Axisymmetric simulations of core-collapse supernovae with spectral neutrino transfer

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Collaboration with
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計算科学研究機構
Advanced Institute for Computational Science

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

Systematics in supernova simulations

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

- **Dimensionality of hydrodynamics** — Iwakami+ 08, Nordhaus+ 10, Hanke+ 11, Takiwaki+ 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
  - Collective oscillation — Raffelt & Smirnov 07, Duan+ 10, Dasgupta+ 10
- **Nuclear equation of state** — Lattimer & Swesty 91, H. Shen+ 98, G. Shen+ 10, Furusawa+ 11, Hempel+ 12
- **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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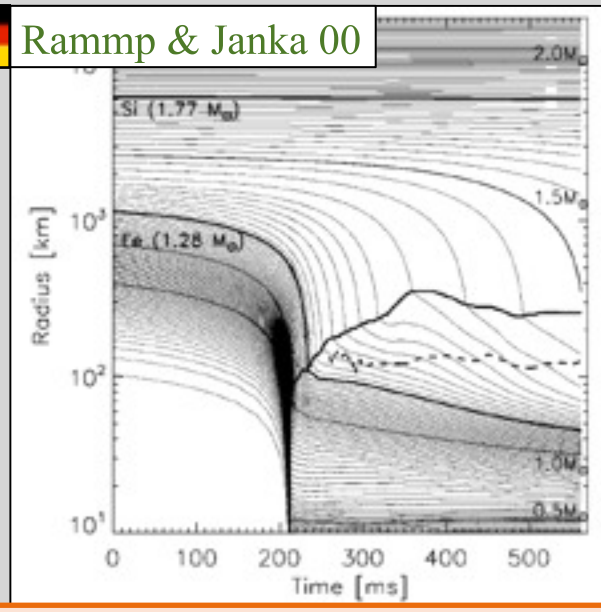
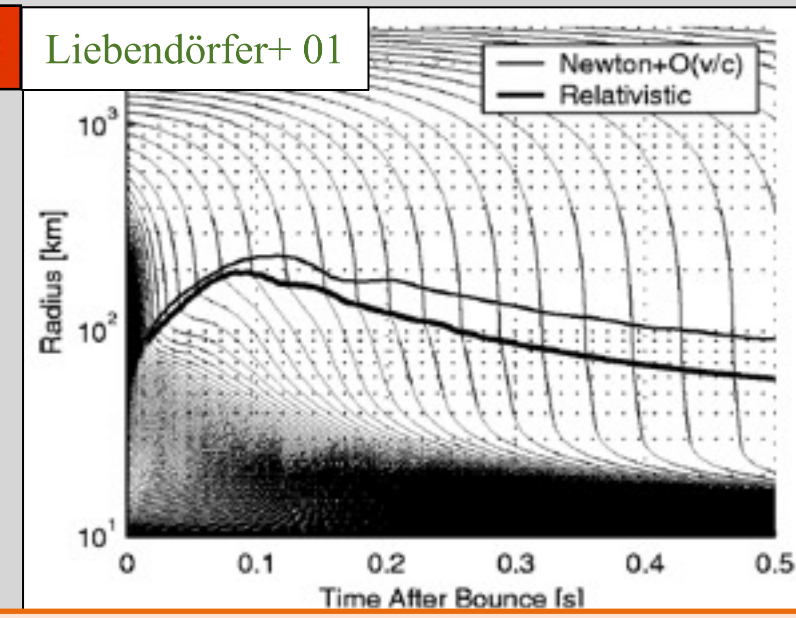
1D simulations: fail to explode

Rammp & Janka 00

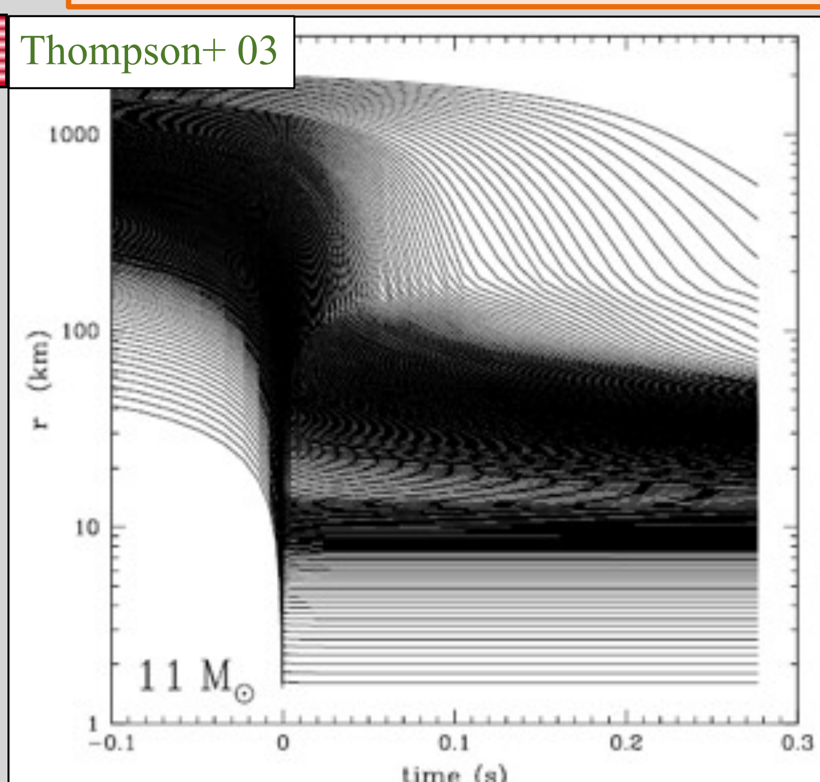


Liebendörfer+ 01

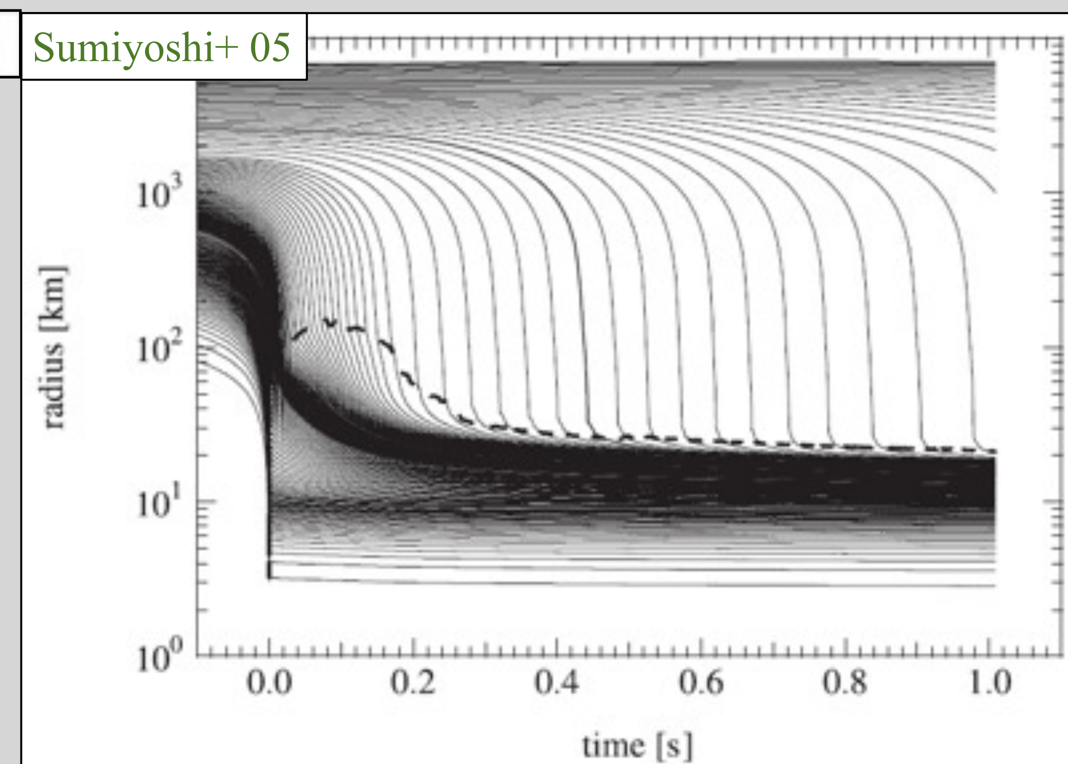


By including all available physics to simulations, we concluded that the explosion cannot be obtained in 1D!
(The exception is an 8.8 M☉ star; Kitaura+ 06)

