

Supernova bounds on axion-like particles coupled with nucleons and electrons

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Abstract. We investigate the potential of type II supernovae (SNe) to constrain axion-like particles (ALPs) coupled simultaneously to nucleons and electrons. ALPs coupled to nucleons can be efficiently produced in the SN core via nucleon-nucleon bremsstrahlung and, for masses exceeding 1 MeV, they would decay into electron-positron pairs, generating a positron flux. In the case of Galactic SNe, the annihilation of the created positrons with the electrons in the Galaxy would contribute to the 511 keV annihilation line. The SPI (SPectrometer on INTEGRAL) observation of this line allows us to exclude a wide range of the axion-electron coupling, $10^{-19} \lesssim g_{ae} \lesssim 10^{-11}$, for $g_{ap} \sim 10^{-9}$. Additionally, ALPs from extra-galactic SNe decaying into electron-positron pairs would yield a contribution to the cosmic X-ray background. In this case, we constrain the ALP-electron coupling down to $g_{ae} \sim 10^{-20}$.

1. Introduction

Featuring large densities and core temperatures $T \sim \mathcal{O}(30)$ MeV, type II supernovae (SNe) allow for the prolific production of ALPs with masses up to 100 MeV. In this contribution we use SNe to constrain ALPs with mass $m_a \gtrsim 1$ MeV coupled to both nucleons and electrons, following a strategy based on the search for *direct* signatures of the SN ALP flux. In particular, we consider ALPs produced via nucleon-nucleon bremsstrahlung through their coupling with nucleons, and then decaying into electron-positron pairs. If the coupling with electrons is sufficiently small, ALPs would leave the SN envelope and decay on their route to Earth. The positrons produced in these decays are expected to efficiently lose energy, slow down, and annihilate almost at rest with the Galactic electron density, leading to a characteristic 511 keV annihilation line signal, well measured by SPI (SPectrometer on INTEGRAL) [1, 2]. Here we constrain the ALP-electron and ALP-nucleon coupling using observations of the 511 keV line flux, and exploiting its spatial characterization. Furthermore, photons from ALPs decaying into electron-positron pairs outside the Galaxy, due to the redshift, would contribute to the Cosmic X-ray diffuse background (CXB), allowing us to place an additional bound. This work is based on the results obtained in Ref. [3], to which we address the interested reader for further details.

The plan of the talk is the following: in Sec. 2 we recall the ALP flux from nucleon-nucleon bremsstrahlung and the possible ALP decays. Using the decay of ALPs into electron-positron pairs, in Sec. 3 we consider Galactic SNe and derive the bound on the ALP couplings from the 511 keV signal, while in Sec. 4 we constrain ALPs from extra-galactic SNe. Finally, in Sec. 5, we comment on our results and conclude.



2. ALPs from Supernovae: production and decays

The ALP interactions with the SM fields are expressed by the following Lagrangian terms [4]

$$\mathcal{L}_{\text{int}} = \sum_{\psi=e,p,n} \frac{g_{a\psi}}{2m_\psi} (\bar{\psi}\gamma_\mu\gamma_5\psi)\partial^\mu a - \frac{1}{4} g_{a\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} a, \quad (1)$$

where $g_{a\psi}$ are the effective ALP couplings with fermions with mass m_ψ , and $g_{a\gamma}$ is the photon-ALP coupling constant.

In this work, we assume the coupling to photons to be small enough to guarantee a much more efficient ALP decay into electron-positron pairs than into photons. With this assumption, in the range of parameters we are exploring, ALPs are mainly produced via the nuclear bremsstrahlung with energies ~ 100 MeV. We estimate the integrated ALP spectrum through the analytical expression in Ref. [5], valid for $m_a \lesssim 30$ MeV.

ALPs with $1 \text{ MeV} < m_a \lesssim 100 \text{ MeV}$ can decay only into photons and electron-positron pairs, with partial decay lengths respectively given by $l_e = \gamma v \frac{8\pi}{g_{ae}^2 m_a} / \sqrt{1 - \frac{4m_e^2}{m_a^2}}$ and $l_\gamma = \gamma v \frac{64\pi}{g_{a\gamma}^2 m_a^3}$, where $\gamma v = \sqrt{E_a^2/m_a^2 - 1}$. The total ALP decay length is $l_{\text{tot}}^{-1} = l_e^{-1} + l_\gamma^{-1}$.

