

Small Progenitors, Large Couplings: Type Ic Supernova Constraints on Radiatively Decaying Particles

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Supernova (SN) 1987A provides classic bounds on gamma-ray flashes from the radiative decay of sub-GeV particles, but the latter may decay so rapidly as to be shielded by the stellar envelope. Using axionlike particles with photon coupling as a benchmark, we show that Type Ic core-collapse supernovae largely evade this attenuation due to their compact progenitors. We identify two regimes. At small couplings, while individual flashes may be missed by Fermi-LAT, the high Type Ic rate enables a stacking analysis of nondetections. At larger couplings, decay photons trigger fireball formation; the absence of a signal from the rare broad-lined Type Ic SN 1998bw excludes this scenario. The resulting bounds significantly exceed those from SN 1987A for short decay lengths.

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Introduction—Feebly interacting particles with mass smaller than the GeV scale are the target of many astrophysical, cosmological, and laboratory searches [1–5]. On Earth, the best way to detect these particles is through beam-dump experiments, in which a beam is shot on a target, and upon the interaction of the former with the latter novel particles might be produced [6–19]. Because of their mass and coupling, novel particles can decay radiatively back to standard model degrees of freedom. The bounds from beam-dump experiments share a universal shape featuring a floor and a ceiling, as the production of particles that interact too feebly is suppressed, but particles that interact too strongly will decay in the shield before reaching the decay volume.

Supernovae (SNe) are gargantuan beam-dump experiments [20]. The hot, dense core of the protoneutron star (PNS, which has a radius $R_{\text{NS}} \simeq 10$ km) serves as both beam and target for the production of radiatively decaying particles such as axions [21–30], dark photons [31–33], and sterile neutrinos [34,35], which are emitted with energies $E \simeq 100$ MeV. We will focus on the case of axionlike particles (ALPs) with a coupling to photons, but the conclusions we will reach apply to any feebly interacting particle featuring decay channels with photons in the final state. Depending on the decay length λ_a of the ALPs, they might decay outside of the stellar layers surrounding the core, so that the photon flux resulting from the decay would show up in gamma-ray [21–23] and x-ray telescopes [36]. However, the stellar envelope can act as a shield (see Refs. [37,38] for the effects of the decay within this shield) so that these bounds have a ceiling akin to the one of beam-dump searches. Sanduleak-69 202, the blue supergiant progenitor of SN 1987A, had a best-estimate radius of $R_{\text{prog}} = 31\text{--}37R_{\odot}$, $R_{\odot} \simeq 7 \times 10^{10}$ cm [39–42]. The main point of our Letter is that the most stringent constraints for decay lengths $\lambda_a \simeq R_{\text{prog}}$ do not come from the closest observed supernova (SN) (i.e., from SN 1987A), but are rather obtained from the most compact core-collapse SNe, even if more distant. Therefore, we show in the following

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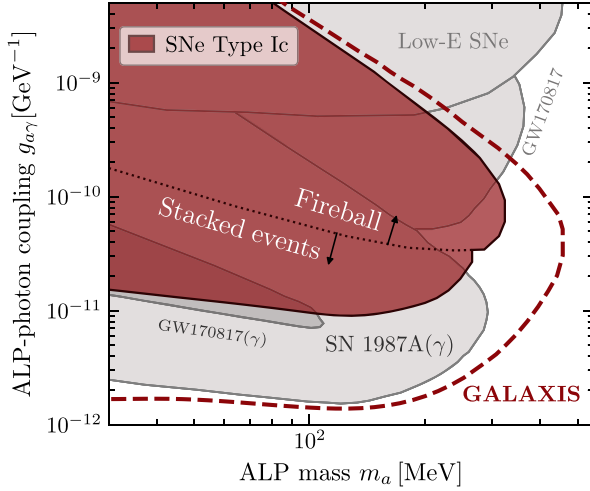


FIG. 1. Novel bounds on ALP-photon coupling from Type Ic SNe from stacked-events strategy and from the nonobservation of a fireball from SN 1998bw. Existing constraints include low-energy SNe [37,38], neutron star mergers [72,73], and gamma-ray and x-ray signals at the Solar Maximum Mission and the Pioneer Venus Observatory [21–23,36]. The red dashed line shows the projected sensitivity for a Type Ic SN at 10 Mpc with a next-generation γ -ray telescope network such as GALAXIS [74].

that Type Ic SNe, which sport radii as small as $R_{\text{prog}} \simeq 0.1\text{--}1R_{\odot}$ [43], can reliably surpass the bounds of SN 1987A and reach couplings larger by one order of magnitude, probing new portions of the parameter space (see Fig. 1).

