Supernova Overview

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- Overview
- Our research
  main collaborator: K. Nakazato
  - Supernova Neutrino Database
  - Supernova Relic Neutrino Database
  - Togashi EOS
  - Proto Neutron-Star Cooling
Stellar Evolution and Supernovae

Mass loss, metallicity, rotation, binary

- Massive Star ($M > 8M_\odot$)
  - Main Sequence (H burning) $\Rightarrow$ Onion Skin Structure
    - ONe core/“Fe” core + envelope (mass loss might occur)
    - Core Collapse $\Rightarrow$ Neutron Star(or Black Hole) + Supernova Explosion with H envelope (Type II SN), w/o H env. (Type Ib), w/o H/He env. (Type Ic)
Supernova neutrinos can be roughly divided into 3 phases (while they are continuous).

1. collapse and bounce phase: \((O(10)\text{msec}), O(10^{51})\text{erg}\)
   - core collapse, inner core bounce, shock launch, neutronization burst of \(\nu_e\)
2. accretion phase: \((O(1)\text{sec}), O(10^{53})\text{erg}\)
   - shock wave propagation, stall, revival (leading to explosion) or BH formation
3. cooling phase: \((O(10) - O(100)\text{sec}), O(10^{53})\text{erg}\)
   - Proto Neutron Star (PNS) cooling

**Figure 14.** Time evolution of neutrino luminosity and average energy (left) and number spectrum of \(\bar{\nu}_e\) (right) from \(\nu\) RHD and PNSC simulations with the interpolation (13) for the model with \((M_{\text{init}}, Z, t_{\text{revive}}) = (13 M_\odot, 0.02, 100 \text{ ms})\). In the left panel, solid, dashed, and dot-dashed lines represent \(\nu_e\), \(\bar{\nu}_e\), and \(\nu_x\) (dot-dashed lines), respectively. In the right panel, the lines correspond, from top to bottom, to 0.1, 0.25, 0.5, 2, 4, and 15 s after the bounce.

Nakazato et al., 2013
1. collapse and bounce phase: $(O(10))$msec
core collapse, inner core bounce, shock launch

- onset of core collapse: core $(M \sim 1.5M_\odot)$ transparent for neutrinos.
  Neutrino source: electron capture $e^- A(N, Z) \rightarrow \nu_e A'(N+1, Z-1)$ when
  $\mu_e + m_A c^2 > m_{A'} c^2$
  Neutrinos: not in thermal/chemical equilibrium with matters.

- neutrino trapping: $\rho_c \gtrsim O(10^{11})g/cm^3$, the core becomes opaque for neutrinos $(\nu_e A \rightarrow \nu_e A)$.
  Inside the neutrinosphere, neutrinos are trapped and diffuse out in time scale of $O(0.1)-O(10)$sec.
In this stage, $\nu_e$'s due to electron capture dominate.
core bounce: $\rho_c \gtrsim O(10^{14})\text{g/cm}^3$, the inner core bounces, launches a shock wave at the boundary between bounced inner core ($M_{\text{inner core}} \sim 0.5\text{--}0.8M_\odot$) and still free-falling outer core.

$E_{\text{shock}} \sim \frac{GM_{\text{inner core}}^2}{R_{\text{inner core}}} \sim \text{several} \times 10^{51}\text{erg} > E_{\text{explosion}}$.

neutronization burst of $\nu_e$ shocked region: $A \rightarrow p, n$, $\sigma_{e-\text{cap}}(p) > \sigma_{e-\text{cap}}(A) \Rightarrow e^-p \rightarrow \nu_en$

When the shock wave passes the neutrinosphere, the emitted $\nu_e$’s behind the shock front can escape from the core immediately

$\Rightarrow \text{neutronization burst} \text{ of } \nu_e$.

$L_{\nu_e} > 10^{53}\text{erg/sec}$, the time scale of the shock propagation through the neutrinosphere $\Delta t \lesssim O(10)\text{msec} \rightarrow E_{\nu_e} \sim L_{\nu_e}\Delta t \sim O(10^{51})\text{erg}$
Comparison of different numerical codes (1D Boltzmann solvers)

Fig. 5.—(a) Shock position as a function of time for model N13. The shock in VERTEX (thin line) propagates initially faster and nicely converges after its maximum expansion to the position of the shock in AGILE-BOLTZTRAN (thick line). (b) Neutrino luminosities and rms energies for model N13 are presented as functions of time. The values are sampled at a radius of 500 km in the comoving frame. The solid lines belong to electron neutrinos and the dashed lines to electron antineutrinos. The line width distinguishes between the results from AGILE-BOLTZTRAN and VERTEX in the same way as in (a). The luminosity peaks are nearly identical; the rms energies have the tendency to be larger in AGILE-BOLTZTRAN.

