PROCEEDINGS OF SCIENCE

Constraints on ALPs from astrophysical probes

Giuseppe Lucente[a,b,*]

[a] *Dipartimento Interateneo di Fisica "Michelangelo Merlin," Via Amendola 173, 70126 Bari, Italy*
[b] *Istituto Nazionale di Fisica Nucleare - Sezione di Bari, Via Orabona 4, 70126 Bari, Italy*

E-mail: giuseppe.lucente@ba.infn.it

Axion-like particles (ALPs), with masses up to a few 100 keV and coupled with photons can be efficiently produced in the Horizontal Branch (HB) stars in Globular Clusters, contributing to a significant energy-loss. For sufficiently large values of the ALP mass and coupling to photons, a significant fraction of ALPs decay inside the star, leading to an efficient energy transfer. Using a new ballistic recipe that covers both the energy-loss and energy-transfer regimes, the first dedicated simulation of GC stars including the ALP energy transfer has been performed, constraining ALPs with $m_a \lesssim 0.4$ MeV and $g_{a\gamma} \lesssim 10^{-5}$ GeV^{-1}. The combination of this bound with constraints from beam-dump experiments and SN 1987A covers a wide region of the heavy ALP parameter space. In this talk I will describe how astrophysical sources, such as HB stars and supernovae, can be used to constrain ALPs coupled with photons, with masses lower than a few 100 MeV.

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1. Introduction

Axion-like-particles (ALPs) are hypotetical pseudoscalar particles introduced in different extensions of the Standard Model [1]. Here we consider the minimal scenario in which ALPs, with mass up to O(100) MeV, couple only with photons with an effective two-photons vertex [1]

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

where $g_{a\gamma}$ is the ALP-photon coupling constant, F the electromagnetic field and $\tilde{F}$ its dual. In this mass range, ALPs can be probed by laboratory experiments and have cosmological and astrophysical implications. In particular, they can modify the standard stellar evolution due to an excessive energy loss.

In this contribution we will describe how astrophysical probes can be used to constrain ALPs, evaluating their impact on the standard stellar evolution. This work is based on the results obtained in Refs. [2] and [3], to which we address the interested reader for further details. The plan of the talk is as follows. In Sec. 2 we present our bound on ALPs from Globular Cluster (GC) stars, while in Sec. 3 we discuss the supernova (SN) cooling bound. Finally, in Sec. 4 we summarize our results and conclude.

2. ALP bound from Globular Clusters

ALPs coupled to photons would be efficiently produced in GC stars, leading to an additional channel of energy-loss and thus altering the stellar evolution. Consequently, the number of stars found in the different evolutionary phases in GCs provides a valuable tool to investigate exotic energy losses in stellar interiors. In this context, the GC R parameter, defined as the number ratio of horizontal branch (HB) to red giants branch (RGB) stars brighter than the HB stars

$$R = \frac{N_{\rm HB}}{N_{\rm RGB}} \ , \tag{2}$$

has been used for a long time to constrain $g_{a\gamma}$.

Light ALPs, with $m_a \lesssim 30$ keV, are produced mainly through the Primakoff process $\gamma + Ze \to \gamma + a$, i.e. the conversion of a photon into an ALP of the same energy in the electric field of charged particles in the stellar plasma. This process is considerably more efficient in HB than in RGB stars, where it is suppressed by the large plasma frequency and electron degeneracy. Therefore, for a sufficiently large ALP-photon coupling, the ALP emission would accelerate the stellar evolution in the HB stage, leaving the RGB phase essentially unchanged and thus leading to a reduction in the R parameter. A comparison with the photometric data for 39 GCs lead to the bound $g_{a\gamma} \lesssim 6.5 \times 10^{-11}$ GeV^{-1} [5, 6] for light ALPs. For heavier ALPs, with mass $m_a \gtrsim 30$ keV, the Primakoff is Boltzmann suppressed and the dominant ALP production mechanism for $m_a \gtrsim 50$ keV becomes the photon coalescence, i.e. the production of an ALP after the annihilation of two photons in a medium of sufficiently high density. This process was included for the first time in the study of the HB bound on ALPs in Ref. [4]. In that study, free-streaming ALPs were included in the GC simulation as a source of energy-loss and the effect of the ALP decay, $a \to \gamma\gamma$, was accounted for only as a reduction of the lost energy. A phenomenological bound was then obtained by searching

