


## Large Neutrino Secret Interactions Have a Small Impact on Supernovae

Damiano F. G. Fiorillo<sup>1</sup>, Georg G. Raffelt<sup>2</sup>, and Edoardo Vitagliano<sup>3</sup>

<sup>1</sup>Niels Bohr International Academy, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark

<sup>2</sup>Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany

<sup>3</sup>Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel

 (Received 4 August 2023; revised 25 October 2023; accepted 13 December 2023; published 11 January 2024)

When hypothetical neutrino secret interactions ( $\nu$ SI) are large, they form a fluid in a supernova (SN) core, flow out with sonic speed, and stream away as a fireball. For the first time, we tackle the complete dynamical problem and solve all steps, systematically using relativistic hydrodynamics. The impact on SN physics and the neutrino signal is remarkably small. For complete thermalization within the fireball, the observable spectrum changes in a way that is independent of the coupling strength. One potentially large effect beyond our study is quick deleptonization if  $\nu$ SI violate lepton number. By present evidence, however, SN physics leaves open a large region in parameter space, where laboratory searches and future high-energy neutrino telescopes will probe  $\nu$ SI.

DOI: [10.1103/PhysRevLett.132.021002](https://doi.org/10.1103/PhysRevLett.132.021002)

*Introduction.*—The cosmic dark-matter problem, the baryon asymmetry of the universe, the  $CP$  problem of QCD, and the unknown origin and nature of neutrino masses all suggest physics beyond the particle-physics standard model. One portal to new particle physics may be provided by hitherto unknown interactions among neutrinos [1], with effects that are notoriously difficult to measure. Such neutrino secret interactions ( $\nu$ SI) must be mediated by a new force carrier of unknown spin parity and mass, and could conserve or violate lepton number. It has long been held [2–20] that a natural test bed should be core-collapse supernova (SN) physics that is famously dominated by neutrinos [21–26].

If coupling  $g_\phi$  and mass  $m_\phi$  of the new force carrier  $\phi$  are small enough, the main effect is energy loss by  $\phi$  radiation, providing the traditional cooling bounds based on the SN 1987A neutrino signal [12,13]. For larger masses,  $\phi \rightarrow \nu\nu$  decays would provide many 100-MeV-range neutrinos, representative of the SN core, in conflict with SN 1987A data [18], and may be investigated also with future galactic SNe [19]. However, the exclusion region in the  $g_\phi$ - $m_\phi$  plane has a ceiling at  $g_\phi$  so large ( $g_\phi m_\phi \gtrsim 10^{-7}$  MeV for  $m_\phi \gtrsim 1$  MeV) that the  $\phi$  would be trapped inside the protoneutron star (PNS). At even larger couplings, such that the neutrino-neutrino mean free path (MFP) is shorter than the PNS radius, several new phenomena emerge.

One possibly dramatic effect arises when  $\nu$ SI violate lepton number as in the traditional majoron models. As much as 0.30 leptons per baryon are initially trapped, providing a large electron chemical potential, and causing the SN core to be rather cold after collapse. Lepton number usually escapes by diffusion and convection over a few seconds. On the other hand, quick deleptonization by  $\nu\nu \rightarrow \bar{\nu}\bar{\nu}$ , partly already during infall, modifies the entire SN paradigm. Still, in contrast to what is sometimes stated, such a scenario is not necessarily excluded because the hydrodynamic shock wave could arise from a thermal bounce [8,27]. These are riveting questions that need addressing in self-consistent SN simulations.

In this Letter we focus on effects unrelated to lepton-number violation: the reputedly large  $\nu$ SI impact on neutrino transport. In an early paper, Manohar suggested that  $\nu$ SI would make neutrinos diffuse in a gas of each other, retarding their flow, and thus violate the SN 1987A burst duration [5]. This misconception was countered by Dicus *et al.* [7] who stressed that strongly coupled neutrinos form a relativistic fluid and studied free expansion after sudden release. Recently, Chang *et al.* [17] have revived this long-dormant topic and advanced two scenarios of neutrino-fluid evolution, dubbed “burst outflow” and “wind outflow,” corresponding respectively to sudden release and steady emission. They questioned if special conditions were needed to realize the latter and if it could occur at all. Their main message was that burst outflow would lead to large observable effects mainly by extending the SN burst duration.

To develop an unambiguous answer, we immediately dismiss burst outflow because the sudden release of a fluid ball bears no resemblance to quasithermal emission by the protoneutron star (PNS) over several seconds. It creates a

---

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP<sup>3</sup>.

