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Axion emission from transient compact stars and conversion into photons: constraints and opportunities

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Transient and compact stars, like the proto-neutron star formed during a core-collapse supernova or after the merging of two neutron stars, are efficient factories of axions. In the small-coupling regime, these axions can escape freely from the source and convert into photons in the magnetic field outside the stars. We use the non-detection of gamma rays from SN 1987A to impose constraints on the axion-photon and the axion-proton couplings, and we examine the projected reach on these couplings with the observation of future astrophysical events of this kind. We study the entire pipeline (emission, conversion and detection) in an analytic, parametric way. We include a new ingredient that had not previously been considered in the context of neutron-star mergers: the material ejected after the merging, which is dense enough to suppress the axion-photon conversion. This contribution is based on the work done in [1] together with D. F. G. Fiorillo, H. T. Janka, G. G. Raffelt and E. Vitagliano.

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1. Introduction

An especially relevant astrophysical environment for the search for axions is the proto-neutron star (PNS) formed in the centre of a core-collapse supernova (SN). The plasma at the core of a PNS features temperatures of tens of MeV, reaches nuclear densities and has a radius of tens of kilometres. This plasma would copiously produce axions that could escape the core, extracting energy from it and cooling it down. An excessive cooling of the core would be in tension with the neutrino signal we observed from SN 1987A, the last supernova that happened in the Milky Way system [2]. This idea leads to the strongest constraints to date on the mass of the QCD axion [1].

However, there are more possible observational signatures from these axions. If there is a coupling $g_{a\gamma}$ between axions and photons, they can convert into gamma-rays in the presence of an external magnetic field, like, for example, the one in the Milky Way. The conversion rate between axions and photons depends mainly on the value of the magnetic field and its coherence length, so the large coherence length of the Milky Way magnetic field leads to important constraints on the axion-photon coupling. In addition to this, it was recently pointed out that the axions can also convert in the magnetic field of the progenitor star [3]. Although the coherence length of this magnetic field is much smaller, we will see that its larger value allows us to probe higher axion masses.

In addition to SNe, a similar astrophysical environment in which this logic can be applied is the merger of two neutron stars, where a hot and dense PNS is also formed, surrounded by a strong magnetic field. The first detection of such an event through the associated gravitational wave signal occurred in 2017 with the observation of the famous GW170817. Unfortunately, the associated gamma-ray burst was not observed by Fermi-LAT, as this telescope had just entered the South Atlantic Anomaly, so this event cannot be used to set bounds on axion couplings. Nevertheless, this idea can be studied in relation to the future detection of neutron-star mergers (NSMs).

Here we will consider two different interactions: an axion-photon one $g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}/4$ and an axion-proton one $g_{ap}\,\overline{p}\gamma^{\mu}\gamma^{5}p\,\partial_{\mu}a/(2m_p)$. The first one, besides the axion-photon conversion, is also responsible for the emission of axions through the Primakoff process $\gamma\, p \rightarrow \gamma\, a$, while the second one is responsible for the emission of axions through bremsstrahlung $n\, p \rightarrow n\, p\, a$.

By studying these transient sources and their axion emissions, as well as the conversion of these axions in the various magnetic fields they traverse, and the potential detection of resulting gamma rays by telescopes, we can constrain axion couplings and examine the parameter space that will be probed by future astrophysical events.

2. Axion production in proto-neutron stars

The axions explored here are not heavier than the QCD axion, the mass of which is constrained to be $m_a \lesssim 10^{-2}$ eV, far below the typical temperatures of the PNS. Therefore, for the emission processes we consider the axions to be massless. If the axion couples exclusively to photons, then Primakoff emission dominates the production. This process can be understood as the conversion of photons into axions in the electric field created by the non-relativistic protons within the PNS. The number of axions emitted per unit volume, unit time and unit energy is reported in [1]; it depends on the temperature T and the proton number density n_p. Ignoring the logarithmic dependence on the Debye screening scale $k_S = 4\pi\alpha\, n_p/T$, the axion production per unit mass is barely dependent on n_p and scales simply as T^3.

If the axion also couples to protons, then they are also produced through nucleon-nucleon bremsstrahlung. Here we assume that, if there is a coupling g_{ap}, then bremsstrahlung emission dominates over Primakoff, as is the case for QCD axions. We do not include a coupling to neutrons for the sake of simplicity, but our results can be easily extended to that case.

The computation of the bremsstrahlung emission of axions is difficult since it depends on the potential mediating the interaction between both nucleons. Different approximations consider the interaction through different mesons, like pions (the popular one-pion-exchange approximation). However, these techniques have never been tested with actual experimental data of nucleon-nucleon scatterings, so here we prefer to take a more phenomenological approach, where the spin fluctuation rate is parametrised as a function of T and the mass density ρ inside the PNS (see the discussion in [1]). The axion production per unit mass is again reported in [1], and it scales as $\rho\, T^{5/2}$.

