Axisymmetric Core-Collapse Supernovae Simulations with CHIMERA

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CHIMERA Collaboration

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- John Blondin, Chris Mauney (NC State University)
- Eirik Endeve, Raph Hix, Austin Harris, Eric Lentz, Bronson Messer, Anthony Mezzacappa, Konstantin Yakunin (ORNL/UTK)
- Former Team Members
  - Reuben Budjiara, Austin Chertkow, Ted Lee

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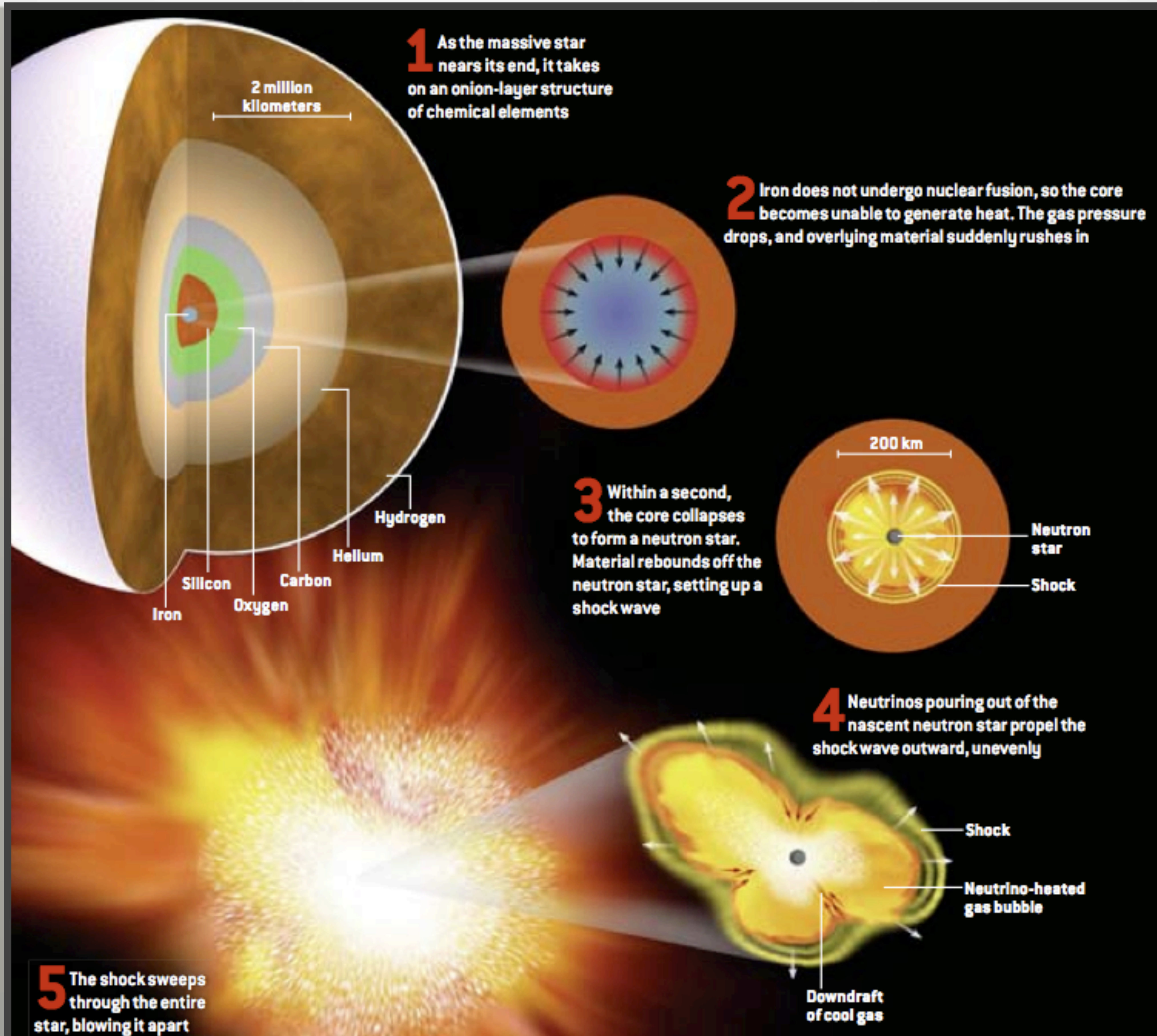


Hillebrandt, Janka, & Müller 2006 (Sci Am)

Neutrino trapping

$$\lambda_\nu = \frac{1}{\sigma_A n_A}$$

$$n_A = \frac{\rho}{A m_u}$$

$$\sigma_A = \frac{1}{16}\sigma_0\left(\frac{E_\nu}{m_e c^2}\right)^2 A^2\left[1 - \frac{Z}{A} + \left(4\sin^2\theta_W - 1\right)\frac{Z}{A}\right]^2$$

During stellar core collapse, the neutrino opacity is dominated by coherent scattering on nuclei.

Freedman, *PRD* **9**, 1389 (1974)

$$\lambda_\nu \approx 100\,\text{km}\left(\frac{\rho}{3\times10^{10}\ \text{g cm}^{-3}}\right)^{-5/3}\left(\frac{A}{56}\right)^{-1}\left(\frac{Y_e}{26/56}\right)^{2/3} \propto \rho^{-5/3}$$

$$R_{\text{core}} \approx \left(\frac{3M_{\text{core}}}{4\pi\rho}\right)^{1/3} \approx 270\ \text{km}\left(\frac{\rho}{3\times10^{10}\ \text{g cm}^{-3}}\right)^{-1/3}\left(\frac{Y_e}{26/56}\right)^{2/3} \propto \rho^{-1/3}$$

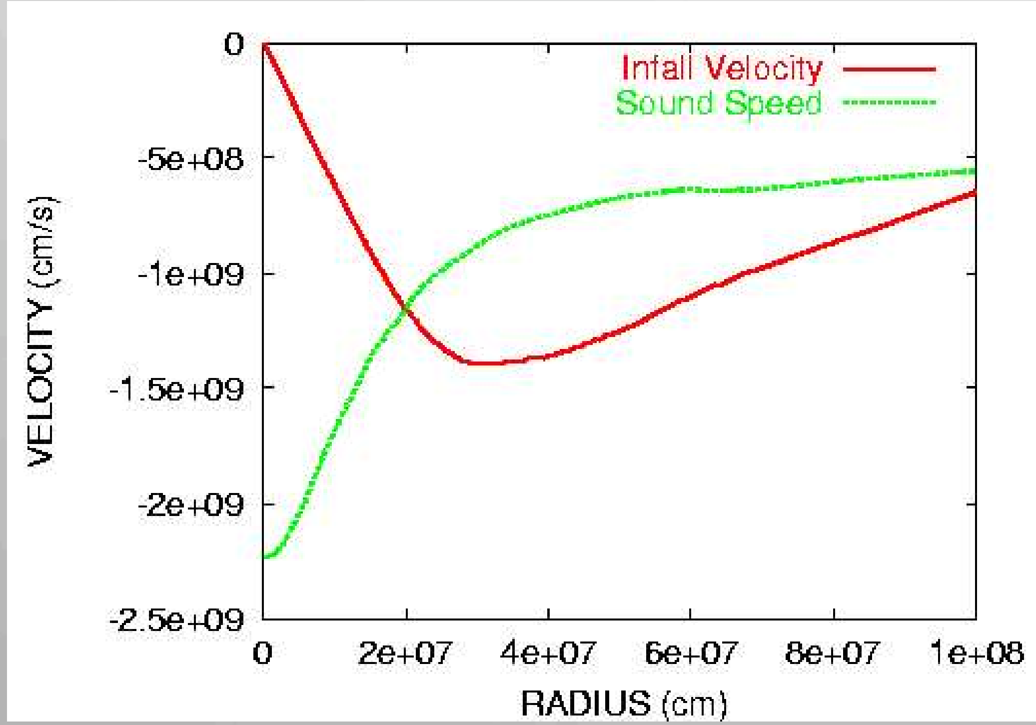
Arnett, *ApJ* **218**, 815 (1977)

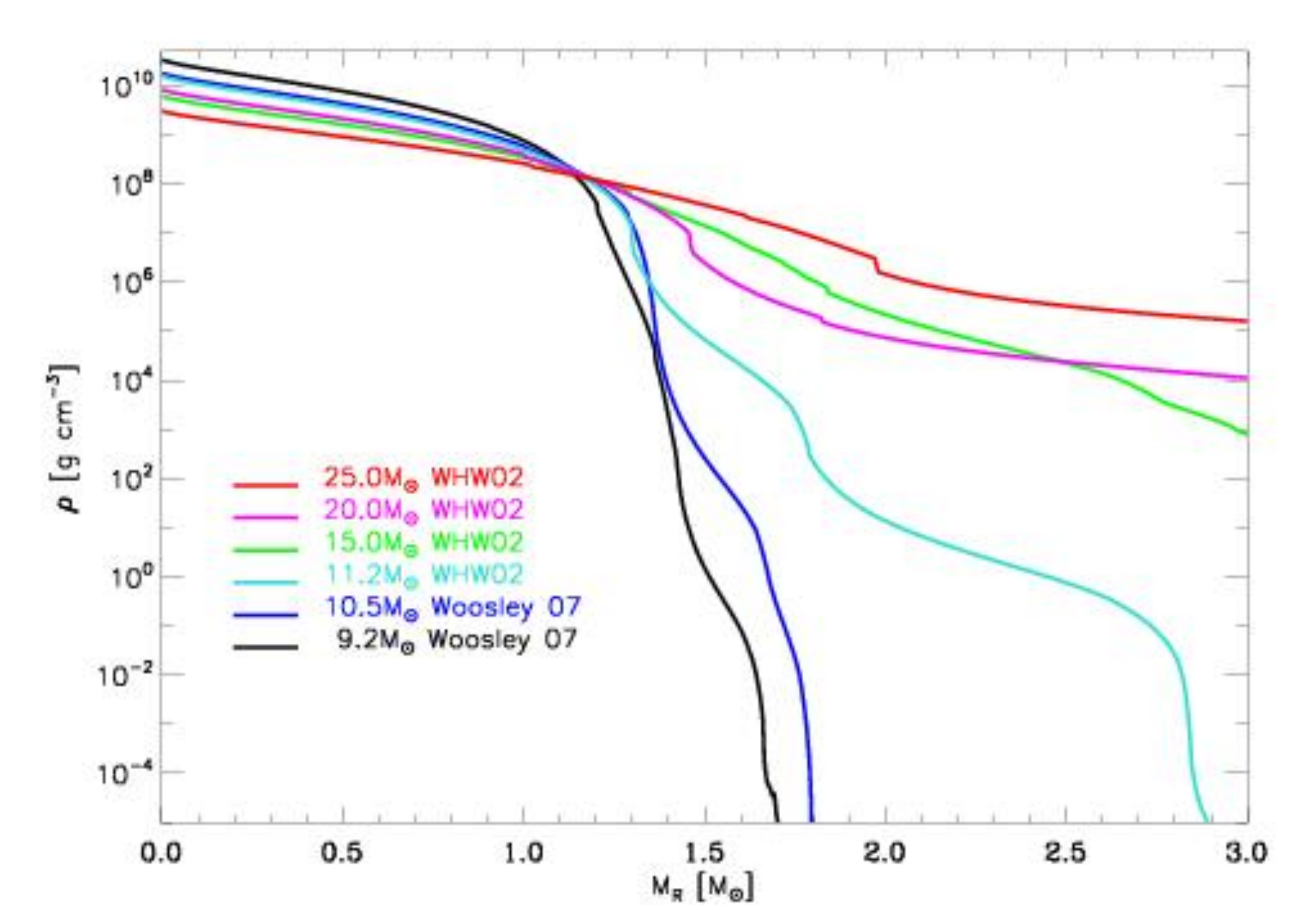
Electron-neutrino mean free path decreases much more rapidly with density than core size, and the neutrinos become trapped in the core.

Degenerate electron-neutrino Fermi sea develops...

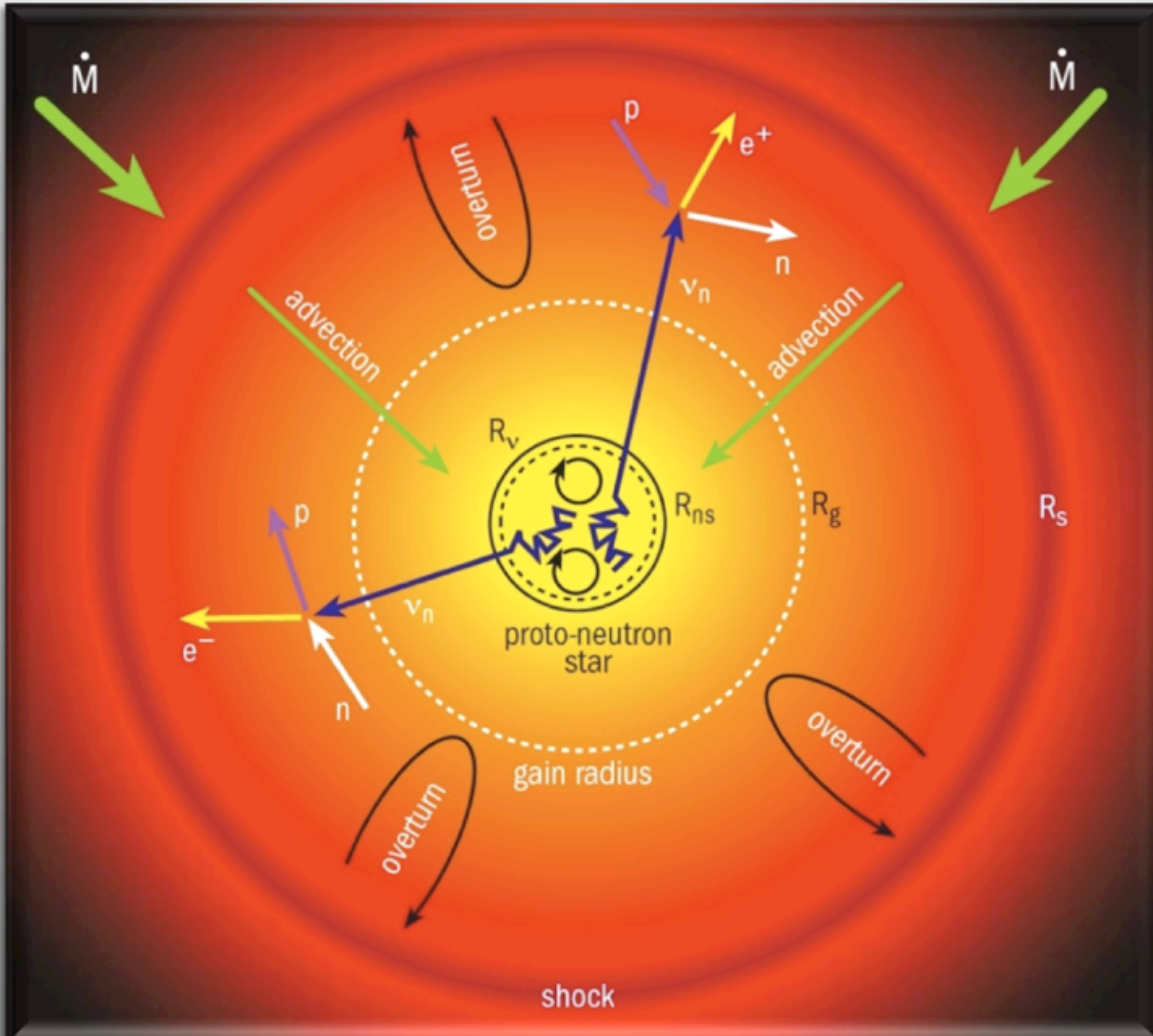
Homologous collapse

- **homologous collapse --> differences in core structure for different progenitors only appear after bounce**



