Multimessenger Constraints on Radiatively Decaying Axions from GW170817

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The metastable hypermassive neutron star produced in the coalescence of two neutron stars can copiously produce axions that radiatively decay into $\mathcal{O}(100)$ MeV photons. These photons can form a fireball with characteristic temperature smaller than 1 MeV. By relying on x-ray observations of GW170817/GRB 170817A with CALET CGBM, Konus-Wind, and Insight-HXMT/HE, we present new bounds on the axion-photon coupling for axion masses in the range 1–400 MeV. We exclude couplings down to 5×10^{-11} GeV^{-1}, complementing and surpassing existing constraints. Our approach can be extended to any feebly interacting particle decaying into photons.

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Introduction.—The first observation of a binary neutron star (NS) merger event in gravitational waves and electromagnetic radiation, GW170817, has shed new light on the properties of NSs, the behavior of matter at nuclear densities, as well as the synthesis of the elements heavier than iron [1–3]. Besides providing crucial insights on fundamental physics, NS mergers can be employed as laboratories to test physics beyond the standard model, such as long-range interactions and general relativity modifications (e.g., [4–17]), and their remnant can produce light axions [18,19] and sterile neutrinos [20], as well as dark photons [21]. Moreover, the compact object resulting from the merger can potentially provide new and complementary information on putative heavy particles beyond the standard model, which could have an impact on cosmology [22–25] or play the role of dark matter mediator [26,27], and that cannot be excluded through the cooling of stars like horizontal branch stars, red giants, or white dwarfs [28,29]. Being hot and dense, the remnant can produce particles with mass $\gtrsim 1$ MeV, akin to core-collapse supernovas (SNs) and other energetic transients [30–42].

The multimessenger signals of GW170817 are consistent with the formation of a metastable hypermassive NS (HMNS) that lived for up to 1 s [43,44] (see later discussion for implication of the lifetime of the remnant) before collapsing into a black hole (BH). We show that one can probe the production of heavy axionlike particles with mass up to several hundreds MeVs with coupling to photons $-(1/4)g_{a\gamma\gamma}aF\tilde{F}$ (axions for short) in the HMNS remnant. After being produced, axions leave the HMNS and decay radiatively into high-energy ($\simeq$100 MeV) photons, as sketched in the top panel of Fig. 1. Since we focus on heavy semirelativistic axions, the daughter photons are dense enough that they do not propagate freely. Rather, they interact with each other rapidly producing a fireball, a plasma shell with temperature $\simeq$100 keV in the HMNS remnant frame, as we have recently pointed out in the context of SNs in Ref. [40]. This gas later evolves similarly to a "standard" fireball propagating in vacuum. Differently from the fireball assumed to power γ-ray bursts (see, e.g., Refs. [45,46]), the axion-sourced fireball features little-to-no baryon loading, is not expected to accelerate nonthermal particles, and forms almost instantaneously after the NS merger (hence, the time of fireball formation can be inferred from gravitational wave observations). The fireball first expands adiabatically and then freely. The resulting photons reach Earth with a quasithermal spectrum with low average energies.

Crucially, the signal arising from axions with a relatively short lifetime produced in a NS merger consists of reprocessed photons that travel to Earth, and it should therefore be detected by x-ray detectors, rather than, as one may naively expect, γ-ray detectors such as Fermi-LAT [47] (see lower panel of Fig. 1). In this Letter, we present novel bounds on axions from the nonobservation of an axion-sourced fireball at GW170817/GRB 170817A by CALET CGBM [48], Konus-Wind [49], and Insight-HXMT/HE [50].

