

Gravitational-Wave Signatures of Nonstandard Neutrino Properties in Collapsing Stellar Cores

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(Received 3 December 2024; revised 10 December 2025; accepted 16 December 2025; published 13 January 2026)

We present a novel multimessenger approach for probing nonstandard neutrino properties through the detection of gravitational waves (GWs) from collapsing stellar cores and associated supernova explosions. We show that neutrino flavor conversion inside the proto-neutron star (PNS), motivated by physics beyond the standard model (BSM), can significantly boost PNS convection. This effect leads to large-amplitude GW emission over a wide frequency range during an otherwise relatively quiescent GW phase shortly after core bounce. Such a signal provides a promising new avenue for exploring nonstandard neutrino phenomena and other BSM physics impacting PNS convection.

DOI: [10.1103/rv17-jm6g](https://doi.org/10.1103/rv17-jm6g)

Introduction—Since their first detection on September 14, 2015, by the LIGO and Virgo collaborations [1], GWs from compact objects have become crucial tools for probing new physics under extreme conditions [2–8]. In this Letter, we demonstrate that GWs produced by collapsing stellar cores and associated supernova (SN) explosions can serve as powerful probes of new physics that influences convection within the hot PNS, with a particular focus on nonstandard neutrino properties.

In the cores of collapsing stars, asymmetric motions of large masses with high velocities leave an imprint on spacetime in the form of GWs. While such signals from SNe have yet to be observed, neutrino-hydrodynamic simulations predict several contributions. In nonrotating progenitors, an initial GW burst arises from “prompt” convection behind the decelerating SN shock shortly after bounce, caused by a negative entropy gradient. This activity calms down after a few 10 ms, followed by a generic phase (around 100 ms) of fairly low GW emission.

Subsequently, violent mass motions connected to hydrodynamic instabilities in the neutrino-heated postshock layer and PNS oscillations, stimulated either by mass downflows from outside or by convection inside the PNS, become the primary sources. Later, GWs also come from long-lasting

PNS convection, accretion of fallback mass, and the asymmetric morphology of expanding explosion ejecta and emitted neutrinos, both leading to a long-term GW strain or “memory” [9–11]. In rotating, collapsing stellar cores, additional sources include the core deformation at bounce, causing different characteristic burst signals, triaxial hydrodynamic (spiral and bar-mode) and magneto-hydrodynamic instabilities, and mass ejection in polar jets (see Refs. [12–18] for reviews).

Neutrino flavor conversion (FC) in the SN environment introduces a major uncertainty in current SN modeling. The high neutrino densities lead to complex, nonlinear, collective FC scenarios that can spawn a range of intriguing phenomena [19–23]. Despite growing evidence of their relevance for SN dynamics, FC has been ignored in most simulations. It is only recently that multidimensional neutrino-hydrodynamic SN simulations have started to include schematic implementations [24–27]. Specifically, the phenomenon of *fast* FC (FFC) was considered, where FC might occur on much smaller scales than other phenomena in the SN core. These studies indicate that FCs can both support or suppress neutrino-driven explosions, depending on the progenitor and the FC region [25].

However, FFCs thus explored [24,25] are not expected *inside* the PNS, at least not during the first few 100 ms after bounce [28–30]. On the other hand, BSM neutrino properties provide several mechanisms for generic FC within a PNS. For instance, resonant conversion and reconversion between active and sterile neutrinos can accelerate the PNS’s neutrino loss [31–33]. Nonstandard neutrino self-interactions (ν NSSI) [34–36] can lead to neutrino flavor equipartition inside the PNS [37]. Likewise, BSM magnetic

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transition moments for Majorana neutrinos can also cause some sort of equipartition between neutrinos and antineutrinos, if there are strong magnetic fields in the PNS [38–40]. Such an equipartition could significantly impact the thermodynamics of SNe [41].

Here we consider FFC as a prototypical example and show that FC inside the PNS, at densities above a few $10^{12} \text{ g cm}^{-3}$, visibly intensifies the GW signal shortly after bounce, during the otherwise relatively GW-quiet phase. This enhancement arises from strong, localized heating caused by the conversions of ν_x and $\bar{\nu}_x$ ($x = \mu, \tau$) to ν_e and $\bar{\nu}_e$, which are immediately absorbed in the medium. This increased heating leads to strong convective activity, which in turn can excite hydrodynamic gravity modes (g modes) near the PNS surface, resulting in strong GW emission. This effect is schematically illustrated in Fig. 1.

