

## Probing axion-like particles with multimessenger observations of neutron star mergers

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In this contribution, I explore possible axion-like particle (ALP) signatures arising from binary neutron star (BNS) mergers. If the ALP–nucleon couplings  $g_{aN}$  are sufficiently large, ALPs can be efficiently produced during these events through nucleon–nucleon bremsstrahlung. The ALP–photon coupling  $g_{a\gamma}$  may then induce conversions of ultralight ALPs into photons in the magnetic fields of both the merger remnant and the Milky Way. This mechanism would generate a short gamma-ray burst nearly coincident with the gravitational-wave (GW) signal emitted during the inspiral phase. Such a signal could be detected through multimessenger observations combining GW detectors and gamma-ray telescopes.

Here, I present the sensitivity of current and proposed MeV gamma-ray experiments to this ALP-induced emission. For a Kim–Shifman–Vainshtein–Zakharov (KSVZ) inspired axion model, the most promising future instruments can reach sensitivities down to  $g_{a\gamma} \gtrsim \text{few} \times 10^{-13} \text{ GeV}^{-1}$  for  $m_a \lesssim 10^{-9} \text{ eV}$  for a BNS merger at 4 Mpc.

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## 1. Introduction

Axion-like particles (ALPs) naturally arise in many extensions of the Standard Model, including string theory [13–15], spontaneously broken supersymmetric theories [16], extended Higgs sectors [18, 19], and quantum field theories on torsionful manifolds [20–22]. Their extremely weak interactions make them compelling dark-sector candidates, but they also render laboratory searches challenging. Astrophysical environments therefore play a key role in probing ALP interactions, an exemplary example being SN 1987A [6, 7].

The multimessenger observation of GW170817 [42–45] opened a promising new avenue for ALP searches: binary neutron star (BNS) mergers [46, 47]. Temperatures of several tens of MeV and densities exceeding nuclear saturation are attained during the merger, enabling significant ALP production through nucleon–nucleon bremsstrahlung. Although these conditions are milder than those in supernova cores, BNS mergers offer a distinct advantage: the GW signal generated during the inspiral phase provides a precise and model-independent time tag for any prompt electromagnetic counterpart.

If ALPs couple to photons, they may convert into gamma rays in the presence of external magnetic fields. The resulting ALP-induced gamma-ray signal would be nearly coincident with the GW signal, enabling targeted, low-background searches at extragalactic distances. Moreover, it would be clearly distinguishable from astrophysical gamma-ray emission associated with short GRBs expected in BNS, which typically occur  $\sim 1$  s after the merger, as observed for GW170817.

This multimessenger synergy motivates the present study. In Sec. 2, I describe the ALP emission expected from BNS merger simulations. Section 3 discusses ALP–photon conversions in astrophysical magnetic fields. Section 4 presents the sensitivity of current and next-generation MeV gamma-ray instruments.

## 2. ALP production in BNS mergers

The model considered here is a KSVZ-inspired ALP [35, 36], in which the nucleon and photon couplings are related via

$$g_{ap} = \frac{2\pi m_N}{\alpha} \frac{C_{ap}}{C_{a\gamma}} g_{a\gamma}, \quad (1)$$

where  $\alpha$  is the fine-structure constant. The model-dependent coefficients take the values  $C_{ap} \simeq -0.47$  and  $C_{a\gamma} \simeq -1.92$  [23]. In the canonical KSVZ model, the neutron coupling satisfies  $g_{an} \simeq 0$ .

In the hot, dense post-merger region, ALPs are mainly produced through nucleon bremsstrahlung,

$$N + N \rightarrow N + N + a.$$

We employ hydrodynamical profiles from a  $1.375\text{--}1.375 M_\odot$  BNS merger simulation using the DD2 equation of state [37]. Temperatures reach  $T \simeq 20\text{--}40$  MeV during the first tens of milliseconds, and densities exceed several times nuclear saturation. Nucleon degeneracy effects, effective masses, and general-relativistic redshift corrections (implemented via the lapse function) are included.

The resulting ALP spectrum peaks at  $E \simeq 30$  MeV and is integrated over the first  $\sim 1$  s of the evolution. Although the emissivity is lower than in core-collapse supernovae—due to lower temperatures, stronger degeneracy, and shorter emission timescales—it can still produce an observable converted photon flux when combined with a GW trigger.

### 3. Conversions in magnetic fields

ALPs may convert into photons via the interaction term  $g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$ . We consider conversions both in the merger remnant magnetic field and in the Milky Way magnetic field.

The merger remnant is expected to host a magnetar-strength dipolar magnetic field,

$$B(r) = B_0 \left( \frac{r_0}{r} \right)^3, \quad (2)$$

where we conservatively take  $r_0 = 10$  km and  $B_0 = 10^{15}$  G [38–41]. For relativistic ALPs on radial trajectories, conversions are computed by solving a Schrödinger-like propagation equation [24–26]. Near the remnant, QED vacuum birefringence suppresses mixing, but beyond  $\sim 10^4$  km conversion becomes efficient. Typical conversion probabilities lie in the range  $P_{a\gamma} \sim 10^{-7}$ – $10^{-9}$  for  $g_{a\gamma} = 10^{-12}$  GeV $^{-1}$ .