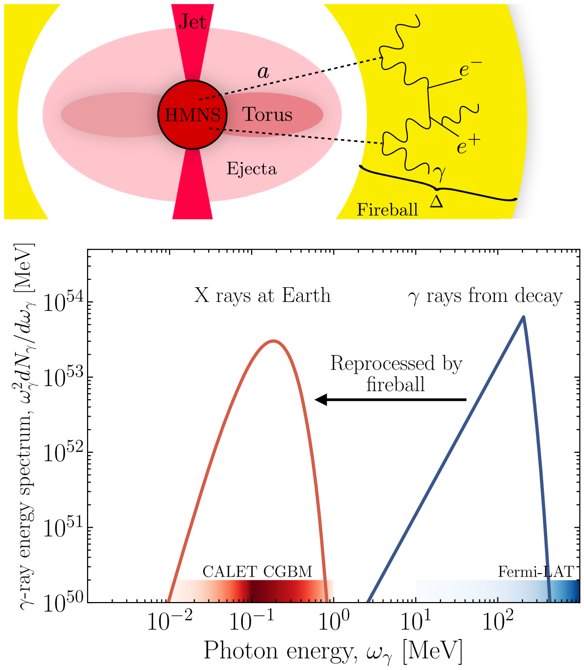

FIG. 1. Upper panel: schematic representation of the NS merger remnant and the fireball produced from axion decay. Lower panel: γ-ray spectrum produced by axion decay (blue line) and final spectrum reprocessed by the fireball (red line). The photon energy is reduced from 100 MeV to less than 1 MeV; the color bars on the bottom show the sensitivity ranges of Fermi-LAT and CALET CGBM, which we use to set bounds. Axion mass and coupling are set to $m_a = 202$ MeV and $g_{a\gamma\gamma} = 2.2 \times 10^{-10}$ GeV^{-1} for illustrative purposes.

Reference neutron star merger remnant model for particle emission.—Observations of GW170817 suggest an asymmetric NS merger with primary mass of 1.36–1.89$M_\odot$ and secondary mass of 1.00–1.36$M_\odot$ assuming high spin (respectively, 1.36–1.60$M_\odot$ and 1.16–1.36$M_\odot$ for low spin scenarios) [51]. In order to compute the axion production rate, we rely on the suite of binary NS merger remnant models presented in Refs. [52–55] and obtained though three-dimensional relativistic particle hydrodynamic simulations (see Refs. [52,53] for more details).

First, we consider as our fiducial model the simulation of two nonrotating NSs with mass of 1.45$M_\odot$ and 1.25$M_\odot$, respectively, and nuclear equation of state (EOS) SFHo. In the HMNS core, where axion production occurs, the typical temperature is a few tens of MeV and the baryon density is around 10^{14} g/cm^3. The benchmark simulation we use tracks the NS merger remnant evolution up to 10 ms, and we assume (in agreement with results from Refs. [56,57]) that the remnant has reached a steady state and does not appreciably change its thermodynamical properties up to 1 s, namely up to the time considered for BH formation; we later investigate the impact of this assumption on the axion bounds. Then, we also compute the uncertainty introduced by the EOS and the mass of the two NSs by considering another EOS (DD2), and different NS masses (symmetric merger model, with two NSs of 1.35$M_\odot$ mass) [52,53,55].

Axion and photon spectra.—Axions are produced in the HMNS mainly via two different processes. One is the Primakoff effect, i.e., photons that convert into axions in the field generated by charged particles ($\gamma + Ze \to a + Ze$), while the other is photon coalescence ($\gamma + \gamma \to a$) [33,35,36]. We obtain the axion spectrum integrating over the volume of the HMNS and time,

$$\frac{dN_a}{d\omega_a} = \frac{1}{2\pi^2}\int dV dt \frac{1}{e^{\omega_a/T}-1} \times \left(\Gamma_{\rm P}\omega_a\sqrt{\omega_a^2-\omega_{\rm P}^2} + \Gamma_{\rm c}\omega_a\sqrt{\omega_a^2-m_a^2}\right), \quad (1)$$

where $\Gamma_{\rm P}$ and $\Gamma_{\rm c}$ are the Primakoff and coalescence production rates, and $\omega_{\rm P}$ is the plasma frequency modifying the photon dispersion relation inside the HMNS, $\omega^2 = k^2 + \omega_{\rm P}^2$. We account for gravitational redshift correction of the energy. We refer the interested reader to the Supplemental Material for additional details [58]. Axions subsequently decay into photons away from the HMNS, at a distance of $\mathcal{O}(10^3$–$10^6)$ km. The photon spectrum right after the axion decay (and before photons interact with each other) is easily found assuming a box spectrum for the daughter photons [35,69,70],

$$\frac{dN_\gamma^i}{d\omega_\gamma} = 2\int_{\omega_\gamma}^{\infty} \frac{dN_a}{d\omega_a}\frac{d\omega_a}{\omega_a}, \quad (2)$$

where i stands for "initial."

