Stellar Explosions: Core-collapse Supernovae and Nuclear Theory

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FRIB Theory Alliance Meeting
1 April 2016

We’ve solved the problem once and for all!!

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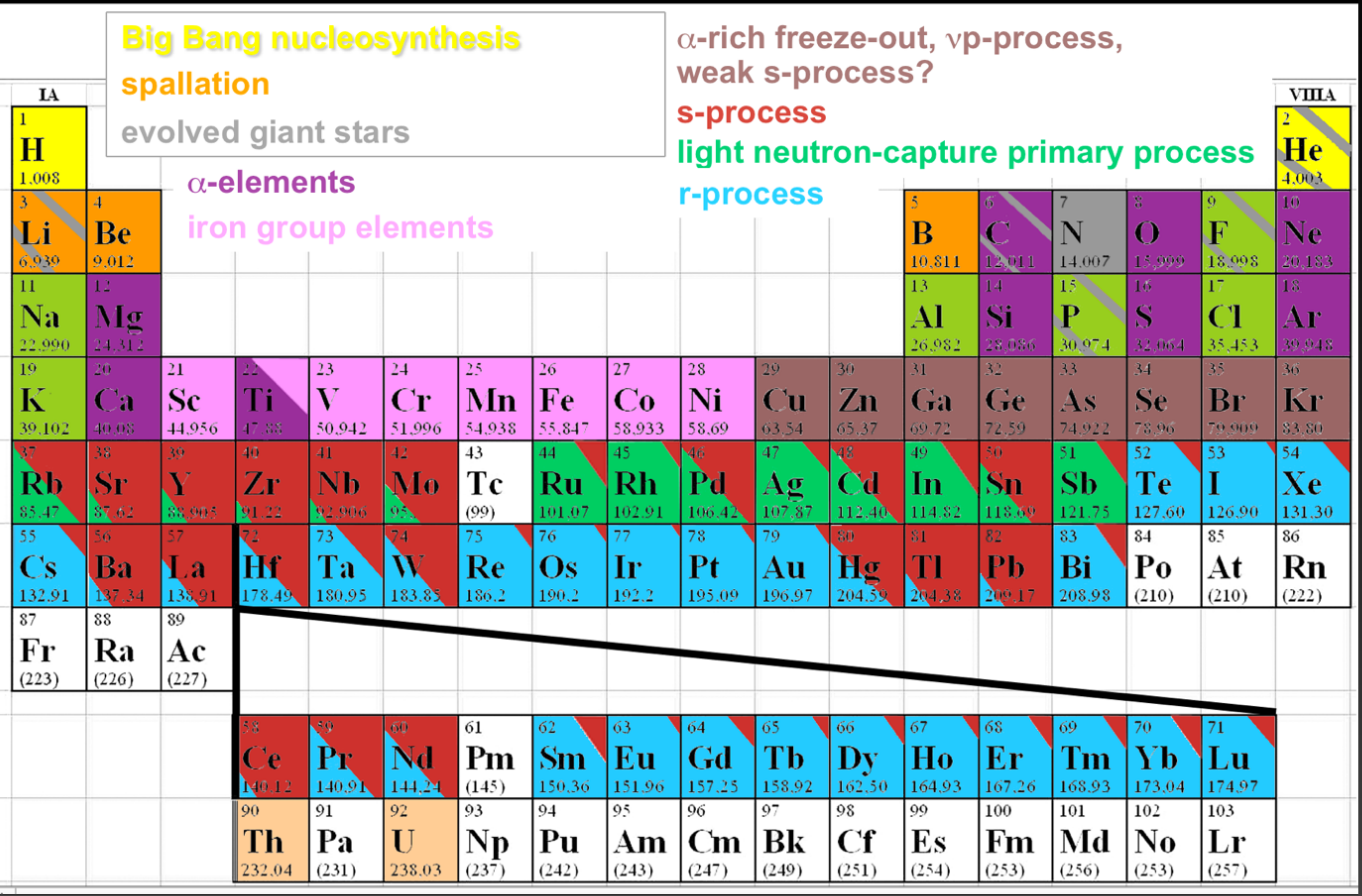
Sorry…. April Fool’s!

Nucleosynthesis from CCSNe



CCSNe dominate the chemical evolution of the universe

A. Frebel, MIT

Nuclear Physics Labs

- Matter at most extreme densities, temperatures, isospin
- Produce most elements in Nature
- Complimentary to experiment at, e.g., NSCL, FRIB, JLAB, ATLAS, RHIC, GSI, TRIUMF,…
- Neutrino and gravitational wave signals encode info about nuclear EOS
- Test BSM physics of neutrinos

Basic Picture of Stellar Collapse

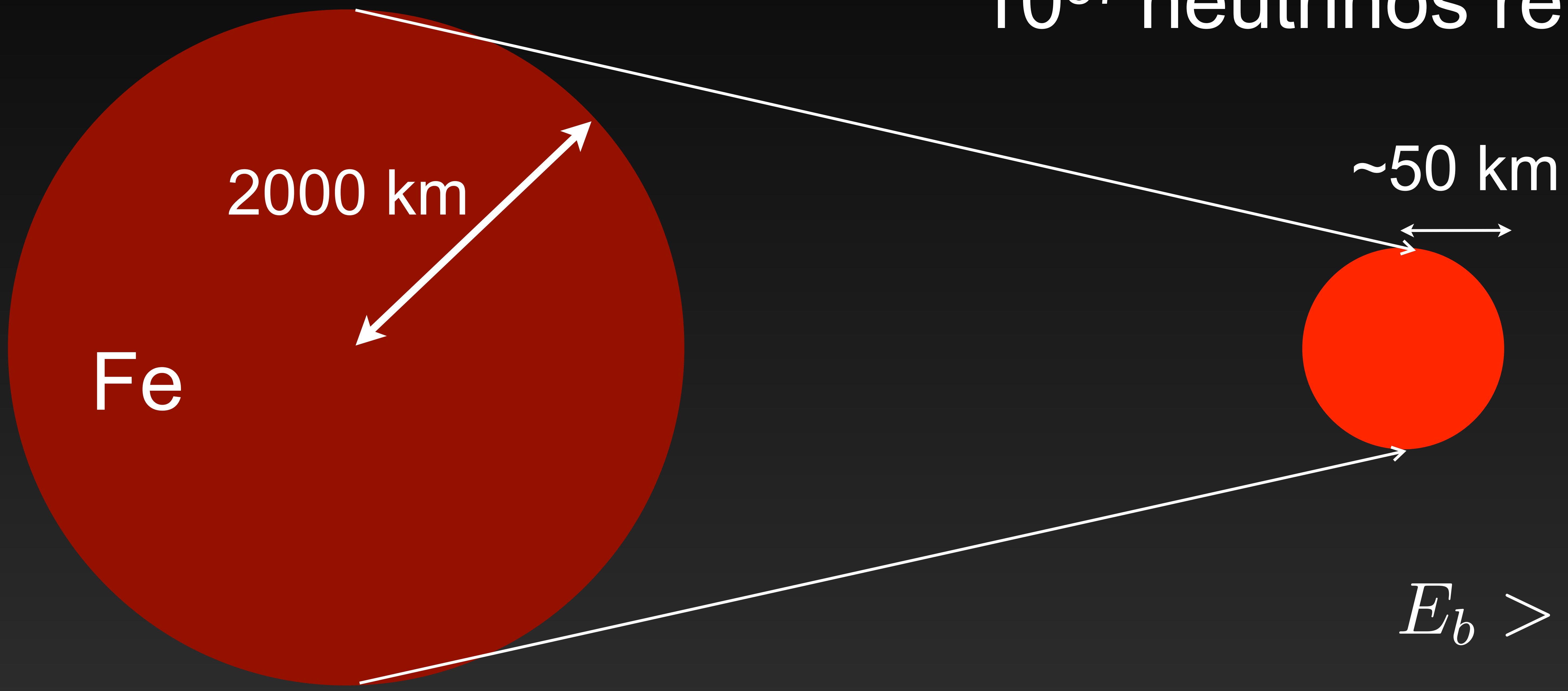
$$M_{Fe} \sim M_{\rm Ch} \sim 1.4\ M_\odot$$

$$\rho_c \sim 10^{10}\ {\rm g\ cm^{-3}}$$

$$Y_e \sim 0.43$$

Basic Picture of Stellar Collapse

10^{57} neutrinos released!!



$$E_b > 10^{53}\ \mathrm{erg}$$

$$M_{Fe} \sim M_{\mathrm{Ch}} \sim 1.4\ M_{\odot}$$

$$p + e^- \rightarrow n + \nu_e$$

$$\rho_c \sim 10^{10}\ \mathrm{g\ cm^{-3}}$$

$$\rho_c > 10^{14}\ \mathrm{g\ cm^{-3}}$$

$$Y_e \sim 0.43$$

$$Y_e \sim 0.27$$

Basic Picture of Stellar Collapse

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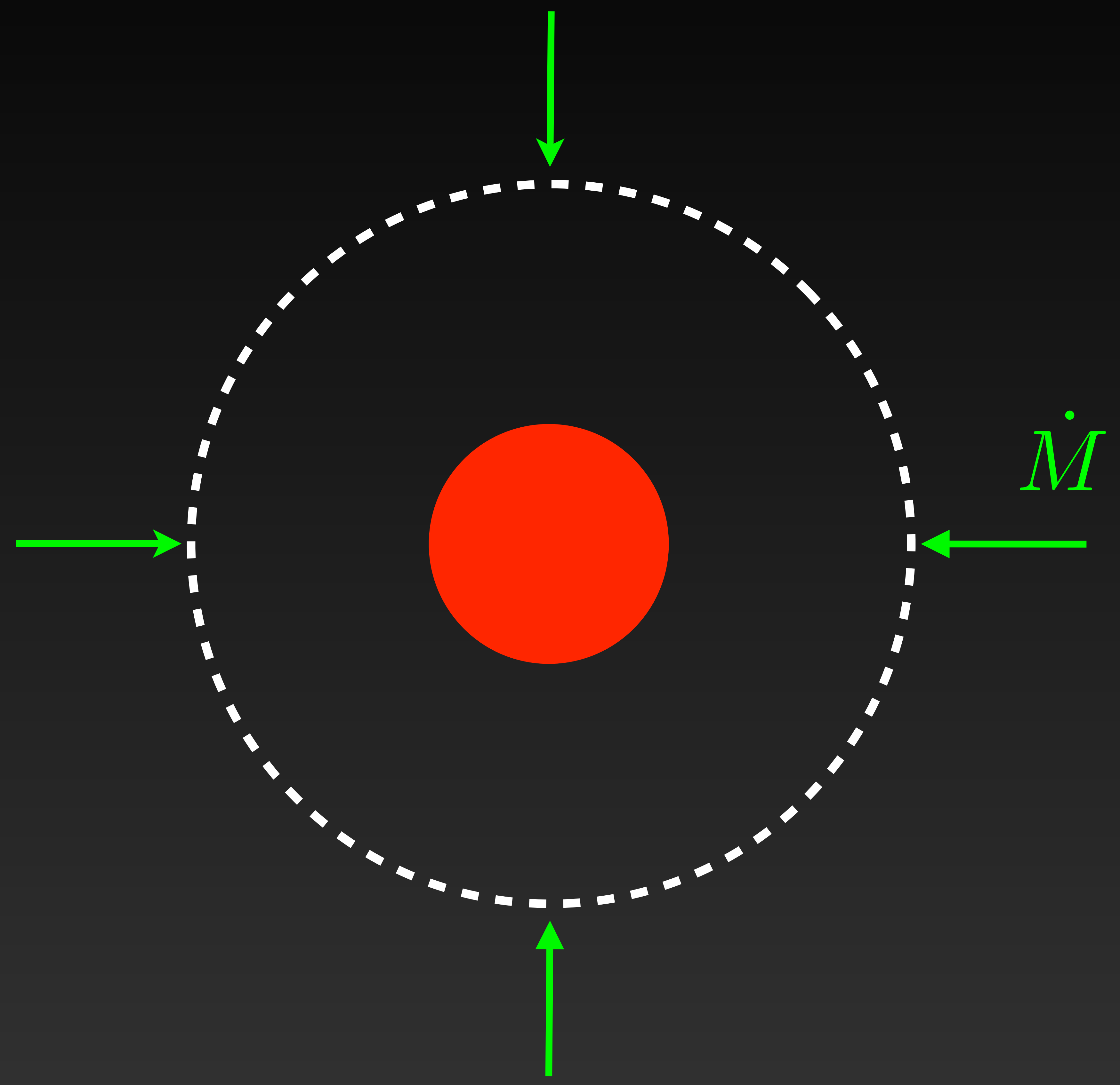