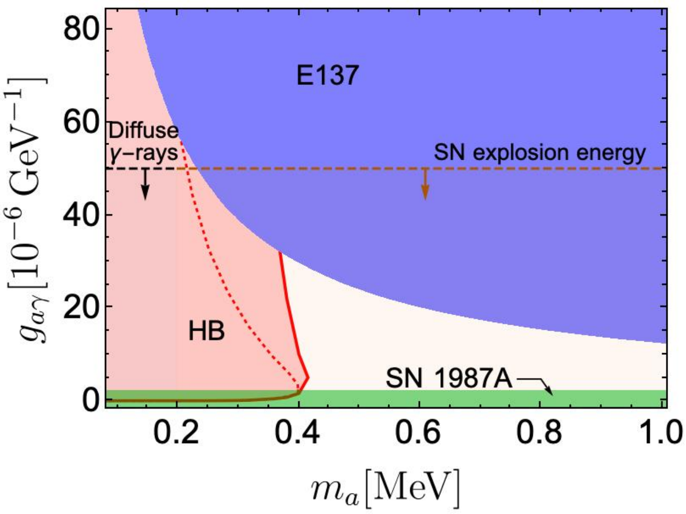

Figure 1: Overview of the parameter space around the HB bound. The region shaded in light red represents the HB bound derived with the ballistic method [2]. The red dotted line is the previous HB bound [4], obtained with an oversimplified recipe for the ALP decays. For details on the other bounds see Ref. [2].

for the $(m_a, g_{a\gamma})$ pairs for which the ALP mean free path was smaller than the convective core, without accounting for the back-reaction of the ALP decay on the star evolution. However, for large enough values of couplings and masses a significant fraction of ALPs is expected to decay inside the star, contributing to the energy transfer. To carry our more realistic analysis self-consistently, the effects of the energy deposited by the decaying ALPs have been included directly into the stellar simulations, through the so called *ballistic method*, which covers both the energy-loss and the energy-transfer regimes. In this approach, we take into account the energy deposited in each shell of the star by adding a new energy source term, representing the rate of energy deposited per unit mass by decaying ALPs, averaged over the ALP emission angle (see Ref. [2] for more technical details on this method). Due to the energy deposited by decaying ALPs, the temperature gradient is reduced and the convective instability recedes, leading to a premature disappearence of the star convective core. For each value of the ALP mass m_a, we find the 95% C.L. bound on $g_{a\gamma}$ by requiring that the HB lifetime must not be shorter than the lifetime of a model including a light ALP with the coupling fixed to the low-mass limit $g_{a\gamma} = 0.65 \times 10^{-10}$ GeV^{-1}. For instance, we find that the bound in Ref. [5] for light ALPs can be reproduced by assuming $m_a = 0.4$ MeV and $g_{a\gamma} = 1.6 \times 10^{-6}$ GeV^{-1}. Larger coupling are excluded since the HB is too short. However, for even larger couplings the HB lifetime begins to increase again, due to the energy deposited by decaying ALPs. Thus, for each value of the ALP mass we get a pair of $g_{a\gamma}$ reproducing the light ALP bound and we exclude all the values between them. The result of our analysis is shown in Fig. 1. The excluded region from HB stars, derived with the ballistic method, is shaded in light red and delimited by the continuous red line, while the dotted line represents the previous bound, from the analysis in Ref. [4]. The new bound is stronger and more robust than before, since it takes into account the back-reaction of ALPs decaying in the star.

3. SN 1987A ALP bound

Due to their large temperature ($T \sim 30$ MeV), core-collapse SNe are efficient laboratories to probe ALPs with masses up to $O(100\,\text{MeV})$. Indeed, the neutrino observations from the SN 1987A confirm the standard picture of the proto-neutron star (PNS) cooling by neutrinos on a time scale of $O(10\text{ s})$. If ALPs transport energy out from the SN core, they will provide a new efficient cooling mechanism, shortening the cooling time scale. In particular, the observed duration of the neutrino signal implies that the ALP luminosity must not exceed the neutrino luminosity in all the six (anti)neutrino degrees of freedom in the cooling phase. This is the so-called "energy-loss argument". Conventionally, it is taken as benchmark the neutrino luminosity value at a post-bounce time $t_{\text{pb}} = 1$ s, i.e.