The axion-proton coupling has also been used in the literature to produce axions through pionic processes, namely $\pi^-\, p \to n\, a$, driven by the possibility of having a π^- condensate within the PNS. However, pions have never been included in PNS simulations and their impact in their evolution is still poorly understood, so these pionic processes will not be included here (see the discussion in Appendix F of [1]).

These emissivity equations are then commonly integrated over post-processed profiles of the different magnitudes given by numerical simulations. Although this procedure is correct, since the backreaction on the evolution of the PNS is negligible for small coupling values, we prefer a simpler approach: using the dependencies of Primakoff and bremsstrahlung emission (T^3 and $\rho\, T^{5/2}$) as weights, we take weighted averages of these numerical profiles (here, we use the Garching models [4]) and obtain one-zone models, where all the relevant magnitudes are considered to be constant.

Quantity	**Cold**	**Hot**	**NSM**
Density ρ [10^{14} g/cm^3]	4.0	6.0	4.0
Temperature T [MeV]	30	45	25
Proton fraction Y_p	0.15	0.15	0.07
Lapse $(1+z)^{-1}$	0.75	0.65	0.85
Exposure of mass Mt [$M_\odot$ s]	5.0	10.0	6.0×10^{-3}

Table 1: Our cold and hot average one-zone SN models as well as our NSM one.

We have built an NSM model, as well as two different ones for the SN case: a hot, optimistic model and a cold, conservative one. These models are reported in Table 1. We have also included the gravitational lapse factor, which considers the gravitational potential energy of the axions within the PNS.

3. Axion-photon conversion in astrophysical magnetic fields

While the axion is escaping from the core, the difference between the effective mass for the photon (given by the very dense plasma inside the star) and the axion mass is too high and the oscillation between the axion and photon fields is suppressed. Once the axion leaves the star and encounters the stellar magnetic field, then a fraction of the emitted axions is converted into photons and a gamma ray is produced.

The mixing between both fields is described by a second-order differential equation system; however, in the case of ultra-relativistic fields, as is the case here, this can be reduced to a first-order one. This system is defined by a mixing matrix with an axion kinetic term $\Delta_a = -m_a^2/(2E)$, a photon kinetic term (here we consider only the vacuum refraction effect $\Delta_\gamma = 7\alpha/(90\pi)\ (B/B_{\rm crit})^2\ E$), and the mixing term $\Delta_{a\gamma} = g_{a\gamma}B/2$, being B the component of the magnetic field perpendicular to the line of sight (the only one relevant for the axion-photon conversion). Here we consider that the magnetic field around the PNSs behaves as a dipole, i.e. $B = B_0\ (R/R_0)^3$, where B_0 is the surface magnetic field and R_0 is the radius of the star.

A key property of a first-order differential equation system is that the total number of particles is conserved. This allows us to introduce the concept of *conversion probability* $P_{a\gamma}$, which represents the proportion of axions converted into photons. Notice that, if the total number of particles was not conserved (e.g. if the photon was non-relativistic due to an effective plasma mass), this concept would be meaningless (see the discussions in [5] and at the end of section 3.2 in [6]).

A detailed discussion of the computation of $P_{a\gamma}$ is given in [1]; here we just report one of the main results. In the SN case, the stellar B-field is small enough for the Δ_γ term to be ignored. In this case, the axion-mass-suppressed probability is given by $P_{a\gamma} \sim \left(g_{a\gamma}\, B_0/\Delta_a\right)^2$, which is independent of the size of the source. This is why, even if the coherence length of the B-field is smaller, the higher the value of the B-field, the higher the values of m_a that can be explored.

The contour of the Milky Way magnetic field cannot be modelled as a simple polynomial profile. In this case, we use the Unger and Farrar models, with which we compute the conversion probability numerically as a function of the mass. This probability is reported in Fig. 6 of [1].

The compact, large surface magnetic fields of the PNS formed during a NSM present a very exciting prospect for a future detection of the axion. However, there is a crucial ingredient in this context that needs to be considered: the ejected material after the formation of the PNS. After the merger, there are large fractions of mass that are ejected with relativistic velocities; simulations report masses of $10^{-7}\, M_\odot$ emitted at velocities round $0.8\, c$ [7]. This implies the presence of a large density that completely blocks the conversion. Therefore, when the ejected material reaches the conversion point $R_{\rm conv}$, the conversion is quenched (see Fig. 5 of [1]).