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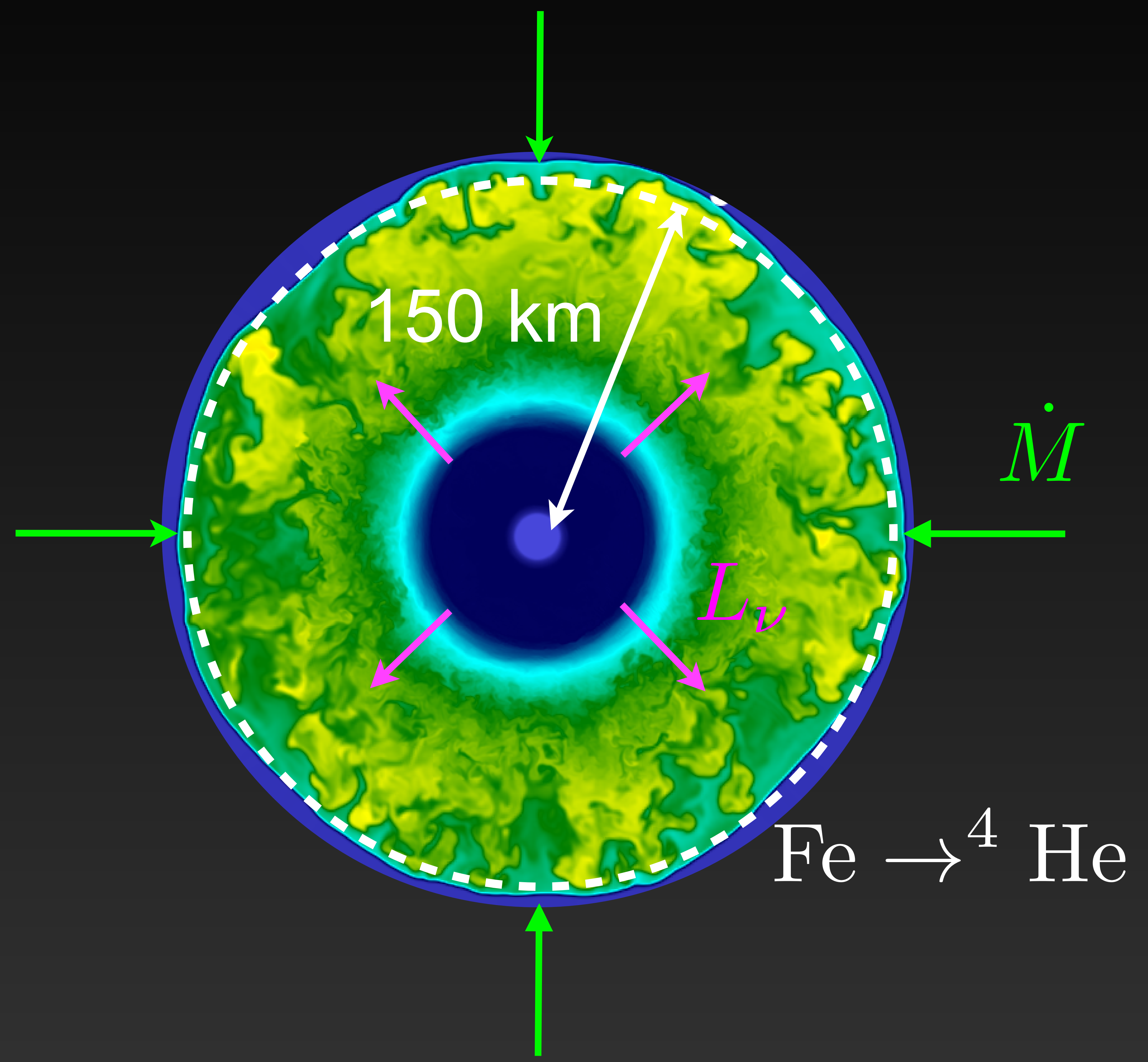
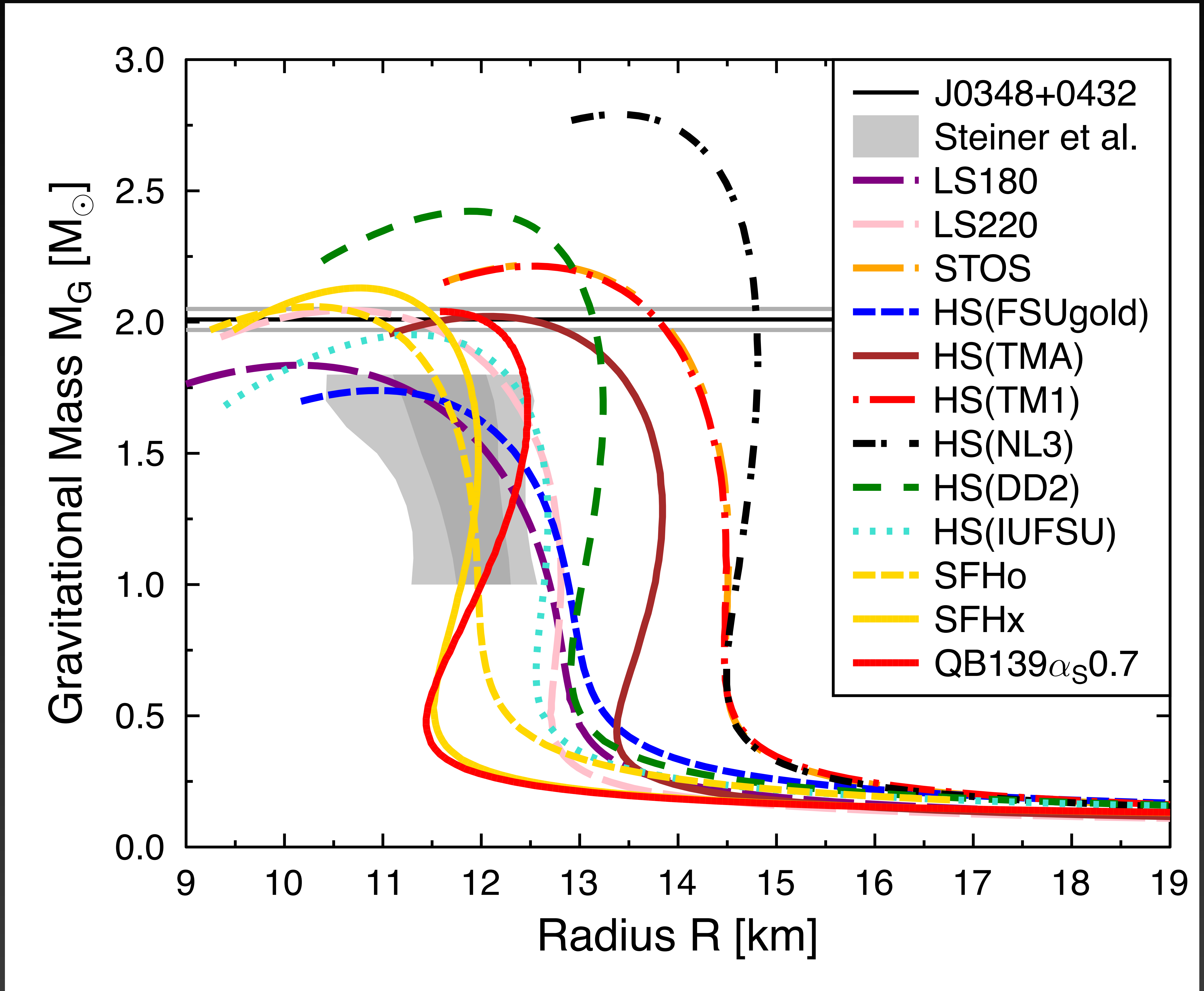


Shock stalls... What revives it??

=> The CCSN "Problem"

Dense Matter Equation of State

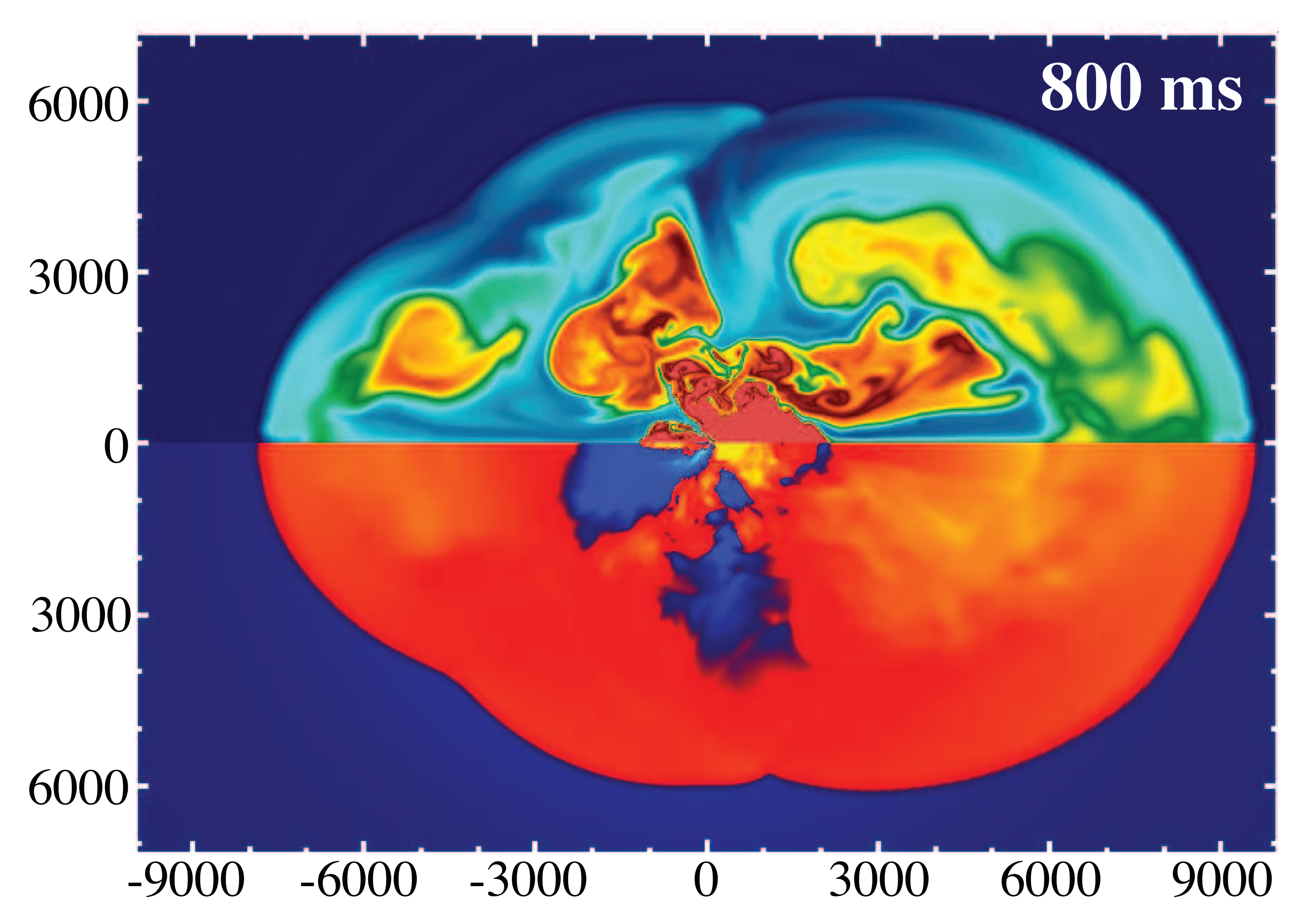
- Can impact:
  - Explosion (Marek et al. 2009; SMC 2013; Suwa et al. 2013)
  - Gravitational wave emission (Marek et al. 2009; Mueller et al. 2013)
  - Neutrino emission (O'Connor & Ott 2013)



