# Multi-Dimensional Core-Collapse Supernova Simulations and the Equation of State Influence

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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

# Systematics in supernova simulations

- Dimensionality of hydrodynamics — Iwakami+ 08, Nordhaus+ 10, Hanke+ 11, Takiwaki+ 12
- General relativity — Liebendörfer+01, Müller+ 12, Kuroda+ 12, Sekiguchi+ 12
- Neutrino physics
  - Scheme to solve Boltzmann equation — Ott+ 08, Shibata+ 11, Sumiyoshi & Yamada 12
  - Interaction rate — Langanke+ 03, Arcones+ 08, Lentz+ 12
- 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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# 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. (2011)
  - relativistic mean field theory (TM1, TMA, FSUGold)

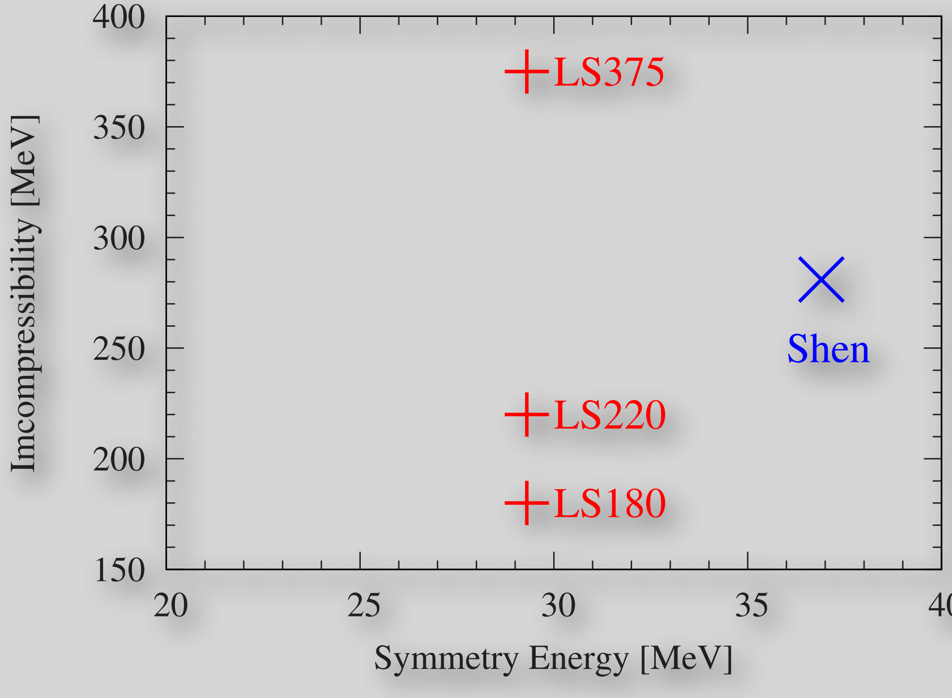
| | incompressibility K [MeV] | symmetry energy J (S) [MeV] | slope of symmetry energy L [MeV] |
|---|---|---|---|
| LS | 180, 220, 375 | 29.3 | --- |
| HShen | 281 | 36.9 | 111 |
| HW | 263 | 32.9 | --- |
| GShen | 271.5 (NL3)<br>230.0 (FSU) | 37.29 (NL3)<br>32.59 (FSU) | 118.2 (NL3)<br>60.5 (FSU) |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

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

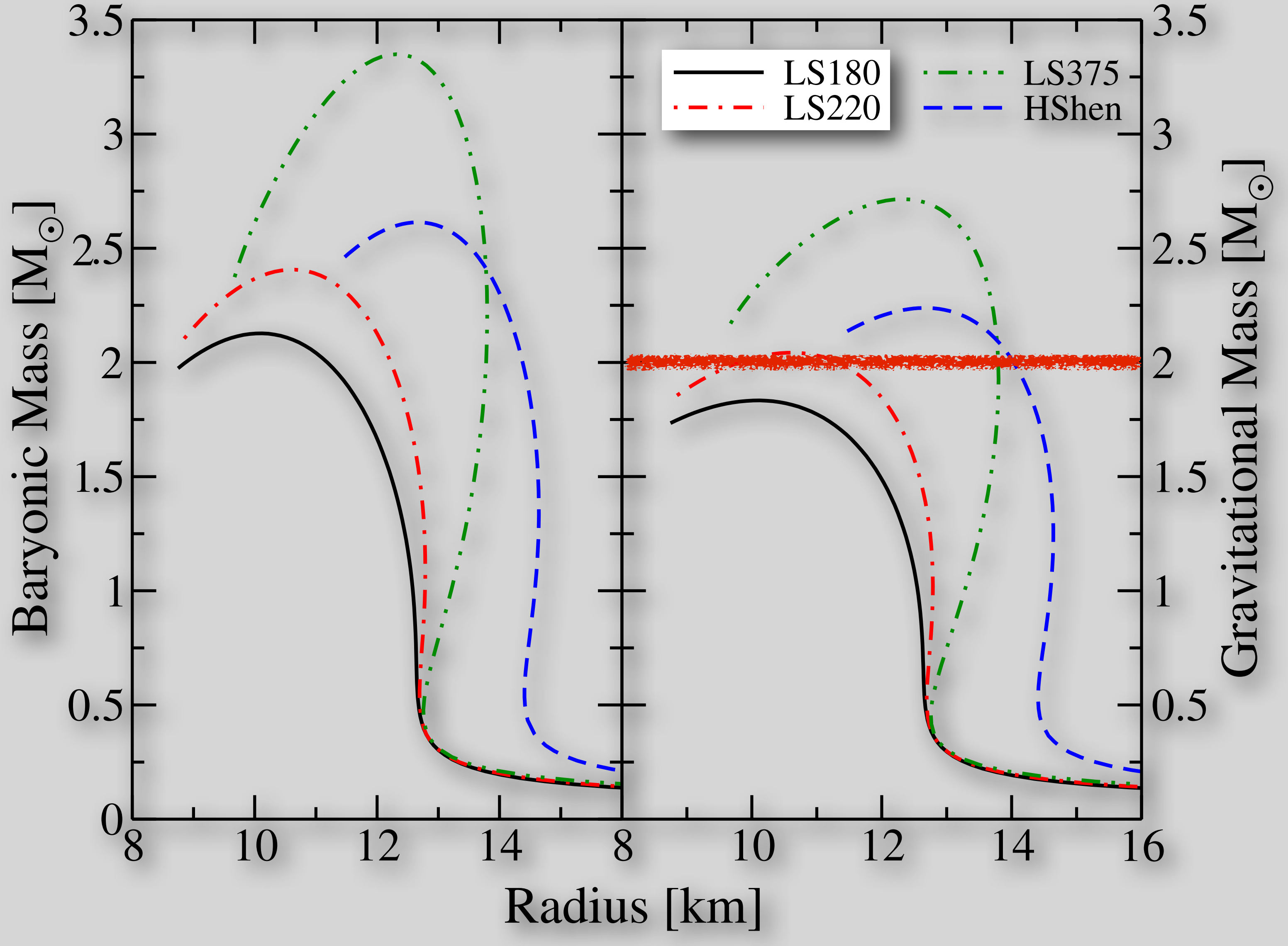
# Equation of state

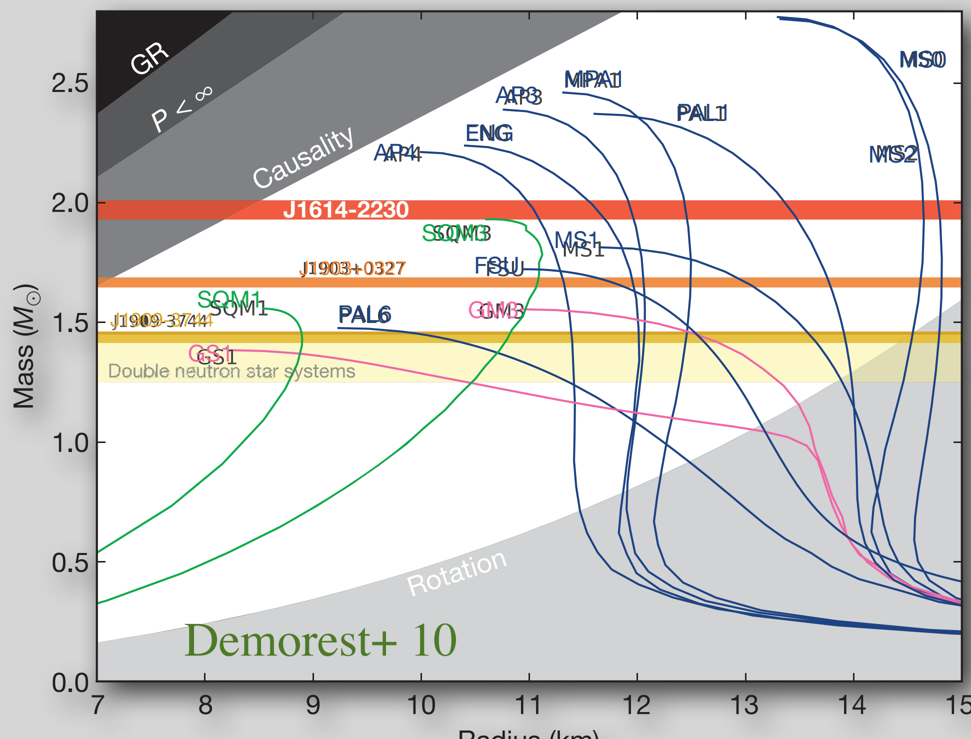
The “standard” equations of state (EOS) in supernova community

