Brainstorming on core-collapse supernova theory with perspectives toward multi-messenger astronomy

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(National Astronomical Observatory of Japan: NAOJ)

with Tomoya Takiwaki (NAOJ), Takami Kuroda (NAOJ), Yudai Suwa (Kyoto), Ko Nakamura (NAOJ), Akihiro Suzuki (NAOJ), and Youhei Masada (Kobe)

INT 12-2a: Core-Collapse Supernovae: Models and Observable Signals
An Analysis of Recent Research Trend of CCSN modeling in 2012

January: E. Mueller + (AA)
          B. Mueller + (ArXiv)
          Kuroda + (ArXiv)
March: Guilet + (MNRAS)
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June: Nordhaus + (MNRAS)
      Lentz + (ArXiv)
      Couch (Arxiv), Pejcha-Thompson (MNRAS)
      Janka (ArXiv)
      Suwa + (ArXiv) (more to come...)

✓ First-principle simulations
- 1D with B-transport
- 2D/3D different scheme extended to GR
Phenomenological modeling
- Liebendoerfer Ye formula
- a light-bulb scheme for following a long-term post-bounce evolution in a qualitative/systematic manner.
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✓ **Novel approaches** proposed
- Shallow water analogue (Foglizzo)
- Ante-sonic condition (Pejcha)
- Radial instability (Fernandes)
- Theory of turbulence (Murphy)
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✓ New algorithms for 6D transport ultimately in GR
- Monte Carlo (see his talk !)
- $S_N$ method in 3D
- M1 formalism (pioneered by Shibata +11, and Kuroda, KK, Takiwaki, O’Conner, Ott (July)
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✓ Theoretical predictions of neutrino, gravitational-wave signals are updated by 3D modeling (Mueller+) with GR (Ott+) for CCNSNe, (explored in collapsars by KK+).
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(more to come...)

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1st topic: 3D simulations with spectral transport

✓ 3D effects: very controversial.
   (Nordhaus+ (2010) Yes vs. Hanke+ (2011) No (so much))

✓ Previously: the light-bulb scheme was employed.
   \( L_\nu = \text{const} \) was given by hand to trigger explosions.

✓ 3D simulations with spectral neutrino transport are (at least) needed to draw a robust conclusion.

Our most up-to-date 3D results


✓ 11.2 Msun progenitor (Woosley, Heger, Weaver: WHW (2002))

✓ Spectral neutrino transport is solved (IDSA: Liebendoerfer+09)

✓ Cooling by mu/nu neutrinos is treated by a leakage scheme.

✓ \( 320(r) \times 64(\theta) \times 128(\varphi) \times 20(\varepsilon) \) (x4 finer than our ApJ paper, 3 deg.)

✓ 8192 cores x 1 CPU month

✓ @ the world-2nd "K" computers.
Animation hidden!
Thanks to Tomohide Wada (CfCA)
Comparison of average shock radii

<table>
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<tr>
<th>Dim.</th>
<th>r x Θ x Φ x ε</th>
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<tr>
<td>3D:</td>
<td>320x64 x128 x 20</td>
</tr>
<tr>
<td>3D low:</td>
<td>200x32x 64 x 20</td>
</tr>
<tr>
<td>2D:</td>
<td>320x64</td>
</tr>
<tr>
<td>1D:</td>
<td>320</td>
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✓ Our 3D model with highest resolution: the most energetic shock propagation.

11.2 Mₚsun star

CAUTION
Slip Hazard
“Stochastic Nature” of neutrino-driven explosions (e.g., KK+09, Iwakami+08)

✓ **2D simulations** for an 11.2 $M_{\odot}$ star (WHW02)
☆ Resolutions fixed $(300(r)x128(\Theta)x20(\varepsilon))$
☆ The only difference: initial random perturbation after shock-stall
“Stochastic Nature” of neutrino-driven explosions

(Takiwaki, KK, Suwa in prep)

From only one realization of our 3D model, nothing solid can be deduced about the 3D effects. Systematic study needed!

(computationally hyper-expensive (Exsa-scale platforms))
Gravitational waveforms in 3D simulation with spectral transport

KK, Takiwaki + in prep

(see also, Mu"ller & Janka (1997), Ott(2009), KK et al. (09,11), Mueller et al. (2012))

The total amplitudes in 3D become ~ one-order-of-magnitude smaller than those in 2D, however within the target for the next-generation detectors (like KAGRA and adv LIGO).
Non-rotating 11.2 Msun star (moderate resolution)

(Relatively) rapidly rotating 11.2 Msun star ($P_0 = 4 \text{ rad/s}$)

✓ Coherent motions in $\Phi$ reduce stochasticity
✓ Explosion energy for a rotating model.
What is interesting about spiral modes?