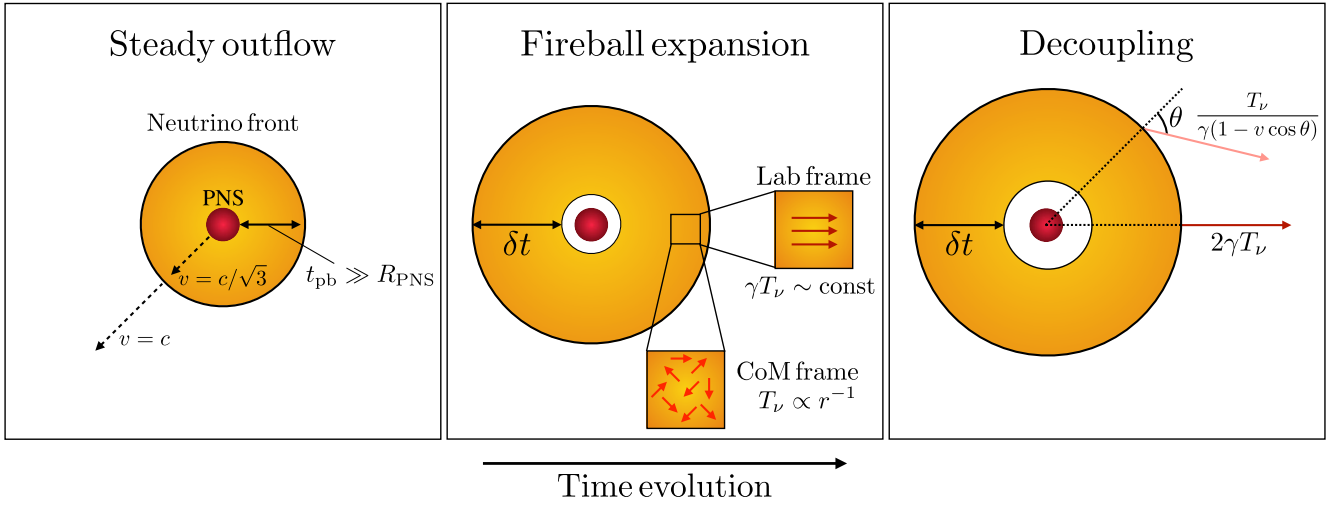


FIG. 1. Schematic evolution of neutrino fluid emission. Left: quasisteady emission from PNS with speed of sound  $v_s = c/\sqrt{3}$ ; front of emission has reached distance  $ct_{pb}$  (postbounce time  $t_{pb}$ ). Middle: shell of neutrinos streams as a fireball, maintaining constant thickness  $c\delta t$  (burst duration  $\delta t$ ). In their comoving frame, neutrinos constantly isotropize by the  $\nu$ SI; in the lab frame, they are boosted and move collinear within an angle  $\gamma^{-1}$ . Right: after they decouple, neutrinos maintain their spectrum. Neutrinos moving radially toward the observer have a large effective temperature of order  $2\gamma T_\nu$ , while neutrinos from the edges have a much lower temperature due to the Lorentz boosting.

ball  $10^5$  times the PNS radius of some 10 km. Moreover, it has long been known [28,29] that a suddenly released ball of relativistic fluid, after a short transient, behaves like a fireball: a constant-thickness shell that expands with the speed of light. The neutrino burst would not lengthen. (We elaborate on the sudden-release fireball solution in the Supplemental Material [30].) On the other hand, while steady wind looks plausible, it sidesteps the question of how it would dynamically arise after SN collapse, and it cannot be related to any physical observable at Earth.

For the first time, we tackle the full dynamical problem in spherical geometry with physical boundary conditions. A simplified source model with a beginning and end of thermal emission spawns a *dynamical* solution with a luminal front expanding into space. Locally near the PNS, it relaxes to steady emission similar wind outflow, and finally morphs to a fireball with constant thickness (see Fig. 1 for a sketch).

The idea circulates that several observables—neutrino average energy [16], time of arrival [5], and signal duration [17]—depend on  $R_{PNS}/\lambda_{\nu\nu}$ , where  $R_{PNS}$  is the proto-neutron star radius and  $\lambda_{\nu\nu}$  the  $\nu\nu$  MFP. In contrast, we find no strong such dependence. The signal duration and flux spectrum are astonishingly similar to the standard case, although tens-of-percent effects may persist and influence both SN physics and high-statistics observations. The groundwork for our study is laid out in a detailed theoretical companion paper [31]. We always use natural units with  $c = \hbar = k_B = 1$ .

*Setup of the problem.*—As  $\lambda_{\nu\nu} \ll R_{PNS}$ , the key premise is treating neutrinos as a relativistic fluid, where  $p = \rho/3$  with  $p$  and  $\rho$  the comoving pressure and energy density.

