超新星爆発シミュレーションと核物質状態方程式

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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
- Transition from a massive stellar core to a neutron star (Birth of neutron stars!)

- 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 $\sim 10^{51}$ 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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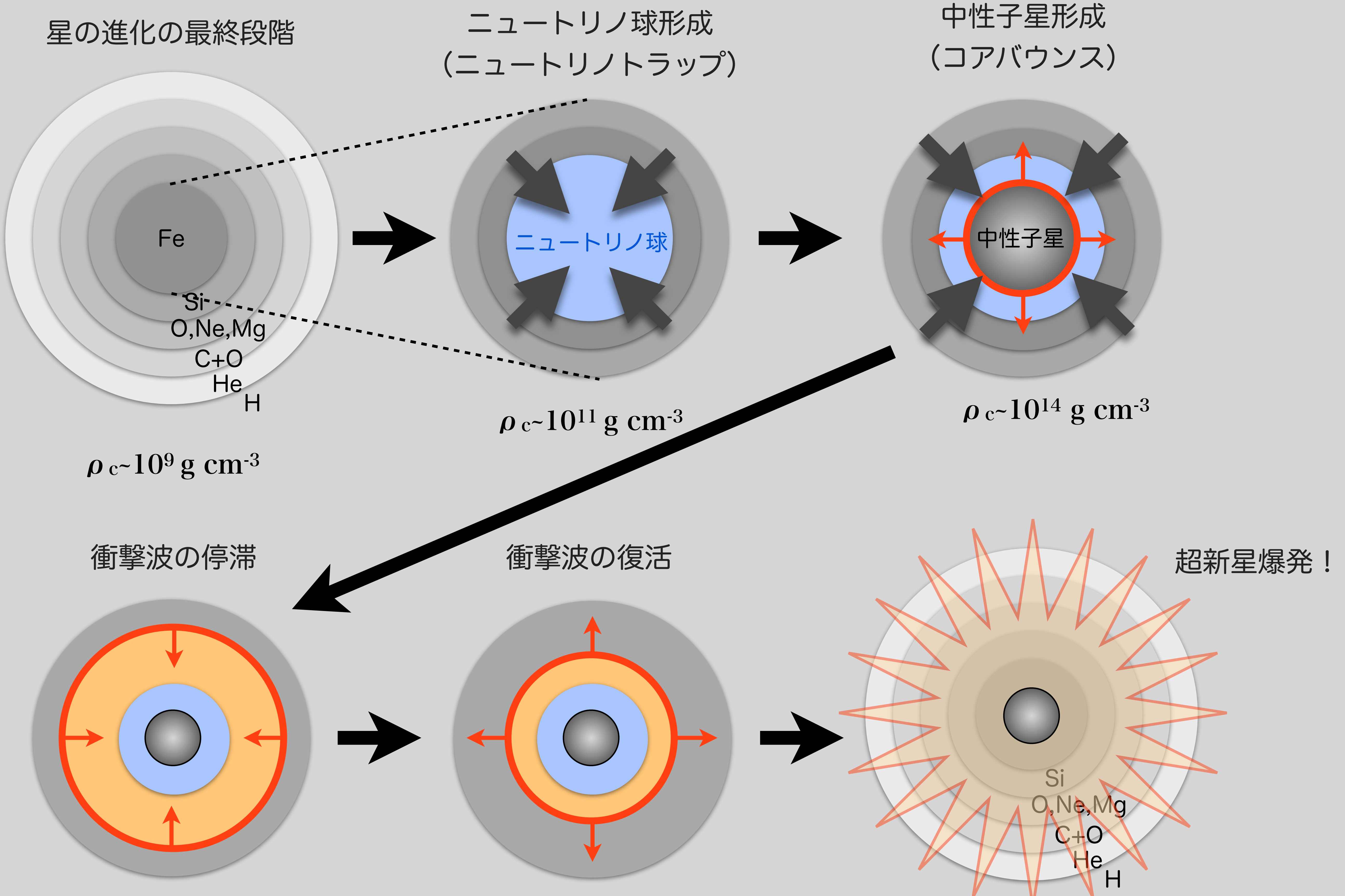
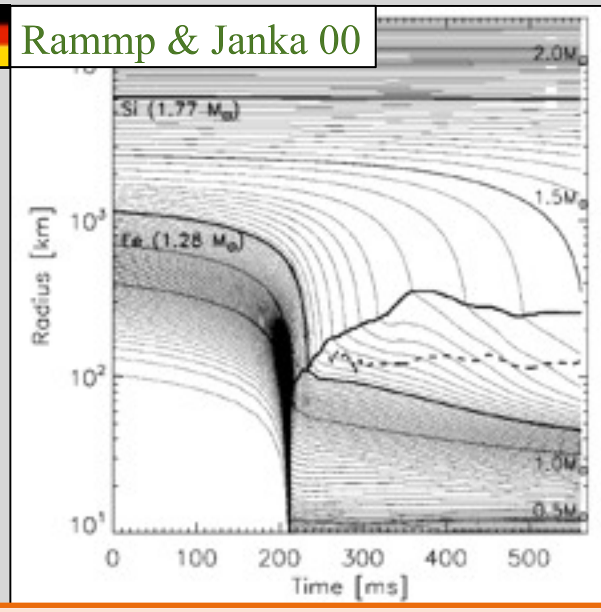
Standard scenario of core-collapse supernovae

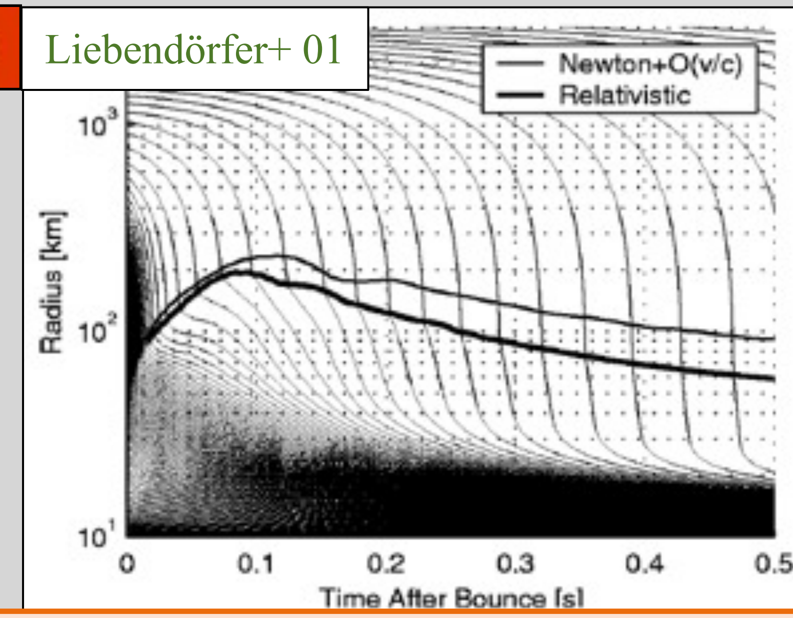


1D simulations: fail to explode

Rammp & Janka 00

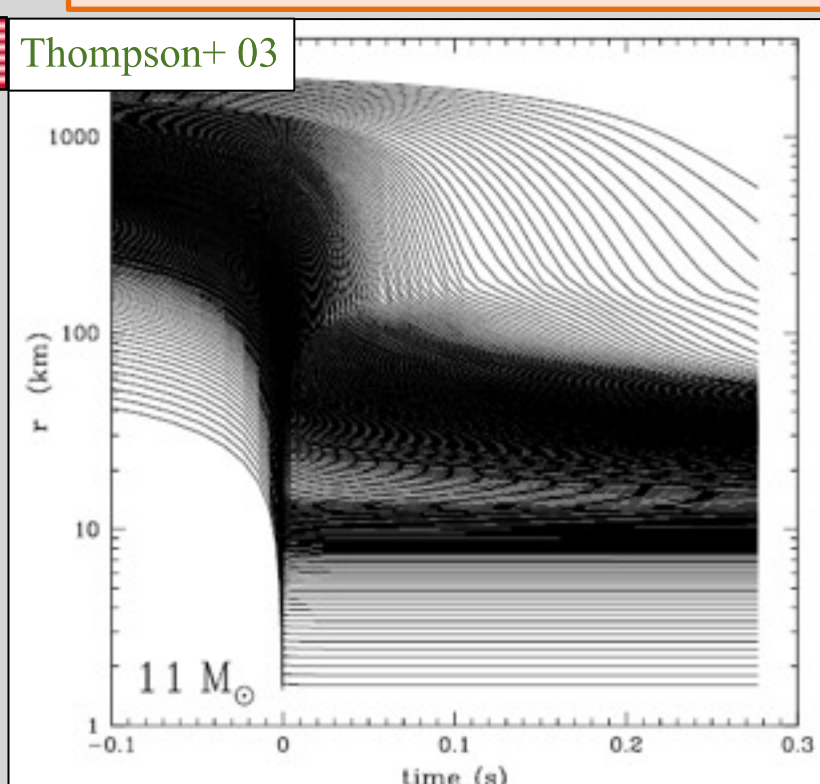


Liebendörfer+ 01

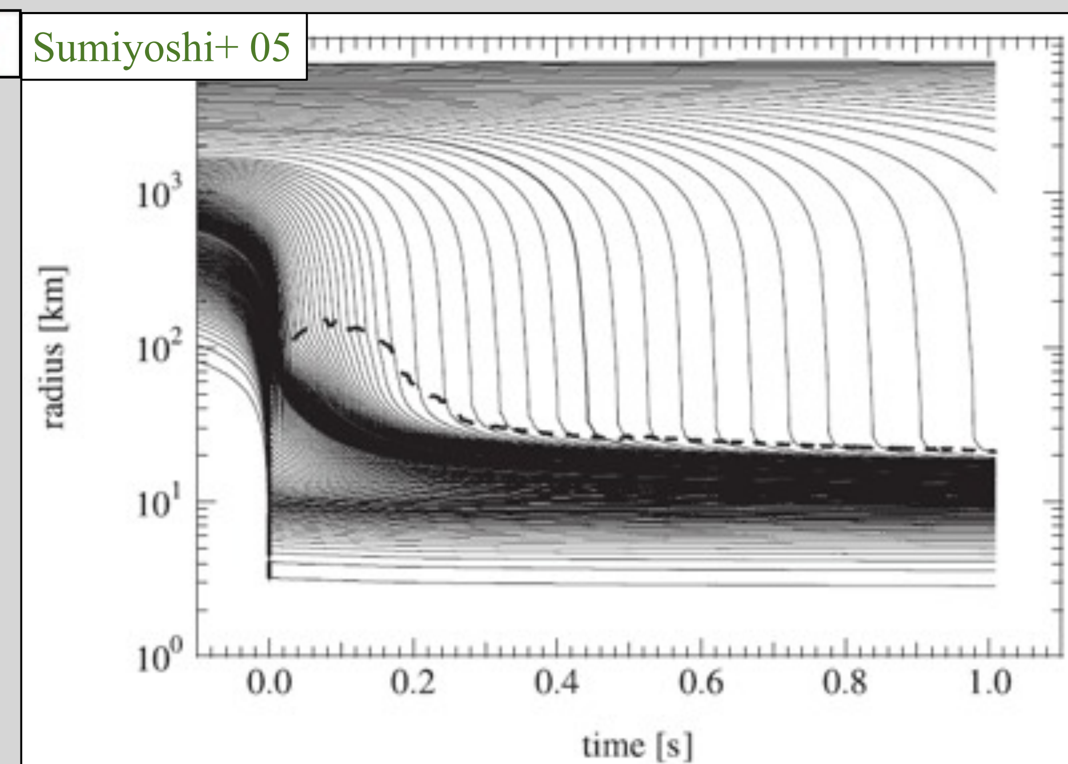


By including all available physics to simulations, we concluded that the explosion cannot be obtained in 1D!
(The exception is an 8.8 $M_\odot$ star; Kitaura+ 06)

