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A glimpse of axion phenomenology in astrophysics

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The old and successful idea of using astrophysical systems as laboratories for fundamental physics is becoming extremely popular nowadays. Axions are a remarkable example of Feebly Interacting Particles playing an important role in astrophysical phenomena. It is well-known that stars are powerful axion factories, giving strong constraints on their properties. Aspects of the axion phenomenology in horizontal-branch stars and supernovae are reviewed.

1 Introduction

The Standard Model (SM) of particle physics is a coherent framework to explain various experimental results in high-energy physics. However, this theory cannot be the ultimate Theory of Nature. Therefore, it is necessary and very timely to search new physics beyond the SM. The two different approaches adopted in this effort are the energy and the intensity frontier. In the first approach, particle accelerators are a tool to reach high energies and probe new particles. By contrast, the intensity frontier explores fundamental physics with intense sources and ultra-sensitive detectors, trying to unveil extremely rare processes that are not predicted by the SM. A remarkable example of high intensity searches is the study of Weakly Interacting Slim Particles (WISPs): light and feebly interacting particles introduced in many SM extensions. One of the most studied WISP is the axion, originally postulated to solve the strong CP problem of Quantum Chromodynamics (the absence of CP violation in the strong sector) and also a good DM candidate. Similar particles, dubbed Axion-Like Particles (ALPs), are predicted in many SM extensions and they share most of the phenomenology of axions. In the following we refer to these particles collectively as axions.

An intense and diverse experimental program is planned for the next decade to detect axions [1] and each of these experiments has the chance to get a breakthrough discovery in particle physics. Moreover, axions might play a major role in astrophysics. Indeed, this exotic particle might strongly modify the stellar evolution in various stages acting as an extra energy sink, subtracting energy from the stellar core. The

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direct consequence is a faster evolution during the phases in which the star copiously produces axions. In this context, Globular Clusters (GCs) are recognized as ideal laboratories to probe exotic energy-losses. GCs are a gravitationally bound system of coeval stars with the same metallicity and different masses (corresponding to a different evolutionary stage). Therefore GCs are a good environment to measure the duration of stellar phases simply counting the number stars in the different stages. In this particular example, axions fasten the phase in which the helium in the core is burnt, allowing astrophysical measurements of GCs to put robust constraints on the axion properties.

Axions are an important extra energy-loss channel also for core-collapse Supernovae (SNe). The SN 1987A explosion was a milestone event in astroparticle physics. The associated neutrino burst was detected by three neutrino observatories for a total of 24 events. Despite the small number of data, these are the only direct detection of Galactic SN neutrinos. WISPs might be copiously produced in the SN, stealing energy from the core and shortening the neutrino burst duration. However, the SN 1987A neutrino data are roughly in agreement with theoretical predictions, placing strong bounds on the emission of exotic particles.

2 Globular cluster bound on ALPs

GCs are clumps of old stars in the Galactic Halo. Because of their age, only low mass stars with a mass smaller than the solar one are still observable. Typically, GCs contain a few millions of stars, populating the various evolutionary phases. The different branches are easily identified, as the Main Sequence (H core burning phase), the Red Giant (RG) branch (H shell burning phase) and the Horizontal Branch (HB, He core burning phase); and the number of stars in any evolutionary phase is proportional to the duration of that phase.

Axions produced by the photon conversion in the electrostatic field of an ion (this process is called Primakoff conversion and shown in Figure 1), would significantly reduce the lifetime of HB stars, without affecting the RG phase. Indeed, the axion production in the RG phase is suppressed compared to HB stars by the higher degeneracy. Therefore, the axion–photon coupling can be constrained by measurements of the R parameter, $R = N_{\rm HB}/N_{\rm RGB}$, a ratio of the duration of the HB ($N_{\rm HB}$) and RGB ($N_{\rm RGB}$) phases, or equivalently of the number of stars in these phases.

Axions with $m_a \lesssim 10$ keV are efficiently produced in stars via the Primakoff process in a HB core where the temperature is $T \sim \mathcal{O}(10)$ keV, accelerating the stellar evolution. The constraint coming from a comparison with the R-parameter is $g_{a\gamma} < 0.66 \times 10^{-10}$ GeV^{-1} at 95% CL [2].

