PROCEEDINGS OF SCIENCE

Supernova bounds on nucleophilic ALPs

Alessandro Lella[a,*]

[a]Dipartimento Interateneo di Fisica "Michelangelo Merlin," Via Amendola 173, 70126 Bari, Italy

[a]Istituto Nazionale di Fisica Nucleare - Sezione di Bari, Via Orabona 4, 70126 Bari, Italy

E-mail: alessandro.lella@ba.infn.it

Axion-like particles (ALPs) coupled to nucleons might be copiously emitted from a supernova core. This work is devoted to the extension of existing bounds on free-streaming ALPs to the case in which these are so strongly-interacting with the nuclear matter to be trapped in the SN core. From SN 1987A neutrino burst observations, two different arguments have been considered to constrain the ALP parameter space: the cooling criterium and the absence of an ALP-induced signal in Kamiokande-II neutrino detector. These lead to the exclusion of ALP-nucleon coupling $g_{aN} \gtrsim 10^{-9}$ for ALP masses $m_a \lesssim 1$ MeV. Remarkably, in the case of canonical QCD axion models, the SN bounds exclude all values of $m_a \gtrsim 10^{-2}$ eV. This result prevents the possibility for current and future cosmological surveys to detect any signatures due to hot dark matter QCD axion mass.

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1. ALP production and absorption in a SN core

Core-collapse Supernovae (SNe) are among the most powerful astrophysical factories of weakly-interacting particles. This is due to the extreme conditions of density and pressure which can be reached in the inner regions of the SN core. In particular, since the observation of the neutrino signal from SN 1987A, the proto-neutron star (PNS) at the center of an exploding SN has been identified as a powerful source of ALPs coupled with nuclear matter, up to masses $O(100)$ MeV. In the hot and dense nuclear medium typical of a young SN, ALPs are produced by means of nucleon-nucleon (NN) bremsstrahlung $N + N \to N + N + a$ [1, 2] and pionic Compton-like processes $\pi + N \to N + a$ [3]. I refer the reader to Ref. [4] for the state-of-the-art calculation of the emissivities for these processes.

For small values of the ALP-nucleon coupling $g_{aN} \lesssim 10^{-8}$, ALPs are in the *free-streaming regime* in which, once produced, they leave the star unimpeded. On the other hand, for sufficiently high values of g_{aN}, ALPs could be reabsorbed in the nuclear medium inside the dense SN core, by means of reverse processes $N + N + a \to N + N$ and $N + a \to N + \pi$, entering the so-called *trapping regime*. Starting from the expressions for the ALP production spectrum $d^2n_a/dE_a dt$, introduced in Ref. [4], the integrated ALP spectrum over a spherically symmetric SN profile can be calculated as [5, 6]

$$\frac{d^2N_a}{dE_a\,dt} = \int_0^\infty 4\pi r^2 dr \left\langle e^{-\tau(E_a^*,r)} \right\rangle \frac{d^2n_a}{dE_a\,dt}\,, \tag{1}$$

where r is the radial position with respect to the center of the SN core and $\tau(E_a^*, r)$ is the optical depth at a given ALP energy and position. In particular, the exponential term $\langle \exp[-\tau(E_a^*, r)] \rangle$ encodes the absorption effects over the ALP emission during the SN cooling and it is obtained by averaging over the emission angle [5].

Fig. 1 displays the behaviour of the ALP spectrum in the massless case for different values of the ALP-proton coupling g_{ap} at $t_{\rm pb} = 1$ s. We observe that in the free-streaming regime the spectrum clearly shows a bimodal shape with two peaks, one at $E_a \simeq 50$ MeV associated to NN bremsstrahlung, and the other one at $E_a \simeq 200$ MeV due to πN process [4]. As the coupling grows, the part of the spectrum due to πN process is progressively suppressed because of pionic re-absorption that lowers the second peak of the spectrum till it washes it out completely in the deep trapping regime. On the other hand, since NN bremsstrahlung is a thermal process, the first peak in the ALP spectrum reflects the temperature of the regions where escaping ALPs are produced. In fact, as the ALP-nucleon coupling increases, ALPs become more and more trapped inside the inner regions of the SN core and the only ones able to escape are those produced in the outer layers, where the temperature is lower.

2. SN 1987A bounds on ALP emission

The emission of ALPs from the PNS would represent an additional cooling channel during a SN explosion. In particular, given the ALP emission spectra, the ALP luminosity can be computed as [5]

$$L_a = \int_0^{R_\nu} 4\pi r^2 dr \int_{m_a/\alpha}^\infty dE_a\, E_a\, \alpha(r)^2 \left\langle e^{-\tau(E_a,r)} \right\rangle \frac{d^2n_a}{dE_a\,dt}\,, \tag{2}$$

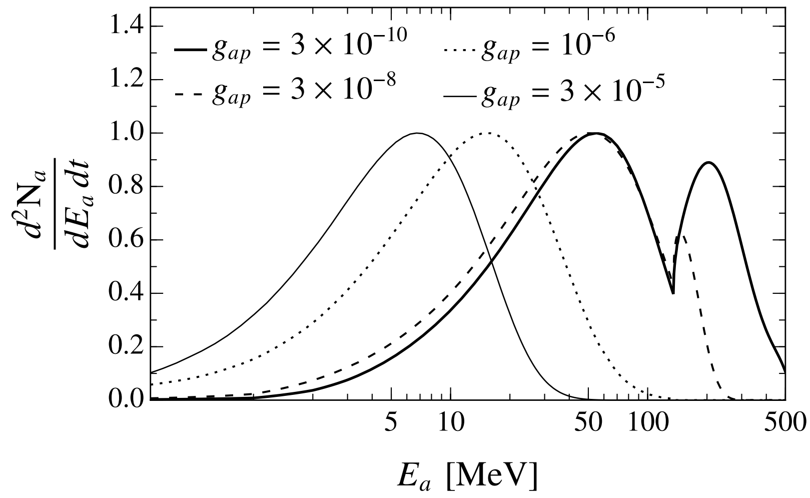

Figure 1: Normalized ALP spectrum in the massless case at $t_{\rm pb} = 1$ s for different values of the ALP-proton coupling g_{ap} and for $g_{an} = 0$.

