PROCEEDINGS OF SCIENCE

Supernova ALPs coupled to nucleons shining into photons

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In this contribution, I explore the phenomenology of massive Axion-Like Particles (ALPs) coupled to quarks and gluons, dubbed 'QCD ALPs', with an emphasis on the associated low-energy observables. ALPs coupled to gluons and quarks not only induce nuclear interactions at scales below the QCD-scale, relevant for ALP production in supernovae (SNe), but naturally also couple to photons similarly to the QCD-axion. I discuss the link between the high-energy formulation of ALP theories and their effective couplings with nucleons and photons. The induced photon coupling allows ALPs with masses $m_a \gtrsim 1$ MeV to efficiently decay into photons, and astrophysical observables severely constrain the ALP parameter space. We show that a combination of arguments related to SN events rule out ALP-nucleon couplings down to $g_{aN} \gtrsim 10^{-11} - 10^{-10}$ for $m_a \gtrsim 1$ MeV – a region of the parameter space that was hitherto unconstrained.

2nd Training School and General Meeting of the COST Action COSMIC WISPers (CA21106) (COSMICWISPers2024)
10-14 June 2024 and 3-6 September 2024
Ljubljana (Slovenia) and Istanbul (Turkey)

*Speaker

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1. The induced photon coupling

The phenomenology of Axion-Like Particles (ALPs) at low energies is typically determined by the effective couplings to photons and matter fields

$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma} a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \sum_N g_{aN} \frac{\partial_\mu a}{2m_N} \bar{N}\gamma^\mu\gamma_5 N + \frac{m_a^2}{2}a^2\,, \tag{1}$$

where $g_{a\gamma}$ is the ALP-photon coupling, $F_{\mu\nu}$ is the electromagnetic field strength tensor, $\tilde{F}^{\mu\nu}$ is its dual, $N = p, n$ represents nucleons with masses m_N, g_{aN} are the ALP-nucleon couplings and m_a is the ALP mass. Many of the theoretical and experimental efforts are focused on the coupling of ALPs with photon $g_{a\gamma}$ in the first term of Eq. (1). In particular, the ALP-photon coupling leads to important signatures in astrophysical photon spectra, from X-ray to PeV energies (see Refs. [1, 2] for recent reviews on astrophysical axion bounds). On the other hand, the ALP-nucleon couplings in Eq. (1) source the most relevant ALP production channels in compact stellar systems, such as neutron stars (NS) and core-collapse Supernovae (SNe), i.e. NN-bremsstrahlung and pion conversion [3–6]. However, the ALP's low-energy couplings to both nucleons and photons may naturally originate from a common high-energy theory and are not completely independent. In particular, the low-energy effective Lagrangian in Eq. (1) provides an effective description of ALP interactions with the Standard Model at energies below the QCD confinement scale. At higher energies, such interactions are expected to be generated by couplings to the fundamental degrees of freedom, i.e. the quarks and gauge fields. In this work, we consider *'QCD ALPs'* with interactions to quarks and gluons given by

$$\mathcal{L}_{\rm aQCD} = c_g \frac{g_s^2}{32\pi^2}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \sum_q c_q \frac{\partial_\mu a}{2f_a}\bar{q}\gamma^\mu\gamma_5 q + \frac{(m_{a,0})^2}{2}a^2\,, \tag{2}$$

where g_s is the coupling constant of QCD, f_a is the axion decay constant, $G^a_{\mu\nu}$ is the gluon field strength tensor, $\tilde{G}^a_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G^{a\rho\sigma}$ its dual, c_g and c_q are model-dependent constants, and $q = u, d, s, c, t, b$ runs over the quark species and $m_{a,0}$ is the bare mass of the QCD ALP. Here, we focus on the phenomenology resulting from the coupling of the massive ALP to quark and gluons in Eq. (2), resulting in an "irreducible" coupling of the ALP to photons in addition to ALP-nucleon couplings. In particular, in Ref. [7] we demonstrated that the two couplings are related by the following equations

$$\begin{aligned} c_g &= 0\,, \qquad g_{a\gamma} \simeq -9.7\times 10^{-4}\,\frac{m_a^2}{m_\pi^2 - m_a^2}\, g_{ap}\ \text{GeV}^{-1}\,, \\ c_g &= 1\,, \qquad g_{a\gamma} \simeq -9.5\times 10^{-4}\, g_{ap}\ \text{GeV}^{-1} \times \left[\frac{1.53}{c_d - 0.33} + \frac{c_d + 0.24}{c_d - 0.33}\frac{m_a^2}{m_\pi^2 - m_a^2}\right], \end{aligned} \tag{3}$$

holding for the cases of a null ($c_g = 0$) and a non-null ($c_g = 1$) coupling to gluons. For the sake of simplicity in the following we will focus on the case $c_g = 0$, while a complete discussion for the $c_g = 1$ scenario is reported in Ref. [7].