Thompson+ 03

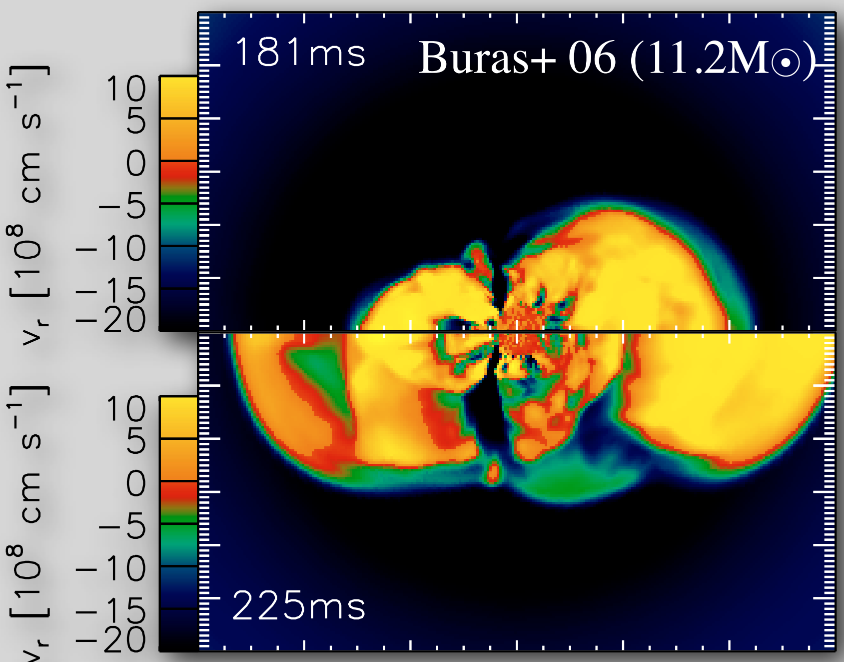


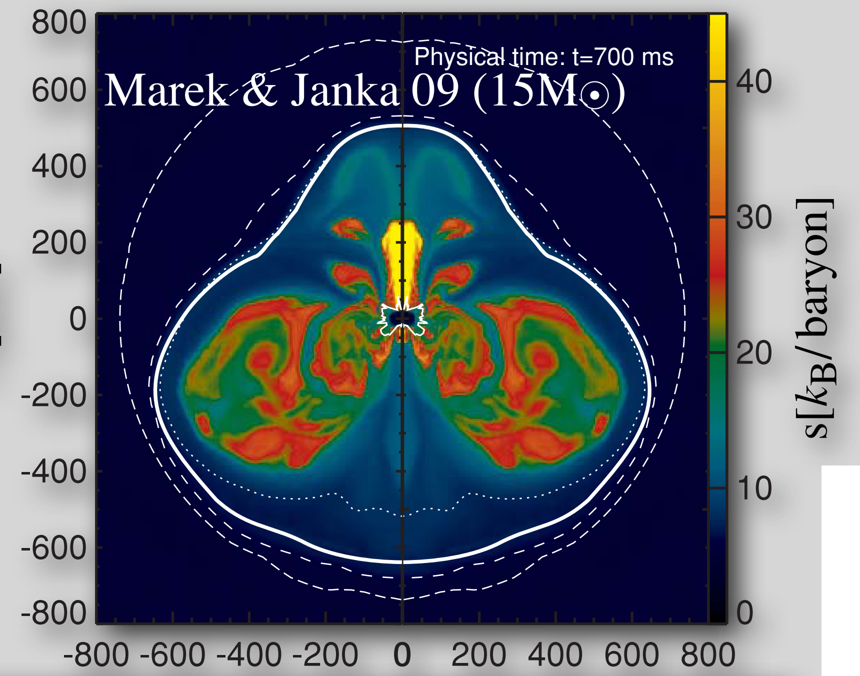
Sumiyoshi+ 05

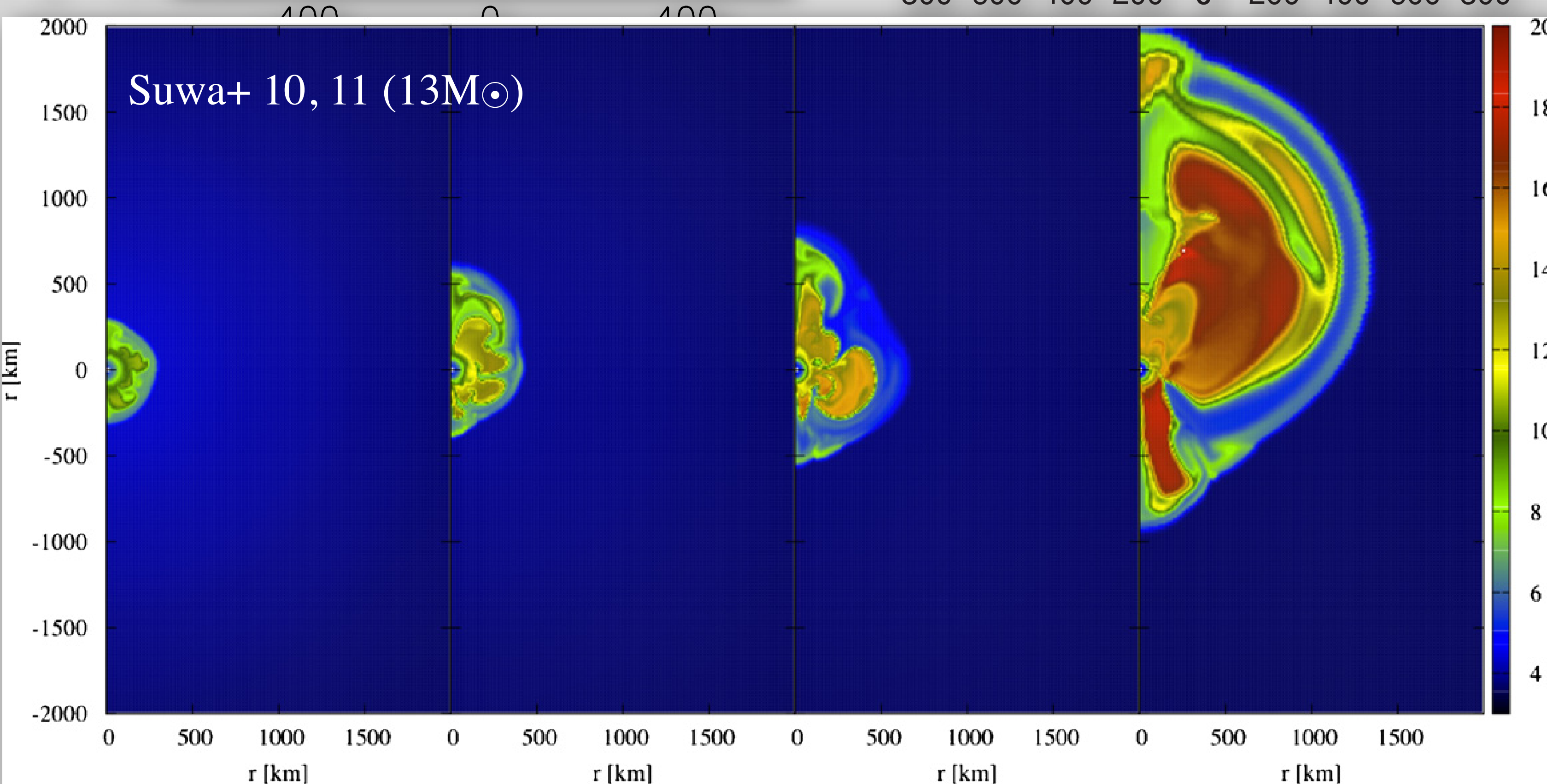


Neutrino-driven explosion

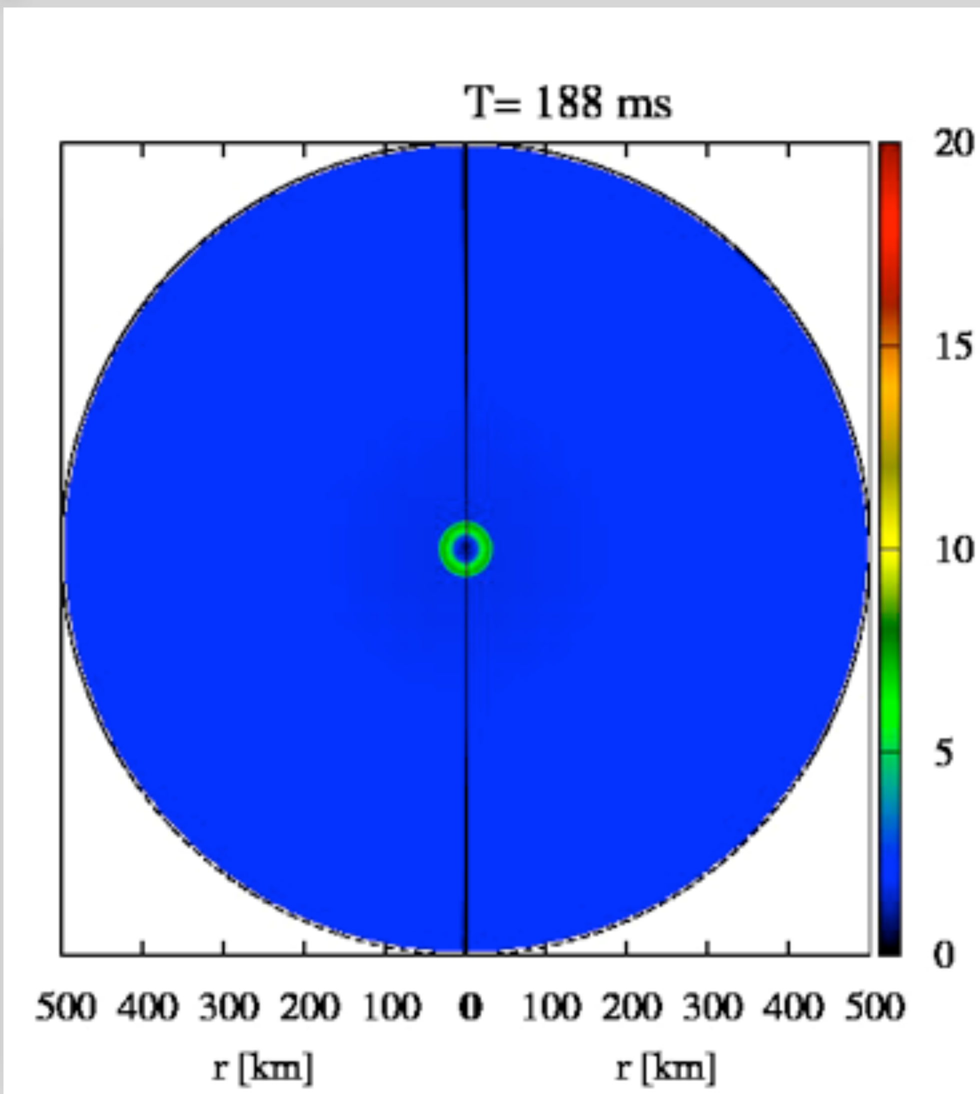
Recently, we have successful exploding models driven by neutrino heating







Suwa+ 12 (15M⊙)



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)

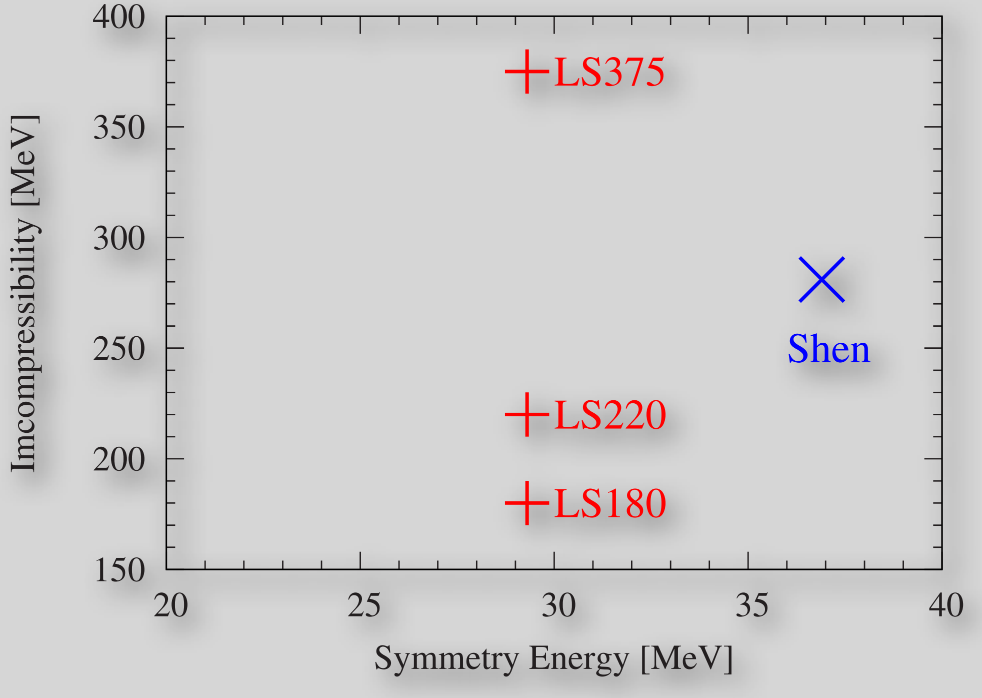
	incompressibility K [MeV]	symmetry energy J (S) [MeV]	slope of symmetry energy L [MeV]
LS	180, 220, 375	29.3	73.8 (from Steiner+ 2012)
HShen	281	36.9	111
HW	263	32.9	---
GShen	271.5 (NL3) 230.0 (FSU)	37.29 (NL3) 32.59 (FSU)	118.2 (NL3) 60.5 (FSU)
Hempel	318 (TMA) 230 (FSU)	30.7 (TMA) 32.6 (FSU)	90 (TMA) 60 (FSU)