$$L_a(t_{\text{pb}} = 1\text{ s}) \lesssim 3 \times 10^{52}\,\text{erg s}^{-1}\,. \tag{3}$$

However, if ALPs are reabsorbed in a region where the neutrino production is still efficient, their energy will be reconverted into neutrinos, without modifying their emission. For this reason, the ALP luminosity is evaluated as [7]

$$L_a = 4\pi \int_0^{R_\nu} dr r^2 \int_{m_a}^{\infty} dE E \frac{d^2 n_a}{dt dE} e^{-\tau_a(r,E,R_{\text{far}})}\,. \tag{4}$$

where $e^{-\tau_a}$ characterizes the probability that an ALP produced in the core region ($r \lesssim R_\nu \approx 20$ km) reaches a radius $R_{\text{far}} \approx 100$ km, beyond which the neutrino production is negligible. The optical depth τ_a is computed as [7], by integrating the inverse mean free path over the SN model.

Since both the ALP production rate and the optical depth increase as $g_{a\gamma}^2$, at fixed value of m_a there are two critical values of the coupling: $g_{a\gamma}^{\text{L}}$ and $g_{a\gamma}^{\text{H}}$. For $g_{a\gamma} < g_{a\gamma}^{\text{L}}$, ALPs are so weakly coupled that they cannot be produced readily enough to affect the PNS evolution. On the other hand, for $g_{a\gamma} > g_{a\gamma}^{\text{H}}$ ALPs are in the trapping regime and the deposited energy is efficiently reconverted into neutrinos. All the values in the range $g_{a\gamma}^{\text{L}} \leq g_{a\gamma} \leq g_{a\gamma}^{\text{H}}$ are excluded since L_a violates the bound in Eq. (3). As shown by the green region in Fig. 2, through this strategy values of the coupling $6 \times 10^{-9} \lesssim g_{a\gamma} \lesssim 10^{-5}\,\text{GeV}^{-1}$ are excluded for $m_a \lesssim 10$ MeV, while for $m_a \gtrsim 200$ MeV, where photon coalescence is dominant, values $g_{a\gamma} \gtrsim 4 \times 10^{-9}\,\text{GeV}^{-1}$ are constrained.

4. Conclusions

In this talk I described how astrophysical sources, such as HB stars and supernovae, can be used to constrain ALPs coupled with photons, with masses lower than O(100) MeV. In particular, ALPs would shorten the HB lifetime and reduce the R parameter. Through a self-consistent inclusion of ALPs in a stellar evolutionary code, we have shown that HB stars can constrain ALPs wih masses up to 400 keV, while ALPs with masses up to 300 MeV can be constrained using observations from SN 1987A. These bounds are complementary to experimental constraints, showing the synergy between Astrophysics and direct searches.

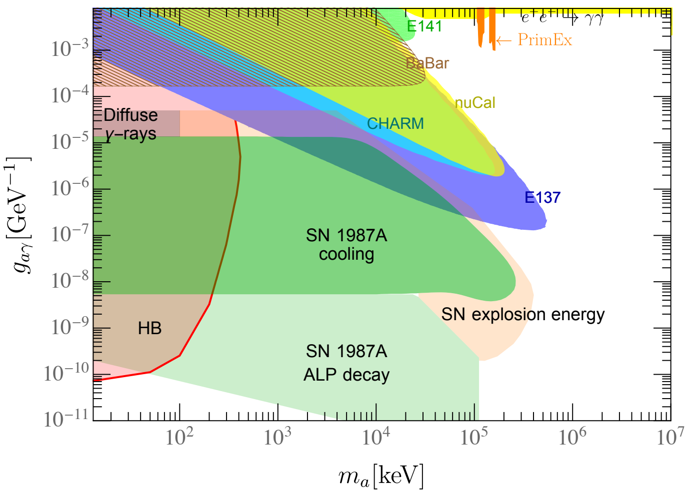

Figure 2: Overview of the heavy ALP parameter space in the plane $g_{a\gamma}$ vs m_a. The red region represents the HB bound [2, 4], while the dark green region is the cooling bound from SN 1987A [3]. For details on the other bounds see Ref. [3] and references therein.

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