2015/6/22@NAOJ

International Symposium on "Physics and Astronomy of Neutron Stars and Supernovae"

"How equation of state affects explosions of core-collapse supernovae"

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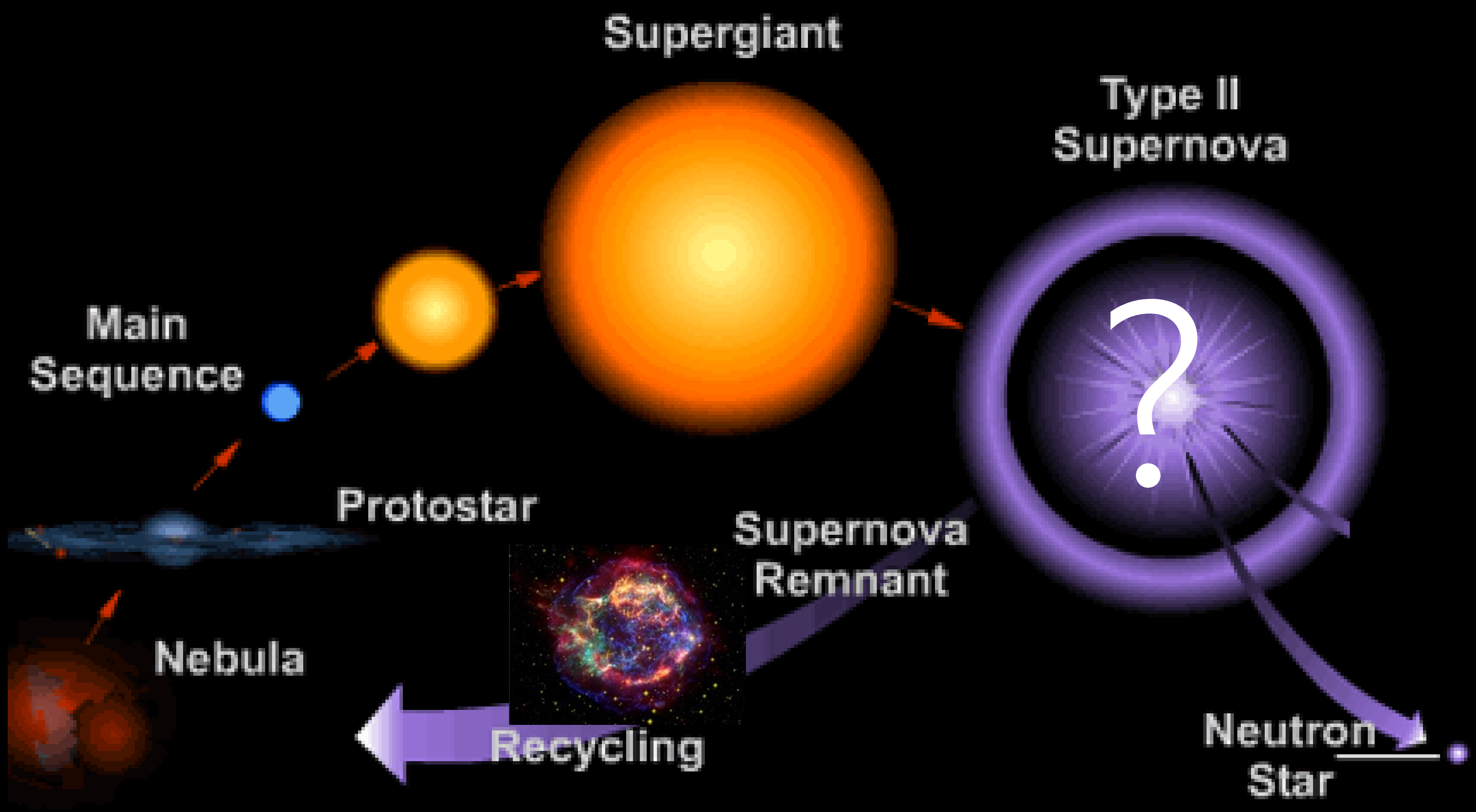
Plan

- Recent status of SN simulations
- Our efforts for making sophisticated model
- How EOS affects the explosion
- Systematic studies of EOS(in progress)

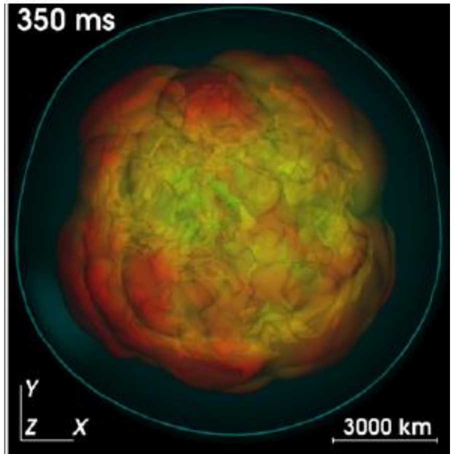
Supernovae: the death of the star



Q:How does the explosion occur?

Current Status of SNe Mechanism

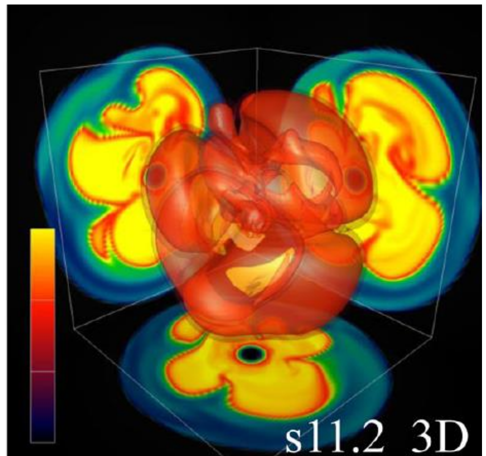
$M < 10M_s$



Melson+15
9.6 M_s
zero metal

Dilute outer layer
Only ν-heating

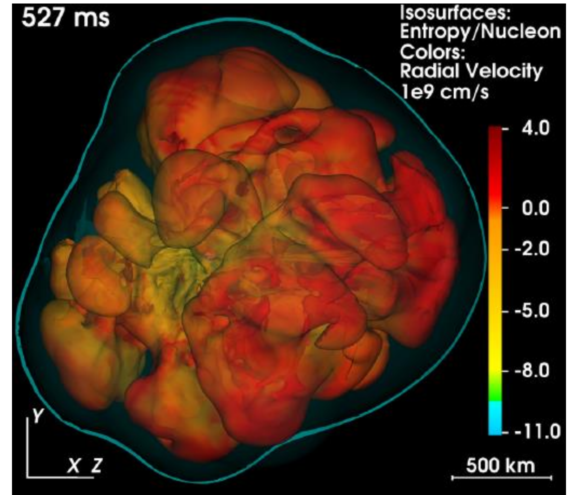
$M < 15M_s$



Horiuchi+14
11.2 M_s

ν-heating and convection

$M < 40M_s$



Melson+15
20.0 M_s

ν-heating, convection and SASI

Self-consistent 3D simulations with MG ν-transport are available.

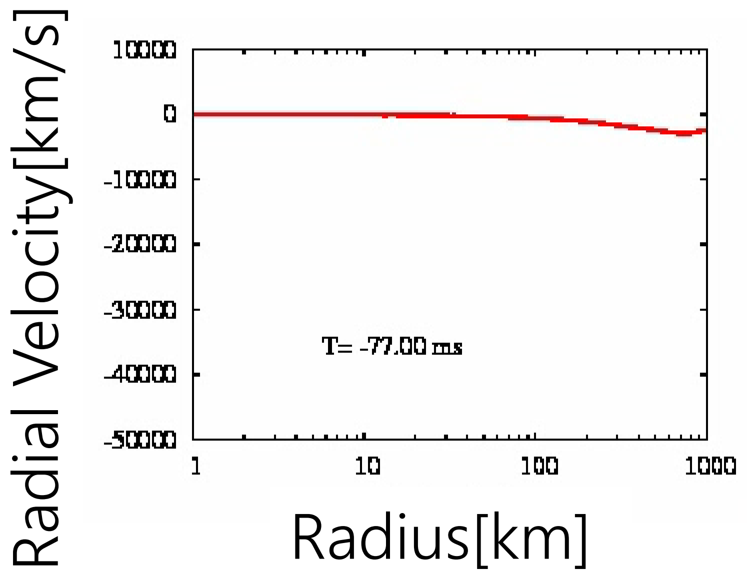
Typical 1D simulation

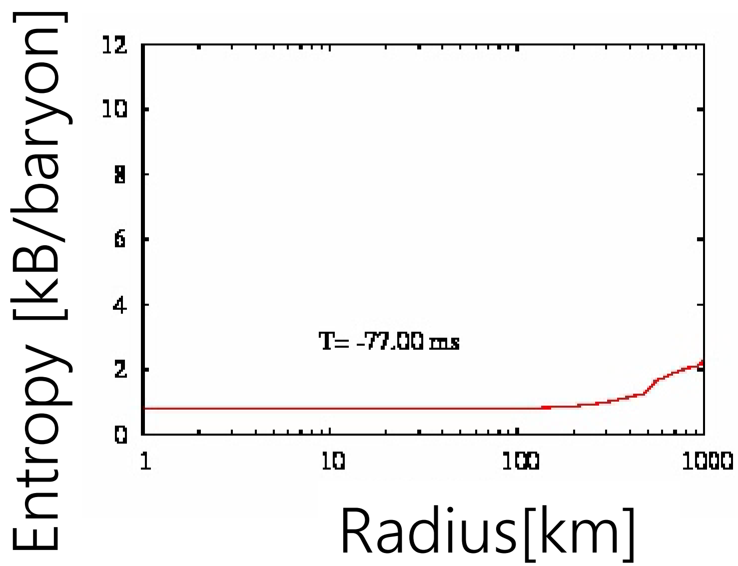
Velocity and Entropy profile in 1D

Entropy:T^3/ρ

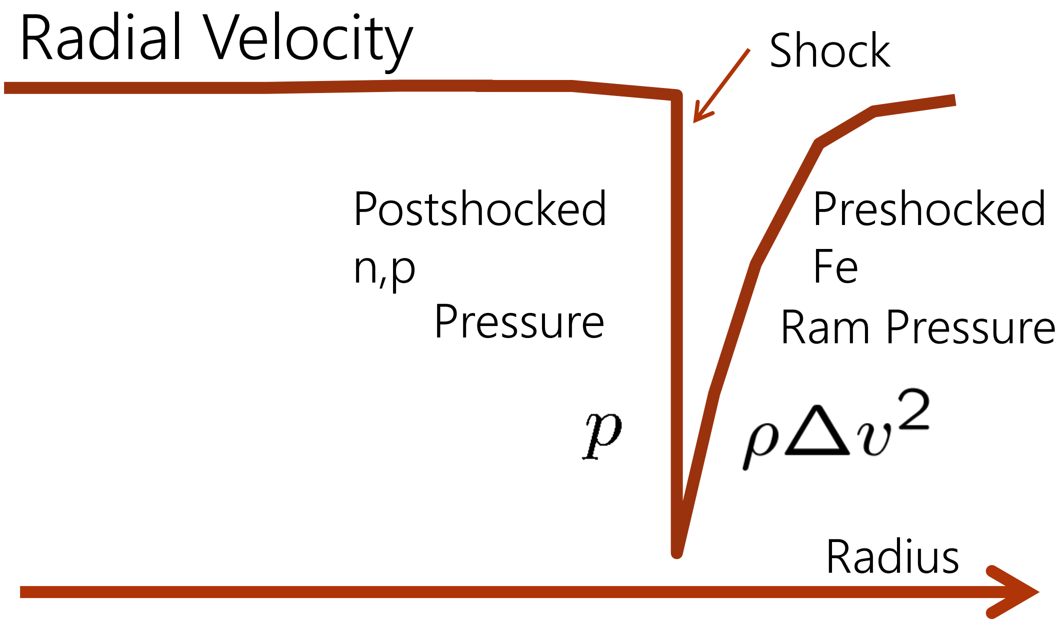
It's a good measure for the shock.

At the shock, kinetic energy is converted to heat and temperature increases(i.e. entropy also increases.)





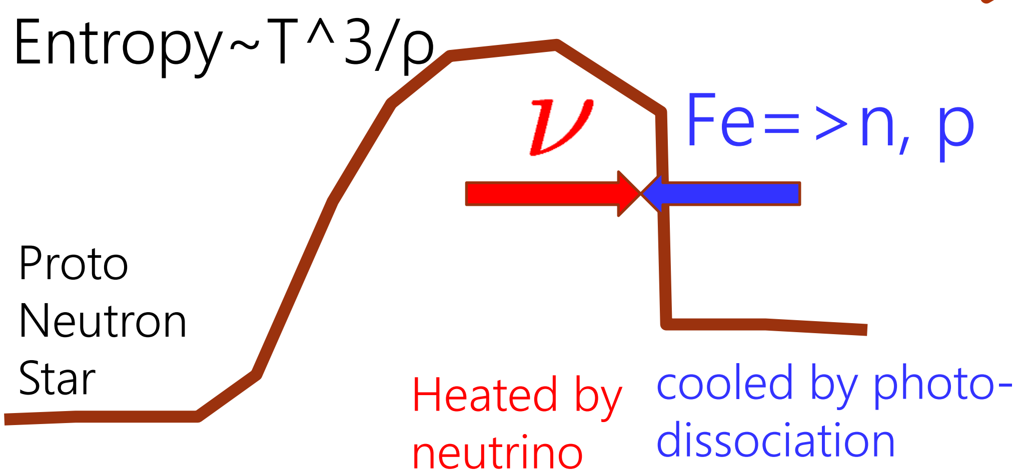
Key aspects of Neutrino Mechanism



When the shock is stalling, Pressure inside and ram pressure out side balances.

$$p \sim \rho \Delta v^2$$

RHS is determined by stellar structure(density profile).



LHS is determined by two ingredients.

