Explosion Mechanism of Core-Collapse Supernovae

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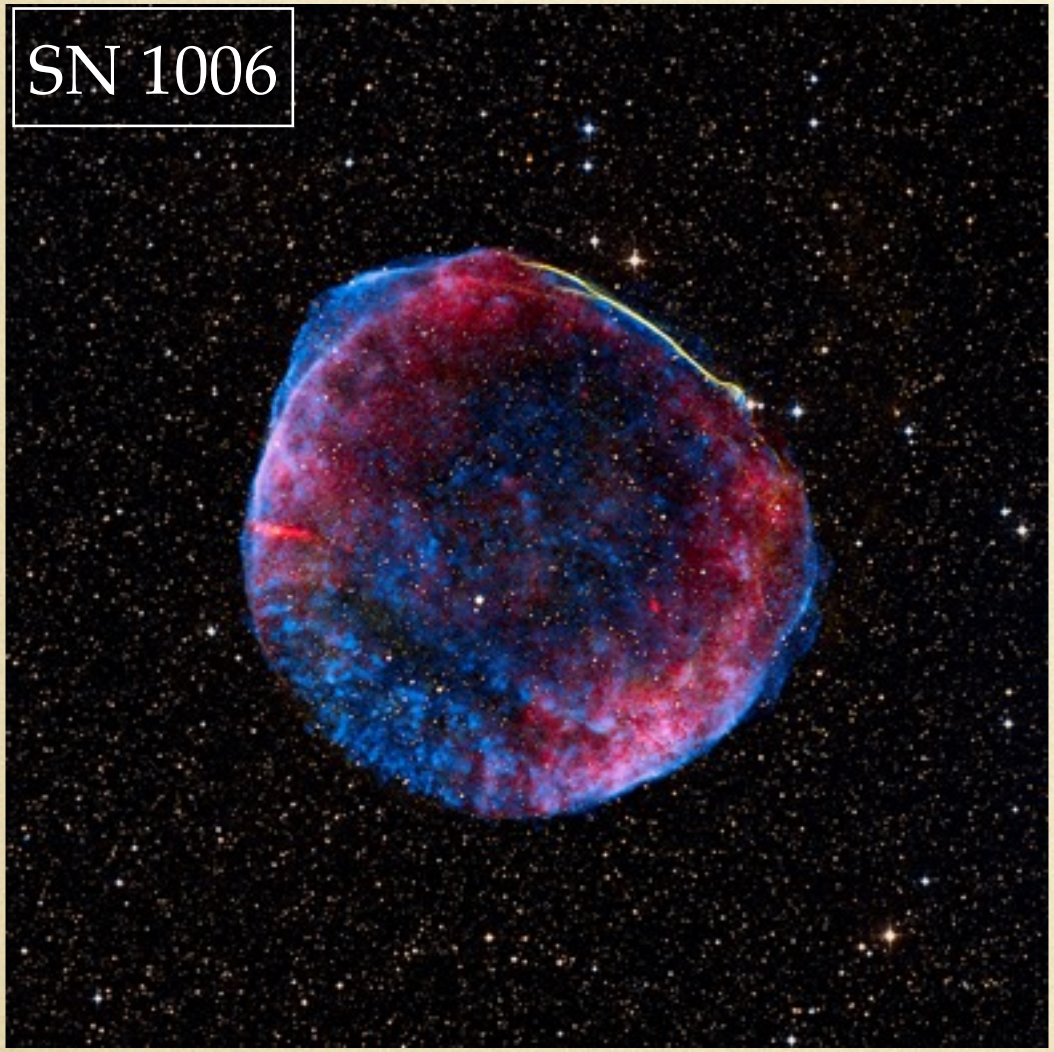
Observations of Supernovae



- ✓ There are lots of observations of supernovae (SNe) from ancient times to today.

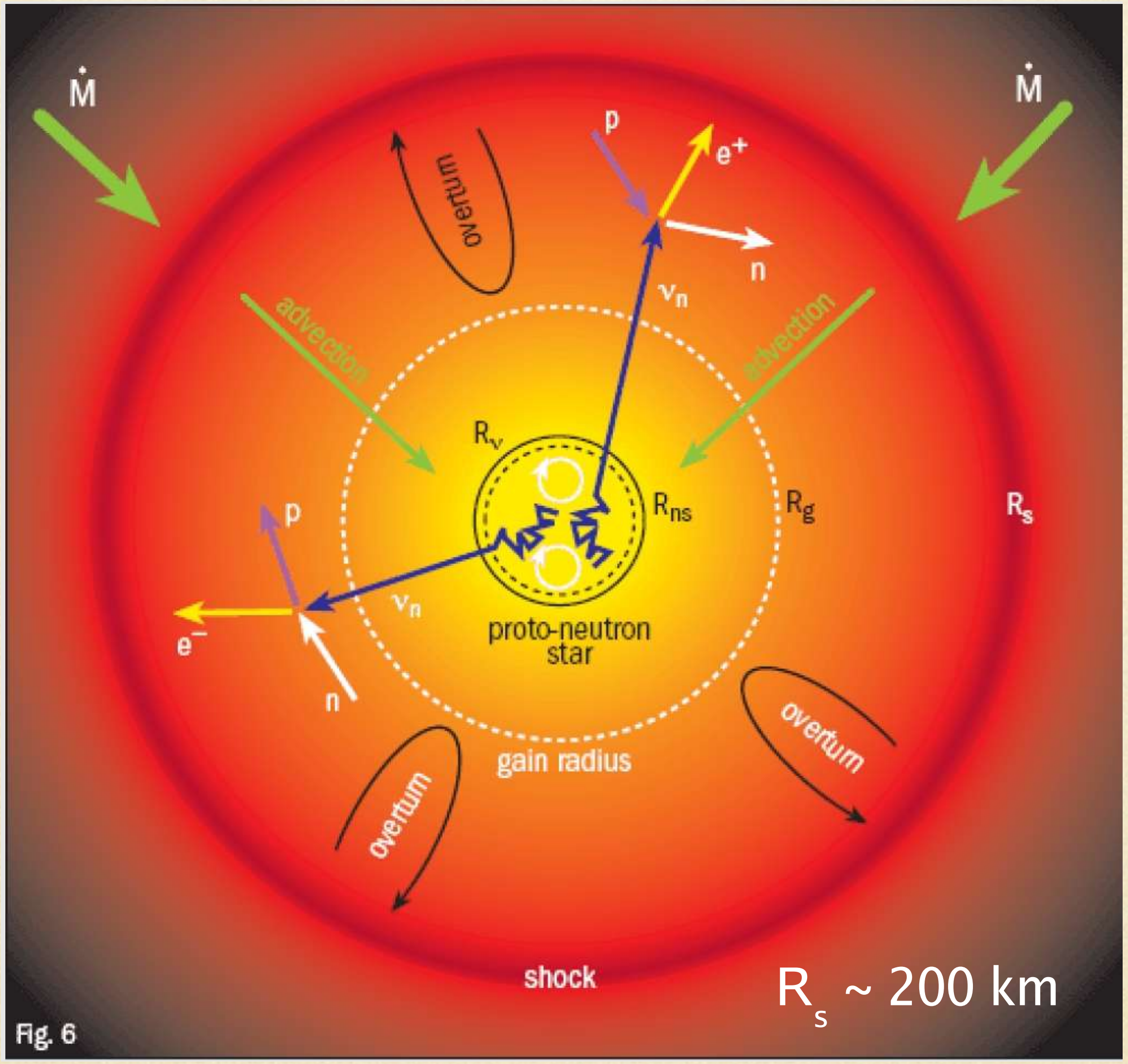
- ✓ The oldest observational record of Supernova (SN 1006) in Japan is left in 明月記 (Meigetsu-ki) written by 藤原定家 (Teika Fujiwara)

  (The oldest in the world is SN185 in 後漢書)

Core-Collapse Supernovae

- One of the most violent 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
- NS/BH formation
- association with Gamma-Ray Bursts
- All four interactions are important!
  - Macrophysics
    - ★gravitation
      - core collapse
    - ★electro-magnetic field
      - pulsar, magnetar
      - magnetorotational explosion
  - Microphysics
    - ★weak interaction
      - neutrino emission / absorption
    - ★nuclear physics
      - equation of state of dense matter

