Dependence of nuclear equation of state on supernova explosion

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Supernovae: the death of the star

Q: How does the explosion occur? How does the nuclear physics affect?
Plan

- Recent status of SN simulations
- Problem of the study and Focus of this talk
- Dependence of $Y_I$ on the SNe explosion
- Dependence of stiffness on the SNe explosion
Current Status of SNe Mechanism

$M < 10 M_\odot$

- Melson+15
  - 9.6 $M_\odot$
  - Zero metal
  - Dilute outer layer
  - Only $\nu$-heating

$M < 15 M_\odot$

- Horiuchi+14
  - 11.2 $M_\odot$
  - $\nu$-heating and convection

$M < 40 M_\odot$

- Melson+15
  - 20.0 $M_\odot$
  - $\nu$-heating, convection and SASI

Self-consistent 3D simulations with MG $\nu$-transport are available. Different mechanisms are found in different environment.

This slide contains my opinion that are not strictly confirmed.
From 1D to 3D
Averaged shock radius and Exp. Energy

Multi dimensional study is essential for successful shock revival.

Resolution
384x64x128
384x128x256(for H)
Key aspects of Neutrino Mechanism (1D)

- **Radial Velocity**
  - Post Shock
  - Postshocked n, p
  - Pressure

- **Shock**
  - Preshocked Fe
  - Ram Pressure

- **Entrophy** ~ \( T^3/\rho \)
  - Fe → n, p

- **RHS** is determined by stellar structure (density profile).
  \[ p = \rho \Delta \nu^2 \]

- **LHS** is determined by two ingredients.
  1. Photodissociation
     \[ \text{Fe} \rightarrow 30\text{n} + 26\text{p} - \Delta Q \]
  2. Neutrino Heating
     \[ \nu_e + \text{n} \rightarrow \text{e}^- + \text{p} + \Delta Q \]
     \[ \bar{\nu}_e + \text{p} \rightarrow \text{e}^+ + \text{n} + \Delta Q \]
Key aspects of Neutrino Mechanism (3D)

Entropy $\sim T^3/\rho$

Convective Energy transport

Turbulent Ram pressure

$P + \rho v_{\text{turb}}^2 = \rho \Delta v^2$

Cooler than the initial state but $\nu$ heat is active

Negative entropy gradient leads Rayleigh-Taylor instability

(Cold heavy matter is put over Hot light matter)

Rayleigh-Taylor convection transfer energy outward.

Hotter than the initial state
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Recent Problem of CC SNe

Results in multi-D models significantly depend on input physics and numerical methods!

2D models for multiple progenitors
- Bruenn+12: all explode
- Mueller+13: almost all explode
- Dolence+14: not explode
- Nakamura+15: all explode
- Suwa +15: half of them explode
- Hanke’s setup: almost all explode
- Pan+15: all explode • O’connor+15: a few explode

3D models for multiple progenitors
- Hanke et al+13: not explode(3model)
  Melason+15 , Mueller+15: explode
- Takiwaki in prep: half of them explode
- Bruenn: a explosion model

We have to update the input physics.
**Explosionability is not monotonic function of the level of sophistication!**

We are approaching to the final answer but much much more effort is required to get it.

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**Simplified Picture on the difference on the method**

<table>
<thead>
<tr>
<th>Explosionability</th>
<th>Newtonian reduced reactions on $ν$</th>
<th>Newtonian full reactions on $ν$</th>
<th>Phenomenological GR full reactions on $ν$</th>
<th>GR full reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only $ν_e, \bar{ν}_e$</td>
<td>Takiwaki+12, Suwa+14</td>
<td>Leakage $ν_\chi$</td>
<td>Hanke’s setup O’connor in prep, Bruenn+12</td>
<td>CFC Mueller+14</td>
</tr>
<tr>
<td>Takiwaki in prep Dolence+14</td>
<td>Nakamura+14, Pan+15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Important ingredients for core-collapse supernovae

We have to update all input physics and numerics.

- Dimensionality
- General Relativity
- Neutrino reactions
- Equation of state
- Progenitor Structure
Two control parameters

EoS and $\nu$–reaction rate determine the two important parameters below.

- Lepton fraction of the Proto –Neutron Star (PNS), $Y_l = (n_e + n_\nu)/n_b$

- Stiffness of PNS matter $P \propto \rho^{\Gamma}$
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From core-collapse to core-bounce

\[ P \propto \rho^{4/3} \]
How does $Y_l$ affect the evolution of the shock?

1. Electron capture rate ↓, $Y_l$ ↑ \[ p + e^- \rightarrow n + \nu_e \]
2. Pressure ↑, Sound speed↑, \[ P \propto (Y_l \rho)^{4/3}, c_s \sim \sqrt{P/\rho} \] starting position of the shock↑
3. Mass of iron to dissociate ↓
   \[ \text{Hot water} \]
4. The energy of the Shock ↑
Neutrino Reactions

\[
p + e^- \leftrightarrow n + \nu_e
\]
\[
n + e^+ \leftrightarrow n + \bar{\nu}_e
\]
\[
\nu + \{n, p, A\} \rightarrow \nu + \{n, p, A\}
\]
\[
\nu + \bar{\nu} \leftrightarrow e^+ + e^-
\]
\[
\nu_e + e^- \rightarrow \nu_e + e^-
\]
\[
A + e^- \rightarrow A' + \nu_e
\]
\[
\nu + \bar{\nu} + N + N \leftrightarrow N + N
\]
\[
\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}
\]

There are still several minor points that are remaining to be updated.

Updated set is roughly consistent with the more sophisticated works (e.g. Mueller+2010).
Unfortunately our 3D model with updated neutrino reaction does not explode. But do not forget that we now ignore GR Effect that should help the explosion!
Dependence on Radiation Hydro

$\text{VE} > \text{M1} > \text{IDSA}$

Density of neutrino could be larger in more sophisticated method.
Smaller $Y_I$ results in smaller shock radius!