Fischer et al. 2014

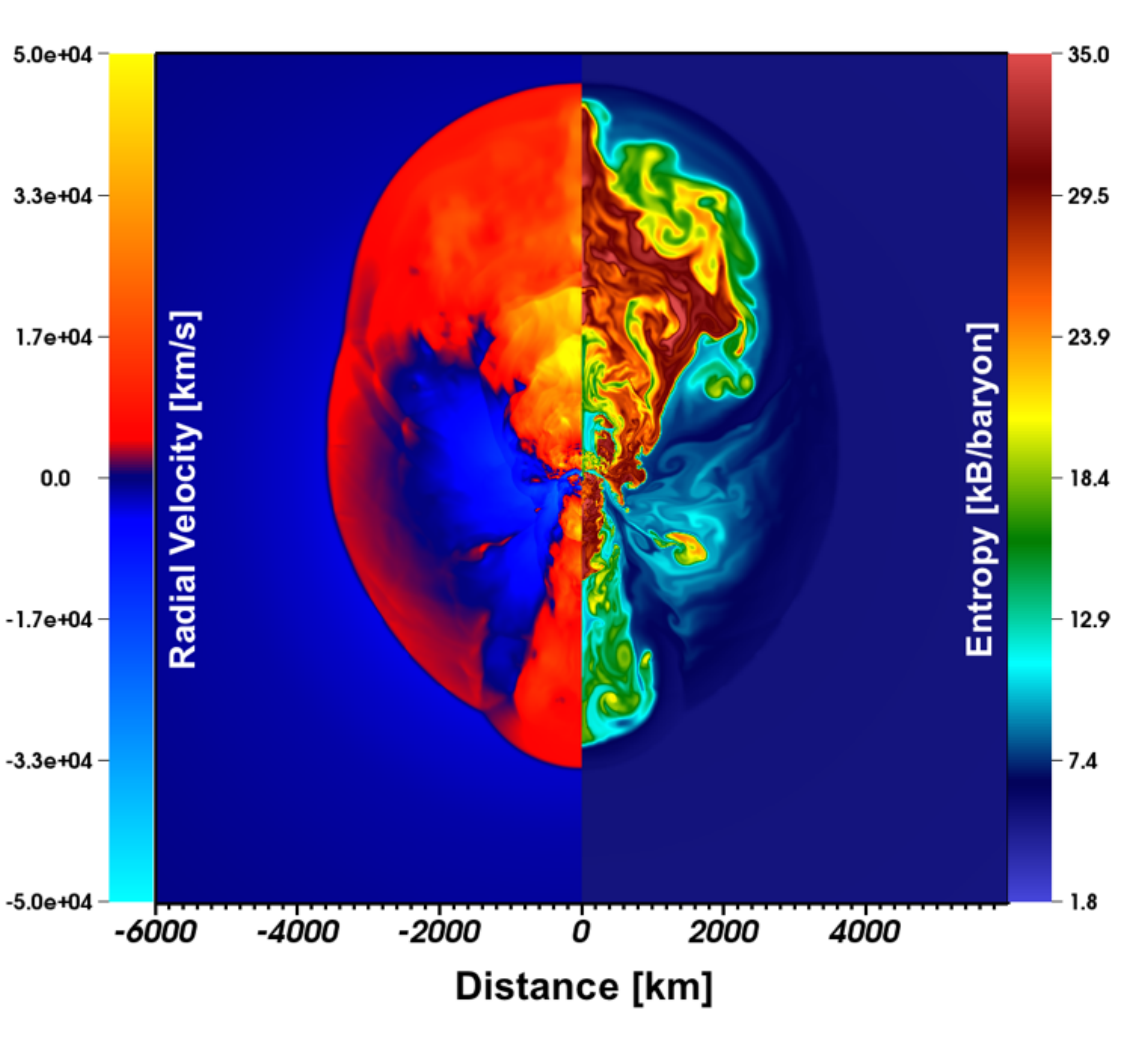
High-Fidelity Explosions in 2D

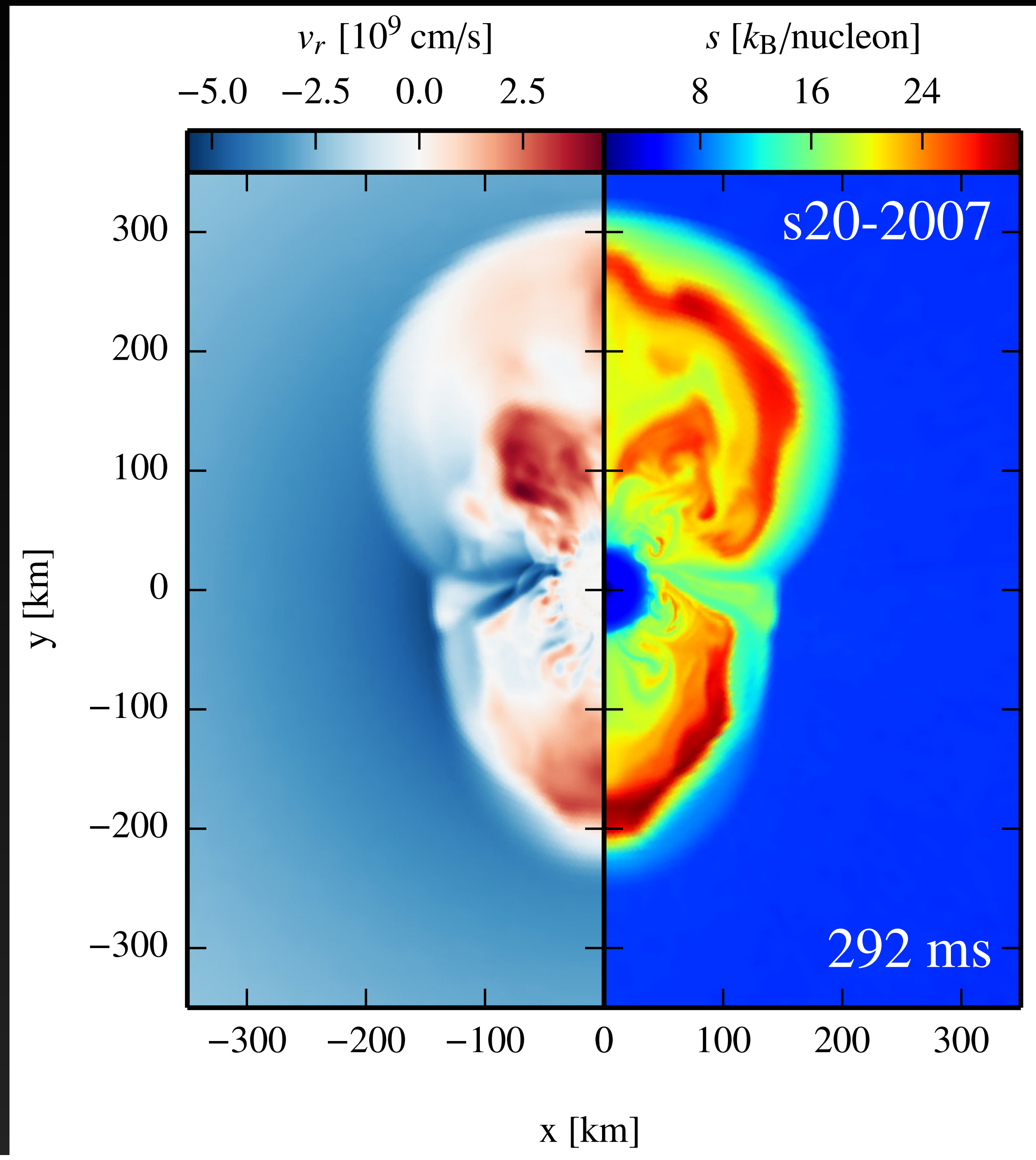
Summa et al. (2015)

