Core-Collapse Supernova Simulation with CHIMERA

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CHIMERA Collaboration

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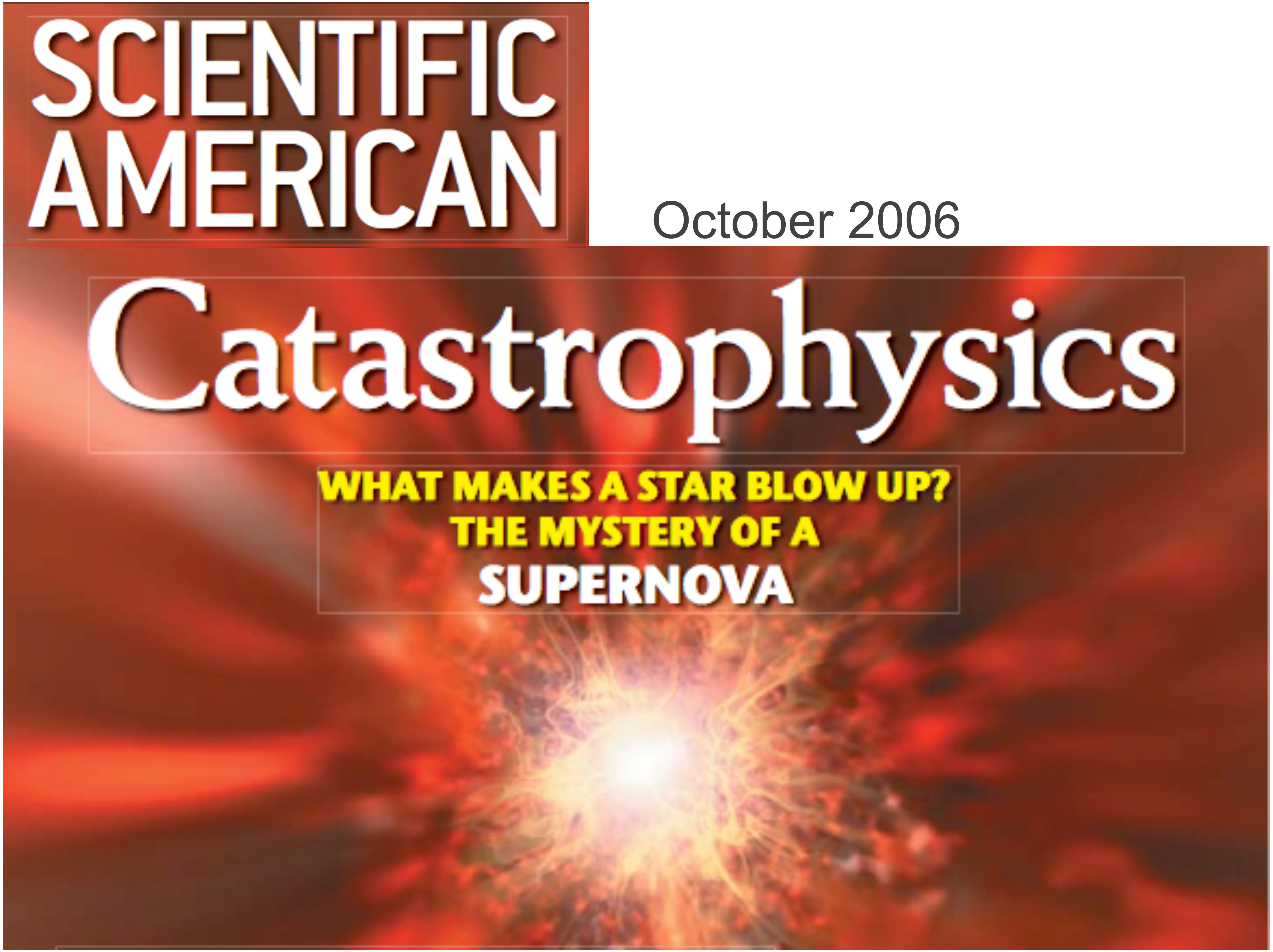