(1) Photo-dissociation

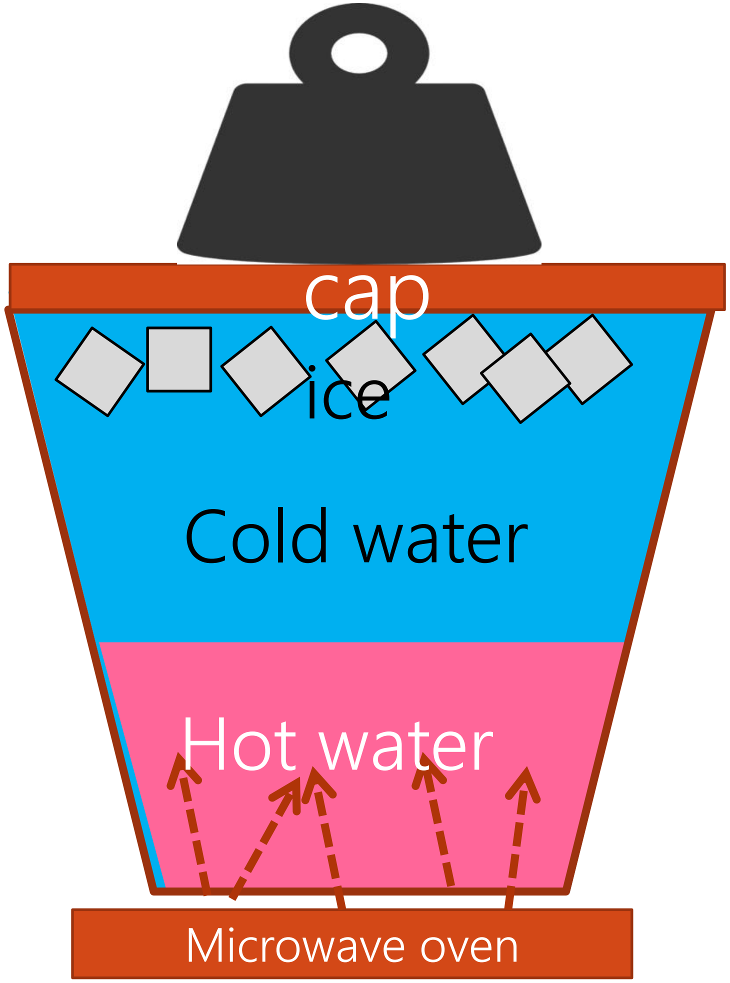
$$\mathrm{Fe} \rightarrow 30\mathrm{n} + 26\mathrm{p} - \Delta Q$$

(2) Neutrino Heating

$$\nu_e + \mathrm{n} \rightarrow \mathrm{e}^- + \mathrm{p} + \Delta Q$$

$$\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n} + \Delta Q$$

Problem



Supernova shock in simulation tends to stall and does NOT explode.

Long-lasting Problem ~1980.

In 2000-2005, state-of-the-art simulations with detailed neutrino transport confirm that!

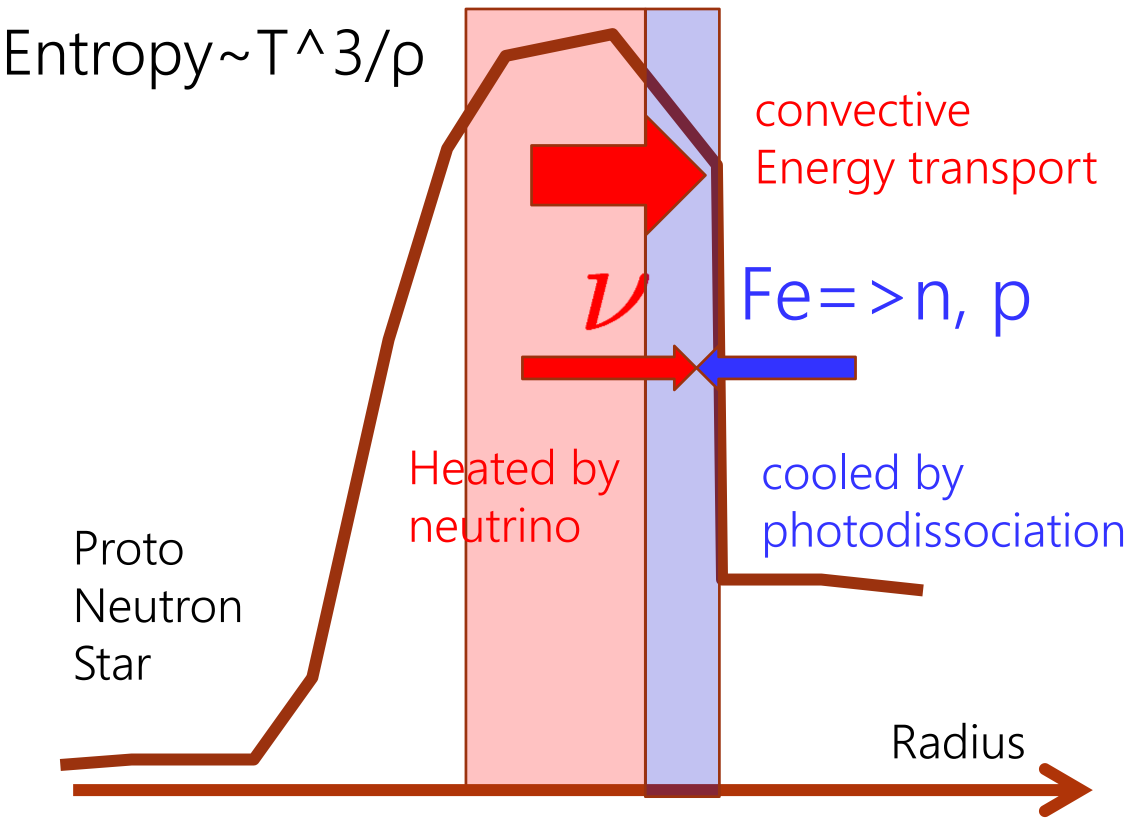
(Liebendoerfer+2001, Rampp+2002, Thompson+2003 and Sumiyoshi+2005)

(in 1D)Neutrino heating < ram pressure

=> fails to explode!

From 1D to 3D

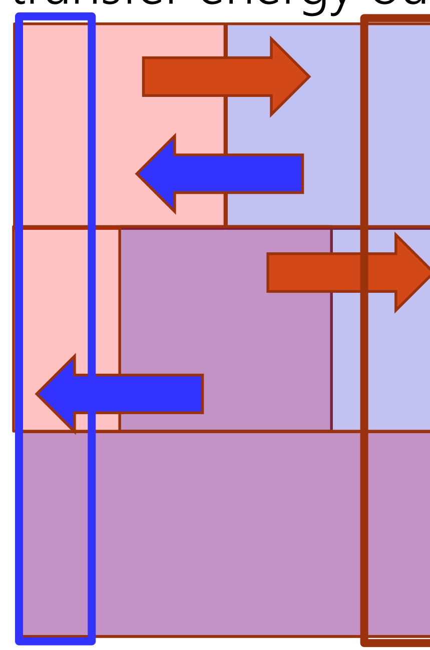
Key aspects of Neutrino Mechanism



Negative entropy gradient leads Rayleigh-Taylor instability

(Cold heavy matter is put over Hot light matter)

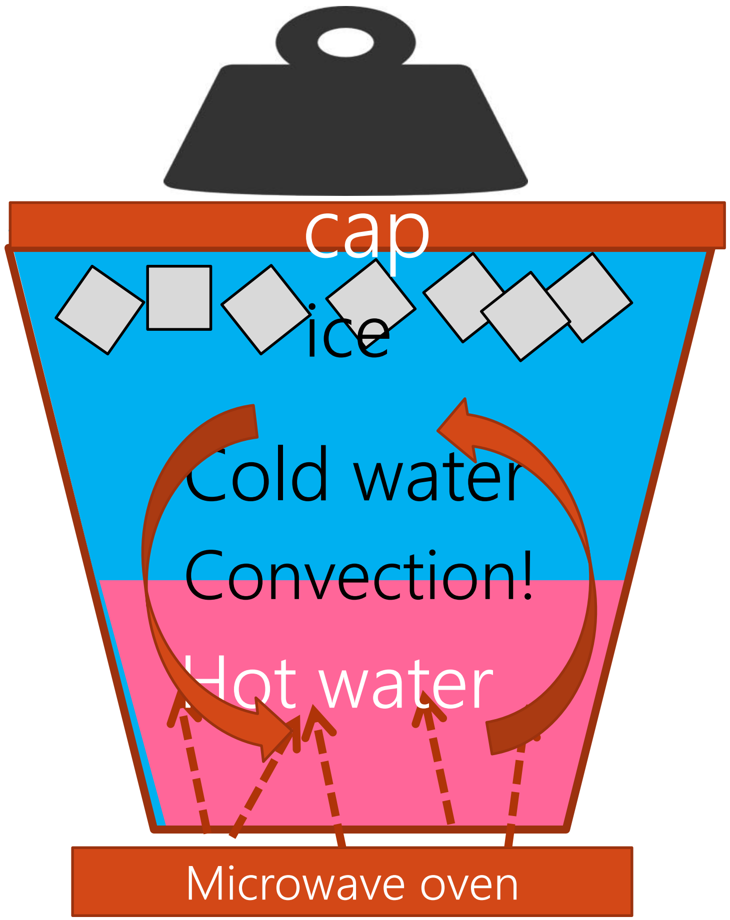
Rayleigh-Taylor convection transfer energy outward.

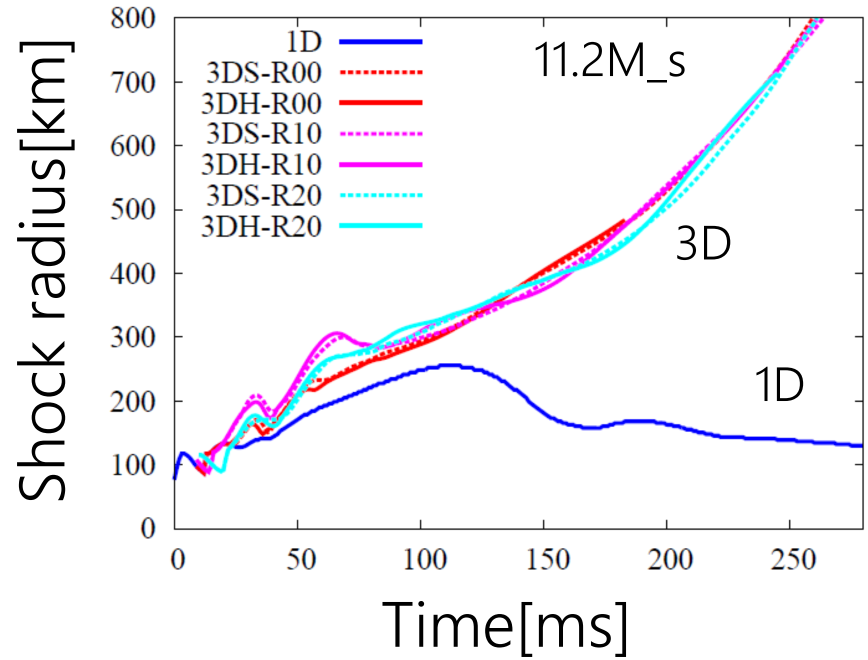


Cooler than the initial state but ν heat is active

Hotter than the initial state

Successful 3D simulation





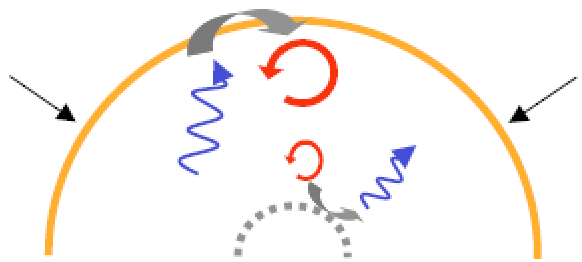
2 month times 16,000 cores are used in K computer

With convection hot water at the bottom is transported near the cap. The pressure at the cap become higher. Explosion occurs with the process.

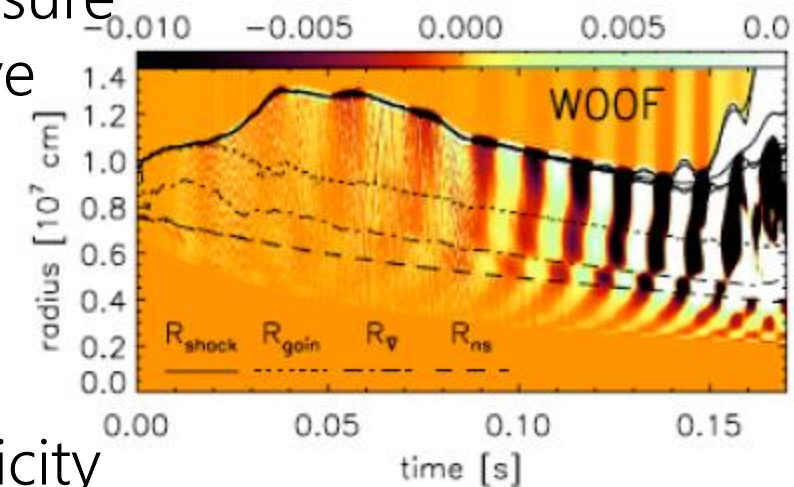
Takiwaki+2012,2014, in prep

S A S I
(Standing Accretion Shock Instability)