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

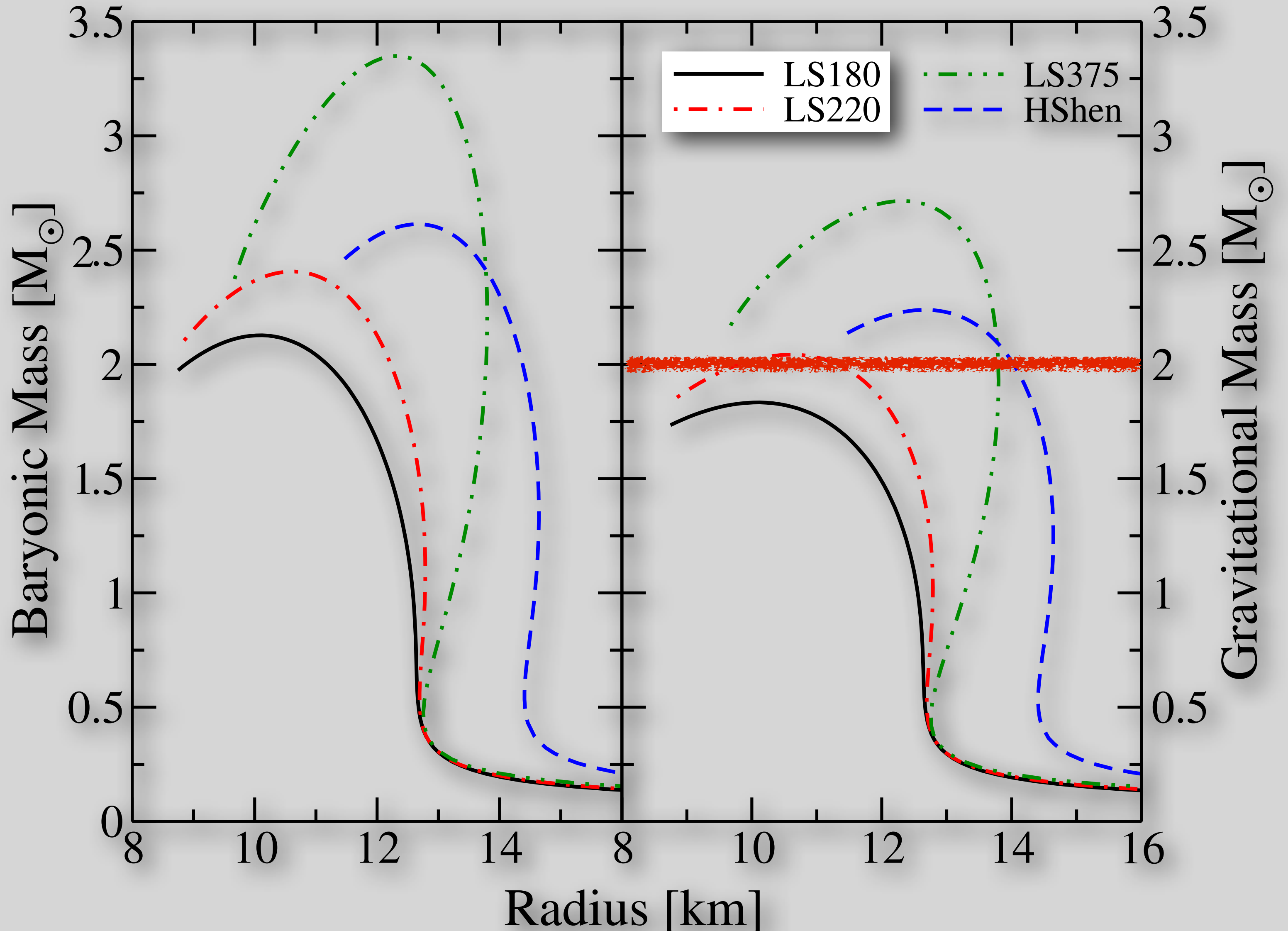
Equation of state

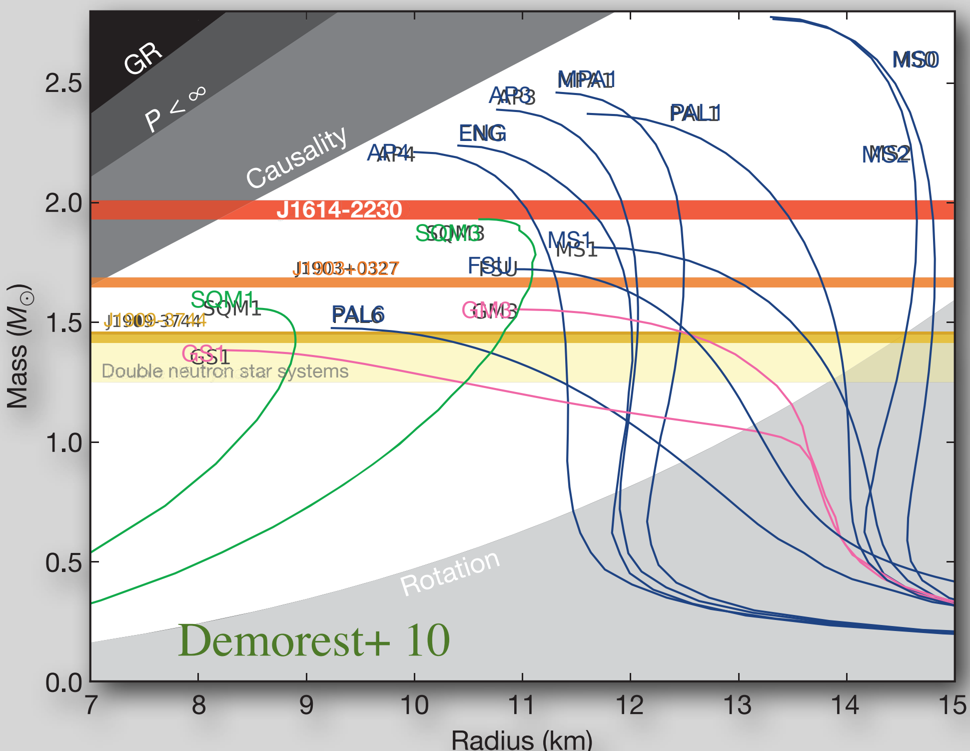
The “standard” equations of state (EOS) in supernova community

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



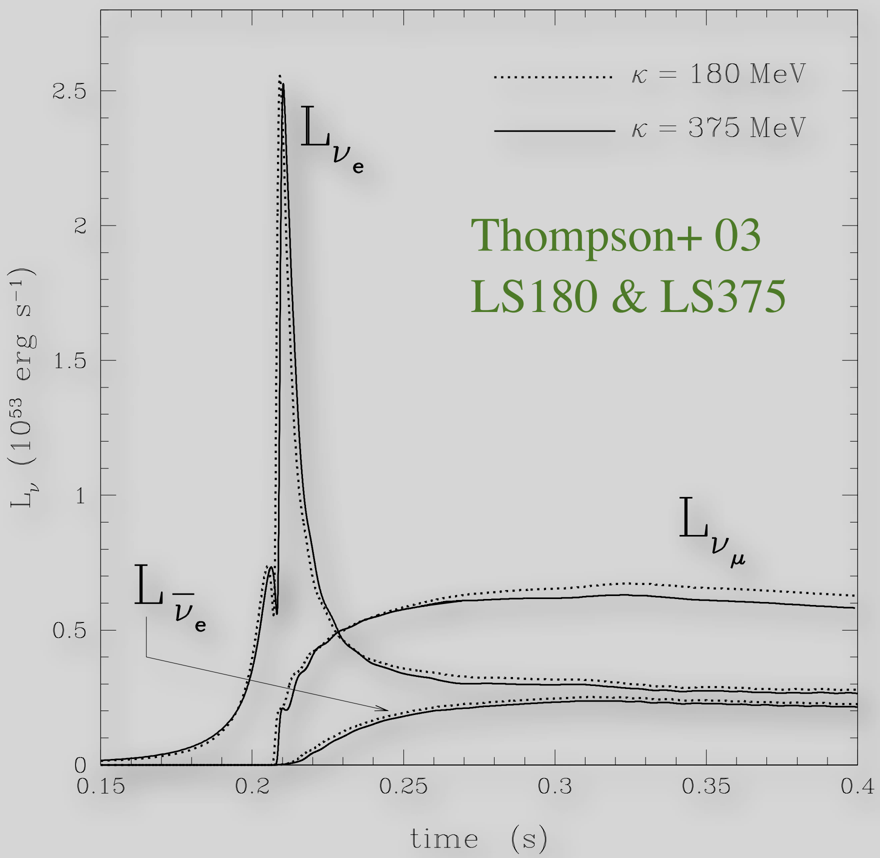
O’Connor & Ott 10

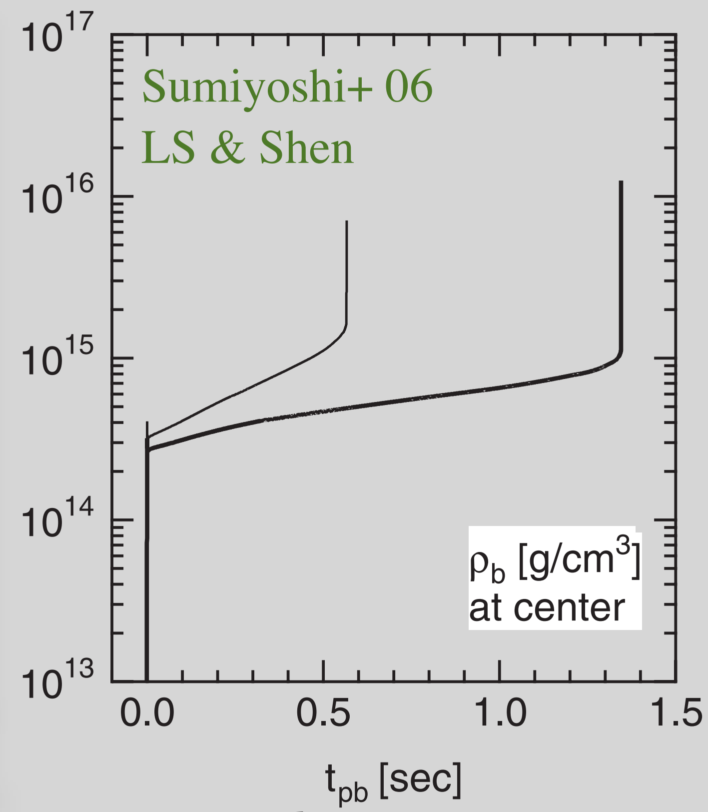


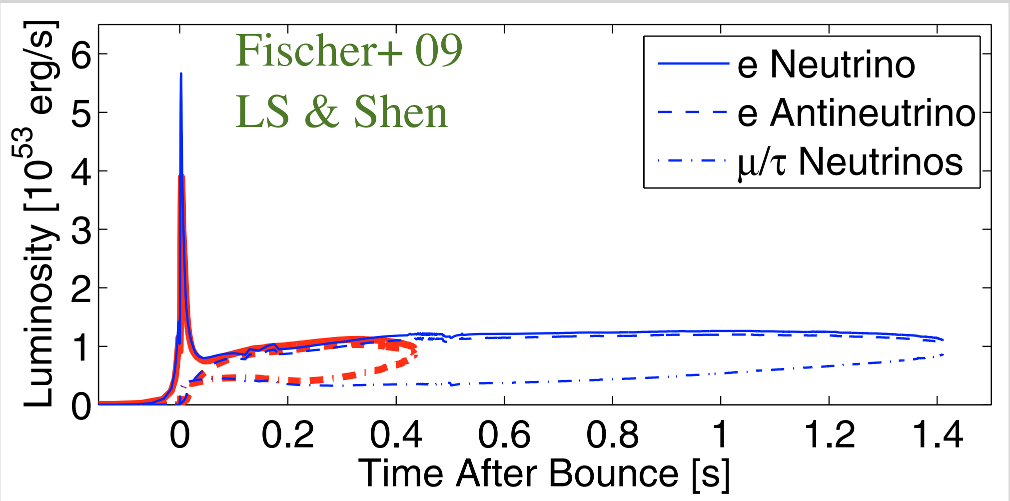


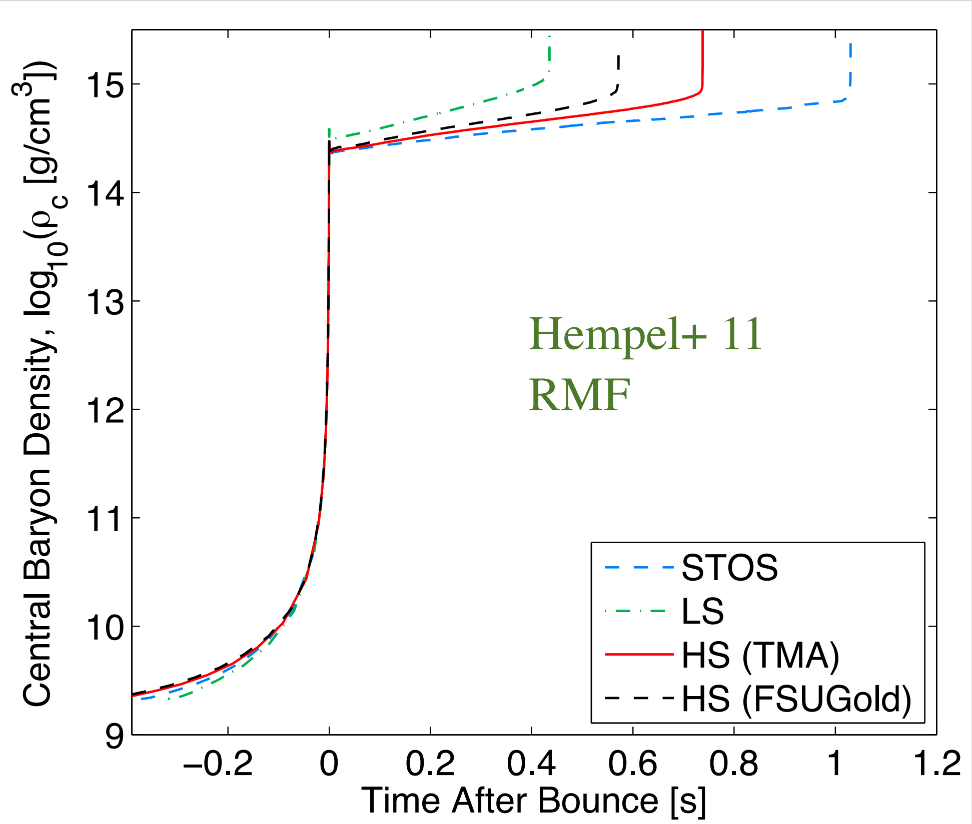
Demorest+ 10

Studies on EOS dependence





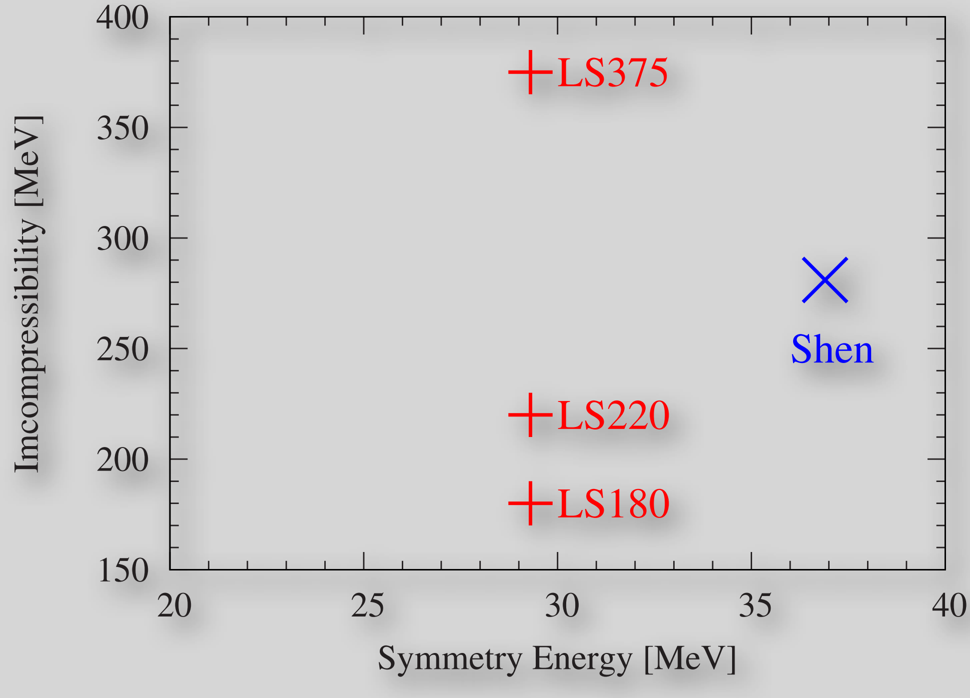




- There are several works, which investigated the EOS dependence with 1D simulation
- Since 1D simulations fail to produce explosion, the representable physical quantities in these studies are
  - BH formation time
  - neutrino luminosity/spectrum evolution
- How about the explosion? Does it produce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

Numerical simulation

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



Note: Of course the other parameters differ as well.