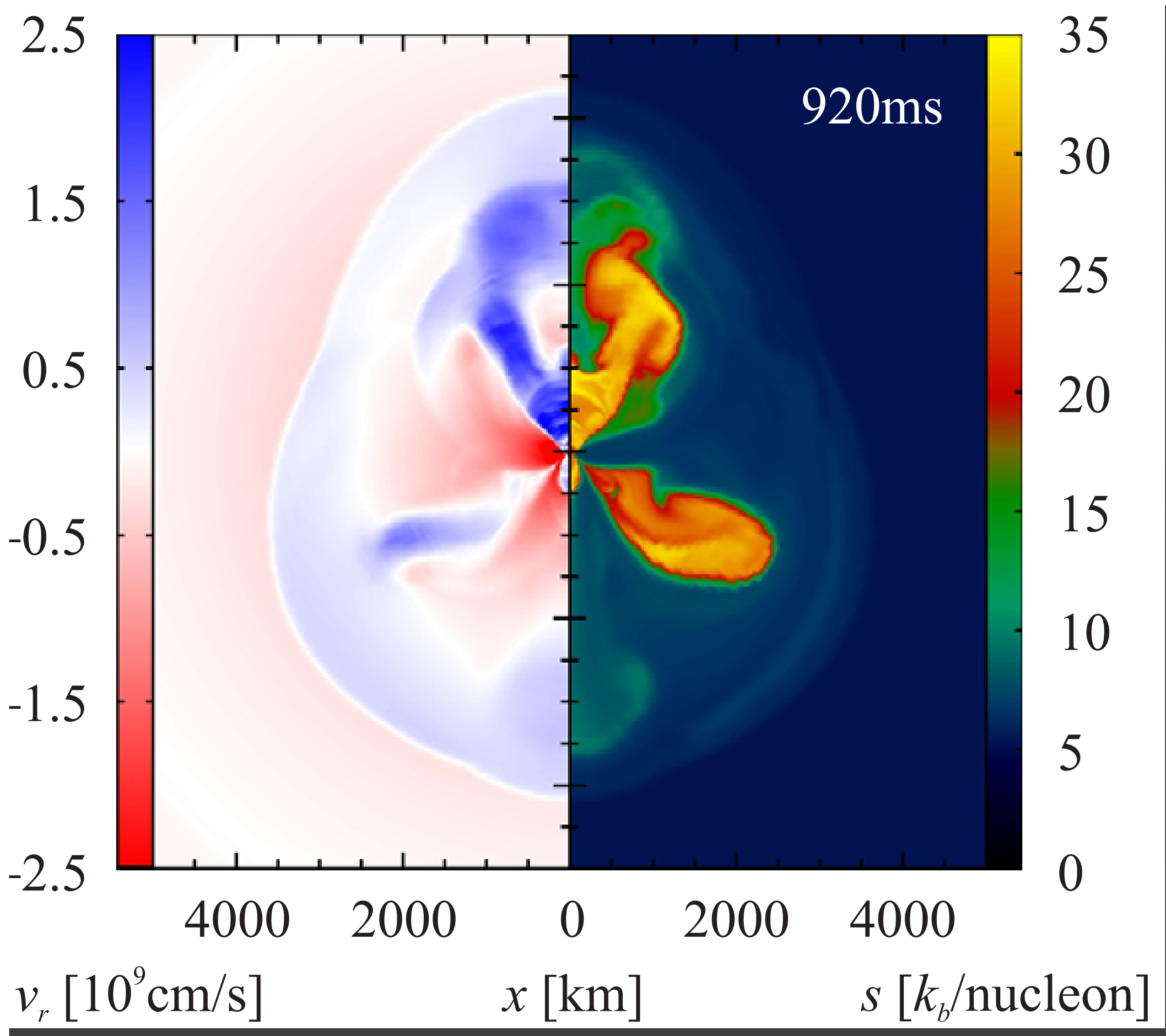


Bruenn et al. (2013,2014)

E. O'Connor & SMC (2016)



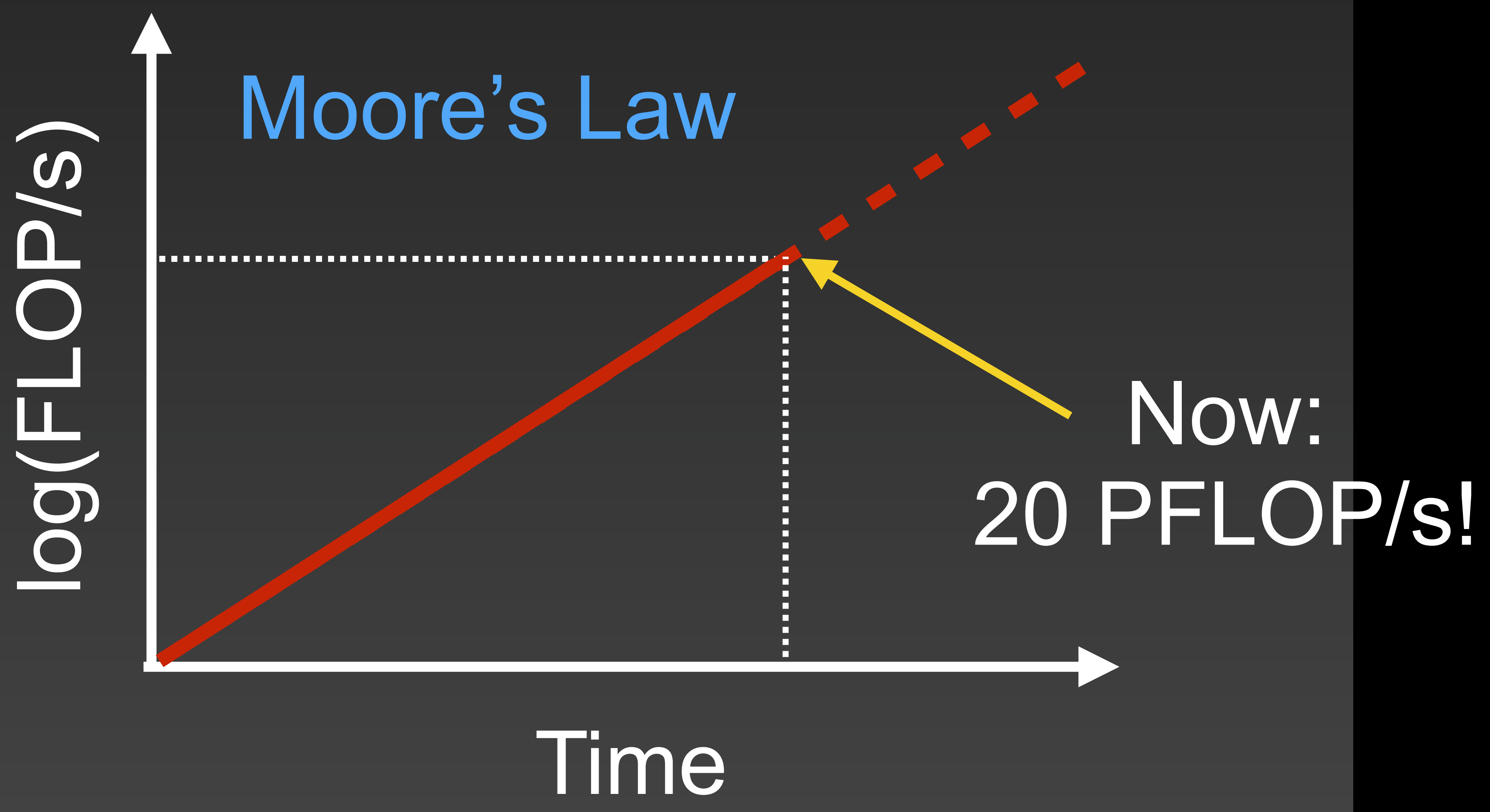


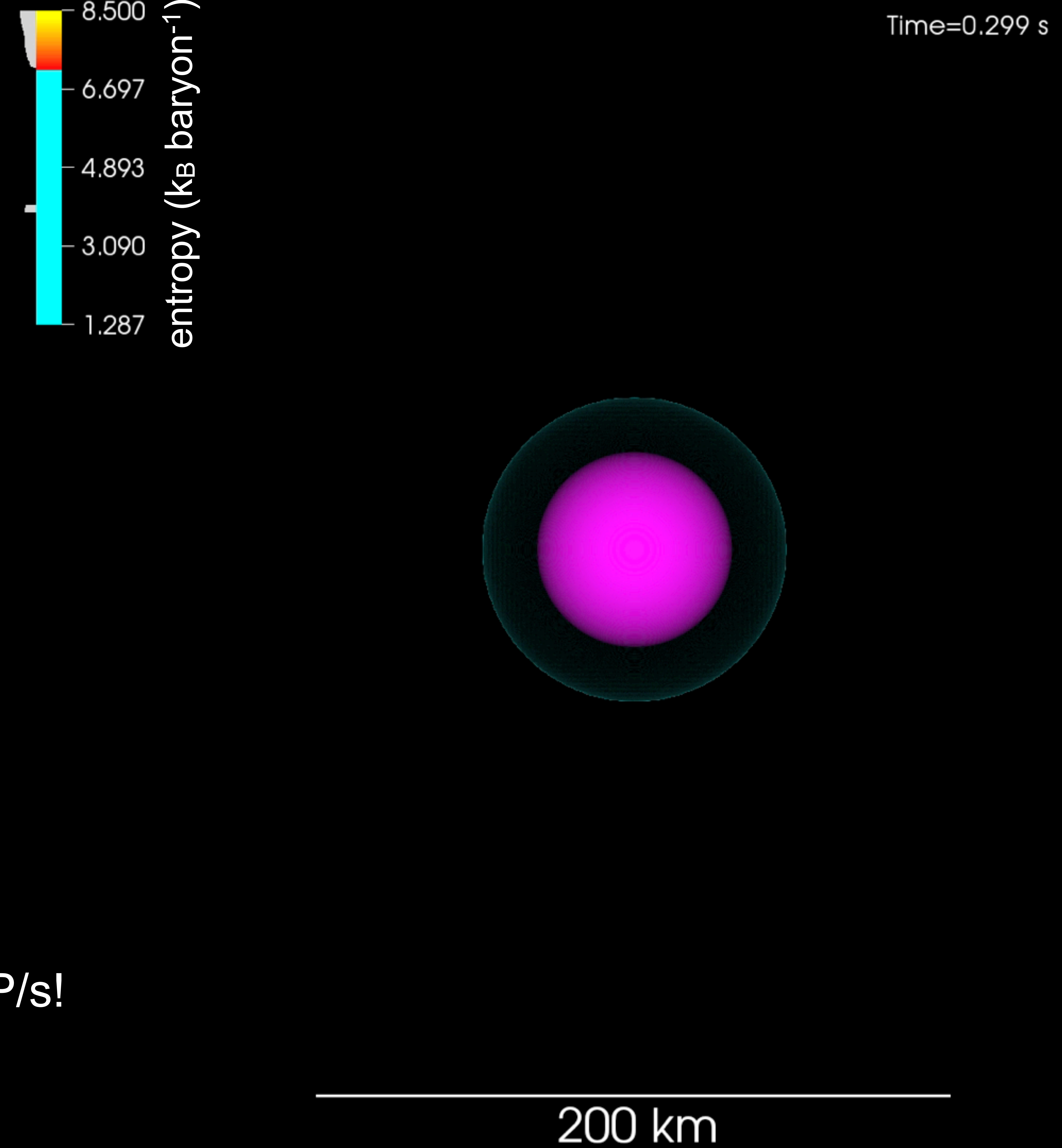


Mueller et al. (2012)

- Princeton group: no 2D explosions (Dolence et al. 2015).
- But see Skinner et al., arXiv:1512.00113