In the following, we will focus on the region of the parameter space in which ALPs are significantly produced during a SN explosion by means of nuclear processes. We point out that,

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due to the induced photon coupling, massive ALPs produced in SNe can rapidly decay into photon pairs giving rise to directly or indirectly observable signatures. Specifically, we focus on the range of ALP masses $1\,\text{MeV} \lesssim m_a \lesssim 700\,\text{MeV}$ where ALP radiative decays are efficient, leading to the limits displayed in Fig. 1.

2. Observable signatures of ALP decays

Depending on the values of the decay length λ_a, ALPs can decay inside or outside the photosphere of the progenitor star with radius R_{env}, giving rise to different signatures. In particular, ALPs with $\lambda_a < R_{\text{env}}$ will predominantly decay inside the SN progenitor star, depositing energy there, while those with $\lambda_a > R_{\text{env}}$ mostly decay outside the volume of the star, leading to a potentially observable gamma-ray signal. Both of these scenarios will be discussed in the following sections.

2.1 Energy deposition in the SN envelope

ALPs with masses $m_a \sim O(10) - O(100)$ MeV can decay inside the SN mantle dumping a large amount of energy inside the volume of the progenitor star [8]. In particular, if ALP decays occur at radii R between the PNS radius R_{PNS} and the envelope radius, the energy deposited by ALP decays could power the ejection of the outer layers of the mantle during the SN explosion event. Nevertheless, this energy deposition must not be larger than the predicted SN explosion energy, otherwise it would gravitationally unbind most of the progenitor mass, independently of neutrino heating or any other hypothetical explosion mechanism [9, 10]. This argument provides a "calorimetric" constraint to ALP decays into photons. Moreover, to severely constrain such a scenario, it is helpful to employ a SN population with particularly low explosion energies as the most sensitive calorimeters [8, 11, 12]. In this case, their low explosion energy requires that the energy released in the mantle by ALP radiative decays E_{dep} has not to exceed about 0.1 B. Following the procedure for the computation of the energy deposition illustrated in Ref. [8], we have employed the explosion-energy argument to obtain the limits displayed as an orange area in Fig. 1. These results extend the region constrained by the SN cooling argument [5] to ALP masses $m_a \gtrsim 200$ MeV.

2.2 ALP induced gamma-ray burst from SN 1987A

If the ALPs produced in the core of a nearby SN can escape the photosphere of the progenitor star and decay at larger radii into gamma-rays, some of these would be able to reach detectors at Earth (see also Ref. [13]). The most constraining system to date is SN 1987A, located in the Large Magellanic Cloud at a distance of $d_{\text{SN}} = 51.4$ kpc. The Gamma-Ray Spectrometer on board the Solar Maximum Mission (SMM) satellite was taking data for $\Delta t = 223$ s after the first signal of SN 1987A, namely the neutrinos, reached Earth; no excess over the gamma-ray background was found [14, 15], and hence the existence of ALPs with certain parameters can be excluded. This argument allowed us to exclude the yellow region in Fig. 1, enlarging down to couplings $g_{aN} \sim 10^{-11}$ the region of the ALP parameter space excluded by the SN cooling argument for ALP masses $100 \lesssim m_a \lesssim 300$ MeV.