Thompson+ 03

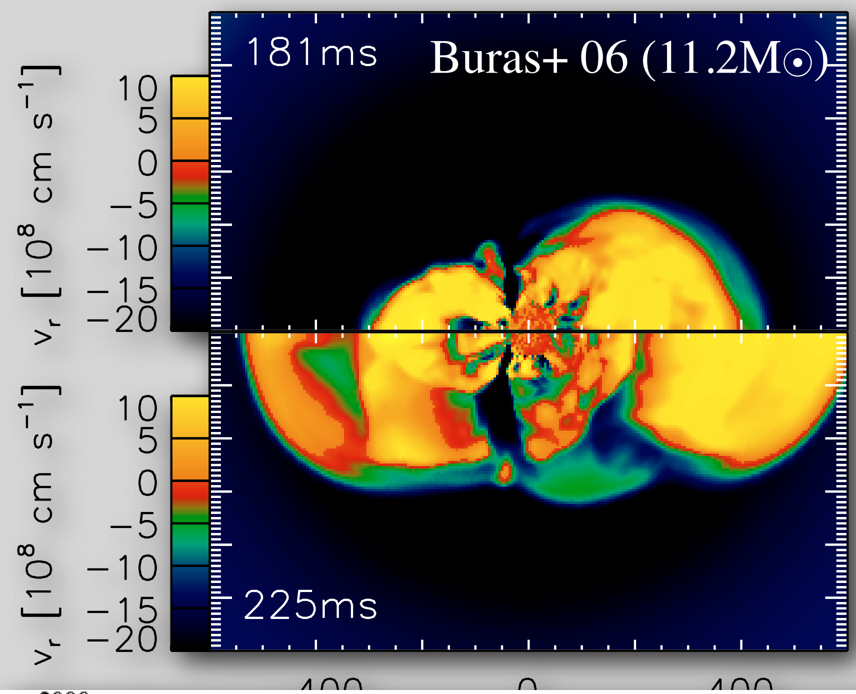


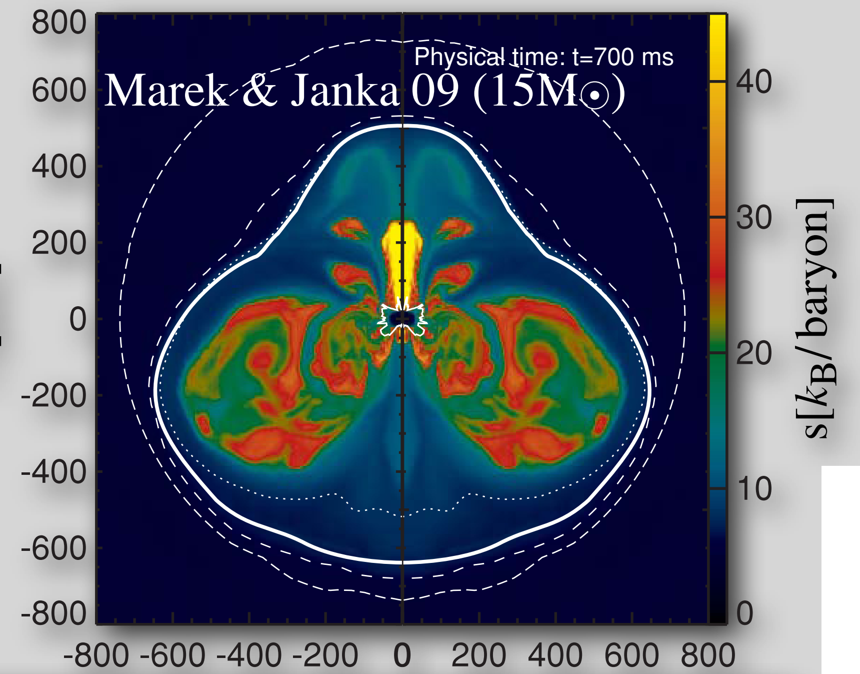
Sumiyoshi+ 05

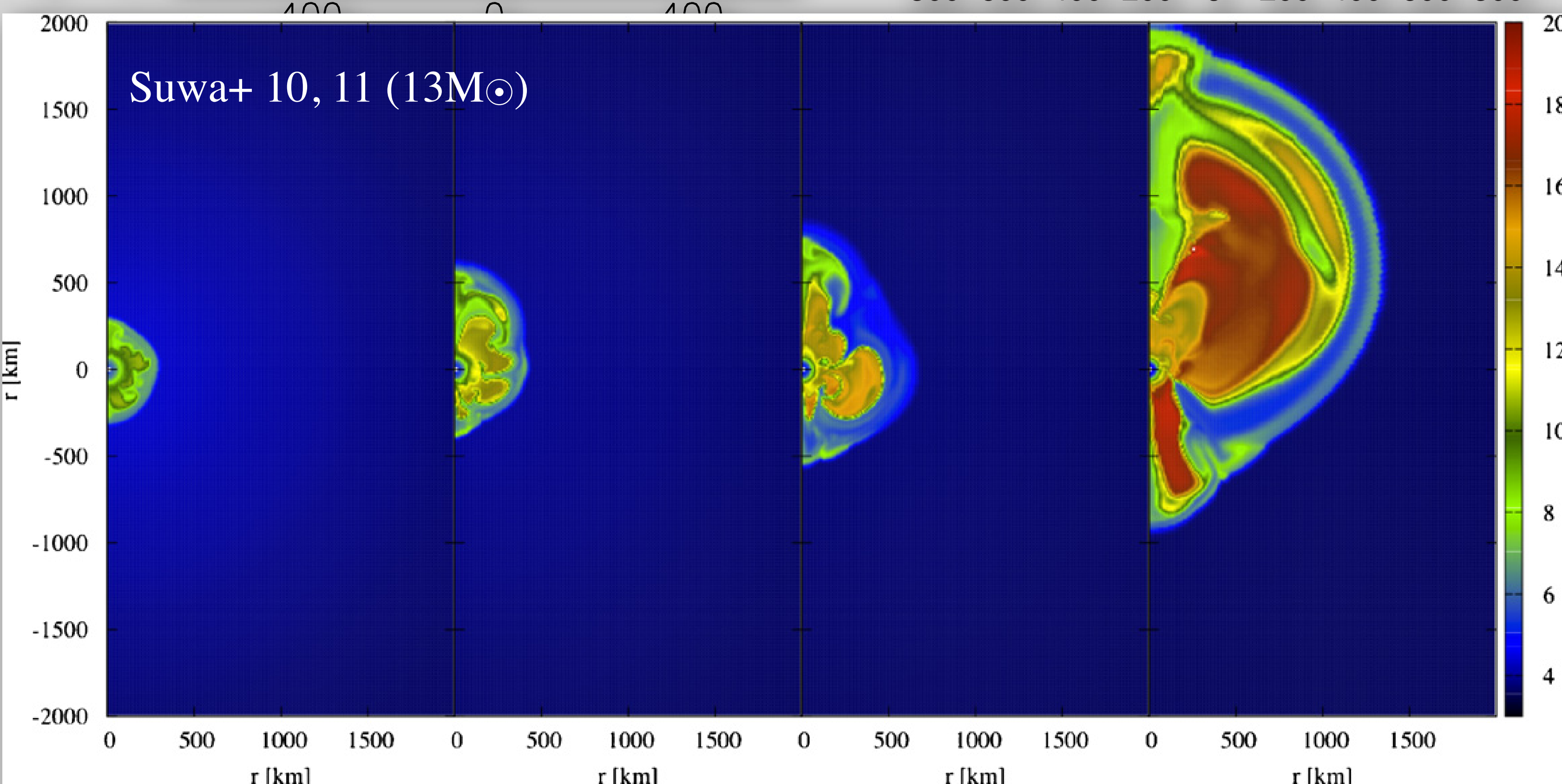


Neutrino-driven explosion

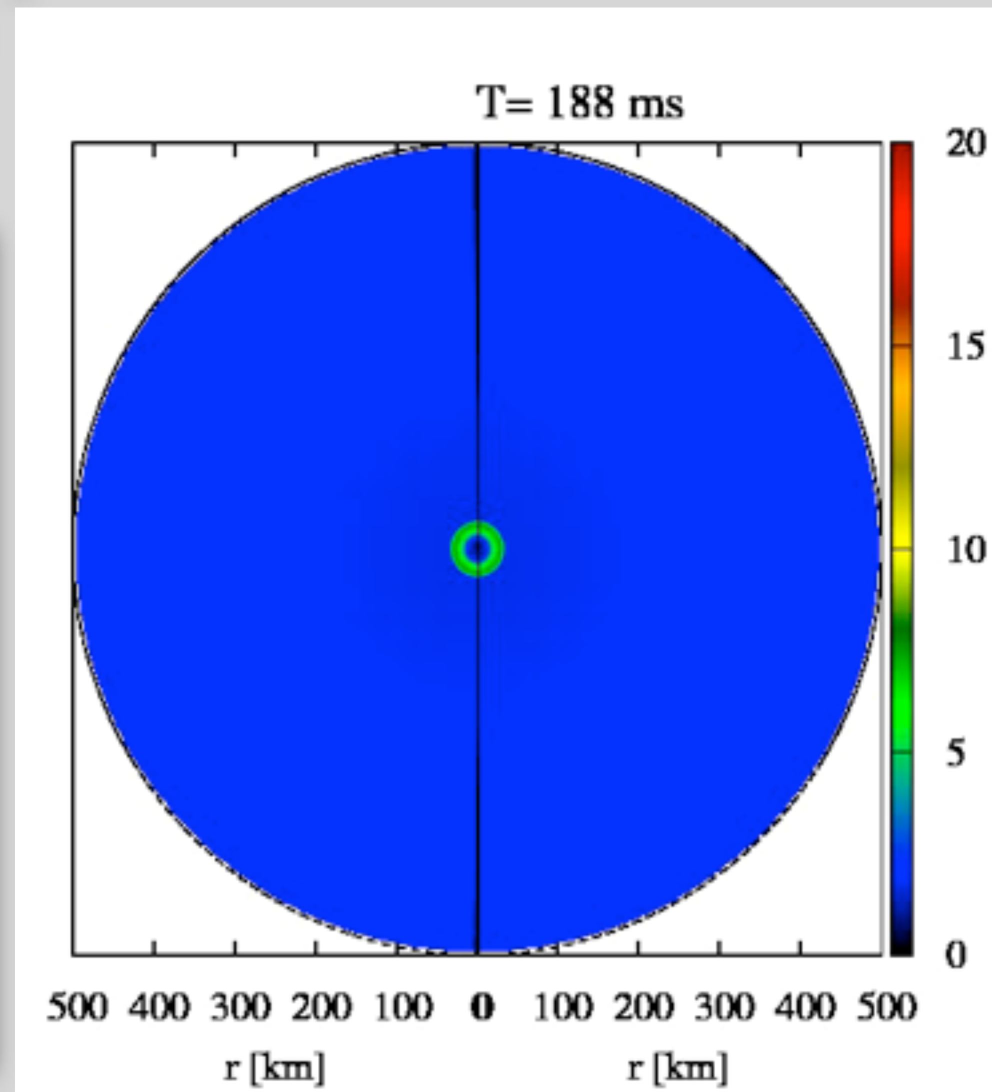
Recently, we have successful exploding models driven by neutrino heating







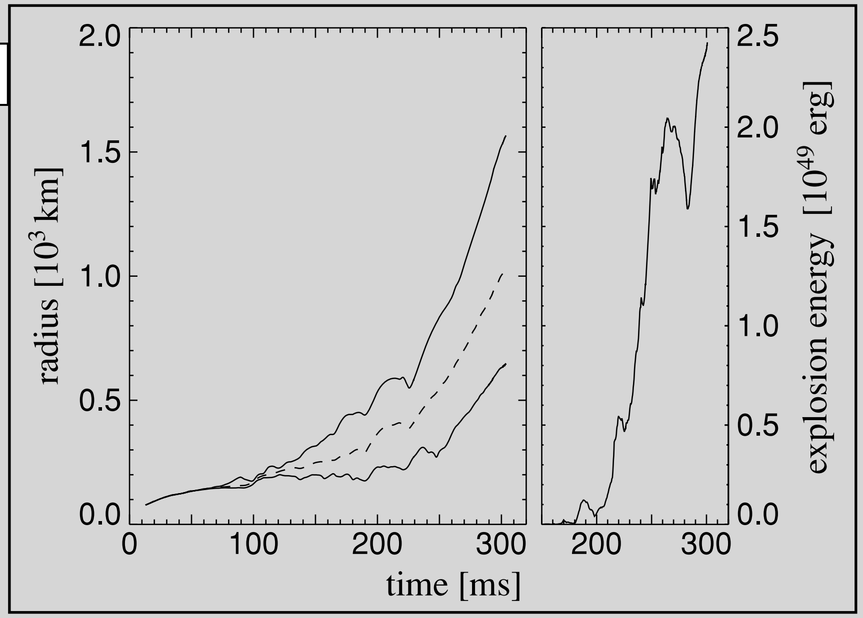
Suwa+ 12 (15M⊙)

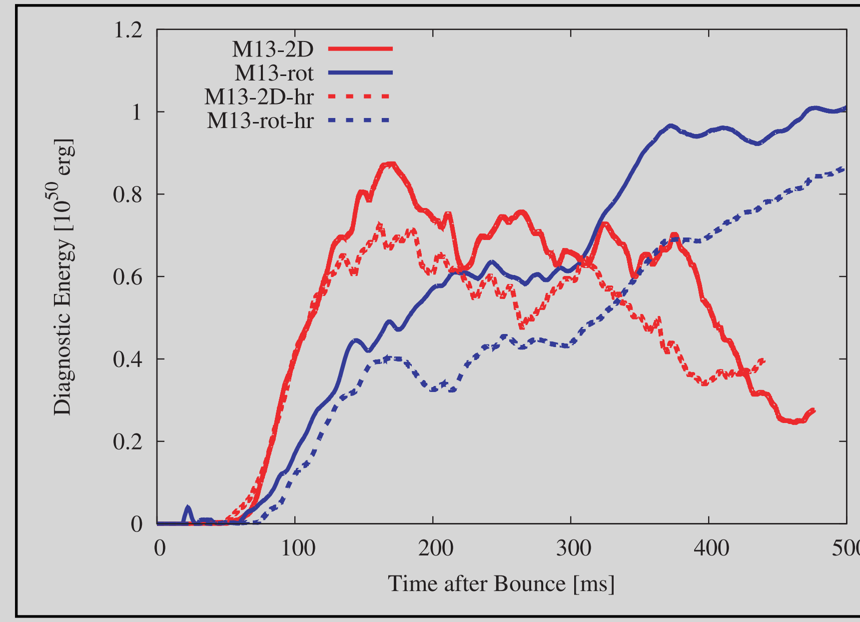


Problems of 2D simulations

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

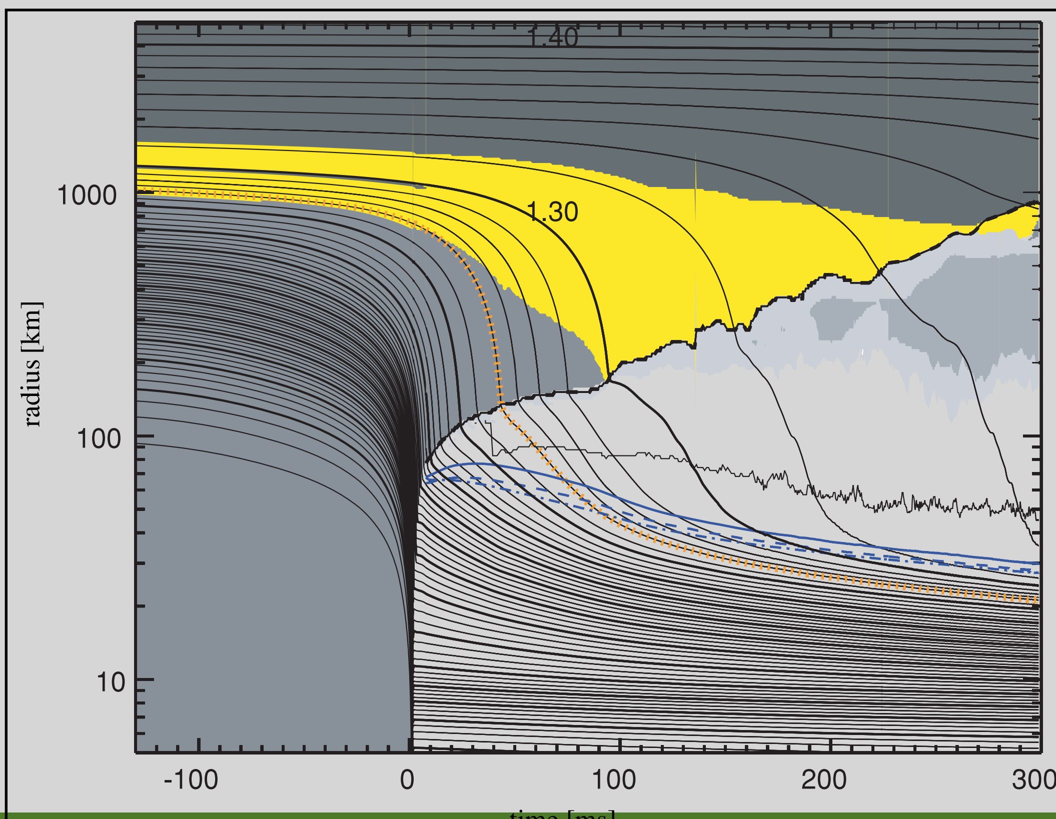
Marek & Janka 09

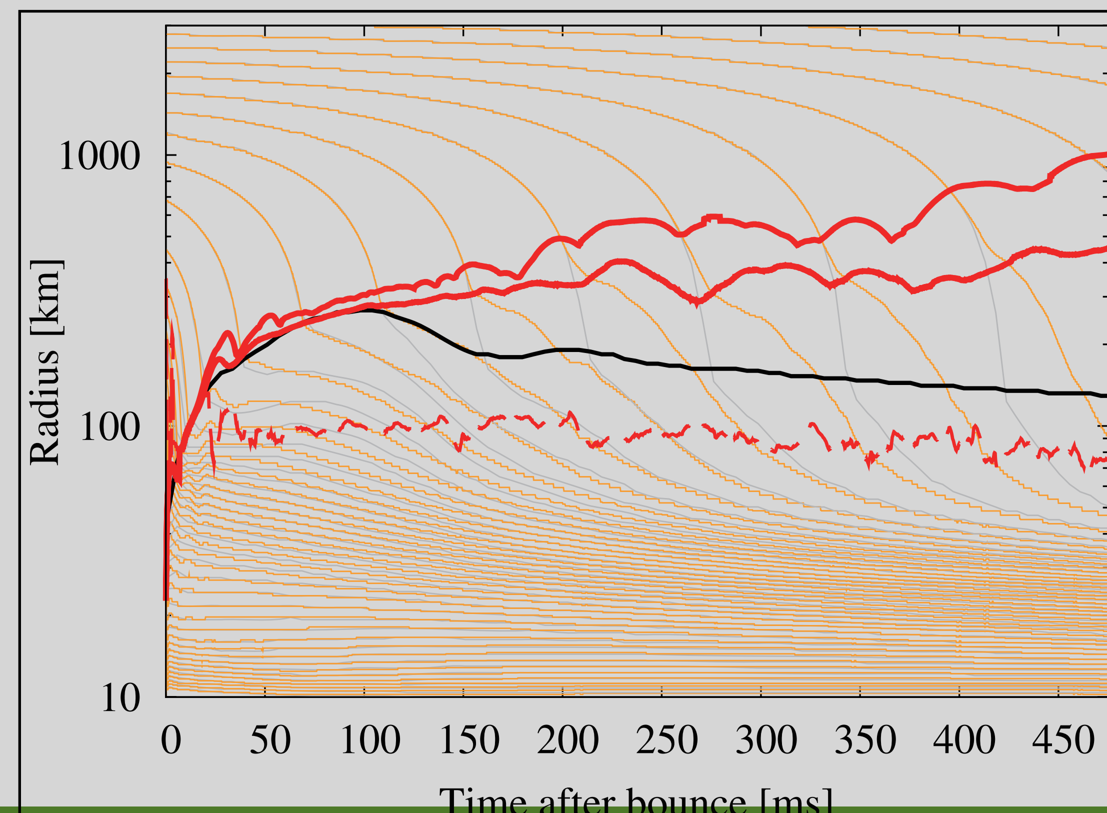




Suwa+ 10

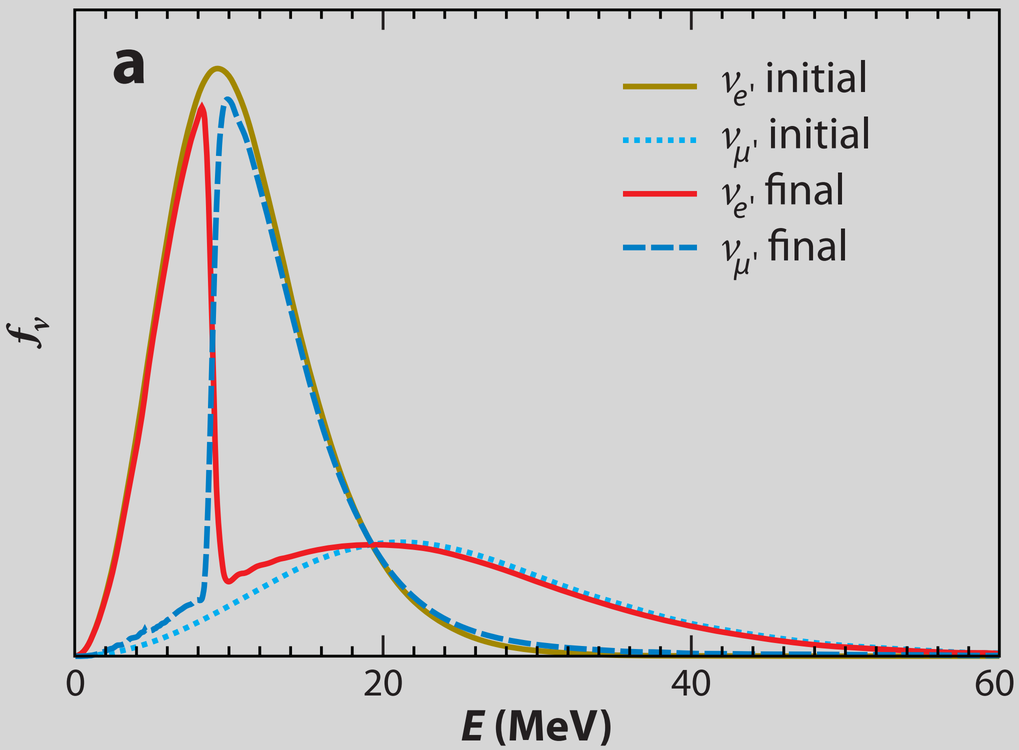
* continuous accretion <=> The remnant is NOT a NS





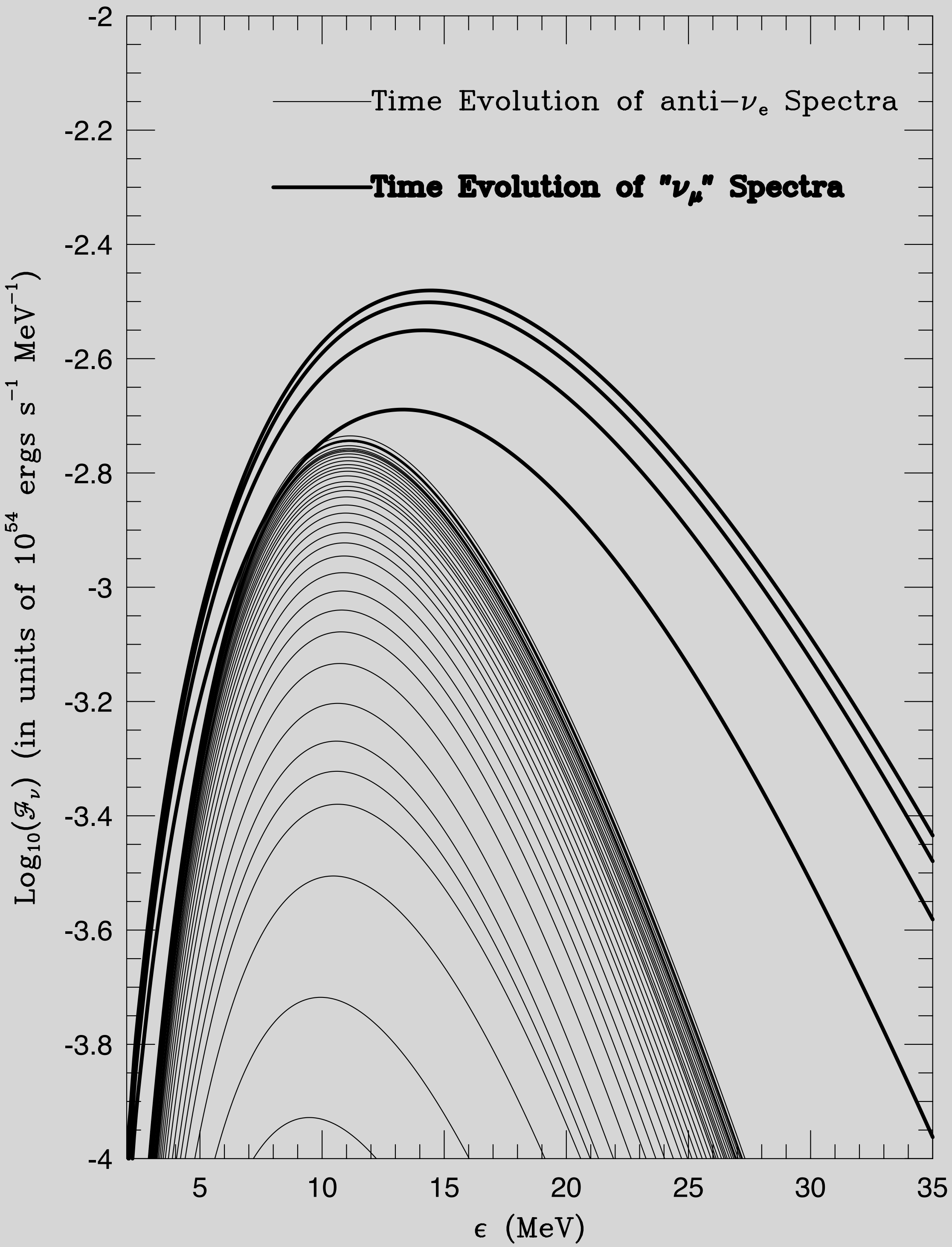
How to solve these problems?