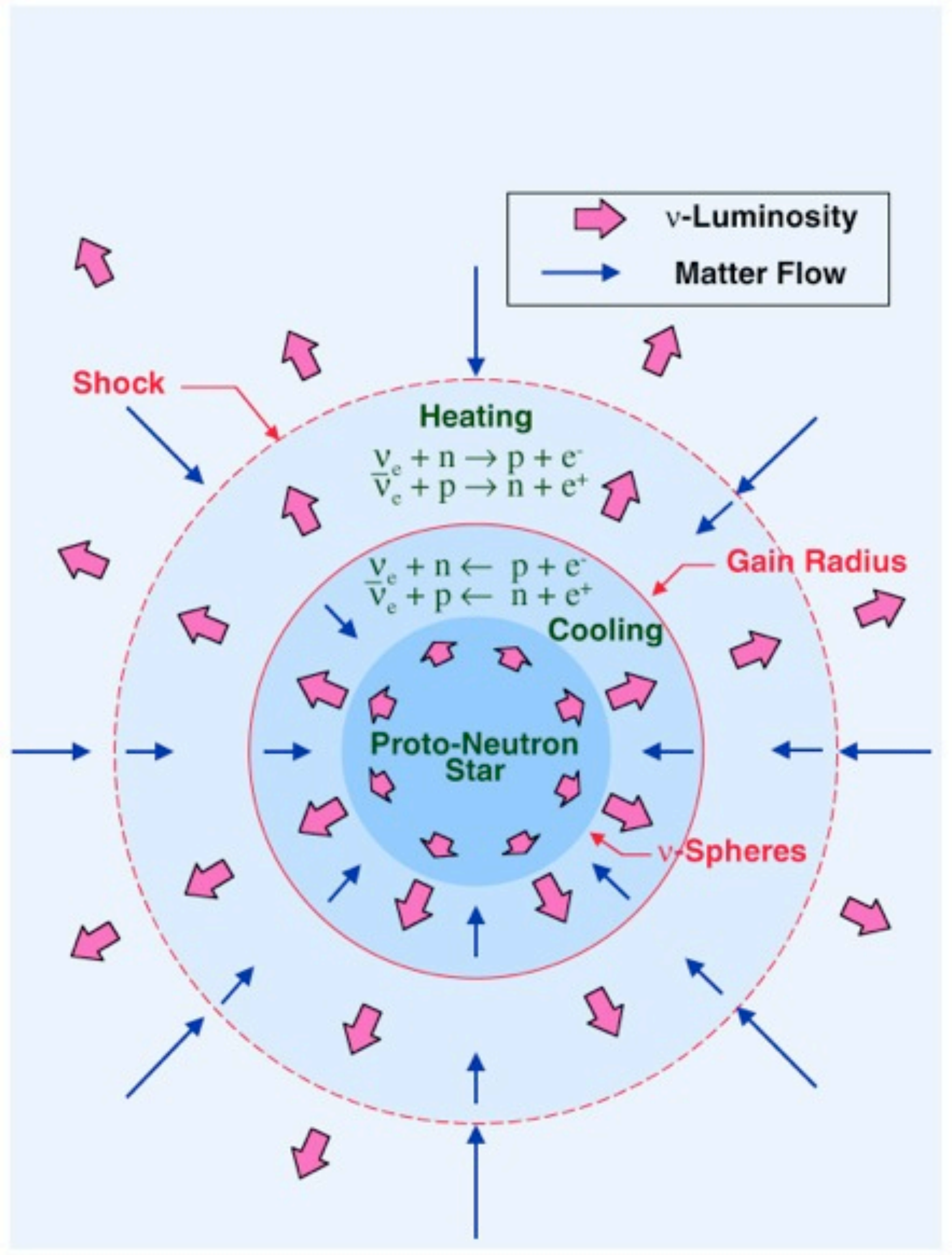


Post-bounce profile



Hillebrandt, Janka, & Müller 2006 (Sci Am)

How is the supernova shock revived?

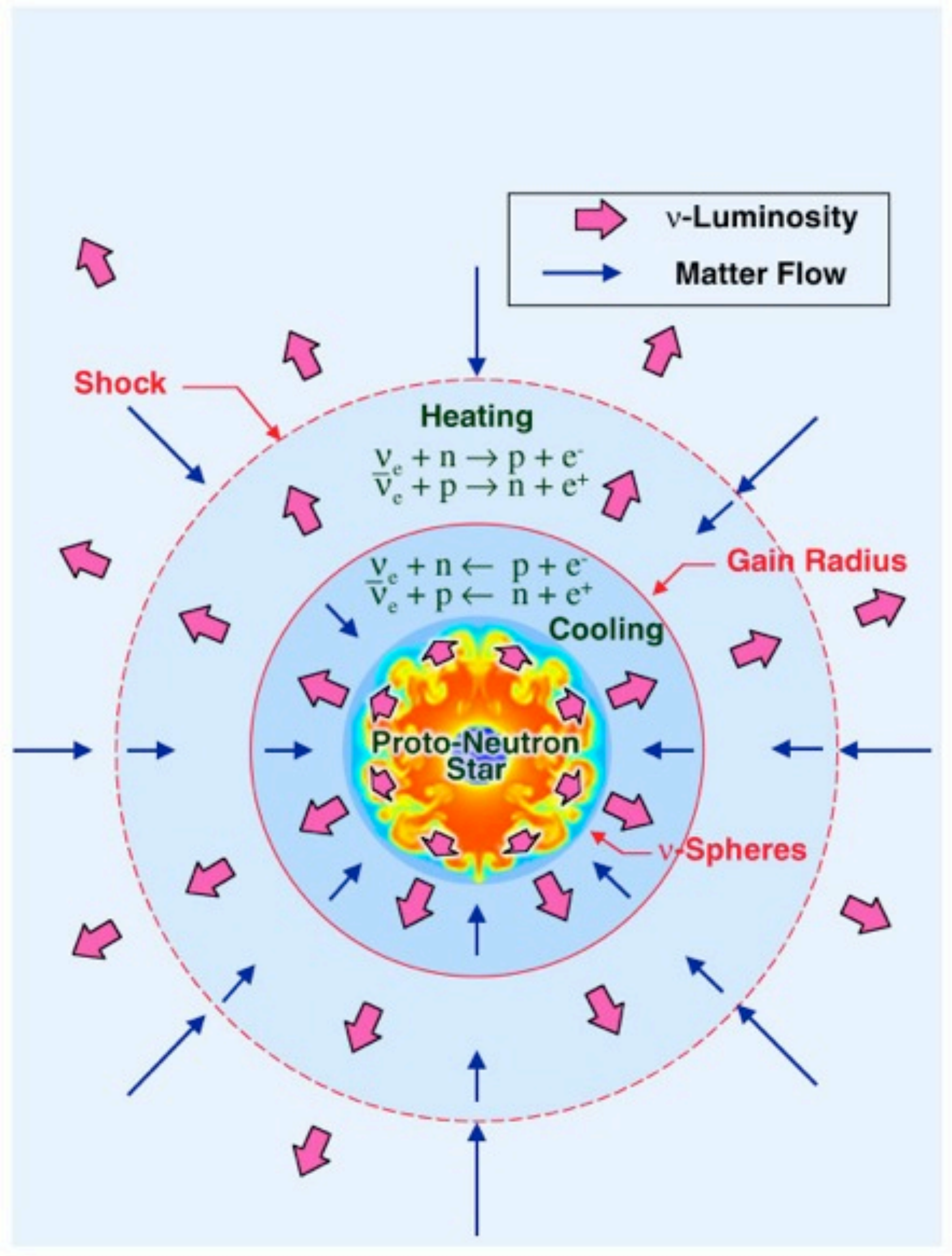


Known, Potentially Important Ingredients

- Gravity
- Neutrino Heating
- Convection
- Shock Instability (SASI)
- Nuclear Burning
- Rotation
- Magnetic Fields

Need 3D models with all of the above, treated with sufficient realism.

How is the supernova shock revived?



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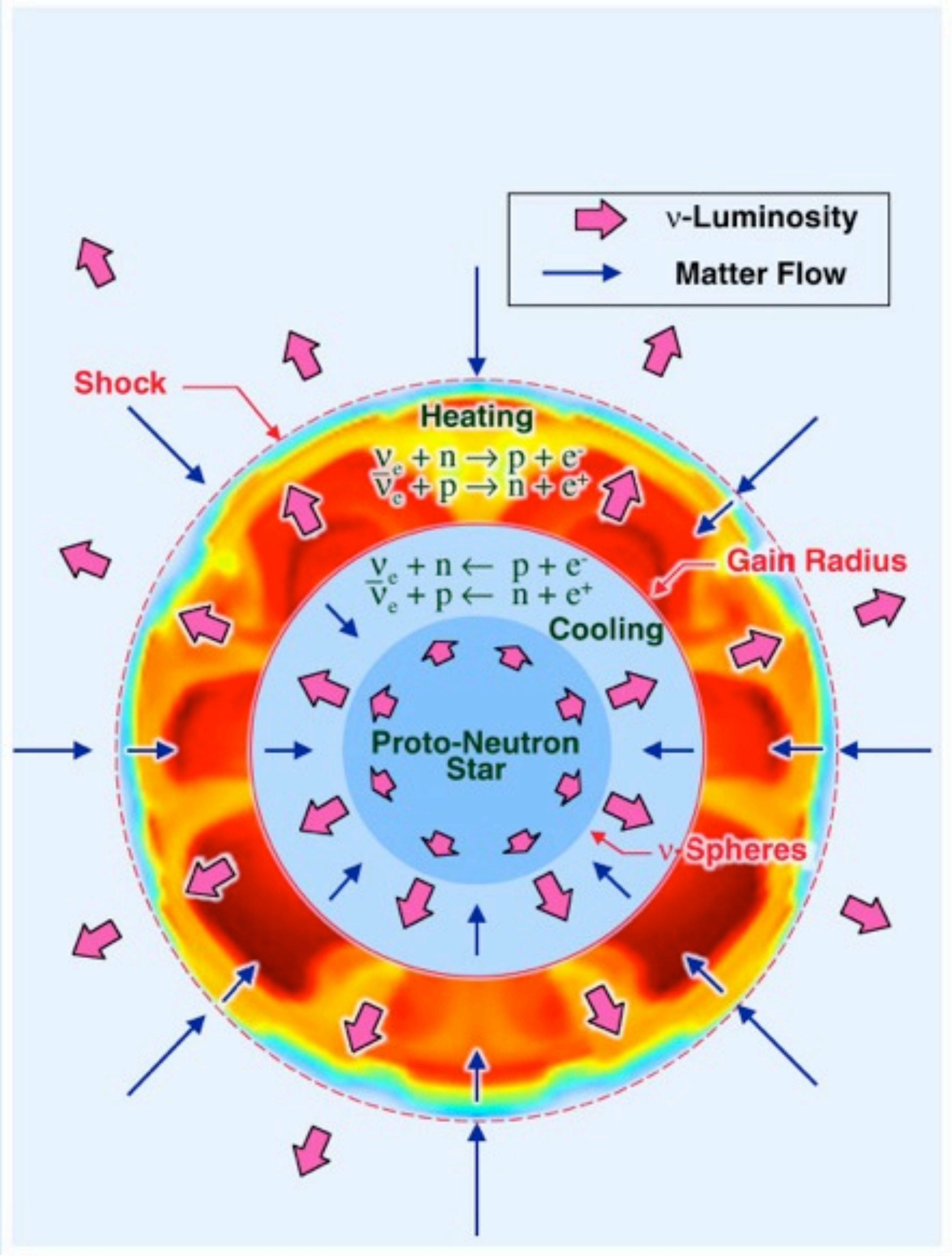

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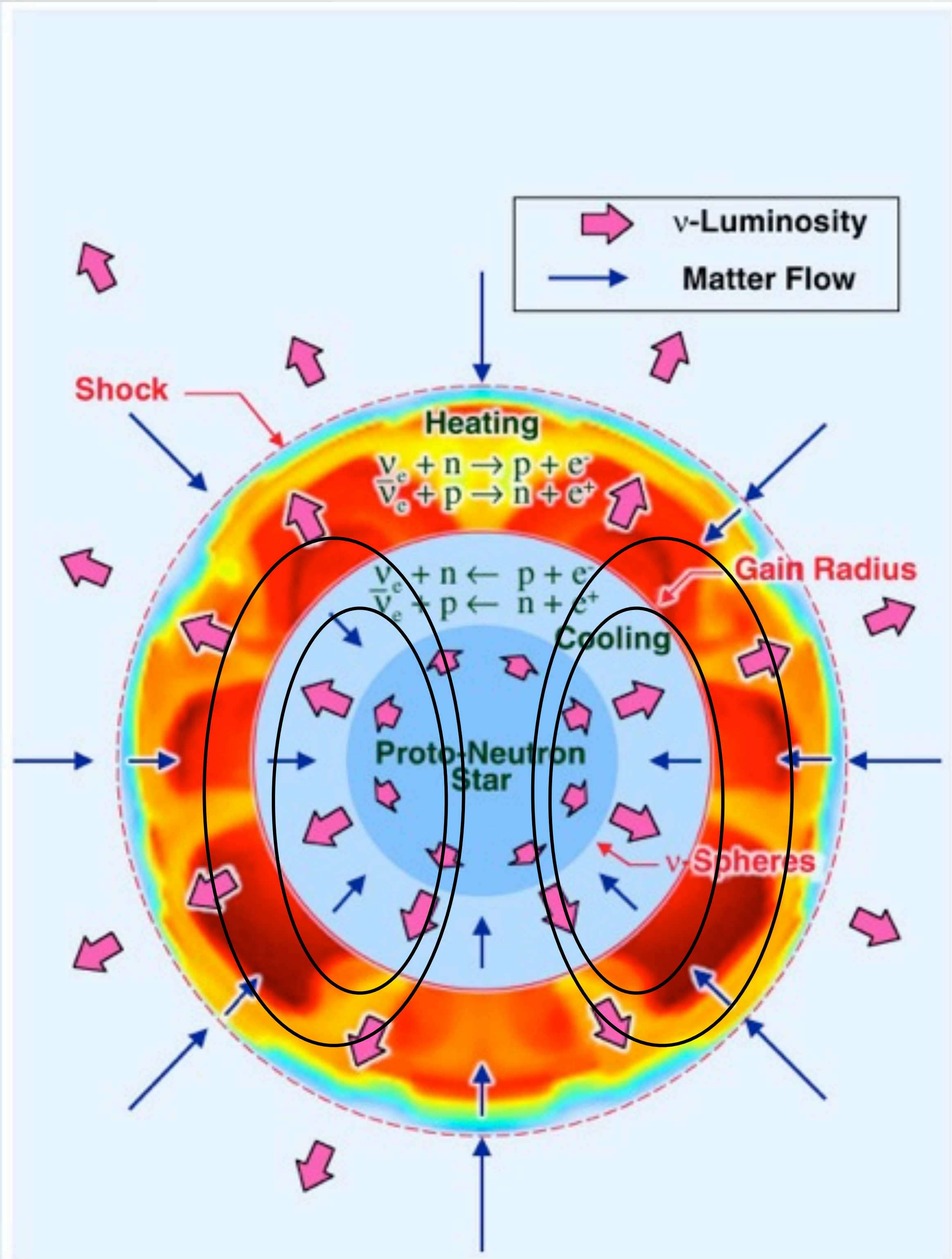

