Systematic Features of CCSN neutrinos

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Basic equations:
\[
\begin{align*}
\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} &= 0, \\
\rho \frac{d\mathbf{v}}{dt} &= -\nabla P - \rho \nabla \Phi \\
\frac{\partial e^*}{\partial t} + \nabla \cdot [(e^* + P)\mathbf{v}] &= -\rho \mathbf{v} \cdot \nabla \Phi + Q_E \\
\frac{dY_e}{dt} &= \Gamma_N \\
\Delta \Phi &= 4\pi G\rho + \text{EOS}
\end{align*}
\]

Energy and electron fraction change due to neutrino interactions.
• Core-collapse supernova
  – Final fate of massive stars (>~10Mo)
  – Unclear mechanism of explosion
  – Neutrino heating mechanism
  – Convection, SASI

(Janka+’06)

\[ \nu_e + n \rightarrow p + e^- \]
\[ \bar{\nu}_e + p \rightarrow n + e^+ \], etc.
• Core-collapse supernova
  – Final fate of massive stars (>~10Mo)
  – Unclear mechanism of explosion
  – **Neutrino heating mechanism**
  – Convection, SASI

![Diagram of core-collapse supernova](image)

**Explosion mechanism of CCSN**

- Neutrino heating mechanism
- Convection, SASI

![Diagram](image)

**Neutrino Trapping**

**Shock Stagnation and Heating,** e, µ, n, etc.

**Neutrino Cooling and Neutrino-driven wind**

**Bounce and Shock Formation** (t ~ 0.11s, \( \rho_c \leq \rho_0 \))

**Spherical inflow**

**Convective motions**

**Density**

**Entropy**

**Order of events**

- Initial Phase of Collapse
- Nuclear matter nuclei
- Spherical inflow
- Mixing
- Neutrinosphere
- Neutrinosphere radius
- Neutrino sphere radius
- PNS radius
- Shock radius
- Iron core radius
- Gain radius

**Figure 1:** Schematic representation of the evolutionary stages from stellar core collapse through the onset of the supernova explosion to the neutrino-driven wind during the neutrino-cooling phase of the proto-neutron star (PNS). The panels display the dynamical conditions in their upper half, with arrows representing velocity vectors. The nuclear composition as well as the nuclear and weak processes are indicated in the lower half of each panel. The horizontal axis gives mass information. The PNS has maximum densities \( \rho \) above the saturation density of nuclear matter \( \rho_0 \).

**Examples:**

- \( \nu_e + n \rightarrow p + e^- \)
- \( \bar{\nu}_e + p \rightarrow n + e^+ \), etc.

**Parameters:**

- \( M = 17 \) Mo
- \( Z = Zo \)
Exploding mechanism of CCSN

- Core-collapse supernova
  - Final fate of massive stars (>~10Mo)
  - Unclear mechanism of explosion
  - Neutrino heating mechanism
  - Convection, SASI

\[ R \sim 3000 \text{ km} \]

\[ M(r) \sim M_{\text{Fe, Ni}} \]

\[ R \sim 100 \text{ g} \]

\[ \nu_e + n \rightarrow p + e^-, \quad \bar{\nu}_e + p \rightarrow n + e^+ \text{, etc.} \]

\[ \tau_{\nu e} > \tau_{\nu \mu, \nu \tau} \]

\[ \rho \geq \rho_0 \]

\[ M = 17 \text{ Mo} \]

\[ Z = Z_0 \]
**Explosion mechanism of CCSN**

**Neutrino transport**
from interior of PNS to outside of the shock

**Energy distribution**
to solve energy-dependent reactions

- **Neutrino heating mechanism**
- Convection, SASI

1D/2D/3D
with appropriate resolution

(Janka+’06)

\[ \nu_e + n \rightarrow p + e^- \]
\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

ex.)
M = 17 Mo
Z = Zo
Time evolution of neutrino luminosity

- Showing 101 models with solar metallicity. The other models with lower metallicity have a similar trend (not shown here).

- The difference of $L_{\nu}$ is more than double. $2-6 \times 10^{52}$ erg/s @ $t = 200$ ms.

※ smoothed over $\Delta t = 20$ ms.
**Compactness parameter**

What determines the CCSN properties is ...

*mass accretion* onto the PNS!

*Too much accretion leads to BH formation and/or failed explosion.*

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**Compactness parameter**  
(O’Connor & Ott ’11)

\[
\xi = \frac{M / M_\odot}{R(M)/1000\text{km}}
\]

(*Not too much) Mass accretion → PNS mass → \(n\) luminosity → Explosion energy → \(^{56}\text{Ni}\) mass

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![Graph showing compactness parameter vs. ZAMS mass](image)
Time evolution of neutrino luminosity

- Showing 101 models with solar metallicity. The other models with lower metallicity have a similar trend (not shown here).

- The difference of $L_{\nu}$ is more than double. $2-6 \times 10^{52}$ erg/s @ $t = 200$ ms.

- The compactness-colored lines show a monotonic trend.

Compactness parameter (O’Connor & Ott 2011)

$$\xi_M \equiv \frac{M/M_\odot}{R(M)/1000\text{km}}$$

※ smoothed over $\Delta t = 20$ ms.
CCSN properties as a function of the compactness parameter $\xi$

- Remnant mass $[M_\odot]$
- E-neutrino luminosity $[10^{52} \text{erg/s}]$
- ZAMS mass $[M_\odot]$
- Explosion energy $[10^{51} \text{erg}]$
- Nickel mass $[10^{-2} M_\odot]$
- ZAMS mass $[M_\odot]$
- Compactness parameter $\xi$

Graphs show the evolution of these properties as a function of the compactness parameter $\xi$. The graphs illustrate the relationship between the compactness parameter and various stellar properties such as remnant mass, E-neutrino luminosity, ZAMS mass, explosion energy, and nickel mass.
Compact progenitor suffers from high mass accretion rate,
so that it takes longer time to revive a stalled shock
Accreted matter releases grav. energy which is carried away by neutrinos.
High neutrino luminosity results in an energetic explosion.
.. and leaves a massive remnants at the center.
Strong shock heating produces ejecta rich in nickel.