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: $\nu_{\mu/\tau} > \nu_e$

Numerical simulation

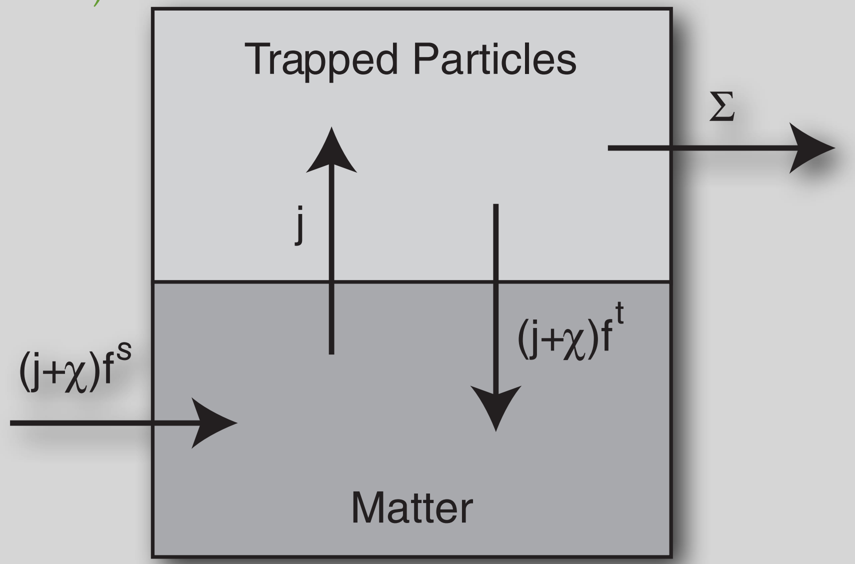
- Axisymmetric simulation (ZEUS-2D; Stone & Norman 92)

- Hydrodynamics + Neutrino transfer

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

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

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



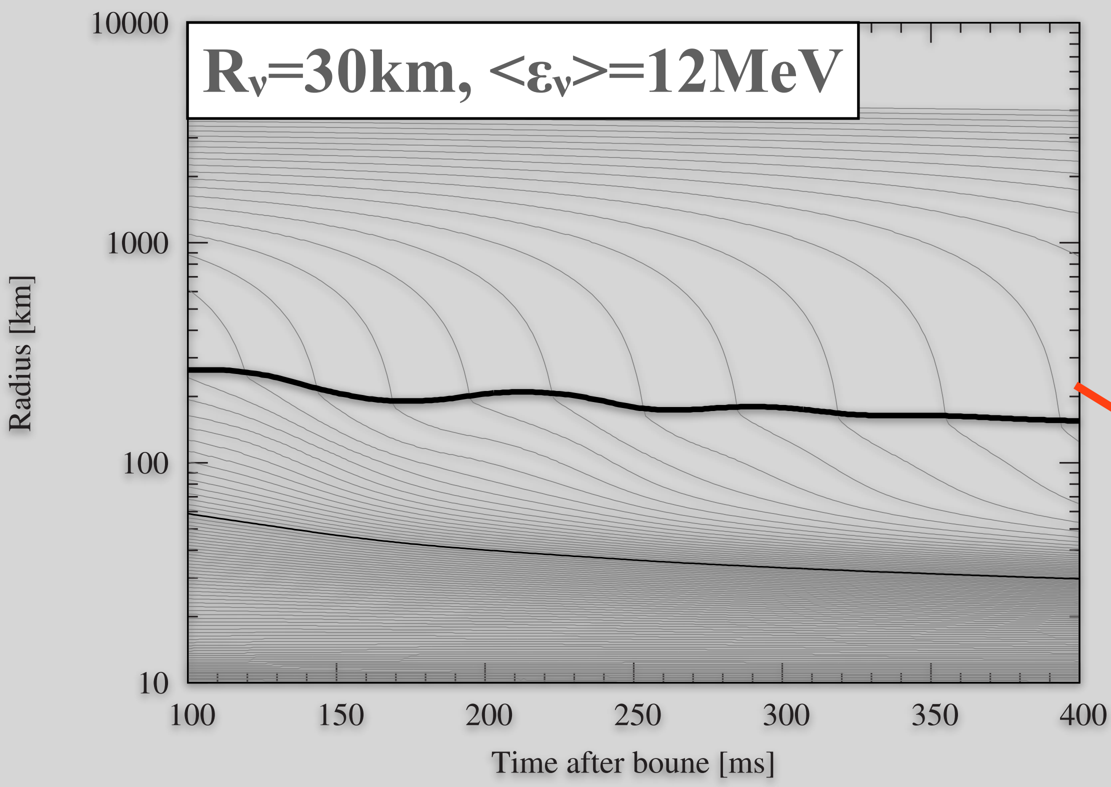
- progenitor: 13 $M_\odot$ (Nomoto & Hashimoto 88)

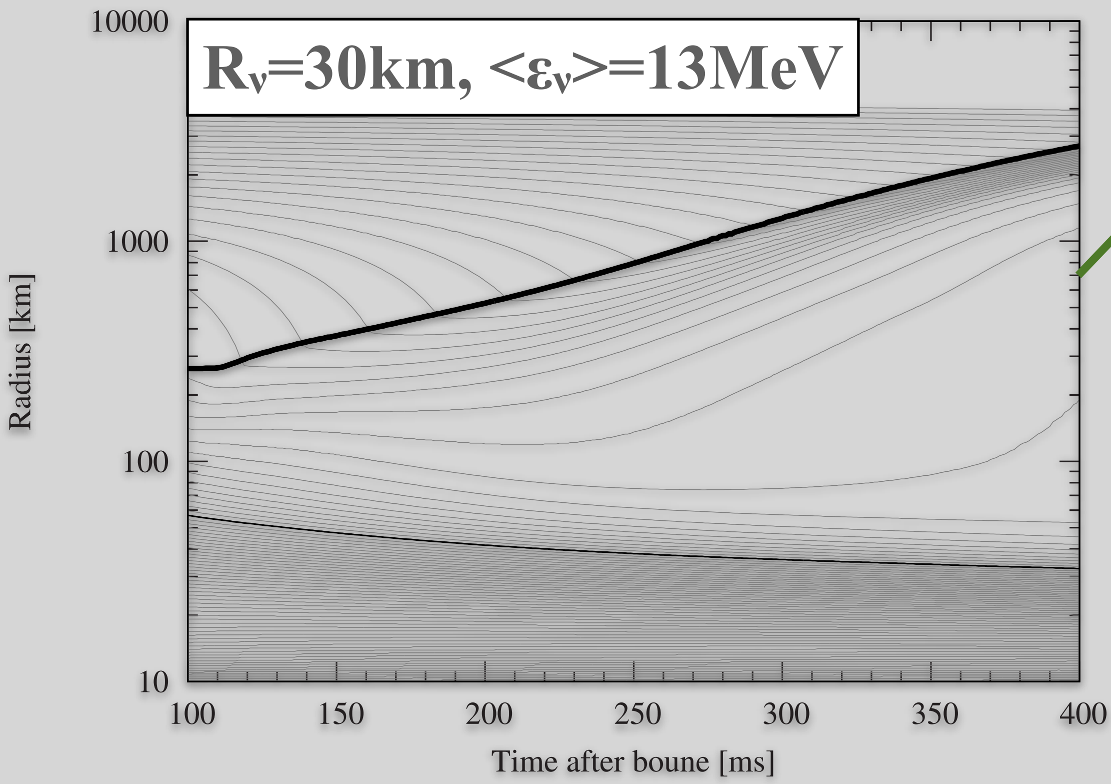
- Collective oscillation parameters: R_ν, $\langle\varepsilon_\nu\rangle$

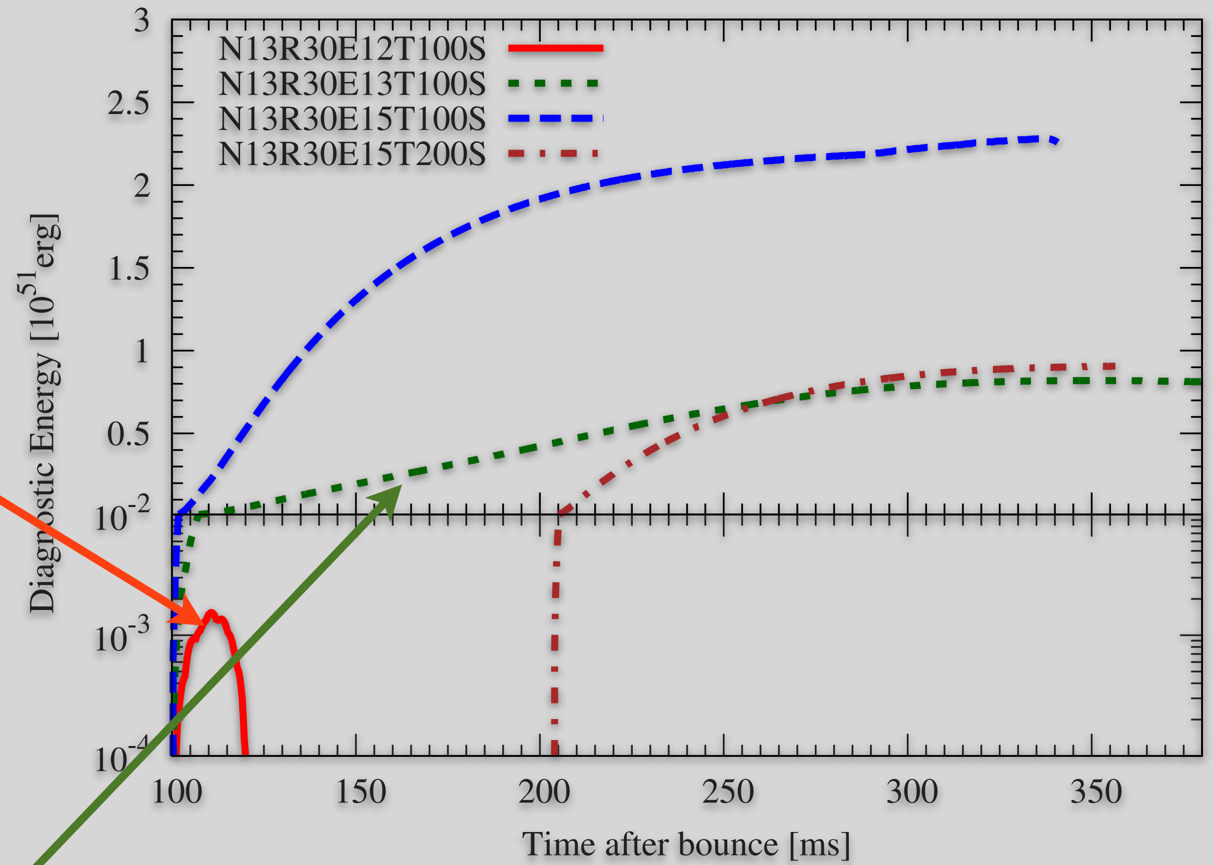
$$L_\nu = 2.62\times10^{52}\left(\frac{\langle\epsilon_\nu\rangle}{15\ \mathrm{MeV}}\right)^4\left(\frac{R_\nu}{30\ \mathrm{km}}\right)^2\ \mathrm{erg\ s^{-1}}$$