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

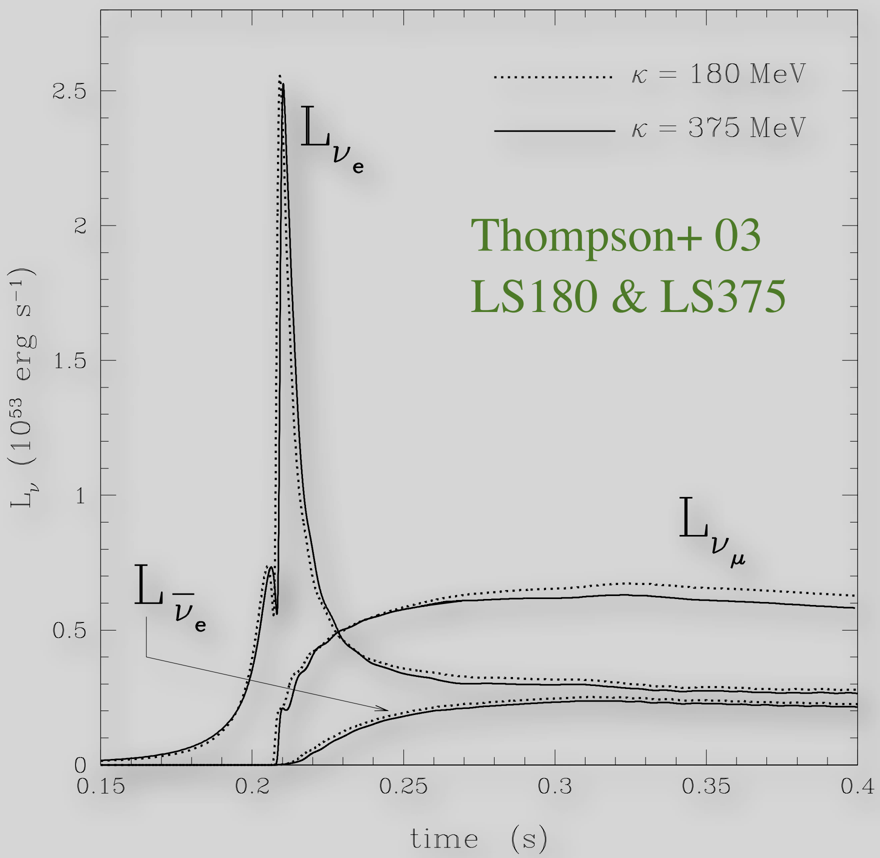


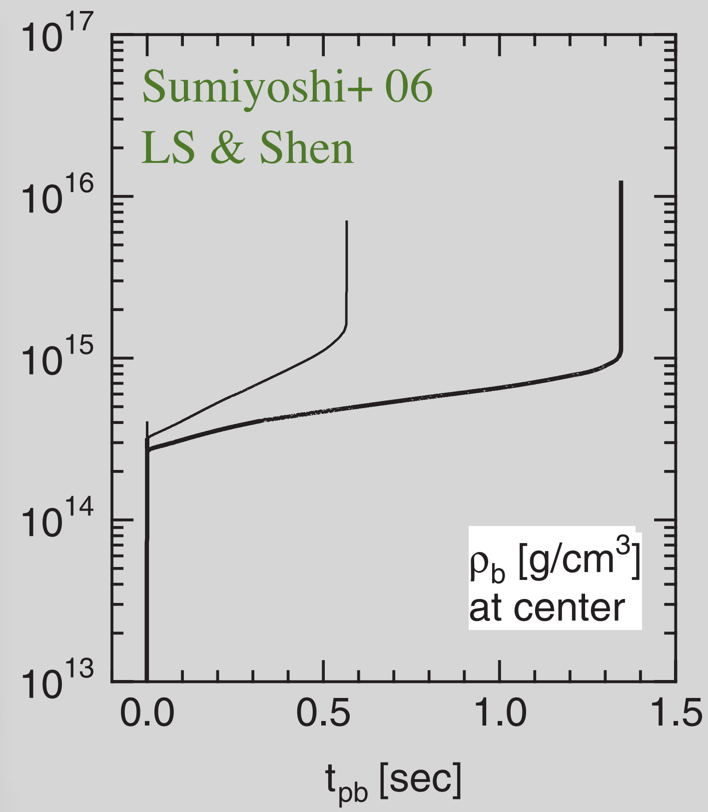

O’Connor & Ott 10

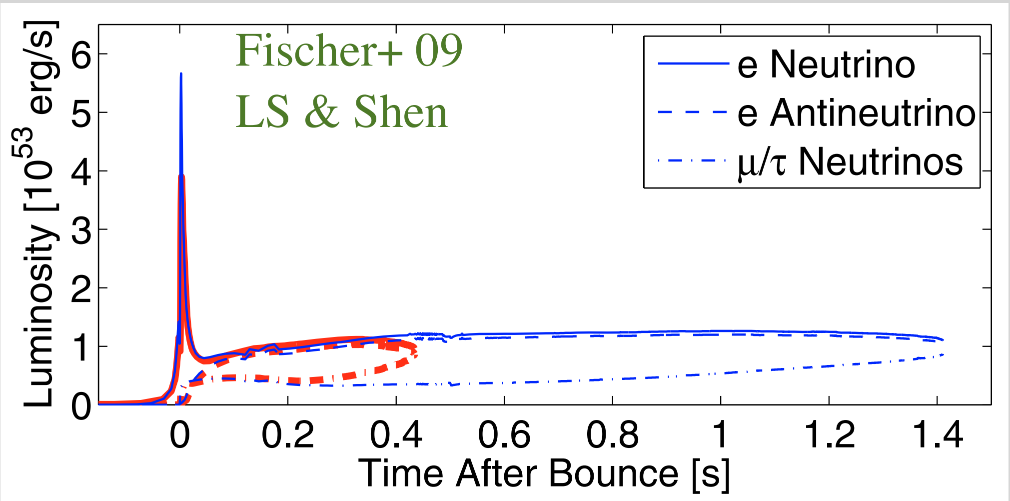


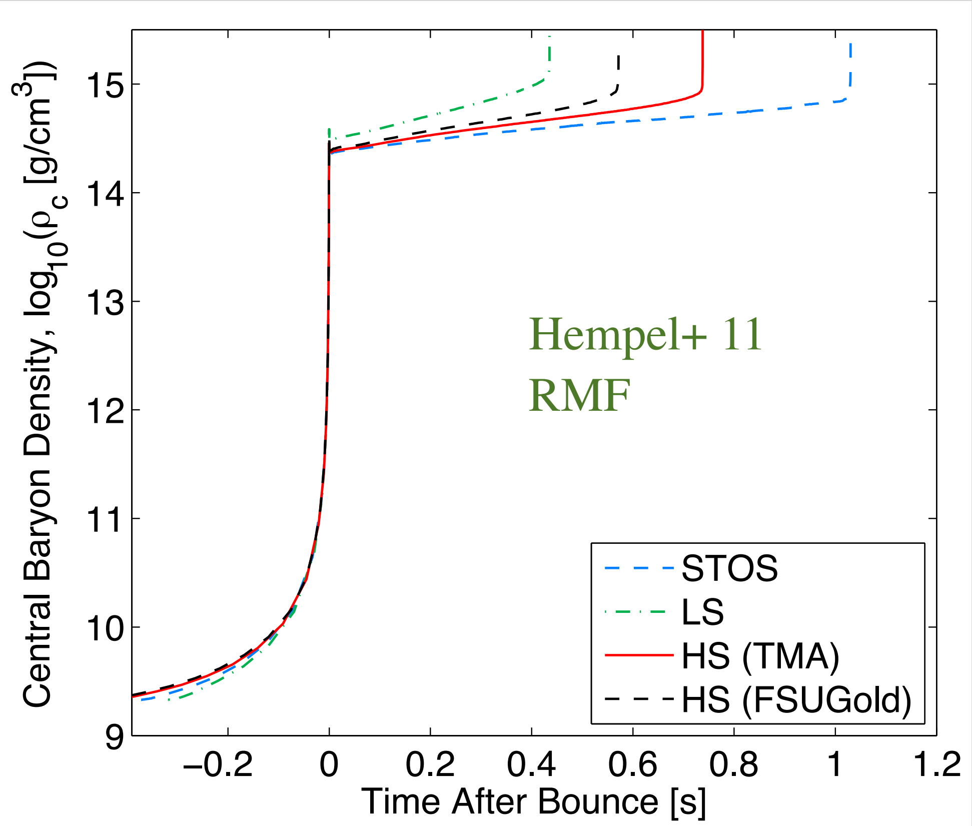



# Studies on EOS dependence



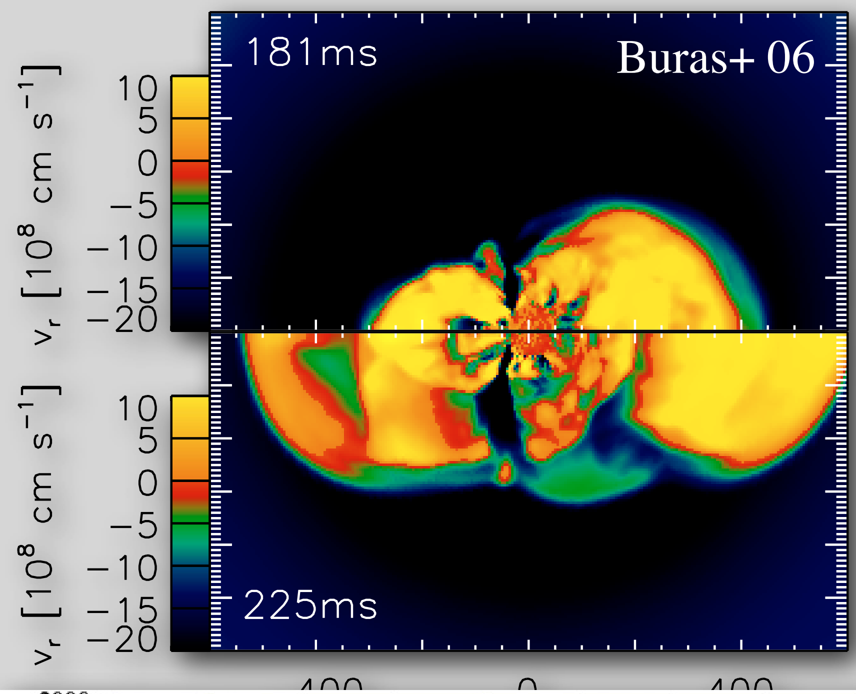



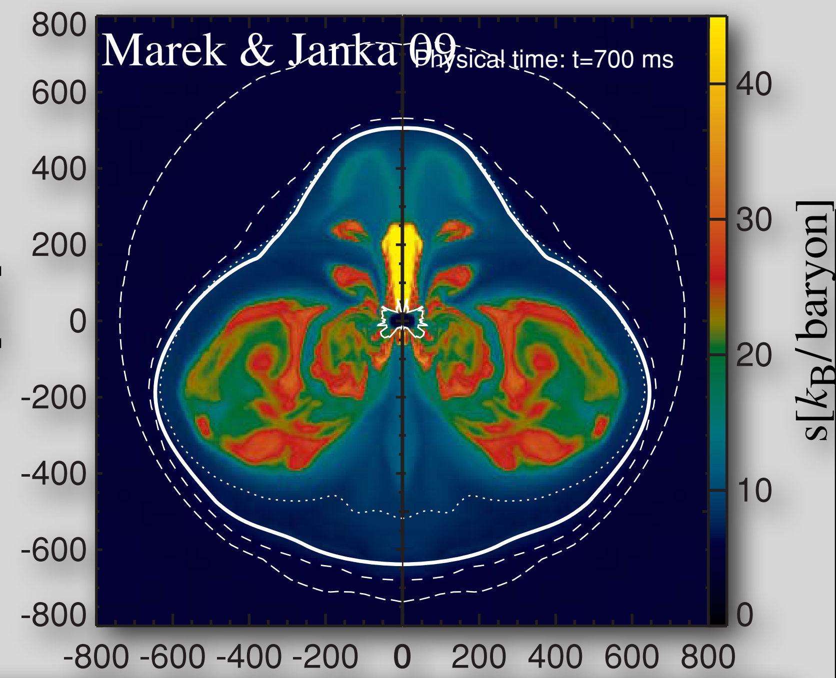



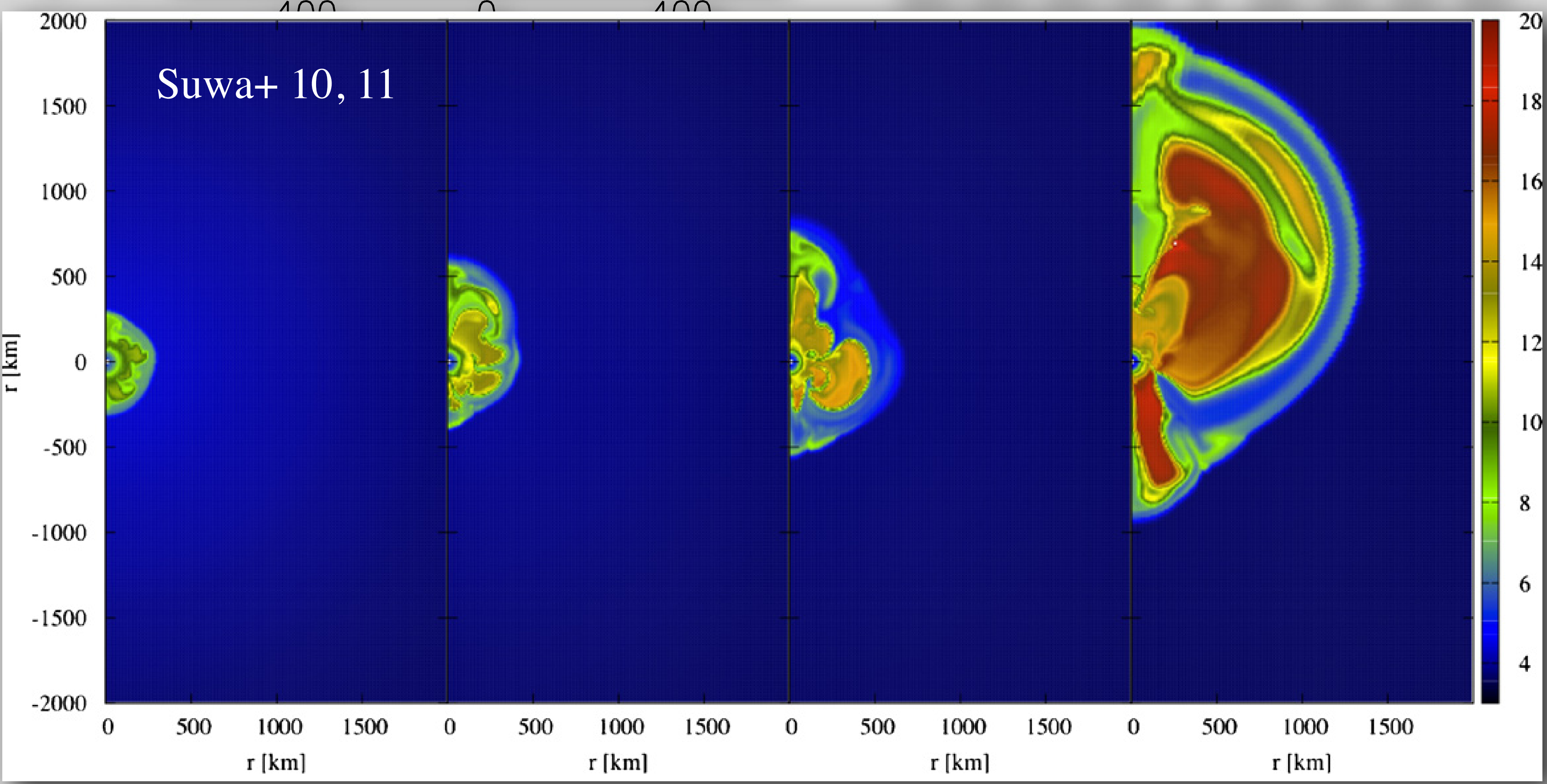

- There are several works, which investigated the EOS dependence with 1D simulation
