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Toward Powerful Probes of Neutrino Self-Interactions in Supernovae

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Neutrinos remain mysterious. As an example, enhanced self-interactions (νSI), which would have broad implications, are allowed. At the high neutrino densities within core-collapse supernovae, νSI should be important, but robust observables have been lacking. We show that νSI make neutrinos form a tightly coupled fluid that expands under relativistic hydrodynamics. The outflow becomes either a burst or a steady-state wind; which occurs here is uncertain. Though the diffusive environment where neutrinos are produced may make a wind more likely, further work is needed to determine when each case is realized. In the burst-outflow case, νSI increase the duration of the neutrino signal, and even a simple analysis of SN 1987A data has powerful sensitivity. For the wind-outflow case, we outline several promising ideas that may lead to new observables. Combined, these results are important steps toward solving the 35-year-old puzzle of how νSI affect supernovae.

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The weakness of neutrinos makes them powerful [1–3]. Because of their near-lack of particle properties, they are a sensitive probe of new physics. Because of their high abundance, they are a sensitive probe of cosmology. And because of their penetrating power, they are a sensitive probe of dense sources in astrophysics. Increasingly, progress in one area connects to the others, especially for testing novel-physics scenarios.

An important example is neutrinos with enhanced self-interactions (νSI, also known as secret interactions as they affect only neutrinos) [4–41], reviewed in Ref. [42]. Laboratory probes allow strong νSI—orders of magnitude stronger than weak interactions—and these have been invoked to explain various anomalies [43–50]. Cosmological probes also allow strong νSI, such that early universe physics could be substantially changed. Future astrophysical probes, for example, those based on high-energy neutrino propagation through the cosmic neutrino background, will be sensitive to νSI [34,36,51].

In principle, core-collapse supernovae should be a powerful probe of νSI, as the high neutrino densities ($\gtrsim 10^{36}$ cm^{-3}) would cause frequent $\nu-\nu$ scattering (even standard model self scattering is non-negligible in supernovae [52–54]). But 35 years after SN 1987A [55–59], we still lack robust observables. The claim by Manohar [60] that νSI would hinder neutrino escape from the proto-neutron star (PNS) was rebutted by Dicus *et al.* [61]; we discuss both papers below. Other constraints are weak, have large uncertainties, or rely on future data [6,25–28]. Nevertheless, it is easy to worry that the effects of νSI could be large enough to alter our

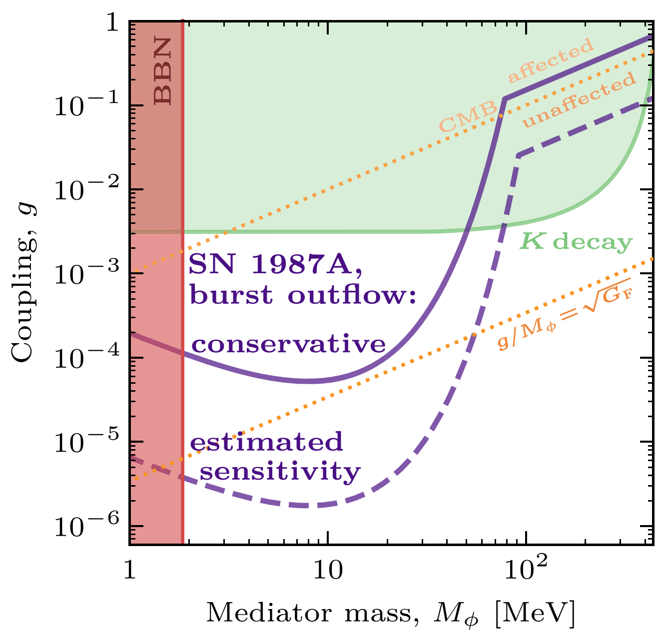

FIG. 1. Potential constraints on νSI from SN 1987A (assuming the burst-outflow case), previous limits, and relevant scales [12,36,86,87]. K-decay bounds apply only to ν_e and ν_μ. Strong νSI would change the time profile of the SN 1987A neutrino signal; we show a conservative analysis (30-s duration), and an estimated sensitivity (3-s smearing).

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deductions about neutrinos and supernovae. New work is needed.