3D CCSN Simulations





SMC & E. O'Connor, ApJ, 785, 123

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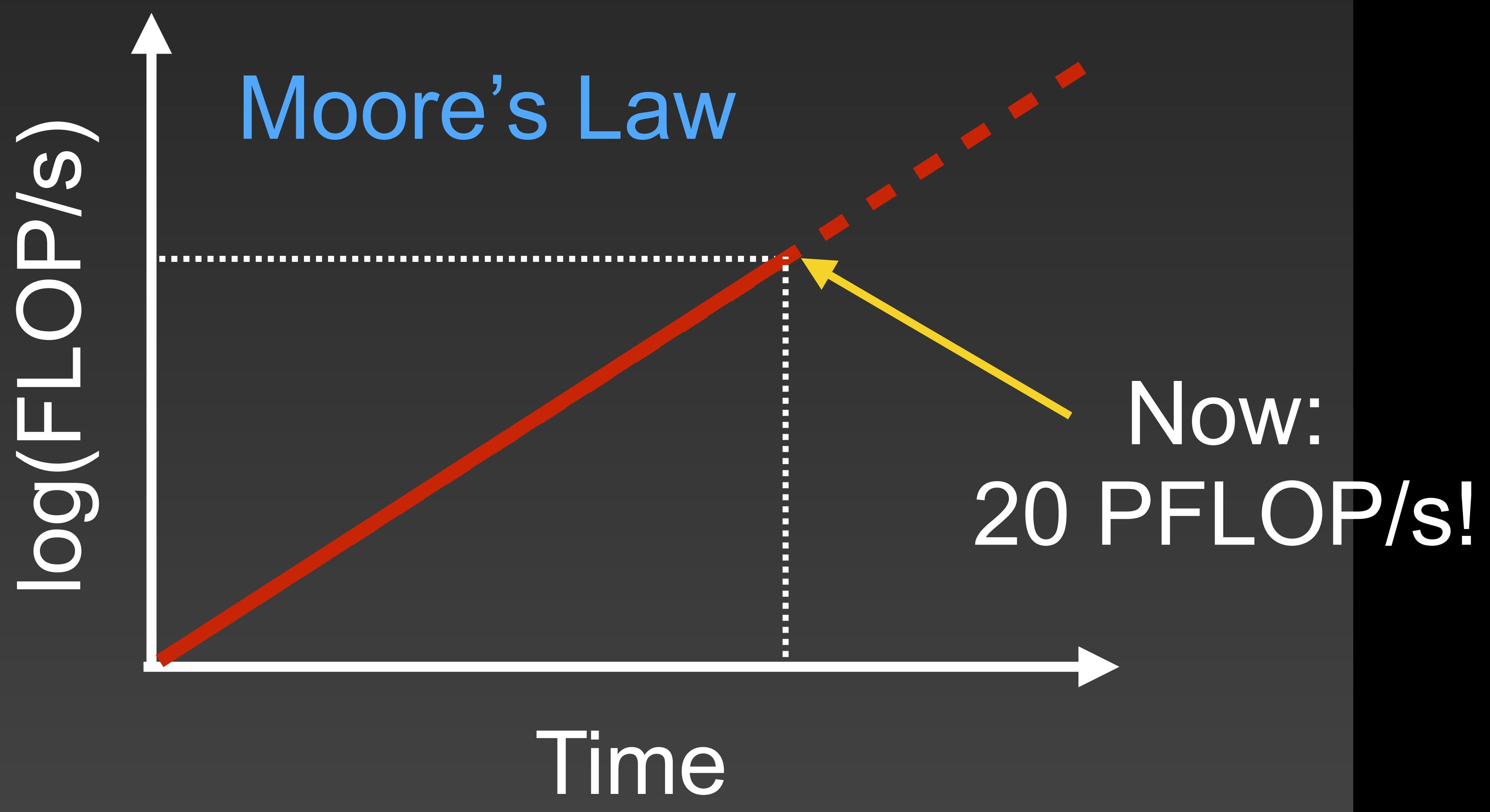
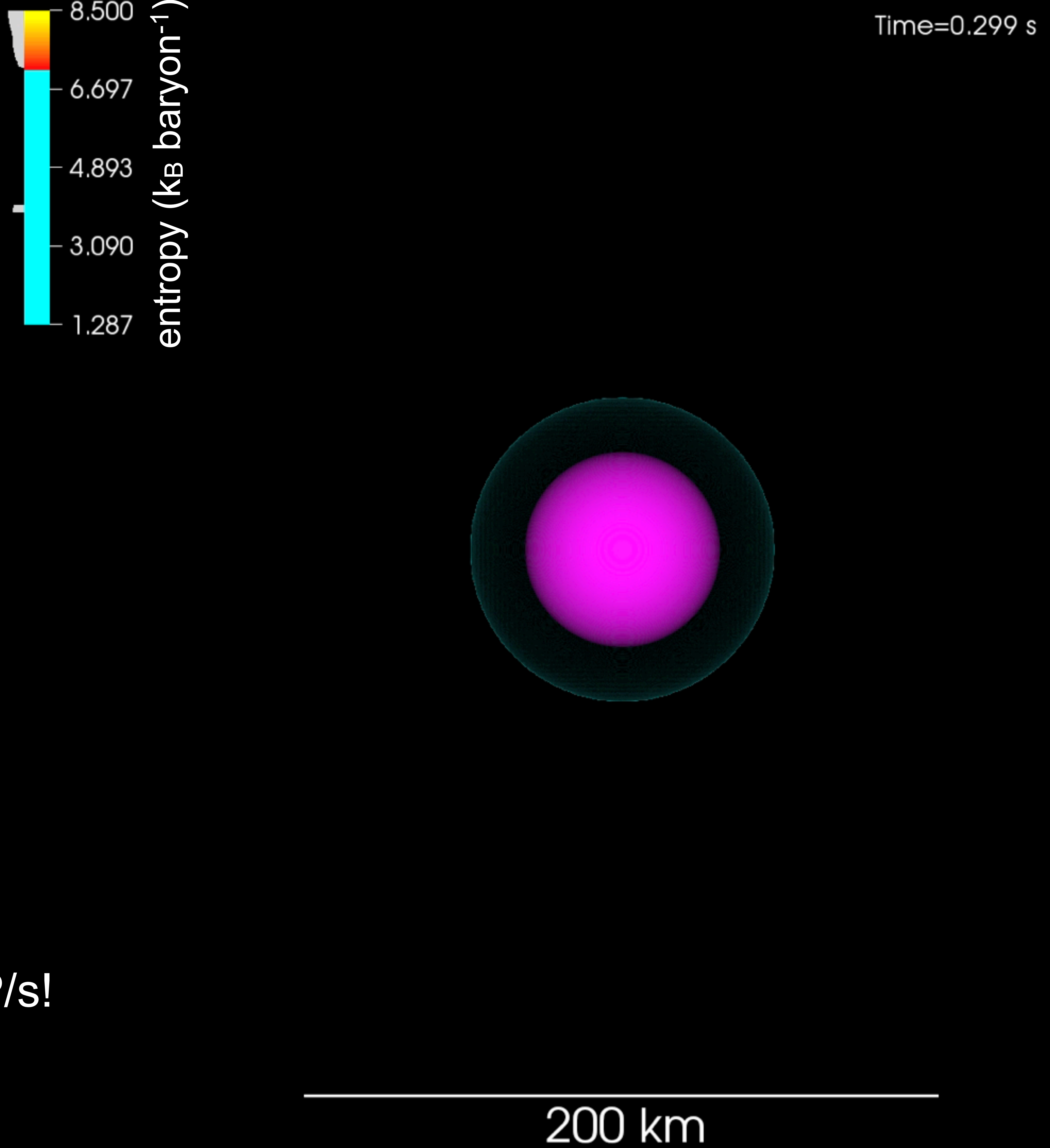
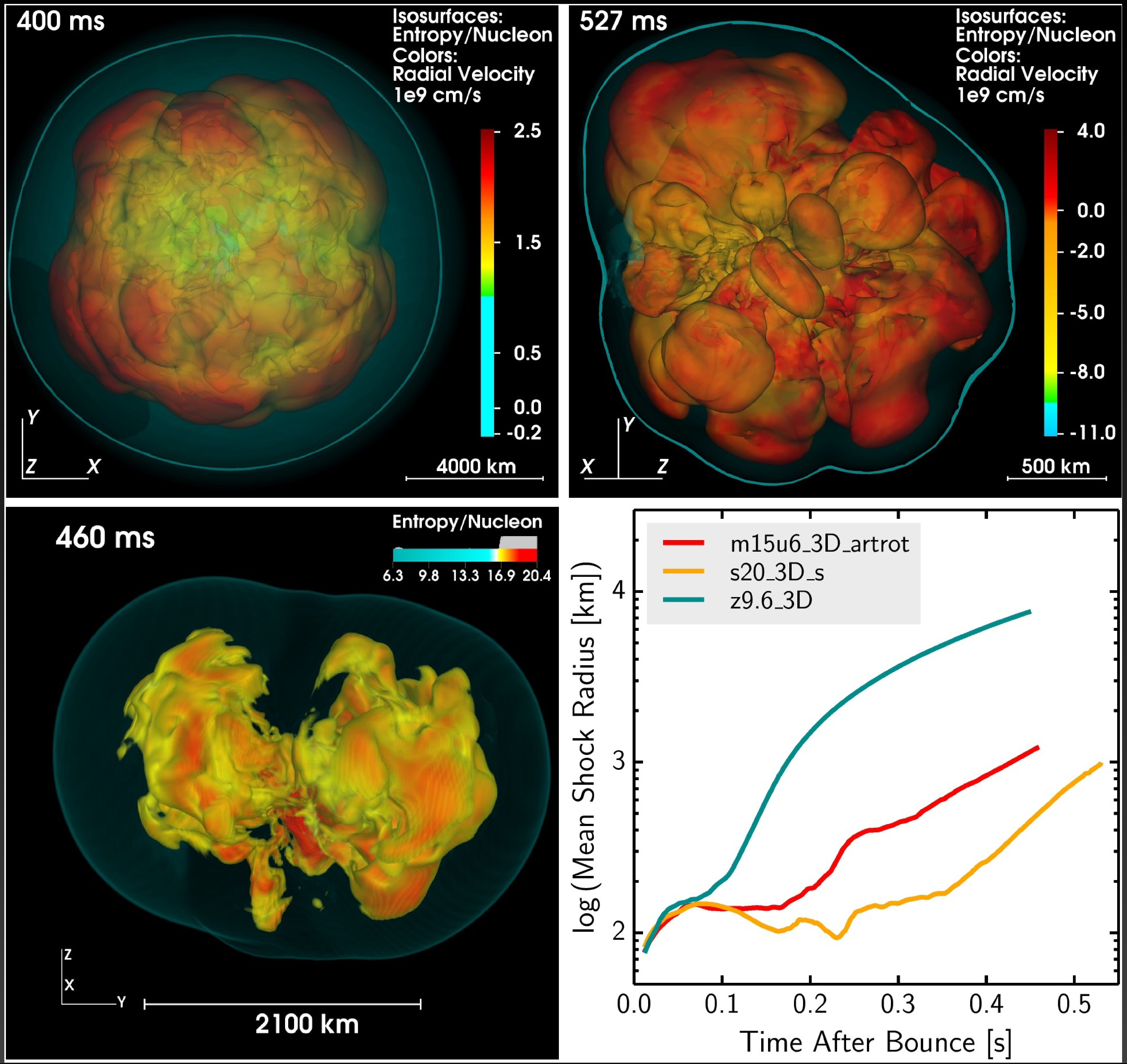




SMC & E. O'Connor, ApJ, 785, 123

3D with Full Nu Transport

Janka, Melson, & Summa (2016)



