文部科学省科学研究費補助金「新学術領域研究」
科研費 KAKENHI
重力波天体の多様な観測による宇宙物理学の新展開
New development in astrophysics through multimessenger observations of gravitational wave sources

京
HPCI戦略プログラム分野5
「物質と宇宙の起源と構造」

Physical ingredients of core-collapse supernova driven by neutrino-heating mechanism

Yudai SUWA
(YITP, Kyoto University)

Collaboration with
T. Takiwaki, K. Kotake (NAOJ), M. Liebendörfer, S.C. Whitehouse (U. Basel), T. Fischer (GSI),
S. Yamada (Waseda U.), K. Sato (NINS & U. Tokyo)

YITP
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

クォーク・ハドロン科学国際共同研究プログラム
Yukawa International Program for Quark-Hadron Sciences (YIPQS)

YIPQS
大
YITP Kyoto

Core-collapse supernovae

- One of the most energetic explosions 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 / slack hole
- Formation of gamma-ray bursts?

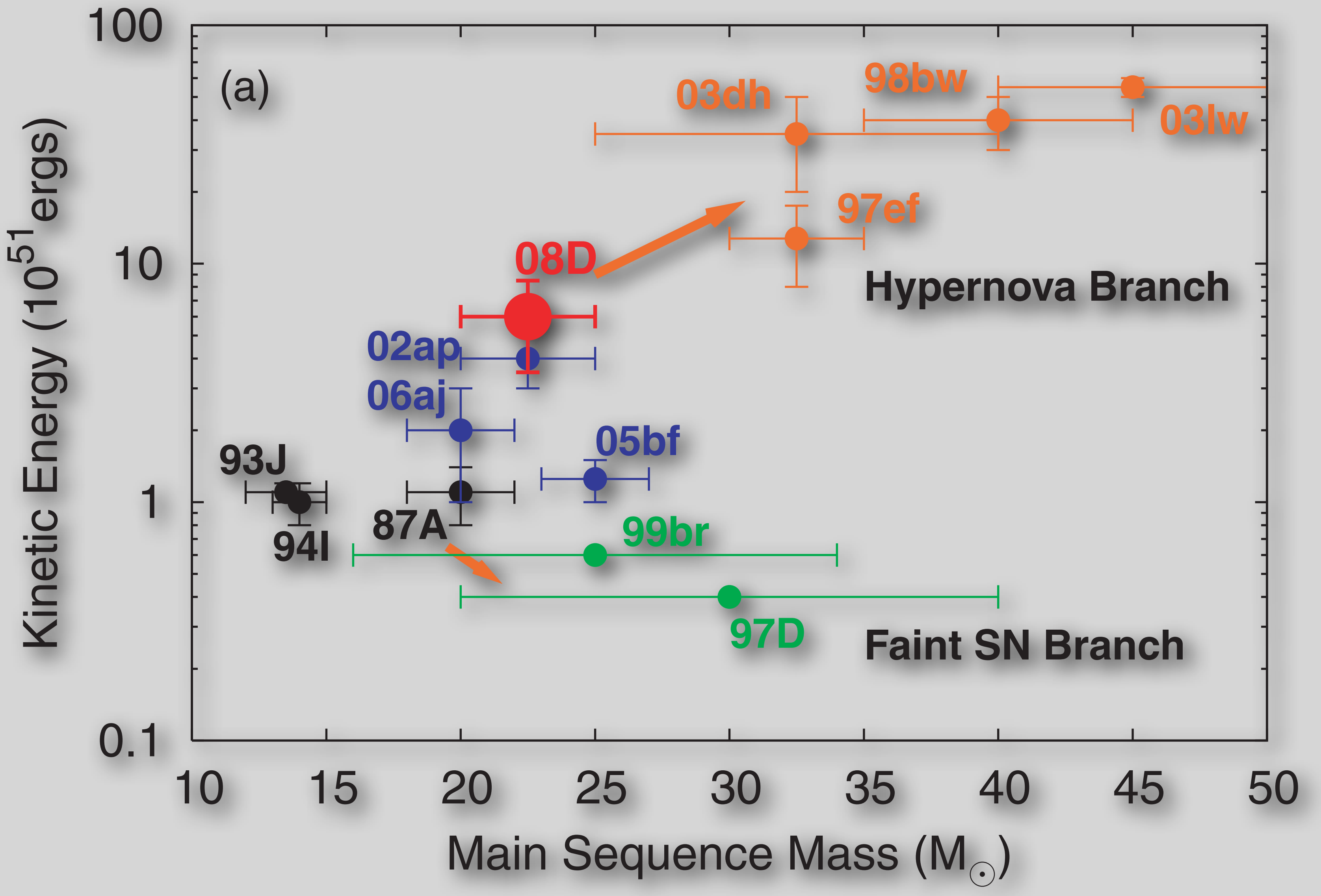
- All known interactions are important

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

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

Explosion energy

Tanaka+ 09



Observationally, there are several classes of SNe

- **Superluminous SNe**
- **Hypernovae/GRBs**
- **Ordinary SNe**
- **Faint SNe**

Where is the upper limit of explosion energy obtainable by neutrino heating mechanism?

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, Ott+ 13

- 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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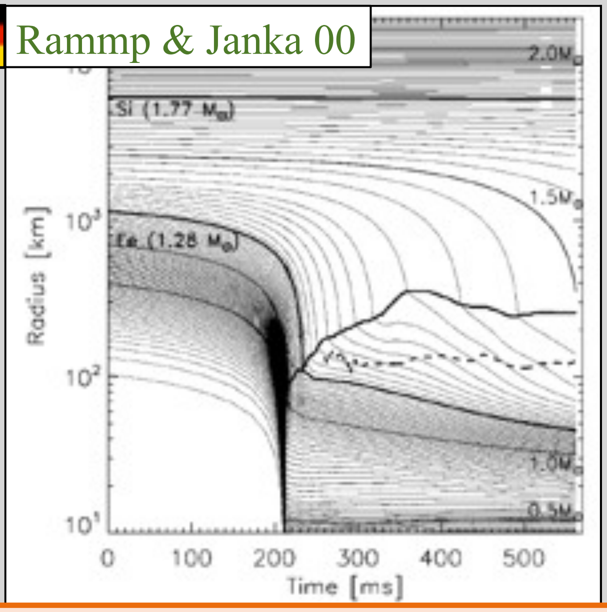
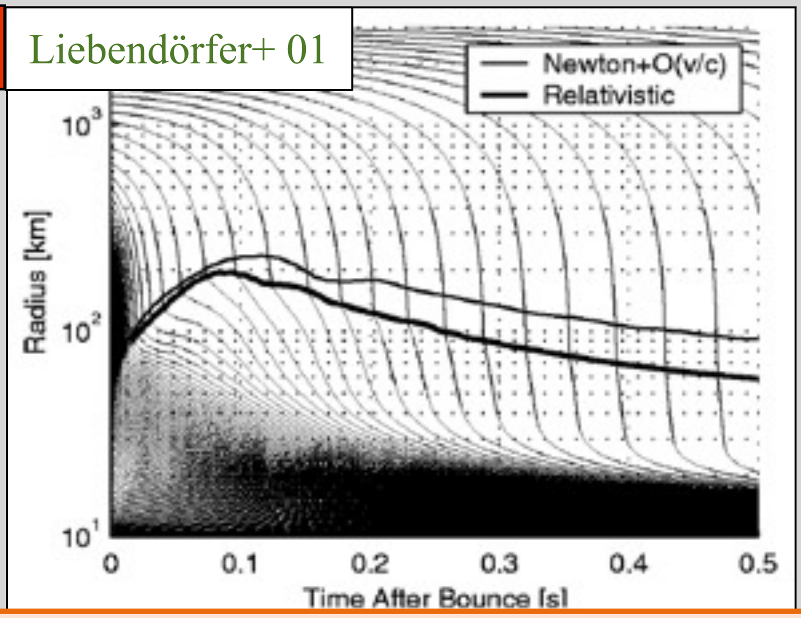
Nomoto & Hashimoto 88, Woosley & Weaver 95, Woosley+ 02, Limongi & Chieffi 06, Woosley & Heger 07, Yoshida+ 12

1D simulations: fail to explode

Rammp & Janka 00



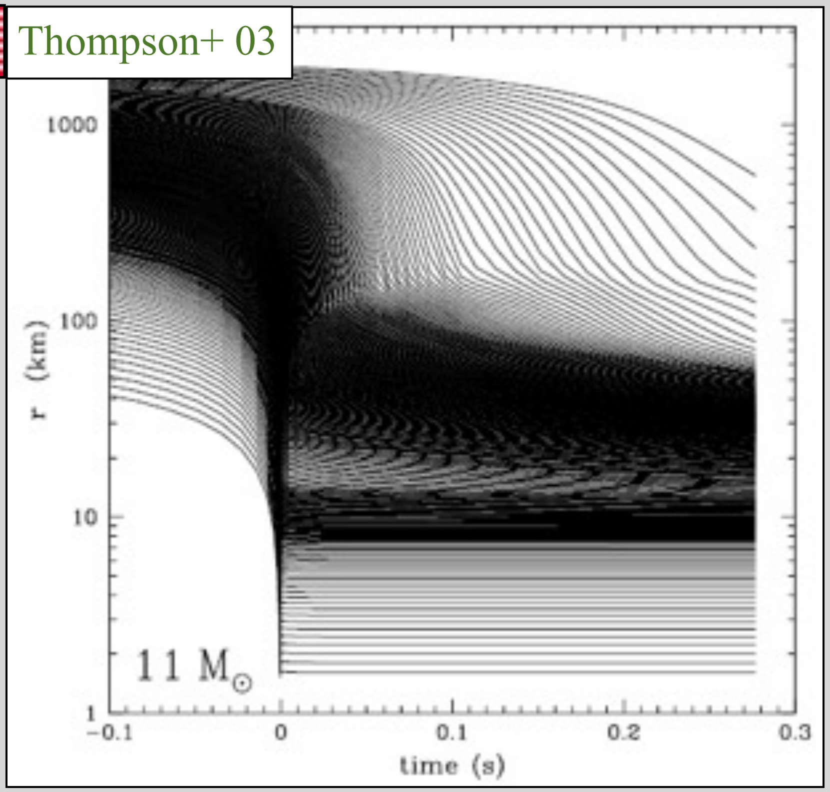
Liebendörfer+ 01



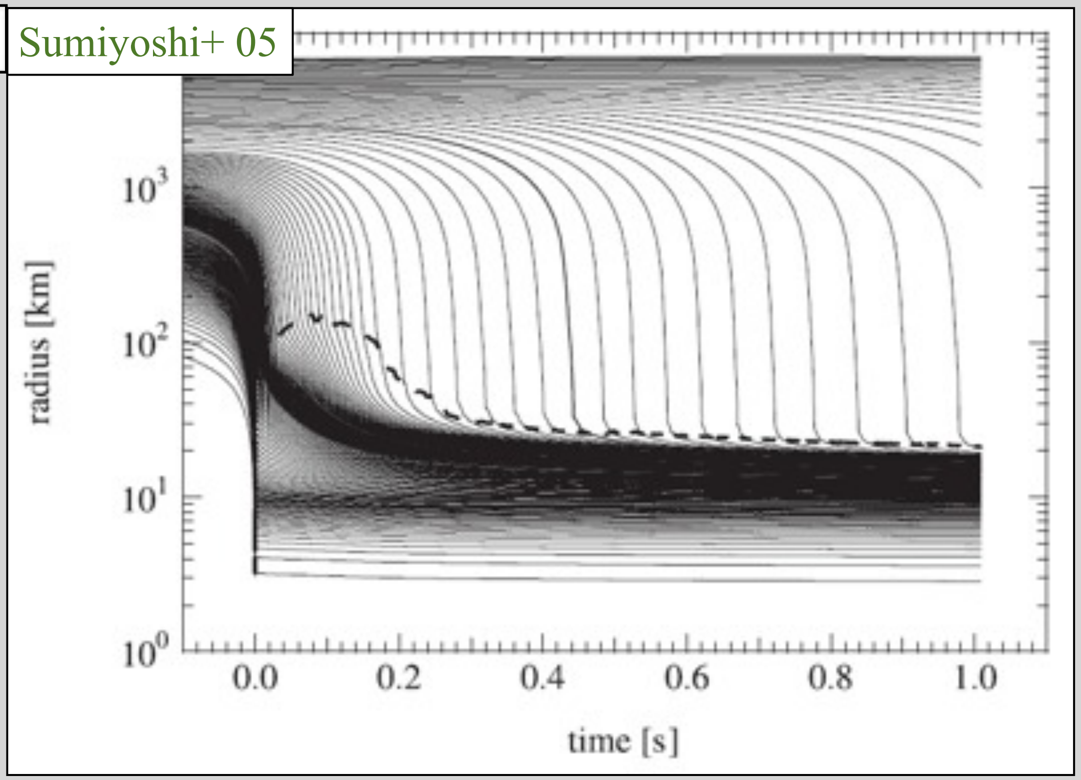
By including all available physics to simulations, we concluded that the explosion cannot be obtained in 1D!