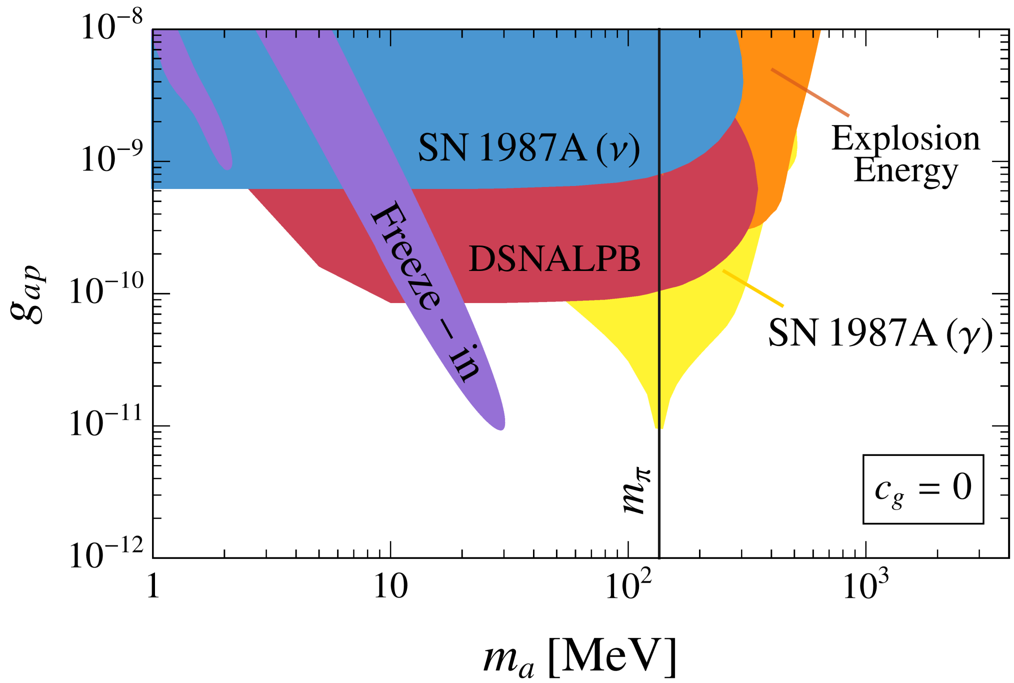

Figure 1: Summary plot of the bounds in the $c_g = 0$ scenario. The blue region displays the SN 1987A cooling bound placed in Ref. [5], while the violet region has been obtained by converting the limit on ALP-photon interactions placed in Ref. [21] by searching for signatures of an irreducible ALP background to a constraint on g_{ap}. The other bounds have been calculated for this work, taking into account the induced photon coupling for ALPs coupled to nucleons. The red region is excluded by the non observation of any signature of a possible DSNALPB, the yellow contour depicts the range of parameters excluded by γ-observations in coincidence with SN 1987A, while the orange region is ruled out by requiring that ALPs do not deposit energy in the SN mantle in excess of observations.

2.3 Diffuse SN ALP background

ALPs produced in all past SN explosions in the observable Universe may have led to a diffuse SN ALP background (DSNALPB) [16]. This phenomenon and its observable consequences have been analyzed in Refs. [4, 17, 18], taking into account the production of ALPs with masses $m_a \sim O(10)$ MeV by means of NN bremsstrahlung and pion conversions. Radiative decays of these heavy ALPs may have produced a contribution to the cosmic photon background, which is measured by gamma-ray telescopes such as *Fermi*-LAT, and hence allows us to constrain the ALP parameters [17]. Differently from the cited previous works, in our study, we analyze the scenario in which both ALP emission and decays are set by the ALP-nucleon coupling g_{aN} and the induced, 'irreducible' photon coupling as in Eq. (3). Following Ref. [19], to constrain this scenario we have employed the isotropic gamma-ray background measurements in the range of energies $E_\gamma \gtrsim 50\,\text{MeV}$ provided by the *Fermi*-LAT Collaboration, while fluxes at lower energies have to be compared to the measurements from the COMPTEL experiment [20]. By requiring that the intensity of the DSNALPB is less than the observed diffuse photon background in the considered energy range we have excluded the red areas of the parameter space shown in Fig. 1, which extends the SN cooling bound for ALP masses 5 MeV $\lesssim m_a \lesssim$ 300 MeV down to $g_{aN} \sim 10^{-10}$.

3. Acknoledgements

This article is based on the work from COST Action COSMIC WISPers CA21106, supported by COST (European Cooperation in Science and Technology).

References

[1] P. Carenza, M. Giannotti, J. Isern, A. Mirizzi and O. Straniero, *Axion Astrophysics*, 2411.02492.

[2] A. Caputo and G. Raffelt, *Astrophysical Axion Bounds: The 2024 Edition*, PoS **COSMICWISPers** (2024) 041 [2401.13728].