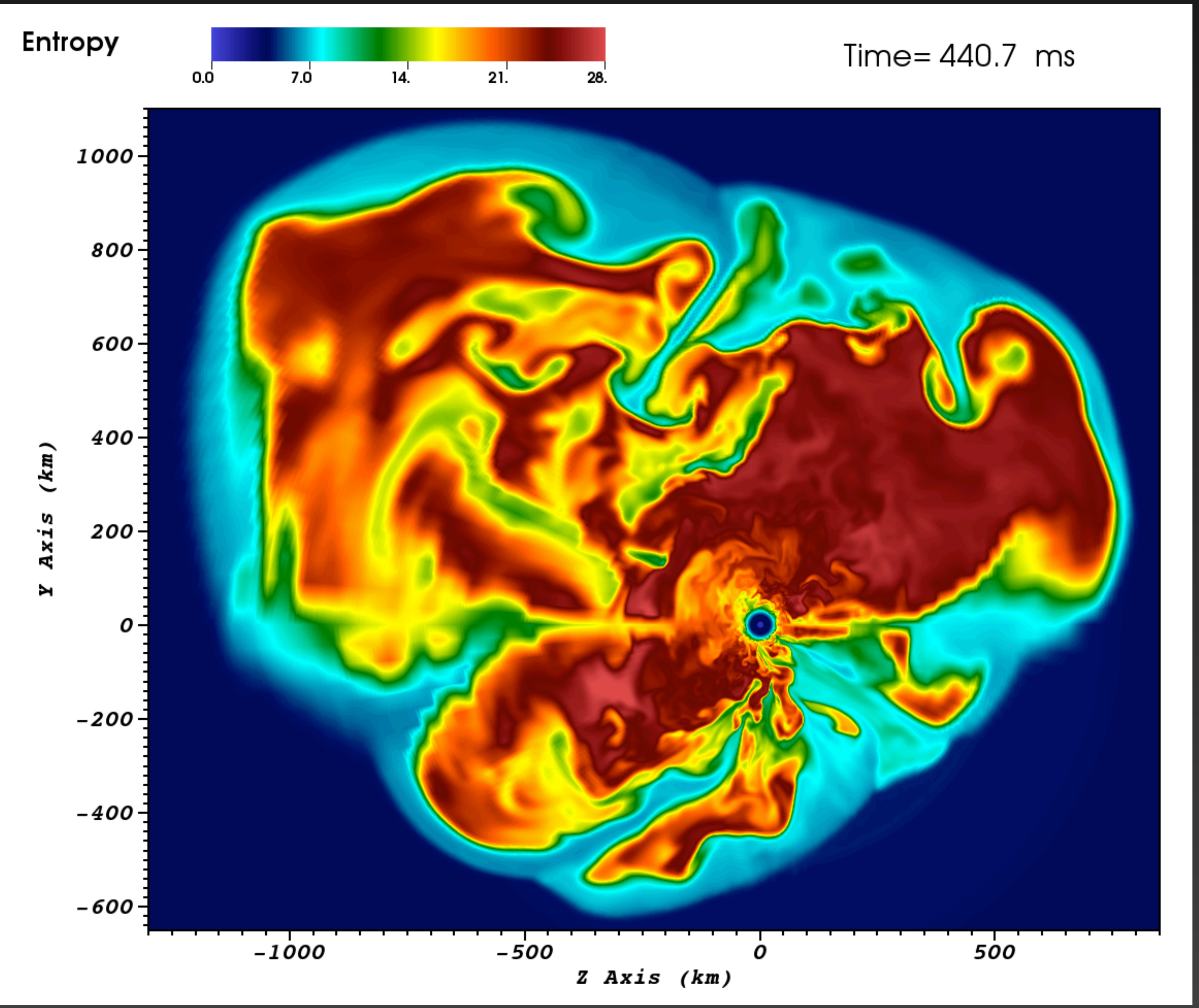
3D explosions required:

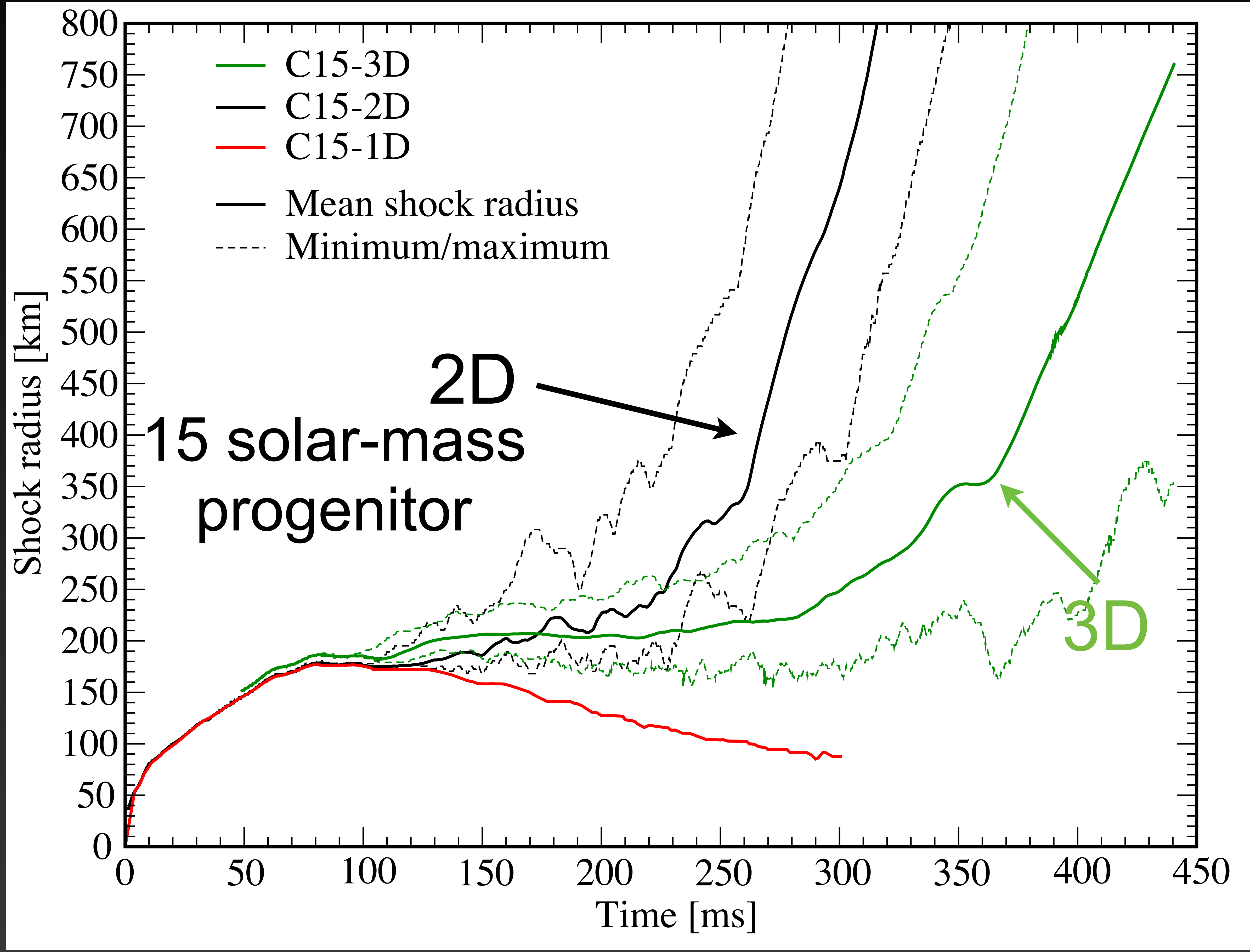
- low-mass progenitor
- (unphysically) large strangeness correction
- rapid rotation

3D with Full Nu Transport

Mezzacappa et al. (2015), Lentz et al. (2015)

Results from Oak Ridge Group





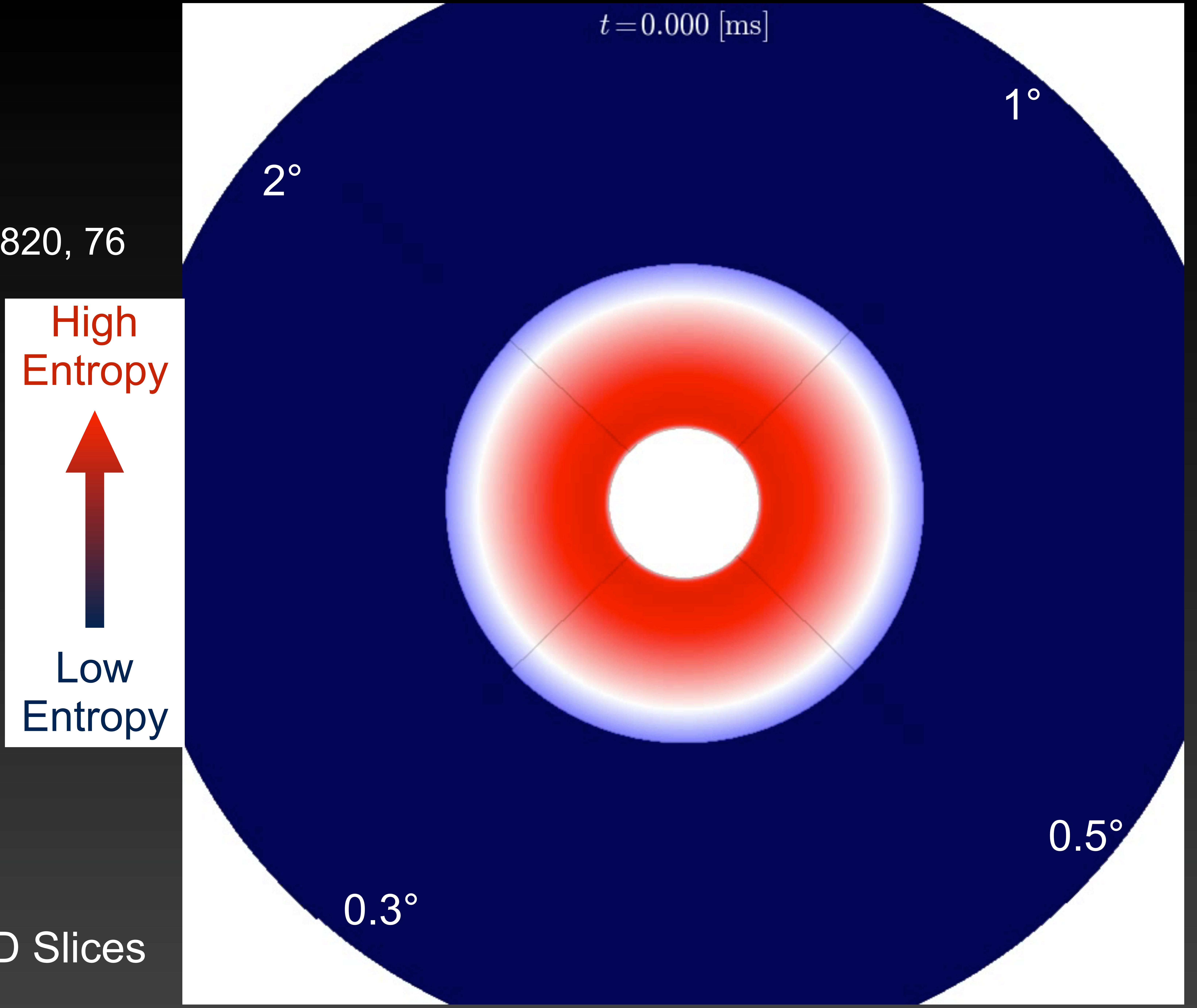
3D explodes later than 2D

Only 2° resolution…

Resolution Dependence

D. Radice, C. Ott, SMC, et al., ApJ, 820, 76

- Analytic accretion shock IC's
- Inner boundary
- Lightbulb heating/cooling
- Fixed-metric GR



