Numerical Simulation of Core-Collapse Supernovae

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Collaboration with

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Core-collapse supernovae

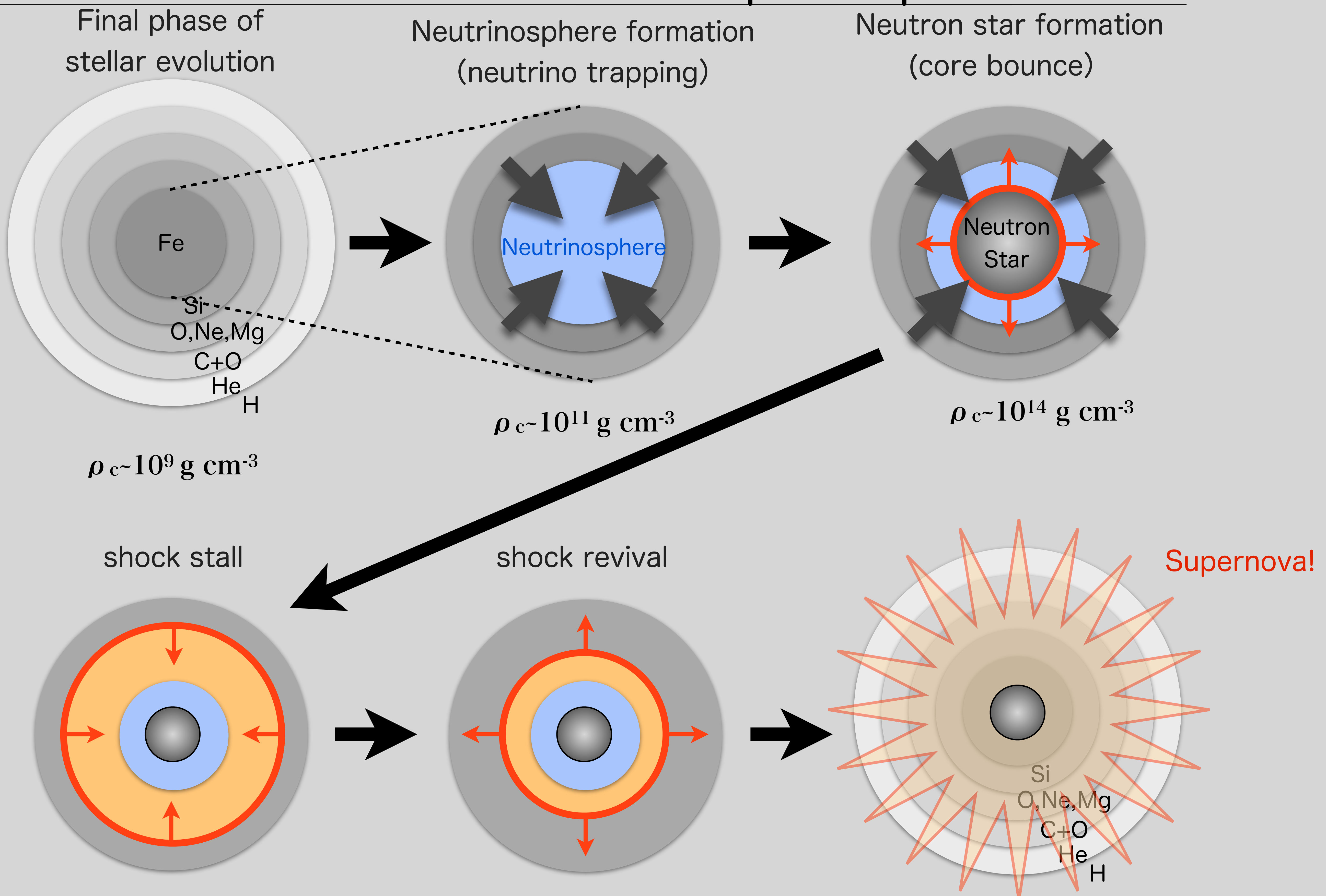
- One of the most energetic explosion in the universe
  - $E_{exp} \sim 10^{51}$ erg
  - $E_{grav} \sim 10^{53}$ erg ($\sim 0.1\ M_\odot\ c^2$)
  - $E_\nu \sim 10^{53}$ erg
- Formation of neutron Star / Black hole
- Formation of gamma-ray bursts?

✤ 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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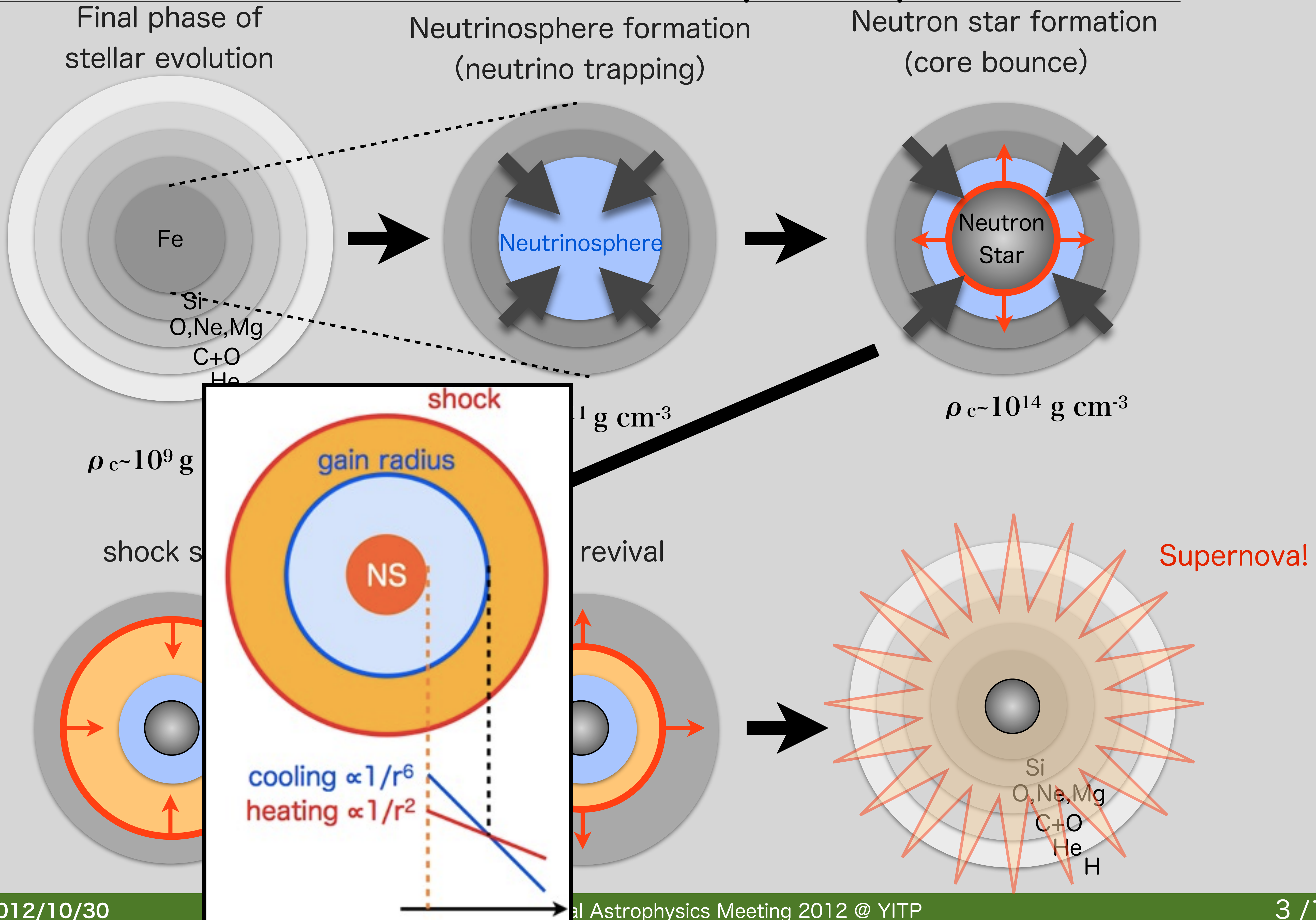