where the lower limit of integration m_a/α cuts away the fraction of heavy ALPs gravitationally trapped in the interior of the core. However, an excess in energy-loss during the SN cooling phase would have shortened the observed duration of the SN 1987A neutrino burst. Therefore, the modified luminosity criterion requires that at $t_{\rm pb} \sim 1$ s [7] the ALP luminosity L_a computed on the unperturbed model must not exceed the total neutrino luminosity L_ν provided by the same SN simulation. Namely, for our benchmark model, at $t_{\rm pb} = 1$ s we have

$$L_a \lesssim L_\nu \simeq 5 \times 10^{52}\ {\rm erg\, s^{-1}}\,, \tag{3}$$

This criterion allows the exclusion of the blue region in Fig. 2.

Strongly-coupled ALPs emitted during a SN explosion may lead to a detectable signal in large water Cherenkov neutrino detectors, as proposed in the seminal paper by Engel *et al.* [8], in which the authors proposed to look for axion-induced excitation of oxygen nuclei with the subsequent emission of a photon to relax the system $a + {}^{16}{\rm O} \to {}^{16}{\rm O}^* \to {}^{16}{\rm O} + \gamma$.

A revised calculation of the cross-section for this process, using state-of-the-art nuclear models, is presented in Ref. [9]. The de-excitation spectrum of ${}^{16}{\rm O}^*$ through γ-cascades and particle emission, has been obtained by the statistical model reaction code SMARAGD [10], accounting for the emission of nucleons and α-particles, as well as the γ-decays of the final nuclides.

During 2.7 days around the SN 1987A time the background at KII was $\overline{n}_{\rm bkg} \simeq 0.02$ events/s [11, 12]. Therefore, one can exclude all values of g_{ap} leading to $N_{\rm ev} \gtrsim 2\sqrt{\overline{n}_{\rm bkg}\Delta t_a}$ in the time window Δt_a of the ALP signal. In particular, this analysis rules out the green region in Fig. 2. For reference, we also show the region excluded by the search for dissociation of deuterons induced by solar ALPs in the Sudbury Neutrino Observatory (SNO) data [13] (in red) and the QCD axion band (in yellow).

These results show that SN bounds strongly constrain the parameter space available for ALPs coupled to nucleons, excluding values of the ALP-proton coupling $g_{ap} \gtrsim 6 \times 10^{-10}$ for ALP masses $m_a \lesssim 1$ MeV. Therefore, in the case of canonical QCD axion models, our arguments rules out QCD axion masses $m_a \gtrsim O(10)$ meV. This is in contrast with the original literature

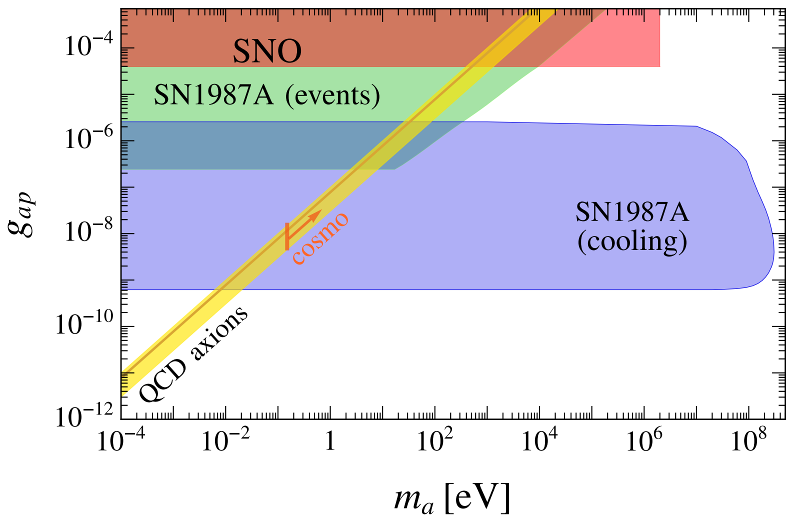

Figure 2: Summary plot of the bounds in the g_{ap} vs m_a plane together with the QCD axion band (in yellow). The region labeled SNO is excluded by the search for $p + d \to {}^3\text{He} + a$ (5.5 MeV) solar ALP flux in SNO data [13]. The green and blue regions labeled SN1987A are ruled out from the non-observation of extra events inside the KII experiment and by the cooling argument. The orange line with the arrow within the QCD axion band shows the sensitivity of current and future cosmological experiments, $m_a \gtrsim 0.15\,\text{eV}$ [15, 16]. See the text for more details.

on the SN 1987A bound, which reported the existence of a window around a QCD axion mass $m_a \sim O(1)$ eV, classicaly dubbed the "hadronic axion window" [14]. Finally, this bound is stronger than the reach of current and future cosmological experiments, which would probe axion masses $m_a \gtrsim 150\,\text{meV}$ [15] (the vertical orange line on the QCD axion band in Fig. 2). Thus, it is unlikely that future cosmological probes would find signatures of the QCD axion mass as hot dark matter.

3. Acknoledgements

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