3D Slices

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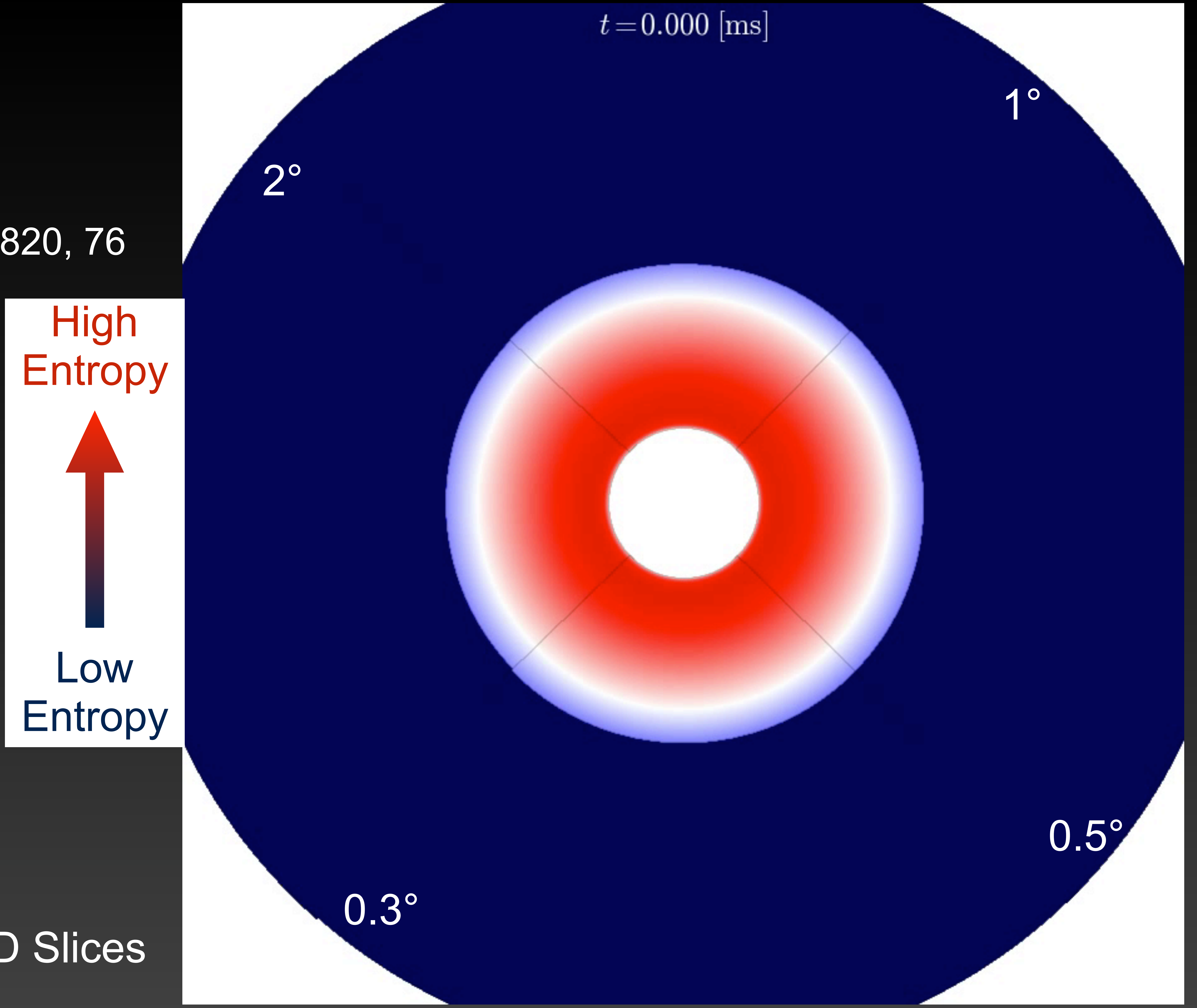

3D Slices

3(D) steps forward, 1(D) step back?

- Success of explosions in 2D may not be recovered in 3D… We must be missing physics, or getting the physics wrong...
- Possibilities:
  - Progenitor structure
  - MHD/rotation
  - Behavior of turbulence/low-resolution
  - Neutrino effects (i.e., oscillation, x-sections, sterile)
  - Equation of state
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CCSN is an Initial Value Problem

…And we have problems with our initial values

- Stars are not (perfectly) spherical
- All stars rotate
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- >50% of SN progenitors in interacting binaries

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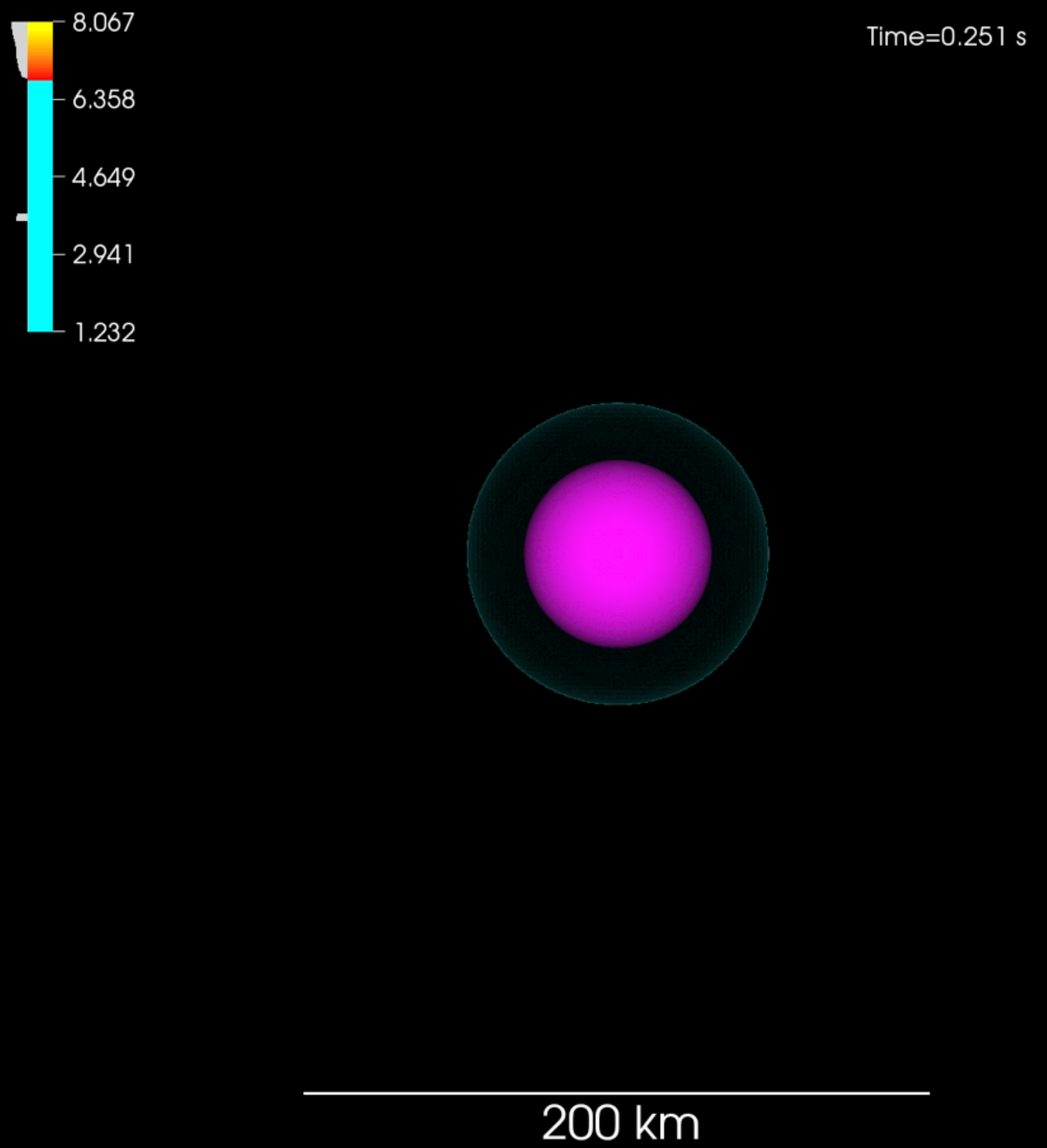
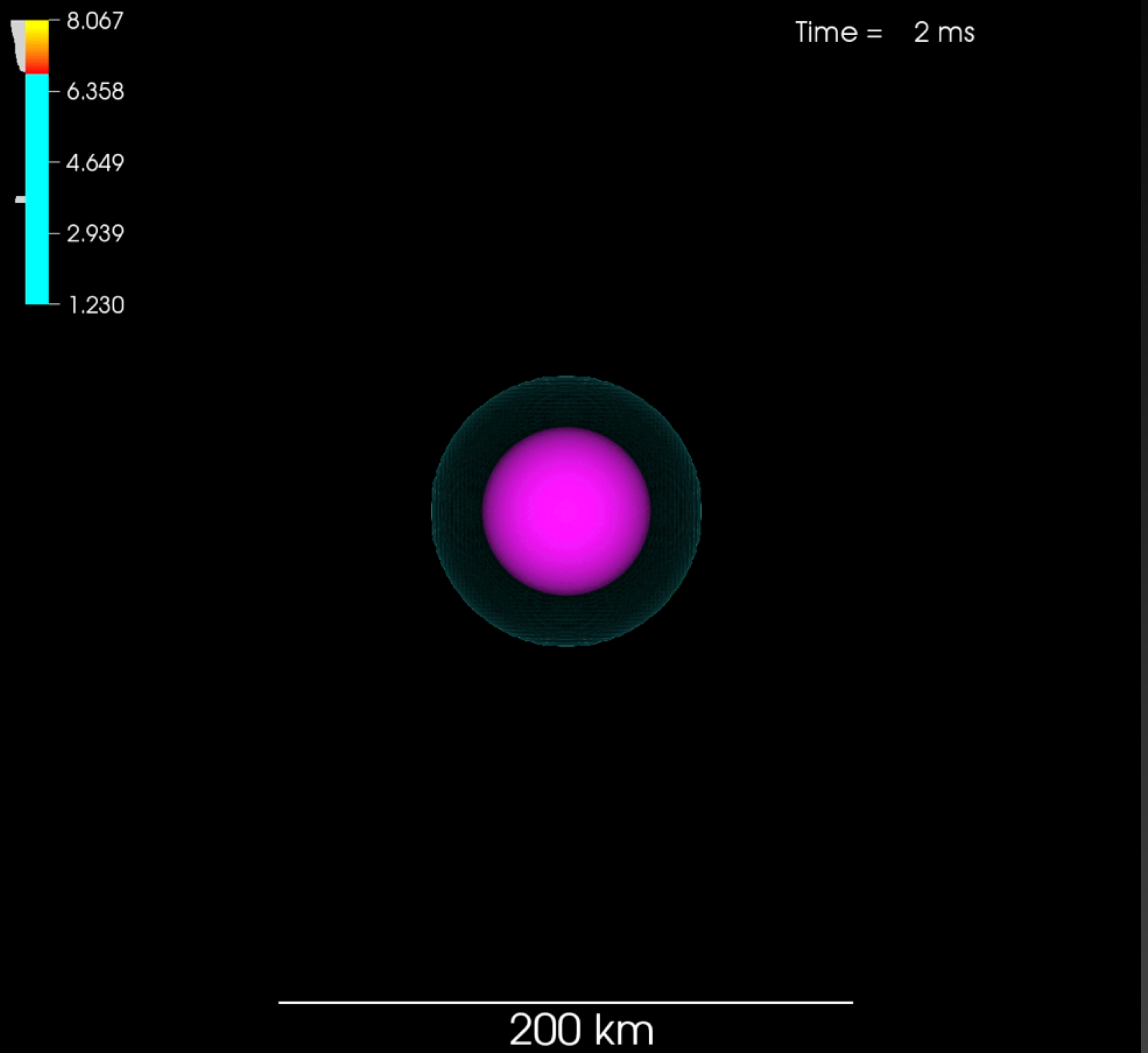
Progenitor Asphericity in 3D

SMC & Ott (2013, 2015); SMC et al. (2015)