Systematics in supernova simulations

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

* Dimensionality of hydrodynamics — Iwakami+ 08, Nordhaus+ 10, Hanke+ 11, Takiwaki+ 12
* 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
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  * progenitor structure (mixing, wind...)
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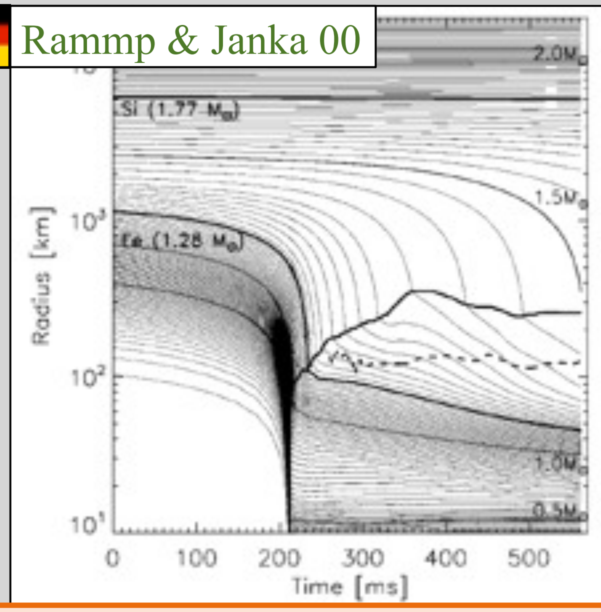
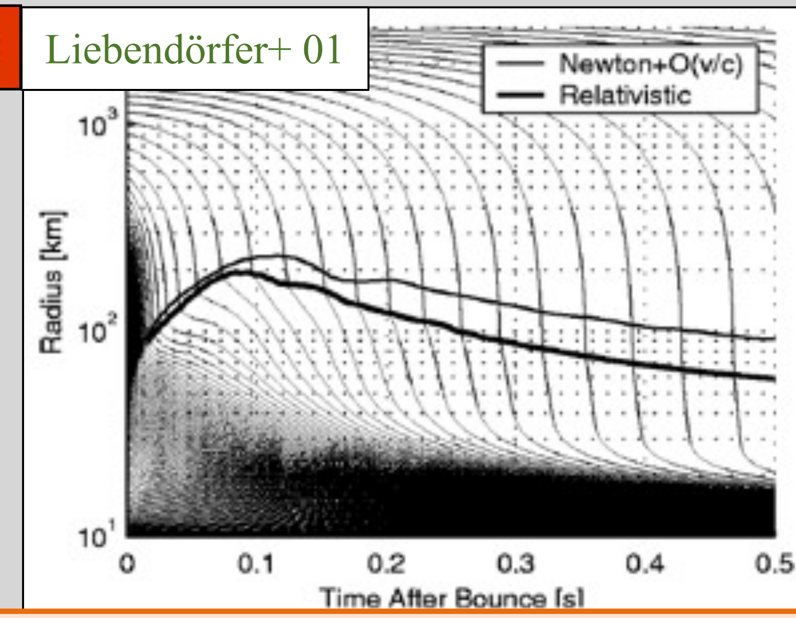
1D simulations: fail to explode