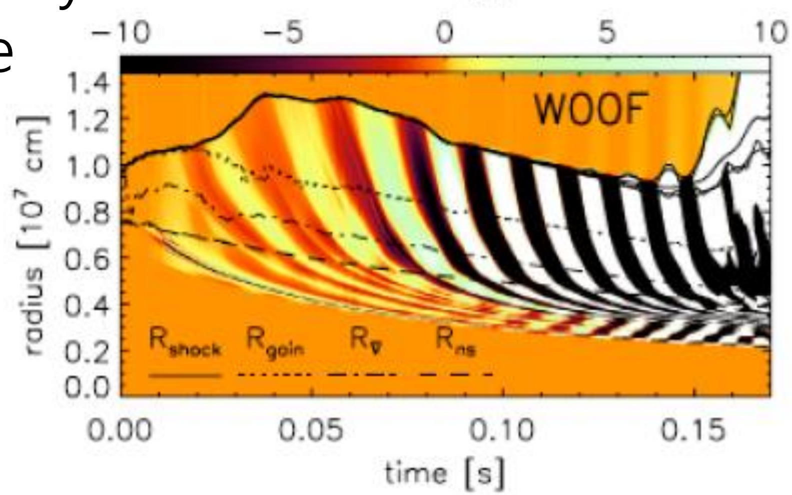
Scheck+ 2008



Pressure Wave



Vorticity Wave

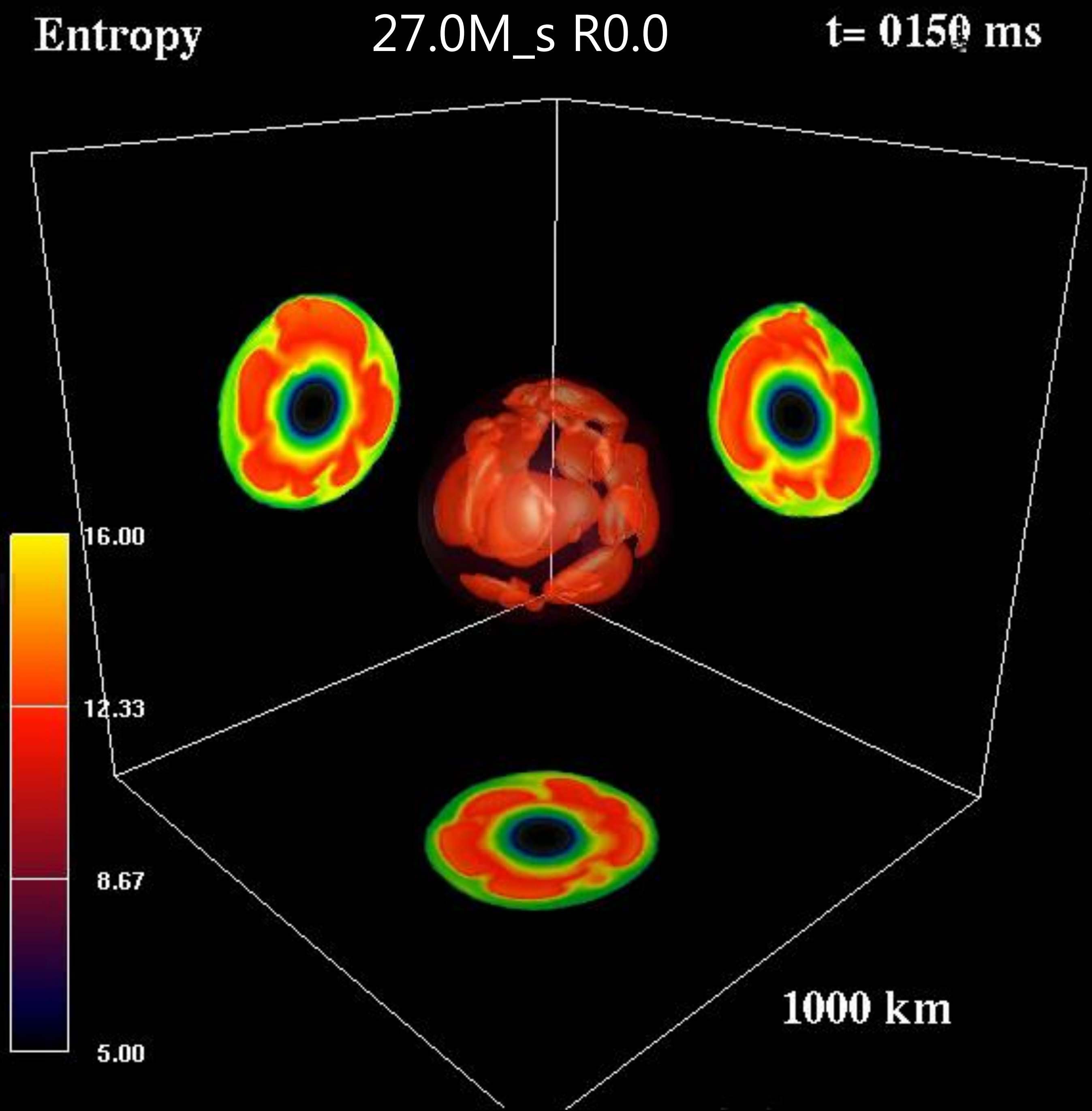


Advective-acoustic cycle

From Foglizzo's slides

Standing Accretion Shock Instability(SASI)

27.0M_s R0.0



Recent Problem of CC SNe

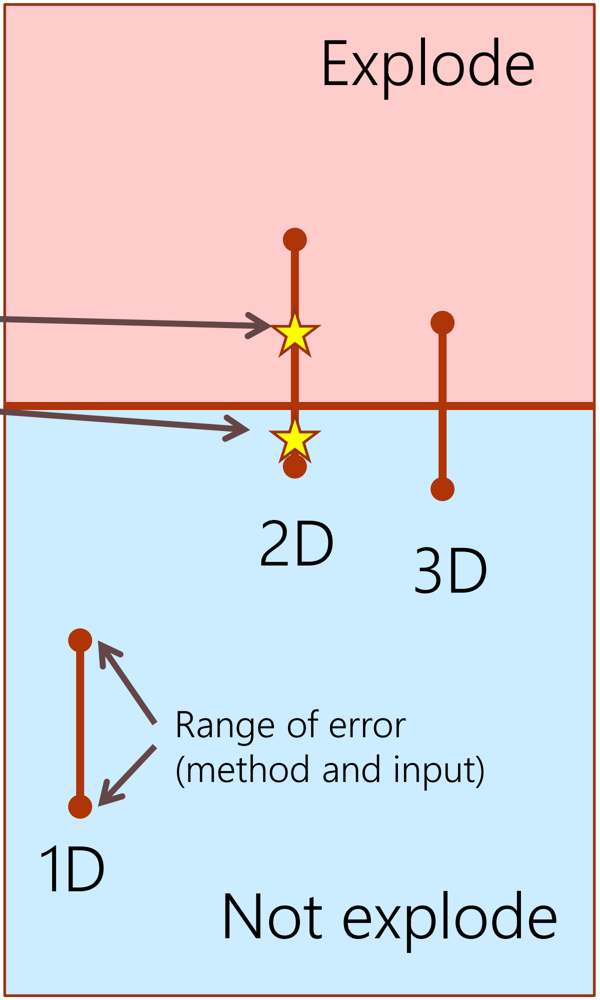
Results in multi-D models significantly depend on input physics and numerical methods!

2D models for multiple progenitors

- Bruenn+12 : all explode
- Mueller+13 : almost all explode
- Dolence+14 : not explode
- Nakamura+14 : all explode
- Suwa +14 : half of them explode
- Hanke's setup: almost all 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.

Plan

- Recent status of SN simulations
- Our efforts for making sophisticated model
- How EOS affects the explosion
- Systematic studies(in progress)

Towards further sophistications

$$p + e^- \leftrightarrow n + \nu_e$$

$$n + e^+ \leftrightarrow n + \bar{\nu}_e$$

$$\nu + \{n, p, A\} \rightarrow \nu + \{n, p, A\}$$

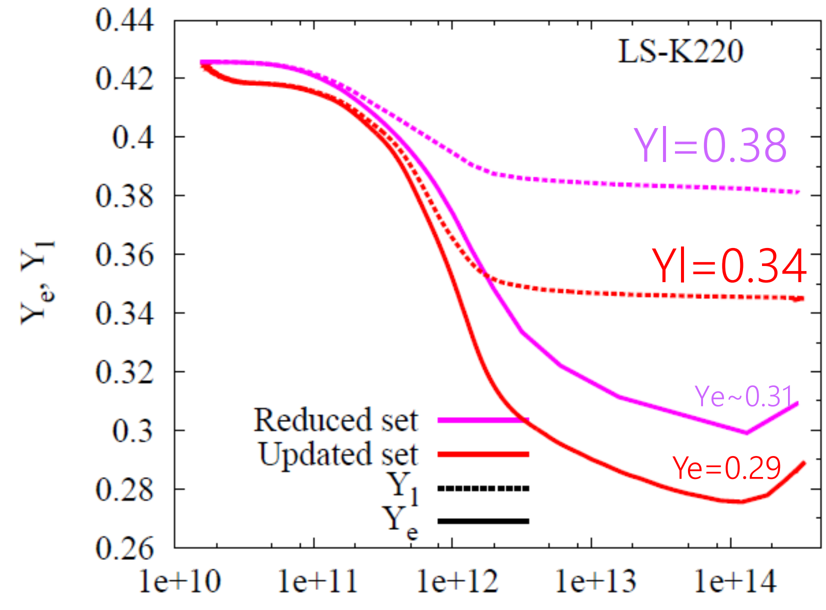
$$\nu + \bar{\nu} \leftrightarrow e^+ + e^-$$

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

$$A + e^- \rightarrow A' + \nu_e$$

$$\nu + \bar{\nu} + N + N \leftrightarrow N + N$$

$$\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$

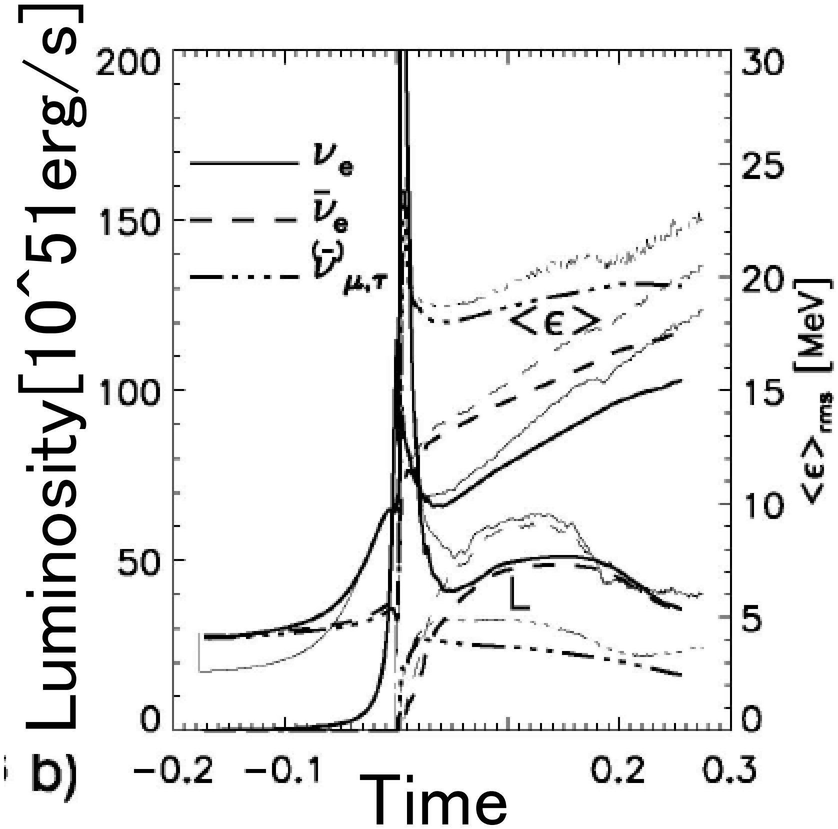


Density[g/cm^3]

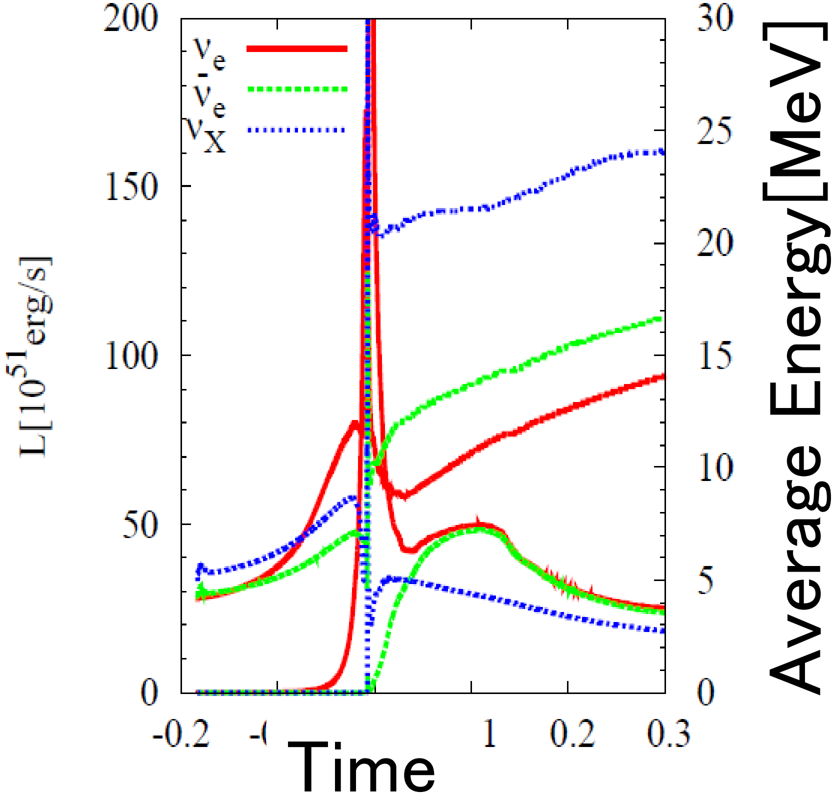
There are still several minor points that are remaining to be updated.

Updated set is roughly consistent with the more sophisticated works(e.g. Mueller+2010).

Towards further sophistications



Liebendoerfer et al 2005



Our newest version of IDSA

Sn and VE

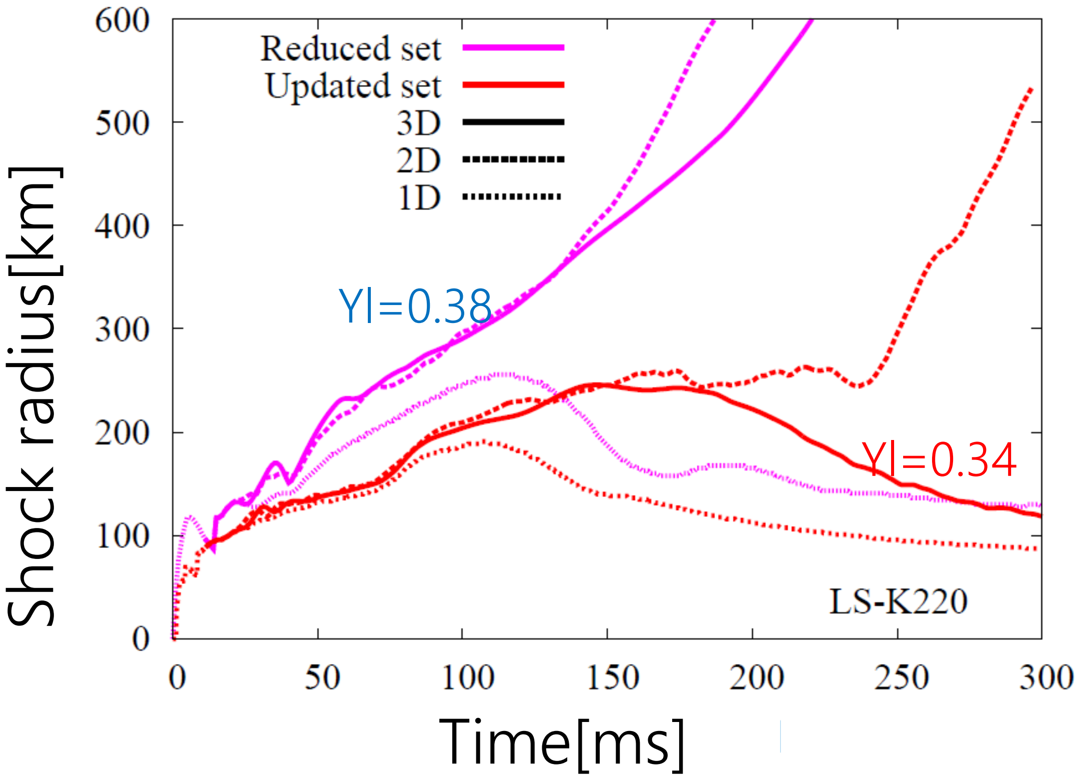
General relativistic simulation

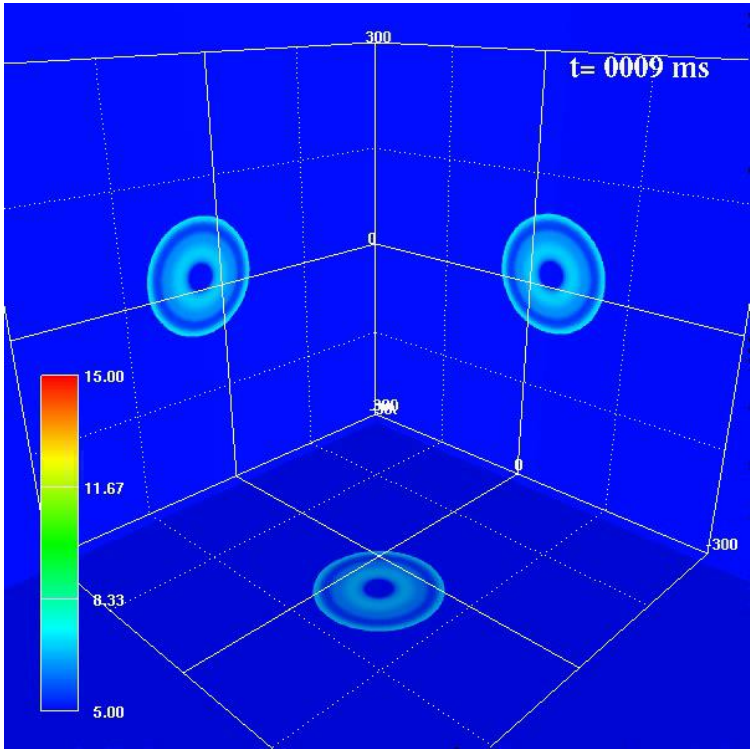
ecp,aecp,eca,csc,nsc,pap,nes,nbr

Newtonian Gravity

Our simulation is roughly consistent with the sophisticated 1D model.