- Since 1D simulations fail to produce explosion, the representable physical quantities in these studies are
  - BH formation time
  - neutrino luminosity/spectrum evolution
- **How about the explosion?**

# Neutrino-driven explosion

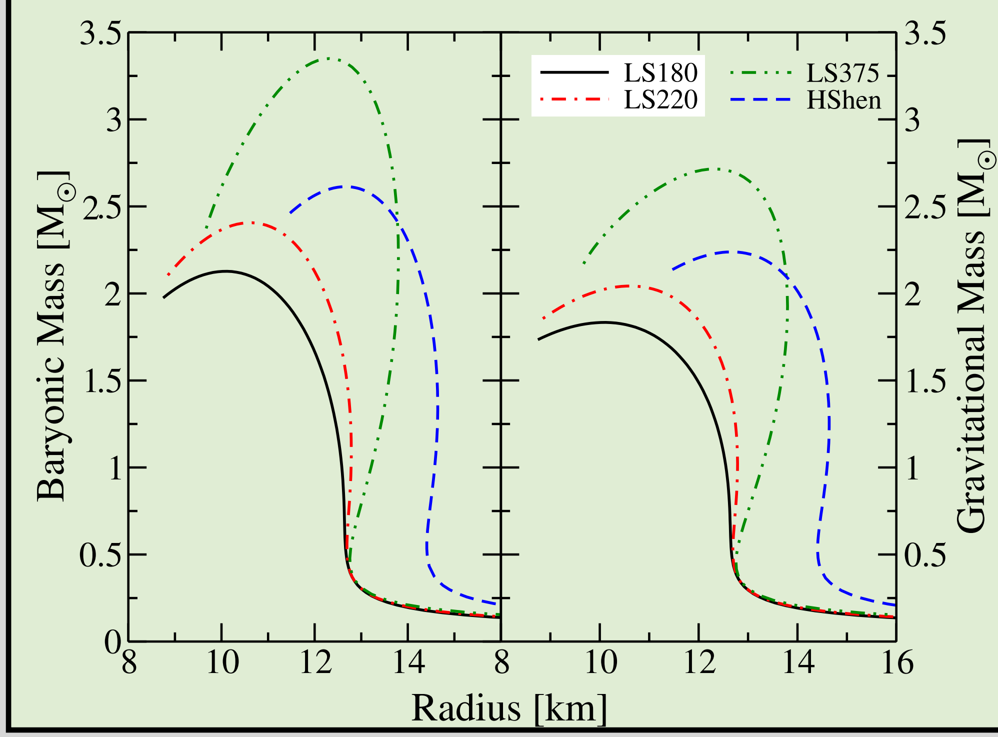
Recently, we have successful exploding models driven by neutrino heating




All of these simulations employ LS180, which, however, cannot support a 2M⊙ NS. How about stiffer EOS?