Liebendörfer et al., ApJ620(2005)840 Fig.5
- relatively good agreement among 1D simulations
- small multidimensional effects
- Emission of the other neutrino species is negligible during this phase
  ⇒ neutrino oscillation effects prominent
2. accretion phase ($O(1)sec$) until the core explosion or BH formation
shock wave propagation, stall, revival (leading to explosion) or BH formation
All types of neutrinos are in equilibrium inside the neutrinosphere and diffuse out
from the hot accreted mantle.

Light ONe core + CO shell ($1.38M_\odot$): weak explosion ($O(10^{50})$erg)
$\nu$-heating + nuclear reaction $\Rightarrow$ weak explosion  (Progenitor: Nomoto 8-10$M_\odot$)

Crab pulsar is thought to be formed in this kind of explosion.

Neutrino luminosities and average energies at infinity for 8.8$M_\odot$ progenitor.
L. Hüdepohl et al., PRL104 (2010) 251101
Modern simulations with GR 1D Boltzmann \( \nu \)-transfer canonical models: no explosion


Rampp et al., ApJ 539 (2000) L33 Fig.1

Thompson et al., ApJ 592 (2003) 434 Fig.5

15\( M_{\odot} \), Shen EOS, Sumiyoshi et al., 2005.

**Neutrino Interactions** (minimal standard: Bruenn’85)

\[
\begin{align*}
e^- p &\leftrightarrow \nu_e n & e^+ n &\leftrightarrow \bar{\nu}_e p & e^- A &\rightarrow \nu_e A' & e^+ A &\rightarrow \bar{\nu}_e A' \\
e^- e^+ &\leftrightarrow \nu \bar{\nu} & \text{plasmon} &\leftrightarrow \nu \bar{\nu} & NN &\rightarrow NN\nu\bar{\nu} & \nu_e \bar{\nu}_e &\leftrightarrow \nu_x \bar{\nu}_x \\
\nu N &\rightarrow \nu N & \nu A &\rightarrow \nu A & \nu e^\pm &\rightarrow \nu e^\pm & \nu\nu' &\rightarrow \nu\nu' \\
\text{e-cap, } \nu \text{ emission, photodissociation} &\rightarrow \text{shock wave weakens and stalls}
\end{align*}
\]
SN1987A aspherical feature

HST image of SN1987A on 1994.2 and 2003.11.28

Multidimensional effects to revive the shock wave

\[ \text{gain radius: net neutrino heating rate}=0 \]
\[ \text{(heating } (T_{\nu SP}^6 \frac{R_{\nu SP}^2}{r^2}) = \text{cooling } (T_{\text{matter}}(r)^6)) \]

- **PNS convection inside neutrinosphere**
  increase neutrino luminosity → more heating
- **instability between shock front and neutrinosphere**
  - neutrino convection: bottom of gain region is heated by $\nu$'s
  - SASI (Standing Accretion Shock Instability)
    accreting matter stay long in gain region: $\Delta t(\text{gain region}) \uparrow$
    $\Delta Q(\nu \text{ heating}) \sim \dot{Q}\Delta t(\text{gain region}) \uparrow$: $\tau_{\text{heating}} < \tau_{\text{advection}} \Rightarrow \text{Exp.}
2D/3D simulations with various approximations (GR, neutrino transfer)

entropy profiles: Janka et al., 2007.

SASI: the shock front sloshes upward/downward

Lentz et al., 2015

Takiwaki et al., 2013

2D/3D simulations → explosions
(but many models: \( E_{\text{exp}} \lesssim \text{obs. } O(10^{51})\text{erg} \))

key physics is still unclear

Neutrino Heating, Standing Accretion Shock Instability (SASI), Convection, Rotation, Magnetic Field, Acoustic Wave, asphericity in Si/O layer?

+ sophistication of EOS and neutrino interaction rates

GR 3D+3D \( f_{\nu}(t, x, y, z, p_{\nu x}, p_{\nu y}, p_{\nu z}) \) simulations for long timescale are required.
Neutrinos from 3D simulations
(results depend on progenitor, EOS, dimensionality, numerical scheme)

![Graph showing neutrino flux properties](image)

**FIG. 5** (color online). Evolution of neutrino flux properties for the $11.2M_{\odot}$ progenitor as seen from a distant observer. For $\nu_e$, $\bar{\nu}_e$, and $\nu_x$ we show the luminosity, average energy, and shape parameter $\alpha$. The Magenta and Blue directions are opposite along the LESA axis, corresponding to the magenta and blue curves in Fig. 4, whereas the Black direction is on the LESA equator (black in Fig. 4).