ALP-induced gamma rays from Type Ic SNe—The inner core of Type Ic SNe is expected to have properties very similar to those of Type II SNe, of which SN 1987A was a member; we exclude here the broad-line SNe Ic, whose powerful energy output is probably connected with rapid rotation of the stellar core and new-born PNS. The PNS is then a similarly efficient factory of putative sub-GeV particles. Here, we focus on radiatively decaying species, of which the prime and most well-studied example is the ALP coupling to photons with the Lagrangian $\mathcal{L} = -\frac{1}{4}g_{a\gamma}aF\tilde{F}$, where a is the ALP field, F is the electromagnetic field tensor with dual $\tilde{F}$, and $g_{a\gamma}$ is the coupling.

The production of ALP coupling to photons is driven primarily by Primakoff conversion $N + \gamma \rightarrow N + a$ and coalescence $\gamma + \gamma \rightarrow a$; the latter dominates for heavy ALPs [37]. The volumetric emissivity from these processes depends on the temperature and density of the hot plasma, and is reviewed in Supplemental Material (SM) [44]. The overall amount of ALPs emitted by the SN core is obtained by integrating this emissivity over the profile of the SN core for the Garching group’s muonic model SFHo-18.8 [61]. This model exhibits a relatively cold core, with a maximum temperature reaching up to 40 MeV, with a baryonic PNS mass of $1.351M_{\odot}$, and thus leads to a conservative estimate for the amount of ALPs that a typical core-collapse SN

could produce; it is often referred to as cold SN model in the literature (e.g., Refs. [22,62–64]). Since we are interested in heavy ALPs, at the kinematic threshold for production and therefore influenced by inhomogeneous regions with high temperature, we do not attempt a reproduction of the resulting ALP emissivity using a one-zone homogeneous scenario. The final result is contained in the total amount of ALPs emitted during the core collapse dN_a/dE_a differential in the ALP energy E_a , which we show in SM [44].

The ALPs produced in the core decay to gamma rays via $a \rightarrow \gamma + \gamma$. Those photons produced outside of the progenitor, with a radius R_{prog} , will source a flash visible at Earth; the resulting time-integrated photon spectrum is

$$\frac{dN_{\gamma}}{dE_{\gamma}} = \int_{E_{\gamma} + \frac{m_a^2}{4E_{\gamma}}}^{+\infty} \frac{2dE_a}{p_a} \frac{dN_a}{dE_a} \exp\left[-\frac{\Gamma_a m_a R_{\text{prog}}}{p_a}\right] F_{\text{sup}}. \quad (1)$$

Here, $\Gamma_a = g_{a\gamma}^2 m_a^3 / 64\pi$ is the decay rate of an ALP at rest with mass m_a , and $p_a = \sqrt{E_a^2 - m_a^2}$ is the axion momentum; see, e.g., Ref. [30] for a derivation. The signal depends on the coupling and mass. We also introduce a suppression factor due to a cap on the time window t_{max} ,

$$F_{\text{sup}} = 1 - \exp\left[-\Gamma_a \left(\frac{2E_{\gamma} t_{\text{max}}}{m_a} - \frac{m_a R_{\text{prog}}}{p_a}\right)\right]. \quad (2)$$

From here we see that the signal is spread over a typical time span determined by the propagation time for photons produced from noncollinear decays and for the slower-than-light ALPs before the decay [64],

$$t_{\text{del}} = \frac{m_a}{2\Gamma_a E_a} \simeq 220 \text{ s } g_{10}^{-2} E_{300}^{-1} m_{10}^{-2}, \quad (3)$$

with $g_{10} = g_{a\gamma} / 10^{-10} \text{ GeV}^{-1}$, $E_{300} = E_a / 300 \text{ MeV}$, and $m_{10} = m_a / 10 \text{ MeV}$. When $t_{\text{del}} \lesssim 5 \text{ s}$, the typical duration of the SN emission of feebly interacting particles (see, e.g., Ref. [65] for the case of neutrinos), the duration of the signal will be determined by the SN emission itself. For our purposes, as we will see, it suffices that the flash lasts less than an hour or so to treat it as an instantaneous pulse, for which only the time-integrated emission in Eq. (1) matters. Hence, we choose t_{max} equal to 1 h, the span of one bin, discussing the implications below.

