# Towards Supernova Explosion


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# Neutrino Heating Mechanism

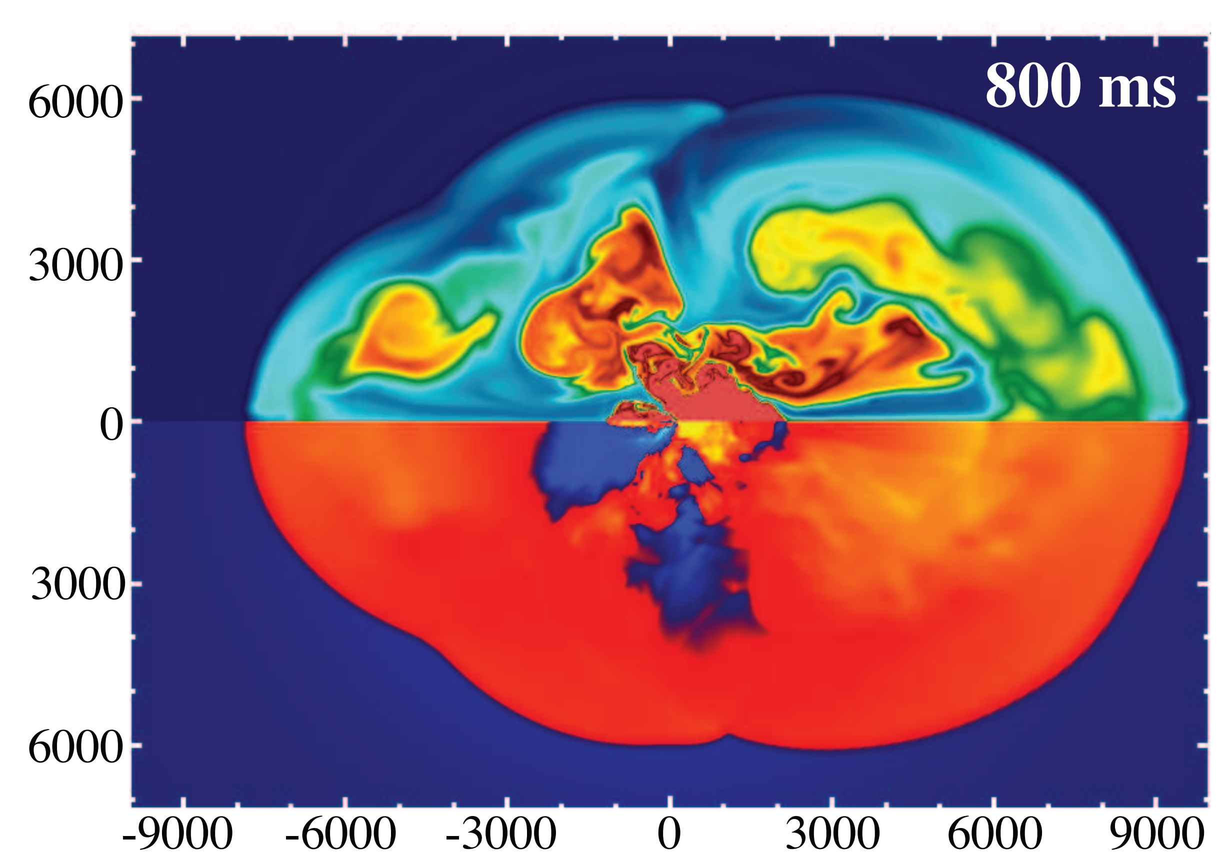
e.g, Colgate & White (1966), Bethe & Wilson (1985)

- Bulk of the core's original binding energy, $>10^{53}$ erg, will be radiated as neutrinos in 10s of sec. following collapse. Mechanism must tap this energy.
- Need only ~1% of this to drive robust explosion. Need high quantitative accuracy!
- Tough to achieve in 1D!

# Why is it Hard?

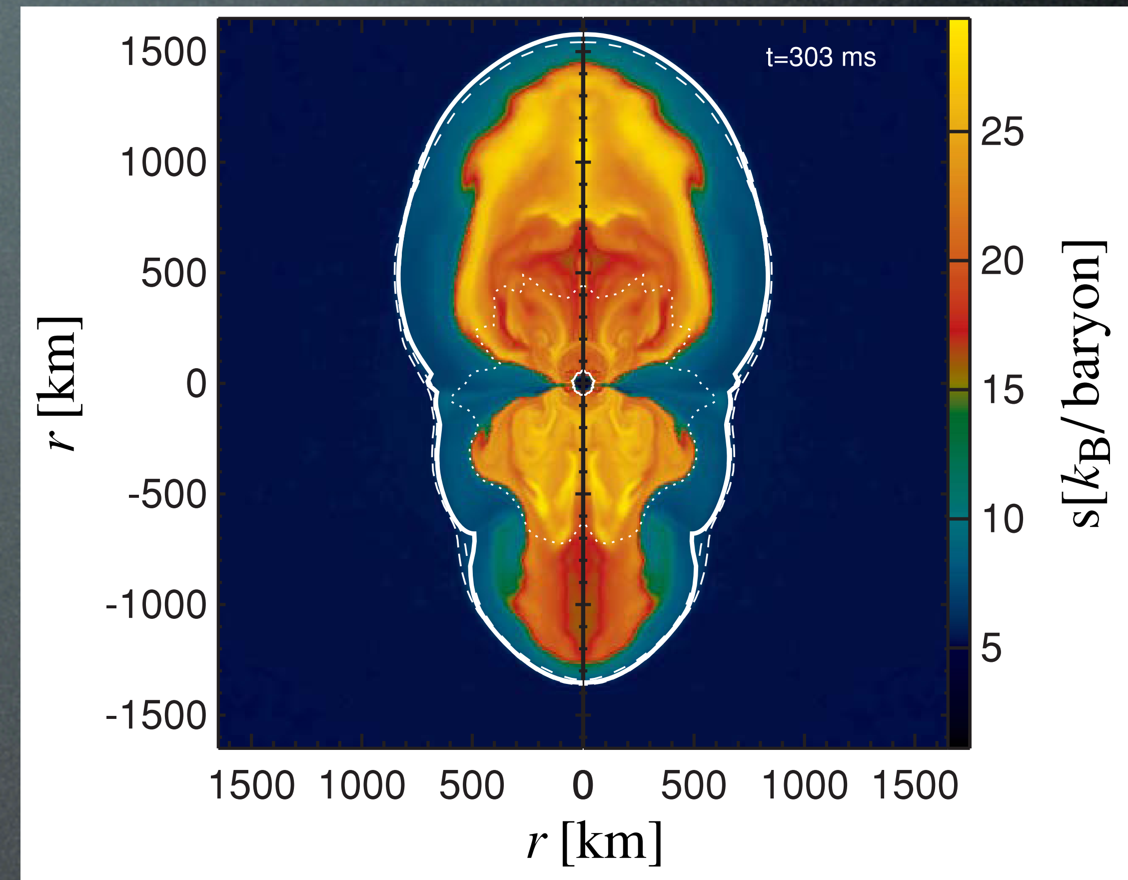
- Magnetohydrodynamics
- General Relativity: extreme gravity
- Microphysics: nuclear EOS, neutrino cross sections/interactions
- Boltzmann transport: neutrinos
- Fundamentally 3D problem!
- Physics fully-coupled!

# 2D ‘ab initio’ Explosions



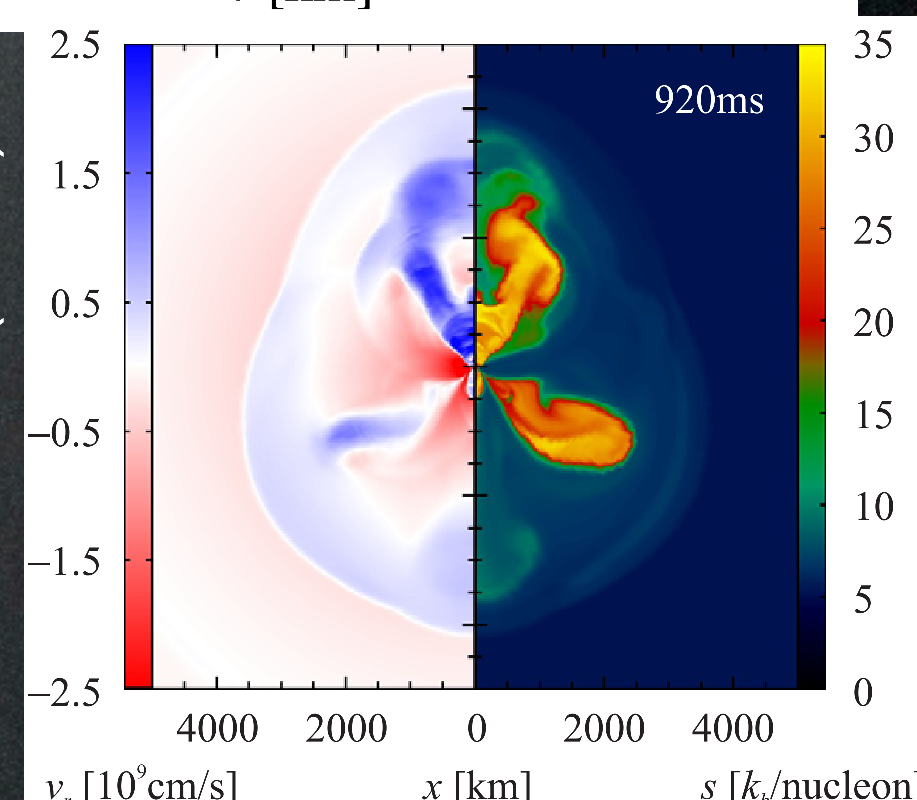

Bruenn et al. (2013)

Marek & Janka (2009)



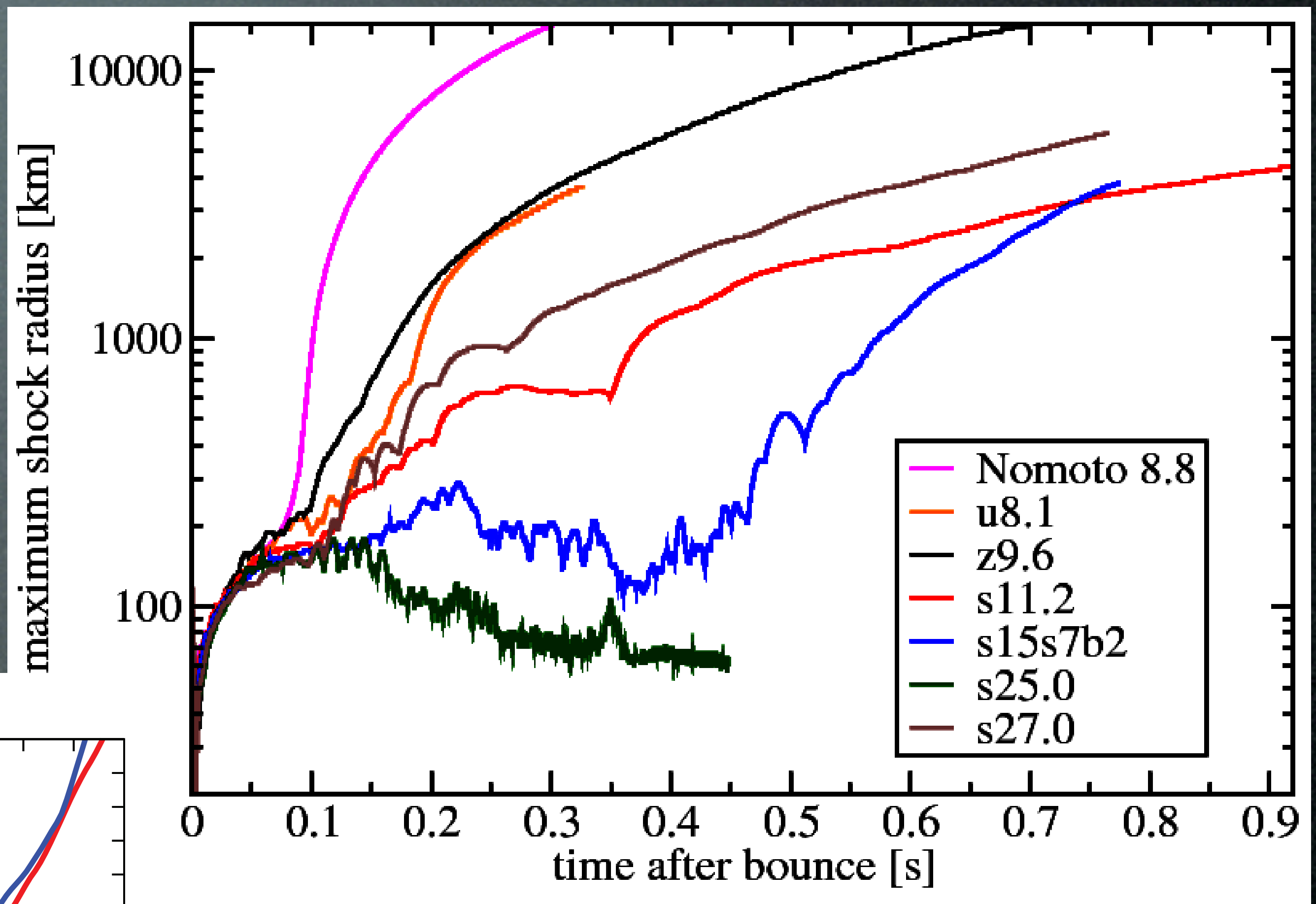

- Handful of 2D explosions. See also Suwa et al. (2010).
- Explosions are weak or marginal.
- Characteristically prolate...
- Princeton group: no 2D explosions.

Mueller et al. (2012)

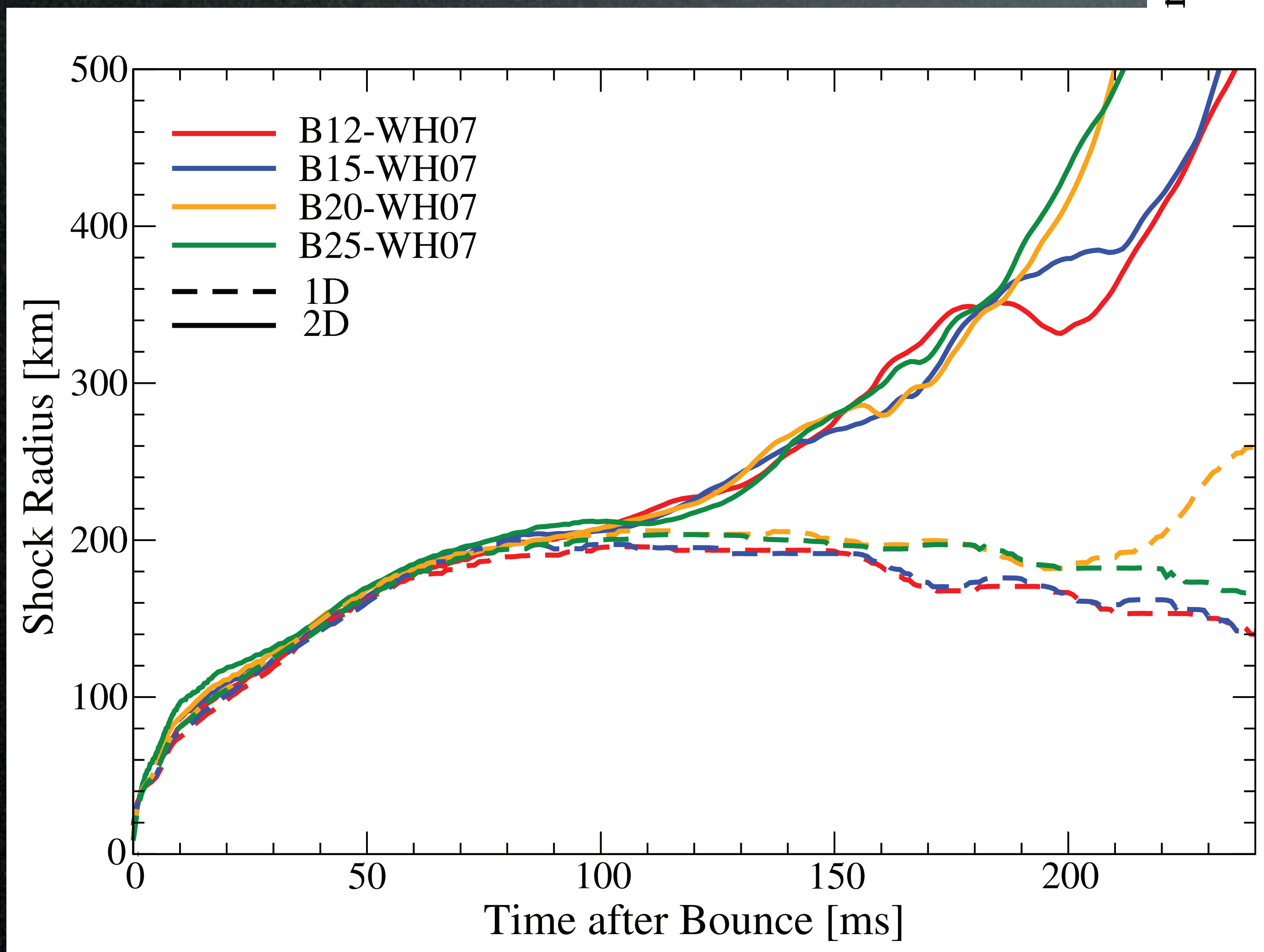


# 2D 'ab initio' Explosions

- Variety of 2D explosions.
- Quantitative disagreement...



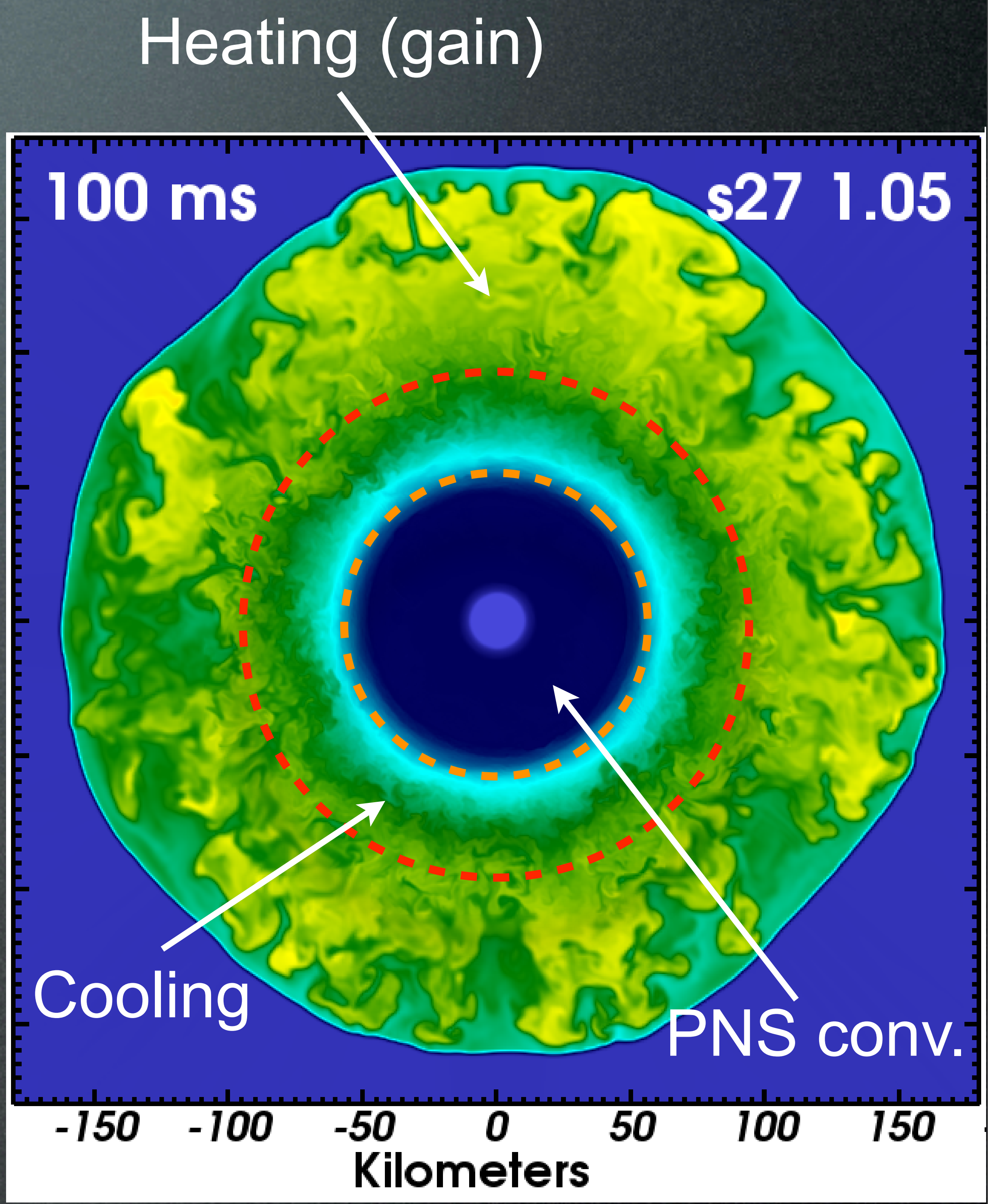

B. Mueller et al.




Bruenn et al. (2013)