(The exception is an 8.8 M☉ star; Kitaura+ 06)

Thompson+ 03



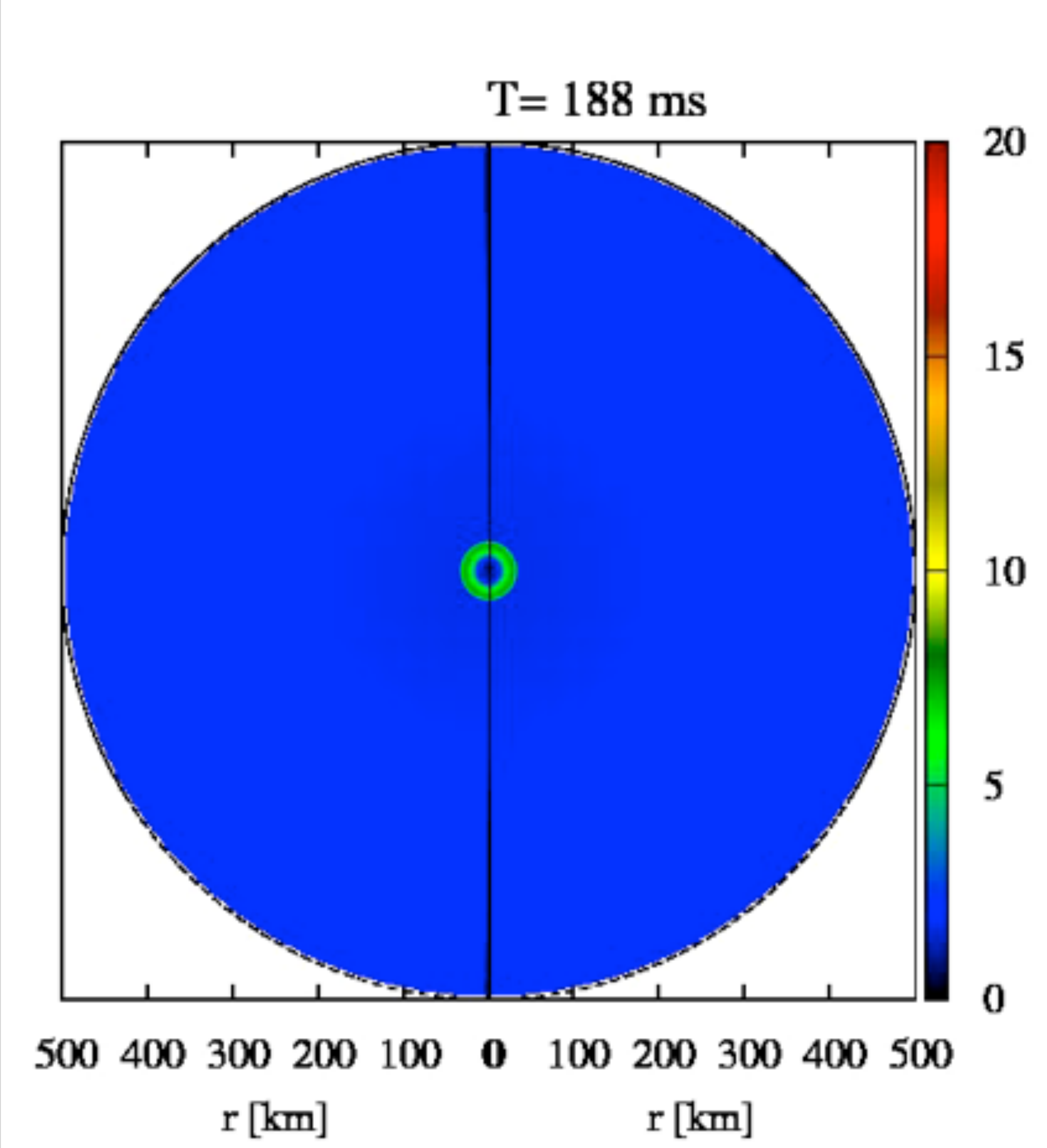
Sumiyoshi+ 05



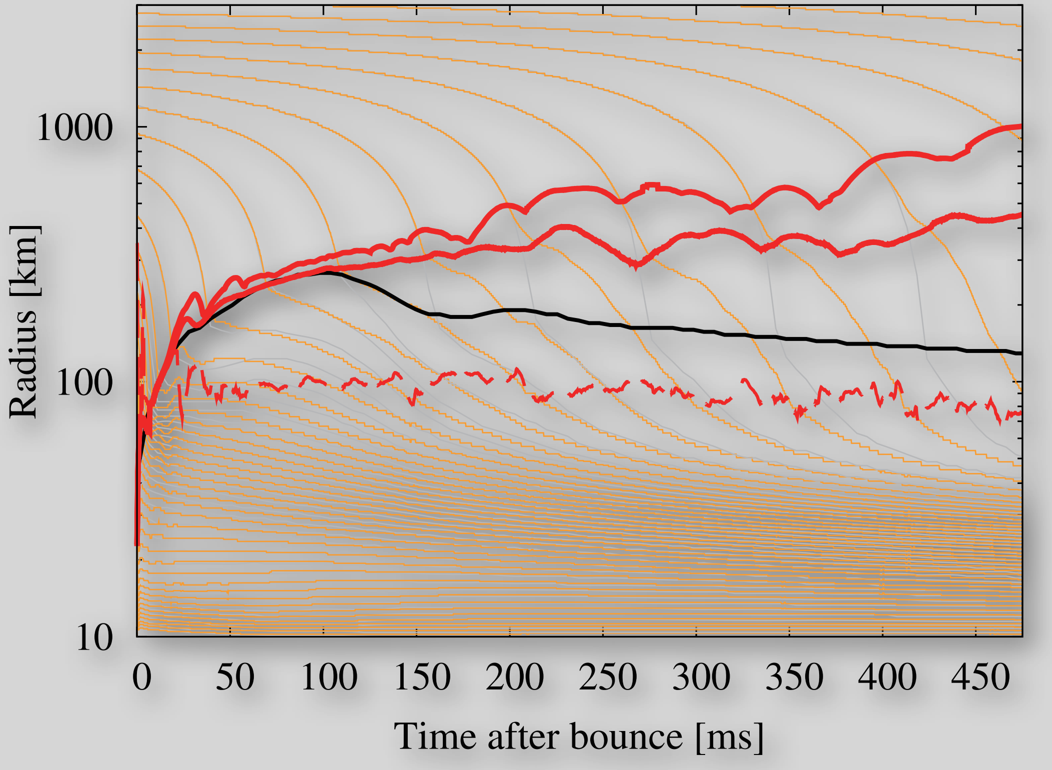
Neutrino-driven explosion in multi-D simulation

Recently, we have successful exploding models driven by neutrino heating

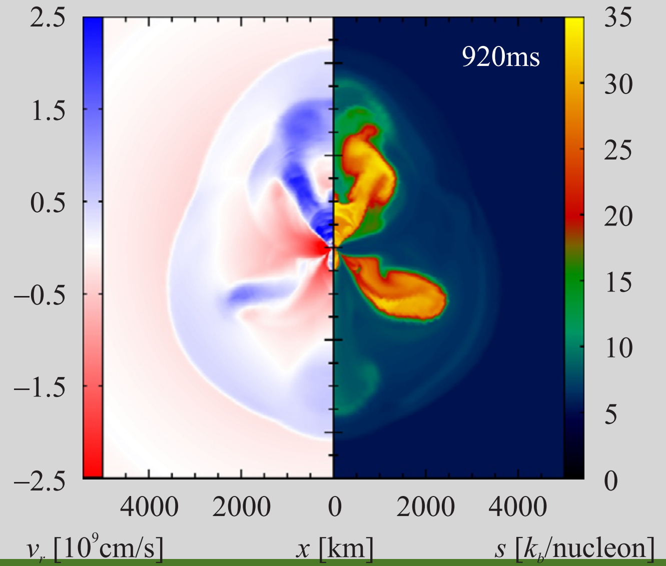
YS, Kotake, Takiwaki, Whitehouse, Liebendörfer, Sato, PASJ, **62**, L49 (2010)



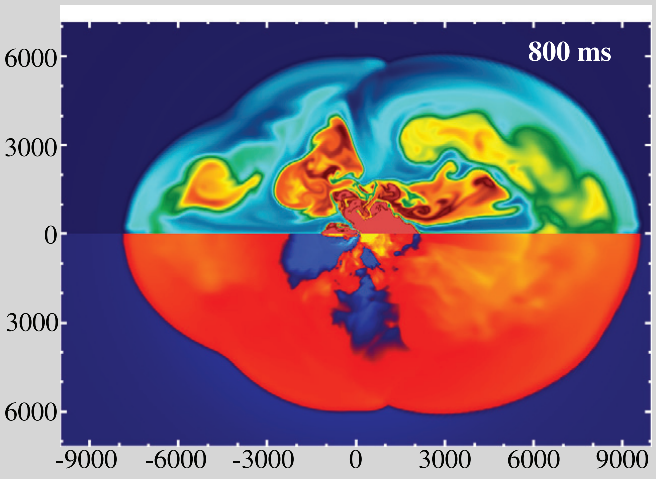
comparison between 1D and 2D



Müller, Janka, Marek (2012)

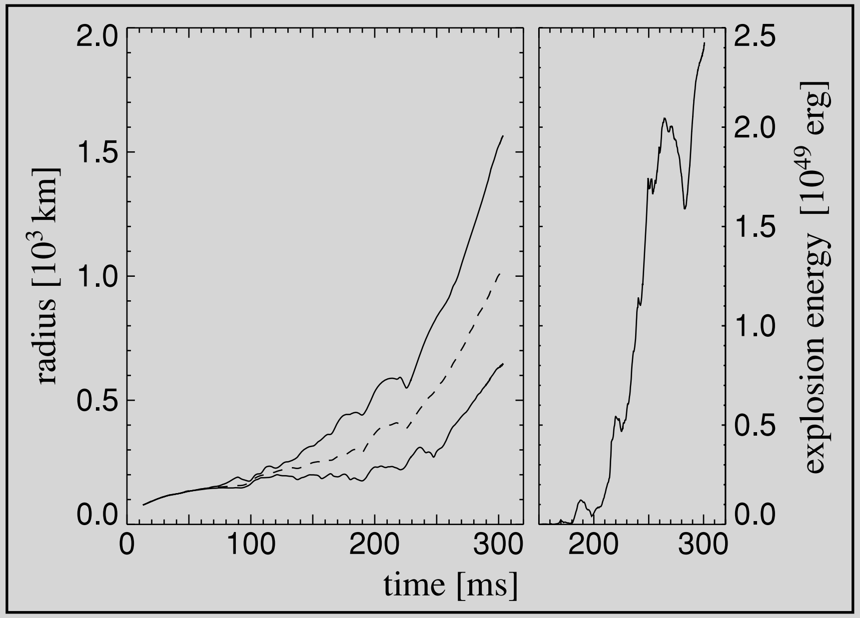


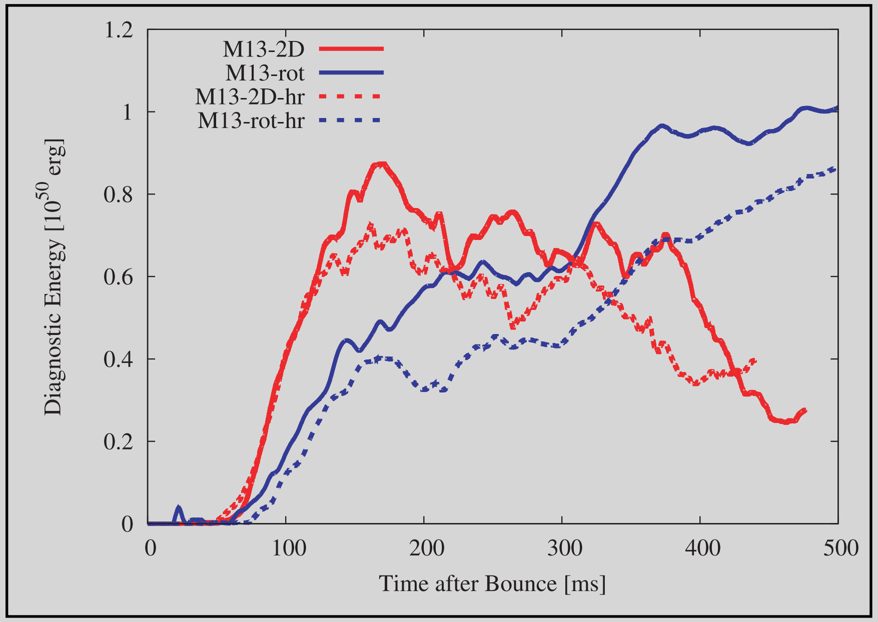
Brruenn et al. (2013)



