Energy Transfer by Feebly Interacting Particles in Supernovae: The Trapping Regime

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(Received 27 March 2025; revised 12 June 2025; accepted 28 July 2025; published 15 August 2025)

Feebly interacting particles, such as sterile neutrinos, dark photons, and axions, can be abundantly produced in the proto-neutron star (PNS) formed in core-collapse supernovae (CCSNe). These particles can decay into photons or charged leptons, depositing energy outside the PNS. Strong bounds on new particles can thus be derived from the observed luminosity of CCSNe, with even tighter bounds obtained from low-energy SNe observations. For the first time we highlight that, at sufficiently large couplings, particle production *outside* the PNS must also be considered. Using the prototypical case of axions coupling to two photons, we show that at large couplings the energy transfer from PNS to its surroundings is diffusive rather than ballistic, substantially reducing the deposited energy. Our findings have implications for the parameter space of particles probed in beam dump experiments and for dark matter models involving a sub-GeV mediator.

DOI: 10.1103/cz94-dqxt

Introduction—Finding feebly interacting particles (FIPs) is the goal of many laboratory, astrophysical, and cosmological searches [1–5]. After they are produced—be it by a beam interacting with a target, in the hot and dense core of protoneutron stars (PNSs), or in the early Universe—sterile neutrinos, dark photons, and axions with masses below the GeV scale can propagate and decay into standard model particles. Decay lengths comparable to the meter scale are constrained by beam-dump experiments (see, e.g., [6–19]), whereas novel particles that survive on cosmological scales would have an effect on big bang nucleosynthesis or the cosmic microwave background (see, e.g., [20–34]). Astrophysical transients cover the gap between these observables: the remnants of neutron star mergers [35–37], core-collapse supernovae (CCSNe) [38–70], or yet rarer events such as hypernovae [71] can abundantly produce FIPs with masses as heavy as the GeV scale.

A CCSN consists of a central PNS enveloped by an extended mantle. Axions decaying into photons would impact the observed features of CCSNe in different ways. If the mean free path of axions produced in the PNS is much larger than the progenitor radius, $\lambda \gtrsim R_{\rm prog}$, bounds are obtained from the putative shortening of the neutrino signal detected from SN 1987A [48,49,72], from x-ray [60] and γ-ray observations of SN 1987A [43,49,54], as well as from the diffuse gamma-ray flux observed at Earth, since the decay of axions produced by all past SNe would contribute to the latter [49,73]. For larger decay lengths, corresponding to smaller masses, massive stars that have not yet exploded are optimal sources, since axions would be produced with smaller Lorentz boost [74]. If, on the other hand, the decay length is shorter than the radius of the progenitor, $\lambda \lesssim R_{\rm prog}$, the axion can decay in the material surrounding the core, transporting energy and resulting in an exceedingly energetic explosions. The requirement that the energy deposited in the mantle of normal CCSNe and low-energy SNe (LESNe) is smaller than the observed values, respectively $1\ \mathrm{B(bethe)} = 10^{51}$ erg and 0.1 B, leads to strong constraints on the existence of novel radiatively decaying particles [51,75,76]. Ultimately, this is a transport of energy from the hot PNS to its surroundings, mediated by axions. While the focus is often on the free-streaming regime, i.e. on axions that interact so feebly that they escape far from the PNS after being produced, here we answer the question: how *small* does the decay length need to be to avoid lighting up normal CCSNe and LESNe?.

Figure 1 summarizes the different transport regimes. At very low axion-photon coupling, the progenitor undergoes *cooling* rather than heating, as the energy lost through

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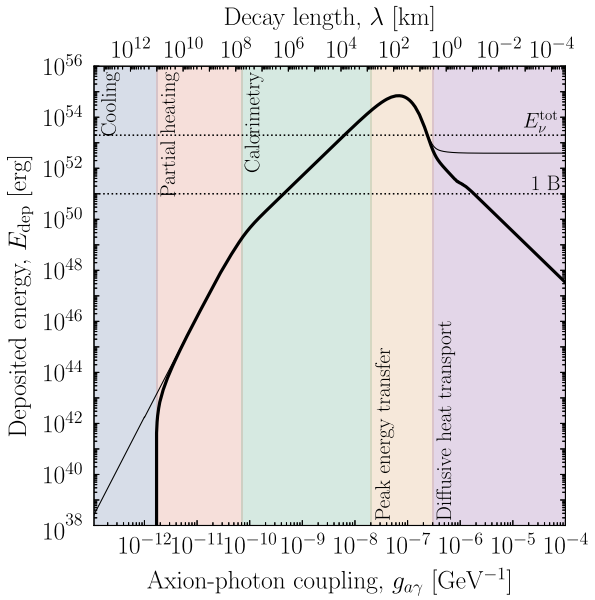


FIG. 1. Energy deposited outside the PNS across different regimes of interaction strength. We choose an axion mass $m_a = 80$ MeV and a progenitor radius $R_1 = 3 \times 10^{12}$ cm. The thin line accounts only for axions produced within the PNS (Eq. (4), the thick line includes production outside of the PNS (Eq. (9). CCSNe can constrain $E_{\rm dep} \gtrsim 1$ B; above $E_\nu^{\rm tot}$, the total energy emitted in neutrinos [56], post-processing the SN model is certainly unphysical. The top axis shows the decay length for an axion with energy $E_a = 300$ MeV.