$11.2M_{\odot}$
Convection develops and SASI does not grow.
Shock wave revives before the SASI grows.

![Graph showing neutrino flux properties](image)

**FIG. 6** (color online). Same as Fig. 5, but for the $27M_{\odot}$ progenitor. The Violet, Black, and Light Blue directions here correspond to the curves of the same color in Fig. 7 that were chosen to show large and small SASI amplitudes, respectively.

$27M_{\odot}$
SASI grows slowly.
$\Rightarrow L_{\nu}(t)$ oscillates with SASI frequency.

2D model explodes, but
3D model does not yet.

Tamborra et al., 2014
Systematics?
Structure of progenitors does not have monotonic relations to initial mass.

**compactness parameter** $\xi_M \equiv \frac{M/M_\odot}{r(M)/1000\text{km}}$ (O’connor and Ott 2011)

progenitors with large $\xi$ cannot explode due to dense surrounding of Fe core.

Figure 4. Quantities characterizing the core structure of the progenitors at the onset of collapse vs. ZAMS mass: deleptonized (“iron”) core mass (top left), binding energy of the matter outside of the iron core in units of $1\text{B} = 10^{51}\text{erg}$ (top right) at the onset of collapse, enclosed mass at the bottom of the oxygen-burning shell (bottom left), and compactness parameter $\xi_{2.5}$ of the innermost $2.5M_\odot$ as defined in Equation (5) (bottom right). Red, gray, and green histogram bars have the same meaning as in Figure 3.

Figure 5. Resultant supernova properties from our 101 simulations as a function of compactness parameter $\xi_{2.5}$. Left: Mass accretion rate (a), and electron neutrino luminosity (b), estimated at time of shock revival $t_{400}$ (c). Right: diagnostic energy (d), mass of proto-neutron star (e), and mass of nickel in outgoing unbound material (f), at $t = t_{\text{fin}}$. Failed models which cannot carry the shock to the outer boundary during our simulation time are excluded from these panels.

Ugliano et al., 2012 and Nakamura et al., 2015

other good parameters? $M_4 \equiv M(s=4) \sim \text{Si/O I/F}$,

$\mu_4 \equiv \frac{300\text{km}}{r(M_4+0.3M_\odot)-r(s=4)} \propto \frac{dM}{dr}|_{s=4}$
full 3D+3D neutrino transfer code \( f_\nu(t, r, \theta, \phi, \nu, \theta_\nu, \phi_\nu) \) by Yamada group

In the central region, neutrino distribution is isotropic.

Outer regions: asymmetric distribution depending on neutrino energy.

Figure 4. Angular distributions in momentum space of the electron-type neutrino at 12 ms after bounce in the laboratory frame. The spatial point is \( r = 10 \text{ km} \) in the optically thick region on the equator. Each panel represents different neutrino energies measured in the laboratory frame: red \( 1 \text{ MeV} \), green \( 4 \text{ MeV} \), blue \( 19 \text{ MeV} \). Arrows with \( e_r, e_\theta, \) and \( e_\phi \) represent the spatial bases of the tetrad (equations (2-4)). All distributions are normalized so that the maximum value is the same, say, unity. In order to make the surfaces smooth, angular interpolation is applied.

Figure 6. The same as figure 5 except that the spatial point is \( r = 167 \text{ km} \) in the optically thin region.
accretion phase: general feature

- thermal neutrino emission (all species)
- hierarchy of mean energy

\[
\begin{align*}
\text{cross section} & : \quad \sigma_{\nu_e} > \sigma_{\bar{\nu}_e} > \sigma_{\nu_x} \\
\rho_{\text{neutrinosphere}} & : \quad \rho_{\nu_e} < \rho_{\bar{\nu}_e} < \rho_{\nu_x} \\
R_{\text{neutrinosphere}} & : \quad R_{\nu_e} > R_{\bar{\nu}_e} > R_{\nu_x} \\
T_{\text{neutrinosphere}} & : \quad T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_x} \\
\text{average energy} & : \quad \langle \omega_{\nu_e} \rangle < \langle \omega_{\bar{\nu}_e} \rangle < \langle \omega_{\nu_x} \rangle
\end{align*}
\]

- \( L_\nu \propto \dot{M} \): indication of shock revival time

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2D explosion by Scheck et al., 2008: thick dotted line is \( L_\nu(t) \) in the right panel.
Failed supernovae (Black Hole formation)
1D implicit GR hydrodynamics + Boltzmann $\nu$ transfer code


Fig. 1.—Radial trajectories of mass elements of the core of a 40 $M_\odot$ star as a function of time after bounce in the SH model. The location of the shock wave is shown by a thick dashed line.