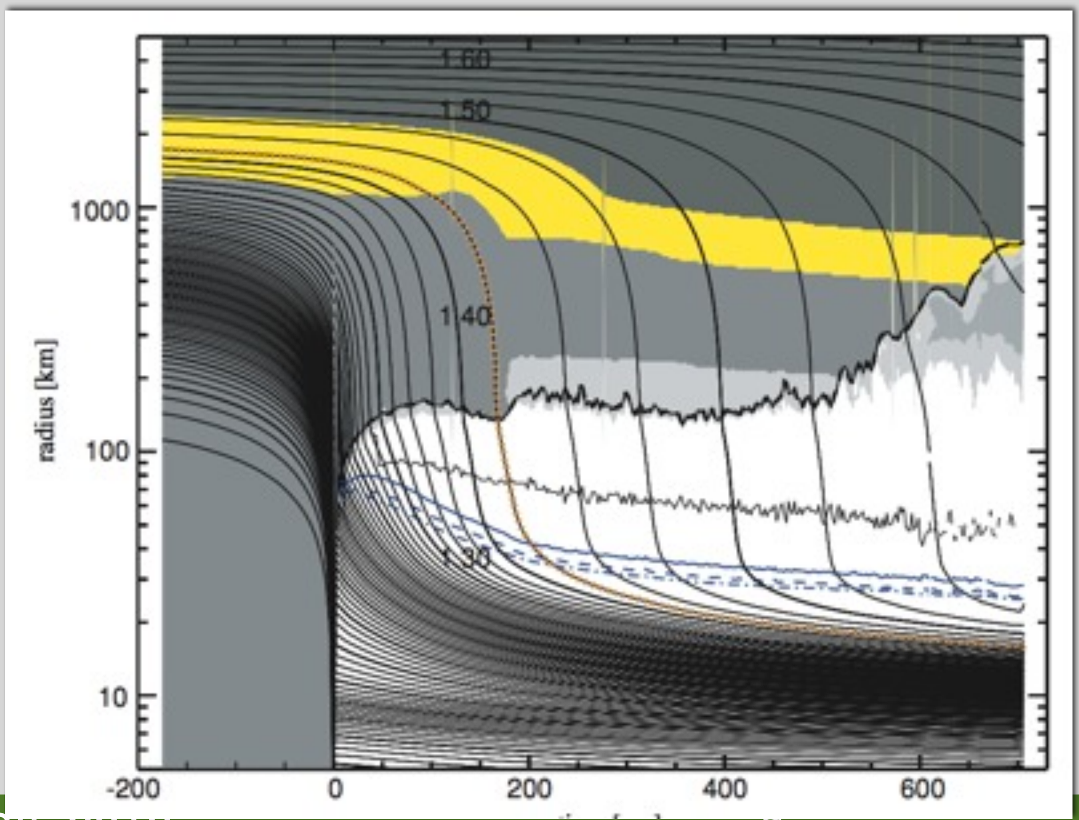
Problems of neutrino-driven explosion

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

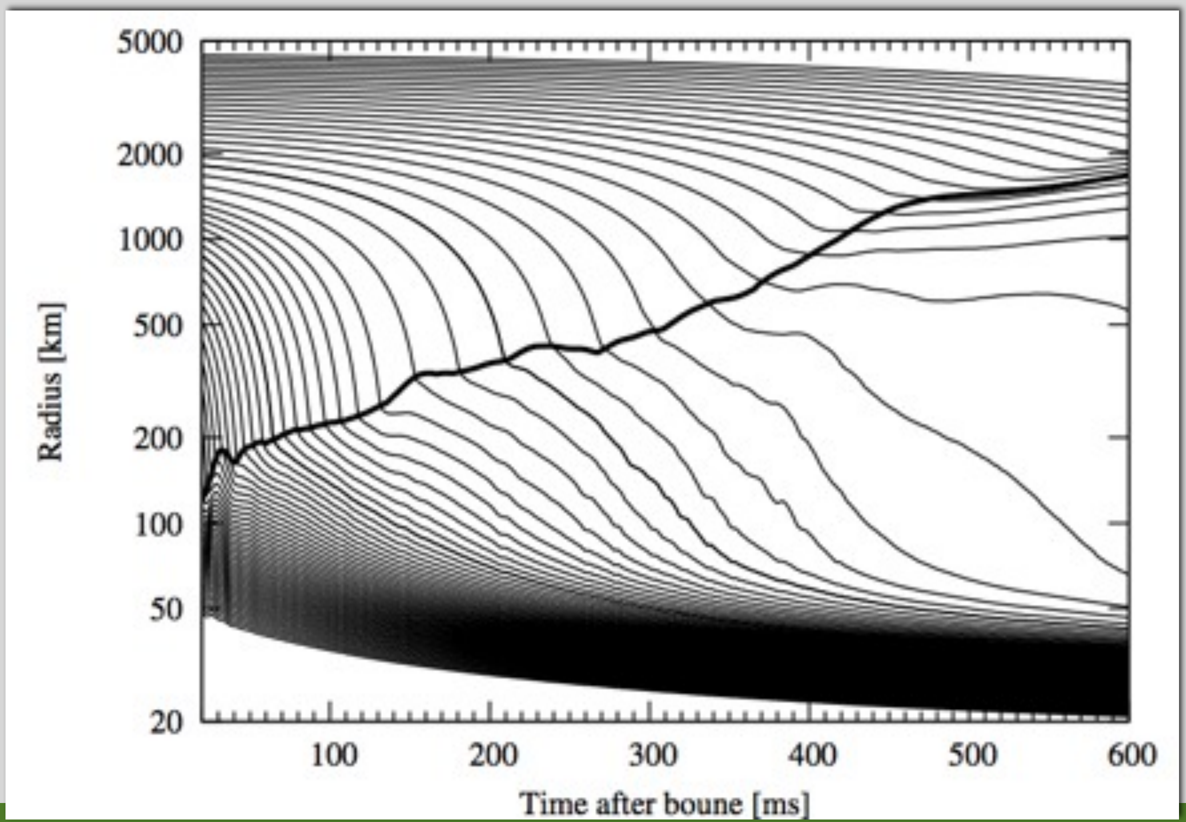




- continuous accretion <=> The remnant is NOT a NS



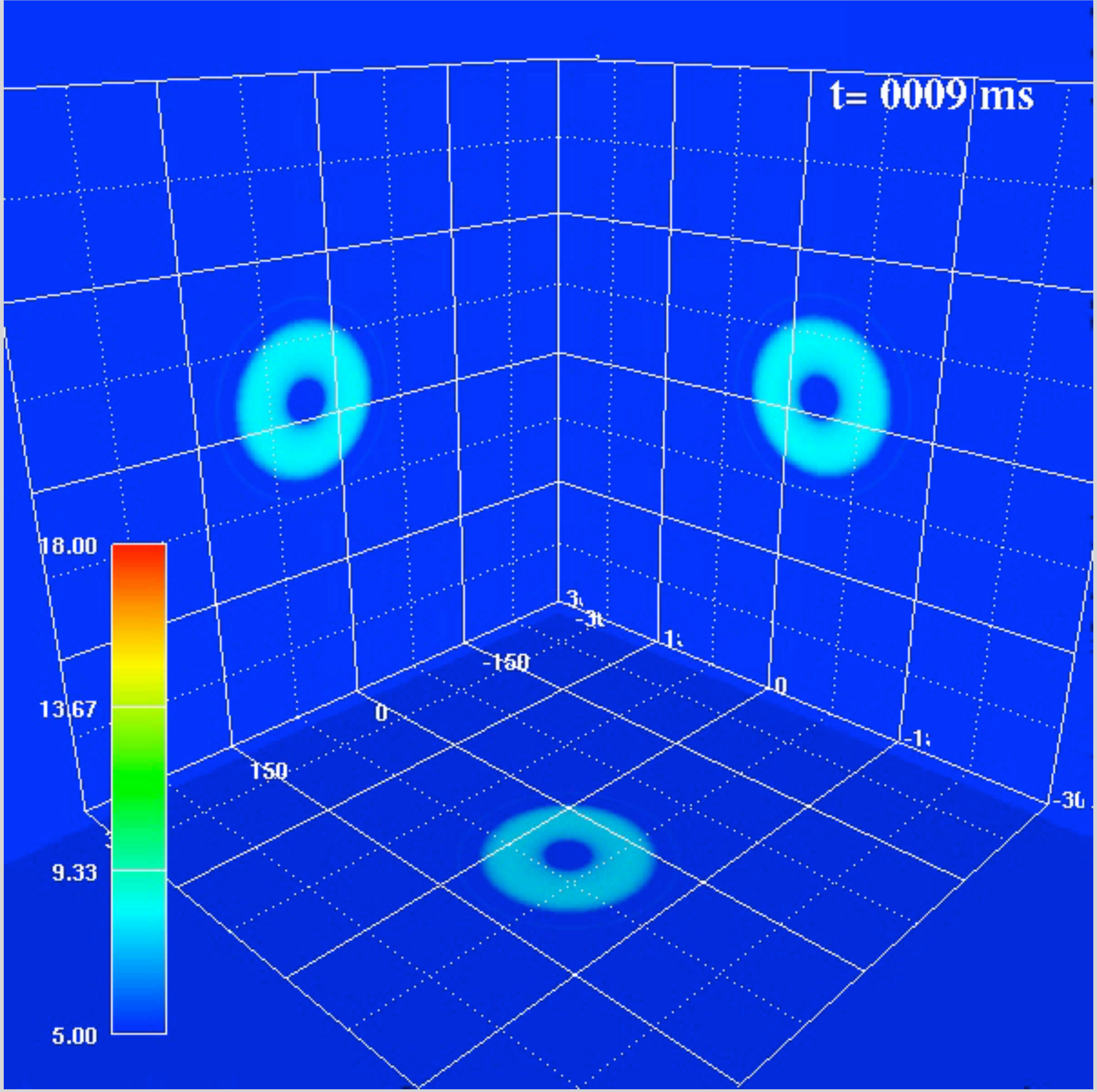
Marek & Janka (2009)



Suwa et al. (2010, 2013)

The first 3D simulation with neutrino transfer

Takiwaki, Kotake, YS, ApJ, **749**, 98 (2012) & recently submitted, arXiv:1308.5755



$320(r) \times 64(\theta) \times 128(\phi) \times 20(E_\nu)$


XT4@NAOJ


T2K-Tsukuba

K computer

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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

Finite temperature EOSs

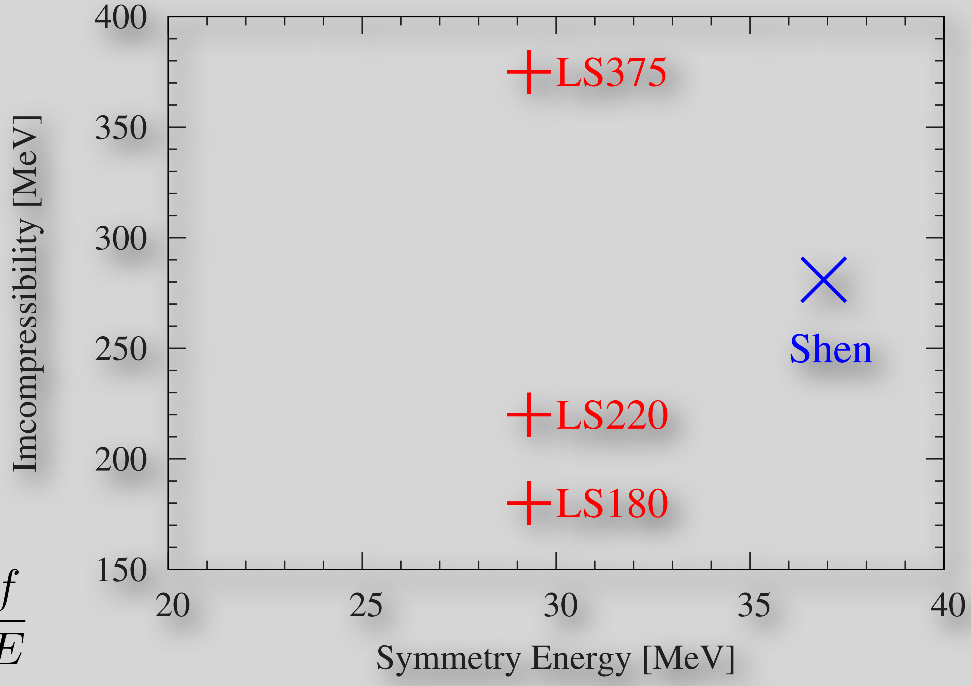
- Lattimer & Swesty (LS) (1991)
  - based on compressible liquid drop model
  - variants with K=180, 220, and 375 MeV
- H.Shen et al. (1998, 2011)
  - relativistic mean field theory (TM1)
  - including hyperon component (~2011)
- Hillebrandt & Wolff (1985)
  - Hartree-Fock calculation
- G.Shen et al.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

