Physical Ingredients in Core-Collapse Supernova Explosion Mechanism

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Collaboration with
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Core-collapse supernovae

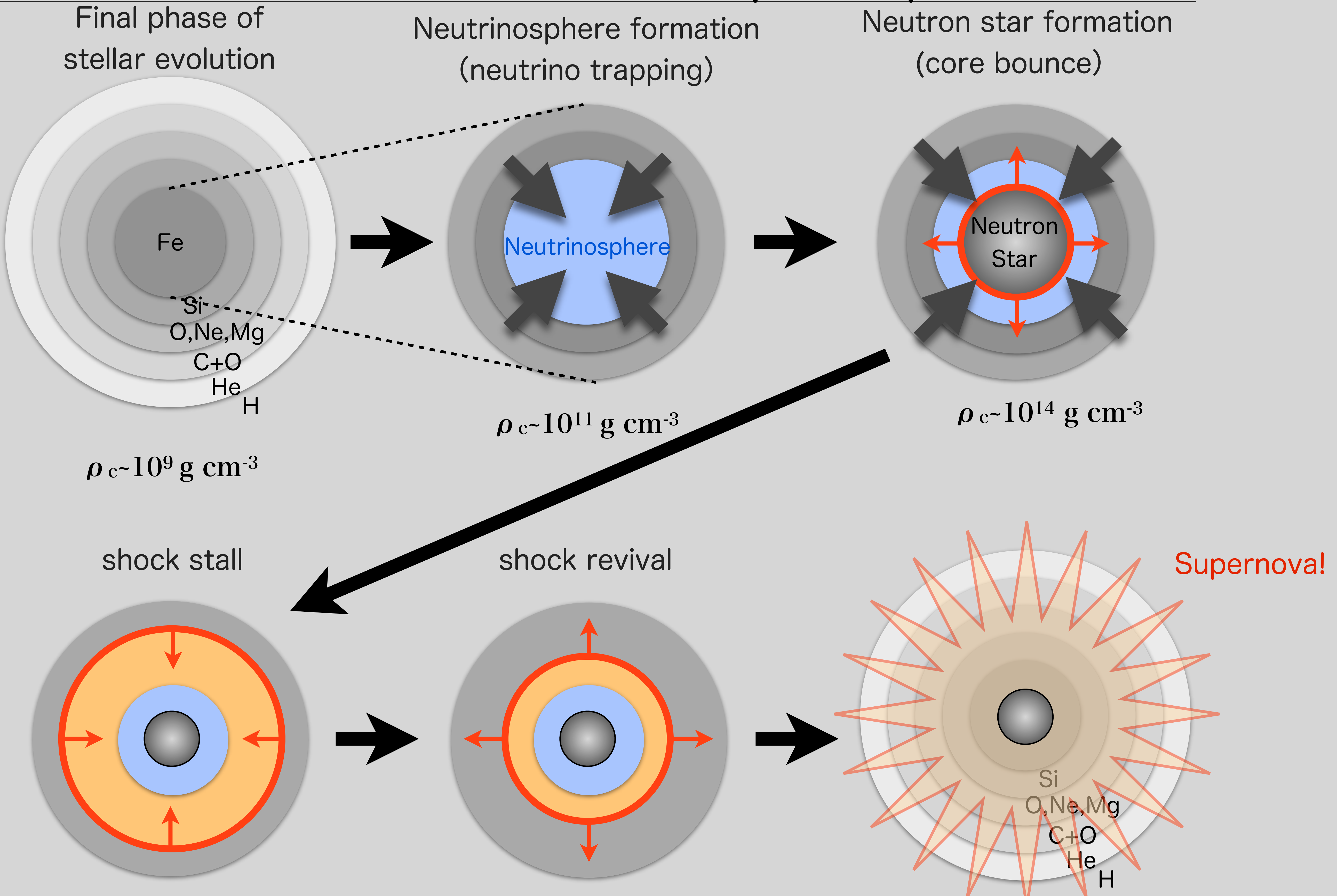
- One of the most energetic explosion in the universe
  - $E_{exp} \sim 10^{51}$ erg
  - $E_{grav} \sim 10^{53}$ erg ($\sim 0.1\ M_\odot\ c^2$)
  - $E_\nu \sim 10^{53}$ erg
- Formation of neutron Star / Black hole
- Formation of gamma-ray bursts?

All known interactions are important

- **Macrophysics**
  - Gravity
    - core collapse
  - Elecromagnetic
    - pulsar, magnetar, magnetorotational explosion

- **Microphysics**
  - Weak
    - neutrino physics
  - Strong
    - equation of state of dense matter

Standard scenario of core-collapse supernovae



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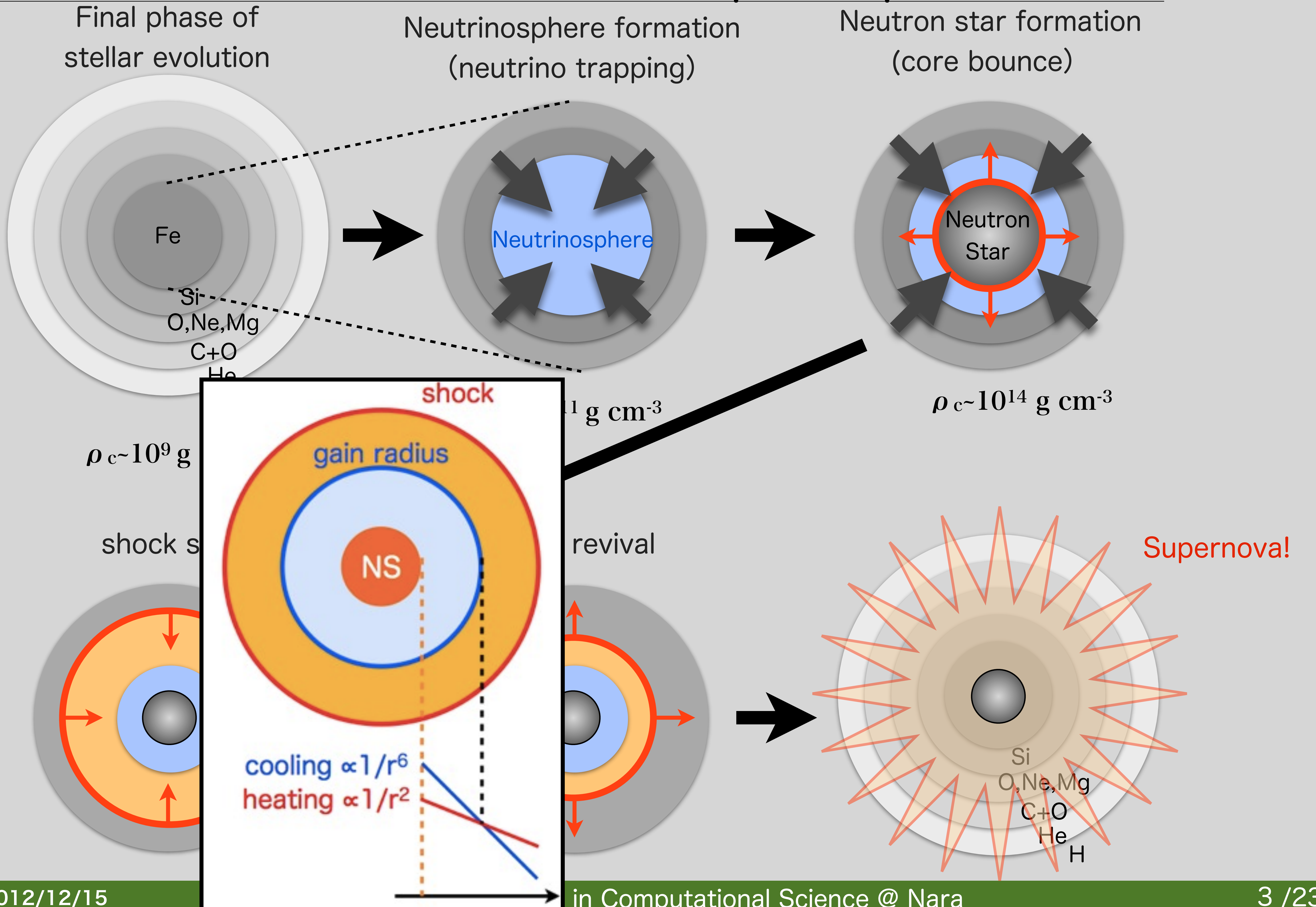

Systematics in supernova simulations

Our Goal: Produce Successful Explosion! of ~10^{51} erg

- Dimensionality of hydrodynamics — Iwakami+ 08, Nordhaus+ 10, Hanke+ 11, Takiwaki+ 12, Couch 12
- General relativity — Liebendörfer+01, Müller+ 12, Kuroda+ 12
- Neutrino physics
  - Scheme to solve Boltzmann equation — Ott+ 08, Shibata+ 11, Sumiyoshi & Yamada 12
  - Interaction rate — Langanke+ 03, Arcones+ 08, Lentz+ 12
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- Initial condition — Nomoto & Hashimoto 88, Woosley & Weaver 95, Woosley+ 02, Limongi & Chieffi 06, Woosley & Heger 07, Yoshida+ 12
  - progenitor structure (mixing, wind...)
  - rotation / magnetic field

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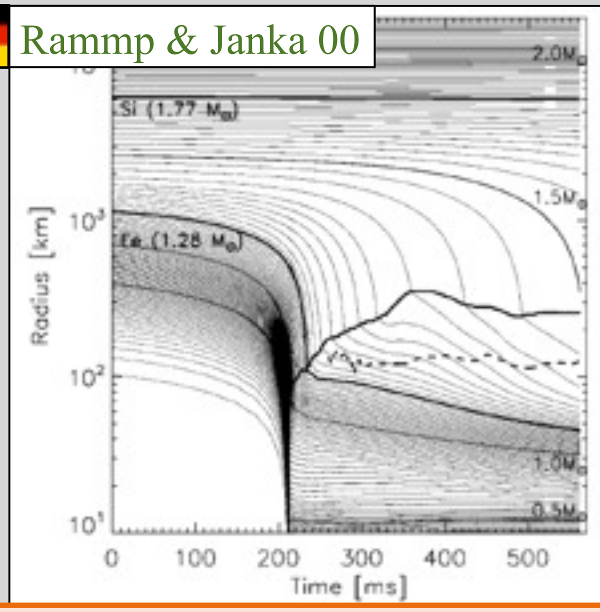
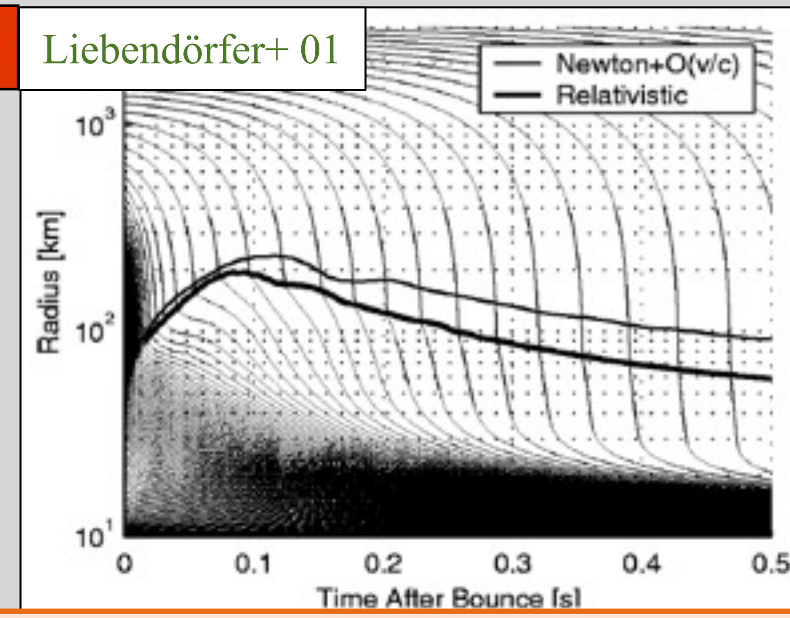
1D simulations: fail to explode