Fig. 2.—Radial trajectories of mass elements of the core of a 40 $M_\odot$ star as a function of time after bounce in the LS model. The location of the shock wave is shown by a thick dashed line.

$L_\nu$ increases due to matter accretion $\nu_x < \nu_e$, $\bar{\nu}_e$ from accreted matter
Burst duration time strongly depends on EOS!

Progenitor 40$M_\odot$, left: Shen EOS (stiffer), right: Lattimer-Swesty EOS 180 (softer)
3. cooling phase: Proto Neutron Star (PNS) cooling ($O(10 - 100)\text{sec}$)

Figure 8. Evolutions of the density, temperature, and electron fraction profiles by the simulation of proto-neutron star cooling for the model with initial mass $M_{\text{init}} = 13\ M_\odot$, metallicity $Z = 0.02$, and shock revival time $t_{\text{revive}} = 100\ \text{ms}$. In all panels, solid, dashed, dotted, and dot-dashed lines correspond to the times at 100 ms, 1 s, 7 s, and 20 s after the bounce, respectively.

Figure 9. Snapshots of entropy profiles for the model with initial mass $M_{\text{init}} = 13\ M_\odot$, metallicity $Z = 0.02$ and shock revival time $t_{\text{revive}} = 100\ \text{ms}$. The line notations are the same as those in Figure 8.

Nakazato et al., ApJS205 (2013) 2

- cooling of mantle, contraction $\rightarrow T_{\text{mantle}} \uparrow$
- $\bar{\nu}_e$ and $\nu_x$ transport energy to the central region $\rightarrow S_{\text{center}}, T_{\text{center}} \uparrow$
- neutronization $\rightarrow \nu$-less $\beta$-equilibrium
- cooling of the whole neutron star
Figure 13. Same as Figure 12 but from the PNSC simulations. In the left panel, signals of \( \nu_e \) (solid lines), \( \bar{\nu}_e \) (dashed lines), and \( \nu_x \) (dot-dashed lines) are shown for the model with \((M_{\text{init}}, Z, t_{\text{revive}}) = (13 M_\odot, 0.02, 100 \text{ ms})\). In the central panel, \( \bar{\nu}_e \) signals are shown for the models with \((Z, t_{\text{revive}}) = (0.02, 100 \text{ ms})\) and \(M_{\text{init}} = 13 M_\odot\) (solid lines), 20 \(M_\odot\) (dashed lines), 30 \(M_\odot\) (dotted lines), and 50 \(M_\odot\) (dot-dashed lines). In the right panel, \( \bar{\nu}_e \) signals are shown for the models with \((M_{\text{init}}, Z) = (13 M_\odot, 0.02)\) and \(t_{\text{revive}} = 100 \text{ ms}\) (solid lines), 200 ms (dashed lines), and 300 ms (dot-dashed lines).

Nakazato et al., 2013, 1D simulations

- nearly spherical again
- differences among the neutrino species become small neutronization and cooling:
  \( n(e^+) \downarrow \), Degeneracy of \( e^- \), p, n \( \uparrow \) (Pauli Blocking)
  \( \Rightarrow \) suppress charged current interactions (origin of differences among \( \nu \) species)
  \( pe^- \rightarrow \nu_e n, ne^+ \rightarrow \bar{\nu}_e p \)
Summary 1

- Collapse and bounce phase: neutronization burst of $\nu_e$ uncertainty is relatively small because the multidimensional effects do not have enough time to grow substantially and because the uncertainty of nuclear EOS is small around the nuclear density (density at which the core bounce occurs).

- Accretion and core explosion phase:
  state-of-the-art 1D simulation: light core explodes weakly, canonical cores do not explode.
  2D/3D simulations: explosion mechanism is still unknown, neutrinos will give us information.
  Instability like SASI might cause time variation of neutrino luminosity.
  At the shock revival, matter accretion onto inner core ceases and the neutrino luminosity drops.
  3D simulations with full general relativity and 3D neutrino transfer are required.

- Cooling phase: after the core explosion (cooling stage of the new-born protoneutron star), differences among neutrino species are small.

Nakazato et al., ApJS205 (2013) 2

- several progenitor models
  Initial stellar mass and metallicity: $M = 13, 20, 30, 50M_\odot$, $Z = Z_\odot, 0.2Z_\odot$
  evolution of neutrino energy spectra for various progenitor models are provided as numerical data.