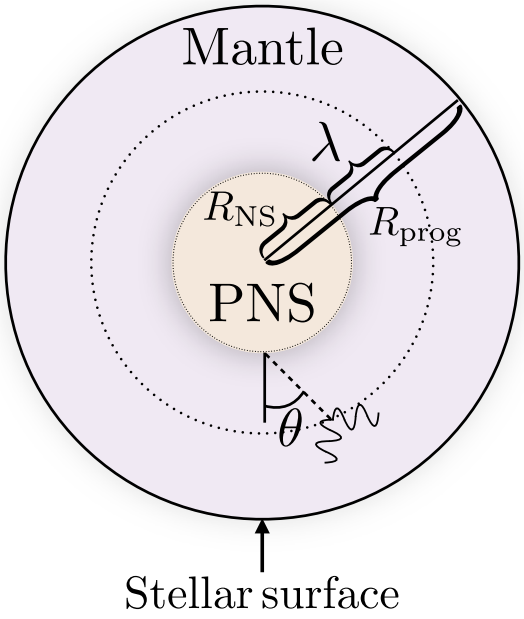


FIG. 2. Schematic geometry of the diffusive heat transfer in the trapping regime: axions are nearly in thermal equilibrium outside the PNS, with a small diffusive flux driven by the temperature gradient; at the axiosphere, where $R \sim \lambda$, they decay, dissipating all the energy locally into heat.

direct axion emission exceeds the energy transported from the PNS into the medium. At higher couplings, a fraction of the axions from the PNS decay within the progenitor, surpassing the cooling rate and leading to *partial heating* of the star. When the axion mean free path becomes comparable to the progenitor radius, the system enters a *calorimetric* regime, where all the energy produced in the PNS is deposited in the progenitor. As the mean free path decreases further and approaches the PNS radius, energy transfer reaches its *peak efficiency*, with axions acting as the most effective transport mechanism. Finally, once axions thermalize within the PNS, transport from the PNS to the star becomes *purely diffusive*. At this stage, axions remain in thermal equilibrium outside of the PNS, with a net heat flux determined by their thermal conductivity; this heat flux will ultimately dissipate into photons at larger radii, when the temperature becomes so small that the axions decay completely. In this regime, the heat transport is conceptually similar to the neutrino-delayed explosion mechanism, except that axions dissipate their energy by decay rather than scattering, and so the entire heat flux is ultimately deposited at radii much smaller than the gain radius. The geometry of this newly identified regime is schematized in Fig. 2. Our key insight is that this regime, rather than the kinetic one, is the relevant trapping mechanism for new particles with masses below a few hundred MeV.

Energy deposition at large couplings—In previous works [51,76], energy deposition has been determined as the difference between the total energy of axions emitted from the PNS (assumed to have a radius of $R_{\rm NS} = 20$ km), and the total energy these axions retain beyond the progenitor radius. These two contributions can be computed as follows. At a given radius r, we assume the energy emission rate is dL/dr, while the absorption rate per unit length, due to either decay or scattering, is $1/\lambda(r)$, where $\lambda(r) = v_a/\tilde{\gamma}_a(r)$ is the mean free path expressed in terms of the reduced absorption coefficient (we review its definition in Supplemental Material (SM) [77]), and provide its explicit expression in the case of axion-photon coupling). The total energy emitted per unit time from the PNS is then

$$\frac{dL^{(1)}_{\rm PNS}}{dE_a} = \int_0^{R_{\rm NS}} dR \frac{dL}{dE_a dR} \int \frac{dx}{2} e^{-\tau(R,R_{\rm NS})}. \qquad (1)$$

Here, E_a is the axion energy, $x = \cos\theta$ represents the angle between the axion trajectory and the radial direction, and $\tau(R, R_{\rm NS})$ is the optical thickness for an axion traversing the distance from R to $R_{\rm NS}$. Although it is more natural to express this in terms of the distance s along the axion trajectory from its production point, the absorption rate $\lambda(r)$ depends on the radius $r = \sqrt{R^2 + s^2 + 2Rsx}$, making it more convenient to express it as a function of r. Thus, we obtain

$$\tau(R,R_{\rm NS})=\begin{cases}\int_R^{R_{\rm NS}}\frac{rdr}{\lambda(r)\sqrt{r^2-R^2\sin^2\theta}}, & x>0\\ \left[\int_{R\sin\theta}^{R}+\int_{R\sin\theta}^{R_{\rm NS}}\right]\frac{rdr}{\lambda(r)\sqrt{r^2-R^2\sin^2\theta}}, & x<0.\end{cases}\tag{2}$$

Since we aim to capture the transition from free streaming to trapping, when axions are near-isotropic close to the PNS surface, we have to retain the angular dependence and cannot assume pure radial propagation. The differential luminosity of axions emitted from the PNS that successfully escape the progenitor is given by

$$\frac{dL^{(2)}_{\rm PNS}}{dE_a}=\int_0^{R_{\rm NS}}dR\,\frac{dL}{dE_a dR}\int\frac{dx}{2}e^{-\tau(R,R_{\rm prog})},\tag{3}$$

where $R_{\rm prog}$ is the progenitor radius. According to our qualitative arguments above, we would expect that the rate of energy extracted from the PNS and deposited in the progenitor is

$$E^{\rm PNS}_{\rm dep}=\int dt\left[L^{(1)}_{\rm PNS}-L^{(2)}_{\rm PNS}\right],\tag{4}$$

which conceptually coincides, e.g., with Eq. (1) of Ref. [51].

So far, we have assumed the axions to be produced exclusively in the PNS. However, this is generally incorrect and becomes inconsistent for short mean free paths. If the particle decays rapidly enough to thermalize outside of the PNS, equally efficient production processes must also exist in that region. In the limit of an arbitrarily small mean free path, $L^{(2)}_{\rm PNS}$ vanishes, while $L^{(1)}_{\rm PNS}$ saturates to a constant value—the Stefan-Boltzmann luminosity from the PNS surface. However, our previous description of energy deposition as a transport process makes it clear that this cannot be correct, as a species with a mean free path shorter than that of neutrinos cannot transport energy more efficiently than them. The key insight is that Eq. (4) must consistently include the negative contribution from axions produced *outside* the PNS; it is convenient to consider separately the axions produced here and decaying either outside of the progenitor or within the PNS. The first contribution is easiest to express, as it is identical to $L^{(2)}_{\rm PNS}$ but integrated only outside the PNS,

$$\frac{dL^{(2)}_{\rm prog}}{dE_a}=\int_{R_{\rm NS}}^{R_{\rm prog}}dR\,\frac{dL}{dE_a dR}\int\frac{dx}{2}e^{-\tau(R,R_{\rm prog})}.\tag{5}$$