Rammp & Janka 00

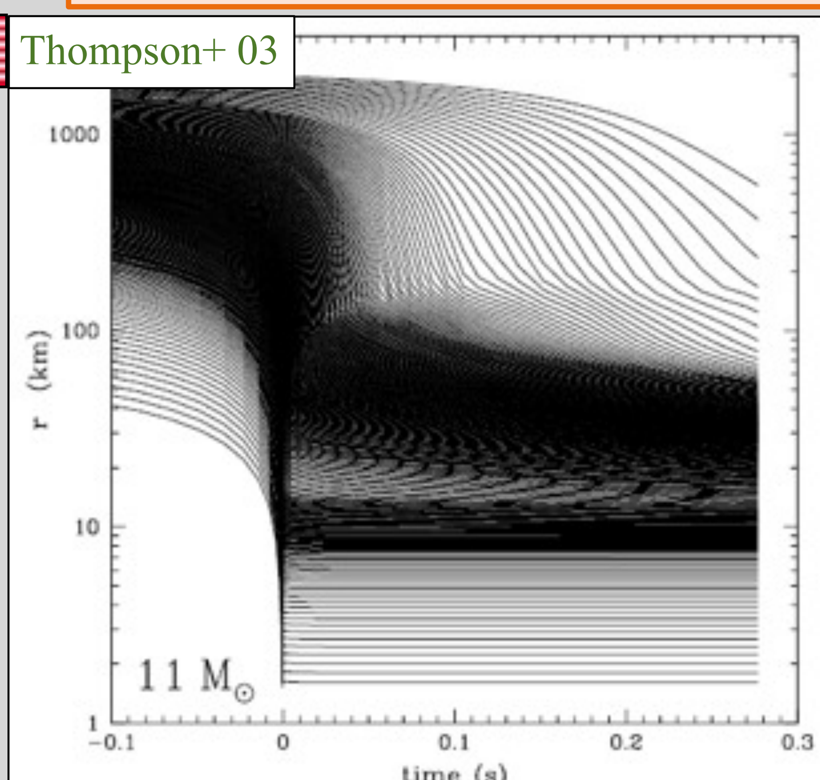


Liebendörfer+ 01

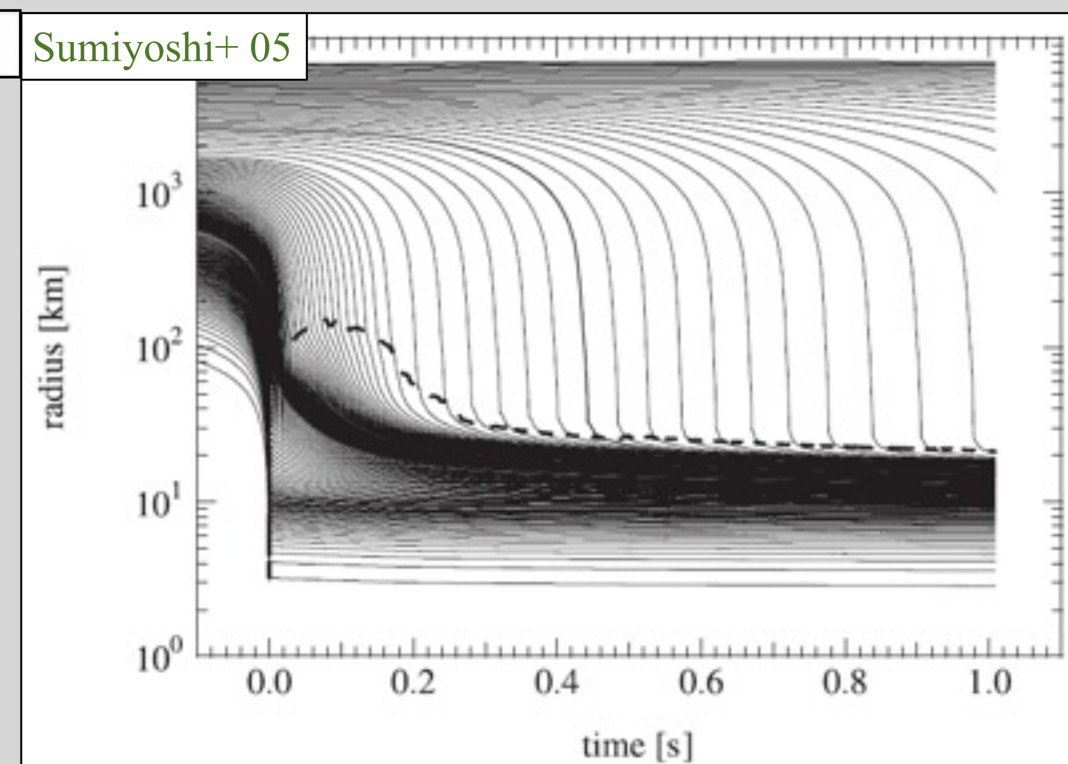


By including all available physics to simulations, we concluded that the explosion cannot be obtained in 1D!
(The exception is an 8.8 $M_\odot$ star; Kitaura+ 06)

Thompson+ 03



Sumiyoshi+ 05



Numerical simulation

YS+, PASJ, **62**, L49 (2010); ApJ, **738**, 165 (2011); ApJ in press (2012)

- Spherically symmetric and axisymmetric simulation

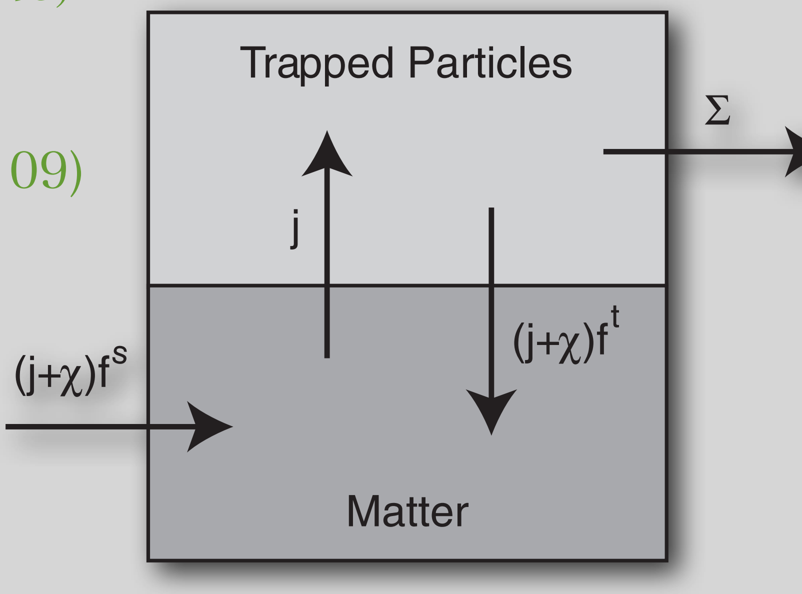
  (ZEUS-2D; Stone & Norman 92)

- Hydrodynamics + Neutrino transfer

$$\frac{df}{cdt} + \mu \frac{\partial f}{\partial r} + \left[\mu \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr}\right)\right](1-\mu^2)\frac{\partial f}{\partial \mu} + \left[\mu^2 \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr}\right) - \frac{v}{cr}\right] D \frac{\partial f}{\partial E}$$
$$= j(1-f) - \chi f + \frac{E^2}{c(hc)^3}\left[(1-f)\int R f' d\mu' - f \int R(1-f')d\mu'\right]$$

(Lindquist 1966; Castor 1972; Mezzacappa & Bruenn 1993)

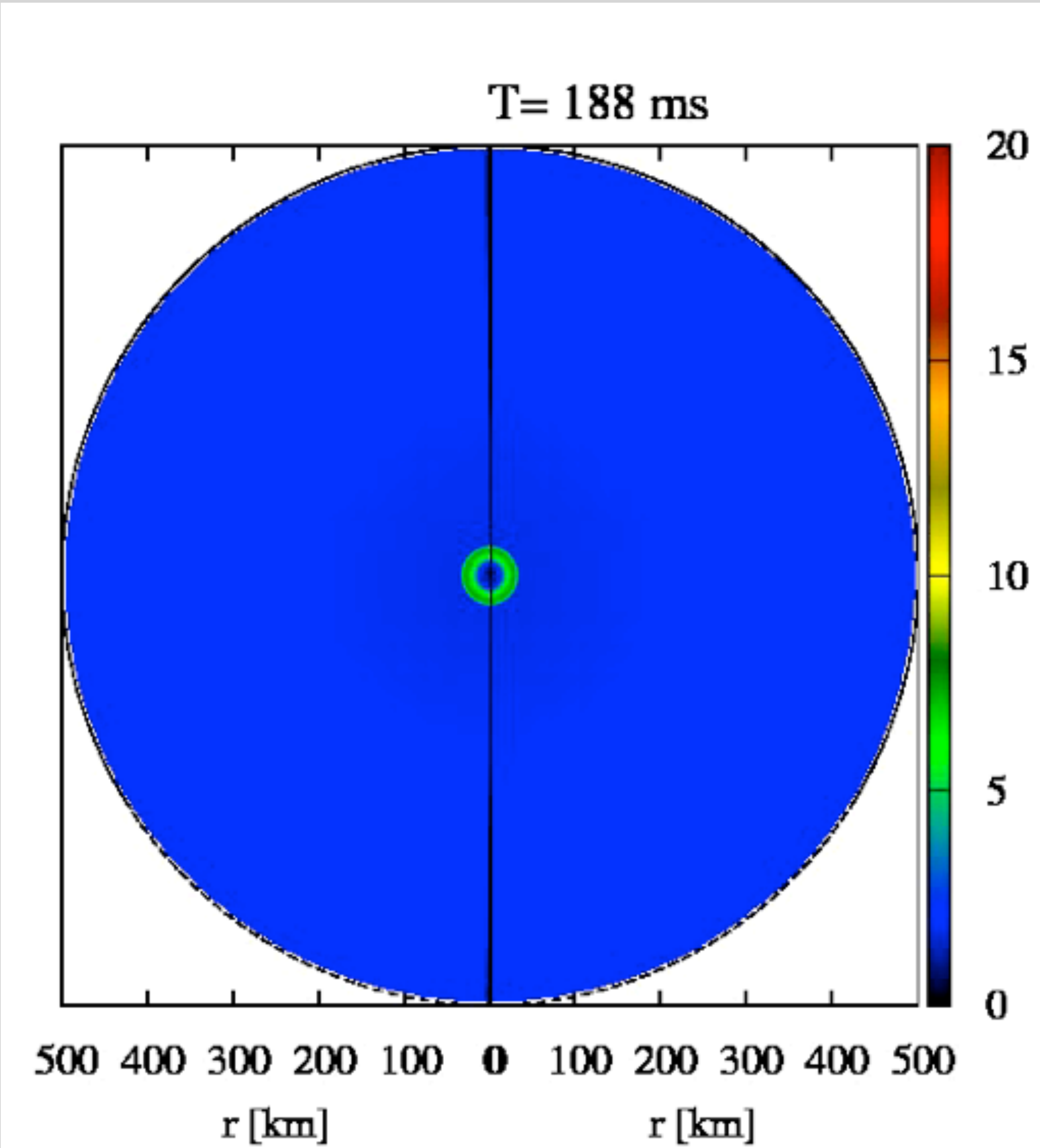
  - Isotropic Diffusion Source Approximation (Liebendörfer+ 09)
  - electron-type neutrino/antineutrino



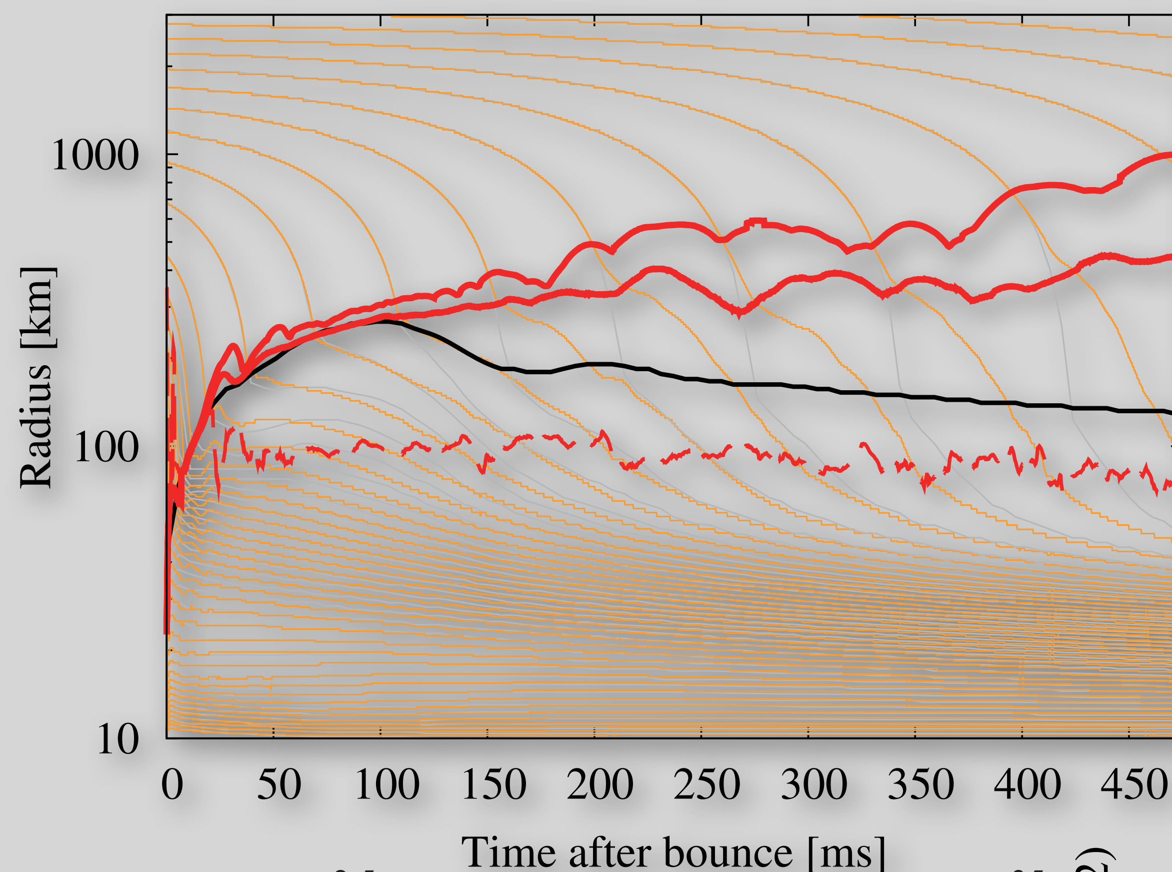
Neutrino-driven explosion in multi-D simulation

