# Multi-Dimensional Core-Collapse Supernova Simulations with the IDSA for Neutrino Transport

**Kuo-Chuan Pan**

**Universität Basel, Switzerland**

(arXiv:1505.02513)

The Basel Supernova Group:

Matthias Liebendörfer
Matthias Hempel
Takami Kuroda
Rubén Cabezón
Friedrich-Karl Thielemann

UNI BASEL

erc

CSCS

# Computational Challenges

- 3D progenitors and 3D evolutions
- Wide density range: $10^{15}$ ~ $<10^{6}$ g cm$^{-3}$
- Wide temperature range: 10 MeV — eV
- Wide range of optical depth (neutrino): from <<1 to >>1
- Neutrino radiation (Boltzmann transport): 7D problem
- General relativity
- Nuclear density (Nuclear EOS)
- Short neutrino tilmestep: dt ~$10^{-6}$ ~ $10^{-7}$ sec
- Binary, rotation and magnetic fields
- <1% accuracy, ($E_{neutrino}$~$10^{53}$ erg -> $E_{kin}$ ~ $10^{51}$erg)
- Turbulence (need high resolution)

**Cas A**

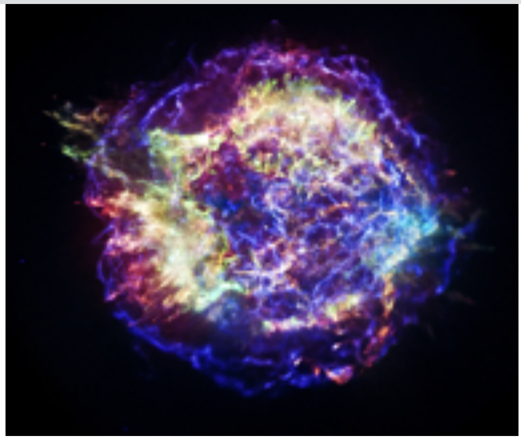


Image credit NASA

**SN 1987A**


Image credit NASA

# Computational Challenges

- **1D** progenitors and **2D/3D** evolutions (**w FLASH**)
- Wide density range: $10^{15} \sim < 10^{6}$ g $cm^{-3}$
- Wide temperature range: 10 MeV — eV
- Wide range of optical depth (neutrino): from <<1 to >>1
- **Approximated Transport (IDSA)**
- **Newtonian**
- **Tabulated** Nuclear density (Nuclear EOS; **HS (DD2)**)
- Short neutrino tilmestep: dt ~ $10^{-7}$ sec
- ~~Binary, rotation and magnetic fields~~
- <1% accuracy, ($E_{neutrino} \sim 10^{53}$ erg -> $E_{kin} \sim 10^{51}$erg)
- Turbulence (need high resolution)