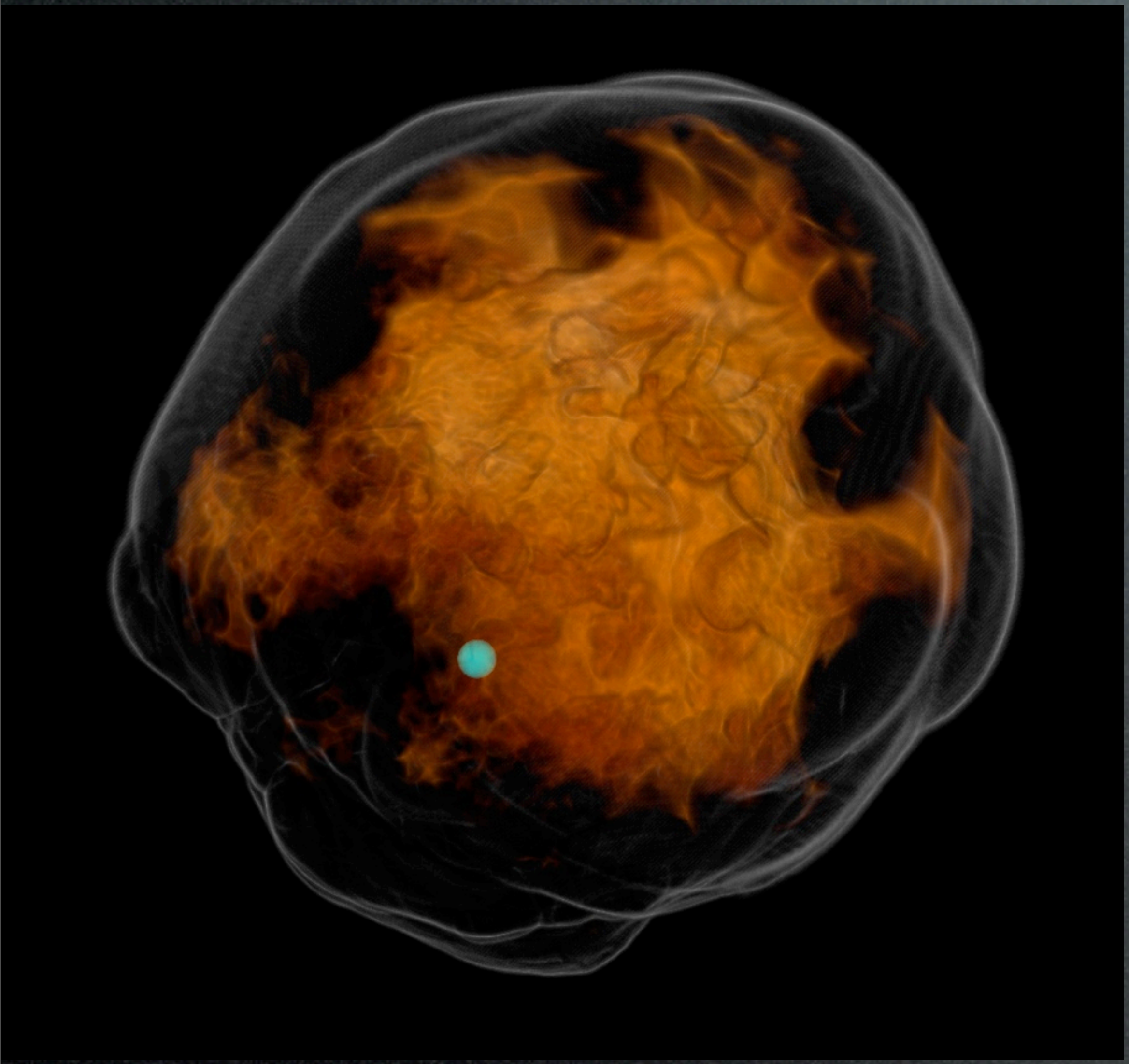
# Multi-D Effects

- Lepton-driven PNS convection => enhances neutrino luminosities
- Entropy-driven gain layer convection => increases matter dwell times
- Standing Accretion Shock Instability => expands gain region




SMC & E. O'Connor (2013)

# Era of 3D CCSN Simulations



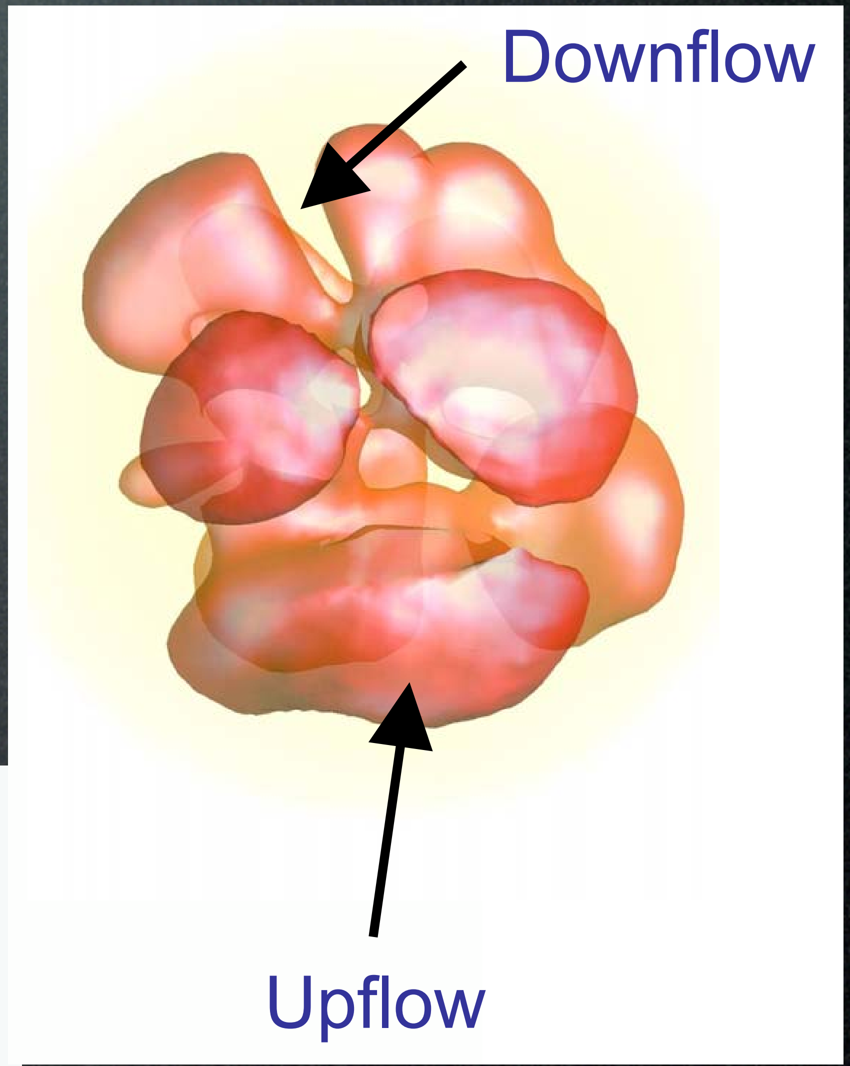
SMC (2013b)

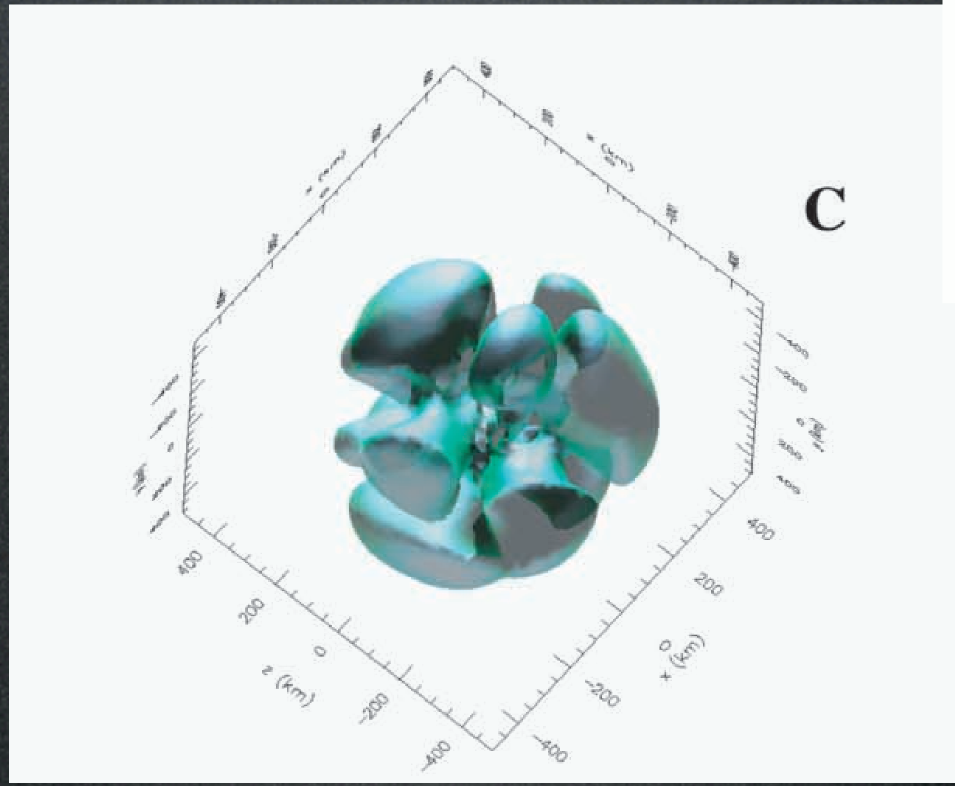
- Grand challenge for peta-scale computational astrophysics.
- Approximations must be made.
- 3D makes an *enormous* impact!
- But 3D is not the "silver bullet..."

# Early 3D Work

Fryer & Warren (2002,2004); Fryer 2004

- Smoothed-particle hydro, accurate EOS, approximate GR.
- Explosions found, likely due to use of grey FLD for neutrinos.
- Important differences from 2D!



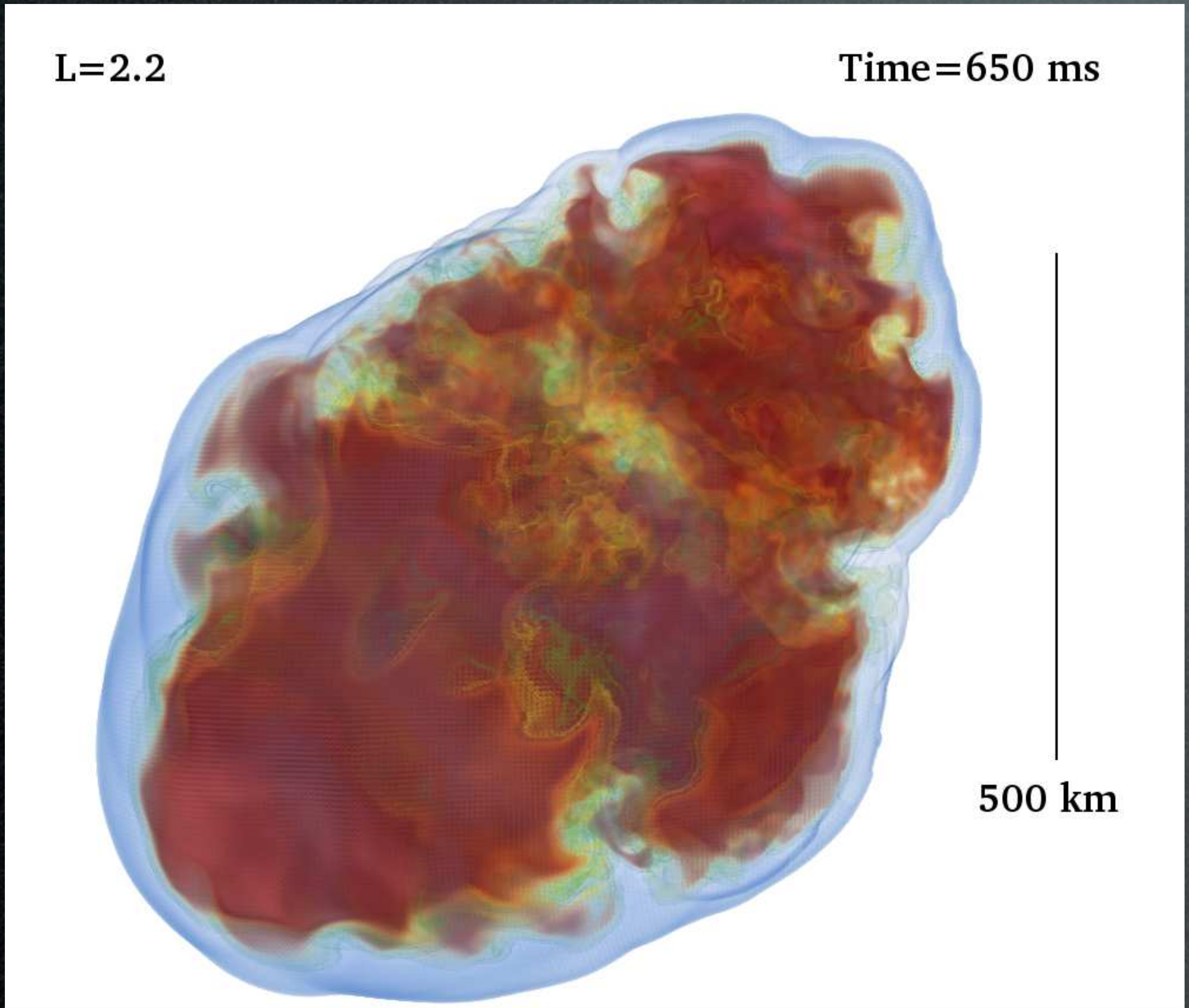




Also, recent SNSPH work on young remnants (Ellinger et al. 2013)

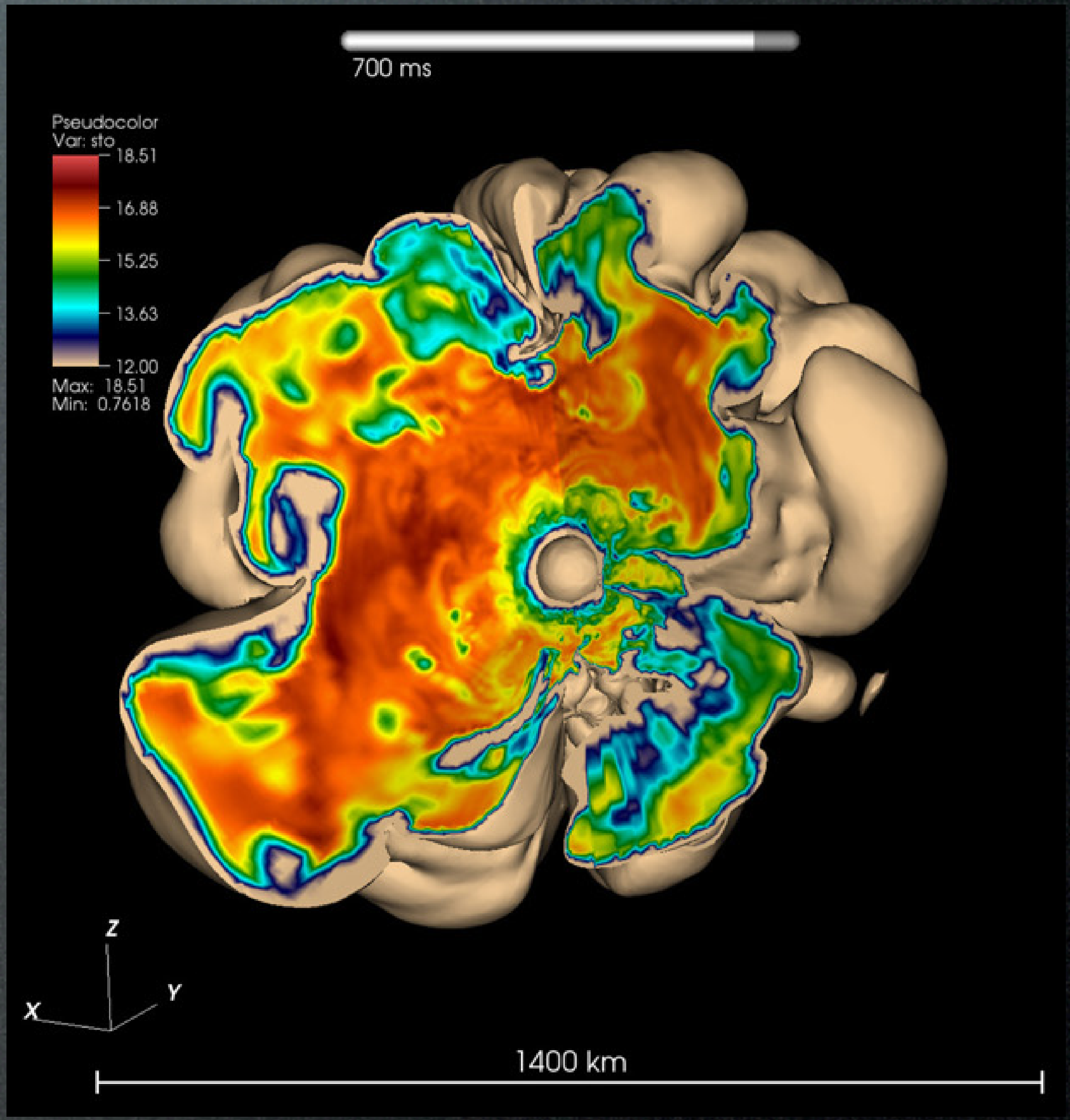
# 3D Parametric Sims

Princeton

Garching



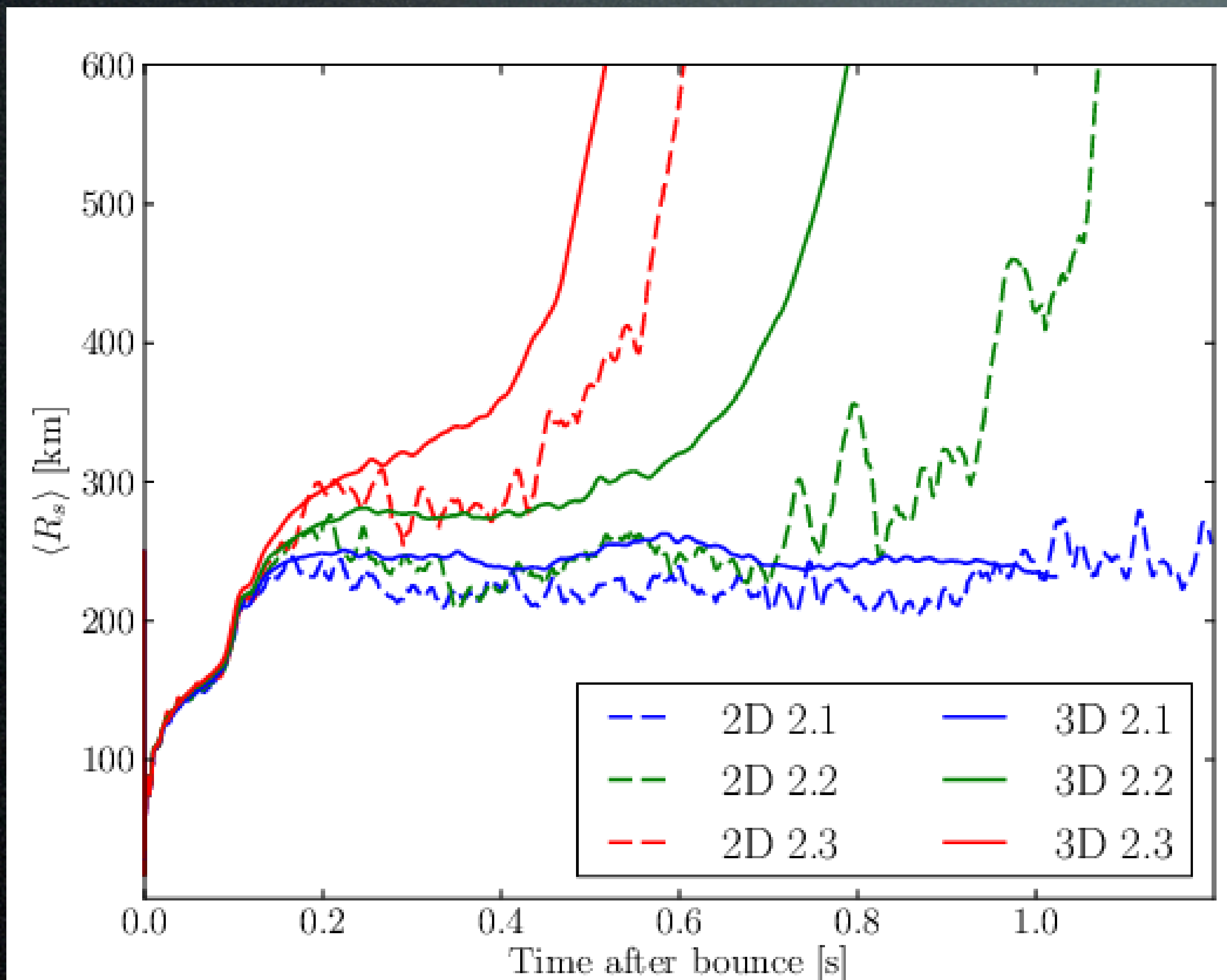

Dolence et al. (2013)