Simulation setup and GW analysis—The considered simulations were discussed in Ref. [25]. They were conducted with the neutrino-hydrodynamics code Alcar [42,43], assuming axial symmetry (2D). Alcar is a state-of-the-art, Eulerian, conservative, higher-order Godunov-type finite-volume solver designed for both 1D and multi-D non-relativistic fluid dynamics, coupled with a two-moment scheme to treat energy-dependent, three-flavor neutrino transport. General relativistic corrections for gravity and transport are included. The key features of the code and the implementation details of the neutrino FCs are described in Ref. [24].

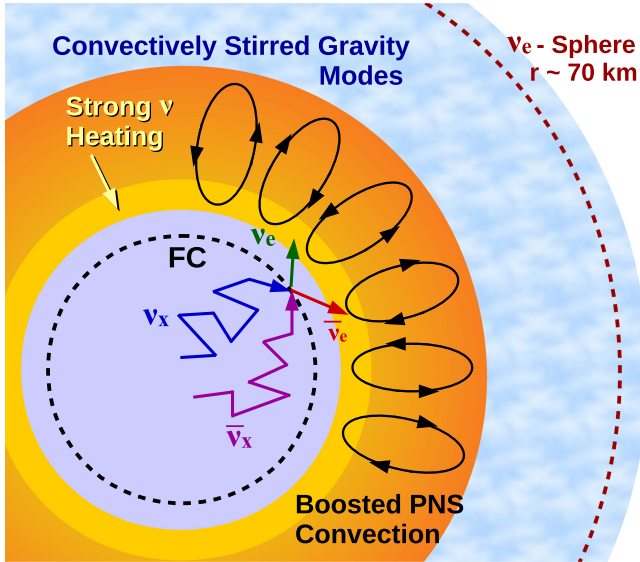


FIG. 1. FC of high-energy ν_x and $\bar{\nu}_x$ create ν_e and $\bar{\nu}_e$ in the PNS interior, an effect assumed to occur at the black dashed circle. If this happens well inside the average electron-type neutrinosphere, the newly created ν_e and $\bar{\nu}_e$ are quickly absorbed by free nucleons. This strong local heating (bright orange layer) enhances PNS convection (orange layer). The convective shell as well as g-mode activity (so-called gravity waves, not to be confused with gravitational waves) instigated in the convectively stable near-surface layer emit GWs.

The FC implementation in Refs. [24,25] was motivated by FFCs, but the parametric representation can be interpreted in terms of any BSM physics that would cause similar effects. For examples, see Supplemental Material (SM) [44], which also includes Refs. [45–68]. The following recipe was used: (1) we assume that pairwise $\nu\bar{\nu}$ FCs are “instantaneous,” meaning that they take place over spatial scales much smaller than the numerical grid cells and over time scales much shorter than the computational time steps [69]. This description is also reasonable for BSM-induced FCs, where the scales are governed, for example, by the BSM neutrino interaction potential or the magnetic field strength [37–40]. (2) We assume that the FCs result in flavor equilibrium under the constraint that lepton number is individually conserved for each flavor, particularly for electron-type neutrinos. BSM physics could violate this restriction, potentially allowing for full flavor equilibration, meaning that our more constraining assumption is conservative. (3) Our FC treatment conserves total energy and momentum, while respecting the Pauli exclusion principle. (4) We activate FCs throughout the region where the matter density ρ is below a chosen threshold value, i.e., $\rho < \rho_c$. Although Ref. [69] backs up a scale-separated treatment for FFC even inside the neutrinosphere, such an effective transport has its limitations [70]. Especially, classical transport cannot capture equilibria with non-zero coherence as pointed out in [71] for collisional ν FC. Our approach should be understood as explorative and generic for FCs occurring on much smaller scales as motivated by ν NSSI and other BSM scenarios with similar effects (for details and resolution tests, see SM [44]).

The simulations were initially evolved in 1D until core bounce and then mapped onto a 2D polar coordinate grid with 640 logarithmically spaced radial zones and 90 equally spaced angular zones. The central core of 2 km was kept 1D, thus permitting larger time steps without significant effects on the evolution. To initiate nonradial hydrodynamic instabilities, which otherwise arise only from uncontrolled numerical noise, we perturbed the local density in every cell of the computational grid during the mapping with a random amplitude of up to 0.1%.