**Cas A**

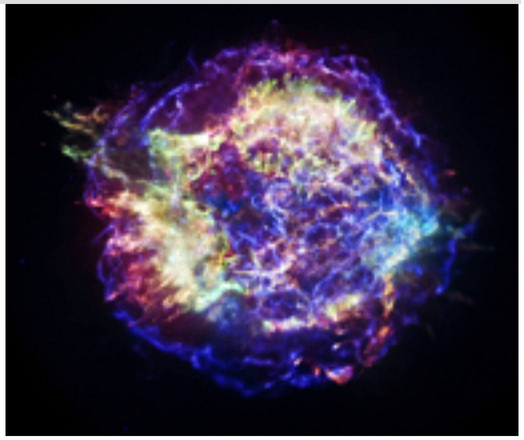


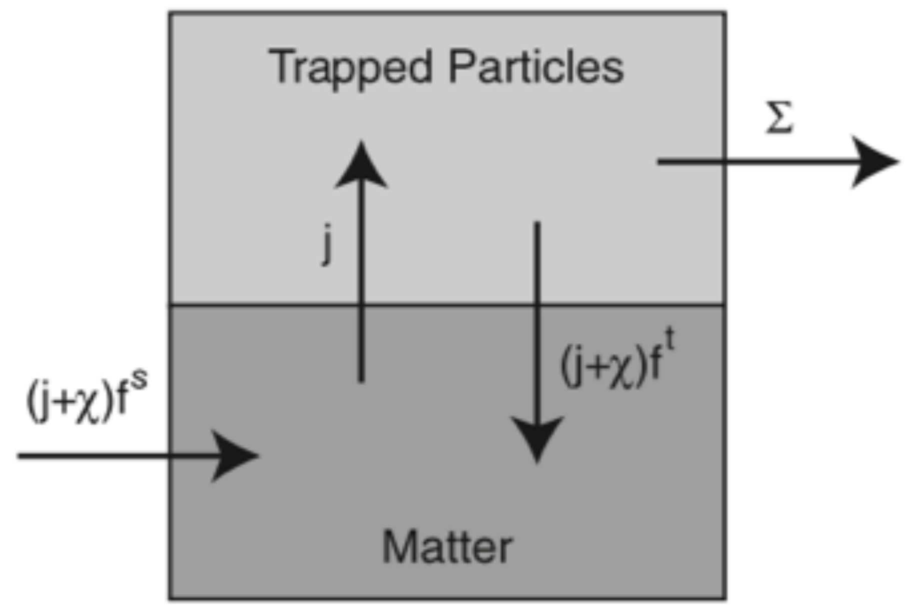
Image credit NASA

**SN 1987A**

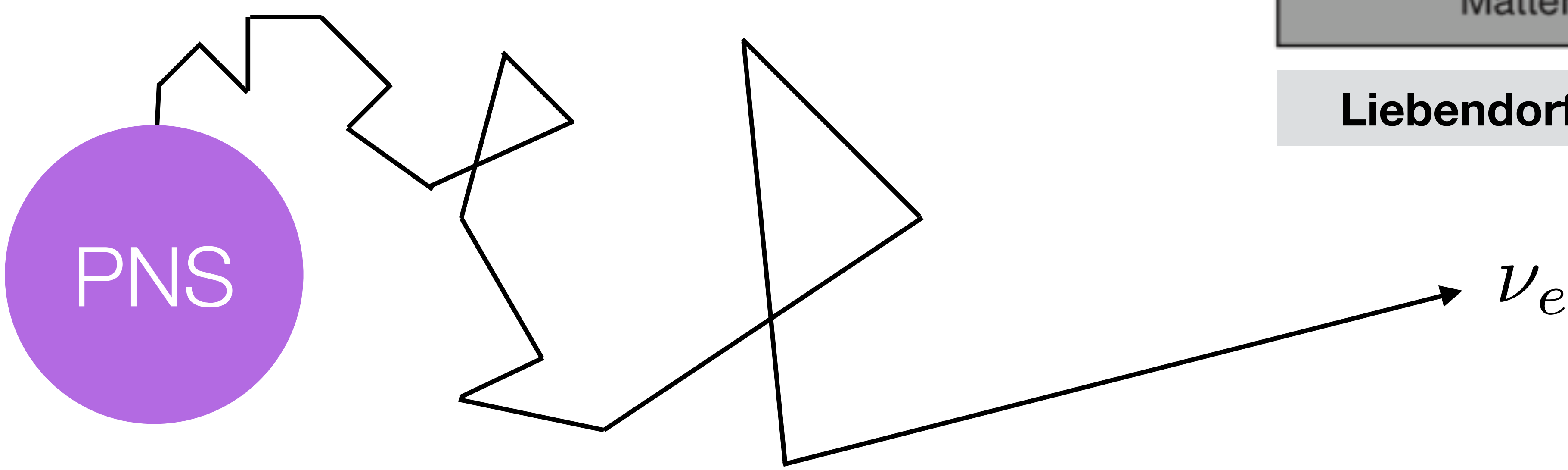

Image credit NASA

# Isotropic Diffusion Source Approximation (IDSA)

- IDSA (Liebendörfer+09)




**Liebendorfer+09**

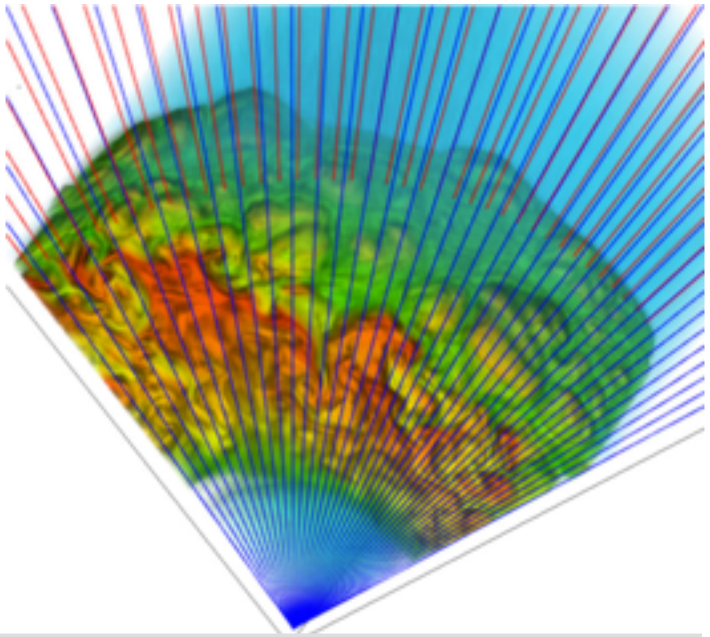



**Opaque** **Semi-transparent** **Transparent**

# FLASH+IDSA

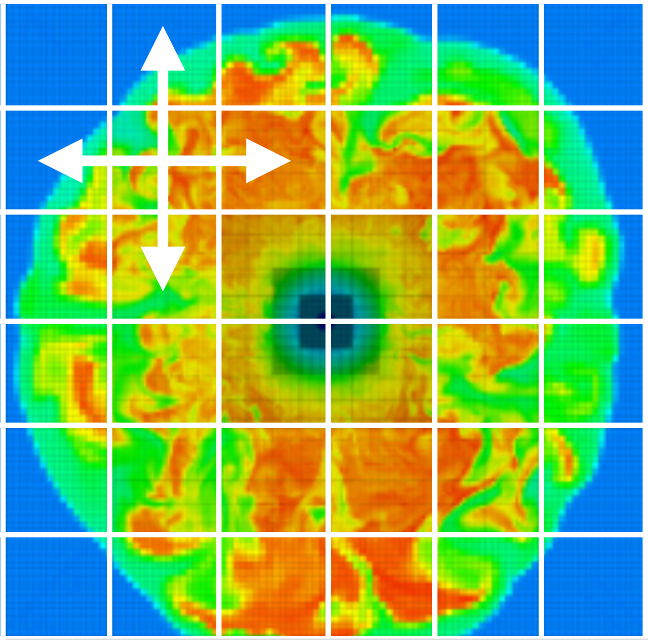
- 2D cylindrical and 3D Cartesian coordinates (Similar to Couch+13)
- Different with the "Ray-by-Ray" approach (Suwa+13, Takiwaki+13, Nakamura +13). We solve the diffusion source and trapped particle component in multi-dimensions, but keep the streaming component in spherical symmetry (Similar to the Elephant code)
- Only for electron type neutrinos (Heavy neutrinos -> Leakage scheme)

