Axion-like particle production in neutron star mergers: gamma-ray signal detectability

Damiano F. G. Fiorillo\textsuperscript{1,2} and Fabio Iocco\textsuperscript{1,2}

\textsuperscript{1}Dipartimento di Fisica "Ettore Pancini", Università degli studi di Napoli “Federico II”, Complesso Univ. Monte S. Angelo, I-80126 Napoli, Italy
\textsuperscript{2}INFN - Sezione di Napoli, Complesso Univ. Monte S. Angelo, I-80126 Napoli, Italy

(Dated: September 23, 2021)

Axion-like particles can in principle be produced in the dense environment of neutron star mergers and core-collapse supernovae, and converted in gamma-rays in the magnetic field intervening between the event and the Earth. While this process has been studied for supernovae, there is no estimate of the gamma-ray signal expected from neutron star mergers.

In this work we explore this new, exotic signature of the merger, and find that for a large region of the ALP parameter space its magnitude is comparable with that of a signal of similar nature from a SN. We show detection forecasts for these events, finding that they could be observable with the e-ASTROGAM telescope, thus opening a new window into both the astrophysics of these cataclysmic events, and of new particles beyond the standard model.

I. INTRODUCTION

Axion-like particles (ALPs) can in principle be produced in the hot environments of extreme astrophysical sources, such as magnetars\cite{1,2}, pulsars\cite{3}, neutron stars\cite{4}, compact binaries\cite{5}, black holes\cite{6}, gamma-ray bursts\cite{7-10}, active galactic nuclei\cite{11-14}, and supernovae (SNe)\cite{15-33}.

Such extreme environments now also list neutron star mergers (NSMs). The actual observation of a NSM through gravitational waves\cite{34} produced in the event has prompted the exploration of a new realm of densities and temperatures, as addressed in\cite{35-43}. In such unique conditions, the bremsstrahlung process of neutrons\textsuperscript{N} + \textsuperscript{N} \rightarrow \textsuperscript{N} + \textsuperscript{N} + \textit{a} could be an efficient way of producing ALPs, a process that has been studied in the context of core-collapse SNe\cite{23,26,44-47}, leading to constraints on the ALPs properties from the non-observation of the SN1987A\cite{15,18,19,21,48,49}, and to forecasts on future SN detections\cite{30,31,33}.

The possibility that ALP production could take place in NSMs has been addressed in\cite{50,51}, where the authors study the impact of ALPs streaming through the dense merger, provoking an additional cooling of the material and modifying its structure. This suggests the possibility of constraining ALP couplings by imposing the limitations arising from current observations of gravitational waves.

Here we ask whether there is a region of the parameter space –still allowed by observations– where ALP emission is sizable, and if so whether any observational signature would be left by ALPs being converted into photons in the magnetic field intervening between us and the merger. We find that for a sizable region in the ALP parameter space the merger structure is preserved, and a signal in soft gamma-rays of energy is potentially observable with the future gamma-ray detector e-ASTROGAM\cite{52} (see Fig. 2), thus opening a new exciting window in the multi-messenger study of NSMs. Due to their longer duration, we find that SNe are still a brighter source than NSMs in terms of ALP production: for this reason, we also determine the projected constraints (see Fig. 3) that e-ASTROGAM could obtain from the non-observation of gamma-rays from a future extragalactic SN.

II. ALP FLUXES FROM SN AND NSM

We consider ALPs produced via nucleon-nucleon ALP bremsstrahlung, a process has been thoroughly studied in the literature\cite{26,46,47,51}. Since strong interactions in dense nucleon environments are poorly known, they are often treated at the level of one-pion exchange (OPE): with this approach, Ref.\cite{51} determines the ALP emissivity in the hypermassive neutron star which forms for a short time at the end of a NSM. Recently, Ref.\cite{26} has shown that going beyond the OPE approximation can lead to a reduction by roughly an order of magnitude in the ALP emissivity. However, for this work we adopt the emissivity from\cite{51}: as discussed in Sec. IV, this procedure does not change the qualitative conclusions of our work\textsuperscript{1}. We use the emissivity for the full phase-space calculation for non-relativistic neutrons, assuming a density equal to the saturation density of neutrons. For relativistic neutrons and for higher densities the emissivity would be larger, so that our choice is conservative.