Neutrinos and Explosion mechanism



Neutrino-heating mechanism

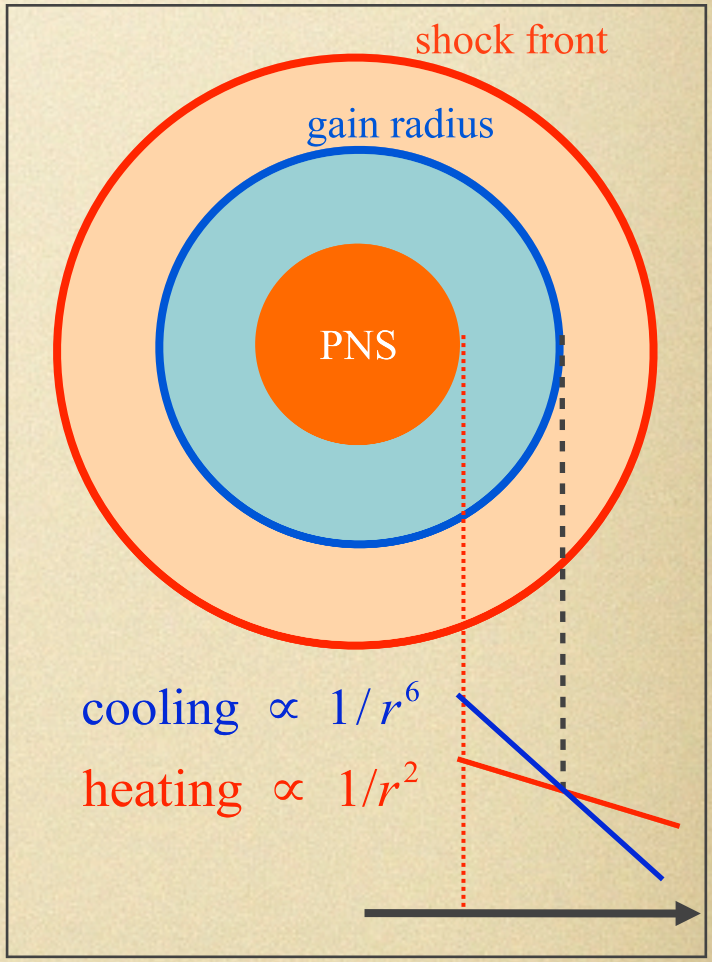
Neutrinos *revive* the stalled prompt shock by energy deposition through neutrino capture and scattering

Convective overturn and Standing Accretion Shock Instability (SASI)

are essentially multi-dimensional effects and play important roles for explosion

Neutrino-heating mechanism

- neutrino cooling (electron capture) rate: $Q_\nu^- \propto T^6 \propto r^{-6}$
- neutrino heating (neutrino capture) rate: $Q_\nu^+ \propto L_\nu r^{-2} \propto r^{-2}$



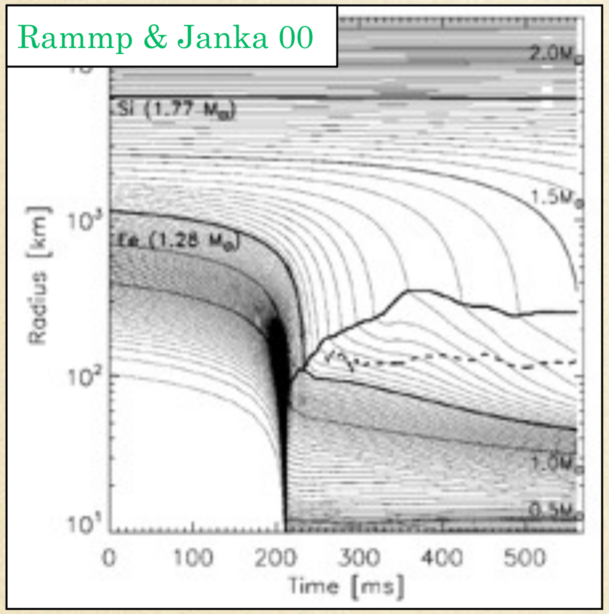
- gain radius: $Q_\nu^- = Q_\nu^+$
- heating between gain radius and shock:

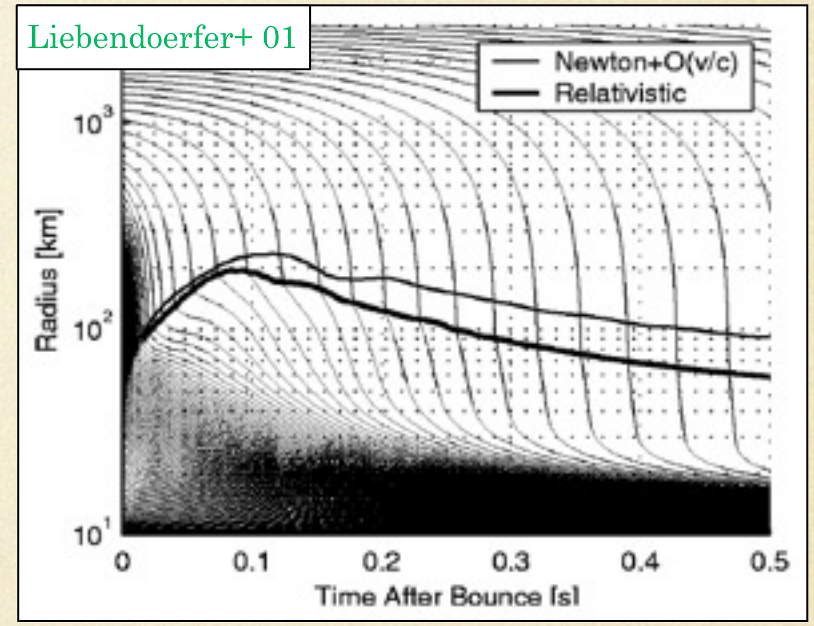
$$L_{\nu,\mathrm{heat}} \sim 3\times 10^{51}\mathrm{erg\ s^{-1}} \left(\frac{M}{0.1M_\odot}\right)\left(\frac{L_\nu}{10^{53}\mathrm{erg\ s^{-1}}}\right)\left(\frac{\langle\varepsilon^2\rangle}{(15\mathrm{MeV})^2}\right)\left(\frac{r}{200\mathrm{km}}\right)^{-2}$$

