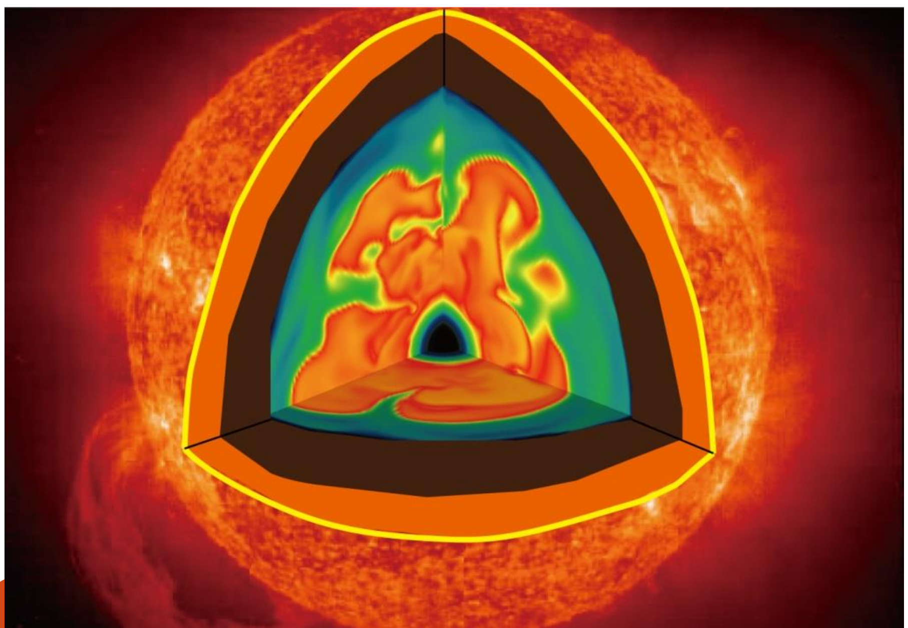
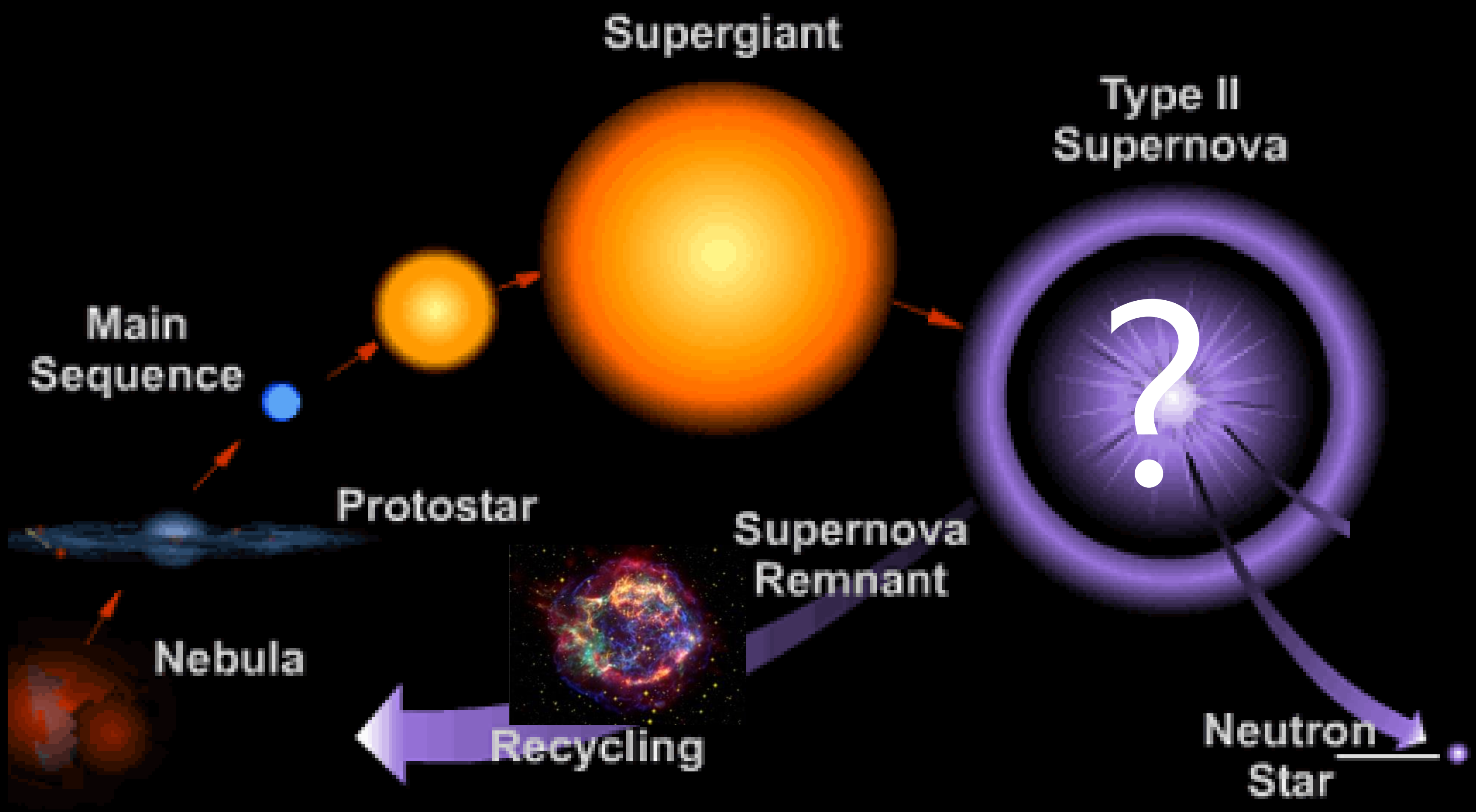
2015/08/18
MICRA2015

How supernova simulations are affected by input physics



Tomoya Takiwaki
(RIKEN)
Kei Kotake(Fukuoka)
Yudai Suwa(Kyoto/MPA)

Supernovae: the death of the star



Q:How does the explosion occur?

Important gradients for SNe Simulations

- Gravity (Newtonian/Phenomenological GR/CFC GR/GR)
- Neutrino Reaction and Transport
- Equation of State
- Turbulent and Instability(1D/2D/3D)
- Progenitor

Important gradients for SNe Simulations

- ~~Gravity (Newtonian/Phenomenological GR/CFC GR/GR)~~
- ~~Neutrino Reactio~~
- ~~Equation of State~~

=> Deep discussion will be given in Friday.

- Turbulent and instability(1D/2D/3D)
- Progenitor

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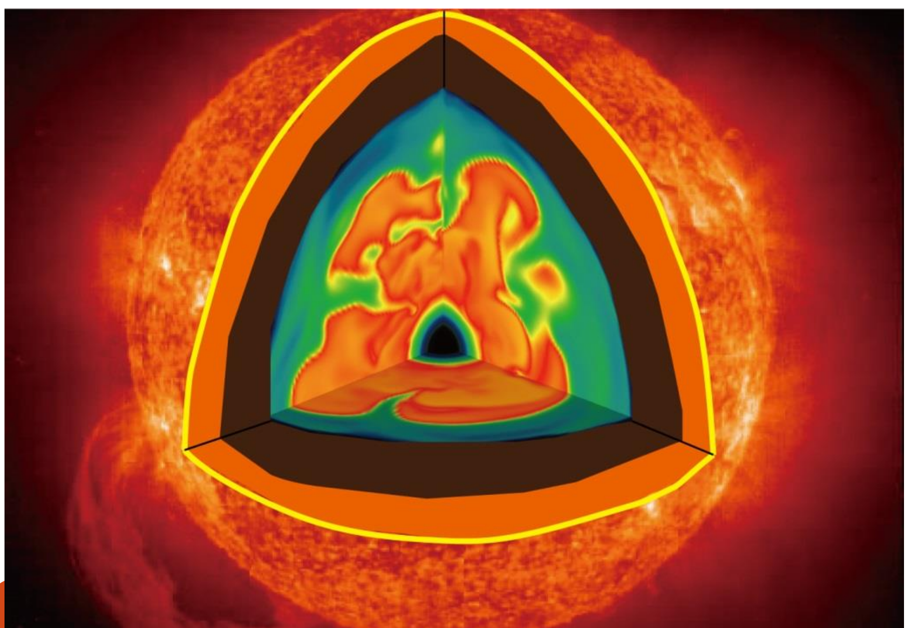
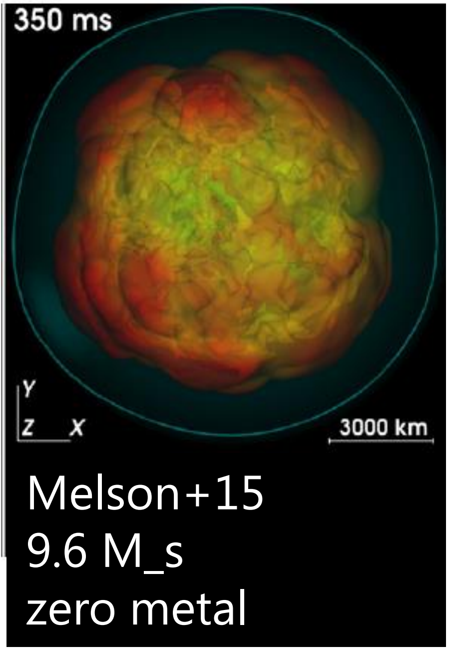
How supernova simulations are affected by “initial condition”



Tomoya Takiwaki
(RIKEN)
Kei Kotake(Fukuoka)
Yudai Suwa(Kyoto/MPA)

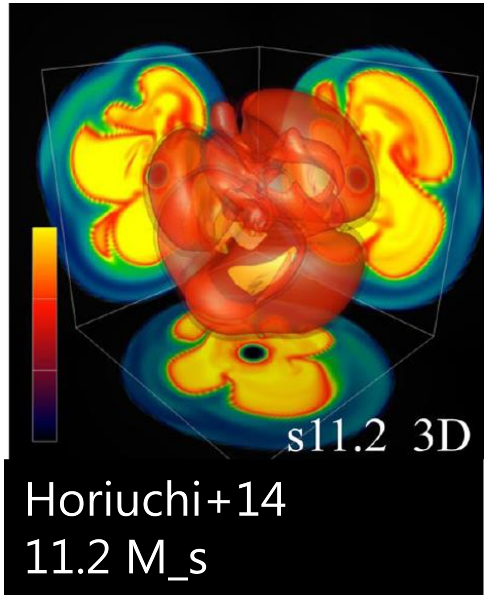
Current Status of SNe Mechanism

$M < 10M_s$



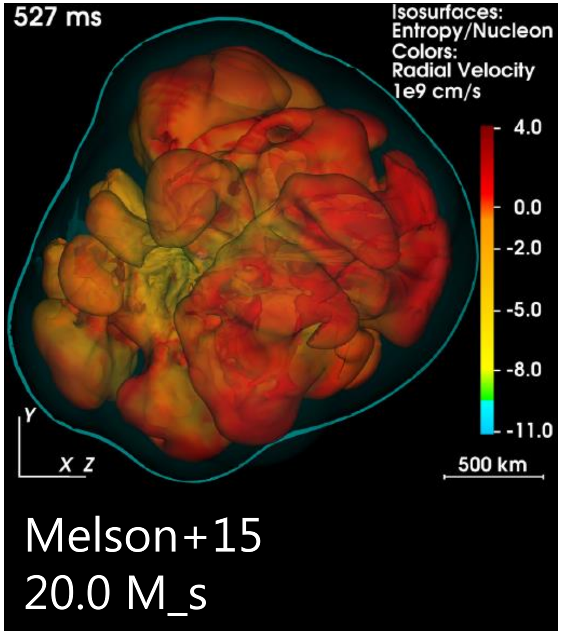
Dilute outer layer
Only ν-heating

$M < 15M_s$



ν-heating and convection

$M < 40M_s$



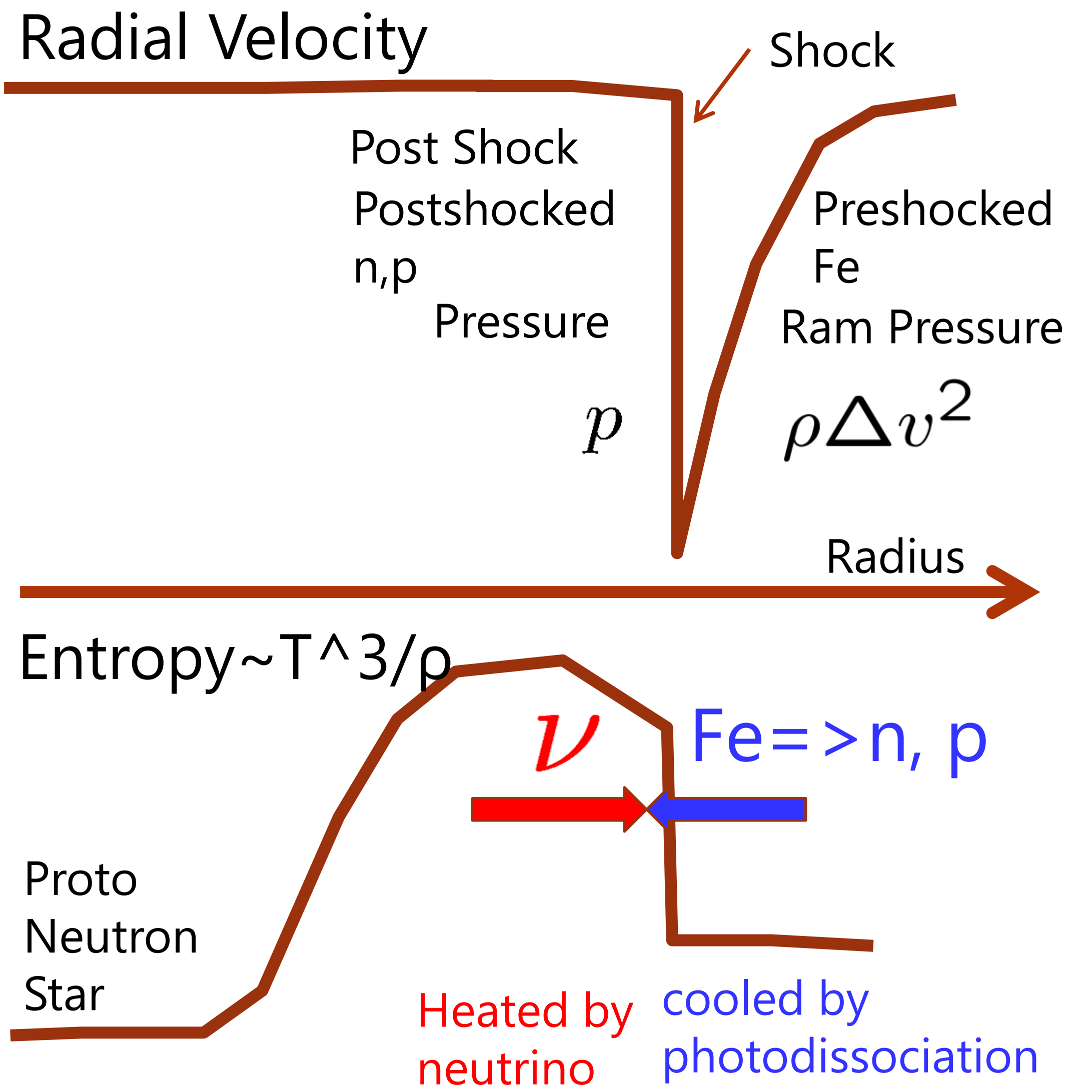
ν-heating, convection and SASI

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

This slide contains my opinion that are not strictly confirmed.