- Users can choose a parameter (shock revival time) which is introduced in order to incorporate multidimensional effects into our 1D simulations.
  Neutrino flux from unexploded dynamical simulations and that from cooling simulations of proto neutron star stripped of the ejecta are interpolated by use of the shock revival time.

**Basic Idea**

Neutrino luminosities from unexploded 1D simulations correspond to the upper bound because the multidimensional effects helping the explosion would prevent the matter accretion onto the SN core ($M \propto L_\nu$).

On the other hand, the neutrino luminosities from protoneutron star cooling simulations correspond to the lower bound because the overlying matter is stripped and no further accretion occurs in the simulations.

We interpolated the two limits to mimic the actual neutrino luminosities with a model parameter corresponding to the shock revival time after which the matter accretion would cease.
Dynamical Phase: 1D simulations (not explode)

\[ F_{\nu_i}(E, t) = F_{\nu_i}^{\text{acc}}(E, t) + F_{\nu_i}^{\text{PNSC}}(E, t) \sim f(t)F_{\nu_i}^{\text{dyn}}(E, t) + (1 - f(t))F_{\nu_i}^{\text{PNSC}}(E, t) \]

\[ F_{\nu_i}^{\text{acc}}(\text{explosion}) = f(t)F_{\nu_i}^{\text{acc,max}} = f(t)(F_{\nu_i}^{\text{dyn}}(\text{no explosion}) - F_{\nu_i}^{\text{PNSC}}(\text{no accretion})) \]

\[ f(t) = \begin{cases} 1 & t < t_{\text{rev}} + t_{\text{shift}} \\ \exp\left(-\frac{t-(t_{\text{rev}}+t_{\text{shift}})}{\tau_{\text{decay}}}\right) & t > t_{\text{rev}} + t_{\text{shift}} \end{cases} \]

model parameter: shock revival time \( t_{\text{rev}} \)

explosion with effective \( \nu \) convection \( \rightarrow \) small \( t_{\text{rev}} \)

if SASI is essential \( \rightarrow \) large \( t_{\text{rev}} \) (larger than growth time of SASI)
SN neutrino database (http://asphwww.ph.noda.tus.ac.jp/snn/)

Nakazato et al., ApJS205 (2013) 2

For the model with $M = 30M_\odot$, $Z = 0.004$, BH will be formed because $M_{\text{Fe core}} > 2.5M_\odot$ is too heavy.

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Table 1
Key Parameters for All Models

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<td>16.8</td>
<td>1.95</td>
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<td>3.19</td>
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<td>1.72</td>
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<td>5.20</td>
<td>4.51</td>
<td>4.61</td>
<td>2.81</td>
<td></td>
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<td></td>
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</table>

Notes. $M_{\text{init}}$ and $Z$ are the initial mass and metallicity of progenitors, respectively. $M_{\text{tot}}$, $M_{\text{He}}$, and $M_{\text{CO}}$ are the total progenitor mass, He core mass, and CO core mass when the collapse begins, respectively. Since models with $M_{\text{init}} = 50M_\odot$ become Wolf–Rayet stars, $M_{\text{init}}$ is not defined and $M_{\text{CO}}$ equals $M_\odot$. $M_{\text{core}}$ is a core mass defined as the region of oxygen depletion. $t_{\text{revive}}$ is the shock revival time. $M_{\text{He}}$ and $M_{\text{CO}}$ are the baryonic mass and gravitational mass of the remnant neutron states, respectively. The mean energy of emitted $\nu_i$ until 20 s after the bounce is denoted as $\langle E_{\nu_i} \rangle \equiv E_{\nu_i}^{\text{tot}}/N_{\nu_i,\text{tot}}$, where $E_{\nu_i}^{\text{tot}}$ and $N_{\nu_i,\text{tot}}$ are the total energy and number of neutrinos, respectively. $\nu_\mu$ stands for $\mu$- and $\tau$-neutrinos and their anti-particles: $E_{\nu_\mu} = E_{\nu_\mu}^{\text{tot}} = E_{\bar{\nu}_\mu} = E_{\bar{\nu}_\mu}^{\text{tot}}$. $E_{\nu_x}^{\text{tot}}$ is the total of neutrino energy summed over all species. The model with $M_{\text{init}} = 30M_\odot$ and $Z = 0.004$ is a black-hole-forming model, for which mean and total neutrino energies emitted up to the black hole formation are shown.