“Seemingly”…. for this model, dominant modes
✓ In the linear regime, spiral modes
  (e.g., Yamasaki & Foglizzo (08))
✓ in the non-linear phase, axisymmetric modes.
  (Should depend on initial rotation rates. More careful analysis is under way !)

Rapidly rotating model
($P_0 = 4$ s)

Color for radial velocity

$\text{t} = 0.228 \text{ ms}$
Neutrino and GW signatures between 3D models with/without rotation

Takiwaki & KK in prep

✓ Luminosities for all species get smaller for the rotating model because the centrifugal forces act against the core-contraction.

✓ Variation timescale of neutrino signals \(\Rightarrow\) longer for rotating models (because the dynamical timescale longer for rotating models) \(\Rightarrow\) would provide one additional clue: the difference between the rotating and non-rotating model (see talks by Lunardini and Lund !).
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Does GR help "multi-D" neutrino-driven explosions?


✓ 3D full GRMHD code developed by Kuroda (NAOJ) (for more details, see Kuroda and Umeda (ApJS 2010))
✓ Adaptive-mesh-refinement approach is taken ($\delta x_{\text{min}} = 450-600\text{m}$).

✓ Neutrino cooling: multi-flavor leakage scheme.
✓ Neutrino heating: by a partial implementation of the Thorne’s moment formalism (Shibata+11).

Color : entropy
\[ \delta x = 600 \text{ m} \]
3D GR rotating model
\( (P_0 = 4 \text{ s}) \)
Color : entropy
\( \delta x = 450 \text{ m} \)
Except for our 3D-GR model, the shock has shown a trend of recession.

Important: why the shock can reach most further out for 3D-GR?
Advantages in 3D-GR model to go explosions!

Two things: GR and 3D

- Deeper potential well: core structures smaller ⇒ making $<E_\nu>$ higher.

- GR can enhance the neutrino luminosity up to 40% compared to the SR counterpart.

Due to non-radial motions, the residency timescale: longer in 3D than in 1D.
⇒ Essential why 3D are supportive compared to 1D.
The combination of 3D and GR
⇒ the most supportive condition of explosions!
✓ 1000ms/(2 -3 ms per day) ~ 300 - 500 days…
Gravitational waveforms from 3D-GR model

(Kuroda & KK in prep)

Rapid rotation (making core-deformation larger) leads to more easier detection for GWs!
Inverted hierarchy \( \sin^2 \Theta_{13} = 0.1 \)

Neutrino luminosity gets smaller for models with larger initial angular momentum.

Rapid rotation \( \Rightarrow \) neutrino signals

- rms energy
- luminosity

(More detailed analysis is coming! KK et al. in prep)
“Full GR code with spectral neutrinos transport (1/4)”

Newton-Raphson method

\[ \delta P_i = A^{-1} b \]

Kuroda, KK, Takiwaki in prep.
Demonstration of our newly developed code (2/4)

3 slices of entropy distribution
For lower energy bin:
$E_{\nu}: 8 \text{ MeV}$

For higher energy bin:
$E_{\nu}: 36 \text{ MeV}$

For intermediate energy bin:
$\langle E_{\nu} \rangle: 18 \text{ MeV}$
The most conservative way to pin-down the mechanism:
(e.g., Mueller (+2012)):
implementation of multi-energy transport in full GR 3D simulations incl. all relevant s.o.a. interactions!
(Horowitz (1997), Burrows Sawyer (1998), Reddy+99)
A steady progress is being made! (it takes a time …)
To obtain the unified picture in the stellar evolution theory,

A grand challenge in computational astrophysics

Time Evolution

Dynamics of black hole formation

Mechanism of Hypernova & GRB

✓ No doubt: 3D GR neutrino rad-hydro sims. needed for handling BH formation and highly anisotropic field.
  (e.g., Ott + (2011), B.Mueller+(12), Sekiguchi-Shibata (2010), Kuroda+(2012))

✓ Typical duration of LGRBs $\sim T_{90} > 20$ s (Elena’s talk !)

✓ Apparently beyond peta-scale platforms.

✓ Some approximate method is needed.

✓ Sitting between two chairs: Perfectionism vs. Pragmatism
Collapsar dynamics and the GW signatures


✓ To follow a long-term evolution, the central BH is cut by hand in 2D SRMHD.

✓ We focus on anisotropic mass motion and anisotropic neutrino emission outside the BH as a source for GWs.

✓ The total GW amplitude from collapsars is dominated by GWs from neutrinos.