Fireball production.—If the injected photons are dense enough, they form a shell of thermalized photon fluid that we dub a fireball, diluting the photon average energy to the sub-MeV range. The physics behind this process is described in Ref. [40], which we refer to for technical details. We model injection as a uniform shell of photons produced by the decay of axions and denote the shell radius with r, and the shell thickness Δ. For each axion mass and coupling, the fireball properties are self-consistently determined following Ref. [40], accounting for only those axions decaying outside a minimum radius of 1000 km, below which photons' free escape would be impeded [21]. Fireball formation requires both pair production, to produce seed electron-positron pairs, and the subsequent bremsstrahlung reaction of $e^\pm$, to increase the number of particles via $e \to e\gamma$, to be fast enough. With this criterion, we identify the region of parameter space in which the fireball can form.

Photons initially thermalize with a large chemical potential $\mu_{\gamma,i} < 0$ and an initial temperature of the order of the axion mass $T_{\gamma,i}$; the electron and positron populations both have the same chemical potential and temperature. As bremsstrahlung proceeds, the average energy per particle is diluted, reducing both $|\mu_\gamma|$ and T_γ; as T_γ becomes smaller than the electron mass, the $e^\pm$ population in the plasma is depleted by pair annihilation. If it becomes sufficiently rarefied, bremsstrahlung stops, with the plasma temperature determined by the freeze-out condition

$$\gamma n_e(T_\gamma, \mu_\gamma) v_{\rm th} \sigma_{ee\to ee\gamma} \Delta = 1, \tag{3}$$

where $n_e(T_\gamma, \mu_\gamma)$ is the electron number density, $v_{\rm th}$ is the thermal velocity, and $\sigma_{ee\to ee\gamma}$ is the bremsstrahlung cross section, and γ the Lorentz factor. If the plasma is dense enough, bremsstrahlung may completely equilibrate the plasma, in which case the final state is rather determined by the condition $\mu_\gamma = 0$. In addition, conservation of the total energy $\mathcal{E}$ and radial momentum $\mathcal{P}$ of the plasma must be enforced. These three conditions together determine the final temperature T_γ, chemical potential μ_γ, and Lorentz factor γ of the fireball. Finally, the spectrum observed at Earth is [40]

$$\frac{dN}{dE} \propto -E \log\left[1 - e^{-\eta - \frac{E}{2\tau}}\right], \tag{4}$$

with $\eta = -\mu_\gamma/T_\gamma$, $\tau = \gamma T_\gamma$, and the spectrum being normalized according to the total energy injected.

Figure 2 shows the average energy $\bar{E} = 4\tau \mathrm{Li}_4(\eta)/\mathrm{Li}_3(\eta)$—where $\mathrm{Li}_s(z)$ is the polylogarithm of order s—of the photons observed at Earth in the region of fireball formation. For a given mass m_a, increasing the coupling first lowers the average energy, since bremsstrahlung becomes more effective in increasing the particle number; however, at some point bremsstrahlung manages to enforce chemical equilibrium $\mu = 0$, after which increasing the coupling only increases the total energy density injected by the axions and therefore also the average energy. For large couplings, most axions decay within the inner optically thick region without forming a fireball. Overall, the typical photon energy in the fireball is below MeV.