Clearly, for higher axion masses this bound would be relaxed because of the reduced axion production. In this case also another production mechanism has to be included: the photon coalescence $\gamma\gamma \to a$ [3, 4]. Note that this process has a kinematic threshold that makes it irrelevant for light axions. Another difference compared to the light axion case is that a considerable fraction of axions may decay inside the star, without contributing to energy loss, but leading to a different energy transfer inside the star. A detailed discussion of this effect in provided in [5]. The obtained GC bound is shown in Figure 2, where the solid red line indicates the constraint at

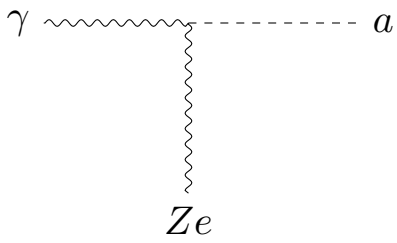


Figure 1 Axion production via Primakoff conversion in an external electric field of an ion of charge Ze.

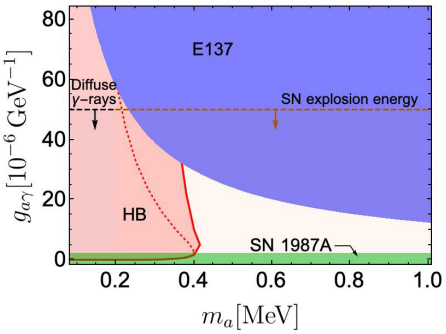


Figure 2 Overview of the parameter space around the cosmological triangle. The region shaded in light red represents the HB bound derived in [5]. The red dotted line is the previous HB bound [3], obtained with an oversimplified recipe. The green region is excluded by SN 1987A and the blue one by the beam dump experiment E137 [6]. The SN diffuse gamma-ray background (black dashed) and the SN explosion energy (orange dashed) bounds are taken from [7].

95 % C.L. while the dashed red line represents the previously estimated bound neglecting the axion energy transfer [3]. The green region in Figure 2 is excluded by the SN 1987A bound for trapped ALPs [4] and the blue region is excluded by direct searches at beam dump experiments. It is interesting that the combination of the astrophysical and experimental bounds leave an unconstrained small triangular area around $m_a \sim 0.5$–1 MeV and $g_{a\gamma} \sim 10^{-5}$ GeV^{-1} dubbed "cosmological triangle", that is only excluded by cosmological bounds. However, in a non-standard cosmological scenario the cosmological triangle is still a viable region of the parameter space, that has to be investigated both theoretically and experimentally.

3 Axion bounds from supernovae

During the stellar evolution, lighter elements are burnt to produce heavier ones and energy. The nuclear fusion begins with the production of helium from hydrogen and, in later stages, helium is burnt obtaining oxygen and carbon. Only for masses greater than $8\,M_\odot$, the carbon burning is possible producing heavier elements which accumulate in the stellar core, forming an onion-like shell structure. If there is no

more fuel to be burnt, a star dies leaving a fossil after its death. Low mass stars, as the Sun, lose the mantle leaving a carbon–oxygen White Dwarf (WD) which cools on a timescale of billion years. For masses larger than $8\,M_\odot$, at some point the stellar core is composed by iron, the most stable nucleus, that cannot be burnt to produce energy. When the core reaches the Chandrasekhar mass, $1.4\,M_\odot$, the electron degeneracy cannot contrast the collapse caused by gravity. The material infalling in the core accretes its mass, reaching a degenerate state: as the mass rises, the radius shrinks to increase the electron Fermi pressure. When the nuclear density is reached, $\rho \sim 10^{14}\,\mathrm{g\,cm^{-3}}$, matter cannot be compressed any more due to the nucleon repulsion and this implosion bounces back, triggering a shock wave which drives the SN explosion. The remaining star is a neutron star with a radius $r \sim 10\,\mathrm{km}$, a density similar to the nuclear one, spinning with a period $t \sim \mathrm{s} - \mathrm{ms}$ and a magnetic field on the surface of $B \sim 10^8$ T. The class of SNe exploding as discussed above are the core-collapse SNe.