To ensure that a putative photon signal is not absorbed by the SN medium, we require that ALPs decay outside the SN envelope, with size $r_{\text{esc}} = 10^{14}$ cm [6]. This requires $g_{ae} \lesssim 10^{-11} - 10^{-12}$, depending on the ALP mass. In the present analysis, we consider ALPs with a negligible coupling to photons, so that the contribution of l_γ to the total decay length is negligible. However, our considerations are valid even for photon couplings of a size expected for typical pseudo-Goldstone bosons, provided that the branching ratio into electrons is dominant, i.e.

$$\frac{BR(a \rightarrow \gamma\gamma)}{BR(a \rightarrow e^+e^-)} = \frac{l_e}{l_\gamma} \approx 10^{-5} \left(\frac{m_a}{10 \text{ MeV}} \right)^2 \left(\frac{10^{-13}}{g_{ae}} \right)^2 \left(\frac{g_{a\gamma}}{10^{-13} \text{ GeV}^{-1}} \right)^2 \ll 1. \quad (2)$$

3. Bound from Galactic supernovae

The positrons generated by ALPs decaying outside the SN envelope are trapped by the $\mathcal{O}(1) \mu\text{G}$ Galactic magnetic field, lose their energy efficiently through Bhabha e^+e^- scatterings (for typical conditions of the interstellar medium, positrons with energies $\lesssim 100$ MeV are expected to travel not more than ~ 1 kpc before annihilating [7]), and annihilate (almost at rest) into two photons, each with an energy ~ 511 keV, on a time-scale $\tau_e \in [10^3 - 10^6]$ years, depending on the free electron density in our Galaxy and the ionization conditions of the interstellare medium [8].

The SPI gamma-ray spectrometer provides measurements of the Galactic 511 keV X-ray line flux, constraining the Galactic center positron annihilation rate to be smaller than a few $\times 10^{43} \text{ s}^{-1}$. Since electron-positron production and annihilation are in equilibrium, this can also be taken as a bound on the positron production rate. Assuming a Galactic SN rate of 2 events per century, in Ref. [6] it was estimated that the previous bound would be saturated if a single SN emits more than 10^{53} positrons. This result was then used, in the same work, to obtain constraints on dark photons emitted from SNe and decaying into electron-positron pairs, without taking into account the specific distribution of the positrons in the Galaxy. In our work, we adopt a more detailed approach, exploiting the spatial distributions of the 511 keV gamma-ray flux provided by an analysis of SPI data [2], and comparing it with the expected 511 keV line signal produced by positrons from ALP decays, as traced by the probability distribution of type II SNe.

The injected positron flux from a SN explosion is given by

$$N_{\text{pos}} = \int dE \frac{dN_a^p}{dE} \exp\left(-\frac{r_{\text{esc}}}{l_e}\right) \left[1 - \exp\left(-\frac{r_G}{l_e}\right)\right], \quad (3)$$

where dN_a^p/dE is the ALP production rate via nucleon-nucleon bremsstrahlung and the two exponential factors guarantee that ALPs decay outside the SN envelope and within our Galaxy.

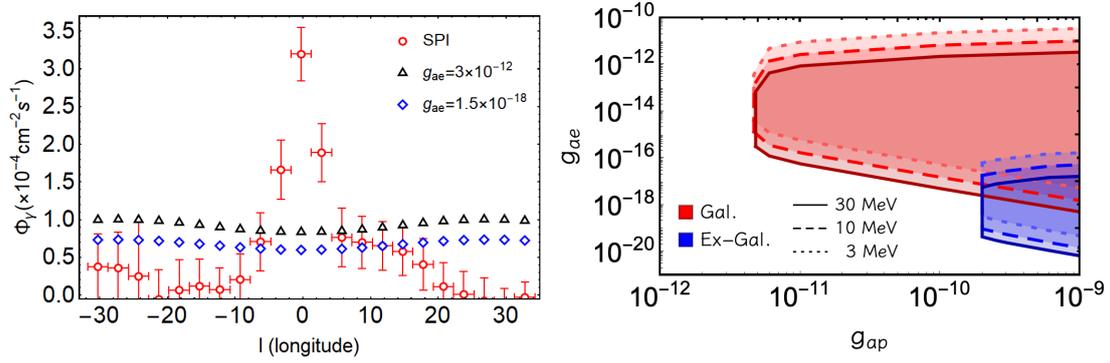


Figure 1. *Left panel:* Comparison of the photon flux produced by ALPs for $g_{ap} = 10^{-9}$, $m_a = 30$ MeV and two different values of g_{ae} with the one measured by SPI [2] as function of the Galactic longitude and integrated over the region $-10.75^\circ < b < 10.25^\circ$. The smearing scale is $\lambda = l_e \ll 1$ kpc for $g_{ae} = 3 \times 10^{-12}$, while $\lambda = 1$ kpc for $g_{ae} = 1.5 \times 10^{-18}$. *Right panel:* Bounds on g_{ae} vs g_{ap} from the diffuse Galactic SNe (reddish bands) and from extra-galactic SNe (bluish bands) for three representative values of the ALP mass $m_a = 3, 10, 30$ MeV.