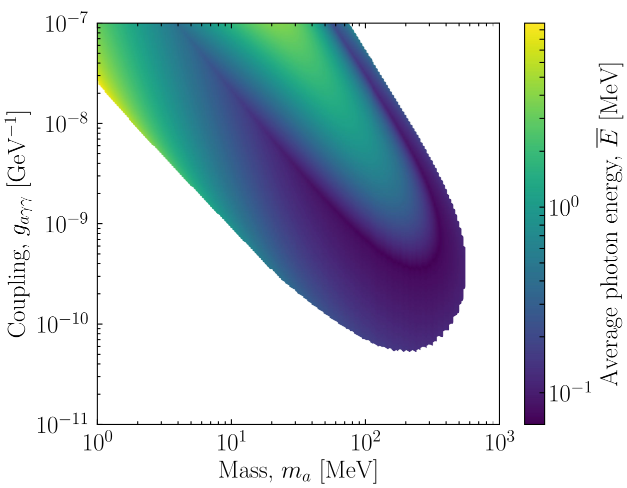

FIG. 2. Isocontours of the average photon energy at the end of the fireball evolution, in the plane spanned by the axion mass and coupling. In the white region, the fireball does not form. As the coupling increases, the average energy first lowers, due to more efficient bremsstrahlung, and then increases, due to the larger axion production and the smaller fireball radius.

Axion constraints.—We now compare our predicted axion spectra with the data collected by CALET CGBM [48], Konus-Wind [49], and Insight-HXMT/HE [50] from GW170817/GRB 170817A (see Table I) [71]. These three experiments were online on August 17, 2017 (at 12:41:04 UTC). Since it is estimated that GW170817/GRB 170817A occurred at a distance of $D_L = 41^{+16}_{-12}$ Mpc assuming high spin or $D_L = 39^{+7}_{-14}$ Mpc for low spin [51], the upper limits on the x-ray emissivity correspond to an integrated luminosity of 3×10^{46} erg. We obtain novel stringent bounds on the axion coupling to photons by requiring that the photon fluence at Earth, integrated with the energy spectrum of Eq. (4) over the sensitivity interval of each experiment, is smaller than the upper limit found by x-ray telescopes, excluding part of the parameter space where an axion-sourced fireball can form.

Even with just a single NS merger event, we can exclude novel parts of the axion parameter space (red region in Fig. 3). While the decay of axions was proposed as a mechanism to produce the fireball powering γ-ray bursts [73], this would require luminosities above 10^{52} erg, in conflict with low energy SNs and GW170817 observations.

One-zone model.—The dependence of the axion bounds on the NS merger remnant model raises the question: what parameters of the HMNS mostly impact our bounds? To answer this question, we work out a one-zone model showing the bound dependence on the NS merger remnant properties. We model the HMNS as a sphere with uniform temperature T and radius R, lasting for a time δt. In the new region excluded in this Letter, the dominant emission process is photon-photon coalescence, so we only consider this process. The total energy injected in axions is

$$\mathcal{E} = \frac{g_{a\gamma\gamma}^2 T^3 m_a^4 R^3 \delta t}{96\pi^2} e^{-m_a/T} \sqrt{\frac{\pi m_a^3}{2T^3}}, \tag{5}$$

while the total number of axions injected is

$$\mathcal{N} = \frac{g_{a\gamma\gamma}^2 T^2 m_a^4 R^3 \delta t}{96\pi^2} e^{-m_a/T} \sqrt{\frac{\pi m_a}{2T}}. \tag{6}$$

The excluded region is determined by two conditions. First, the fireball must form, so that photons are reprocessed

TABLE I. X-ray upper limits from the telescopes online during GW170817/GRB 170817A. All the quoted upper limits are at 90% confidence level and are taken from Ref. [1].

Telescope	Flux upper limit (erg cm^{-2} s^{-1})	Energy band
CALET CGBM	1.3×10^{-7}	10–1000 keV
Konus-Wind	3.0×10^{-7} (erg cm^{-2})	10 keV–10 MeV
Insight-HXMT/HE	3.7×10^{-7}	0.2–5 MeV