Collective oscillation

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



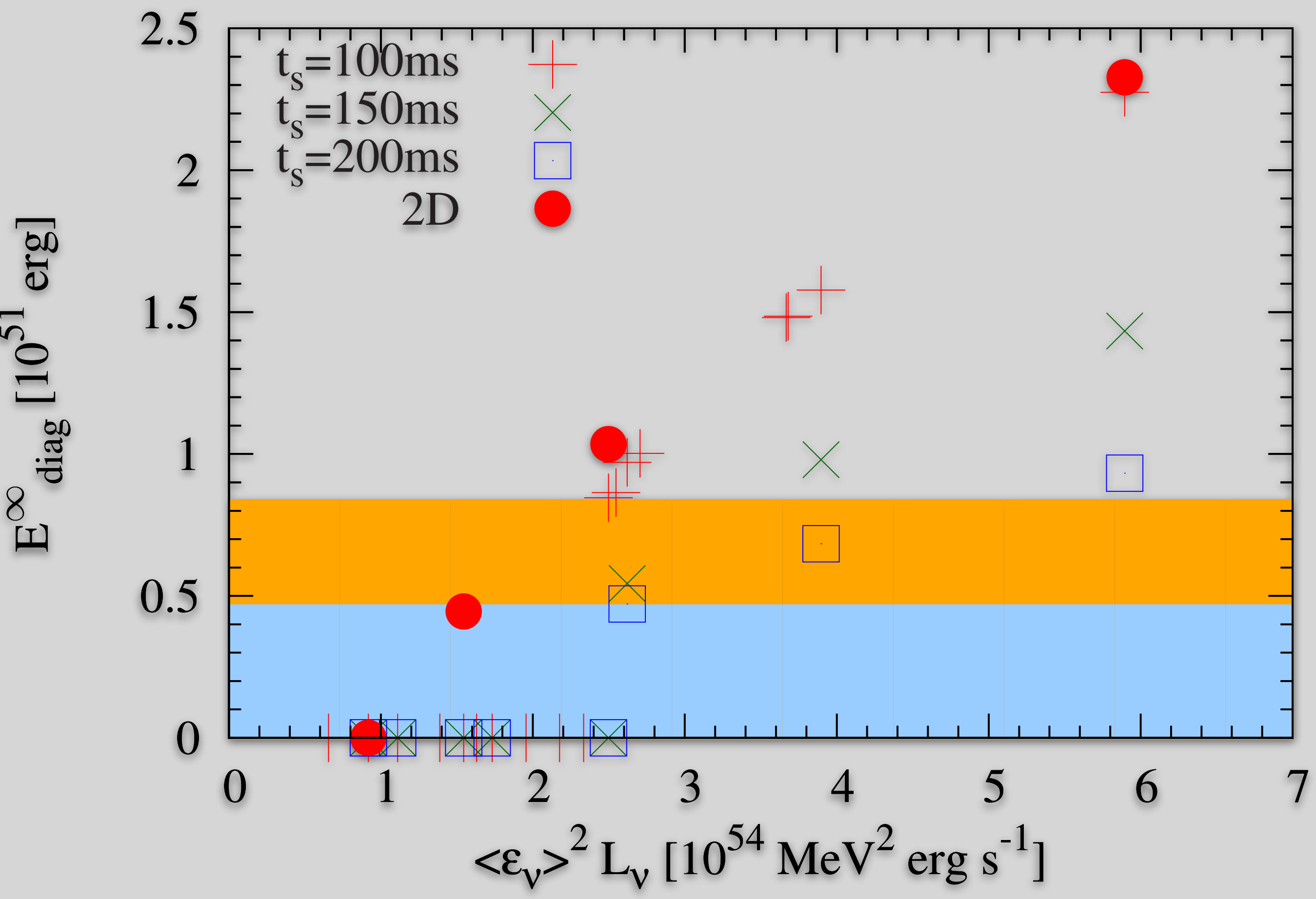


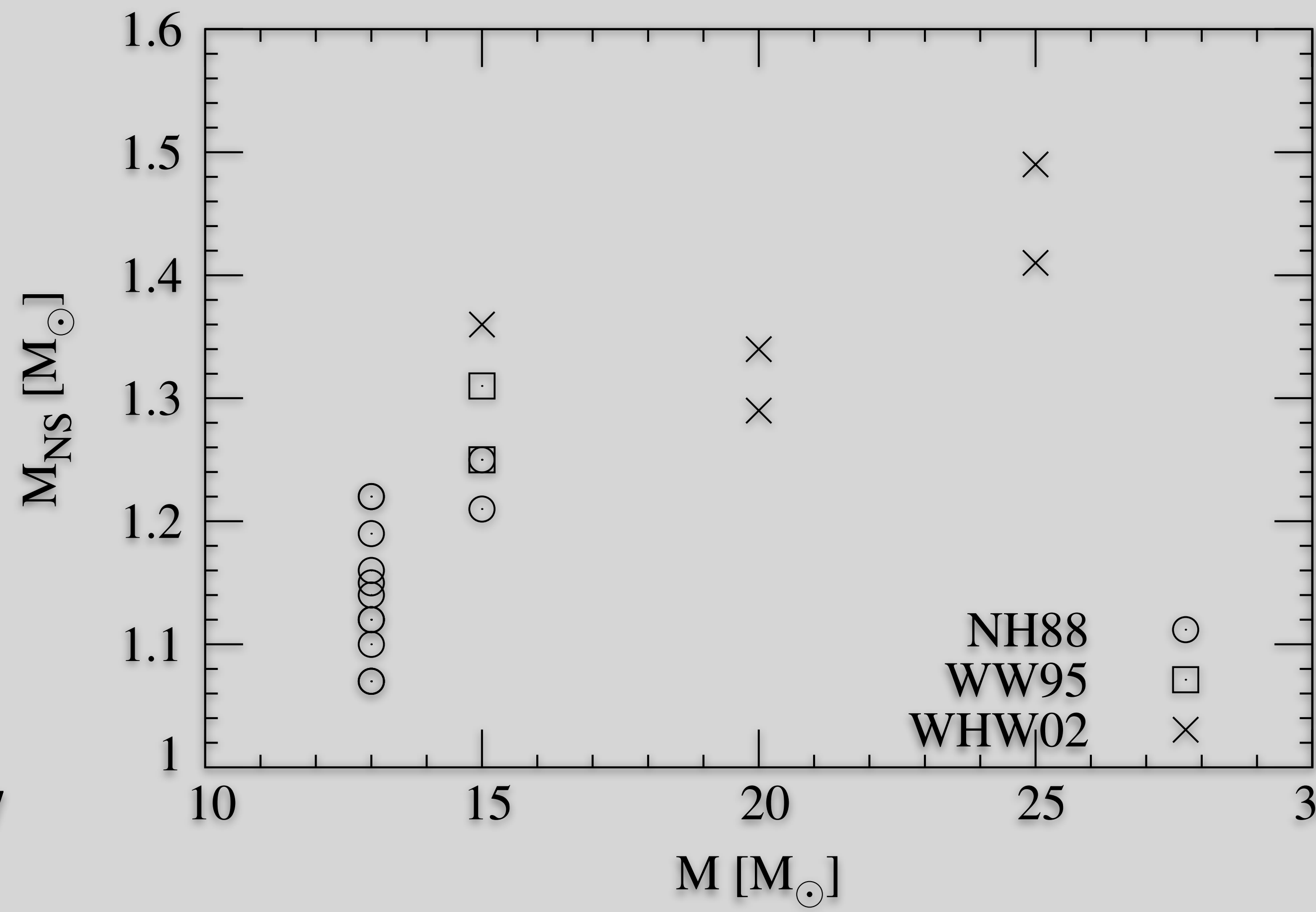


- critical heating rate
- explosion energy~10^{51} erg
- PNS (~1$M_\odot$)

Explosion energy and remnant mass

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

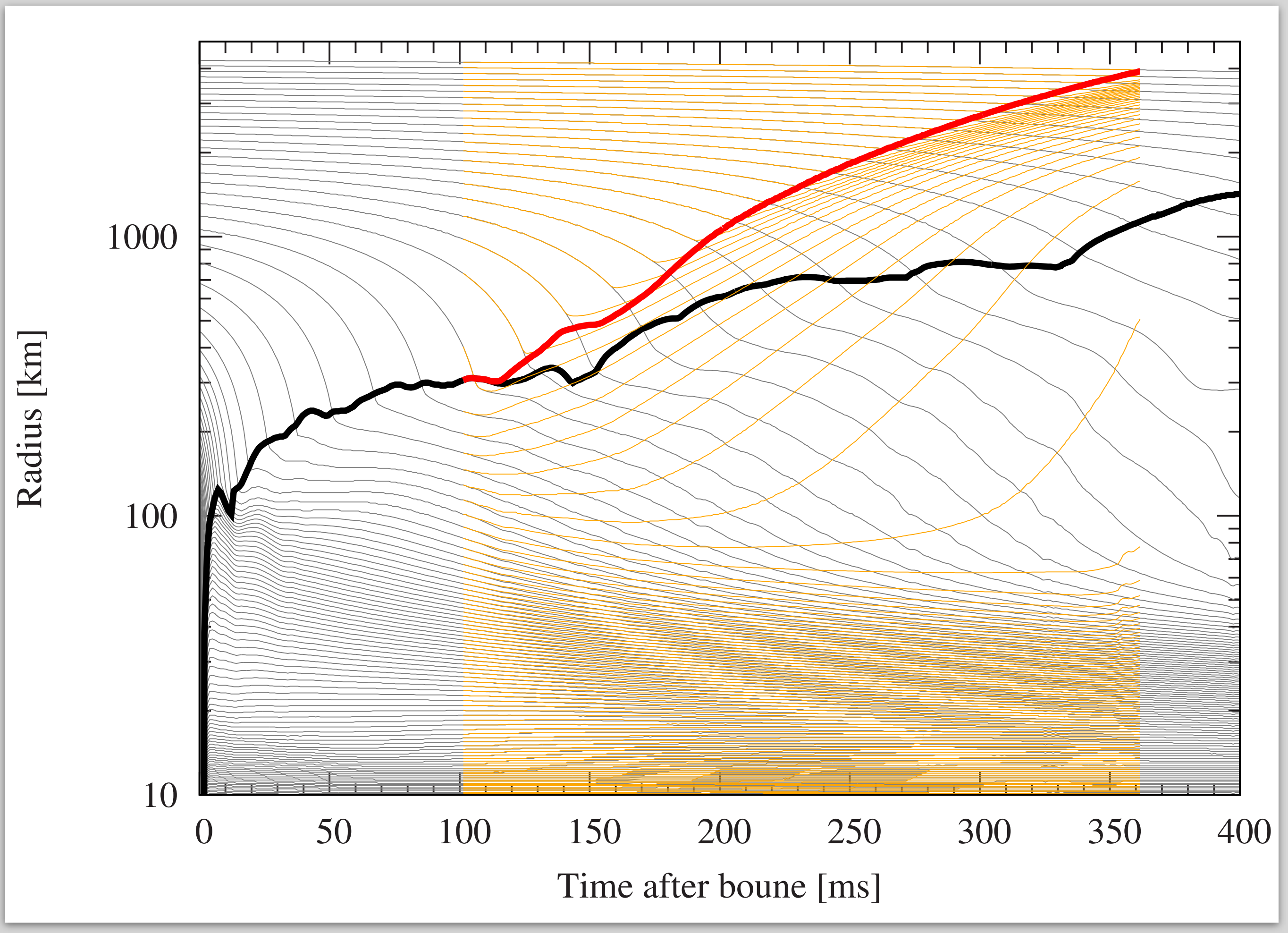


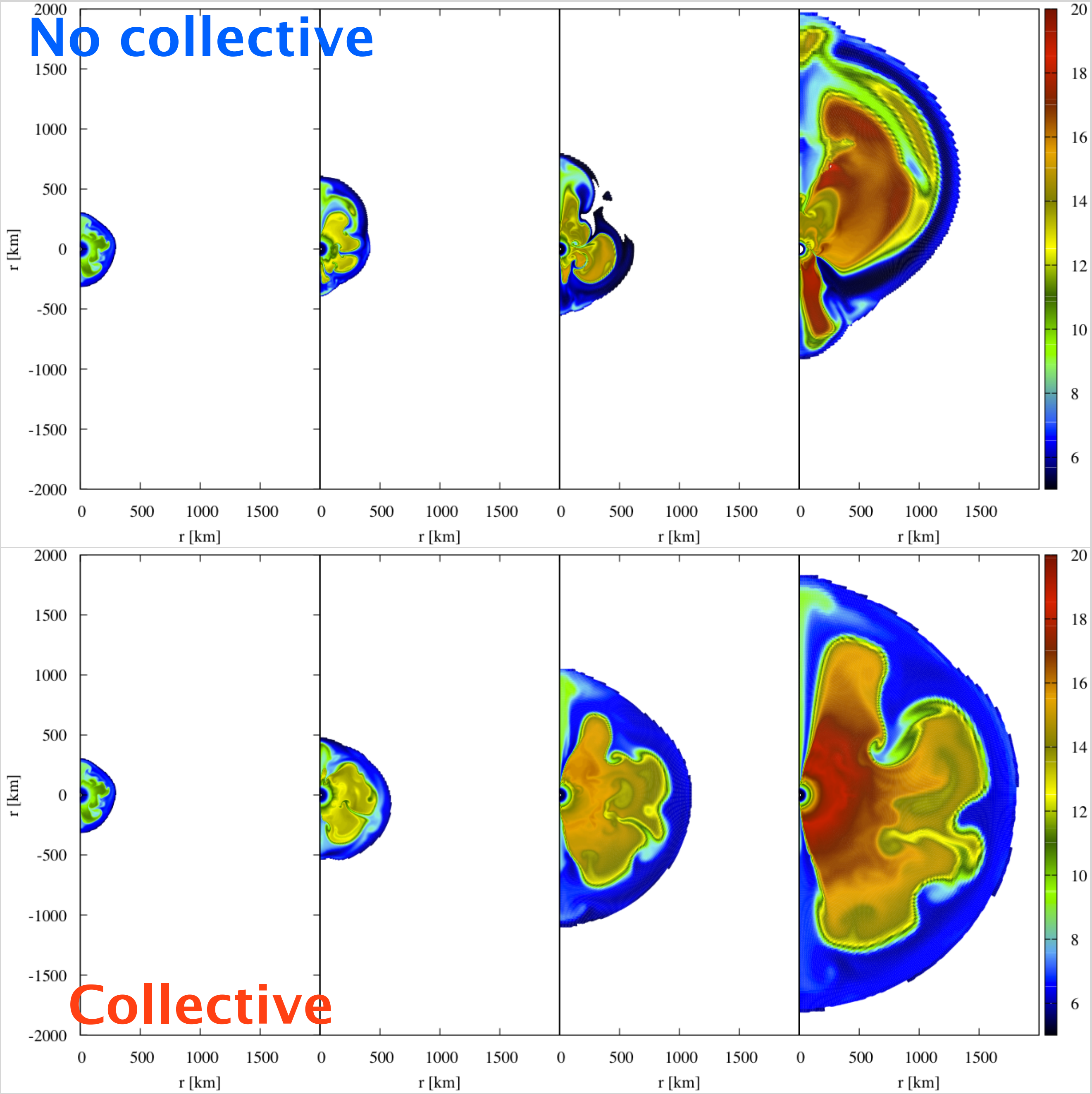


- It is possible to produce strong explosion (E_{exp}>10^{51}erg!) by collective oscillation/spectral swapping.
  - 2D effects leads to even higher explosion energy.
  - The remnant mass is reasonable (~1 $M_\odot$) as well.

2D effect

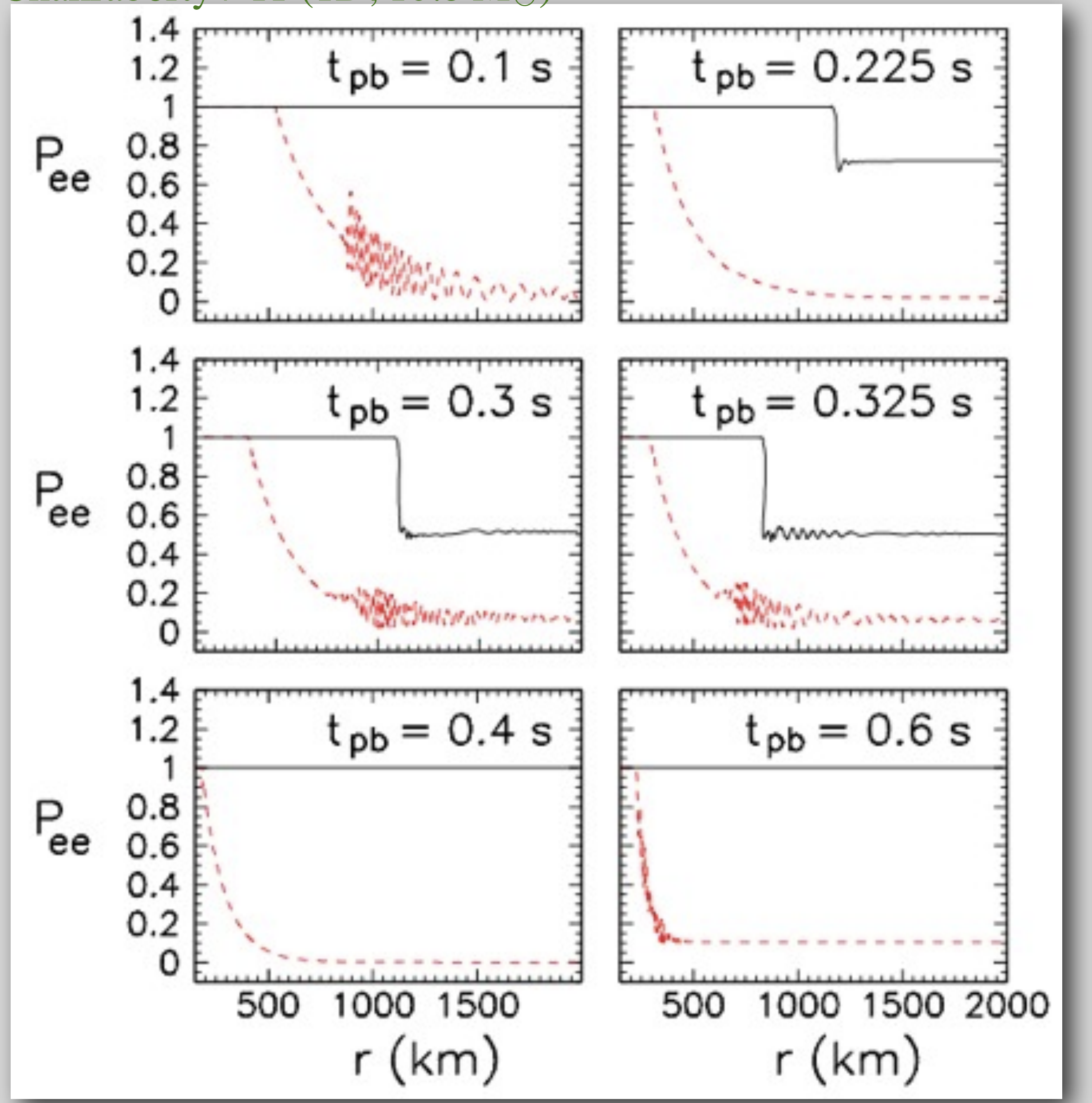
YS, Kotake, Takiwaki, Liebendörfer, Sato, ApJ, 738, 165 (2011)