Let us now consider the axions produced outside of the PNS and decaying inside the PNS. If an axion is produced at a distance $R>R_{\rm NS}$, it can only decay inside the PNS if it is emitted at an angle $x<-\sqrt{1-R^2_{\rm NS}/R^2}$; here we neglect any distortion of the axion trajectory due to gravity. The energy extracted from the progenitor due to these axions is therefore

$$\frac{dL^{(1)}_{\rm prog}}{dE_a}=\int_{R_{\rm NS}}^{R_{\rm prog}}dR\,\frac{dL}{dE_a dR}\times\int_{-1}^{-\sqrt{1-\frac{R^2_{\rm NS}}{R^2}}}\frac{dx}{2}e^{-\tau_1(R)}(1-e^{-\tau_2}),\tag{6}$$

where

$$\tau_1(R)=\int_{R_{\rm NS}}^{R}\frac{rdr}{\lambda(r)\sqrt{r^2-R^2\sin^2\theta}}\tag{7}$$

is the optical depth accumulated from the production point to the point where the axion enters the PNS, and

$$\tau_2=2\int_{R\sin\theta}^{R_{\rm NS}}\frac{rdr}{\lambda(r)\sqrt{r^2-R^2\sin^2\theta}}\tag{8}$$

is the optical depth accumulated along the part of the trajectory within the PNS. We have assumed that the SN profile is stationary, since the typical timescale over which the medium changes, a fraction of a second, is longer than the light-crossing time through the profile itself.

Therefore, our final expression for the energy deposited within the progenitor is

$$E_{\rm dep}=\int dt\left[L^{(1)}_{\rm PNS}-L^{(2)}_{\rm PNS}-L^{(1)}_{\rm prog}-L^{(2)}_{\rm prog}\right].\tag{9}$$

Equation (9) encompasses all the regimes identified in Fig. 1; we use it for the axion coupling to photons, which is produced primarily by Primakoff conversion $\gamma N\to aN$ and photon-photon coalescence $\gamma\gamma\to a$. At small couplings, $L^{(1)}_{\rm PNS}$ and $L^{(2)}_{\rm PNS}$ are very similar, since the vast majority of axions decays outside the progenitor; their difference vanishes in proportion to $g^4_{a\gamma}$, since the fraction of axions decaying within the progenitor decreases as $R_{\rm prog}/\lambda\propto g^2_{a\gamma}$. Hence, Eq. (4) would predict $E^{\rm PNS}_{\rm dep}\propto g^4_{a\gamma}$. However, in Eq. (9) the term $L^{(2)}_{\rm prog}$ grows as $g^2_{a\gamma}$ and must dominate at sufficiently small couplings; this is the cooling regime of Fig. 1. This regime is relatively unimportant for axion constraints. At higher couplings, $E^{\rm PNS}_{\rm dep}$ dominates, and the axions produced inside the PNS deposit part or all of their energy in its surroundings. Across the phases of partial heating, calorimetry, and peak energy transfer, Eq. (4) correctly represents the deposited energy, with the transport being dominated by the energy emitted inside the PNS and deposited outside of it. However, when the axion reaches full thermalization at the PNS surface and the "axiosphere"—the sphere at which axions decouple from the medium, with $\lambda(R)\lesssim R$—moves outside of it, Eq. (4)

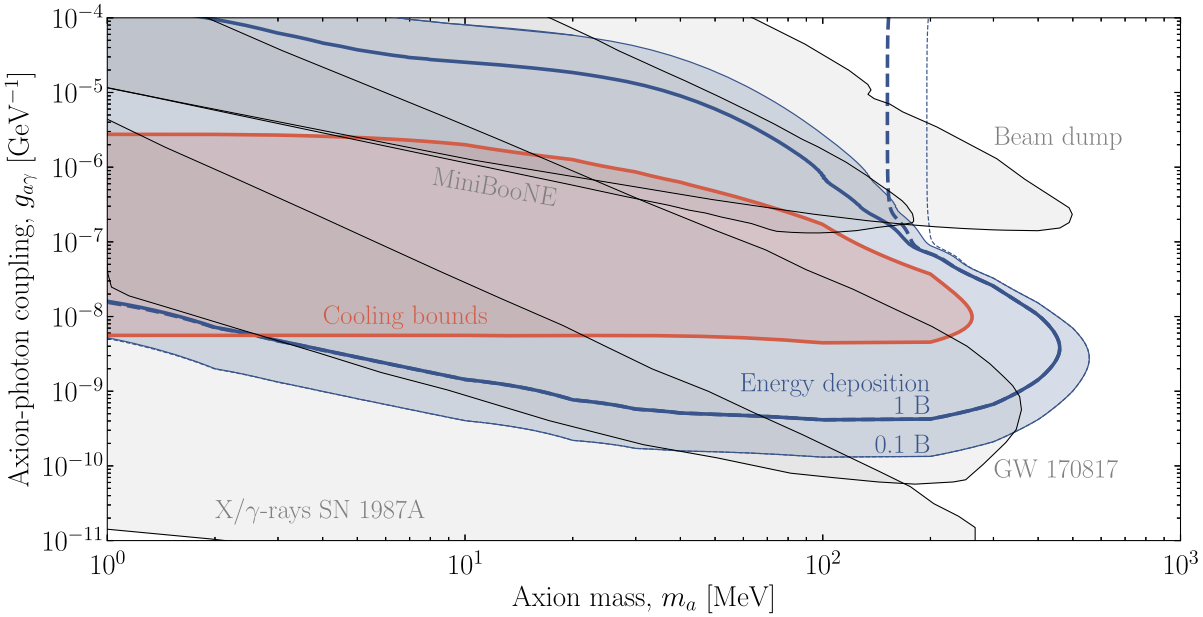


FIG. 3. Energy-deposition and cooling constraints on axion-photon coupling. Similarly to Ref. [51], energy-deposition constraints are shown both for a large progenitor ($R_{\rm prog} = 5 \times 10^{13}$ cm) with an explosion energy $E_{\rm dep} = 0.1$ B $= 10^{50}$ erg, and for a smaller progenitor ($R_{\rm prog} = 3 \times 10^{12}$ cm) with an explosion energy $E_{\rm dep} = 1$ B. For the latter, we also show with a dashed line the constraints that would be drawn using Eq. (4), neglecting particle production outside of the PNS. Previous Earth-based [6–10,17] and astrophysical [36,43,54,60] constraints are shown in gray.