The advantage of Type Ic SNe, compared with SN 1987A, appears now clear; the smaller R_{prog} , the larger couplings can be probed without the exponential decay term in Eq. (1) suppressing the signal. For a typical Type Ic SN, the progenitor radius used throughout this Letter is $R_{\text{prog}} = 10^{11} \text{ cm}$. The typical radii of C + O/He composition interfaces in red supergiants are much lower, ranging from $3 - 6 \times 10^9 \text{ cm}$ (e.g., Ref. [66]). For naked C + O stars, observational constraints are harder to come by. Simulations of helium stars including mass loss lead to

typical radii of 10^{10-11} cm [67,68], but Type Ic are for the larger part expected to have lost the helium envelope as well. Nevertheless, since we will consider a sample of Ic SNe, we cannot exclude that some of them may have some residual helium. Ultrastripped progenitors may sport radii as low as 10^{10} cm [43]. For individual Type Ibc SNe, the radii obtained from light-curve fitting can be 10^{10} cm [69,70]. For comparison, the radius of Sanduleak, the progenitor of SN 1987A, had a radius of about $35R_{\odot} \simeq 2.5 \times 10^{12}$ cm, more than 2 orders of magnitude larger [39–42]. Since the decay rate grows with the square of the axion-photon coupling, by this simple argument we can probe couplings one order of magnitude larger than SN 1987A, provided we identify potential sources from which a gamma-ray flash should have been visible.

Fermi-LAT detection of gamma-ray flash—If the decay length were long enough, the photons produced in the decay of ALPs would propagate freely, arriving at Earth and potentially showing up at gamma-ray telescopes. Here we focus on a collection of SNe, motivated by their close distance and the possibility of pinpointing rather precisely their explosion time t_{coll} ; all sources are collected in SM (Table I) [44], together with their distance d from Earth. The corresponding differential fluence expected at Earth is then $\mathcal{F}_{\gamma} = (1/4\pi d^2) dN_{\gamma}/dE_{\gamma}$.

Barring fireball formation (see below), ALPs coupling to photons should produce a gamma-ray flash at 100-MeV energies, i.e., at energies much larger than the usually observed energies of gamma-ray bursts (GRBs), for all Type Ic SNe. We therefore ask whether such a signal should have been observable with the Fermi Large Area Telescope (LAT), which is sensitive to γ -rays from 20 MeV to beyond 300 GeV [71].

At first glance, constraining gamma-ray flashes from Type Ic SNe with Fermi-LAT appears impossible due to a timing issue. The axion-induced flash lasts between a few seconds and a few hours, and its initial time is impossible to pinpoint in the absence of a visible neutrino burst due to the large distance from the source. While a candidate SN can be precisely identified, the beginning of the explosion is usually uncertain; the stellar core collapse happens much earlier and the explosion becomes observable with a delay determined by the propagation time of the shock wave through the progenitor, which is typically less than a minute for the considered compact progenitors. The difficulty in estimating the time of arrival of the putative fireball implies that we cannot even know if Fermi-LAT, which only sees a portion of the sky of about 20% at any given time, and whose field of view varies over timescales of minutes, was actually sensitive during the collapse. Indeed, if a clear timing of the onset of the explosion is not available, a single Type Ic SN cannot individually provide constraints; it is always possible that the explosion occurred while Fermi-LAT was not observing the correct direction. (Notice that this statement does not necessarily hold for a broad-lined