The stress-energy tensor is  $T^{\mu\nu} = \frac{4}{3}\rho u^\mu u^\nu - \frac{1}{3}\rho g^{\mu\nu}$  with  $u^\mu$  the bulk velocity. The general hydrodynamical equations are [32]  $\partial_\nu T^{\mu\nu} = S^\mu$ , including a source term on the right-hand side for the exchange of energy and momentum with the background medium. In free space,  $S^\mu = 0$ , and then these equations simply express the local conservation of energy and momentum. In spherical symmetry, there is only the radial velocity  $v$  such that  $u^0 = \gamma = (1 - v^2)^{-1/2}$  and  $u^r = \gamma v$ . There remain only two hydrodynamical equations. One is for the lab-frame energy density  $e(r, t)$

$$\partial_t e + \frac{\partial_r(e\xi r^2)}{r^2} = \frac{e_{\text{eq}} - e}{\lambda_{\nu N}}, \quad (1)$$

where  $e_{\text{eq}}$  is the energy density when the fluid is in local thermal equilibrium (LTE) with the nuclear medium,  $\lambda_{\nu N}$  the neutrino MFP for absorption, and  $\xi = 4v/(3 + v^2)$  a modified velocity variable that gives us the energy flux when it multiplies the energy density. A second equation is for momentum

$$\begin{aligned} \partial_t(e\xi) + \frac{1}{3r^2}\partial_r\left[e\left(5 - 2\sqrt{4 - 3\xi^2}\right)r^2\right] \\ - \frac{2e}{3r}\left(\sqrt{4 - 3\xi^2} - 1\right) = -\frac{e\xi}{\lambda_{\nu N}}. \end{aligned} \quad (2)$$

In contrast to a kinetic treatment, neutrinos as particles do not appear in the complete set of Eqs. (1) and (2) for the functions  $e(r, t)$  and  $\xi(r, t)$  or  $v(r, t)$ .

In the comoving frame, neutrinos are isotropic with the energy density  $\rho = 3e/(4\gamma^2 - 1)$ . The distribution is

thermal with separate chemical potentials for  $\nu$  and  $\bar{\nu}$  if number-changing processes  $\nu\bar{\nu} \rightarrow \nu\bar{\nu}\nu\bar{\nu}$  are slow, or chemical equilibrium with  $\mu_\nu = -\mu_{\bar{\nu}}$  if they are fast, or  $\mu_\nu = \mu_{\bar{\nu}} = 0$  if collisions violate lepton number. If the fluid cannot internally establish chemical equilibrium, lab-frame number densities  $N(r, t)$  are conserved other than by exchange with the background according to

$$\partial_t N + \frac{\partial_r(Nvr^2)}{r^2} = \frac{N_{\text{eq}} - N}{\lambda_{\nu N}}. \quad (3)$$

$N_{\text{eq}}$  is the distribution obtained in local and thermal equilibrium with the background. To solve a physical problem, these equations must be complemented with appropriate initial and/or boundary conditions.

*Energy transport in the PNS.*—Before energy can be radiated into space, it must be transported to the PNS surface. The usual diffusion flux is  $F = -(\bar{\lambda}/3)\nabla e_{\text{eq}}$ , where  $\bar{\lambda}$  is the Rosseland average neutrino MFP. How is this affected by  $\nu\text{SI}$ ? With or without them, the right-hand side of Eq. (2) is a force balanced by neutrino pressure, and  $F$  turns out to be the same [31]. This conclusion was also mentioned in Ref. [20] based on momentum conservation in neutrino collisions; however, since the energy flux comes out of balance with neutrino-nucleon collisions, which do not conserve the neutrino momentum, our conclusion can only be reached using the hydrodynamical approach.

Between collisions with the medium, neutrinos thermalize in the fluid frame, so  $\bar{\lambda}$  denotes a somewhat different average if  $\lambda_{\nu N}$  depends on energy [31]; for quadratic energy dependence it is about  $2/3$  smaller. Moreover,  $e_{\text{eq}}$  includes all flavors, so  $\bar{\lambda}$  is a flavor average, and if  $m_\phi$  is small enough,  $\phi$  also contributes to  $e_{\text{eq}}$ . Therefore,  $\nu\text{SI}$  change the exact mean opacity, but on the other hand, PNS cooling strongly depends on convection [33–38]. Therefore, we worry less about how energy streams up from deeper layers and focus on fluid decoupling near the surface.

*Steady emission.*—To get a first sense, we begin with a stationary solution for a simplified emission model: an isothermal sphere (radius  $r_s$ , temperature  $T$ ) and energy-independent  $\lambda_{\nu N}$ . In Fig. 2 we show the resulting flow parameters for a numerical solution with  $r_s = 10$  km and  $\lambda_{\nu N} = 0.2$  km for  $r < r_s$ , and increasing with  $e^{6(r-r_s)/\text{km}}$  for larger  $r$  mainly to avoid a step function.  $T$  is represented by  $e_{\text{eq}}$  constant inside, and outside following the same suppression profile. The fluid accelerates near the surface and quickly reaches luminal speed, similar to free-streaming neutrinos that become ever more collinear after a distance of a few  $r_s$ . In the fluid, neutrinos are locally isotropic and thermal in the comoving frame with an ever decreasing  $T_\nu$ , whereas in the lab frame, most of them stream away radially.