Furthermore, Ref.\cite{51} only considers the ALP production due to neutron-neutron ALP bremsstrahlung.

\textsuperscript{1} A possible discrepancy between that adopted here and the one in Ref.\cite{26} would not affect our conclusions on the detectability. In fact, the normalization of the ALP flux depends on the coupling $G_{an}$, for which the main constraints come from the ALP emission in SN1987A (either because of cooling or because of ALP to gamma conversion). Therefore a discrepancy in the emissivity is reabsorbed in a redefinition of the coupling $G_{an}$: in other words, if the emissivity were 10 times lower, the constraints on $G_{an}$ would be a factor of 3 weaker, and therefore the signal we obtain would still be allowed by the present parameter space.
As suggested in Ref. [53], neutron stars could also contain a population of protons and pions. In Ref. [54] an analogous situation for SN leads to an enhanced axion emissivity via the process $\pi^-p \rightarrow na$. This component would also be harder, with ALPs produced mostly with hundreds of MeV. Furthermore, in the presence of protons, neutron-proton ALP bremsstrahlung would also contribute to the emissivity. For this work, we do not consider these components, because of the large uncertainties in the concentrations of pions and protons within the NSM.

Following Ref. [51], we define the interaction Lagrangian for neutrons and ALPs as

$$\mathcal{L}_{an} = G_{an} \partial_\mu a N \gamma^\mu \gamma_5 N,$$  \hspace{1cm} (1)

where $G_{an}$ is the coupling constant. For future convenience, we parameterize the ALP emissivity (measured in erg cm$^{-3}$ s$^{-1}$) as a function of the temperature $T$ as $Q(T) = \left(\frac{G_{SN}}{G_{an}}\right)^2 Q_{SN}(T)$, where $G_{SN} = 7.8 \times 10^{-10}$ GeV$^{-1}$ and $Q_{SN}(T)$ is extracted from Fig. 7 of [51]; $G_{SN}$ is the maximum coupling allowed by the observation of SN1987A based on energy-loss arguments.

The ALPs produced are assumed to freely escape, as shown in [51]. For their spectral distribution we follow the Fermi surface approximation of [55] in the degenerate neutrons limit, which gives a slightly modified blackbody spectrum. We have also tested a simpler blackbody emission finding no significant differences in the final result. For the total number of ALPs emitted by the source we integrate over the volume of the source. The temperature profile of the object is quite uncertain. The curve we use, shown in Fig. 1, is a spherically symmetric broken power-law, adapted to reproduce the order of magnitude of the profile in Fig. 4, left panel of Ref. [56]. The two profiles roughly bracket the upper and lower temperature envelope to the order of magnitude. This profile was obtained by a simulation after 25 ms from the start of the merger. At shorter times even larger temperatures could be reached (as shown in Fig. 3 of [56]).

The duration of the event is also quite uncertain. Studies on the NSM connected with the gravitational wave GW170817 conclude that the supermassive neutron star at the center survived for about 1 s [51, 57], and simulations report the temperature profiles for times up to about 25 ms after the burst beginning. Here we assume a duration of 1 s. The duration of the burst may actually be shorter, and/or the temperature profile we have adopted—and on which the emissivity depends crucially—may not hold for the entire duration of the burst. This would of course affect our conclusions: a duration of the burst of only 10 ms (100 times shorter than the one shown in the plots) would make only a SN1987A-like in the LMC visible with e-ASTROGAM. It is however unlikely that all conditions above would conjure for reducing the flux as much, also given that our other assumptions are conservative: in particular, we are using a constant density

![Temperature profile of the NSM](image)

**FIG. 1. Temperature profile of the NSM.** We show the band of spherically symmetric temperature profiles adopted for our calculation as a function of the radius. The profiles have been obtained as a broken power-law spectrum adapted from those shown in Fig. 4, left panel of [56].

III. GAMMA FLUX AT THE EARTH

In [51] the effects of the cooling via ALP production on the neutron star merger were emphasized. A complementary possibility for detectability, is the observation of the ALPs after their conversion into gamma-rays in the galactic magnetic field$^2$.