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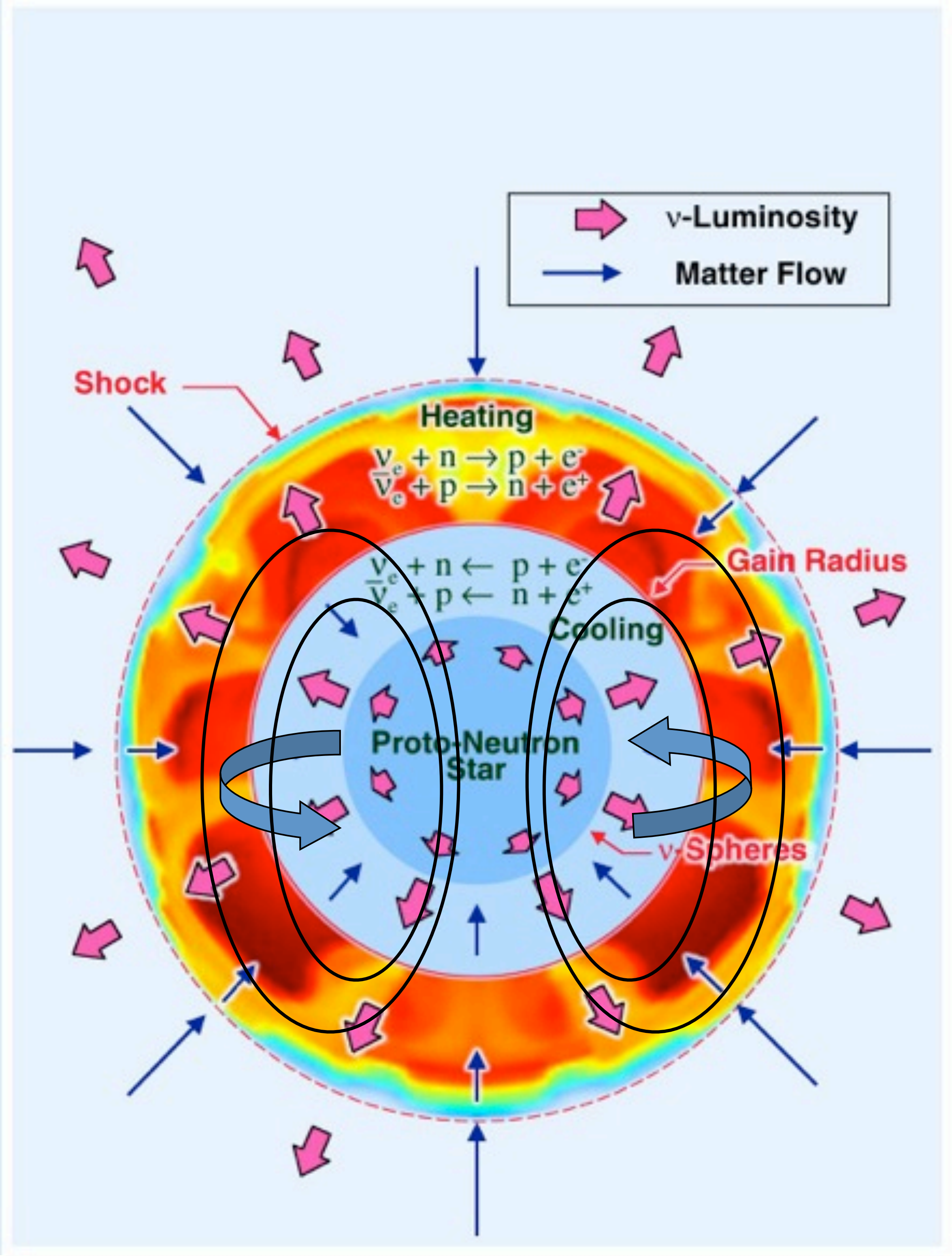

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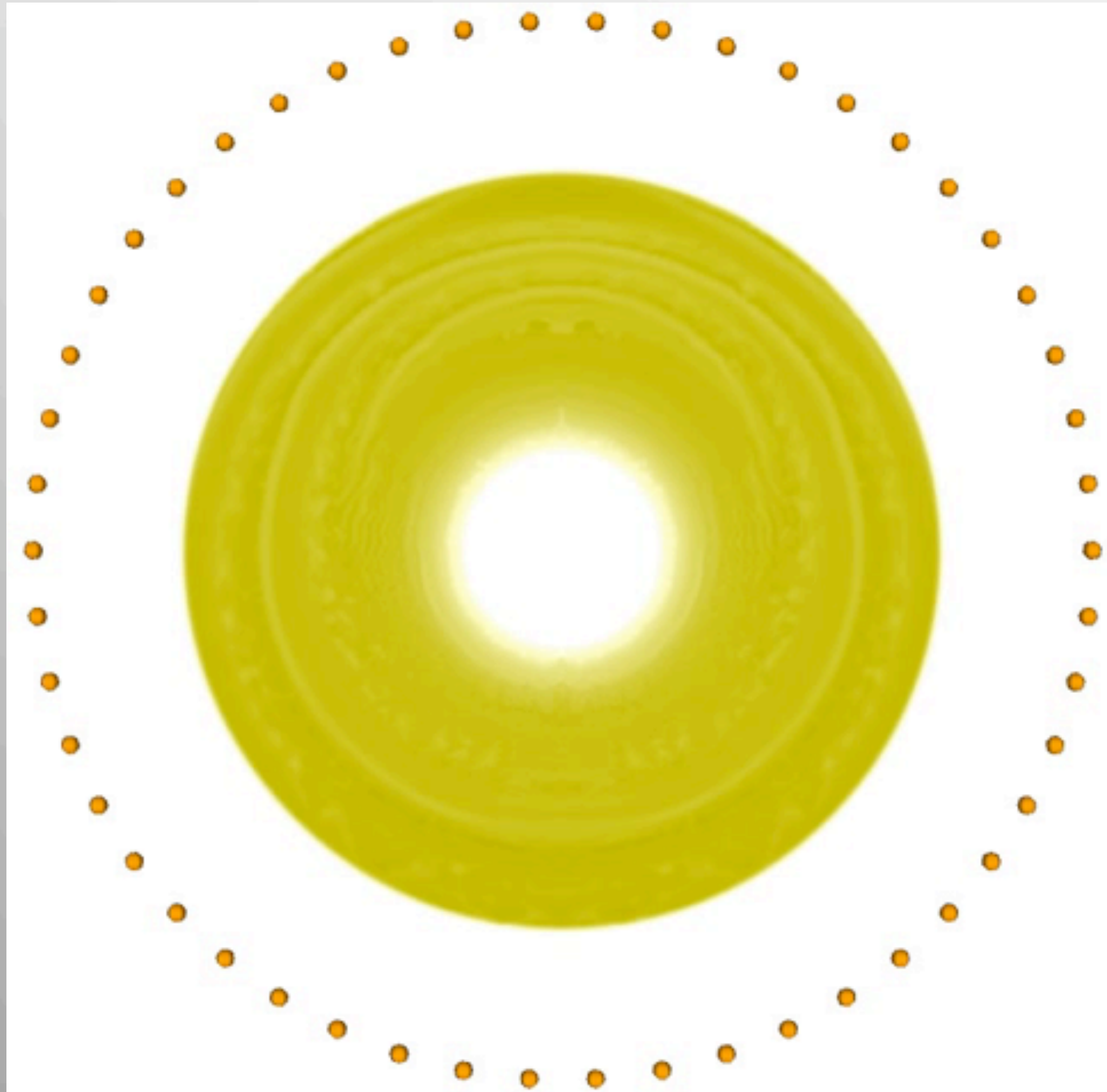
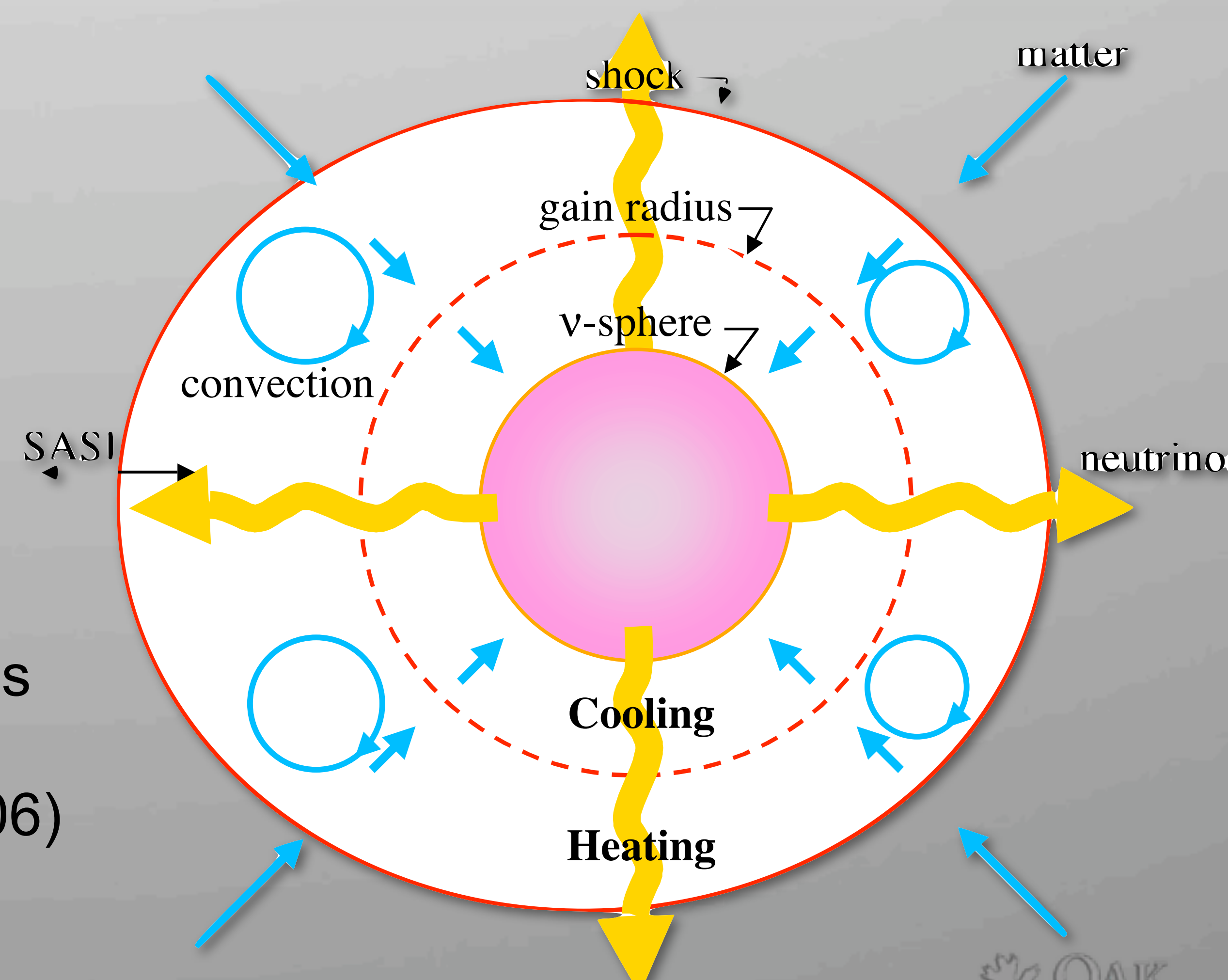
Stationary Accretion Shock Instability (SASI)



Shock wave unstable to non-radial perturbations.

Blondin, Mezzacappa, & DeMarino, *Ap.J.* **584**, 971 (2003)

- Decreases advection velocity in gain region.
- Increases time in the gain region.
- Generates convection.



SASI has *axisymmetric and nonaxisymmetric* modes that are both linearly unstable!

– Blondin and Mezzacappa, *Ap.J*. **642**, 401 (2006)
– Blondin and Shaw, *Ap.J.* **656**, 366 (2007)

CHIMERA

- "Ray-by-ray-Plus" MGFLD Neutrino Transport
  - O(v/c), GR time dilation and redshift, GR aberration
- 2D PPM Hydrodynamics
  - GR time dilation, effective gravitational potential
  - adaptive radial grid
- Lattimer-Swesty EOS + low-density BCK EOS
  - K=220 MeV
  - low-density EOS "bridges" LS to network
- Nuclear (Alpha) Network
  - 14 alpha nuclei between helium and zinc
- 2D Effective Gravitational Potential
  - Marek et al. A&A, 445, 273 (2006)
- Neutrino Emissivities/Opacities
  - "Standard" + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung

Important neutrino emissivities/opacities

"Standard" Emissivities/Opacities

Bruenn, *Ap.J. Suppl.* (1985)
- Nucleons in nucleus independent.
- No energy exchange in nucleonic scattering.

$e^- + p, A \leftrightarrow \nu_e + n, A'$ — Langanke et al. *PRL*, **90**, 241102 (2003)
- Include correlations between nucleons in nuclei.

$e^+ + e^- \leftrightarrow \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$

★ $\nu + n, p, A \rightarrow \nu + n, p, A$ — Reddy, Prakash, and Lattimer, *PRD*, **58**, 013009 (1998); Burrows and Sawyer, *PRC*, **59**, 510 (1999)
- (Small) Energy is exchanged due to nucleon recoil.
- Many such scatterings.

$\nu + e^-, e^+ \rightarrow \nu + e^-, e^+$

★ $N + N \leftrightarrow N + N + \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$ — Hannestadt and Raffelt, *Ap.J.* **507**, 339 (1998); Hanhart, Phillips, and Reddy, *Phys. Lett. B*, **499**, 9 (2001)
- Additional source of neutrino-antineutrino pairs.