We selected three progenitors with different zero-age main-sequence masses: exploding $9M_\odot$ [43,72–77] and $11.2M_\odot$ models [78–82], and a nonexploding $20M_\odot$ model [43,76,83–85]. Our corresponding core-collapse simulations are therefore named M9, M11.2, and M20. For cases without FC, the name is supplemented with “noFC” or else with the choice for the FC threshold density ρ_c . The 2D models considered here differ slightly from those of [25] in being mapped to 2D 5 ms earlier, which is relevant for prompt postshock convection, and including the many-body corrections discussed in [86].

GW signals are postprocessed, employing a variant of the standard quadrupole formula [e.g., Eq. (34) in Ref. [87]; see also SM [44]]. The algorithm makes use of the Euler

equations to avoid the second time derivative and associated numerical errors. Spectrograms are calculated from the strain using a short-time Fourier transformation with a sliding window of 20 ms. Due to axisymmetry in 2D models, the cross mode is zero in all directions and both cross and plus modes vanish for polar observers. Therefore we only report on the plus mode, h_+ , observed in the equatorial plane at a distance of 10 kpc.

Results and discussion—A dynamically relevant consequence of FC inside the PNS is enhanced convective activity. This triggers and strengthens GW emission. The convective velocities become several times higher than without FC. At densities exceeding a few $10^{12} \text{ g cm}^{-3}$, weak processes hinder the presence of $\bar{\nu}_e$ due to e and ν_e degeneracy. Therefore, the dominant FC channel at high ν_x energies is $\nu_x, \bar{\nu}_x \rightarrow \nu_e, \bar{\nu}_e$. The newly produced ν_e and $\bar{\nu}_e$ are quickly absorbed by the surrounding medium (see Ref. [24] for a detailed discussion of this effect in 1D). Additional, local heating fosters vigorous convective mass motions inside the PNS, as illustrated by Fig. 1 and visible in our simulations (Fig. 2).

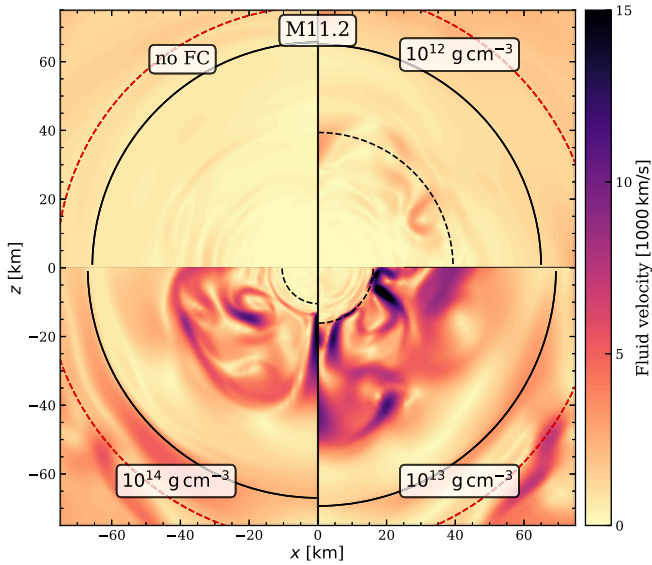


FIG. 2. Convective mass motions inside the PNS for our 2D SN model M11.2 of an $11.2M_\odot$ progenitor with different neutrino FC scenarios. The four quadrants display the color-coded magnitude of the stellar gas velocity 40 ms after core bounce for the model without FCs (labeled by noFC) and values of $\rho_c = 10^{12}$, 10^{13} , and $10^{14} \text{ g cm}^{-3}$ for the threshold density below which FC is assumed to occur (clockwise from top left). The black dashed circular lines indicate these inner boundaries of the FC regions. Convection is almost nonexistent within the PNS at this early time after bounce in model noFC, whereas in all cases with FCs, significantly stronger convective activity has already developed. The red dashed circular lines indicate the average energy spheres of ν_e , and the solid black circular lines mark the locations where the matter density is $10^{11} \text{ g cm}^{-3}$, which effectively coincide with the average energy spheres of $\bar{\nu}_e$.

The intense convection caused by FCs in the PNS excites gravity-mode (g-mode) oscillation of the convectively stable outer PNS layer. Both PNS convection and g-mode activity generate large-amplitude GW emission over a broad frequency range, occurring shortly after core bounce, in particular for our models with $\rho_c = 10^{13}$ and $10^{14} \text{ g cm}^{-3}$, as visible in Fig. 3.