✓ Anisotropic neutrino flow from the accretion disk is the dominant source of GWs in the long-term evolution!
Collapsar dynamics and the GW signatures


Typical amplitude of neutrino GWs:

$$h_\nu(t) = \frac{2G}{c^4 R} \int_0^t dt L_\nu(t') \alpha(t')$$

Neutrino anisotropy: degree of anisotropic neutrino radiation (zero if spherical)

Table 1: This table shows average event rate of the neutrinos from the collapsar. "with" means with the collective effects, and "without" means without the collective effects.

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<th>model B</th>
<th>model C</th>
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<tr>
<td></td>
<td>with</td>
<td>without</td>
<td>with</td>
</tr>
<tr>
<td>1Mpc</td>
<td>15.144</td>
<td>8.194</td>
<td>110.095</td>
</tr>
<tr>
<td>5Mpc</td>
<td>0.606</td>
<td>0.328</td>
<td>4.400</td>
</tr>
<tr>
<td>10Mpc</td>
<td>0.152</td>
<td>0.082</td>
<td>1.110</td>
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Neutrino astronomy of collapsars is hard (even by next.gen. detectors.) (the closest example: SN’98bw-GB980425 : D ~ 40 Mpc)

Kawagoe, KK+ in prep

Hyper-Kamiokande

Events of DECIGO and BBO ! will be feasible !
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5. Theoretical predictions of SN multi-messengers: neutrino, gravitational-wave elemag. signals

(more to come...)
Jet’s are ubiquitous in MHD simulations!

The magnetic field strength is proportional to our ignorance.

John Hawley
3D local simulations of MRI in the supernova cores

Masada et al. in prep. (pioneered by Obergaulingler +09,10)

✓ Degree of differential rotation is systematically investigated in our study.

Formation of channel flow

Decays to turbulent state
How much energy tapped as shear-rotational energy could be dissipated by MRI-driven turbulence?

Masada, Takiwaki, KK, Sano in prep

Given a post-bounce rotation rate, 
\[ L_{\text{MRI}} \sim 10^{51} \text{ erg/s} \]

✓ For canonical CCSN progenitors, MRI never important.
✓ For collapsars, energy supply by MRI-driven heating likely affects the outflow formations! (Masada et al. to be submitted)
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5. **Theoretical predictions of neutrino, gravitational-wave signals**
Seeking some candidates to foster explosions:
✓ Impacts of nuclear burning revisited
(e.g., Janka et al. (2001), Mezzacappa et al. (2007))

\[ L_{\nu_e} = L_{\bar{\nu}_e} = L_{\nu_0} \exp \left( -(t - t_{\text{bounce}})/t_d \right) \]

\( L_{\nu_0} \) initial Ln [e52 erg/s]

\( t_d \) decay time [s]

1D/2D light-bulb simulation

15 M_{\odot} (Nakamura, 1995)

WW15 model

Explosion

Disappear!

No Explosion

Nakamura KK+ in prep

Chieff (2006)
Not for all but for some progenitor models, nuclear burning can help the onset of explosions!
3D light-bulb simulations in progress in NAOJ

Nakamura, Kuroda, KK+ in prep

L = 2.5 \times 10^{52} \text{ erg/s} (non-rotating)

L = 2.5 \times 10^{52} \text{ erg/s} (rapidly rotating: \Omega_0 = 0.5 \pi \text{ rad/s})

Very dangerous:
- magnetorotational effects by manual explosion models.
  (especially by pure light-bulb).

but ... Very attractive
- blast morphology
- light curve modeling
- spin/kick of newly-born pulsars
  (see A.Wongwathanarat’s talk for a better transport scheme!)
Light-curve asymmetry at the shock-breakout signatures

Suzuki, Takana, KK et al. in prep (pioneered by Kifonidis+2003, Hammer+10)

Need to list all observational signatures:

- to clarify links between “multi-D supernova mechanism” and “their multi-messenger signatures”.
- Not easy, but the only way to make the dream come true!
On the 3D effects:
we’ve not obtained a clear-cut answer, hampered by stochastic nature of explosions.

✓ Parametric studies in the first-principle 3D simulations by changing resolutions, perturbations, and so on) should be done!
⇒ Need peta- or exa-scale supercomputers!
(see our recent review (accepted to PTEP: Kotake et al. toward 6D simulations with exact Boltzmann transport in full general relativity!)

Our 1st generation GR results: the combination of GR and 3D provides the most favorable condition.
✓ Just find the way to hold the wedding between spectral neutrino transport and GR hydro-code.
✓ MRI should affect the MHD mechanism especially for collapsars.
★ Integrated analysis between GWs, neutrinos, and photons is needed, which is a big virgin territory yet to be studied.