would predict a constant thermal energy flux, corresponding to $L^{(1)}_{\rm PNS}$. However, this flux is canceled by $L^{(1)}_{\rm prog}$, so that the only residual flux is diffusive energy transport; axions have become part of the fluid that constitutes the medium, and can only contribute to its heating and cooling via their thermal conductivity. In fact, it is more convenient to determine this residual flow directly, rather than relying on Eq. (9), which involves a near-cancellation that is difficult to capture numerically. To do so, we use the standard transport solution for the axion phase-space distribution f at the PNS surface, which locally depends only on r and on the angle with the radial direction since $\lambda(R_{\rm NS}) \ll R_{\rm NS}$,

$$f \simeq f^{\rm eq} - \lambda x \frac{\partial f^{\rm eq}}{\partial r}, \tag{10}$$

where $f^{\rm eq} = (e^{E_a/T} - 1)^{-1}$ is the equilibrium distribution. From here, we can compute the energy flux passing through the PNS surface as $q = \int f E_a v_a x d^3\mathbf{p}/(2\pi)^3$, with $\mathbf{p}$ the axion momentum, so that the total rate of energy deposited outside the PNS is

$$\frac{dE_{\rm dep}}{dt} = 4\pi R^2_{\rm NS} q = \frac{-2R^2_{\rm NS}\partial T/\partial z}{3\pi T^2} \int dE_a \frac{\lambda(E_a) E_a^2 p_a^2 e^{E_a/T}}{(e^{E_a/T} - 1)^2}, \tag{11}$$

where all quantities are evaluated at the PNS radius. The deposited energy drops as $g_{a\gamma}^{-2}$, and it smoothly connects with the numerical prediction of Eq. (9), as visible in Fig. 1. Crucially, the heat flux we determine is extracted from the PNS, but in its immediate surroundings this energy remains in the form of axions, which are still in thermal equilibrium. This energy will ultimately be deposited when the medium temperature drops significantly below the mass of the axion, so that the entire axion population decays into photons and heats the medium.

Although our focus is on the energy deposition argument, a similar issue applies to the well-established cooling bounds, based on the argument that a rapid PNS cooling would shorten the duration of the neutrino burst [72,78–82] (see, however, Ref. [83] for a critical discussion). In practice, one often requires that the axion luminosity *at infinity* exceeds the neutrino luminosity. However, only the energy extracted directly from the PNS can influence the neutrino signal, making the axion luminosity at infinity an unreliable proxy for this effect. For decaying particles, this is particularly clear, as the axion luminosity at infinity vanishes—all particles eventually decay. Thus, here we use as a proxy the energy lost by the PNS $L = L^{(1)}_{\rm PNS} - L^{(1)}_{\rm prog}$ at 1 s, requiring that it does not exceed the neutrino luminosity (for our reference model $L_\nu = 4.4 \times 10^{52}$ erg/s [51,56]).

Particle constraints in the trapping regime—We now examine the practical impact of diffusive energy transfer on the constraints for new particles. Figure 3 presents these constraints using our newly derived Eq. (9), compared to those of Eq. (4). Even in the free-streaming regime, our constraints differ by 10% from those in Ref. [51] because

we do not account for gravitational lapse effects. These effects are significantly smaller than the uncertainties in the SN emission model, which we take to be the Garching group's muonic model SFHo-18.8 [84]. This model, often referred to as the "cold model," has been widely used to set limits on new particles, as in Refs. [49,51,56,66,67,85]. Moreover, in the trapping regime, a fully consistent treatment of gravitational effects would be considerably more complex, since axion trajectories would be influenced by gravity to an extent comparable to redshift effects.

For large masses, Eqs. (4) and (9) coincide, since the axion mass is so large that even the peak energy transfer in Fig. 1 reaches the 1 B threshold. The constraints are dominated by the non-diffusive energy transfer region—the axiosphere is well within the PNS, and Eq. (4) holds. However, as the mass decreases, the constraints derived from Eq. (4) abruptly extend to infinitely large couplings; even with an infinitesimal mean free path, Eq. (4) predicts a constant energy flux exceeding the limit set by LESNe. It is now clear that this is unphysical and that the energy transport instead enters the diffusive regime, leading to a ceiling in the constraints. In Ref. [51], for smaller masses, the constraints were extrapolated as a power law. However, Fig. 3 shows that in reality, they deviate from this behavior, shifting trend due to the transition to diffusive heat transport—precisely corresponding to the slope change in Fig. 1 from peak energy transfer to the diffusive transport region. At lower masses, the constraints in the trapping regime can be accurately obtained using the much simpler Eq. (11).

Discussion and outlook—Energy deposition in the material surrounding the protoneutron star formed in core-collapse supernovae has long been recognized as a powerful probe for feebly interacting particles decaying into photons and charged leptons [49–51,64,69,75,76]. For the first time, we have extended these constraints to the trapping regime, imposing bounds based on the requirement that the total explosion energy of normal core-collapse supernovae and low-energy supernovae does not exceed 1 B and 0.1 B, respectively. Our main conclusion is that previously proposed methods can yield constraints dramatically different from our revised results. Energy deposition in the trapping regime is diffusive, with axions nearly in equilibrium extracting heat from the PNS, and dissipating it via decay at larger radii. A potential concern is that this dissipation might happen within material still infalling on the PNS; thus, we also show a very conservative estimate in SupM [77] where only the energy deposited after 300 ms, when the explosion has set in and there is no further accreting material, is considered.

Although we have focused on the case of an axion coupling to two photons, our argument, encapsulated in Eq. (9), applies to any radiatively decaying particle, including sterile neutrinos, novel gauge bosons, and axions coupling to charged leptons. Many of these particles are actively searched for in beam-dump experiments, and low-energy SNe provide a complementary probe by closing the parameter space from below. For instance, our new argument is essential to confirm that regions such as the so-called "cosmological triangle" [86]—a region of the axion parameter space previously excluded only by cosmology—are in tension with the energy deposition. For novel gauge bosons, for example, $U(1)_{L_\mu - L_\tau}$ models, our approach could be used to probe parameter regions that are relevant to particle physics and cosmological tensions [26]. Likewise, our bounds should apply to heavy neutral leptons; see, e.g. [13]. As an immediate application, we revisit in an upcoming paper the constraints on axion-electron couplings including the new prescription for trapping [87].