$\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Janka et al. *PRL*, **76**, 2621 (1996) (for $\nu + n, p, A \rightarrow \nu + n, p, A$)
Buras et al. *Ap.J.*, **587**, 320 (2003) (for $\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$)

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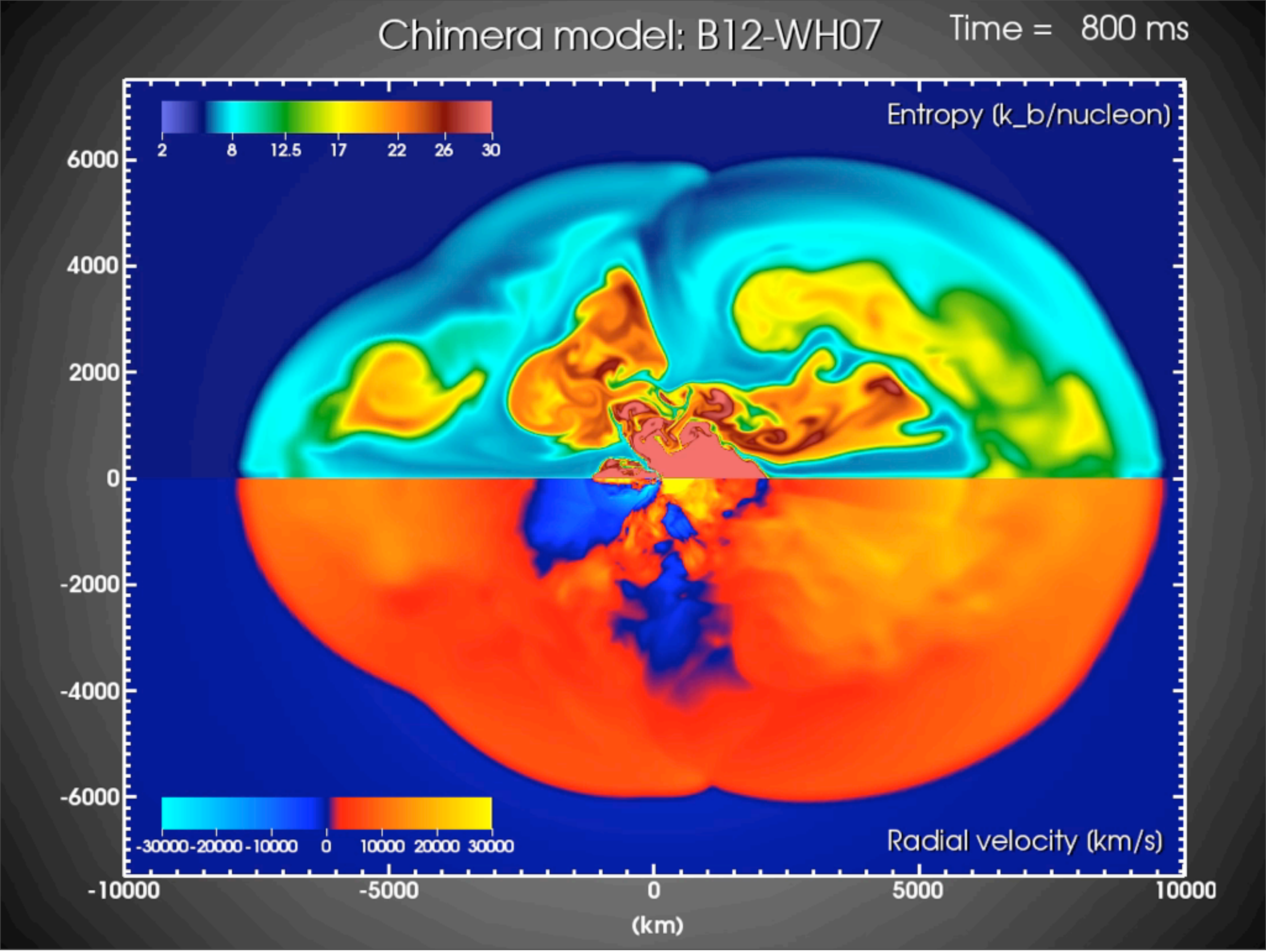
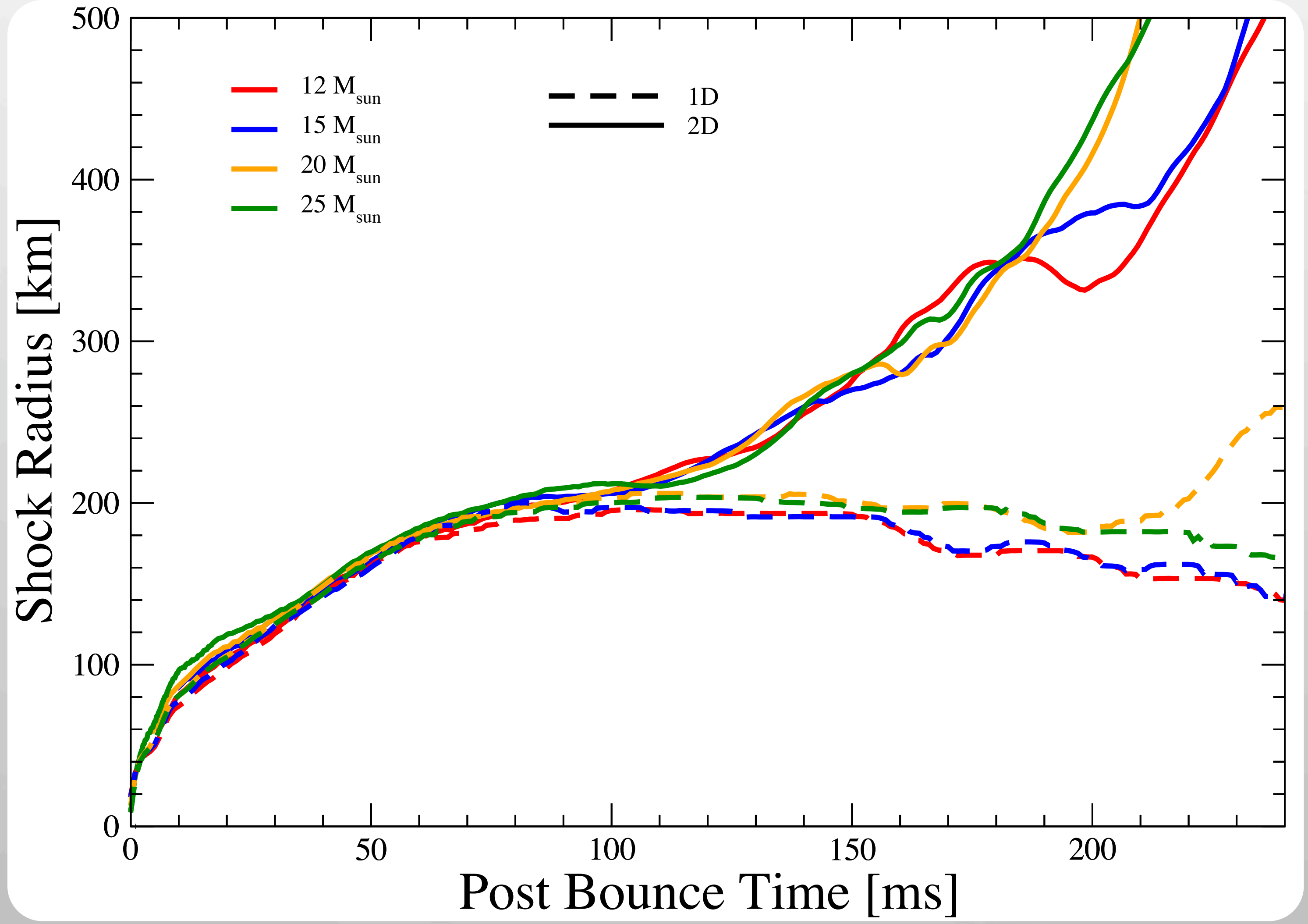
Bruenn et al., *J. Phys. Conf. Ser.*, **46**, 393 (2006)
Mezzacappa et al., *AIP Conf. Proc.*, **924**, 234 (2007)
Messer et al., *J. Phys. Conf. Ser.*, **78**, 012049 (2007)


Chimera model: B12-WH07
Time = 800 ms
Entropy (k_b/nucleon)
2 8 12.5 17 22 26 30
6000
4000
2000
0
-2000
-4000
-6000
-30000 -20000 -10000 0 10000 20000 30000
Radial velocity (km/s)
-10000 -5000 0 5000 10000
(km)

The early phase



- For the first ~100 ms after bounce, the supernova shock is essentially spherical, with 1D models identical to 2D models.
- Once the Standing Accretion Shock Instability (SASI) and neutrino-driven convection begin, the shock deforms and gradually progresses outward in radius.
- Neutrino-driven convection precedes the development of the SASI at low mass (12 $M_\odot$) and trails the development of the SASI at high mass (25 $M_\odot$).
- One notable feature is the considerable delay in launching an explosion.
  (cf. (Herant et al. 1994): <100ms)

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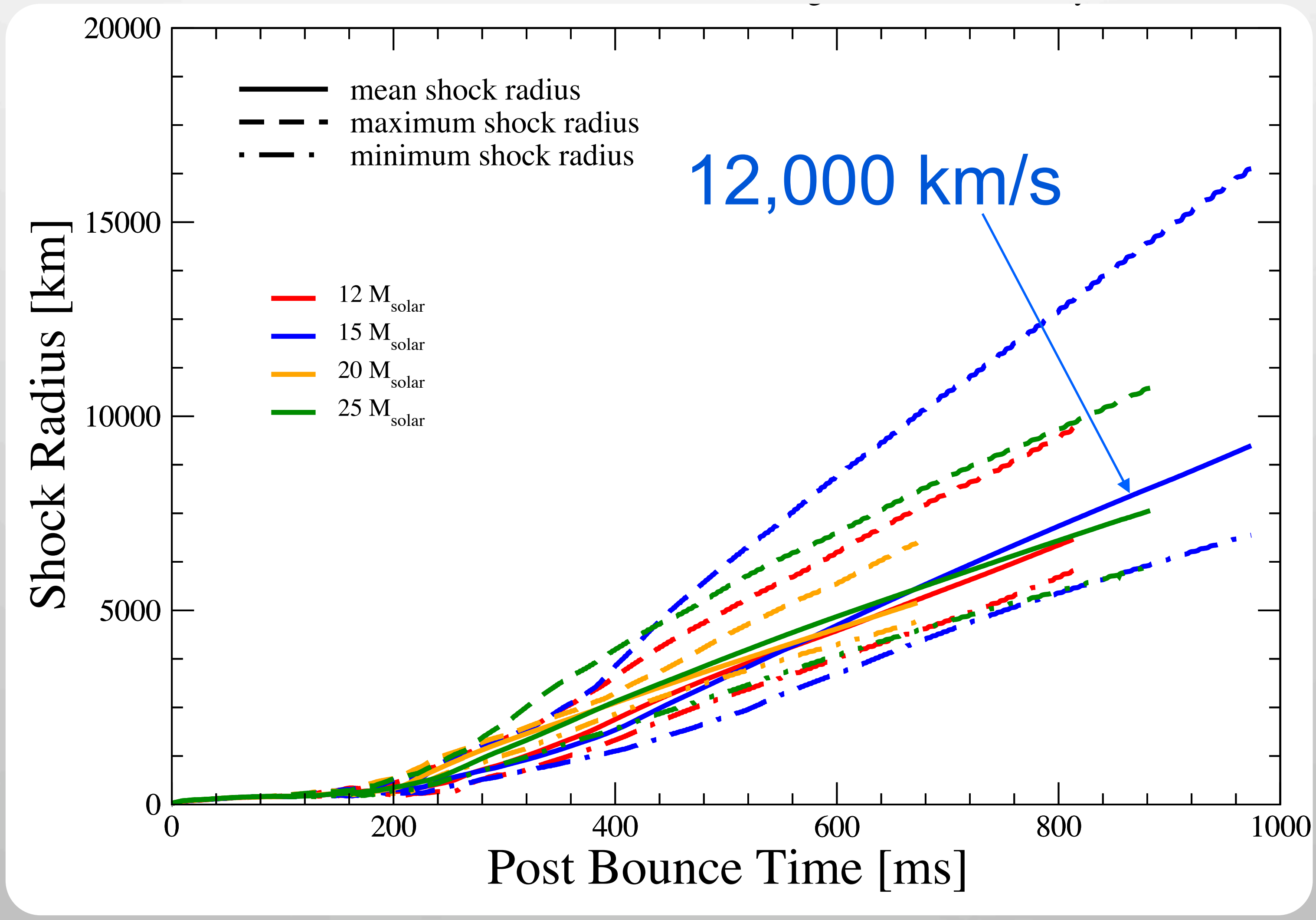
The early phase



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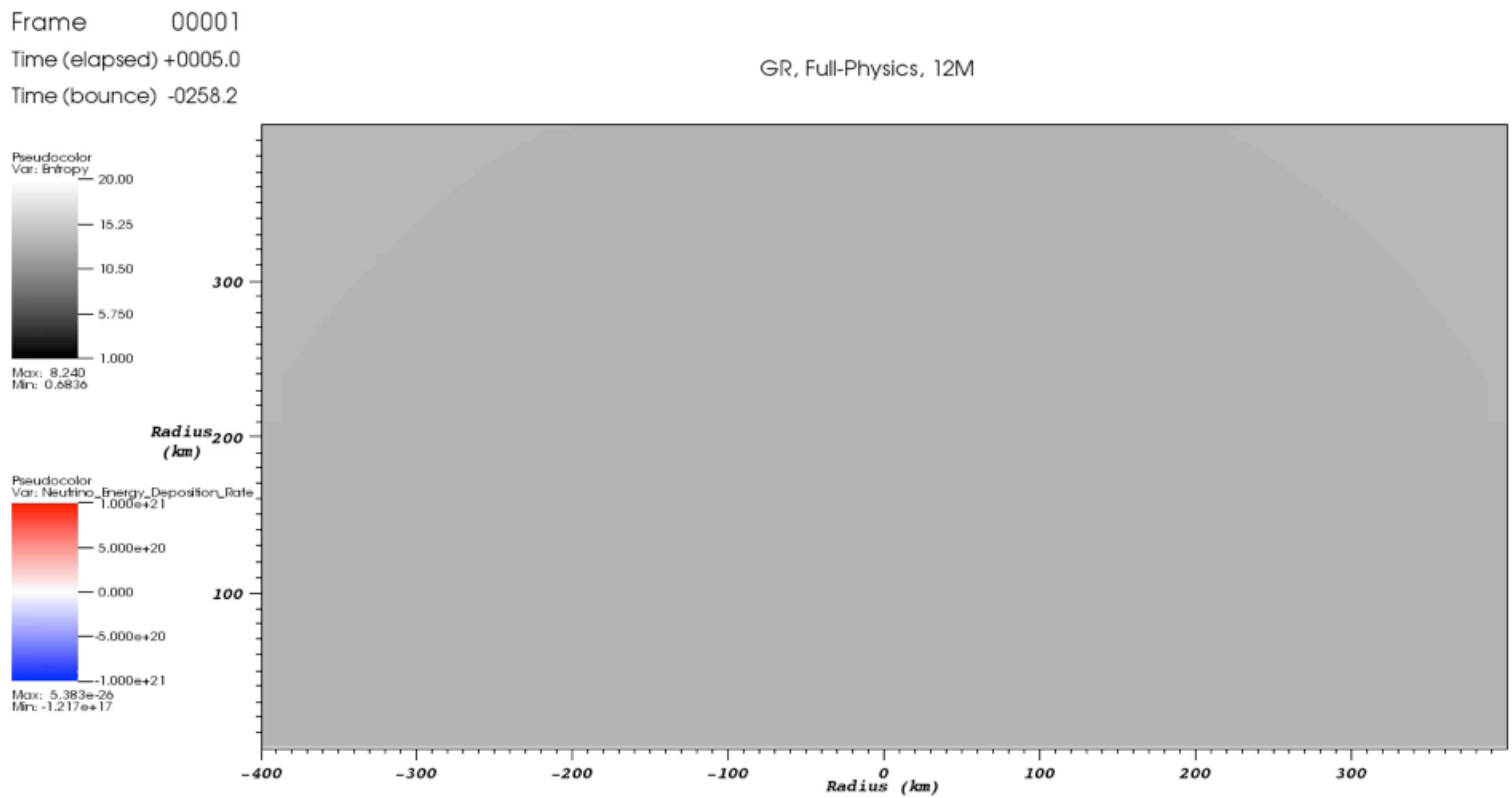
Working neutrinos