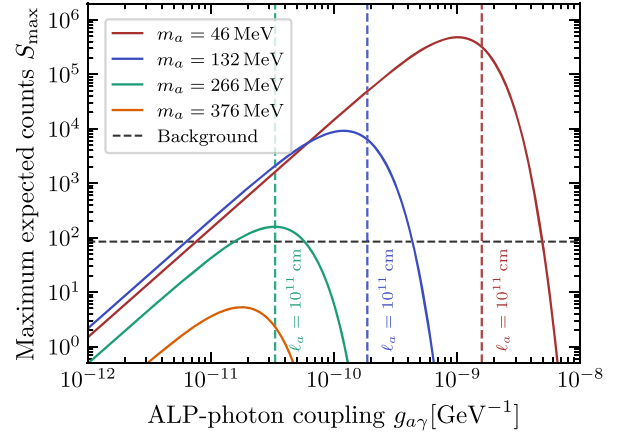


FIG. 2. Expected signal counts for SN 2020oi as a function of $g_{a\gamma}$ for different ALP masses. We obtain the expected counts from the time-integrated model fluence, assuming the maximum exposure among all the 1-h time bins within the time window of interest. The horizontal line shows the mean expected background counts per 1-h bin in the time window v_1 . The vertical lines correspond to a decay length ℓ_a for an ALP with energy 300 MeV equal to the progenitor radius.

Type Ic SN associated with a detected high-energy burst, for which t_{coll} could be constrained accurately.) However, the relative frequent occurrence of Type Ic SNe allows us to circumvent this difficulty, since the probability of a missed observation for all the SNe within a sample is significantly suppressed.

Motivated by this simple argument, we consider a sample of 15 Type Ic SNe, and consider their expected signal at Fermi-LAT. We use time bins of 1 h, consistently with our choice of t_{max} , and neglect any portion of the signal beyond that limit. We comment on the impact of this choice in our discussion. The details of the Fermi-LAT analysis we perform are reported in SM [44].

In Fig. 2, we show the number of signal events for one of our SNe (SN 2020oi), as a function of the coupling $g_{a\gamma}$, for various ALP masses. At low couplings, the expected signal grows quadratically with the coupling, while at large couplings it drops exponentially, due to a large fraction of ALPs decaying within the mantle of the progenitor. The threshold coupling at which exponential suppression begins is determined by the approximate condition $\Gamma_a R_{\text{prog}} \gtrsim 1$ [see Eq. (1)], as we can clearly see from the vertical lines in Fig. 2; since R_{prog} is much lower for our Type Ic SNe compared with Type II SNe, the signal remains large at much higher couplings than SN 1987A and other candidate SNe.

To finally constrain the ALP-photon coupling, we consider for each SN (indexed by Latin letters i) in our sample the probability that Fermi-LAT would not observe any gamma-ray flash within a ± 3 -day window around t_{coll} . This window was selected based on the uncertainty on t_{coll} , as discussed in SM [44]. Using the reconstructed

uncertainty, we determine the probability that the flash happened in each temporal bin (indexed by Greek letters α) $P_{i,\alpha}$, the number of background events $B_{i,\alpha}$, the observed number of events $N_{i,\alpha}$, and the expected number of events $S_{i,\alpha}$. For many of the bins the experiment is blind, so $S_{i,\alpha} = 0$.

We assume a Poisson likelihood for the number count $N_{i,\alpha}$, and denote the overall likelihood, including all bins and SNe, as $\Pi(g_{a\gamma}, m_a)$, with the renormalized log-likelihood $\Lambda(g_{a\gamma}, m_a) = -2 \log[\Pi/\Pi^0]$, where Π^0 is the likelihood in the absence of a gamma-ray flash. We then define a test statistic as the log-likelihood ratio with the best-fit case,

$$\chi(g_{a\gamma}, m_a) = \Lambda(g_{a\gamma}, m_a) - \Lambda(\hat{g}_{a\gamma}(m_a), m_a), \quad (4)$$

where $\hat{g}_{a\gamma}(m_a)$ is the ALP-photon coupling maximizing the likelihood for each value of m_a . For a 90% confidence level we set constraints by requiring $\chi(g_{a\gamma}, m_a) = 2.71$. With this strategy, even if a single SN has a large probability f_i for the gamma-ray flash to be missed, for N SNe this probability drops exponentially with N , allowing to set constraints.