A steady-state solution is unphysical because there must have been a beginning of emission and concomitant luminal wave front at a large distance. In our companion

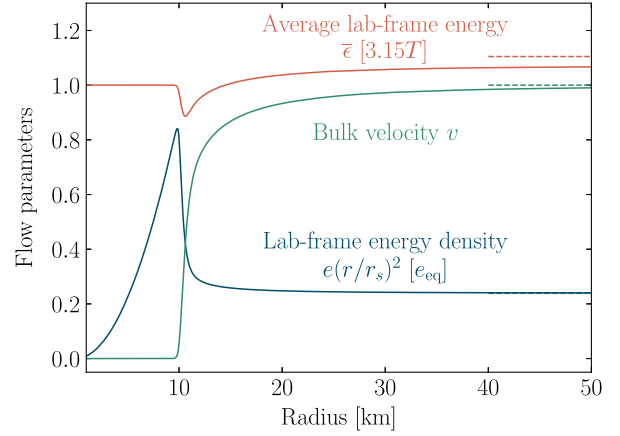


FIG. 2. Flow parameters for steady fluid emission from an isothermal blackbody sphere (temperature  $T$ ), using a smoothed surface at  $r_s = 10$  km as described in the text. Asymptotic values for  $r \rightarrow \infty$  as dashed lines. The average lab-frame neutrino energy  $\bar{e}$  assumes full efficiency for number-changing  $\nu\text{SI}$  interactions.

paper [31], we circumvent this issue with an outer shell at vanishing  $T$  that absorbs the radiation. Between the shells, the analytical velocity profile is given by

$$v(1 - v^2) = \frac{2}{3\sqrt{3}} \left( \frac{r_s}{r} \right)^2, \quad (4)$$

assuming a hard surface at  $r_s$ . At the surface, the fluid emerges with the speed of sound  $v_s = 1/\sqrt{3} = 0.577$ , a general result also found in Ref. [17]. With increasing radius,  $v$  rapidly rises from  $v_s$  to  $c$  and asymptotically reaches a Lorentz factor

$$\gamma \simeq \frac{3^{3/4}}{\sqrt{2}} \frac{r}{r_s} \simeq 1.61 \frac{r}{r_s}. \quad (5)$$

Analogously, the comoving energy and number densities reach asymptotic values of  $\rho \simeq (0.21e_{\text{eq}}/3)(r_s/r)^4$  and  $n \simeq (0.29/3^{3/4})n^{\text{th}}(r_s/r)^3$ , the lab-frame energy density  $e \simeq 4\gamma^2\rho/3 \propto r^{-2}$ .

From the numerical solution (with a slightly softened surface), we see in Fig. 2 how  $e(r)$  quickly drops from within the source body to its asymptotic behavior. Together with increasing  $v$ , the energy flux  $F = \xi e$  is conserved outside the source. Surprisingly, the blackbody emits an energy flux that is numerically only 3%–4% smaller than  $F_{\text{bb}} = e_{\text{th}}/4$  given by the Stefan-Boltzmann law for standard neutrino radiation. We have no fundamental explanation why blackbody emission of a fluid should be so similar, yet not identical, to that of a gas. Whatever the answer to this conceptual question, it defines the practical boundary condition at the source.

Our stationary solution looks similar to wind outflow of Ref. [17], with the crucial difference that our fluid is

steadily produced by the source, not fed by a reservoir of trapped neutrinos that would be quickly exhausted. Our treatment of the boundary connects the thermal properties of the PNS to those of the escaping fluid.

In the comoving frame, the fluid is in equilibrium and thus characterized by its internal  $T_\nu$ . If the source emits  $\nu$  and  $\bar{\nu}$  equally, and if number-changing processes by  $\nu$ SI are fast so neutrinos reach internal chemical equilibrium, the asymptotic  $\rho$  implies  $T_\nu = 0.514T(r_s/r)$ , a drop that is compensated by the work needed for the expansion, or equivalently, the increasing bulk radial motion: the particles simply become more collinear. The increasing  $\gamma$  implies a constant asymptotic lab-frame neutrino energy of  $\bar{\epsilon} = 3.48T$ . Without  $\nu$ SI, the lab-frame spectrum is thermal with the emitter's  $T$  and thus  $\bar{\epsilon} = 3.15T$ .

If number-changing reactions are not in equilibrium, but still equal  $\nu$  and  $\bar{\nu}$  emission by the source, a non-vanishing degeneracy parameter  $\eta = \mu_\nu/T_\nu$  develops, based on number and energy flux conservation. The asymptotic values are  $\eta = -0.363$ ,  $T_\nu = 0.561T(r_s/r)$ , and lab-frame  $\bar{\epsilon} = 3.75T$ . Constant  $\eta$  implies entropy conservation (adiabatic expansion) once the fluid has settled into steady motion at  $r$  larger than a few  $r_s$ .