We expect our results to be pertinent also to scalars coupling to leptons or nucleons, which are often considered a viable portal between dark matter and ordinary matter in sub-GeV dark matter searches (see, e.g., [88–104], and the Snowmass proceeding [105]). It is possible that the region between the trapping regime of the cooling bound—as treated in the existing literature [106–109]—and laboratory constraints is ruled out by energy deposition up to masses of several hundreds of MeV. If so, the cross section for dark matter interacting via a light mediator would be constrained to very small values. We plan to explore these possibilities further in future work.

The criterion we propose generalizes the energy-deposition argument to the region of large couplings, the most essential for the interplay with Earth-based searches, showing that in this regime axions are produced in the proto-neutron star and decay in its immediate surroundings, *and vice versa*, with a net heat flux into the surrounding material. Our argument defines a new state of the art for bounds obtained postprocessing supernova models; the final word on the effect that novel particles have on supernova physics can be written only through three-dimensional simulations self-consistently accounting for their existence, which currently seem still unfeasible. The discovery of feebly-interacting particles at beam-dump experiments close to a region excluded by our argument would imply the daunting need to include novel particles in both supernova simulations and in the analysis of supernova light curves.

Acknowledgments—We thank Yonit Hochberg, Hans-Thomas Janka, and Georg Raffelt for comments on a first draft of the paper. D. F. G. F. is supported by the Alexander von Humboldt Foundation (Germany). T. P. acknowledges support from NSF Grant No. PHY-2020275 [Network for Neutrinos, Nuclear Astrophysics, and Symmetries (N3AS)]. E. V. acknowledges support from the Italian MUR Departments of Excellence Grant No. 2023-2027, "Quantum Frontiers," and the Istituto Nazionale di Fisica Nucleare (INFN) through the Theoretical Astroparticle Physics (TAsP) project.

Data availability—No data were created or analyzed in this study.

[1] R. Essig *et al.*, Working group report: New light weakly coupled particles, in *Snowmass 2013: Snowmass on the Mississippi* (2013), arXiv:1311.0029.

[2] P. Agrawal *et al.*, Feebly-interacting particles: FIPs 2020 workshop report, Eur. Phys. J. C **81**, 1015 (2021).

[3] A. M. Abdullahi *et al.*, The present and future status of heavy neutral leptons, J. Phys. G **50**, 020501 (2023).

[4] J. M. Berryman *et al.*, Neutrino self-interactions: A white paper, Phys. Dark Universe **42**, 101267 (2023).

[5] M. Baryakhtar *et al.*, Dark matter in extreme astrophysical environments, in *Snowmass 2021* (2022), arXiv:2203.07984.

[6] F. Bergsma *et al.* (CHARM Collaboration), Search for axion like particle production in 400-GeV proton—Copper onteractions, Phys. Lett. **157B**, 458 (1985).

[7] E. M. Riordan *et al.*, A search for short lived axions in an electron beam dump experiment, Phys. Rev. Lett. **59**, 755 (1987).

[8] J. Blumlein *et al.*, Limits on neutral light scalar and pseudoscalar particles in a proton beam dump experiment, Z. Phys. C **51**, 341 (1991).

[9] D. Banerjee *et al.* (NA64 Collaboration), Search for axionlike and scalar particles with the NA64 experiment, Phys. Rev. Lett. **125**, 081801 (2020).

[10] M. J. Dolan, T. Ferber, C. Hearty, F. Kahlhoefer, and K. Schmidt-Hoberg, Revised constraints and Belle II sensitivity for visible and invisible axion-like particles, J. High Energy Phys. 12 (2017) 094; 03 (2021) 190(E).

[11] M. Bauer, M. Neubert, and A. Thamm, Collider probes of axion-like particles, J. High Energy Phys. 12 (2017) 044.

[12] M. Bauer, P. Foldenauer, and J. Jaeckel, Hunting all the hidden photons, J. High Energy Phys. 07 (2018) 094.

[13] G. Magill, R. Plestid, M. Pospelov, and Y.-D. Tsai, Dipole portal to heavy neutral leptons, Phys. Rev. D **98**, 115015 (2018).

[14] G. Krnjaic, G. Marques-Tavares, D. Redigolo, and K. Tobioka, Probing muonphilic force carriers and dark matter at kaon factories, Phys. Rev. Lett. **124**, 041802 (2020).

[15] P. D. Bolton, F. F. Deppisch, and P. S. Bhupal Dev, Neutrinoless double beta decay versus other probes of heavy sterile neutrinos, J. High Energy Phys. 03 (2020) 170.

[16] L. Calibbi, D. Redigolo, R. Ziegler, and J. Zupan, Looking forward to lepton-flavor-violating ALPs, J. High Energy Phys. 09 (2021) 173.

[17] F. Capozzi, B. Dutta, G. Gurung, W. Jang, I. M. Shoemaker, A. Thompson, and J. Yu, New constraints on ALP couplings to electrons and photons from Argo-NeuT and the MiniBooNE beam dump, Phys. Rev. D **108**, 075019 (2023).

[18] S. Knapen, T. Opferkuch, D. Redigolo, and M. Tammaro, Displaced searches for axion-like particles and heavy neutral leptons at Mu3e, J. High Energy Phys. 06 (2025) 189.

[19] H. Li, Z. Liu, and N. Song, Probing axion and muon-philic new physics with muon beam dump, arXiv:2501.06294.

[20] J. Redondo and M. Postma, Massive hidden photons as lukewarm dark matter, J. Cosmol. Astropart. Phys. 02 (2009) 005.

[21] D. Cadamuro and J. Redondo, Cosmological bounds on pseudo Nambu-Goldstone bosons, J. Cosmol. Astropart. Phys. 02 (2012) 032.