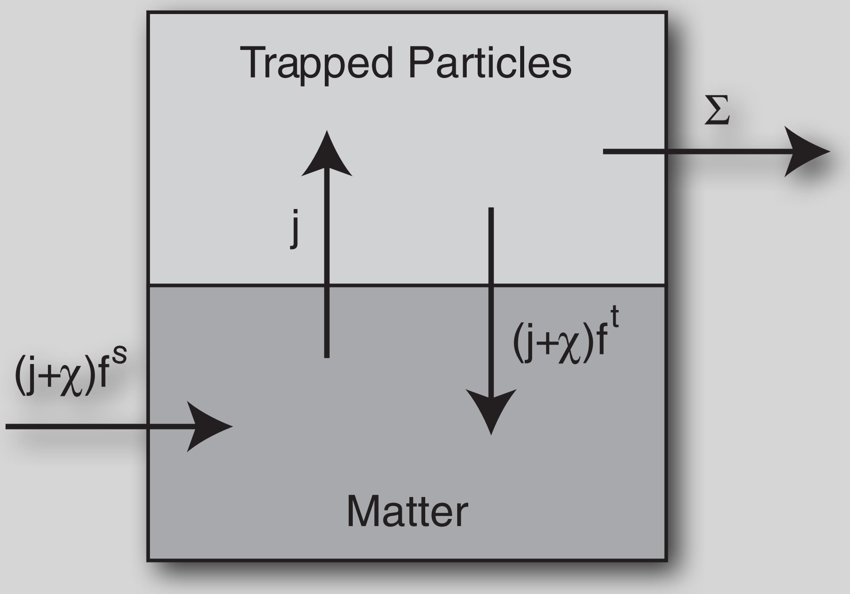
- Axisymmetric simulation (ZEUS-2D; Stone & Norman 92)
- Hydrodynamics + Neutrino transfer

$$\frac{df}{cdt} + \mu\frac{\partial f}{\partial r} + \left[\mu\left(\frac{d\ln\rho}{cdt}+\frac{3v}{cr}\right)\right](1-\mu^2)\frac{\partial f}{\partial \mu} + \left[\mu^2\left(\frac{d\ln\rho}{cdt}+\frac{3v}{cr}\right)-\frac{v}{cr}\right]D\frac{\partial f}{\partial E}$$

$$= j(1-f) - \chi f + \frac{E^2}{c(hc)^3}\left[(1-f)\int Rf'd\mu' - f\int R(1-f')d\mu'\right]$$

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

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

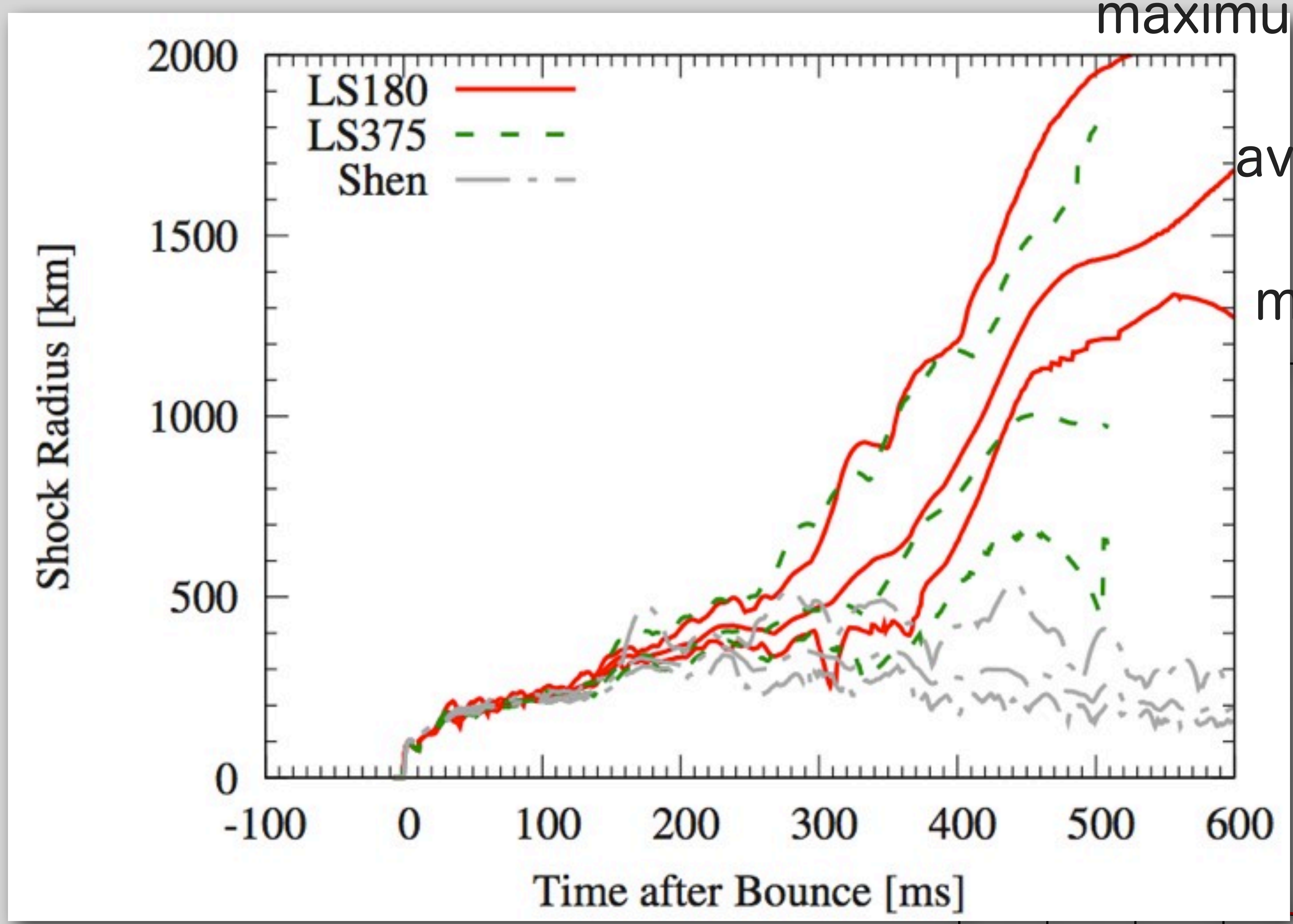


- progenitor: 15 $\mathrm{M}_\odot$ (Woosley & Weaver 95)

Shock radius evolution depending on EOS

YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato, ApJ **764**, 99 (2013)

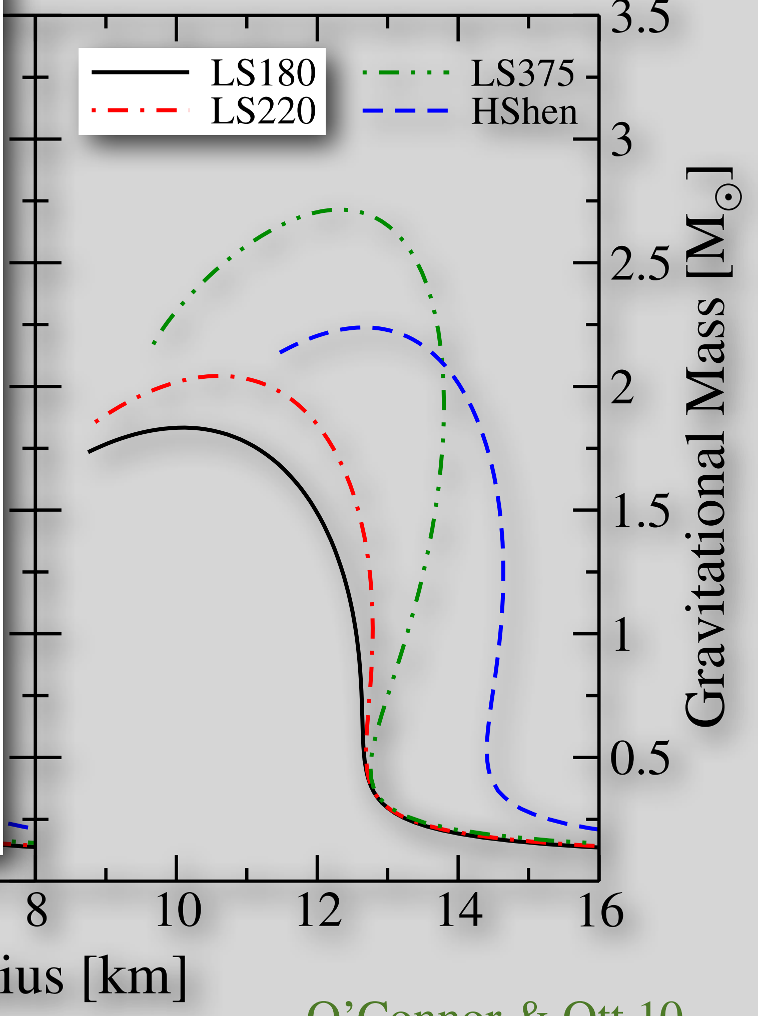
15 $M_\odot$ of Woosley
& Weaver (1995)