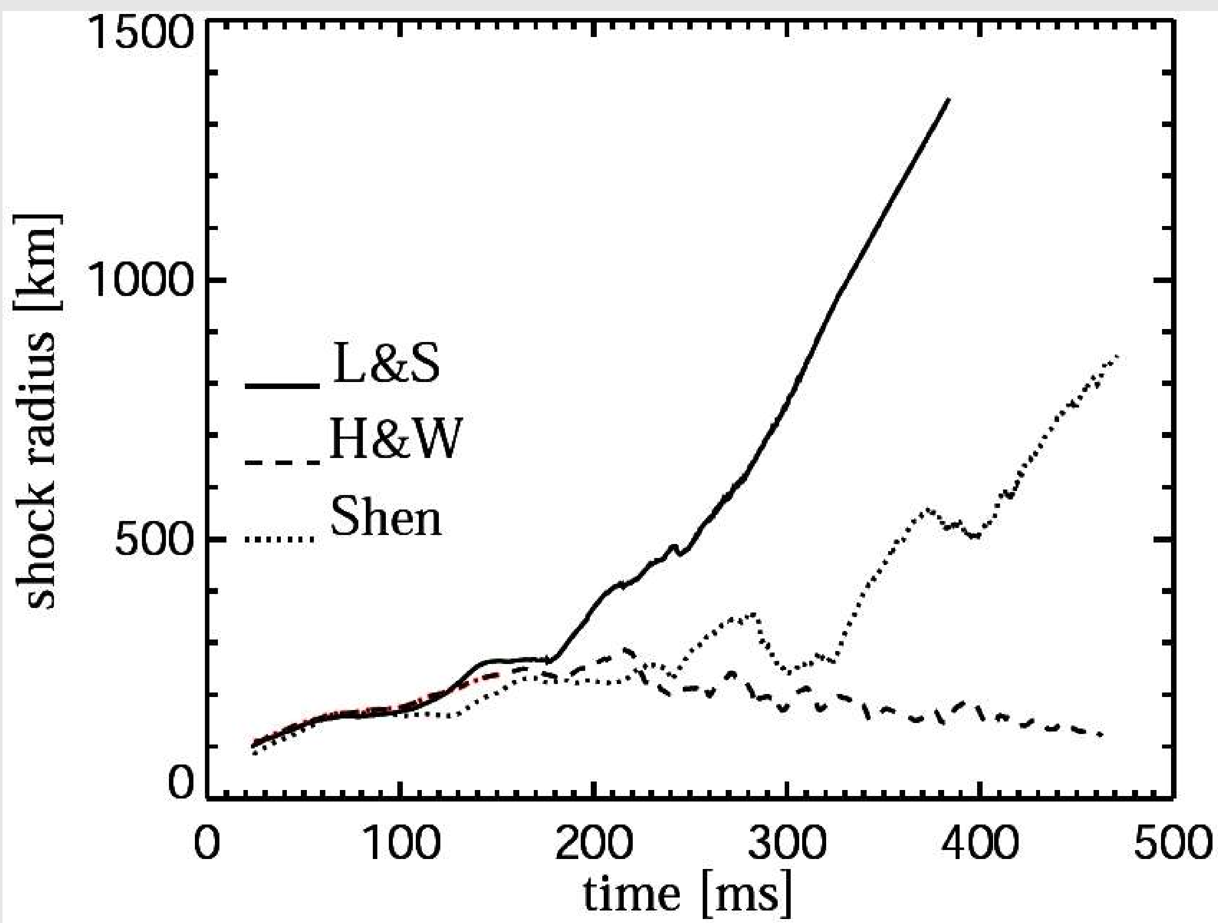


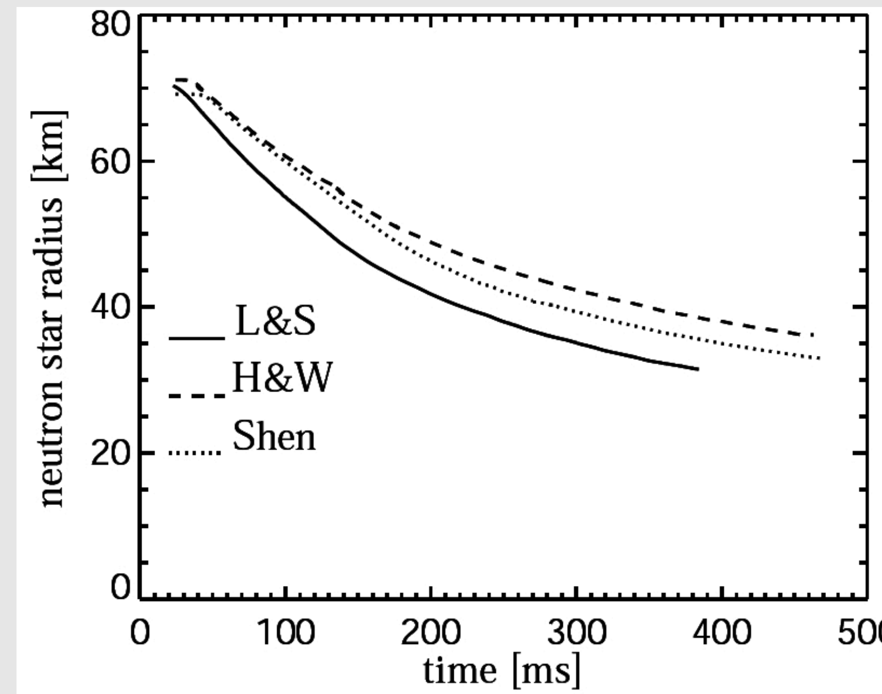
# EOS and shock evolution

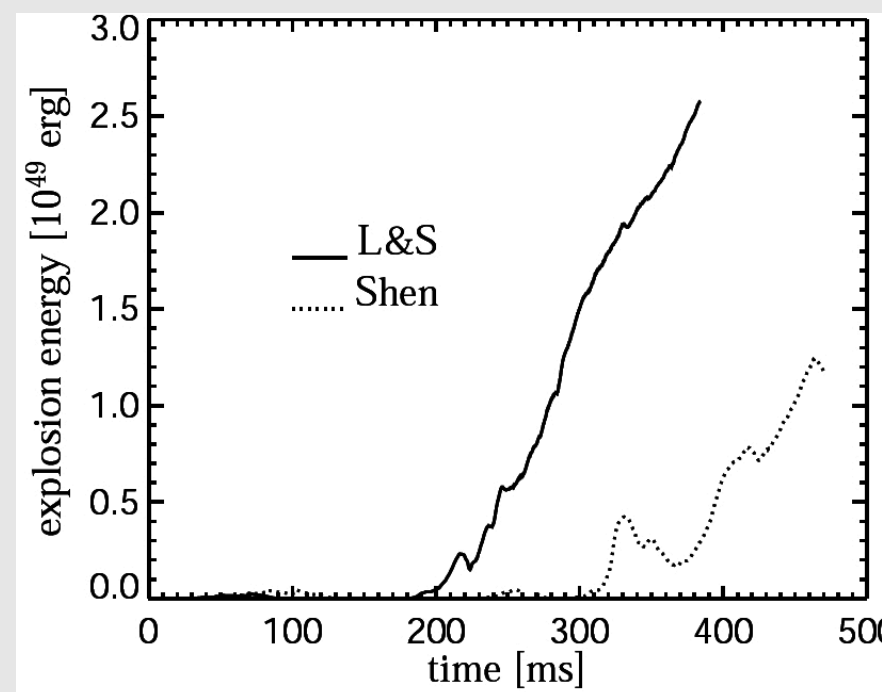
from H.-Th. Janka's presentation

## 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)

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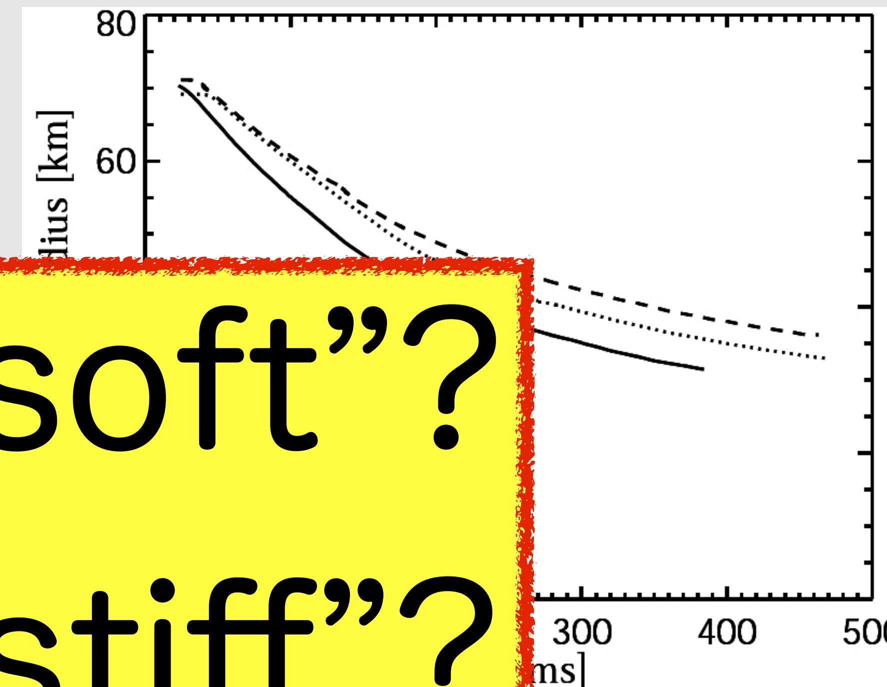
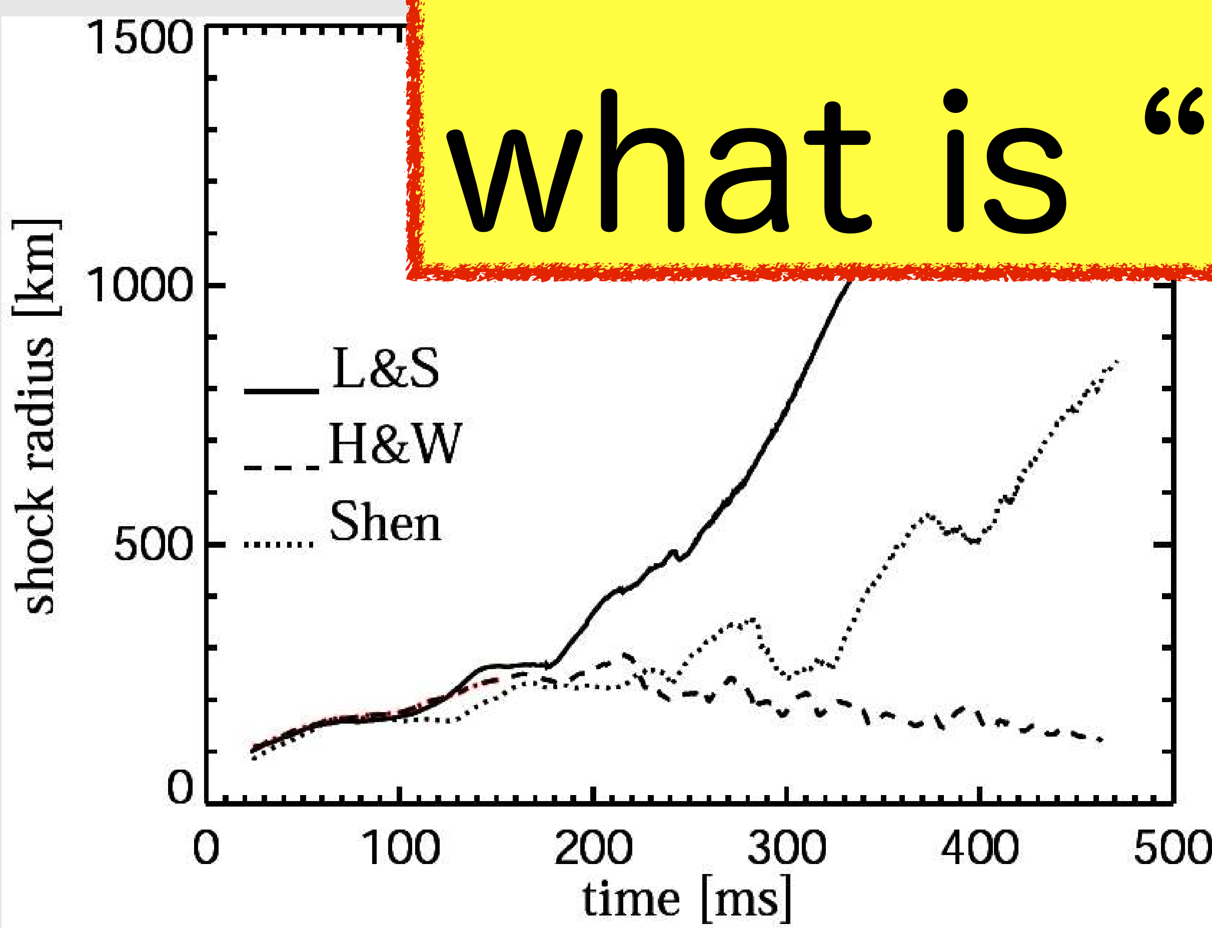
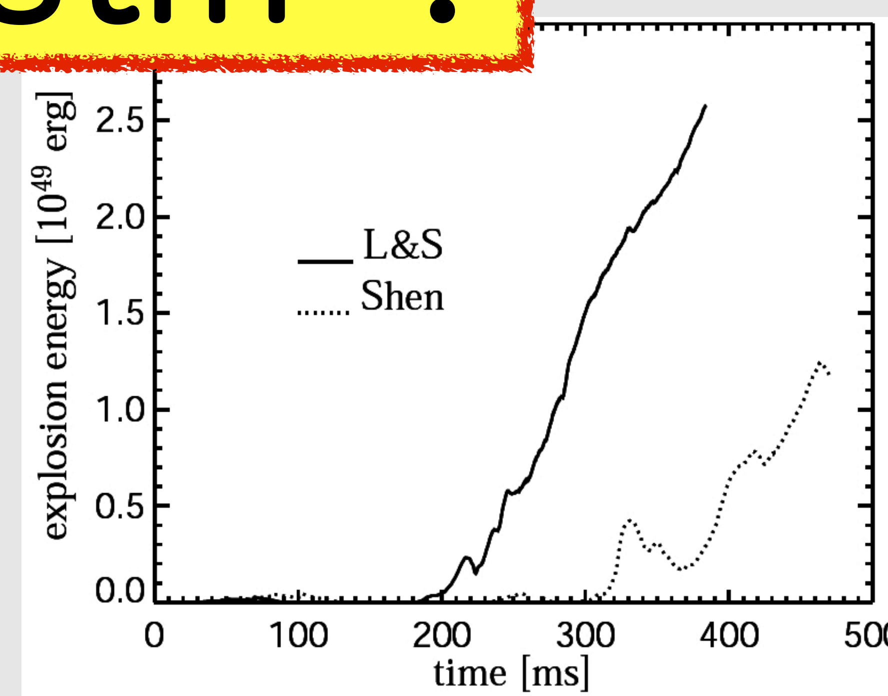
- "Softer" (L&S) PNS leads to