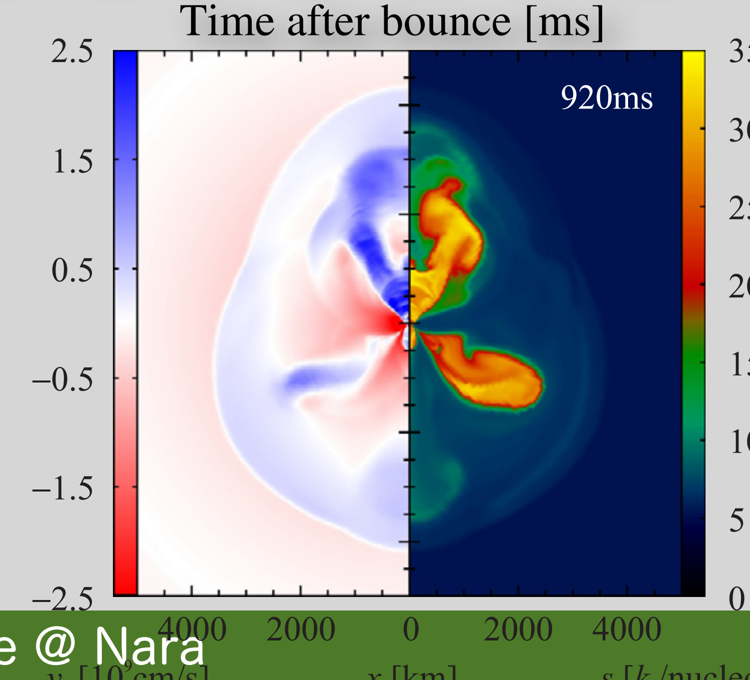
Recently, we have successful exploding models driven by neutrino heating

YS, Kotake, Takiwaki, Whitehouse, Liebendörfer, Sato, PASJ, **62**, L49 (2010)



comparison between 1D and 2D

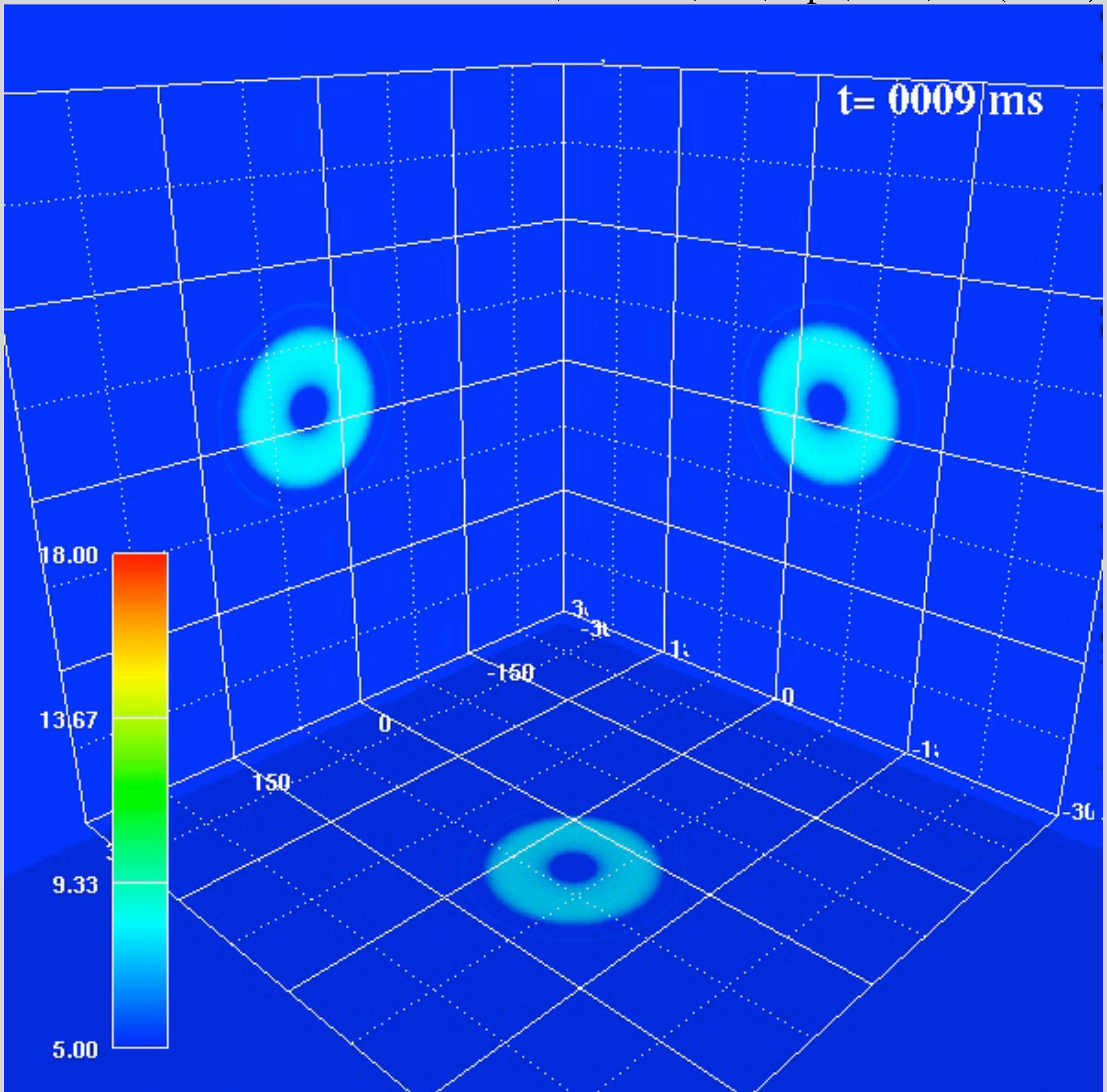




Müller, Janka, Marek (2012)

The first 3D simulation with neutrino transfer

Takiwaki, Kotake, YS, ApJ, **749**, 98 (2012)



320(r)x64(θ)x128(ϕ)x20(E_ν)

XT4@NAOJ

T2K-Tsukuba

K computer

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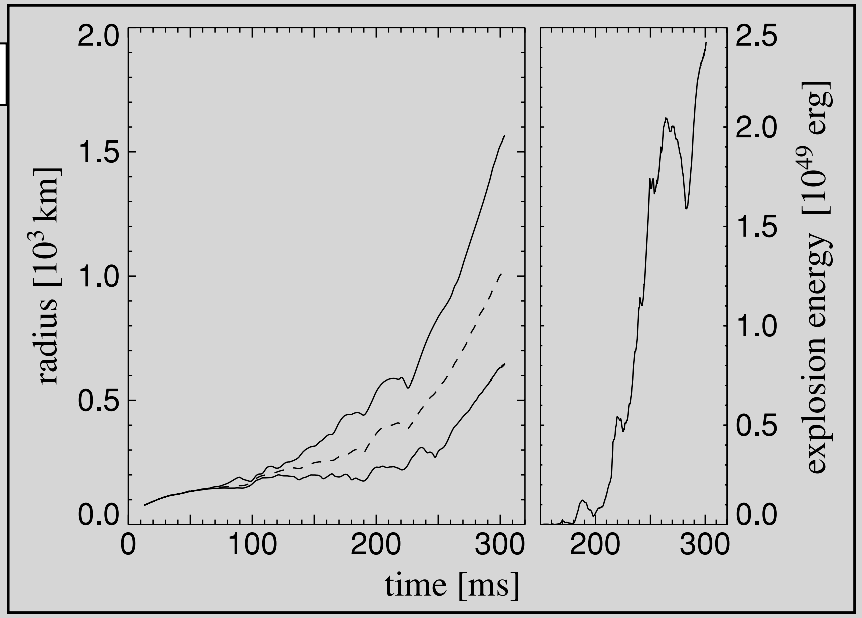
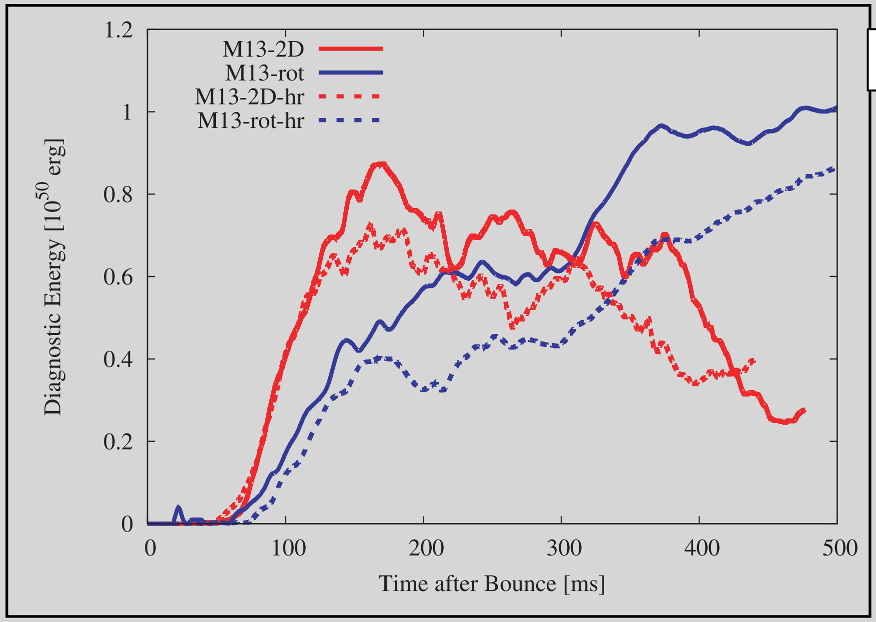
Problems of multi-D explosions

* small explosion energy (~10^{49}-10^{50} erg)