maximum

average

minimum



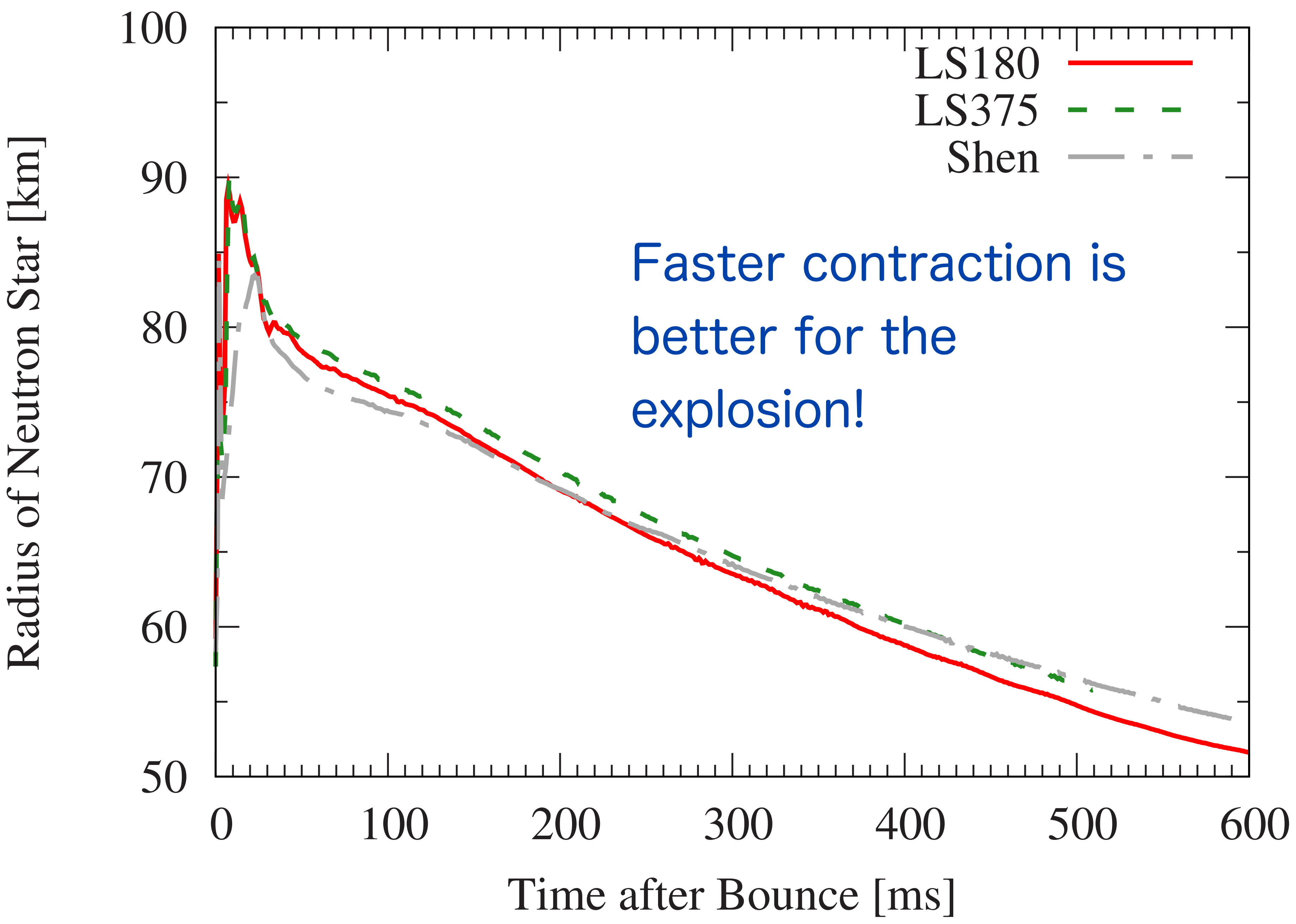
O'Connor & Ott 10

LS180 and LS375 succeed the explosion

Shen EOS fails

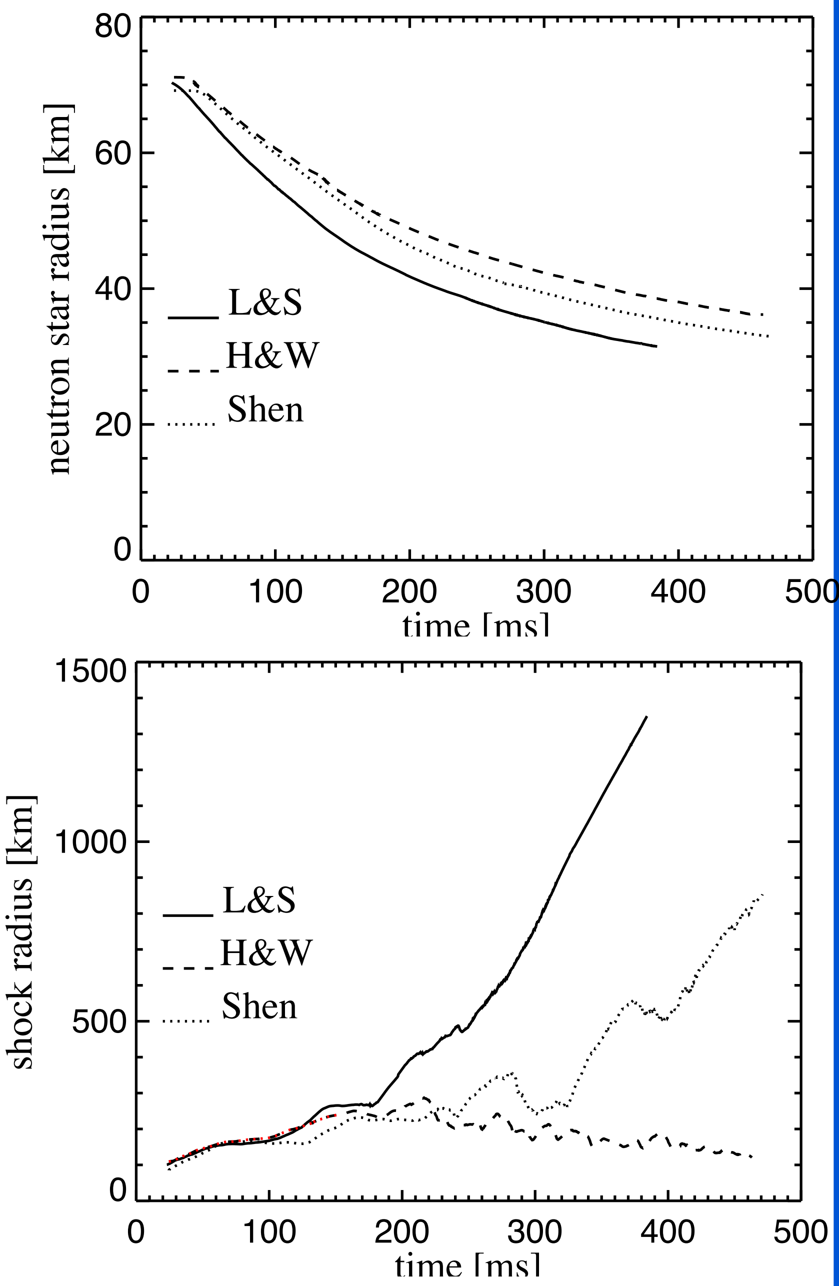
Radius of neutron star

YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato, ApJ **764**, 99 (2013)



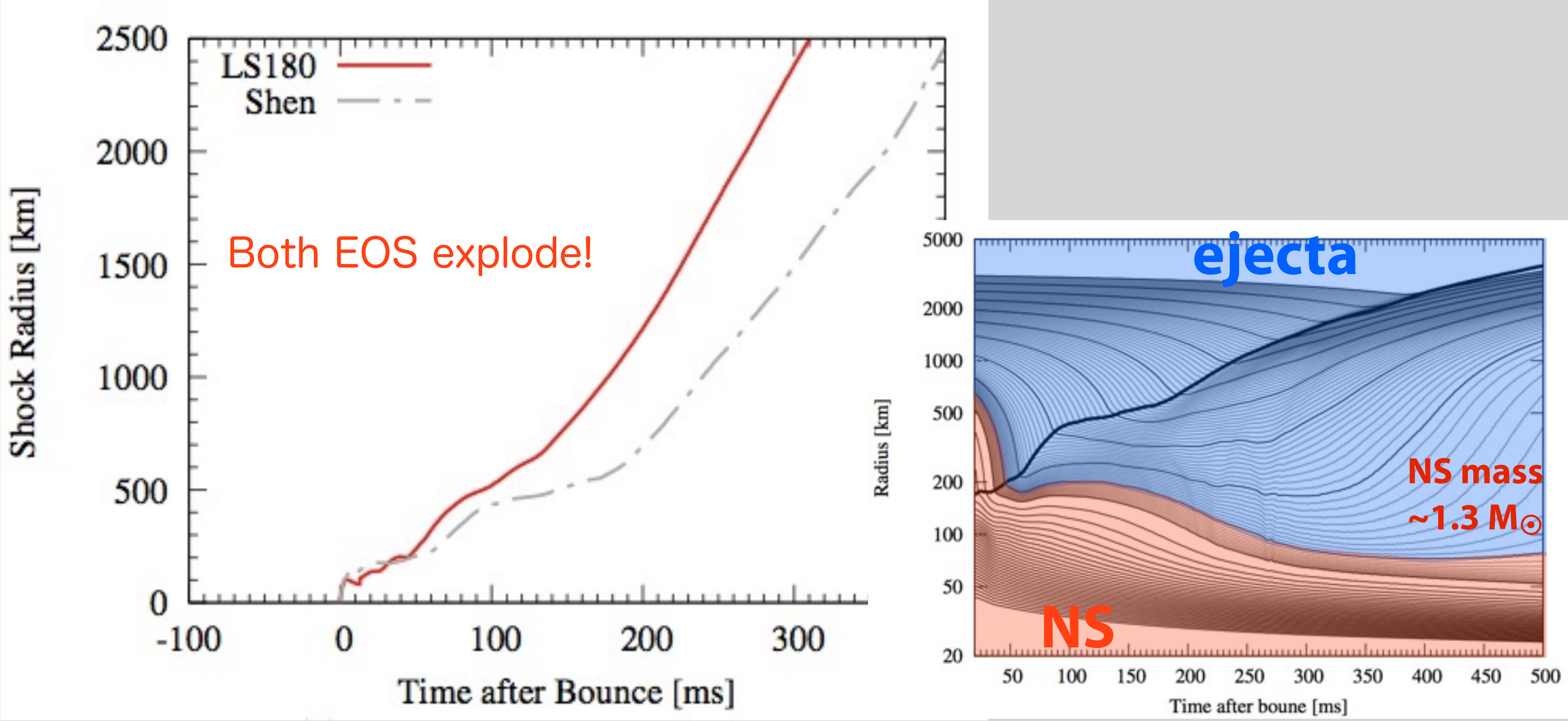
Faster contraction is better for the explosion!

Janka, arXiv:1206.2503



Progenitor dependence would be more critical

When we use 11.2 $M_\odot$ as an initial condition



YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato, ApJ **764**, 99 (2013)

But still the explosion enegy is ~10^{50} erg...

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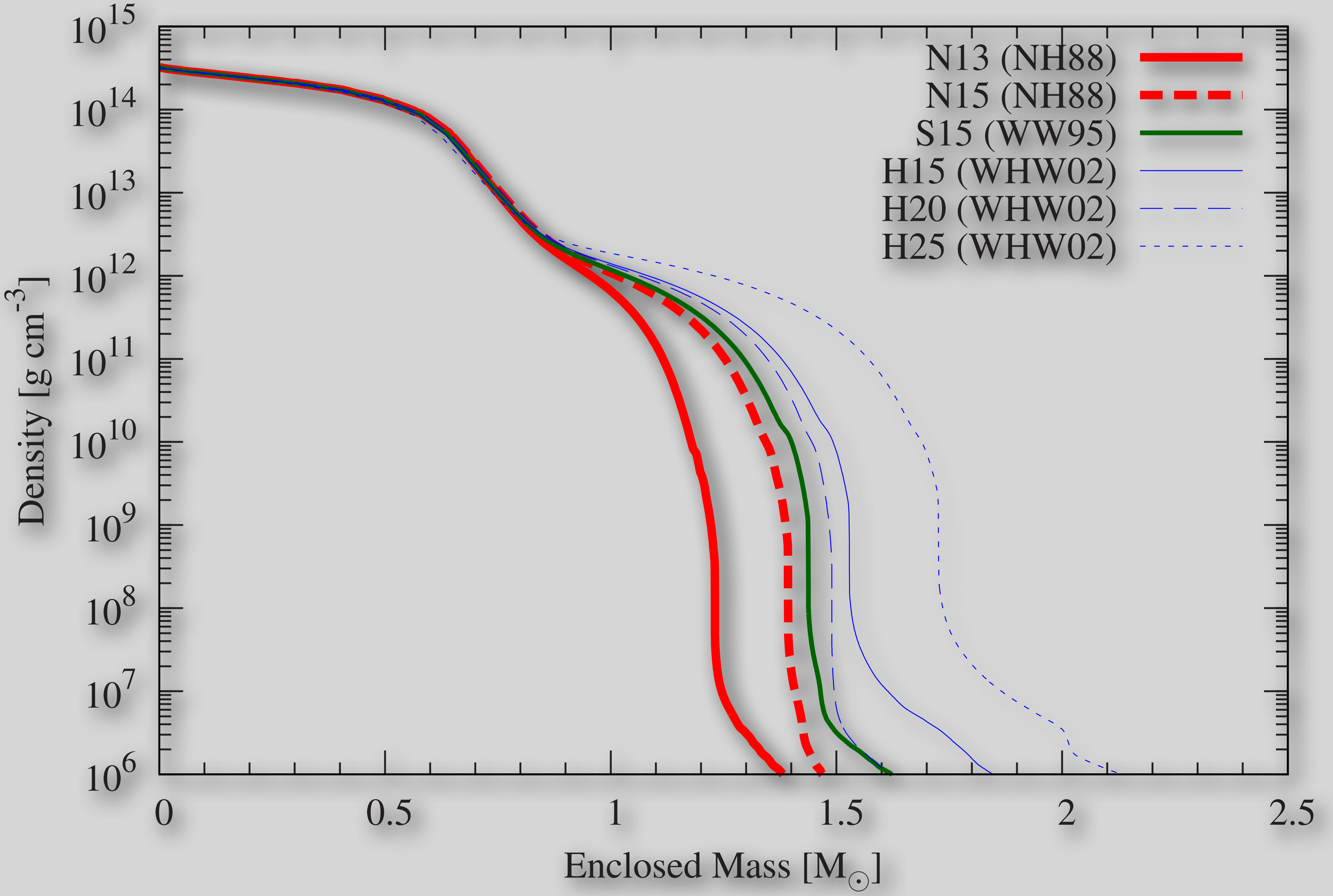
Progenitor dependence

NH: Nomoto & Hashimoto (1988)
WW: Woosley & Weaver (1995)
WHW: Woosley, Heger, & Weaver (2002)

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



- Density profiles 100 ms after the bounce
- Almost same for $M<0.8M_\odot$
- Profile for $M>0.8M_\odot$ reflect the initial profile