\( @t=t_{400} \)

\( @t=t_{\text{fin.}} \)

\( L_{\nu e} \times 10^{52} \text{erg s}^{-1} \)

\( \dot{M}_{\text{dia.}} \times 10^{51} \text{erg s}^{-1} \)

\( t_{400} \text{[ms]} \)

\( M_{\text{Ni}} \times 10^{-2} \text{M}_\odot \)

\( M_{\text{PNS}} \text{[M}_\odot\text{]} \)

\( \xi_{2.5} \)

\( KN+ '15, \text{PASJ} \)
Neutrino signals & detectors

- Water-Cherenkov detector
  - Super Kamiokande (-Gd)
  - Hyper Kamiokande

- Reaction channels
  - inverse beta decay
  - electron scattering

Gd-loaded SK can drastically suppress the background noise (Beacom & Vagins '04).
Water-Cherenkov detector
- Super Kamiokande (-Gd)
- Hyper Kamiokande

Reaction channels
- inverse beta decay
- electron scattering

Observed event rate:
\[
\frac{dN_e}{dT_e} = N_t \int_{E_{\text{min}}}^{\infty} dE_{\nu} \frac{dF_\nu}{dE_{\nu}} (E_{\nu}) \frac{d\sigma}{dT_e}(E_{\nu}, T_e)
\]
Number of targets

\[
\frac{dF_\nu}{dE_{\nu}} (E_{\nu}) = \frac{L_\nu}{4\pi d^2 \langle E_{\nu} \rangle} f(E_{\nu})
\]
Galactic event @ 8.5 kpc

- Water-Cherenkov detector
  - Super Kamiokande (-Gd)
  - Hyper Kamiokande

- Reaction channels
  - inverse beta decay
  - electron scattering

- Observed event rate:

\[
\frac{dN_e}{dT_e} = N_t \int_{E_{\text{min}}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu} (E_\nu) \frac{d\sigma}{dT_e}(E_\nu, T_e)
\]

Number of targets

\[
\frac{dF_\nu}{dE_\nu} (E_\nu) = \frac{L_\nu}{4\pi d^2 \langle E_\nu \rangle} f(E_\nu)
\]

- Timing information (via IBD):
  the bounce time within \(\pm 3.0\) ms (HK)
  at 95% confidence level.

- Pointing information (via \(e^-\) scattering):
  \(\sim 6^\circ\) (SK), \(\sim 3^\circ\) (SK-Gd), \(\sim 2^\circ\) (HK)
  \(\sim 0.6^\circ\) (HK-Gd)
Field of views (FOV) of optical telescopes

KN+ ’16, MNRAS

FOV diameter (deg)

Optical magnitude

-5 0 5 10 15 20 25 30

bright dark→ ←

-5 0 5 10 15 20 25 30

Naked eye

Evryscope

1-2m 4m >8m

ASAS-SN ZTF

Pan-STARRS LSST

Blanco Subaru

CFHT SK

SK-Gd

dark→
Time sequence of observations

Red Supergiant (RSG) progenitor → Type II SN

Wolf-Rayet (WR) progenitor → Type Ib/c SN

(pre-SN neutrino)

neutrino burst

R* ~ $10^{13-14}$ cm, shock velocity ~ $10^9$ cm/s
→ $\Delta t \sim R^*/v \sim 10^{4-5}$ s (a few hours - a day)

R* ~ $10^{11}$ cm
→ $\Delta t \sim R^*/v \sim 100$ s (a few minutes)!

Distribute ALERT!
(SN Early Warning System; SNEWS)

Smith+’11, MNRAS
Pinning down the progenitor compactness

Template of neutrino light curves from numerical simulations

Expected detection events

$\bar{\nu}_e$

neutrino luminosity [10$^{52}$ erg/s]

time after bounce [s]

Post-bounce time [s]

Events @ HK [per 1ms bin]

Electron scattering
Inverse-beta decay

$8.5$ kpc

Template of neutrino light curves from numerical simulations

Expected detection events

$KN+ '16, MNRAS$
Observed event rate depends on the distance to SN.

\[
\frac{dN_e}{dT_e} = N_t \int_{E_{\text{min}}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu}(E_\nu) \frac{d\sigma}{dT_e}(E_\nu, T_e)
\]

\[
\frac{dF_\nu}{dE_\nu}(E_\nu) = \frac{L_\nu}{4\pi d^2} f(E_\nu)
\]

Horiuchi, KN+’17, J. Phys. G

The ratio can be a distance-independent indicator.
Uncertainty (2) - rotation

- Core rotation affects SN neutrino properties.

2D simulations for s20.0 progenitor with initial $\Omega_0 = 0.0 - 2.5$ rad/s.
Systematic study of CCSN properties (neutrino, explosion energy, etc.):
• Numerical simulations covering a wide range of progenitor mass (10.8 - 75 $M_{\odot}$, ~400 models) are demonstrated.
• Compactness is a good index of the explosion properties.

Neutrinos from a Galactic CCSN:
• The could tell us the compactness of CCSN progenitor,
• as well as the core bounce time (± 3.0 ms by HK),
• and the direction to the CCSN (~ 6° by SK, ~ 3° by SK-Gd, ~ 2° by HK).

Possible uncertainties in pinning down the compactness:
• distance to the CCSN
• rotation