- shock revival by neutrino heating

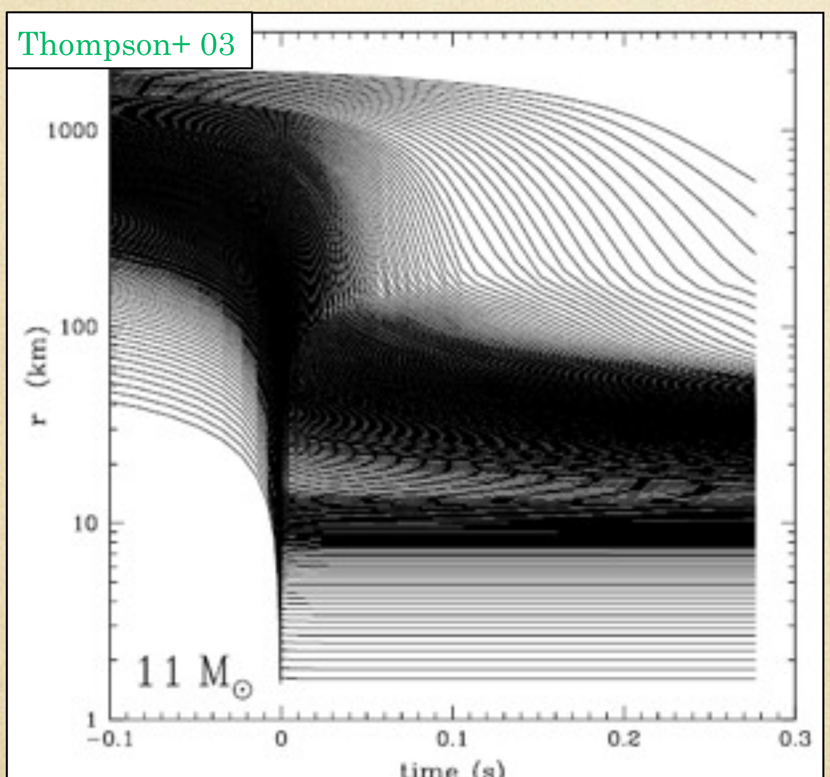
→ ***"delayed explosion"***

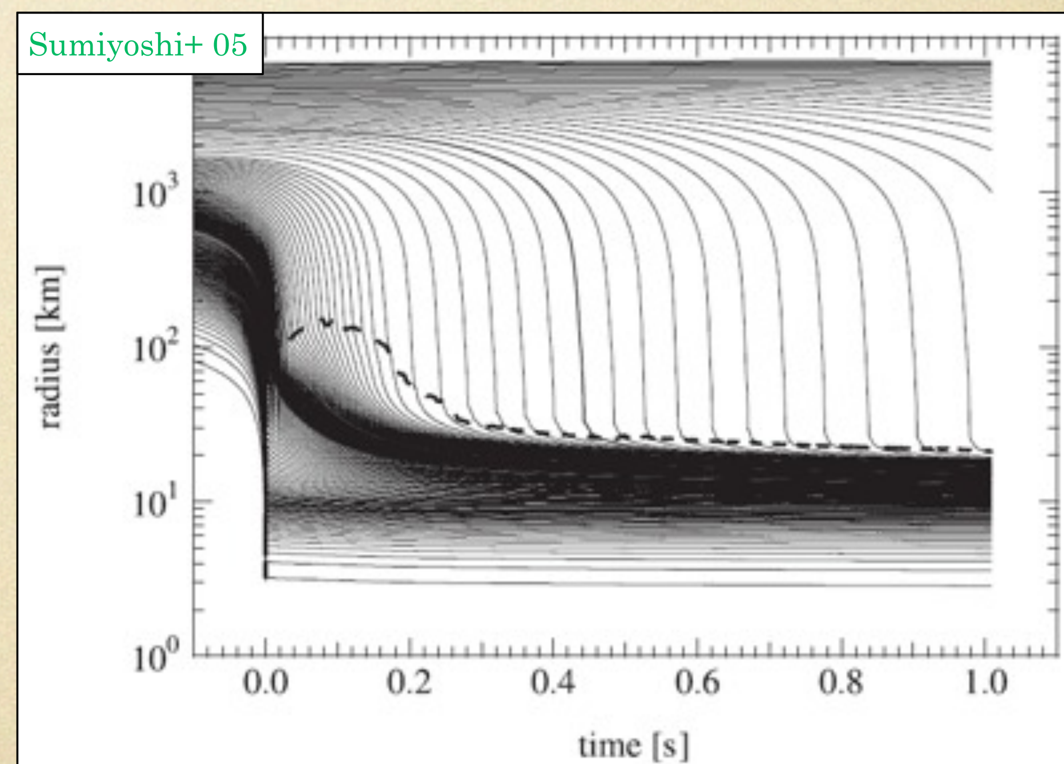
Current status of 1D





state-of-the-art simulations do not obtain explosion!

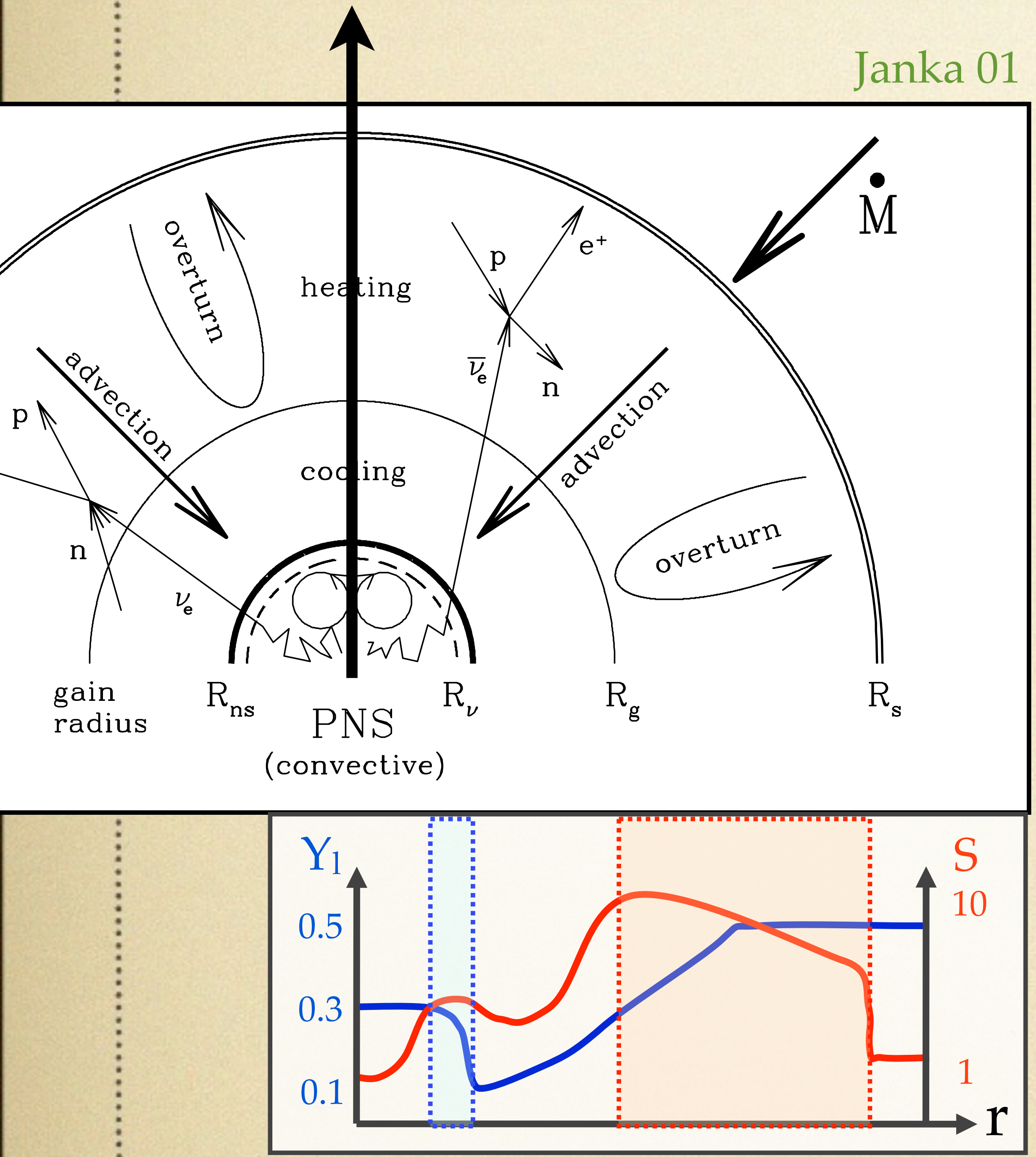




Importance of multi-D

- Observations suggest that almost all SN ejecta are asymmetric Wang+ 01,02; Maeda+ 08
- The central engine itself asymmetric?
- The multi-dimensional simulations are required
- What makes the core asymmetric?

Convectively unstable regions



- ❖ PNS convection
  - ✦ induced by negative Y_l gradient due to neutrino cooling
- ❖ Neutrino-driven convection
  - ✦ induced by negative entropy gradient due to neutrino heating

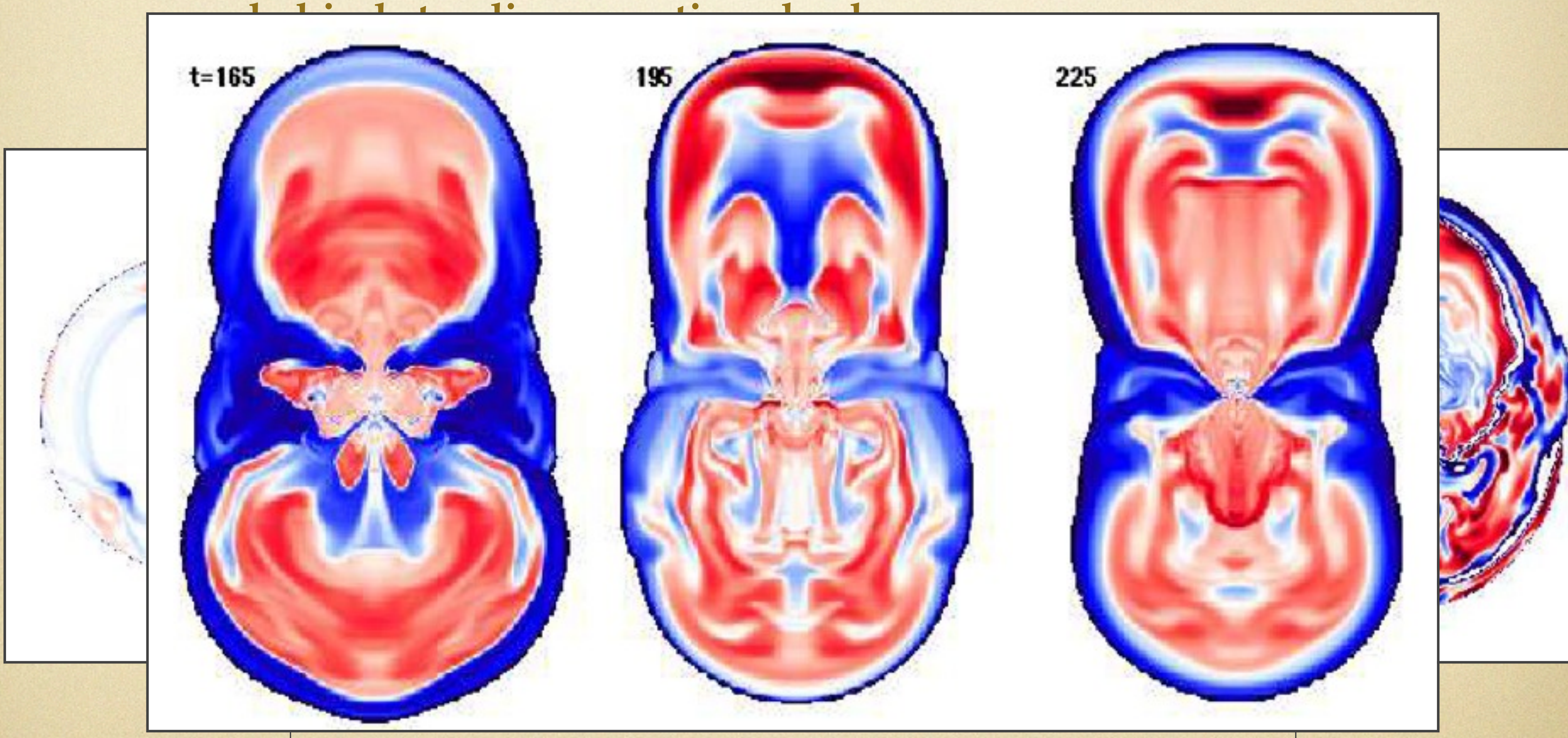
Ledoux criterion

$$\left(\frac{\partial\rho}{\partial s}\right)_{P,Y_l}\frac{dS}{dr}+\left(\frac{\partial\rho}{\partial Y_l}\right)_{P,S}\frac{dY_l}{dr}>0$$

unstable condition

SASI

- Standing Accretion Shock Instablity
  - Non-radial, non-local low-mode (*l=1,2*) instability of flow