Rammp & Janka 00



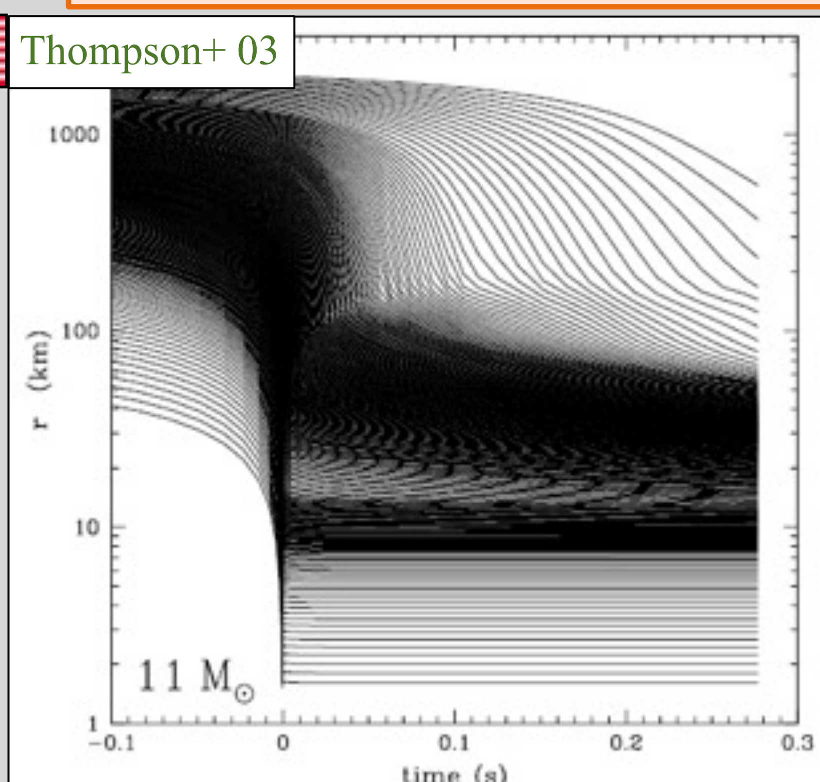
Liebendörfer+ 01



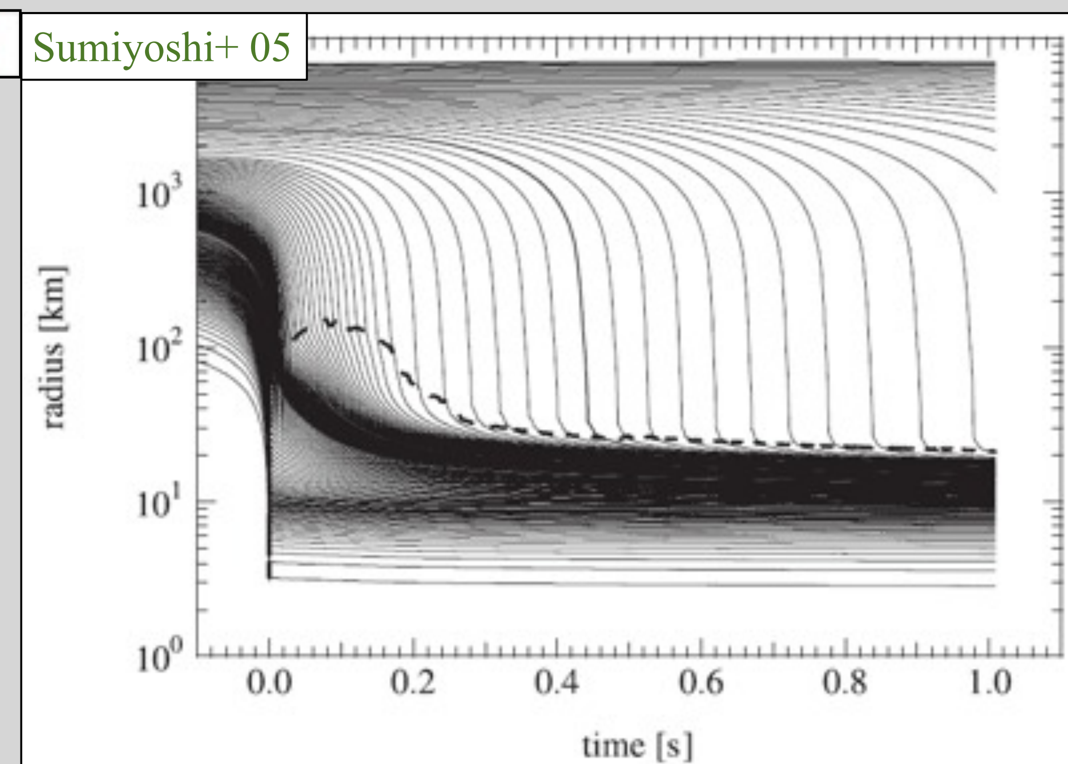
By including all available physics to simulations, we concluded that the explosion cannot be obtained in 1D!

(The exception is an 8.8 $M_\odot$ star; Kitaura+ 06)

Thompson+ 03



Sumiyoshi+ 05



Numerical simulation

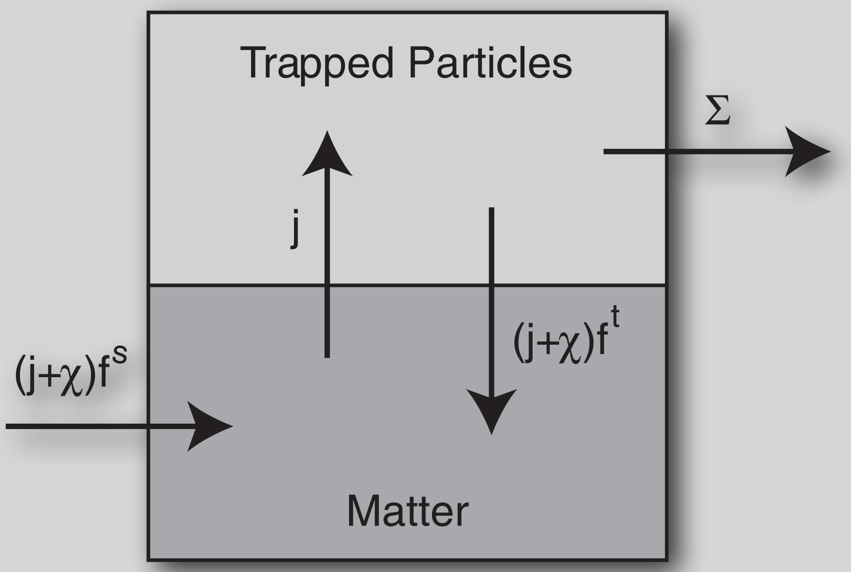
* Axisymmetric simulation (ZEUS-2D; Stone & Norman 92)

* 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)

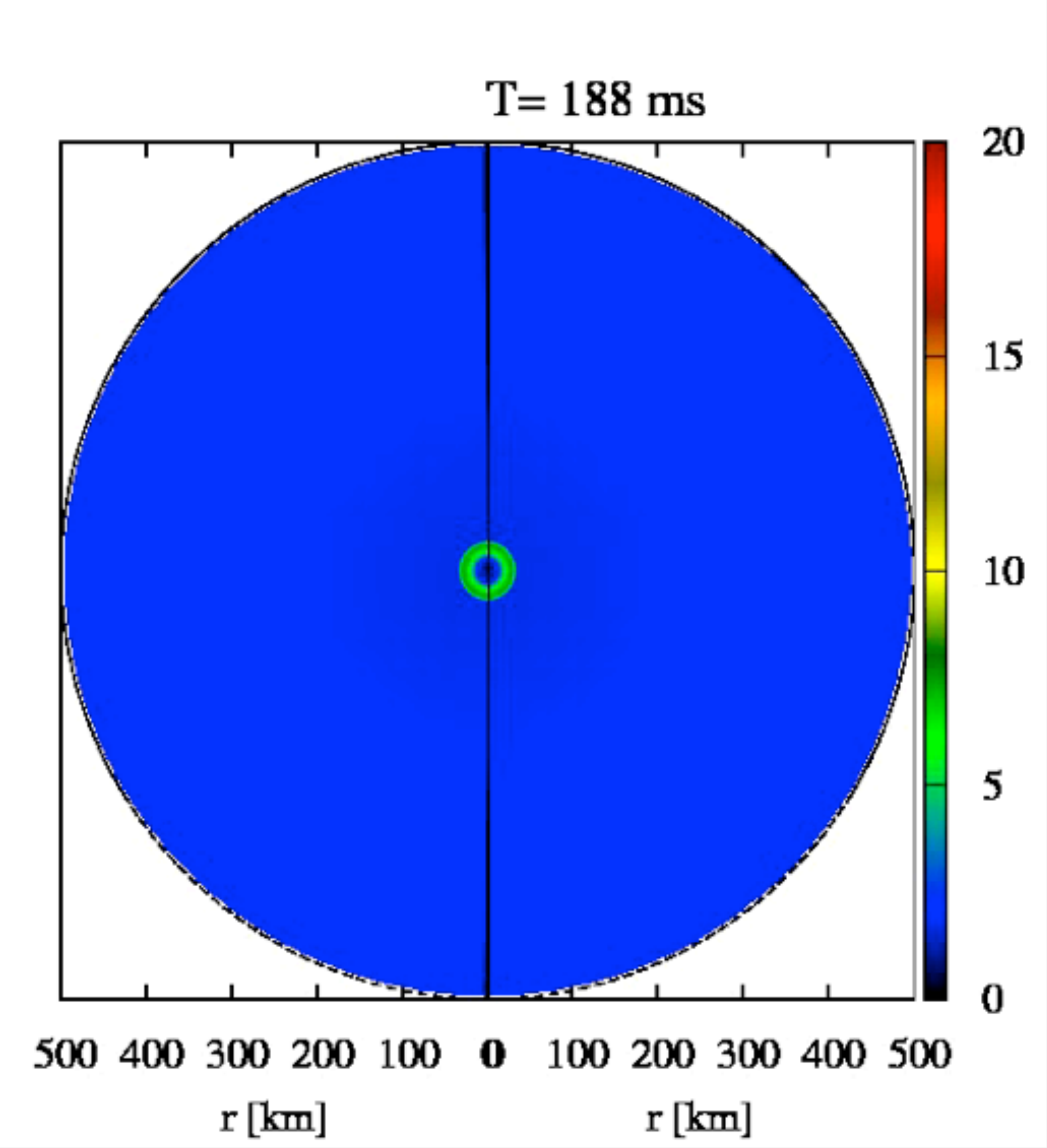
  - Isotropic Diffusion Source Approximation (Liebendörfer+ 09)
  - electron-type neutrino/antineutrino