In this Letter, we reexamine this problem, producing a major first step and a roadmap for the next ones. We show that for strong νSI, even self-scattering *outside the PNS* leads to a tightly coupled, expanding neutrino fluid. There are two possible cases for the outflow—a burst or a steady-state wind—and further work is needed to decide when each obtains. In the burst-outflow case, the *observed neutrino signal duration* is a powerful, model-independent probe of νSI. The neutrino fluid would have a radial extent much greater than the PNS, with individual neutrinos moving in all directions. When decoupling begins, at a time that depends on the νSI strength, neutrinos would free-stream towards the Earth from the *whole* extended fluid, leading to a longer signal than observed for SN1987A. In the wind-outflow case, decoupling would take place much closer to the PNS. We will explore this separately, though here we note promising ideas.

Figure 1 previews our results for the burst-outflow case, which we focus on In this first paper. In the following, we review supernova neutrino emission, discuss the impact of νSI, calculate how they affect the signal duration, contrast this with SN 1987A data, and conclude by outlining future directions. Our approach is simple but conservative, aiming for factor-two precision. In the Supplemental Material [62] that includes Refs. [63–85], we show more detailed calculations and assess the impact of our assumptions.

Supernova neutrino emission without νSI.—For orientation, we describe the basic features of supernova neutrino emission; details are given in the Supplemental Material [62]. The broad agreement of these predictions with SN 1987A data sets the stage to probe νSI. Our estimates are confirmed by supernova simulations that include many important complications [88–95].

A supernova begins when electron capture and nuclear photodissociation rob the massive star's core of pressure support, leading to runaway collapse [96–99]. The outcome of the collapse is a compact PNS with a mass $M \sim 1.5 M_{\odot}$ and a radius $R \sim 10$ km. The collapse leads to a loss of gravitational potential energy of the core $|\Delta E_{\rm b}| \sim 3 \times 10^{53}$ ergs. Ultimately, almost all of this energy is released in neutrinos.

These neutrinos diffuse through matter until they reach the neutrinosphere, where they decouple and escape. As diffusion suppresses energy flow, their average energy outside the PNS is $\langle E_\nu \rangle \sim 10$ MeV [100]. Because of diffusion, the neutrino signal duration is $\sim$10 s [1,101–103]. Far outside the PNS, this ultimately results in a neutrino shell of thickness $\ell_0 \simeq c \cdot 10$ s that free-streams away at the speed of light.

Supernova neutrino emission with νSI.—Because of enhanced $\nu - \nu$ elastic scattering because of νSI, neutrinos do not free-stream after exiting the PNS. This happens

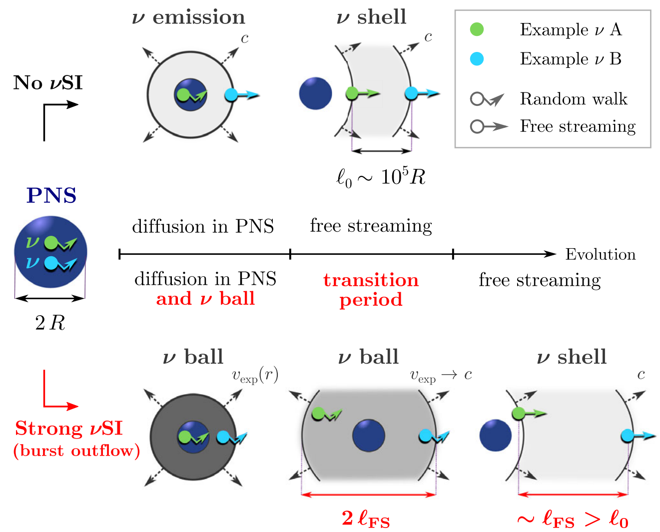

FIG. 2. Macroscopic evolution of a neutrino outflow from a supernova (lengths not to scale). Without νSI, the final width of the neutrino shell is $\ell_0 \sim c \cdot 10$ s, much larger than the PNS and set by neutrino diffusion therein. With strong νSI, neutrinos diffuse in the expanding neutrino ball. In the burst-outflow case, the size of the ball when neutrinos start decoupling from each other, $\ell_{\rm FS}$, sets the final width of the neutrino shell. The duration of the observed neutrino signal will thus be significantly extended when $\ell_{\rm FS} > \ell_0$.

because, as we quantify below, the mean free path is initially tiny, on the μm scale. Neutrinos emitted in all outward directions from each surface element of the PNS promptly scatter with each other. This makes them move in all directions, including inwards, under a random walk (see Supplemental Material [62], where we also discuss how the process conserves momentum). Macroscopically, the coupled neutrino fluid, denoted as the ν *ball* below, expands as a pressurized gas in vacuum. On the relevant length scales—much larger than the mean free path—the behavior of the ball is described by relativistic hydrodynamics. As we detail in the Supplemental Material [62], there are two cases to consider.