A SN explosion is a rare event, only a few SNe per century are expected in the Milky Way. The Galactic events are very rare but easily detectable, providing a huge number of data for both astrophysics and particle physics. Neutrinos are the most important messengers from SNe. Indeed, the observation of SN 1987A in the Large Magellanic Cloud, a small satellite galaxy of the Milky Way at a distance of 51.4 kpc, was useful to test the knowledge about SNe and neutrinos. The SN 1987A progenitor was Sanduleak $-69°202$, a blue supergiant with a mass of $\sim 20\,M_\odot$. Different detectors measured the neutrino burst from SN 1987A within a few seconds about 7 : 35 : 40 UT (universal time) on 23$^{\mathrm{th}}$ February 1987 and the subsequent optical signal was seen at 10 : 38 UT. The small sample of neutrino events was studied in detail suggesting that the observed signal is compatible with the standard neutrino-driven explosion [8].

The SN neutrino burst is a clean laboratory to look for WISPs footprints. An exotic emission would constitute an additional energy-loss channel, stealing energy from the SN core and reducing the neutrino burst duration. Remarkably, the efficient production of exotic particles needs, not only high temperatures, but also high densities and the SN cooling phase features both of these requirements. A shorter neutrino burst corresponds to fewer events from the observed SN 1987A, ultimately the predicted neutrino events would be incompatible with the measurements. A constraint

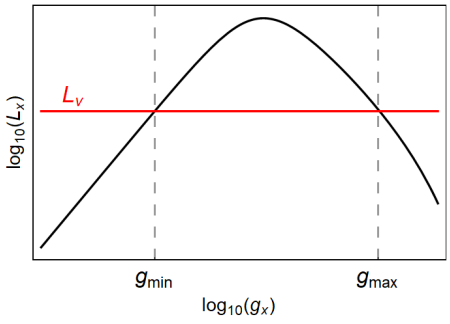


Figure 3 Schematic behaviour of the exotic particle luminosity L_x as function of the coupling g_x. The horizontal line indicates when L_x exceeds the neutrino luminosity.

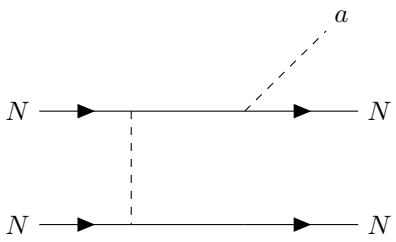


Figure 4 Feynman diagrams for the NN axion bremsstrahlung.

based on this observable is called energy-loss or cooling bound, that is conveniently formulated as a constraint on the exotic luminosity per unit mass as [9]

$$\epsilon \lesssim 10^{19}\,\mathrm{erg\,g^{-1}\,s^{-1}}\ , \tag{1}$$

where this emissivity is calculated for typical SN conditions $T = 30\,\mathrm{MeV}$, $\rho = 3 \times 10^{14}\,\mathrm{g\,cm^{-3}}$ and $Y_e = 0.3$. Precisely, if an exotic particle interacts with nuclear matter, electrons or photons with a coupling g_x, it might be copiously produced in a SN. For a small coupling the exotic energy-loss is negligible compared to the neutrino one and there are no observable consequences. In Figure 3 this behaviour is described on the left of $g_{\min}$. As g_x increases, the luminosity L_x grows and this is the free-streaming regime. Exotic particles are emitted from the entire volume of the PNS and escape because of the weakness of their interactions. When the coupling exceeds $g_{\min}$, the luminosity L_x becomes comparable or larger than the neutrino one, thus the SN evolution is affected in an observable way. The signature is the reduction of the SN 1987A neutrino burst duration. As shown in Figure 3, at some point, the exotic particles are so strongly coupled with the matter, that the luminosity starts to decrease since particles are in the trapping regime. In this case, particles produced in the inner core are absorbed by matter before escaping: the stellar matter is an optically thick medium. Moving outwards from the core, temperature and density decrease, and also the absorption rate drops. Hence, only particles produced at radii larger than some radius (called "axion-sphere" in the case of axions, in analogy with the neutrino-sphere) safely escape from the stellar interior. Exotic particles are emitted as a blackbody spectrum from this surface, whose temperature fixes the mean energy of the exotic particles. Clearly, as g_x grows, this last-scattering surface moves outwards, where the SN temperature drops, lowering the exotic luminosity. Eventually, for couplings larger than $g_{\max}$, the exotic losses are negligible compared to the neutrino ones and, again, the impact on the SN evolution is small.

[10] applied the cooling bound to axions coupled with nucleons produced by Nucleon–Nucleon (NN) bremsstrahlung, $NN \to NNa$, see Figure 4. The largest uncertainty on this emissivity is related to the nuclear interaction model that, in first approximation, is modelled by the exchange of a single pion, the One-Pion Exchange (OPE) approximation.