For Milky Way conversions, we use the Jansson–Farrar magnetic field model [27], with parameters updated by *Planck* (“Jansson12c”) [28, 30–32]. We evaluate the conversion probability along the direction of GW170817,  $(\ell, b) = (308.38^\circ, 39.30^\circ)$ , where  $\ell$  and  $b$  denote Galactic longitude and latitude, respectively. The probability conversion in the Milky Way are of the order  $10^{-5}$  –  $10^{-6}$  for  $g_{a\gamma} = 10^{-12}$  GeV $^{-1}$ . The resulting photon flux is given by

$$\frac{d\phi_\gamma}{dE_\gamma}(E, L) = \frac{1}{4\pi d^2} \frac{dN}{dE}(E) P_{a\gamma}(E, L). \quad (3)$$

where  $d$  is the distance of the BNS merger event and  $\frac{dN}{dE}(E)$  is the ALP-spectra produced by  $NN$  bremsstrahlung processes.

### 4. Sensitivity of gamma-ray experiments

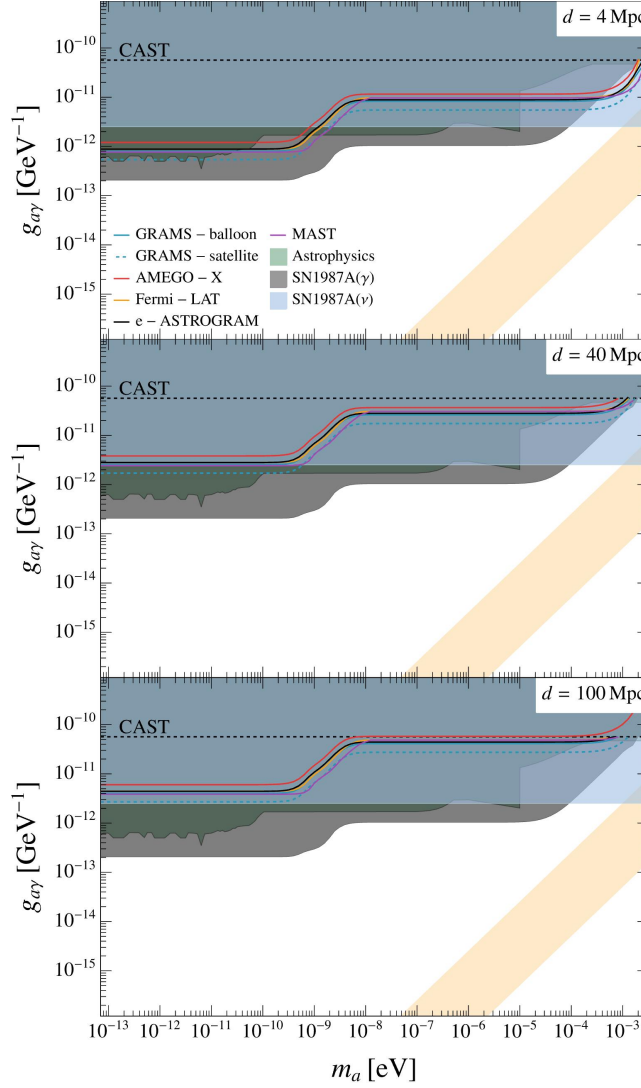
The detectability of the ALP-induced gamma-ray burst depends on the characteristics of MeV gamma-ray detectors. In this analysis, we consider the currently operational *Fermi*-LAT [3] and the proposed experiments e-ASTROGRAM [1], AMEGO-X [2], GRAMS-balloon and GRAMS-satellite [4], and MAST [5].

For all instruments considered, the expected background within a 10 s time window is below unity. We therefore estimate the sensitivity by requiring at least three detected photons in 10 s, corresponding to a 95% confidence level following the Feldman–Cousins procedure [33]. The corresponding sensitivities are shown in Fig. 1. Using the KSVZ relation between  $g_{a\pi}$  and  $g_{a\gamma}$ , a BNS merger at a distance of 40 Mpc yields sensitivities of

$$g_{a\gamma} \gtrsim \text{few} \times 10^{-12} \text{ GeV}^{-1} \quad (m_a \lesssim 10^{-9} \text{ eV}),$$

for the most promising proposed missions, which are already excluded by the SN 1987A bound.

The probability of a joint GW and ALP-induced gamma-ray detection depends on the instrument field of view and the BNS detection rate of GW observatories. Wide-field-of-view missions such as GRAMS may expect roughly one joint detection per decade for BNS mergers within 100 Mpc. Third-generation GW detectors, such as Einstein telescope [48], will substantially increase this rate by giving a warning of the events hours or days in advance.



**Figure 1:** Sensitivities of e-ASTROGRAM [1], AMEGO-X [2], *Fermi*-LAT [3], GRAMS-balloon and GRAMS-satellite [4], and MAST [5] in the  $(g_{a\gamma}, m_a)$  plane, assuming the KSVZ-inspired relation between  $g_{ap}$  and  $g_{a\gamma}$ . The BNS source is placed at the sky location of GW170817 at distances of  $d = 4, 40,$  and  $100$  Mpc. The SN 1987A gamma-ray bound [6, 7], the CAST solar-axion limit [8], and other astrophysical bounds [9, 10, 12, 34] are also shown.

## 5. Conclusions

Binary neutron star mergers provide a novel multimessenger avenue for ALP searches, combining precise GW timing with sensitive MeV gamma-ray observations. Although ALP production is weaker than in supernovae, the excellent GW time tagging and wide-field gamma-ray instruments make ALP-induced gamma-ray bursts detectable even at extragalactic distances. For ultralight ALPs with KSVZ-like couplings, sensitivities down to  $g_{a\gamma} \sim \text{few} \times 10^{-13} \text{ GeV}^{-1}$  are achievable.

Future MeV gamma-ray missions and next-generation GW detectors will significantly enhance these prospects, establishing BNS mergers as a valuable tool in multimessenger particle astrophysics.

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