Neutrino-driven explosion

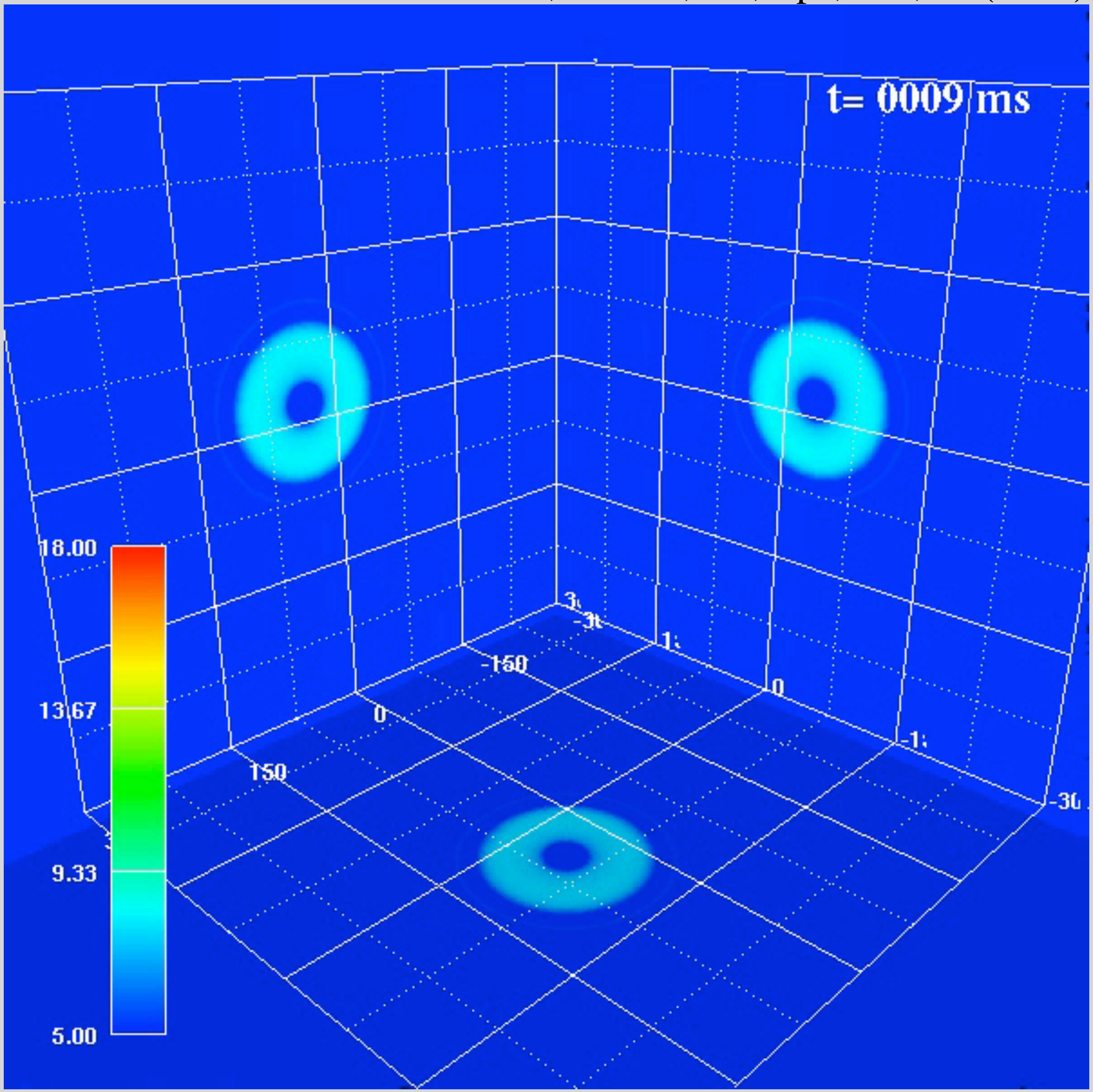
Recently, we have successful exploding models driven by neutrino heating

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



3D simulation with neutrino transfer

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



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

XT4@NAOJ

T2K-Tsukuba

K computer

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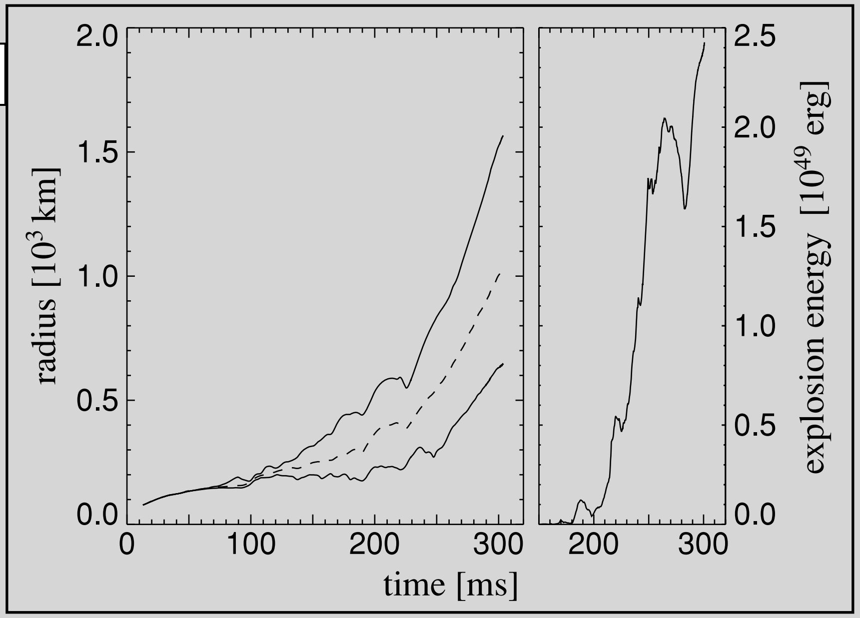
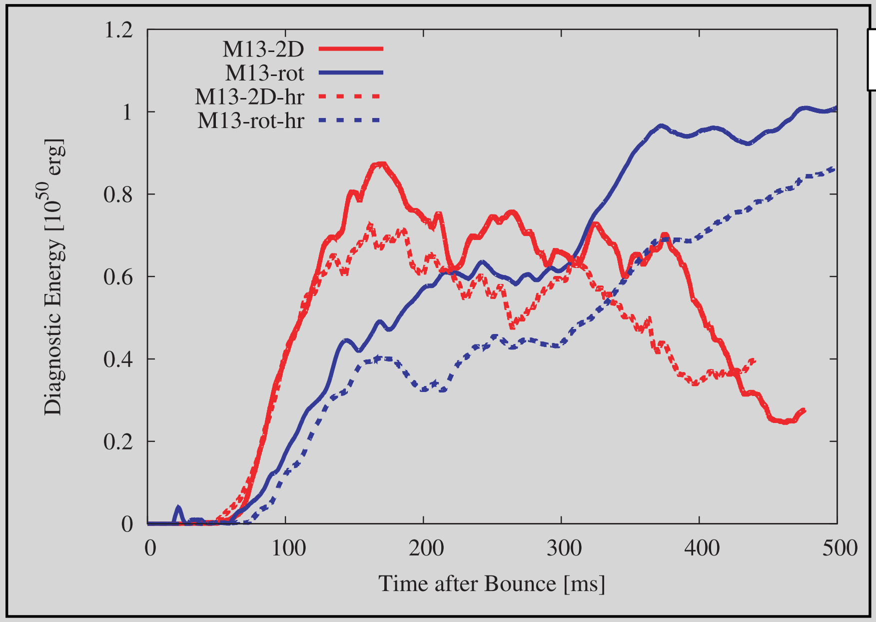
Problems of multi-D explosoins