Ray-by-Ray



**Ott +12**

3D

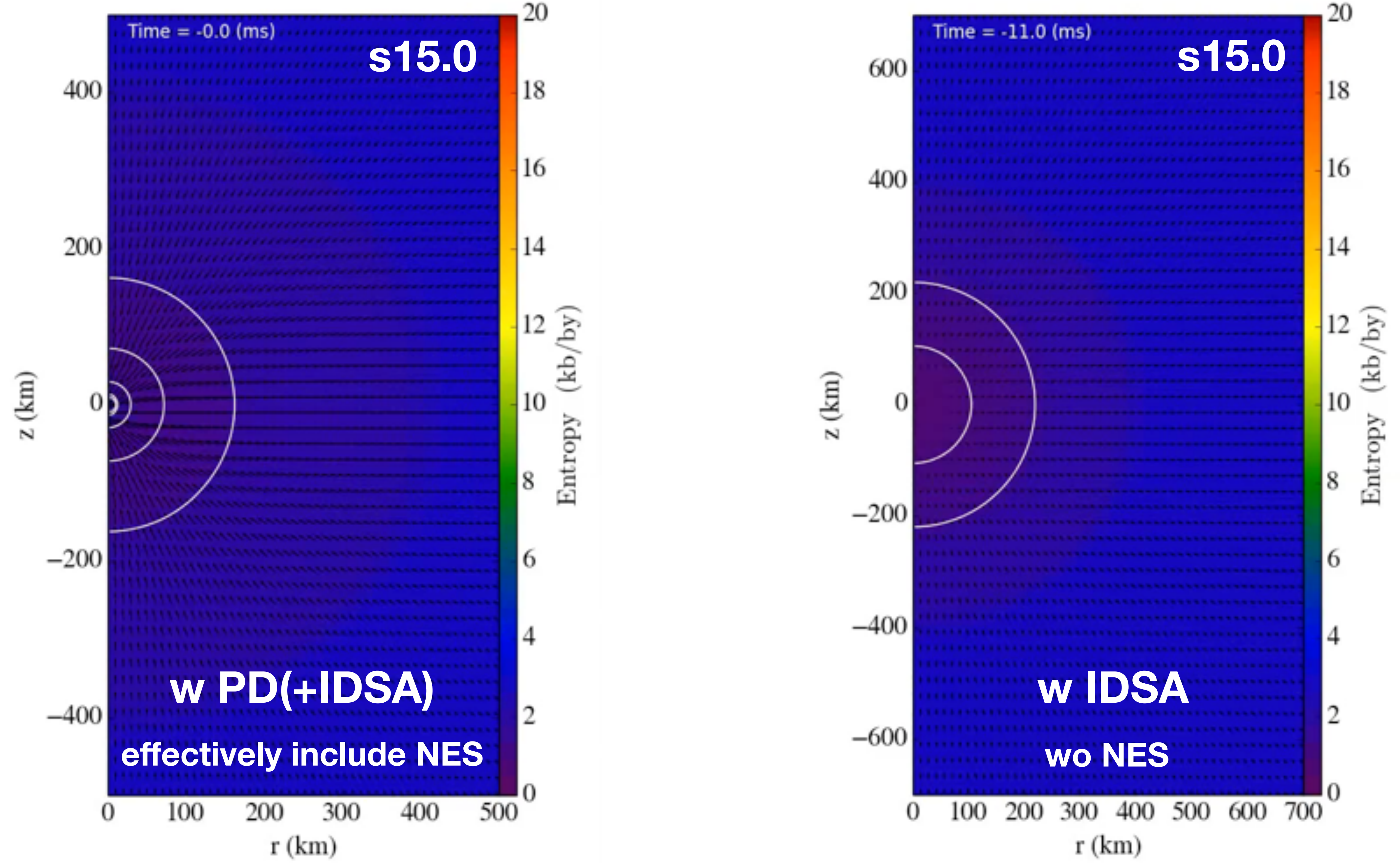


**This work**

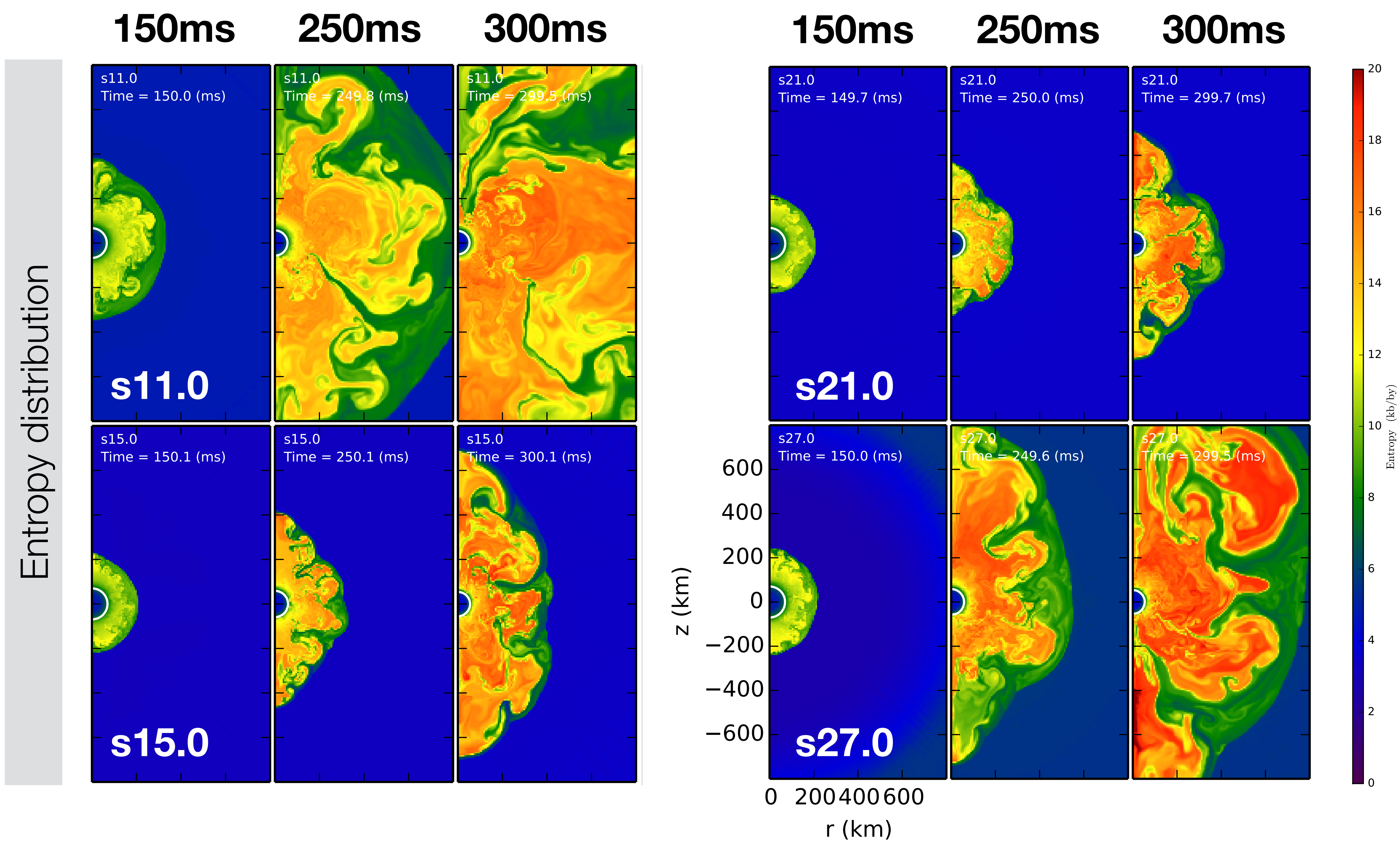
# PD vs. IDSA scheme

## Two sets of Simulations

Entropy distribution