Many improvements beyond the OPE approximation have been proposed. Precisely, the following corrections, that generally reduce the axion emissivity compared to the OPE case, are included in the most recent calculation of the axion emissivity [11]:

- **Non-zero pion mass in the pion propagator** At a temperature T, the typical nucleon momentum is $(3m_N T)^{1/2}$, corresponding to the typical momentum transfer in collisions, which is comparable to the pion mass for $T \lesssim 30\,\mathrm{MeV}$. It means that the pion mass cannot be neglected. This effect becomes less important at higher temperature, where the pion mass is more safely neglected.
- **Two-pions exchange** For interaction scales below 2 fm, nuclear interactions become more complicated including, for example, the exchange of two pions. This effect is approximated by the exchange of a single effective ϱ meson, with effective mass $m_\varrho = 600$ MeV. This effect is less relevant at low temperature, where the ϱ meson is frozen out.
- **Effective nucleon mass** In the relativistic mean-field treatment, nucleon masses are reduced due to scalar interactions at high density. The density-dependent effective nucleon mass replaces the vacuum mass. In the very dense SN core the effective mass is up to a factor 2 smaller than the vacuum mass.
- **Nucleon multiple scatterings** Also many-body effects caused by multiple nucleon scatterings reduce the axion emissivity. The continuous nucleon self-interactions introduce a finite width for the nucleon propagator proportional to $\rho\sqrt{m_N T}$.

The analysis in [11] highlights a reduction of the OPE emissivity up to more than one order of magnitude when all the corrections are accounted for. Considering a reference $18\,M_\odot$ SN model, the bound $L_a \lesssim L_\nu \simeq 2 \times 10^{52}\mathrm{erg\ s^{-1}}$ results into a constraint on the axion–nucleon couplings

$$g_{an}^2 + 0.61 g_{ap}^2 + 0.53 g_{an} g_{ap} \lesssim 8.26 \times 10^{-19}\,, \tag{2}$$

where g_{an} is the axion–neutron coupling and g_{ap}, axion–proton one.

In the literature about the SN axion bound, the NN bremsstrahlung was thought to be the leading axion production mechanism. Another process was known, the pion–axion Compton process $\pi^- p \to n a$ (Figure 5), which was identified as the dominant contribution to the axion emissivity for a sufficiently high pion abundance. However, a thermal pion population is not enough for the pion reaction to be competitive. Thus, this process in SNe was largely ignored in further investigations. Stimulated by a recent evaluation of the non-thermal contribution to the pion abundance in a SN core (in the range 1%–5%) [12], [13] estimated an increase in the axion luminosity of a factor 4, that results in a bound twice more stringent on the coupling and mass.



Figure 5 Feynman diagram of the pion–axion Compton process.

4 The diffuse supernova axion background

4.1 Light axions

Axions emitted from all past SNe would lead to a diffuse flux with energies $\mathcal{O}(50)$ MeV: the Diffuse SN Axion Background (DSNAB, or DSNALPB in the case of ALPs). The DSNAB shows direct signatures that potentially constrain ALPs. The Primakoff conversion introduced above is the main axion production mechanism for low-mass axions ($m_a \lesssim 50$ MeV), for higher masses the photon coalescence $\gamma\gamma \to a$ dominates as explained in [4]. The energy-loss argument for axion coupled with photons gives a bound competitive with other searches only for masses $m_a \gtrsim 50$ keV. However, axions produced in a SN might convert into γ-rays in the Galactic magnetic field giving an observable signal. Heavier axions [$m_a \sim \mathcal{O}(0.1\text{–}100)$ MeV] might decay into γ-rays before reaching Earth and also in this case stringent bounds are obtained.

For sure, a SN explosion gives a lot of information about axions. However, Galactic SNe are rare and unpredictable events. Therefore, it is interesting to investigate the existence of a steady axion flux from SNe without waiting for the next Galactic explosion. The DSNAB is calculated as [14]

$$\frac{d\phi_a(E_a)}{dE_a} = \int_0^\infty (1+z) \frac{dN_a(E_a(1+z))}{dE_a} [R_{SN}(z)] \left[\left| c \frac{dt}{dz} \right| dz \right] , \tag{3}$$

where z is the redshift, $R_{SN}(z)$ is the SN explosion rate where the normalization is $R_{cc} = 1.25 \times 10^{-4}$ yr^{-1}Mpc^{-3}, $|dt/dz|^{-1} = H_0(1+z)[\Omega_\Lambda + \Omega_M(1+z)^3]^{1/2}$ with the cosmological parameters taken from [15].