Towards further sophistications





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!

Plan

- Recent status of SN simulations
- Our efforts for making sophisticated model
- How EOS affects the explosion
- Systematic studies on EOS (in progress)

Important ingredients for core-collapse supernovae

We have to update all input physics and numerics.

- Dimentionality
- General Relativity
- Neutrino reactions
- <u>Equation of state</u>
- Progenitor Structure

Stiffness of EOS

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SUPERNOVA EXPLOSIONS AND THE SOFT EQUATION OF STATE

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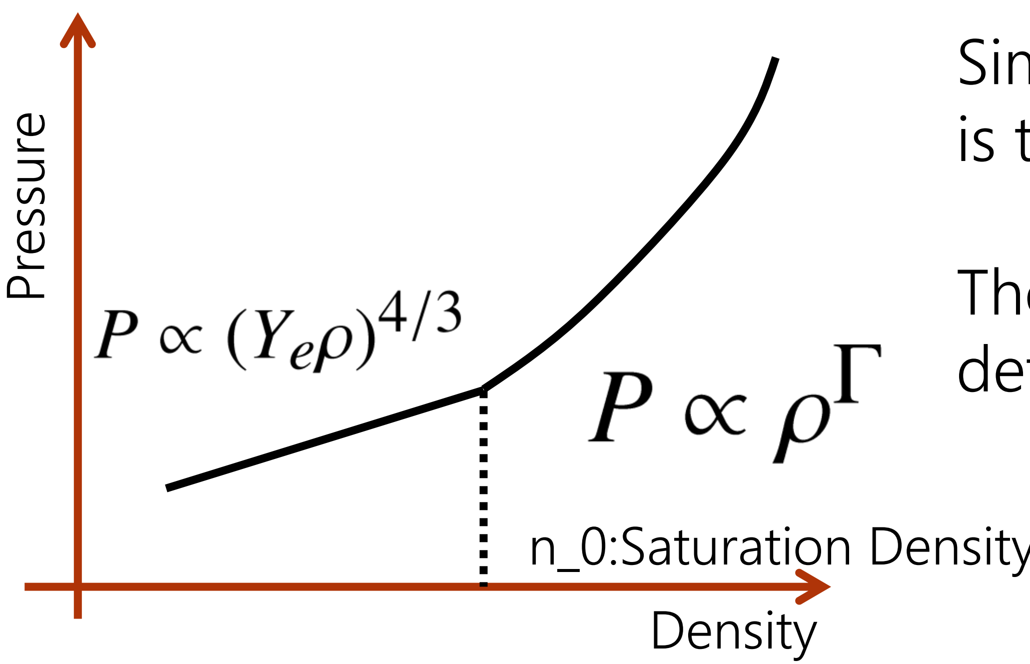
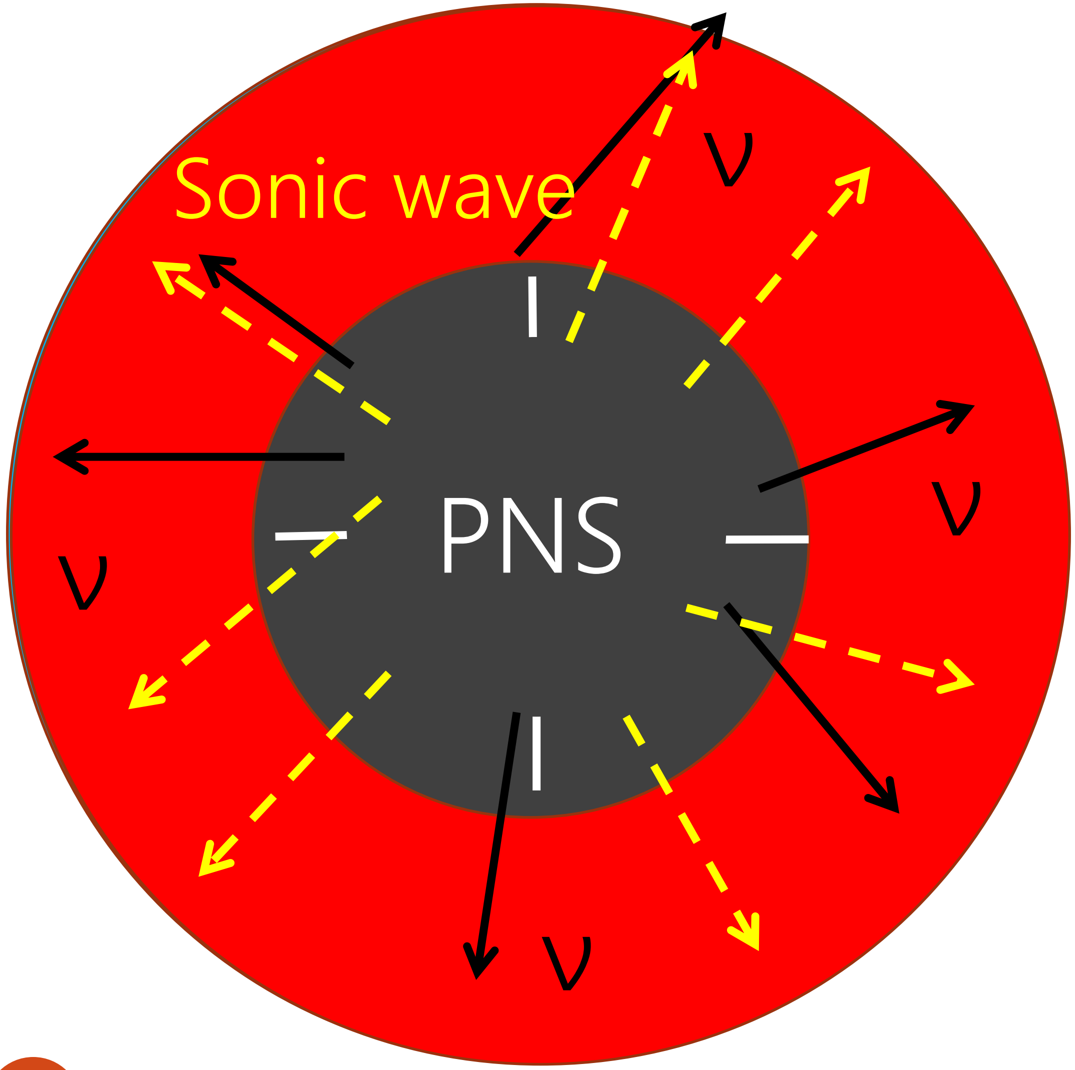
Received 1987 May 29; accepted 1988 May 28



Simply speaking, stiffness is the value of Γ.

The evolution of PNS is determined by that.

Basic idea to connect EOS and Explosion

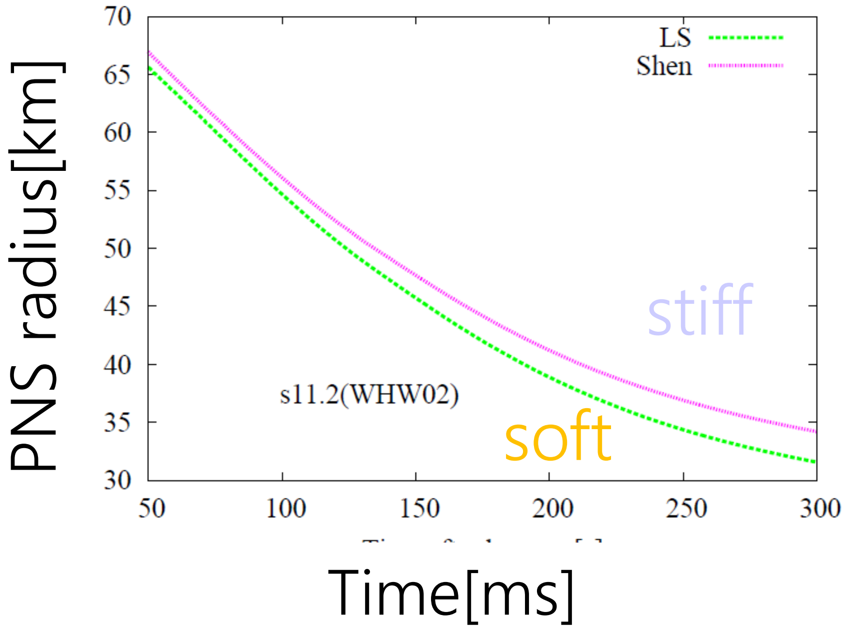


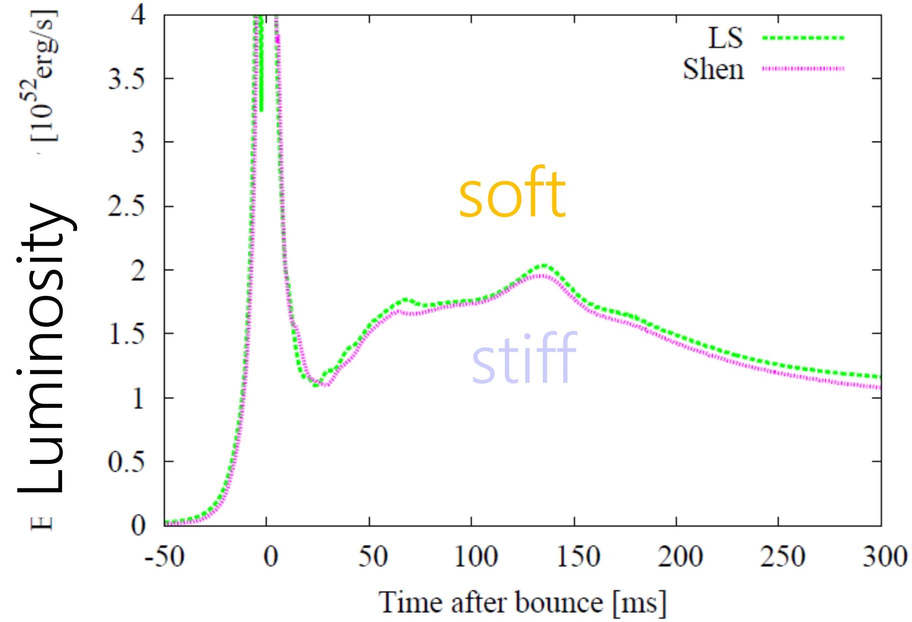
1. The PNS gradually shrinks by the gravity.
2. E_grav is released.
3. E_thermal is increased.
4. The L_ν and sonic waves are emitted from the surface of PNS.

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

Softer EOS is preferable to the explosion.