If, similar to the setup in Dicus *et al.* [61], we consider the sudden free expansion of a fluid in vacuum, we obtain a burstlike outflow. The ball stays homogeneous, with a near-constant density that decreases as it expands. Any density gradient would rapidly vanish due to the associated pressure difference. We have verified this with the PLUTO hydrodynamics code [104], where we also find that the asymptotic expansion is homologous, i.e., $v_{\rm exp}(r) \propto r$ inside the ball, with $v_{\rm exp} = c$ at the outer boundary. Microscopically, homogeneity is ensured by the random walks mentioned above: any void would be rapidly filled by the randomly moving surrounding neutrinos.

If, on the contrary, given the diffusive nature of the outflow *inside* the PNS, we consider the steady-state case, there is a unique solution, a wind analogous to the well-known relativistic fireball [105] (see details in the

Supplemental Material [62]). Then the outflow is very different from the burst case, as individual neutrino motions become radial relatively close to the PNS, causing the density outside it to fall as $\sim r^{-2}$. Diffusive systems tend to reach steady-state solutions, but further work is needed to understand the conditions and timescales under which a wind may develop. We outline possible observables below, which will develop in a separate paper.

Figure 2 shows how the neutrino fluid evolves without or with νSI in the burst-outflow case. With νSI, the neutrino ball expands homogeneously, with a near-constant density that decreases as it expands (bottom left). The scattering between neutrinos within the ball ends when expansion sufficiently dilutes the density. We denote the radius of the ball when decoupling begins as $\ell_{\rm FS}$ (bottom center). At this stage, neutrinos go out in all directions (decoupling is almost instantaneous; see below). The ball then becomes a free-streaming shell with thickness $\sim\ell_{\rm FS}$, from which neutrinos ultimately move radially outward (bottom right). The critical impact of νSI on supernova neutrino emission is now clear: they introduce a new length scale, $\ell_{\rm FS}$, that depends on the νSI strength and thus connects the macroscopic behavior of the fluid with the microphysics of $\nu-\nu$ scattering. The neutrino signal duration with strong νSI, $\sim\ell_{\rm FS}/c > \ell_0/c$ $(\ell_0 \sim c\cdot 10\ {\rm s} \sim 10^5 R)$, is significantly lengthened. In the wind-outflow case, the neutrino fluid would not be homogeneous nor would neutrinos move in all directions, hence this argument does not apply.

In earlier work, the effects of νSI on supernova timing were debated, leading to a community consensus that this observable does not provide limits. Manohar [60] claimed that νSI hinder neutrinos from escaping the PNS, and that the signal duration would be given by the $\nu-\nu$ diffusion time inside the PNS. In turn, Dicus *et al.* [61] argued that a tightly coupled fluid expands no matter how strong its self-interactions are, hence no limit could be obtained. However, for the burst outflow, the observed duration is set by the size of the neutrino ball at decoupling, which does depend on the νSI cross section, as we compute next. This would lead to powerful new sensitivity.

Sensitivity to $\boldsymbol{\nu}$SI *models.*—Here we describe our approach (burst-outflow case) to compute $\ell_{\rm FS}$, relate it to the νSI cross section, and constrain νSI models.

Figure 3 illustrates the microphysics. As we discuss above, scattering makes neutrinos move in all directions. Decoupling begins when τ is small, with $\tau=\tau(\ell)$ the νSI optical depth, as the number of scatterings a neutrino will undergo when traveling a distance ℓ is $\sim\tau^2$. We denote the optical depth at this stage as $\tau_{\rm FS}\equiv\tau(\ell_{\rm FS})$. For $\tau\lesssim\tau_{\rm FS}$, the ball becomes a shell.

The average optical depth for a neutrino traveling a distance ℓ is

$$\tau(\ell) = \int \langle n_\nu \sigma_{\nu\nu}\rangle {\rm d}r \sim \langle N_\nu \sigma_{\nu\nu}\rangle \left(\frac{4\pi}{3}\ell^3\right)^{-1}\ell, \qquad (1)$$