Figure 1 shows our final constraints on the ALP-photon coupling in the small-coupling regime, marked by “stacked events.” As expected, these constraints reach decay lengths shorter than the ones excluded by SN 1987A because the more compact progenitor lets ALPs escape more easily.

ALP-sourced fireball at SN 1998bw—A peculiarity of the region we are constraining is that, if photons are injected in a compact enough region, they produce electron-positron pairs that subsequently lower their energy by radiating more photons via bremsstrahlung. The gamma rays, originally at hundreds of MeV, are reprocessed into a *fireball* [36], and their final energy ends up in the hundreds of keV range. (Similar fireballs can also be formed for strongly self-interacting neutrinos [75,76] and dark particles [63].) The region of fireball formation is deduced following the procedure in Refs. [36,72], which we recollect in SM [44], and is shown in Fig. 3; in this region, Fermi-LAT constraints do not apply, and must be complemented by an analysis of the x-ray signal from the direction of the relevant SNe. We show the fireball region for two alternative models of the SN core: the cold SN model, which is meant to represent qualitatively a scenario with formation of a rotating protomagnetar [77,78], and the so-called hot SN model LS220-20.0 with a typically higher temperature in the core [61,79] cut off at 1 s postbounce, meant to represent the more typical scenario for broad-lined SN in which the jet launching follows the formation of a black hole that shuts down emission from the PNS [80,81]. For our fiducial bounds in Fig. 1, we conservatively use the former scenario.

Crucially, the rare broad-lined Type Ic SN 1998bw has famously been related to GRB 980425, resulting in the first corroboration of the link between GRBs and SNe [82,83].

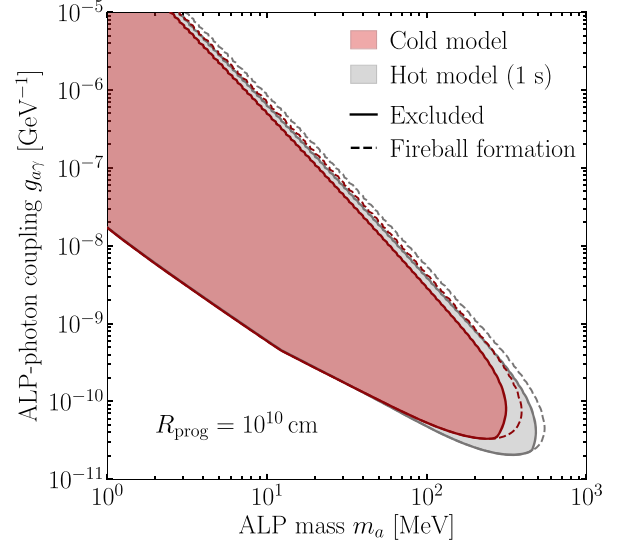


FIG. 3. Region of fireball formation (dashed) and constrained region from fireball nonobservation (solid; shaded). Our fiducial model for ALP production is the cold SN Garching simulation (red); we also show results using a hot SN model (gray) capped at 1 s postbounce, coarsely modeling a black hole formation in the broad-lined SN 1998bw.

The GRB was observed by the Burst and Transient Source Experiment (BATSE) instrument on the Compton Gamma-Ray Observatory [84] and by BeppoSAX [85], as both experiments were online on April 25, 1998, at 21:49 UTC. Differently from the SNe considered in the Fermi-LAT analysis, we can constrain the time of collapse quite accurately, thanks to the burst produced by the jet launched by the spinning protomagnetar or the black hole eventually formed after the collapse. The estimated distance was ~ 40 Mpc [86–88]; the measured fluence integrated above 20 keV from BATSE was $(4.0 \pm 0.6) \times 10^{-6}$ erg/cm² [84], so that a limit on the gamma-ray flash from ALP decay is 7×10^{47} erg. This allows us to set constraints on the nonobservation of the reprocessed gamma-ray signal in the fireball region, constraining the total energy injected in ALPs. Notice that we are extremely conservative through this criterion, since in reality no gamma rays were observed above 300 keV, and the constrained fluence refers to a duration of 23 s, while our ALP signal would be spread over roughly 1 s. The energy range of BATSE coincides with the range in which the fireball spectrum is reprocessed [72]. The overall region constrained by the fireball argument is shown in Fig. 1. We finally stress that Fig. 3 is obtained for $R_{\text{prog}} = 10^{10}$ cm, which was obtained for the specific case of SN 1998bw from light-curve fitting [70], while the stacked-events bound assumes $R_{\text{prog}} = 10^{11}$ cm. Therefore, at least part of the fireball formation region in Fig. 3 can be excluded also with the Fermi-LAT analysis.