Typical 1D simulation

Key aspects of Neutrino Mechanism



The shock is stalling.
Pressure inside and ram pressure out side balances.

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

RHS is determined by stellar structure(density profile).

LHS is determined by two ingredients.

(1) Photodissociation

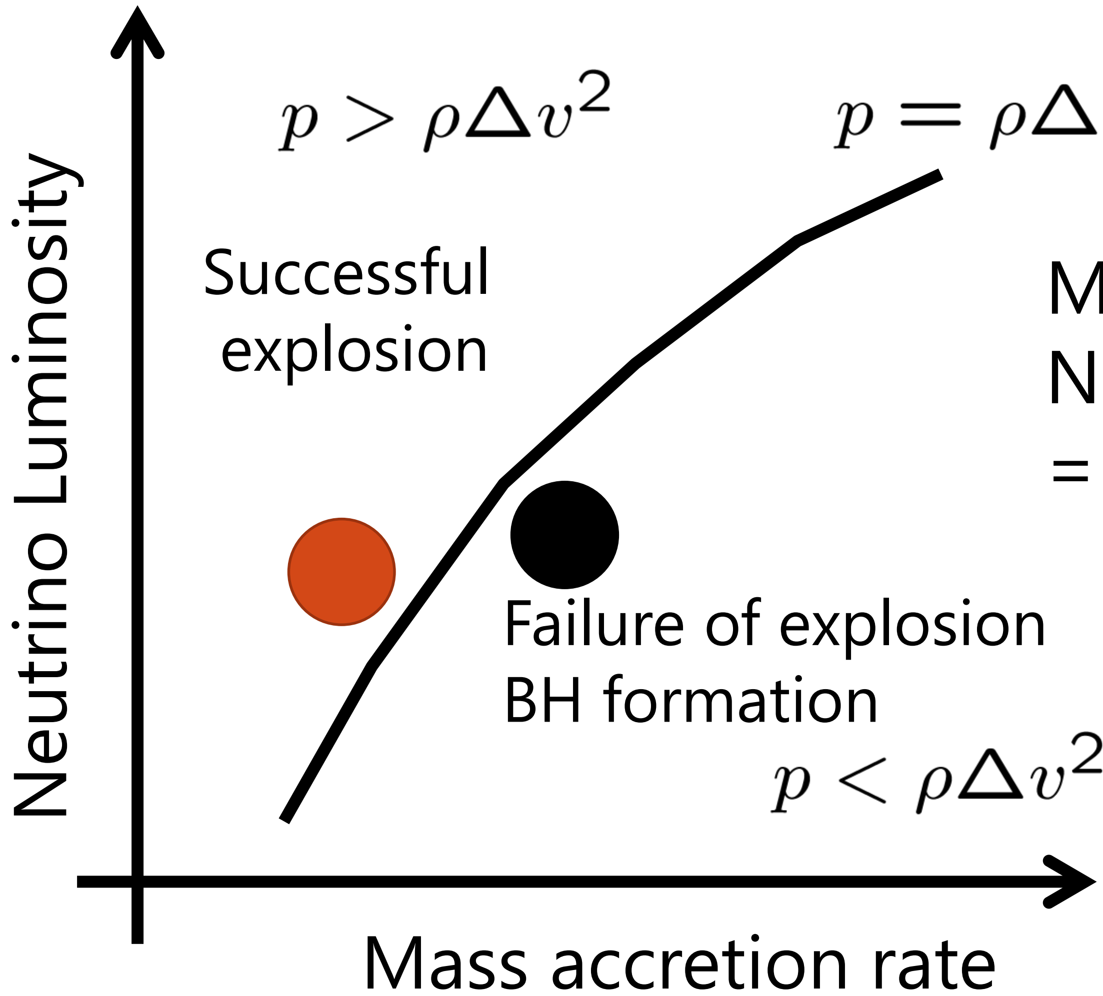
$$\mathrm{Fe} \rightarrow 30\mathrm{n} + 26\mathrm{p} - \Delta Q$$

(2) Neutrino Heating

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

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

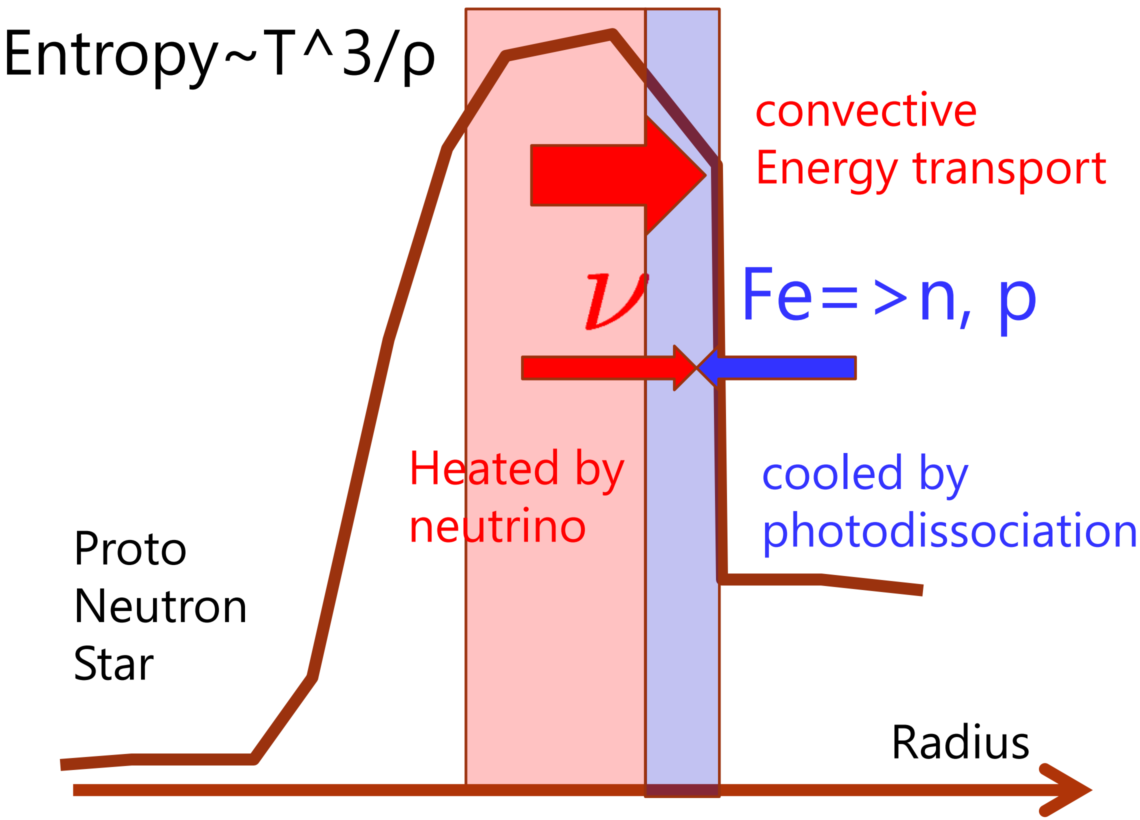
Mass accretion vs neutrino heating



Mass accretion rate vs Neutrino Luminosity
=>critical curve

From 1D to 3D

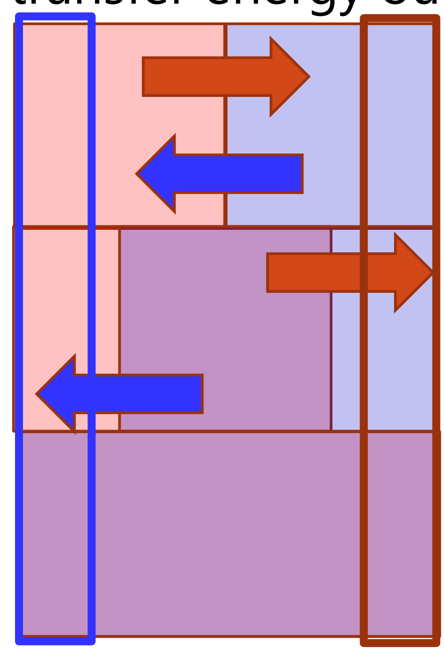
Key aspects of Neutrino Mechanism



Negative entropy gradient leads Rayleigh-Taylor instability

(Cold heavy matter is put over Hot light matter)

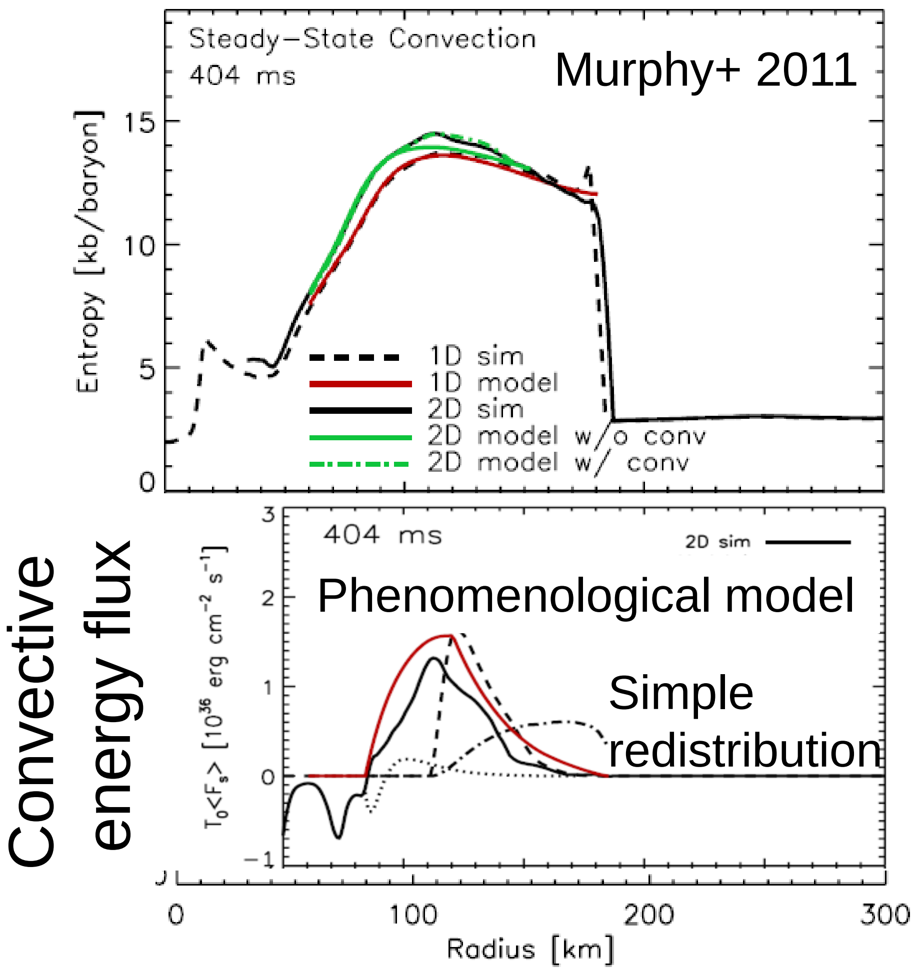
Rayleigh-Taylor convection transfer energy outward.



Cooler than the initial state but ν heat is active

Hotter than the initial state

Question on ν −driven convection

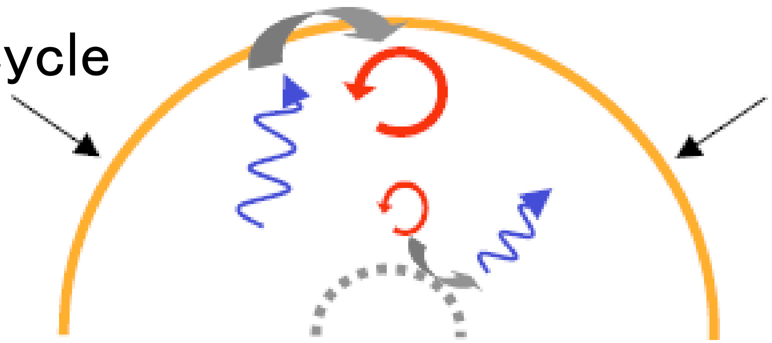


- Do we reproduce real energy transport?
- Not obeying simple redistribution of entropy. Effect of ν-heating should be considered.
- Is our resolution and hydro-method enough to capture the feature correctly?