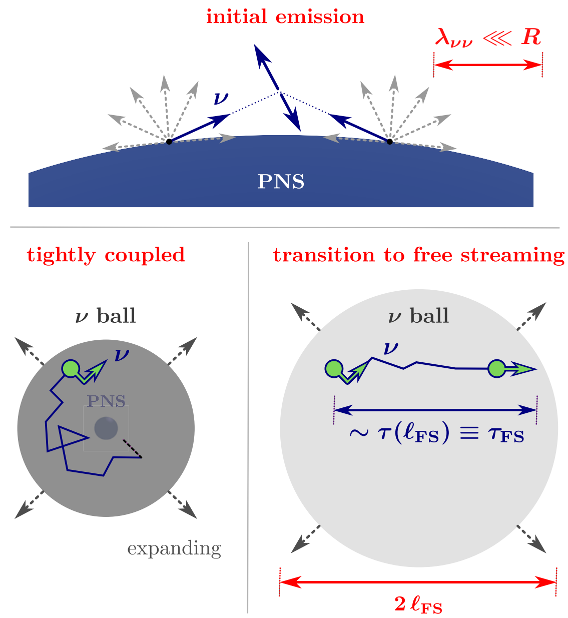

FIG. 3. Microscopic evolution of neutrino scattering due to νSI at different times for the burst-outflow case (lengths not to scale). Neutrinos move in all directions until the νSI optical depth becomes small. After then, neutrinos are no longer significantly deflected and the ball becomes a shell.

where $n_\nu \sim N_\nu/(4\pi\ell^3/3)$ is the neutrino number density, $\sigma_{\nu\nu}$ is the νSI cross section, and $N_\nu \sim |\Delta E_{\rm b}|/\langle E_\nu\rangle$ is the number of neutrinos in the ball. We take N_ν to be the same as without νSI, as $\nu-\nu$ scattering conserves the neutrino number except for the largest couplings [28] (our results are robust against this; see Supplemental Material [62]). The brackets $\langle\ldots\rangle$ denote the average with respect to the neutrino phase space distributions (see Supplemental Material [62]). Since the number of scatterings ($\sim\tau^2$) decreases as ℓ^{-4} as the ball expands, decoupling takes place over a short timescale.

In Eq. (1), $\sigma_{\nu\nu}$ depends on the parameters of the νSI model. As a general case of high interest, we consider νSI among active neutrinos parametrized by the Lagrangian $\mathcal{L}_{\nu{\rm SI}} = -1/2 g\bar{\nu}\nu\phi$ (for UV completions, see Refs. [11–14,49]), where ϕ is the mediator with mass M_ϕ, which for simplicity we take to be a scalar. We consider Majorana neutrinos, hence the $1/2$ factor. Our results also hold for Dirac neutrinos (see Supplemental Material [62]). We assume flavor-independent νSI (see the Supplemental Material [62] for generalizations).

For the mediator mass range we consider, the cross section is s-channel dominated [31,36],

$$\sigma_{\nu\nu} = \frac{g^4}{16\pi}\frac{s}{(s-M_\phi^2)^2 + M_\phi^2\Gamma^2}, \qquad (2)$$

where $\Gamma = g^2 M_\phi/16\pi$ is the scalar decay width and $s \equiv 2E_1E_2(1-\cos\theta_{12})$, with E_1 and E_2 the energies of the incoming neutrinos and θ_{12} their relative angle.

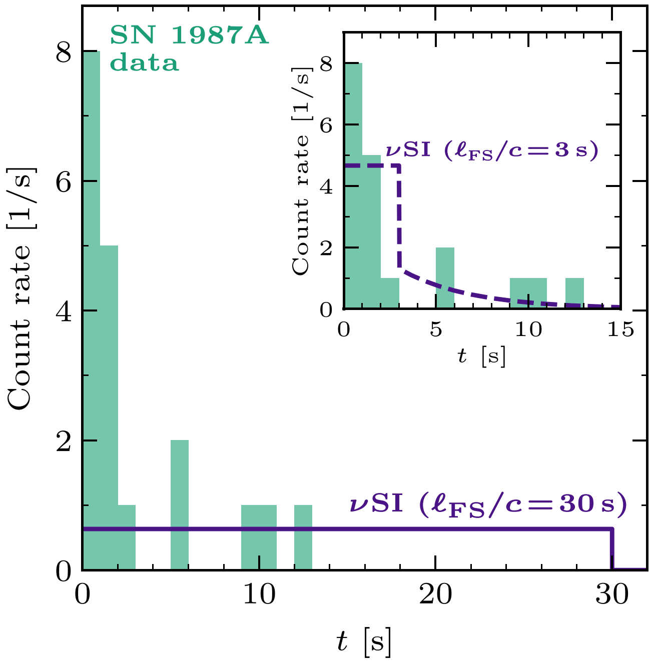

FIG. 4. Observed time profile of SN 1987A neutrinos compared to schematic predictions with νSI for the burst-outflow case. The main figure is for our conservative analysis and the inset for our estimated sensitivity. νSI corresponding to the conservative analysis are clearly incompatible with observations, while those for the estimated sensitivity could be probed with a dedicated analysis.