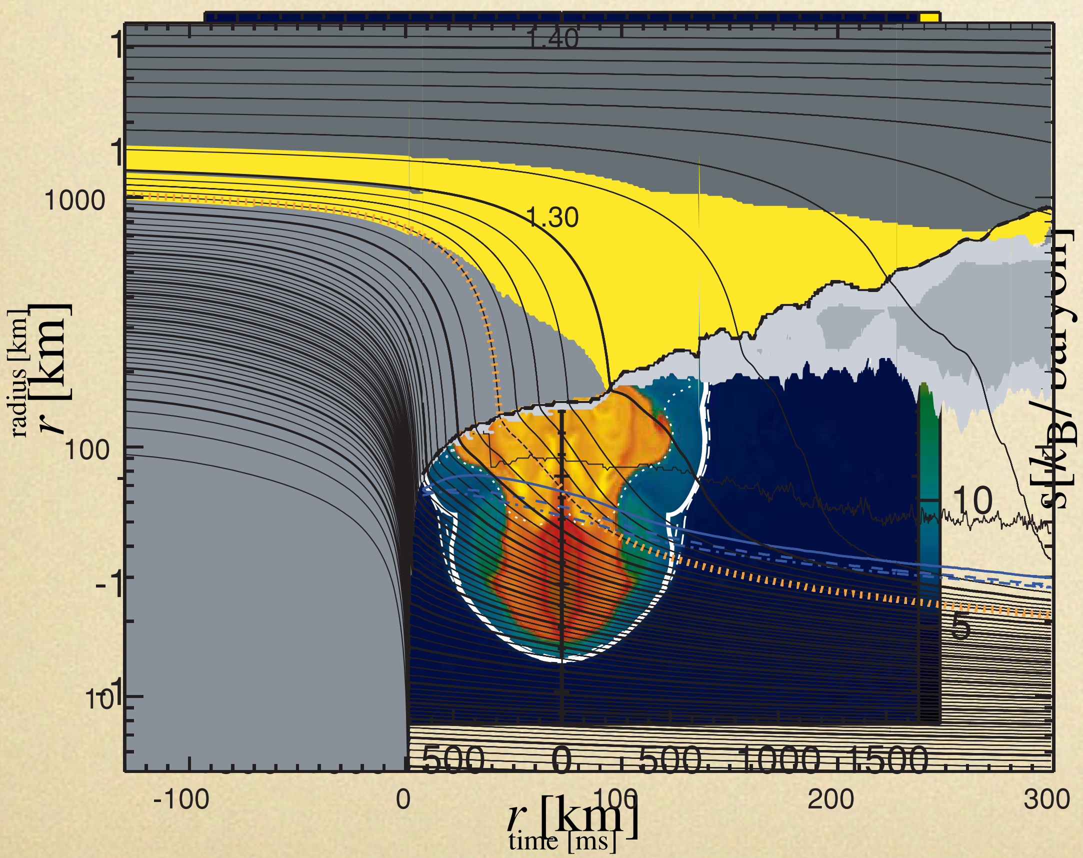
Bolondon+ 2003, 2006

SASI-aided SN explosion

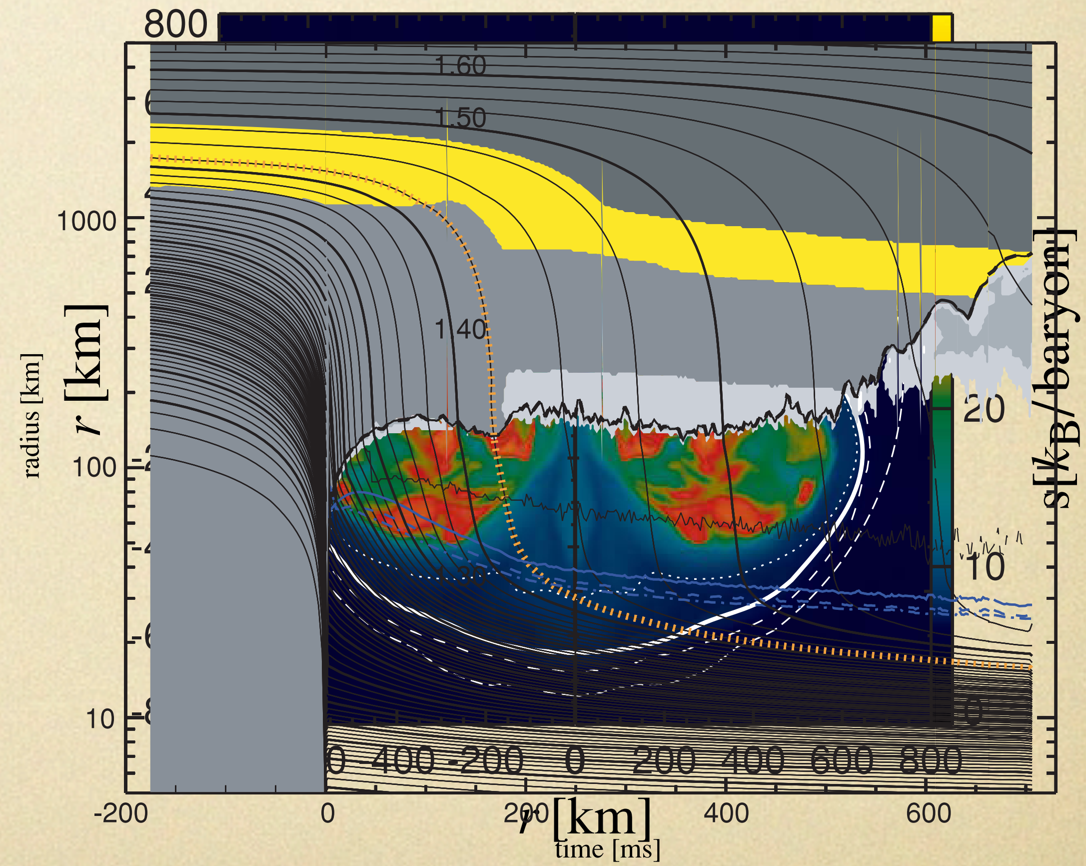
- SASI develops and deforms the accretion
  - ➡ The convection grows and leads larger neutrino-heating efficiency
  - ➡ Explosion!