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

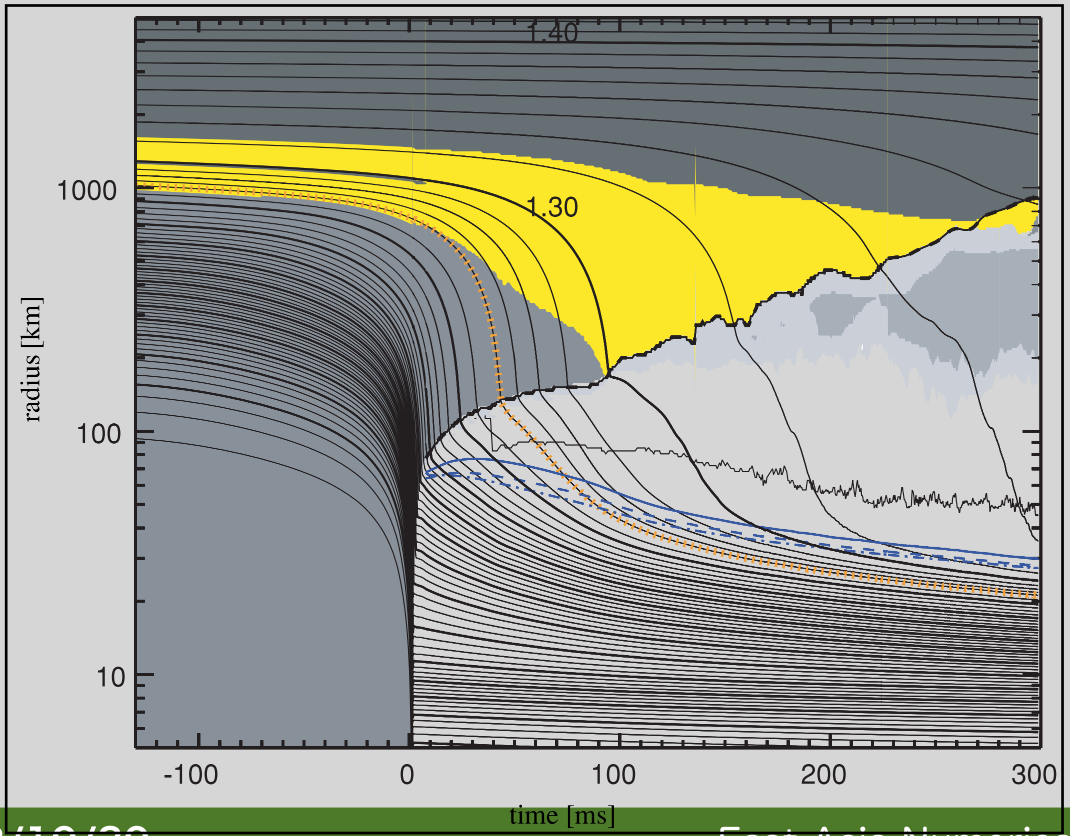
Marek & Janka 09

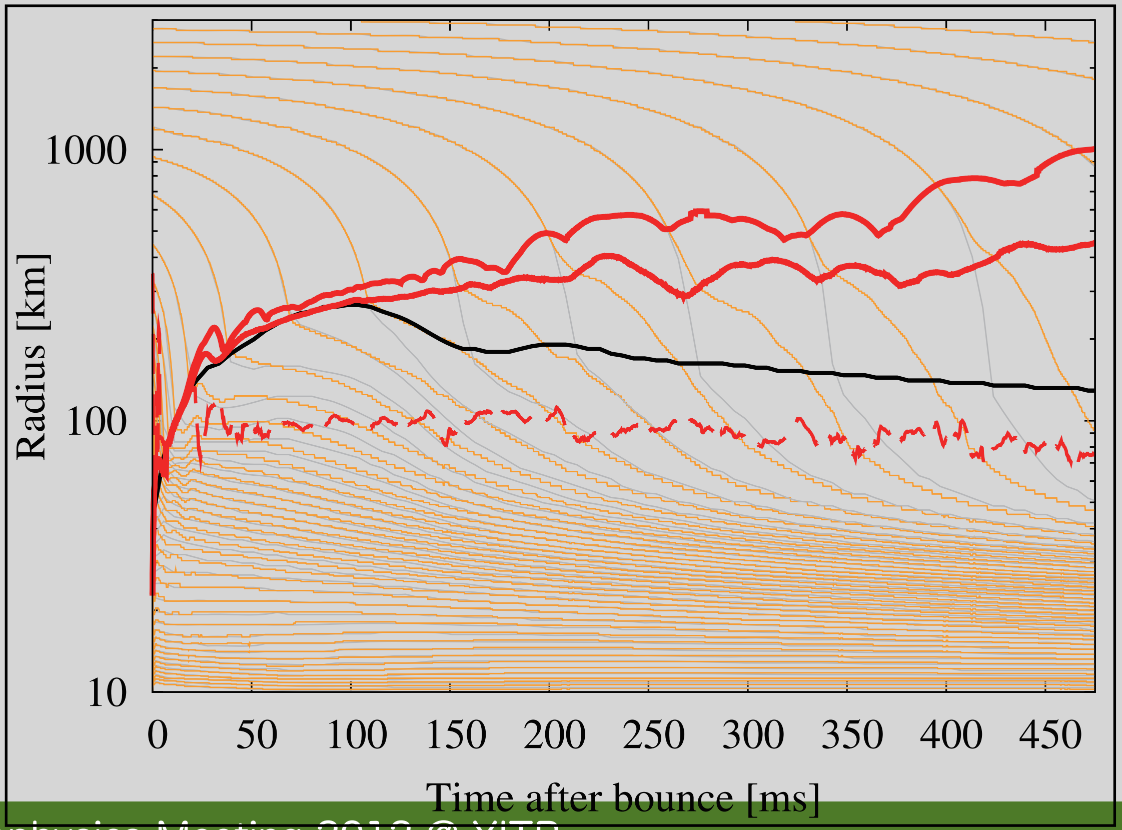




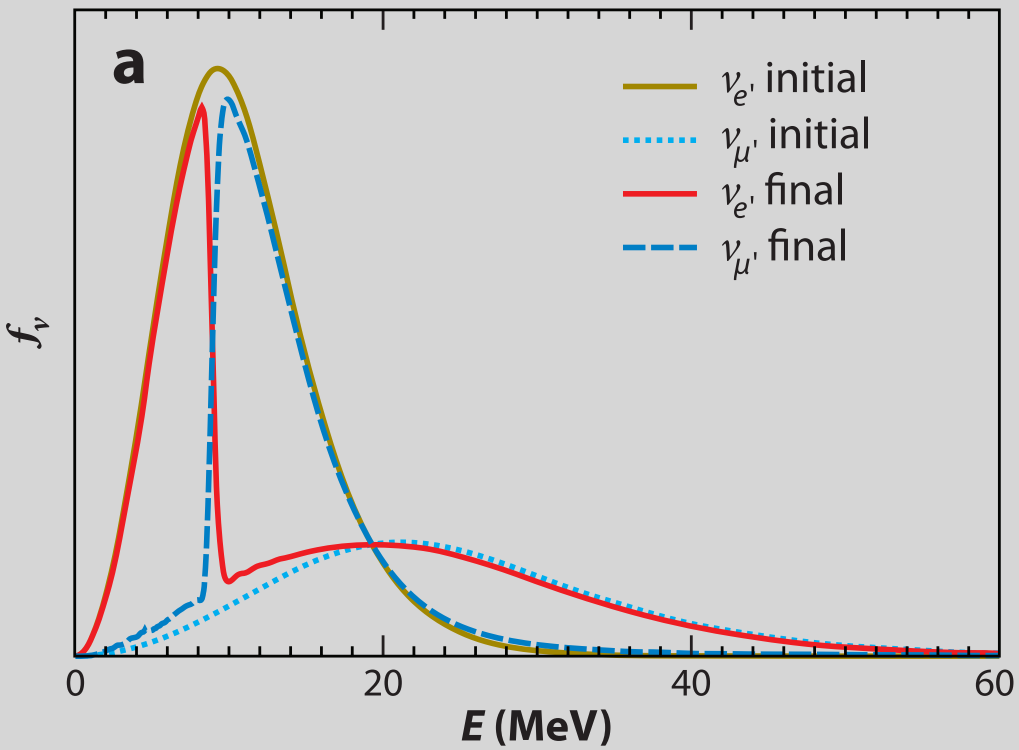
Suwa+ 10

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