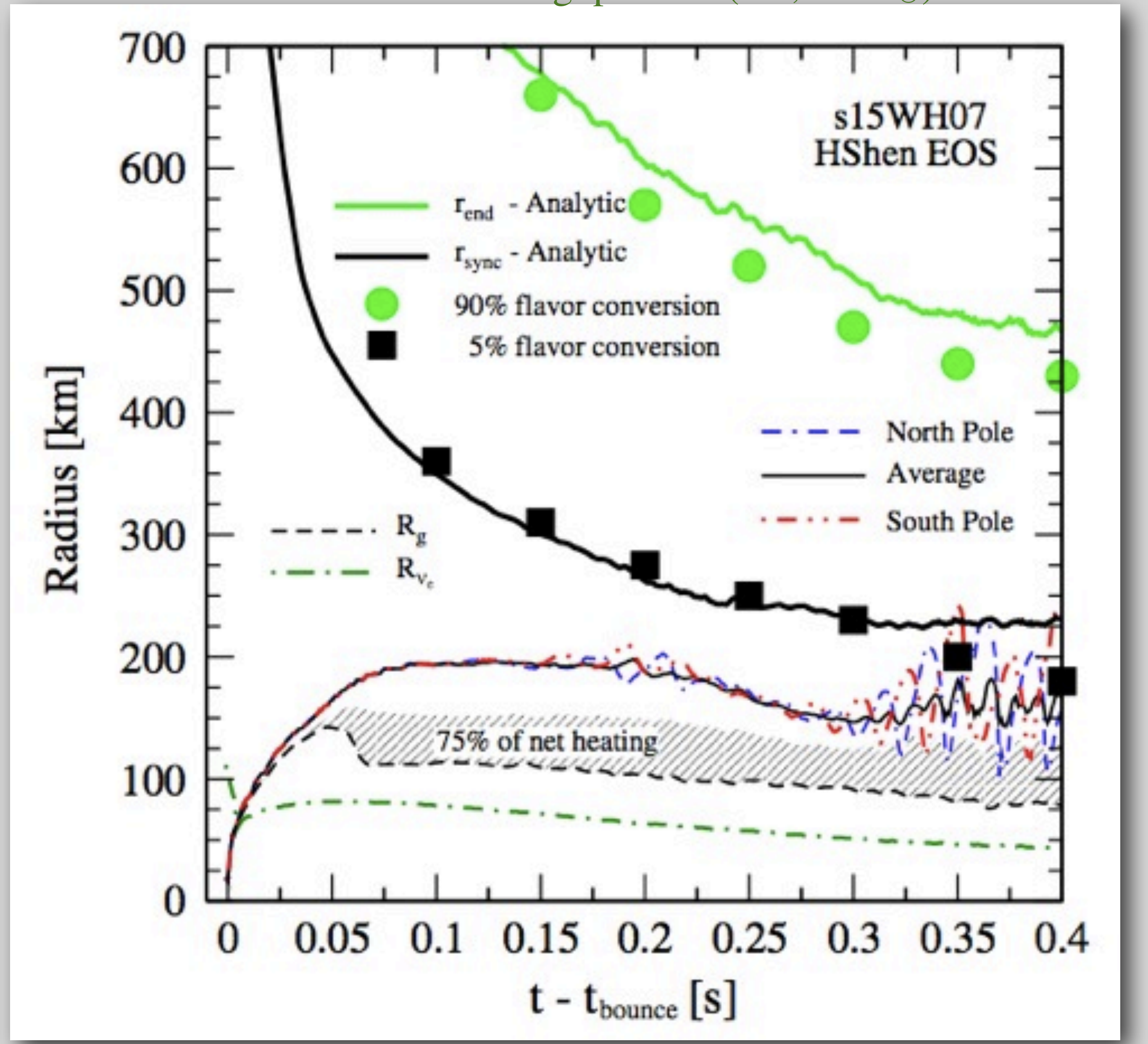


Important note

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



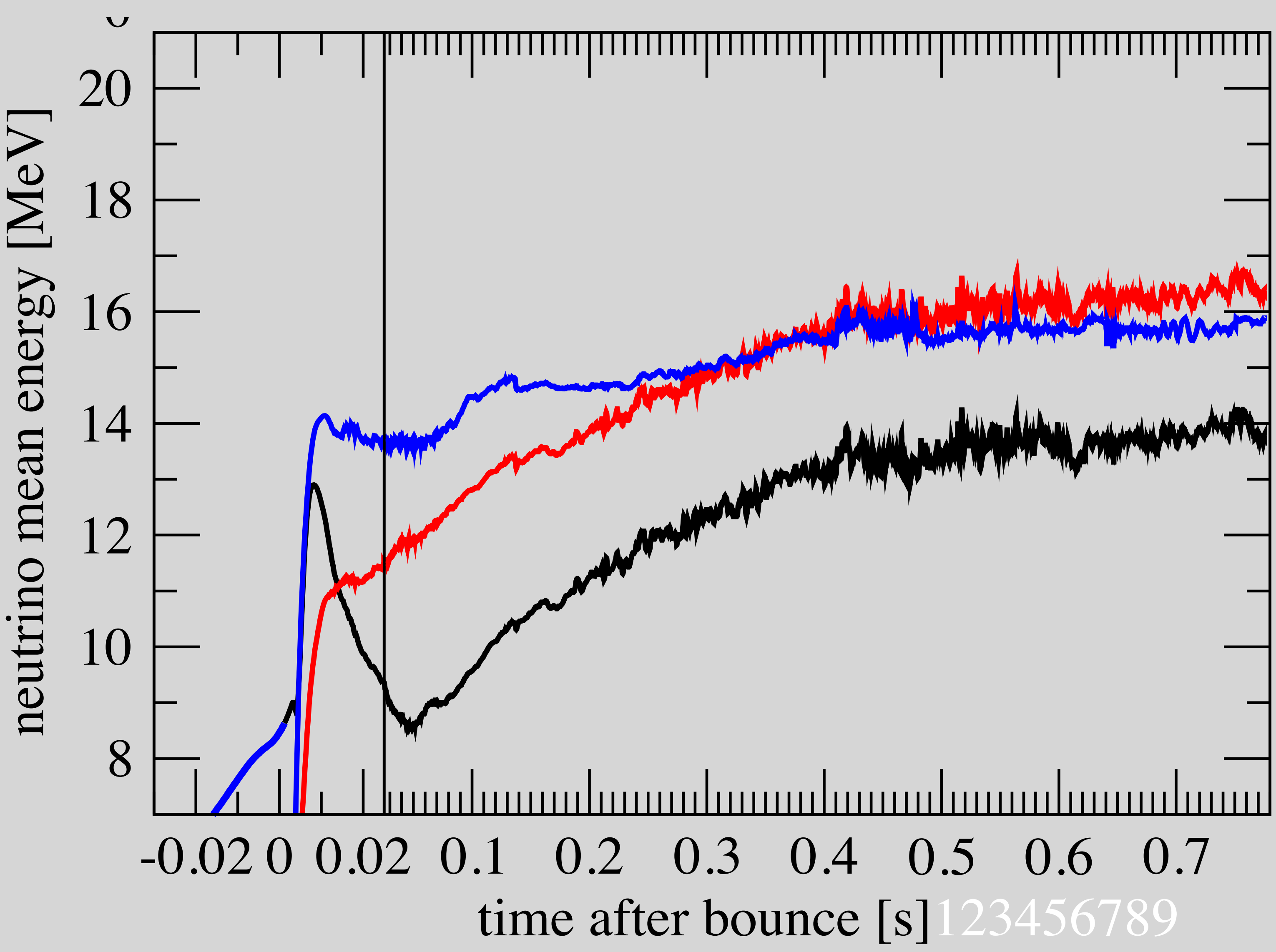
Dasgupta+ 12 (2D, 15 $M_\odot$)



* 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!

Important note-2

Janka (2012) arXiv:1206.2503, from B. Müller's simulation



- In the current state-of-the-art simulation suggests that the average energies of $\bar{\nu}_e$ and ν_X are similar
- In this case the spectral swapping between these two flavors do not affect the heating rate
- How about unknown interaction inclusion?

Systematics in supernova simulations

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  * progenitor structure (mixing, wind...)
  * rotation / magnetic field

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)

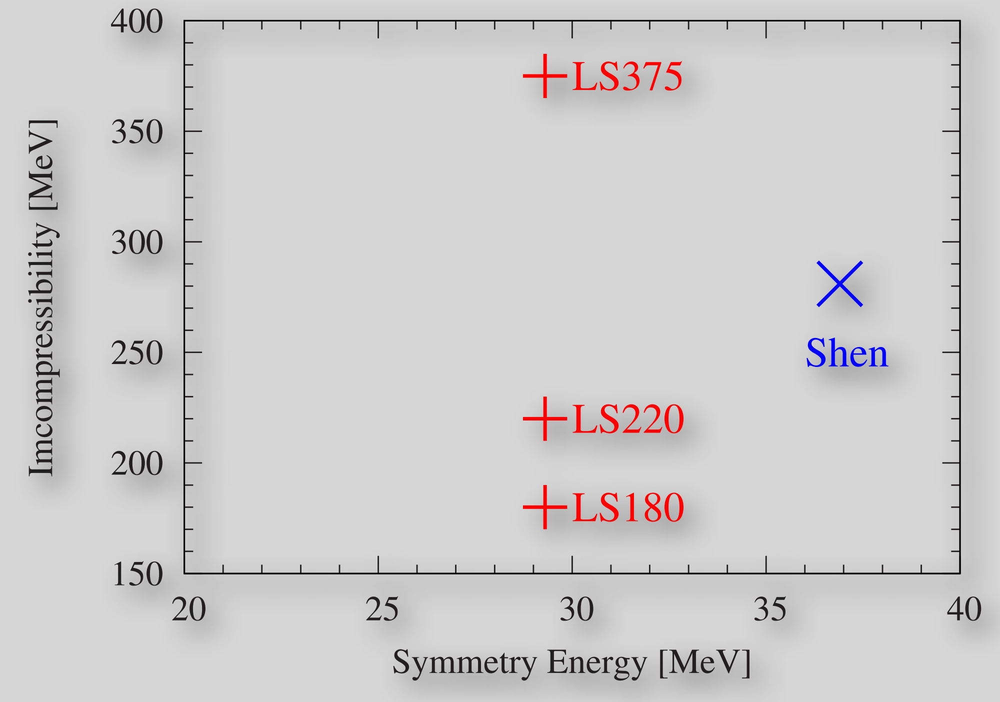
	incompressibility K [MeV]	symmetry energy J (S) [MeV]	slope of symmetry energy L [MeV]
LS	180, 220, 375	29.3	---
HShen	281	36.9	111
HW	263	32.9	---
GShen	271.5 (NL3) 230.0 (FSU)	37.29 (NL3) 32.59 (FSU)	118.2 (NL3) 60.5 (FSU)
Hempel	318 (TMA) 230 (FSU)	30.7 (TMA) 32.6 (FSU)	90 (TMA) 60 (FSU)

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

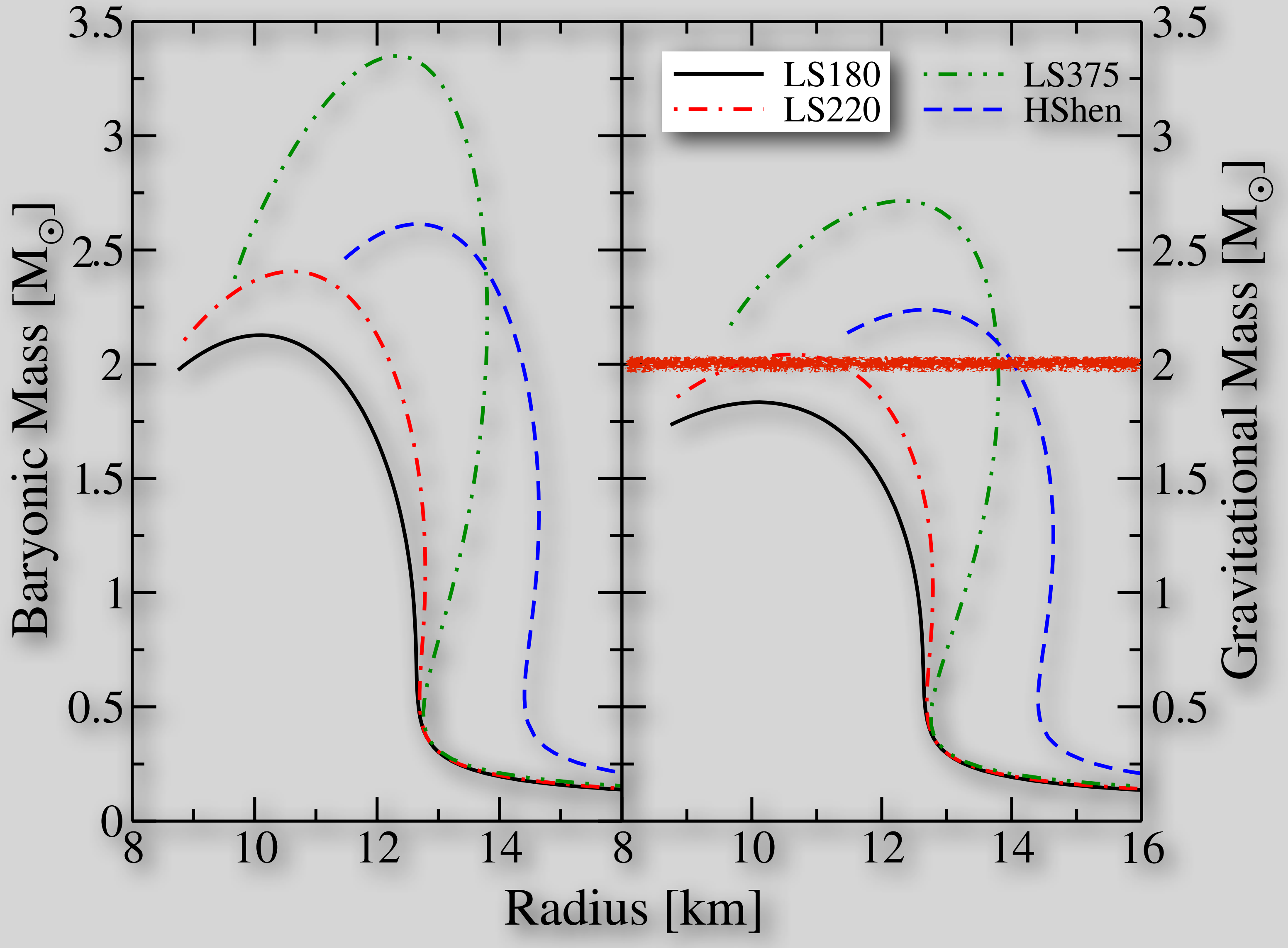
Equation of state

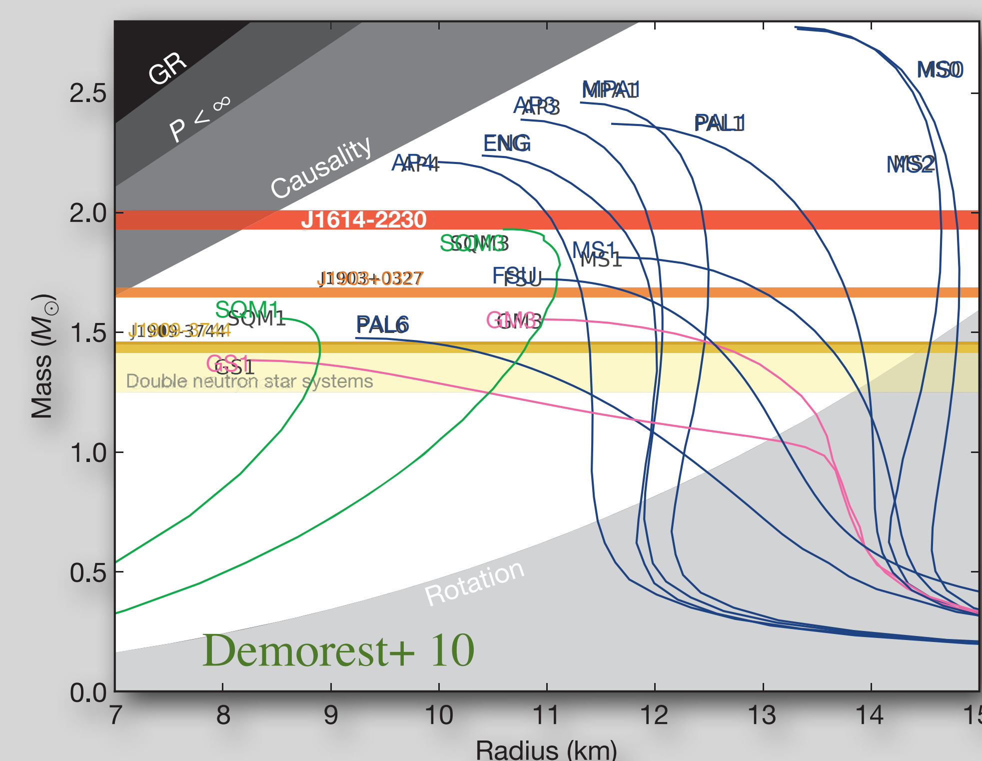
The “standard” equations of state (EOS) in supernova community