[3] P. Carenza, M. Lattanzi, A. Mirizzi and F. Forastieri, *Thermal axions with multi-eV masses are possible in low-reheating scenarios*, *JCAP* **07** (2021) 031 [2104.03982].

[4] A. Lella, P. Carenza, G. Lucente, M. Giannotti and A. Mirizzi, *Protoneutron stars as cosmic factories for massive axionlike particles*, *Phys. Rev. D* **107** (2023) 103017 [2211.13760].

[5] A. Lella, P. Carenza, G. Co', G. Lucente, M. Giannotti, A. Mirizzi and T. Rauscher, *Getting the most on supernova axions*, *Phys. Rev. D* **109** (2024) 023001 [2306.01048].

[6] P. Carenza, *Axion emission from supernovae: a cheatsheet*, *Eur. Phys. J. Plus* **138** (2023) 836 [2309.14798].

[7] A. Lella, E. Ravensburg, P. Carenza and M. C. D. Marsh, *Supernova limits on QCD axionlike particles*, *Phys. Rev. D* **110** (2024) 043019 [2405.00153].

[8] A. Caputo, H.-T. Janka, G. Raffelt and E. Vitagliano, *Low-Energy Supernovae Severely Constrain Radiative Particle Decays*, *Phys. Rev. Lett.* **128** (2022) 221103 [2201.09890].

[9] S. W. Falk and D. N. Schramm, *Limits From Supernovae on Neutrino Radiative Lifetimes*, *Phys. Lett. B* **79** (1978) 511.

[10] A. Sung, H. Tu and M.-R. Wu, *New constraint from supernova explosions on light particles beyond the Standard Model*, *Phys. Rev. D* **99** (2019) 121305 [1903.07923].

[11] G. Stockinger et al., *Three-dimensional Models of Core-collapse Supernovae From Low-mass Progenitors With Implications for Crab*, *Mon. Not. Roy. Astron. Soc.* **496** (2020) 2039 [2005.02420].

[12] H. Yang and R. A. Chevalier, *Evolution of the Crab nebula in a low energy supernova*, *Astrophys. J.* **806** (2015) 153 [1505.03211].

[13] E. Müller, P. Carenza, C. Eckner and A. Goobar, *Constraining MeV-scale axionlike particles with Fermi-LAT observations of SN 2023ixf*, *Phys. Rev. D* **109** (2024) 023018 [2306.16397].

[14] E. L. Chupp, W. T. Vestrand and C. Reppin, *Experimental Limits on the Radiative Decay of SN1987A Neutrinos*, *Phys. Rev. Lett.* **62** (1989) 505.

[15] L. Oberauer, C. Hagner, G. Raffelt and E. Rieger, *Supernova bounds on neutrino radiative decays*, *Astropart. Phys.* **1** (1993) 377.

[16] G. G. Raffelt, J. Redondo and N. Viaux Maira, *The meV mass frontier of axion physics*, *Phys. Rev. D* **84** (2011) 103008 [1110.6397].

[17] C. Eckner, F. Calore, P. Carenza, M. Giannotti, J. Jaeckel, F. Sivo and A. Mirizzi, *Constraining the diffuse supernova axion-like-particle background with high-latitude Fermi-LAT data*, *PoS* **ICRC2021** (2021) 543.

[18] F. Calore, P. Carenza, C. Eckner, T. Fischer, M. Giannotti, J. Jaeckel, K. Kotake, T. Kuroda, A. Mirizzi and F. Sivo, *3D template-based Fermi-LAT constraints on the diffuse supernova axion-like particle background*, *Phys. Rev. D* **105** (2022) 063028 [2110.03679].

[19] F. Calore, P. Carenza, M. Giannotti, J. Jaeckel and A. Mirizzi, *Bounds on axionlike particles from the diffuse supernova flux*, *Phys. Rev. D* **102** (2020) 123005 [2008.11741].

[20] J. G. Stacy, W. Collmar, A. Strong, V. Schonfelder and A. Carraminana, *Limits on MeV Gamma-Ray Emission from Active Galaxies and Other Unidentified High-Latitude Gamma-Ray Sources Observed with COMPTEL*, in *International Cosmic Ray Conference*, vol. 3 of *International Cosmic Ray Conference*, pp. 1085–1088, Jan., 2008.

[21] K. Langhoff, N. J. Outmezguine and N. L. Rodd, *Irreducible Axion Background*, *Phys. Rev. Lett.* **129** (2022) 241101 [2209.06216].