4. Results and discussion

The gamma rays produced by the conversion of axions could be detected by our telescopes. No gamma-ray detection was associated with the neutrino signal detected from SN 1987A; the primary experiment in the MeV range when this SN was observed was the Solar Maximum Mission (SMM). As shown in Appendix G of Ref. [1], SMM would have observed an excess if the photon fluence had been greater than 0.35 cm^{-2} (at 3σ). Knowing that SN 1987A happened 51.4 kpc away from Earth, this implies a constraint on the axion couplings; these constraints are shown in Fig. 1 as a function of the axion mass, both for $g_{a\gamma}$ alone (assuming that the axion emission is dominated by Primakoff emission) and for the combination $g_{ap} \times g_{a\gamma}$ (assuming that the emission is dominated by bremsstrahlung, while $g_{a\gamma}$ is still responsible for the conversion). There are no new excluded parts of the parameter space for an axion that couples exclusively to photons. However, for an axion that also couples to protons, these are the most stringent constraints to date for some part of the parameter space. In any case, it is important to stress that the only reliable bounds are those coming from the conversion in the magnetic field of the Milky Way. Bounds derived from the stellar magnetic field should be seen as indicative, as no measurements of the B-field of Sanduleak, the progenitor of SN 1987A, are available.

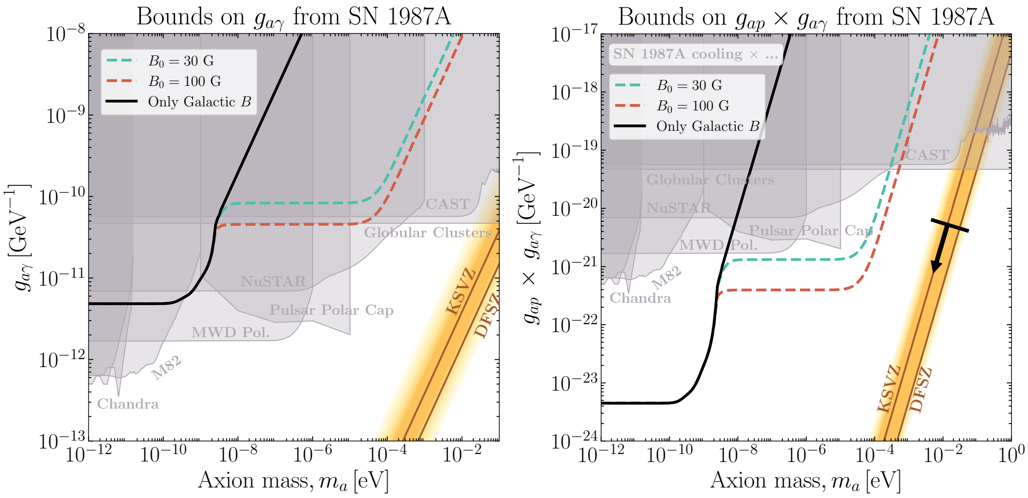

Figure 1: Constraints on the axion-photon coupling $g_{a\gamma}$ (*left panel*) and the product with the axion-proton coupling $g_{ap} \times g_{a\gamma}$ (*right panel*) from the SMM non-detection of γ-rays from SN 1987A, assuming Primakoff production alone and using the cold one-zone model to describe the SN core. The black lines assume conversion only in the galactic B-field, and dashed red and blue curves include conversion in the stellar one for two different values of the surface B-field. The progenitor radius is fixed to $R_0 = 30\ R_\odot$. The yellow band represents QCD axions and the limits from other sources are shown in shaded grey. The black arrow in the right panel indicates the SN 1987A cooling constraint on KSVZ axions of $m_a < 13$ meV, corresponding to the g_{ap} limit [1].

Current and future telescopes are much more sensitive than SMM, making future galactic SNe much more promising. In Fig. 2 we show the projected reach on the axion couplings, assuming the detection of 100-MeV gamma rays with a Fermi-LAT-like telescope, which is the current most sensitive experiment in the frequency range of interest. We assume that the telescope would observe the gamma ray if the number of signal events at the telescope is at least 3, using the Fermi-LAT effective are shown in Fig. 7 of [1]. Our results demonstrate that, even under conservative assumptions, new regions of the parameter space would be explored. Furthermore, even the detection of the QCD axion is possible in more optimistic scenarios. Here, as in Ref. [3], we assumed that the future galactic SN will have blue supergiant progenitor. However, it has recently been found that a Type Ibc galactic supernova is a much more exciting scenario for two reasons: first, they are much more frequent; and second, the surface magnetic fields have larger values [8].