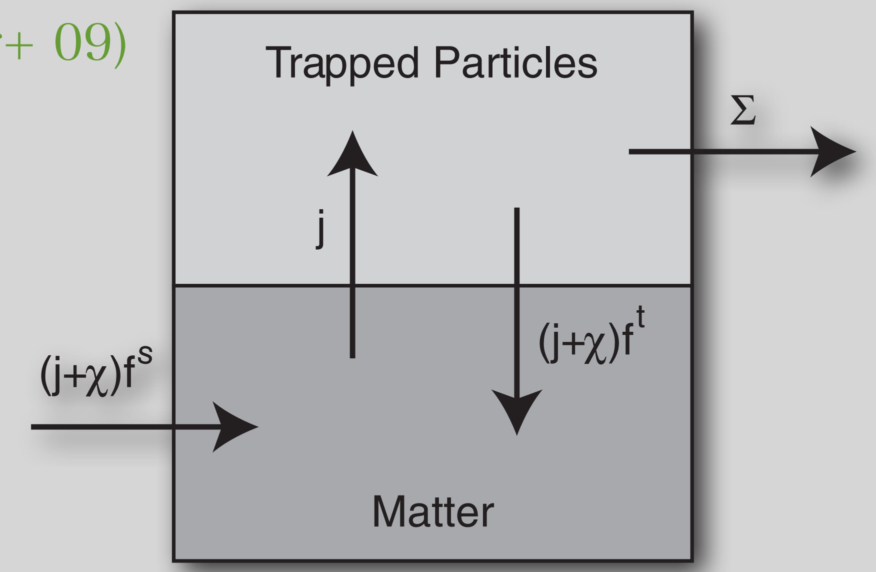
- Axisymmetric simulation (ZEUS-2D; Stone & Norman 92)

- 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

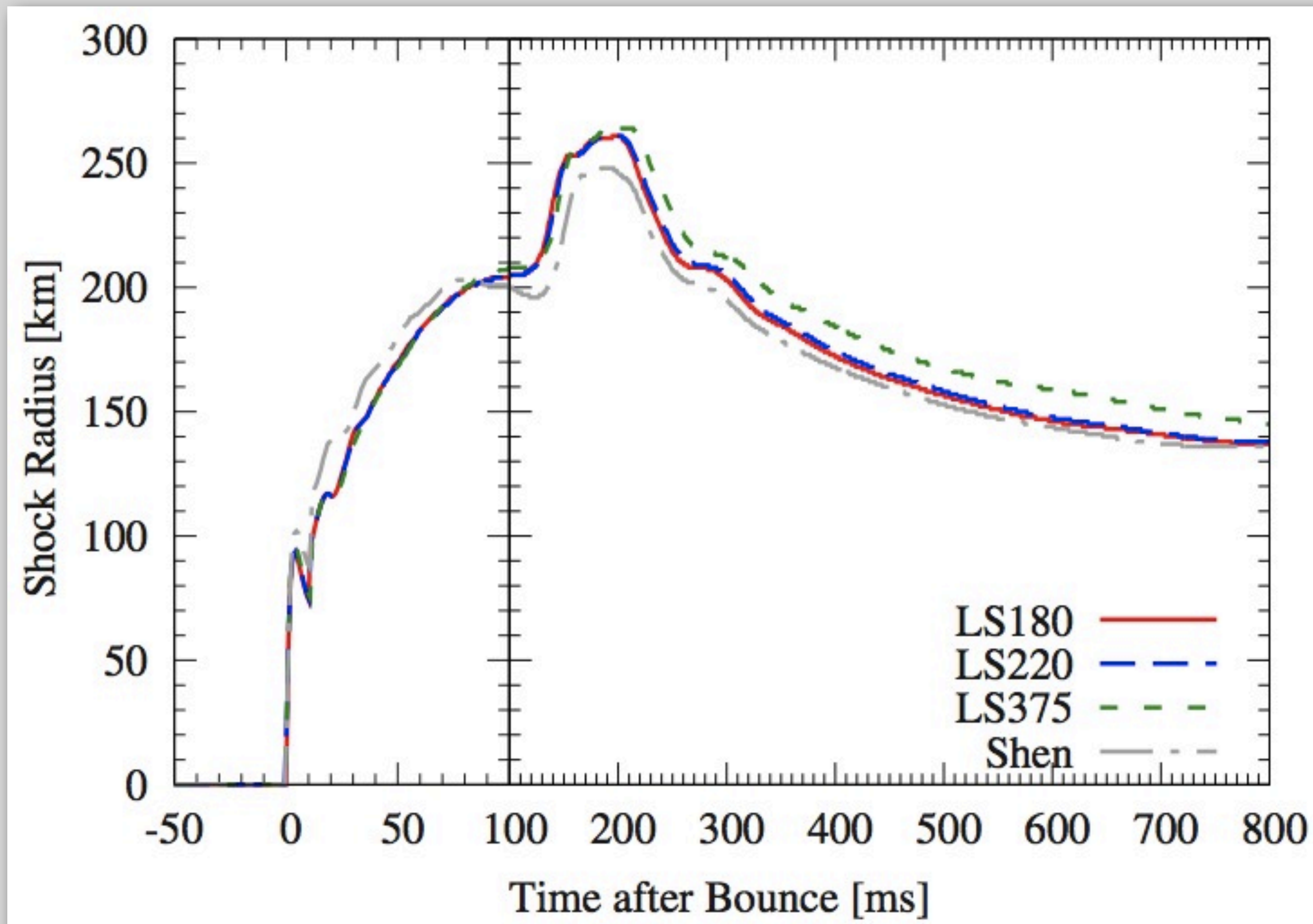


- progenitor: 15 M⊙ (Woosley & Weaver 95)

Results in 1D simulation

Evolution of shock radius

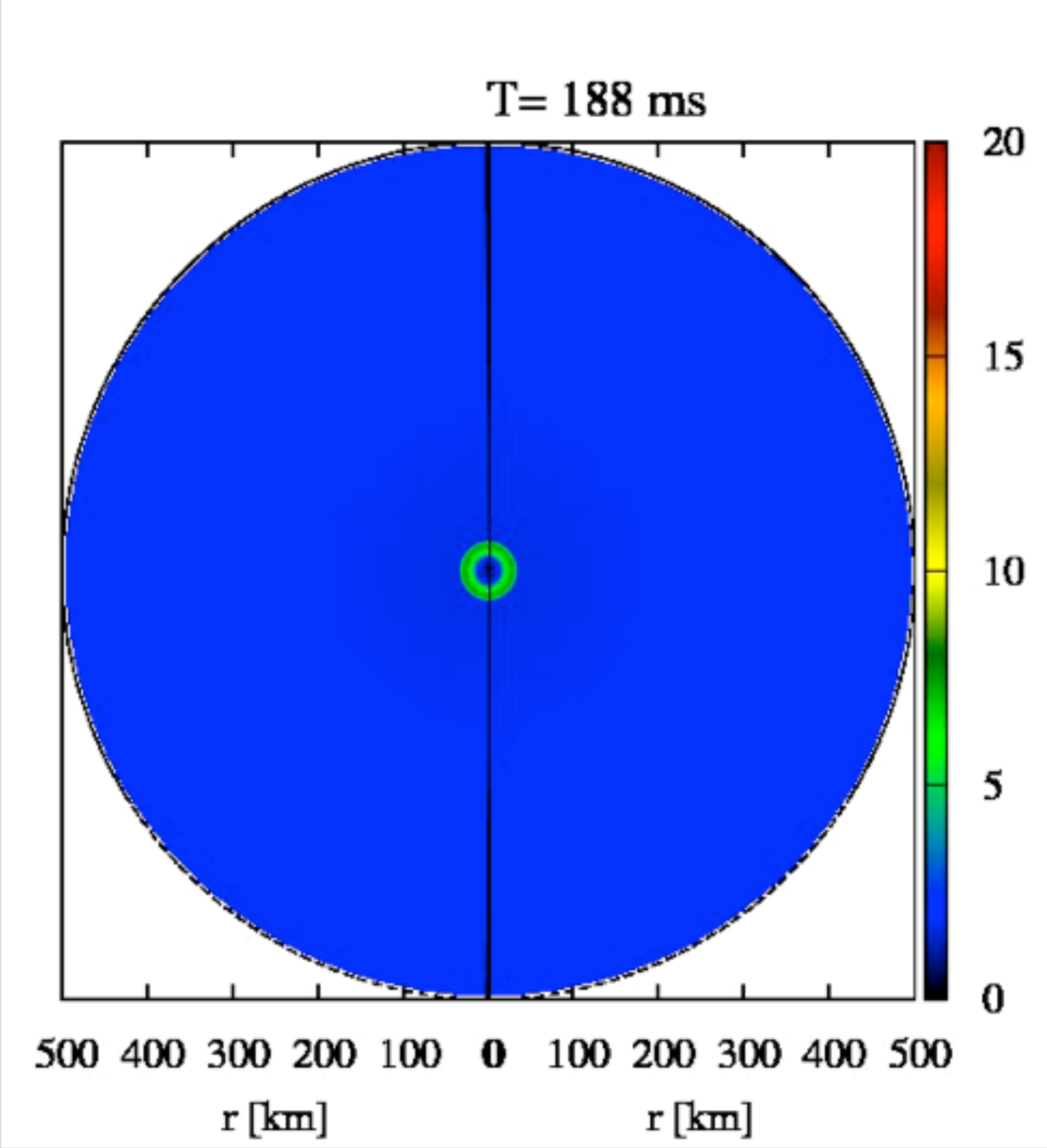
YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato arXiv:1206.6101