Neutrino Luminosity



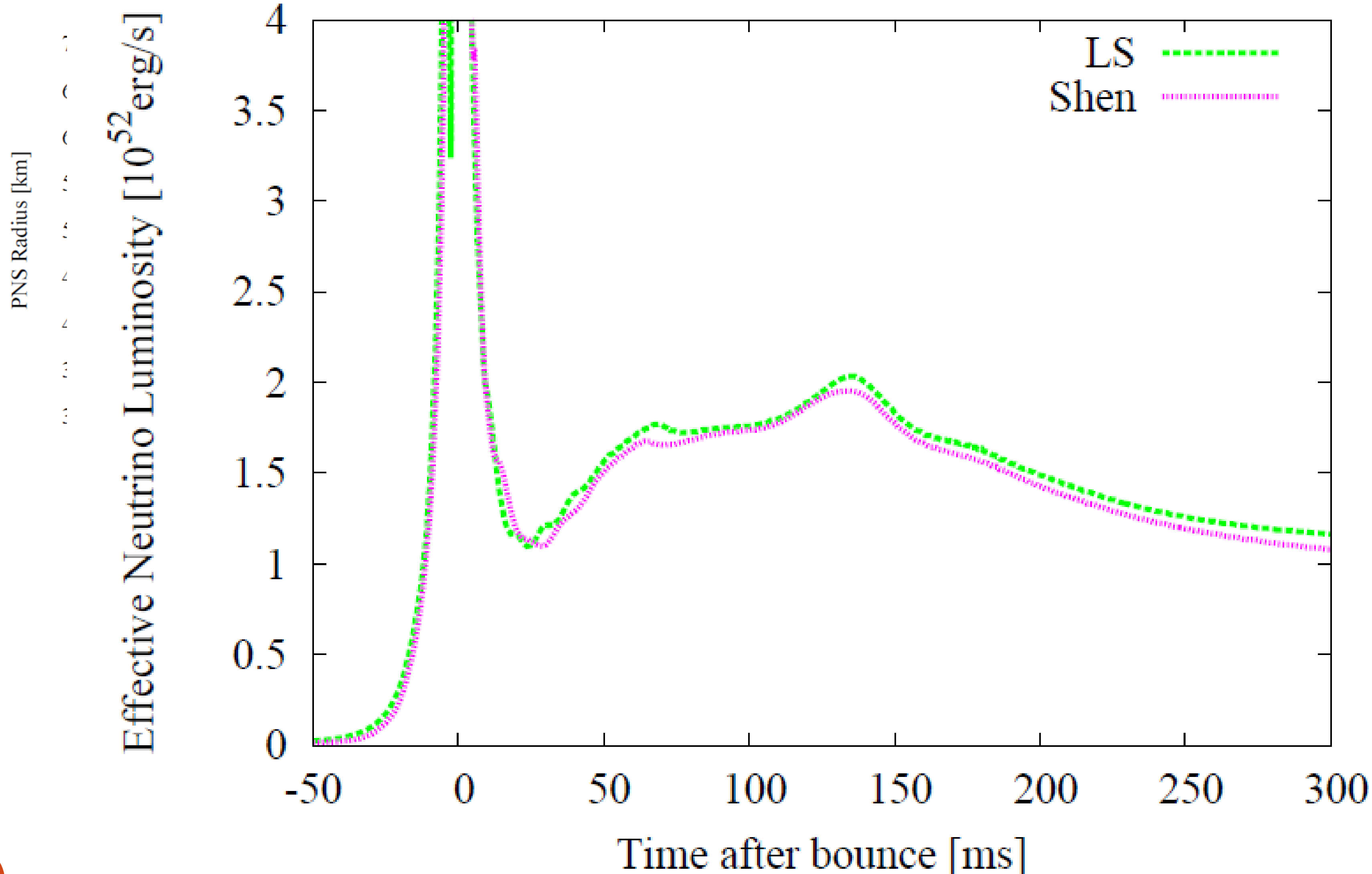


LS(K220):Soft EOS => rapidly shrink => Large L_ν

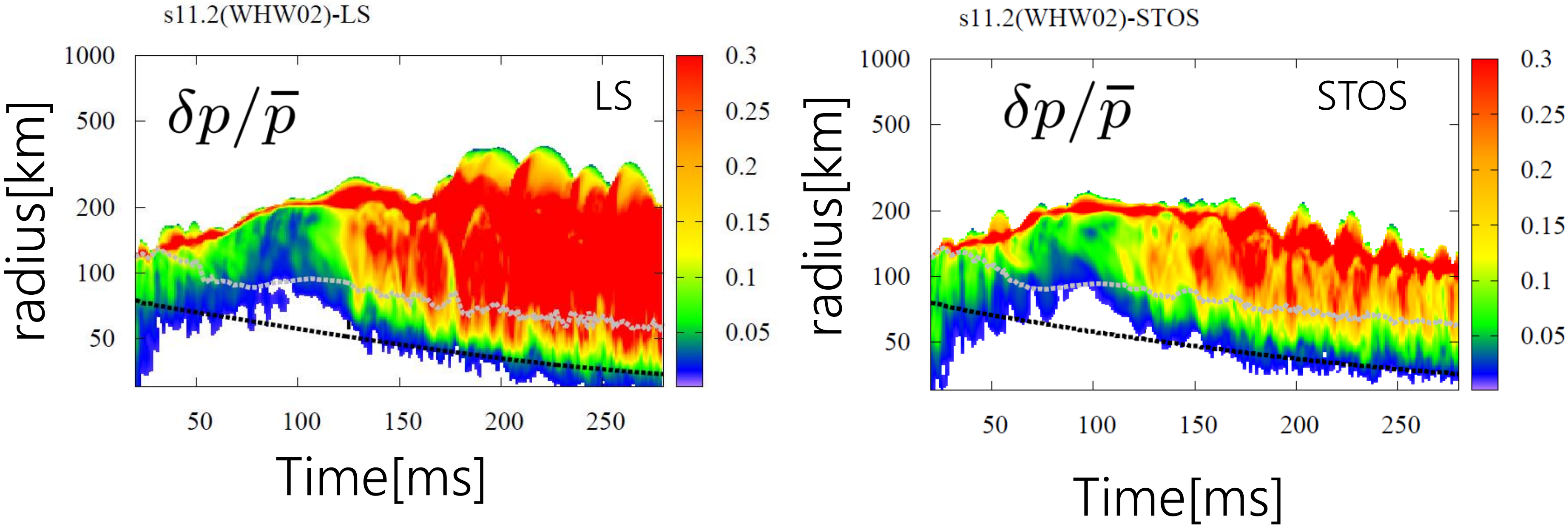
Shen: Stiff EOS => slowly shrink => small L_ν

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

Neutrino Luminosity



Sonic Wave

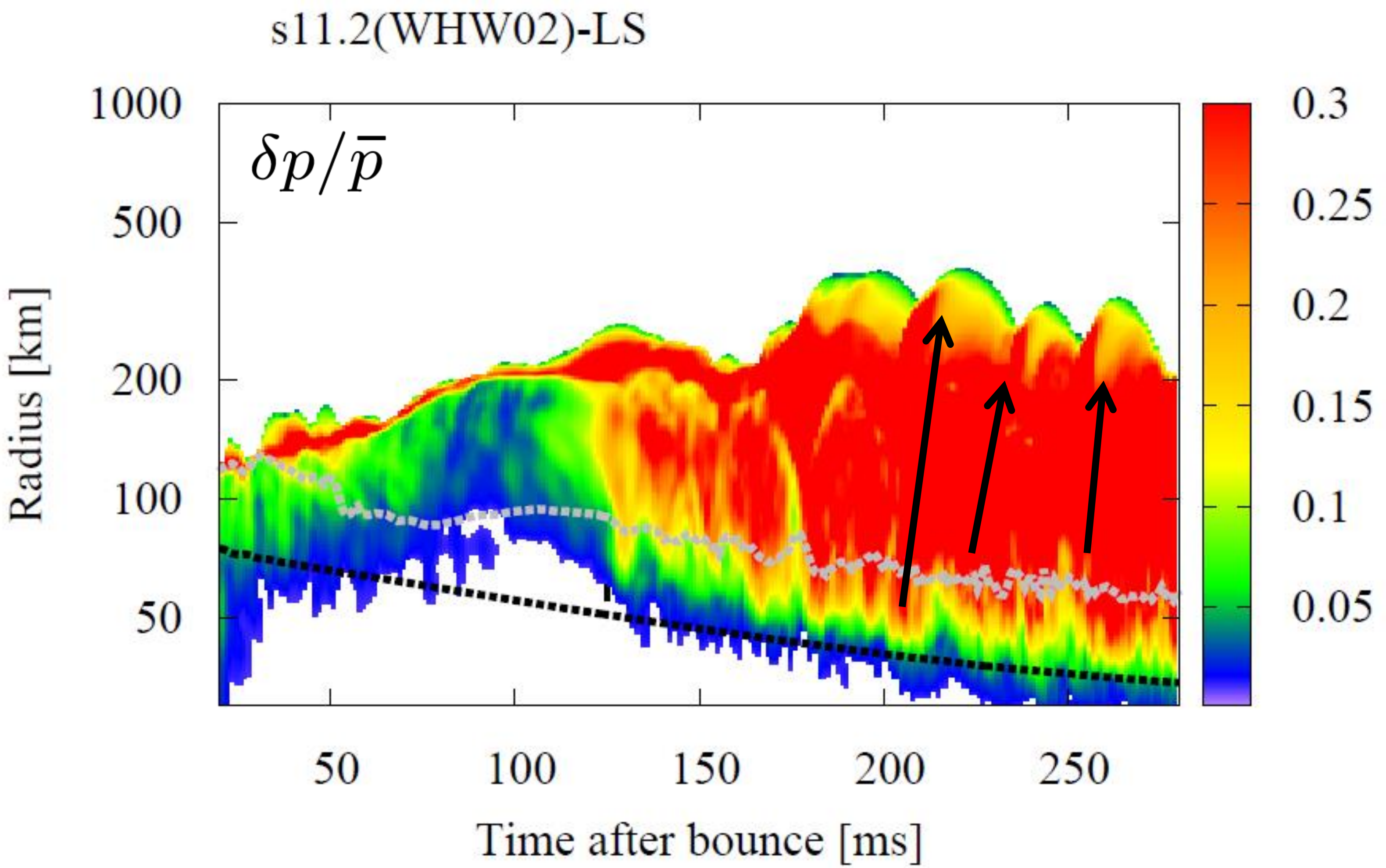


Gray: gain radius, black PNS radius

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

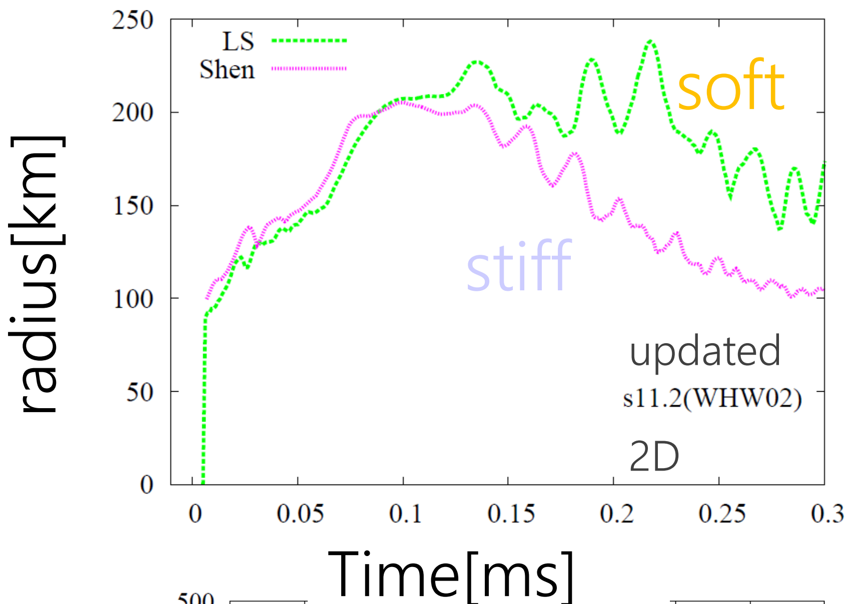
(Couch 2013 and Suwa+ 2013 show similar results.)

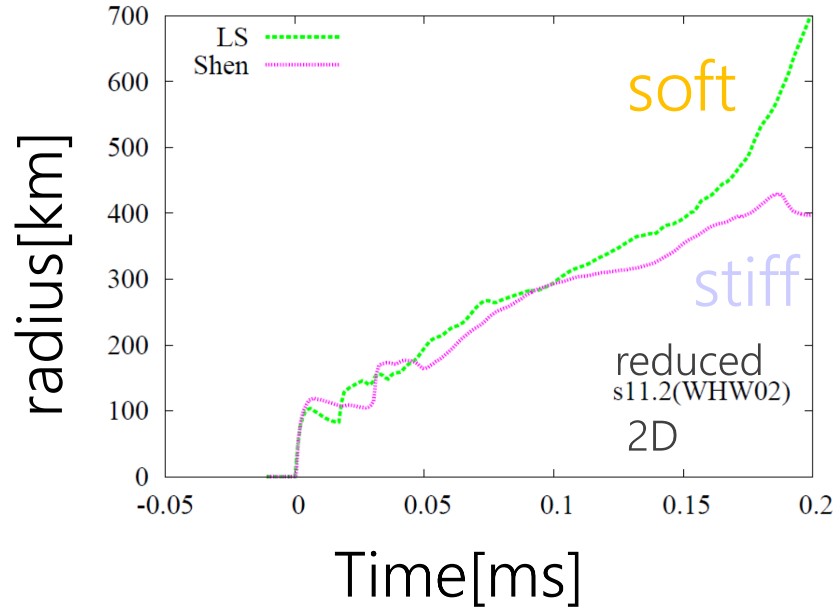
Sonic Wave

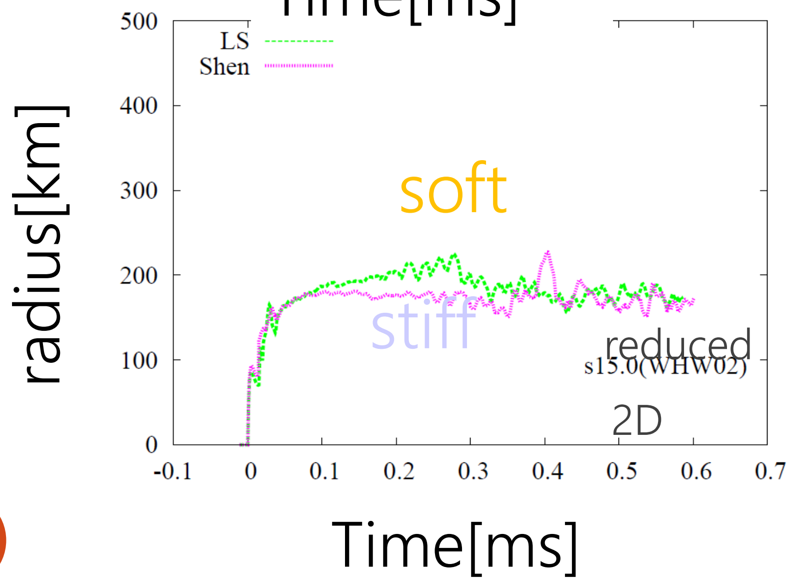


Gray: gain radius, black PNS radius

Evolution of the shock







Softer EOS shows larger shock radius.