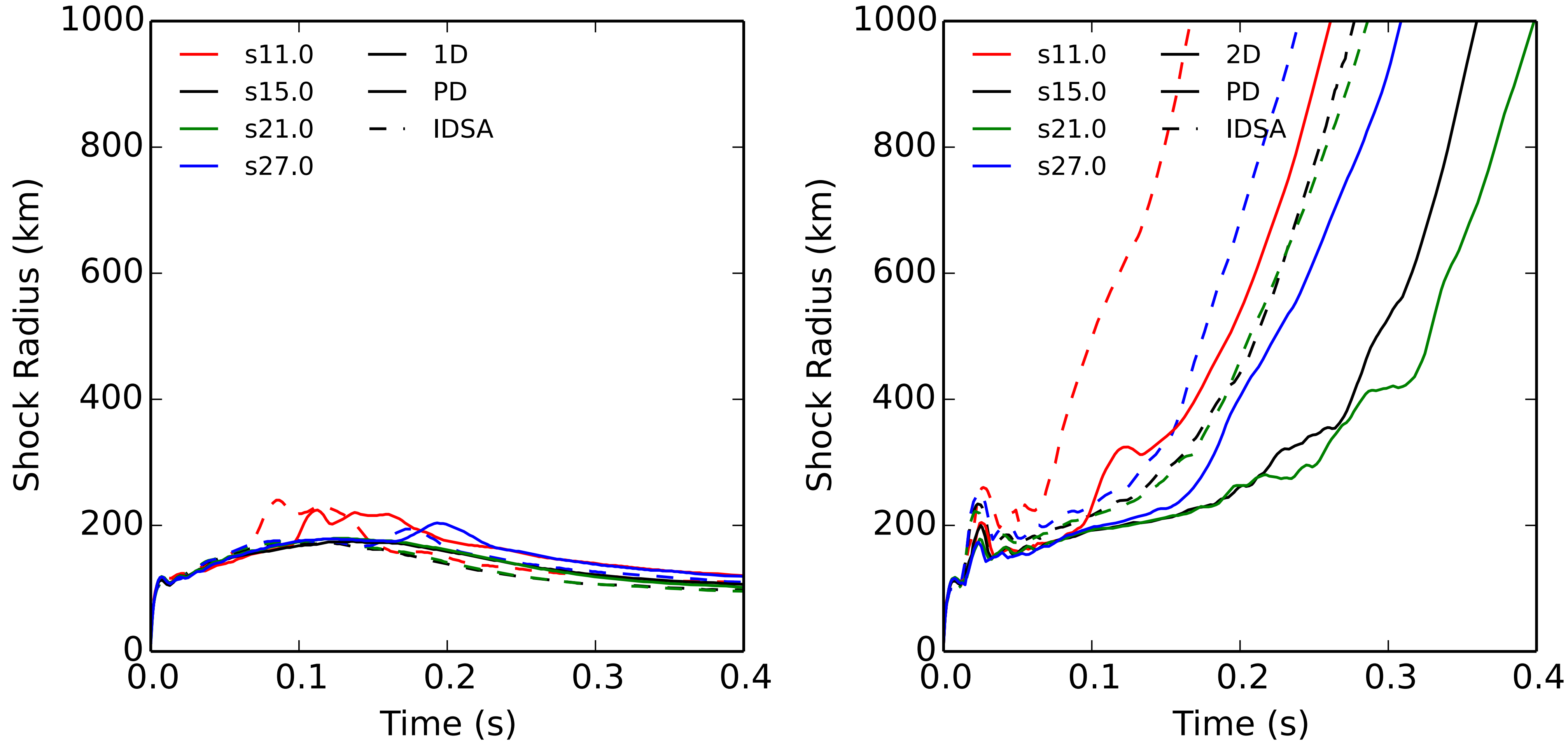
# 2D FLASH-IDSA results



# 2D FLASH-IDSA results

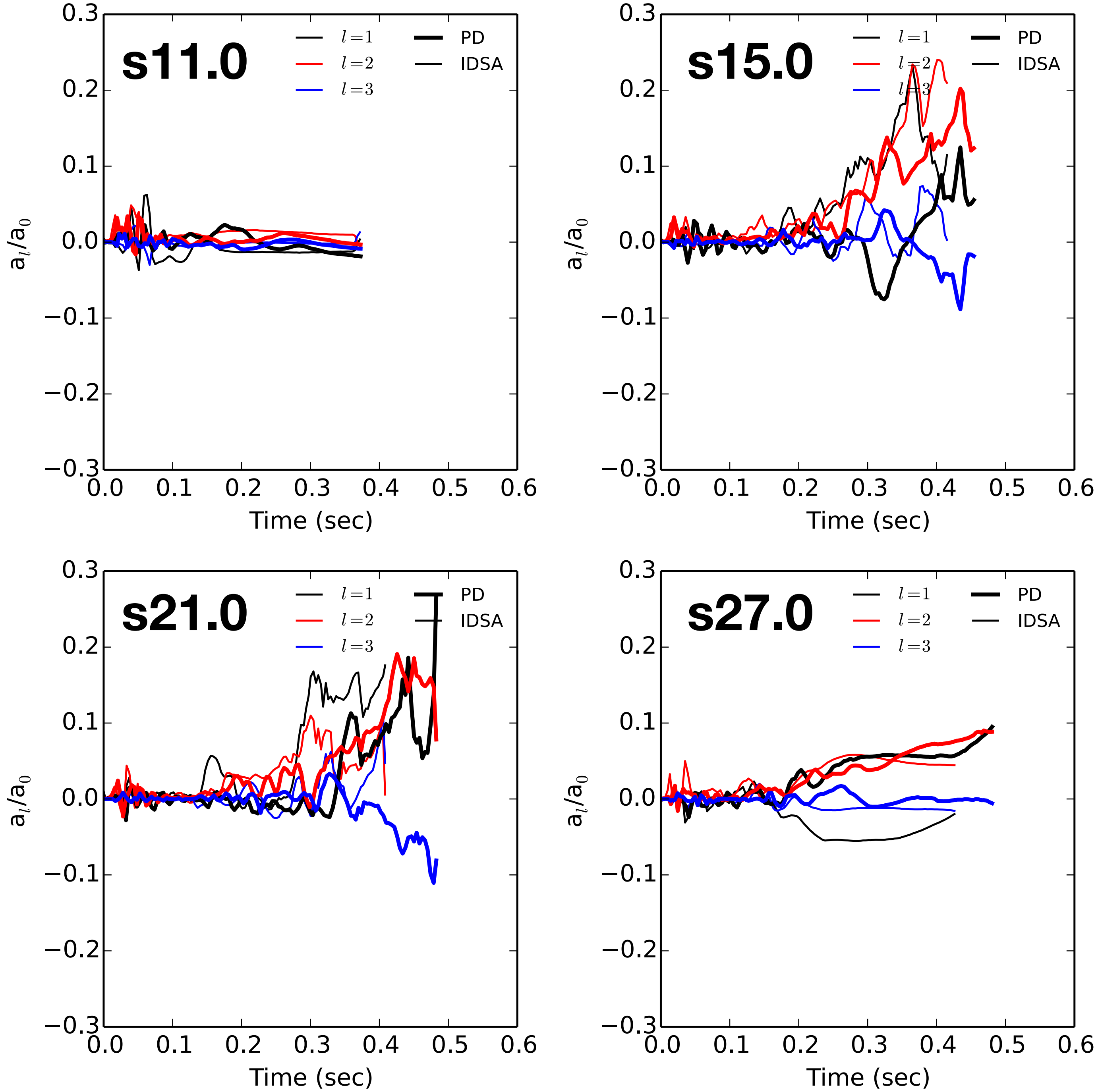
- 1D always failed (except some very low mass progenitors)
- 2D all explode! (both PD and IDSA)