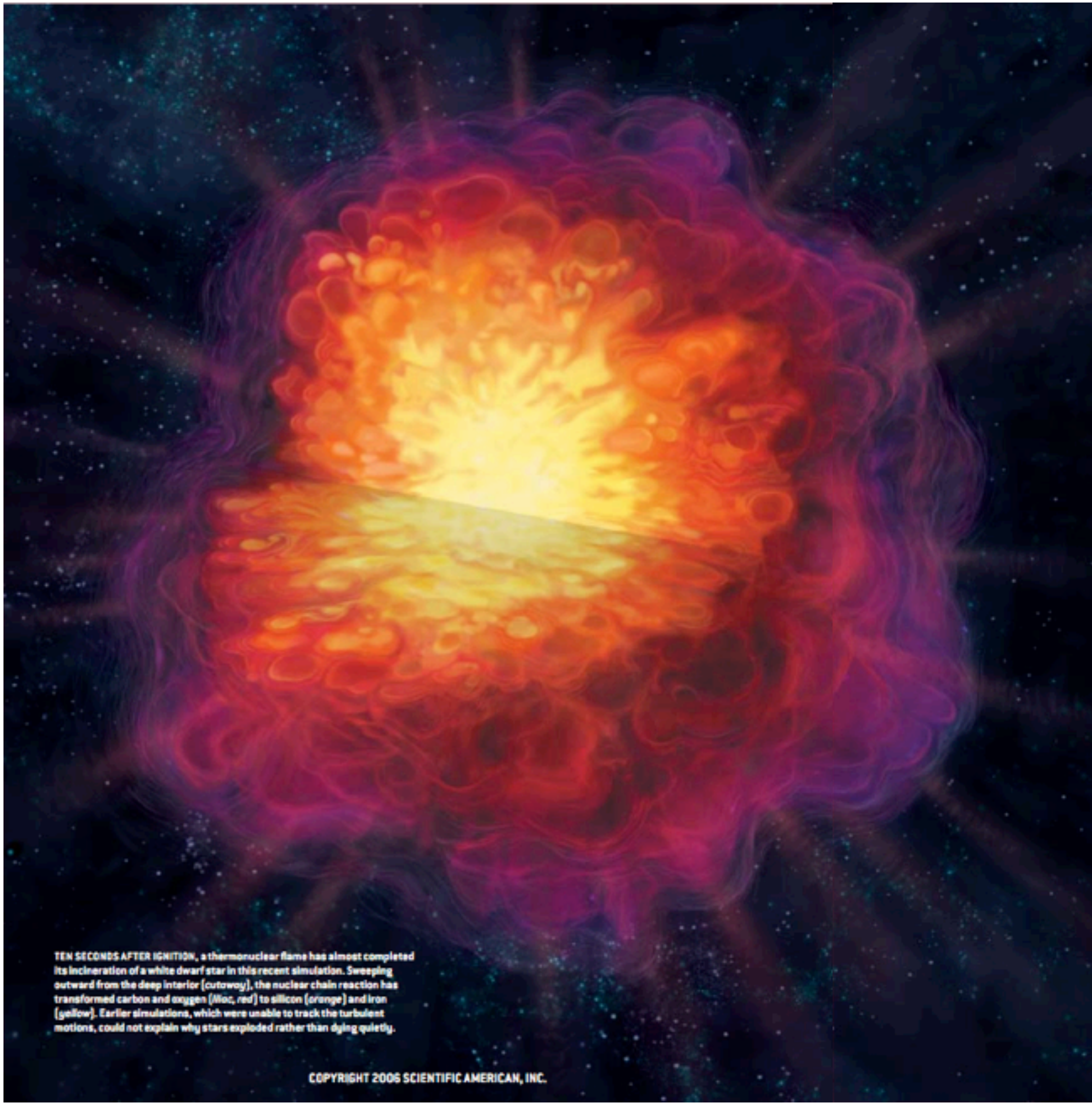
- John Blondin (NC State University)
- Anthony Mezzacappa, Eirik Endeve, Raph Hix, Eric Lentz, Bronson Messer, Suzanne Parete-Koon (ORNL/UTK)
- Konstantin Yakunin (FAU), Reuben Budjiara, Austin Chertkow (UTK)