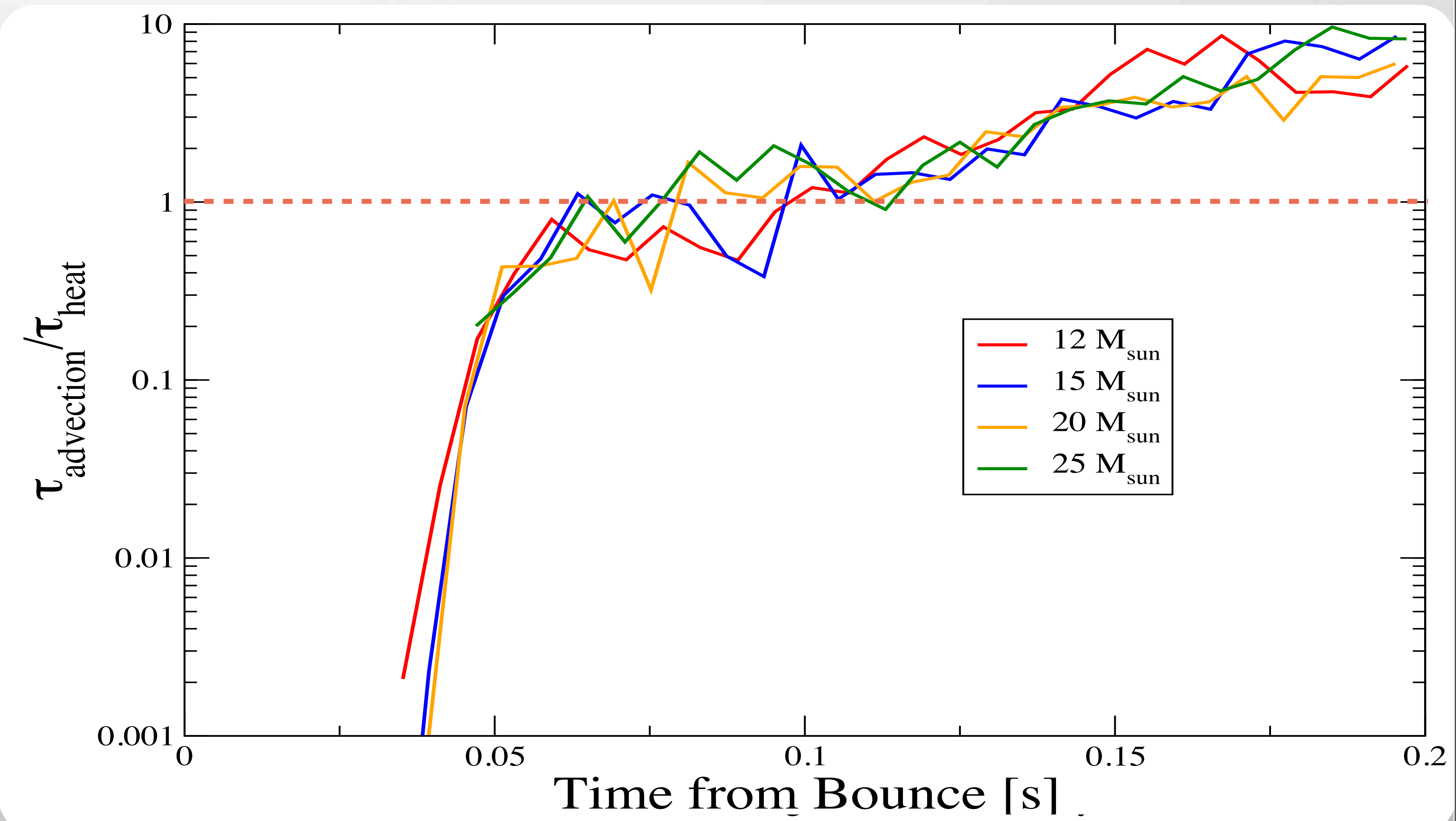
- **The initially spherical gain surface between the cooling and heating regions begins to distort ~70 ms after bounce.**
- **Beginning at ~120 ms, the heating region is characterized by low-entropy downflows and high-entropy upflows, with the strongest heating at the bases of the impinging downflows.**

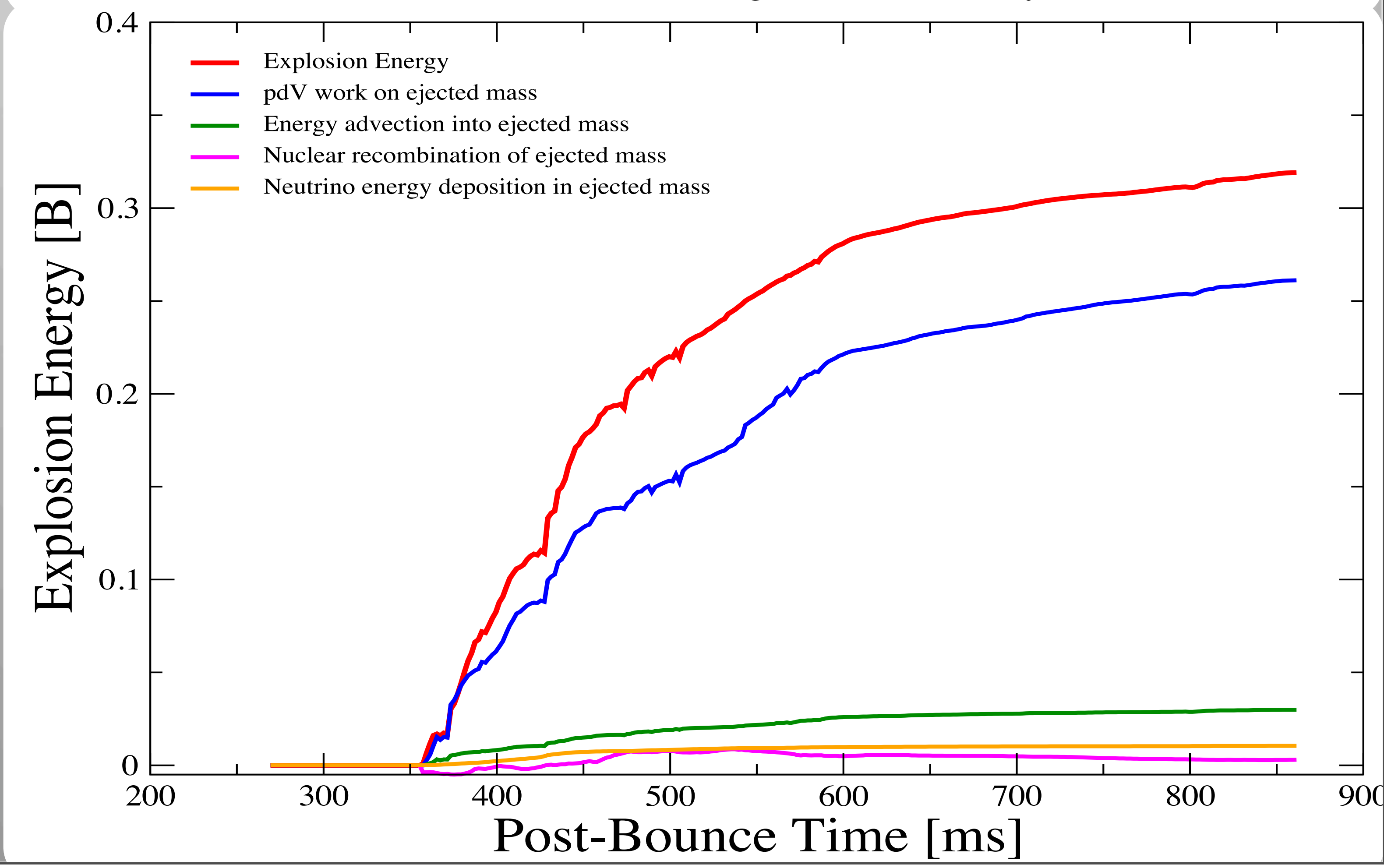


How to make an explosion

- SASI gradually pushes the shock outward, increasing the size of the heating region until heating timescale ($\tau_{heating}$) is smaller than advection timescale ($\tau_{advection}$).

- Much of the explosion energy comes from the neutrino heating region, below the ejecta, in the form of PdV work and advected internal energy.





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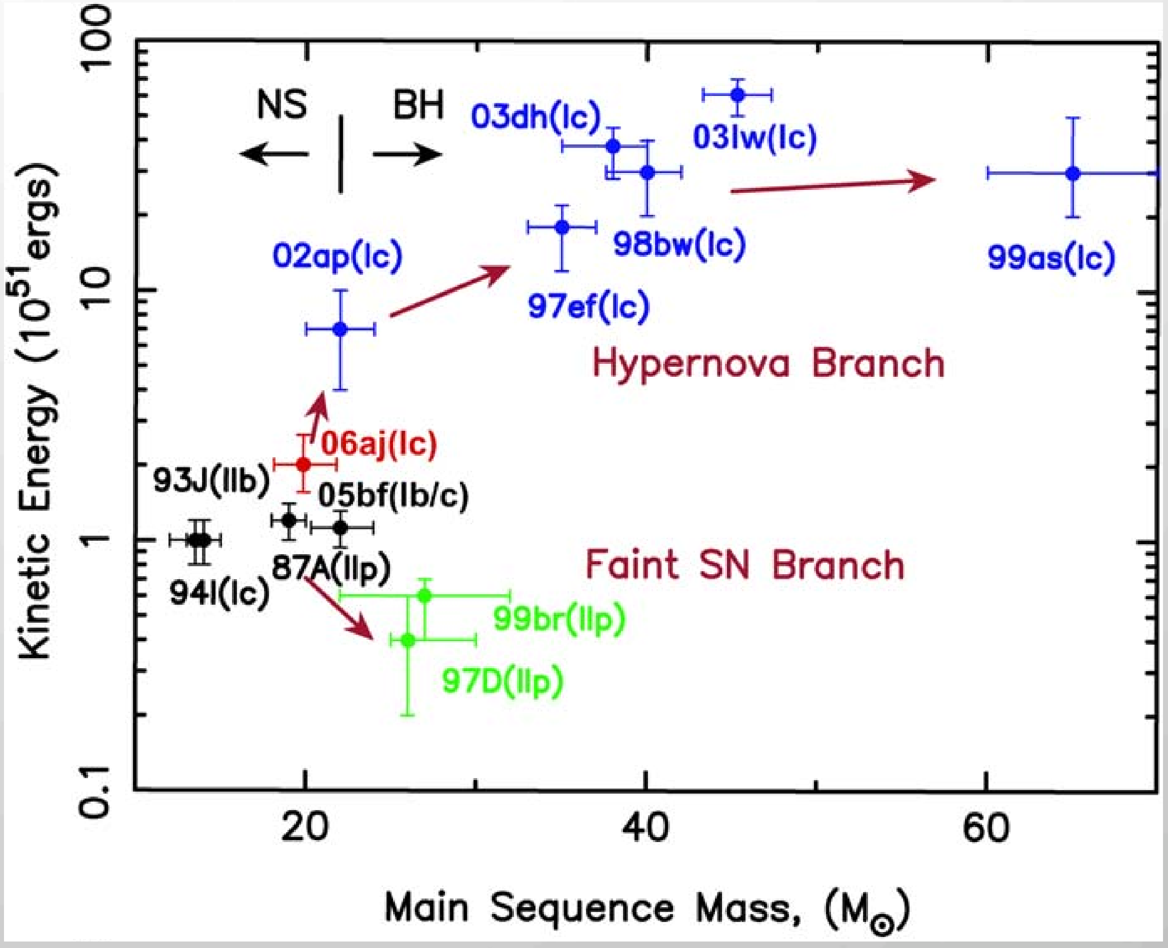
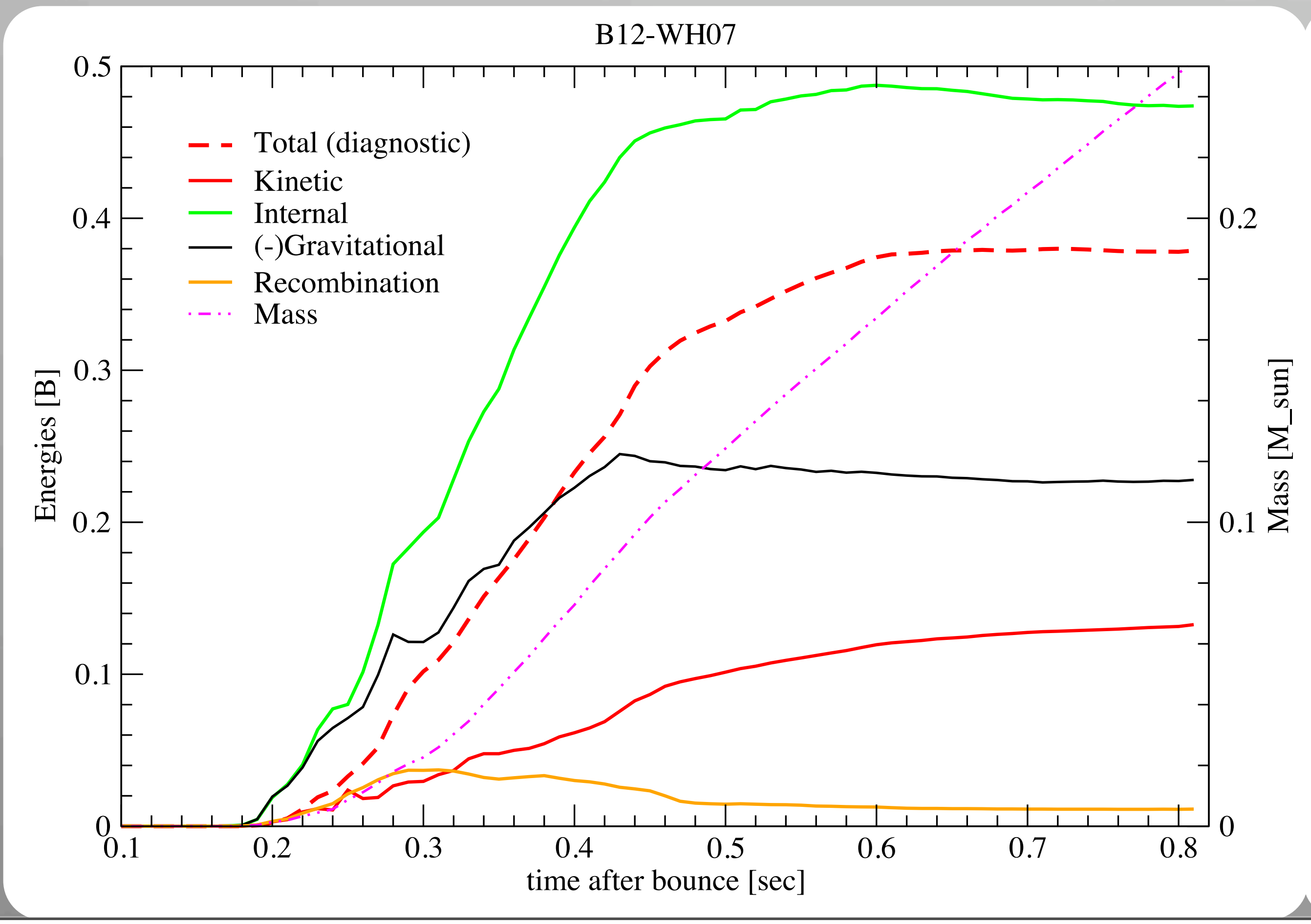
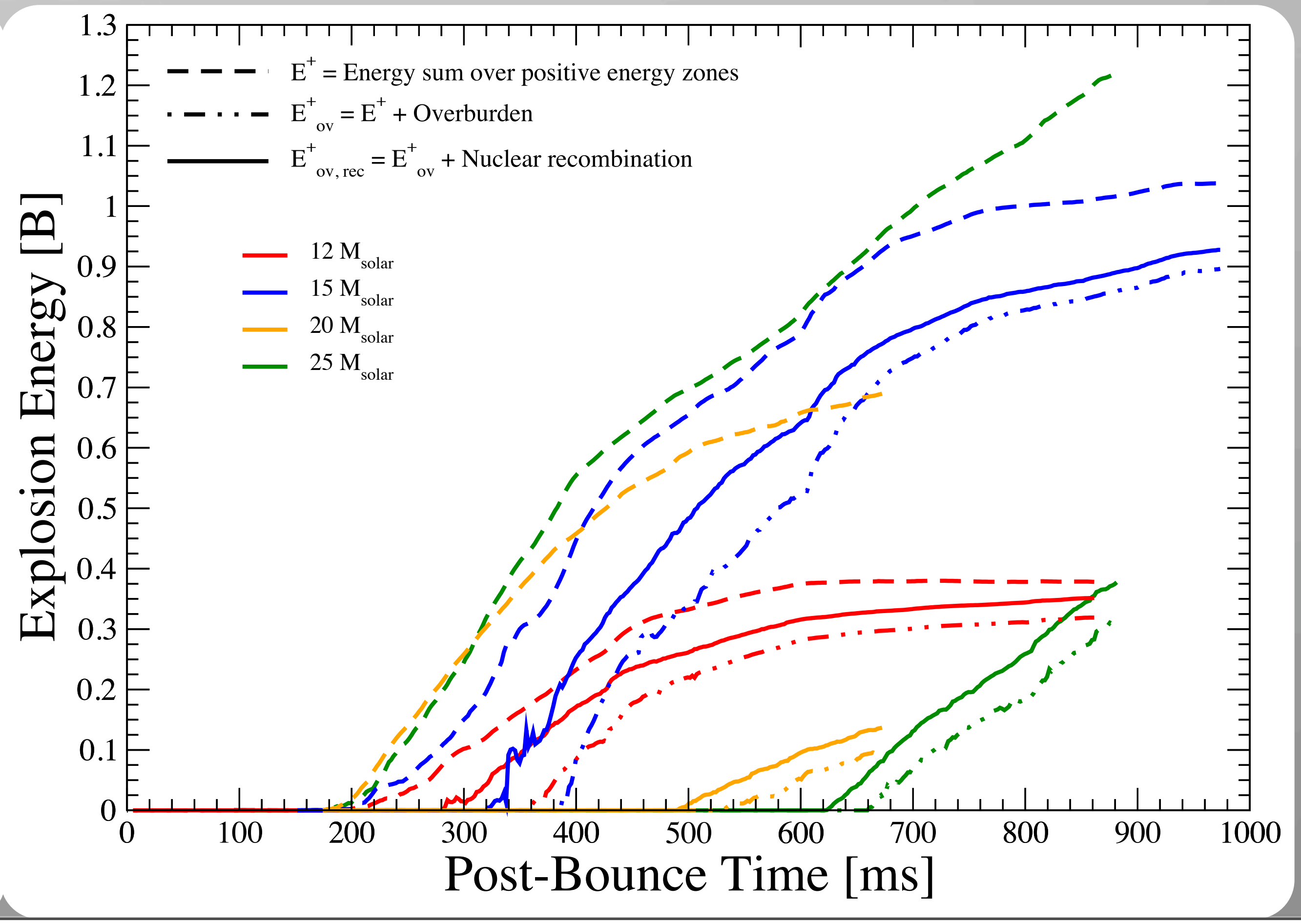
Explosion energies