During the propagation in the Milky Way ALPs can convert into gamma-rays via two-photon coupling with the galactic magnetic field. The interaction term in the Lagrangian is

$$\mathcal{L}_{\gamma\gamma} = -\frac{1}{4} g_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} a,$$ \hspace{1cm} (2)

where $a$ is the ALP field, $F_{\mu\nu}$ is the electromagnetic field tensor, $F^{\mu\nu}$ is the dual field tensor, and $g_{\gamma\gamma}$ is the coupling constant. To estimate the probability of conversion

$^2$ We conservatively neglect the intergalactic magnetic fields, whose strength is largely uncertain.
FIG. 2. Gamma-ray fluence from conversion of ALPs produced in the NSM. We show the gamma-ray fluence of a NSM (blue), obtained for the band of temperature profiles in Fig. 1, and of a SN (magenta), for a benchmark choice of ALP parameters shown in the text. We consider the event happening in the LMC (top), as in the case of SN1987A, and in M33 (bottom). We show in black the 90% sensitivity of the e-ASTROGAM experiment, obtained from the effective area in Table IV of Ref. [52] and assuming no background (for exposure times of 10 s the background rate provided in the Table leads to less than 1 event). The ALP mass is chosen as smaller than $10^{-13}$ eV.

The gamma-ray fluence emitted over the entire duration of the event is shown in Fig. 2 (top panel) both for the NSM (blue) and for a reference SN (magenta), with a temperature profile taken from Ref. [26]. For the SN we use for consistency the same emissivity adopted for the NSM. We study a source placed in the Large Magellanic Cloud (top panel), as in the case of SN1987A, and in M33 (bottom panel). The ALP couplings $G_{aN}$ and $g_{a\gamma}$ have been chosen so as to saturate the bounds from SN1987A observations by EGRET. With this choice, a SN in the same conditions as SN1987A would now give rise to a signal nearly three orders of magnitude larger than the 90% sensitivity of the future gamma-ray telescope e-ASTROGAM [52]. Interestingly, also a NSM in the same position would give rise to a signal detectable by e-ASTROGAM. For a SN and a NSM in the M33 galaxy, with a distance of more than one order of magnitude larger than LMC, the fluxes are correspondingly suppressed. While a SN would still be completely observable, the signal from a NSM may be below the e-ASTROGAM sensitivity, given the uncertainties on the temperature profile.

We do not include any background radiation produced by the SN and the NSM. This is certainly reasonable, as no radiation has been detected in the hundreds of MeV range for a SN event. On the other hand, NSMs have long been associated with short gamma-ray bursts, whose radiation can indeed be prominent in the hundreds of MeV range. However, the significant case of GW170817 led to a gamma-ray burst detected almost two seconds later than the merger [61]. Therefore, the two signals could potentially be distinguished on temporal basis.

Finally, we comment on the observability of the diffuse gamma-rays emitted by the whole population of NSMs. The rate of NSMs is much lower than that of core-collapse SNe, so that the diffuse production associated to the NSM population is much lower than that of SNs. The ALP–induced diffuse gamma–ray production from a SN population has been studied in Ref. [33], where it is shown that the constraints from individual SN1987A are much stronger than the ones from diffuse production. We have explicitly checked that this is true for diffuse production from NSMs, due to their lower rate, as from the literature [34, 62–64].

IV. CONSTRAINTS FROM E-ASTROGAM

What constraints could be drawn if e-ASTROGAM observed no gamma-ray signal from a SN or a NSM? We focus on the former, given the larger fluence and the higher chance of SN compared to NSM.

Constraints from the non-observation of gamma-rays by EGRET at the time of SN1987A have been drawn on the coupling $g_{a\gamma}$ [27–29]. These depend only on the Primakoff production of ALPs. Here we focus on ALP production via nucleon bremsstrahlung, which can only constrain the product $g_{a\gamma}G_{aN}$, since $G_{aN}$ determines the rate of ALP production and $g_{a\gamma}$ determines the conversion in galaxy. This approach is followed in Ref. [33], where it is shown that the constraints on $g_{a\gamma}$ are determined for a fixed value of $G_{aN} = 5.33 \times 10^{-10}$ GeV$^{-1}$.