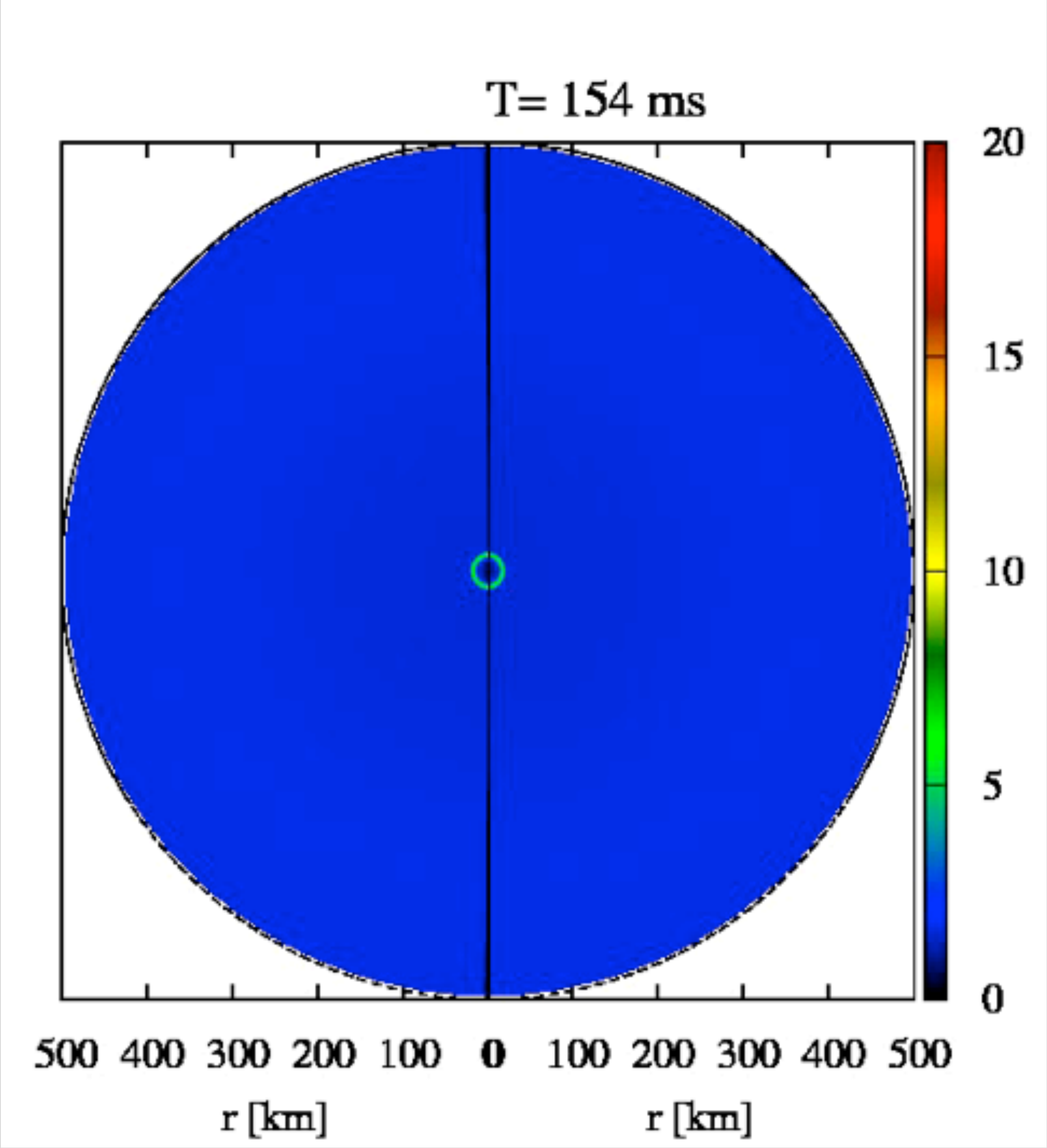
Entropy evolution

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

LS180

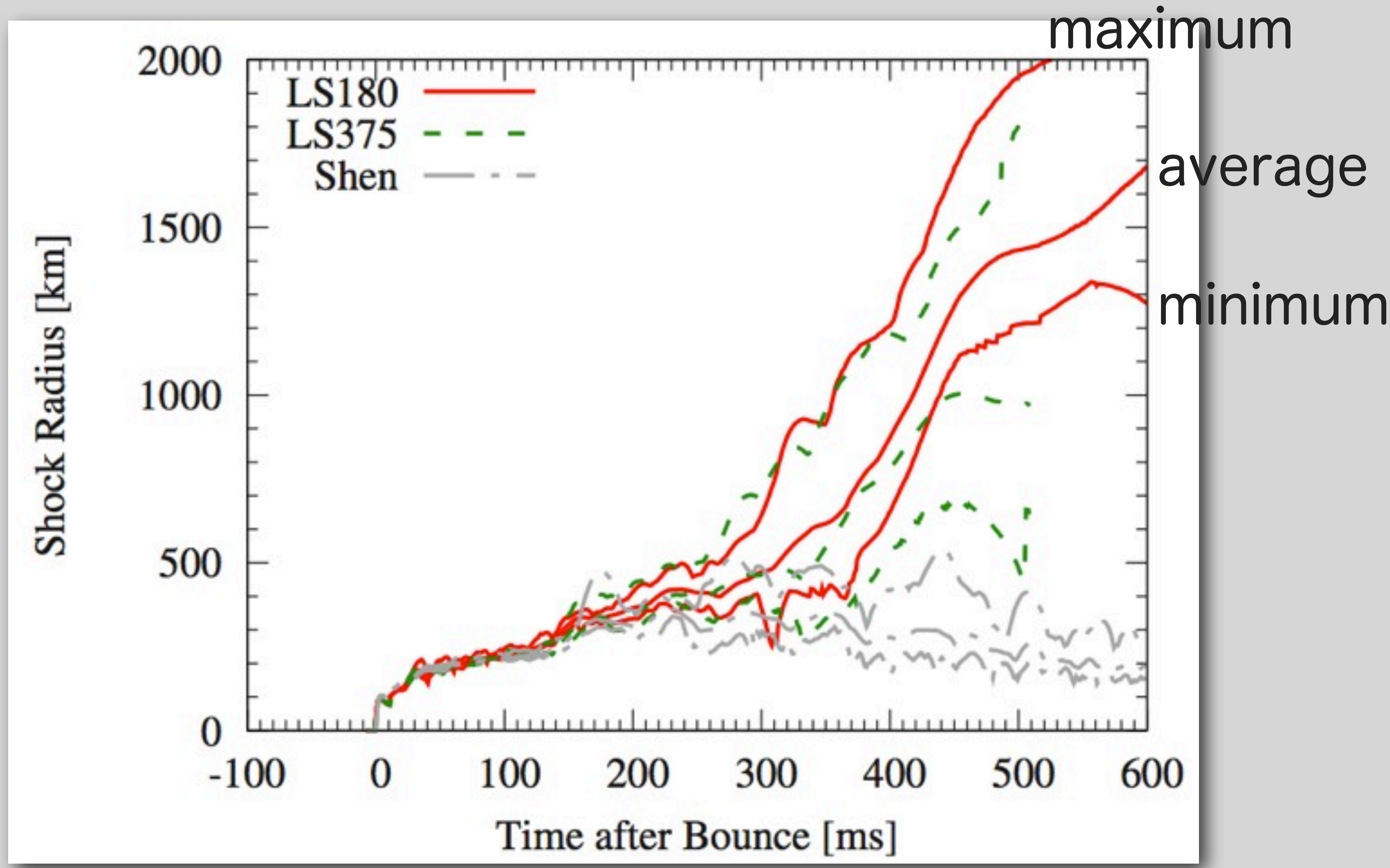


Shen



Shock radius

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

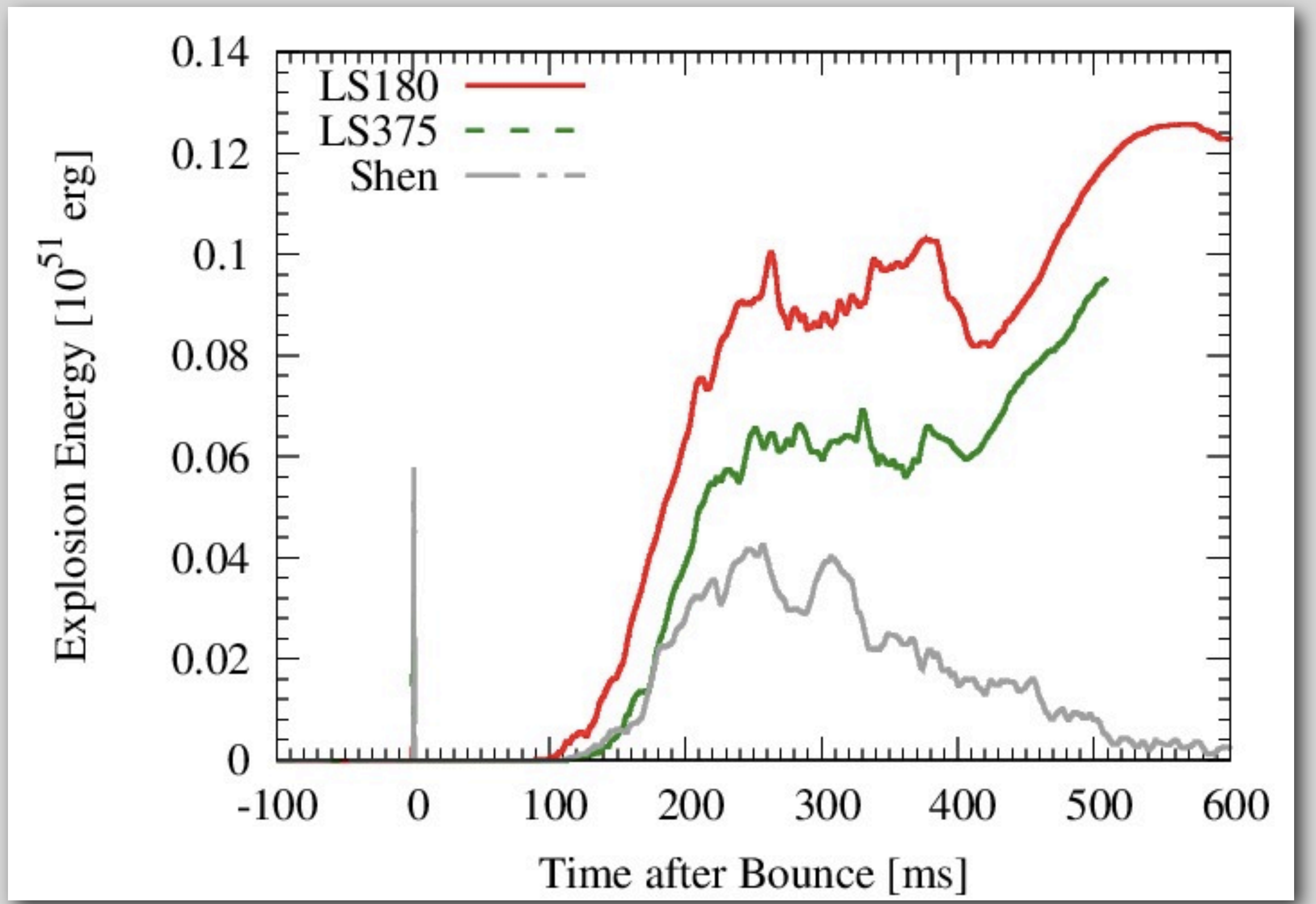


LS180 and LS375 succeed the explosion

Shen EOS fails

Explosion energy

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



Dispersion of the moment

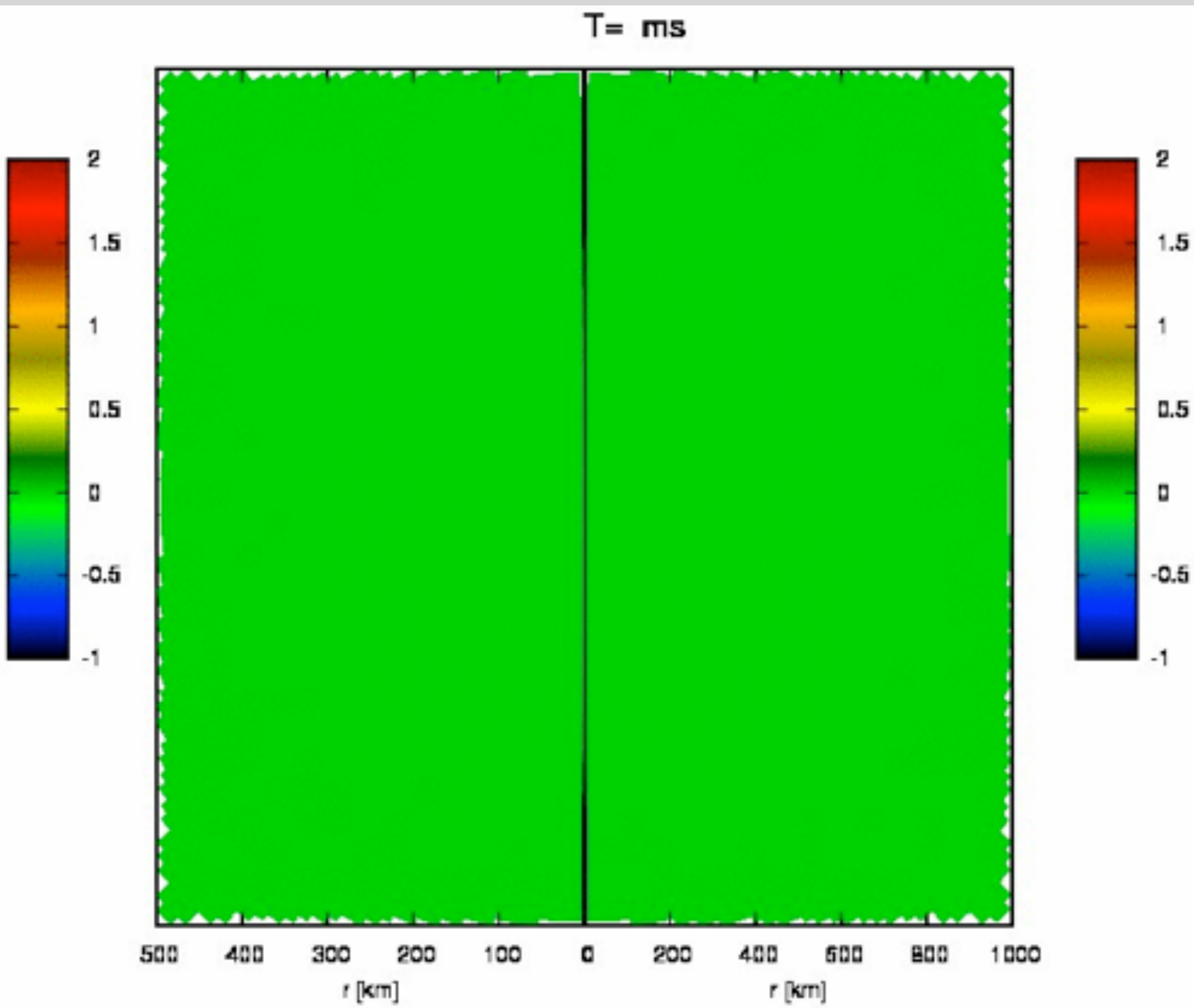
$$\frac{\mathcal{M}(r,\theta)-\overline{\mathcal{M}}(r)}{\overline{\mathcal{M}}(r)}$$

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

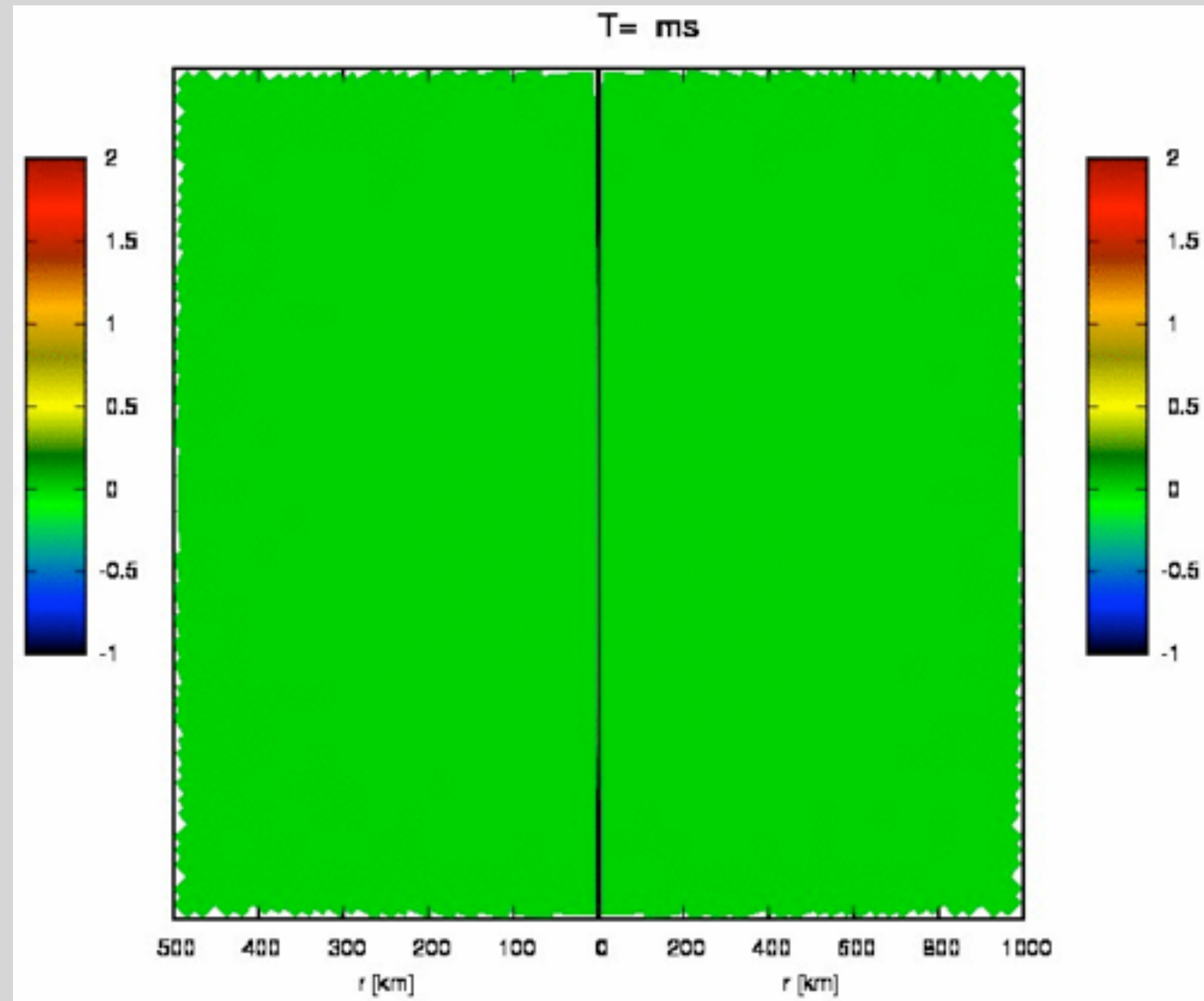
$$\overline{\mathcal{M}}(r) \equiv \frac{1}{2}\int_0^\pi \mathcal{M}(r,\theta)\sin\theta d\theta.$$