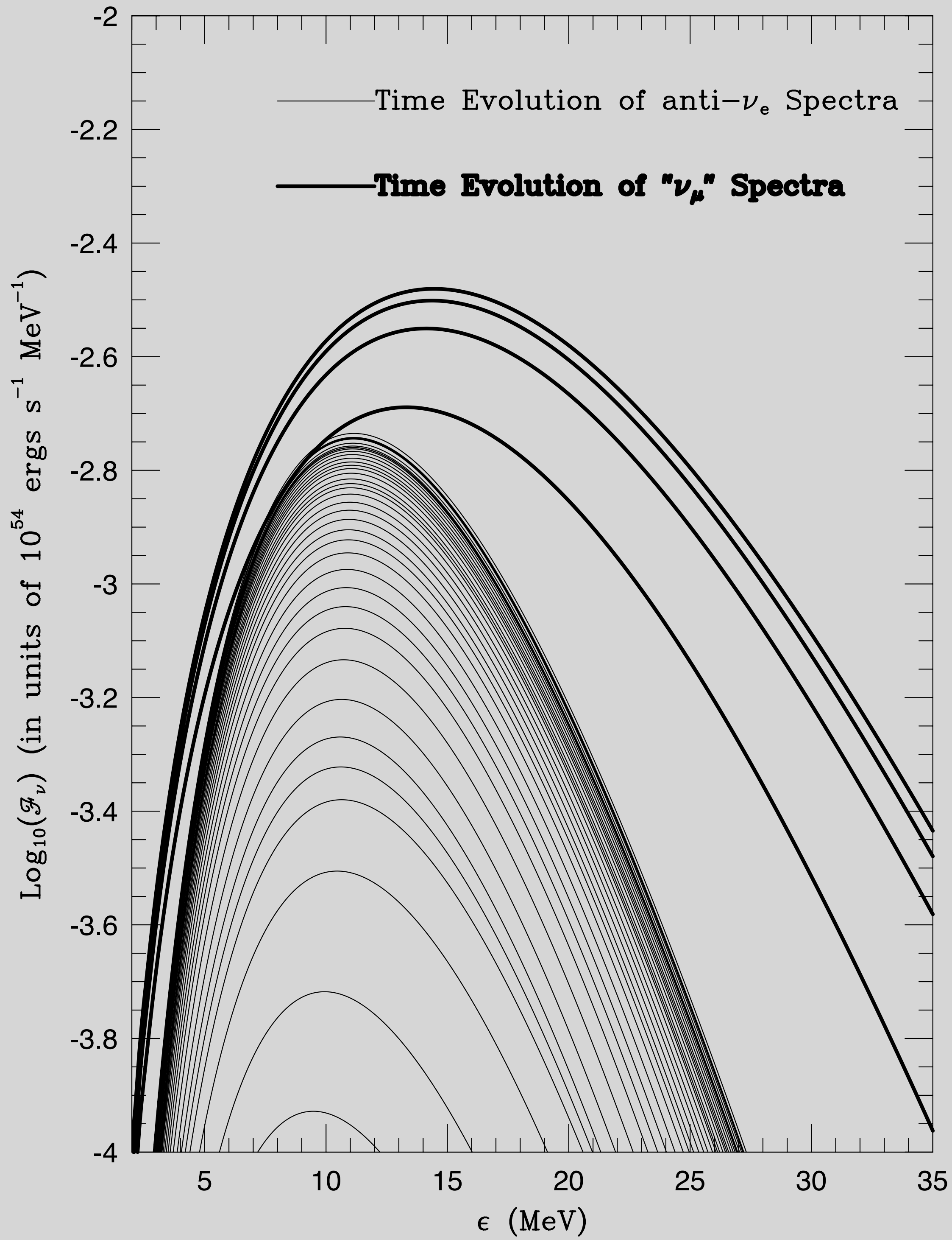


A possibility: the collective oscillation of neutrinos



Duan+ 10

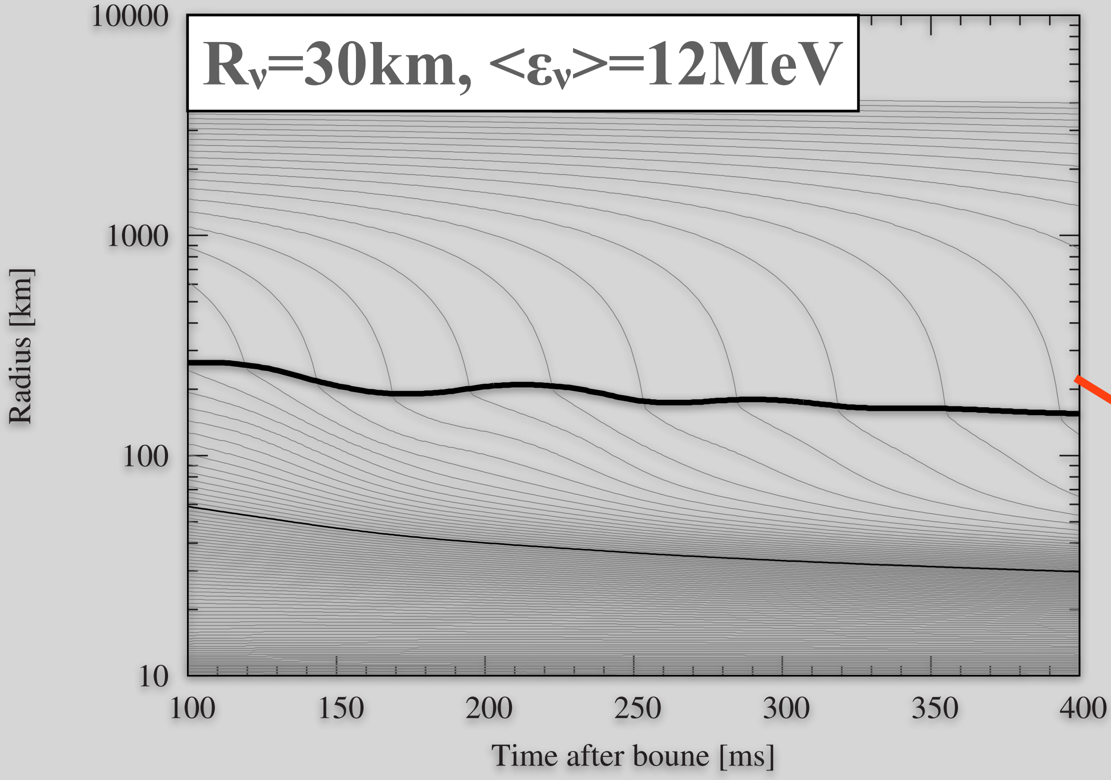
Burrows & Thompson 02

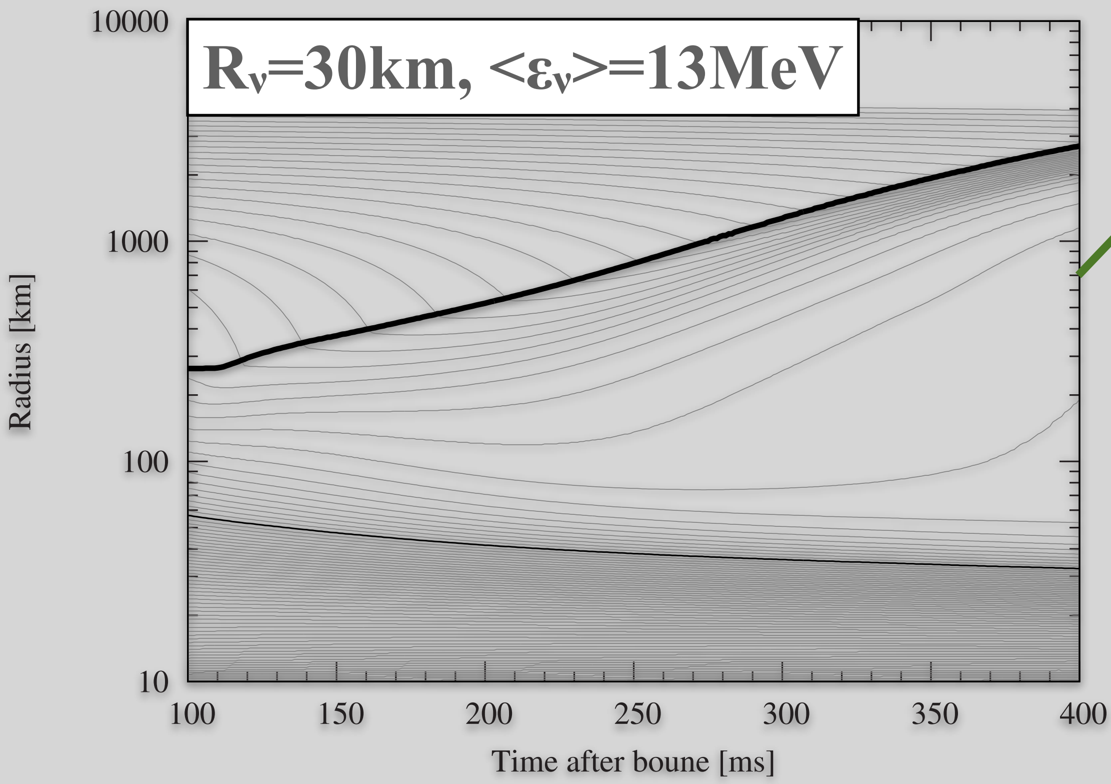


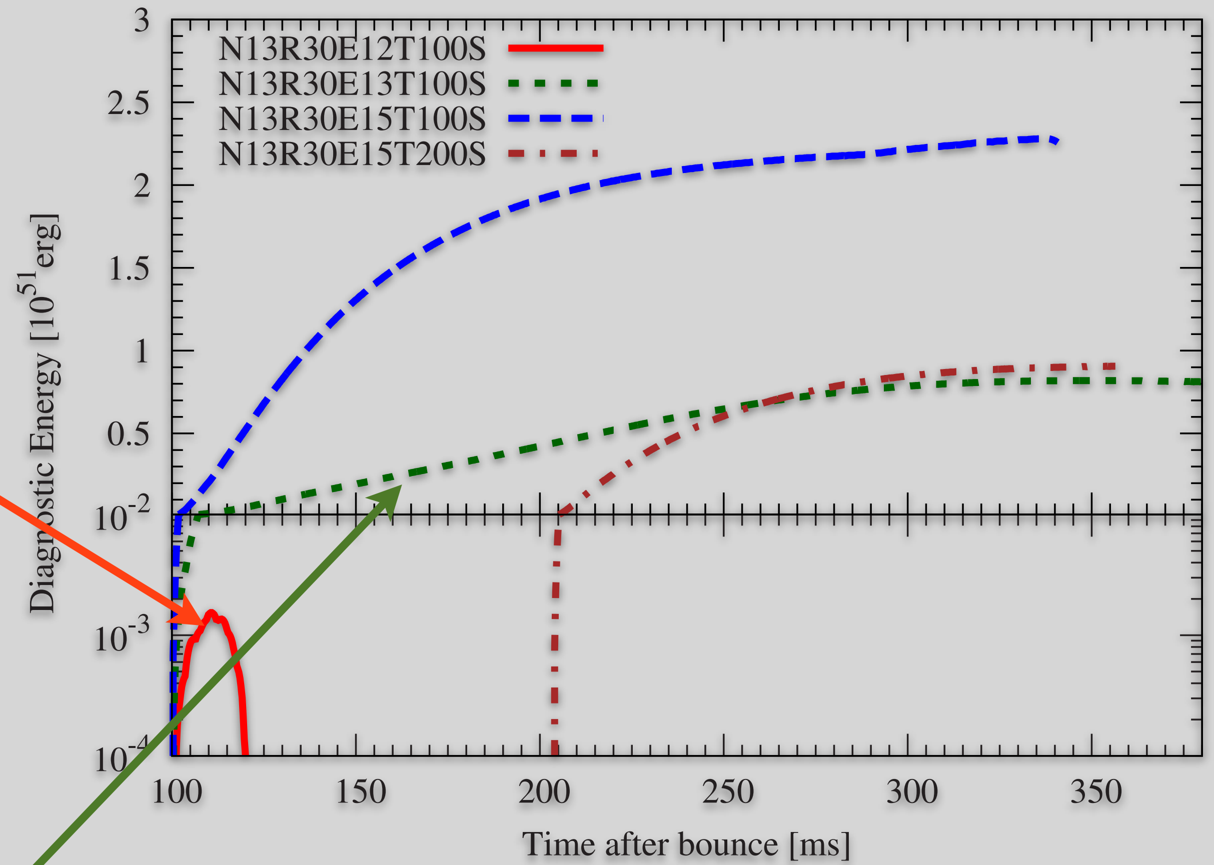
- Because of the mass of neutrinos, the flavor oscillates in propagation
- The spectrum can be different at the emission and absorption site.
- **Especially, $\nu_{\mu/\tau} \to \nu_e$ is important**
  - Reaction rate: $\sigma \propto E^2$
  - Average energy: $\nu_{\mu/\tau} > \nu_e$