*Relaxation to steady state.*—If thermal emission begins suddenly at SN collapse, a luminal neutrino fluid front is launched into space. While physically plausible, we have explicitly checked numerically that this dynamical solution asymptotically approaches steady outflow near the source [31]. Though our treatment of the source is schematic, we are confident that it correctly captures the transient. The main innovation is to include energy exchange with the nuclear medium, allowing the PNS to act as an energy reservoir that feeds neutrino emission for a long time compared with the PNS size, completely different from sudden fluid release, a concept that would only apply to the initial front wave.

*Neutrino fireball expansion.*—As the PNS cools, neutrino emission drops. After  $\delta t$  of a few seconds, a shell of width  $\delta t$  has been emitted. The subsequent evolution is well understood in the context of fireballs in gamma-ray bursts [39] (see also Refs. [28,29] for early theoretical studies and Refs. [40,41] for particle bounds from astrophysical transients). Since most of the fluid moves with  $v \simeq 1$ , the shell thickness cannot change, but its radius gradually expands. Within the shell, our steady-state flow parameters remain valid.

This is also seen because, in steady state, a disturbance in the fluid travels with  $v_s$  in the comoving frame, the latter however accelerating with increasing radius. There is a sound horizon  $r_h \simeq 1.13r_s$  [31]. The fluid at larger  $r$  is unaware of anything happening at the emission surface, such as the source turning off.

As the thickness does not change, the fireball is not a self-similar solution because it contains a characteristic length  $\delta t$ . In fact, for free expansion of a relativistic gas,

self-similar solutions with regular behaviors do not seem to exist. In our case, regular behavior is attained because, for energy injection over a period  $\delta t$ , the system always keeps memory of the scale  $\delta t$  (see, e.g., Refs. [28,29]), even after a time  $t \gg \delta t$ .

*Observable neutrino signal.*—Within the fireball, neutrinos possess a boosted blackbody spectrum. However, at some radius  $r_d$ , the density is so low that  $\nu$ SI decouple and then neutrinos stream freely. The large Lorentz factor of Eq. (5) reveals that we observe neutrinos with nearly the same angular spread for both free streaming or fluid propagation, so time-of-flight effects are minimal. We thus picture the observable flux at a distance  $d_{\text{SN}} \gg r_d$  to be steadily emitted by a spherical shell of radius  $r_d$ , taken to be the same for all energies.

Thus at a large distance one observes the superposition of the boosted blackbody spectra from each point on that sphere (right panel in Fig. 1). While the comoving  $T_{\nu,d}$  and Lorentz factor  $\gamma_d$  are the same for all points, they are seen under different angles, producing different spectra due to Doppler boosting. The limb of the sphere looks much colder (effective temperature of order  $T_{\nu,d}/\gamma_d$ ) than the center (effective temperature of order  $2T_{\nu,d}\gamma_d$ ). Explicitly, the superposed number flux spectrum for a single species is found to be [40]

$$\frac{d\Phi}{d\epsilon} = \frac{r_d^2}{4\pi^2 d_{\text{SN}}^2} \frac{\tilde{T}\epsilon}{\gamma_d^2} \log \left[ 1 + e^{\eta - \epsilon/2\tilde{T}} \right], \quad (6)$$

where  $\tilde{T} = \gamma^d T_\nu^d = \gamma T_\nu$  if we recall the constancy of  $\gamma T_\nu$  during fireball expansion. When  $\nu$ SI number-changing reactions are in equilibrium near the PNS,  $\tilde{T} = 0.828T$  and  $\eta = 0$ . For the opposite case of number-conserving dynamics,  $\tilde{T} = 0.903T$  and  $\eta = -0.363$ .

Finally, using the Lorentz factor of Eq. (5), the observer spectrum is

$$\frac{d\Phi}{d\epsilon} = \frac{r_s^2}{6\sqrt{3}\pi^2 d_{\text{SN}}^2} \tilde{T}\epsilon \log \left[ 1 + e^{\eta - \epsilon/2\tilde{T}} \right]. \quad (7)$$

Nothing depends on  $r_d$ , justifying our earlier assumption of taking decoupling to be instantaneous. This is to be compared with the blackbody radiation without  $\nu$ SI

$$\left( \frac{d\Phi}{d\epsilon} \right)_{\text{bb}} = \frac{r_s^2}{8\pi^2 d_{\text{SN}}^2} \frac{\epsilon^2}{e^{\epsilon/T} + 1}. \quad (8)$$

One can check that the integrated energy flux from Eq. (7) is indeed 0.96 the one from Eq. (8), thus maintaining exactly the energy outflow stated earlier [31].

