Correlated Signatures of Gravitational-Wave and Neutrino Emission in Three-Dimensional General-Relativistic Core-Collapse Supernova Simulations

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ABSTRACT

We present results from general-relativistic (GR) three-dimensional (3D) core-collapse simulations with approximate neutrino transport for three non-rotating progenitors (11.2, 15, and 40 $M_\odot$) using different nuclear equations of state (EOSs). We find that the combination of progenitor’s higher compactness at bounce and the use of softer EOS leads to stronger activity of the standing accretion shock instability (SASI). We confirm previous predications that the SASI produces characteristic time modulations both in neutrino and gravitational-wave (GW) signals. By performing a correlation analysis of the SASI-modulated neutrino and GW signals, we find that the correlation becomes highest when we take into account the time-delay effect due to the advection of material from the neutrino sphere to the proto-neutron star core surface. Our results suggest that the correlation of the neutrino and GW signals, if detected, would provide a new signature of the vigorous SASI activity in the supernova core, which can be hardly seen if neutrino-convection dominates over the SASI.

Subject headings: supernovae: general — hydrodynamics — gravitational waves — neutrinos

1. Introduction

Core-collapse supernovae (CCSNe) have been attracting attention of theoretical and observational astrophysicists for many decades. From multi-wavelength electromagnetic (EM) wave signals,
a wide variety of observational evidence have been reported so far including ejecta/line morphologies, spatial distributions of heavy elements, and proper motions of pulsars, which have all pointed toward CCSNe being generally aspherical (e.g., Larsson et al. (2016); Grefenstette et al. (2017); Tanaka et al. (2017); Holland-Ashford et al. (2017) and references therein). Unambiguously important these discoveries are, the EM signals could only provide an indirect probe of the explosion mechanism of CCSNe, because they snapshot images of optically thin regions far away from the central engine.

Neutrinos and gravitational waves (GWs) are expected to provide direct probes of the inner-workings of CCSNe (e.g., Mirizzi et al. (2016); Kotake (2013) for a review). Currently multiple neutrino detectors capable of detecting CCSN neutrinos are in operation (e.g., Scholberg (2012) for a review). The best suited detectors are Super-Kamiokande (Super-K) and IceCube that can detect rich dataset of neutrino events (for example $\sim 10^4$ for Super-K) from future Galactic CCSNe (Ikeda et al. 2007; Abbasi et al. 2011a). In the past thirty years after SN1987A - the only CCSN with neutrino detection to date (Hirata et al. 1987; Bionta et al. 1987), significant progress has been also made in GW detectors (e.g., Sathyaprakash & Schutz (2009) for a review). The sensitivity has been significantly enhanced enough to allow the first detection by the LIGO collaboration for the black hole merger event (Abbott et al. 2016). The second-generation detectors like advanced VIRGO (Hild et al. 2009) and KAGRA (Aso et al. 2013) will be online in the coming years. Furthermore third-generation detectors like Einstein Telescope and Cosmic Explorer are recently being proposed (Punturo et al. 2014; Abbott et al. 2017). At such a high level of sensitivity, CCSNe are also expected as one of the most promising astrophysical sources of GWs (e.g., Kotake & Kuroda (2016); Fryer & New (2011); Ott (2009) for review).

From a theoretical point of view, neutrino radiation-hydrodynamics simulations of CCSNe are converging to a point that multi-dimensional (multi-D) hydrodynamics instabilities including neutrino-driven convection (e.g., Couch (2013); Murphy et al. (2013); Hanke et al. (2012)) and the Standing-Accretion-Shock-Instability (SASI, Blondin et al. (2003); Foglizzo et al. (2006); Fernández (2013)) play a crucial key role in facilitating the neutrino mechanism of CCSNe (Bethe 1990). In fact, a number of self-consistent models in two or three spatial dimensions (2D, 3D) now report revival of the stalled bounce shock into explosion by the “multi-D” neutrino mechanism (see, Janka (2017); Müller (2016); Foglizzo et al. (2015); Burrows (2013); Kotake et al. (2012) for reviews).

Conventionally the GW and neutrino signatures from CCSNe have been studied rather separately. For the neutrino signals, Tamborra et al. (2013) were the first to find the SASI-induced modulations in the neutrino signals using results from full-scale 3D CCSN models (Hanke et al. 2013). They found that the SASI-induced modulation is clearly visible for two high-mass pro-

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1 Here we shall consider canonical CCSN progenitors (Heger et al. 2005) where rotation/magnetic fields play little role in the explosion dynamics (see, however, Mösta et al. (2014); Takiwaki et al. (2016); Obergaulinger & Aloy (2017)).
genitors (20 and 27 $M_{\odot}$) where high SASI activity was observed in the postbounce (pb) phase (Tamborra et al. 2014b). They pointed out that the frequency of the SASI-induced neutrino emission peaks around $\sim 80$ Hz, which can be detectable by IceCube or the future Hyper-Kamiokande (Hyper-K) for a Galactic event at a distance of $\sim 10$ kpc (see also Marek et al. (2009); Lund et al. (2010); Brandt et al. (2011); Müller & Janka (2014)).