what is "soft"?

what is "stiff"?

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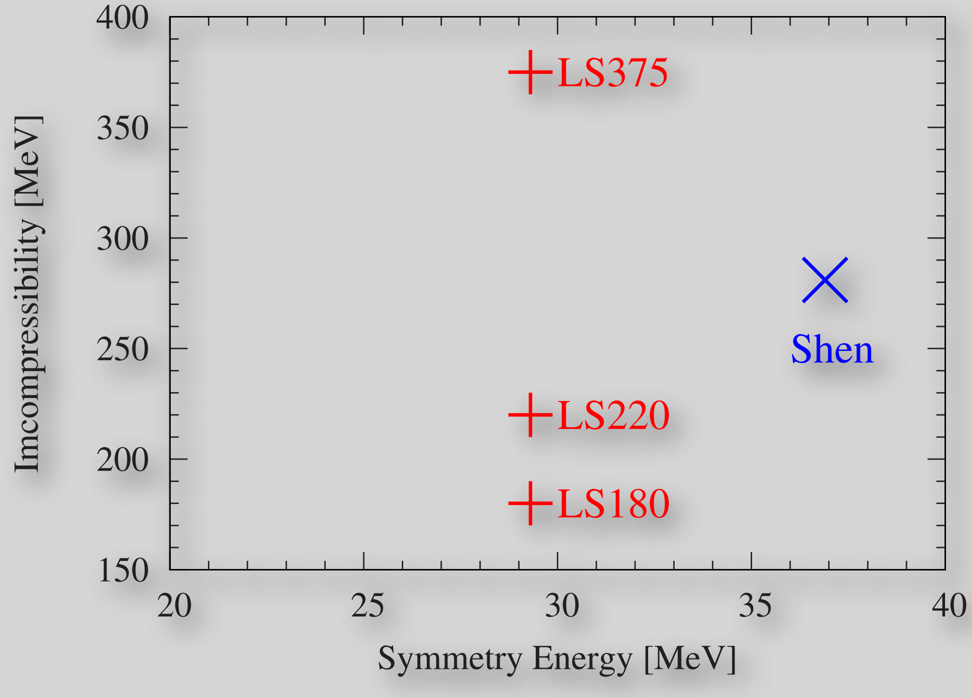
# Numerical simulation




- EOS: LS180, (LS220,) LS375, and Shen
- Axisymmetric simulation (ZEUS-2D; Stone & Norman 92)
- Hydrodynamics + Neutrino transfer

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

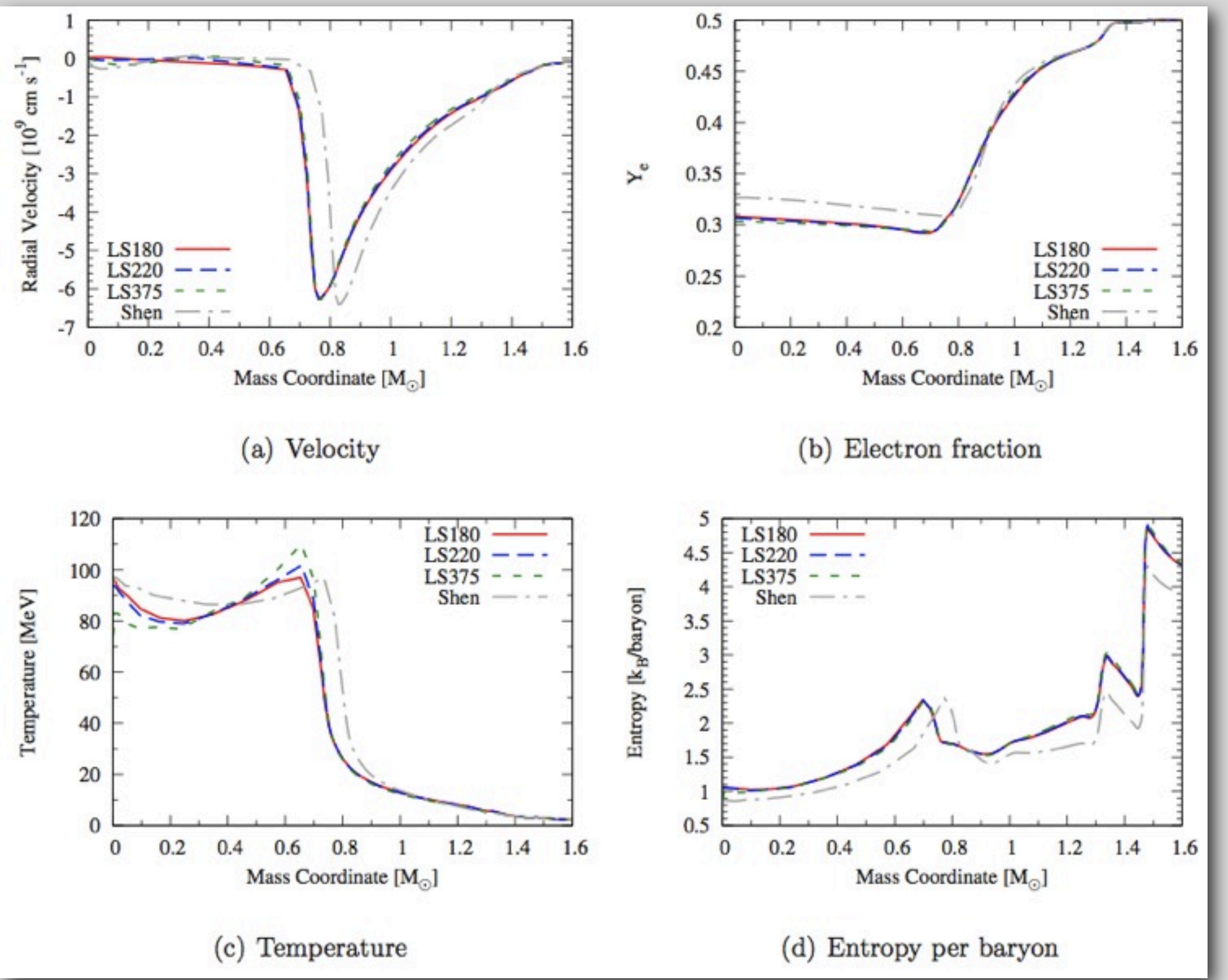
(Lindquist 1966; Castor 1972; Mezzacappa & Bruenn 1993)