- Lattimer & Swesty EOS (liquid drop)
- Shen EOS (relativistic mean field)

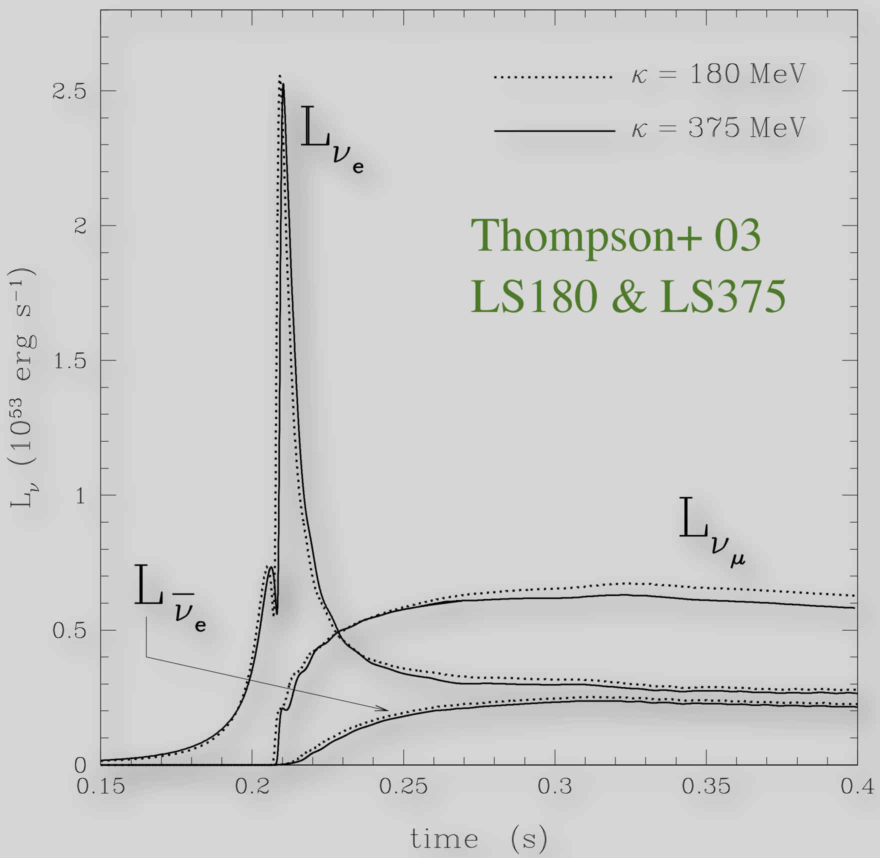


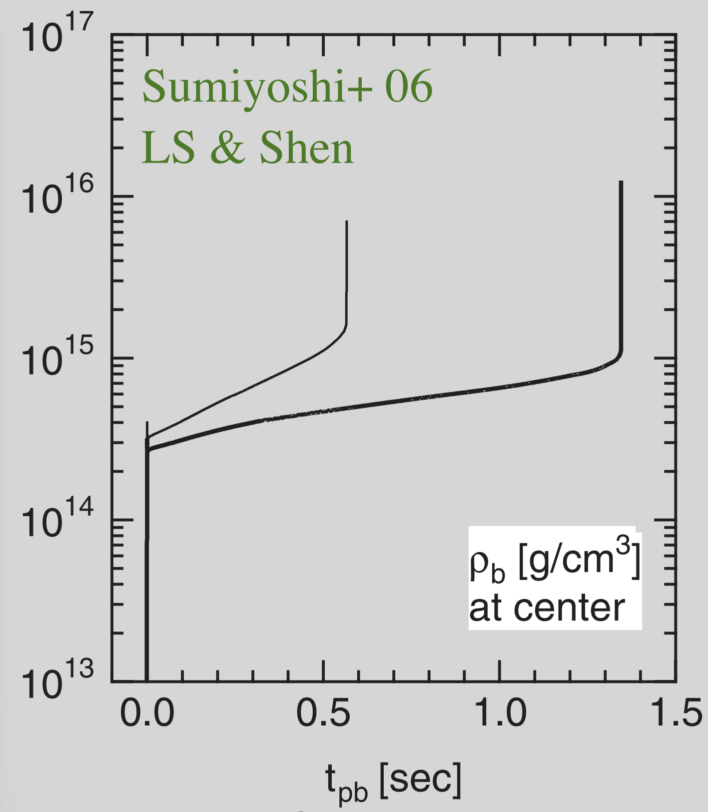
O’Connor & Ott 10

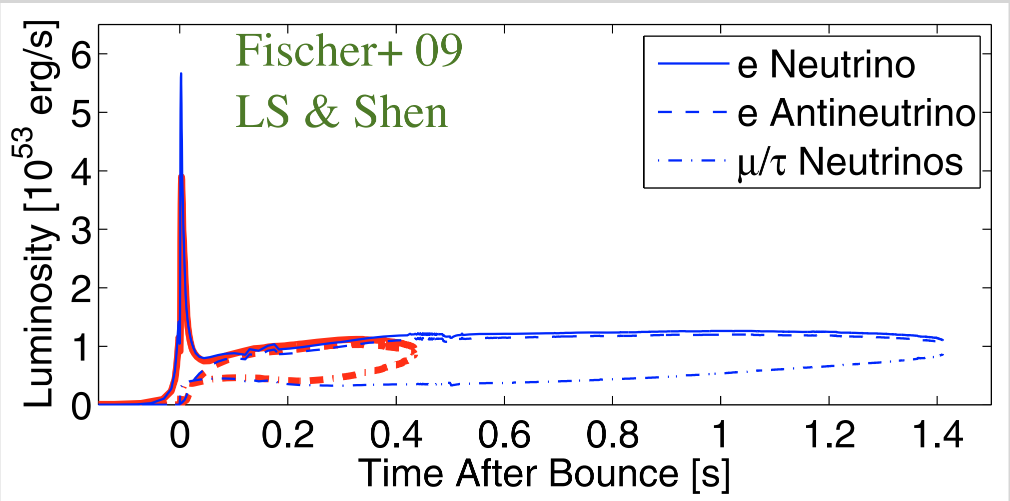


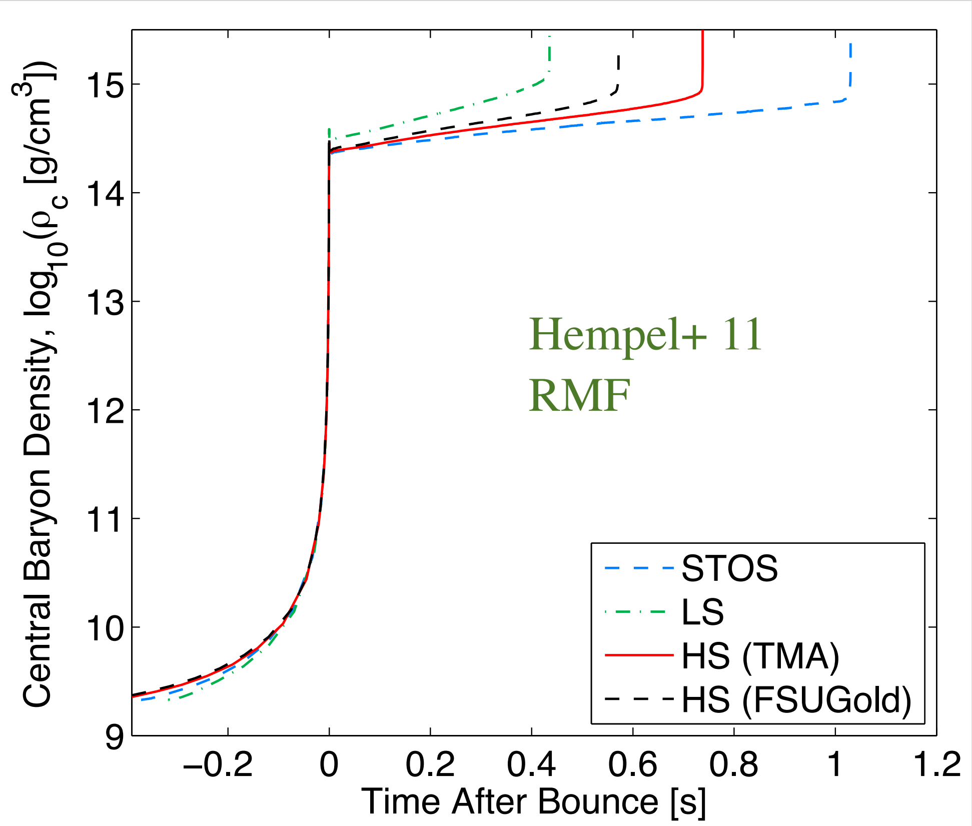


Studies on EOS dependence





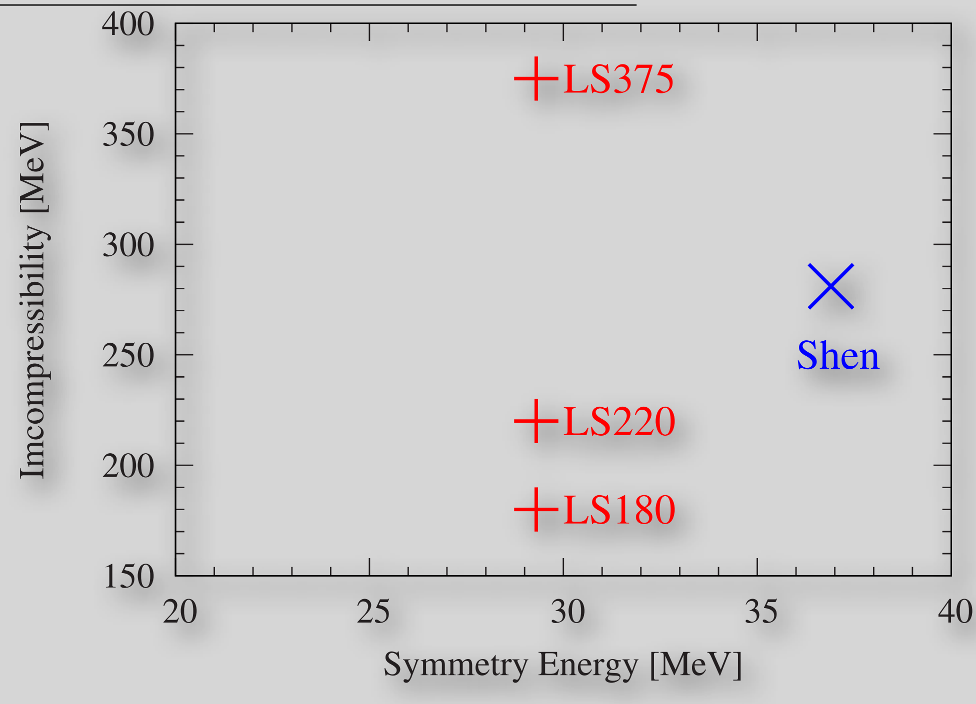




- There are several works, which investigated the EOS dependence with 1D simulation
- Since 1D simulations fail to produce explosion, the representable physical quantities in these studies are
  - BH formation time
  - neutrino luminosity/spectrum evolution
- How about the explosion? Does it produce 10^{51} erg explosion?

Numerical simulation

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



Note: Of course the other parameters differ as well.

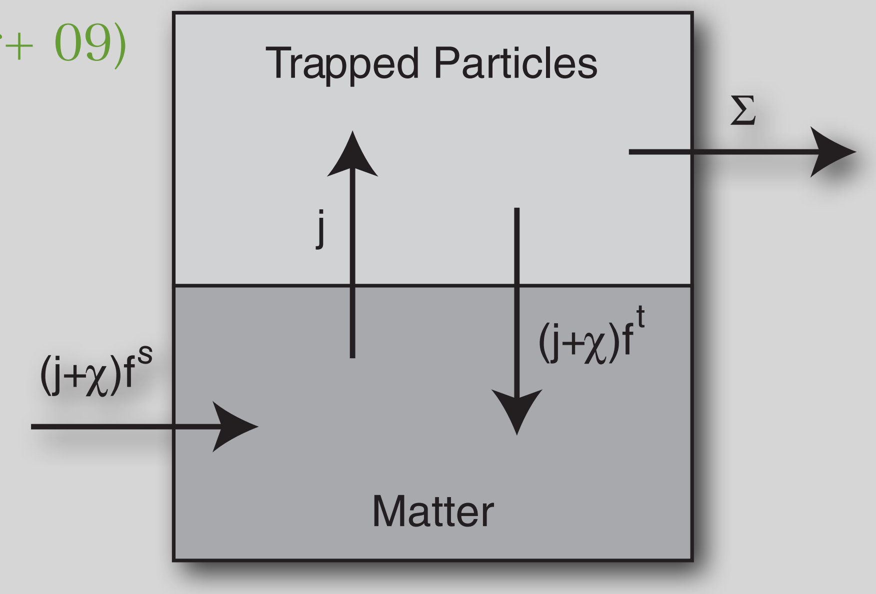
* Axisymmetric simulation (ZEUS-2D; Stone & Norman 92)

* Hydrodynamics + Neutrino transfer

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

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

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

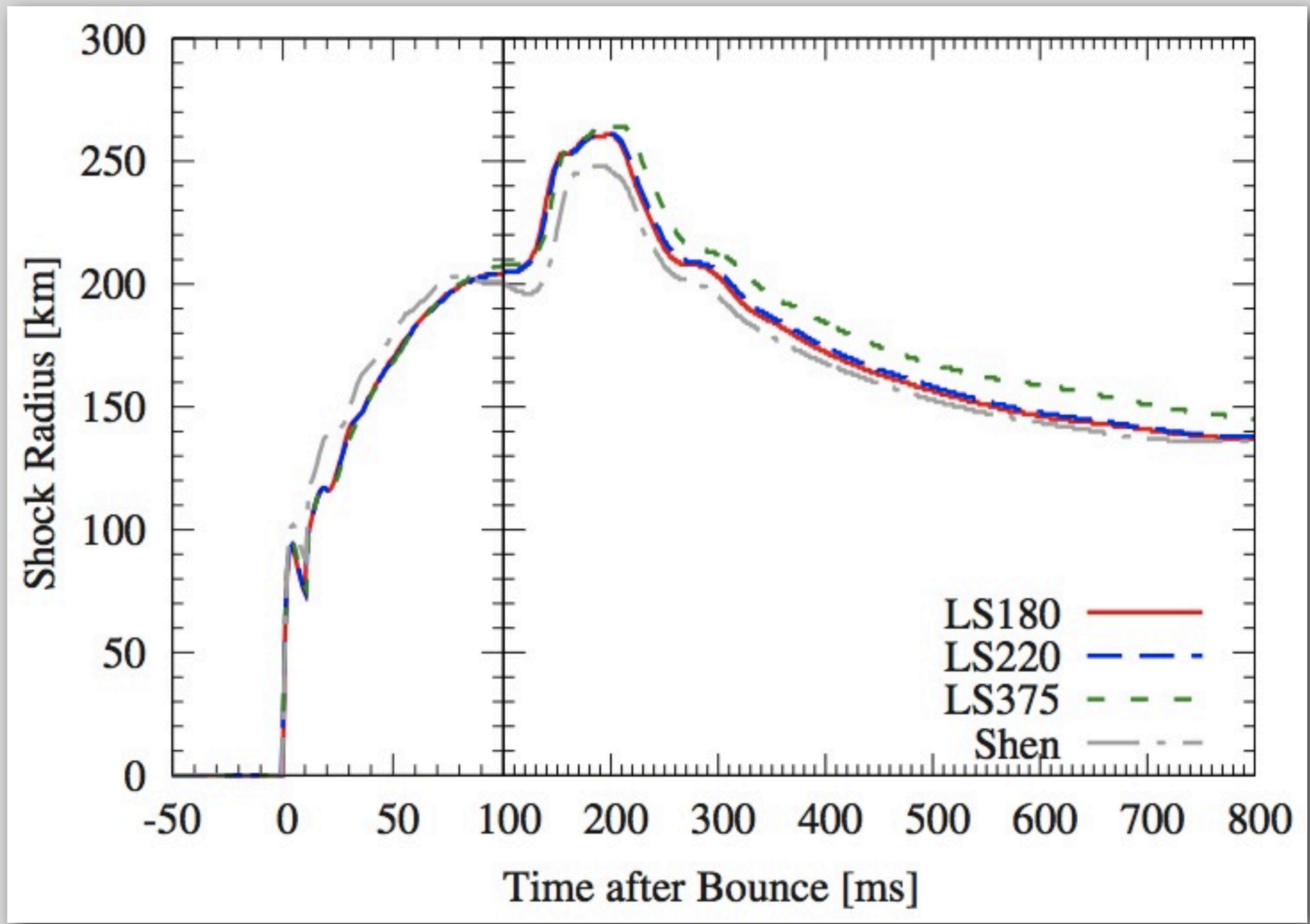


* progenitor: 15 M⊙ (Woosley & Weaver 95)