From recent self-consistent 3D models, it becomes clear that the SASI also produces a characteristic signature in the GW emission (Kuroda et al. 2016a; Andresen et al. 2017). There are several GW emission processes in the postbounce phase including prompt convection, neutrino-driven convection, proto-neutron star (PNS) convection, the SASI, and $g$-mode oscillation of the PNS surface (e.g., Müller & Janka (1997); Müller et al. (2004); Murphy et al. (2009); Kotake et al. (2009); Müller et al. (2013); Cerdá-Durán et al. (2013)). Among them, the most distinct GW emission process generically seen in recent self-consistent CCSN models is the one from the PNS surface oscillation (Müller et al. 2013; Kuroda et al. 2016a; Andresen et al. 2017; Yakunin et al. 2017). The characteristic GW frequency increases almost monotonically with time due to an accumulating accretion to the PNS, which ranges from $\sim 100$ Hz to $\sim 1000$ Hz in the typical simulation timescales. On the other hand, the GW frequency from the SASI appears in the lower frequency range of $\sim 100$ to 250 Hz and persists when the SASI dominates over neutrino-driven convection (Kuroda et al. 2016a; Andresen et al. 2017). Andresen et al. (2017) pointed out that third-generation detectors (like ET) could distinguish SASI- from convection-dominated case among their full-scale 3D models (Hanke et al. 2013; Melson et al. 2015) at a distance of $\sim 10$ kpc.

These findings may raise a simple question whether there is some correlation between the SASI-induced neutrino and GW signals. Spotted by the neutrino and GW astronomy in the advanced era, the time is ripe to study in detail what we can learn about the explosion mechanism from the future simultaneous detection of neutrinos and GWs using outcomes of multi-D CCSN models. In our previous work (Kuroda et al. 2016a), we have investigated the GW signatures based on 3D full-GR simulations with approximate neutrino transport for a non-rotating 15$M_{\odot}$ star, using three different EOSs. In this work, we will compute two more progenitors of low- or high-progenitor compactness (11.2 and 40 $M_{\odot}$). Following Tamborra et al. (2014b), we estimate neutrino event rates in both Hyper-K and IceCube from our 3D-GR models. We perform a correlation analysis between the GW and neutrino signals. We discuss what we can learn about the supernova engine if the simultaneous detection is made possible for a next CCSN event.

This paper is organized as follows. We first give a short summary of the numerical setup and the extraction of GWs in Section 2. In Section 3 we present a short overview of hydrodynamics of our models. We then present analysis on the GW signatures in Section 4. The correlation analysis between the GW and neutrino signals is presented in Section 5. We summarize the results and discuss its implications in Section 6.
2. Numerical Methods and Initial Models

The numerical schemes for our 3D-GR models are essentially the same as those in Kuroda et al. (2016a). For the metric evolution, we employ the standard BSSN variables (\(\tilde{\gamma}_{ij}\), \(\phi\), \(\tilde{A}_{ij}\), \(K\) and \(\tilde{\Gamma}_i\) (Shibata & Nakamura 1995; Baumgarte & Shapiro 1999)). Solving the evolution equations of metric, hydrodynamics, and neutrino radiation in an operator-splitting manner, the system evolves self-consistently as a whole satisfying the Hamiltonian and momentum constraints (Kuroda et al. 2012, 2014). The total stress-energy tensor is \(T^{\alpha\beta}_{\text{total}} = T^{\alpha\beta}_{\text{fluid}} + \sum_\nu T^{\alpha\beta}_{\nu}\), where \(T^{\alpha\beta}_{\text{fluid}}\) and \(T^{\alpha\beta}_{\nu}\) are the stress-energy tensor of fluid and the neutrino radiation field, respectively. We consider three flavors of neutrinos (\(\nu \in \nu_e, \bar{\nu}_e, \nu_x\)) with \(\nu_x\) representing heavy-lepton neutrinos (i.e. \(\nu_\mu, \nu_\tau\) and their anti-particles). All radiation and hydrodynamical variables are evolved in a conservative form. To follow the 3D hydrodynamics up to \(\lesssim 200\) ms postbounce, we shall omit the energy dependence of the radiation in this work (see, however, Kuroda et al. (2016b); Roberts et al. (2016)).

We use three EOSs based on the relativistic-mean-field theory with different nuclear interaction treatments, which are DD2 and TM1 of Hempel & Schaffner-Bielich (2010) and SFHx of (Steiner et al. 2013). For SFHx, DD2, and TM1, the maximum gravitational mass \(M_{\text{max}}\) and the radius \(R\) of cold neutron star (NS) in the vertical part of the mass-radius relationship are \(M_{\text{max}} = 2.13, 2.42,\) and \(R \sim 12, 13,\) and, \(14.5\) km, respectively (Fischer et al. 2014). SFHx is thus softest followed in order by DD2, and TM1. Among the three EOSs, DD2 is constructed in a way that fits well with nuclear experiments (Lattimer & Lim 2013), whereas SFHx is the best fit model with the observational mass-radius relationship (Steiner et al. 2013). All EOSs are compatible with the \(\sim 2M_\odot\) NS mass measurement (Demorest et al. 2010; Antoniadis et al. 2013).