To be conservative, we fix the Galactic radius $r_G = 1$ kpc, which ensures that we stay inside the Galaxy in all directions (including, in particular, the direction perpendicular to the plane).

In our Galaxy, positrons annihilate mostly after the formation of positronium. In particular, two photons of 511 keV energies originate from the singlet para-positronium state. Since the positron annihilation time τ_e is much larger than the typical time interval between galactic SNe ~ 50 years, at any given time we receive signals from a sizable number of past SNe. This allows us to average over the Galactic distribution to get an estimate of the flux distribution. In this context, the angular distribution in the Galactic sky-map of the 511 keV line photon signal produced by positron-electron annihilation through para-positronium formation is given by

$$\frac{d\phi_\gamma^{511}}{d\Omega} = 2k_{ps}N_{\text{pos}}\Gamma_{cc} \int ds s^2 \frac{n_{cc}(s, b, l)}{4\pi s^2}, \quad (4)$$

where $k_{ps} = 1/4$ accounts for the fraction of positrons annihilating through parapositronium, $\Gamma_{cc} = 2$ SNe/century is the SN explosion rate, s is the SN distance from the Sun, l is the Galactic longitude, b is the Galactic latitude and n_{cc} is the normalized SN volume distribution taken from Ref. [9], which follows the regions of high star formation and is peaked off the Galactic center.

In first approximation, the photon flux produced by ALP decays follows the Galactic SN distribution. However, depending on their decay length ALPs may decay far from the SN and the produced positrons may travel some distance before annihilation. We estimate the influence of both effects by performing an exponential smearing of the signal over a scale λ . In the left panel of Fig. 1 we show the longitudinal distribution of the 511 keV photon flux Φ_γ measured by SPI, as derived in Ref. [2], and the ALP-induced photon signal for $m_a = 30$ MeV and two values of the coupling g_{ae} , obtained through a smearing over a scale $\lambda = \min(l_e, 1 \text{ kpc})$. The observed signal is strongly peaked at $l = 0$, where the ALP signal has a dip related to the SN distribution. The bound on ALPs is set by the first bin where the predicted signal exceeds the data at 2σ . In our case, the most constraining bin is at $l \in [28.25^\circ, 31.25^\circ]$, where the observed flux is almost flat and the ALP-induced flux has a peak due to the SN distribution.

In the right panel of Fig. 1, we plot the bound (red region) on the ALP-electron coupling g_{ae} as a function of the ALP-nucleon coupling g_{ap} in the range below the SN 1987A energy-loss bound, for three different values of the ALP mass and a smearing scale $\lambda = 1$ kpc. The boundaries of the excluded band $g_{ae}^L \lesssim g_{ae} \lesssim g_{ae}^H$ are given by the following arguments. For $g_{ae} \gtrsim g_{ae}^H$, ALPs

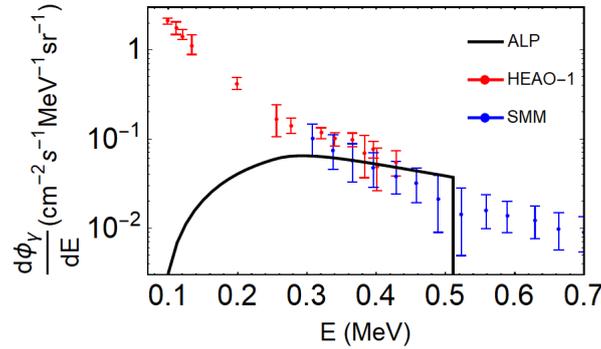


Figure 2. Photon flux from CXB measured by HEAO-1 [10] and SMM [11] with 2σ error bars, compared with the X-ray flux from ALP decays from extra-galactic SNe for $m_a = 30$ MeV, $g_{ap} = 10^{-9}$, $g_{ae} = 7 \times 10^{-21}$ (solid curve).

would decay inside the SN envelope, while, for $g_{ae} \lesssim g_{ae}^L$, ALPs would escape our Galaxy before decaying into pairs, without contributing to the 511 keV signal. We see that for $g_{ap} \sim 10^{-9}$, the range $10^{-19} \lesssim g_{ae} \lesssim 10^{-12}$ is excluded. Reducing the value of g_{ap} , the exclusion region becomes smaller and we reach a point at which ALPs are not abundant enough to produce a detectable signal even though they decay entirely into positrons. This threshold is represented in the right panel of Fig. 1 by the vertical left end of the exclusion region. In addition, the shape of the exclusion region is rather independent of the ALP mass. The dominant effect is that the bound is shifted towards larger couplings as m_a decreases, due to the dependence of the ALP decay length on the mass. We finally note that our bound might be translated into the requirement that a single SN should emit no more than $\sim 10^{52}$ positrons. More precisely, we find $N_{\text{pos}} \lesssim 1.6 \times 10^{52}$ with a smearing over $\lambda = 1$ kpc.