Results in 1D simulation

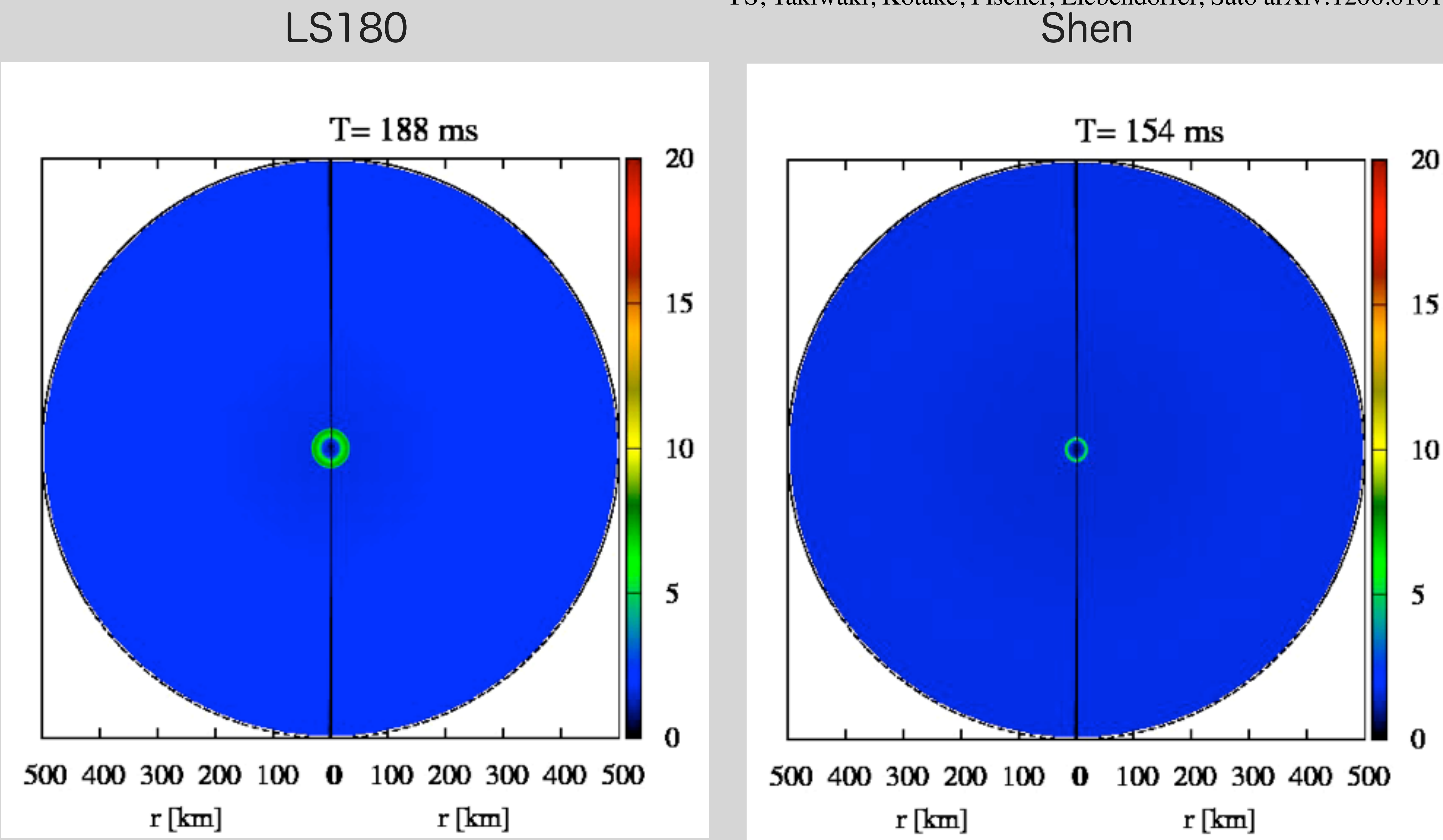
Evolution of shock radius

YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato arXiv:1206.6101



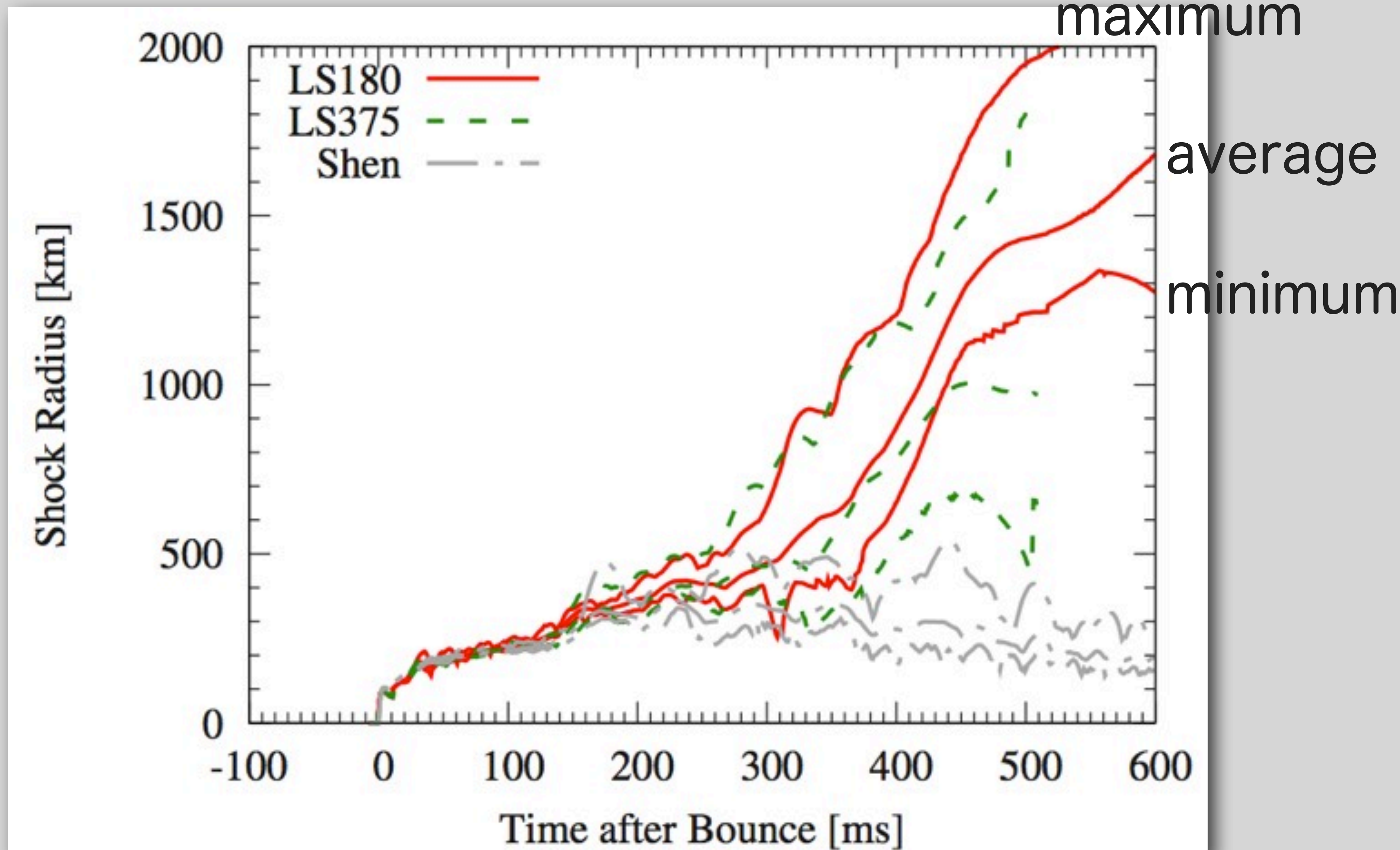
Entropy evolution

YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato arXiv:1206.6101



Shock radius

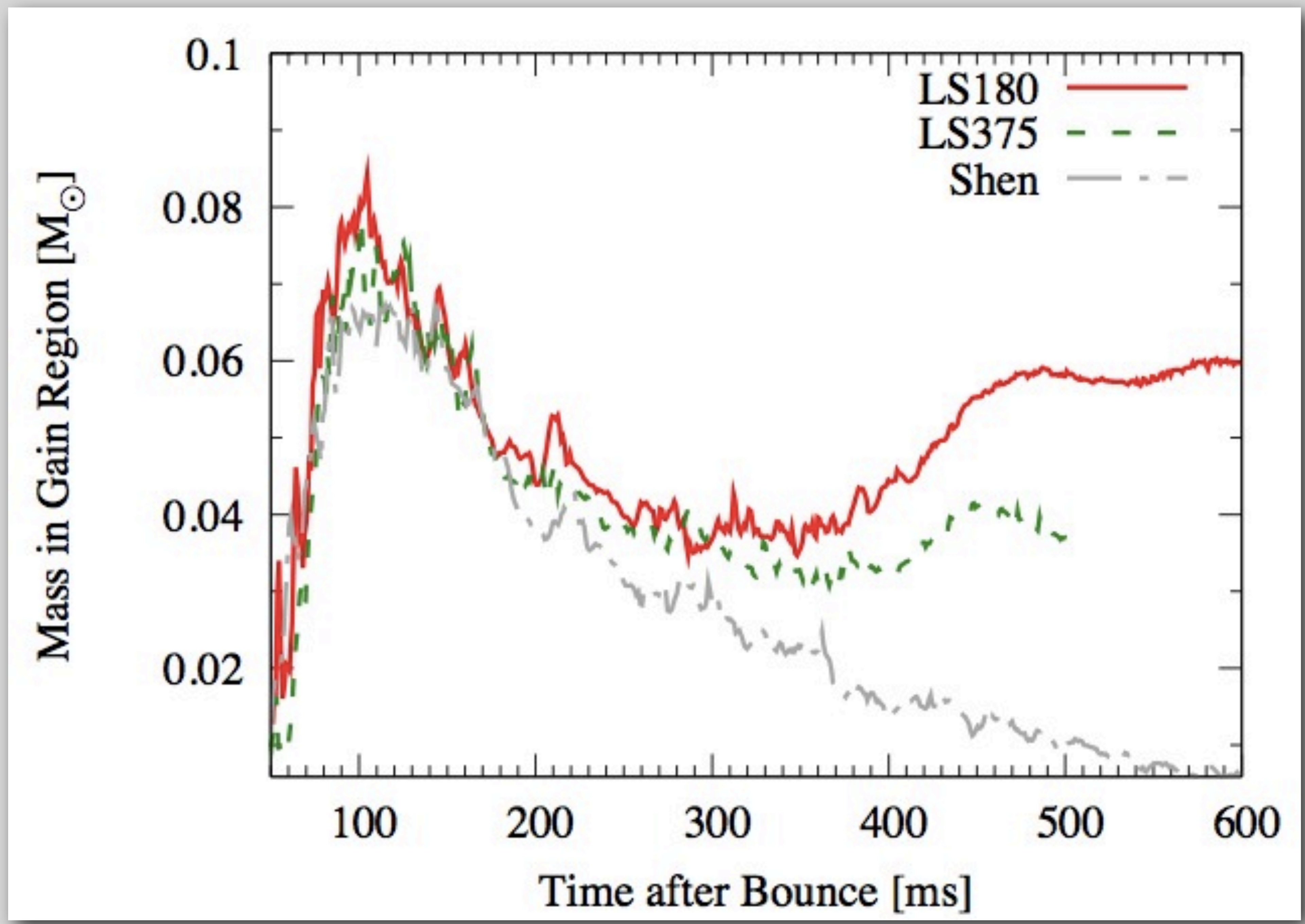
YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato arXiv:1206.6101



LS180 and LS375 succeed the explosion

Shen EOS fails

Mass in gain region



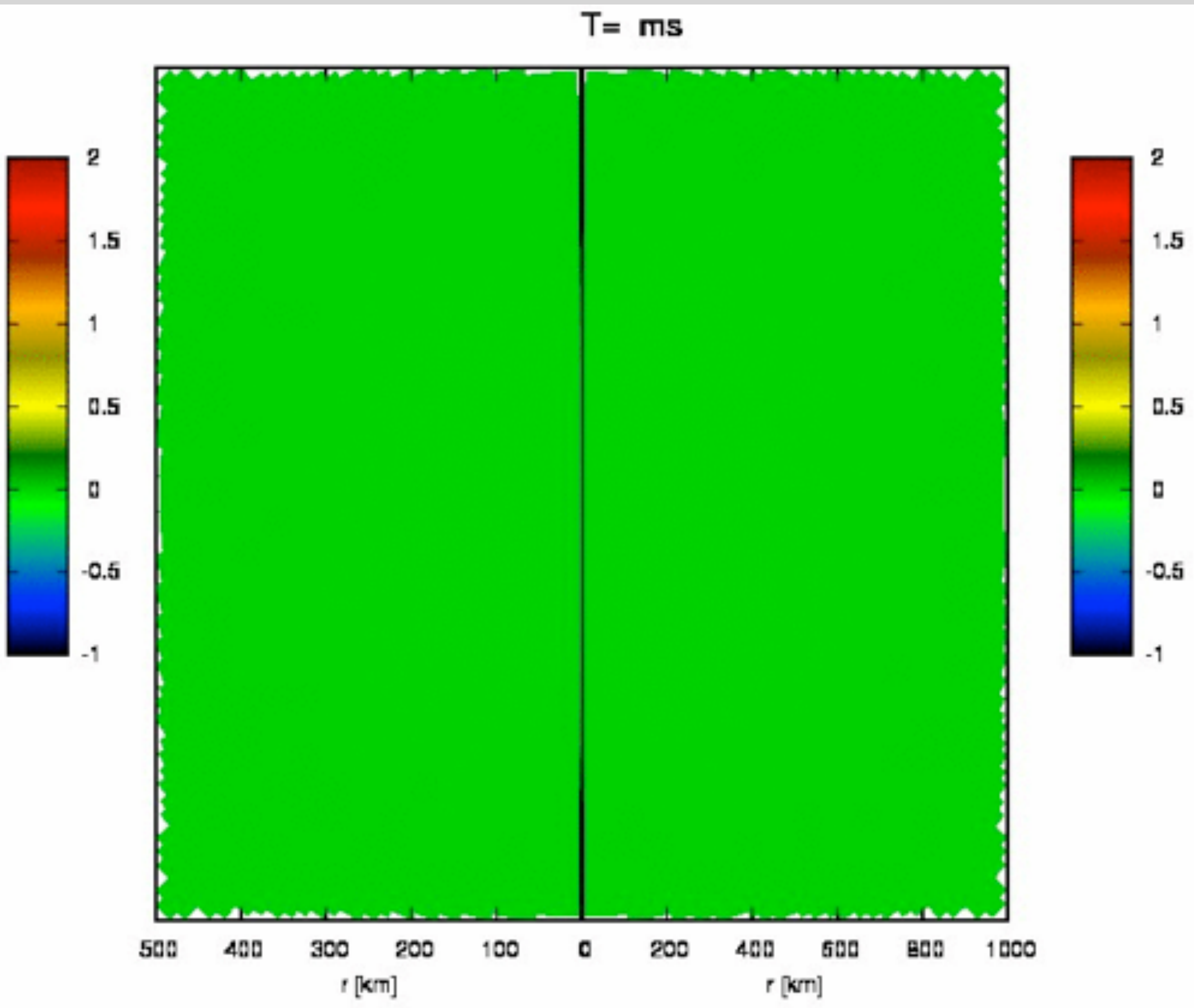
Dispersion of the moment

$$\frac{\mathcal{M}(r,\theta)-\overline{\mathcal{M}}(r)}{\overline{\mathcal{M}}(r)}$$