Figure 14. Time evolution of neutrino luminosity and average energy (left) and number spectrum of $\bar{\nu}_e$ (right) from $\nu RHD$ and PNSC simulations with the interpolation (13) for the model with $(M_{\text{init}}, Z, t_{\text{bounce}}) = (13M_\odot, 0.02, 100 \text{ ms})$. In the left panel, solid, dashed, and dot-dashed lines represent $\nu_e$, $\bar{\nu}_e$, and $\nu_\mu$ (dot-dashed lines), respectively. In the right panel, the lines correspond, from top to bottom, to 0.1, 0.25, 0.5, 2, 4, and 15 s after the bounce.

http://asphwww.ph.noda.tus.ac.jp/snn/
Supernova Relic Neutrino (SRN)
Diffuse Supernova Neutrino Background (DSNB)

- Core-Collapse Supernova Rate $R_{CC}(z, M, Z)$
  $\Leftarrow$ Star Formation Rate (SFR), Initial Mass Function (IMF), metallicity evolution ($z$: red-shift $\leftrightarrow$ cosmic time), $M$: progenitor mass, $Z$: metallicity
- Energy spectra from individual supernova $\frac{dN_{\nu}(E'_\nu, M, Z)}{dE'_\nu}$ using our SN neutrino database
- Cosmic expansion $\rightarrow$ red-shift of $\nu$ energy

$$
\frac{dF_{\nu}(E_{\nu}, t_0)}{dE_{\nu}} = c \int_{t_0}^{t_0} \int_{M_{\min}}^{M_{\max}} \int_{Z_{\min}}^{Z_{\max}} \frac{d^2R_{CC}(z, M, Z)}{dMdZ} dZ \frac{dN_{\nu}(E'_\nu, M, Z)}{dE'_\nu} \frac{dE'_\nu}{dE_{\nu}} dt
$$

$$
dt = - \frac{dz}{(1 + z)H(z)}, \quad H(z) = \sqrt{\Omega_m(1 + z)^3 + \Omega_\Lambda H_0}, \quad dE'_\nu = (1 + z)dE_{\nu}
$$

contributions from $0 < z < 1$, $1 < z < 2$, $2 < z < 3$, $3 < z < 4$, $4 < z < 5$, Nakazato et al., 2015
Luminosity and spectra of SN$\nu$ depend on progenitors. Initial Mass $M$ and metallicisty $Z$ affect density profiles of pre-collapse cores.

\[
\Rightarrow \frac{dN_{\nu}(E'_\nu, M, Z)}{dE'_\nu} + \text{oscillation } (\phi^{\text{obs}}_{\nu_e}(E) = \bar{P}\phi^{SN}_{\nu_e}(E) + (1 - \bar{P})\phi^{SN}_{\nu_x}(E)), \; \bar{P} = 0.68(\text{NH}) \text{ or } 0(\text{IH})
\]

Figure 4. Density profiles at times with the central density of $10^{11}$ g cm$^{-3}$ for progenitor models with metallicity $Z = 0.02$ (left panel) and 0.004 (right panel). In both panels, solid, dashed, dotted, and dot-dashed lines correspond to the models with initial mass $M_{\text{init}} = 13 M_\odot, 20 M_\odot, 30 M_\odot,$ and $50 M_\odot,$ respectively. (A color version of this figure is available in the online journal.)

Density profiles of progenitors with various $M, Z$ : Nakazato et al., 2013
Supernova rate and Cosmic Chemical Evolution

Our model:

\[
\frac{d^2 R_{CC}(z, M, Z)}{dM dZ} dZ dM = R_{CC}(z) \psi_{ZF}(z, Z) dZ \psi_{IMF}(M) dM
\]

Supernova (Core-Collapse) Rate

\[
R_{CC}(z) = \dot{\rho}_*(z) \times \frac{\int_{M_{\text{min}}}^{M_{\text{max}}} \psi_{IMF}(M) \ dM}{\int_{0.1 M_\odot}^{100 M_\odot} M \psi_{IMF}(M) \ dM} \text{ [yr}^{-1} \text{ Mpc}^{-3}]\]

Initial Mass Function (IMF): \( \psi_{IMF}(M) \propto M^{-2.35} \) (Salpeter type)

Star formation rate with initial mass of \( M \sim M + dM \) [yr\(^{-1}\)] \( \propto \psi_{IMF}(M) dM \)

Cosmic Star Formation Rate Density (CSFRD): \( \dot{\rho}_*(z) [M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}] \)

Several models of CSFRD as a function of redshift. Dashed, solid and dotted lines correspond to the models in Hopkins & Beacom’06, DA08 and Kobayashi et al.’13, respectively.
Evolution of Metallicity Distribution: $\psi_{ZF}(z, Z)$

Normalized cumulative metallicity distribution function, which represents the fraction of progenitors with metallicity less than $Z$, for the models in DA08+Maiolino’08 (left) and Langer & Norman’06 (right). The lines correspond, from bottom to top, to redshifts of $z = 0, 1, 2, 3, 4$ and $5$.