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

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

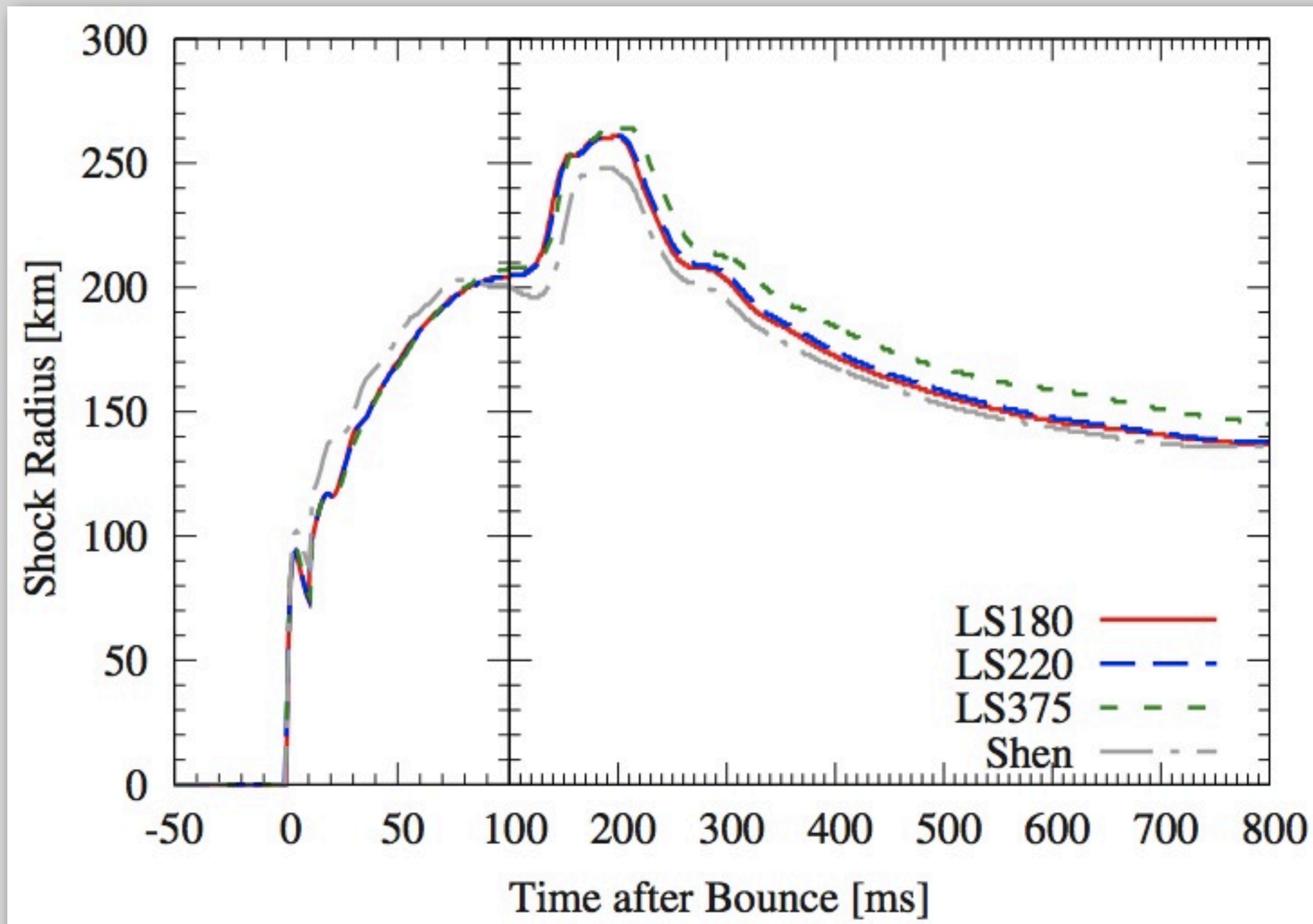
# Results in 1D simulation

Physical quantities at core bounce



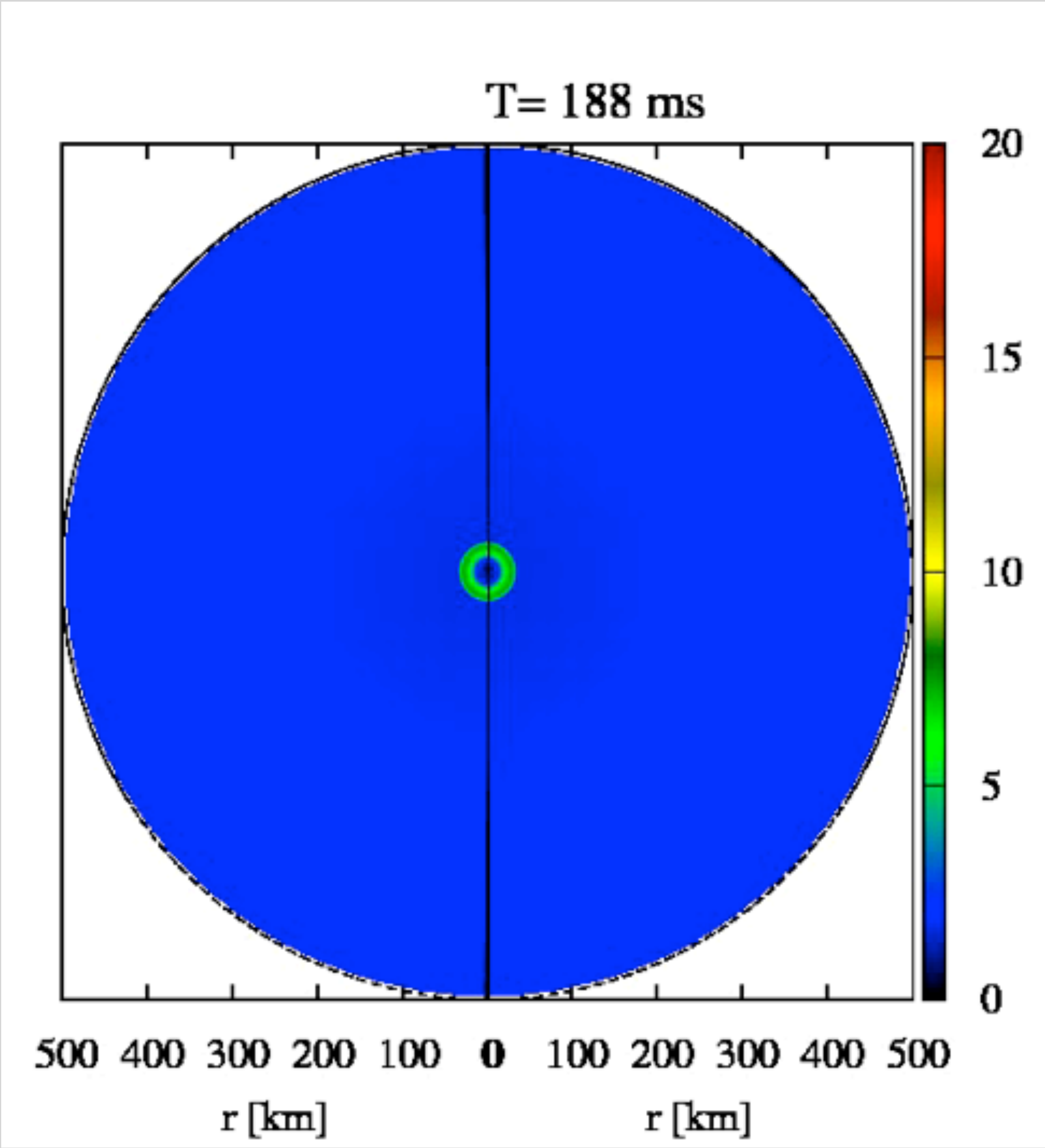
# Results in 1D simulation

Evolution of shock radius

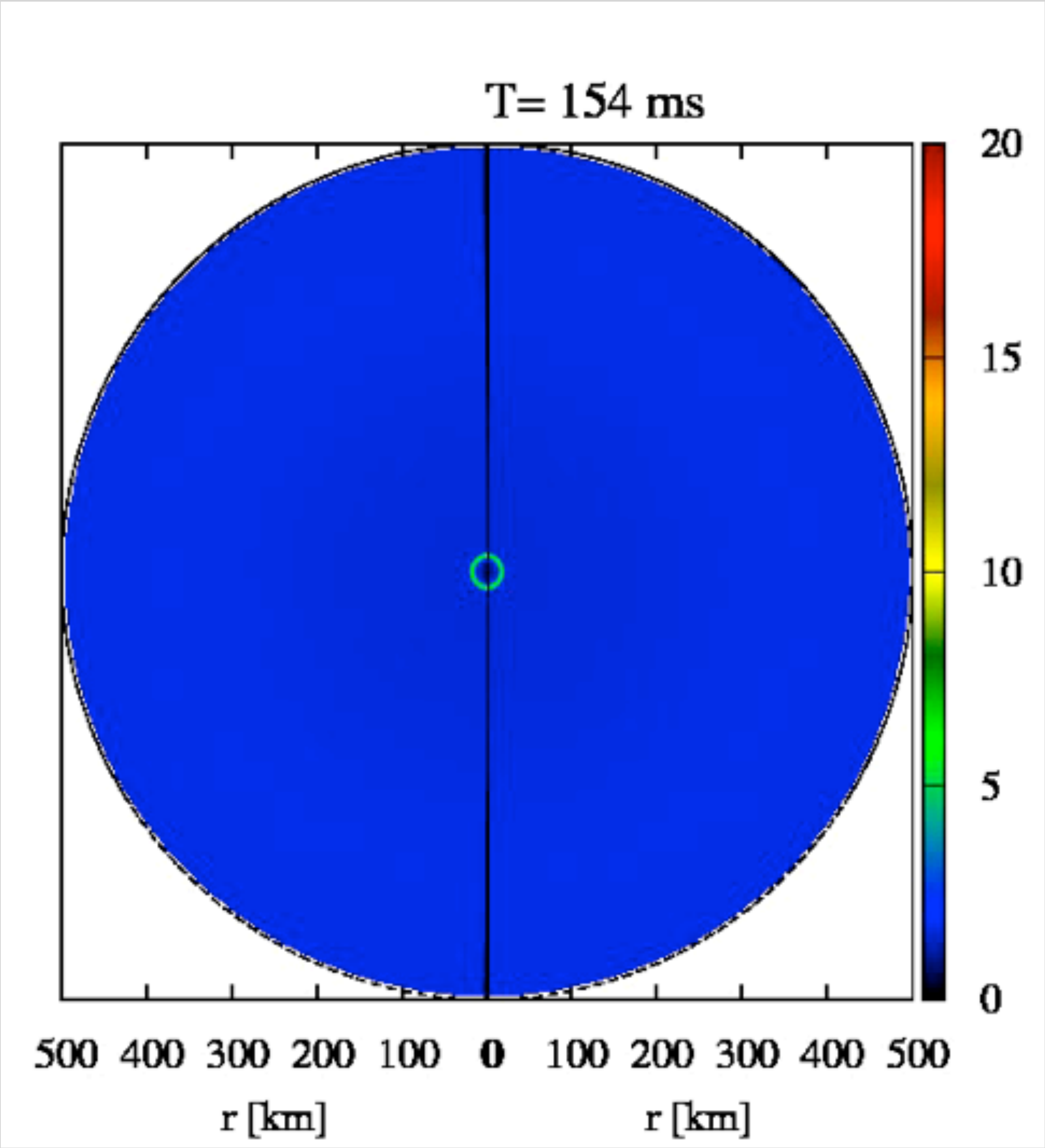


# Entropy evolution

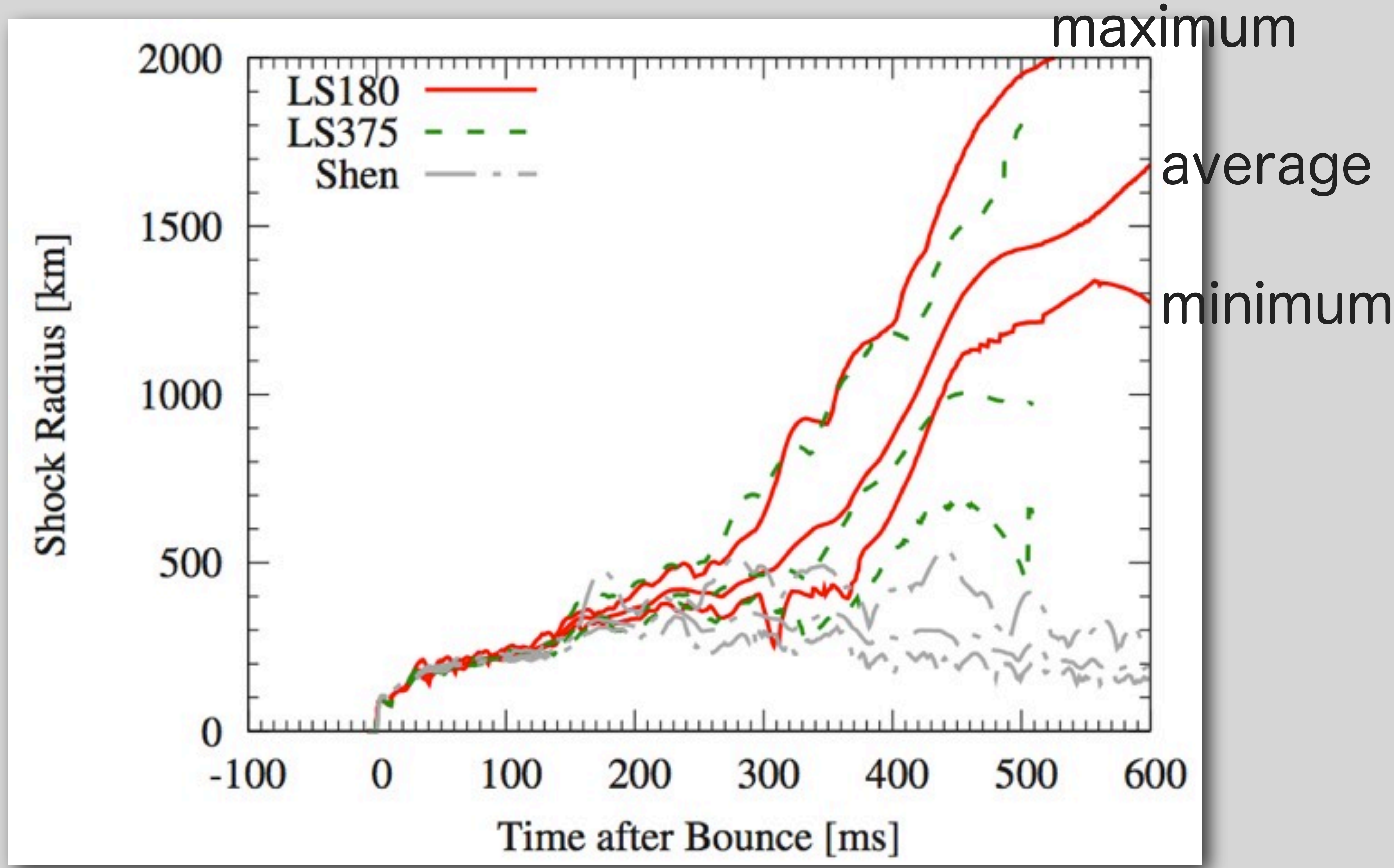
LS180




Shen



# Shock radius




LS180 and LS375 succeed the explosion

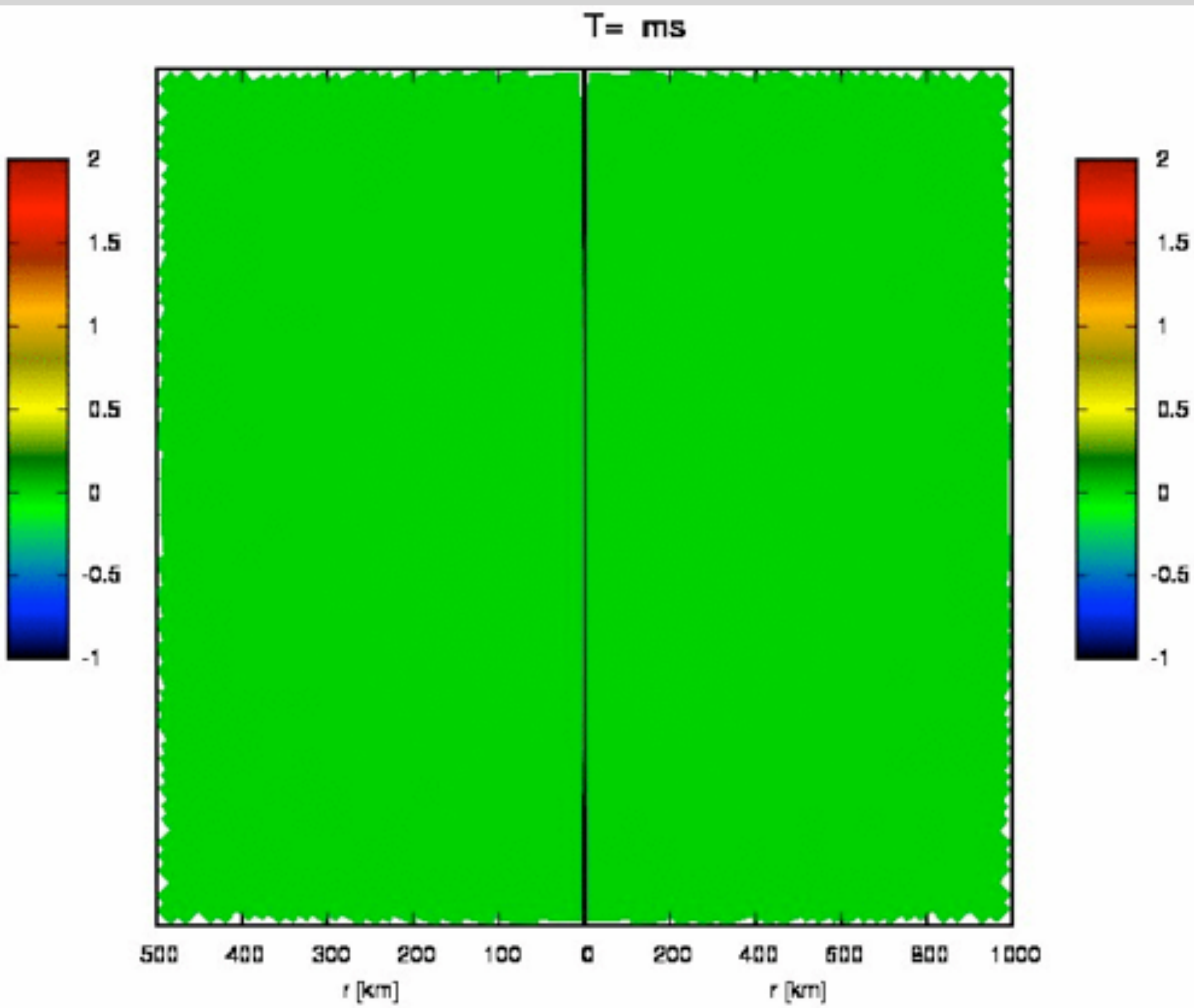
Shen EOS fails

