Neutrino Signatures of *Tumbling* Supernova Cores:
From 3D radiation-hydro simulations

Kei Kotake
(Fukuoka University)

with Takami Kuroda (U. Basel), Tomoya Takiwaki (NAOJ),
S. Horiuchi (Virginia Tech), Ko Nakamura (Waseda Univ.)

Flavor observations with SN Neutrinos
INT, August, 2016
Quiz: Depending on (a), non-axisymmetric instabilities (incl. the SASI) can develop vigorously in CCSN cores.

(a SN shock can dance because of (a).)

3D full General Relativistic (GR) simulations (BSSN) with 3 flavor neutrino transport (gray, M1 scheme)
see multi-energy version available!
in Kuroda, Takiwaki, & KK. ApJS (2016))

Choice (1) Progenitor mass / compactness
Quiz: Depending on \( (a) \), non-axisymmetric instabilities (incl. the SASI) can develop vigorously in CCSN cores.

\( \text{a SN shock can dance because of } (a). \)

3D full General Relativistic (GR) simulations (BSSN) with 3 flavor (gray) neutrino transport (M1)


see multi-energy version available!

in Kuroda, Takiwaki, & KK. ApJS (2016))

Choice (1) Progenitor mass / compactness

Choice (2) Precollapse rotation rate

Choice (3) Equation of State

Choice (4) More important ingredients.

11.2M\(_{\odot}\) (WHW02)

Convection-dominant

27M\(_{\odot}\)

SASI-dominant
Neutrino luminosity ($\bar{\nu}_e$) and Spectrogram Analysis

⇒ SASI-induced modulation is visible in the luminosity.
⇒ Confirmation of Tamborra, Hanka, Mueller, Janka, Raffelt (2013, 2014)) by 3D-GR simulations (Kuroda et al. in prep.)
⇒ Detectable by IceCube and Hyper-K out to Galactic events.
Quiz: Depending on \( (a) \), non-axisymmetric instabilities (incl. the SASI) can develop vigorously in CCSN cores.

(a SN shock can dance because of \( (a) \).)

Choice (2) Precollapse rotation rate

3D rotating core-collapse of 27 \( M_{\text{sun}} \) star \( (\Omega_0 = 2 \text{ rad/s}) \) with IDSA transport.

- ✓ One-armed (low \( T/|W| \)) instability
- ✓ Spiral waves enhance energy transport from PNS to gain region!

Rotation-assisted explosion!
Neutrino signatures from rapidly rotating explosion of 27 $M_{\text{sun}}$ star

Quasi-periodic variation! May survive with coll. oscillation

$\delta L_{\bar{\nu}_e}$: RMS deviation from the angle-average luminosity $T = 10 \text{ ms}$

"Lighthouse effect" Seen from equator
Quiz: Depending on (a), non-axisymmetric instabilities (incl. the SASI) can develop vigorously in CCSN cores. (or, a SN core can be a dancing queen because of (a).)

Choice (1) Progenitor mass / compactness
Answer (1): Yes. (More progenitors needed!)

Choice (2) Precollapse rotation rate
Answer (2): Yes. The rotational frequency of the spiral arm is marked in the neutrino signals. ← The “lighthouse effect”.

Choice (3) Equation of State
Neutrino signals from 3D-GR models with different EOSs (1/2)

✓ Two EOSs → **SFHx** (Steiner et al. (2013), fits well with experiment/NS radius, Steiner+(2011)), **HS(TM1)** (Shen et al. (1998), Hempel & Schaffner-Bielich (2010)).

✓ 15 M$_{\text{sun}}$ star (Woosley & Weaver (1995))

**SFHx** : softer  
**TM1** : stiffer

✓ **SASI activity higher for softer EOS** (due to shorter growth rate, e.g., Foglizzo et al. ('06)).
Neutrino signals from 3D-GR models with different EOSs (2/2) Kuroda, KK, Takiwaki in prep

SFHx: softer

@ Hyper-K, 10kpc

TM1: stiffer

@ Hyper-K, 10kpc

The \textit{SASI} modulation appears more clearly in 3D-GR model with best EOS available!

The modulation freq. from the \textit{SASI} and rapid rotation: in the range (100 – 200 Hz).

So... how to tell the difference?
Gravitational Wave (GW): the key!
(Kuroda, KK, & Takiwaki submitted, see also Andresen et al.)

<table>
<thead>
<tr>
<th>SFHx</th>
<th>TM1</th>
</tr>
</thead>
<tbody>
<tr>
<td>softer</td>
<td>stiffer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensitivity curves and model predictions</th>
<th>The reconstructed GW spectrogram</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Graph showing sensitivity curves and model predictions" /></td>
<td><img src="image" alt="Spectrogram showing GW signal" /></td>
</tr>
</tbody>
</table>

- The quasi-periodic modulation is associated with SASI, clearly visible with soft EOS.
- By **coherent network analysis** of LIGOx2, VIRGO, and KAGRA, the signal detectable out to the LMC (50 kpc, Hayama, Kuroda, KK et al. (2015, PRD)).
- The SASI activity, if very high, results in characteristic signatures in both GWs and neutrino signals (even for non-rotating progenitors!).
Quiz: Depending on (a), non-axisymmetric instabilities (incl. the SASI) can develop vigorously in CCSN cores.

Choice (1) Progenitor mass / compactness
Ans: Yes!
⇒ the SASI modulation is a smoking gun of the dancing shock.

Choice (2) Precollapse rotation rate
Answer(2): Yes!
The rotational frequency of the spiral arm is imprinted in the neutrino signals.
← The "lighthouse effect".

Choice (3) Equation of State
Answer(3): Yes!
The SASI modulation is more clearly visible in 3D-GR model with soft EOS.

Choice (4) More important ingredients?
Answer(4): Keep it secret!

Our proposal:
Break the degeneracy of the neutrino signals from between non-rotating and rapidly rotating case,
detection of GW is the key!
(albeit not easy).

Thanks!