Marek & Janka 2009

11.2 $M_\odot$



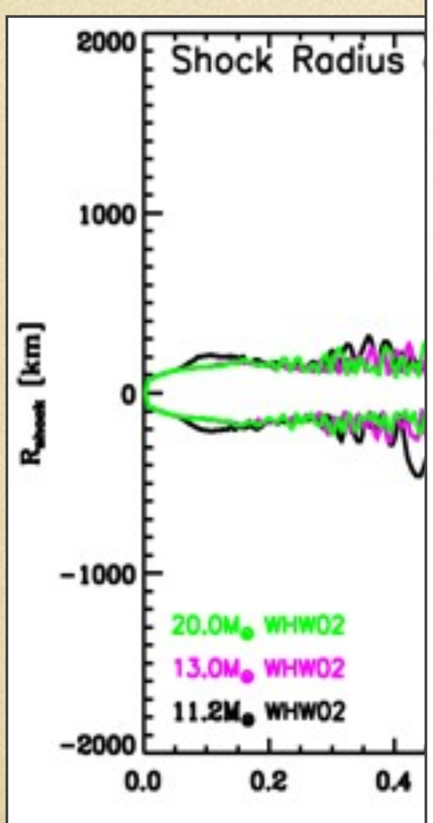
15 $M_\odot$

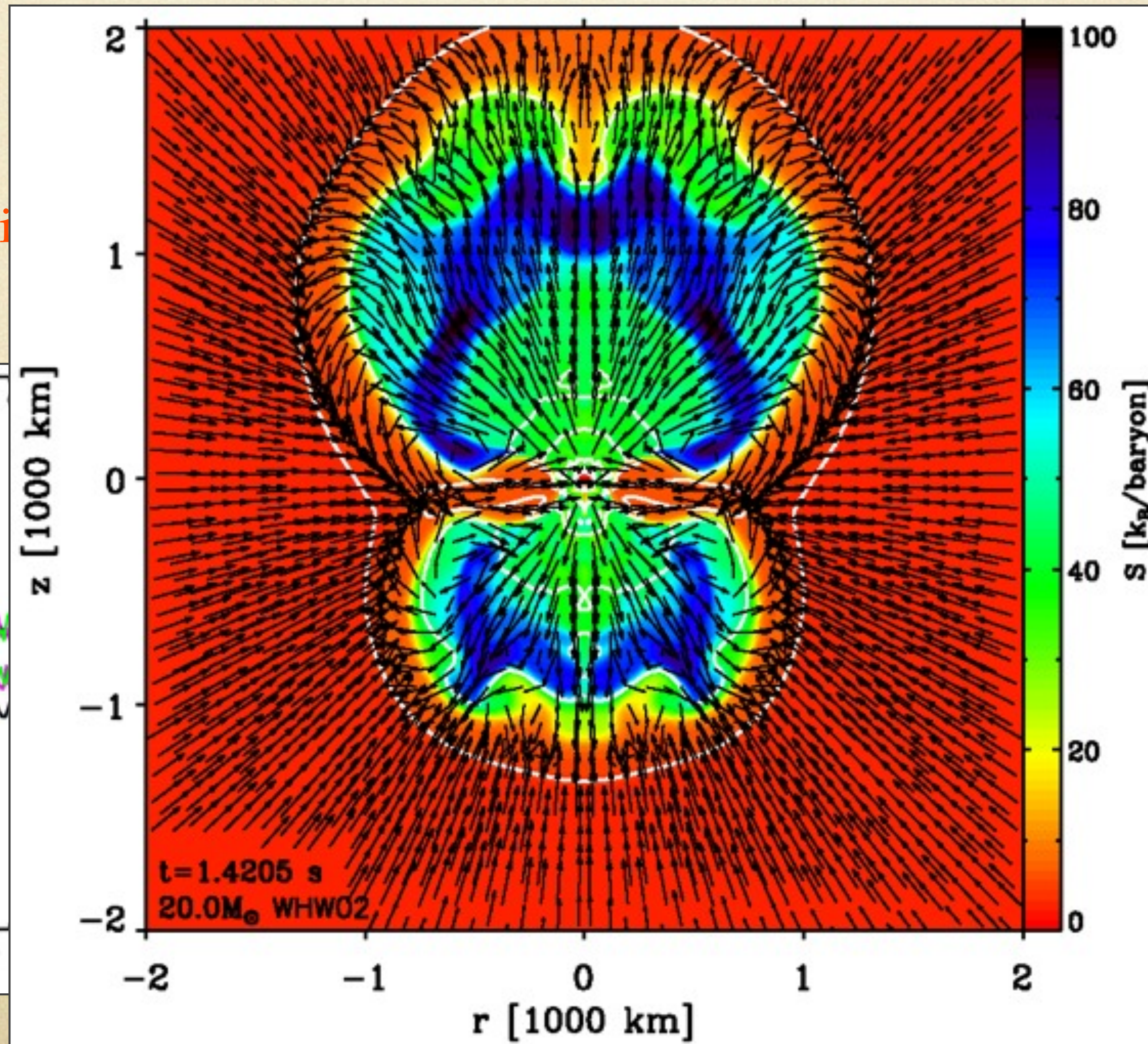


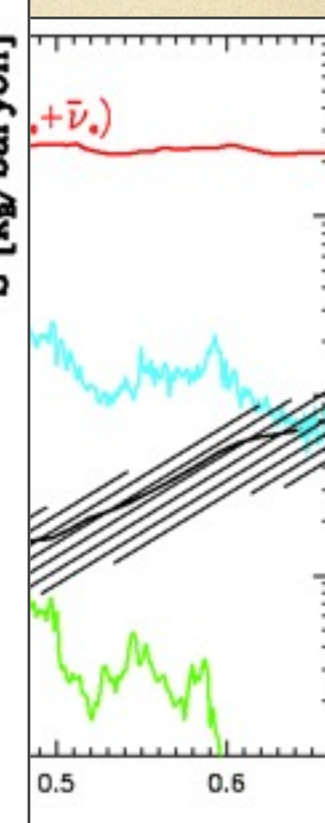
Acoustic mechanisms

(Burrows+ 06,07)

- PNS is excited to l=1 g-mode oscillation by non-spherical accretion
- Transfer … more efficient …
- Shock revi…



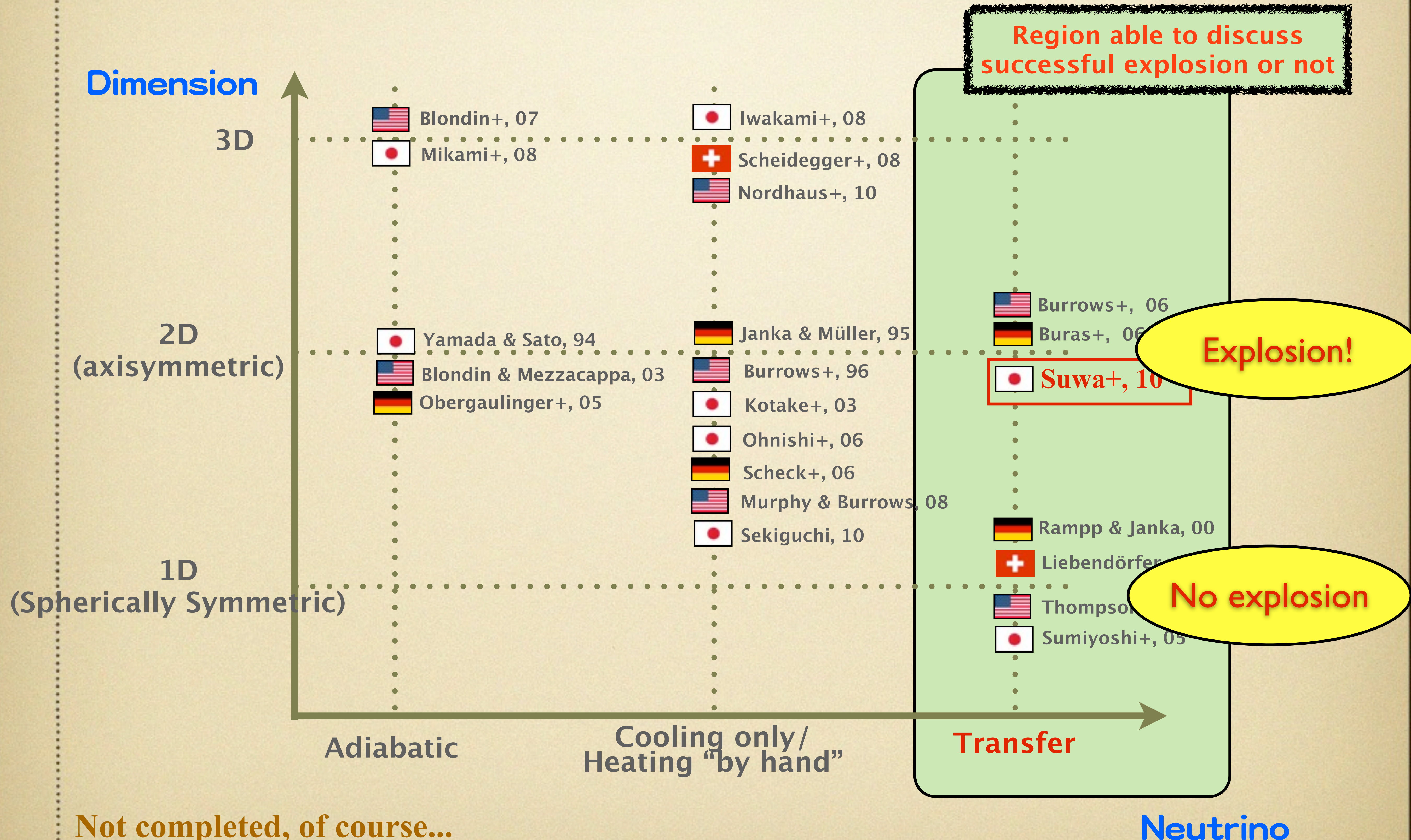




Summary of explosion mechanisms

- Neutrino-heating mechanism
  - "standard" scenario
  - only one group (@ ) obtain explosion
- Acoustic mechanism
  - Impedance mismatch between g-mode and SASI
  - takes longs time (~ 1sec) to be induced
  - only one group (@ ) obtain explosion