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

LS180



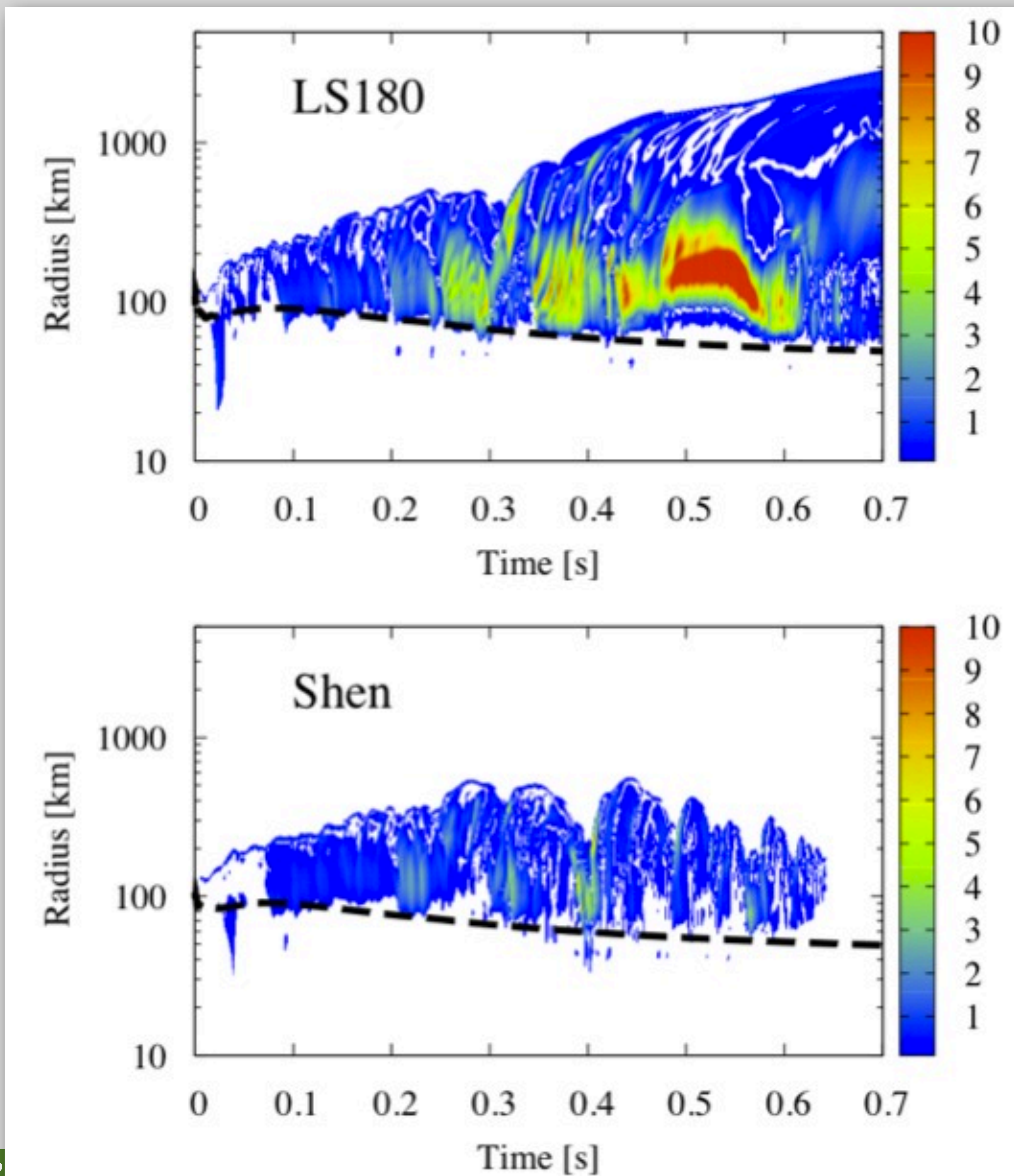
Shen



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

Dispersion of the moment

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



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

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

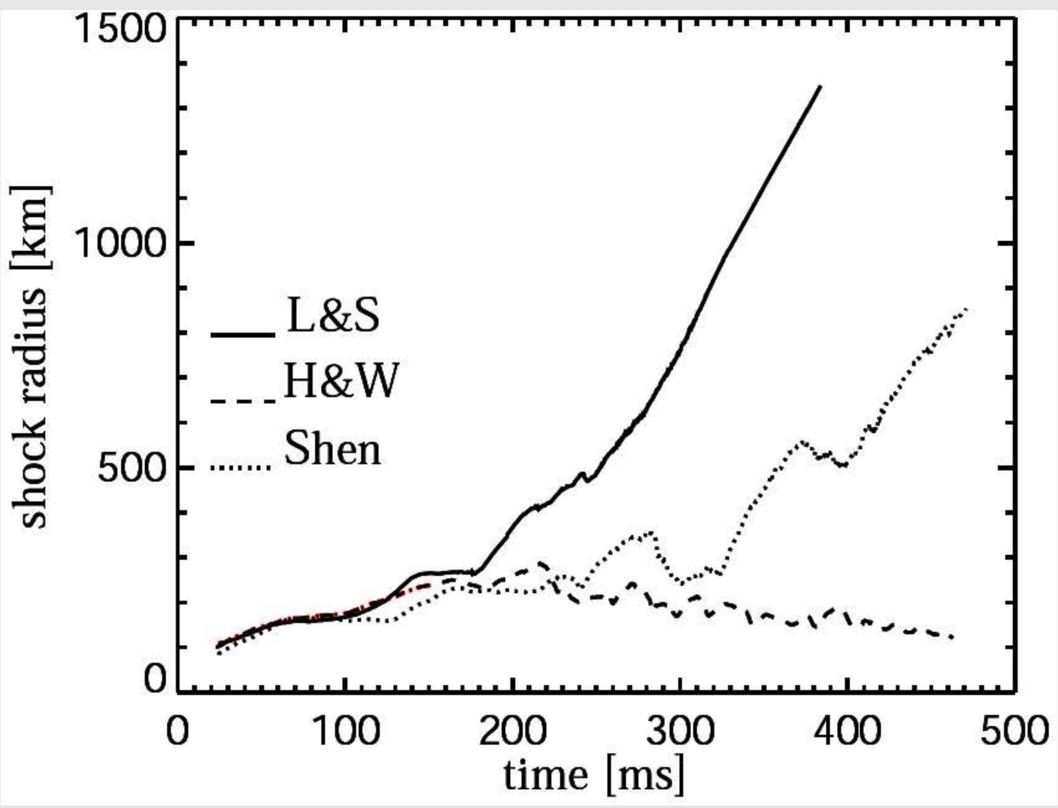
$$\overline{\mathcal{M}}(r) \equiv \frac{1}{2}\int_0^\pi \mathcal{M}(r,\theta)\sin\theta d\theta.$$

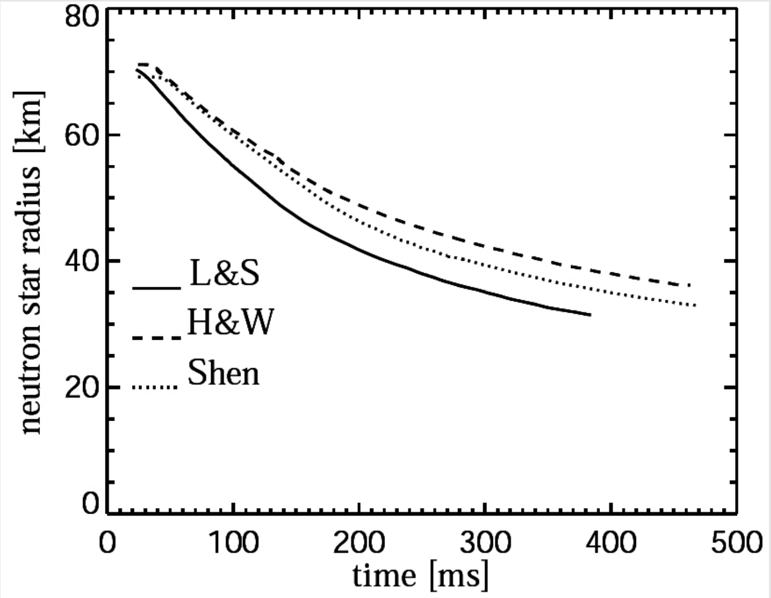
Radius of neutron star

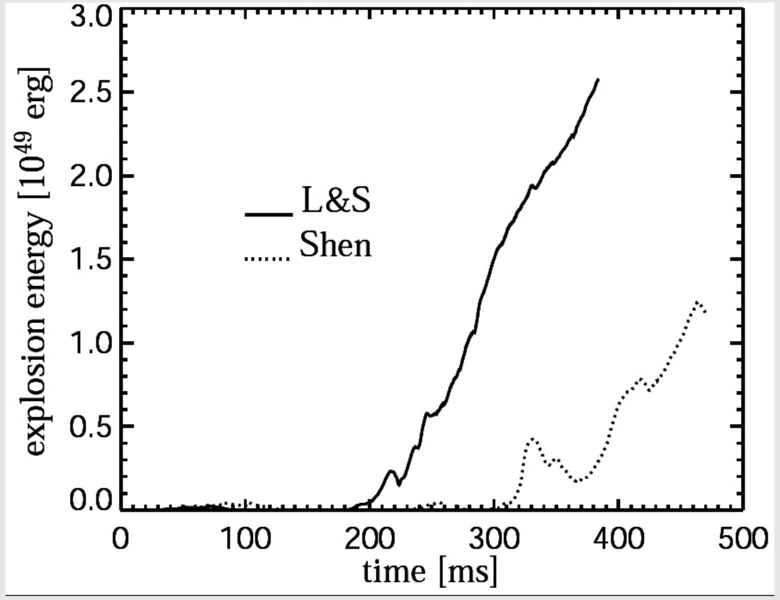
Janka (2012)

2D Explosions of 11.2 M_{sun} star : Test of EoS Influence

- Simulations for 3 different nuclear EoSs: Lattimer & Swesty (L&S), Hillebrandt & Wolff (H&W), Shen et al.
- "Softer" (L&S) EoS and thus more compact PNS leads to earlier explosion



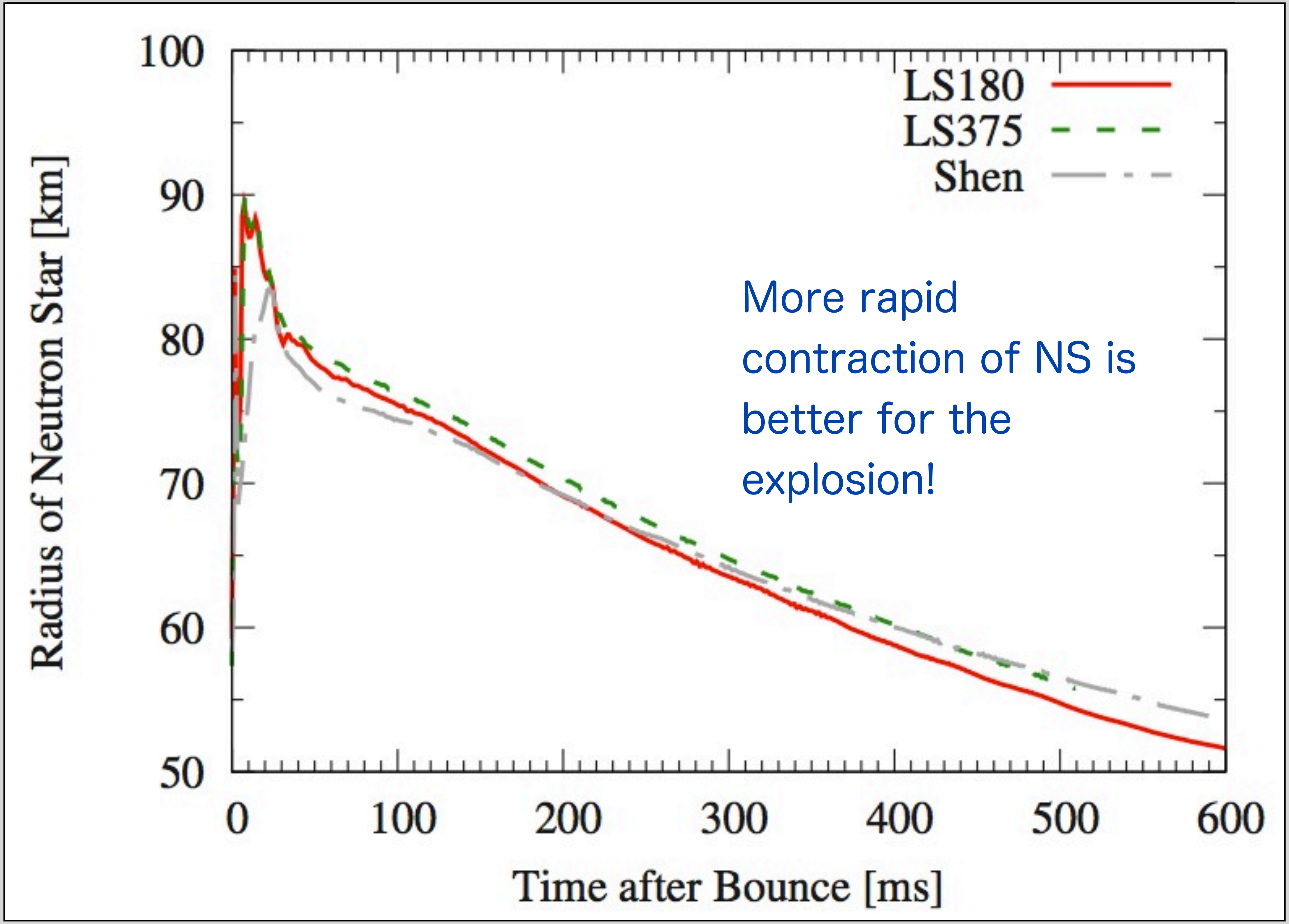




(Marek & THJ, 2009, in preparation)

19/24

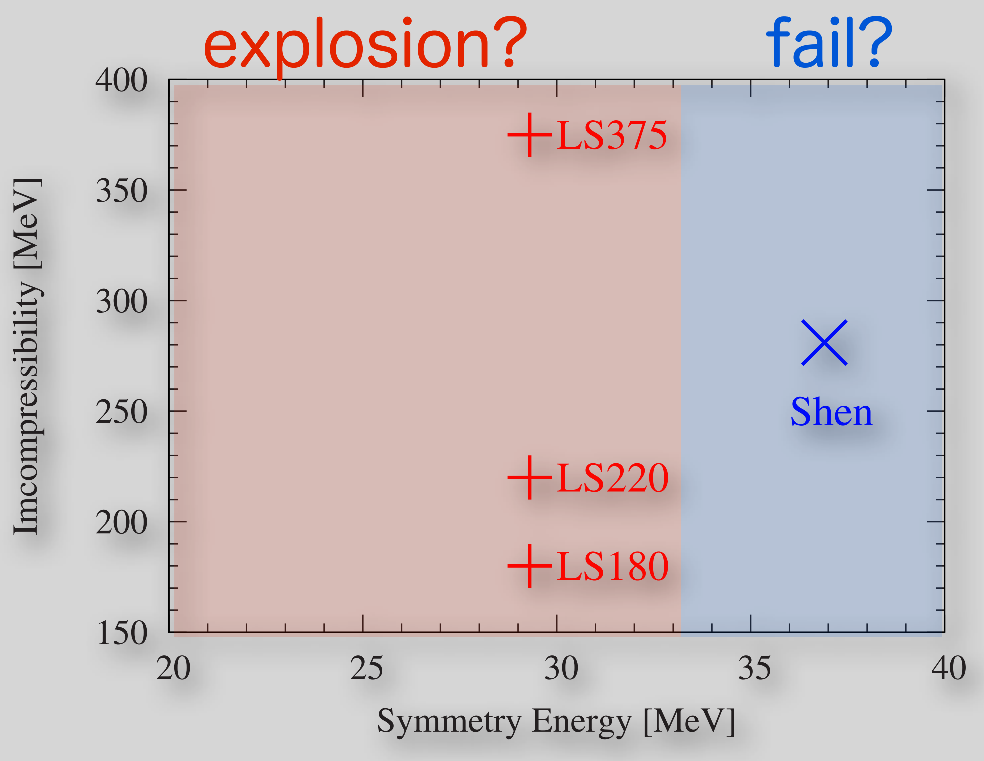
Radius of neutron star



More rapid contraction of NS is better for the explosion!