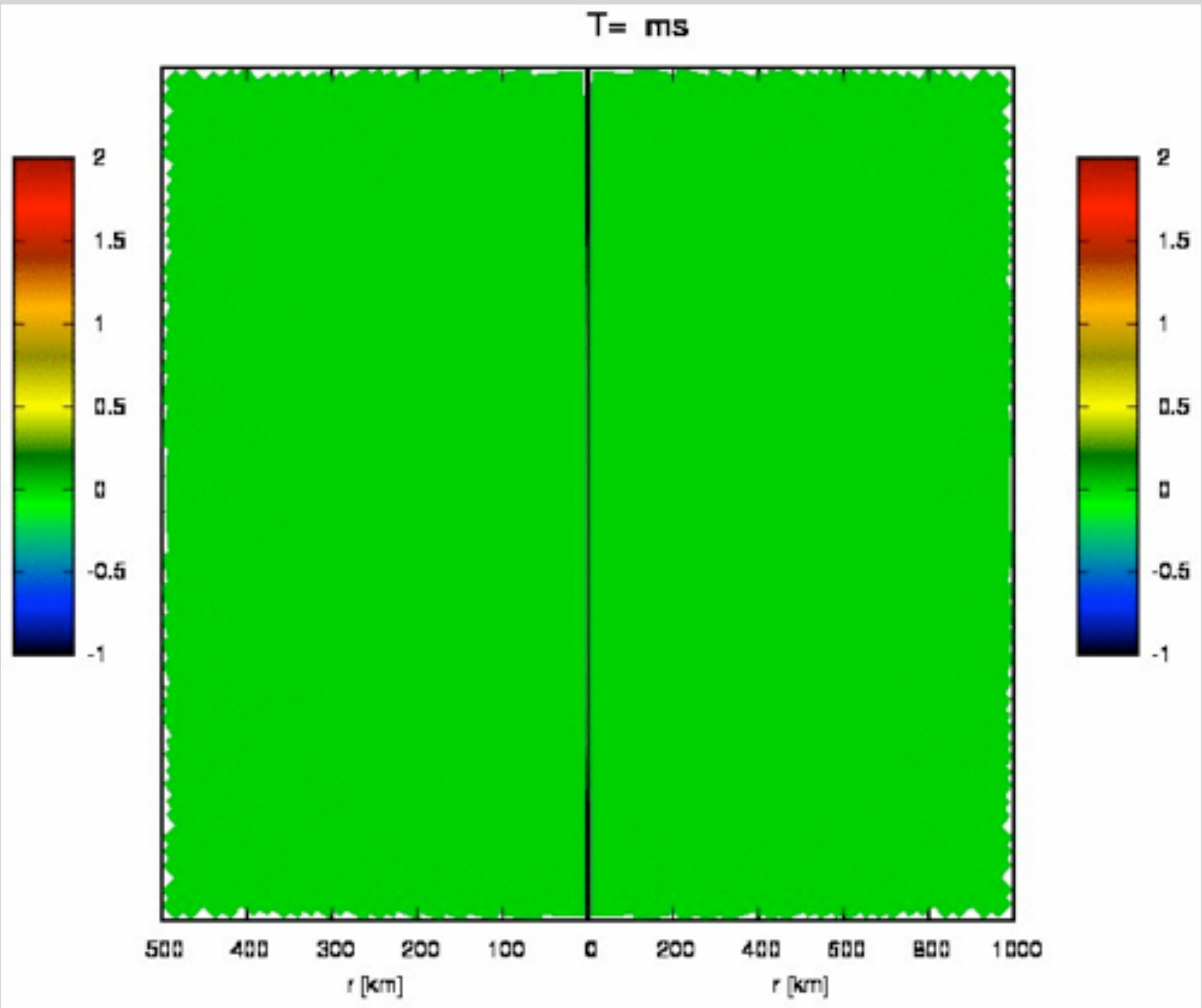
$$\mathcal{M}(r,\theta) \equiv \rho(r,\theta)v_r^2(r,\theta) + P(r,\theta),$$
$$\overline{\mathcal{M}}(r) \equiv \frac{1}{2}\int_0^\pi \mathcal{M}(r,\theta)\sin\theta d\theta.$$

YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato arXiv:1206.6101

LS180



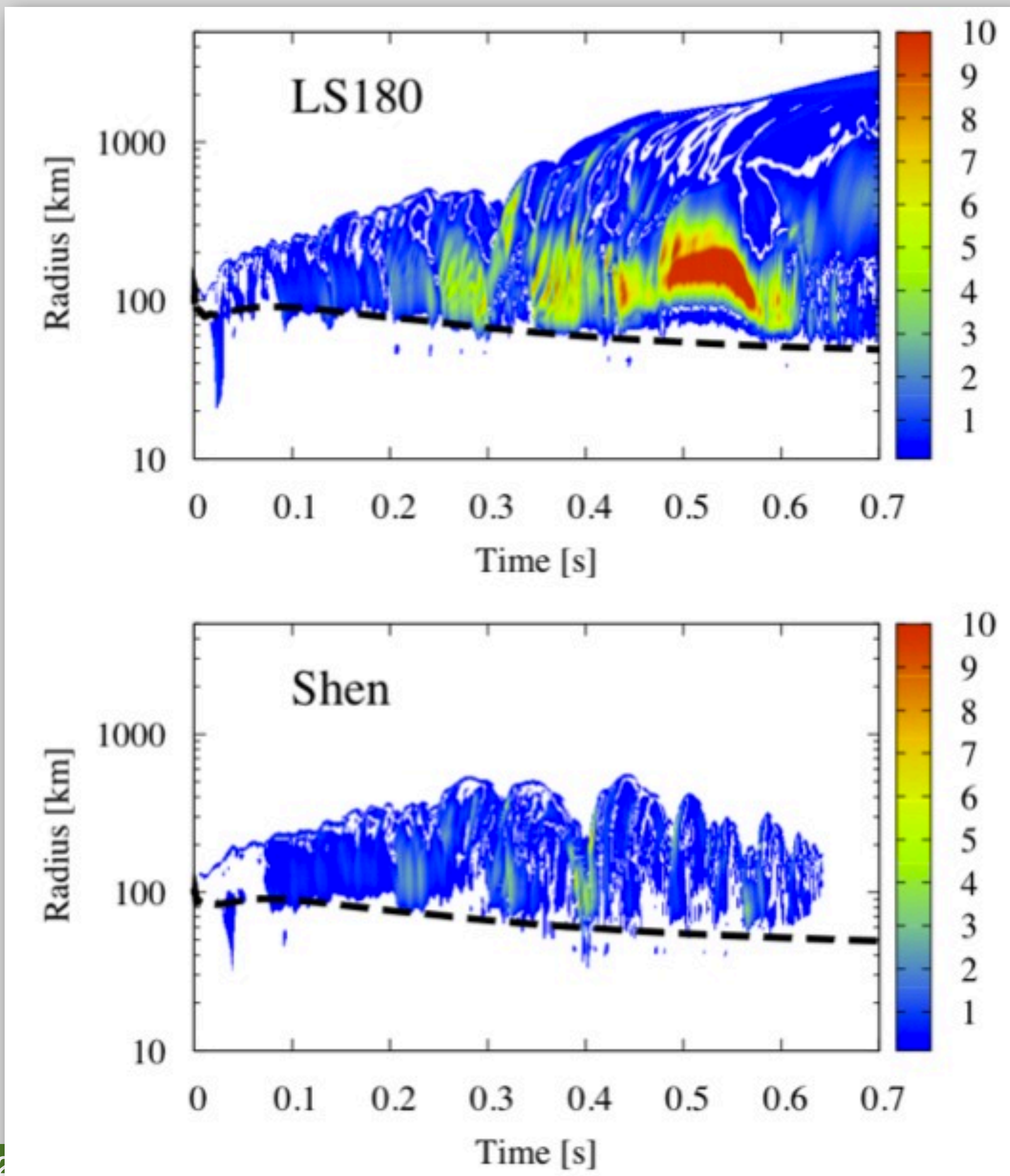
Shen



$$cf.\ \frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla(\cdot \rho \boldsymbol{u}\boldsymbol{u} + P) = 0$$

Dispersion of the moment

YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato arXiv:1206.6101



$$\frac{\left\{\frac{1}{2}\int_0^\pi \left[\mathcal{M}(r,\theta) - \overline{\mathcal{M}}(r)\right]^2 \sin\theta d\theta\right\}^{1/2}}{\overline{\mathcal{M}}(r)}$$

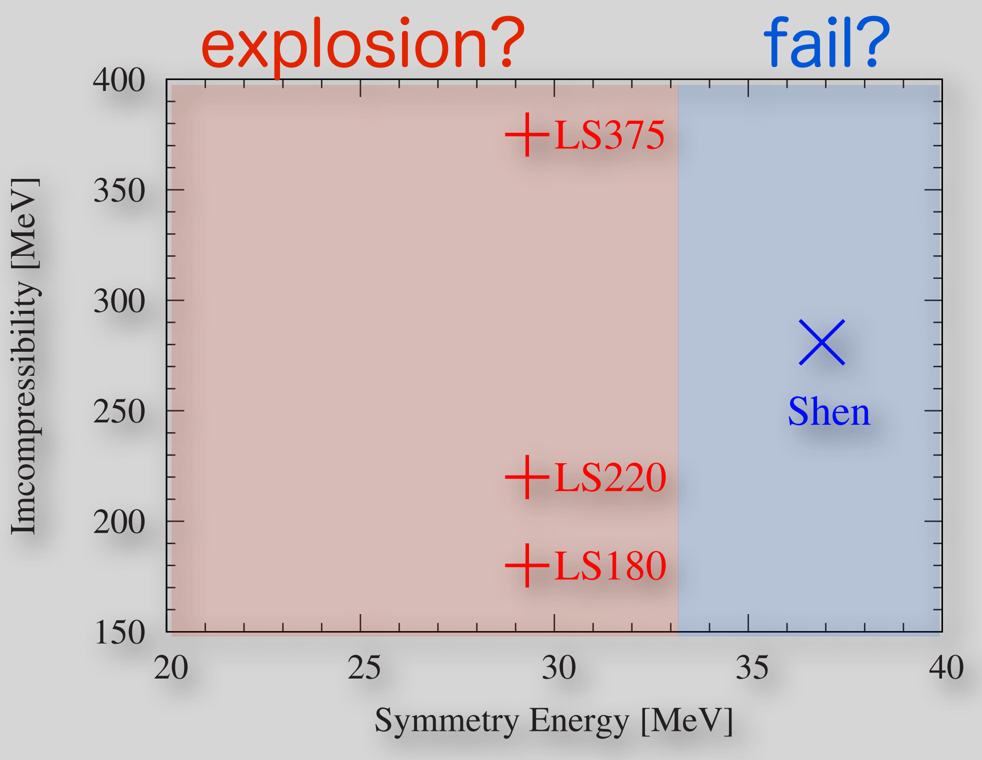
$$\mathcal{M}(r,\theta) \equiv \rho(r,\theta)v_r^2(r,\theta) + P(r,\theta),$$

$$\overline{\mathcal{M}}(r) \equiv \frac{1}{2}\int_0^\pi \mathcal{M}(r,\theta)\sin\theta d\theta.$$

Summary and discussion

* We perform 1D and 2D simulations in a parametric manner focusing on the impact of the collective oscillation, which changes the neutrino spectrum
  * The spectral swapping could amplify the explosion
  * 2D effects lead to stronger explosion
  * The possibility of spectral swapping is still under debate

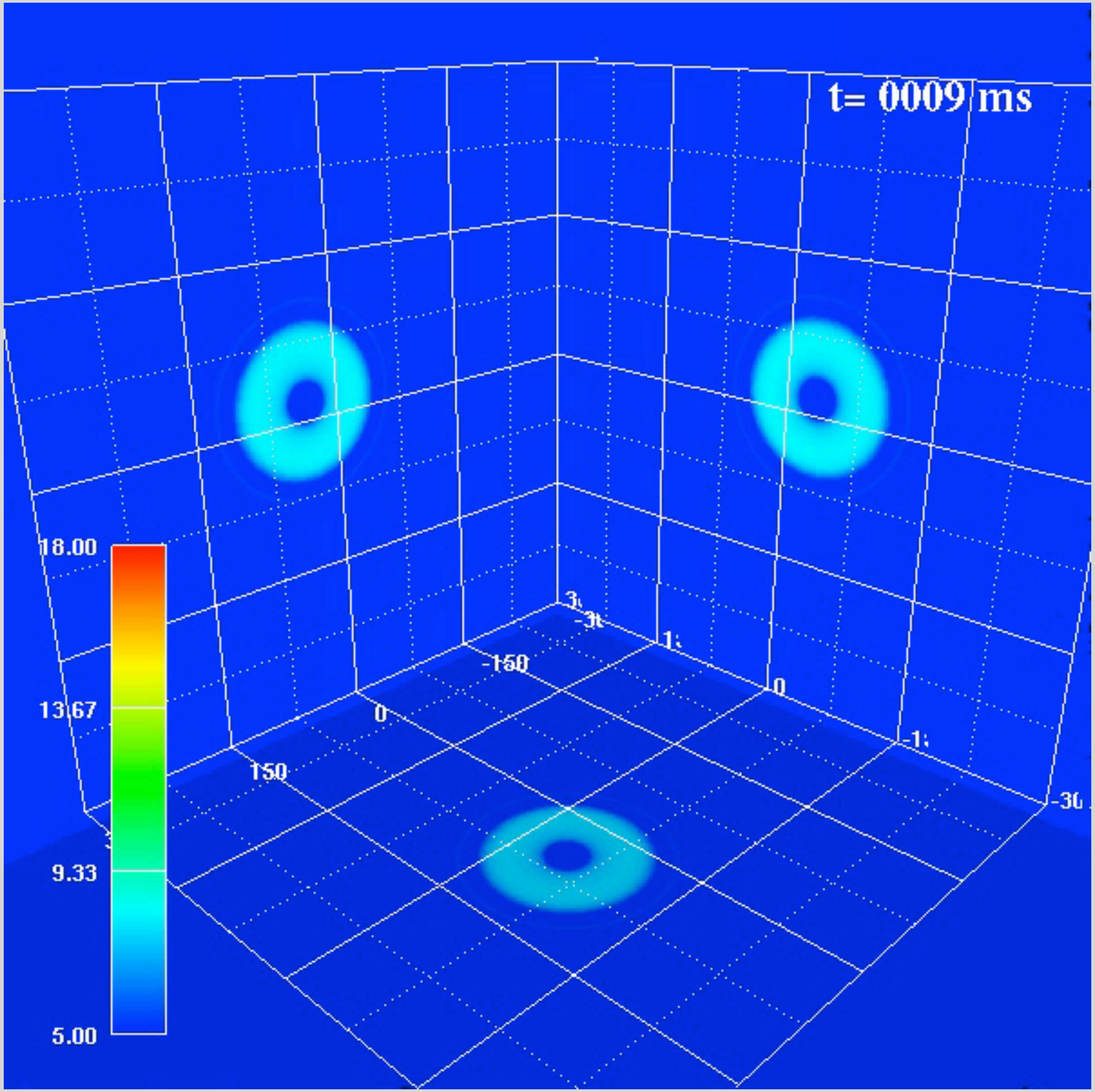
* We perform axisymmetric simulations of a core-collapse supernova driven by the neutrino heating and investigate the dependence on the equation of state
  * Lattimer & Swesty EOS: explosion
  * Shen EOS: failure



* In order to make the complete understanding of EOS impacts, a more systematic study is strongly required!

Appendix: 3D simulation with neutrino transfer

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



320(r)x64(θ)x128(ϕ)
x20(E_ν)