Progenitor dependence

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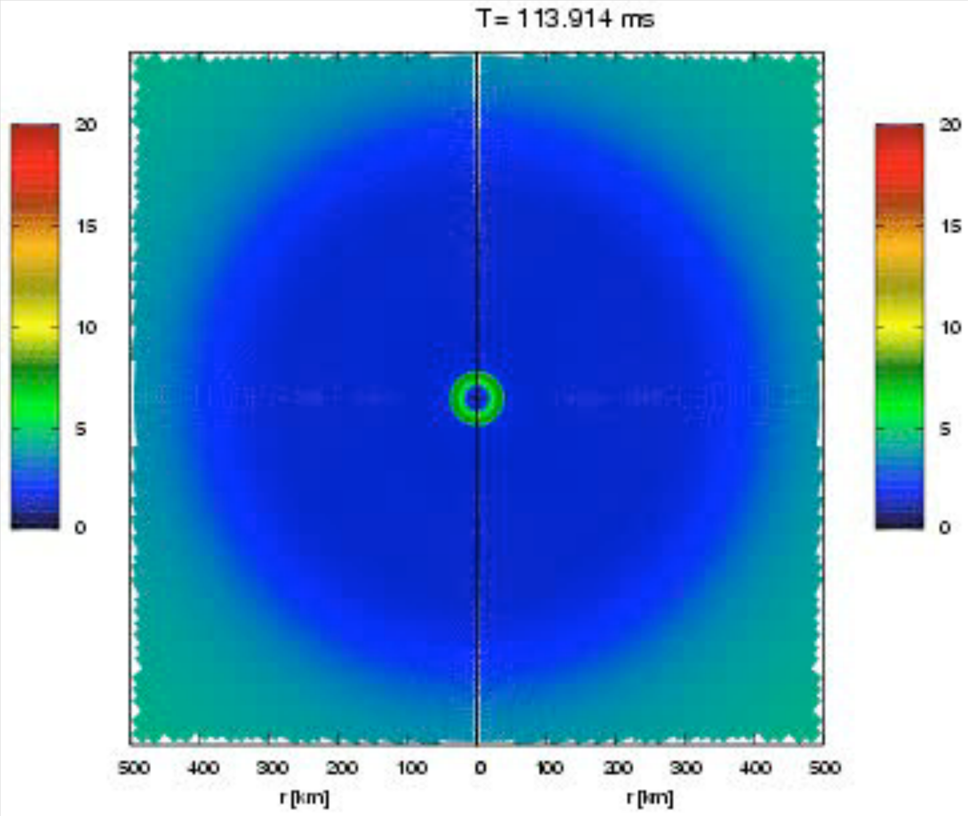
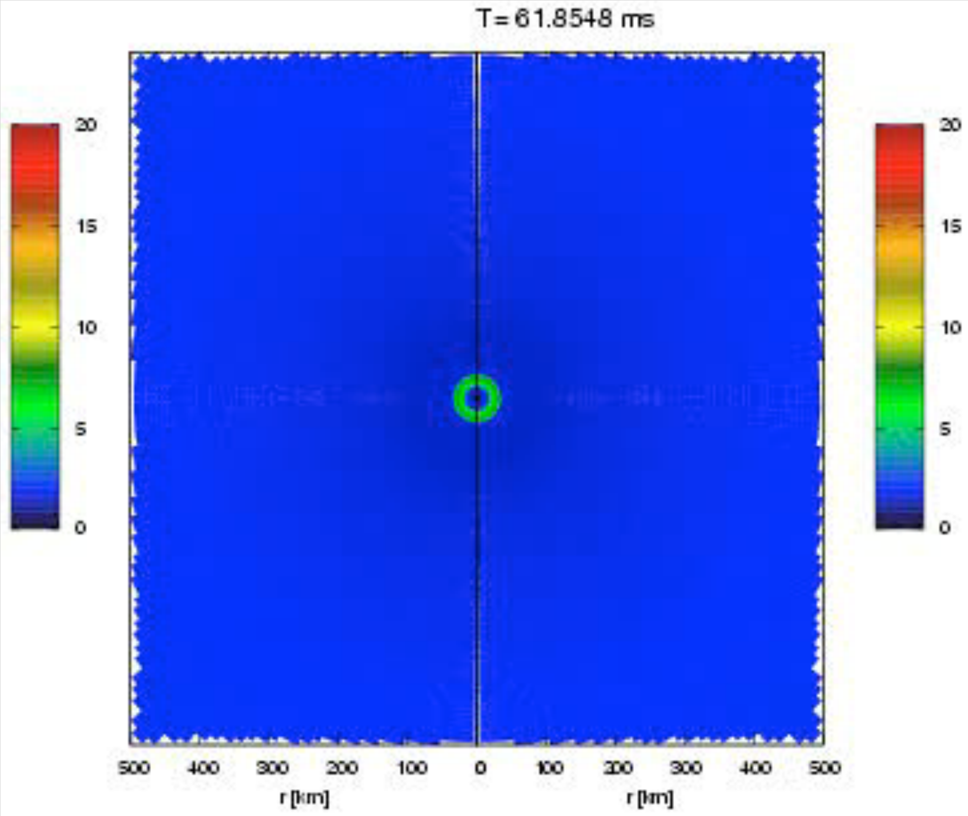
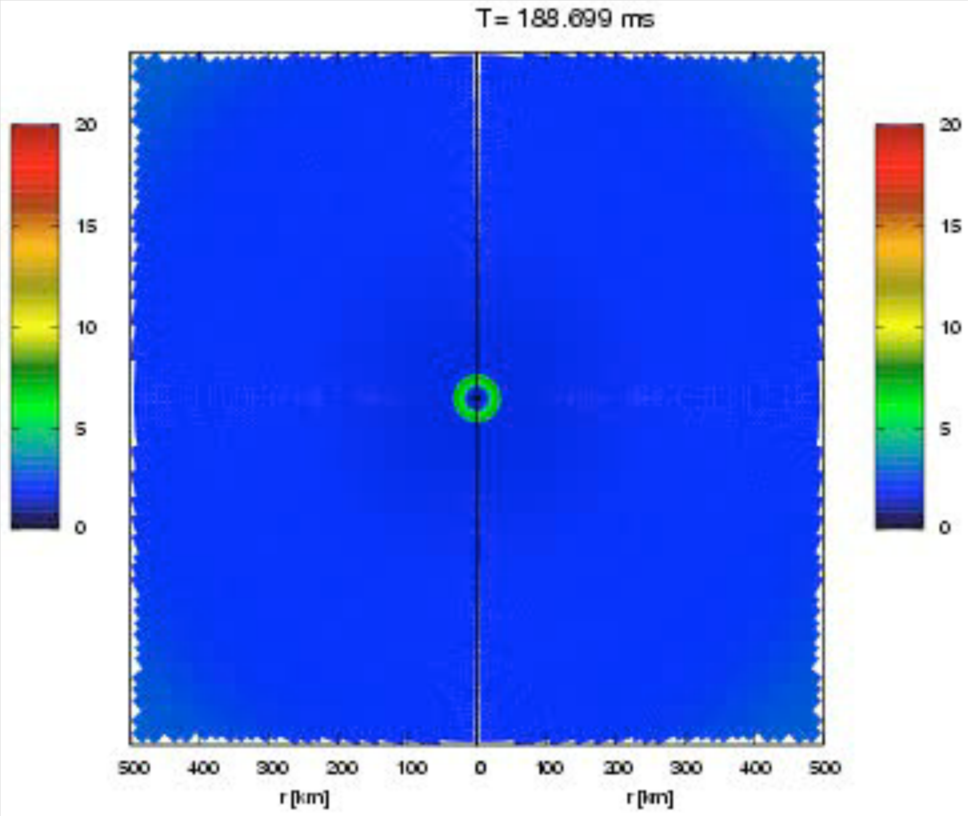
13M⊙
NH88

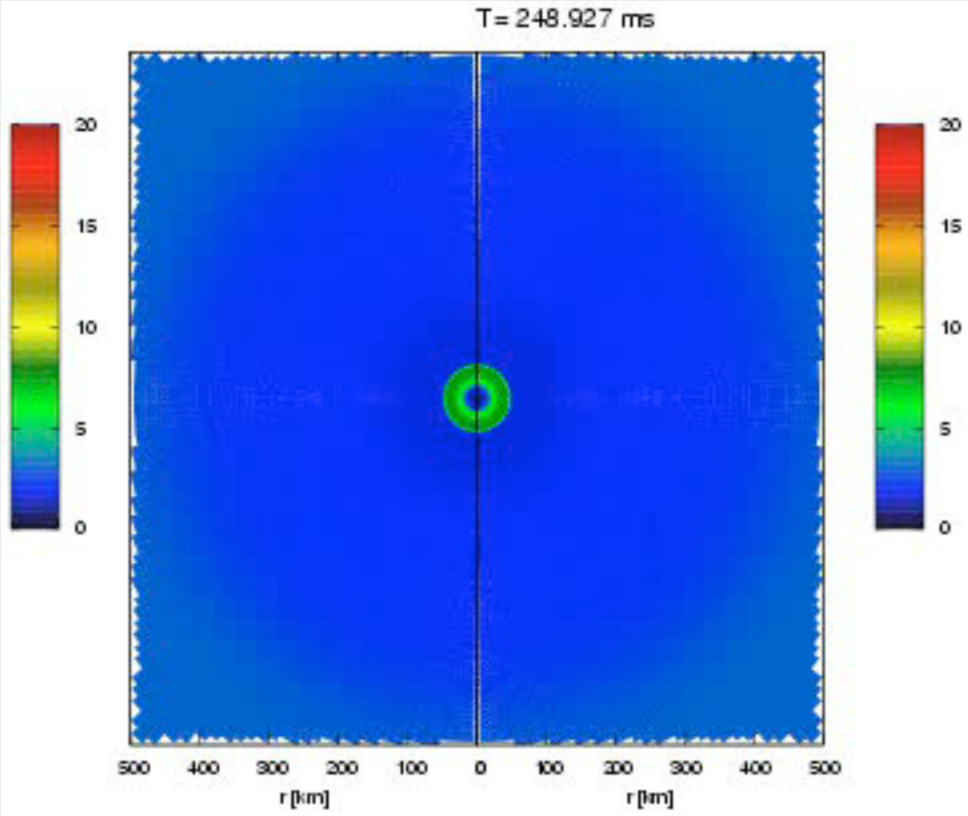




15M⊙
NH88



15M⊙
WW95

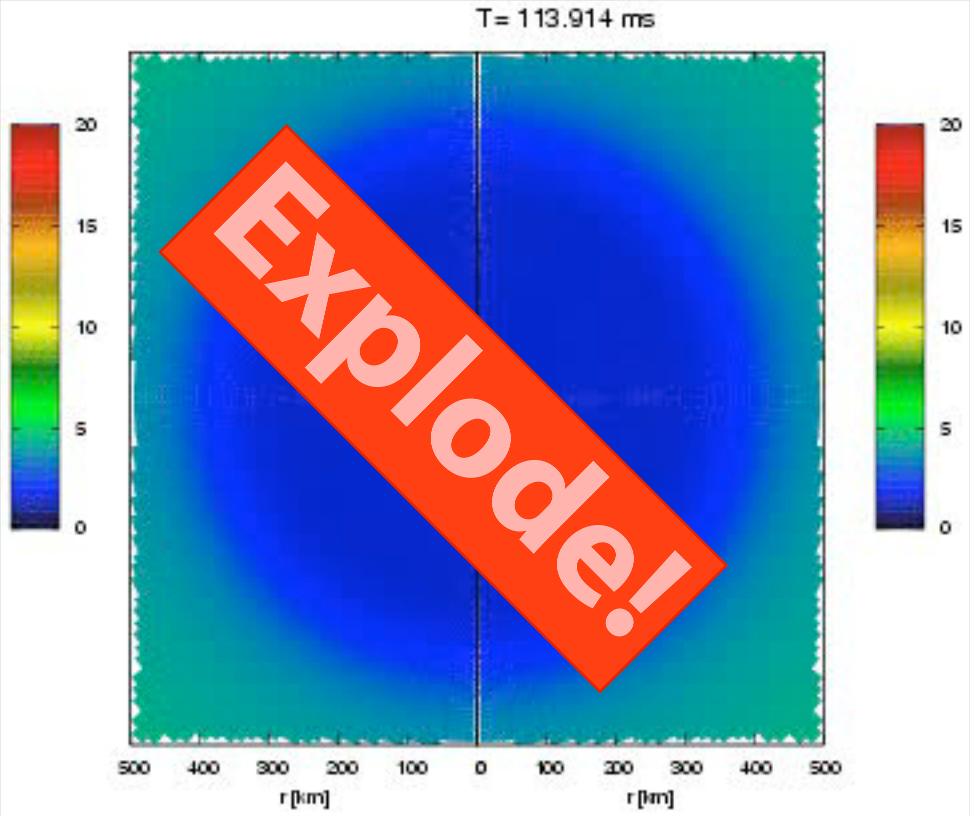


15M⊙
WHW02

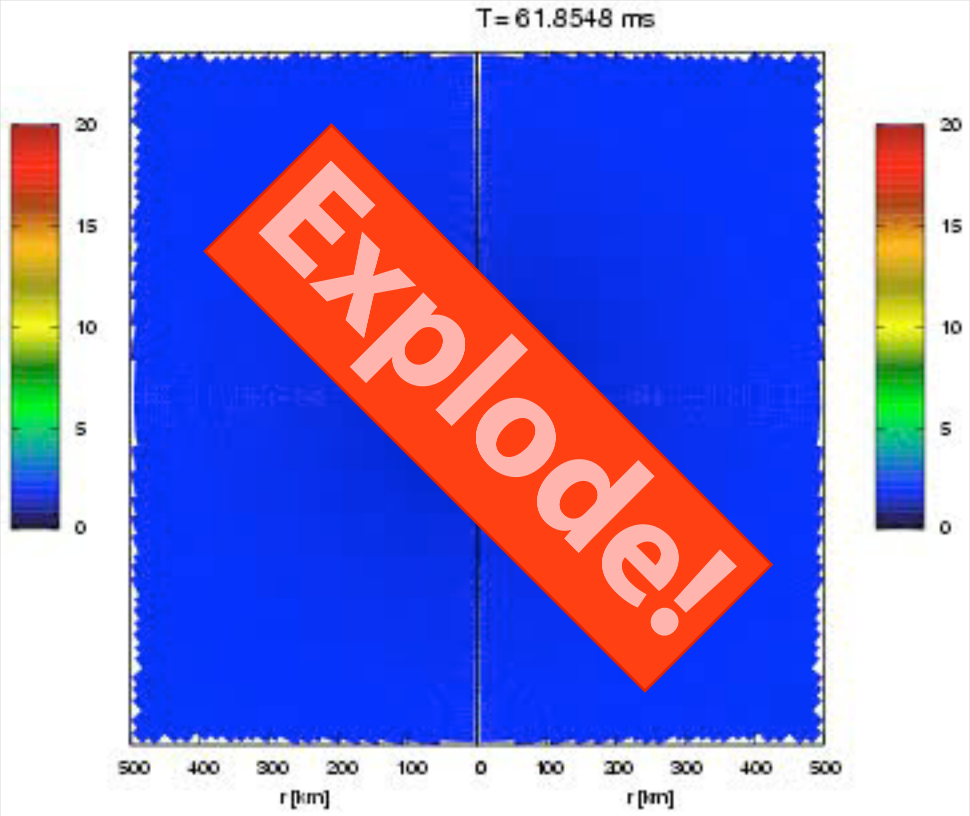
Progenitor dependence

NH: Nomoto & Hashimoto (1988)
WW: Woosley & Weaver (1995)
WHW: Woosley, Heger, & Weaver (2002)