**1D** Shock Radius vs. Time **2D**

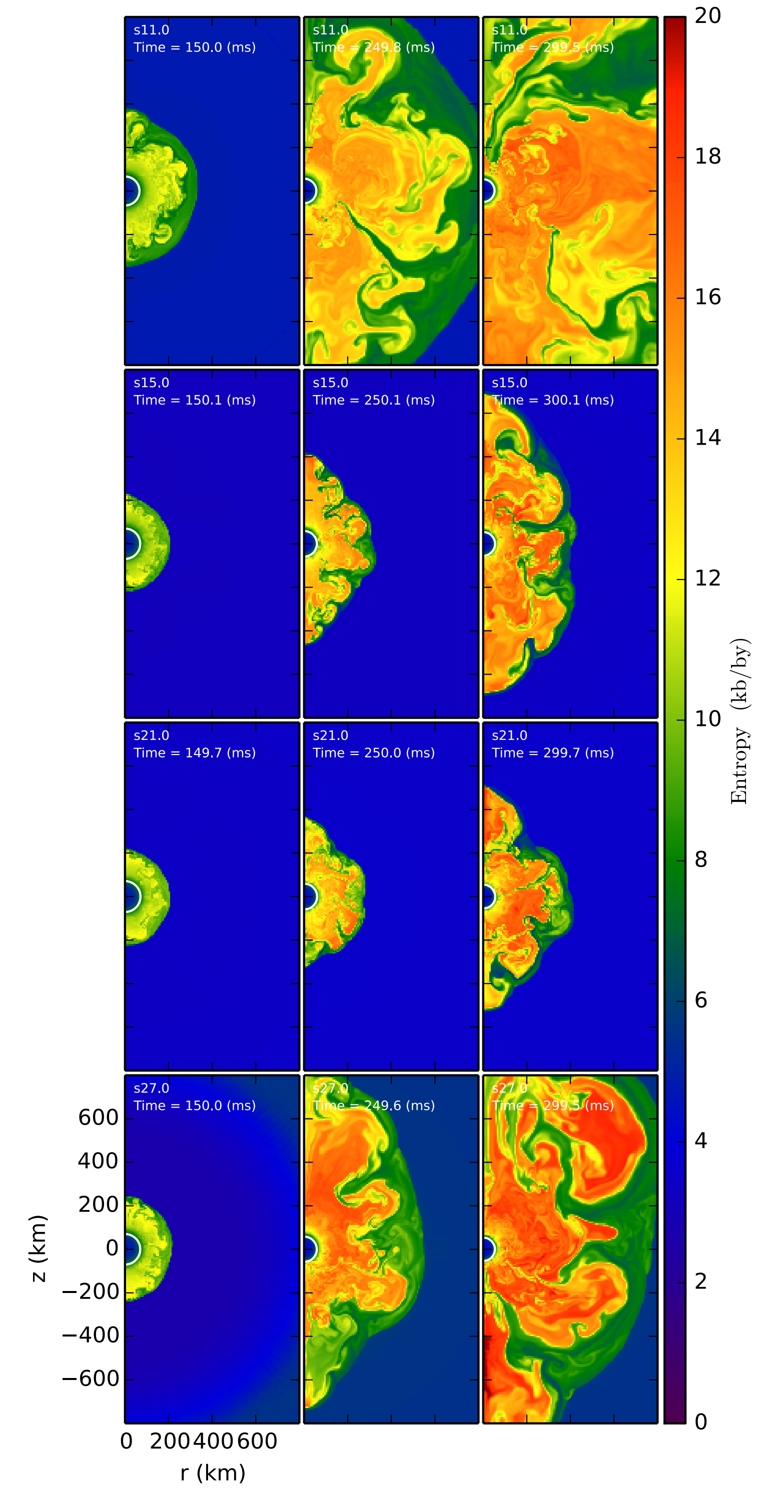


# SASI (conti.)

## SASI Amplitudes

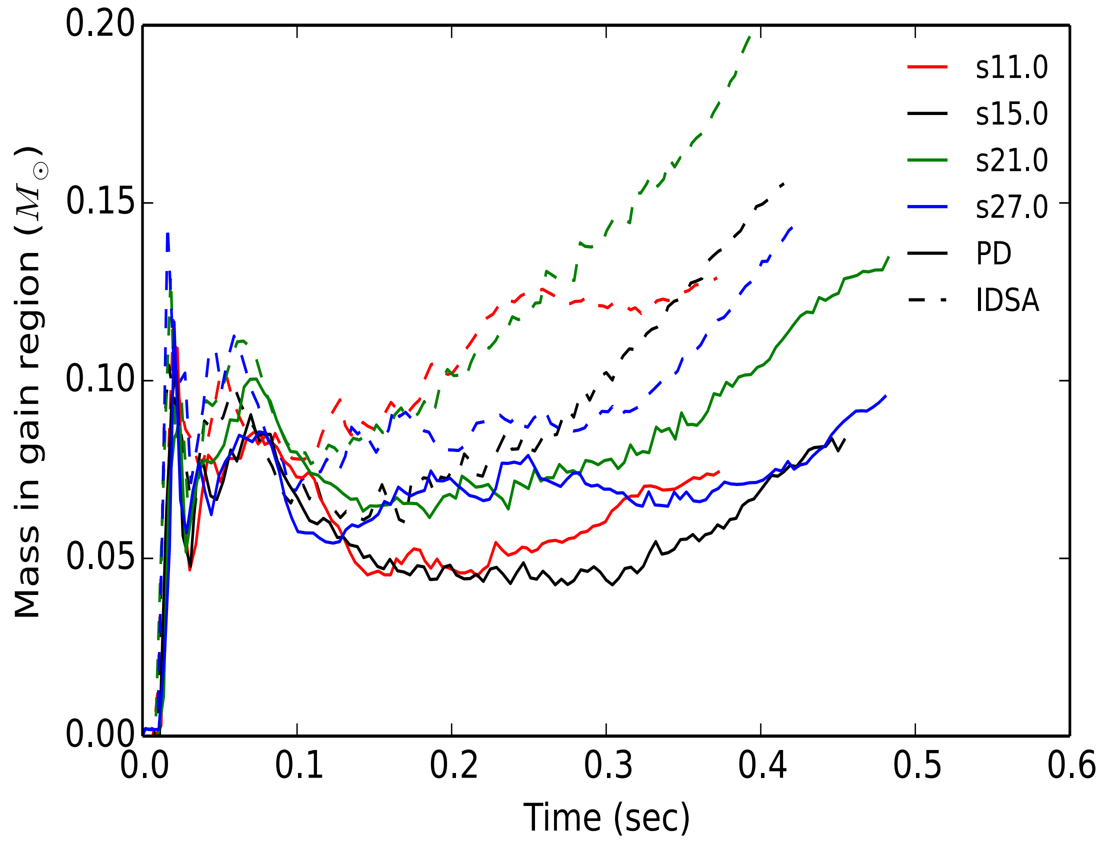



## Entropy distribution

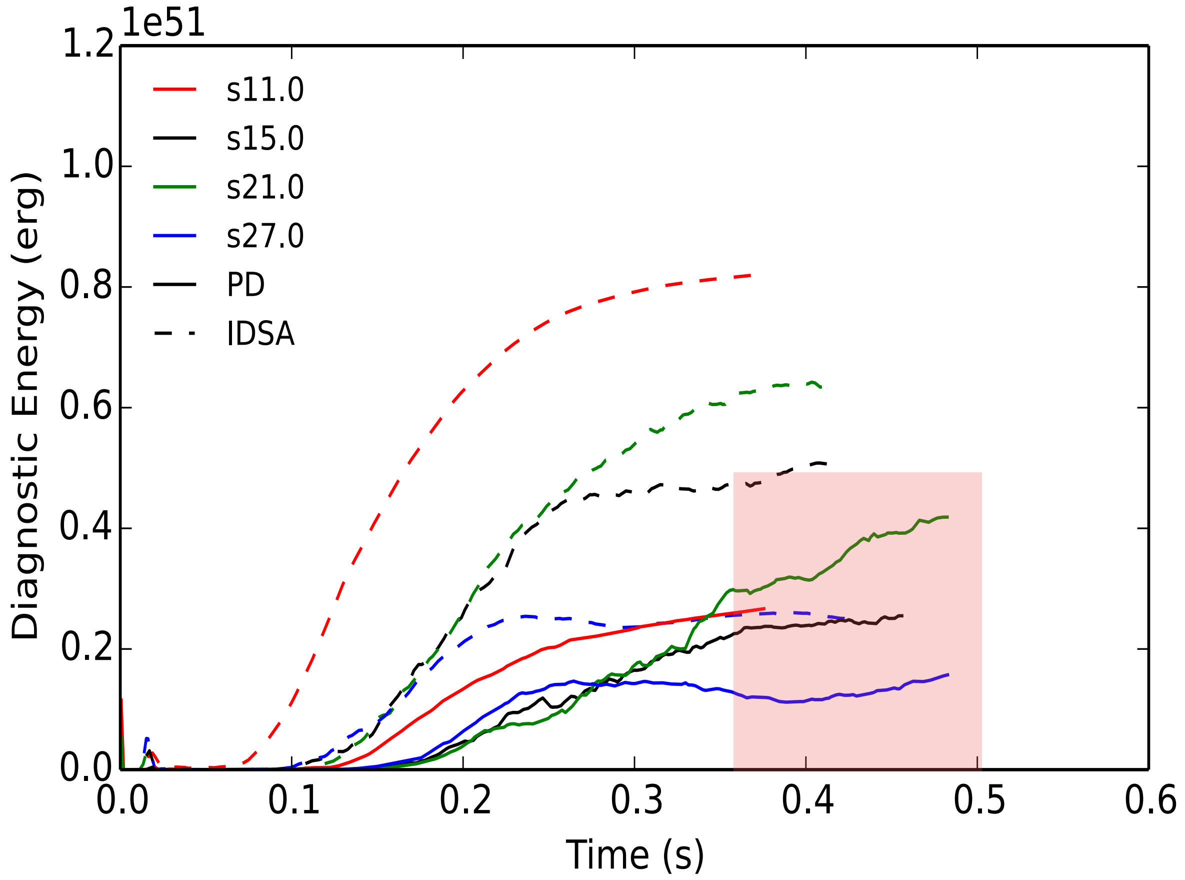