Collective oscillation

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







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

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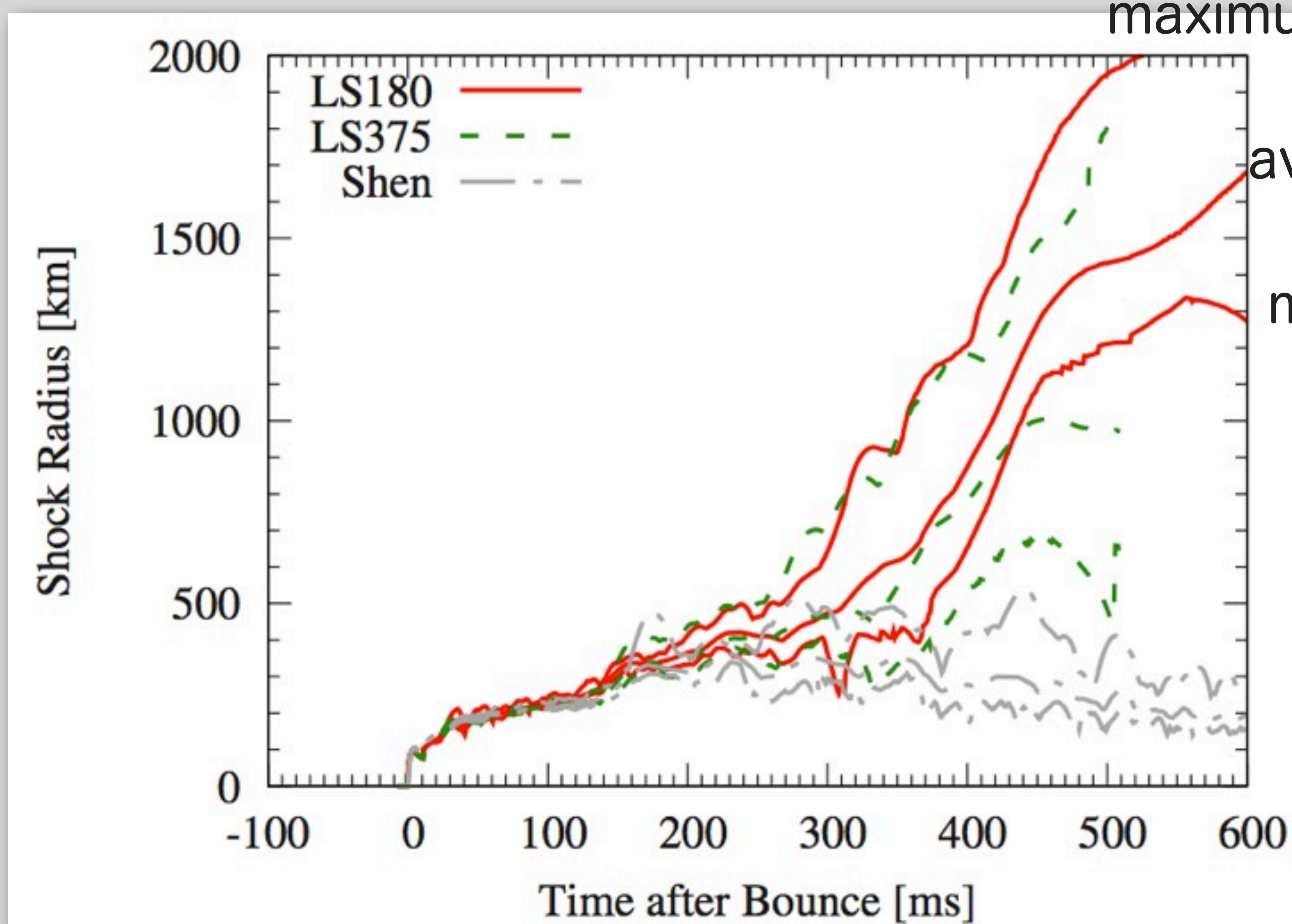
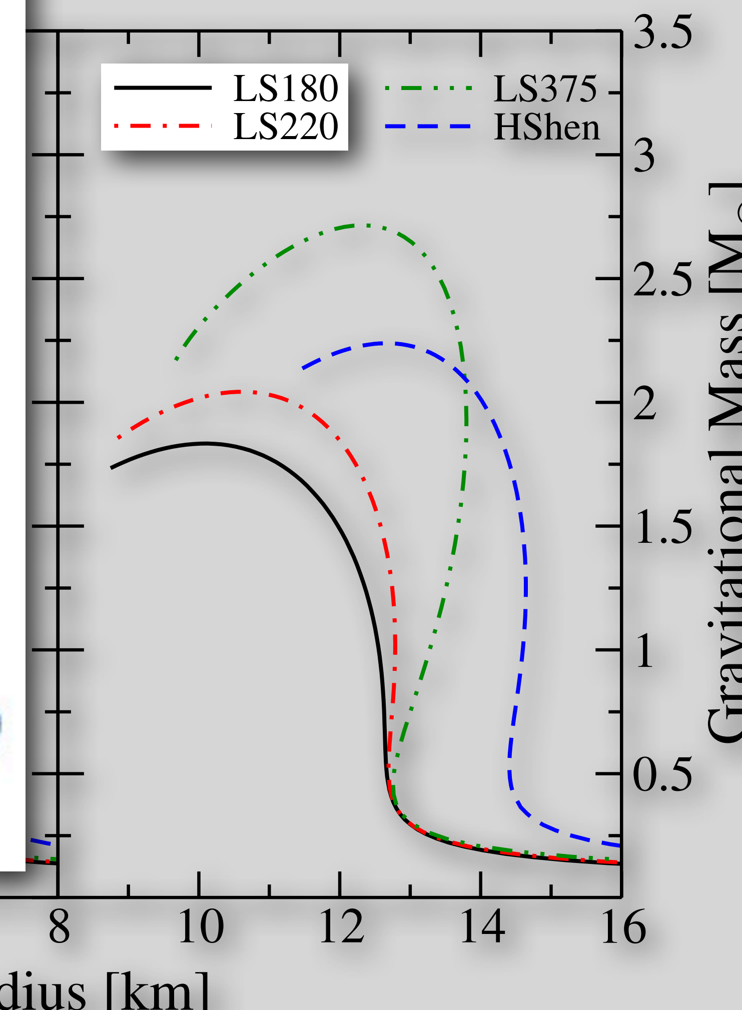
Shock radius

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





O'Connor & Ott 10

LS180 and LS375 succeed the explosion

Shen EOS fails

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
    * Effect of neutrino oscillation
    * Impacts of nuclear equation of state

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