We study frequently used solar-metallicity models of a 15 \(M_\odot\) star (Woosley & Weaver 1995), an 11.2 \(M_\odot\) and a 40 \(M_\odot\) star of Woosley et al. (2002), respectively. The 3D computational domain is a cubic box with 15000 km width and nested boxes with 8 refinement levels are embedded. Each box contains \(128^3\) cells and the minimum grid size near the origin is \(\Delta x = 458\) m. In the vicinity of the stalled shock at a radius of \(\sim 100\) km, our resolution achieves \(\Delta x \sim 1.9\) km, i.e., the effective angular resolution becomes \(\sim 1^\circ\). Our 3D-GR models are named by the progenitor mass with the EOS in parenthesis like S15.0(SFHx) which represents the progenitor mass of 15.0 \(M_\odot\) and the EOS SFHx are used.

We extract GWs from our simulations using the conventional quadrupole formula (Misner et al., 3Note in Kuroda et al. (2016a) the data up to 350 ms postbounce were shown. However, we are only able to compute up to \(\sim 200\) ms postbounce for the newly added models (11.2 and 40\(M_\odot\)) simply due to limited computational resources. To make the comparison fair (especially regarding the detectability (Figure 5)), we shall often limit the analysis up to \(\sim 200\) ms postbounce in this work (see, however, Figure 7).

3The symmetry energy \(S\) at nuclear saturation density is \(S = 28.67, 31.67,\) and \(36.95\) MeV, respectively. (e.g., Fischer et al. 2014)
The transverse and the trace-free gravitational field $h_{ij}$ is,

$$h_{ij}(\theta, \phi) = \frac{A_+(\theta, \phi)e_+ + A_\times(\theta, \phi)e_\times}{D},$$

where $A_{+/\times}(\theta, \phi)$ represent amplitude of orthogonally polarized wave components with emission angle $(\theta, \phi)$ dependence (Müller & Janka 1997; Scheidegger et al. 2010; Kuroda et al. 2014), $e_+/e_\times$ denote unit polarization tensors. In this work, we extract GWs along the north pole $(\theta, \phi) = (0, 0)$ and assume a source at a distance of $D = 10$ kpc.

3. Overview of Hydrodynamics Features

In this section, we first present a short overview of hydrodynamics features in our 3D models for later convenience.

| Model         | $\xi_{1.5}$ | $\rho_{cb}(10^{14} \text{ g cm}^{-3})$ | $M_{cb}(M_\odot)$ | $M_{cb}/R_{cb}(\%)$ |
|---------------|-------------|----------------------------------------|-------------------|---------------------|
| S15.0(SFHx)   | 0.592       | 4.50                                   | 0.751             | 7.72                |
| S15.0(DD2)    | 0.592       | 3.75                                   | 0.749             | 5.21                |
| S15.0(TM1)    | 0.592       | 3.69                                   | 0.688             | 4.51                |
| S11.2(SFHx)   | 0.195       | 4.23                                   | 0.663             | 4.84                |
| S40.0(SFHx)   | 0.990       | 4.47                                   | 0.765             | 5.07                |

Table 1: Progenitor’s compactness parameter ($\xi_{1.5}$) and key quantities at core bounce (labeled as “cb” in the table) for all the computed models. Except for the compactness parameter (see text for definition), the maximum (rest-mass) density $\rho_{cb}$, the (unshocked) core mass $M_{cb}$, and its non-dimensional relativistic parameter $M_{cb}/R_{cb}(=G M_{cb}/c^2 R_{cb}$ in the cgs unit) are estimated at core bounce.

Table 1 compares progenitor’s compactness parameter (O’Connor & Ott 2011; Nakamura et al. 2015) and several key quantities at core bounce for all the computed models. For the compactness parameter, we adopt $M_{\text{bary}} = 1.5M_\odot$ at $t = 0$ of $\xi_{1.5} \equiv M_{\text{bary}}/M_\odot(R(M_{\text{bary}} = M)/1000\text{km})^{-1}$ in the table. For the given progenitor mass (S15.0), one can see that the maximum density $\rho_{cb}$ becomes higher for model with softest EOS (SFHx). This is consistent with Fischer et al. (2014). Also the compactness parameter at bounce ($M_{cb}/R_{cb}$) has a correlation with the stiffness of the EOS. This is because the softer EOS leads to more compact and massive unshocked core, which makes $M_{cb}/R_{cb}$ higher. For the given EOS (SFHx), one can also see that the initial core compactness ($\xi_{1.5}$) has non monotonic impact on the compactness at bounce (compare $M_{cb}/R_{cb}$ for S15.0(SFHx) and S40.0 (SFHx)). This is simply because the higher density profile in the precollapse phase leads to more massive inner-core (compare $\xi_{1.5}$ with $M_{cb}$ in the table), which also makes the radius of the forming bounce shock bigger.