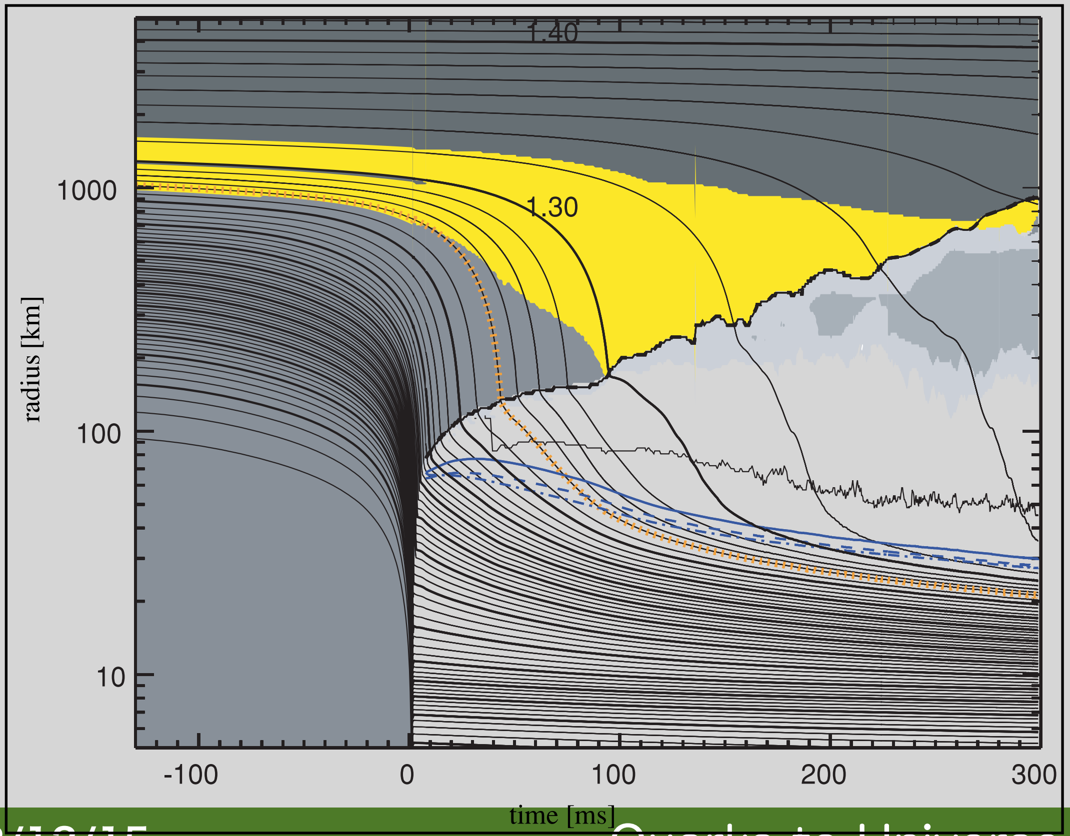
Marek & Janka 09

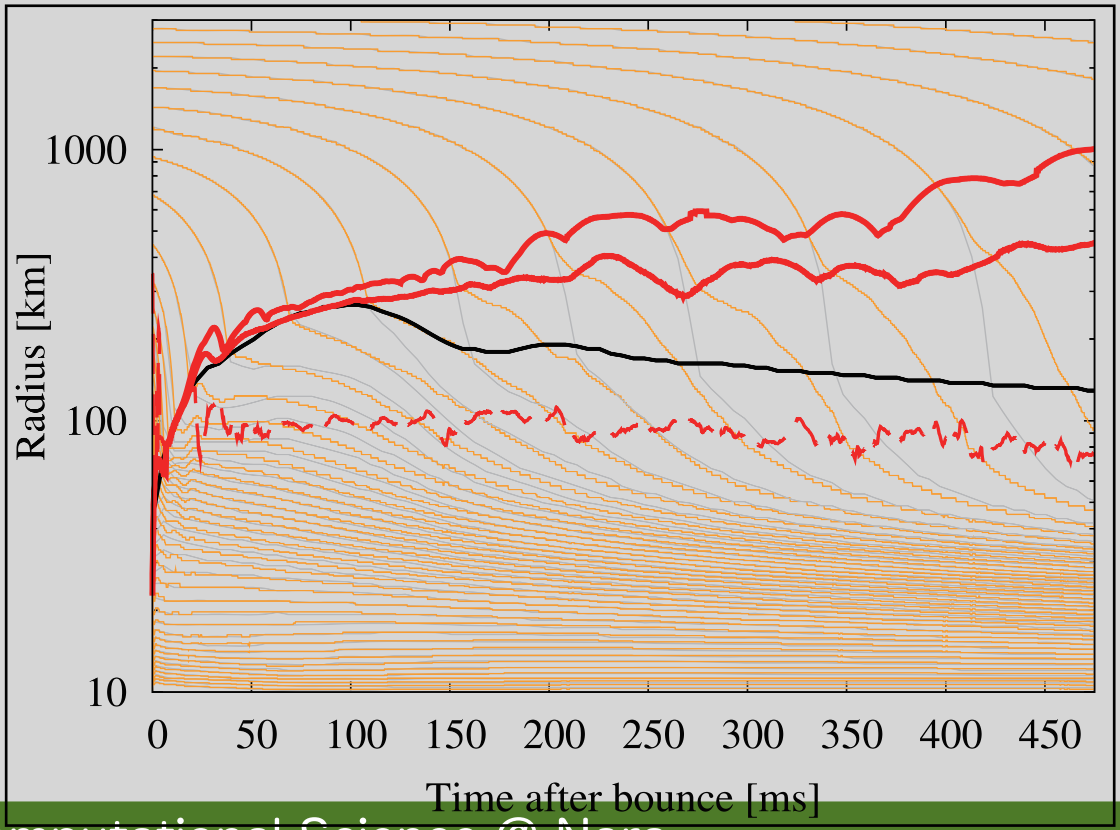




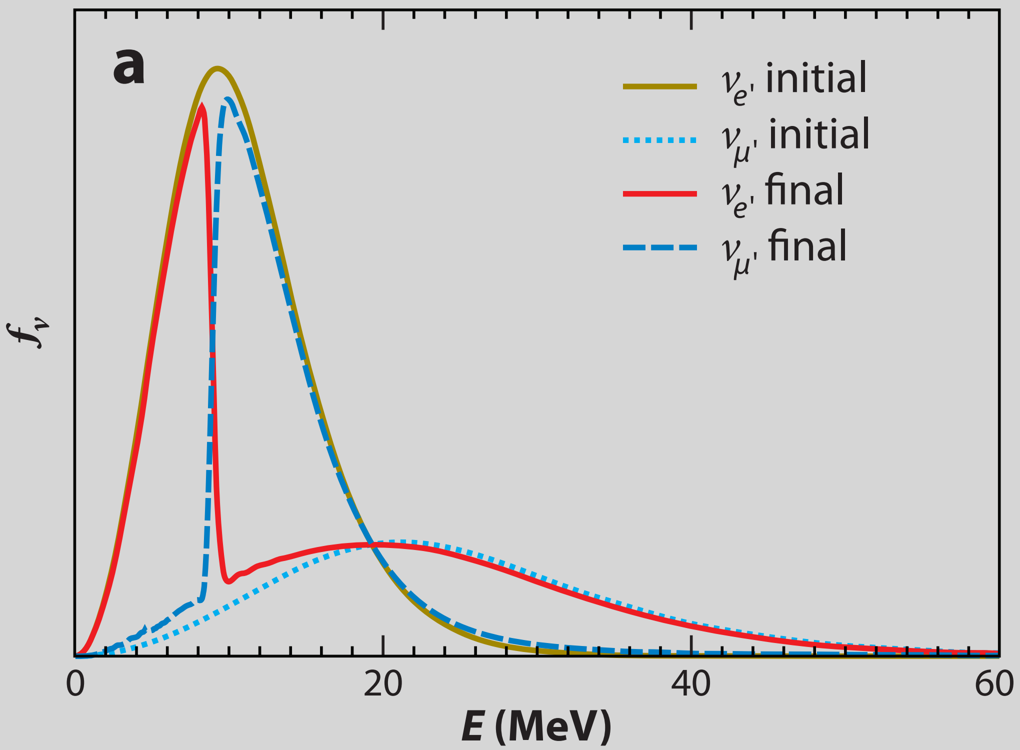
Suwa+ 10

* continuous accretion <=> The remnant is NOT a NS



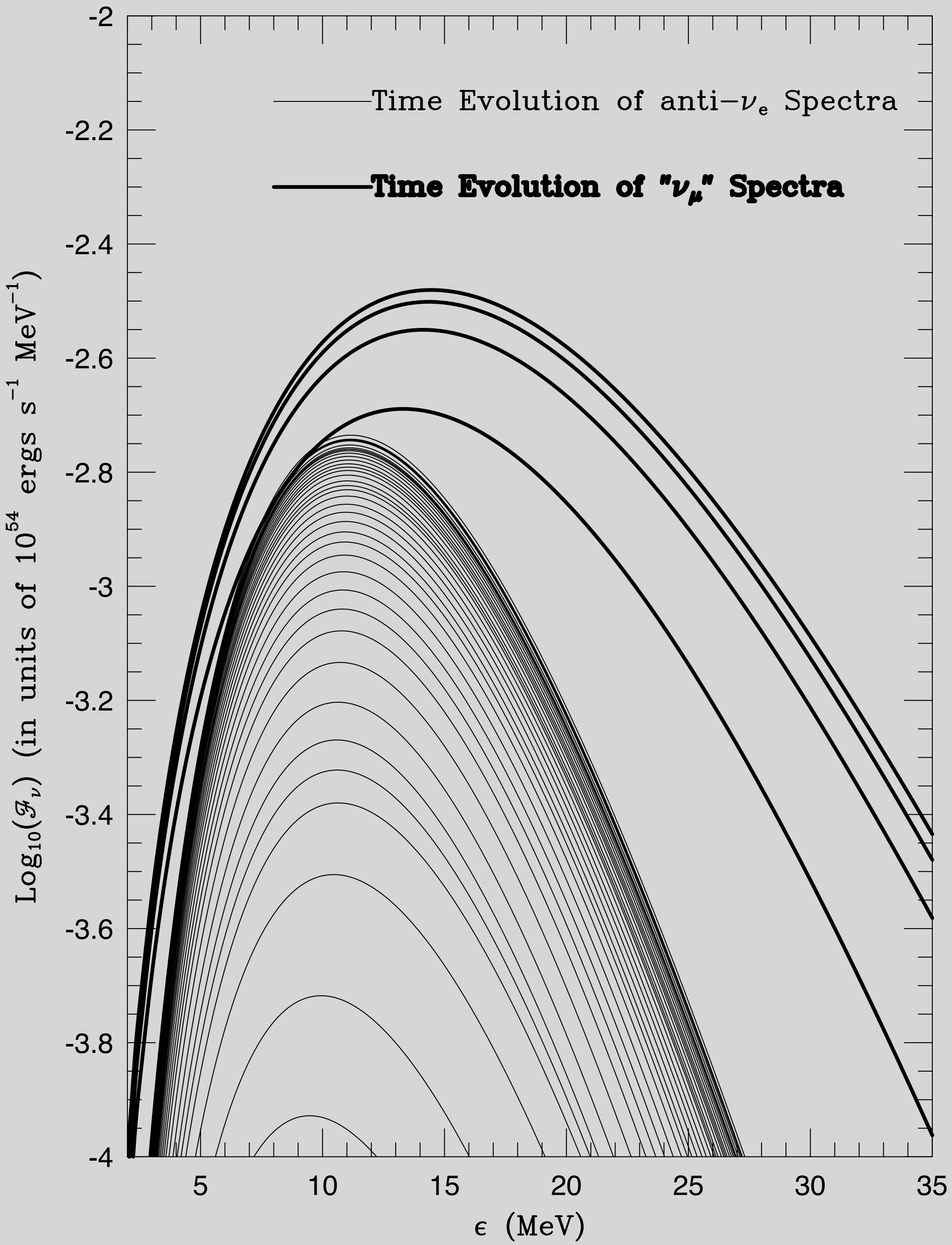


A possibility: the collective oscillation of neutrinos



Duan+ 10

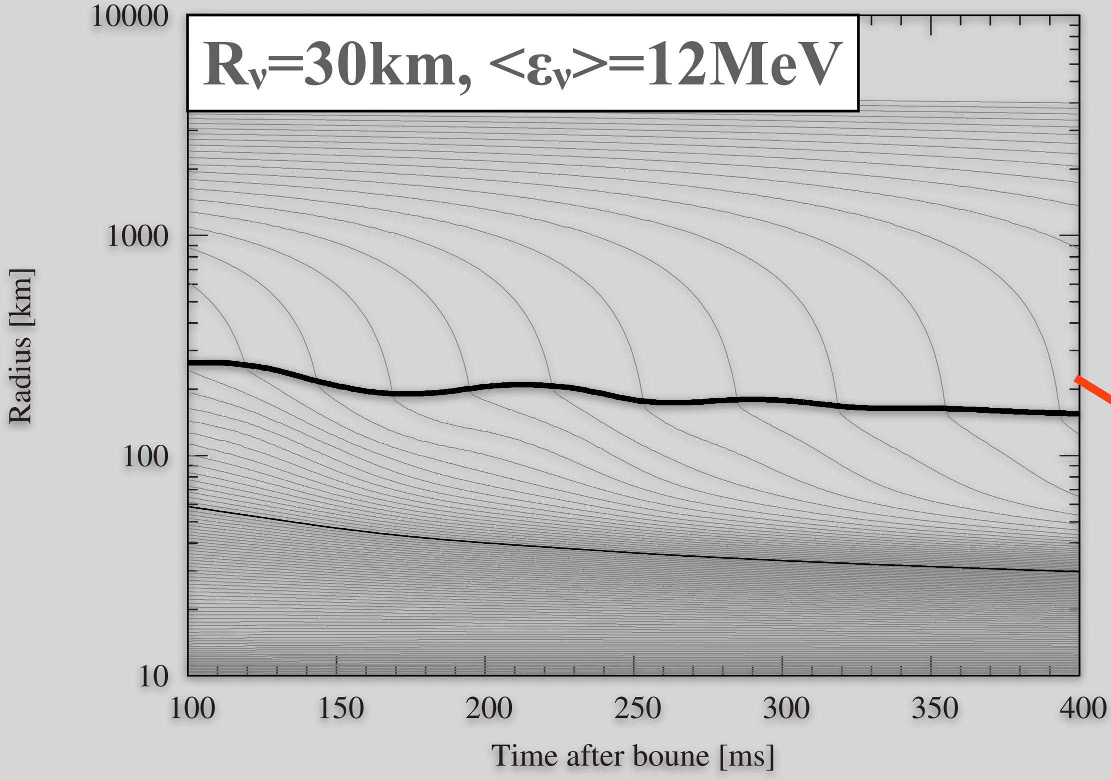
Burrows & Thompson 02

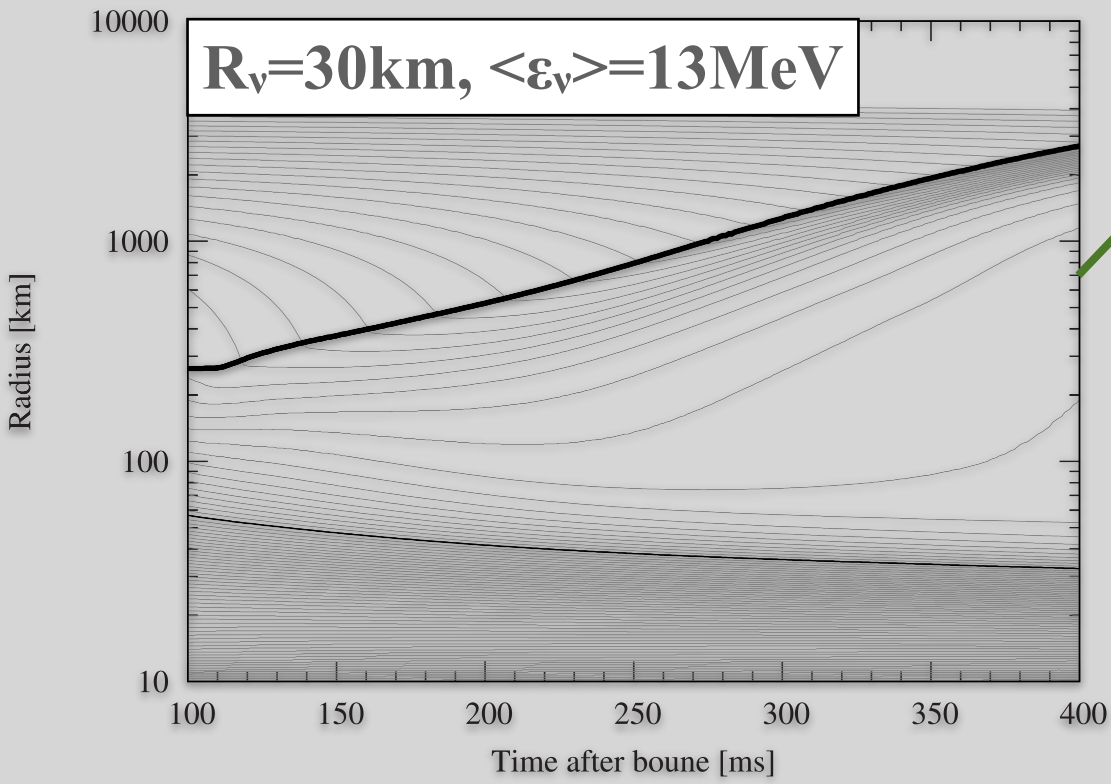


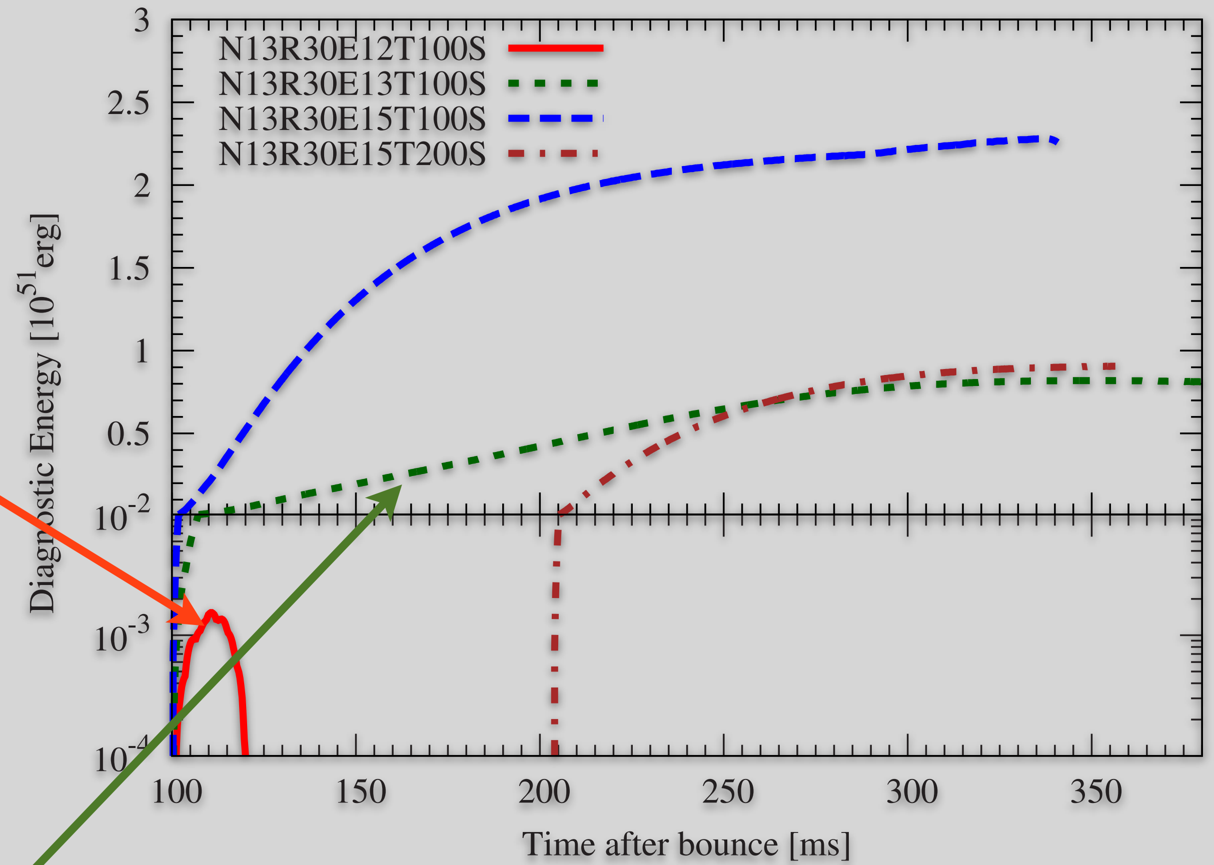
- Because of the mass of neutrinos, the flavor oscillates in propagation
- The spectrum can be different at the emission and absorption site.
- **Especially, $\nu_{\mu/\tau} \rightarrow \nu_e$ is important**
  - Reaction rate: $\sigma \propto E^2$