Plan

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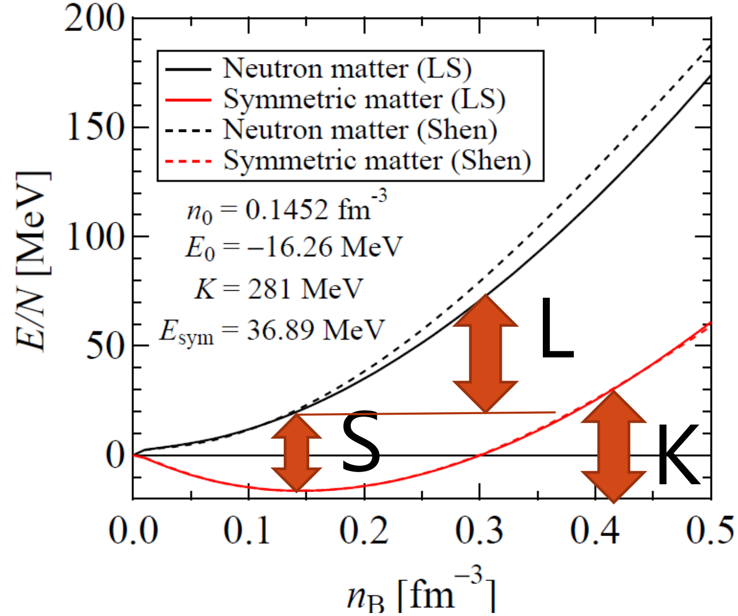
Many theories for EOS

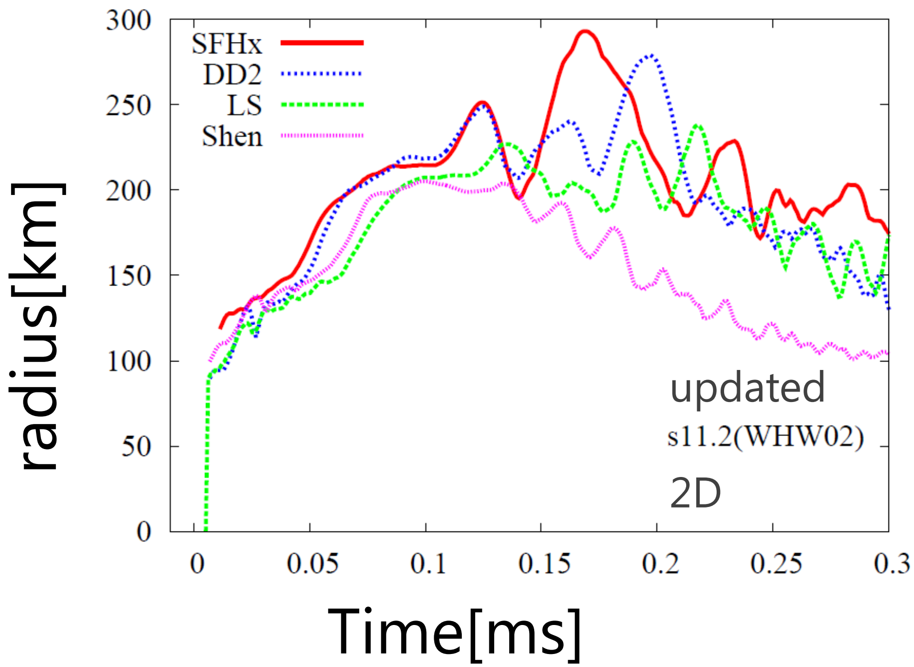


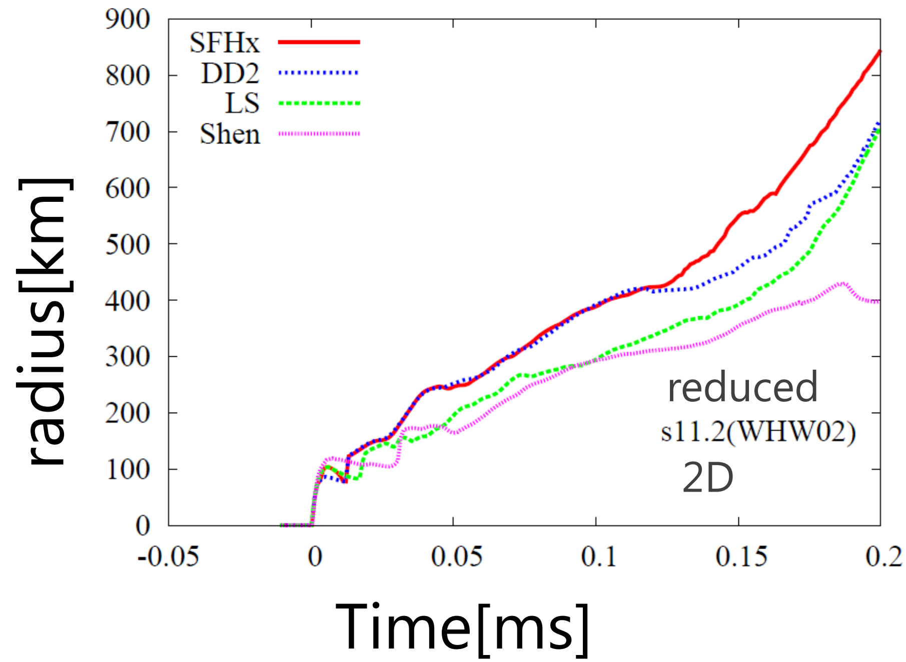
$$p = n^2 \frac{\partial (E/N)}{\partial n} \, .$$

Fisher+2014

EOS	n_0 [fm^{-3}]	E_0 [MeV]	K [MeV]	S [MeV]	L [MeV]	$R_{1.4}$ [km]	M_{max} [$M_\odot$]
SFHo	0.1583	16.19	245	31.57	47.10	11.89	2.06
SFHx	0.1602	16.16	238	28.67	23.18	11.99	2.13
HS(TM1)	0.1455	16.31	281	36.95	110.99	14.47	2.21
HS(TMA)	0.1472	16.03	318	30.66	90.14	13.85	2.02
HS(FSUgold)	0.1482	16.27	229	32.56	60.43	12.55	1.74
HS(DD2)	0.1491	16.02	243	31.67	55.04	13.22	2.42
HS(IUFSU)	0.1546	16.39	231	31.29	47.20	12.68	1.95
HS(NL3)	0.1482	16.24	272	37.39	118.49	14.77	2.79
STOS(TM1)	0.1452	16.26	281	36.89	110.79	14.50	2.22
LS (180)	0.1550	16.00	180	28.61	73.82	12.16	1.84
LS (220)	0.1550	16.00	220	28.61	73.82	12.67	2.05
Exp.	~ 0.15	~ 16	240 ± 10[a]	29.0–32.7[b]	40.5–61.9[c]	10.4–12.9[c]	$\gtrsim 2.0$[d],[e]

New EOS





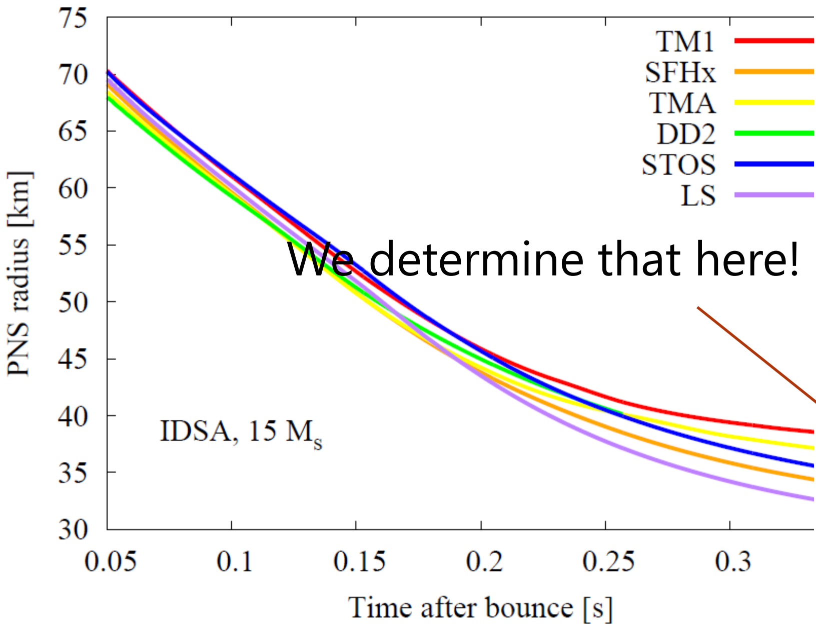
Again, softer EOS shows larger shock radius.

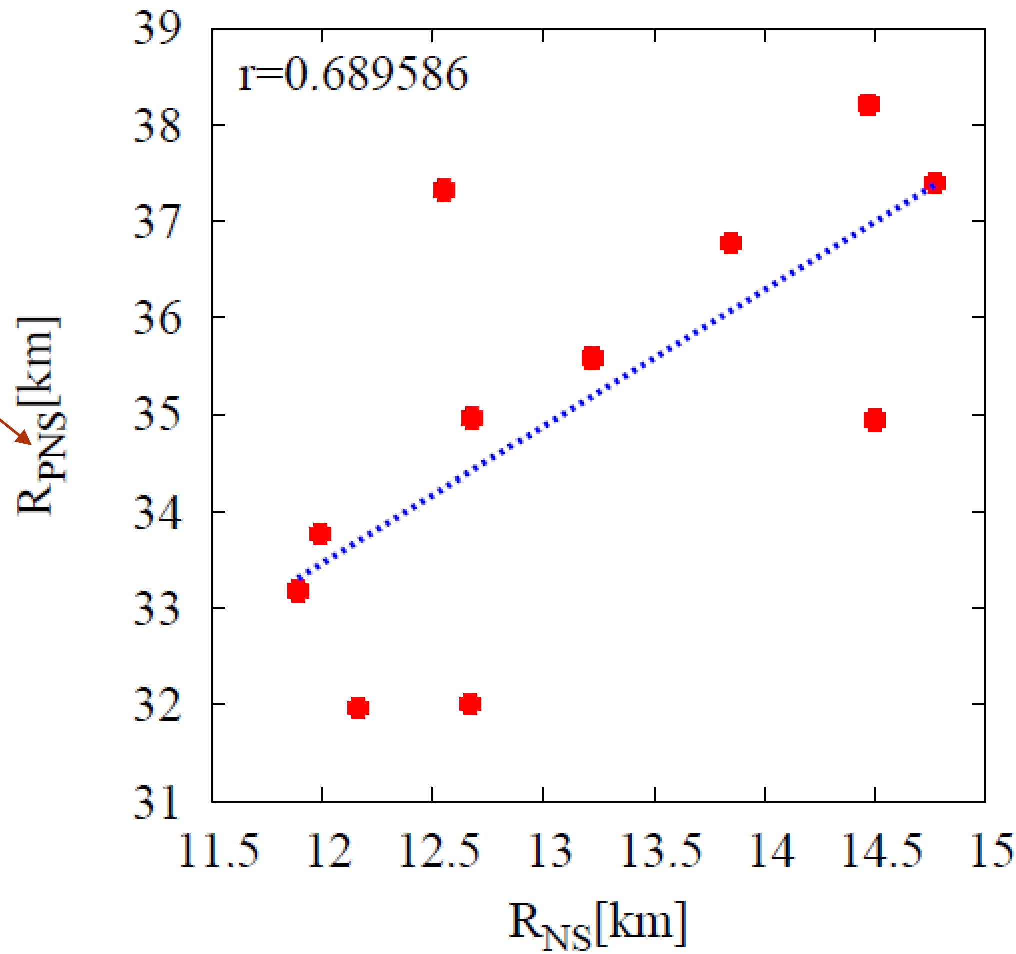
SFHx and DD2: Multi species of heavy nuclei is included.

SFHx and DD2 > LS and Shen.

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

NS radius vs PNS radius





Takiwaki in p

PNS radius:
TM1 > TMA ~ DD2> SFHx
STOS > LS

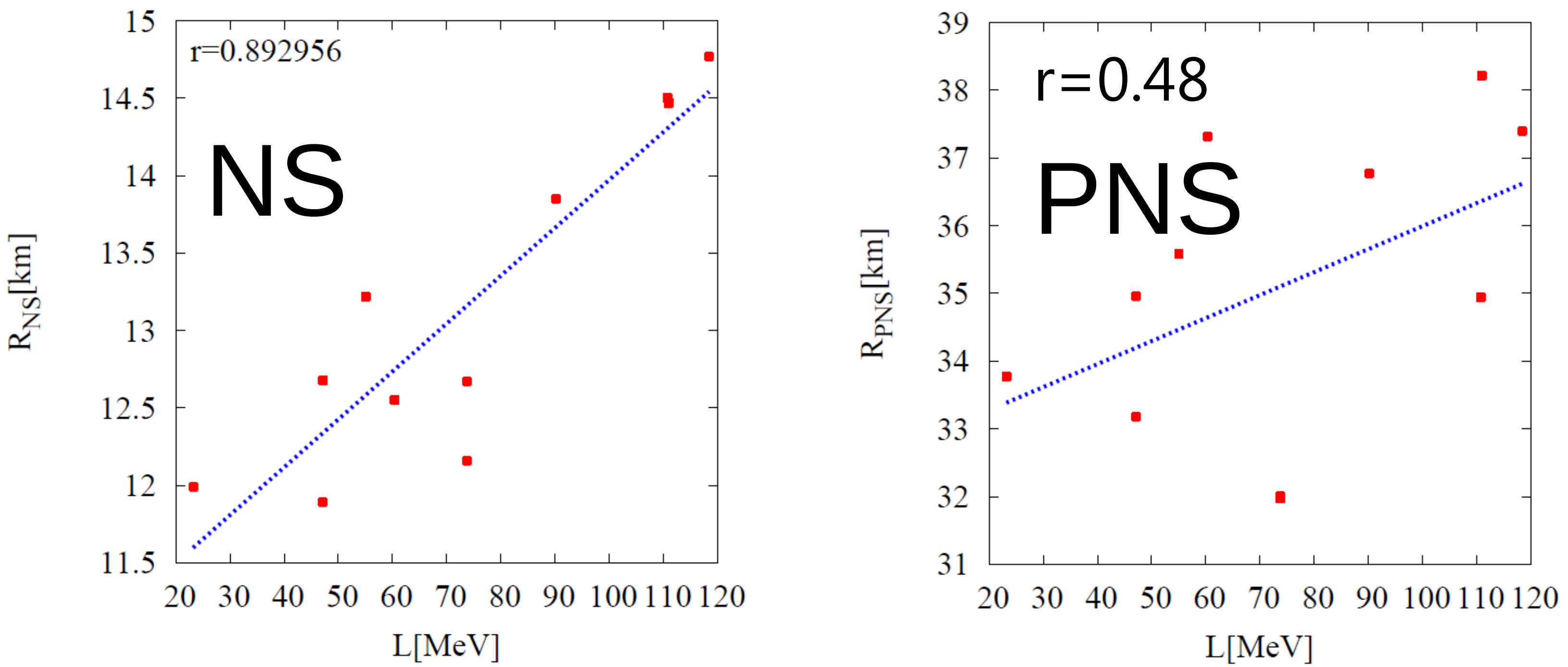
PNS radius is "roughly" predicted by the NS radius at zero-temperature.

Towards more general understanding

In SNe simulations, the radius of PNS is focused as the key ingredients for successful explosion.

Can we predict the radius of PNS from the parameters of nuclear physics.