Summary and discussion

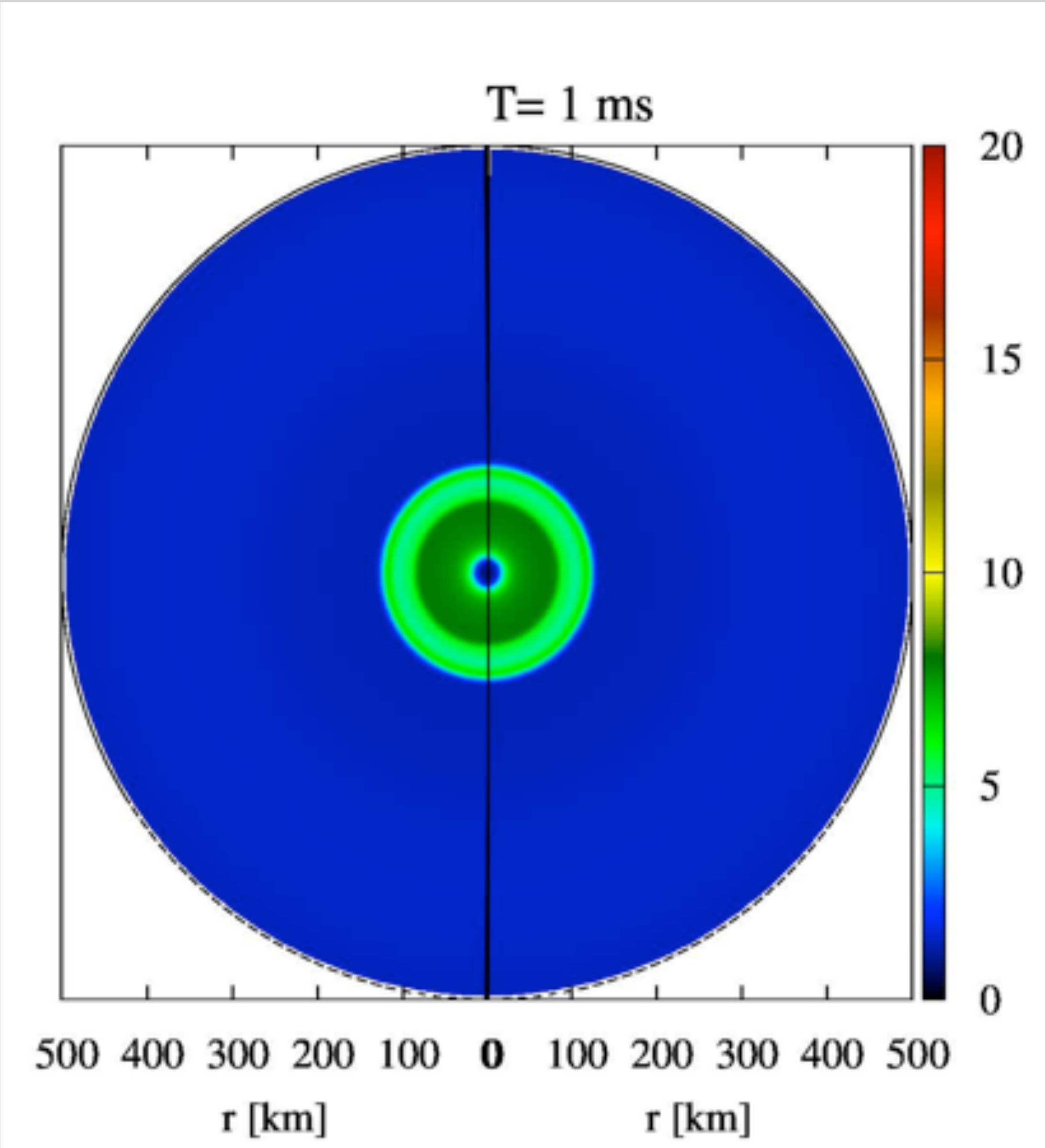
* We perform axisymmetric simulations of a core-collapse supernova driven by the neutrino heating and investigate the dependence on the equation of state
  * Lattimer & Swesty EOS: explosion
  * Shen EOS: failure

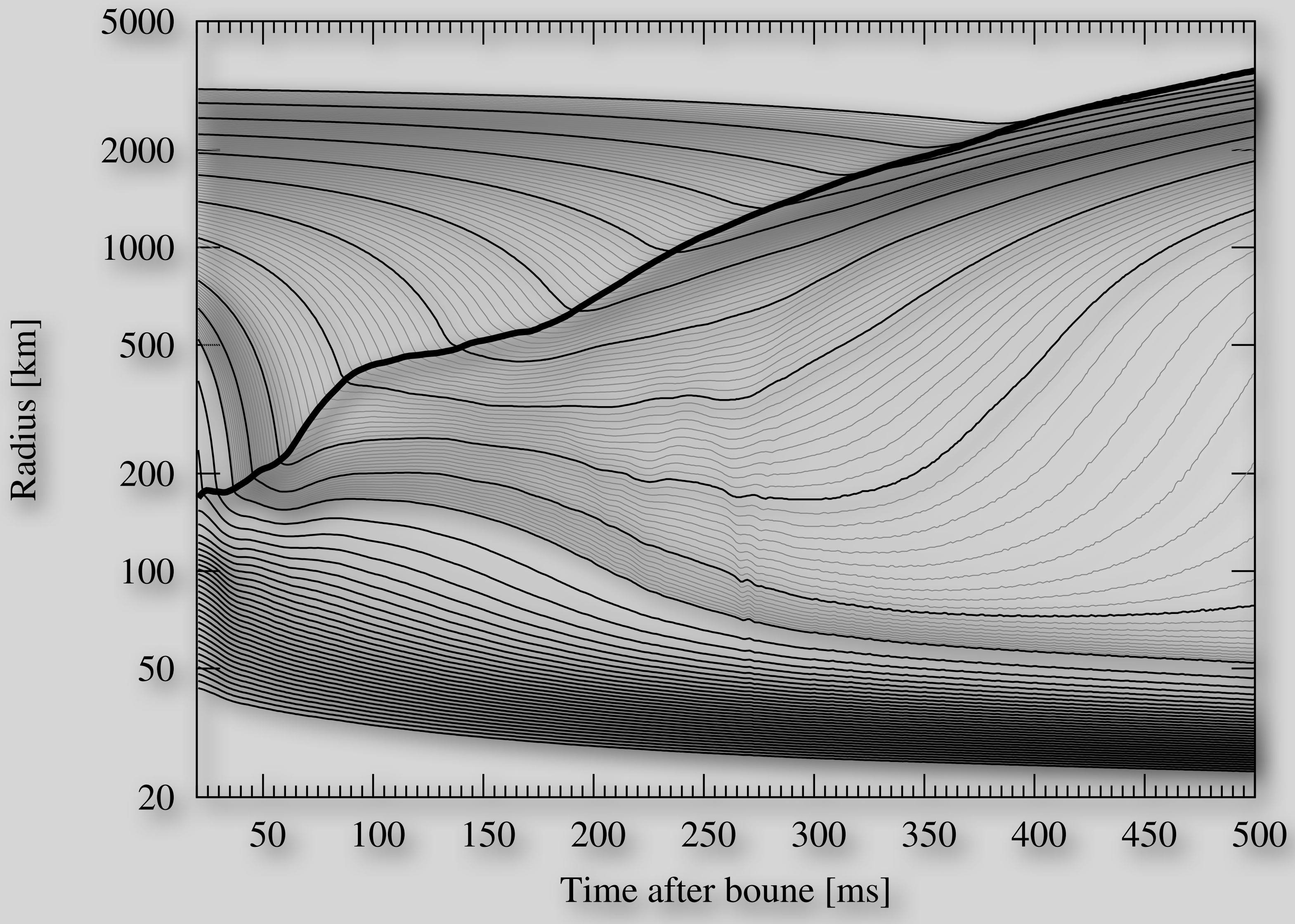


Note: Of course the other parameters differ as well.

* The EOS with faster contraction of the neutron star is better for the explosion
* In order to make the complete understanding of EOS impacts, a more systematic study is strongly required!