=> see David Radice's talk

SASI (Standing accretion shock instability)

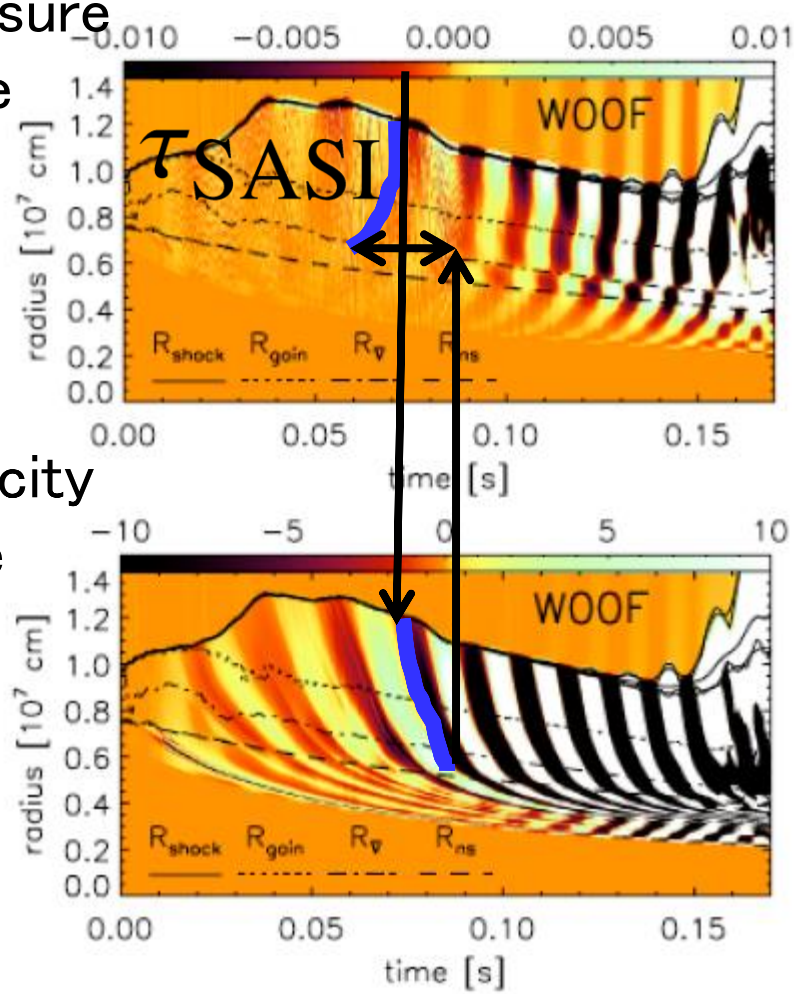
Advective–acoustic cycle



Foglizzo's slides

Pressure Wave

Vorticity Wave



Standing Accretion Shock Instability(SASI)

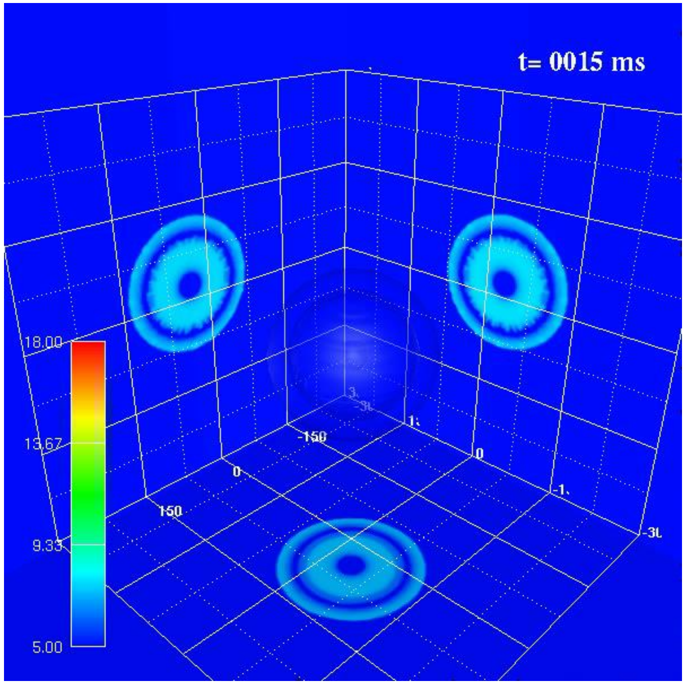
$$\tau_{\mathrm{SASI}} \sim R_{\mathrm{sh}}/v_r$$

$\dot{M}\uparrow, v_r\uparrow, \tau_{\mathrm{SASI}}$ Rapid!

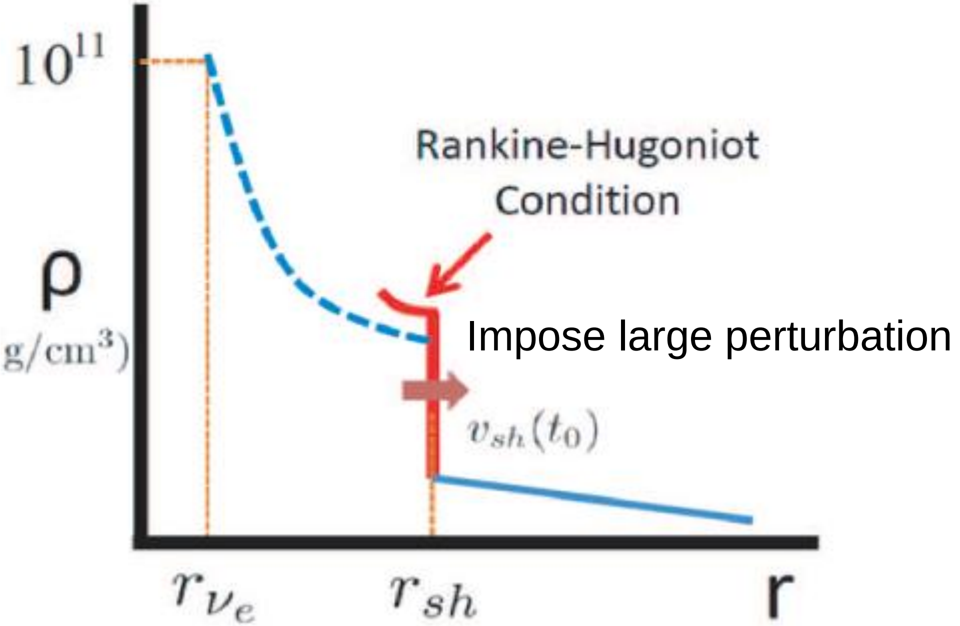
Scheck+ 2008

S A S I

2D Axi-symmetric



Takiwaki+2012

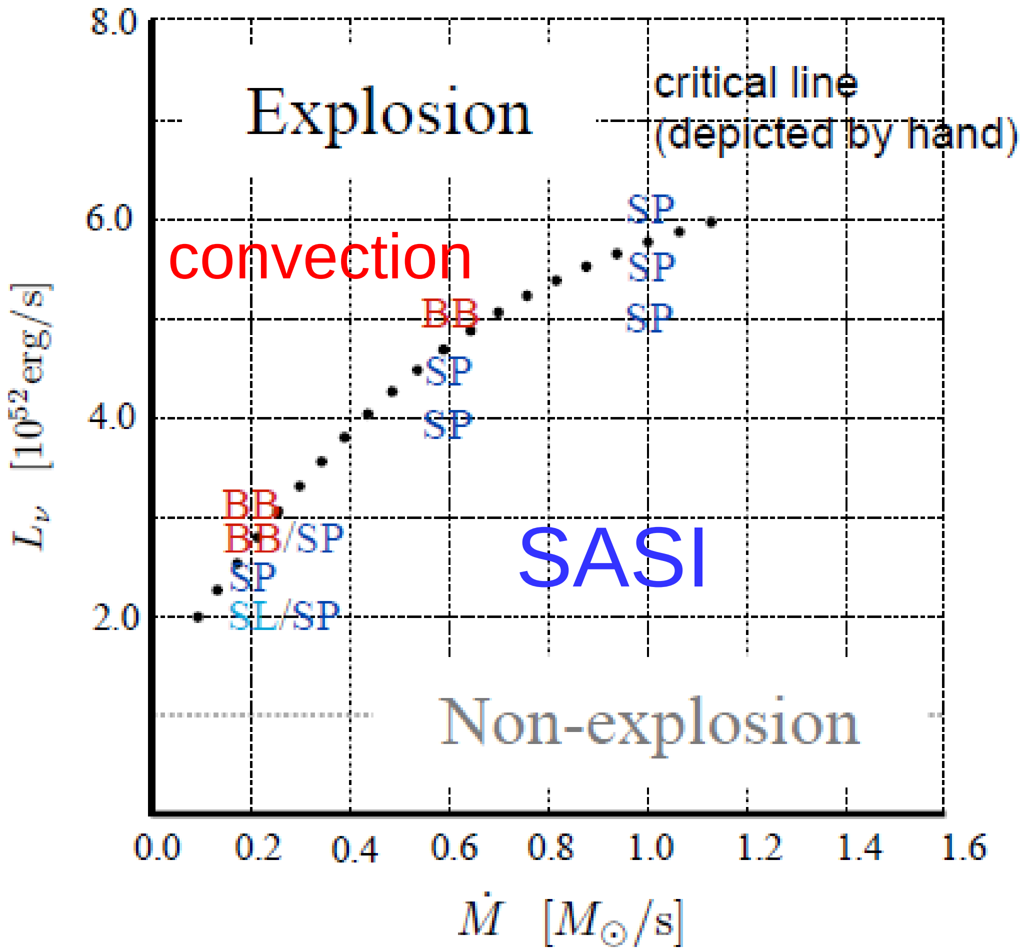


$$f_{crit} \sim 0.8 \times (M_{in}/1.4 M_{\odot}) \times \{1 - (r_{sh}/10^8 \mathrm{cm})\}$$

Nagakura+2012

SASI focus energy at one direction!
~70% of increase in total pressure can revive the shock.

Dominant instability in Mdot−L plane



Iwakami+ 2013

=> Light progenitor

Neutrino driven convection grows under low mass accretion rate.

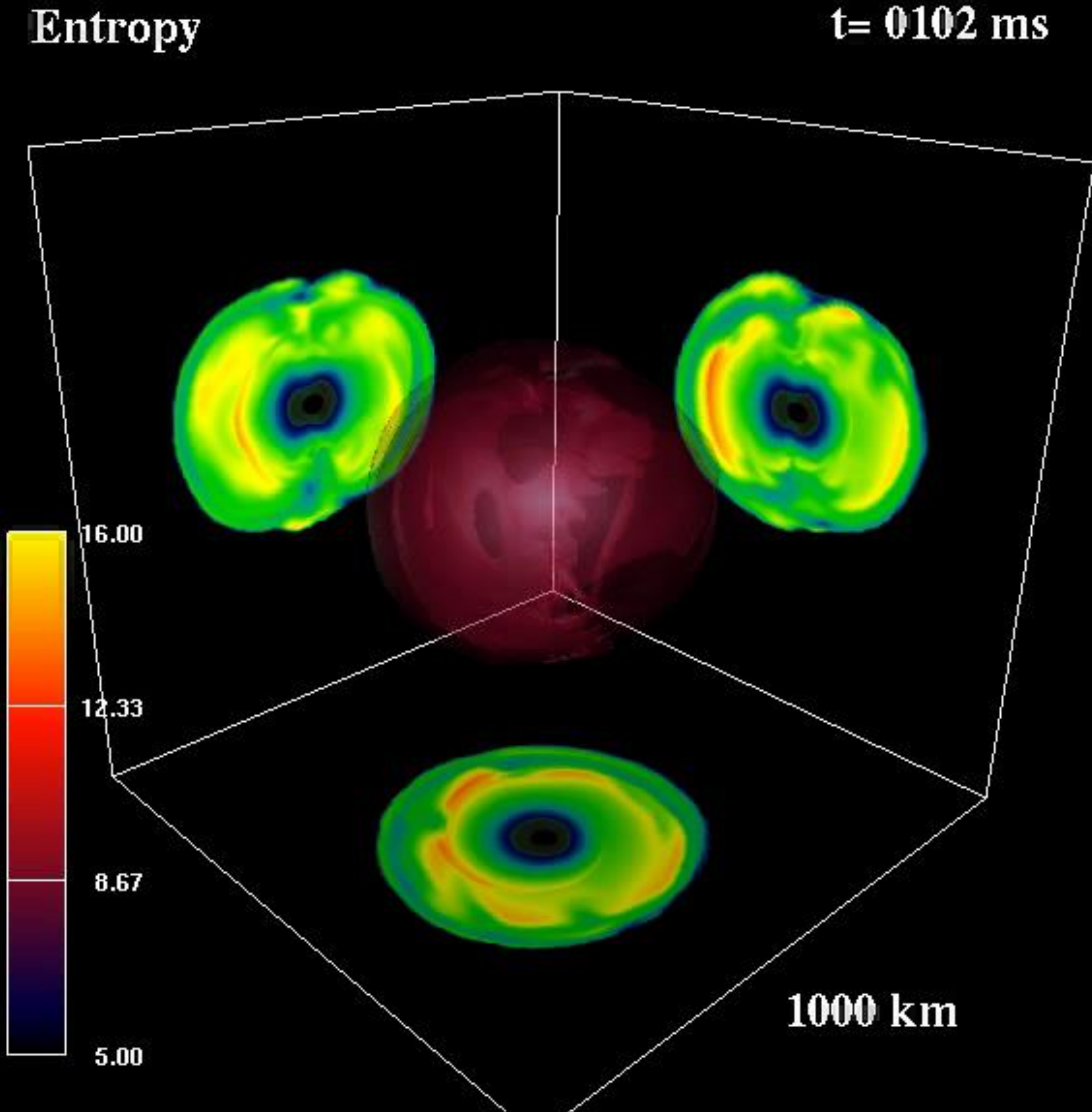
=> Heavy progenitor

SASI grows under high mass accretion rate.

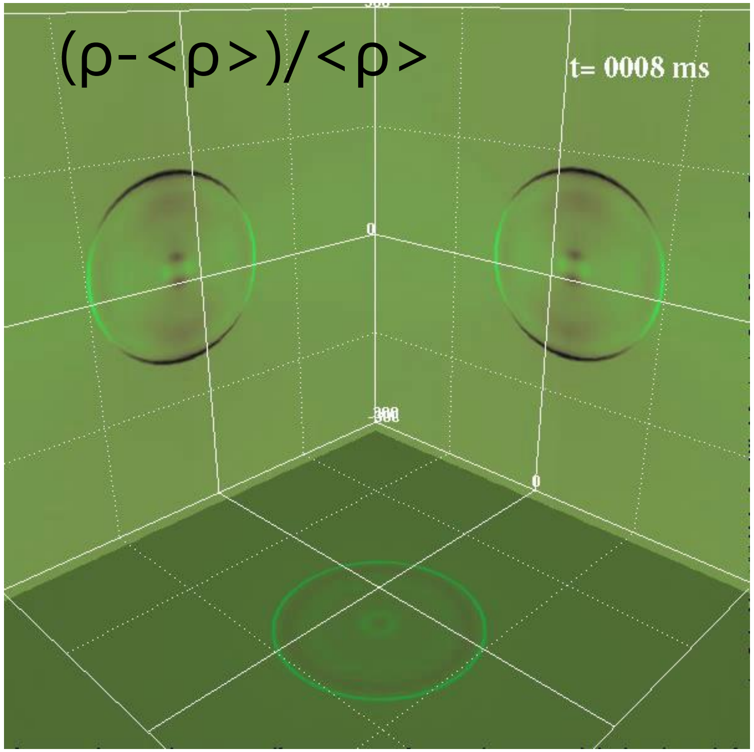
Question:
Is this expectation true?