For $s(E_1 E_2, \theta_{12}) \sim M_\phi^2$ (i.e., $M_\phi \sim \langle E_\nu \rangle$) νSI are resonantly enhanced, leading to large effects. Assuming that neutrinos follow a Maxwell-Boltzmann distribution (our results are insensitive to this, see Supplemental Material [62]), Eq. (1) and (2) imply an optical depth in the resonant regime of

$$\tau_{\rm res}(\ell) = \left(\frac{3}{2}\right)^7 \frac{|\Delta E_{\rm b}|}{6\langle E_\nu \rangle} \frac{g^2}{M_\phi^2} \frac{1}{\ell^2} \mathcal{F}\left(\frac{M_\phi}{\langle E_\nu \rangle}\right), \tag{3}$$

with $\mathcal{F}(x) \equiv x^5 K_1(3x)/3$ and K_1 the Bessel function. When neutrino emission begins, $\tau \sim 4 \times 10^9 (\ell/10\ \text{km})$ at the edge of our conservative sensitivity in Fig. 1 for typical neutrino densities $\sim 10^{36}\ \text{cm}^{-3}$. This corresponds to a neutrino mean free path $\ell/\tau \sim \mu\text{m}$, as noted above.

Given the optical depth at decoupling, $\tau_{\rm FS} \equiv \tau(\ell_{\rm FS})$, the νSI strength g, and the mediator mass M_ϕ, Eq. (3) gives an estimate for the signal duration $\ell_{\rm FS}$. Conversely, given $\ell_{\rm FS}$ and $\tau_{\rm FS}$, we calculate the sensitivity to g in the resonant regime,

$$\begin{aligned} g \sim 6 \times 10^{-5} \left(\frac{\tau_{\rm FS}}{10}\right)^{1/2} \left(\frac{\ell_{\rm FS}/c}{30\ \text{s}}\right) \left(\frac{M_\phi}{10\ \text{MeV}}\right) \\ \times \left(\frac{|\Delta E_{\rm b}|}{3 \times 10^{53}\ \text{ergs}}\right)^{-1/2} \left(\frac{\langle E_\nu \rangle}{10\ \text{MeV}}\right)^{1/2} \\ \times \left[\frac{\mathcal{F}(M_\phi/\langle E_\nu \rangle)}{\mathcal{F}(1)}\right]^{-1/2}. \end{aligned} \tag{4}$$

Numerically, the last factor in Eq. (4) stays between 1 and 10 as long as M_ϕ does not deviate from $\langle E_\nu \rangle$ by more than a factor ~ 5. We take into account this variation as well as the nonresonant sensitivity (see Supplemental Material [62]).

Constraints from SN 1987A.—Figure 4 shows that, if the burst-outflow case is realized, we can set strong limits on νSI. For the SN 1987A neutrino data from Kam-II and IMB [55–58], we assume a common start time. Based on the arguments above, the data conservatively exclude νSI that lead to $\ell_{\rm FS}/c \gtrsim 30$ s. Even if $\ell_{\rm FS}/c$ is smaller than the observed duration ~ 10 s, νSI will still homogenize the neutrino ball, smearing features at times $\lesssim \ell_{\rm FS}/c$. A detailed νSI simulation with a full statistical analysis could probe down to $\ell_{\rm FS}/c \sim 3$ s, the smallest timescale at which the data show clear features.

Figure 1 shows the corresponding sensitivities to νSI parameters, following the procedure described above. Because the cross section is largest at the resonance, the sensitivity is best for $M_\phi \sim \langle E_\nu \rangle \sim 10$ MeV. For our conservative analysis, we assume that decoupling starts when the neutrino optical depth falls below $\tau_{\rm FS} = 10$ (~ 100 $\nu - \nu$ scatterings). For our estimated sensitivity, we take $\tau_{\rm FS} = 1$ (~ 1 scattering); then the sensitivity to g in the resonant regime improves by a factor ~ 30: a factor 10 from the decrease in $\ell_{\rm FS}$, and a factor $\sqrt{10} \sim 3$ from the decrease in $\tau_{\rm FS}$. In Supplemental Material [62], we display results over a wider mediator mass range and show that decoupling begins for $\tau \lesssim 10$ in our primary region of interest.