Collapsing nonrotating stars without neutrino FCs in the PNS interior exhibit a short post-bounce pulse of GW emission caused by an initial phase of prompt postshock convection due to negative entropy and electron-fraction gradients behind the decelerating core-bounce shock. This phase of 20–50 ms is followed by a more quiescent period of 50–100 ms with significantly weaker GW activity, before the GW emission amplifies again due to the onset of violent mass motions in the postshock layer, connected to large-scale shock-deformation modes and convective overturn triggered by neutrino heating behind the stalled SN shock (left panels of Fig. 3 and [58,88–92]).

The quiescent period is absent in our models with FCs below $\rho_c = 10^{13}$ and $10^{14} \text{ g cm}^{-3}$. Instead, the GW emission setting in right after bounce has a more than 10 times larger GW strain h_+ than the noFC case (see Fig. 3 for the strain at source distance $D = 10 \text{ kpc}$) with quadrupole amplitudes $A_{20}^{E2} = 8\sqrt{\pi/15}Dh_+$ up to 50–110 cm, depending on the model, for observers at 90° inclination angle to the 2D symmetry axis. This is the strongest GW signal witnessed for nonrotating stellar collapse in 2D so far, and it bridges the otherwise calmer phase with a continuous high level of GW activity.

This finding is generally valid without stellar rotation, although the GW amplitudes from prompt convection, the subsequent, more silent phase, and the pre-explosion postshock instabilities vary substantially between different progenitors, explosion behaviors, and modeling details [58,88–95]. Our GW signal from FC-induced PNS convection is somewhat weaker for $\rho_c = 10^{14}$ than $\rho_c = 10^{13} \text{ g cm}^{-3}$, because the ν_x fluxes are smaller deeper inside and $\nu_x, \bar{\nu}_x \rightarrow \nu_e, \bar{\nu}_e$ FC at higher densities decelerates neutrino diffusion out of the PNS core. Models with $\rho_c = 10^{12} \text{ g cm}^{-3}$ show only moderately increased PNS convection (Fig. 2) and GW amplitudes (see SM [44]), since the lower ν_e degeneracy favors the $\nu_e, \bar{\nu}_e \rightarrow \nu_x, \bar{\nu}_x$ channel over $\nu_x, \bar{\nu}_x \rightarrow \nu_e, \bar{\nu}_e$.

Although the basic GW components in nonrotating 2D and 3D models are similar, their amplitudes are 10–20 times lower in 3D [60,96–101]. Assessing their detectability therefore requires 3D models. Thus downscaling the initial FC-induced 50–100 ms GW pulse of our models in Fig. 3, we estimate that it might be captured by current LIGO-Virgo-KAGRA searches for galactic SNe up to roughly a kpc with signal-to-noise ratios of around 10. In view of their relatively broad frequency range, these GWs may become observable to $D > 10 \text{ kpc}$ by upcoming interferometers such as the Einstein Telescope and the