[22] A. Fradette, M. Pospelov, J. Pradler, and A. Ritz, Cosmological constraints on very dark photons, Phys. Rev. D **90**, 035022 (2014).

[23] J. Berger, K. Jedamzik, and D. G. E. Walker, Cosmological constraints on decoupled dark photons and dark Higgs, J. Cosmol. Astropart. Phys. 11 (2016) 032.

[24] P. F. Depta, M. Hufnagel, K. Schmidt-Hoberg, and S. Wild, BBN constraints on the annihilation of MeV-scale dark matter, J. Cosmol. Astropart. Phys. 04 (2019) 029.

[25] A. Fradette, M. Pospelov, J. Pradler, and A. Ritz, Cosmological beam dump: Constraints on dark scalars mixed with the Higgs boson, Phys. Rev. D **99**, 075004 (2019).

[26] M. Escudero, D. Hooper, G. Krnjaic, and M. Pierre, Cosmology with a very light $L_\mu - L_\tau$ gauge boson, J. High Energy Phys. 03 (2019) 071.

[27] P. F. Depta, M. Hufnagel, and K. Schmidt-Hoberg, Robust cosmological constraints on axion-like particles, J. Cosmol. Astropart. Phys. 05 (2020) 009.

[28] P. F. Depta, M. Hufnagel, and K. Schmidt-Hoberg, Updated BBN constraints on electromagnetic decays of MeV-scale particles, J. Cosmol. Astropart. Phys. 04 (2021) 011.

[29] L. Mastrototaro, P. D. Serpico, A. Mirizzi, and N. Saviano, Massive sterile neutrinos in the early universe: From thermal decoupling to cosmological constraints, Phys. Rev. D **104**, 016026 (2021).

[30] N. Sabti, A. Magalich, and A. Filimonova, An extended analysis of heavy neutral leptons during big bang nucleosynthesis, J. Cosmol. Astropart. Phys. 11 (2020) 056.

[31] A. Boyarsky, M. Ovchynnikov, O. Ruchayskiy, and V. Syvolap, Improved big bang nucleosynthesis constraints on heavy neutral leptons, Phys. Rev. D **104**, 023517 (2021).

[32] K. Langhoff, N. J. Outmezguine, and N. L. Rodd, Irreducible axion background, Phys. Rev. Lett. **129**, 241101 (2022).

[33] F. D'Eramo, A. Tesi, and V. Vaskonen, Irreducible cosmological backgrounds of a real scalar with a broken symmetry, Phys. Rev. D **110**, 095002 (2024).

[34] K. Akita, G. Baur, M. Ovchynnikov, T. Schwetz, and V. Syvolap, New physics decaying into metastable particles: Impact on cosmic neutrinos, Phys. Rev. Lett. **134**, 121001 (2025).

[35] M. D. Diamond and G. Marques-Tavares, γ-ray flashes from dark photons in neutron star mergers, Phys. Rev. Lett. **128**, 211101 (2022).

[36] M. Diamond, D. F. G. Fiorillo, G. Marques-Tavares, I. Tamborra, and E. Vitagliano, Multimessenger Constraints on radiatively decaying axions from GW170817, Phys. Rev. Lett. **132**, 101004 (2024).

[37] P. S. Bhupal Dev, J.-F. Fortin, S. P. Harris, K. Sinha, and Y. Zhang, First constraints on the photon coupling of axion-like particles from multimessenger studies of the neutron star merger GW170817, Phys. Rev. Lett. **132**, 101003 (2024).

[38] L. Oberauer, C. Hagner, G. Raffelt, and E. Rieger, Supernova bounds on neutrino radiative decays, Astropart. Phys. **1**, 377 (1993).