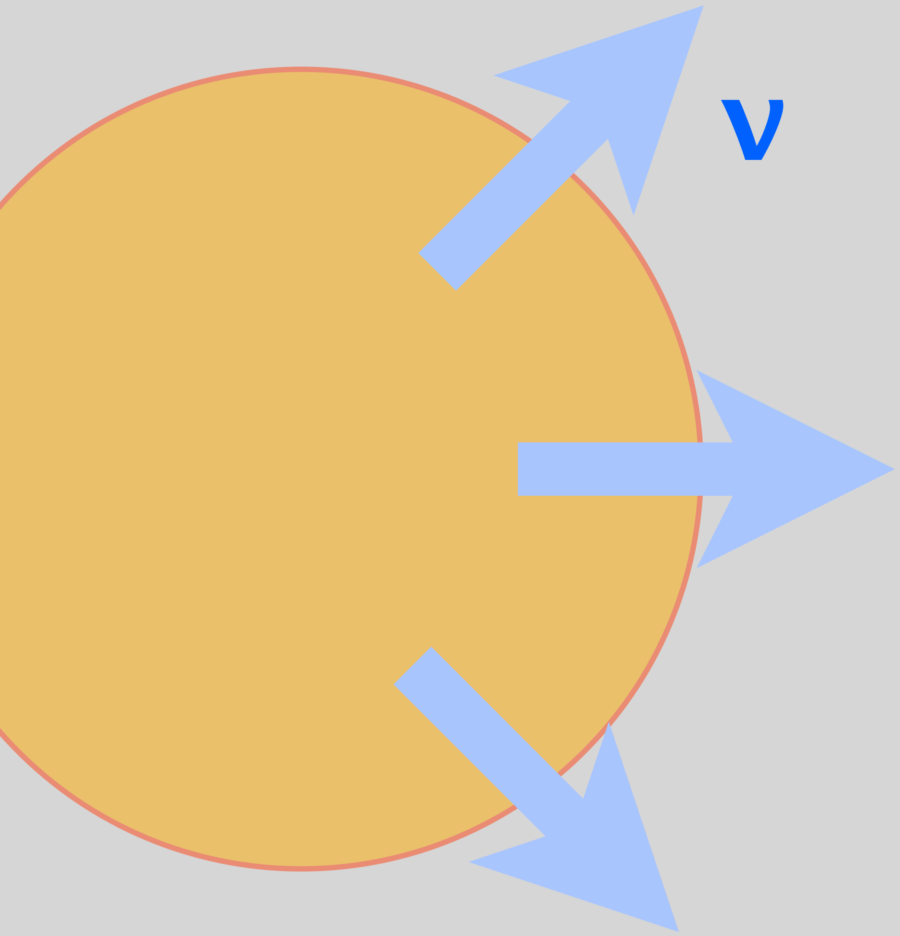
Extra Bonus: From SN to NS

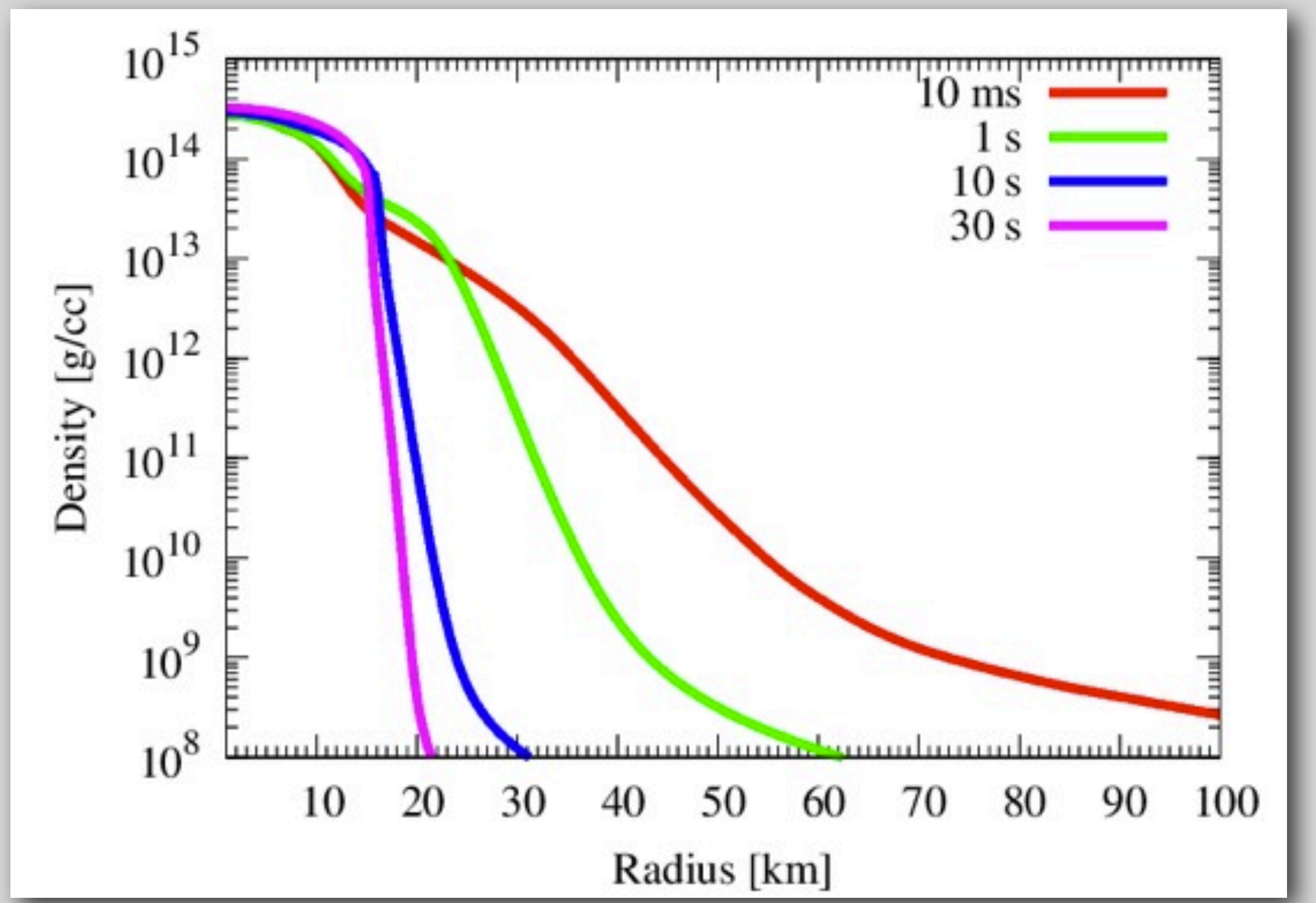




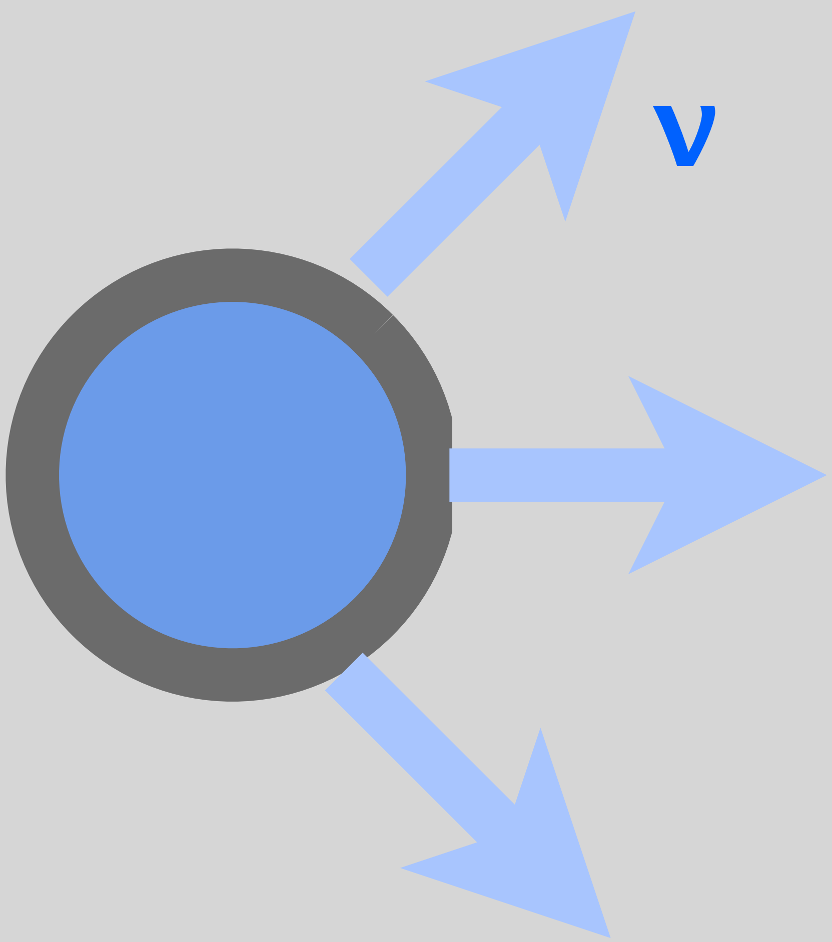
- Progenitor: 11.2 $M_{\odot}$ (Woosley+ 2002)
- Successful explosion! (but still weak with E_{exp}~10^{50} erg)
- The mass of NS is ~1.3 $M_{\odot}$
- **The simulation is continued in 1D to follow the PNS cooling phase up to ~70 s after bounce**

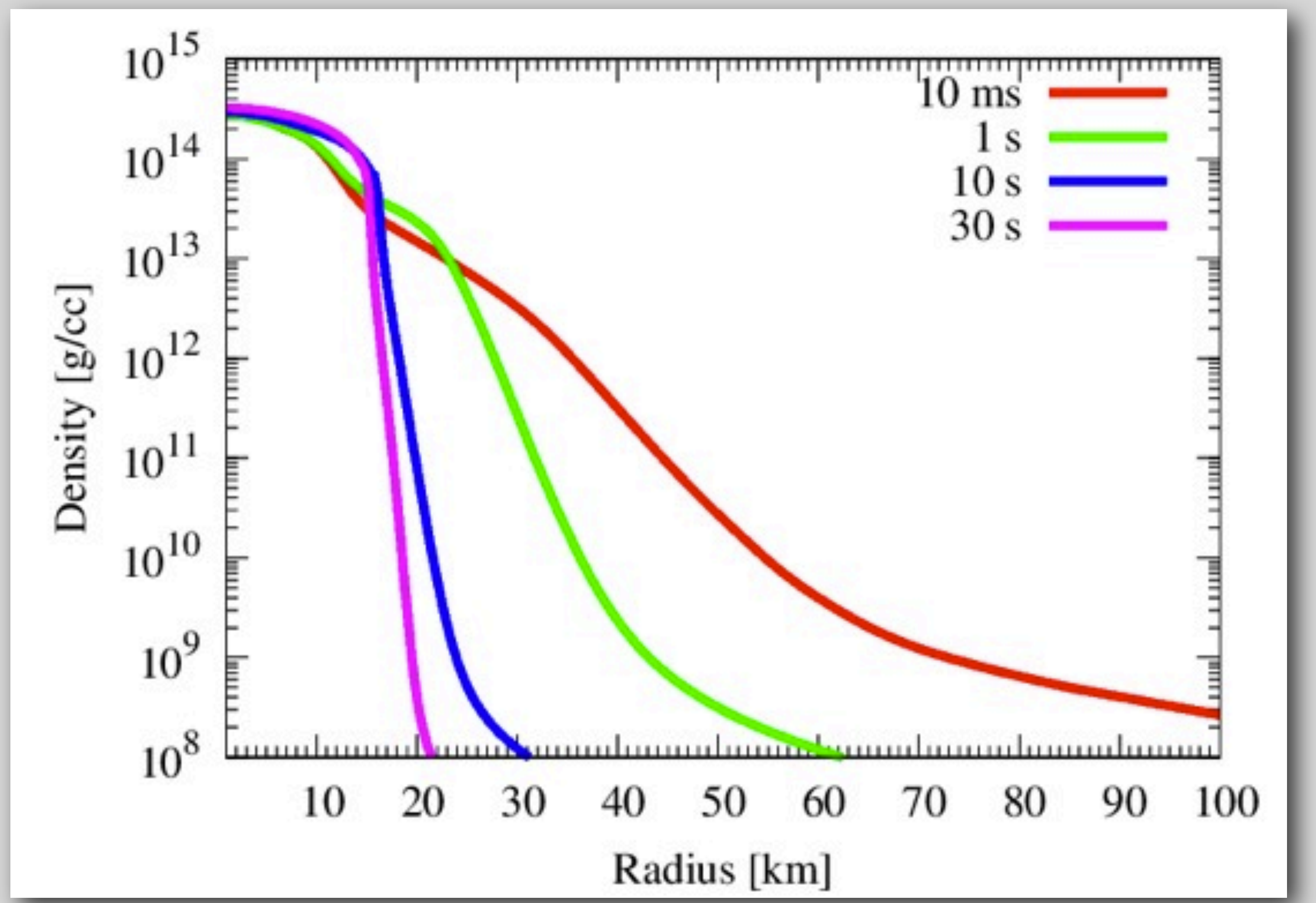
Extra Bonus: From SN to NS



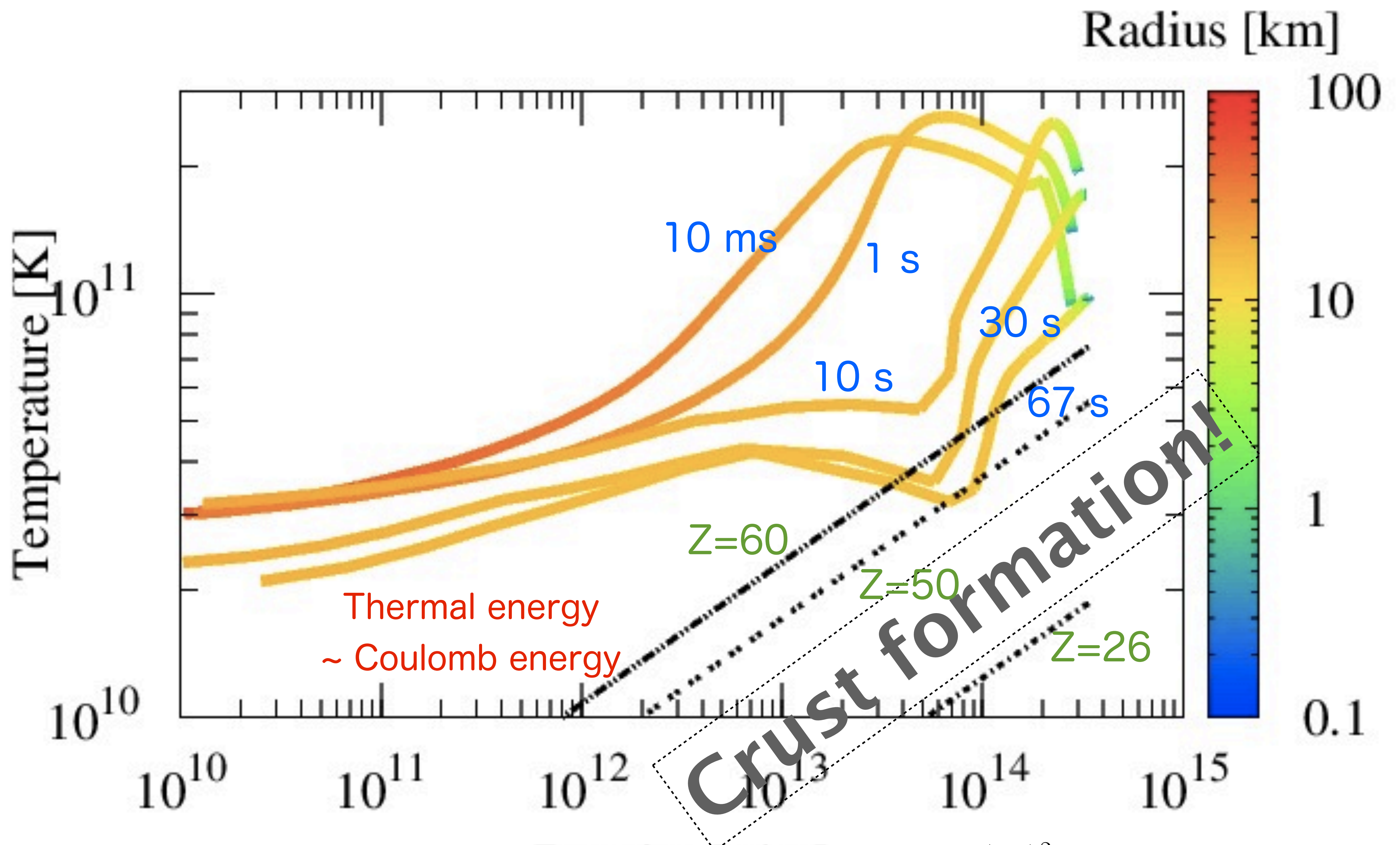


Extra Bonus: From SN to NS





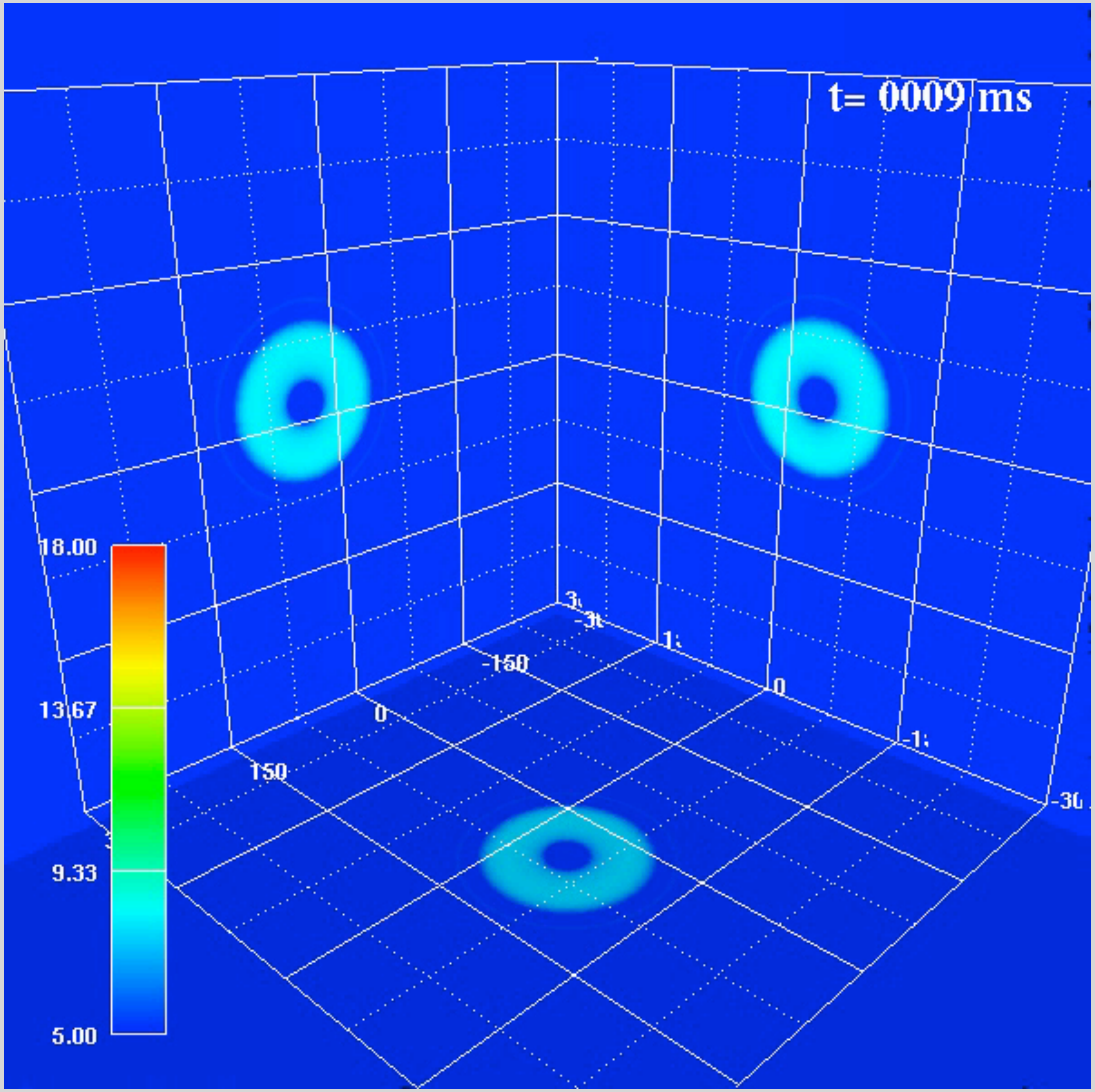
Extra Bonus: From SN to NS



$$\Gamma \equiv \frac{(Ze)^2}{rkT} = \frac{\text{Coulomb energy}}{\text{Thermal energy}} \sim 100$$

Appendix: 3D simulation with neutrino transfer

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



320(r)x64(θ)x128(ϕ)
x20(E_ν)