Fraction of black-hole-forming progenitors as a function of redshift. Dot-dashed and solid lines correspond to the models with the metallicity evolution of LN06 and DA08+M08, respectively. $Z_{\text{crit}} \equiv \sqrt{Z_{\odot} \cdot 0.2Z_{\odot}}$
Dependence on various models
Shock revial time: convection or SASI?

Neutrino number spectra of supernova with $30M_\odot$, $Z = 0.02$ and shock revival times of $t_{\text{revive}} =$ 100 ms (dotted), 200 ms (solid) and 300 ms (dashed). The left, central and right panels correspond to $\nu_e$, $\bar{\nu}_e$ and $\nu_x$ ($= \nu_\mu = \bar{\nu}_\mu = \nu_\tau = \bar{\nu}_\tau$), respectively.

For models in which the shock wave revive later, the accretion phase lasts longer and therefore relatively high energy neutrinos related to the mass accretion are increased.
In the case of normal hierarchy (large survival probability of $\tilde{\nu}_e (P \sim 0.68)$), dependence on the shock revival time is prominent.
Neutrinos from BH forming case depend on EOS

TABLE 1

Numerical results for black hole formation of progenitor with \((M, Z) = (30M_{\odot}, 0.004)\).

<table>
<thead>
<tr>
<th>EOS</th>
<th>(t_{BH}) (ms)</th>
<th>(&lt;E_{\nu_e}&gt;) (MeV)</th>
<th>(&lt;E_{\bar{\nu}_e}&gt;) (MeV)</th>
<th>(&lt;E_{\nu_x}&gt;) (MeV)</th>
<th>(E_{\nu_e,\text{tot}}) (10^{52} \text{ erg})</th>
<th>(E_{\bar{\nu}_e,\text{tot}}) (10^{52} \text{ erg})</th>
<th>(E_{\nu_x,\text{tot}}) (10^{52} \text{ erg})</th>
<th>(E_{\nu\text{all,\text{tot}}\text{}}) (10^{53} \text{ erg})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shen</td>
<td>842</td>
<td>17.5</td>
<td>21.7</td>
<td>23.4</td>
<td>9.49</td>
<td>8.10</td>
<td>4.00</td>
<td>3.36</td>
</tr>
<tr>
<td>LS(220 MeV)</td>
<td>342</td>
<td>12.5</td>
<td>16.4</td>
<td>22.3</td>
<td>4.03</td>
<td>2.87</td>
<td>2.11</td>
<td>1.53</td>
</tr>
</tbody>
</table>

Note. — \(t_{BH}\) is the time to black hole formation measured from the core bounce. The mean energy of the emitted \(\nu_i\) until black hole formation is denoted as \(<E_{\nu_i}\> = E_{\nu_i,\text{tot}}/N_{\nu_i,\text{tot}}\), where \(E_{\nu_i,\text{tot}}\) and \(N_{\nu_i,\text{tot}}\) are the total energy and number of neutrinos, respectively. \(\nu_x\) stands for \(\mu^-\) and \(\tau^-\)-neutrinos and their anti-particles: \(E_{\nu_x} = E_{\nu_\mu} = E_{\bar{\nu}_\mu} = E_{\nu_\tau} = E_{\bar{\nu}_\tau}\). \(E_{\nu\text{all,\text{tot}}\text{}}\) is the total neutrino energy summed over all species.

Neutrino number spectra for black hole formation with \(30M_{\odot}, Z = 0.004\) and Shen EOS (solid) and LS EOS (dotted). The left, central and right panels correspond to \(\nu_e, \bar{\nu}_e\) and \(\nu_x\) (\(=\nu_\mu = \bar{\nu}_\mu = \nu_\tau = \bar{\nu}_\tau\)), respectively.

Softer EOS has smaller maximum of NS and leads to earlier BH formation. \(\Rightarrow\) Shorter accretion phase, less neutrino emission.
Neutrinos from BH forming case depend on EOS

Comparison of virtual models without metallicity evolution
BH formation events contribute to high energy part of SRN.
But soft EOS resulting in too early BH formation is not the case.
BH forming events contribute to high energy $\bar{\nu}_e$. In the case of normal hierarchy (large survival probability of $\bar{\nu}_e (\bar{P} \sim 0.68)$), contribution of BH form in case is prominent. Difference between metallicity evolution models (DA08+M08 and LN06) is small.
Differences among CSFRD become large at $z > 0.5$. ⇒ influences on low energy part of SRN
Summary of model dependences

- Reference model
- lower limit model
- upper limit model

Nakazato et al., 2015.