Hanke et al. (2012)

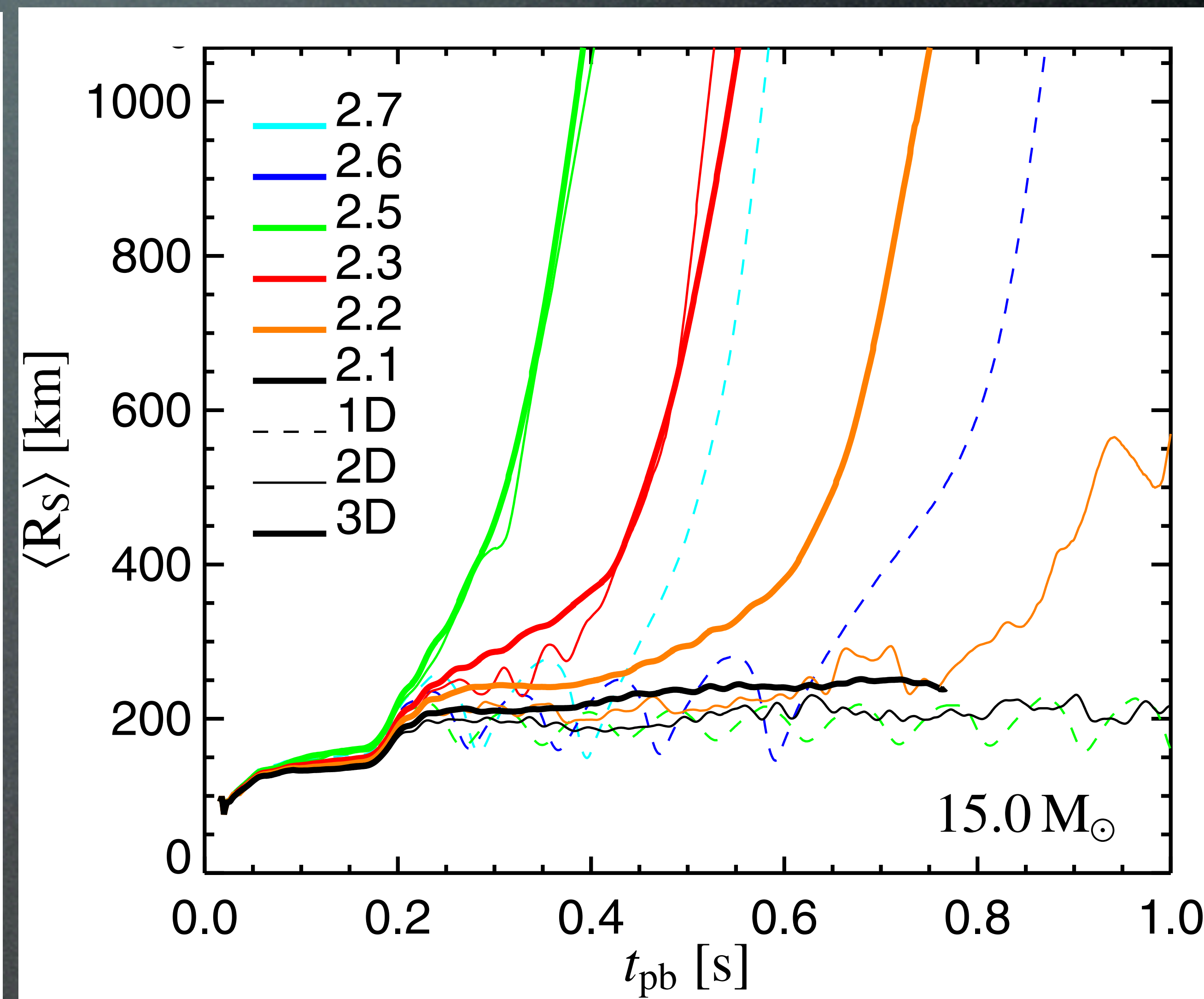
# 3D Parametric Sims

## Princeton




Dolence et al. (2013)
(also Nordhaus et al. 2010)

## Garching



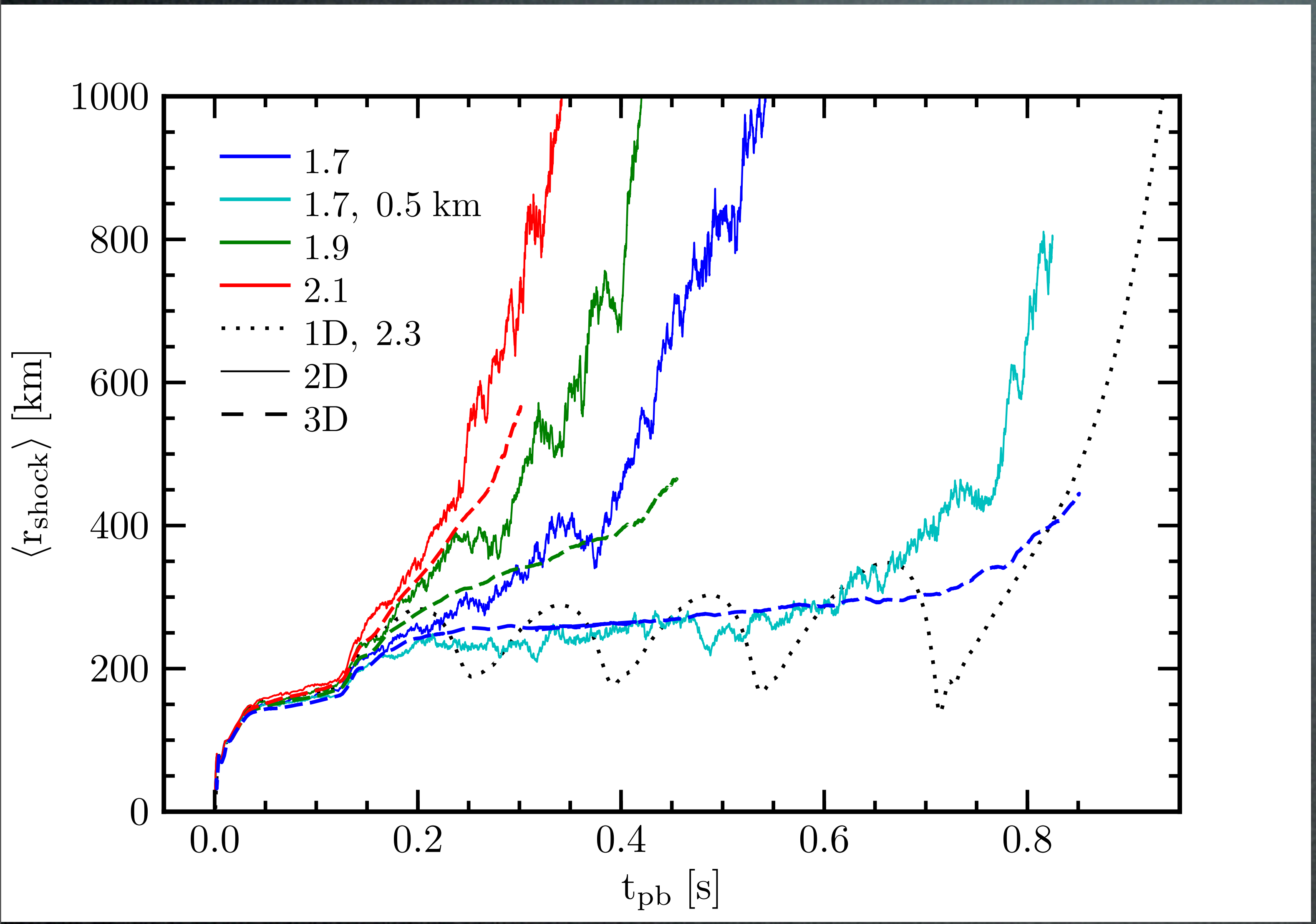

Hanke et al. (2012)

Easier in 3D

About the same (?)

# 3D Parametric Sims

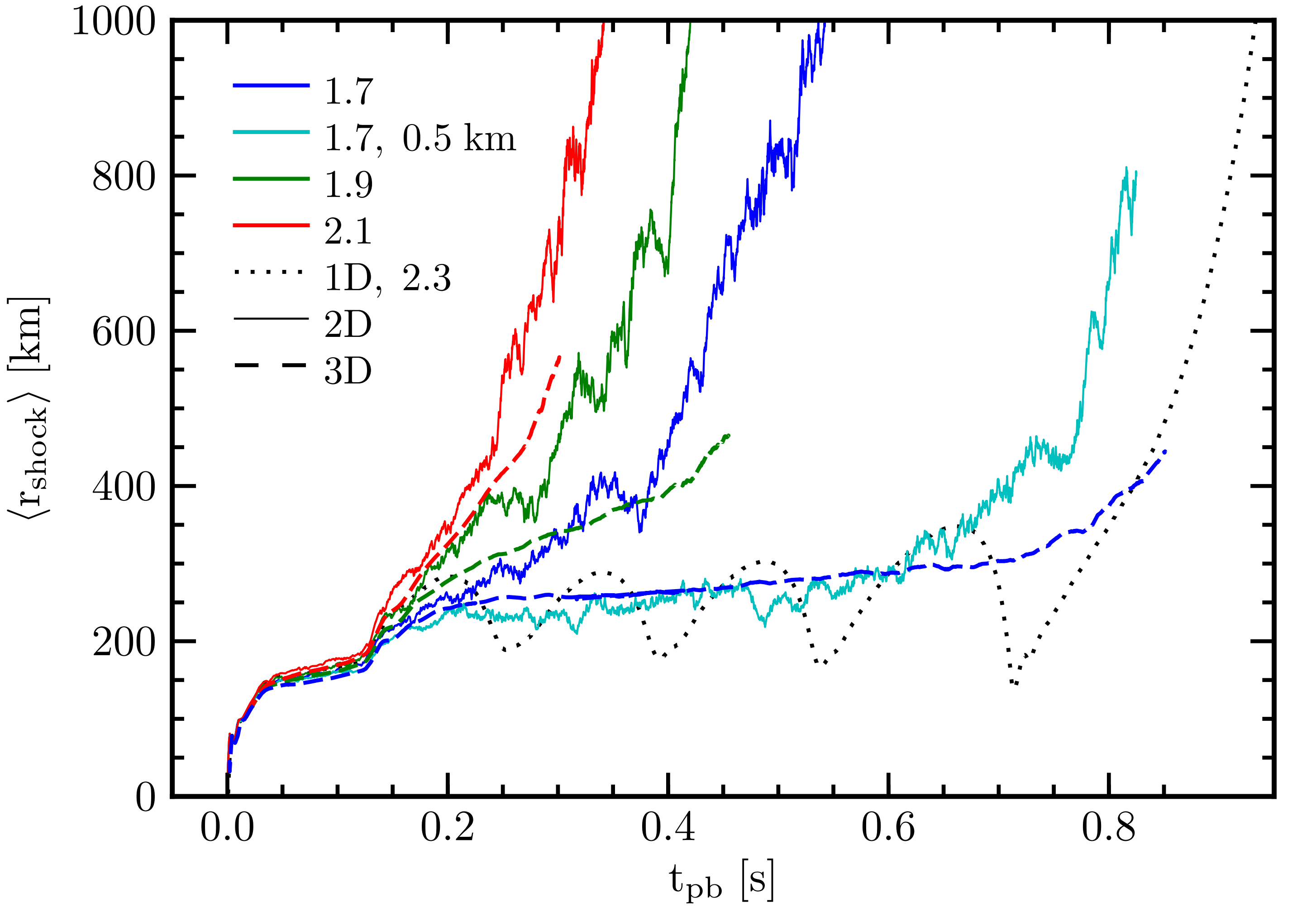
SMC, 2013, ApJ, 775, 35




3D explosions
later than 2D!

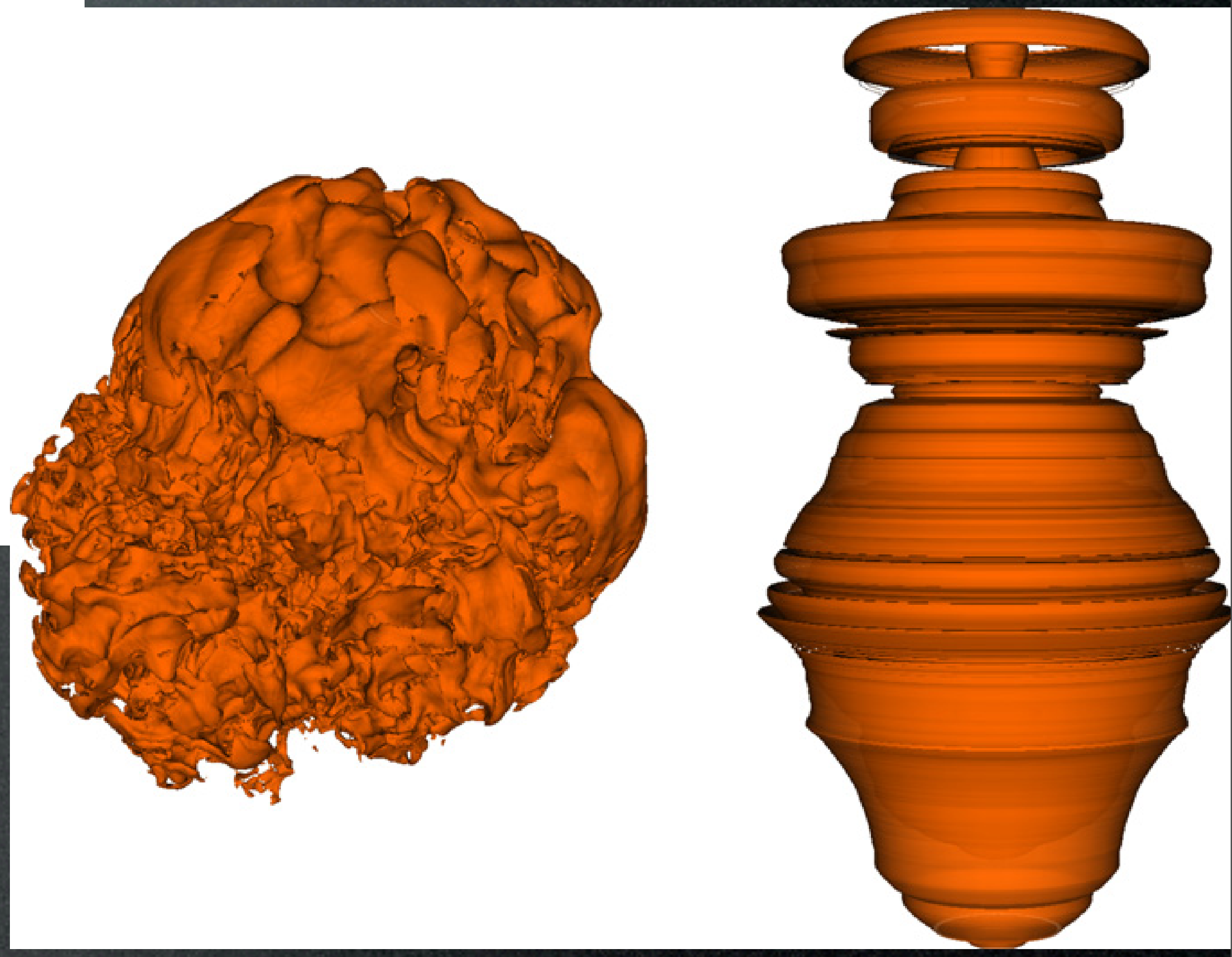
# 3D Parametric Sims

SMC, 2013, ApJ, 775, 35




2D qualitatively, quantitatively very different from 3D!

3D 2D



3D explosions <u>later</u> than 2D!

# Results with $\nu$-Lightbulb

SMC 2013, ApJ, 775, 35

- Nordhaus et al. (2010) and Dolence et al. (2013) find easier explosion in 3D vs. 2D.
- Result not confirmed by Hanke et al. (2012) who find strong resolution-dependence.
- I find explosion is *harder* in 3D compared with 2D.

# Neutrino Leakage

SMC & E. O'Connor, arXiv:1310.5728,
SMC & C. Ott, ApJL, 778, L7

- Not transport, but approximates the results of transport *much* better than lightbulb.
- Cooling, number emission/absorption due to electron neutrinos /antineutrinos, and heavy-lepton neutrinos.
- Heating due to electron neutrino/ antineutrinos.

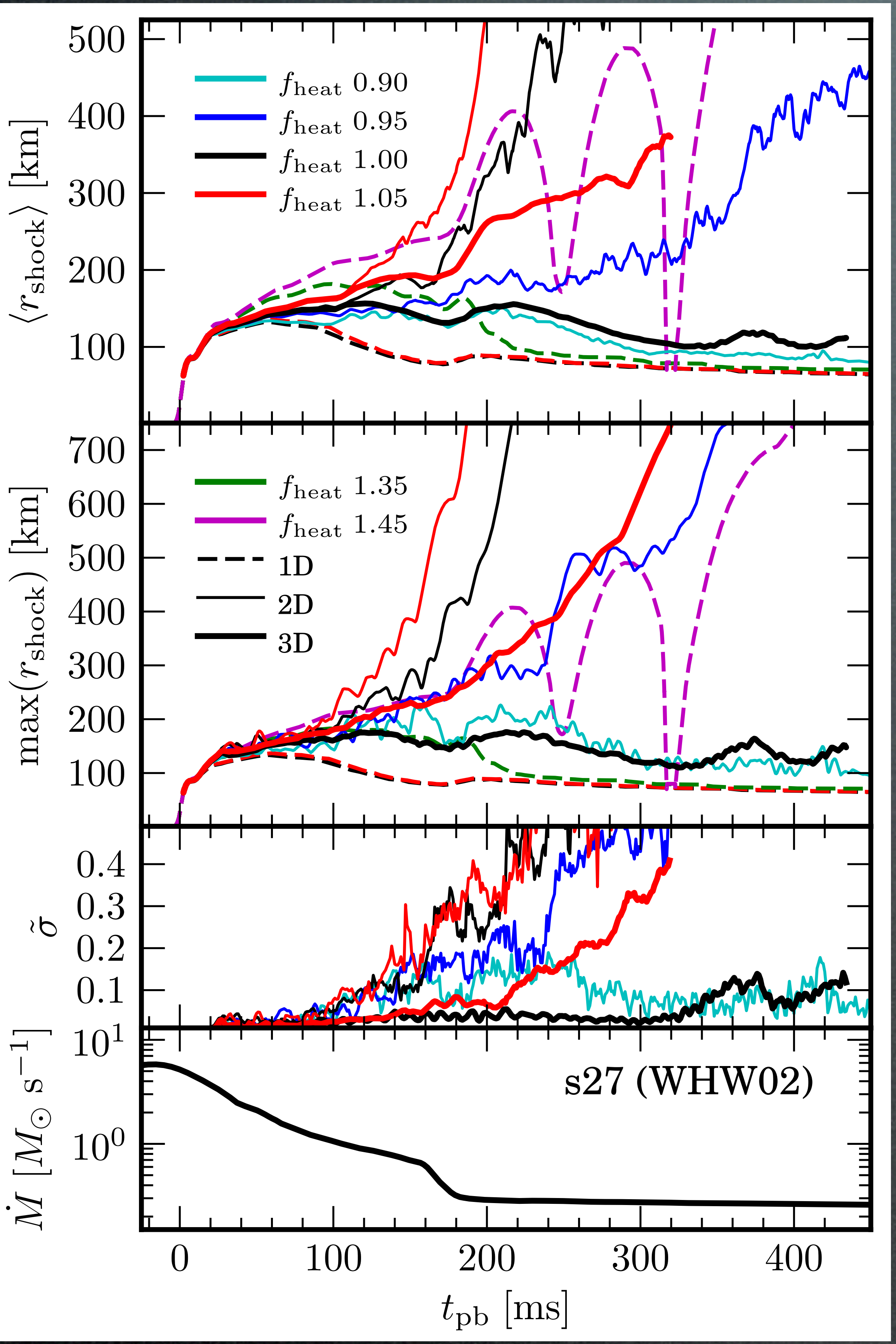
# 3D FLASH Leakage Sims

SMC & E. O'Connor, arXiv:1310.5728,
SMC & C. Ott, ApJL, 778, L7

- 3D Cartesian with AMR in FLASH.
- 0.49 km resolution up to r ~ 100 km.
- Beyond 100 km, "angular" resolution of 0.43 degrees.
- 37x75x1000, θ-ϕ-r resolution for leakage rays.
- Multipole gravity of SMC, Graziani, & Flocke (2013, ApJ, 778, 181).
- Lattimer & Swesty EOS (K=220 MeV).