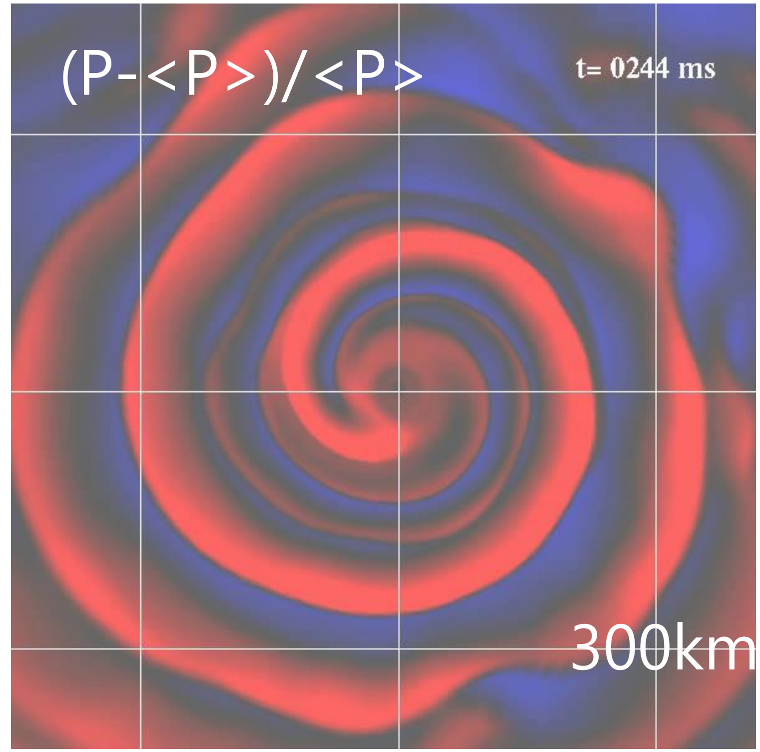
3D model with rotation

27.0M_s R2.0



Spiral Mode





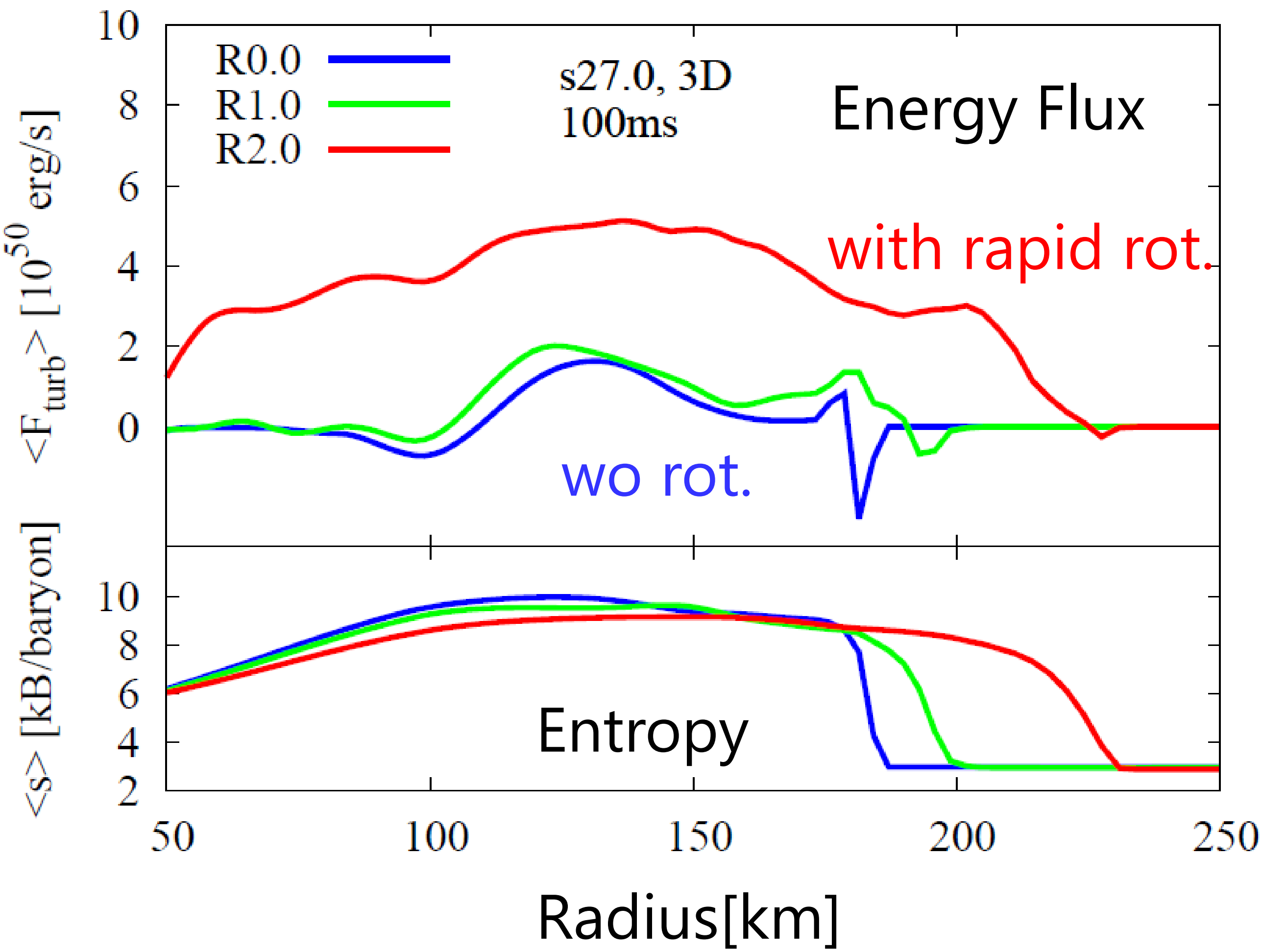
Rotational energy(T)/gravitational energy(W) reach some criteria => Spiral mode arises

In the rigid ball: 14%

Ott+ 2005

In SNe case: ~ 6% (Called low-T/W instability)

Energy Transport by spiral mode

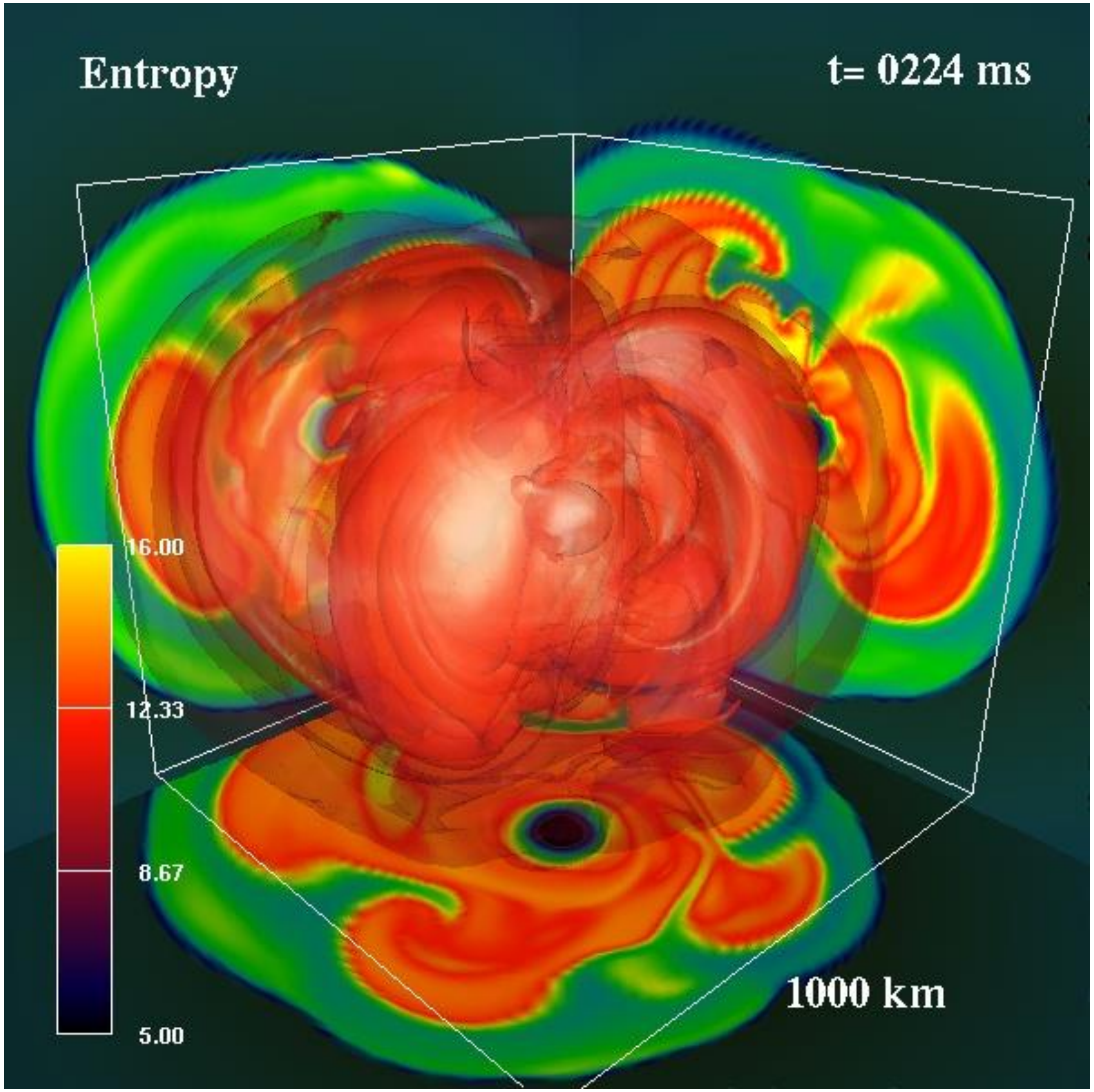


Power of ν heating = 10^52 erg/s

Power of Spiral mode = 0.5 x 10^52 erg/s

Spiral mode transport energy from center to outer region and helps explosion.

Rotational Explosion



Strong expansion is found at equatorial plane

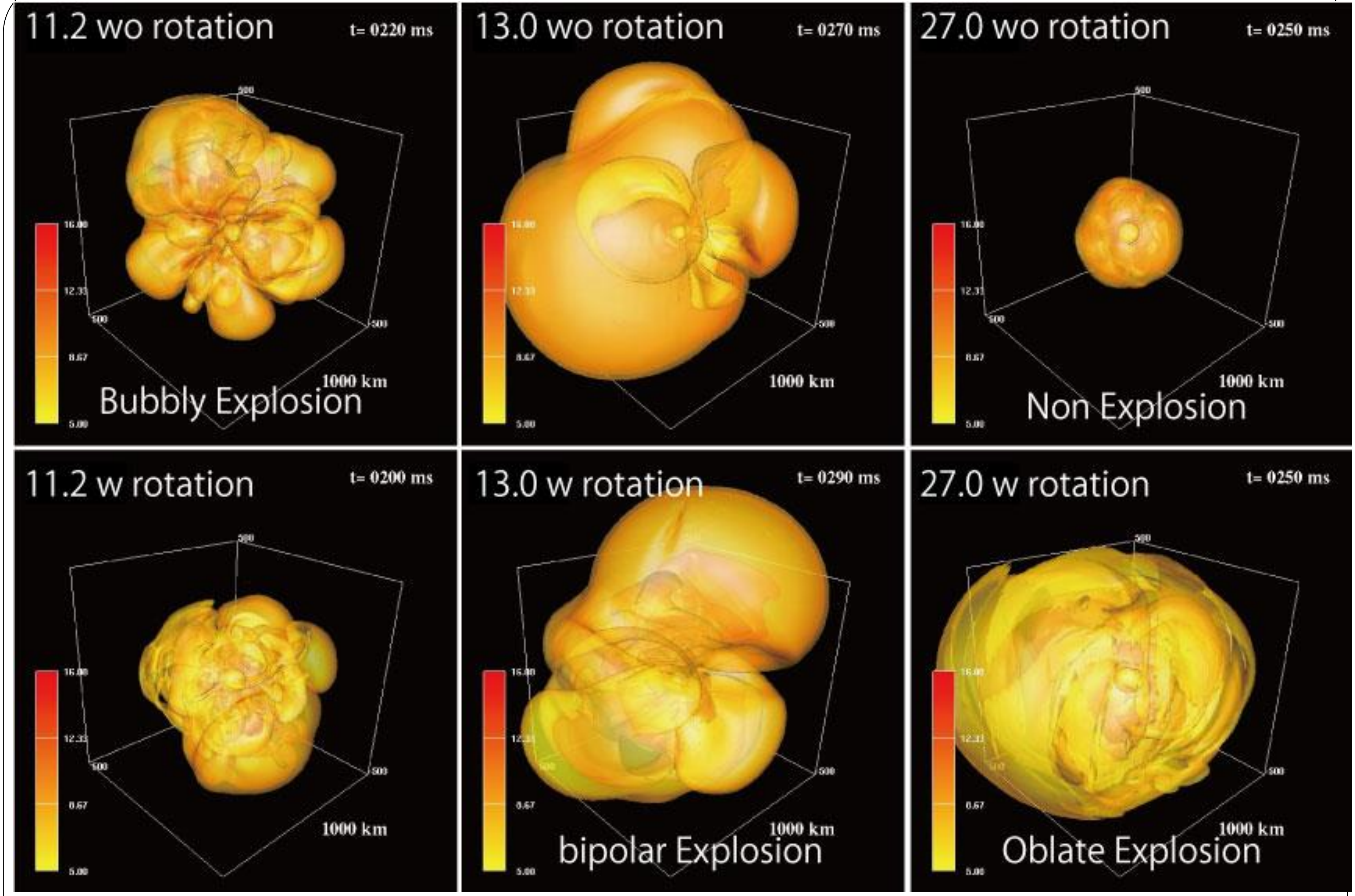
Eexp~5x10^50erg

Nucleosynthesis?

(see also Nakamura+14 and Iwakami+14)

Question on rotational explosion

- In my model, initial Ω= 2 rad/s and final Ω=2000 rad/s at 400 ms after bounce.
- Period of the zero-age pulsar is expected as ~10ms, Ω=100rad/s. Ott+ 2006
- Is the fast rotation allowed?
  Very efficient angular transport are required to justify the model.