Current status of SN simulations



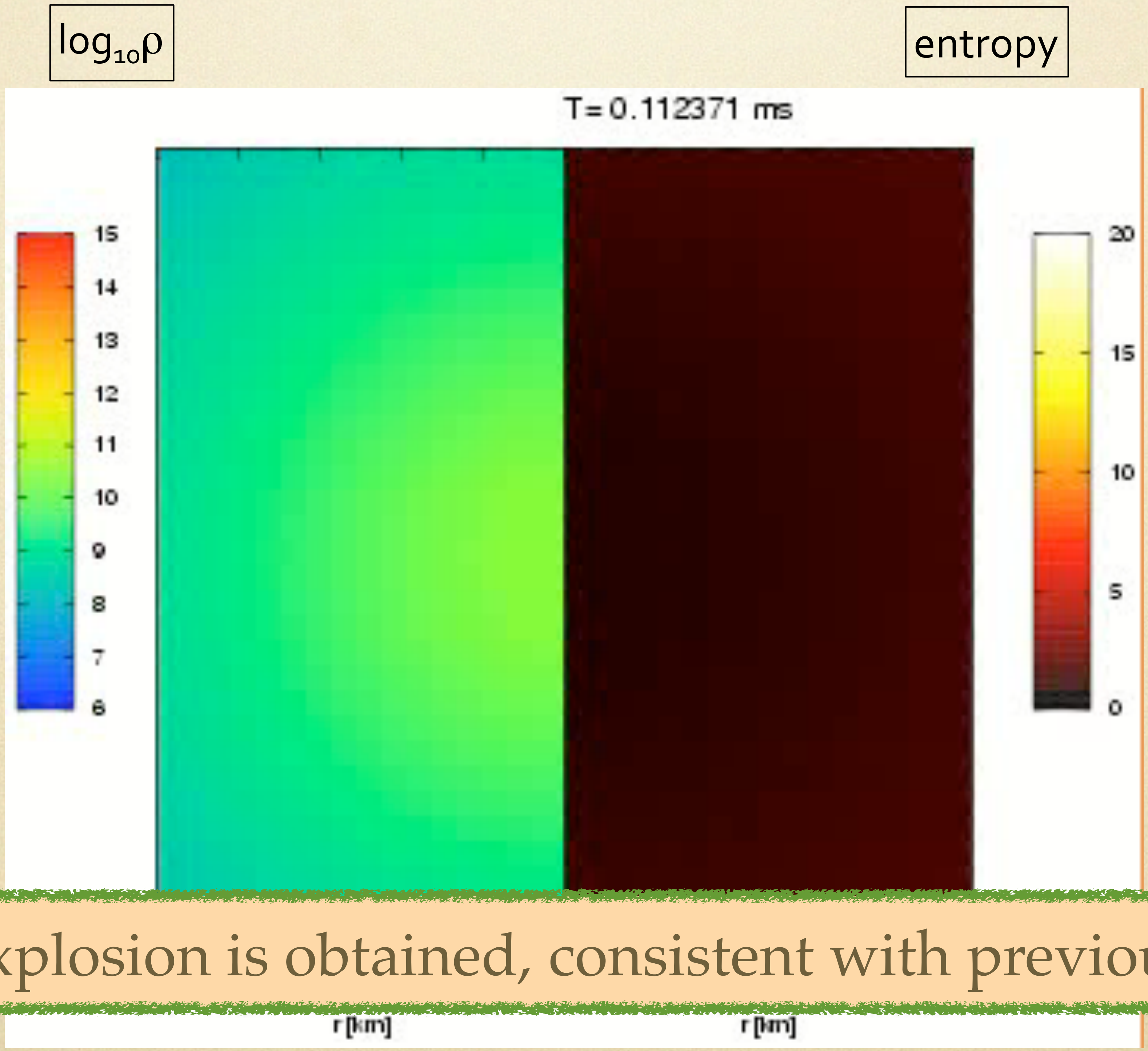
Not completed, of course...

Numerical simulation

- 2D hydrodynamics (ZEUS-2D) (Stone & Norman 92)
- Neutrino radiative transfer
  - Isotropic Diffusion Source Approximation (Liebendörfer+ 09)
  - electron-type neutrino and anti-neutrino (only charged current interactions are included)
- EOS: Lattimer & Swesty (K=180MeV)
- Progenitor: 13 $M_\odot$ (Nomoto+ 88)

Simulation Result

Spherically symmetric case

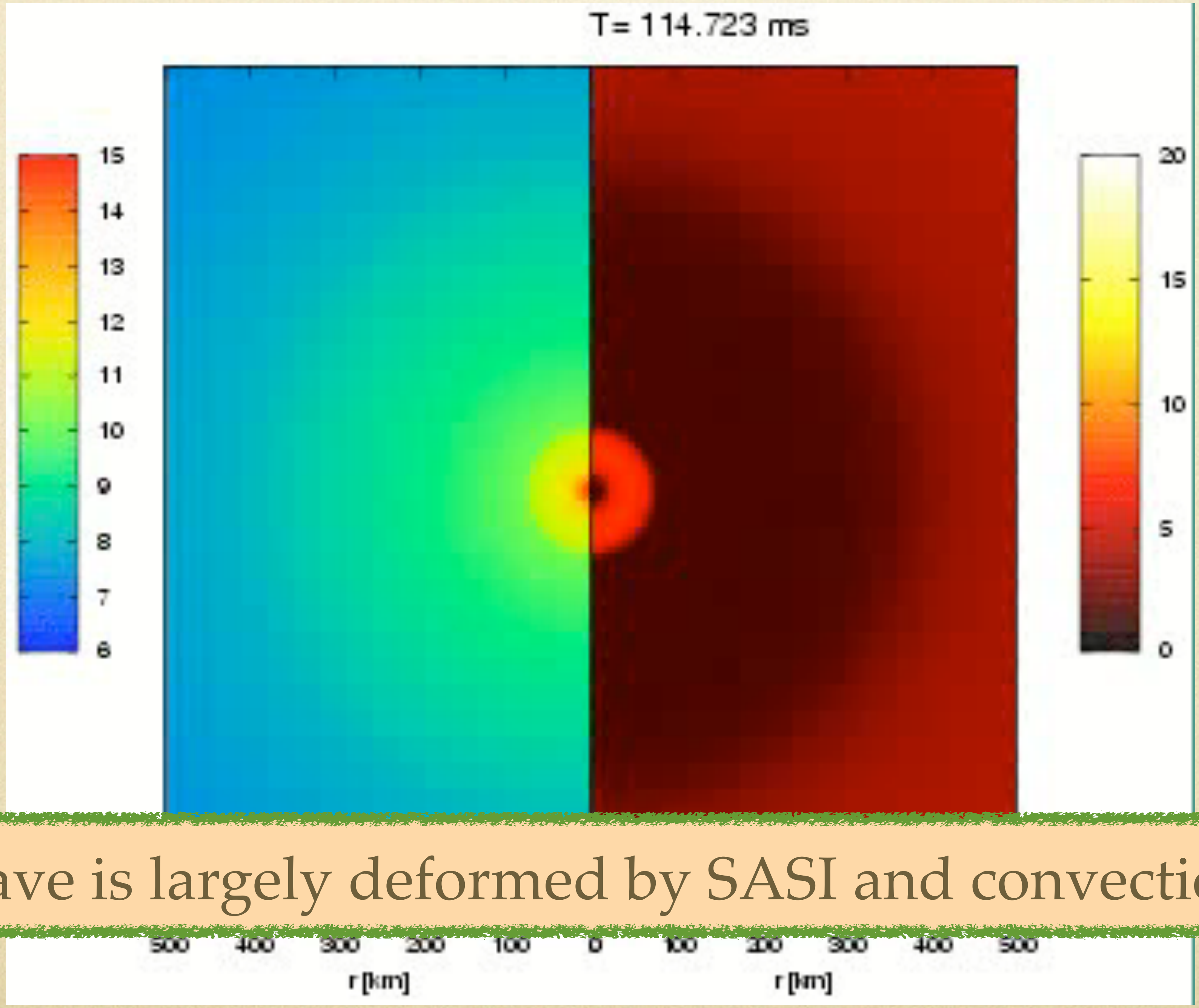


No explosion is obtained, consistent with previous works.