Figure 1 compares evolution of the average (thick lines) and maximum (dash-dotted lines)
Fig. 1.— Time evolution of average (solid line) and maximum (dotted-dashed line) shock radii for all the models. The left and right panel compares the effect of EOSs and the progenitor masses, respectively.

shock radii for models with different EOSs (panel (a)) and with different progenitor masses (panel (b)), respectively. Before $T_{pb} \sim 150$ ms (panel (a)), the average and maximum shock radii are smallest for SFHx (red thick line), followed in order by DD2 (turquoise line) and TM1 (black line), which is exactly the same as the stiffness of the EOS (SFHx:softest, TM1:stiffest). However, after the non-linear phase sets in ($T_{pb} \gtrsim 150$ ms) when neutrino-driven convection and the SASI develop vigorously with time, the maximum shock radii of SFHx become biggest followed in order by DD2 and TM1. This reversal of the maximum shock radius before and after the non-linear phase is due to the more stronger growth of the SASI for softer EOS. As previously identified (Scheck et al. 2008; Hanke et al. 2013), this is because the smaller shock radius and the more compact core ($M_{cb}/R_{cb}$ in Table 1) lead to more efficient advective-acoustic cycle, i.e., the SASI activity (Foglizzo 2002; Foglizzo et al. 2006). Figure 2 visually supports this, where the large-scale shock deformation is most clearly seen for S15.0(SFHx) (top left panel), whereas the shock deformation is more modest for S15.0(D2) (middle left panel) and for S15.0(TM1) (bottom left panel).

Panel (b) of Figure 1 compares the shock radii for the different progenitors with the same EOS (SFHx). S11.2(SFHx) shows the largest shock radii (average/maximum, blue lines) before $T_{pb} \lesssim 160$ ms. This is because prompt convection develops much more strongly for S11.2(SFHx). As consistent with Müller et al. (2013), this is because the prompt shock propagates rapidly due to the smaller mass accretion rate. Prompt convection is observed by formation of small-scale convective motions behind the roundish stalled shock (see the top right panel of Figure 2). The absence of clear SASI activity of this model is in accord with Hanke et al. (2013); Müller (2016) where the 11.2 $M_\odot$ star was used in their self-consistent 3D models (but with different EOSs used). In the panel (b), the average shock radius is slightly more compact for S15.0(SFHx) than S40.0(SFHx) in the linear phase ($T_{pb} \lesssim 150$ ms). In both S15.0(SFHx) and S40.0(SFHx), the SASI activity was similarly observed in the non-linear phase (bottom panel of Figure 2), whereas
Fig. 2.— Snapshots showing hydrodynamics features of all the computed models at representative time snapshots. Shown are the isentropic surfaces for \( s = 7 \) \( k_B \) baryon\(^{-1} \) (transparent shell) and for \( s = 17 \) \( k_B \) baryon\(^{-1} \) (red bubbles) (from top to bottom, left column; S15.0(SFHx), S15.0(DD2), and S15.0(TM1), right column; S11.2(SFHx) and S40.0(SFHx)). \( T_{pb} \) denotes the postbounce time. The contours on the cross sections in the \( x = 0, y = 0, \) and \( z = 0 \) planes are projected on the sidewalls. The left column focuses on the EOS dependence. Top left and right column show the progenitor mass dependence.
the maximum shock radius is generally bigger for S15.0(SFHx). We ascribe this to the high SASI activity of S15.0(SFHx) compared to S40.0(SFHx) predominantly due to the more compact core ($M_{cb}/R_{cb}$ in Table 1).

**4. GW signatures**

In this section, we summarize how the hydrodynamics features in Section 3 impact the GW emission.

Figure 3 shows time evolution of the GW amplitude (only plus mode $A_+$ and extracted along positive $z$-axis, black line) in the top panels and the characteristic wave strain in the frequency-time domain ($\tilde{h}(F)$, e.g., Eq. (44) of Kuroda et al. (2014)) in the bottom ones. Here $F$ denotes the GW frequency. The top panels show a consistent GW behavior as previously identified in self-consistent models of Müller et al. (2013); Kuroda et al. (2016a); Andeen et al. (2017); Yakumin et al. (2015). After bounce, the wave amplitude deviates from zero with low/high-frequency and relatively large spikes until $T_{pb} \sim 50$ ms. This is due to prompt convection. The GW from the prompt convection is shown to be biggest for S11.2(SFHx) (middle right panel). This comes from the vigorous prompt convection activity of this model as already mentioned in Section 3 (e.g., Figure 1(b)). It is consistent with Müller et al. (2013), who also showed a factor of $\sim 1.5$ larger GW amplitude from prompt convection in the 11.2 $M_\odot$ model (G11.2) compared to that of 15$M_\odot$ model (G15).

After prompt convection, no common features in the waveforms can be found among the models reflecting stochastic nature of the postbounce GWs. However, guided by the black line (Figure 3), one can see a relatively narrow-banded spectrum for all the models that shows an increasing trend in its peak frequency. In addition to this PNS g-mode contribution (Müller et al. 2013; Murphy et al. 2009; Cerdá-Durán et al. 2013), the SASI-induced low-frequency component is clearly seen for S15.0(SFHx) (e.g., the excess around $100 \lesssim F \lesssim 150$ Hz at $T_{pb} \gtrsim 150$ ms in the spectrogram (top left panel)). Note that this is also observed in Andeen et al. (2017).

So far, we show results only for one representative observer direction (along positive $z$-axis) which is not a special direction relative to the SASI motion. Tamborra et al. (2014b) showed that the time modulation in neutrino signal has a dependence on the observer angle relative to the (sloshing) SASI motion. According to their results, neutrino detection rate is significantly larger and also the time modulation is more clearly seen when the observer is along the axis of sloshing motion.