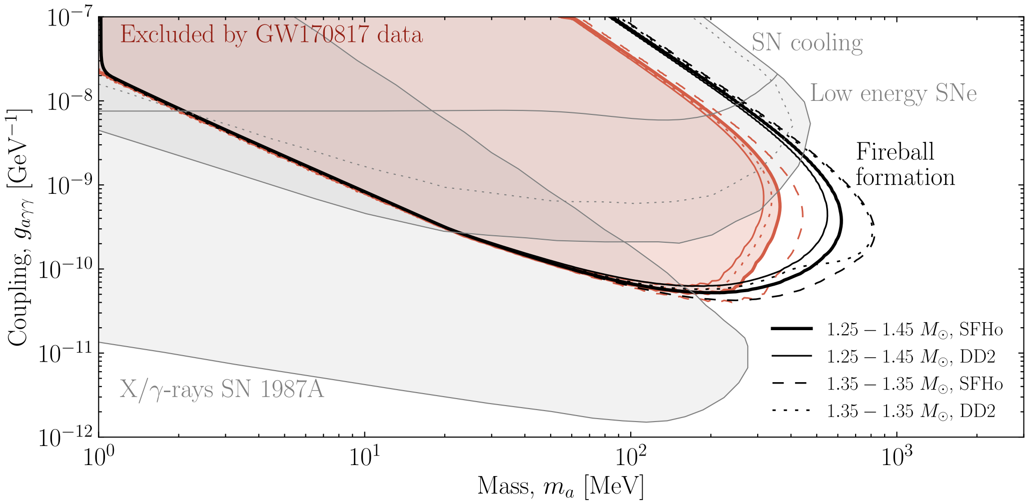

FIG. 3. Constraints on the axion mass and coupling, obtained by investigating under which conditions fireball formation occurs (black lines; below 1 MeV no fireball formation can occur since pair production cannot happen). The bounds due to the nonobservation of an axion-sourced fireball from GW170817/GRB 170817A are shown in red. For comparison, the SN 1987A cooling bounds [35,36], bounds from low energy SNs [36] (dotted and solid lines for conservative and fiducial bounds, respectively), γ-ray [39] and x-ray [40] bounds due to axion decays from SN 1987A are also shown. The thick and thin solid, dashed and dotted contours have been obtained for our two different EOSs, as well as for symmetric and asymmetric NS merger remnant models. The nonobservation of an axion-sourced fireball from GW170817/GRB 170817A excludes a new region of the parameter space, complementary to the one excluded from core-collapse SNs.

in the region below the MeV range. In the large mass region, it is sufficient that pair annihilation is fast enough. Assuming that axions decay at a typical radius equal to their rest-frame decay length, and parametrizing the pair annihilation cross section as $\sigma_{\gamma\gamma\to e^+e^-} = 8\pi\alpha^2/m_a^2 \log(m_a/m_e)$ evaluated at the typical center-of-mass energy of the photons $m_a/2$, we find

$$\frac{g_{a\gamma\gamma}^6 m_a^8 \alpha^2 T^2 R^3 \delta t}{98304\pi^4} e^{-m_a/T} \sqrt{\frac{\pi m_a}{2T}} \log\left(\frac{m_a}{m_e}\right) > 1. \quad (7)$$

This qualitative condition determines the floor of our new bounds. The second requirement is that the total injected energy is larger than the threshold that would have been visible at the x-ray telescopes, $\bar{\mathcal{E}} = 4\pi D_L^2 \mathcal{F} \delta t$, where we estimate $\delta t = 1$ s, D_L is the luminosity distance, and $\mathcal{F}$ is the upper bound on the observed flux:

$$\frac{g_{a\gamma\gamma}^2 T^3 m_a^4 R^3 \delta t}{96\pi^2} e^{-m_a/T} \sqrt{\frac{\pi m_a^3}{2T^3}} = \bar{\mathcal{E}}. \quad (8)$$

This condition determines the largest masses at which our new bound closes to the right in Fig. 3.

From these equations, we see that the main remnant parameters affecting our new bounds are the average temperature of the HMNS (T), the average space volume, and time duration of the event ($R^3\delta t$). Notice that the bottom tail of the bounds in Fig. 3 is determined by Eq. (7) and depends very mildly on these parameters, given the strong $g_{a\gamma\gamma}^6$ dependence. The ballpark of our bounds for our suite of NS merger remnant models can be inferred by the typical values $T \simeq 18$ MeV, $R = 16$ km, and $\delta t \simeq 1$ s.