It’s strange but reduced set is closer to the trajectory of more sophisticated calculation.

Our old results are not so bad?

It’s important to compare in same input physics.

Smaller $Y_I$ results in smaller shock radius!

It’s strange but reduced set is closer to the trajectory of more sophisticated calculation.
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Simply speaking, stiffness is the value of $\Gamma$.

The evolution of PNS is determined by that.
Basic idea to connect EOS and Explosion

1. The PNS gradually shrinks by the gravity.
2. E_grav is released.
3. E_thermal is increased.
4. The L_ν and sonic waves are emitted from the surface of PNS.

Soft EOS releases large energy and makes the PNS dense, that produce strong acoustic wave.

Softer EOS is preferable to the explosion.
Neutrino Luminosity

LS(K220): Soft EOS $\Rightarrow$ rapidly shrink $\Rightarrow$ Large $L_\nu$
Shen: Stiff EOS $\Rightarrow$ slowly shrink $\Rightarrow$ small $L_\nu$

(Sumiyoshi+2005 and Fisher+ 2013 show similar results.)
Sonic Wave

Strong sonic wave is reflected at the PNS! (It is a little bit hard to see, but) softer EOS make stronger sonic wave.

(Couch 2013 and Suwa+ 2013 show similar results.)
Sonic Wave

s11.2(WHW02)-LS

\[ \frac{\delta \rho}{\bar{\rho}} \]

Radius [km]

Time after bounce [ms]

Gray: gain radius, black PNS radius
Evolution of the shock

Softer EOS shows larger shock radius.

Soft EoS shows larger shock radius.
Emergence of Multi-species EOS

SFHx and DD2: Multi species of heavy nuclei is included. SFHx and DD2 \( \triangleright \) LS and STOS

Employing MS may help SNe explosion.

But in one-dimensional GR sim, that situation is contradictory. (Fisher+2014)
In other words?

We understand the radius of PNS is very important probe to determine success or failure of supernovae.

Is the result translated to the terms of nuclear physics?
PNS radius is "roughly" predicted by the NS radius at zero-temperature.
Many theories for EOS

\[ p = n^2 \frac{\partial (E/N)}{\partial n} \]

\[
\begin{array}{cccccccc}
\text{EOS} & n_0 & E_0 & K & S & L & R_{1.4} & M_{\text{max}} \\
\text{SFHo} & 0.1583 & 16.19 & 245 & 31.57 & 47.10 & 11.89 & 2.06 \\
\text{SFHx} & 0.1602 & 16.16 & 238 & 28.67 & 23.18 & 11.99 & 2.13 \\
\text{HS(TM1)} & 0.1455 & 16.31 & 281 & 36.95 & 110.99 & 14.47 & 2.21 \\
\text{HS(TM2)} & 0.1472 & 16.03 & 318 & 30.66 & 90.14 & 13.85 & 2.02 \\
\text{HS(FSUgold)} & 0.1482 & 16.27 & 229 & 32.56 & 60.43 & 12.55 & 1.74 \\
\text{HS(DD2)} & 0.1491 & 16.02 & 243 & 31.67 & 55.04 & 13.22 & 2.42 \\
\text{HS(IUFSU)} & 0.1546 & 16.39 & 231 & 31.29 & 47.20 & 12.68 & 1.95 \\
\text{HS(NL3)} & 0.1482 & 16.24 & 272 & 37.39 & 118.49 & 14.77 & 2.79 \\
\text{STOS(TM1)} & 0.1452 & 16.26 & 281 & 36.89 & 110.79 & 14.50 & 2.22 \\
\text{LS (180)} & 0.1550 & 16.00 & 180 & 28.61 & 73.82 & 12.16 & 1.84 \\
\text{LS (220)} & 0.1550 & 16.00 & 220 & 28.61 & 73.82 & 12.67 & 2.05 \\
\text{Exp.} & \sim 0.15 & \sim 16 & 240 \pm 10^{(a)} & 29.0–32.7^{(b)} & 40.5–61.9^{(c)} & 10.4–12.9^{(c)} & \gtrsim 2.0^{(d),(e)} \\
\end{array}
\]
Radius of NS (T~0 and Y_e~0) is determine by L. 
Radius of PNS is not determine by L. 
S and K have stronger correlation to PNS. 
r=0.71 for S. r= 0.69 for K.
Employing LS’ s parameter sets, we construct number of equation of states.
Non-uniform matter: LS K=220MeV
The radius of PNS is more sensitive to S than K! 1-2 km of difference is found at 300 ms after bounce.
Evolution of neutrino luminosity

The neutrino luminosity is more sensitive to S than K! 10% of difference is found at 300 ms after bounce.
Evolution of the shock

Divergence due to non linear evolution of 2D smoothed out the difference of equation of state at uniform density.

Preliminary Results are shown.
Question

R1. LS and STOS show large difference. 
R2. We change EOS of uniform matter parametrically. The difference between them is not so significant.

Q1. Is the part of non-uniform matter important? 
Q2. Does the shape of the function substantially affect? Not parameter? 
Q3. Different progenitor? GR effects?

We continue to investigate these issues.
Summary

- Multi-D simulations that naturally employ convection. Those are promising, but the results are sensitive to the input physics.
- Neutrino reaction rates significantly affect the fate of the star if that changes the lepton fraction of PNS.
- Equation of State is also important ingredients. If that is sufficiently soft, the PNS rapidly shrinks and help explosion via the emission of ν-Luminosity and reflection of sonic wave.
- Many EOS is available now but systematic studies are difficult. Parametric EOS is useful tool to investigate that.