  - Average energy: $\nu_{\mu/\tau} > \nu_e$

Collective oscillation

YS, Kotake, Takiwaki, Liebendörfer, Sato, ApJ, **738**, 165 (2011)



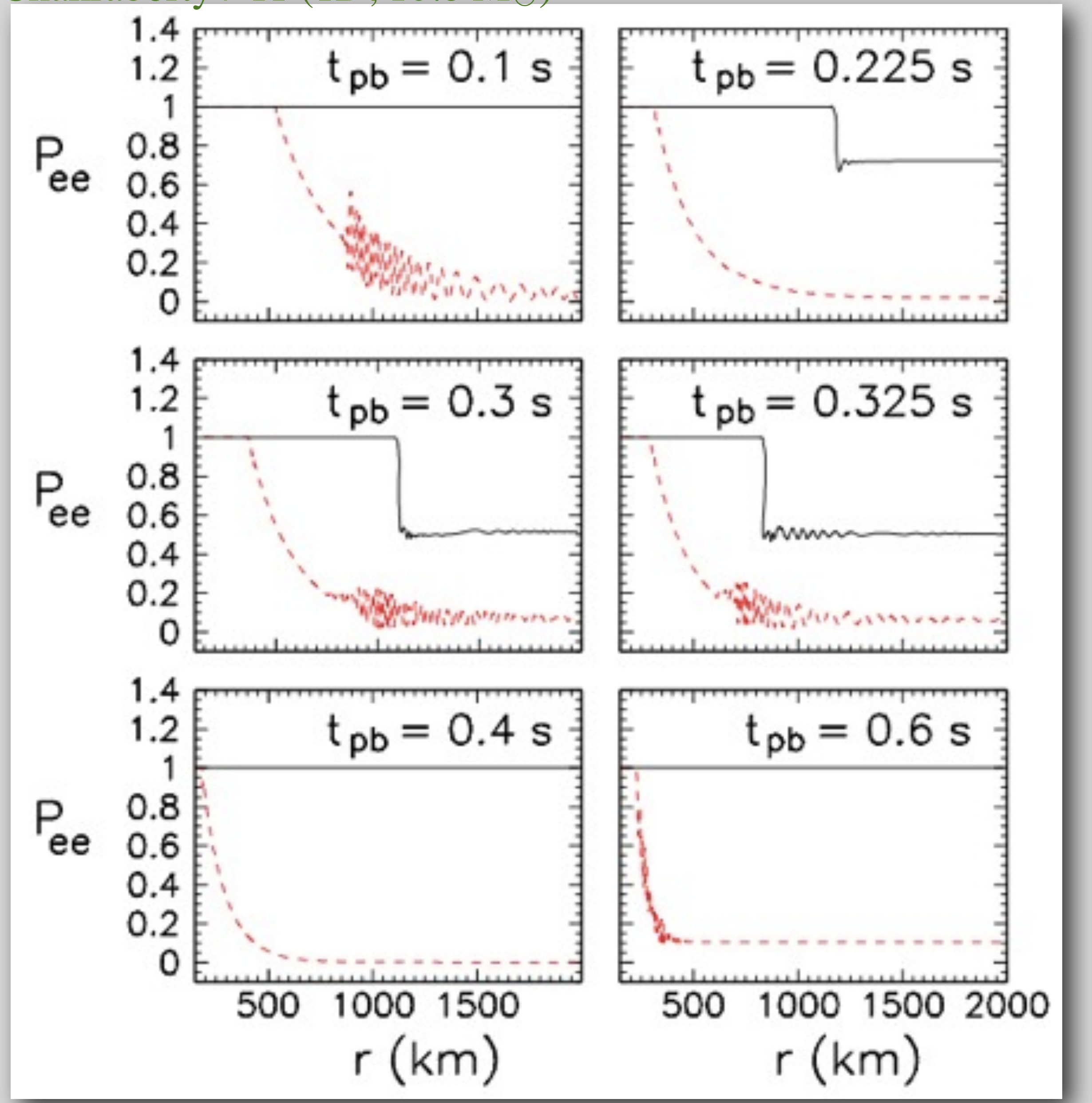




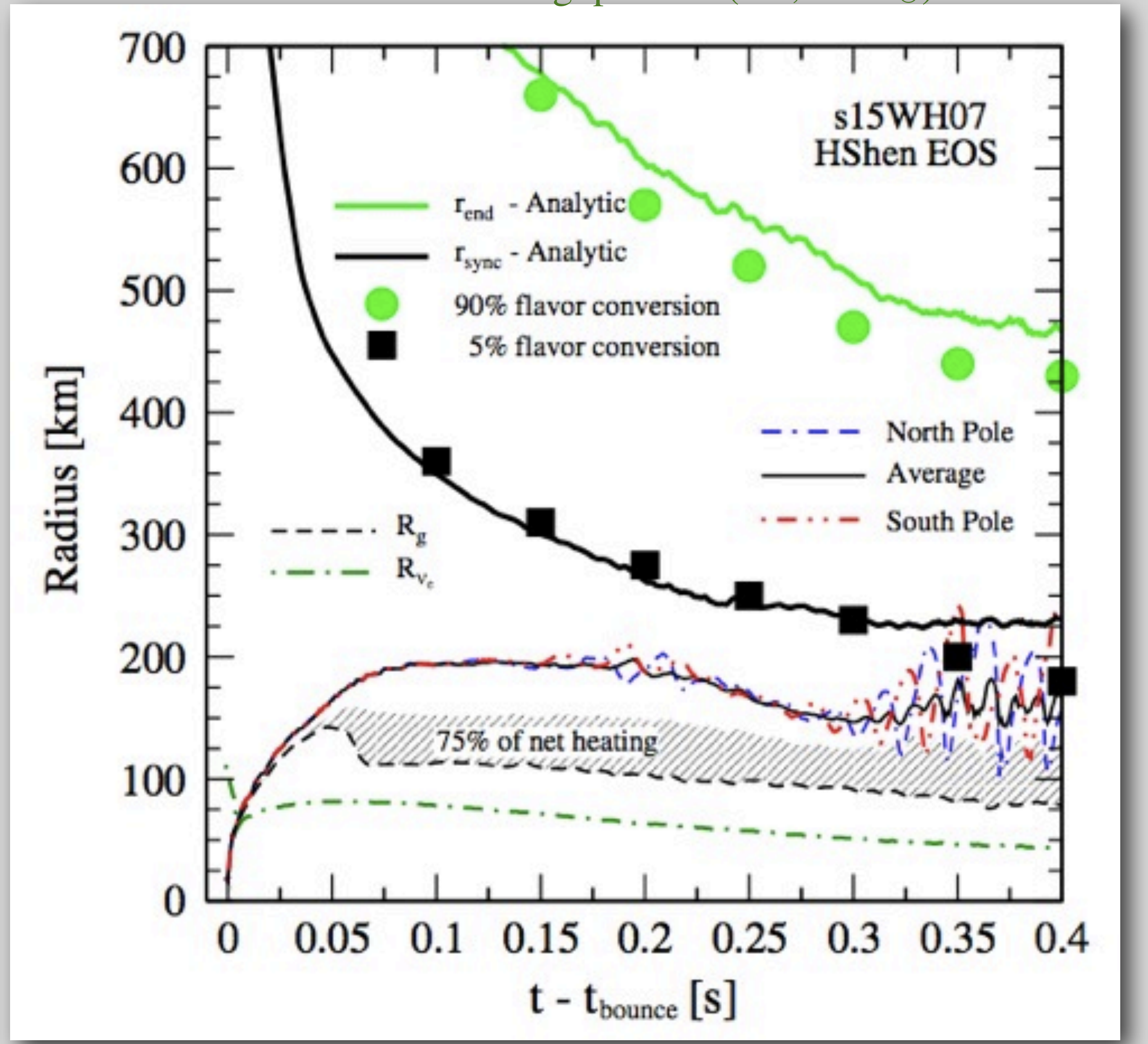
- critical heating rate
- explosion energy~10^{51} erg
- PNS (~1$M_\odot$)

Important note

Chakraborty+ 11 (1D, 10.8 $M_{\odot}$)



Dasgupta+ 12 (2D, 15 $M_{\odot}$)



* The matter density would suppress the collective oscillation
* However, after the onset of the explosion the swapped spectrum might enhance the heating rate and amplify the explosion stronger
* Numerical simulations that include the neutrino collective oscillations in a self-consistent way are required to pin down this problem!