Simulation Result

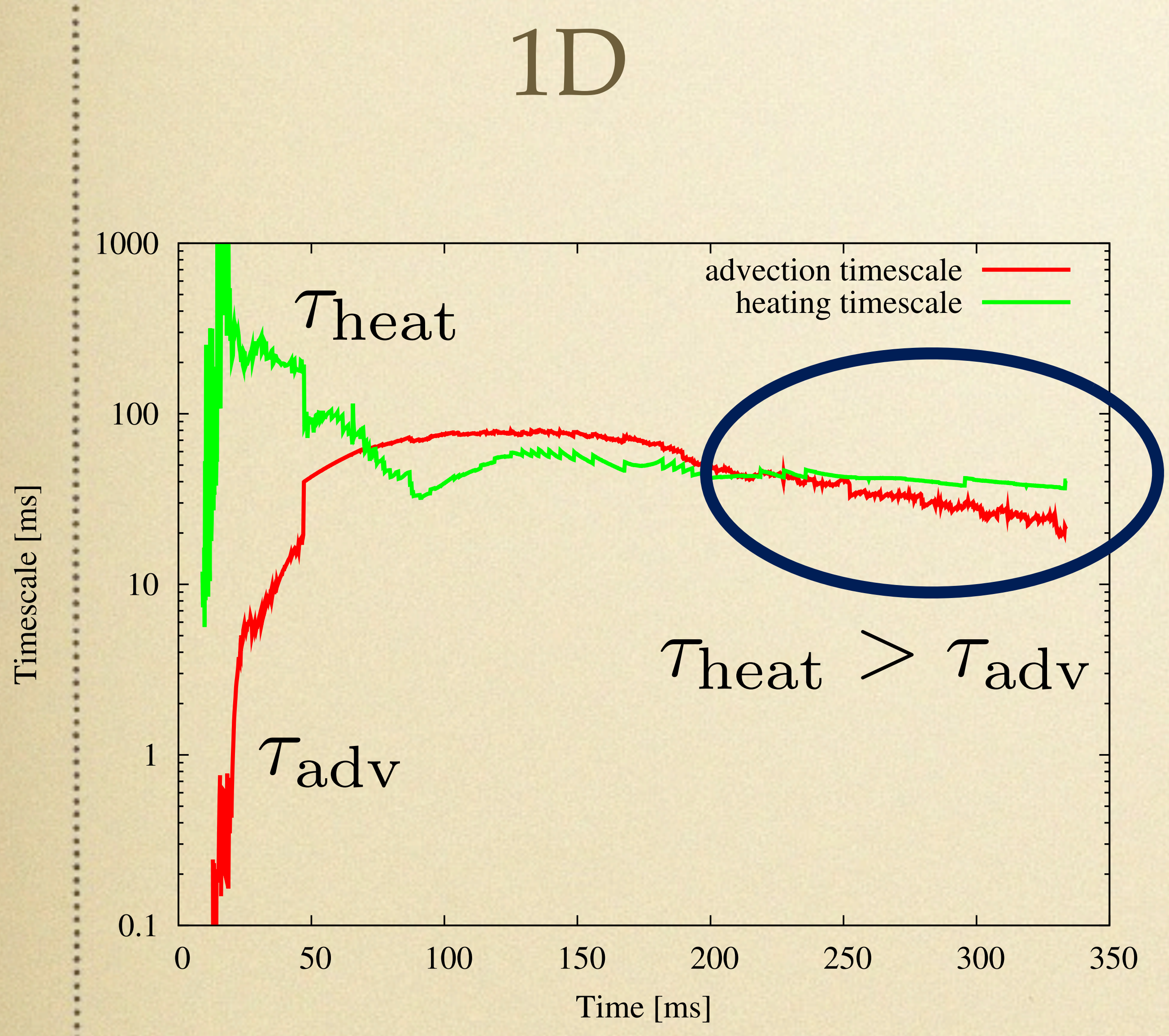
Axisymmetric case

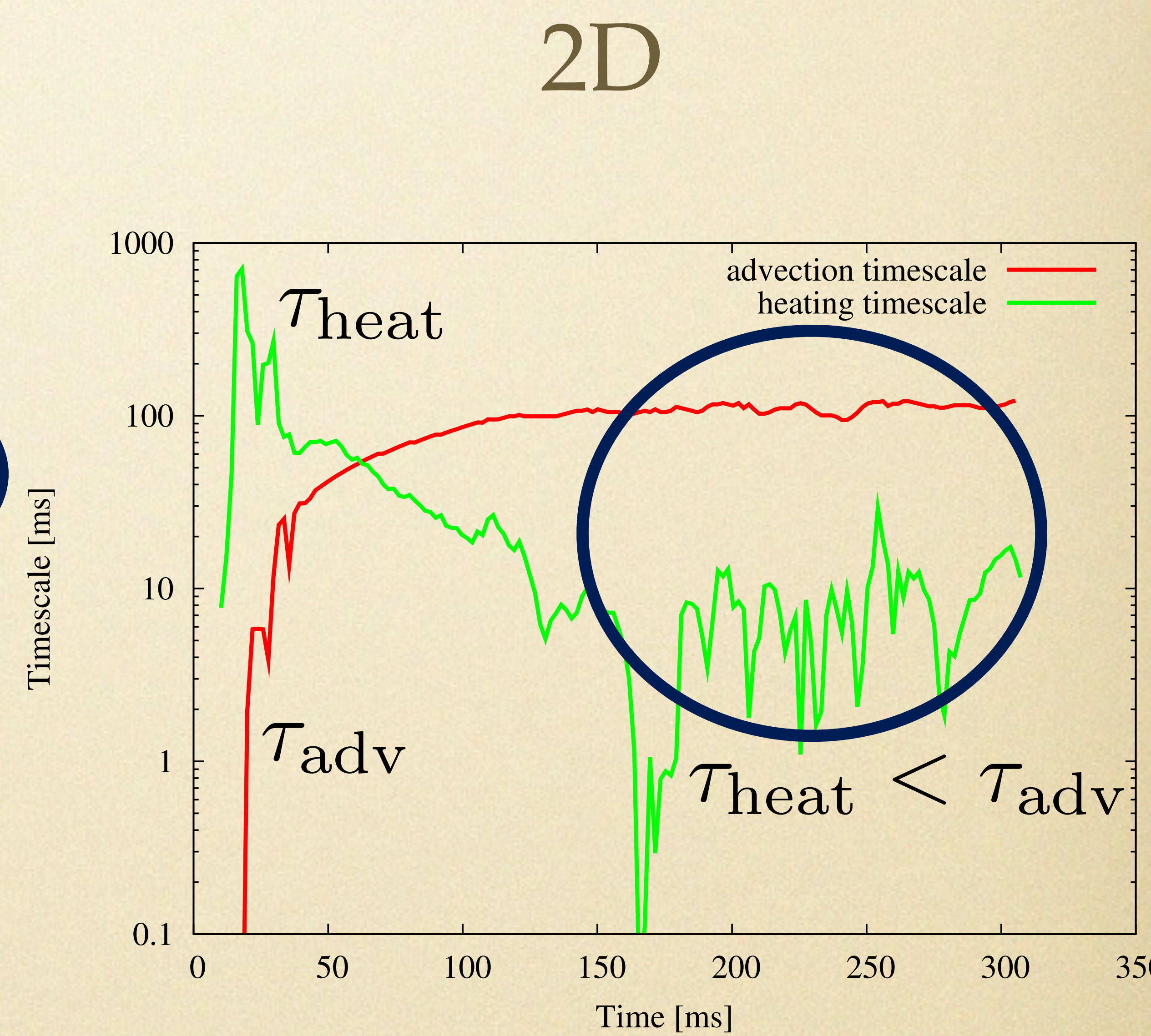
log$_{10}\rho$ entropy



The shock wave is largely deformed by SASI and convection in 2D case!