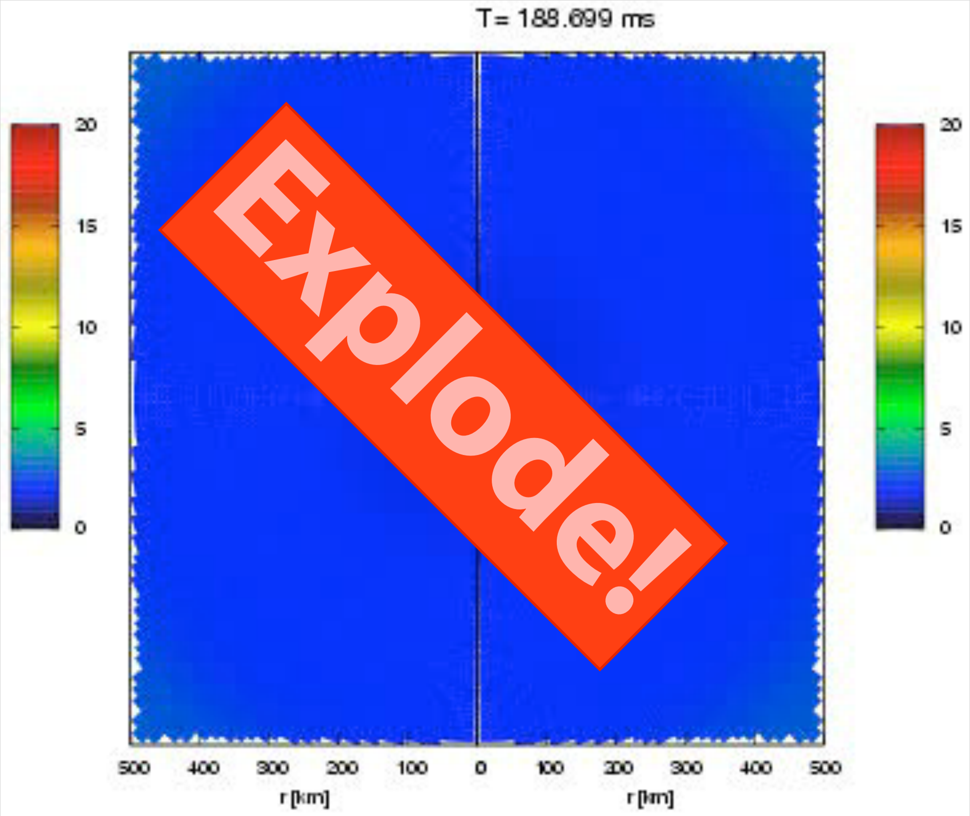
$13M_\odot$
NH88



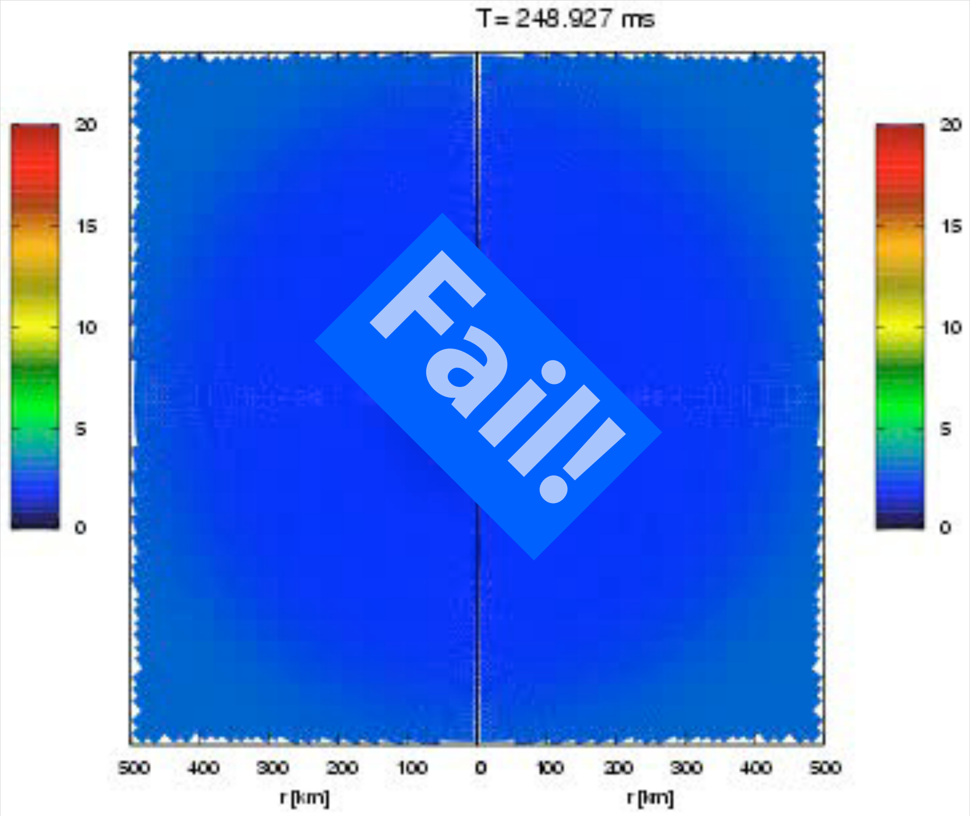
$15M_\odot$
NH88



$15M_\odot$
WW95

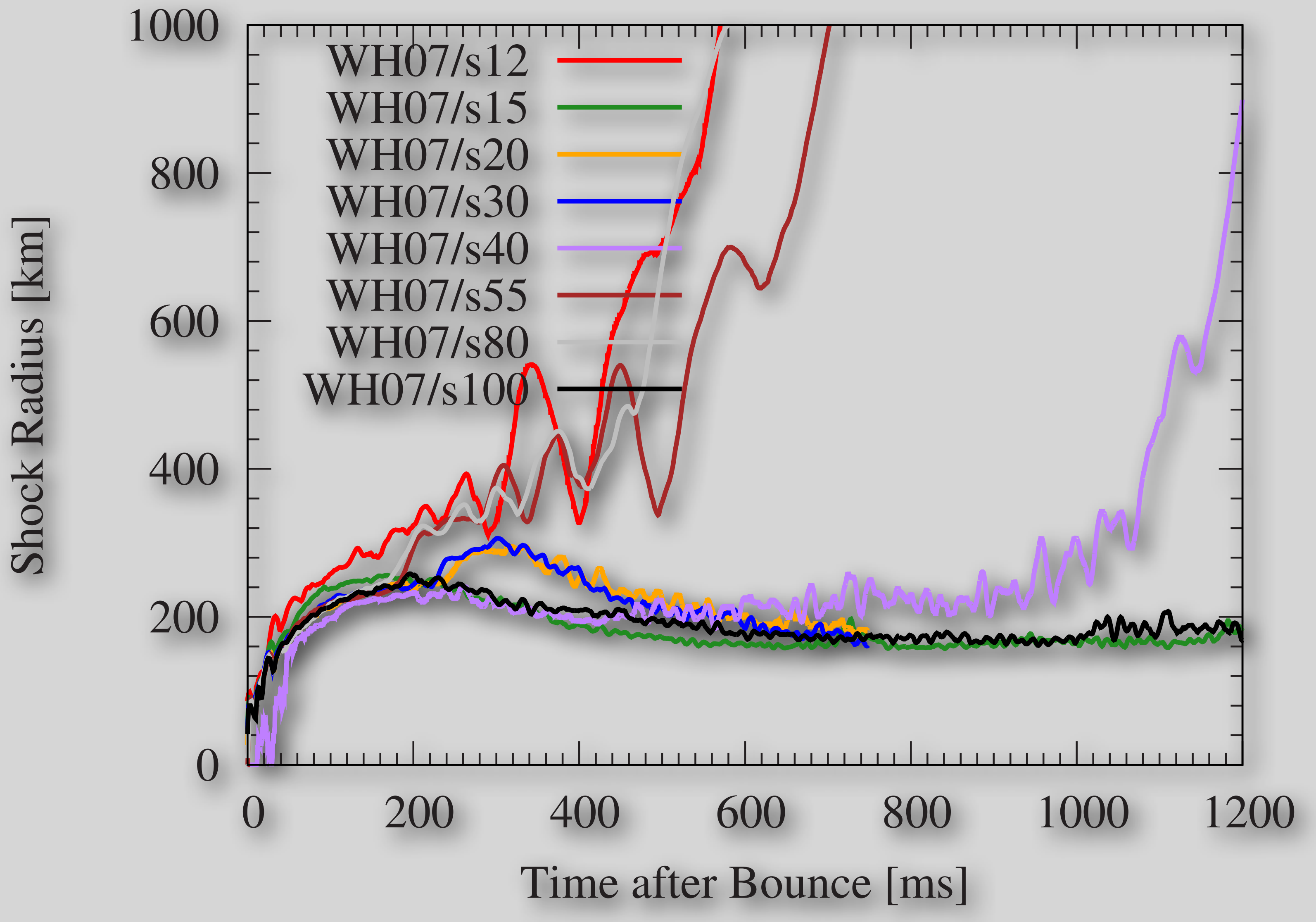


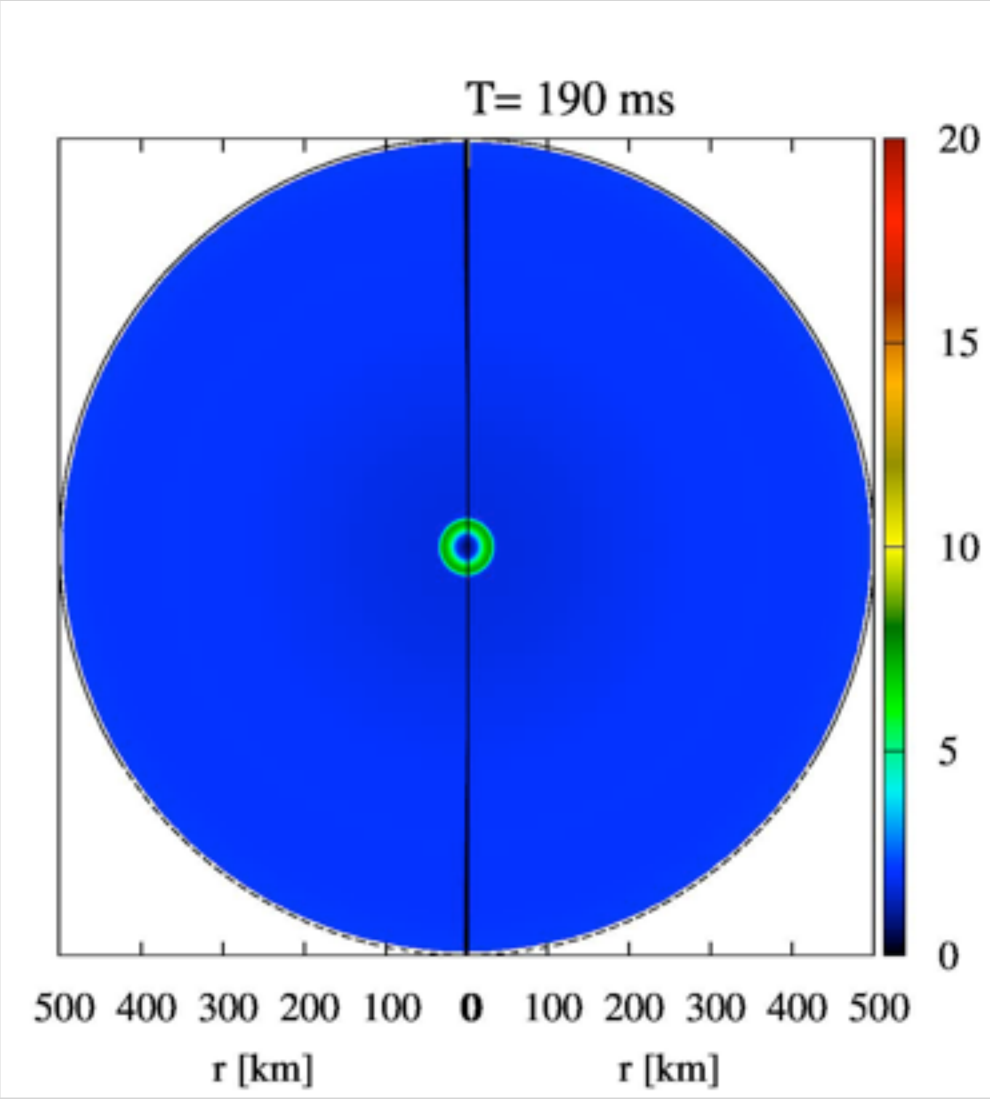
$15M_\odot$
WHW02



Shock evolution in 2D simulation

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

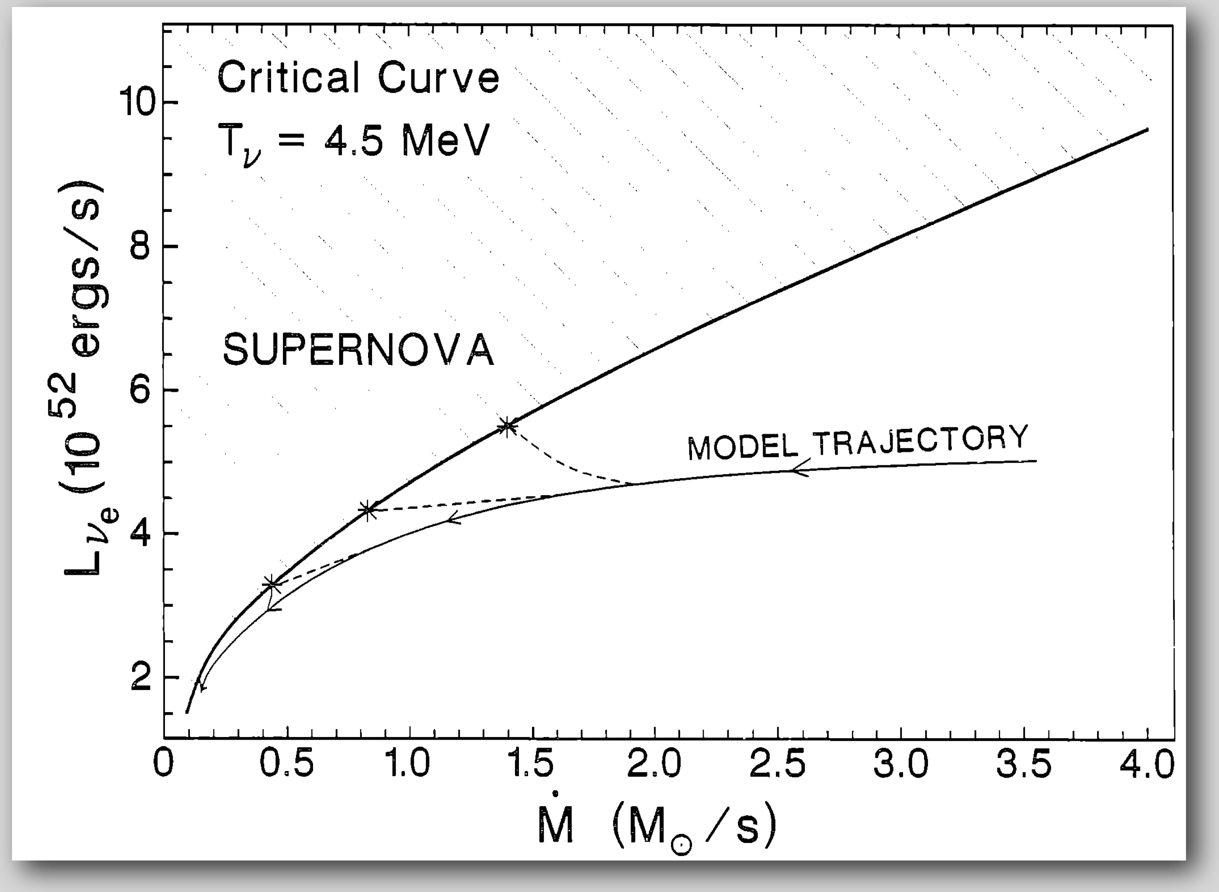


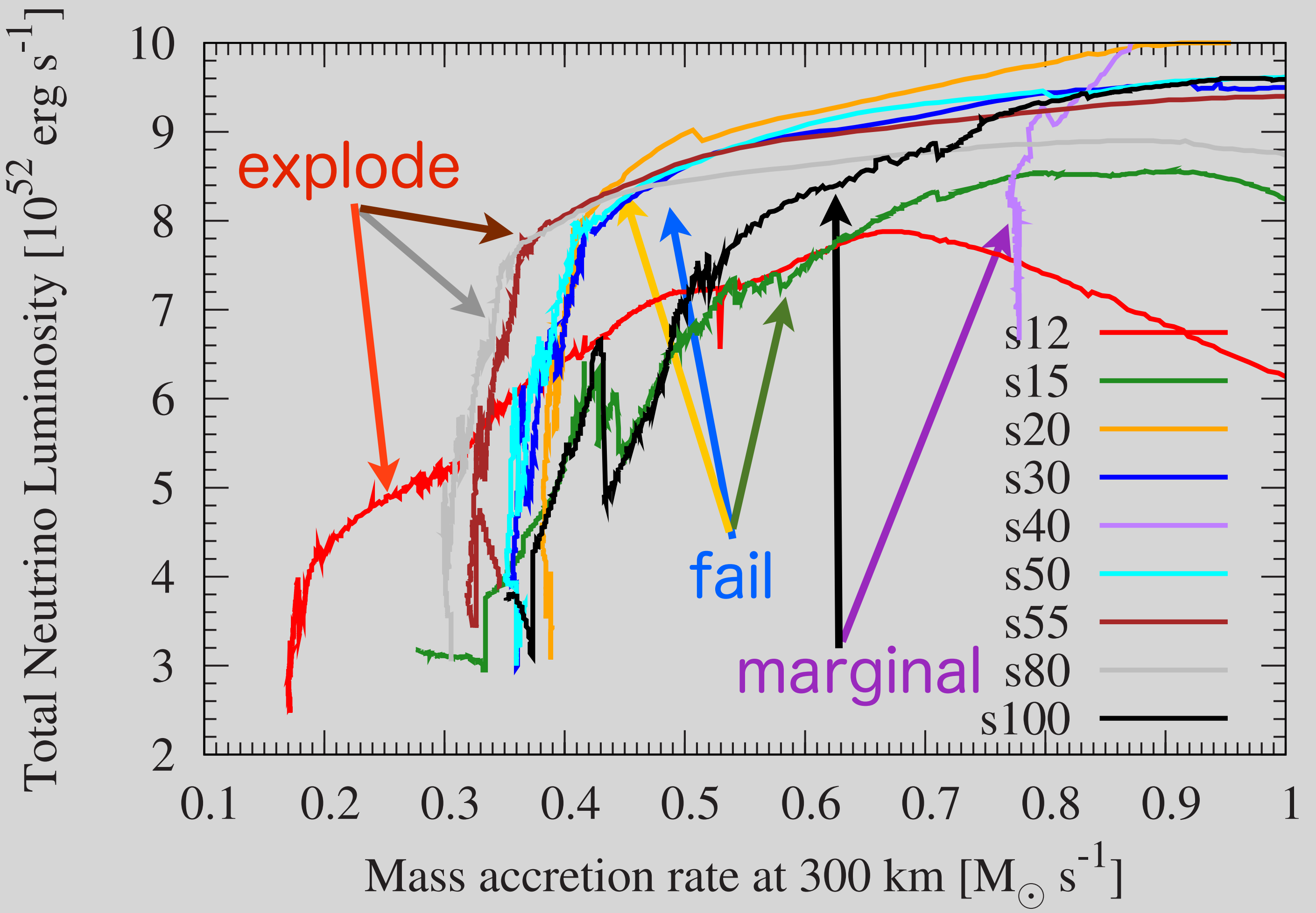


- Several progenitors lead to shock expansion
- No monotonic trend is found
- What determines the difference?

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

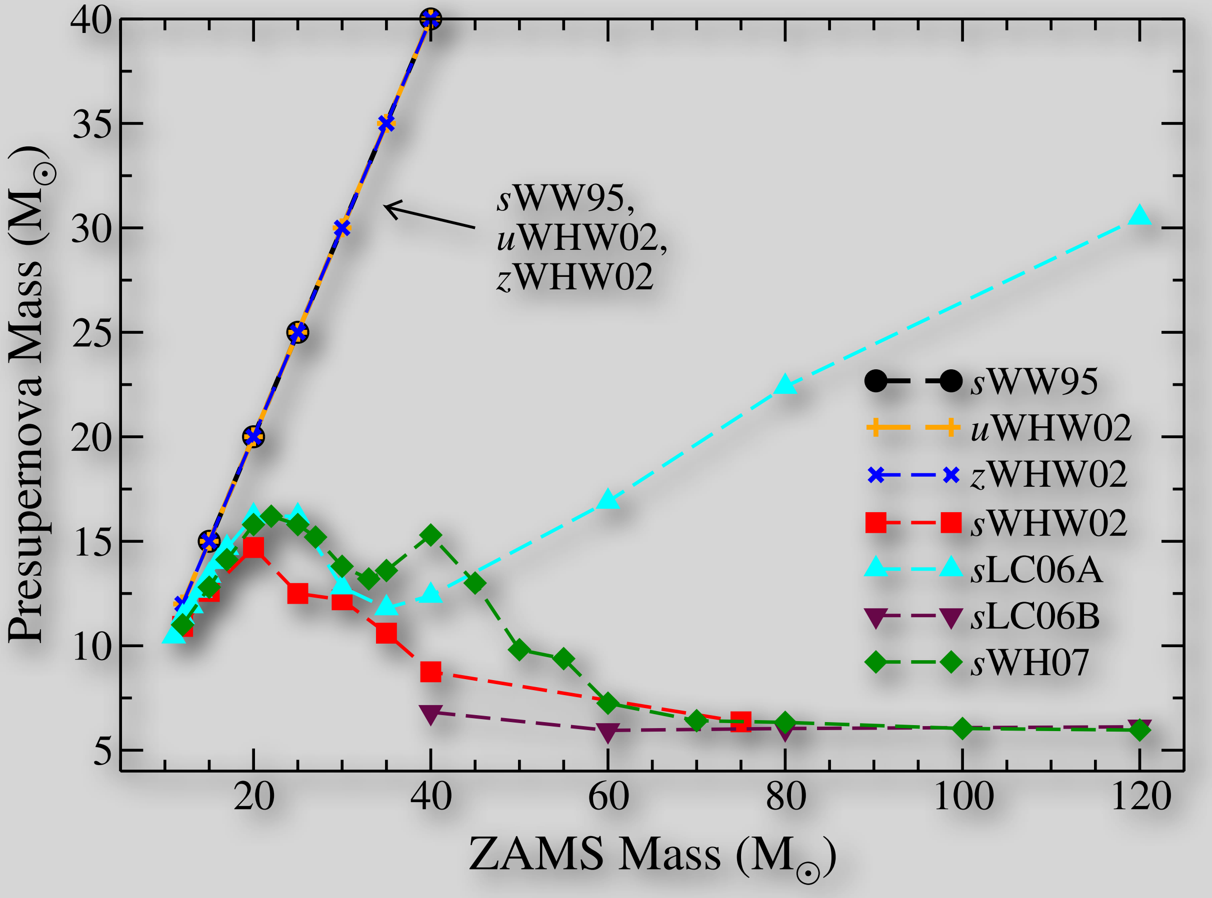
Burrows & Goshy 93





- 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...

Discussion


O’Connor & Ott 11

Mass	Explosion / Failure
12	○
15	×
20	×
30	×
40	△
55	○
80	○
100	△

- Smaller presupernova mass seems to be better for at least neutrino-driven explosion
- Model systematics around 15-30 are smaller compared to the other mass range and these progenitors are difficult to explode

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, 2013)
  - Effect of neutrino oscillation **[potentially strengthen the explosion]** (YS+ 2011)
  - Impacts of nuclear equation of state **["softer" is better]** (YS+ 2013)
  - Dependence of Progenitor structure **[under investigation…]** (YS+ in progress)

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