11.2 wo rotation
t= 0220 ms
Bubbly Explosion
1000 km
13.0 wo rotation
t= 0270 ms
1000 km
27.0 wo rotation
t= 0250 ms
Non Explosion
1000 km
11.2 w rotation
t= 0200 ms
1000 km
13.0 w rotation
t= 0290 ms
bipolar Explosion
1000 km
27.0 w rotation
t= 0250 ms
Oblate Explosion
1000 km

Summary

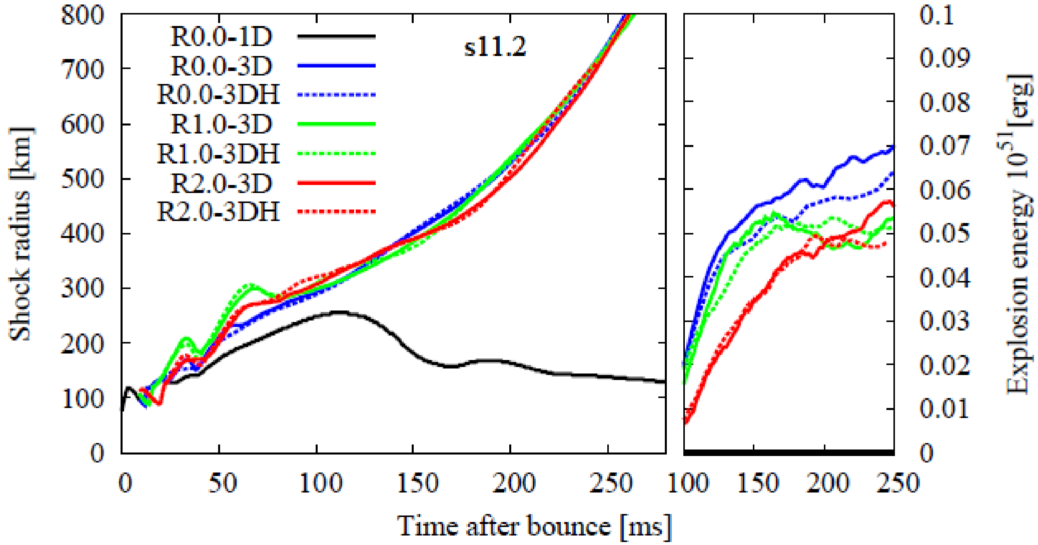
- Simulations of SNe depend on the employed methods (will be discussed in Friday).
- The energy Transport of turbulence plays important role. That’s why 1D fails and 2D or 3D tend to succeed.
- SASI can be important for heavier progenitor.
- We found interesting type of explosion.
  With rapid rotation, low-T/W instability arises.
  Spiral mode is promoted. Energy transport due to that helps explosion.

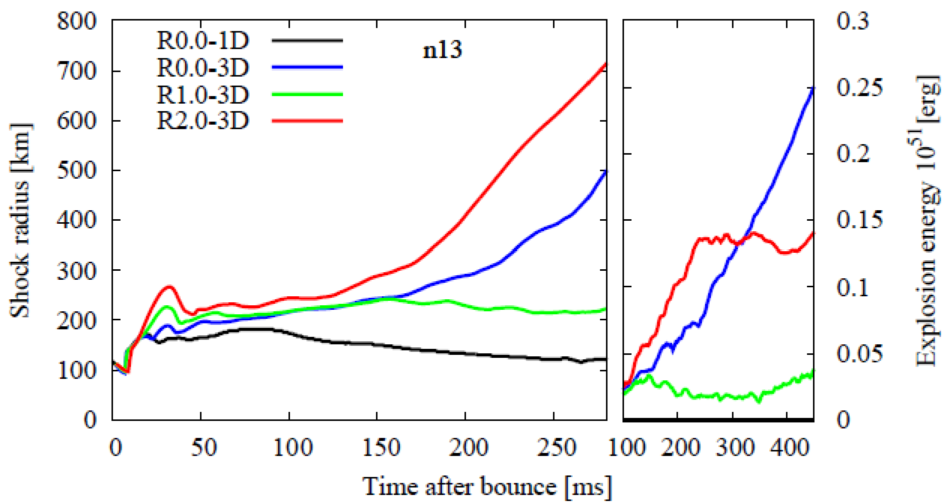
Questions

- Can we grasp the feature of convection?
- Is the expectation below is correct?
  For light progenitor, with only ν-heating SNe explode.
  For normal progenitor convection helps SNe explosion.
  For heavy progenitor convection and SASI helps SNe explosion.
- Explosion triggered by fast rotation is allowed?

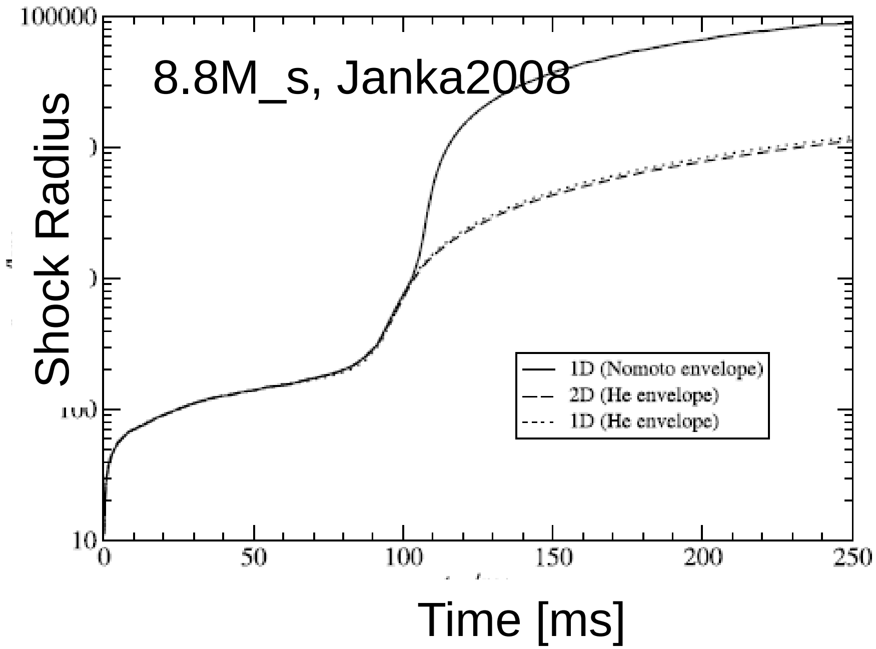
Appendix

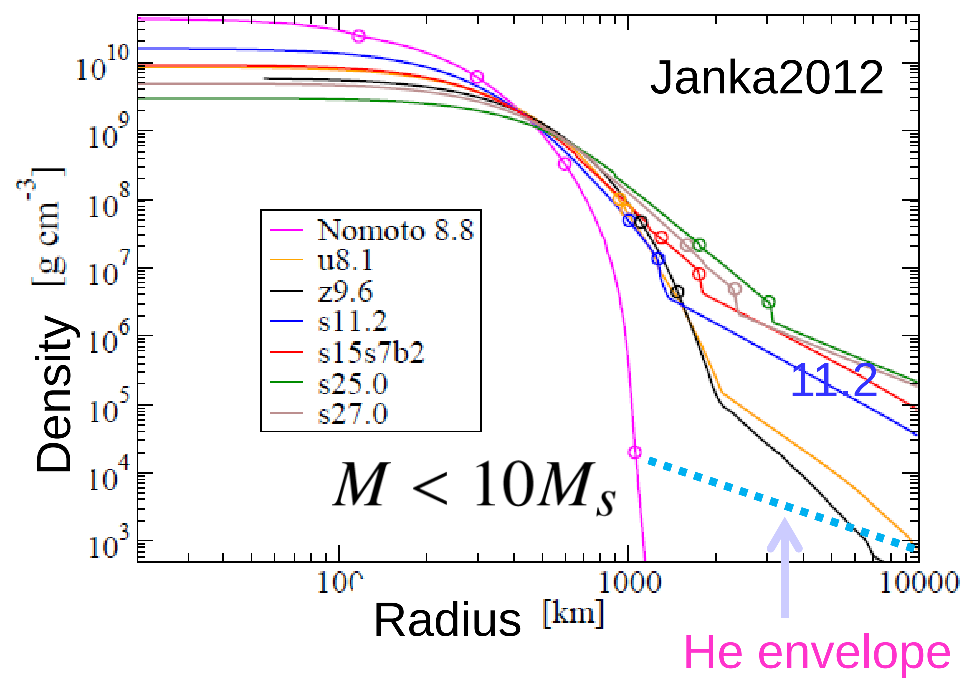
Averaged shock radius and Exp. Energy





Pure ν heating

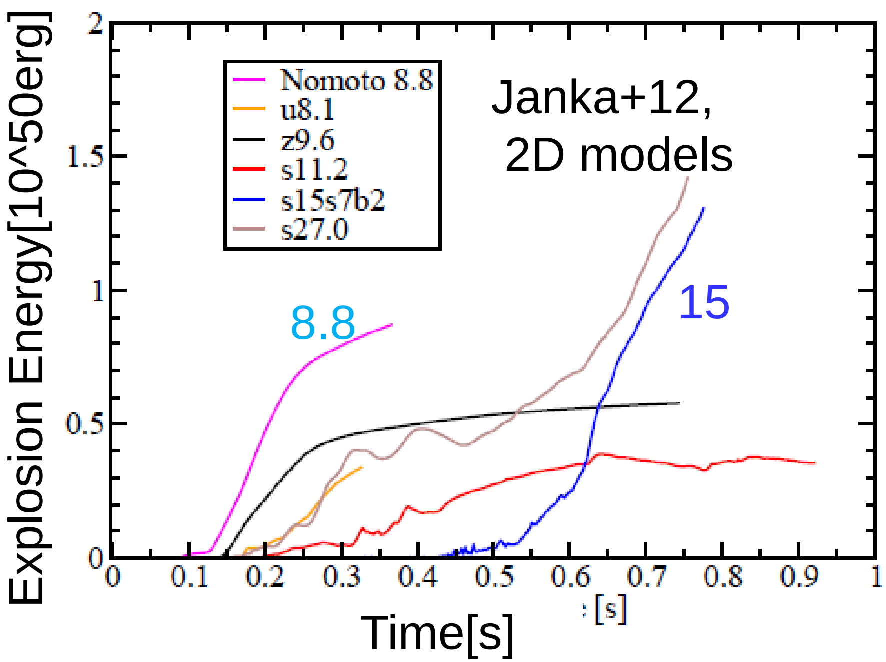


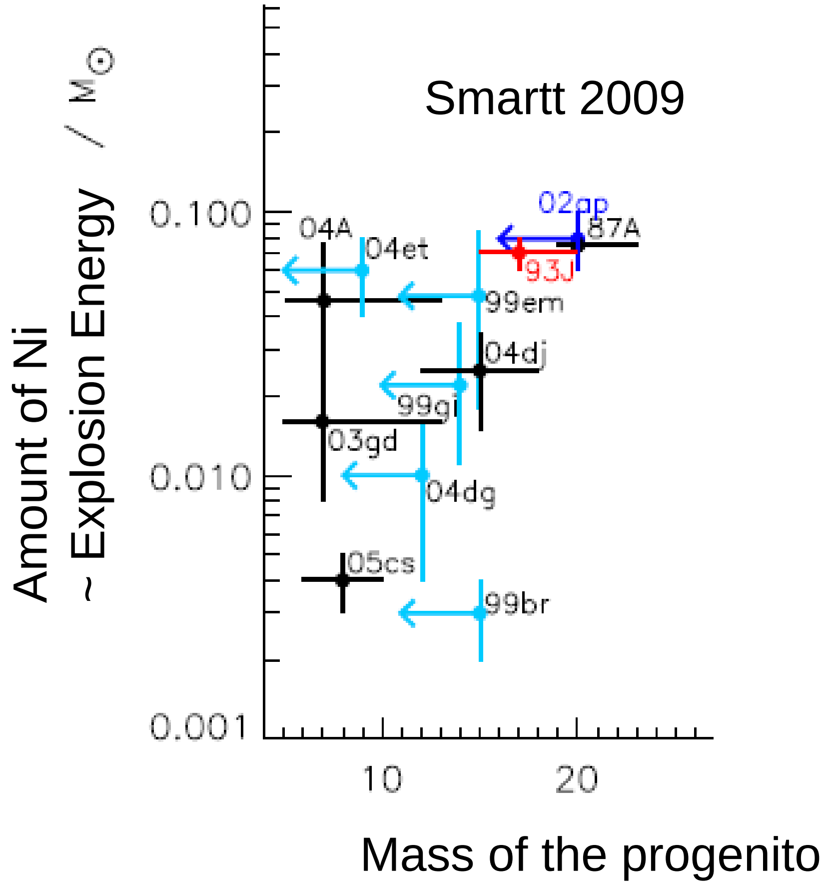


Easy shock revival

Dilute outer layor

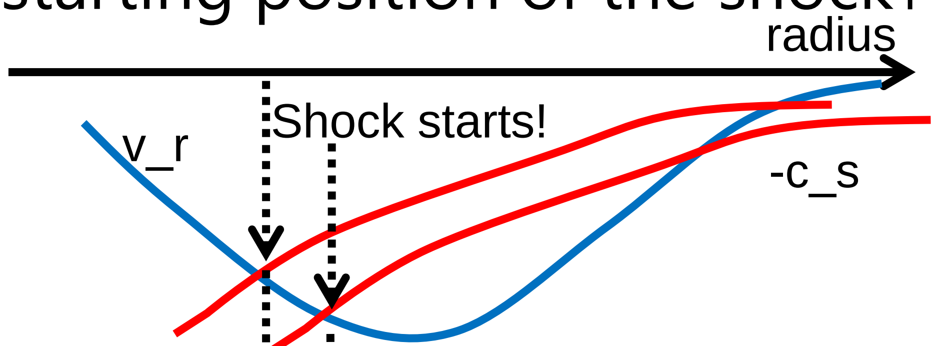
Pure ν heating





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 ↓

4. The energy of the Shock ↑

Neutrino Reactions

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

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

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

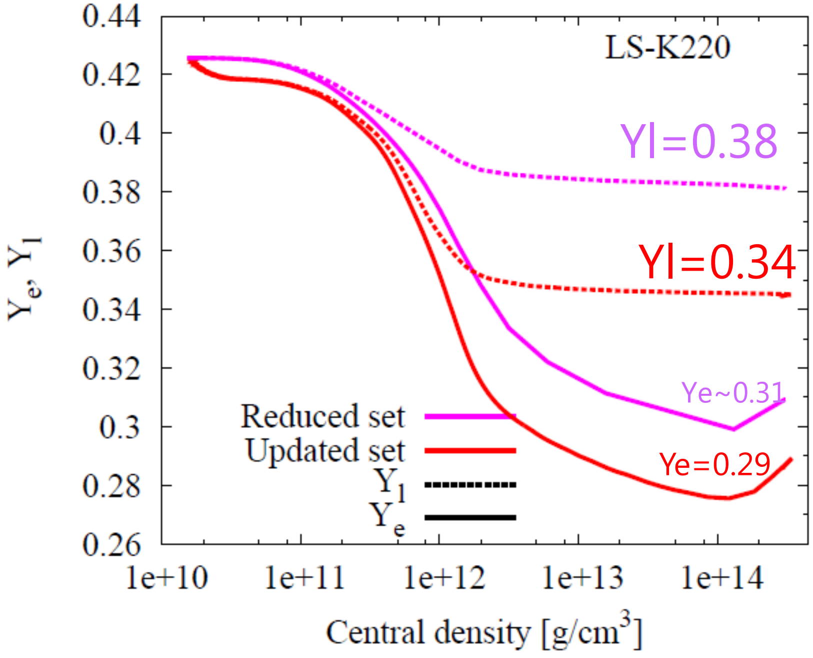
$$\nu + \bar{\nu} \leftrightarrow e^+ + e^-$$