If the burst-outflow case is realized, our results are robust. First, we conservatively make minimal assumptions (emission of $\sim |\Delta E_{\rm b}|/\langle E_\nu \rangle \sim 10^{58}$ neutrinos with energies ~ 10 MeV) and focus on the effects of νSI on $\nu - \nu$ scattering far outside the PNS. Additional effects inside or near the PNS (possible extra delays, $2\nu \to 4\nu$ processes, neutrino mixing effects, etc.) would either amplify the signal-lengthening signature of νSI or be subdominant. Second, as shown in Eq. (4), the sensitivity to g depends only mildly on the inputs. Third, for even slightly larger g values or earlier times, scattering would be much more frequent (the number of scatterings increases as τ^2, where $\tau \propto g^2/\ell^2$ in the resonant regime and g^4/ℓ^2 otherwise) and νSI effects would be enhanced. Well above our limit, the duration of the signal, scaling as $g/\sqrt{\tau_{\rm FS}}$, would be extreme. For example, for $M_\phi = 10$ MeV and $g \sim 10^{-3}$, this would be 10 minutes, leading to an event rate 10 times below Kam-II backgrounds.

Conclusions and future directions.—Neutrinos are poorly understood and may hold surprises. An example is νSI, for which large effects are allowed by laboratory, cosmology, and astrophysics data. This fact is an opportunity. It is also a liability, as the effects of νSI may be biasing our deductions about other physics. As an example, collective mixing effects can be significantly affected by neutrino scattering (reviewed in Ref. [106]).

In this Letter, we reexamine how νSI affect supernova neutrino emission. We show that the emitted neutrinos form a tightly coupled fluid, with two possible cases for the outflow: burst or wind. Here we focus on the burst case. Although a wind may be more likely, further work is needed to understand when each case obtains.

For the burst-outflow case, we show that the observed duration of a supernova neutrino signal is a robust, powerful signature of νSI. Frequent $\nu - \nu$ scattering outside the PNS leads to a large, tightly coupled, radially expanding ball of neutrinos, internally moving in all directions. This ball decouples with a size depending on the νSI strength, prolonging and smearing the signal in time. νSI causing too long of a duration are strongly excluded, greatly improving upon prior constraints (see Fig. 1).

Future work may significantly improve sensitivity. Focusing on νSI effects *far outside* the PNS, the SN 1987A data could be reanalyzed with a detailed νSI simulation and a full statistical treatment. For a future galactic supernova, the gains could be much more dramatic, because of the much more precise information on the time profile, flavors, and spectra [107,108], which will also solidify the astrophysical model used to test new physics. Probing the short-timescale features predicted by supernova simulations with high statistics, including the possibility of black hole formation, is especially interesting. Flavor sensitivity will help probe νSI strengths in different flavors, complementary to other probes [36,109,110].

For the wind-outflow case, further work and detailed simulations are needed to understand the observable consequences. Relativistic timing effects have been predicted for similar systems [111]. The wind outflow is the *only* steady-state solution to the equations of relativistic hydrodynamics with physical boundary conditions; hence, if it is realized, the entire neutrino fluid *both* outside and inside the PNS would have to relax to it. *Outside* the PNS, this could lead to shocks and other time features that have been observed in numerical explorations of similar systems [112]. As a steady-state outflow requires constant energy injection, when the PNS neutrino emission drops [113], a burst outflow could be recovered, leading to potential observables. *Inside or near* the PNS, the changes could be more dramatic. Differences in the neutrino radial profile between the wind and the no-νSI cases could affect the supernova.

In both outflow cases, further observables will likely follow from the physics *inside or near* the PNS. If neutrinos form a tightly coupled fluid, new ways of energy transfer might be possible. These could affect the temperature and density gradients of matter within the PNS and in the region near the supernova shock. All of this could be made more complex by changes to neutrino flavor evolution. The sensitivity is potentially exquisite, as at the burst-outflow νSI limit, the νSI optical depth inside the PNS is above $\sim 10^9$, to be compared to a neutrino-nucleon optical depth of $\sim 10^4$.

The physical conditions in supernovae offer unique opportunities to test both extreme astrophysics and fundamental physics, provided that each is adequately understood. For 35 years, the impact of νSI on SN 1987A and future supernovae has been an unsolved puzzle. A full understanding is needed before the next galactic supernova, so that its data will provide clear new insights.

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