As we have discussed in the previous Sec. 3 (see also Kuroda et al. 2016a), some of our models show vigorous sloshing SASI motion. To see the observer angle dependence on the GW, we plot the GW amplitudes (only for the cross mode, top) and shock positions (bottom) as a function of postbounce time in Fig. 4 for model S15.0(SFHx). To plot this figure, we first determine two lines of sight. One is parallel to the sloshing axis and the other is an arbitrary direction but perpendicular to the sloshing axis. Then the color in Fig. 4 represents that the observer direction is parallel (blue)
Fig. 3.— In each set of panels, we plot (top) the GW amplitude of plus mode $A_+$ [cm] and (bottom) the characteristic wave strain in the frequency-time domain $\tilde{h}$ in a logarithmic scale that is overplotted by the analytical GW frequency $F_{\text{peak}}$ (black line) of the PNS $g$-mode oscillation (Marek & Janka 2009; Müller et al. 2013; Cerdá-Durán et al. 2013). We note that SFHx (top left) is the softest EOS followed in order by DD2 (middle left), and TM1 (bottom left), respectively. The top and middle right and panels are for S11.2(SFHx) and S40.0(SFHx), respectively.
Fig. 4.— Time evolutions of the GW amplitudes (cross mode, top) and shock positions (bottom). The color represents that the observer direction is parallel to the sloshing SASI axis (blue line) or perpendicular to the sloshing axis (red line, for a given azimuthal direction) in the top panel. In the bottom panel, the shock positions are measured along the two lines of sight with the same color in the top panel, where the solid and dotted curves correspond to the shock position at the nearest or farthest to the observer along the line of sight, respectively.

As one can see from the bottom panel, the shock position oscillates largely along the sloshing axis (blue lines) with nearly the opposite phase between the solid and dotted lines. On the other hand, the red lines show significantly smaller deviations. After the sloshing motion reaches its maxima at $T_{pb} \sim 180$ ms, the GW emitted toward the perpendicular direction reaches $\sim 5$-6 cm at $180 \lesssim T_{pb} \lesssim 200$ ms. In the meantime, the GW amplitude reaches merely $\sim 2$ cm along the parallel direction. Thus, contrary to the neutrino emission, the GW emission is stronger toward the orthogonal direction to the sloshing motion. This is analogous to the stronger GW emission toward the equatorial plane in the rotating progenitor model at bounce.

Regarding the EOS dependence, the GW spectrum extends to higher frequency for our model with the stiffest EOS (S15.0(TM1), black line in the left panel of Figure 5), whereas the GW spectrum for the softest EOS (S15.0(SFHx), red line) concentrates more in the lower-frequency domain. Note that an excess around $100 \lesssim F \lesssim 200$ Hz in the spectrum of S15.0(SFHx) corresponds to the SASI-induced GW emission mentioned above.
Fig. 5.— Same as Figure 1, but for the characteristic GW strain spectra for a source of distance at 10 kpc. We estimate the spectra for the time integration of the GW energy in the range of $0 \leq T_{pb} \leq 200$ ms. Solid thin black curves denote the sensitivity curves of LIGO (Harry & LIGO Scientific Collaboration 2010) and KAGRA (Aso et al. 2013).

As for the progenitor dependence, S40.0(SFHx) shows stronger GW emission compared to S11.2/15.0(SFHx) (e.g., bottom panel of Figure 3). In fact, the right panel of Figure 5 (green line) shows that the GW spectrum dominates over that of the other models over the wide frequency range. For this model, the signal to noise ratio reaches $\sim 10$ around the best sensitivity around $F \sim 100$ Hz and a Galactic event could be likely to be detectable. But, in order to discuss the detectability of the signals more quantitatively, one needs a dedicated analysis (e.g., Hayama et al. (2015); Powell et al. (2016); Gossan et al. (2016)), which is beyond the scope of this work.

5. Correlation between GW and Neutrino Emission

In this section, we present a correlation analysis between the GW (Section 4) and the neutrino signals.

For all the computed (five) models, we plot in Figure 6 the expected neutrino event rate ($N_\nu [\text{ms}^{-1}]$, red line) for Hyper-K (fiducial mass 440 kton, Abe (2016)) and the GW amplitude $A_+$ (black line) in the top panel. In the bottom panel, the contours (red curves) correspond to the Fourier-decomposed anti-electron type neutrino event rates (two arbitrary chosen values of $dN_\nu/dF = 0.4$ (thin red line) and 0.8 (thick red line), only for $T_{pb} \geq 100$ ms) that is superimposed on the GW spectrograms. As similar to Fig. 3, the observer direction for both neutrinos and GWs is fixed along the $z$-axis with a source distance of $D = 10$ kpc. Following the methods in Appendices A and B of Tamborra et al. (2014a), we estimate the expected neutrino event rate from
Fig. 6.— For each model, the top panel shows the neutrino event rate $N_\nu [\text{ms}^{-1}]$ (red and green lines are for $\bar{\nu}_e$ and $\nu_x$, respectively) for Hyper-K and the GW amplitude $A_+ [\text{cm}]$ (black line), whereas in the bottom panel we plot contours (red curves, only for $T_{pb} \geq 100 \text{ ms}$) of the anti-electron type neutrino spectra that are superimposed on the color-coded GW spectrum. The observer’s direction is fixed along the z-axis for a source at a distance of $D = 10 \text{ kpc}$.
our 3D models, where the flux-projection effects are also taken into account. As consideration of collective neutrino oscillation is apparently beyond the scope of this work (e.g., Duan et al. (2010); Mirizzi et al. (2016); Chakraborty et al. (2016) for reviews), we show two extreme cases where the detector measures the original $\bar{\nu}_e$ (red line) or $\nu_x$ (green line) flux. The latter case corresponds to the complete flavor conversion through the Mikheyev-Smirnov-Wolfenstein (MSW) effect (Wolfenstein 1978; Mikheyev & Smirnov 1985).