- Because models are still in the stage where internal energy dominates, we must estimate the explosion energy by assuming efficient conversion of $E_i \Rightarrow E_k$.
- One can construct a "diagnostic" energy, $E_+ = E_i + E_g + E_k$, summed over zones where $E_+ > 0$.
- To this we add contributions from nuclear recombination and removing the envelope.



Nomoto, Tominaga, et al. (2006)





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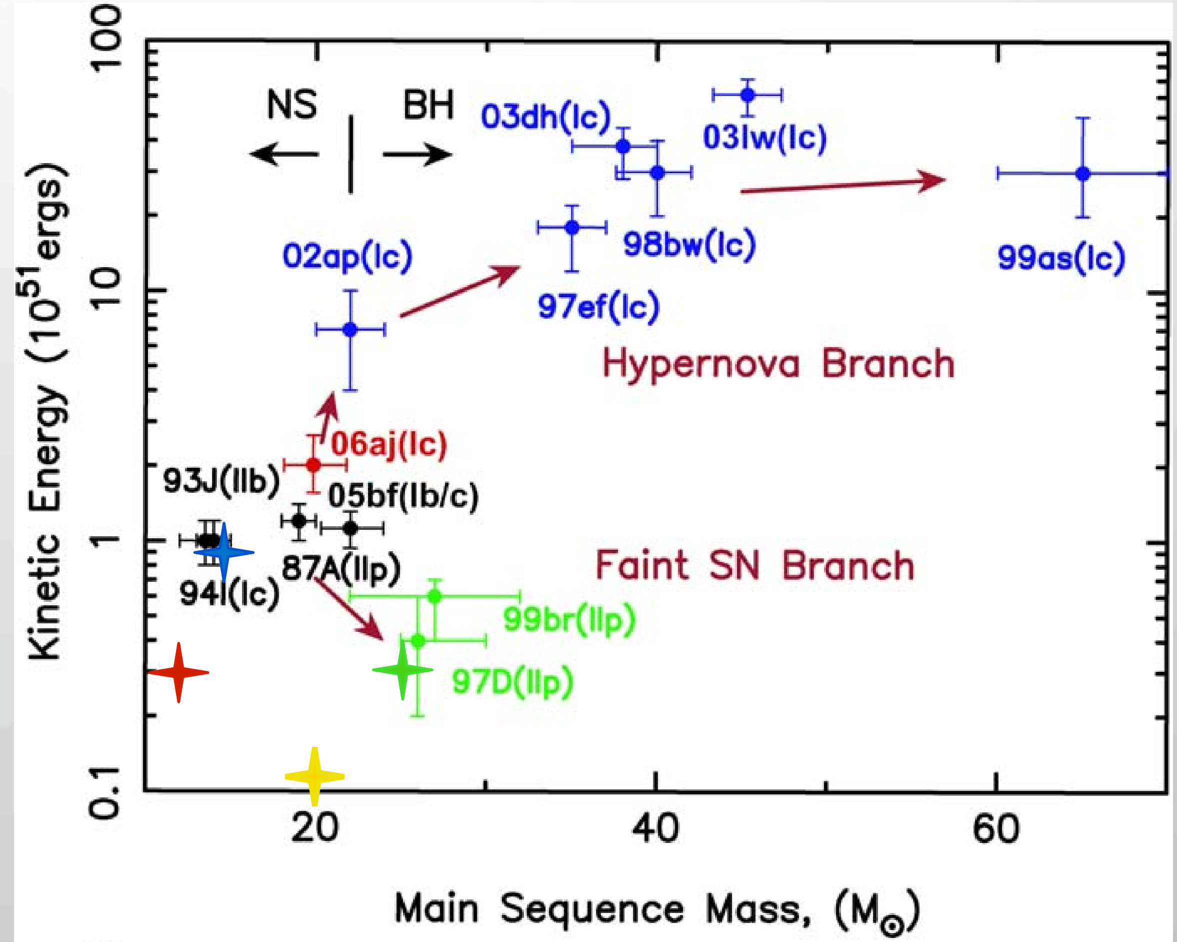

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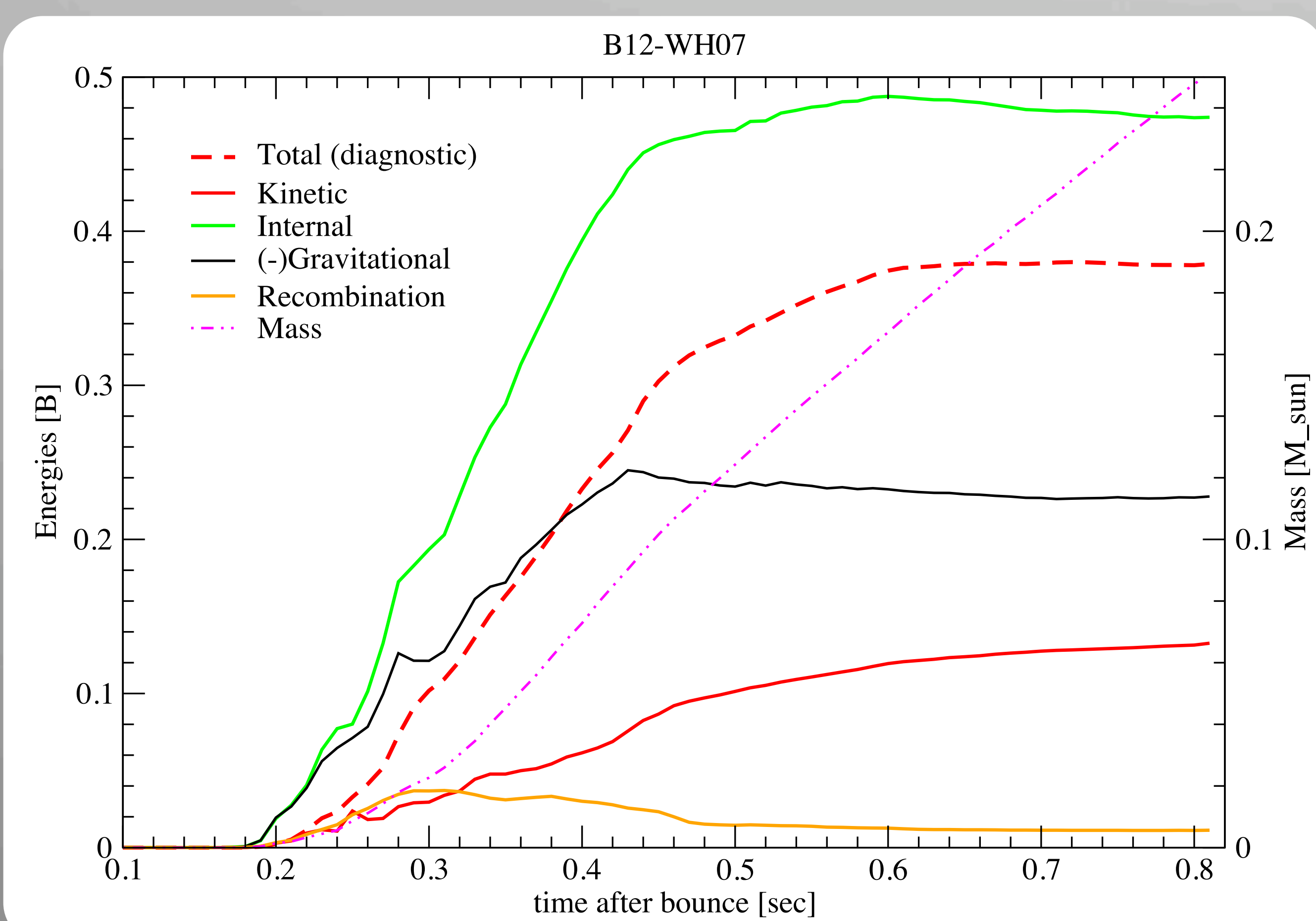
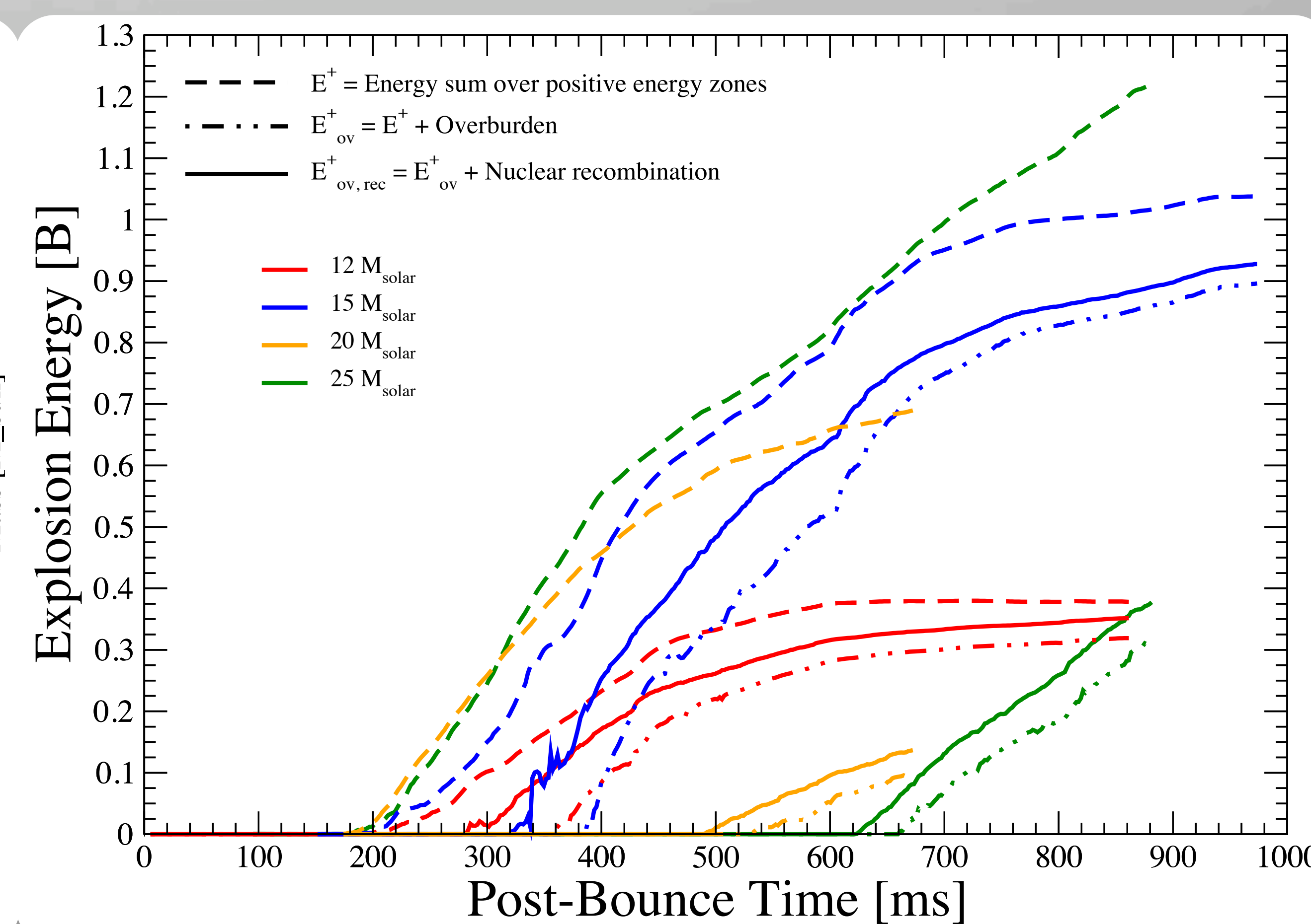
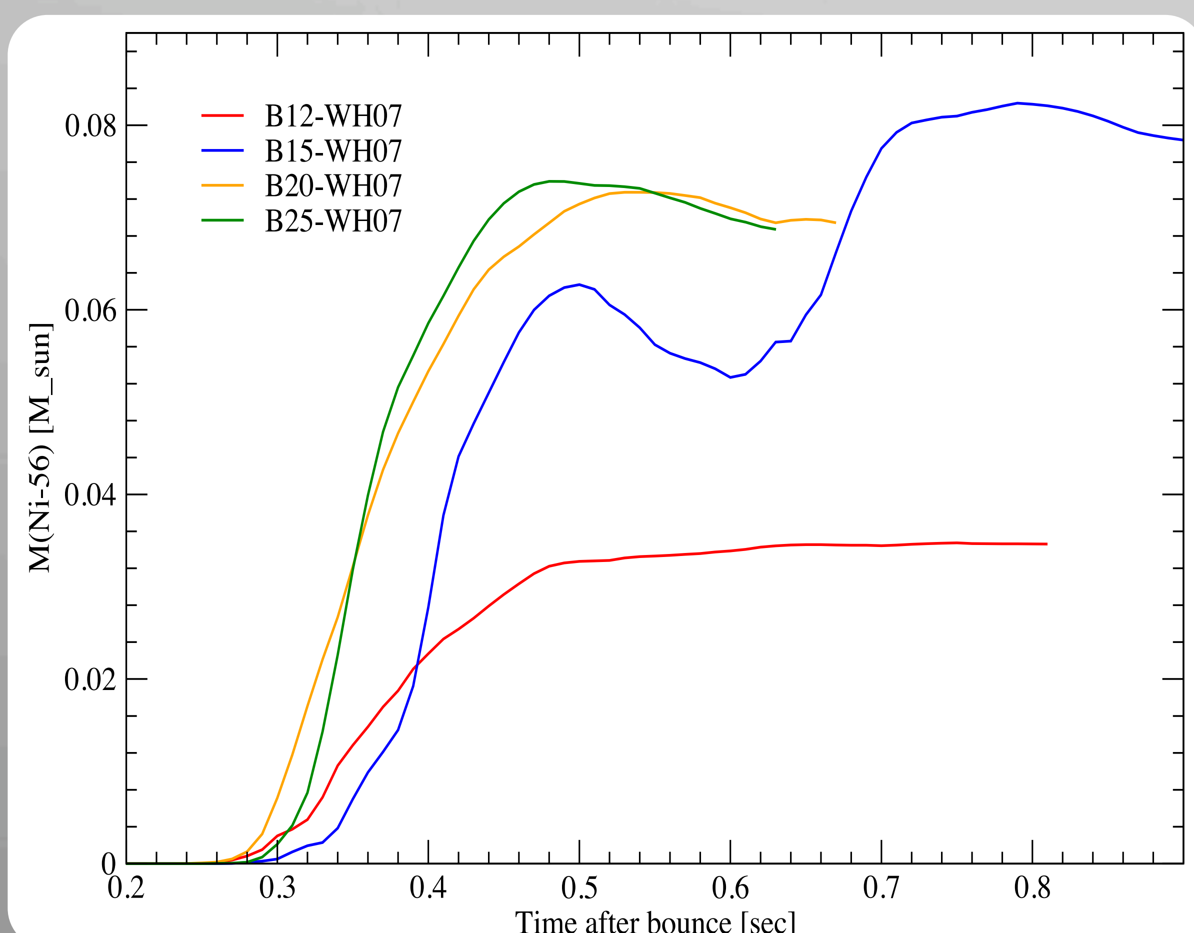
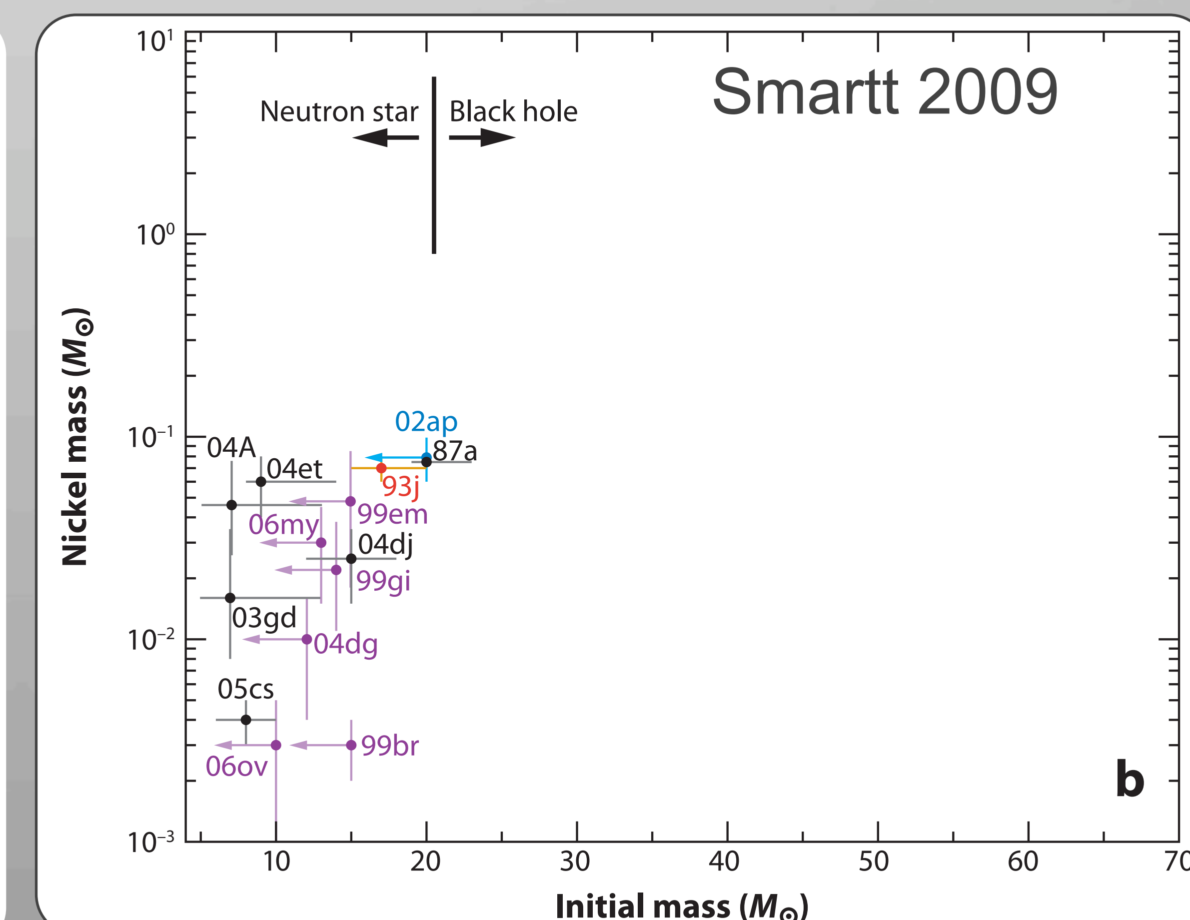