Unperturbed



Perturbed



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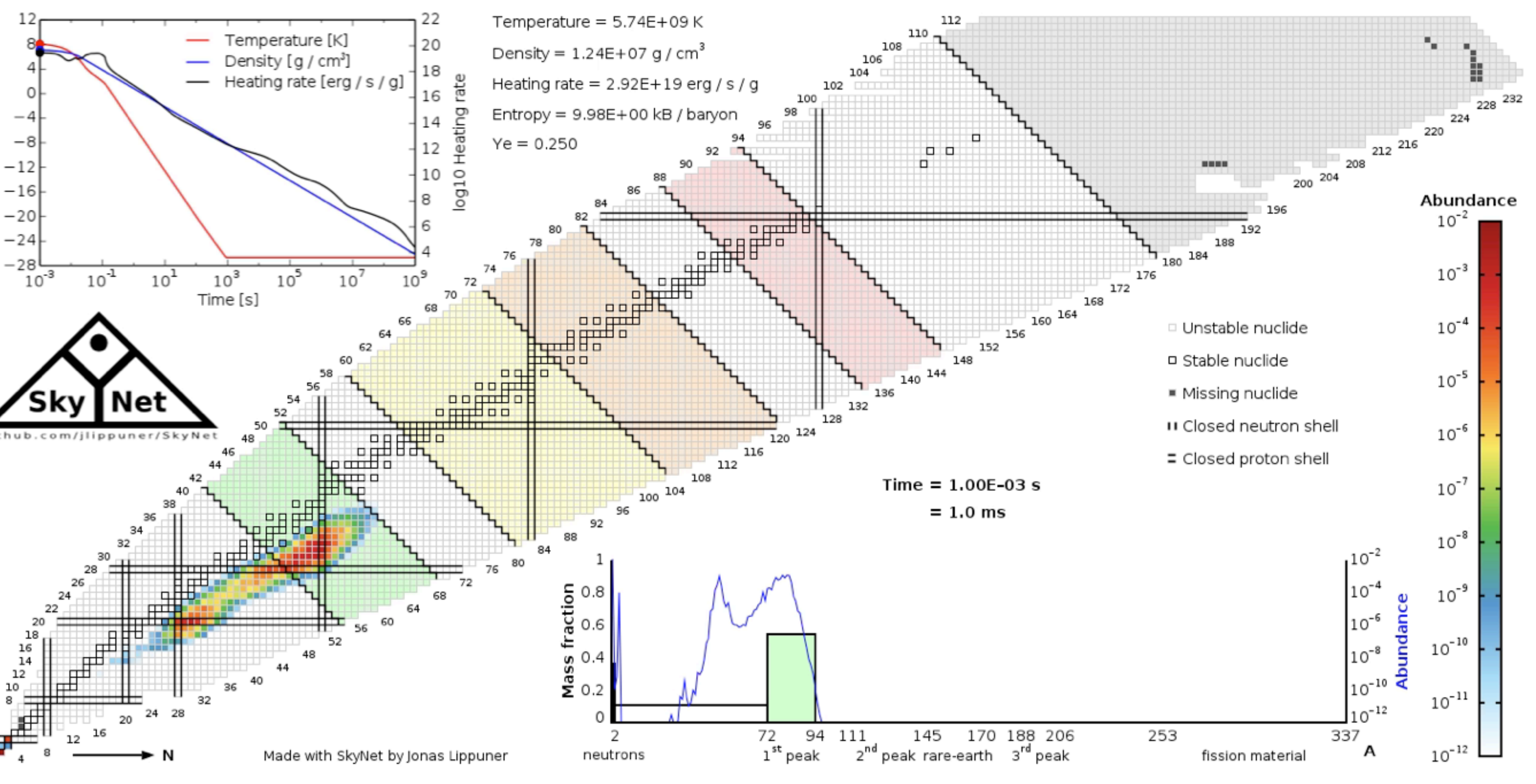
Connecting to Observation

GW strain

With an explosion model:

- Gravitational Waves
- Neutrinos
- NS/BH mass distributions
- Nucleosynthesis
- Light curves/spectra
- Nuclear data



J. Lippuner, L. Roberts

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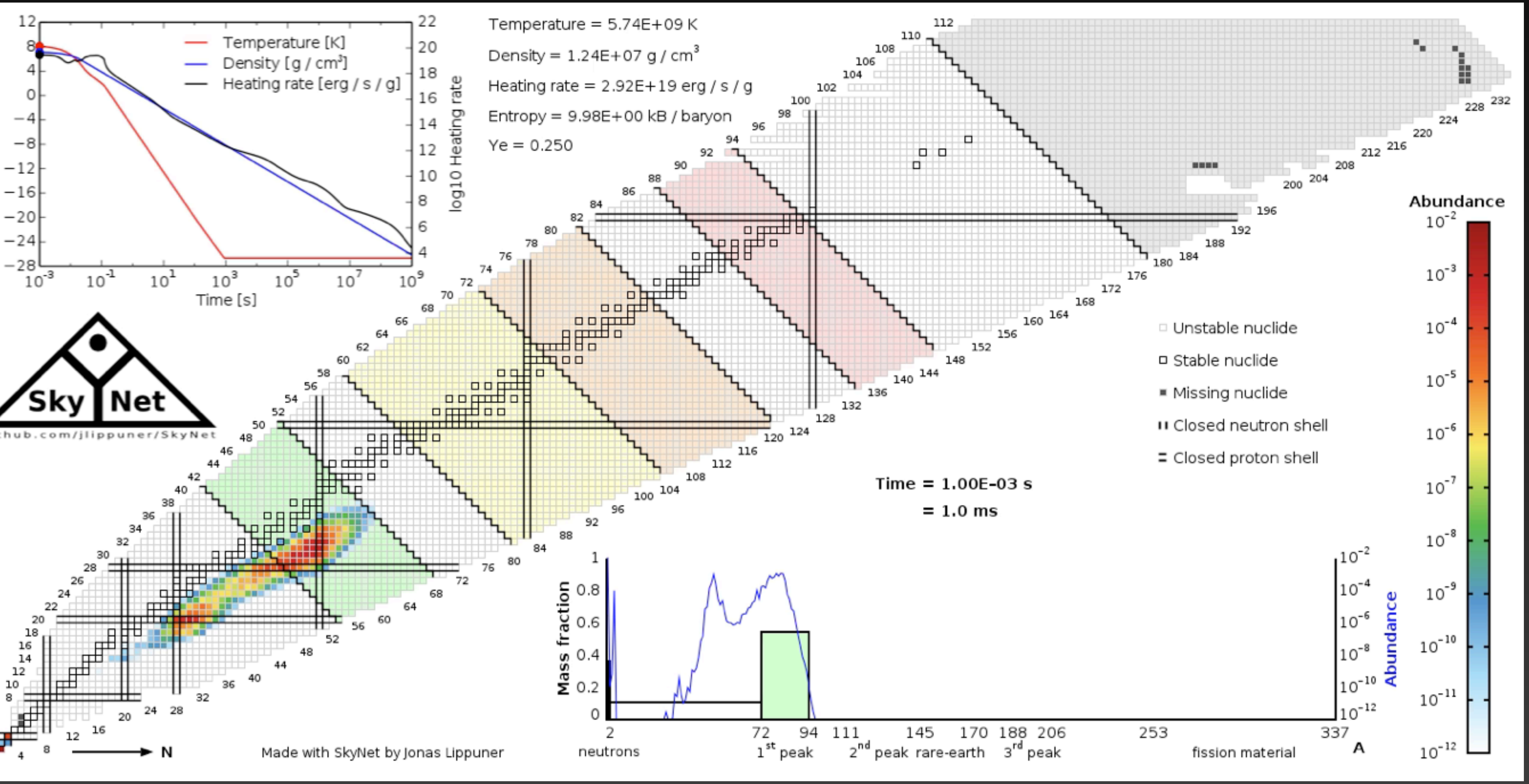

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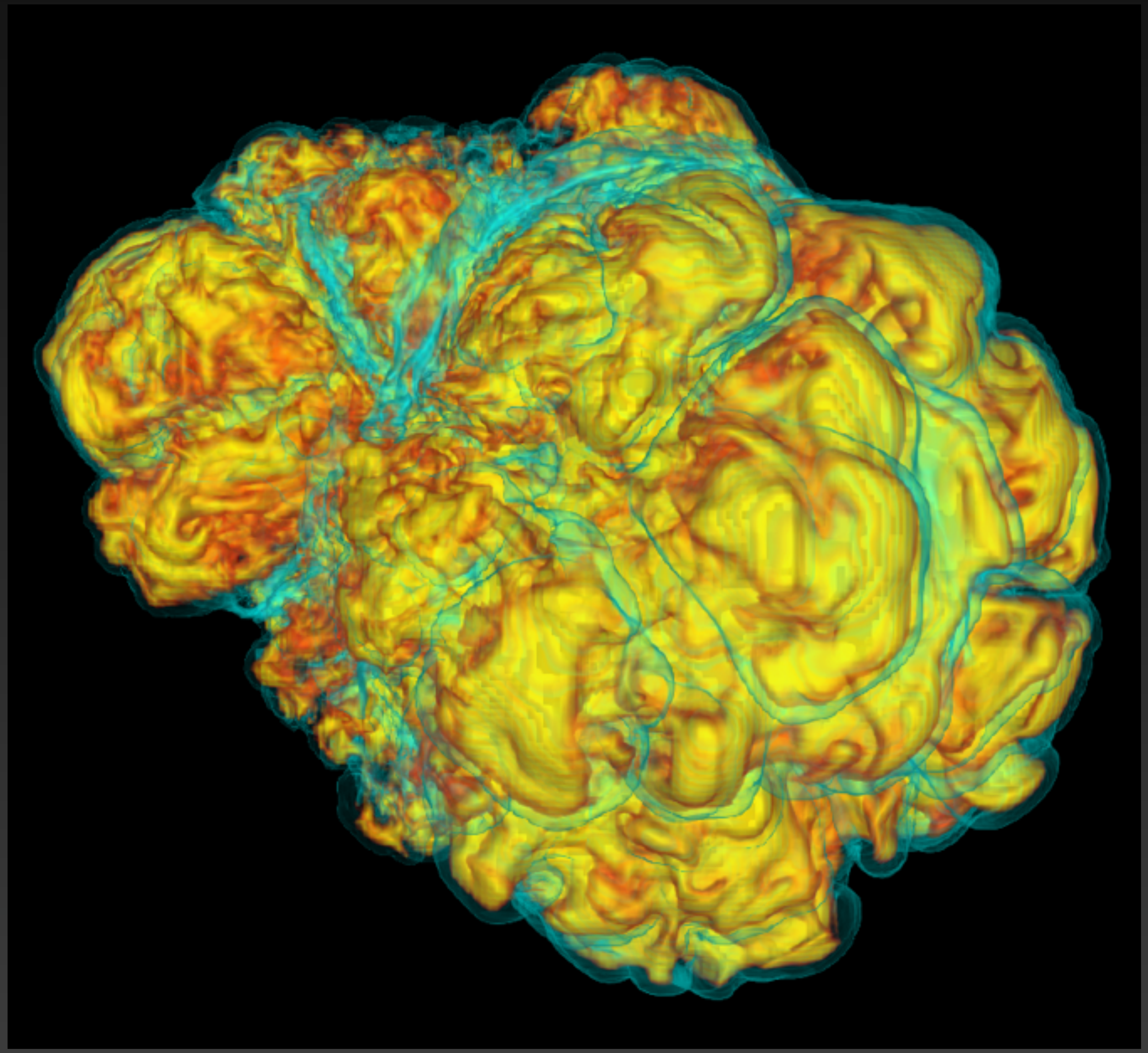
Toward predictive CCSN theory

- Modern high-performance computing revolutionizing CCSN theory
- CCSN mechanism depends critically on nuclear theory input
- Understanding sensitivity to nuclear physics requires robust explosion model
- Goal of predictive CCSN theory within reach!



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