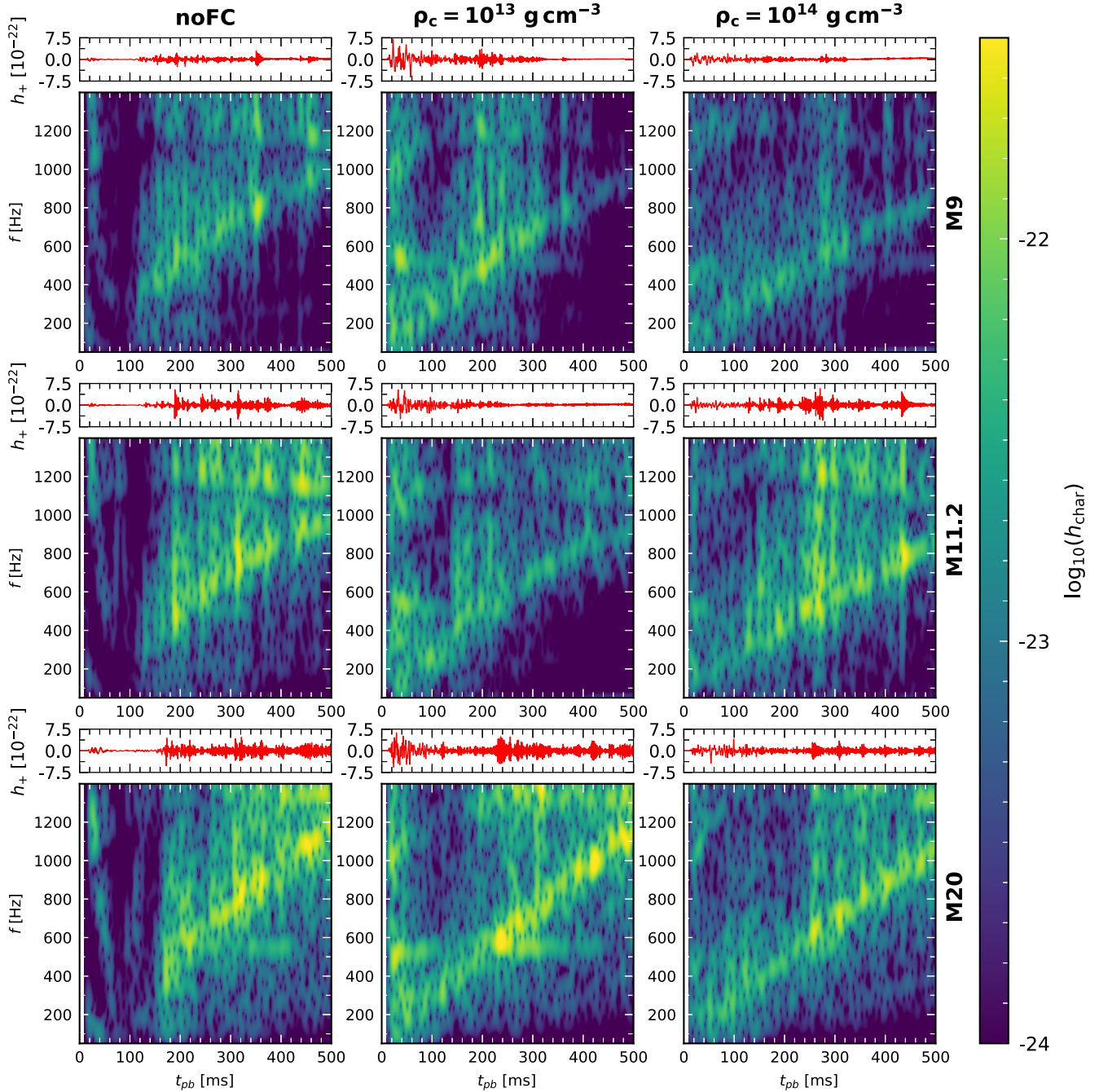


FIG. 3. GW strains and their spectrograms for a SN distance of 10 kpc vs time after bounce and an observer at the equator. The different panels correspond to our 2D SN simulations of $9M_{\odot}$ (top row), $11.2M_{\odot}$ (middle row), and $20M_{\odot}$ progenitors (bottom row), considering different FC scenarios: noFC (left panels), FC at $\rho < \rho_c = 10^{13} \text{ g cm}^{-3}$ (middle column), and at $\rho < \rho_c = 10^{14} \text{ g cm}^{-3}$ (right panels). Our noFC models possess extended periods (lasting 70–100 ms) of relative quiescence after a short post-bounce phase of GW activity due to prompt postshock convection, whereas the models with FCs exhibit strong GW emission over a wide frequency range during this time interval. Analogous results for $\rho_c = 10^9, 10^{10}, 10^{11}$, and $10^{12} \text{ g cm}^{-3}$ are provided in SM [44].

Cosmic Explorer [102,103], potentially including the entire Milky Way (for details, see SM [44]).

To link the particle-physics related burst to the phase preceding the otherwise quiescent window, the core-bounce time needs to be accurately determined by measuring the neutronization burst in current SN neutrino detectors; and

to discriminate the pulse from the bounce and post-bounce signal of rapidly rotating stellar cores [93,98,104,105], other characteristic GW signatures associated with high angular momentum must be identified, e.g., frequency shifts of the dominant characteristic quadrupolar g- and f-mode PNS oscillations [94,98,106] or narrow-band,

quasiperiodic waveforms due to spiral modes [57,107] that are possibly correlated with rotation-induced modulations of the neutrino signal [59,108,109].

Thus GWs may be used in a multimessenger approach as one of the most sensitive probes of nonstandard neutrino properties under extreme conditions and, indirectly, even of neutrino self-interactions. Otherwise, if an FC-induced GW burst is not observed, very stringent constraints on nonstandard neutrino properties could be placed. For instance, resonant conversions of sterile neutrinos inside the PNS [31–33] would be disfavored for parameters where enhanced PNS convection is triggered. More such possibilities are discussed in SM [44].