Nickel mass

- Another important observable, related to the explosion energy and very relevant to the nucleosynthesis, is the mass of ^{56}Ni.
- Only in the 12 M☉ case has the ^{56}Ni mass saturated.
- Mass of other iron-peak species is comparable to ^{56}Ni.
- Results are reasonable, though fallback over longer timescales is uncertain. Recent studies are finding differing results on fallback.





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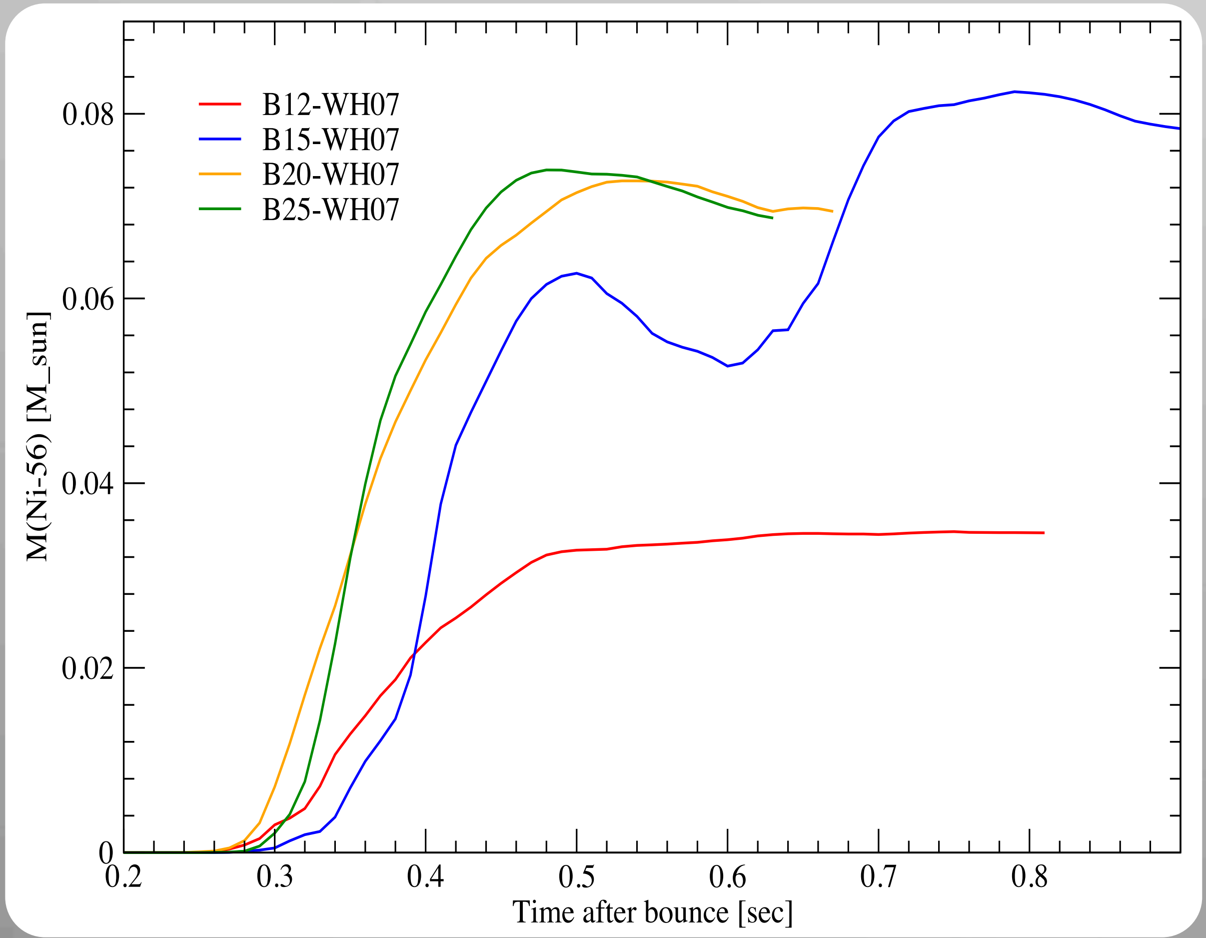
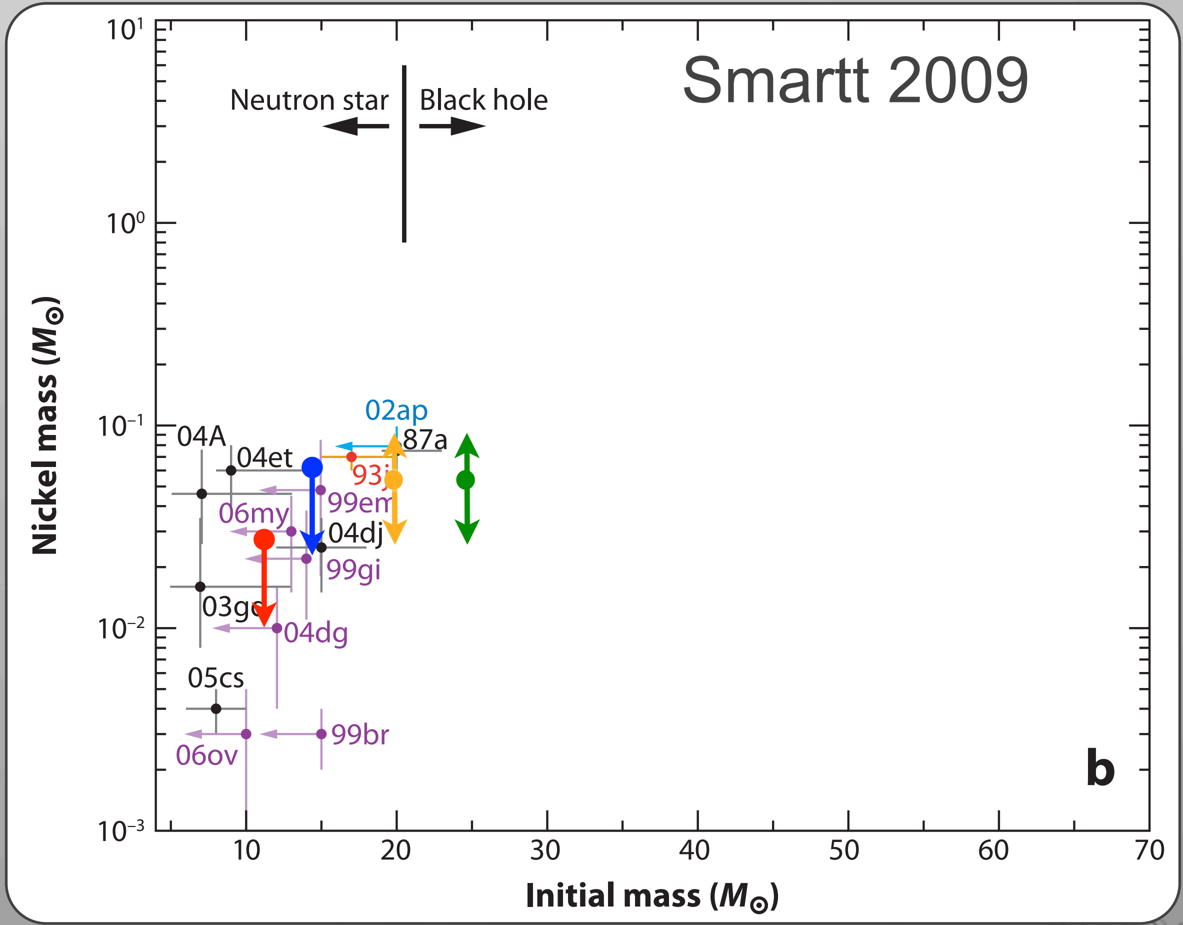
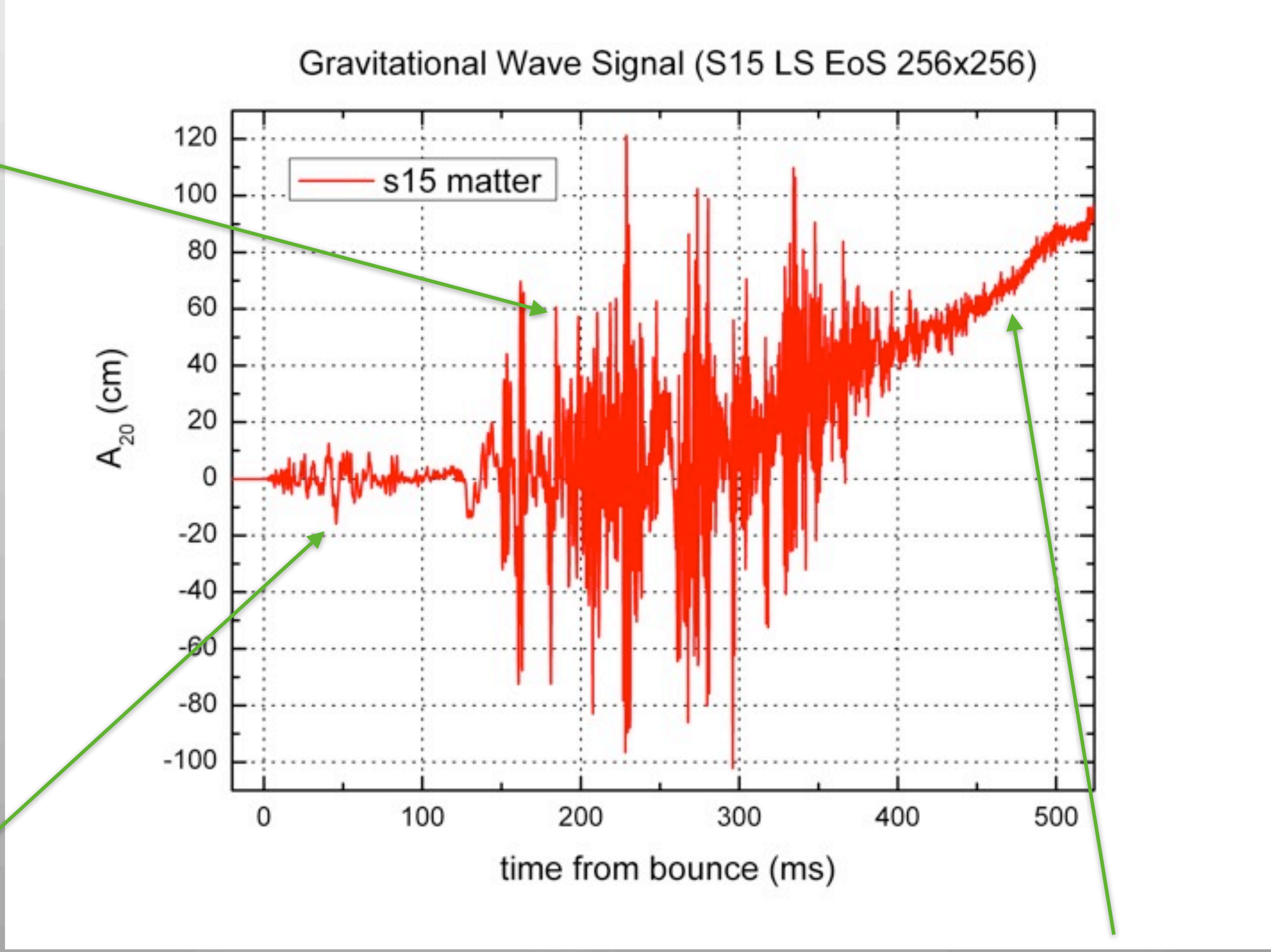