# Multi-D Results for s27

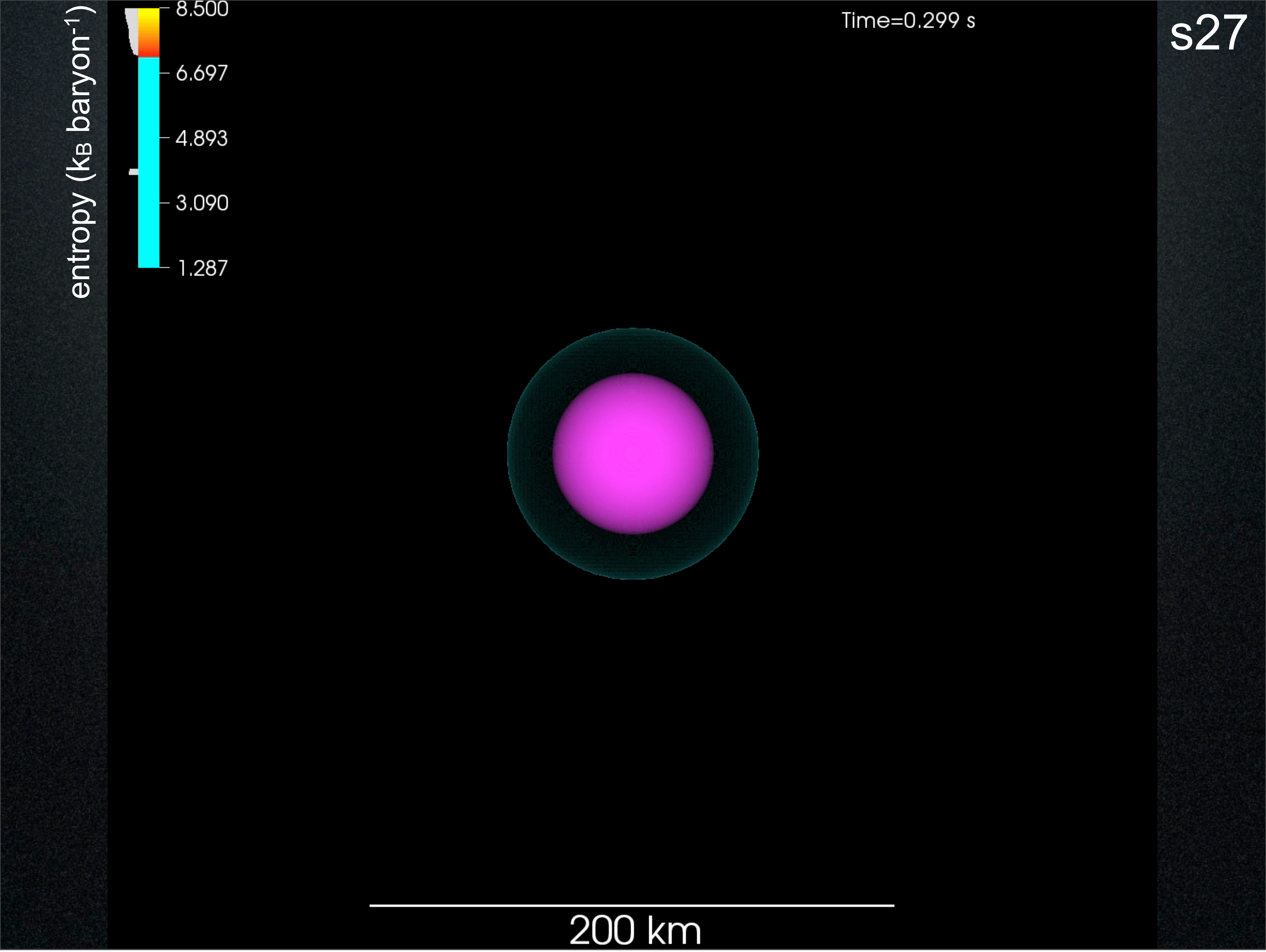
SMC & E. O'Connor, arXiv:1310.5728



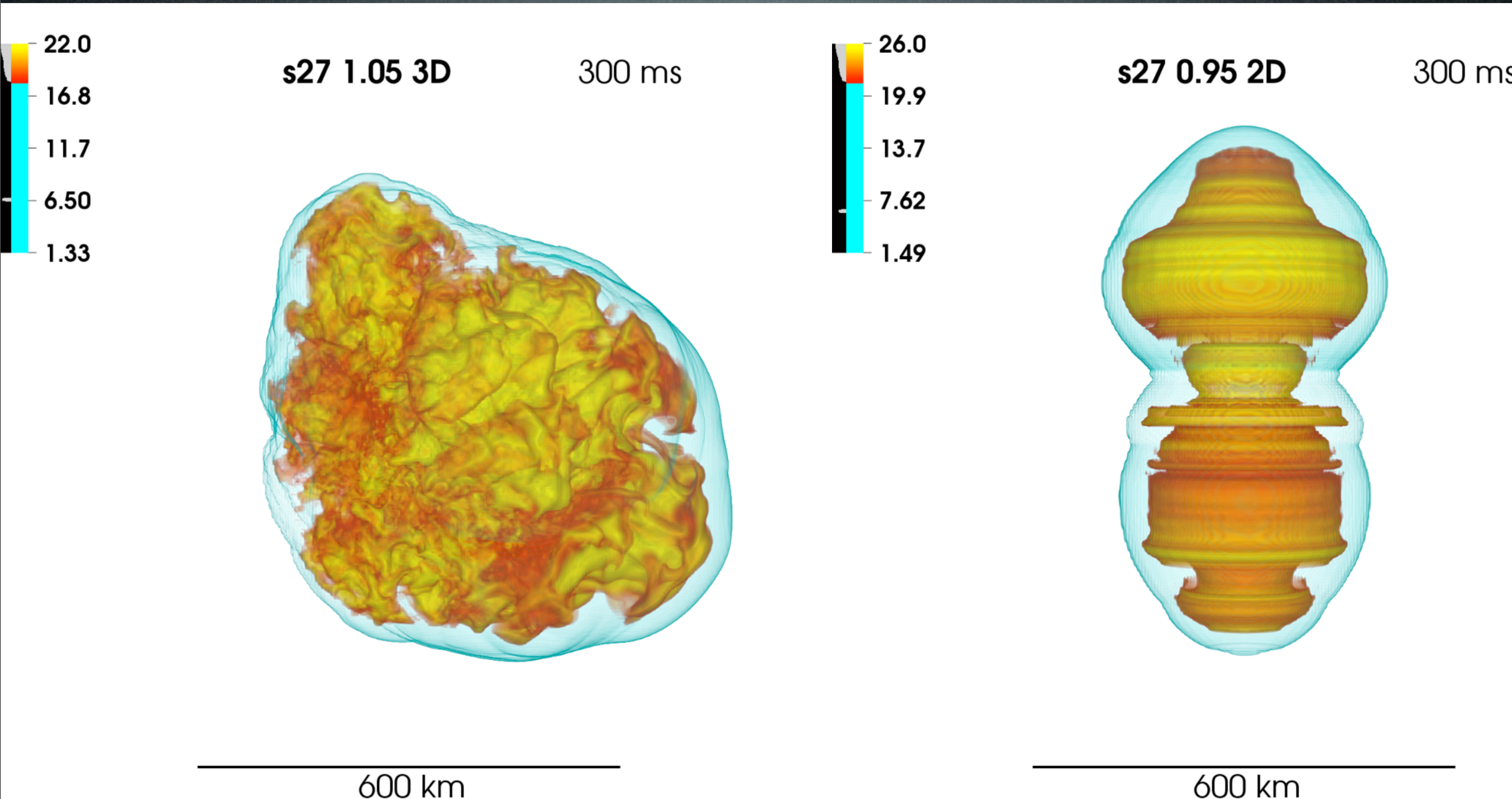

$$Q_{\nu_i} = \boxed{f_{\rm heat}} \frac{L_{\nu_i}(r)}{4\pi r^2} \left\langle \frac{1}{F_{\nu_i}} \right\rangle \sigma_{\nu_i} \frac{\rho X_{(n/p)}}{m_{\rm amu}} e^{-2\tau_{\nu_i}}$$

- 2D explodes for lower heat factor, and more vigorously for same heat factor, than 3D.
- Compare to Hanke et al. (2013).
- Much greater shock asymmetry in 2D.

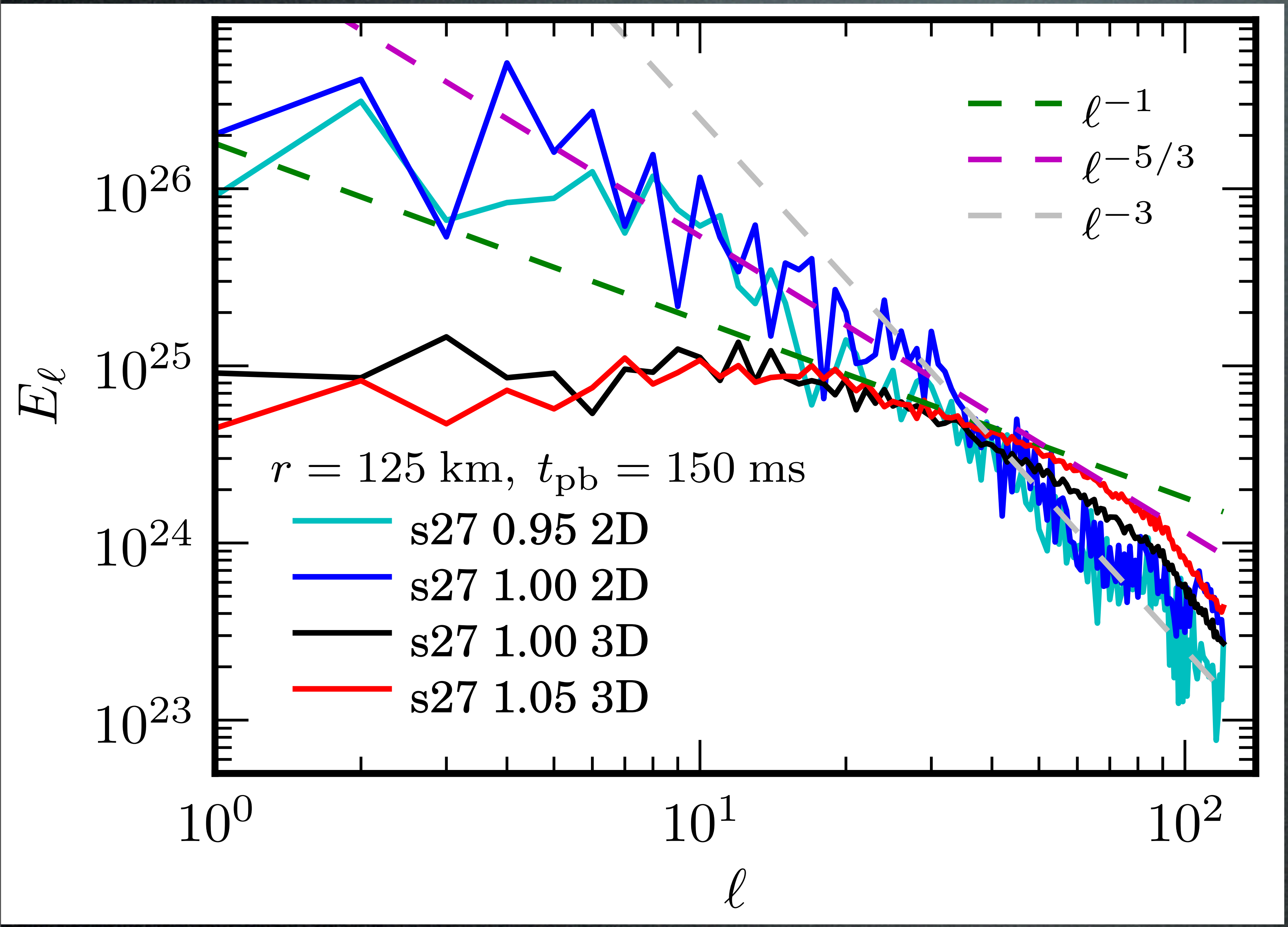
entropy ($k_B$ baryon$^{-1}$)


entropy ($k_B$ baryon$^{-1}$)
8.500
6.697
4.893
3.090
1.287
Time=0.299 s
s27
200 km

# 2D v. 3D


22.0
16.8
11.7
6.50
1.33
s27 1.05 3D
300 ms
600 km
26.0
19.9
13.7
7.62
1.49
s27 0.95 2D
300 ms
600 km

# Turbulent Energy Spectra



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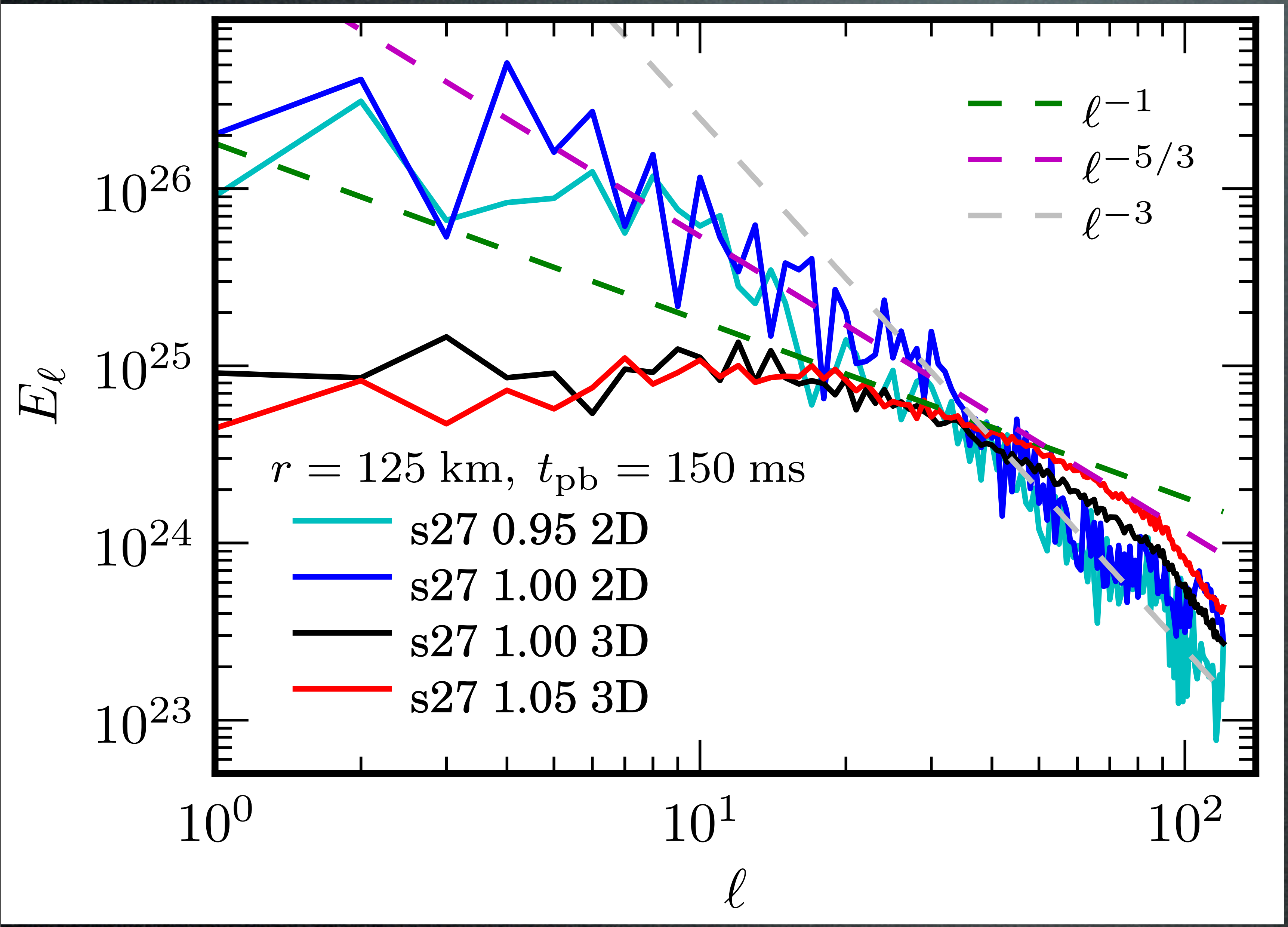


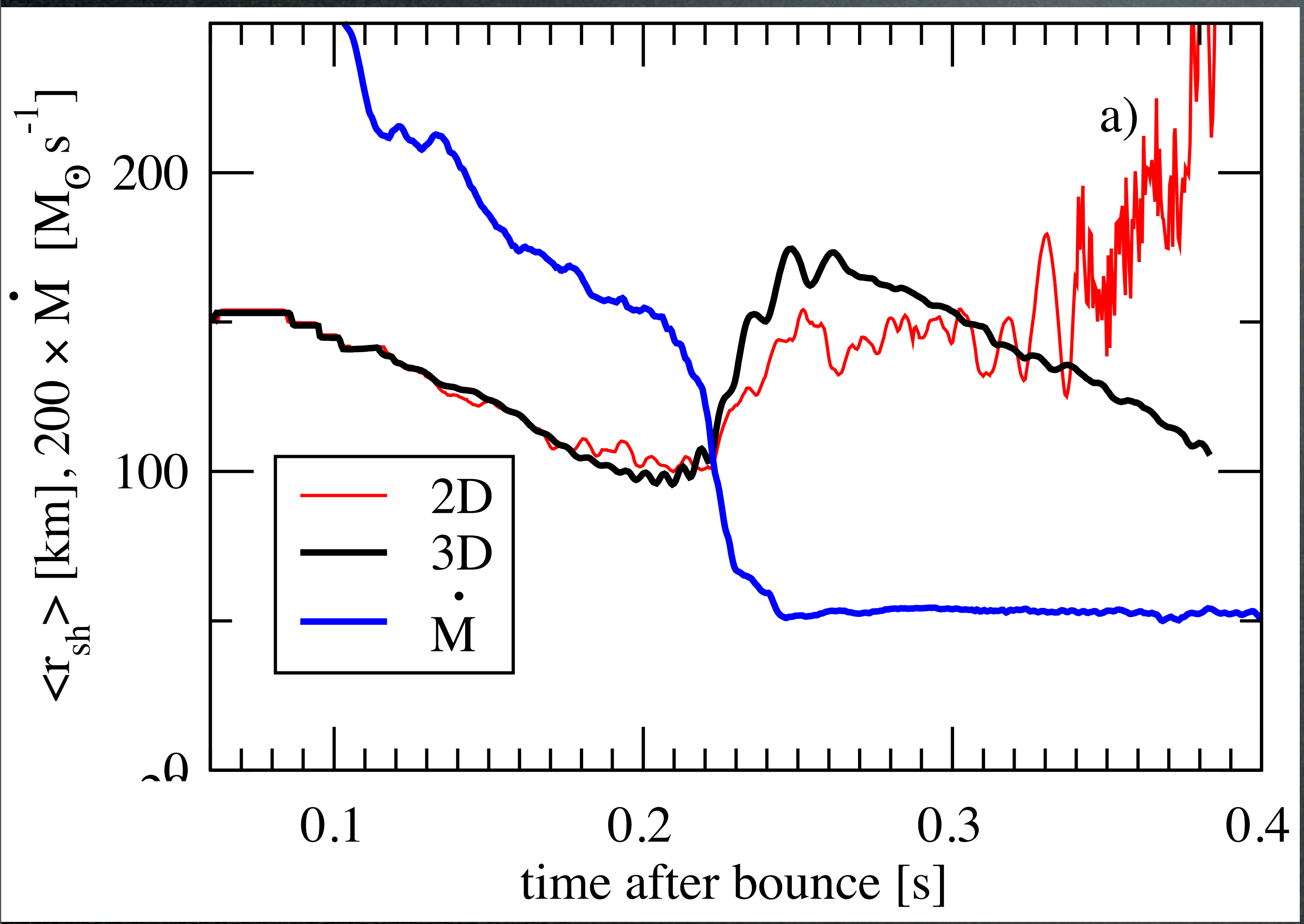

- Early gain-region turb. E
- Much more E in 2D at large scales!
- Inverse cascade causes crucial differences.