Before comparing with Ref. [33], however, we observe that the emissivity we are using differs from the emissivity used in Refs. [26, 33], as already mentioned in Sec. II. The difference can be as large as one order of
FIG. 3. Projected constraints on ALP parameter space by future observations of SN. We show the forecast for the constraints from a non-observation of gamma-rays from ALP conversion after a SN in LMC (same position as SN1987A, magenta) and M33 (green), for a value of $G_{\alpha N} = 5.3 \times 10^{-10}$ GeV$^{-1}$. We also show the constraints obtained in Ref. [33] from the non-observation of SN1987A with the same $G_{\alpha N}$ (cyan region), and our reproduction of the same constraints (blue); for the slight difference between the two, see the text. We also show the existing constraints (independent of $G_{\alpha N}$) from the CHANDRA observations of NGC1275 [65].

magnitudes. Therefore, the projected constraints in our approach would be much stronger than the ones from SN1987A because of the spurious difference in the emissivities, and not because of a real improvement in the detector capabilities.

To ensure consistency, we independently compute the 95% constraints on $g_{\alpha \gamma}$ from the non-observation of gamma-rays from SN1987A by EGRET, requiring that the photon fluence in the interval from 25 MeV to 100 MeV from SN1987A was smaller than $0.6 \text{ cm}^{-2}$ [29]. We show the corresponding constraint in Fig. 3 as a blue solid line, to be compared with the cyan exclusion region obtained in Ref. [33]. The blue curve is stronger by about a factor of 3: since the energy fluence is proportional to $g_{\alpha \gamma}^2$, this implies a factor of 10 difference in the gamma-ray fluxes, which coincides with what we expected for the different emissivities adopted.

We obtain projected constraints from e-ASTROGAM—for a given future SN—by computing the gamma-ray flux at the Earth and determining the number of events expected at e-ASTROGAM over the entire duration of the SN, using the effective area in Ref. [52]. We require this number to be equal to 3.09, the background-free Feldman-Cousins 95% limit for zero observed events [66]. In the same Fig. 3, we show in green (magenta) the projected constraints for a SN in M33 (Large Magellanic Cloud, similar to SN1987A). The former case is slightly more pessimistic, due to the larger distance of M33, but even in this case the constraints that could be drawn are nearly an order of magnitude lower than the ones obtained by SN1987A. For a SN in the Large Magellanic Cloud, the results are even more positive, leading to constraints that are by more than an order of magnitude stronger than the ones obtained by SN1987A.

V. CONCLUSIONS

High-energy astrophysical events are progressively expanding our opportunities to explore physics beyond the Standard Model. In this analysis, we focus on NSMs and SNe as a source of ALPs potentially detectable at Earth after their conversion in gamma-rays in the galactic magnetic field. We focus on the nucleon-nucleon ALP bremsstrahlung mechanism for the production of ALPs in NSMs, a possibility that has not been previously discussed in the literature. Our results point both to SNe and to NSMs as sources of ALPs potentially observable in gamma-rays within the $\sim 10$-500 MeV range.

We estimate the expected gamma-ray flux from NSM, self-consistently applying the same method to estimate the expected gamma-ray flux from SN, finding that both a NSM and a SN in the nearby galaxies LMC and M33 could lead to a signal observable by the future gamma-ray detector e-ASTROGAM, within the ALP parameter space still allowed by present constraints. Furthermore, we present the first projected constraints in the case that no gamma-rays are observed for a SN in LMC and M33 by e-ASTROGAM. These constraints can be up to one order of magnitude stronger than the present ones from SN1987A.

Acknowledgments We are grateful to Pierluca Carenza, Marco Chianese, Alessandro Mirizzi, Giuseppe Lucente, and Pasquale D. Serpico for useful comments. This work has been supported by the Italian grant 2017W4HA7S “NAT-NET: Neutrino and Astroparticle Theory Network” (PRIN 2017) funded by the Italian Ministero dell’Istruzione, dell’Università e della Ricerca (MIUR), and Iniziativa Specifica TAsP of INFN.

Whereas we are glad to notice that their “recipes” for the local physics (NSM duration, temperature and density profile), and

---

3 While this paper was in preparation, Ref. [58] appeared, discussing an idea similar to ours: namely that dark photons may be produced in neutron star mergers and be detected at Earth.
that their conclusions about the detectability are similar to ours, our paper focuses on an entirely different production mechanism via ALPs rather than dark photons. For similar reasons, we also focus on the prospects for constraints on the ALP parameter space at e-ASTROGAM with future SN observations.