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

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

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

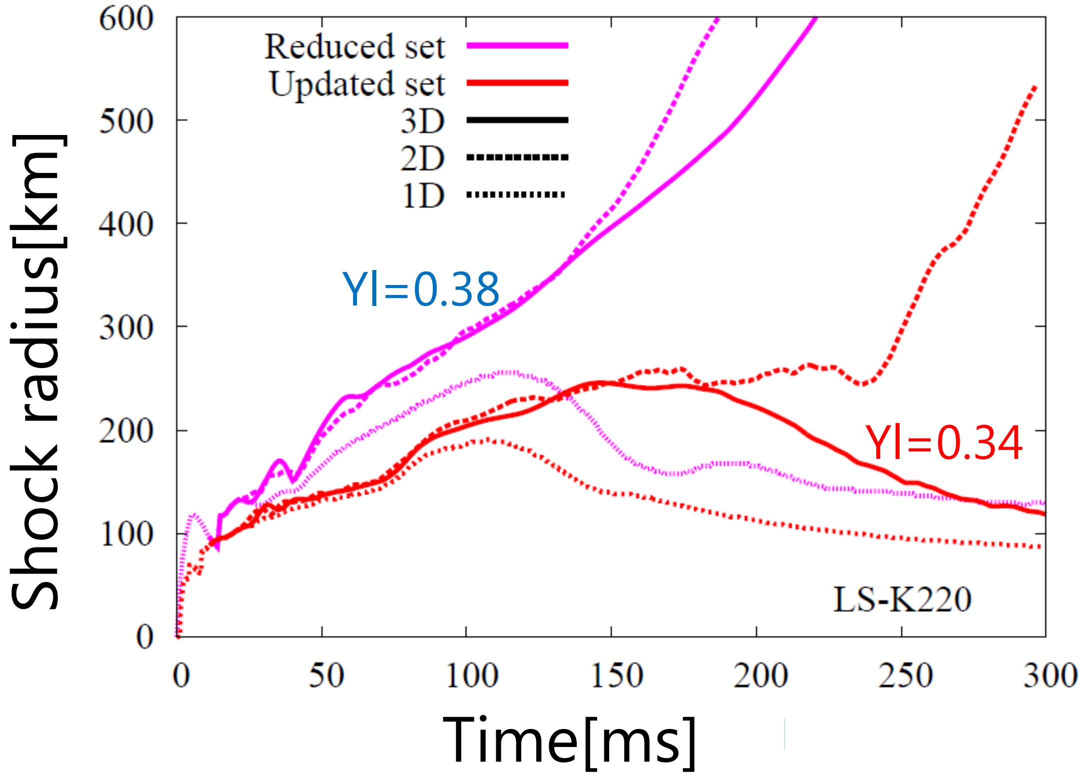
$$\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$

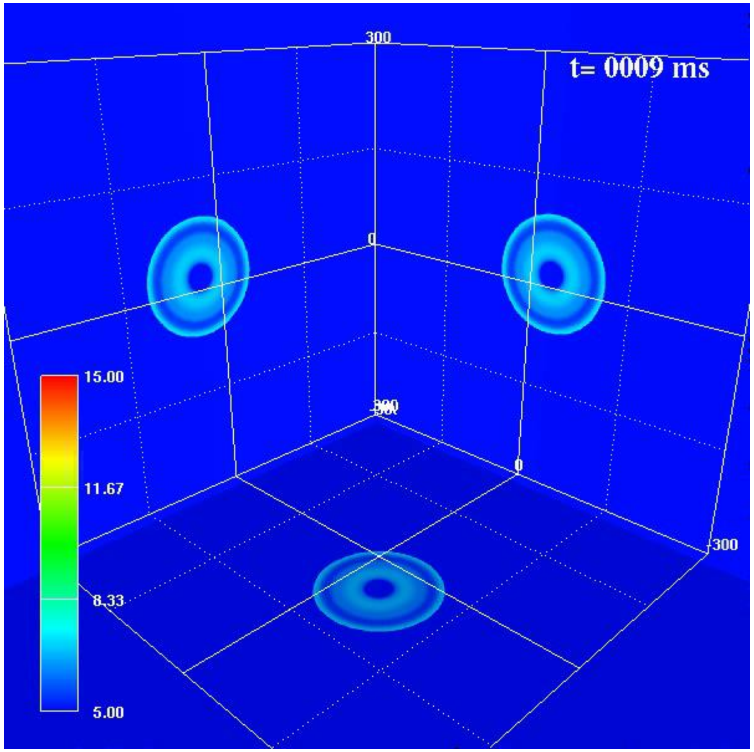


There are still several minor points that are remaining to be updated.

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

Multi-Dimensional Simulations

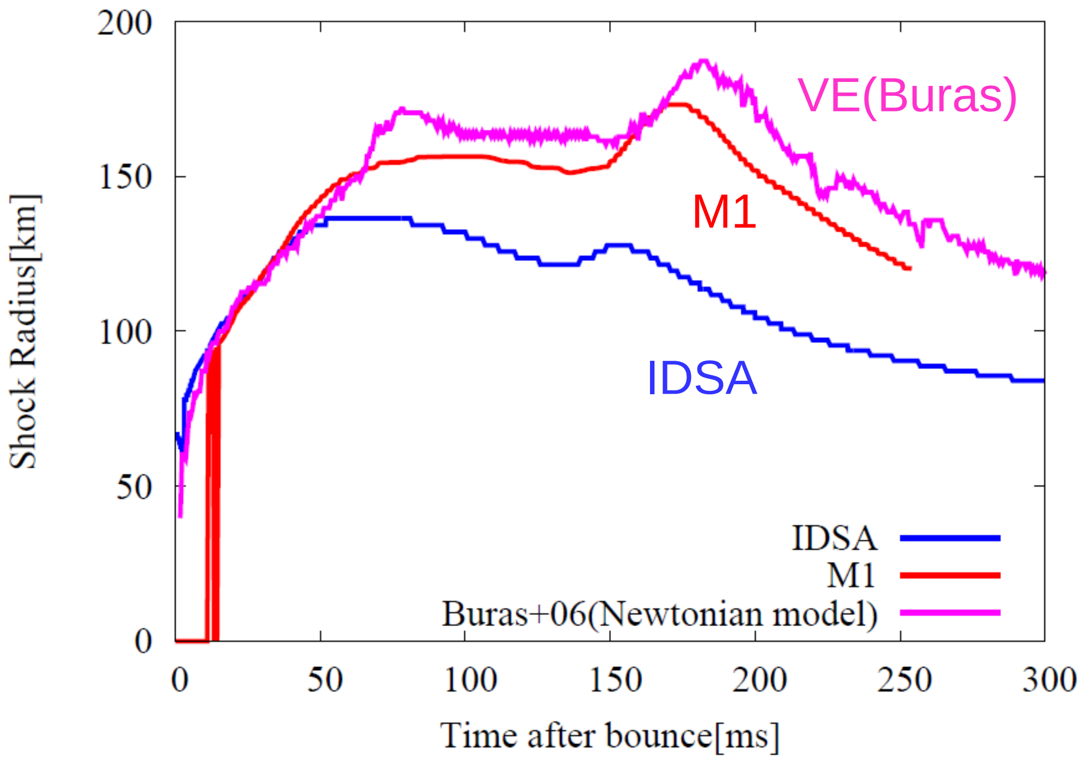




Unfortunately our 3D model with updated neutrino reaction does not explode.

But do not forget that we now ignore GR Effect that should help the explosion!

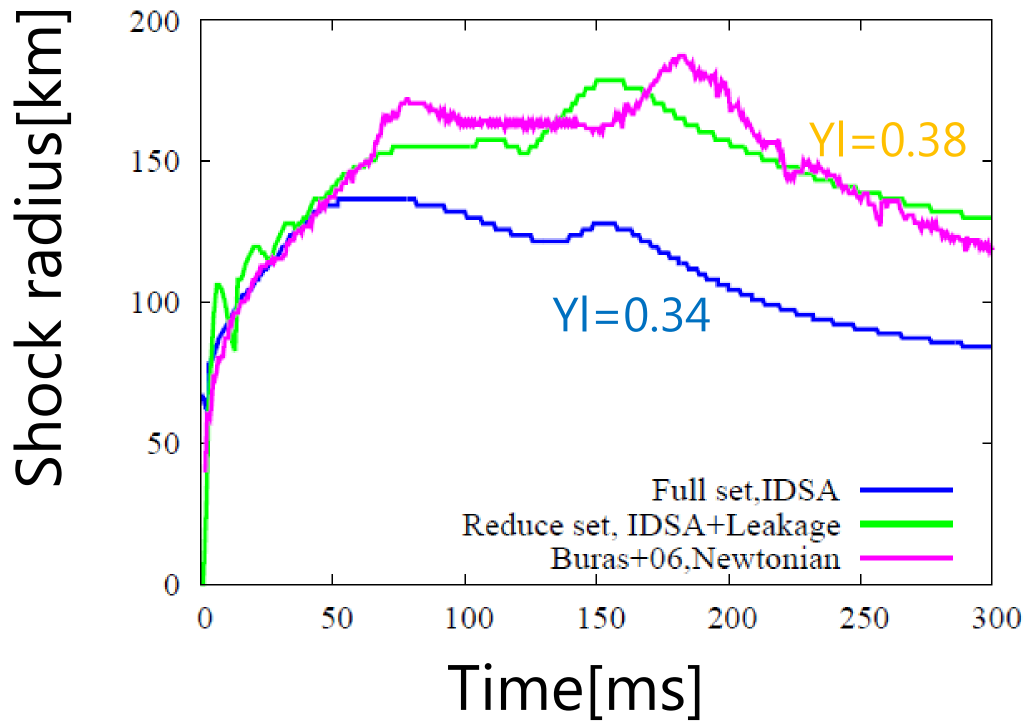
Dependence on Radiation Hydro



VE > M1 > IDSA

Density of neutrino could be larger in more sophisticated method.

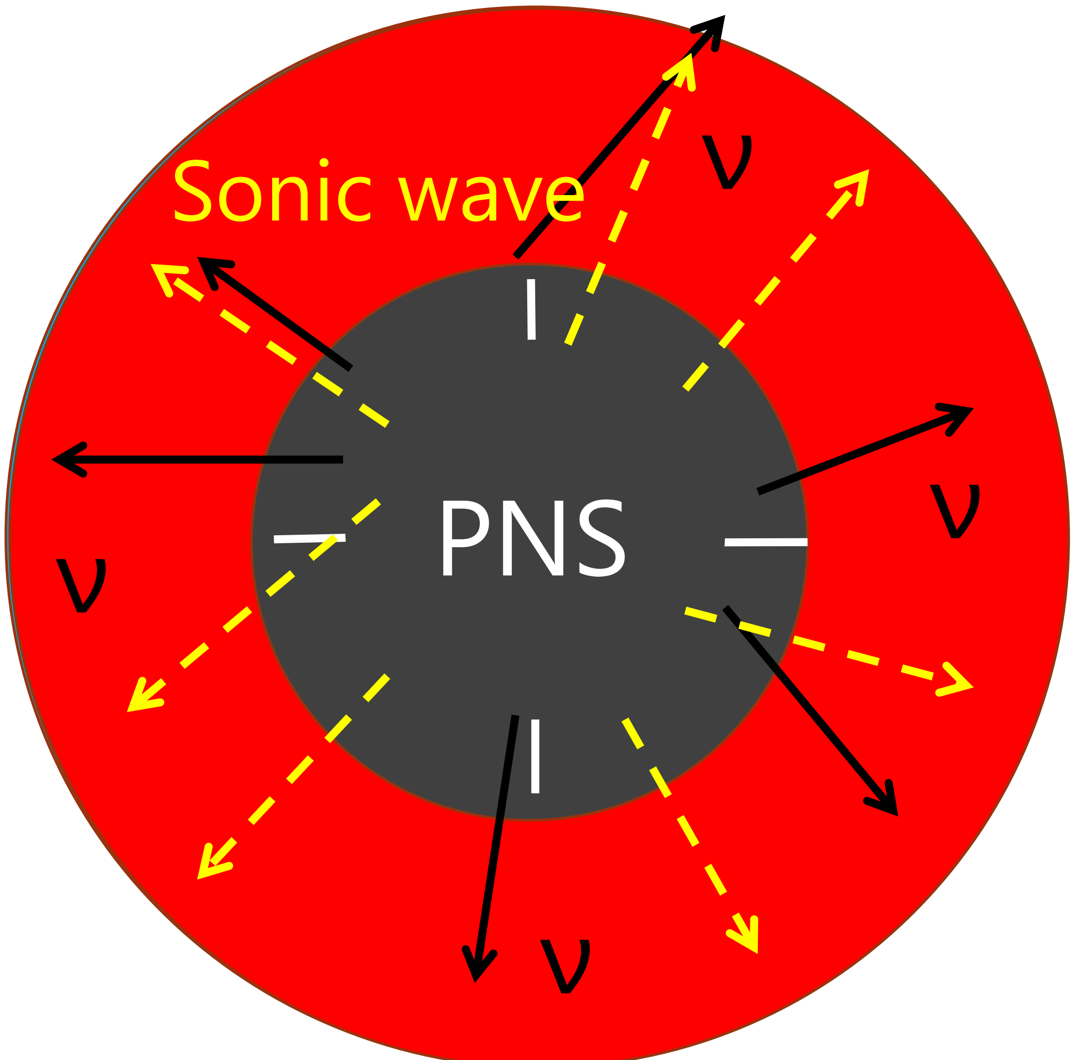
Comparison of the shock radius in 1D



Smaller Y_l results in smaller shock radius!