# 2D v. 3D

- 2D explodes more easily and vigorously than 3D (see also Couch 2013, Hanke et al. 2013, Takiwaki et al. 2013).
- 2D symmetry axis encourages artificial growth of both SASI and convection.
- Inverse cascade pumps turbulent energy to large scales in 2D.
- 2D buoyant plumes remain larger (ring-like).

# 3D with Full Nu Transport

## Hanke et al. (2013, ApJ, 770, 66)

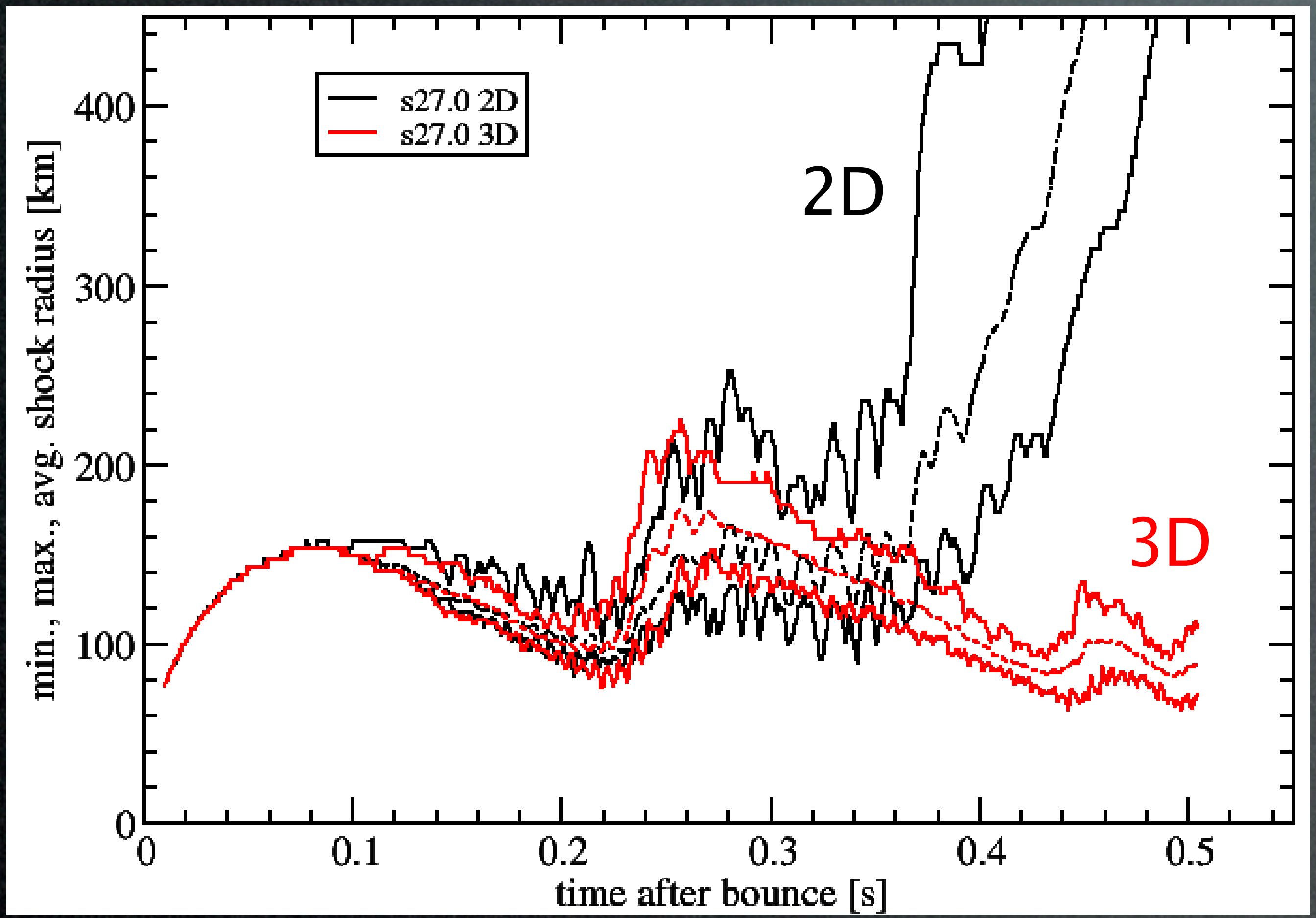


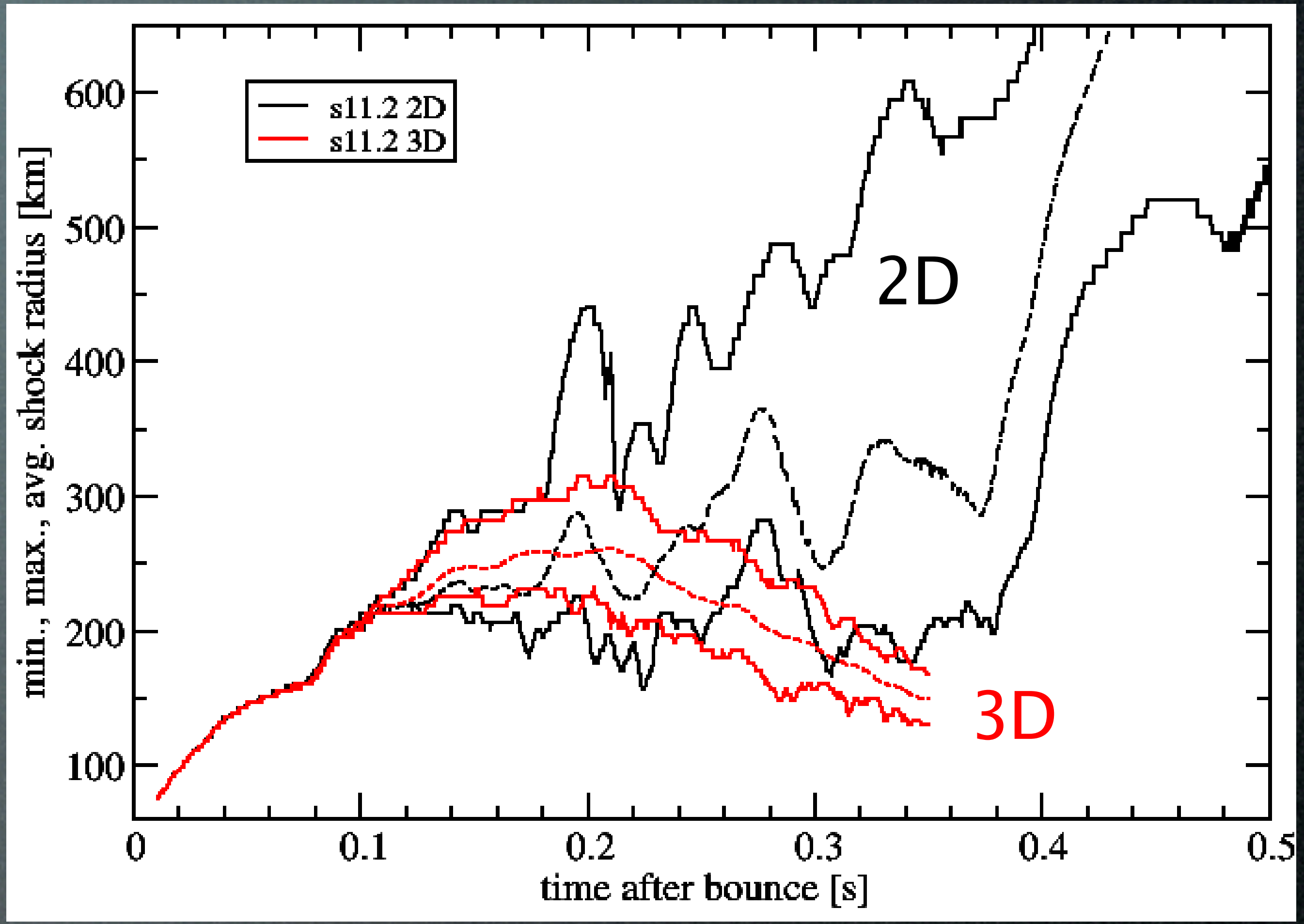


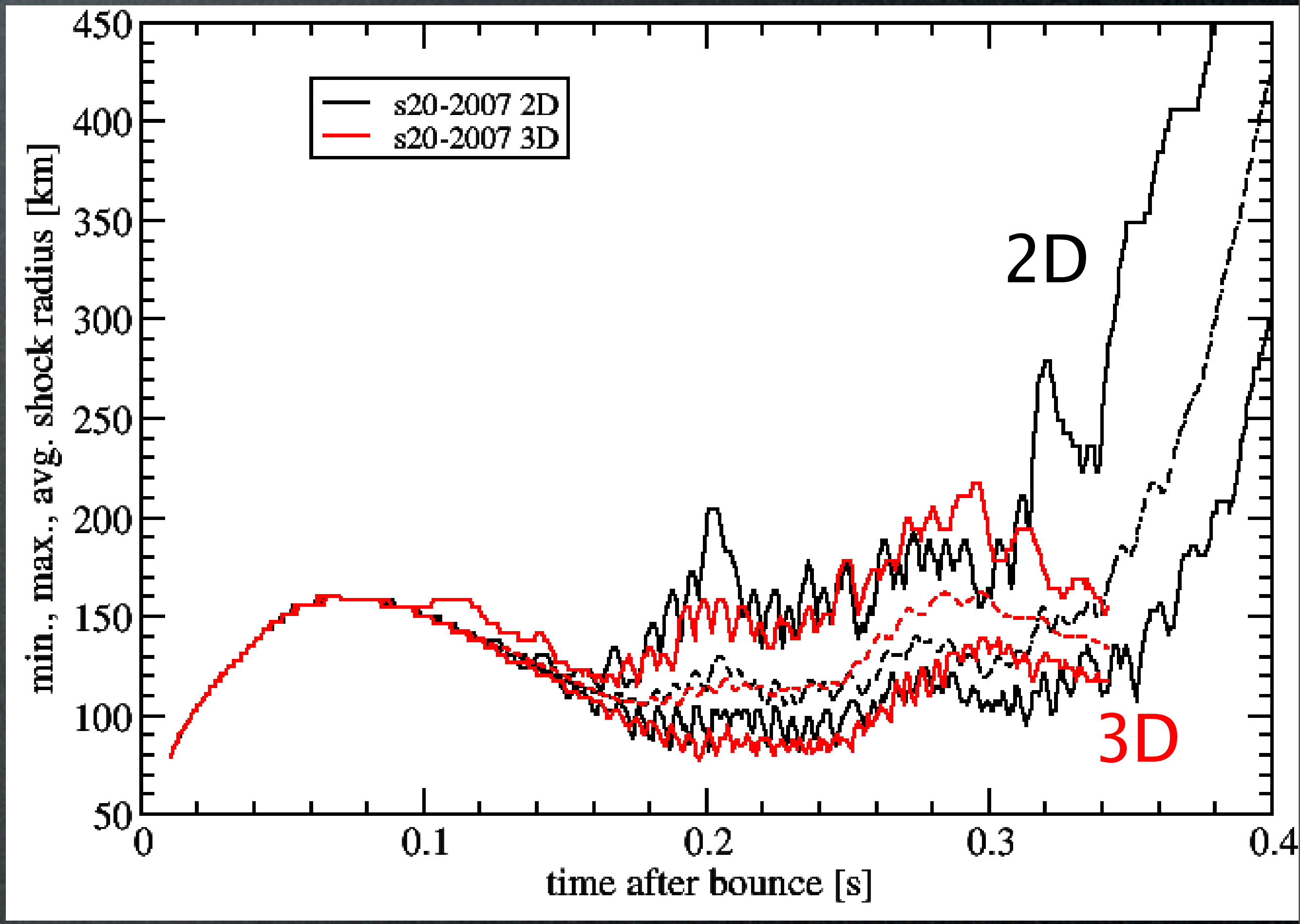
- 3D does not blow up but 2D does!!
- But...Low-resolution could impact results.

# 3D with Full Nu Transport

Hanke et al. (in prep.)



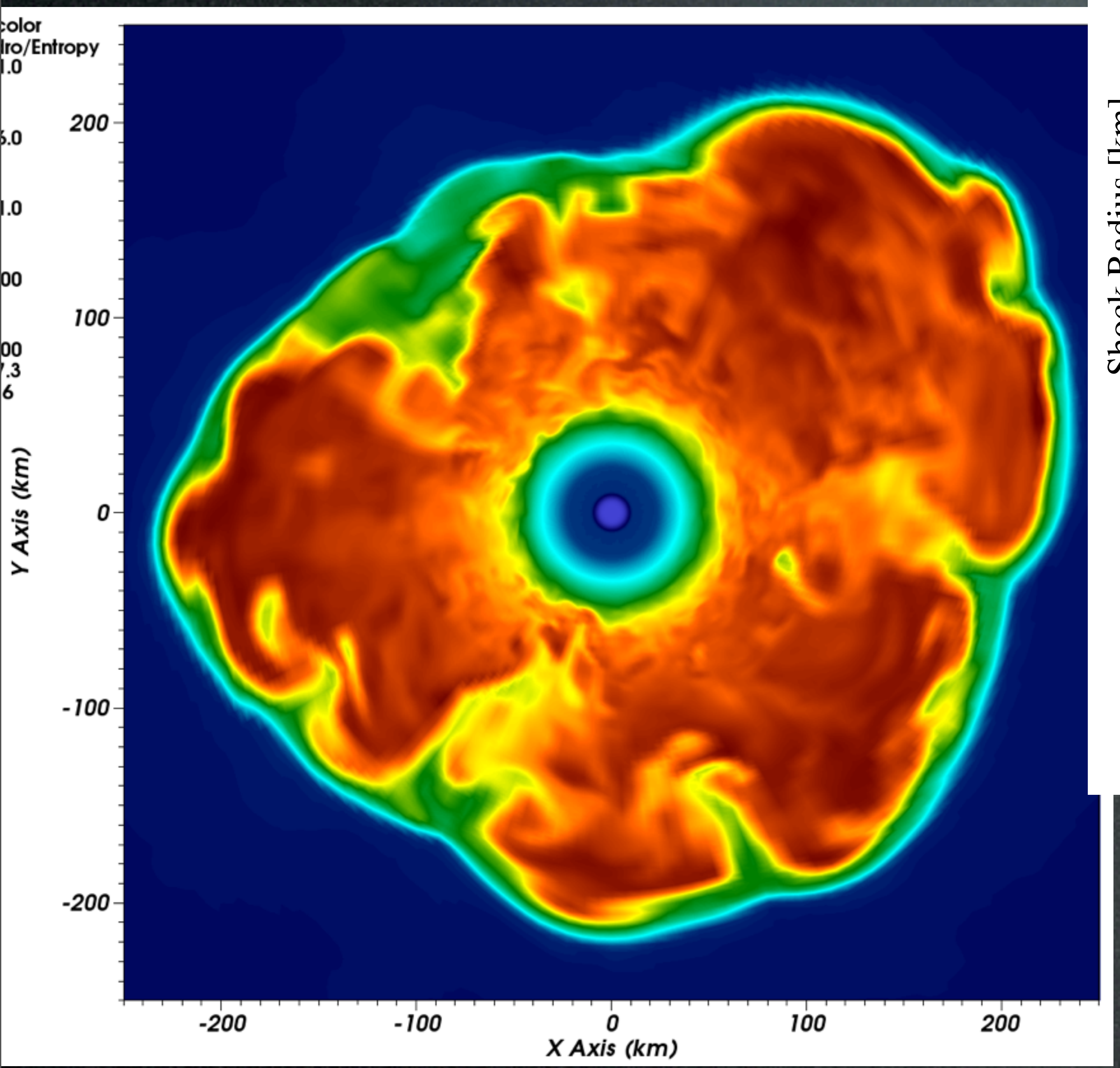



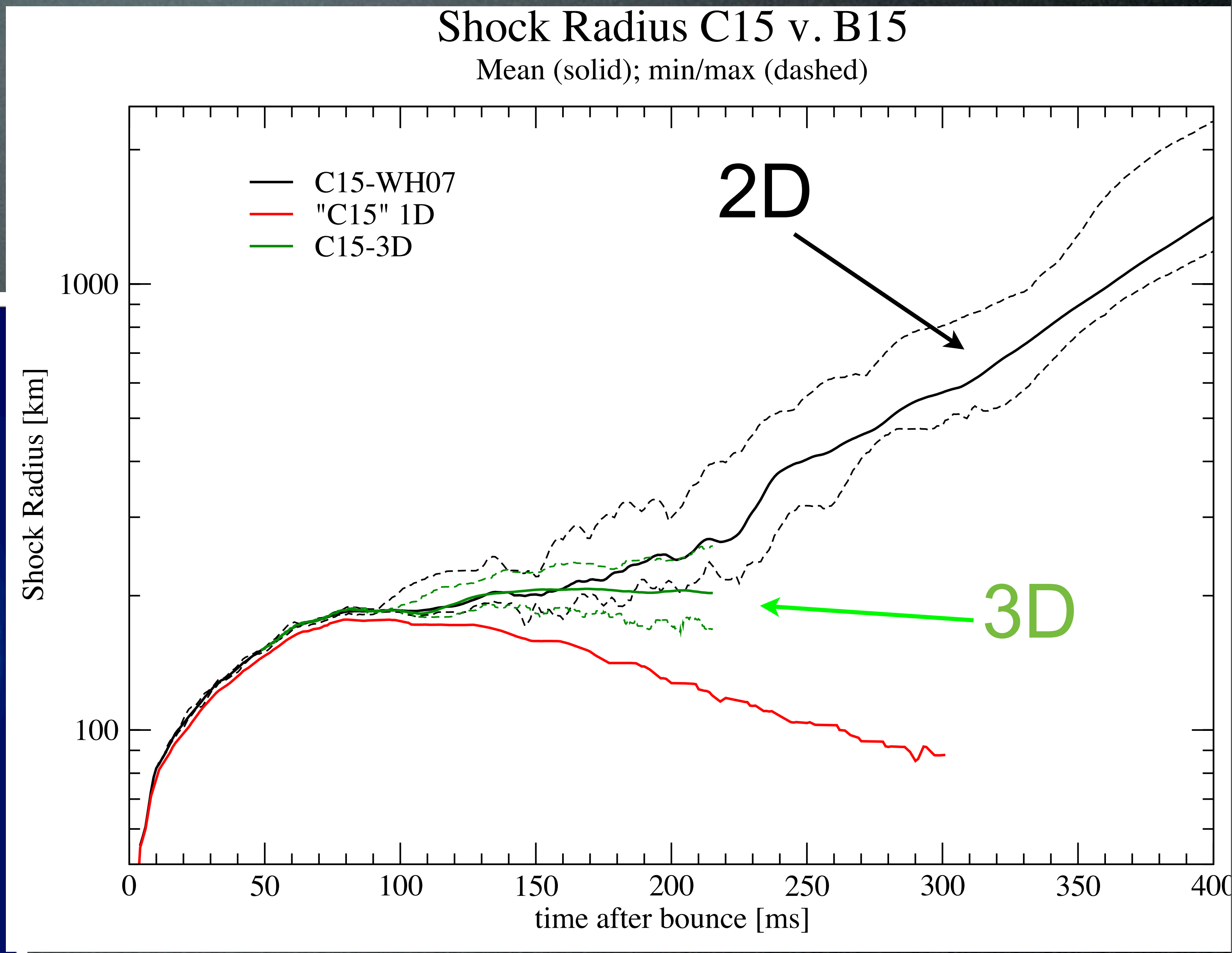

No 3D explosions!