What parameter determine PNS radius

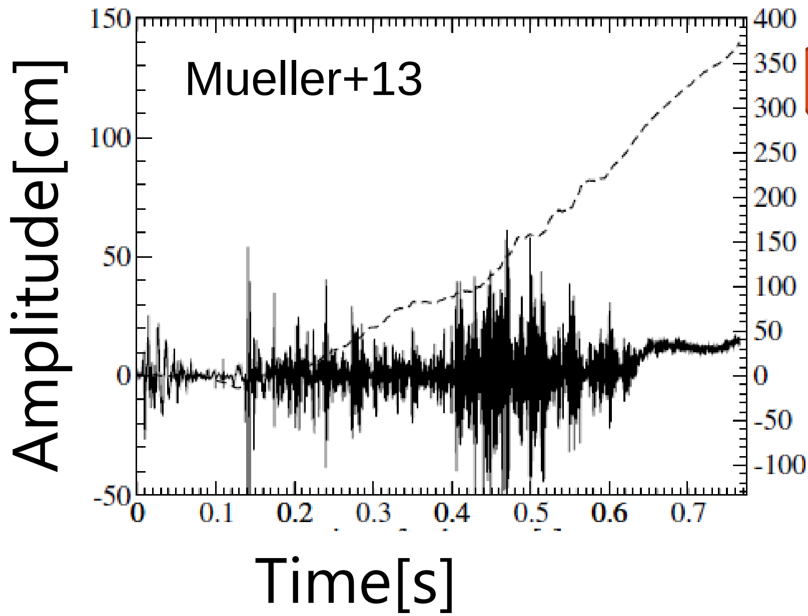


Radius of NS (T~0 and Y_e~0) is determine by L. (or $(KL^2)^{1/3}$)

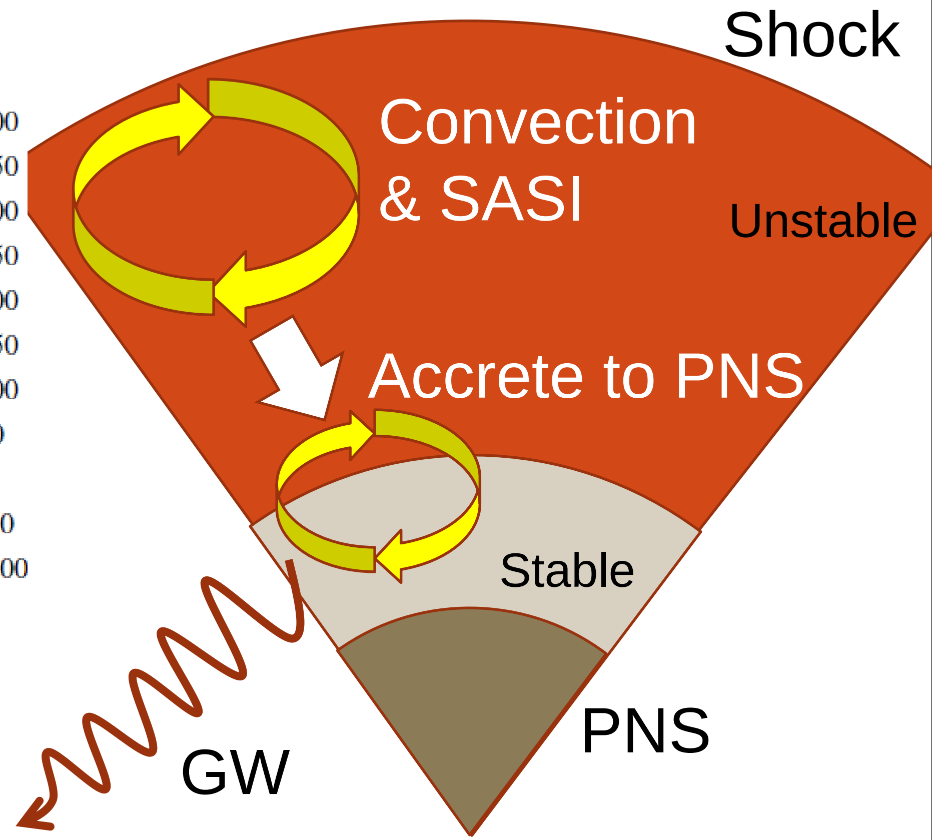
Radius of PNS is not determine by L.
S and K have stronger correlation to PNS.
r=0.71 for S. r= 0.69 for K.

Gravitational Wave from Convection & SASI

Activity of convection and SASI is printed in the waveform of GW indirectly.



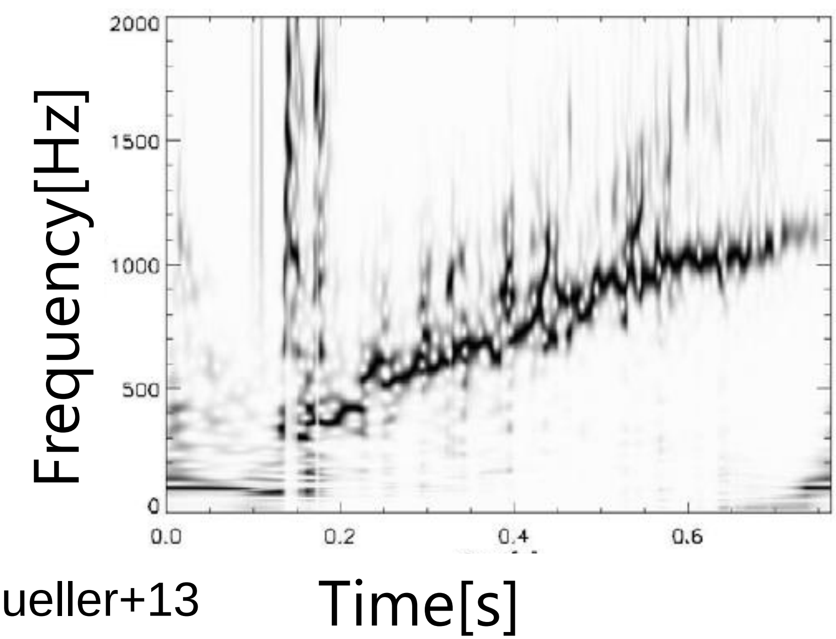
Convection & SASI



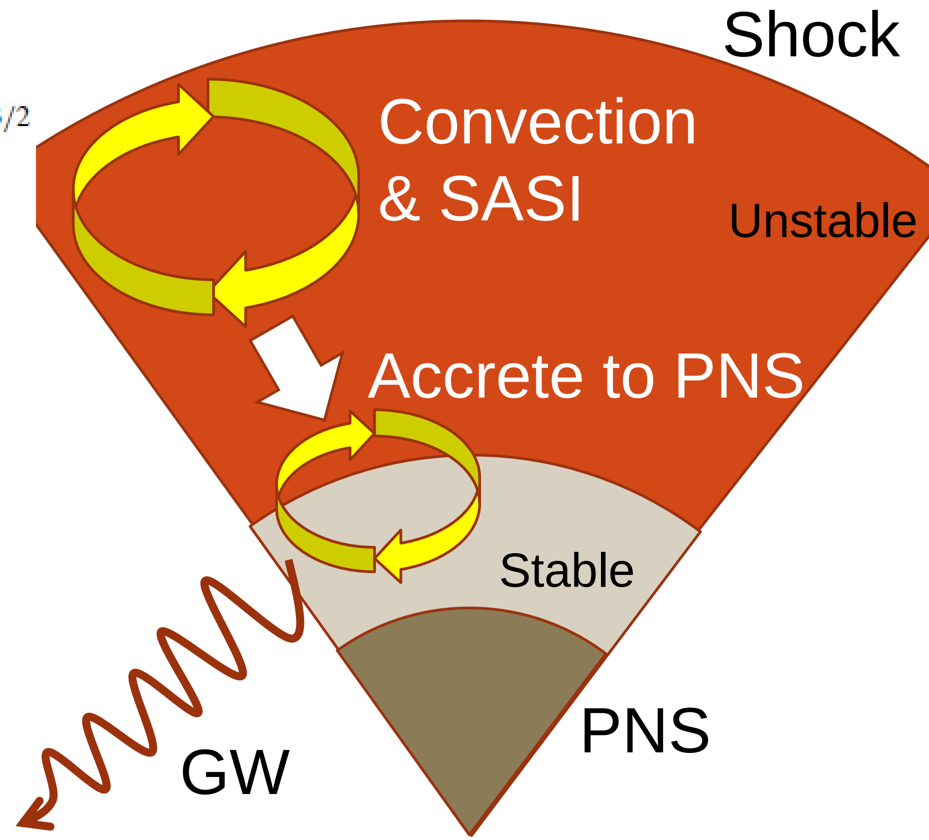
Gravitational Wave from Convection

Mass, radius and temperature of PNS determine the typical frequency.

$$f_p = \frac{N}{2\pi} = \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{\frac{(\Gamma-1)m_n}{\Gamma k_b T}}\left(1-\frac{GM}{Rc^2}\right)^{3/2}$$



Mueller+13

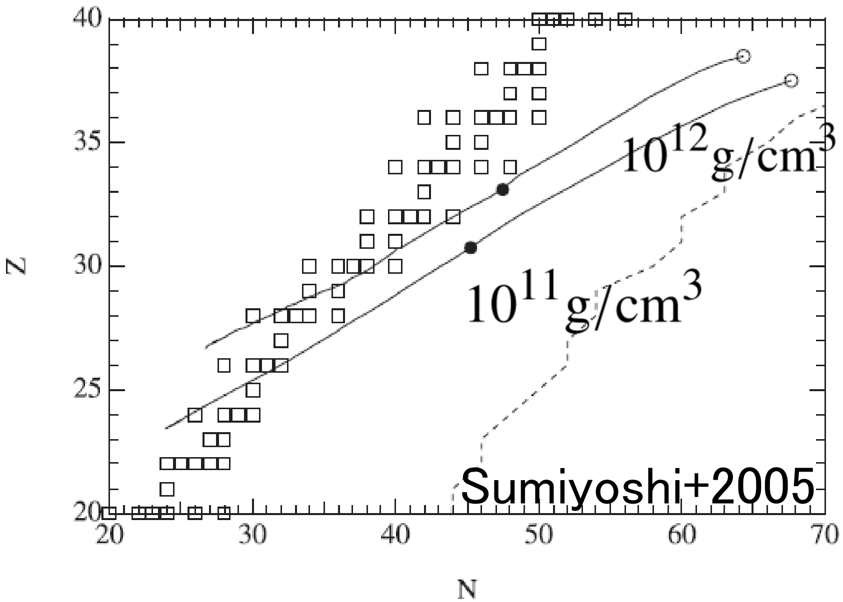


The results of my 3D calculation is coming soon.

Summary

- Multi-D simulations that naturally employ convection. Those are promising, but the results are sensitive to the input physics.
- Neutrino reaction rates significantly affects 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.
- Radius of PNS are roughly correlated with S and K. The result is not fully interpreted and should be fully investigated urgently.

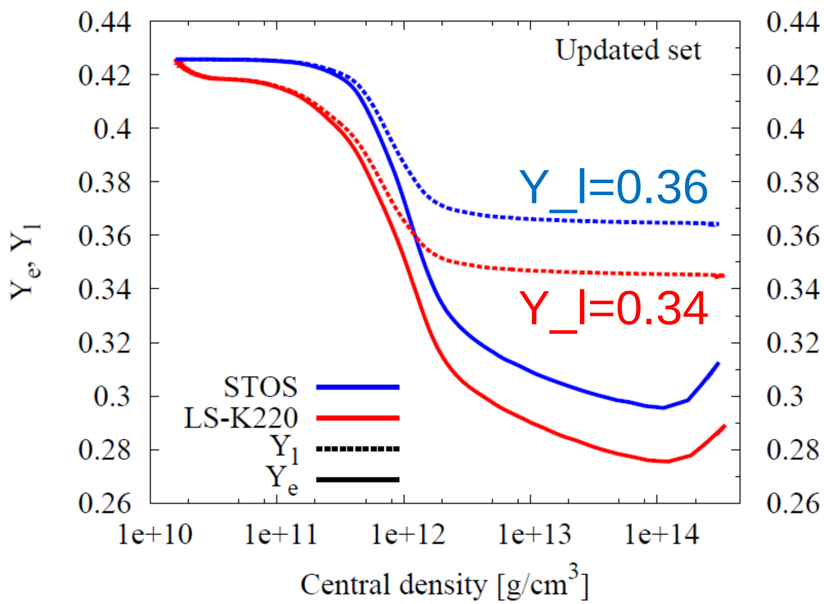
EOS dependence on Y_l

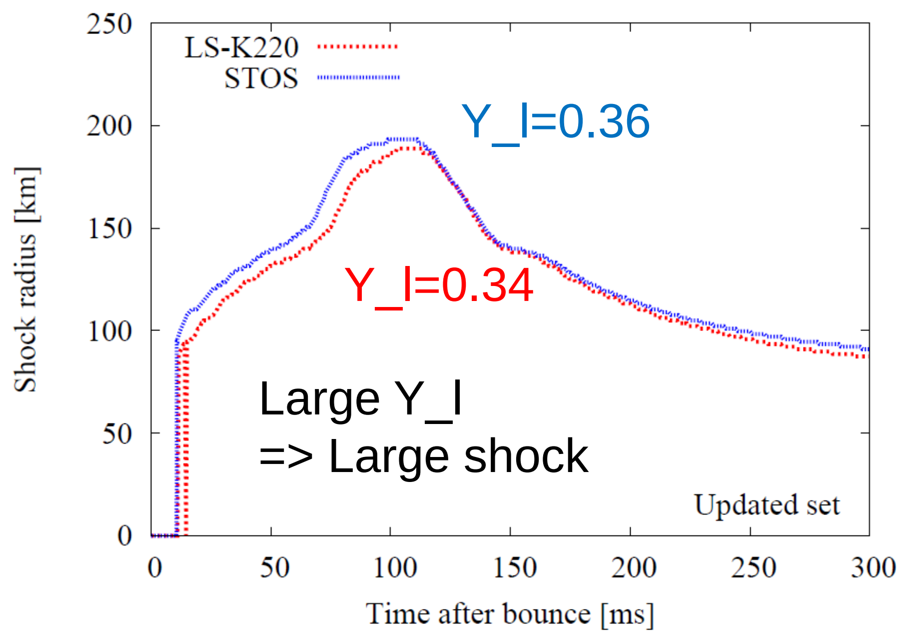


EOS changes the species of heavy nuclei.