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Finite temperature EOSs

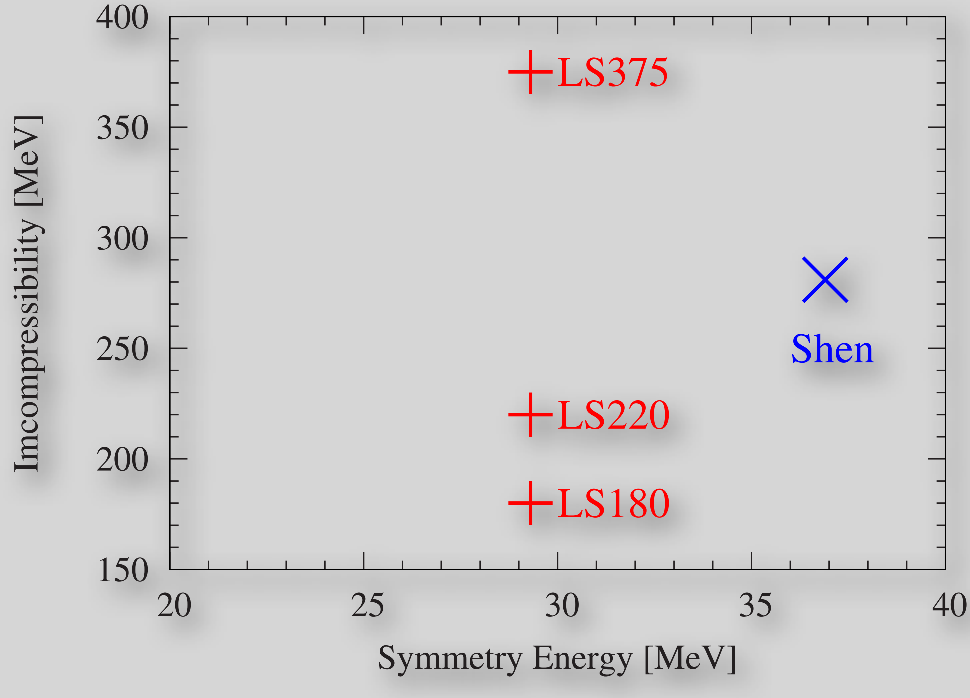
- Lattimer & Swesty (LS) (1991)
  - based on compressible liquid drop model
  - variants with K=180, 220, and 375 MeV
- H.Shen et al. (1998, 2011)
  - relativistic mean field theory (TM1)
  - including hyperon component (~2011)
- Hillebrandt & Wolff (1985)
  - Hartree-Fock calculation
- G.Shen et al. (2010, 2011)
  - relativistic mean field theory (NL3, FSUGold)
- Hempel et al. (2012)
  - relativistic mean field theory (TM1, TMA, FSUGold)

	incompressibility K [MeV]	symmetry energy J (S) [MeV]	slope of symmetry energy L [MeV]
LS	180, 220, 375	29.3	---
HShen	281	36.9	111
HW	263	32.9	---
GShen	271.5 (NL3) 230.0 (FSU)	37.29 (NL3) 32.59 (FSU)	118.2 (NL3) 60.5 (FSU)
Hempel	318 (TMA) 230 (FSU)	30.7 (TMA) 32.6 (FSU)	90 (TMA) 60 (FSU)

$$E(x,\beta) = -E_0 + \frac{1}{18}Kx^2 + \frac{1}{162}K'x^3 + \dots$$
$$+\beta^2\left(J + \frac{1}{3}Lx + \dots\right) + \dots,$$

Numerical simulation

- EOS: LS180, (LS220,) LS375, and Shen



Note: Of course the other parameters differ as well.

- Axisymmetric simulation (ZEUS-2D; Stone & Norman 92)

- Hydrodynamics + Neutrino transfer

$$\frac{df}{cdt} + \mu\frac{\partial f}{\partial r} + \left[\mu\left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right)\right](1-\mu^2)\frac{\partial f}{\partial \mu} + \left[\mu^2\left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right) - \frac{v}{cr}\right] D\frac{\partial f}{\partial E}$$
$$= j(1-f) - \chi f + \frac{E^2}{c(hc)^3}\left[(1-f)\int R f' d\mu' - f\int R(1-f')d\mu'\right]$$

(Lindquist 1966; Castor 1972; Mezzacappa & Bruenn 1993)

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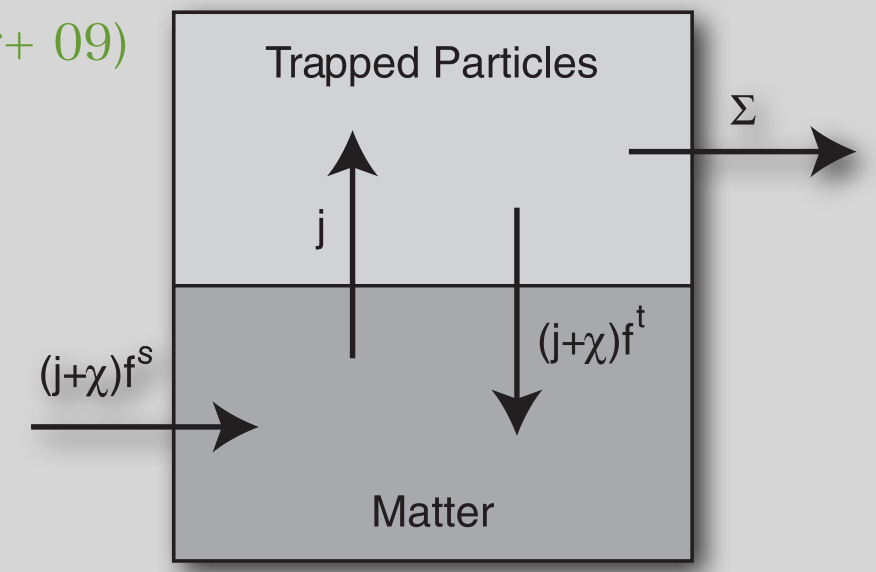
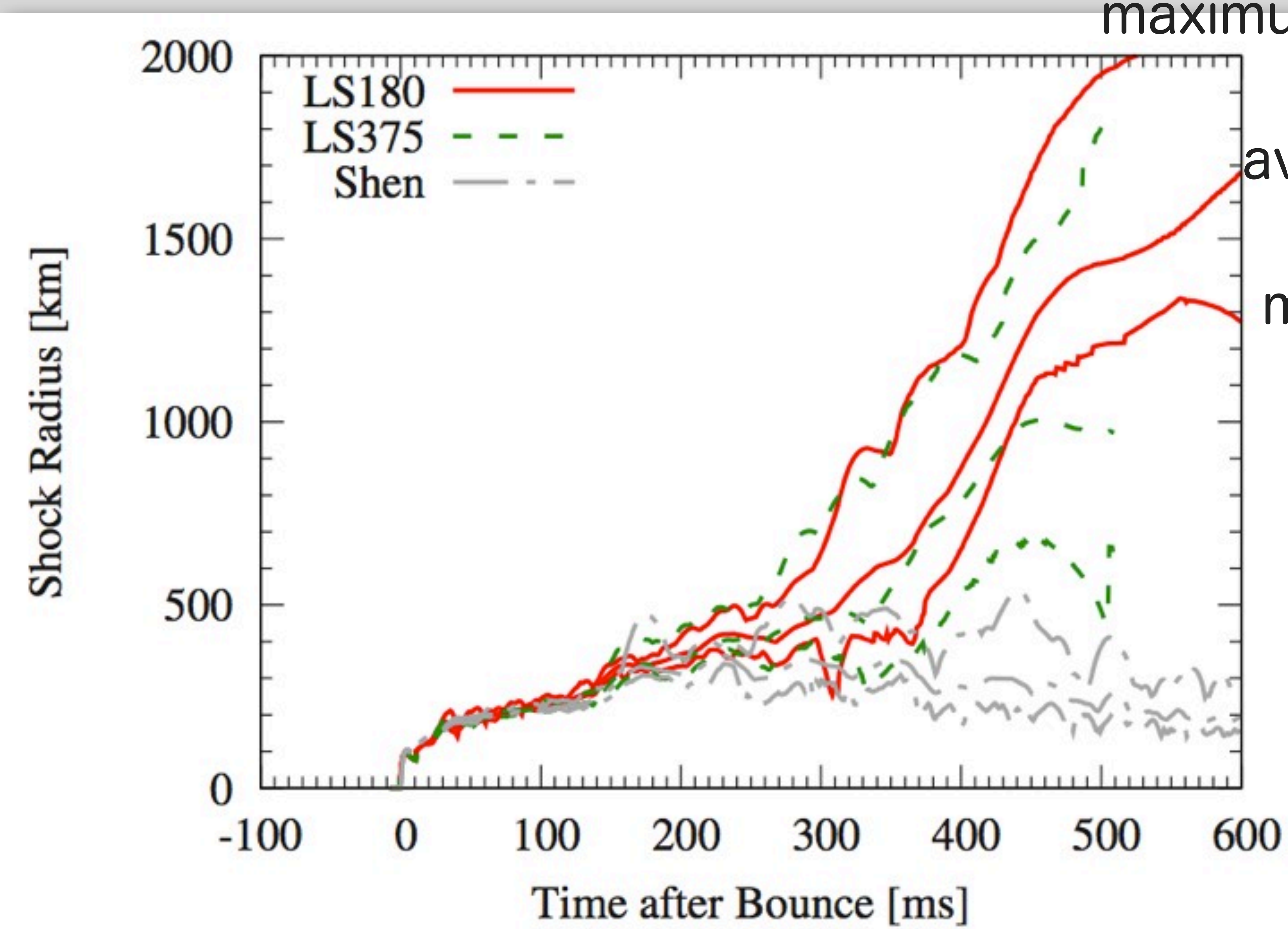
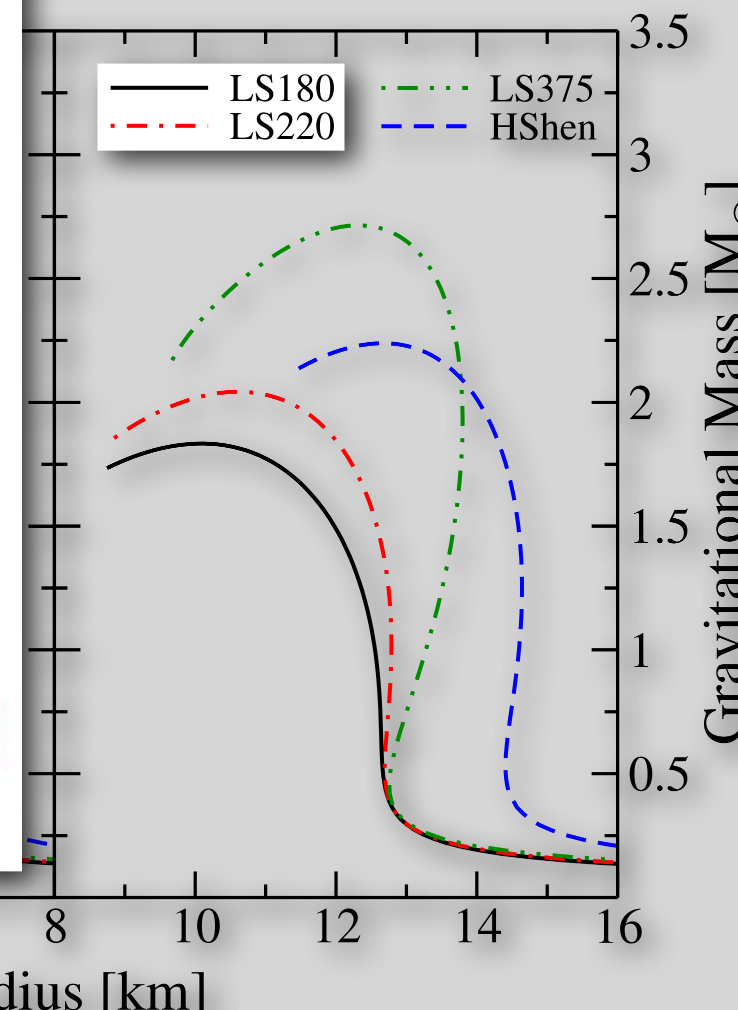


- progenitor: 15 $M_\odot$ (Woosley & Weaver 95)

Shock radius evolution depending on EOS

YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato, ApJ in press, arXiv:1206.6101





