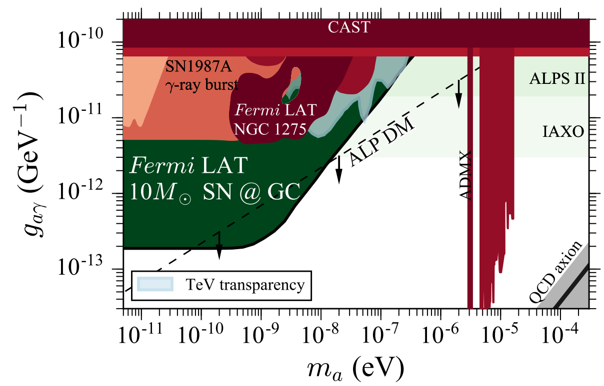

FIG. 2. Comparison of the expected *Fermi*-LAT sensitivity (dark green) with limits (red) and sensitivities of future experiments (green). The QCD axion band is shown in gray. The transparency anomaly hint could be explained by ALPs within the blue shaded region. ALPs with parameters below the dashed line could constitute the entire dark matter.

In light of this potential, the question arises how probable it is that the *Fermi* LAT will observe a Galactic SN within its remaining lifetime. The Galactic SN rate has been estimated to be roughly 2−3 per century [e.g. 54–56]. Under the assumption that SN explosions occur as a Poisson process, the chance for one or more supernovae to occur in one year is $\sim 2{-}3\,\%$. The *Fermi* LAT observes

$\sim 20\,\%$ of the full sky at any given moment. Assuming for instance a total lifetime of the *Fermi* mission of 15 years this results in a $\sim 2.4-3.5\,\%$ chance to observe at least one such event in the next 7 years of the mission. In case of a close SN, $d < 2\,$kpc, neutrino detectors could measure a signal from the Silicon burning pre-SN phase [57] and *Fermi*-LAT target of opportunity observations could further increase the detection possibility. The Gamma-ray Burst Monitor (GBM) on-board the *Fermi* satellite observes γ rays up to 40 MeV over the whole sky not occulted by Earth and has therefore a higher chance to observe the next Galactic SN. A sensitivity study for the GBM is left for future work. Despite the low observation probability, our analysis demonstrates that the next Galactic SN will not only shed light on the SN explosion mechanism but could also be used as a powerful probe of fundamental physics. Future γ-ray missions such as e-ASTROGAM [58], ComPair [59], or PANGU [60] are planned to have a high sensitivity to γ rays at tens of MeV and are expected to have an improved angular resolution of $\sim 1^\circ$ at 100 MeV (68 % containment radius). Given their foreseen large fields of view, similar to the one of the *Fermi* LAT, such missions will be well suited to search for an ALP-induced γ-ray burst from a Galactic or even extragalactic SN.

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