Example of multi-messenger observables: Anatomy of a GW signature

Yakunin et al. *Class. Quantum Grav.* 27 **194005** (2010)



• Lower-frequency envelope: SASI-induced shock excursions

• Higher-frequency variations: Impingement of downflows on PNS from neutrino-driven convection and SASI

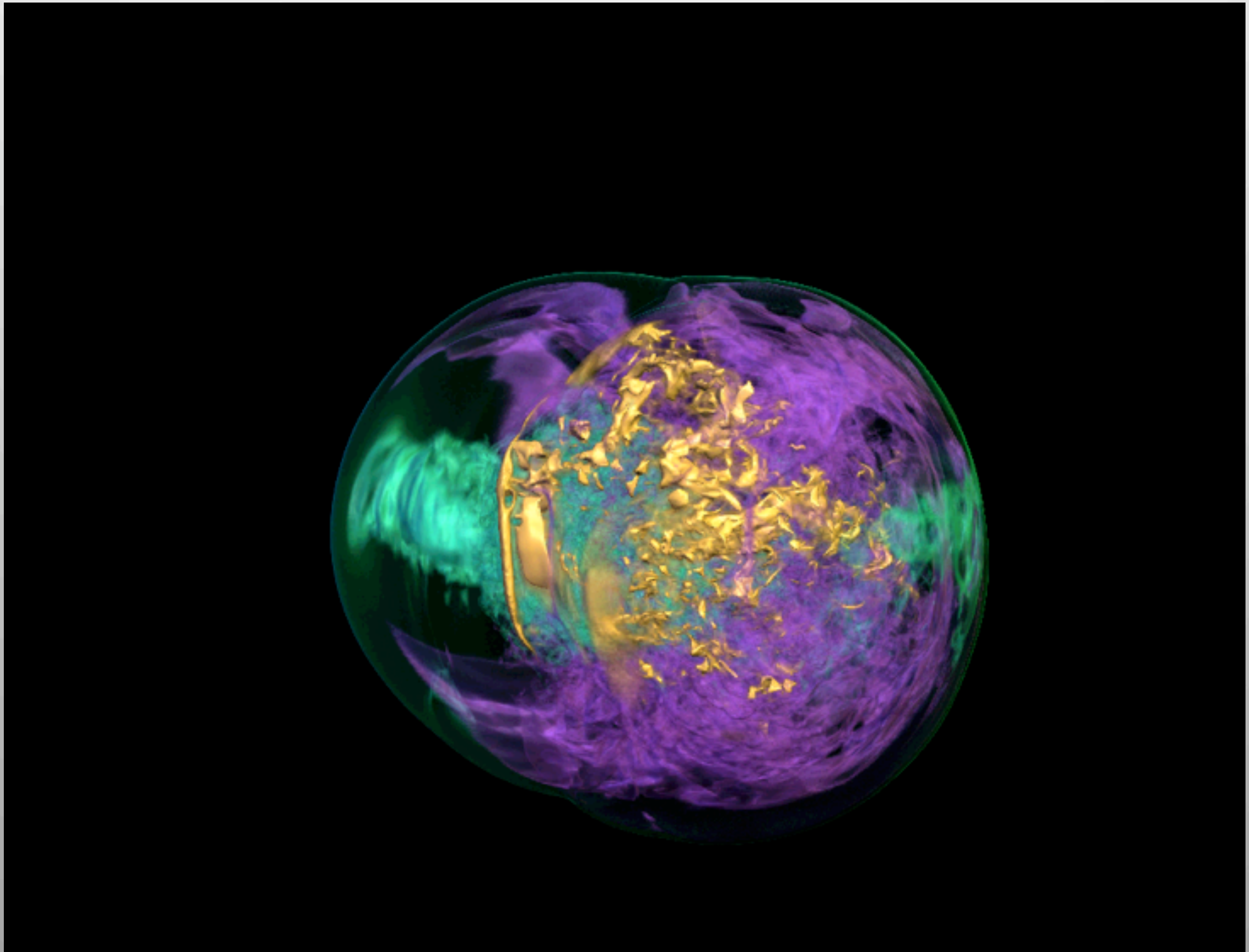
• Prompt Convection
• Early Shock Deceleration

• Later Rise: Prolate Explosion/Deceleration at Shock

SASI in 3D

Blondin & Mezzacappa *Nature* **445**, 58 (2007)

SASI in 3D



Blondin & Mezzacappa *Nature* **445**, 58 (2007)

Monday, April 15, 2013

3D simulations

- *“RbR-Plus” MGFLD Neutrino Transport*
  - *O(v/c), GR time dilation and redshift,*
  - *GR aberration (in flux limiter)*

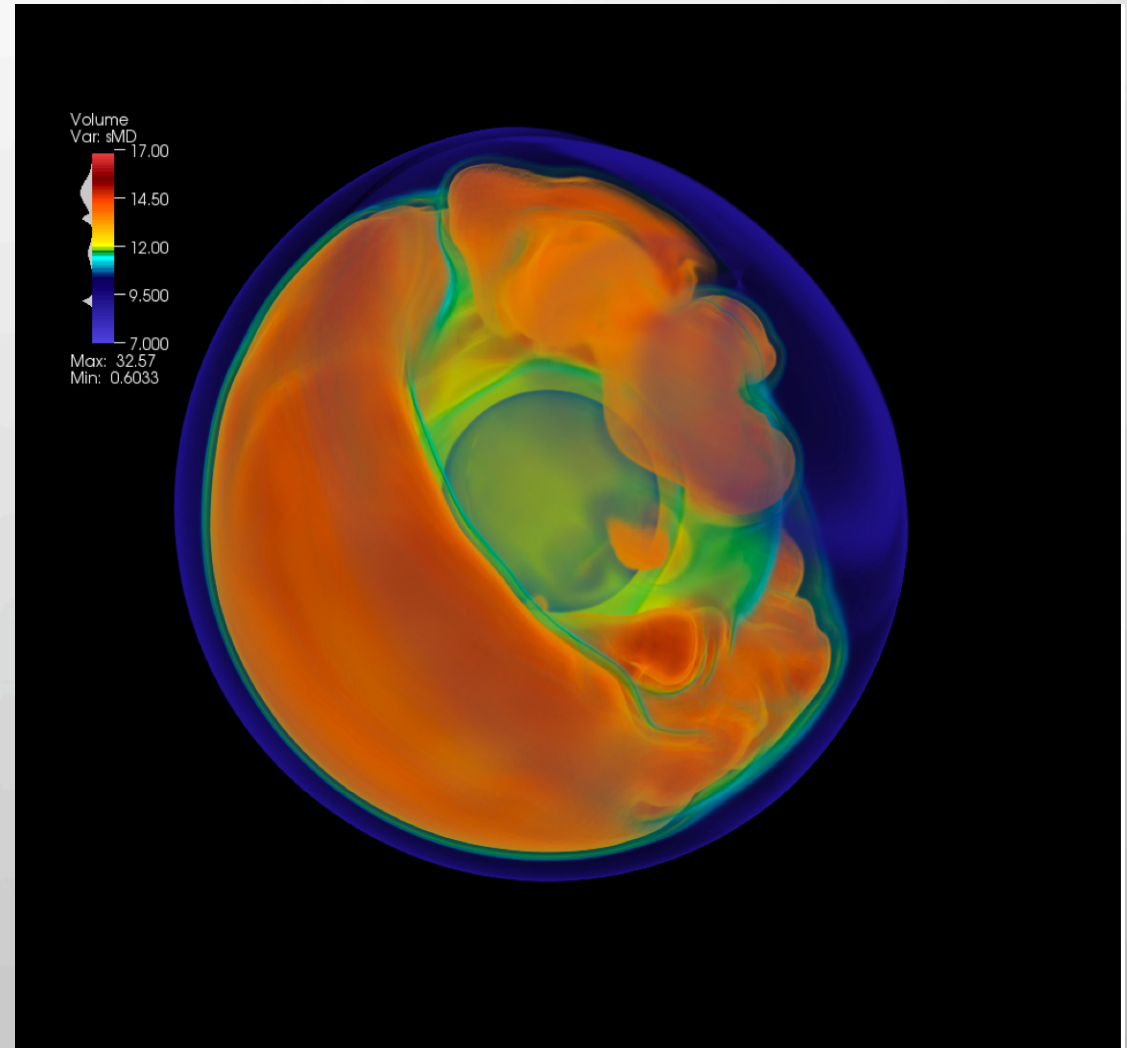
- *3D PPM Hydrodynamics*
  - *GR time dilation, effective gravitational potential*
  - *adaptive radial grid*

- *Lattimer-Swesty EOS*
  - *180 MeV nuclear compressibility*
  - *29.3 MeV symmetry energy*

- *Nuclear (Alpha) Network*

- *3D Effective Gravitational Potential*
  - Marek et al. *A&A*, **445**, 273 (2006)

- *Neutrino Emissivities/Opacities*
  - *“Standard” + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung*



Resolution

304 X 76 X 152

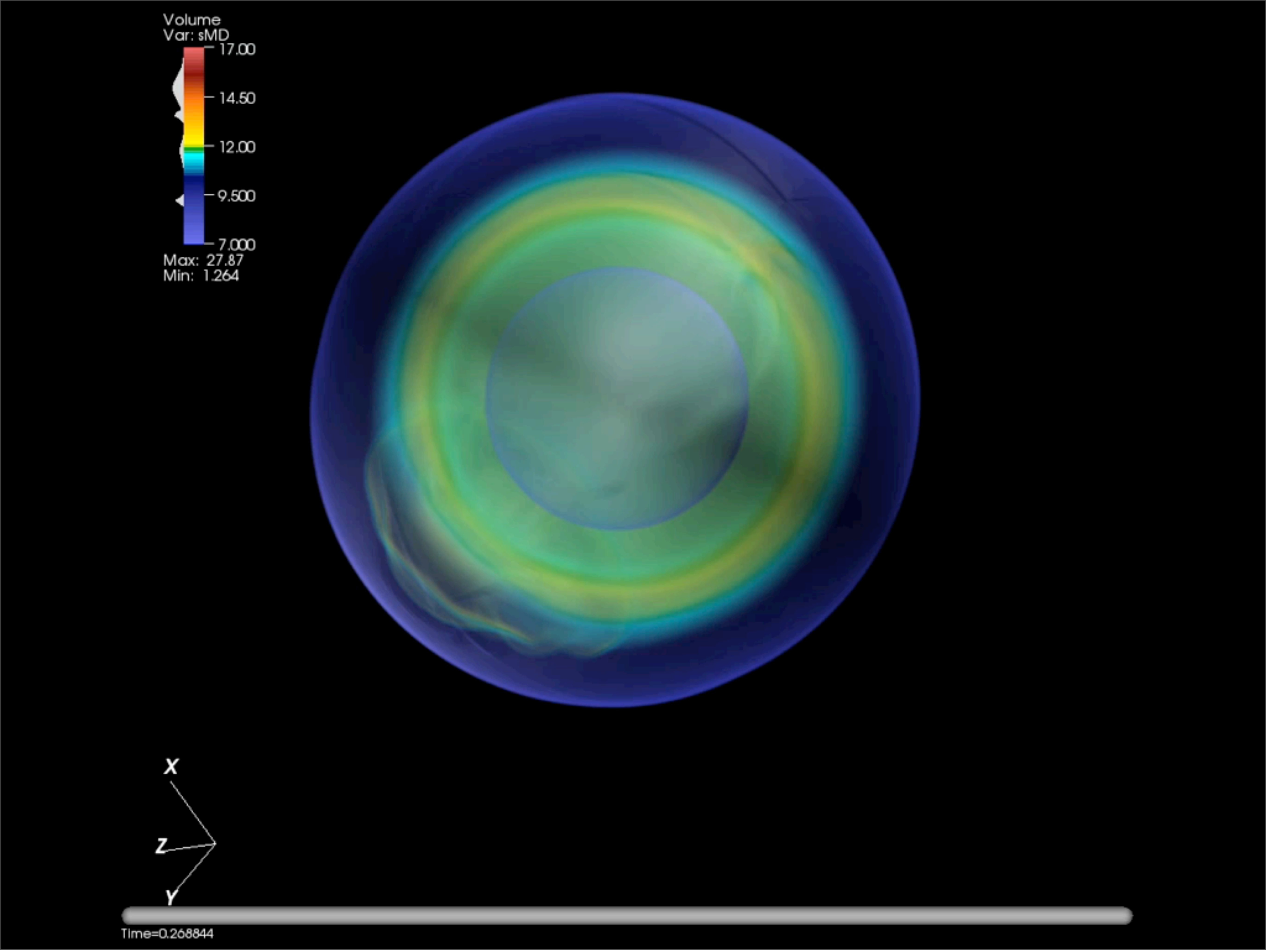
⇒ 11,552 MPI tasks

576 X 96 X 192 (current production size)

⇒ 18,432 MPI tasks

512 X 256 X 512

⇒ 131,072 MPI tasks



Volume
Var: sMD
17.00
14.50
12.00
9.500
7.000
Max: 27.87
Min: 1.264
X
Z
Y
Time=0.268844

Summary

- Ongoing CHIMERA models confirm successful prolate explosions across a range of progenitors from 12-25 $M_\odot$ driven by neutrino heating and SASI.
- Though differences persist with simulations from Garching group, self-consistent CHIMERA simulations point to a successful neutrino-reheating mechanism, with the explosion delayed by 300 ms or more after bounce, at least in 2D.
- Self-consistent 3D simulations, while very expensive, are possible. They are critical to teach us the value of our 2D simulations.