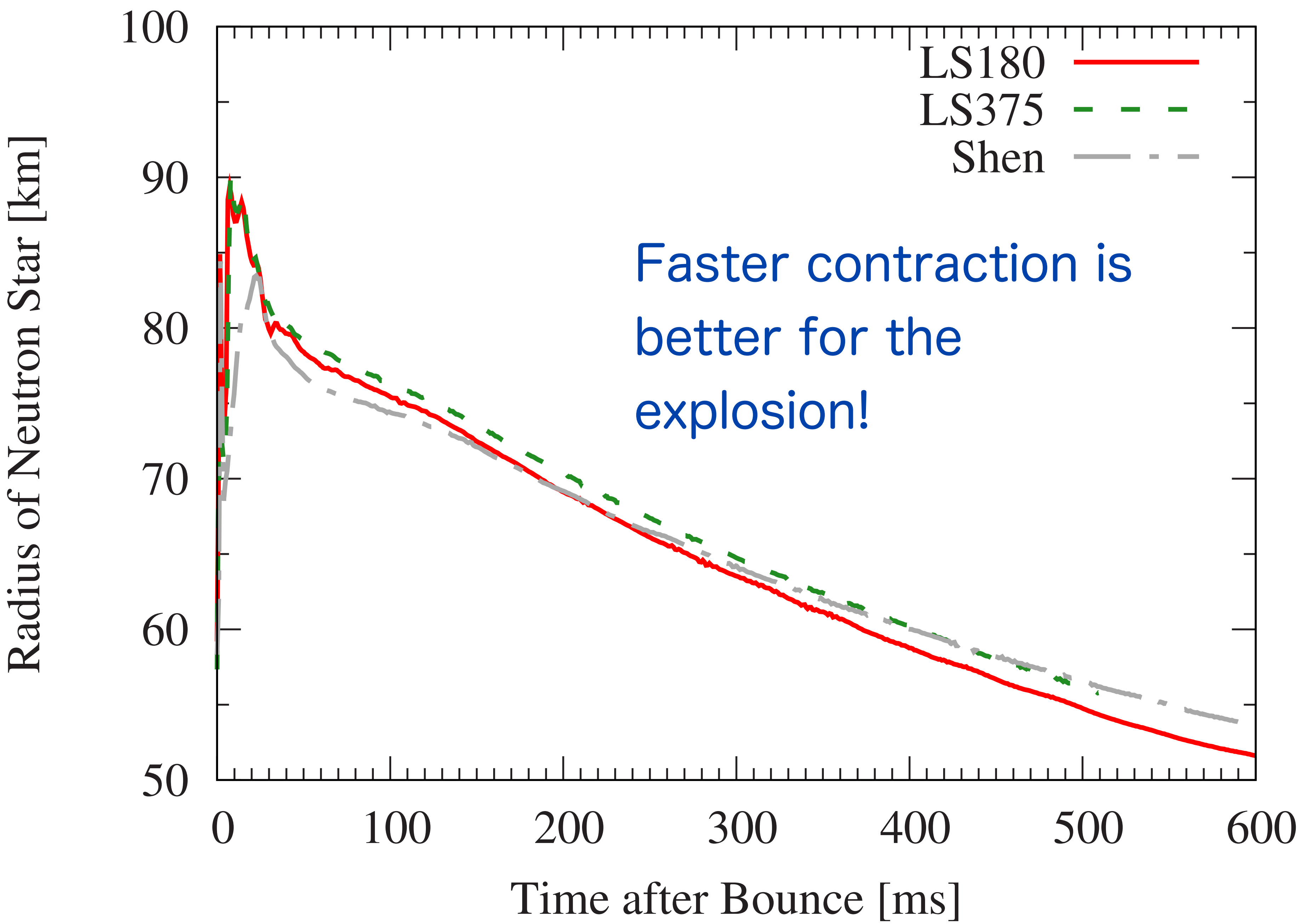
O'Connor & Ott 10

LS180 and LS375 succeed the explosion

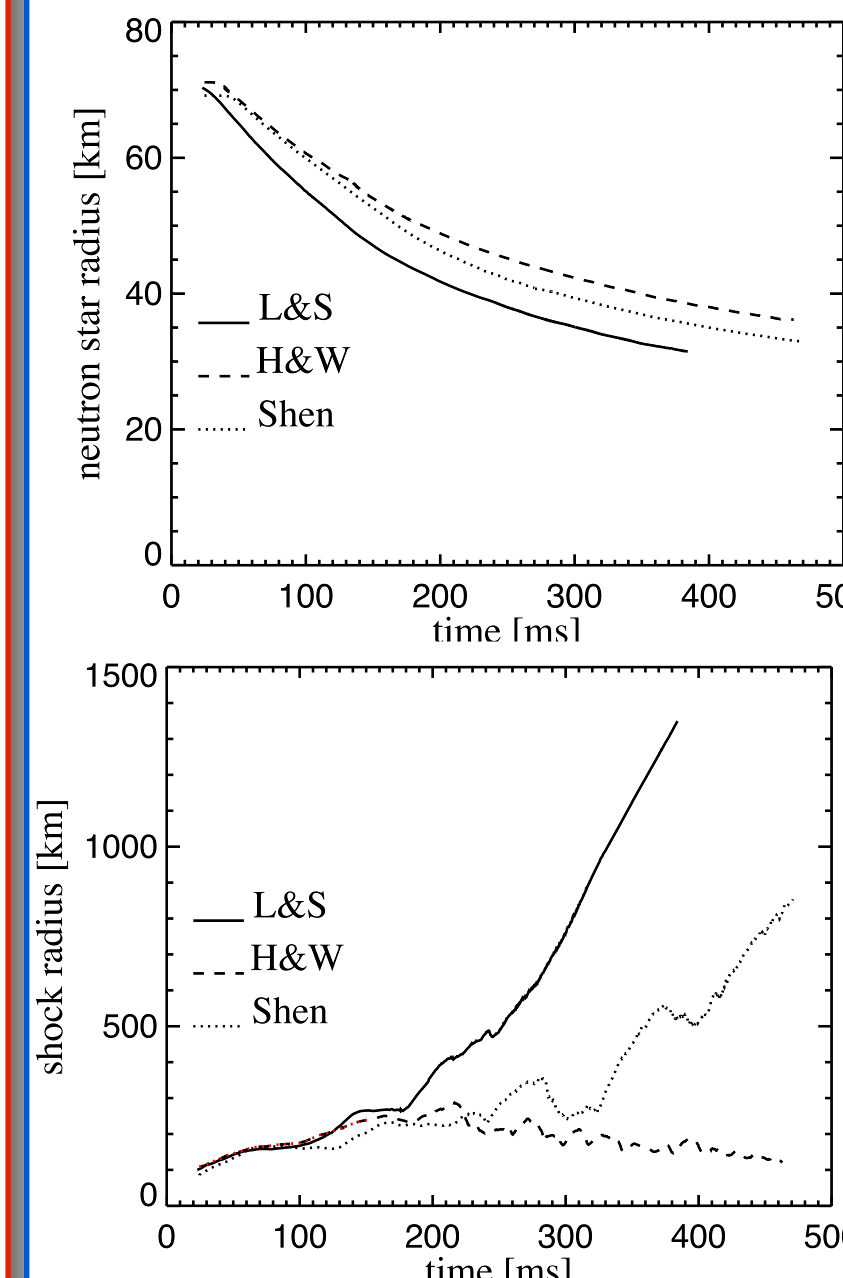
Shen EOS fails

Radius of neutron star

YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato, ApJ in press, arXiv:1206.6101



Janka, arXiv:1206.2503



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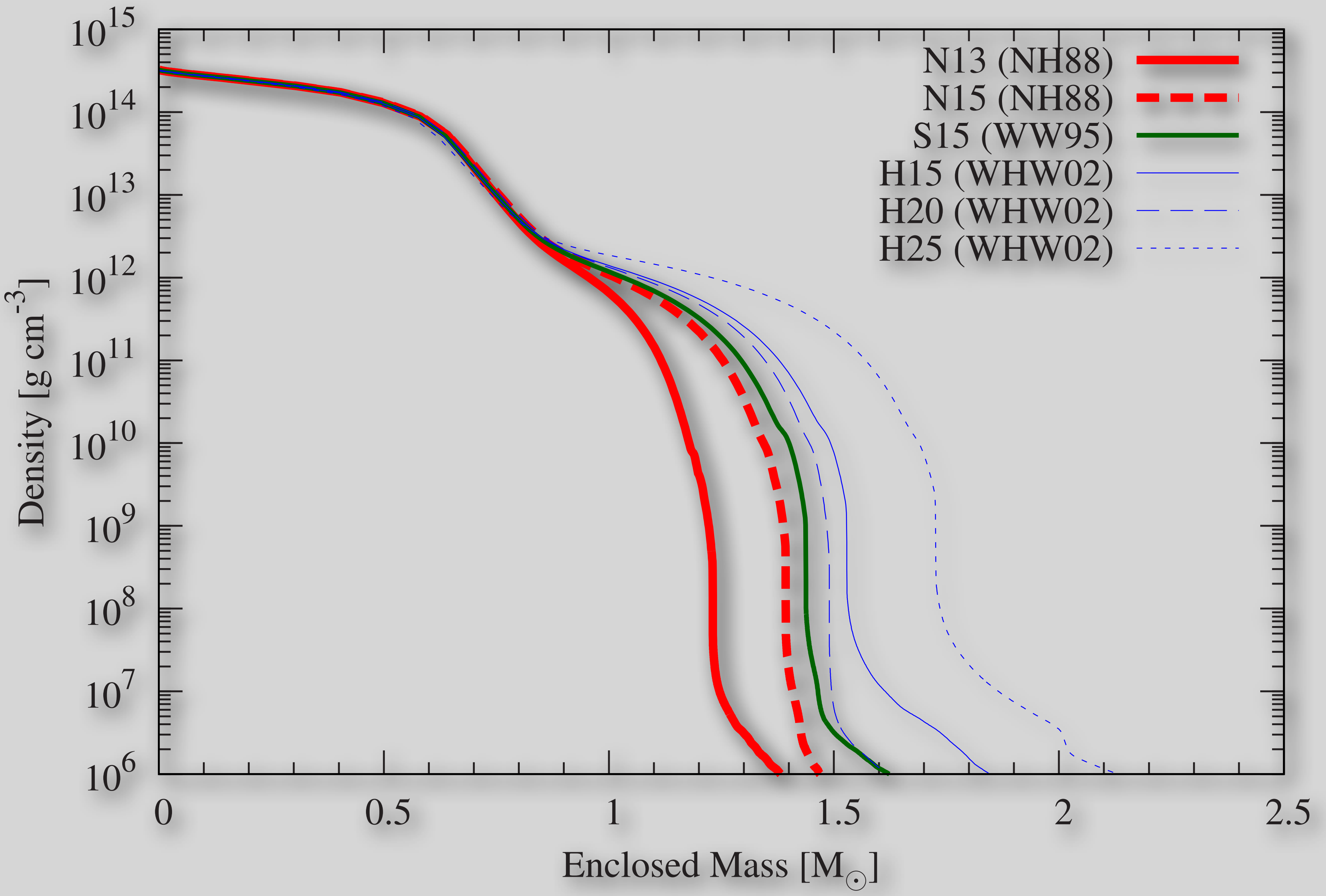
Progenitor dependence

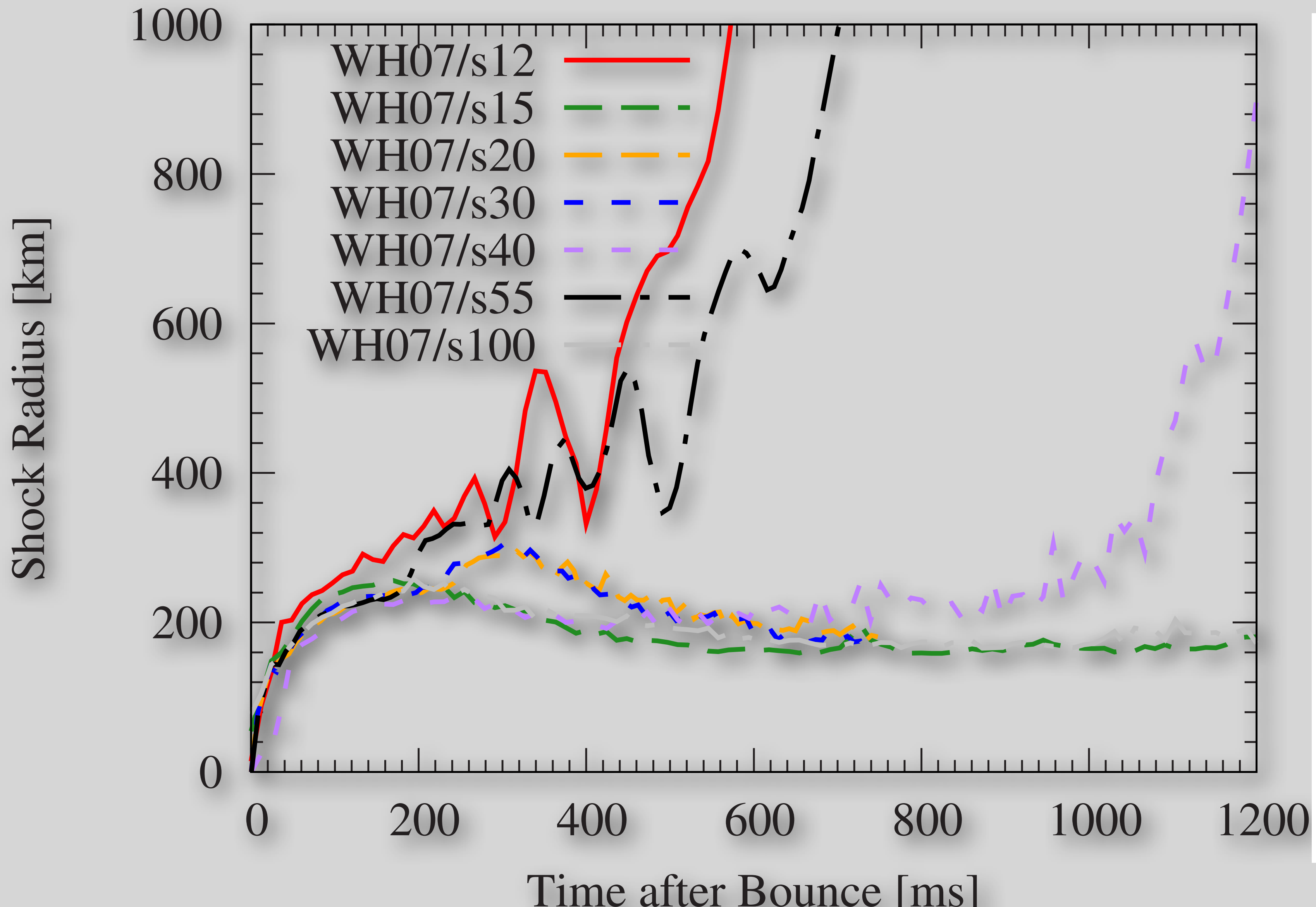
YS, Kotake, Takiwaki, Liebendörfer, & Sato (2011)