Among the models in Figure 6, the top left panel (S15.0(SFHx)) shows clearest overlap between the neutrino modulation (see red contours in the spectrogram) and the GW modulation at $T_{\text{pb}} \gtrsim 150$ ms in the frequency range of $F \sim 100$-150 Hz. For S15.0(TM1) with stiffest EOS (middle left panel), the overlap between the quasi-periodic neutrino and GW signals can be marginally seen only at higher frequency range $F \sim 400$-500 Hz after $T_{\text{pb}} \sim 150$ ms, which is significantly weaker compared to S15.0(SFHx). Comparing S15.0(TM1) with S15.0(DD2) (top right panel), one can see a clearer quasi-periodic oscillation in the neutrino event rate for softer EOS (top right panel), although there is little correlation between the GW and neutrino signal in the spectrogram. In the smallest mass progenitor of S11.2(SFHx), we do not find any remarkable simultaneous oscillation of the neutrino and GW signals. For this model, the neutrino event rate becomes smallest among the five models and shows little time modulation (after $T_{\text{pb}} \sim 100$ ms), which is consistent with Tamborra et al. (2014b). On the other hand, the most massive progenitor of S40.0(SFHx) has a largest overlap in the spectrogram (red contours) over the wide frequency range $50 \lesssim F \lesssim 500$ Hz.

When the complete flavor conversion between $\bar{\nu}_e$ and $\nu_x$ is assumed (green line at $T_{\text{pb}} \gtrsim 150$ ms of model S15.0(SFHx) in Fig. 6), the time modulation is significantly suppressed as already reported in Tamborra et al. (2013). This is because that the neutrino spheres of heavy-lepton neutrinos are located much deeper inside compared to those of anti-electron neutrinos. Consequently they are less affected by the SASI activity and the correlation between the GW and the neutrino event rate becomes weaker in the case of the complete flavor swap.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig7.png}
\caption{The power spectrum of the IceCube event rate for the time interval of $100 \leq T_{\text{pb}} \leq 200$ ms.}
\end{figure}

We plot in Figure 7 power spectra of the neutrino events in IceCube (Abbasi et al. 2011b)
to see impacts of the EOS and the progenitor. A pronounced peak is seen around $\sim 120$ Hz in S15.0(SFHx) (red line), which is absent for other S15.0 models with weak SASI activity (green and blue lines). This is again consistent with Tamborra et al. (2013, 2014b). The absence of the SASI signature of the 11.2 $M_\odot$ model is in line with Tamborra et al. (2013). S40.0(SFHx) that has a relatively high compactness parameter (Table 1) exhibits a SASI activity and shows a peak at $F \sim 160$ Hz. In addition to the biggest peak, some secondary peaks are also seen on the black line as well as in other models, e.g., at $F \sim 60$ Hz on the red line. In Tamborra et al. (2013), these secondary peaks are hard to see in most of the employed progenitors except for the 20$M_\odot$ model. We consider that this difference might be partially due to our simplified transport scheme, where the neutrino matter coupling is controlled via several parameters (see Kuroda et al. (2012) for more details). Because of this, our neutrino signals may change more sensitively in response to the matter motion compared to those obtained in CCSN models with more sophisticated neutrino transport. For example, during the prompt convection phase ($T_{pb} \lesssim 50$ms), our neutrino event rate shows an oscillatory behavior (see red/green line in every top panel in Fig. 6) which is not seen in Tamborra et al. (2013). To clarify this, we need to perform 3D-GR simulations with more elaborate neutrino transport scheme which is, unfortunately, computationally unaffordable at this stage.

Fig. 8.— Schematic drawing to illustrate the different radial positions of SASI-induced neutrino and GW emission in the postbounce core. Below the stalled shock (dashed blue line, labeled as “The stalled shock”), non-spherical flows (dashed red line with arrow) hit first the (average) neutrino sphere then penetrates into the PNS core surface. $R_{cor}$ represents the distance between the neutrino sphere ($\bar{\nu}_e$ in this case) and the PNS. $V_{adv}$ is the typical velocity of the downflows there.

From Figures 6 and 7, it has been shown that both of the SASI modulation frequency of the GW and neutrino signals is relatively close (i.e., in the range of 100 $\sim$ 200 Hz). Figure 8 illustrates how the two signals could be spatially correlated. In the figure, the SASI flows (red dashed arrows) advecting from the shock first excite oscillation in the neutrino signal at the (average) neutrino sphere. Afterward, it reaches to the PNS core surface (the blue thick arrows), leading to the modulation in the GW signal (see also Kuroda et al. (2016a) for the detailed analysis). We can roughly estimate the time delay $\Delta T$ as follows. The radius of anti-electron type neutrino sphere
is $R_{\bar{\nu}_e} \sim 37 \text{ km}$ and the PNS core surface is $R_{\text{PNS}} \sim 15 \text{ km}$ (at $T_{\text{pb}} = 200 \text{ ms}$ for S15.0(SFHx)), then the correlation distance is $R_{\text{cor}} = R_{\bar{\nu}_e} - R_{\text{PNS}} \sim 20 \text{ km}$. An angle-average accretion velocity at $R = 40(20) \text{ km}$ is $V_{\text{adv}} \sim -1 \times 10^8 (-1 \times 10^7) \text{ cm s}^{-1}$ at $T_{\text{pb}} = 200 \text{ ms}$, leading to $\Delta T$ of a few 10 ms.

