Constraining the diffuse supernova axion-like-particle background with high-latitude Fermi-LAT data

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ABSTRACT. Axions and axion-like particles (ALPs) are thought to be produced along with Standard Model particles in a variety of astrophysical processes. Core-collapse supernovae (CCSNe) have been identified as a promising target to probe the existence of these hypothetical particles, which could make up at least a fraction of the universe's dark matter content. The cumulative signal from all past SNe events would contain an ALP component and create a diffuse flux peaked at $\mathcal{O}(50)$ MeV. Due to their coupling to photons and the related Primakoff process, the diffuse SNe ALP flux is converted into a diffuse gamma-ray flux while traversing the magnetic field of the Milky Way. The spatial morphology of this signal is expected to follow the shape of the Galactic magnetic field lines. We perform a template-based analysis to constrain the ALP parameter space via the spatial structure of this ALP-induced diffuse gamma-ray flux using 12 years of Fermi-LAT data and an energy range from 50 MeV to 500 GeV. We find an improvement of the upper limit on the ALP-photon coupling constant $g_{a\gamma}$ of about a factor of two compared to a previous analysis solely based on the spectral shape of the signal. Our results are robust against variations in the modelling of high-latitude Galactic diffuse emission and systematic uncertainties of the LAT, and only mildly depend on the SN spectral modelling.

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1. Axion-like particles from core-collapse supernovae

In a minimal scenario, ALPs may couple to Standard Model photons via the interaction Lagrangian [1]

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}\, g_{a\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} a = g_{a\gamma}\, \vec{E}\cdot\vec{B}\, a,$$

which gives rise to the so-called Primakoff effect [2], i.e. the conversion of an incident photon into an ALP within an external magnetic field. This process takes place during supernovae where the electrostatic field of ions, electrons and protons converts thermal photons into ALPs.

The particle emission from CCSNe has already been used to constrain the viable parameter space of axions and ALPs. As a paramount example, the lack of a gamma-ray burst following the neutrino signal from the Galactic supernova SN 1987A currently places the most stringent bounds on the coupling of ALPs to photons of $g_{a\gamma} < 5.3\cdot 10^{-12}\,\mathrm{GeV}^{-1}$ for ALP masses $m_a < 4\cdot 10^{-10}$ eV [3].

2. Deriving the diffuse SN ALP flux

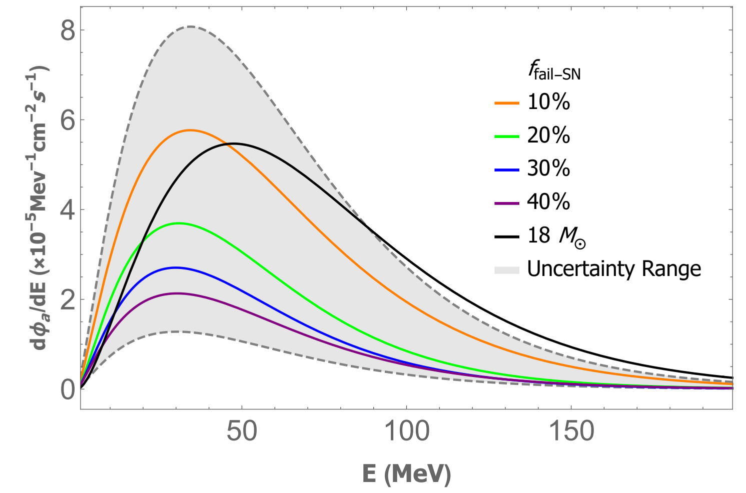
Without a recent CCSN event in the Milky Way, we instead focus on the cumulative emission from all CCSNe in the universe that have occurred since the Big Bang.

We trace the cumulative CCSN ALP flux $\mathrm{d}\phi_a/\mathrm{d}E_a$ throughout the history of the universe via

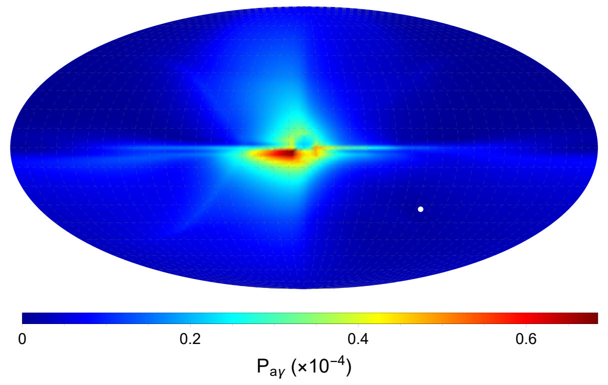
$$\frac{\mathrm{d}\phi_a(E_a)}{\mathrm{d}E_a} = \int_0^\infty (1+z)\frac{\mathrm{d}N_a^{CC}(E_a(1+z))}{\mathrm{d}E_a} R_{SN}(z)\left|c\frac{\mathrm{d}t}{\mathrm{d}z}\right|\mathrm{d}z$$

where z is the redshift, $R_{SN}(z)$ is the SN explosion rate, and $|dt/dz|^{-1} = H_0(1+z)[\Omega_\Lambda + \Omega_M(1+z)^3]^{1/2}$ reflects the evolution of the universe with redshift for which we adopt the current cosmological parameters found by Planck.