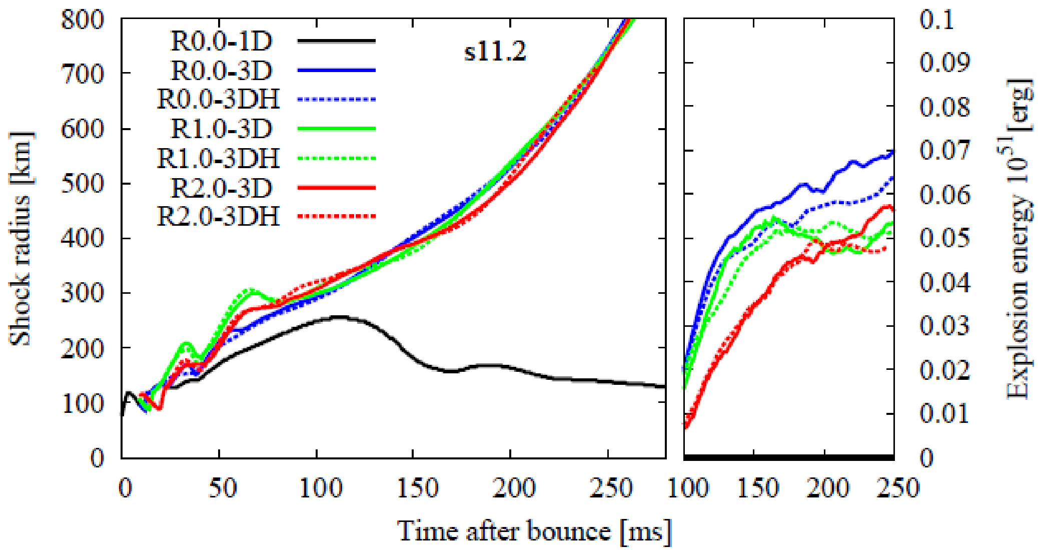
$$A + e^- \rightarrow A' + \nu_e$$

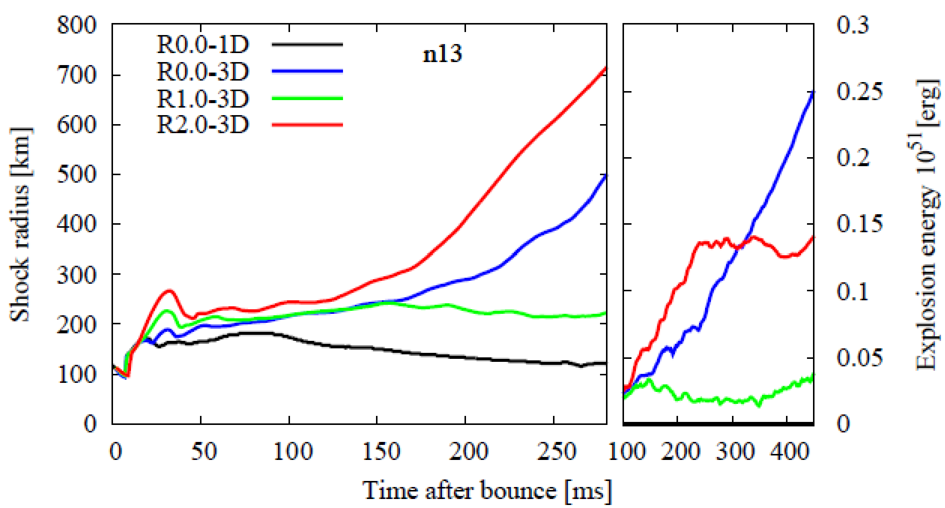
Electron capture rate significantly depends on the species of the nuclei.



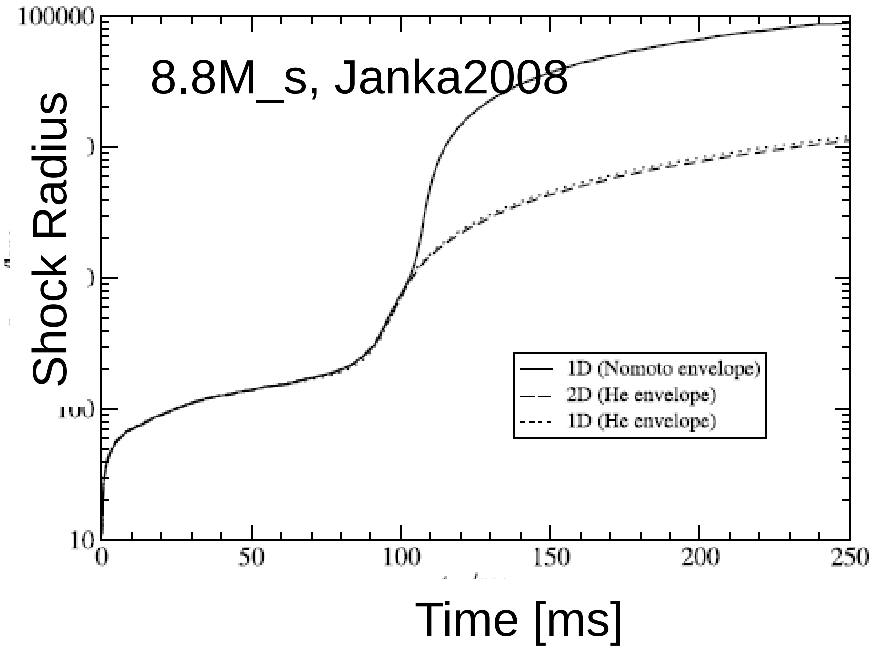


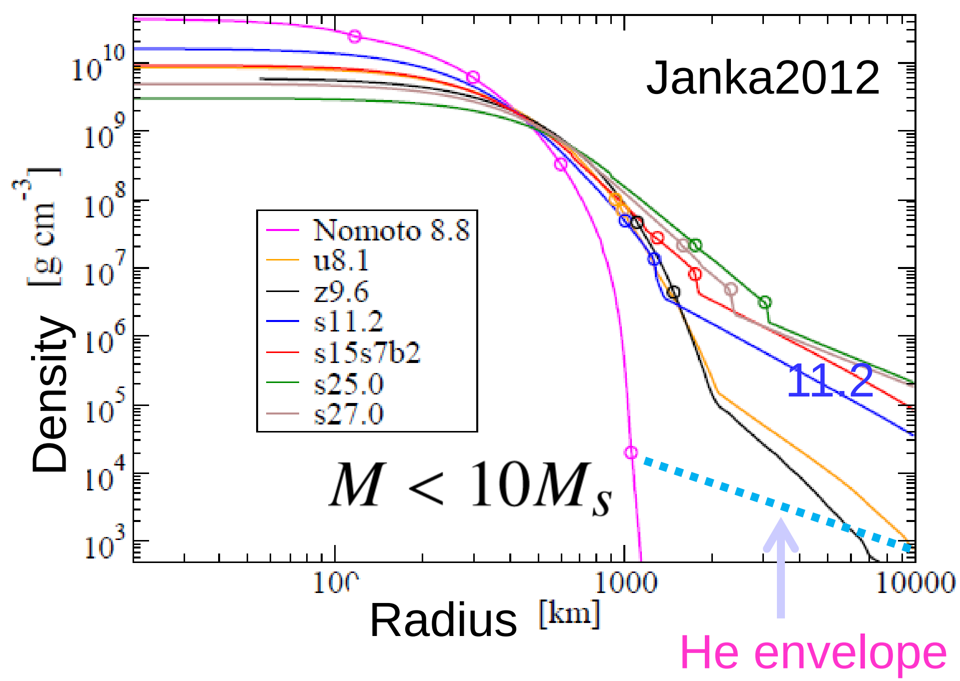
Averaged shock radius and Exp. Energy





Pure ν heating

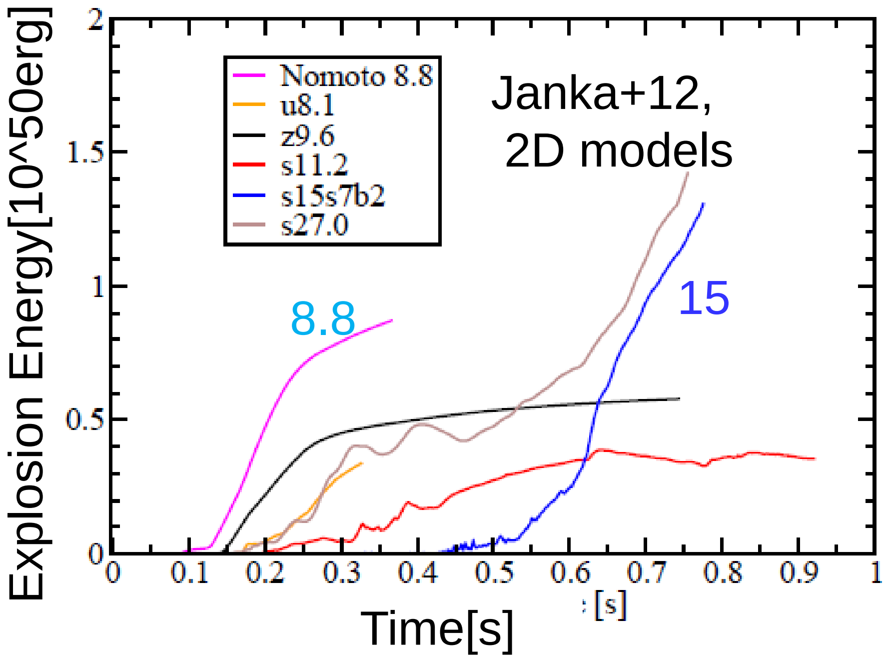


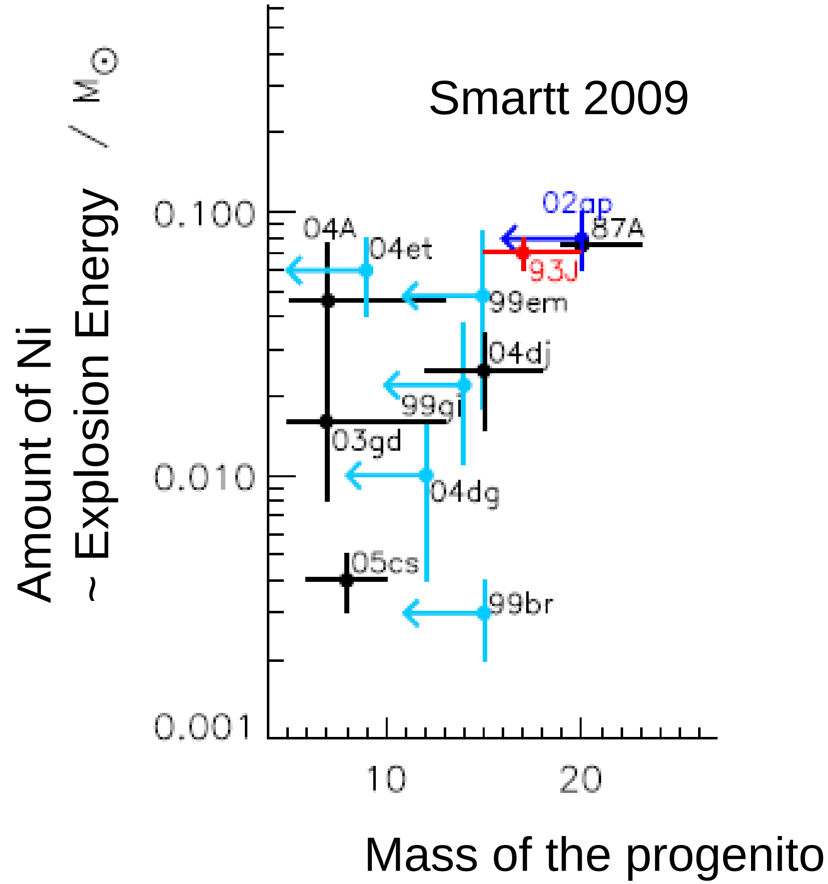


Easy shock revival

Dilute outer layor

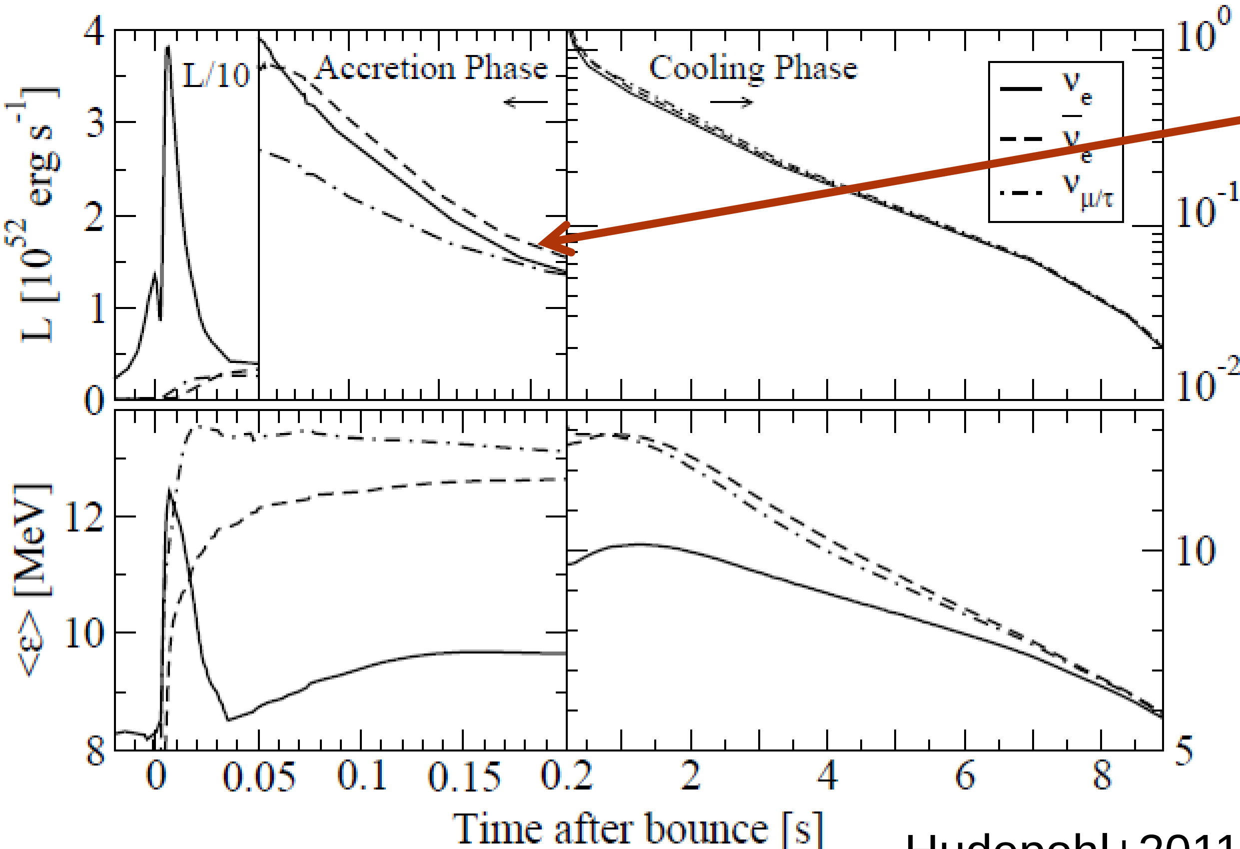
Pure ν heating





軽い親星の爆発は、爆発エネルギーが典型的に
~10^50 ergで普通の超新星の1/10程度。
観測のトレンドとは合っている(ような？)

Pure ν heating(１Ｄでも爆発)



200ms
このモデルだと
1.5x10^52erg/s
15M_sだと
5x10^52erg/s

Hudepohl+2011

バウンス時は他と似たようなものだが、accretion phase以降でν光度が低い。後期までνのライトカーブをとることで、他と区別可能だと思われる。