# 3D with Full Nu Transport

## Lentz et al. (in prep.)

Results from Oak Ridge Group



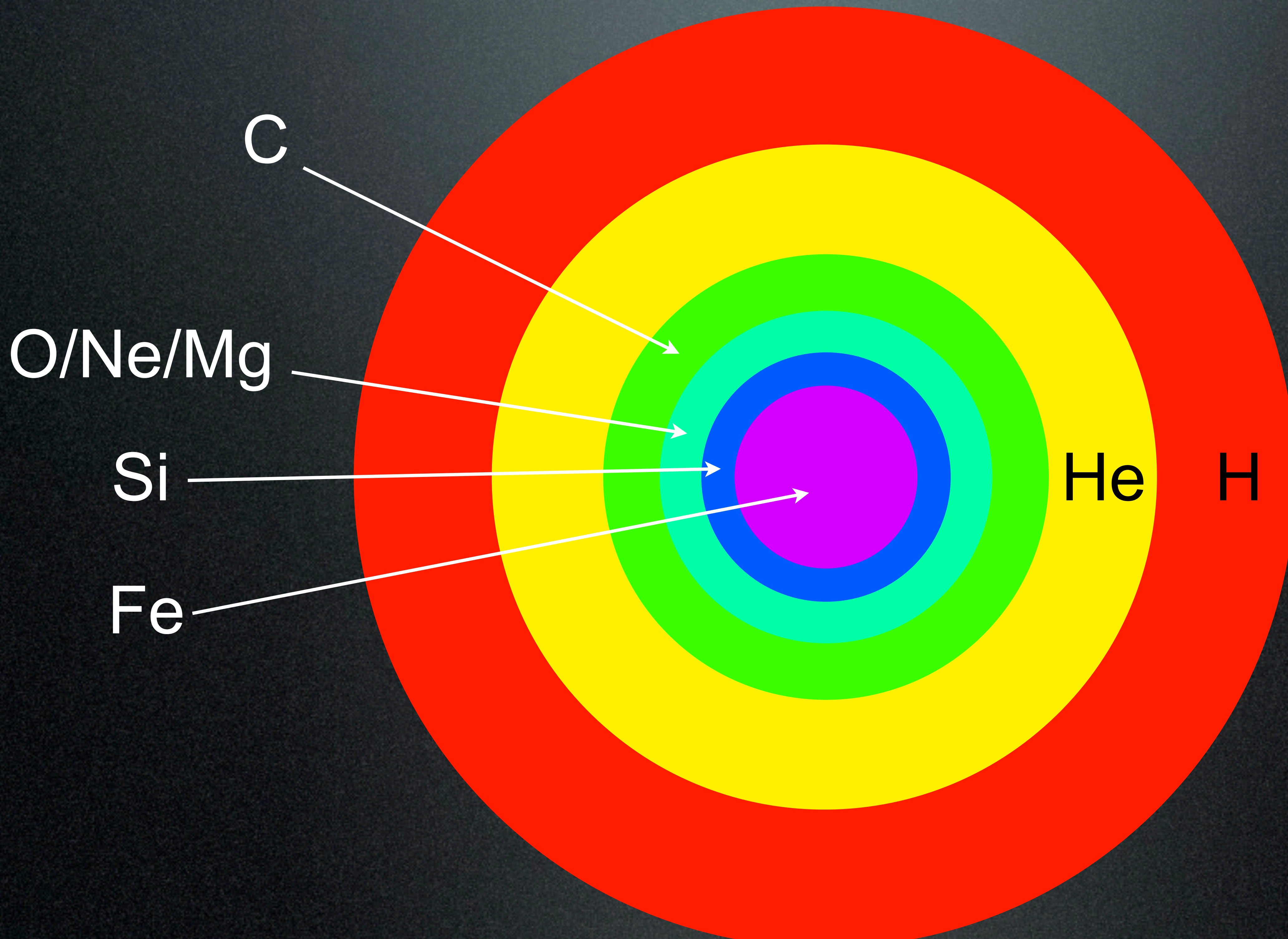




3D hasn't exploded...yet.

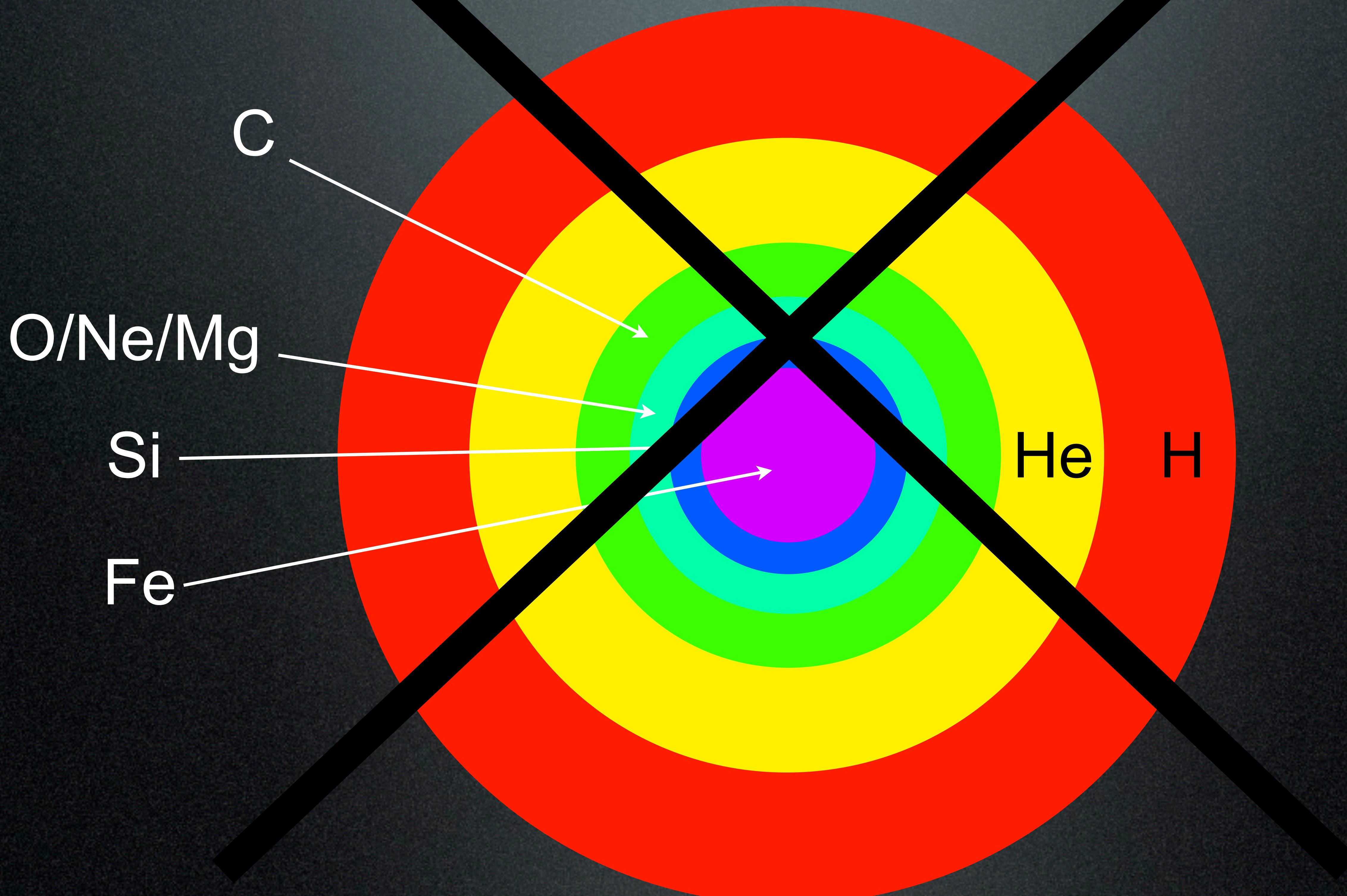
# Neutrinos in Trouble?

- Lack of 3D explosions is telling us we are missing physics, or getting the physics wrong...
- Possibilities:
  - Progenitor structure
  - MHD/rotation (e.g., Dessart et al. 2008)
  - Neutrino effects (i.e., flavor swap, x-sections)
  - Equation of state
- But... neutrino effects may not be likely...

# Massive Stellar Evolution: A Solved Problem

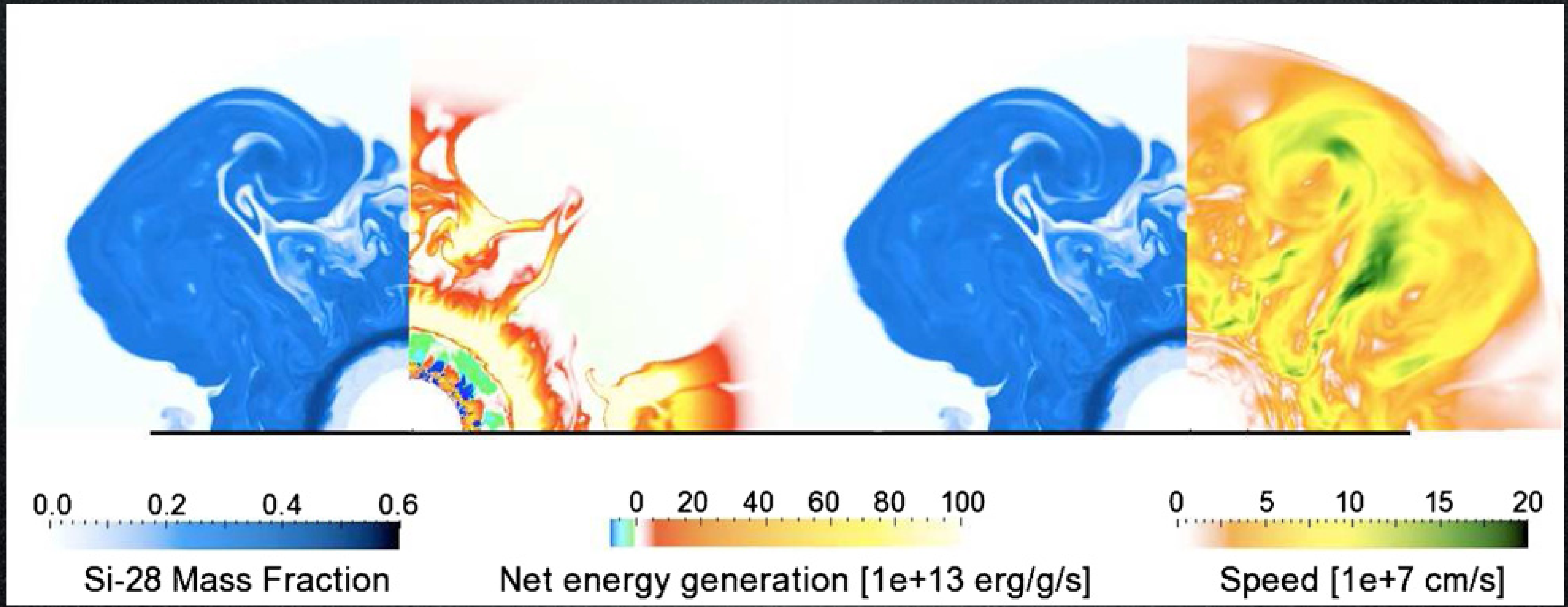


# Massive Stellar Evolution: A Solved Problem



# Real Stars Are Not Spherical

- Essentially spherical IC's assumed in sims.
- Late convective burning is violent and strong.
- Large perturbations exist upon collapse.
- What effect will this have on the mechanism?

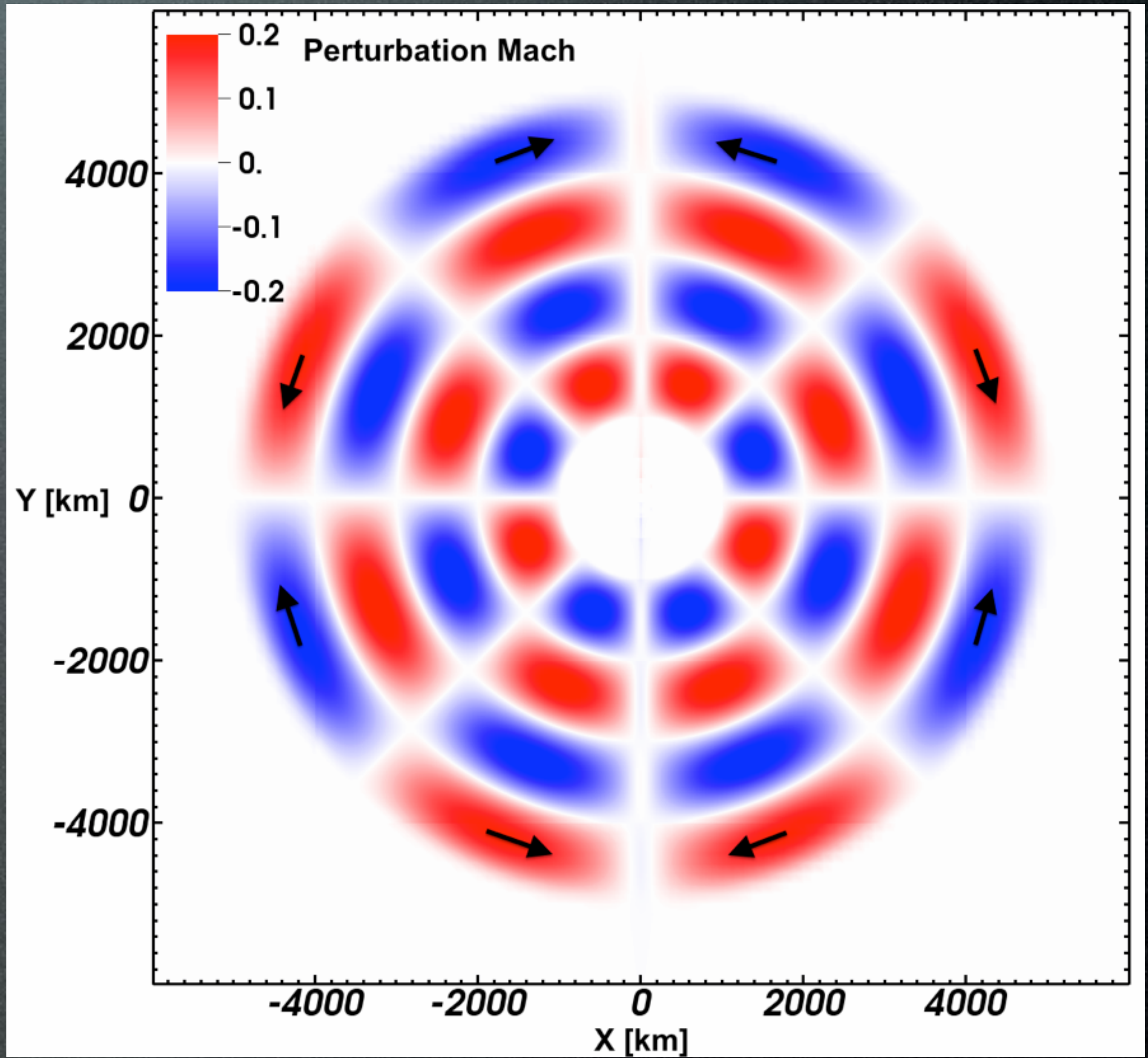



Arnett & Meakin (2011, ApJ, 733, 78)

# Progenitor Asphericity

SMC & C. Ott (2013, ApJL, 778, L7)

- Perturb tangential velocities in Si/O shell.
- Simple convolution of sinusoids.
- Peak amplitudes chosen from Arnett & Meakin (2011).
- Added $E_k < 10^{-4}$ of $E_i$!

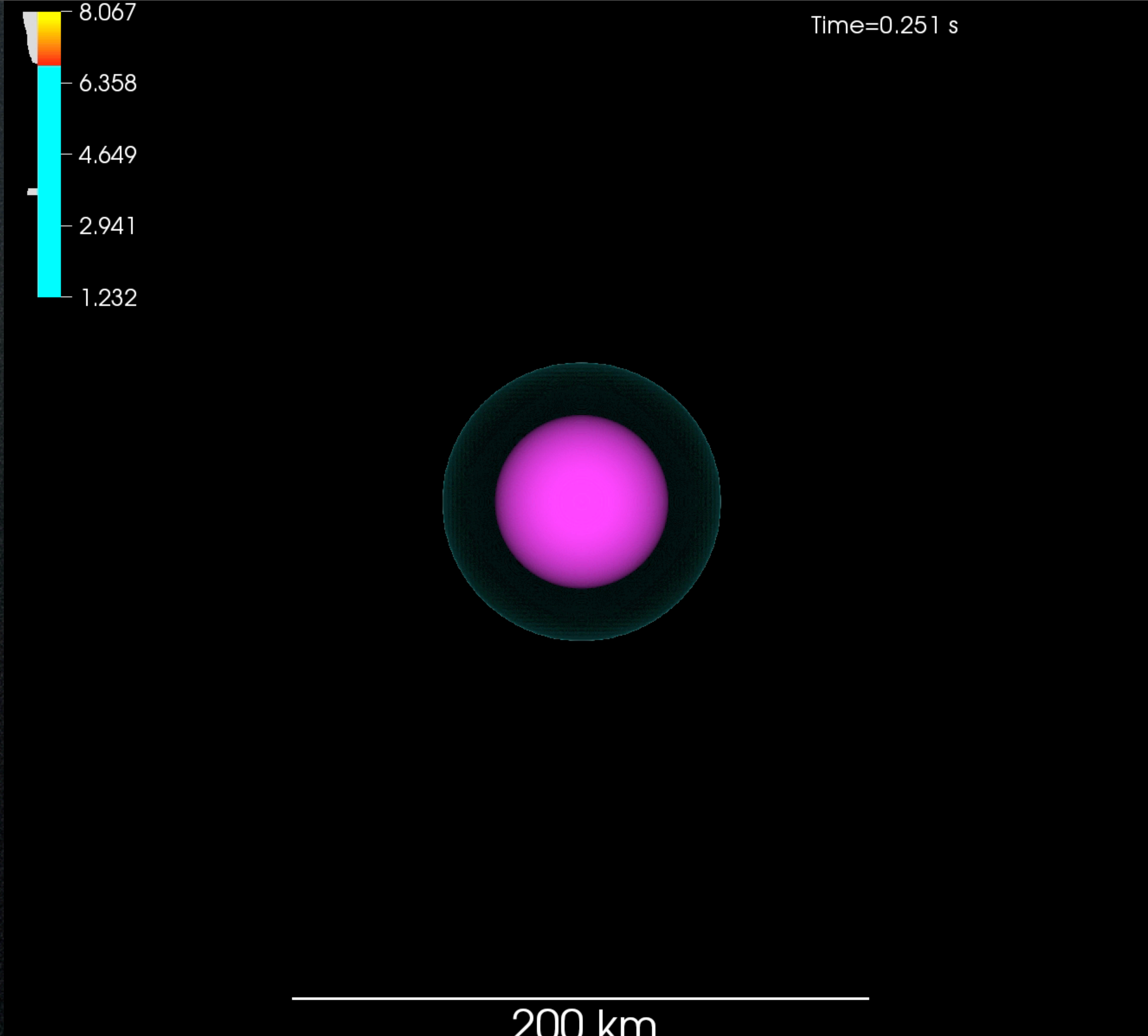


s15

entropy ($k_B$ baryon$^{-1}$)

Unperturbed

entropy ($k_B$ baryon$^{-1}$)