The different spectra are shown in Fig. 3. Compared with the usual blackbody spectrum,  $\nu$ SI increase  $\langle \epsilon \rangle$  by 10% (19%) if  $\nu$ SI do not conserve (do conserve) the neutrino number, and increase  $\langle \epsilon^2 \rangle$  by 37% (60%). The impact of

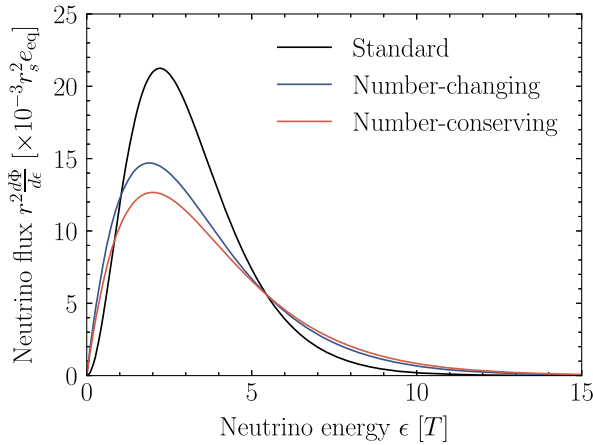


FIG. 3. Spectrum of neutrino number flux  $\Phi$  at Earth, distorted by  $\nu$ SI (red and blue line), assuming that without  $\nu$ SI, a blackbody flux is emitted (black line).

number-changing processes is very limited; particle number does not change in the fireball expansion, and only slightly changes at the emission from the neutrinosphere. In this sense, our results differ markedly from those of Ref. [16], where only the  $\nu\bar{\nu} \rightarrow \nu\bar{\nu}\nu\bar{\nu}$  reactions had been considered without accounting for the inverse reactions. In reality, the latter are as fast as the direct reactions, and at equilibrium they do not produce any large change in the average energy, lifting the bounds proposed in Ref. [16]. In the region of interest, for mediator masses above the MeV scale, only bounds based on laboratory, cosmology, and high-energy astrophysical neutrinos remain valid (see references in Ref. [1]).

One observable we have not discussed is flavor. In the standard case, this issue is not fully understood, given the uncertainties on neutrino flavor conversion. On the other hand, assuming that all flavors are affected by  $\nu$ SI without overly hierarchical couplings, the spectra will be equalized, simplifying the situation somewhat.

*Discussion and outlook.*—We have investigated the emission, propagation, and observed spectrum of SN neutrinos, assuming they behave as a relativistic fluid caused by large  $\nu$ SI, drawing on theoretical foundations elaborated in our companion paper [31]. We have used the simplest possible toy model of an isothermal and homogeneous source, but our results are generic up to factors of order unity. We find that the time profile is not modified by  $\nu$ SI—it is set by emission at the source, not by modified fluid propagation. On the other hand, the energy spectrum is somewhat harder than a blackbody spectrum, all else being equal. It is not obvious in which exact direction the neutrino energies and fluxes would change in a self-consistent SN treatment.

At present, we cannot estimate the realistic quantitative impact of different tens-of-percent effects due to  $\nu$ SI, as other modifications of this magnitude can play an important role [42–45]. Moreover, there is a region in the  $g_\phi$ – $m_\phi$

plane in which  $\phi$  are trapped, but neutrinos do not behave as a fluid, and our results do not apply here. For the time being, while a future galactic SN might still be useful to unveil  $\nu$ SI, laboratory searches and future high-energy neutrino telescopes seem to be the best probe in large parts of the open parameter space [1].

Treating neutrinos with large  $\nu$ SI as a relativistic fluid as pioneered by Dicus *et al.* [7] has vastly simplified the discussion both conceptually and analytically. The uncanny smallness of the modifications caused by the fluid nature is the main surprise of this investigation and mandates a self-consistent study to understand the exact quantitative effects in SN physics.

We thank Shashank Shalgar, Irene Tamborra, Mauricio Bustamante, Po-Wen Chang, Ivan Esteban, John Beacom, Todd Thompson, Christopher Hirata, and Thomas Janka for informative discussions and/or comments on the manuscript. D. F. G. F. is supported by the Villum Fonden under Project No. 29388 and the European Union’s Horizon 2020 Research and Innovation Program under the Marie Skłodowska-Curie Grant Agreement No. 847523 “INTERACTIONS.” G. G. R. acknowledges partial support by the German Research Foundation (DFG) through the Collaborative Research Centre “Neutrinos and Dark Matter in Astro- and Particle Physics (NDM),” Grant SFB-1258-283604770, and under Germany’s Excellence Strategy through the Cluster of Excellence ORIGINS EXC-2094-390783311. E. V. acknowledges support by the European Research Council (ERC) under the European Union’s Horizon Europe Research and Innovation Program (Grant No. 101040019). This article is based upon work from COST Action COSMIC WISPerS CA21106, supported by COST (European Cooperation in Science and Technology).