[39] S. Davidson, S. Hannestad, and G. Raffelt, Updated bounds on millicharged particles, J. High Energy Phys. 05 (2000) 003.
[40] M. Giannotti, L. D. Duffy, and R. Nita, New constraints for heavy axion-like particles from supernovae, J. Cosmol. Astropart. Phys. 01 (2011) 015.
[41] D. Kazanas, R. N. Mohapatra, S. Nussinov, V. L. Teplitz, and Y. Zhang, Supernova bounds on the dark photon using its electromagnetic decay, Nucl. Phys. **B890**, 17 (2014).
[42] J. H. Chang, R. Essig, and S. D. McDermott, Revisiting supernova 1987A constraints on dark photons, J. High Energy Phys. 01 (2017) 107.
[43] J. Jaeckel, P. C. Malta, and J. Redondo, Decay photons from the axionlike particles burst of type II supernovae, Phys. Rev. D **98**, 055032 (2018).
[44] J. H. Chang, R. Essig, and S. D. McDermott, Supernova 1987A Constraints on Sub-GeV dark sectors, millicharged particles, the QCD axion, and an axion-like particle, J. High Energy Phys. 09 (2018) 051.
[45] V. Brdar, A. Greljo, J. Kopp, and T. Opferkuch, The neutrino magnetic moment portal: Cosmology, astrophysics, and direct detection, J. Cosmol. Astropart. Phys. 01 (2021) 039.
[46] D. Croon, G. Elor, R. K. Leane, and S. D. McDermott, Supernova muons: New constraints on Z' bosons, axions and ALPs, J. High Energy Phys. 01 (2021) 107.
[47] J. M. Camalich, J. Terol-Calvo, L. Tolos, and R. Ziegler, Supernova constraints on dark flavored sectors, Phys. Rev. D **103**, L121301 (2021).
[48] G. Lucente, P. Carenza, T. Fischer, M. Giannotti, and A. Mirizzi, Heavy axion-like particles and core-collapse supernovae: Constraints and impact on the explosion mechanism, J. Cosmol. Astropart. Phys. 12 (2020) 008.
[49] A. Caputo, G. Raffelt, and E. Vitagliano, Muonic boson limits: Supernova redux, Phys. Rev. D **105**, 035022 (2022).
[50] F. Calore, P. Carenza, M. Giannotti, J. Jaeckel, G. Lucente, L. Mastrototaro, and A. Mirizzi, 511 keV line constraints on feebly interacting particles from supernovae, Phys. Rev. D **105**, 063026 (2022).
[51] A. Caputo, H.-T. Janka, G. Raffelt, and E. Vitagliano, Low-energy supernovae severely constrain radiative particle decays, Phys. Rev. Lett. **128**, 221103 (2022).
[52] A. Caputo, G. Raffelt, and E. Vitagliano, Radiative transfer in stars by feebly interacting bosons, J. Cosmol. Astropart. Phys. 08 (2022) 045.
[53] R. Z. Ferreira, M. C. D. Marsh, and E. Müller, Strong supernovae bounds on ALPs from quantum loops, J. Cosmol. Astropart. Phys. 11 (2022) 057.
[54] S. Hoof and L. Schulz, Updated constraints on axion-like particles from temporal information in supernova SN1987A gamma-ray data, J. Cosmol. Astropart. Phys. 03 (2023) 054.
[55] A. Lella, P. Carenza, G. Lucente, M. Giannotti, and A. Mirizzi, Protoneutron stars as cosmic factories for massive axionlike particles, Phys. Rev. D **107**, 103017 (2023).
[56] D. F. G. Fiorillo, G. G. Raffelt, and E. Vitagliano, Strong supernova 1987A constraints on bosons decaying to neutrinos, Phys. Rev. Lett. **131**, 021001 (2023).
[57] K. Akita, S. H. Im, and M. Masud, Probing non-standard neutrino interactions with a light boson from next galactic and diffuse supernova neutrinos, J. High Energy Phys. 12 (2022) 050.
[58] D. F. G. Fiorillo, G. G. Raffelt, and E. Vitagliano, Supernova emission of secretly interacting neutrino fluid: Theoretical foundations, Phys. Rev. D **109**, 023017 (2024).
[59] D. F. G. Fiorillo, G. G. Raffelt, and E. Vitagliano, Large neutrino secret interactions have a small impact on supernovae, Phys. Rev. Lett. **132**, 021002 (2024).
[60] M. Diamond, D. F. G. Fiorillo, G. Marques-Tavares, and E. Vitagliano, Axion-sourced fireballs from supernovae, Phys. Rev. D **107**, 103029 (2023); **108**, 049902(E) (2023).
[61] A. Lella, P. Carenza, G. Co', G. Lucente, M. Giannotti, A. Mirizzi, and T. Rauscher, Getting the most on supernova axions, Phys. Rev. D **109**, 023001 (2024).
[62] P. Carenza, G. Lucente, L. Mastrototaro, A. Mirizzi, and P. D. Serpico, Comprehensive constraints on heavy sterile neutrinos from core-collapse supernovae, Phys. Rev. D **109**, 063010 (2024).
[63] K. Akita, S. H. Im, M. Masud, and S. Yun, Limits on heavy neutral leptons, Z' bosons and majorons from high-energy supernova neutrinos, J. High Energy Phys. 07 (2024) 057.
[64] G. Chauhan, S. Horiuchi, P. Huber, and I. M. Shoemaker, Low-energy supernovae bounds on sterile neutrinos, J. Cosmol. Astropart. Phys. 03 (2025) 052.
[65] A. Lella, E. Ravensburg, P. Carenza, and M. C. David Marsh, Supernova limits on QCD axionlike particles, Phys. Rev. D **110**, 043019 (2024).
[66] D. F. G. Fiorillo and E. Vitagliano, Self-interacting dark sectors in supernovae can behave as a relativistic fluid, Phys. Rev. Lett. **133**, 251004 (2024).
[67] B. Telalovic, D. F. G. Fiorillo, P. Martínez-Miravé, E. Vitagliano, and M. Bustamante, The next galactic supernova can uncover mass and couplings of particles decaying to neutrinos, J. Cosmol. Astropart. Phys. 11 (2024) 011.
[68] J. N. Benabou, C. A. Manzari, Y. Park, G. Prabhakar, B. R. Safdi, and I. Savoray, Time-delayed gamma-ray signatures of heavy axions from core-collapse supernovae, Phys. Rev. D **111**, 095029 (2025).
[69] G. Chauhan, S. Horiuchi, P. Huber, and I. M. Shoemaker, Probing the sterile neutrino dipole portal with SN1987A and low-energy supernovae, Phys. Rev. D **110**, 015007 (2024).
[70] J. Alda, G. Levati, P. Paradisi, S. Rigolin, and N. Selimovic, Collider and astrophysical signatures of light scalars with enhanced τ couplings, J. High Energy Phys. 06 (2025) 008.
[71] A. Caputo, P. Carenza, G. Lucente, E. Vitagliano, M. Giannotti, K. Kotake, T. Kuroda, and A. Mirizzi, Axionlike particles from hypernovae, Phys. Rev. Lett. **127**, 181102 (2021).
[72] G. G. Raffelt, *Stars as Laboratories for Fundamental Physics: The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles* (University of Chicago Press, 1996).
[73] F. Calore, P. Carenza, M. Giannotti, J. Jaeckel, and A. Mirizzi, Bounds on axionlike particles from the diffuse supernova flux, Phys. Rev. D **102**, 123005 (2020).
[74] F. R. Candón, D. F. G. Fiorillo, G. Lucente, E. Vitaglianom, and J. K. Vogel, NuSTAR bounds on radiatively decaying particles from M82, Phys. Rev. Lett. **134**, 171004 (2025).