Which among these parameters are more uncertain?—The largest uncertainty is associated to δt, the duration over which the NS merger remnant thermodynamic properties can be considered constant before BH formation. For simplicity, we assume $\delta t \simeq 1$ s, although our benchmark NS merger remnant simulations run up to 10 ms. On the other hand, existing work shows that the time it takes for a HMNS to collapse into a BH can be anywhere between 20 ms and more than 1 s [56,74–81], depending on the EOS, NS masses, and angular momentum of the compact HMNS. As for GW170817/GRB 170817A, Ref. [82] presents at least two arguments in support of $\delta t \simeq 1$ s, based on the time needed to eject enough material to power the observed optical and UV emission and on the delay time of 1.74 s between the gravitational waves and the electromagnetic signal. Other studies on the subject reach similar conclusions [83–86], and also the end-to-end simulations presented in Ref. [87] support the delayed BH formation of GW170817. Yet, the delay of the electromagnetic signal is not sufficient to conclusively claim that the HMNS lasted for 1 s; in fact the prompt γ-ray emission may have been produced by the shock breakout driven by the circumstellar material [88]. Even in this case, a delay between the merger and jet breakout should have been of the order of about 1 s, so the collapse should still have happened after about 700 ms. For the sake of simplicity, in the following, we assume the temperature to be constant between 10 ms and the time of BH formation, as found in numerical simulations; see, e.g., Refs. [56,57]. Notice that even if the collapse happened earlier than 1 s our bounds would not suffer significantly: our one-zone model shows that the floor of the bound would be weaker by a factor $(\delta t/1\ \mathrm{s})^{1/6}$. The right boundary of the excluded region would weaken at most by a factor $(\delta t/1\ \mathrm{s})^{1/2}$, following the one-zone model. However, it is the highest temperatures that determine the right boundary, and such temperatures are reached in the first 10 ms; thus, the change is mild.

The thermodynamic properties of our benchmark NS merger remnant simulations are conservative. Existing models, e.g., the ones of Ref. [57,89], reach peak temperatures several times larger than the ones assumed here, e.g., up to $\mathcal{O}(100)$ MeV. Therefore, axion emission could be even substantially larger than our estimate and extend to larger axion masses. On the other hand, the trapping of the fireball by the ejecta expelled after the merger can impact the chances of successfully detecting the fireball, as discussed in the Supplemental Material [58]. Since these two effects go in opposite directions, we conclude that our results fall in the right ballpark.

Discussion and outlook.—Multimessenger observations of NS merger remnants provide us with the unique chance to constrain the physics of feebly interacting particles decaying radiatively. We compute the electromagnetic emission due to axions produced in the HMNS resulting from the NS coalescence. The daughter photons produced by the axions decaying after leaving the HMNS form a shell whose temperature becomes smaller and smaller, until the gas first expands adiabatically, converting the temperature into bulk momentum, and finally expands freely. The low-energy photons (~100 keV) produced through these mechanism should have been observed by the x-ray telescopes online at the time of the GW170817/GRB 170817A detection. Since CALET CGBM, Konus-Wind, and Insight-HXMT/HE reported null results, we rely on their flux upper limits to constrain the axion parameter space. Intriguingly, we place bounds for a new region of the parameter space and complement existing core-collapse SN bounds.

Our analysis can be applied to other particles decaying into photons, such as heavy neutral leptons [90–93]. More precise bounds could be derived in the future once long-term sophisticated NS merger simulations will become available. Moreover, dedicated differential energy analyses of x-ray telescopes would improve the bounds, since the method that we have adopted to compute the photon differential spectrum can be used to compare the predicted and observed emissivity per energy interval. Finally, if upcoming observations of NS mergers should feature a very hot HMNS, it will be possible to probe axions with masses up to the GeV scale. Therefore, future multimessenger observations may provide us with the tantalizing opportunity of observing an axion-sourced fireball, with a quasithermal spectrum. Conversely, its nonobservation would give further, stringent constraints on heavy axions coupling to photons.

Note added.—We recently became aware of Ref. [94], which proposes constraints on long-lived axions from GW170817 by relying on γ-ray observations. In contrast, our Letter focuses on shorter axion lifetimes (which Ref. [94] does not constrain). Moreover, compared to Ref. [94], we assume a different NS merger remnant benchmark model that reaches lower temperatures, leading to more conservative axion constraints. More importantly, we account for the fireball formation; the latter allowed us to obtain novel bounds in unconstrained regions of the parameter space, and invalidates part of the future reach projections of Ref. [94].

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