The DSNAB flux is a homogeneous flux that might be observed thanks to axion-photon conversions in the Milky Way magnetic field. Figure 6 shows a sky-map of the axion–photon conversion probability obtained considering a Galactic magnetic field described by the Jansson–Farrar model [16]. The conversion probability is larger toward the Galactic center due to the higher magnetic field and has a large out-of-plane extension due to the X-shaped field. Since the ALP signal follows the structure in Figure 6, a comparison with the most recent measurement of *Fermi*-LAT [17] might reveal or exclude a similar structure in the data. This study was performed in [18]

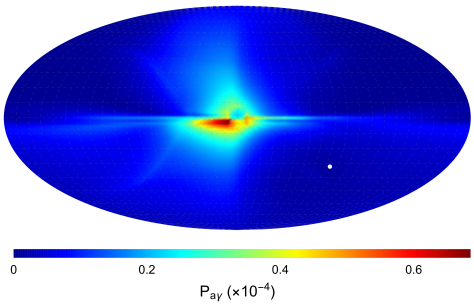


Figure 6 Sky-map of the conversion probability in Galactic coordinates. The initial condition is a pure axion beam outside the Galaxy. The axion energy is $E = 50$ MeV, the coupling is $g_{a\gamma} = 3 \times 10^{-13}$ GeV^{-1} and $m_a \ll 10^{-11}$ eV. The white circle indicates the direction of SN 1987A.

obtaining a constraint $g_{a\gamma} < 3.76 \times 10^{-11}$ GeV^{-1} at 95% CL for $m_a \ll 10^{-11}$ eV. This bound is comparable or better than the CAST bound from solar ALPs [19].

4.2 Heavy axions

Axions coupled to photons might decay into a photon pair with a decay rate given by

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\pi} \,, \tag{4}$$

increasing with the axion mass. A large fraction of axions with a mass above a few keV might decay into photons before arriving to Earth, contributing to the γ-ray background. This flux must be smaller than the flux measured by *Fermi*-LAT, giving a constraint $g_{a\gamma} \lesssim 5 \times 10^{-11}$ GeV^{-1} for $m_a \ll 1$ MeV [14]. Axions with a mass $m_a \gtrsim 1$ MeV might also decay into electron–positron pairs, reducing the total number of photons from decays. This effect is so relevant that also a small axion–electron coupling $\mathcal{O}(10^{-17})$ significantly relaxes this bound (see also [20, 21] for bounds on WISPs coupled with both nucleons and electrons).

5 Conclusions

In conclusion, understanding the astrophysical implications of axions is timely because these particles are among the most studied exotic particles. In the next decade the physics community is going to witness a massive experimental program for axion searches in many theoretically motivated regions of the parameter space. This huge experimental effort must be followed by a similar work on the astrophysical axion searches, where new precision data are expected in the nearby future.

We discussed that astronomical measurements of GCs give precious data on the duration of each stellar phase. Axions coupled with photons affect the stellar evolution due to the faster cooling making possible to constrain axion properties with observations of HB stars by requiring that the helium burning phase is not too severely shortened. This constraint is complementary with the SN bound, cosmological bounds on Big Bang Nucleosynthesis and beam-dump experiments that are part of an intense experimental program.

Moreover, SNe are an efficient laboratory to produce and probe axions. Indirect constraints come from the SN cooling bound, which constitutes one of the strongest method to constrain the emission of light particles from SNe. In particular, this argument is applied to axions coupled with nucleons. Some direct constraints are based on the absence of unexpected γ-ray signals due to conversions in the Galactic magnetic field or decay into photons. This is the idea behind the study of the DSNAB, the cumulative axion flux produced by all the past SNe in the Universe. The properties of a similar flux strongly depend on the particular axion couplings, but a common feature is the possibility of detecting a diffuse γ-ray flux with current experiments.

All these different methods are important in the perspective of detecting axions. Indeed, one method might confirm or disprove hints coming from the other. In next future, synergy among different approaches is a high-winning strategy to probe the

axion parameter space. This short discussion confirms that the discovery of the axion would have an immense impact not only on fundamental particle physics, but also on astrophysics.

Acknowledgements

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