- 
- [1] J. M. Berryman *et al.*, Neutrino self-interactions: A white paper, *Phys. Dark Universe* **42**, 101267 (2023).
  - [2] D. A. Dicus, E. W. Kolb, and D. L. Tubbs, Spontaneous lepton-number violation and de-leptonization in stellar collapse, *Nucl. Phys.* **B223**, 532 (1983).
  - [3] G. B. Gelmini, S. Nussinov, and M. Roncadelli, Bounds and prospects for the majoron model of left-handed neutrino masses, *Nucl. Phys.* **B209**, 157 (1982).
  - [4] E. W. Kolb and M. S. Turner, Supernova 1987A and the secret interactions of neutrinos, *Phys. Rev. D* **36**, 2895 (1987).
  - [5] A. Manohar, A limit on the neutrino-neutrino scattering cross section from the supernova, *Phys. Lett. B* **192**, 217 (1987).
  - [6] Z. G. Berezhiani and M. I. Vysotsky, Neutrino decay in matter, *Phys. Lett. B* **199**, 281 (1987).
  - [7] D. A. Dicus, S. Nussinov, P. B. Pal, and V. L. Teplitz, Implications of relativistic gas dynamics for neutrino-neutrino cross sections, *Phys. Lett. B* **218**, 84 (1989).