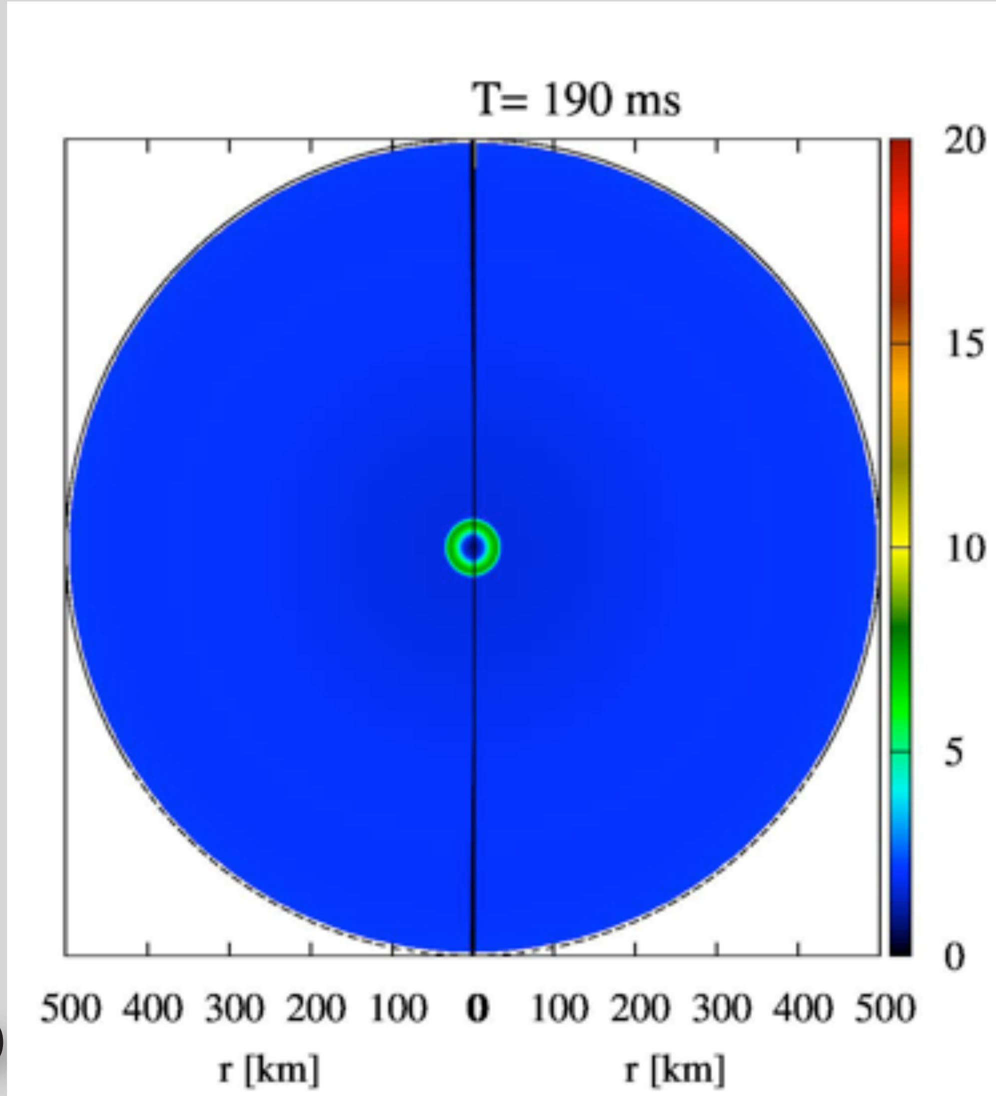


* Density profiles 100 ms after the bounce
* Almost same for M<0.8M⊙
* Profile for M>0.8M⊙ reflect the initial profile

Shock evolution in 2D simulation

2D simulation using progenitors from Woosley & Heger (2007)

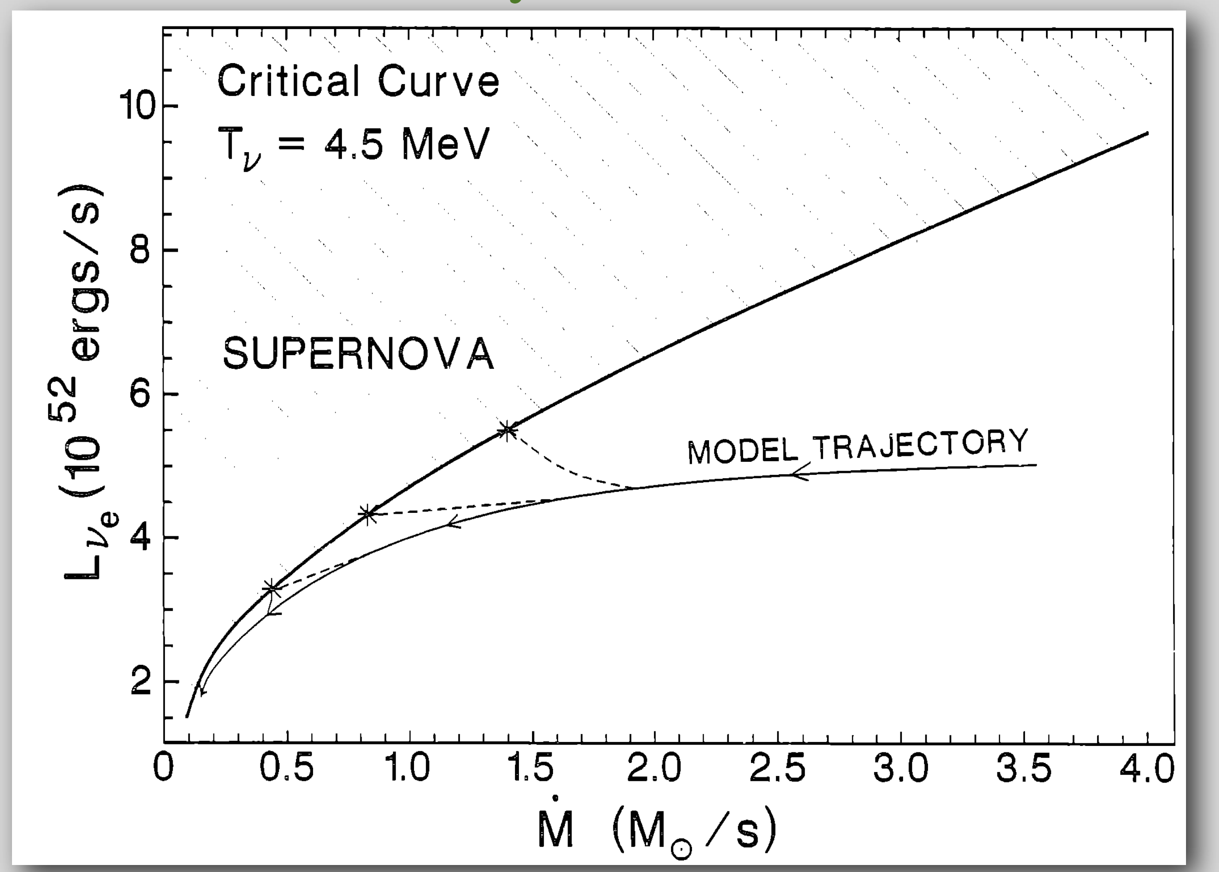


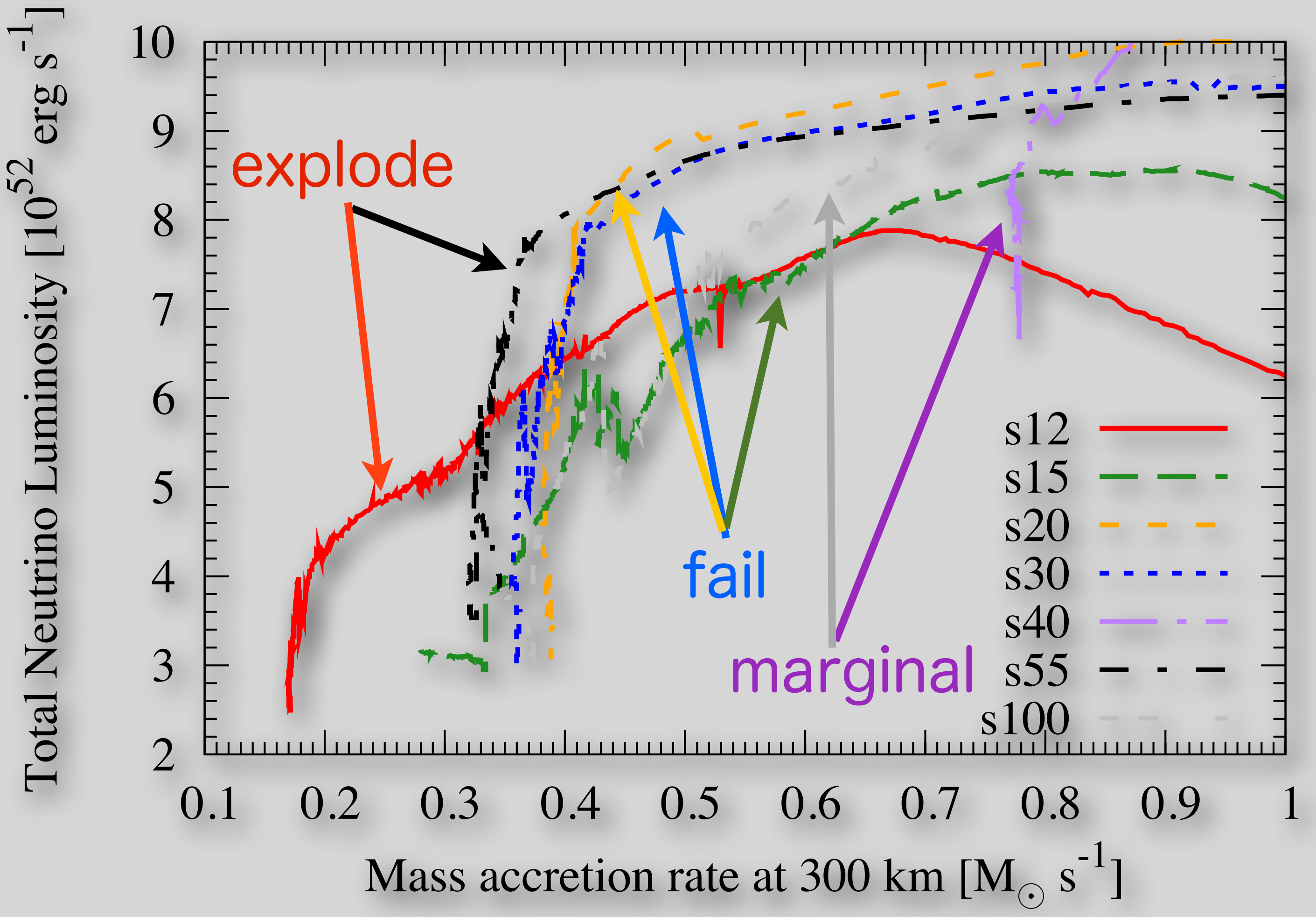


- Several progenitors lead to shock expansion
- No monotonic trend is found
- What determines the difference?

What makes difference?: $\dot{M}$-L_ν curve

Burrows & Goshy 93





- Low $\dot{M}$ and high L_ν are achieved for several progenitors, which produce the explosion
- In order to unveil the relationship between the progenitor structure and trajectories in this plane, more systematic study is necessary...

Summary

- **For supernova modeling, there are a lot of ingredients to pin down the explosion mechanism**
- **We performed multi-dimensional neutrino-radiation hydrodynamic simulations of core-collapse supernovae**
- **The physical parts investigated are**
  - Multi dimensionality **[1D<2D<?3D]** (YS+ 2010; Takiwaki, Kotake, YS 2012)
  - Effect of neutrino oscillation **[potentially strengthen the explosion]** (YS+ 2011)
  - Impacts of nuclear equation of state **["softer" is better]** (YS+ 2012)
  - Dependence of Progenitor structure **[under investigation…]** (YS+ 2013?)

- **There are still a lot of tasks to do to unveil the explosion mechanism of core-collapse supernovae…**