In order to estimate the correlation between the neutrino and GW signal more quantitatively, we evaluate the correlation function $X(t, \Delta T)$ in Figures 9 and 10. Note Figures 9 and 10 are for S15.0(SFHx) and S11.2(SFHx) showing highest and invisible SASI activity in this work, respectively.

The top panel of Figure 9 shows the GW amplitude (blue line) and the neutrino event rate (black and red lines) in arbitrary units for S15.0(SFHx). For the red line, the monotonically time-changing component of the black line is subtracted ($T_{\text{pb}} \lesssim 170 \text{ ms}$) in order to focus on the SASI-induced modulation. Same as the top panels, middle panels ($b+/\times$) show the correlation function $X(t, \Delta T)$ between the GW amplitude (blue line ($top$)) and the event rate (red line ($top$)) with several time delay $\Delta T$ (see text for definition) which is indicated in the upper left part as 0, 4, 8, 12, 16, 20, 24 [ms]. Bottom panels ($c+/\times$) show $\Delta T_{\text{max}}$ that gives the delay-time with the maximum correlation in the middle panels. Note when we obtain $\Delta T_{\text{max}}$, we set an arbitral threshold as $|X(t, \Delta T)| \geq 0.7$ not to extract insignificant values.

The top panel of Figure 9 shows the GW amplitude (blue line) and the neutrino event rate (black and red lines) in arbitrary units. In order to focus on the SASI-induced modulation, the red curve is the event rate after the monotonically time-changing component is subtracted from the original curve (black line).

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As one can see from the red line in each top panel in Fig. 9, the neutrino event rate for $0 \lesssim T_{\text{pb}} \lesssim 150 \text{ ms}$ is approximately fitted by a linear function (as a function of postbounce time) with positive slope, whereas it
We then evaluate the correlation between the GW (blue line) and neutrino (red line) signal by calculating the following normalized correlation function \( X(t, \Delta T) \)

\[
X(t, \Delta T) = \frac{\int d\tau H(t - \tau) A_{\nu}(\tau + \Delta T) A_{GW}(\tau)}{\sqrt{\int d\tau H(t - \tau)(A_{\nu}(\tau + \Delta T))^2} \sqrt{\int d\tau H(t - \tau)(A_{GW}(\tau))^2}},
\]

where \( t \) is the postbounce time and \( H(t - \tau) \) is the Hann window with the window size of \( |t - \tau| \leq 10 \) ms. \( A_{\nu}(t) \) and \( A_{GW}(t) \) is the neutrino event rate without the DC component and the GW amplitude, respectively. \( \Delta T \) [ms] represents the time delay between the neutrino and GW signal and we take \( 0 \leq \Delta T \leq 24 \) ms with time interval of 4 ms. In the middle panel, we plot \( X(t, \Delta T) \) for all \( \Delta T \) in different colors as shown in the upper part of the panel. The bottom panel shows \( \Delta T_{\text{max}} \), which gives the maximum \( X(t, \Delta T) \).

From the middle panels of Figure 9 we find a clear increment in \( |X(t, \Delta T)| \) at \( T_{\text{pb}} \sim 150 \) ms for both GW polarized modes. At this point of time, the SASI activity becomes strongest (see Fig.3 in Kuroda et al. (2016a)). If we look at panel (b+), \( |X(t, \Delta T)| \) with larger \( \Delta T \) increases faster. \( X(t, \Delta T = 24 \text{ms}) \) increases fast with positive value and then \( X(t, \Delta T = 20 \text{ms}) \) comes next, but with negative value. Afterward, \( X(t, \Delta T = 16 \text{ms}) \), \( X(t, \Delta T = 12 \text{ms}) \), \( \cdots \), follow with the same manner. Completely an opposite trend can be seen in the \( \times \) mode of the polarization (panel (b\times)), i.e., \( X(t, \Delta T = 24 \text{ms}) \), \( X(t, \Delta T = 16 \text{ms}) \), \( \cdots \), show negative values and \( X(t, \Delta T = 20 \text{ms}) \), can be fitted by a linear function with a negative slope plus the SASI modulation thereafter. When we evaluate the correlation function \( X(t, \Delta T) \) in Eq. (2), the large offset can be a hindrance for an appropriate evaluation of \( X(t, \Delta T) \). We thus roughly remove the quasi-monotonically changing component, i.e., the offset, in a simple way as \( A_{\nu}(t) \) → \( A_{\nu}(t) - (A_{\nu}(t + \tau/2) + A_{\nu}(t - \tau/2))/2 \). Here \( \tau \) is a time window and we usually use \( \tau = 60 \) ms.
$X(t, \Delta T = 12\text{ms}), \cdots$, show positive values. This can be explained by the correlation frequency $F \sim 120$ Hz (see top left panel in Fig. 6 and left one in Fig. 7). The corresponding time period $\sim 8$ ms of $F \sim 120$ Hz leads to a cycle of negative and positive correlations if we shift neutrino count event with half of its value, i.e., $\sim 4$ ms. Furthermore, the opposite trend between $(b+)$ and $(b\times)$ can be understood by the phase shift with half period between the plus and cross mode of GWs, since the leading term of the PNS deformation is the quadrupole ($l = 2$) mode \cite{kuroda2016a}. From panels (c+/×), $\Delta T_{\text{max}}$ with $\sim 18$ ms appears first in both polarization modes. It means that there is a time delay of GWs from neutrinos as $\Delta T \sim 18$ ms. Remarkably, this value is consistent with our previous rough measurement for the accretion timescale of a few 10 ms. Note that we have also done the same analysis for the rest of our models and found no significant correlation. As a reference, Figure 10 is shown for S11.2(SFHx) where there is no significant correlation between the GW and neutrino signals for this convection-dominated model.