# Neutrino Heating (conti.)

## Mass in the gain region




## Diagnostic Explosion Energy



# 2D vs 3D

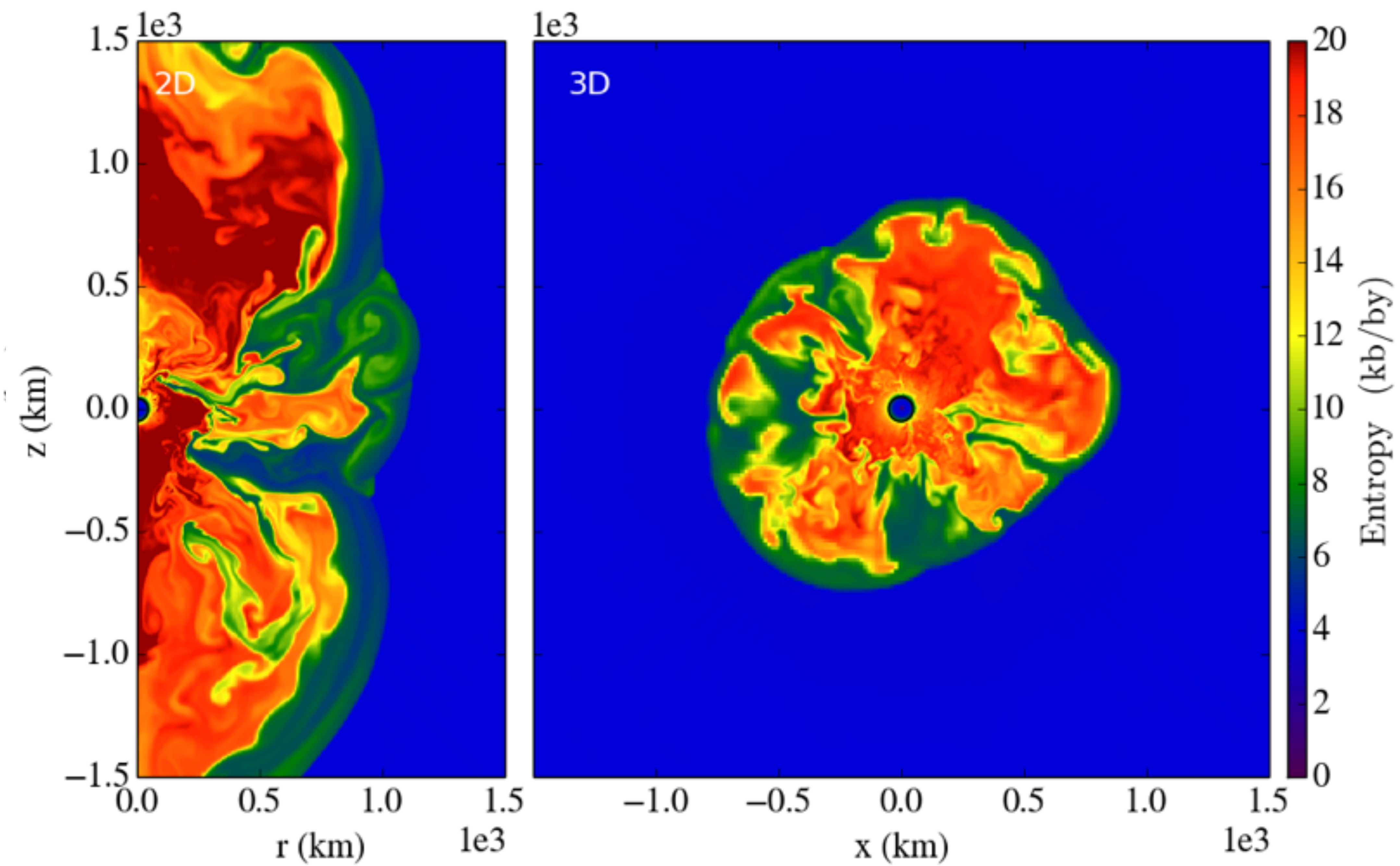
# 3D FLASH+IDSA results

**Pan et al. (in prep.)**

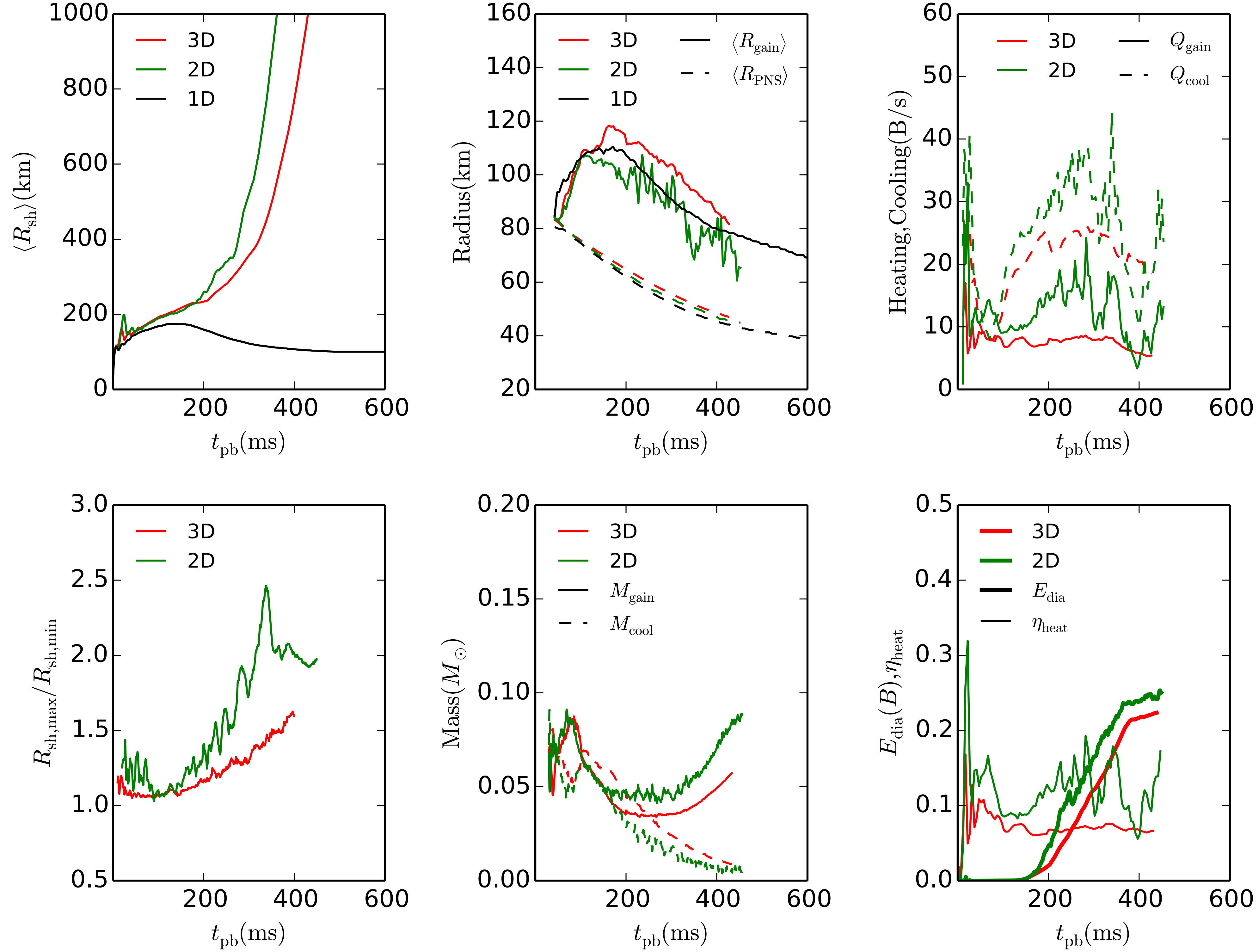
- 3D PD+IDSA
- $15M_{sun}$ (WHW+02)
- HS (DD2) EoS
- Newtonian
- Resolution: ~$2^0$
- Only ~0.5M cpu-hrs

# 2D vs 3D

Time = 400 ms



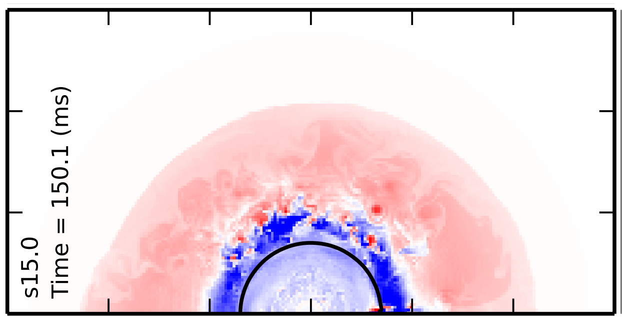
# 2D vs 3D (Conti.)