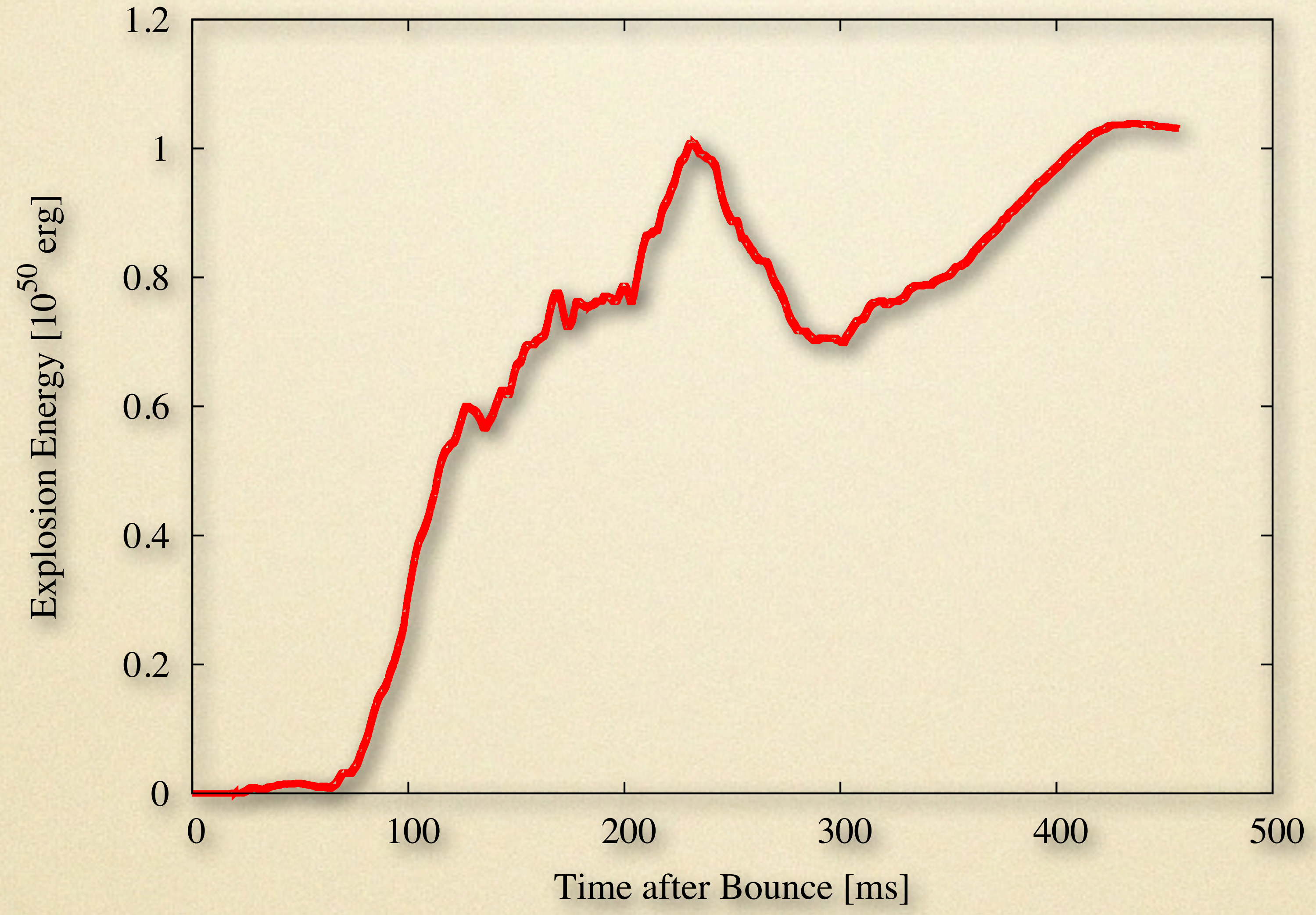
Timescales





The efficiency of neutrino heating is much better in 2D than 1D!

Explosion energy



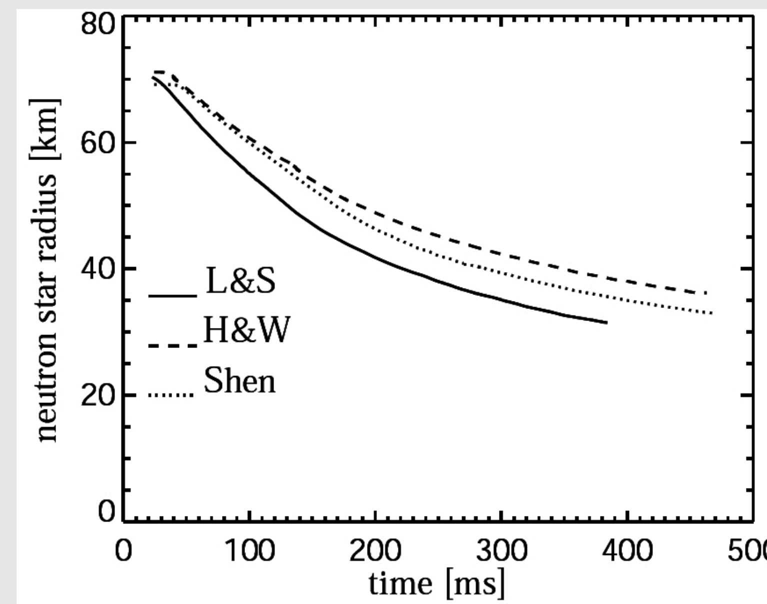
Not enough to explain the observational explosion energy(~10^{51} erg)...
Collective oscillation of neutrinos might amplify >10^{51} erg (Suwa+ 11 in prep)

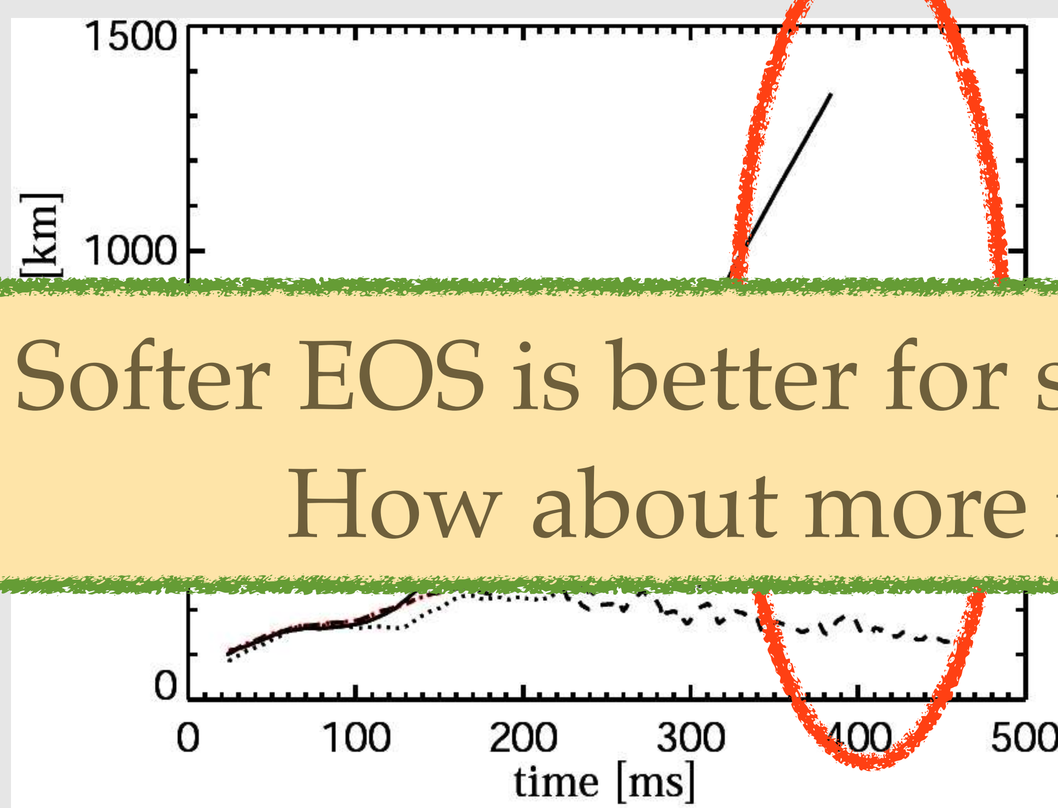
EOS

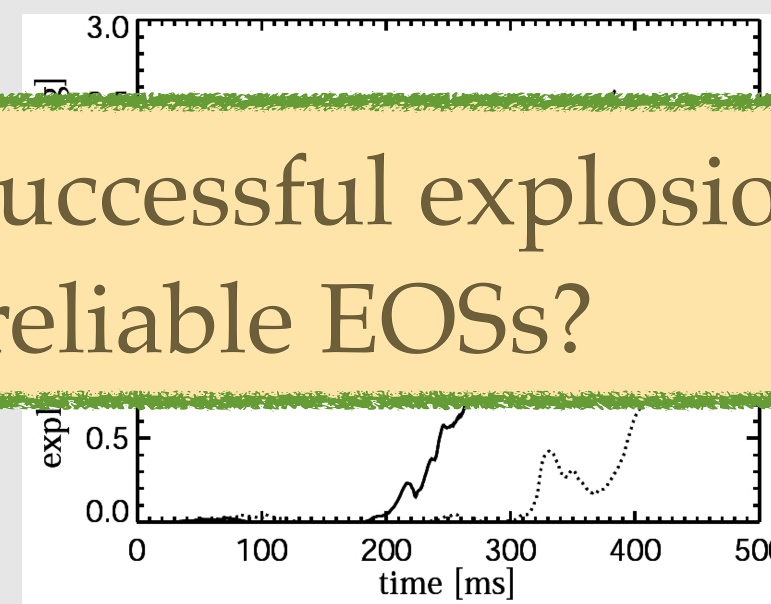
from H.-Th. Janka's presentation

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 EOS is better for successful explosion.
How about more reliable EOSs?

Summary

- We have performed spherically symmetric and axisymmetric simulation including neutrino radiative transfer
- The SASI and convection make the advection timescale longer and aid the neutrino-heating enough for successful explosion in the case of 13 $M_{\odot}$.
- The influence of different progenitor mass and EOS will be investigated soon.

Thank you for attention!