Results and outlook—We have provided the first proof-of-principle use of Type Ic SNe in constraining new

radiatively decaying particles by relying on two different observables: the direct observation of gamma rays produced in the decay (small-coupling regime), and the observation of ALP-sourced fireballs (large-coupling regime). The new perspectives offered by Type Ic SNe arise from their compact progenitors, less shielding on particles with short decay length. By a similar token, these compact progenitors host stronger magnetic fields with a new target of opportunity for axion-photon conversions [89].

The stacked-events strategy is efficient at relatively small couplings, yet still reaches above the SN 1987A bounds at large masses. Our choice of integrating the signal only within $t_{\text{max}} = 1$ h is conservative, but most importantly inessential at the large couplings where our constraints supersede the SN 1987A. The typical delay overshoot t_{max} only for very small couplings, corresponding to the kink in the constraint in Fig. 1 around $m_a \sim 130$ MeV, a region largely excluded by SN 1987A.

Part of the fireball region overlaps with the region excluded from the neutron star merger GW170817 [72]. On the other hand, the latter carries strong intrinsic uncertainty due to the potential presence of ejected material from the merger that could trap the photons from decay; its impact on the GW170817 bounds is visible in Supplemental Material of Ref. [72]. Hence, our new bounds, which are entirely insensitive to this systematics, are a powerful addition to the constraining strategies on decaying particles.

Next-generation γ -ray instruments with 4π continuous sky coverage, such as the proposed constellation of SmallSats GALAXIS in the energy range 100–500 MeV [74], could strengthen our constraints substantially by removing the temporal dead times inherent to scanning single telescopes such as Fermi-LAT. Figure 1 shows a projected exclusion for a future Type Ic SN at a distance of 10 Mpc—multiple SNe in our samples lie at comparable distances—with progenitor radius $R_{\text{prog}} = 10^{10}$ cm. We use the highest exposure time bin in the SN2020oi signal window, and set bounds from the Poisson likelihood for a nondetection. Hence, an extragalactic Type Ic SN, coupled with a gamma-ray detector with 4π coverage, would surpass the SN 1987A bounds at all ALP masses. When considering extragalactic distances, Type Ic SNe have a large occurrence rate: core-collapse SNe account for nearly 70% of all SNe, and of the core-collapse SNe 23% are SNe Ibc. In turn, Type Ic SNe constitute around 40% of SNe Ibc (60% when including broad-line SNe Ic-BL) [90]. Therefore, using the local core-collapse SN rate from [91], the SN Ic rate is around 0.2 per year up to 10 Mpc, and around 0.7 per year up to 20 Mpc (including SNe Ic-BL these numbers are 0.3 and 1.05 per year, respectively).

The new observables follow the track of a general collection of new strategies to observe or constrain sub-GeV particles, based either on their energy deposition in stellar progenitors [37,38,92,93] or outside of them, with the production of visible messengers (neutrinos [62,64,94,95] or

photons, either directly [21–23,28,96–101] or through a reprocessing due to fireball formation [36,72]). Such observables extend far beyond the simple ALP-photon coupling; while we use this case as a benchmark, analogous bounds can be drawn on any model with particles decaying to leptonic or hadronic sectors, such as ALPs coupling to electrons—see, e.g., the recent compilation of constraints in Ref. [30]—or sterile neutrinos [34].

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Data availability—The Fermi-LAT data used in this work are publicly available from the Fermi Science Support Center. The supernova sample used in the analysis are compiled in Table I of Supplemental Material [44]. The numerical data and custom scripts used to generate the figures and constraints are available from the authors upon reasonable request.

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