6. Summary and Discussion

We have presented results from our 3D-GR core-collapse simulations with approximate neutrino transport for three non-rotating progenitors (11.2, 15, and 40 $M_\odot$) using three different EOSs. Among the five computed models, the SASI activity was only unseen for an 11.2$M_\odot$ star. We have found that the combination of progenitor’s higher compactness at bounce and the use of softer EOS leads to the stronger SASI activity. Our 3D-GR models have confirmed previous predications that the SASI produces characteristic time modulations both in the neutrino and GW signals. Among the computed models, a 15.0 $M_\odot$ model using SFHx EOS exhibited the most violent SASI motion, where the SASI-induced modulation in both GWs and neutrinos were most clearly observed. The typical modulation frequency is in the range of $\sim 100$-$200$ Hz, which is consistent with the oscillation period of the SASI motion. By performing a correlation analysis between the SASI-induced neutrino and GW signatures, we have found that the correlation becomes highest when we take into account the time-delay effect due to the advection of material from the neutrino sphere to the PNS core surface. Our results suggest that the correlation of the neutrino and GW signals, if detected, could provide a new signature of the vigorous SASI activity in the supernova core, which can be barely seen (like for the 11.2 $M_\odot$ model) if neutrino-convection dominates over the SASI.

In order to enhance predicative power of the neutrino and GW signals in this work, we need to at least update our M1 scheme from gray to multi-energy transport as in \cite{kuroda2016a, roberts2016}. Inclusion of detailed neutrino opacities is also mandatory (e.g., \cite{buras2006, lentz2012, martinez-pinedo2012, fischer2016, burrows2016, horowitz2017, roberts2017, bollig2017}). Impacts of rotation and magnetic fields (\cite{mosta2014, takiwaki2016, obergaulinger2017}) on the correlation between the GW and neutrino signals (\cite{ott2012, yokozawa2013}) should be also revisited with 3D-GR models including more sophisticated neutrino transport scheme with elaborate neutrino opacities.
In order to clarify whether we can or cannot detect the SASI-induced modulation in the GW and neutrino signals, we primarily need to perform a GW signal reconstruction study (e.g., Hayama et al. (2015); Powell et al. (2016); Gossan et al. (2016)) using non-stationary and non-Gaussian noise (Powell et al. 2016, 2017). This is the most urgent task that we have to investigate as a sequel of this work. For a Galactic event, we apparently need third-generation detectors for observing the SASI-modulated GW signals (e.g., Andresen et al. (2017)), whereas the neutrino signals could be surely detected by IceCube and Super-K (Tamborra et al. 2013). The neutrino burst can be used to determine the core bounce time (Halzen & Raffelt 2009), which raises significantly the detection efficiency of the GWs (e.g., Gossan et al. 2016, Nakamura et al. 2016). Our current study extends the horizon of previous prediction such as, when we would succeed the simultaneous detection of neutrino and GW signals from future nearby CCSN event, we could infer the supernova triggering dynamics (e.g., the SASI) from the following specific features (1) the low frequency ($F \sim 100 \text{ Hz}$) modulation in both GW and neutrino signal and (2) a few 10 ms time delay of the SASI-modulated GW signal from the SASI-modulated neutrino event rate. We finally note that the non-detection of the correlation could be hypothetically used as a measure to constrain the nuclear EOSs. From our limited number of the EOS used in this work, one cannot obtain any quantitative conclusion. Recently, a number of nuclear EOS is available (see Oertel et al. (2017) for a review). Using such rich variety of the EOSs, one could in principle do this, but only if one could afford enough computational time to make the many 3D CCSN runs doable.

TK was supported by the European Research Council (ERC; FP7) under ERC Advanced Grant Agreement N° 321263 - FISH and ERC StG EUROPIUM-677912. Numerical computations were carried out on Cray XC30 at Center for Computational Astrophysics, National Astronomical Observatory of Japan. KK was thankful to stimulating discussions with E. Müller, H.T. Janka, and T. Foglizzo. This study was supported by JSPS KAKENHI Grant Number (JP15H00789, JP15H01039, JP15KK0173, JP17H01130, JP17H05206, JP17K14306, and JP17H06364) and JIC-FuS as a priority issue to be tackled by using Post ‘K’ Computer.

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