Vagins, NPB PS 143(2005) 456, Fig.2
http://asphwww.ph.noda.tus.ac.jp/srn/
Togashi EOS based on the realistic nuclear force model

- EOS for uniform phase $\approx$ variational many body theory with the AV18 two-nucleon potential and UIX three-nucleon potential
- EOS for non-uniform phase $\approx$ Thomas-Fermi (TF) approximation: minimization of free energy of Wigner-Seitz cells (following Shen EOS) assuming a single representative nucleus
  $\Leftrightarrow$ Furusawa’s EOS with nuclear ensemble (Liquid drop model + Nuclear Statistical Equilibrium) (Furusawa et al. 2017)

Consistent with GW data of the binary NS merger (GW170817)

Togashi EOS: softer than Shen EOS and smaller symmetry energy
**EOS dependence of PNS cooling**

![Graphs showing luminosities and mean energies of emitted neutrinos as a function of time for different EOS models.](image)

**FIG. 1.** Luminosities (upper plots) and mean energies (lower plots) of the emitted neutrinos as a function of time after the bounce. The panels correspond, from left to right, to $\nu_e$, $\bar{\nu}_e$, and $\nu_x$ ($=\nu_\mu$, $\nu_\tau$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$). Solid, dashed, and dot-dashed lines are for the Togashi EOS, Shen EOS, and T+S EOS, respectively.

The time scale of neutrino emission and total energy emitted by neutrinos: Togashi EOS $\sim$ T+S $>$ Shen $\Leftarrow$ Togashi EOS is softer and has a more compact PNS (Togashi EOS: $R(50s)=11.8$ km, $\rho_{Bc}=7.73 \times 10^{14}$ g cm$^{-3}$, Shen EOS: $R=14.1$ km, $\rho_{Bc}=4.87 \times 10^{14}$ g cm$^{-3}$).

While Togashi EOS and T+S EOS (interpolation between Togashi EOS for high density and Shen EOS for low density) are similar as for softness, neutrino mean energies at $t > 20$ s are higher for Togashi EOS than T+S EOS. $\Leftarrow$ Crust composition
Togashi (Variational) EOS prefers heavy nuclei just below the nuclear density compared with Shen EOS.

The density derivative coefficient of the symmetry energy $L$: Togashi EOS ($L = 35$ MeV) $<\text{Shen EOS } (L = 111$ MeV) $\Rightarrow$ Symmetry energy at subnuclear densities and proton (electron) fraction: Togashi $>\text{Shen}$
Main opacity source: coherent scattering off heavy nuclei:
\[ \sigma \propto A^2, \ n_A \propto \rho_B X_A / A, \] mean free path \( \lambda \propto 1/(\rho_B X_A A) \):
\[ \lambda(\text{Togashi}) < \lambda(\text{T} + \text{S}) \]

For the Togashi EOS, neutrinos efficiently interact with the matter and keep the matter hot near the PNS surface. Reflecting the temperature there, the neutrino mean energy remains higher for the case with the Togashi EOS.
Summary

- We provide numerical data of the time evolution of emitted neutrino spectra obtained by our 1D models of supernova explosion and of the formation of a black hole.
- Neutrinos from failed supernovae are good probe to high density matter
- Estimation of Supernova Relic Neutrino (SRN) spectra with uncertainties on metallicity evolution, cosmic star formation rate density (CSFRD), shock revival timescale, equation of state (EOS) for high density matter
- Shock revival timescale and EOS affect the high energy part of SRN ($\bar{\nu}_e$) (Especially for the case of normal hierarchy)
- CSFRD affects the low energy part of SRN ($\bar{\nu}_e$)
- SK with Gd might observe 4 - 9 SRN events (10-18MeV)/10years
- Togashi EOS based on realistic nuclear force potential is ready for supernova simulations.
- The neutrino luminosity and mean energy are higher and the cooling time scale is longer for the softer EOS. Meanwhile, the neutrino mean energy and the cooling time scale are also affected by the low-density EOS because of the difference in the population of heavy nuclei. Heavy nuclei have a large scattering cross section with neutrinos owing to the coherent effects and act as thermal insulation near the surface of a PNS. The neutrino mean energy is higher and the cooling time scale is longer for an EOS with a large symmetry energy at low densities, namely a small density derivative coefficient of the symmetry energy, $L$. 