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

Basic idea to connect EOS and Explosion

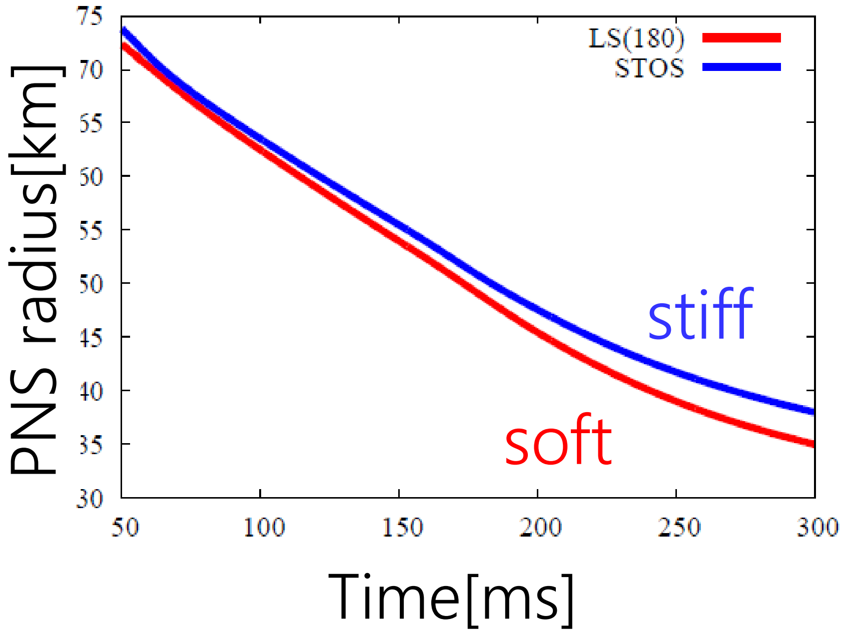


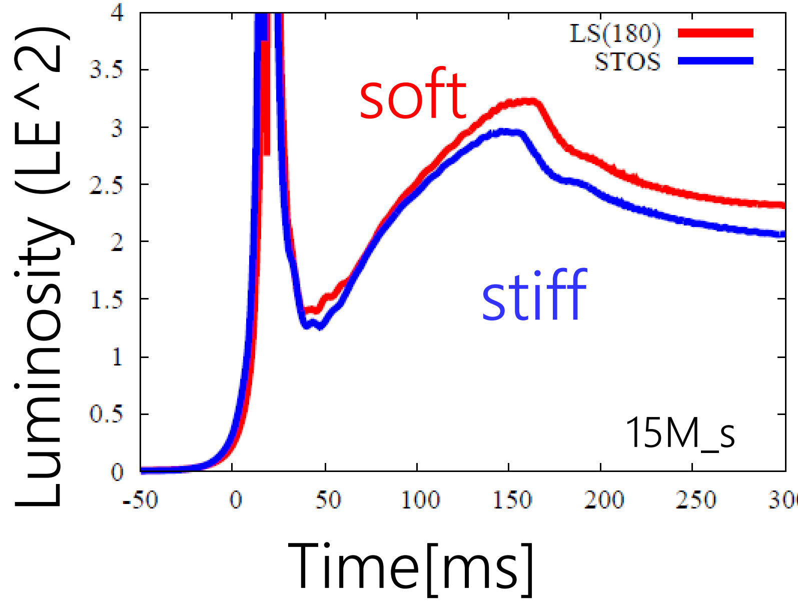
1. The PNS gradually shrinks by the gravity.
2. E_grav is released.
3. E_thermal is increased.
4. The L_ν and sonic waves are emitted from the surface of PNS.

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

Softer EOS is preferable to the explosion.

Neutrino Luminosity



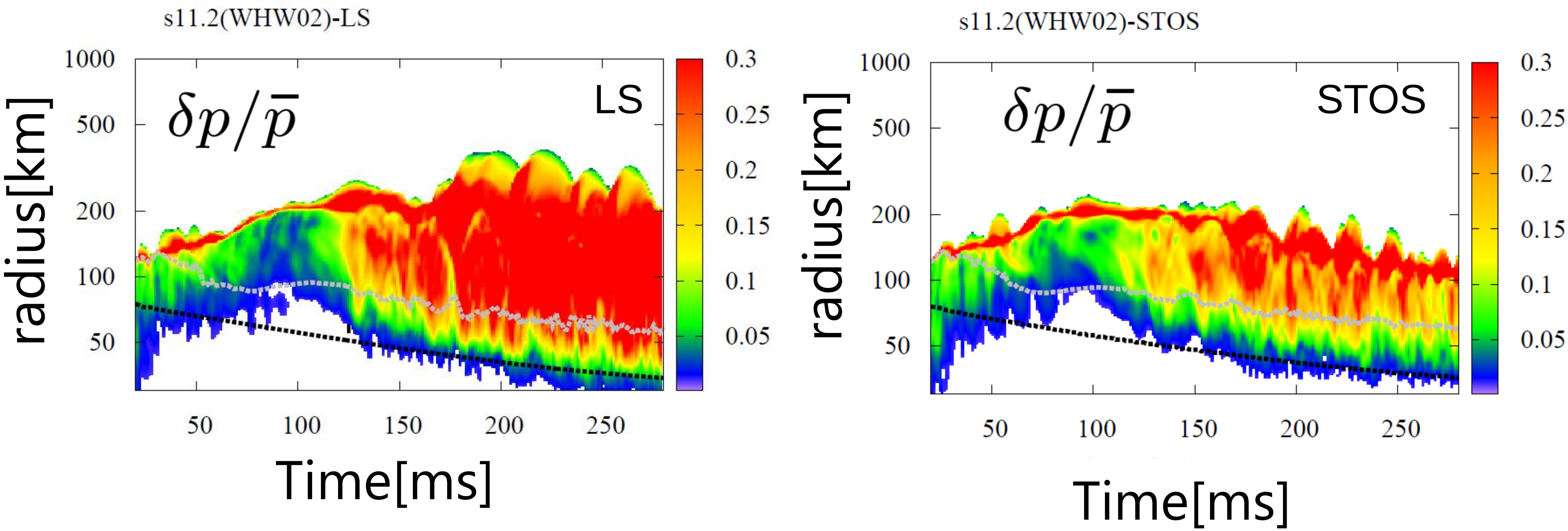


LS(K220):Soft EOS => rapidly shrink => Large L_ν

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

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

Sonic Wave

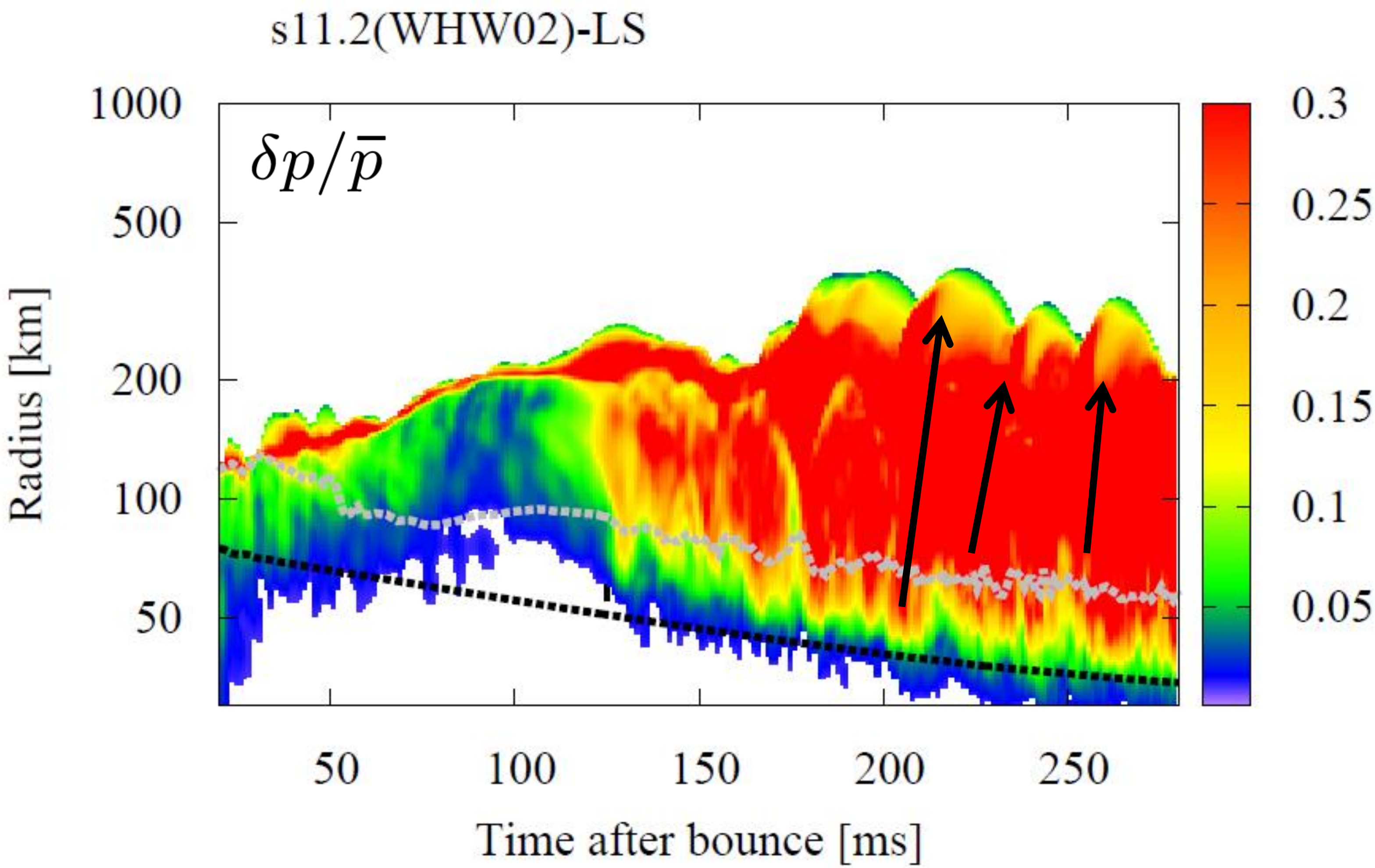


Gray: gain radius, black PNS radius

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

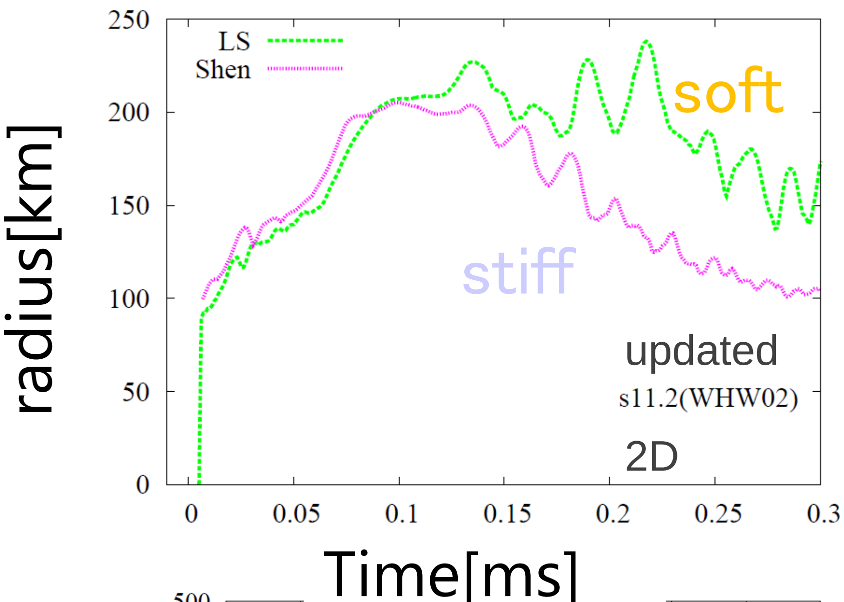
(Couch 2013 and Suwa+ 2013 show similar results.)