We base this approach on simulations of CCSNe using four distinct progenitor masses to derive the time-integrated differential ALP yield per $\mathrm{d}N_a/\mathrm{d}E_a$ of a single SN event. These results are linearly interpolated in the progenitor mass range $M \in [8,30]\, M_\odot$. We obtain the cumulative spectrum of all past CCSNe, $\mathrm{d}N_a^{CC}/\mathrm{d}E_a$, at a certain redshift z by weighing it [4] with the initial mass function adopting the Salpeter A law [5]. Within the full range of progenitor masses $M \in [8,125]\, M_\odot$, we consider different scenarios for the ratio of failed SNe and successful CCSNe ($f_{\mathrm{fail-SN}}$) based on the predictions of a set of numerical simulations [4]. For light ALPs with masses $m_a \ll 10^{-11}$ eV and $g_{a\gamma} = 10^{-11}\,\mathrm{GeV}^{-1}$, the derived spread of ALP fluxes is within a factor of about 8.



In the Milky Way's magnetic field, the incoming ALPs are converted back into gamma rays with a probability $P_{a\gamma}$ depending on the traversed distance, ALP mass and energy as well as the transversal component of the Galactic magnetic field (c.f. model Jansson12c [6]).



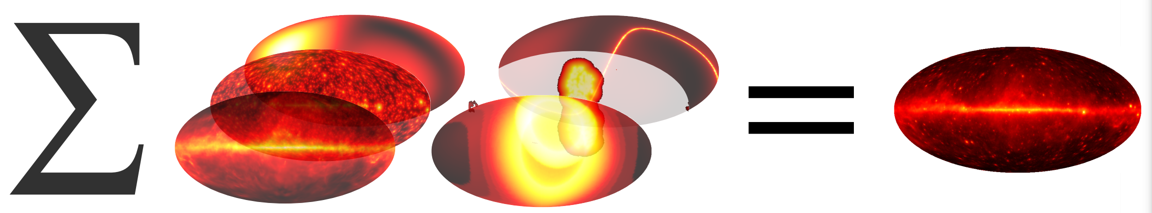
3. A template-based Fermi-LAT analysis

We aim to perform a templated-based analysis utilising 12 years of Fermi-LAT data in the energy range from 50 MeV to 500 GeV to set upper limits on $g_{a\gamma}$. We incorporate LAT systematic errors at 3% via a weighted log-likelihood, whose weights w_{ip} per pixels are derived from the LAT data using the Fermi Science Tools [7].

$$\ln \mathcal{L}_w\left(\mu \,\middle|\, n\right) = \sum_{i,p} w_{ip}\left(n_{ip}\ln\mu_{ip} - \mu_{ip}\right).$$

Our gamma-ray sky model consists of various characterisations of the interstellar emission along the Milky Way's disc [8,9], detected gamma-ray point and extended sources, the Fermi Bubbles, LoopI, the isotropic gamma-ray background as well as emission due to the Sun and the Moon.

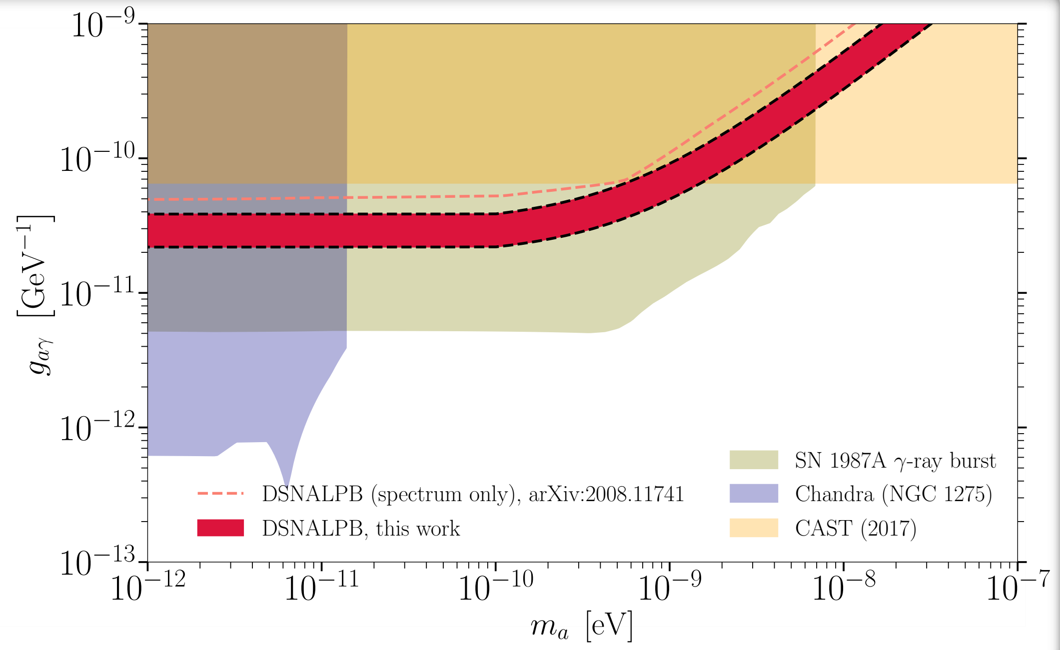
We conduct an iterative fitting approach to derive a baseline model of astrophysical components only. This model is used to the study the region of interest that guarantees statistically sound upper limits on the ALP parameter space.



While keeping the general rationale of the analysis pipeline identical, we split the total LAT data set in two parts: $E < 200$ MeV and $E \geq 200$ MeV, as the low-energy data require a refined treatment due to the large PSF. The final limits are set via a joint-likelihood approach.

4. Results and conclusions

- The Southern hemisphere with $b < -30°$ is best-suited to set upper limits on $g_{a\gamma}$.
- Compared to a previous analysis merely utilising spectral data of the arrival diffuse gamma-ray flux due to the CCSNe ALP background, we achieve an improvement by a factor of ~2.
- Although being a factor of uncertainty, the ratio of failed to successful CCSNe has a limited impact on the final results.
- The structure of the Galactic magnetic field is a more prominent source of uncertainty.



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