Our FC treatment assumed lepton number conservation for each flavor individually. However, this assumption can be maximally violated in certain BSM models, potentially achieving total flavor equipartition [37–40]. Such scenarios with stronger FC than in our conservative prescription might amplify the effects of PNS convection, because even without maximal FC the impact is significant according to our results. This highlights the broader relevance of our findings. However, due to the nonlinear and coupled nature of SN physics, extrapolations are insufficient, but detailed simulations are necessary for each specific FC scenario to fully assess its consequences.

While neutrino FC scenarios can be studied using the neutrino signal from a future galactic SN, our proposed GW analysis offers an intriguing tool to probe the dynamical effects of FC. In fact, the neutrino signal can only reveal the final state of neutrinos as they exit the SN, making it almost impossible to pinpoint the location and physics causing FC. For example, FC due to ν NSSI or sterile neutrinos can also take place farther away from the PNS, but with the GW analysis one can gain insights whether the FC occurred within the PNS.

Summary and outlook—We have investigated the GW signals generated by 2D simulations of stellar collapse, specifically focusing on the presence of neutrino FC inside PNSs. Our findings indicate that such FCs can lead to a new component in the GW signal during an otherwise much more quiescent phase of GW emission. This phenomenon arises from enhanced local heating in the PNS interior due to absorption of ν_e and $\bar{\nu}_e$ produced via the $\nu_x, \bar{\nu}_x \rightarrow \nu_e, \bar{\nu}_e$ FC channel. This boosts PNS convection and thus excites g modes in the near-surface layer of the PNS, causing the strongest 50–100 ms long GW pulse witnessed in non-rotating SN models shortly after core bounce so far, followed by GW activity that bridges the otherwise GW-silent phase between prompt postshock convection and hydrodynamic instabilities in the neutrino-heated postshock layer.

Given its broad frequency range, the FC-induced GW signal with amplitudes expected for corresponding 3D sources may be detectable from distances up to a kpc with current facilities and out to $D > 10$ kpc with future laser

interferometers. If such a signal is not observed, stringent constraints on some BSM neutrino scenarios including nonstandard neutrino interactions could be inferred. This strategy offers one of the most promising avenues for exploring nonstandard neutrino physics under extreme conditions with neutrino and GW information.

While in this study we considered neutrino FC enhancing convection inside the PNS, its convection may also be affected by other BSM physics. Of particular interest is, e.g., axion emission [110,111]. Though such an energy-loss channel is, in principle, expected to accelerate PNS neutrino cooling, nonlinear feedback between the additional particle cooling and convection could yield unexpected effects, also modifying the GW emission. We leave such possibilities for future dedicated investigations.

Although our focus was on GWs from collapsing stars, BSM physics could also impact GW emission from binary NS mergers (NSMs). Specifically, BSM particle production might influence the characteristic ring-down peak feature in NSM GW spectra [112–115], shifting the peak frequency or damping the quadrupole oscillations of the NSM remnant that are responsible for this feature.

In view of our promising results, a wide variety of questions demand further exploration. The incorporation of nonstandard physics in 3D SN simulations is crucial to predict the exact properties and detectability distance of the signals, because the GW strain is known to be systematically lower in 3D compared to 2D [60,96–101].

We acknowledge use of the software Matplotlib [116], NumPy [117], SciPy [118], and IPython [119].

Acknowledgments—This work was supported by the German Research Foundation (DFG) through the Collaborative Research Centre “Neutrinos and Dark Matter in Astro- and Particle Physics (NDM),” Grant No. SFB-1258–283604770, and under Germany’s Excellence Strategy through the Cluster of Excellence ORIGINS No. EXC-2094-390783311. J. E. received funding as International Research Fellow of the Japan Society for the Promotion of Science (Postdoctoral Fellowships for Research in Japan). K. N. and K. K. were supported in part by Grants-in-Aid for Scientific Research of the Japan Society for the Promotion of Science (JSPS, No. JP23K20862, No. JP23K22494, and No. JP24K00631) and the funding from Fukuoka University (Grant No. GR2302), and JICFuS as “Program for Promoting Researches on the Supercomputer Fugaku” (Structure and Evolution of the Universe Unraveled by Fusion of Simulation and AI; Grant No. JPMXP1020230406).

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