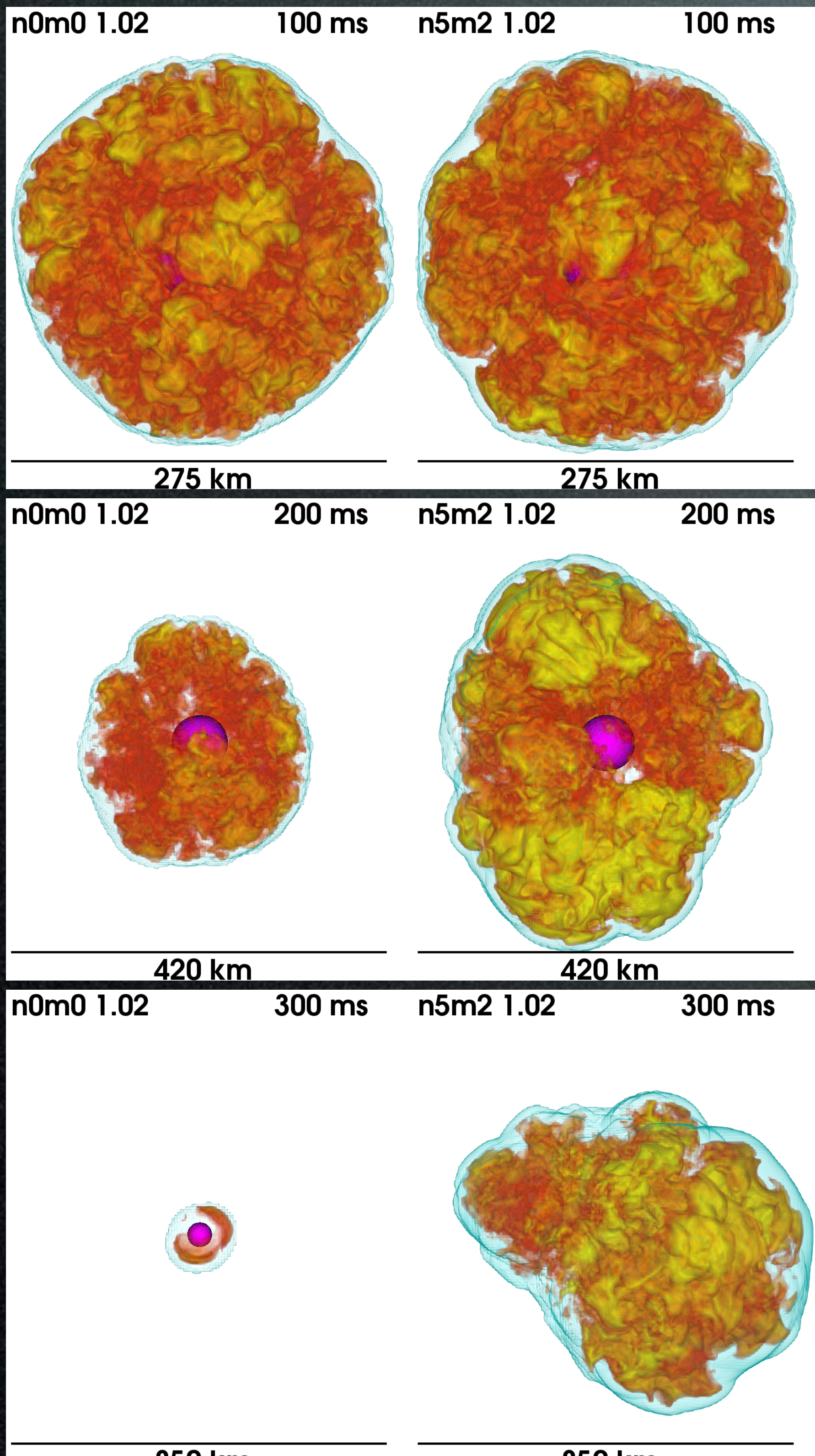

s15

Unperturbed

# Triggered Explosion

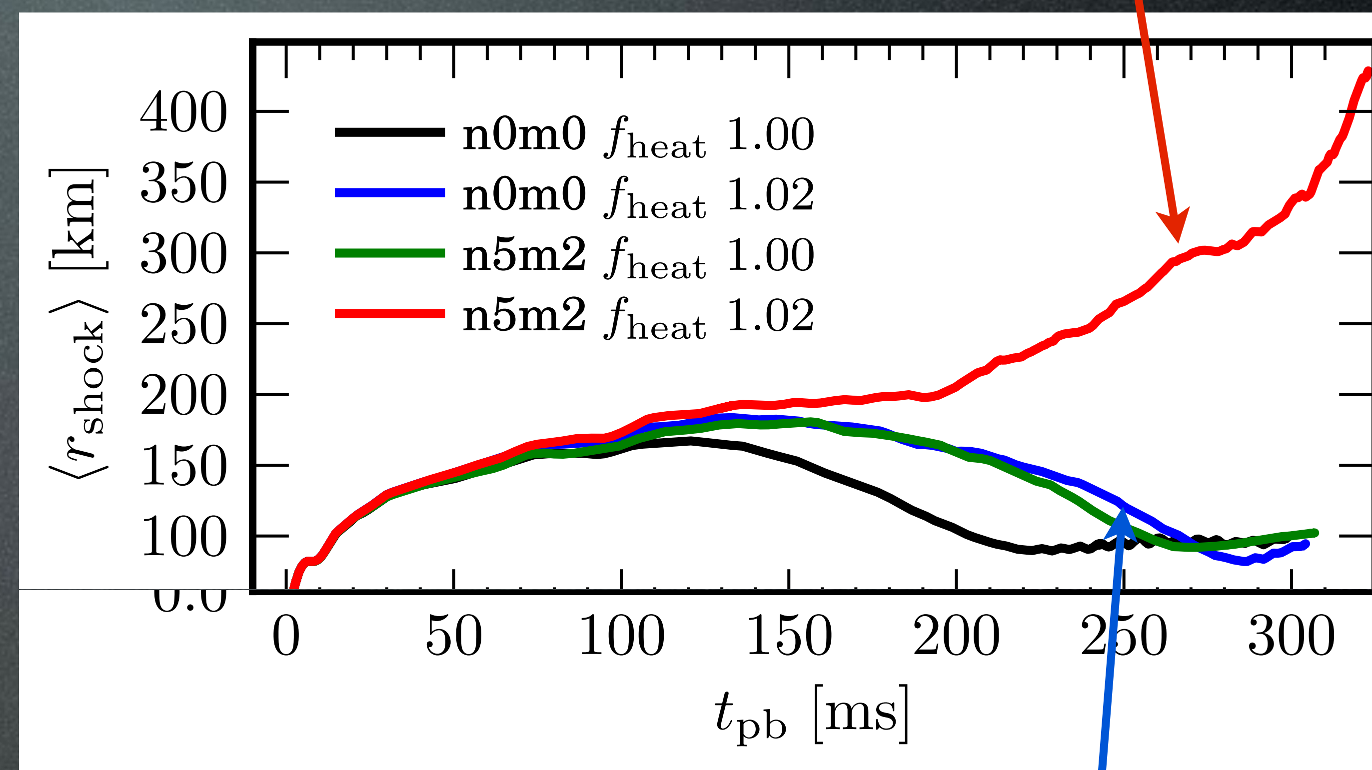
SMC & C. Ott (2013, ApJL, 778, L7)

Unperturbed




Perturbed

Perturbed

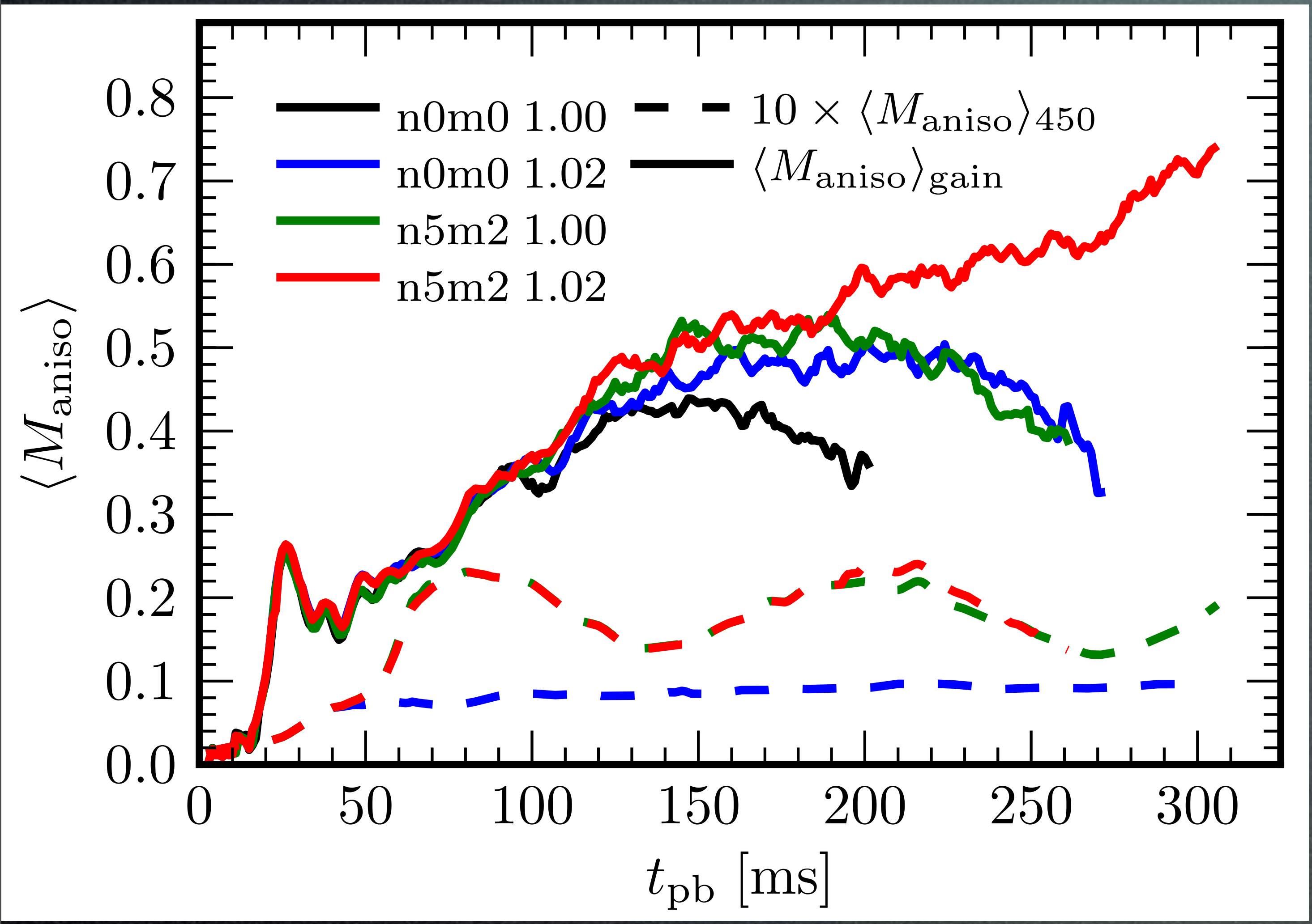



Unperturbed

Some extra, artificial heating still needed!

# Enhanced Anisotropic Motion

SMC & C. Ott (2013, ApJL, 778, L7)



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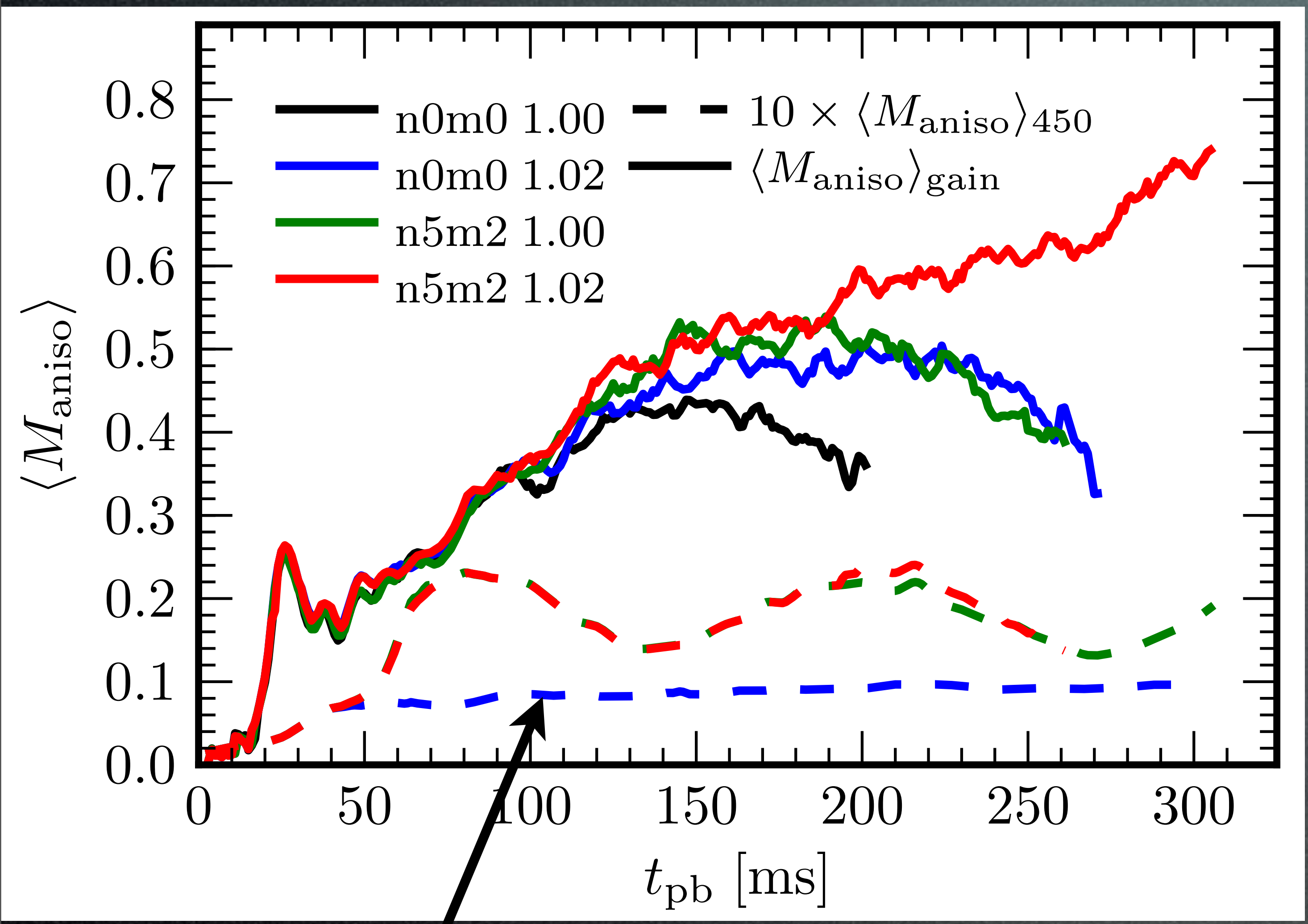
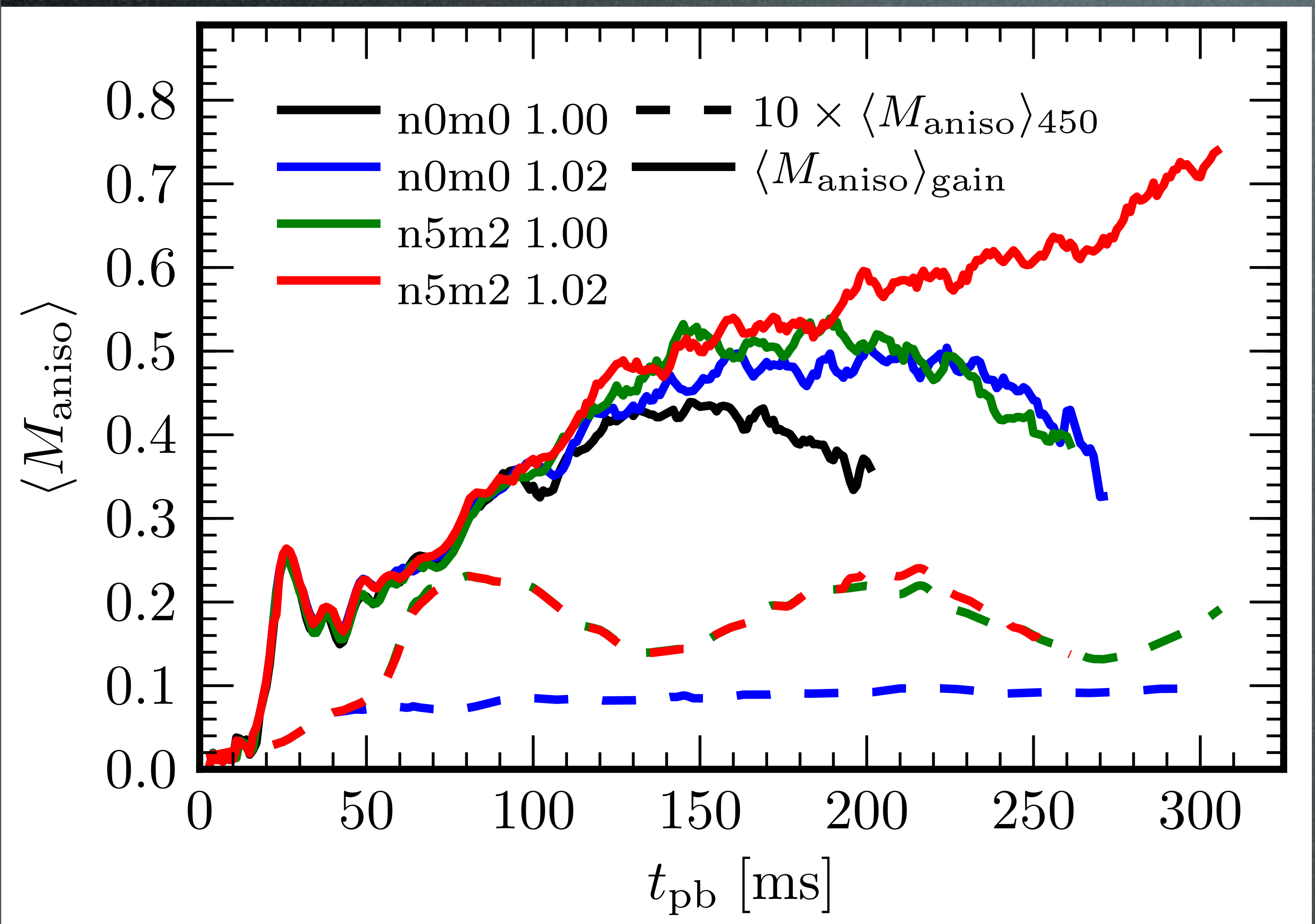
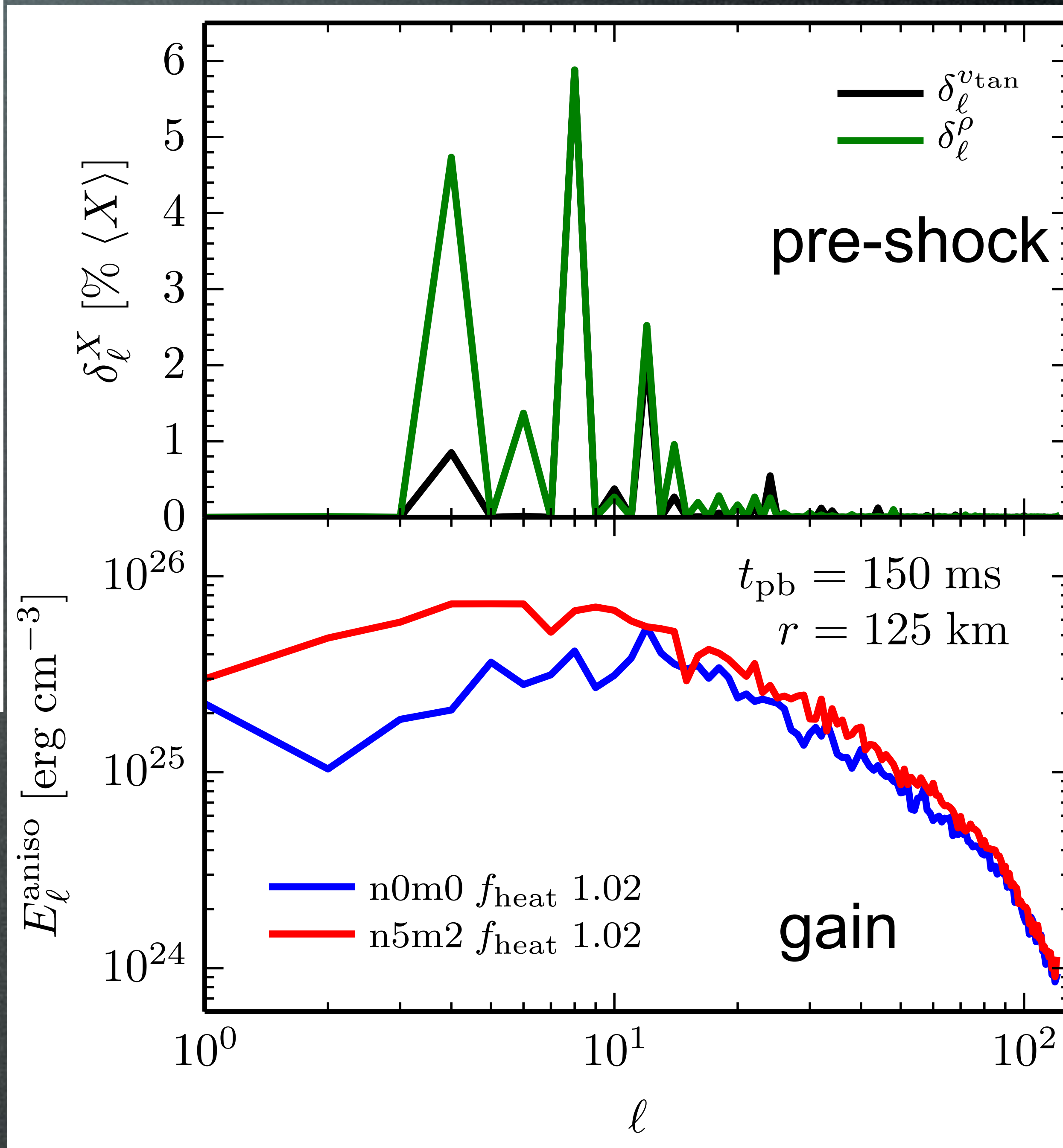