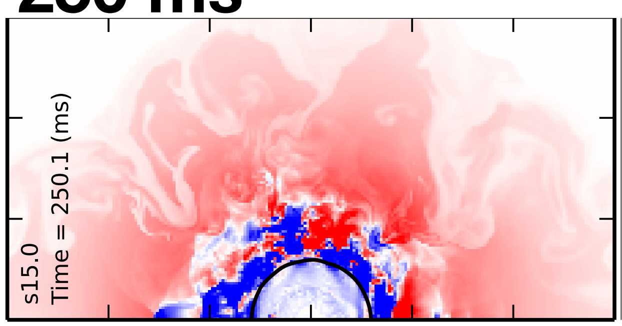
# Neutrino Heating/Cooling

**2D**

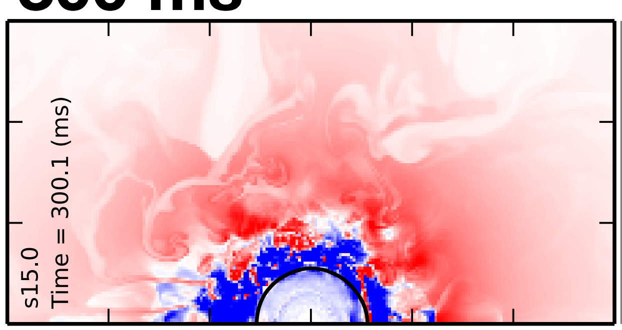
**150 ms**

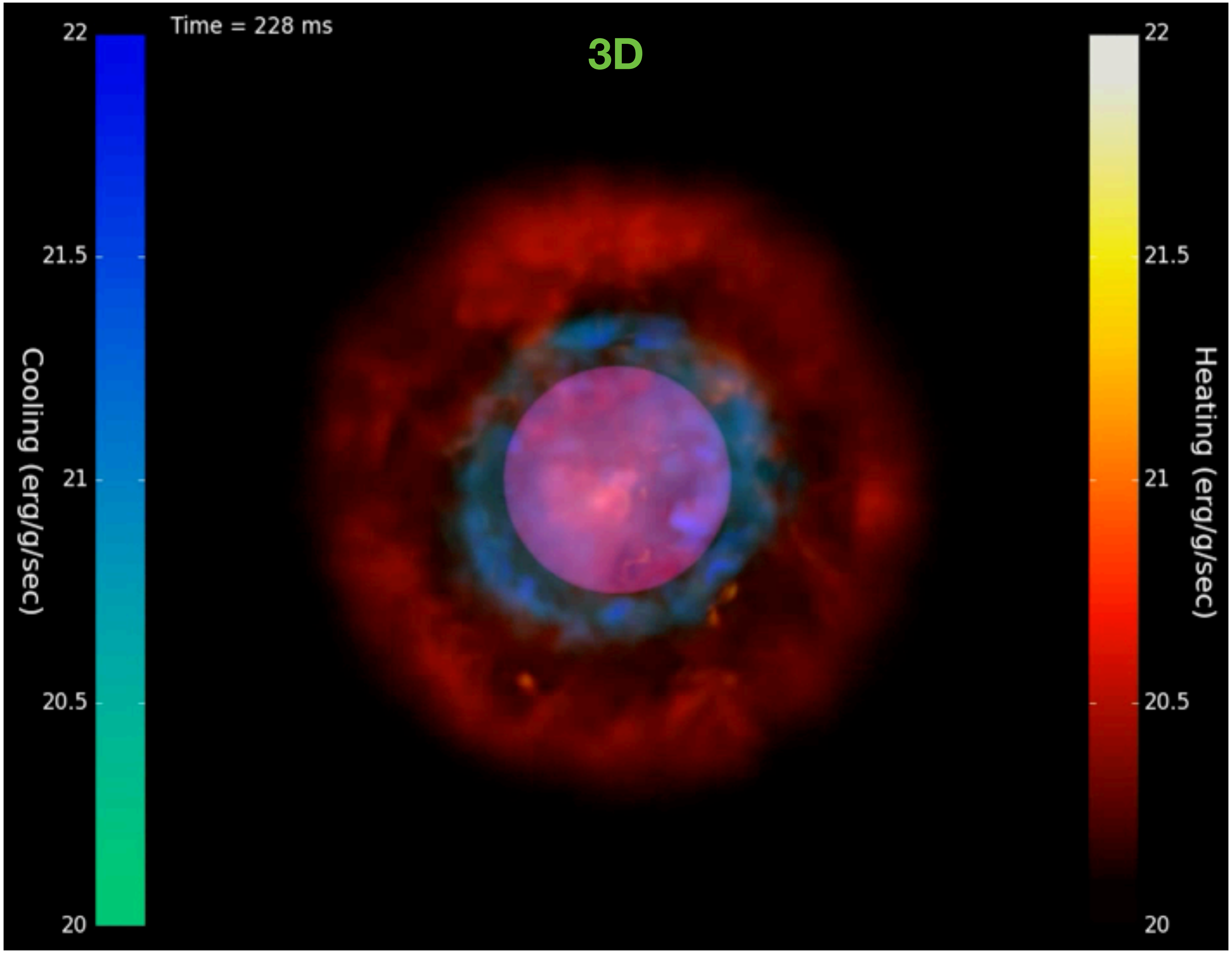



**250 ms**




**300 ms**



# Conclusions

- Our IDSA implementation seems robust (all 2D and 3D models exploded) with diagnostic explosion energies ~0.1-0.5 B (at ~400ms)
- Neutrino interactions (e.g. NES) during collapse are important (need ab initio simulations)
- Neutrino-driven convection with little SASI
- First multi-dimensional simulations with the new HS(DD2) EoS
- DD2 is slightly easier to explode than LS220
- 3D seems harder to explode than 2D
- IDSA is promising to achieve high-resolution 3D simulations (good for progenitor studies, long-term evolutions and nuclear synthesis)