# Dispersion of the moment

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

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

LS180

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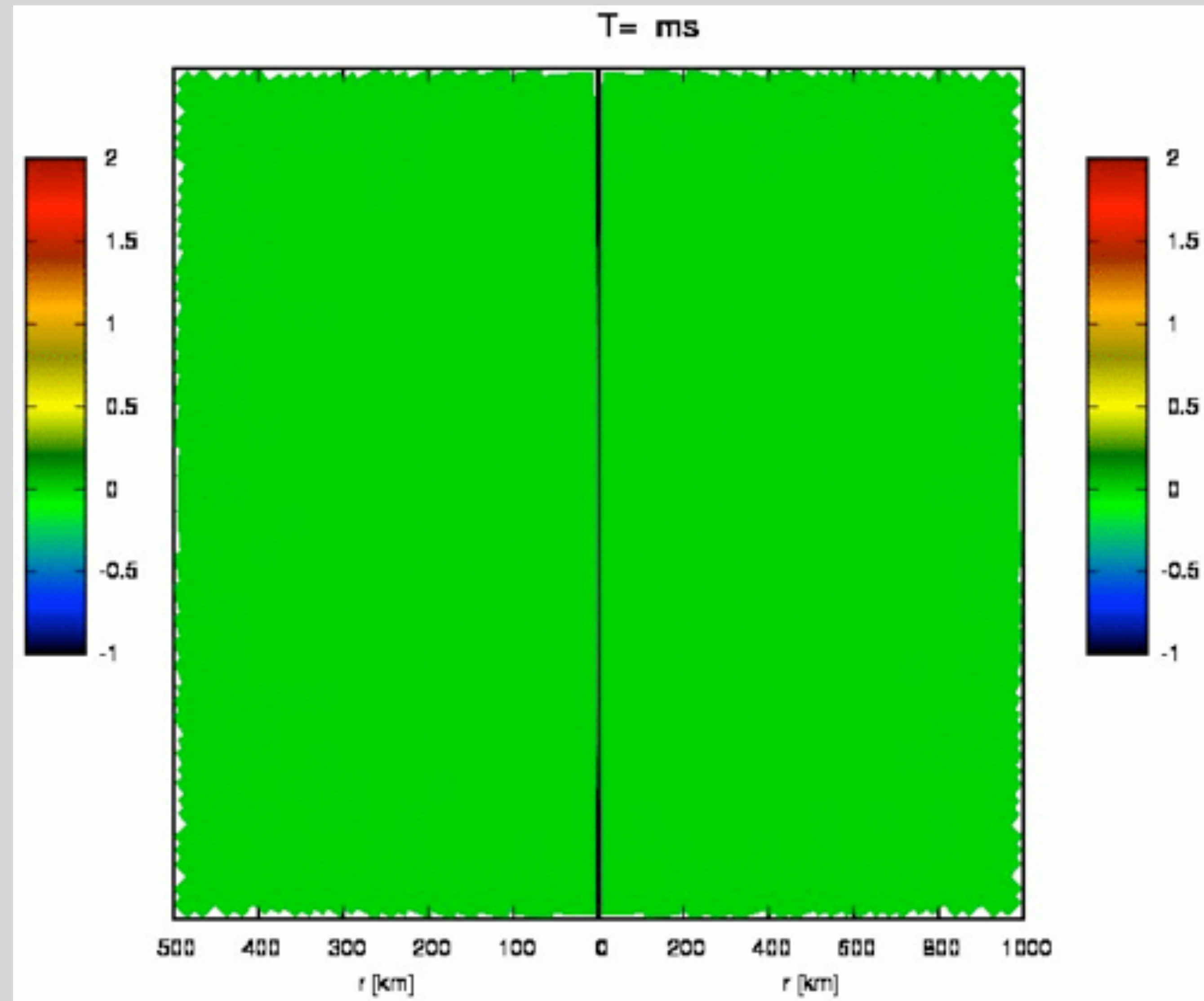


$$cf.\ \frac{\partial \rho \boldsymbol{u}}{\partial t}+\nabla(\cdot\rho\boldsymbol{u}\boldsymbol{u}+P)=0$$

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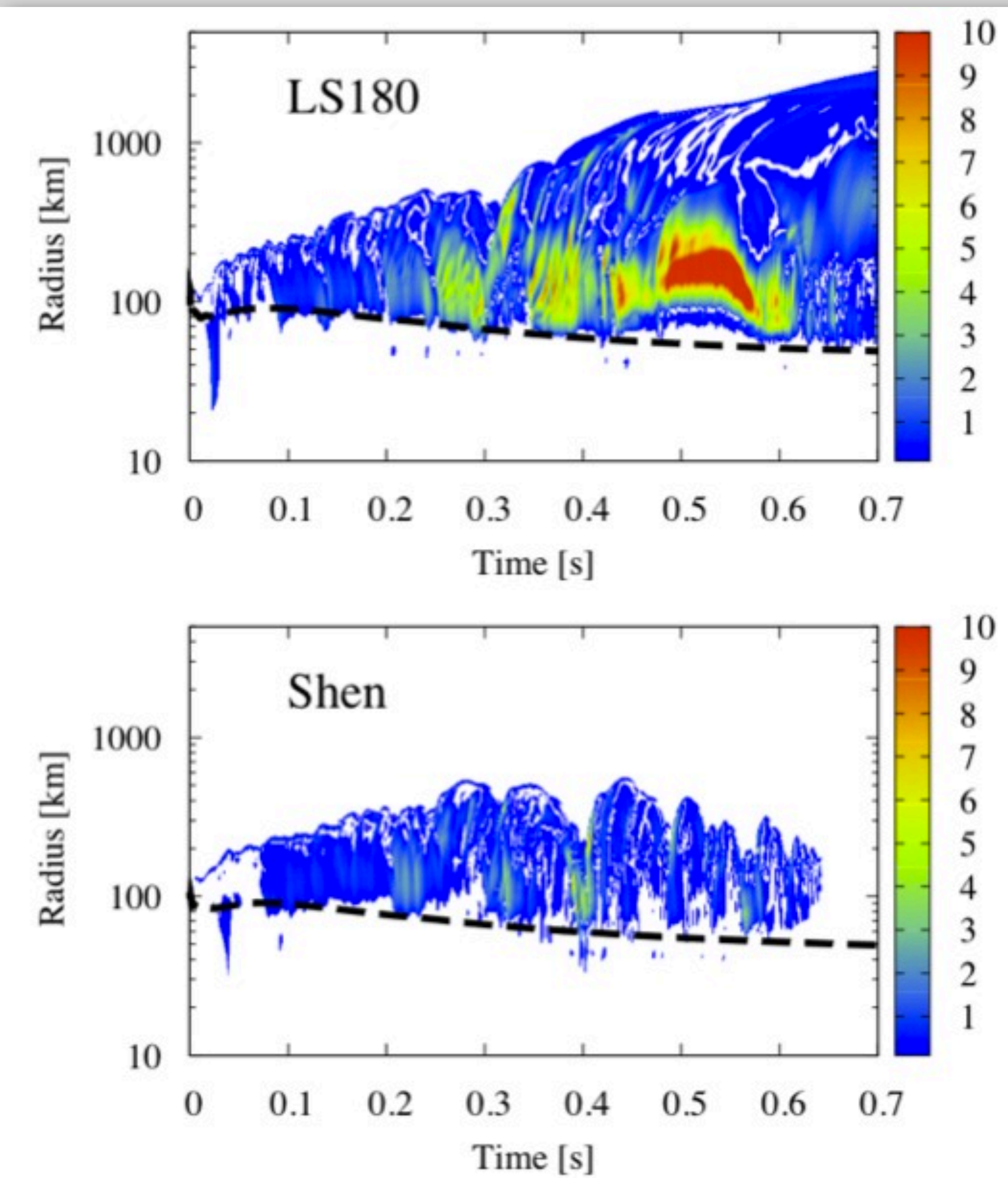


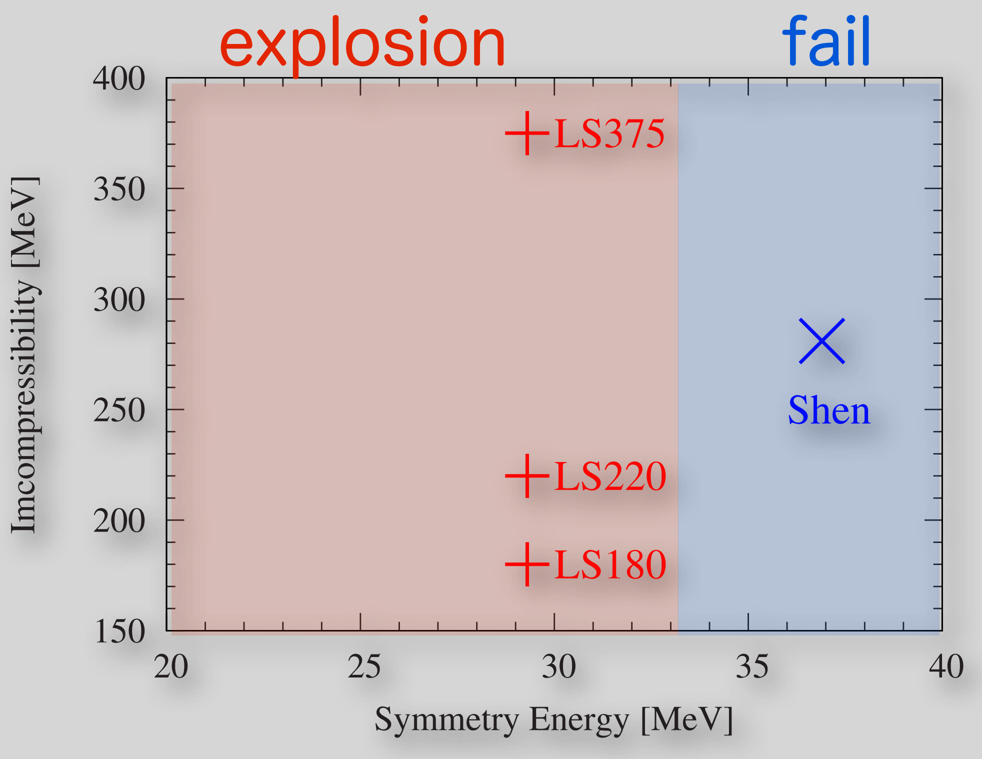

$$\frac{\left\{\frac{1}{2}\int_0^\pi \left[\mathcal{M}(r,\theta)-\overline{\mathcal{M}}(r)\right]^2 \sin\theta d\theta\right\}^{1/2}}{\overline{\mathcal{M}}(r)}$$

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

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

# Summary and discussion

* We perform 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




* The symmetry energy would have greater impact than the incompressibility
* The difference of the incompressibility does not affect the dynamics very much at least with the current setup
* In order to make the complete understanding of EOS impacts, a more systematic study is strongly required!