Grid-scale perturbations

# Enhanced Anisotropic Motion

SMC & C. Ott (2013, ApJL, 778, L7)



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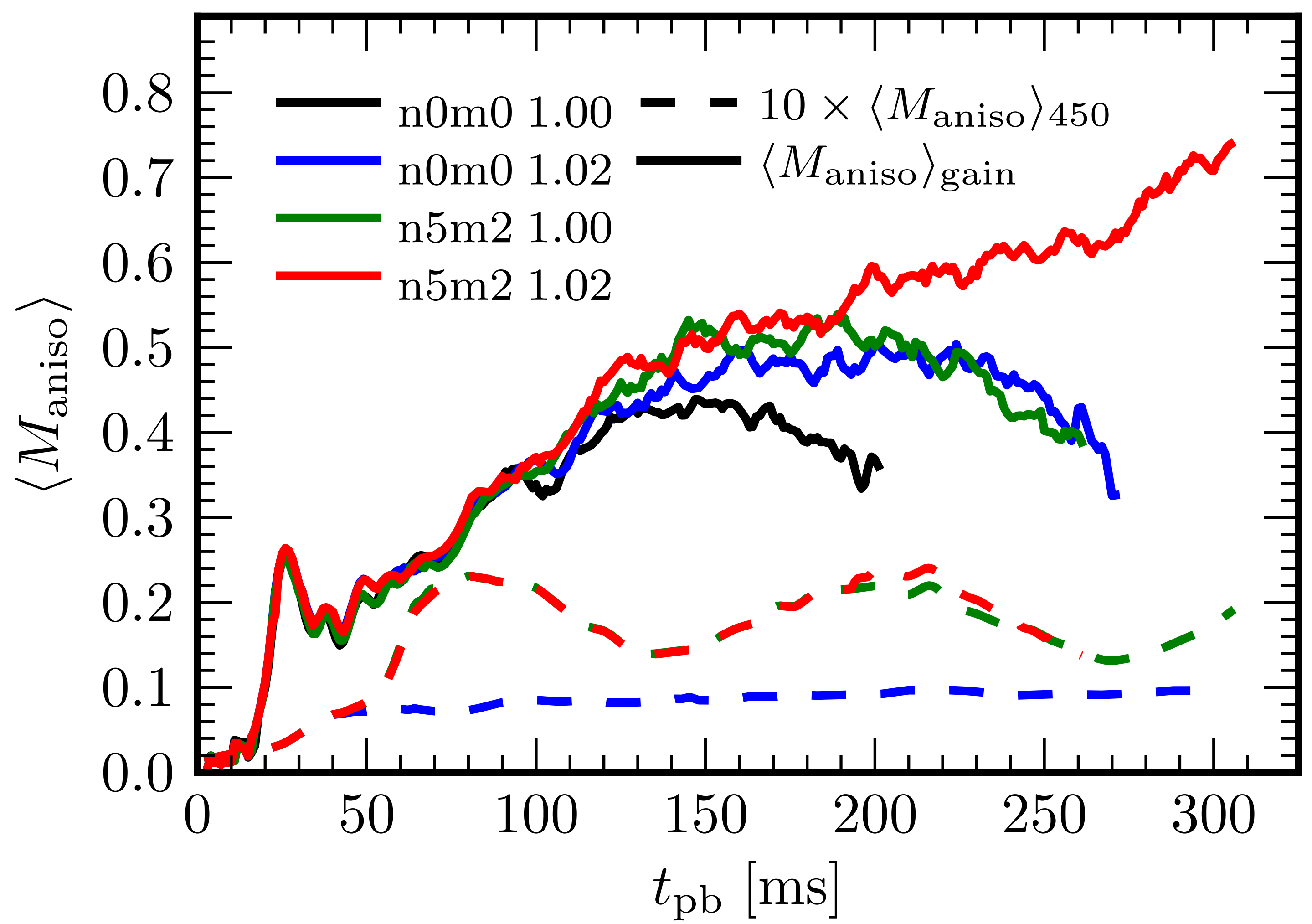
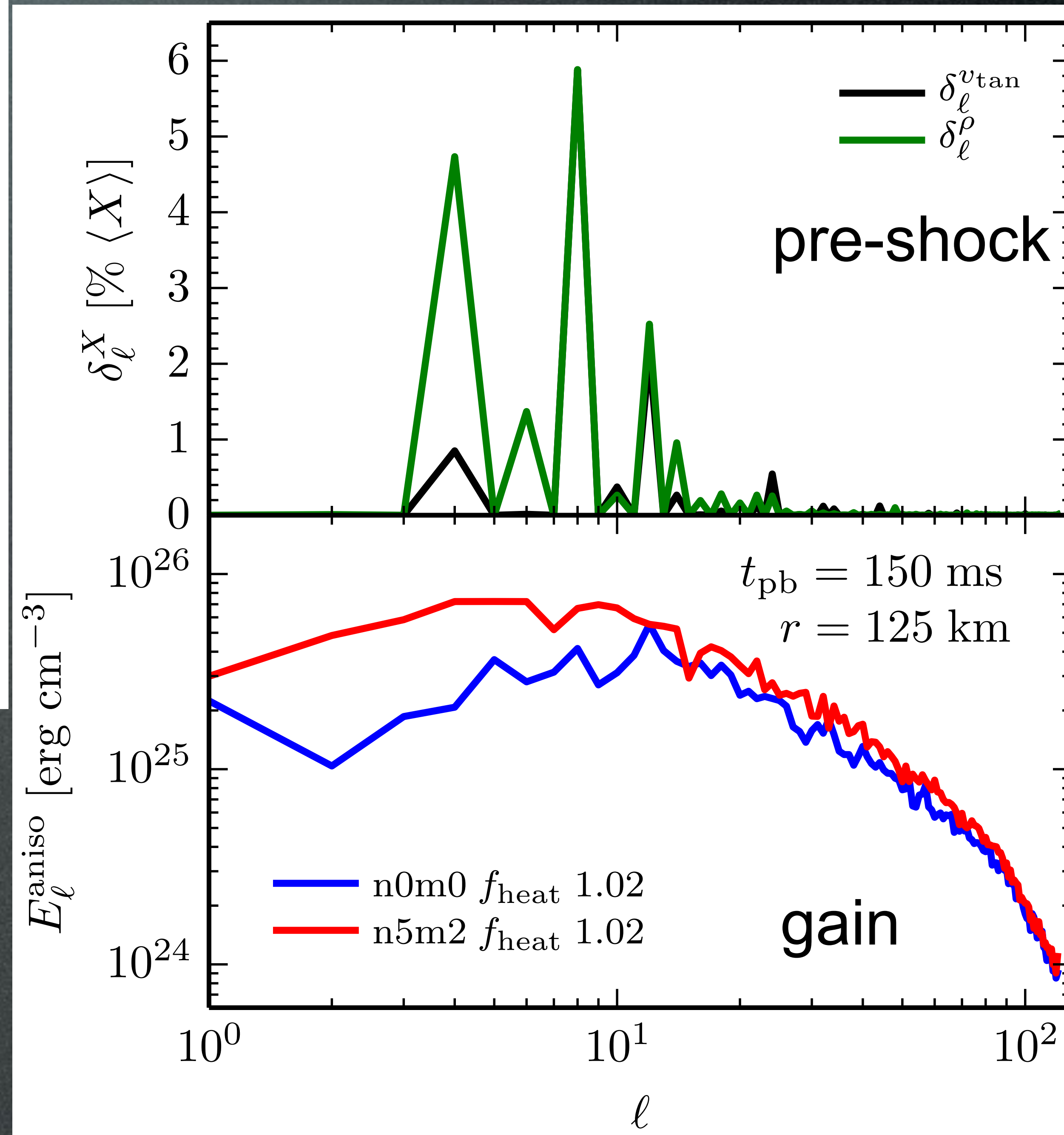



see also Foglizzo et al. 2006, Scheck et al. 2008




Perturbations => stronger turbulence/convection in gain => longer dwell times => more heating => explosion!

# Progenitor Structure Matters

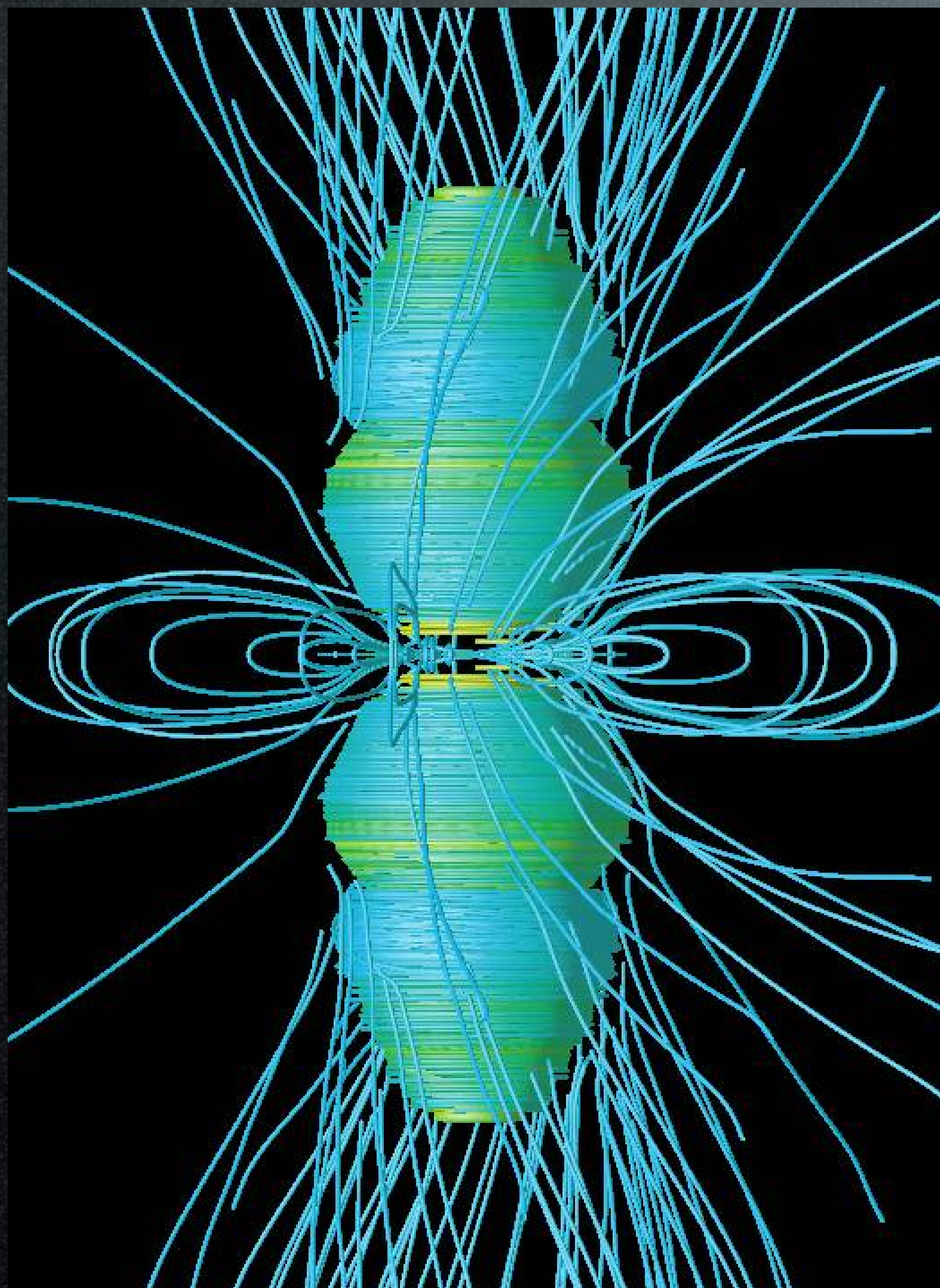
- Progenitor asphericity *qualitatively* alters post-bounce evolution. Can trigger explosions from duds!
  - We need realistic 3D progenitors.
- The CCSN mechanism is essentially an initial value problem!
- In fact, the 1D models we use employ MLT for convection, telling us there are regions of significant asphericity.
  - Thus, using 1D models without perturbations is not truly self-consistent.

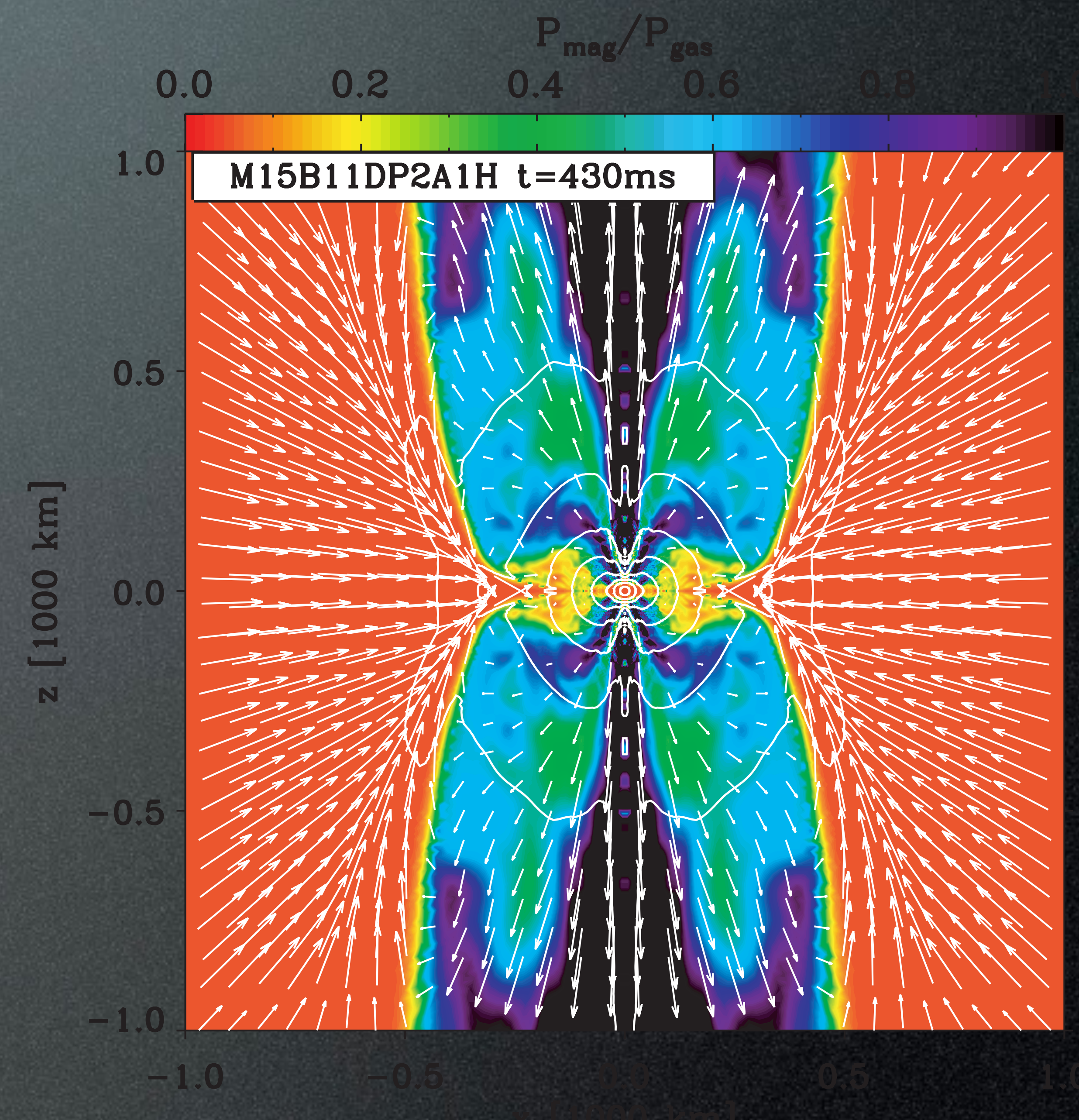
# Magnetorotational Effects

- All stars rotate and have B-fields. How much?
- During & after collapse, MRI will tap rotation E to amplify B & drive turbulence (Akiyama et al. 2003). But how much?
- Saturation field strength could be as high as $10^{16}$ G!
- But... magnetic breaking in stars could slow core rotation (Heger, Woosley & Spruit 2005).
- Could matter for $10^{-4}$ of CCSNe, but what about typical CCSNe?

# Magnetorotational Explosions

Burrows, Dessart, et al. (2007)

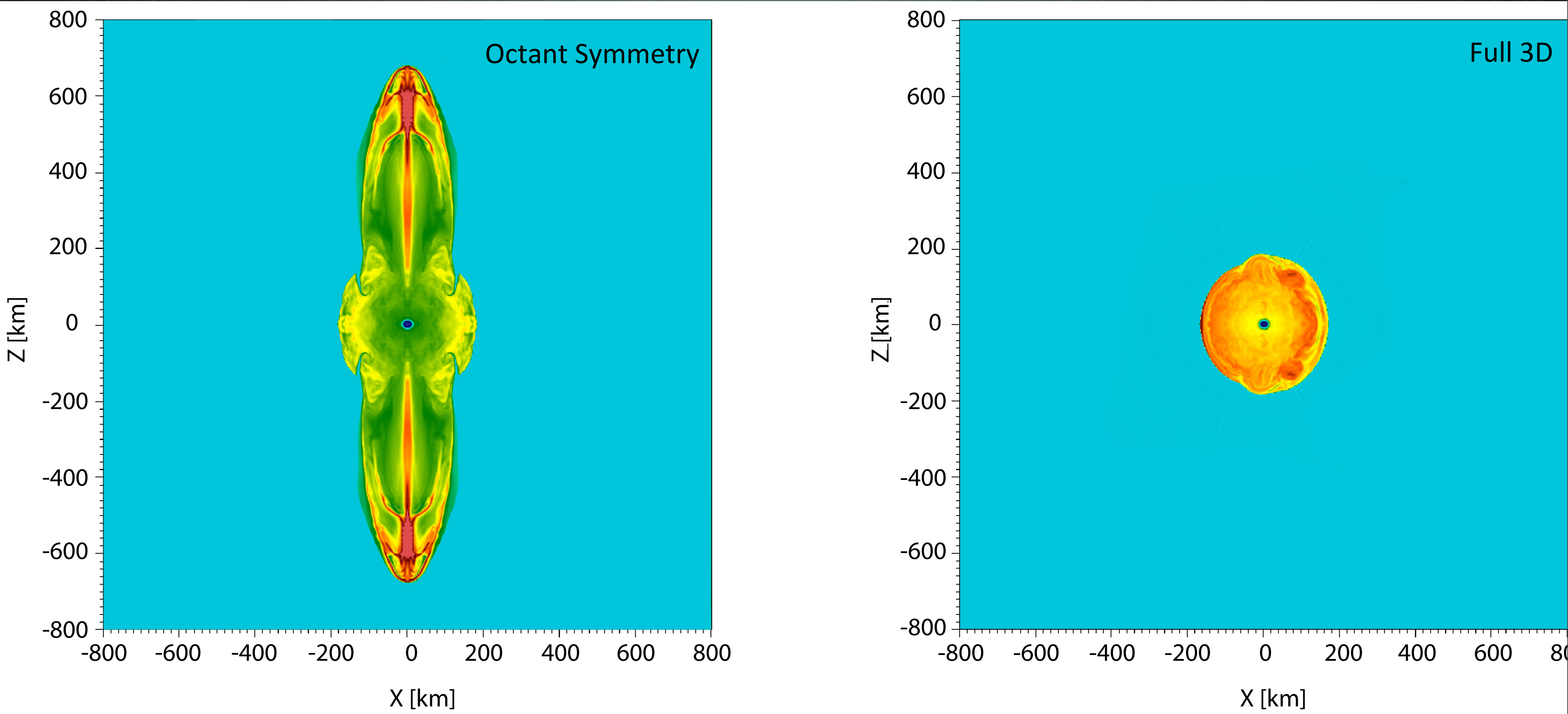




# Jets in 3D?

Moesta, Ott, et al. (in prep.)

(See also Porth, Komissarov, & Keppens 2013)




GRMHD, neutrino leakage, realistic EOS, large B, small P

# At the Edge of Explosion...

- 2D is a poor approximation of 3D; Can't trust quantitative results of 2D!
- Current generation of 3D sims with moderate and high fidelity neutrino treatment fail to explode (without extra heating).
- Progenitor asphericity can trigger explosion in marginal cases; multi-D progenitor structure is crucial!
- MHD effects could matter in typical CCSNe, as well as LGRB progenitors.

# Questions?