The observation of future NSMs is in principle an appealing scenario due to the large magnetic fields formed after the merger. The projected reach on the axion couplings for the case in which the observation of an excess of gamma rays was associated with a future NSM is shown in Fig. 3 for a future NSM happening at a distance of 30 Mpc away from us. However, the prospects for this case are much less promising than for a future SN, both because of the weaker axion emission and

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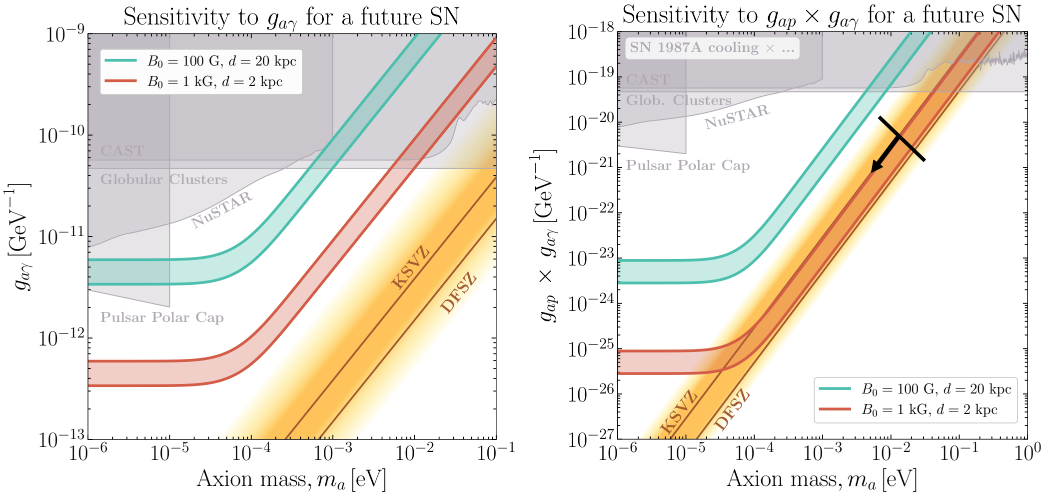

Figure 2: Projected reach on $g_{a\gamma}$ (*left panel*) and $g_{ap} \times g_{a\gamma}$ (*right panel*) as a function of the axion mass, assuming that Fermi-LAT or a similar satellite observes 100-MeV-range gamma-rays coming from a future SN. We consider two different choices for the surface magnetic field and the distance. The edges of the shaded bands are defined by the hot and cold one-zone models. The progenitor radius is fixed to be $R_0 = 30R_\odot$.

because of the presence of the ejected material, which suppresses the conversion when it reaches the conversion radius.

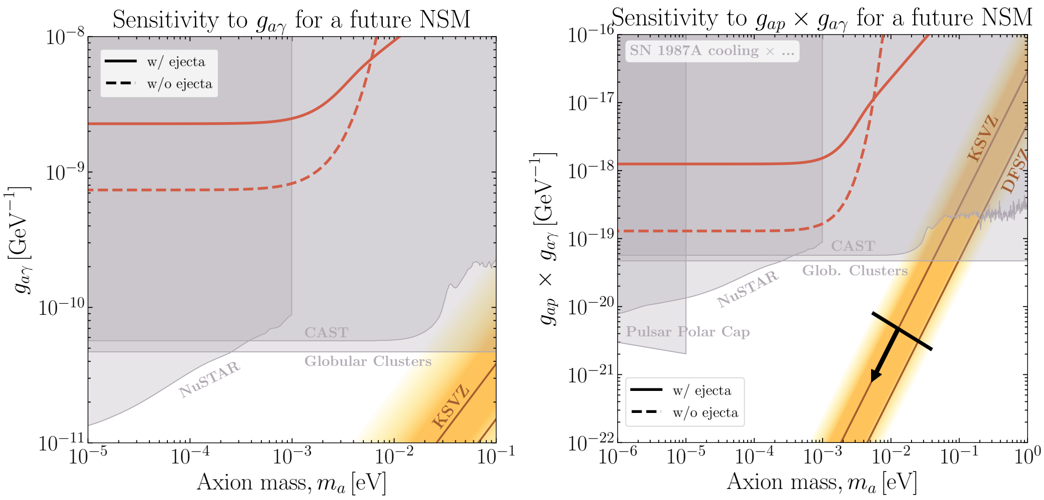

Figure 3: Projected reach on $g_{a\gamma}$ (*left panel*) and on $g_{ap} \times g_{a\gamma}$ (*right panel*) as a function of the axion mass, assuming a NSM 30 Mpc away from Earth. The solid line corresponds to the bound obtained including the ejecta, while the dashed line corresponds to the case where the ejected material is not taken into account. We assume the HMNS to have a radius $R_0 = 10$ km and a surface magnetic field $B_0 = 10^{14}$ G, and we fix the velocity of the ejected material to be $0.8c$.

As a final remark, it is worth stressing that here we have treated the whole pipeline in a simple, parametric way. Seemingly more refined treatments often hide physical uncertainties and do not offer any real benefit; our parametric analysis highlights the relevant physical parameters and facilitates the reproduction of results.

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