[75] S. W. Falk and D. N. Schramm, Limits from supernovae on neutrino radiative lifetimes, Phys. Lett. **79B**, 511 (1978).
[76] A. Sung, H. Tu, and M.-R. Wu, New constraint from supernova explosions on light particles beyond the standard model, Phys. Rev. D **99**, 121305(R) (2019).
[77] See Supplemental Material at http://link.aps.org/supplemental/10.1103/cz94-dqxt for a recollection of standard results on axion production, and for the revised constraints neglecting the energy deposited before the explosion.
[78] R. Mayle, J. R. Wilson, J. R. Ellis, K. A. Olive, D. N. Schramm, and G. Steigman, Constraints on axions from SN 1987a, Phys. Lett. B **203**, 188 (1988).
[79] M. S. Turner, Axions from SN 1987a, Phys. Rev. Lett. **60**, 1797 (1988).
[80] A. Burrows, M. S. Turner, and R. P. Brinkmann, Axions and SN 1987a, Phys. Rev. D **39**, 1020 (1989).
[81] R. Mayle, J. R. Wilson, J. R. Ellis, K. A. Olive, D. N. Schramm, and G. Steigman, Updated constraints on axions from SN 1987a, Phys. Lett. B **219**, 515 (1989).
[82] A. Burrows, M. T. Ressell, and M. S. Turner, Axions and SN1987A: Axion trapping, Phys. Rev. D **42**, 3297 (1990).
[83] D. F. G. Fiorillo, M. Heinlein, H.-T. Janka, G. Raffelt, E. Vitagliano, and R. Bollig, Supernova simulations confront SN 1987A neutrinos, Phys. Rev. D **108**, 083040 (2023).
[84] Garching core-collapse supernova research archive, https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/.
[85] R. Bollig, W. DeRocco, P. W. Graham, and H.-T. Janka, Muons in supernovae: Implications for the axion-muon coupling, Phys. Rev. Lett. **125**, 051104 (2020); **126**, 189901(E) (2021).
[86] V. Brdar, B. Dutta, W. Jang, D. Kim, I. M. Shoemaker, Z. Tabrizi, A. Thompson, and J. Yu, Axionlike particles at future neutrino experiments: Closing the cosmological triangle, Phys. Rev. Lett. **126**, 201801 (2021).
[87] D. F. G. Fiorillo, T. Pitik, and E. Vitagliano, Supernova production of axion-like particles coupling to electrons, reloaded, arXiv:2503.15630.
[88] R. Essig, J. Mardon, and T. Volansky, Direct detection of Sub-GeV dark matter, Phys. Rev. D **85**, 076007 (2012).
[89] Y. Hochberg, Y. Zhao, and K. M. Zurek, Superconducting detectors for superlight dark matter, Phys. Rev. Lett. **116**, 011301 (2016).
[90] Y. Hochberg, M. Pyle, Y. Zhao, and K. M. Zurek, Detecting superlight dark matter with fermi-degenerate materials, J. High Energy Phys. 08 (2016) 057.
[91] S. Knapen, T. Lin, and K. M. Zurek, Light dark matter in superfluid helium: Detection with multi-excitation production, Phys. Rev. D **95**, 056019 (2017).
[92] K. Schutz and K. M. Zurek, Detectability of light dark matter with superfluid helium, Phys. Rev. Lett. **117**, 121302 (2016).
[93] S. Knapen, T. Lin, M. Pyle, and K. M. Zurek, Detection of light dark matter with optical phonons in polar materials, Phys. Lett. B **785**, 386 (2018).
[94] Y. Hochberg, Y. Kahn, M. Lisanti, K. M. Zurek, A. G. Grushin, R. Ilan, S. M. Griffin, Z.-F. Liu, S. F. Weber, and J. B. Neaton, Detection of sub-MeV dark matter with three-dimensional Dirac materials, Phys. Rev. D **97**, 015004 (2018).
[95] G. B. Gelmini, V. Takhistov, and E. Vitagliano, Scalar direct detection: In-medium effects, Phys. Lett. B **809**, 135779 (2020).
[96] Y. Hochberg, Y. Kahn, N. Kurinsky, B. V. Lehmann, T. C. Yu, and K. K. Berggren, Determining dark-matter–electron scattering rates from the dielectric function, Phys. Rev. Lett. **127**, 151802 (2021).
[97] S. Knapen, J. Kozaczuk, and T. Lin, Dark matter-electron scattering in dielectrics, Phys. Rev. D **104**, 015031 (2021).
[98] S. Knapen, J. Kozaczuk, and T. Lin, Python package for dark matter scattering in dielectric targets, Phys. Rev. D **105**, 015014 (2022).
[99] Y. Hochberg, B. V. Lehmann, I. Charaev, J. Chiles, M. Colangelo, S. W. Nam, and K. K. Berggren, New constraints on dark matter from superconducting nanowires, Phys. Rev. D **106**, 112005 (2022).
[100] Z. Y. Zhang *et al.* (CDEX Collaboration), Constraints on Sub-GeV dark matter–electron scattering from the CDEX-10 experiment, Phys. Rev. Lett. **129**, 221301 (2022).
[101] C. Boyd, Y. Hochberg, Y. Kahn, E. D. Kramer, N. Kurinsky, B. V. Lehmann, and T. C. Yu, Directional detection of dark matter with anisotropic response functions, Phys. Rev. D **108**, 015015 (2023).
[102] R. Catena, D. Cole, T. Emken, M. Matas, N. Spaldin, W. Tarantino, and E. Urdshals, Dark matter-electron interactions in materials beyond the dark photon model, J. Cosmol. Astropart. Phys. 03 (2023) 052.
[103] J. Gao, Y. Hochberg, B. V. Lehmann, S. W. Nam, P. Szypryt, M. R. Vissers, and T. Xu, Detecting light dark matter with kinetic inductance detectors, arXiv:2403.19739.
[104] L. Baudis *et al.* (QROCODILE Collaboration), A new bite into dark matter with the SNSPD-based QROCODILE experiment, arXiv:2412.16279.
[105] R. Essig *et al.*, Snowmass2021 cosmic frontier: The landscape of low-threshold dark matter direct detection in the next decade, in *Snowmass 2021* (2022), arXiv:2203.08297.
[106] G. Krnjaic, Probing light thermal dark-matter with a Higgs portal mediator, Phys. Rev. D **94**, 073009 (2016).
[107] S. Knapen, T. Lin, and K. M. Zurek, Light dark matter: Models and constraints, Phys. Rev. D **96**, 115021 (2017).
[108] S. Balaji, P. S. B. Dev, J. Silk, and Y. Zhang, Improved stellar limits on a light CP-even scalar, J. Cosmol. Astropart. Phys. 12 (2022) 024.
[109] E. Hardy, A. Sokolov, and H. Stubbs, Supernova bounds on new scalars from resonant and soft emission, J. High Energy Phys. 04 (2025) 013.