- [8] G. M. Fuller, R. Mayle, and J. R. Wilson, The majoron model and stellar collapse, *Astrophys. J.* **332**, 826 (1988).
- [9] A. V. Berkov, Y. P. Nikitin, A. L. Sudarikov, and M. Y. Khlopov, Possible manifestations of anomalous 4 neutrino interaction, *Sov. J. Nucl. Phys.* **48**, 497 (1988).
- [10] R. V. Konoplich and M. Y. Khlopov, Constraints on triplet majoron model due to observations of neutrinos from stellar collapse, *Sov. J. Nucl. Phys.* **47**, 565 (1988).
- [11] Z. G. Berezhiani and A. Y. Smirnov, Matter induced neutrino decay and supernova SN1987A, *Phys. Lett. B* **220**, 279 (1989).
- [12] Y. Farzan, Bounds on the coupling of the majoron to light neutrinos from supernova cooling, *Phys. Rev. D* **67**, 073015 (2003).
- [13] L. Heurtier and Y. Zhang, Supernova constraints on massive (pseudo)scalar coupling to neutrinos, *J. Cosmol. Astropart. Phys.* **02** (2017) 042.
- [14] M. Blennow, A. Mirizzi, and P. D. Serpico, Nonstandard neutrino-neutrino refractive effects in dense neutrino gases, *Phys. Rev. D* **78**, 113004 (2008).
- [15] A. Das, A. Dighe, and M. Sen, New effects of non-standard self-interactions of neutrinos in a supernova, *J. Cosmol. Astropart. Phys.* **05** (2017) 051.
- [16] S. Shalgar, I. Tamborra, and M. Bustamante, Core-collapse supernovae stymie secret neutrino interactions, *Phys. Rev. D* **103**, 123008 (2021).
- [17] P.-W. Chang, I. Esteban, J. F. Beacom, T. A. Thompson, and C. M. Hirata, Toward powerful probes of neutrino self-interactions in supernovae, *Phys. Rev. Lett.* **131**, 071002 (2023).
- [18] 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).
- [19] 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.
- [20] D. G. Cerdeño, M. Cermeño, and Y. Farzan, Constraints from the duration of supernova neutrino burst on on-shell light gauge boson production by neutrinos, *Phys. Rev. D* **107**, 123012 (2023).
- [21] H.-T. Janka, Explosion mechanisms of core-collapse supernovae, *Annu. Rev. Nucl. Part. Sci.* **62**, 407 (2012).
- [22] H.-T. Janka, Neutrino-driven explosions, in *Handbook of Supernovae*, edited by A. W. Alsabti and P. Murdin (Springer, New York, 2017), p. 1095.
- [23] A. Burrows, D. Radice, D. Vartanyan, H. Nagakura, M. A. Skinner, and J. C. Dolence, The overarching framework of core-collapse supernova explosions as revealed by 3D FORNAX simulations, *Mon. Not. R. Astron. Soc.* **491**, 2715 (2020).
- [24] E. Vitagliano, I. Tamborra, and G. Raffelt, Grand unified neutrino spectrum at earth: Sources and spectral components, *Rev. Mod. Phys.* **92**, 045006 (2020).
- [25] A. Mezzacappa, E. Endeve, O. E. B. Messer, and S. W. Bruenn, Physical, numerical, and computational challenges of modeling neutrino transport in core-collapse supernovae, *Living Rev. Comput. Astrophys.* **6**, 4 (2020).
- [26] A. Burrows and D. Vartanyan, Core-collapse supernova explosion theory, *Nature (London)* **589**, 29 (2021).
- [27] M. Rampp, R. Buras, H.-T. Janka, and G. Raffelt, Core-collapse supernova simulations: Variations of the input physics, [arXiv:astro-ph/0203493](https://arxiv.org/abs/astro-ph/0203493).
- [28] P. Vitello and M. Salvati, Hydrodynamic free expansion of a localized relativistic plasma, *Phys. Fluids* **19**, 1523 (1976).
- [29] M. Yokosawa and S. Sakashita, Relativistic hydrodynamics of a free expansion and a shock wave in one-dimension, *Astrophys. Space Sci.* **72**, 447 (1980).
- [30] See Supplemental Material, which includes Refs. [46,47], at <http://link.aps.org/supplemental/10.1103/PhysRevLett.132.021002> for a detailed discussion of the hydrodynamical treatment, a description of the fireball solution, and its comparison to the burst outflow proposed in the previous literature.
- [31] D. F. G. Fiorillo, G. Raffelt, and E. Vitagliano, companion paper, Supernova emission of secretly interacting neutrino fluid: Theoretical foundations, *Phys. Rev. D* **109**, 023017 (2024).
- [32] S. Weinberg, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity* (John Wiley and Sons, New York, 1972).
- [33] R. I. Epstein, Lepton-driven convection in supernovae, *Mon. Not. R. Astron. Soc.* **188**, 305 (1979).
- [34] A. Burrows and J. M. Lattimer, Convection, type II supernovae, and the early evolution of neutron stars., *Phys. Rep.* **163**, 51 (1988).
- [35] W. Keil, H.-T. Janka, and E. Müller, Ledoux convection in protoneutron stars—A clue to supernova nucleosynthesis?, *Astrophys. J. Lett.* **473**, L111 (1996).
- [36] H.-T. Janka, K. Kifonidis, and M. Rampp, Supernova explosions and neutron star formation, in *Physics of Neutron Star Interiors*, edited by D. Blaschke, N. K. Glendenning, and A. Sedrakian (Springer, New York, 2001), Vol. 578, p. 333.
- [37] L. Dessart, A. Burrows, E. Livne, and C. D. Ott, Multidimensional radiation/hydrodynamic simulations of proto-neutron star convection, *Astrophys. J.* **645**, 534 (2006).
- [38] H. Nagakura, A. Burrows, D. Radice, and D. Vartanyan, A systematic study of proto-neutron star convection in three-dimensional core-collapse supernova simulations, *Mon. Not. R. Astron. Soc.* **492**, 5764 (2020).
- [39] T. Piran, A. Shemi, and R. Narayan, Hydrodynamics of relativistic fireballs, *Mon. Not. R. Astron. Soc.* **263**, 861 (1993).
- [40] M. Diamond, D. F. G. Fiorillo, G. Marques-Tavares, and E. Vitagliano, Axion-sourced fireballs from supernovae, *Phys. Rev. D* **107**, 103029 (2023).
- [41] M. Diamond, D. F. G. Fiorillo, G. Marques-Tavares, I. Tamborra, and E. Vitagliano, Multimessenger constraints on radiatively decaying axions from GW170817, [arXiv:2305.10327](https://arxiv.org/abs/2305.10327).
- [42] R. Bollig, H.-T. Janka, A. Lohs, G. Martínez-Pinedo, C. J. Horowitz, and T. Melson, Muon creation in supernova matter facilitates neutrino-driven explosions, *Phys. Rev. Lett.* **119**, 242702 (2017).

- [43] T. Melson, H.-T. Janka, R. Bollig, F. Hanke, A. Marek, and B. Müller, Neutrino-driven explosion of a 20 solar-mass star in three dimensions enabled by strange-quark contributions to neutrino–nucleon scattering, *Astrophys. J. Lett.* **808**, L42 (2015).
- [44] J. Ehring, S. Abbar, H.-T. Janka, G. Raffelt, and I. Tamborra, Fast neutrino flavor conversion in core-collapse supernovae: A parametric study in 1D models, *Phys. Rev. D* **107**, 103034 (2023).
- [45] J. Ehring, S. Abbar, H.-T. Janka, G. Raffelt, and I. Tamborra, Fast neutrino flavor conversions can help and hinder neutrino-driven explosions, *Phys. Rev. Lett.* **131**, 061401 (2023).
- [46] R. D. Blandford and C. F. McKee, Fluid dynamics of relativistic blast waves, *Phys. Fluids* **19**, 1130 (1976).
- [47] I. B. Zeldovich, Y. P. Raizer, and W. D. Hayes, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* (Academic Press, New York, 1966), Vol. 1.