4. Bound from extra-Galactic supernovae

In the case of extra-galactic SNe, the positrons produced by ALPs decaying outside our Galaxy are trapped by $B \sim \mathcal{O}(1)$ nG in the extra-galactic medium, slow down and annihilate at rest on a timescale $\tau_e \lesssim 10^{10}$ yrs, giving two photons, each with energy m_e , as in the previous case. However, such photons are redshifted and thus do not contribute to the 511 keV line. Rather, they contribute to the CXB, measured by different experiments, e.g. the High Energy Astronomy Observatory (HEAO) [10] and the Solar Maximum Mission (SMM) [11]. In this context, the cumulative energy flux of escaping ALPs from past type II SNe, and decaying into electron-positron pairs in the small redshift interval between $[z_d : z_d - dz_d]$ is given by [5]

$$\left(\frac{d^2 \phi_a(E_a)}{dE_a dz_d} \right)_{\text{dec}} = \int_{z_d}^{\infty} (1+z) \frac{dN_a(E_a(1+z))}{dE_a} [R_{SN}(z)] \exp\left(-\frac{z-z_d}{H_0 l_e}\right) \frac{1}{H_0 l_e} \left[\left| \frac{dt}{dz} \right| dz \right], \quad (5)$$

where z is the redshift and $R_{SN}(z)$ is the SN explosion rate. Furthermore, $|dt/dz|^{-1} = H_0(1+z)[\Omega_\Lambda + \Omega_M(1+z)^3]^{1/2}$ with the cosmological parameters $H_0 = 67.4$ km s $^{-1}$ Mpc $^{-1}$, $\Omega_M = 0.315$, $\Omega_\Lambda = 0.685$. Since the major contribution to the ALP flux comes from $z \lesssim 2$, the photons produced by the annihilation of the positrons, originated from ALP decays, are not absorbed and, due to the redshift, the photon flux arriving on Earth is given by

$$\frac{d\phi_\gamma}{dE_\gamma} = 2k_{ps} \frac{m_e}{E_\gamma^2} \int_{m_a}^{\infty} dE_a \left(\frac{d^2 \phi_a(E_a)}{dE_a dz_d} \right)_{\text{dec}}. \quad (6)$$

In Fig. 2, we compare our result for the photon flux produced by ALP decays from extra-galactic SNe (assuming $m_a = 30$ MeV, $g_{ap} = 10^{-9}$, $g_{ae} = 7 \times 10^{-21}$) to the CXB flux measured by

HEAO-1 [10] and SMM [11]. By requiring that the ALP-induced photon flux does not exceed the measured CXB by more than 2σ , we exclude the light blue regions in the right panel of Fig. 1. In this case, the upper limit is obtained by requiring that the decayed photons are in the X-ray band accessible to the instruments used for detection, while the lower limit is given by the requirement that ALPs decay before reaching our Galaxy. At $g_{ap} = 10^{-9}$, the lower bound is one order of magnitude more stringent than the bound from Galactic SNe for the corresponding ALP mass. In particular, values $g_{ae} \gtrsim 10^{-20}$ are excluded for $g_{ap} = 10^{-9}$ and $m_a = 30$ MeV. The trend of g_{ae} vs g_{ap} is similar to what observed in the Galactic case. However, the value of g_{ap} can be lowered only by less than one order of magnitude before the bound disappears.

5. Discussion and Conclusions

In this work we have investigated the physics potential of Galactic and extra-Galactic type II SNe to constrain ALPs coupled with nucleons and electrons. In such a situation, ALPs are produced in the SN core via nucleon-nucleon bremsstrahlung and decay into electron-positron pairs. The positrons are stopped by interactions with matter and then annihilate with electrons to produce 511 keV photons. For Galactic SNe this produces a 511 keV X-ray line. Using observations of the spectrometer SPI [2], we obtain stringent constraints for the electron-ALP coupling, excluding the range $10^{-19} \lesssim g_{ae} \lesssim 10^{-12}$ for $g_{ap} \sim 10^{-9}$. In the case of extra-galactic SNe, due to the redshift, the ALP-originated photons contribute to the cosmic X-ray background and data from its observation [11] improves the previous bound down to $g_{ae} \sim 10^{-20}$. Further improvement could result from observations of the future eASTROGAM and AMEGO and from a more detailed modelling of the positron propagation, which determines the signal morphology. Beyond our result on ALPs, we also note that we obtain an improved result on the maximum number of positrons that may be emitted by an SN outside its envelope $N_{\text{pos}} \lesssim 10^{52}$, which takes into account the SN distribution inside the Galaxy.

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