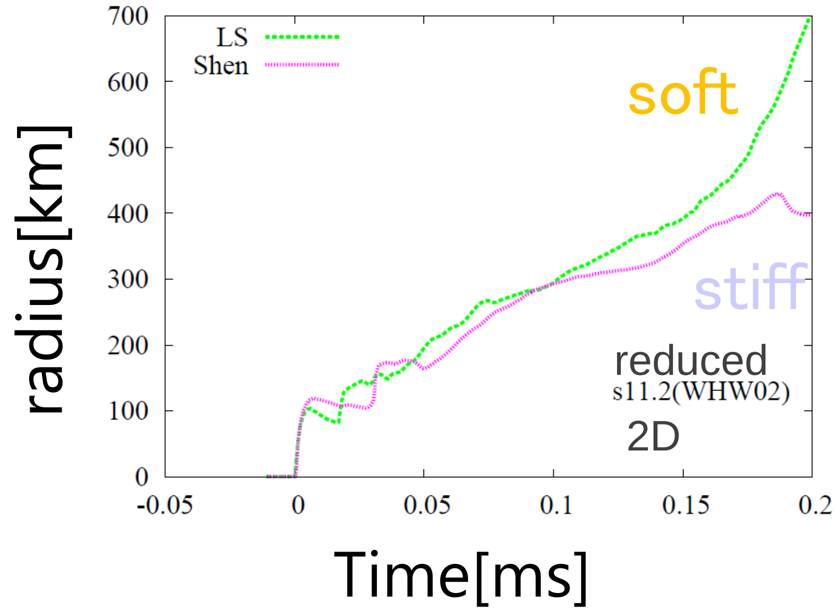
Sonic Wave

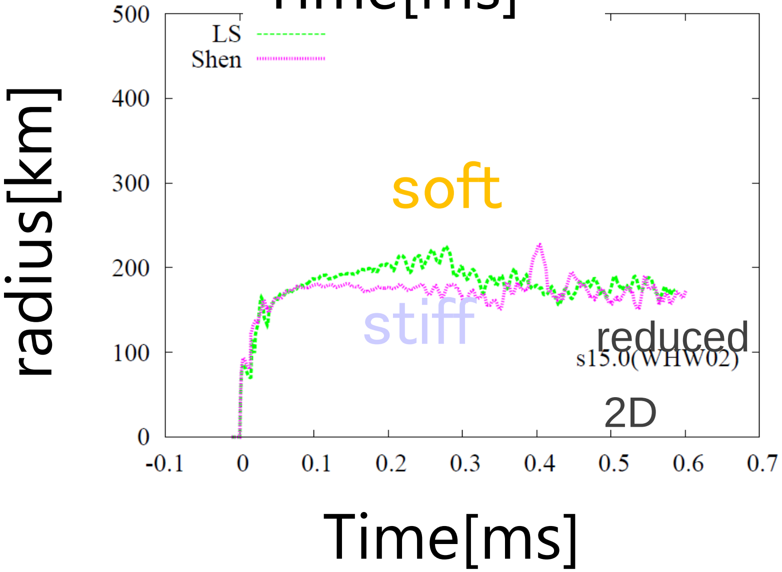


Gray: gain radius, black PNS radius

Evolution of the shock

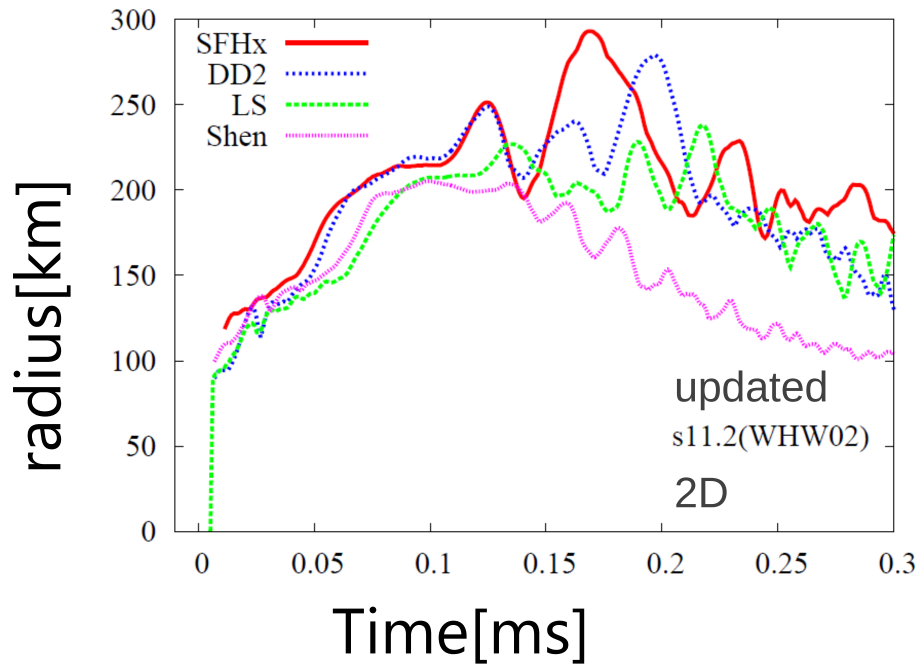


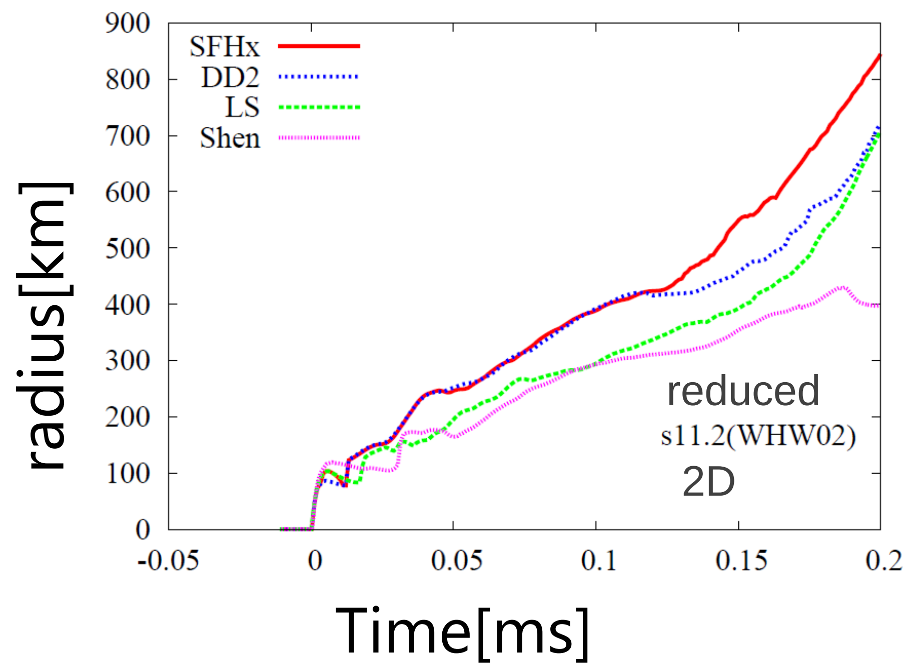




Softer EOS shows larger shock radius.

Emergence of Multi-species EOS





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

SFHx and DD2 ＞ LS and STOS

Employing MS may help SNe explosion.

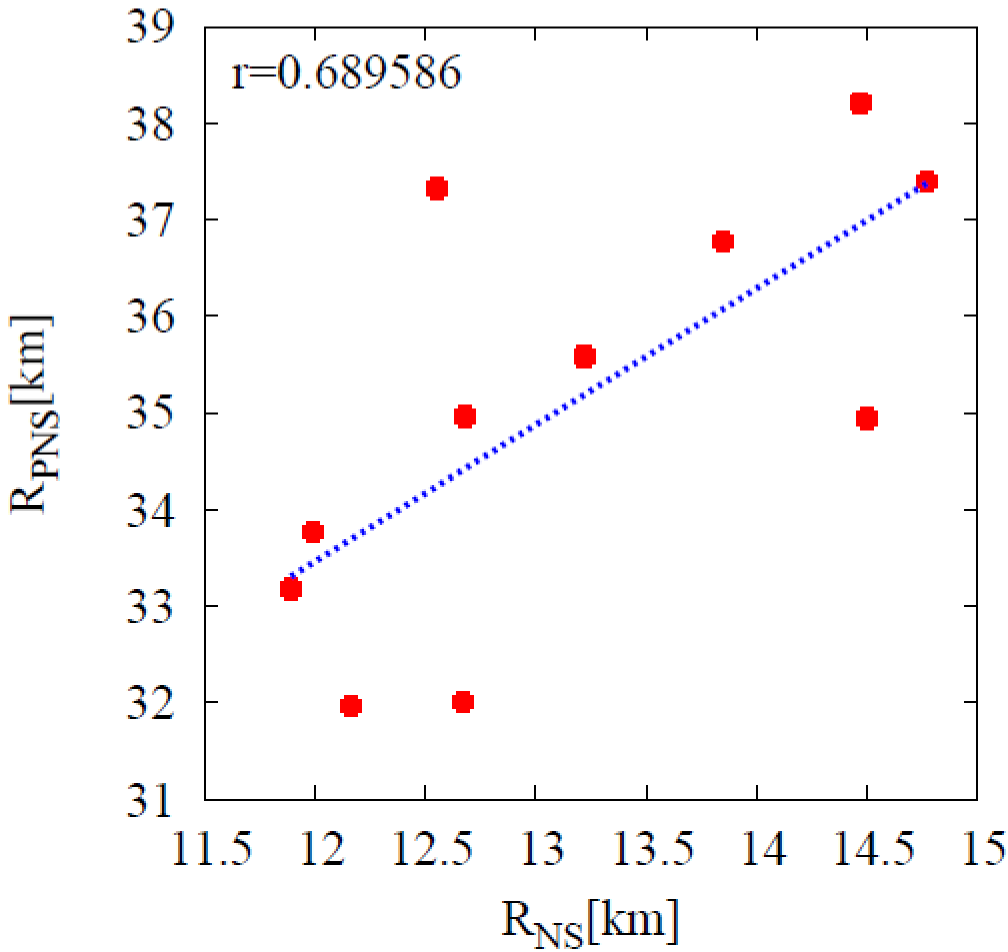
But in one-dimensional GR sim, that situation is contradictory. (Fisher+2014)

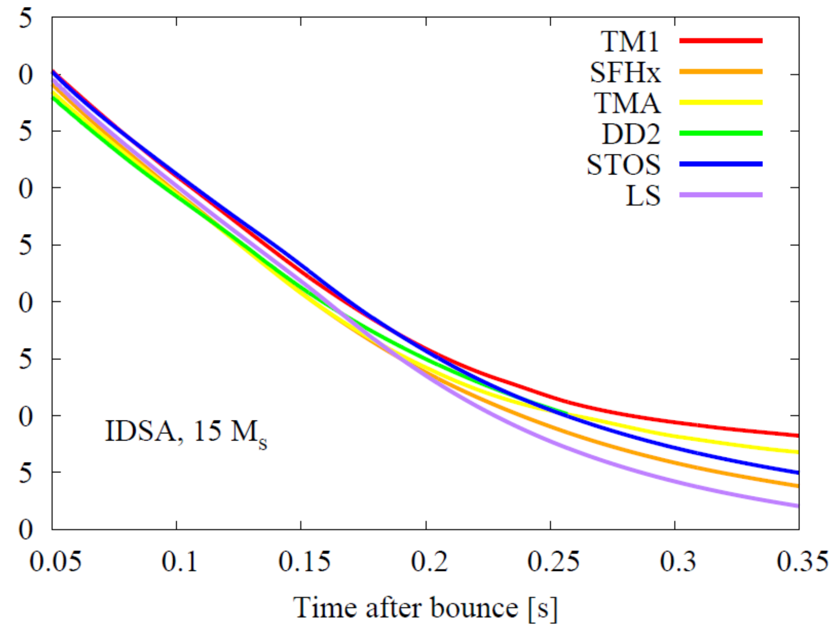
In other words?

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?

NS radius vs PNS radius

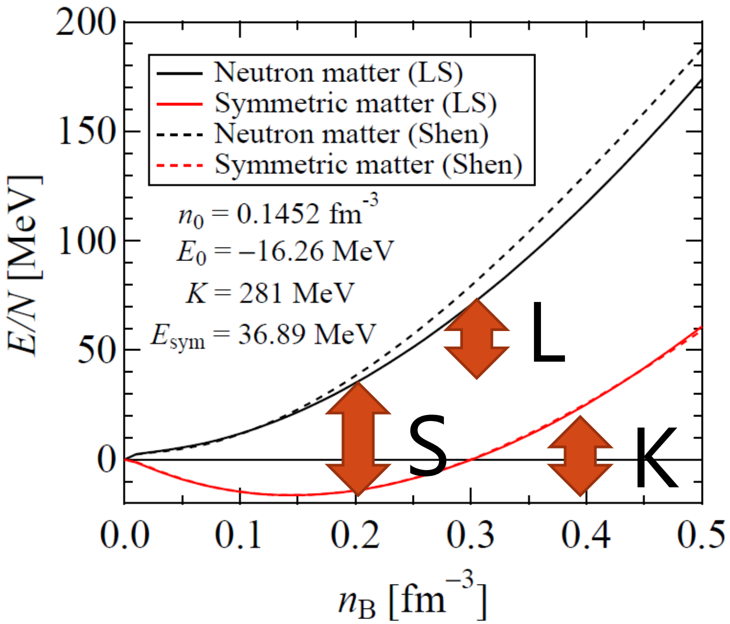




Takiwaki in prep

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

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



Many theories for EOS

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

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)]

Parametric EoS

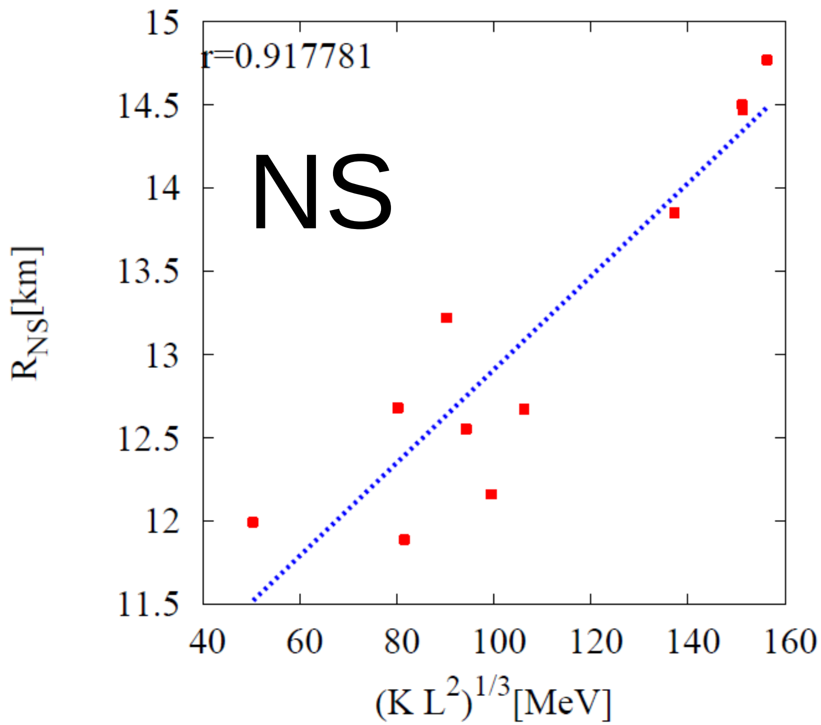
EOS	n_0 [fm^3]	E_0 [MeV]	K [MeV]	E_{sym} [MeV]	L [MeV]
STOS (original)	0.1452	−16.26	281	36.89	110.79
LS (original)	0.1550	−16.00	180/220/375	29.30	73.82
STOS (low) + LS (high)	0.16	−15.80	180	25.00	60.62
STOS (low) + LS (high)	0.16	−15.80	180	30.00	75.62
STOS (low) + LS (high)	0.16	−15.80	180	35.00	90.62
STOS (low) + LS (high)	0.16	−15.80	230	25.00	60.62
STOS (low) + LS (high)	0.16	−15.80	230	30.00	75.62
STOS (low) + LS (high)	0.16	−15.80	230	35.00	90.62
STOS (low) + LS (high)	0.16	−15.80	280	25.00	60.62
STOS (low) + LS (high)	0.16	−15.80	280	30.00	75.62
STOS (low) + LS (high)	0.16	−15.80	280	35.00	90.62
STOS (low) + LS (high)	0.1452	−16.26	281	36.89	97.19

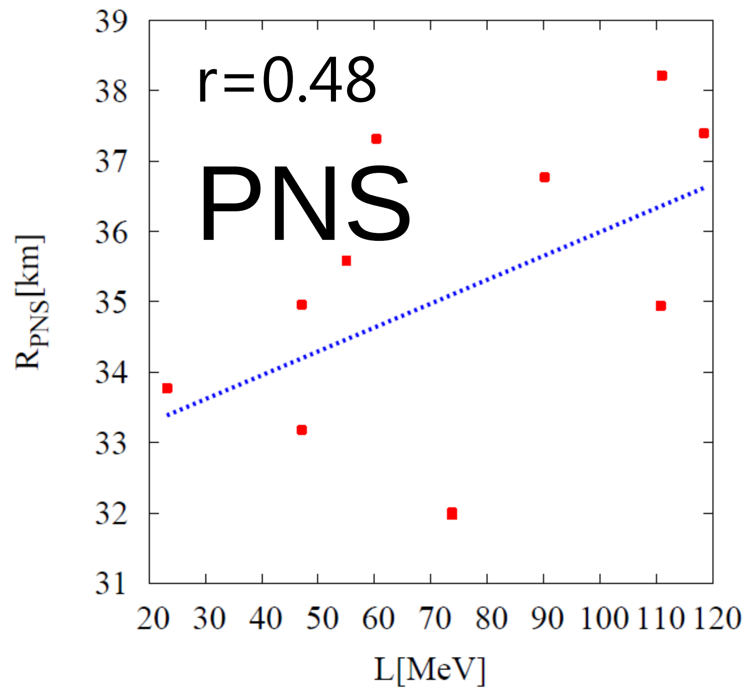
Togashi+ in prep

Is it fair to compare the EOS using different “theory”? Togashi-san uses LS parametrization and make EOSs of different K,S,L.

That enable us to compare the EOS fairly and extract information of K,S and L from the simulations.

What parameter determine PNS radius





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.