Sponsors

- DOE Office of Science
  - NP
  - ASCR
- NSF PetaApps Program
- NASA Astrophysics Theory and Fundamental Physics Program



October 2006



TEN SECONDS AFTER IGNITION, a thermonuclear flame has almost completed its incineration of a white dwarf star in this recent simulation. Sweeping outward from the deep interior (*cutaway*), the nuclear chain reaction has transformed carbon and oxygen (*lilac, red*) to silicon (*orange*) and iron (*yellow*). Earlier simulations, which were unable to track the turbulent motions, could not explain why stars exploded rather than dying quietly.

How to Blow Up a Star

By Wolfgang Hillebrandt, Hans-Thomas Janka and Ewald Müller

It is not as easy as you would think. Models of supernovae have failed to reproduce these explosions—until recently

On November 11, 1572, Danish astronomer and nobleman Tycho Brahe saw a new star in the constellation Cassiopeia, blazing as bright as Jupiter. In many ways, it was the birth of modern astronomy—a shining disproof of the belief that the heavens were fixed and unchanging. Such "new stars" have not ceased to surprise. Some 400 years later astronomers realized that they briefly outshine billions of ordinary stars and must therefore be spectacular explosions. In 1934 Fritz Zwicky of the California Institute of Technology coined the name "supernovae" for them. Quite apart from being among the most dramatic events known to science, supernovae play a special role in the universe and in the work of astronomers: seeding space with heavy elements, regulating galaxy formation and evolution, even serving as markers of cosmic expansion.

Zwicky and his colleague Walter Baade speculated that the explosive energy comes from gravity. Their idea was that

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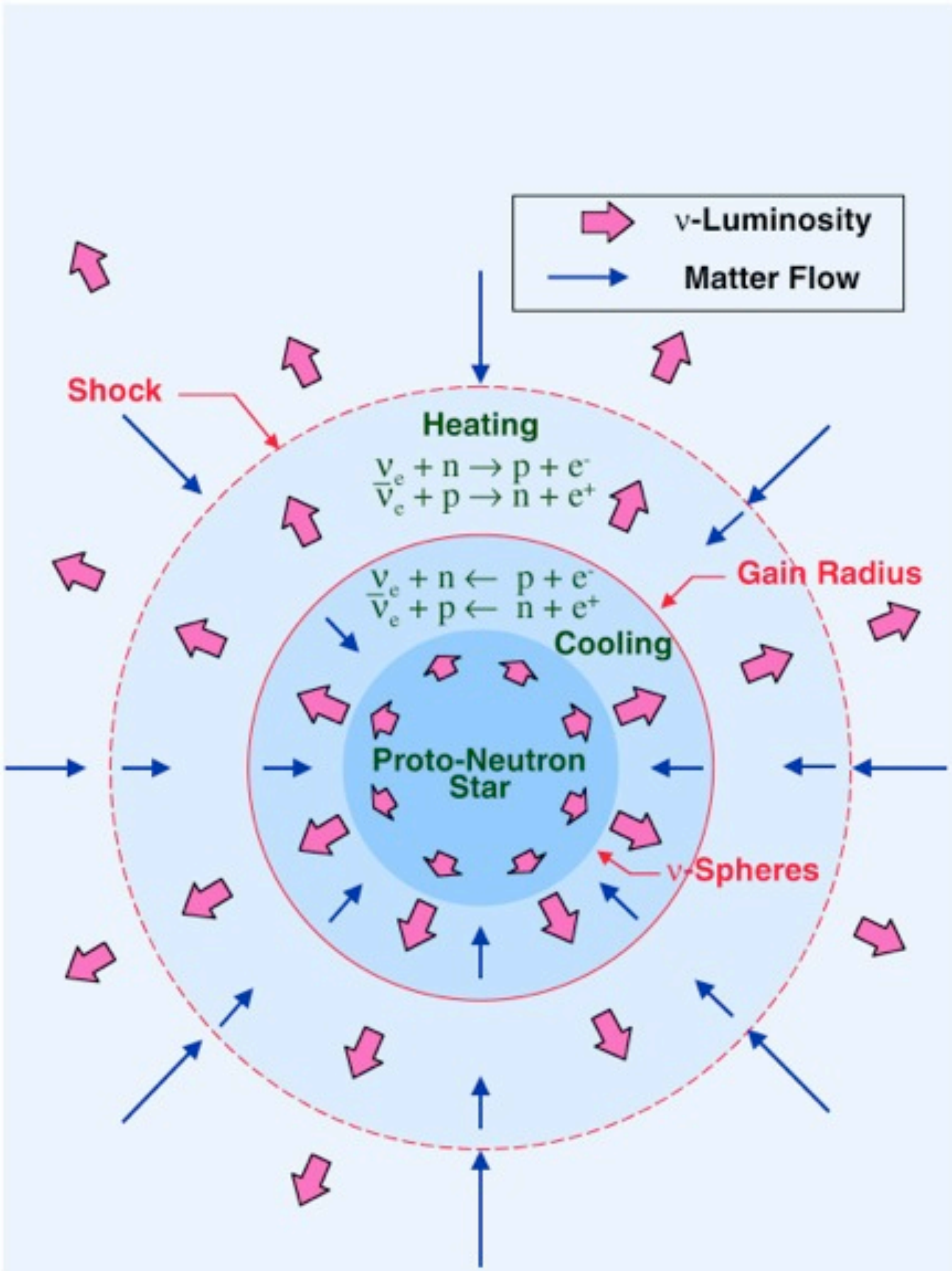
How is the supernova shock revived?



Known, Potentially Important Ingredients

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

5

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

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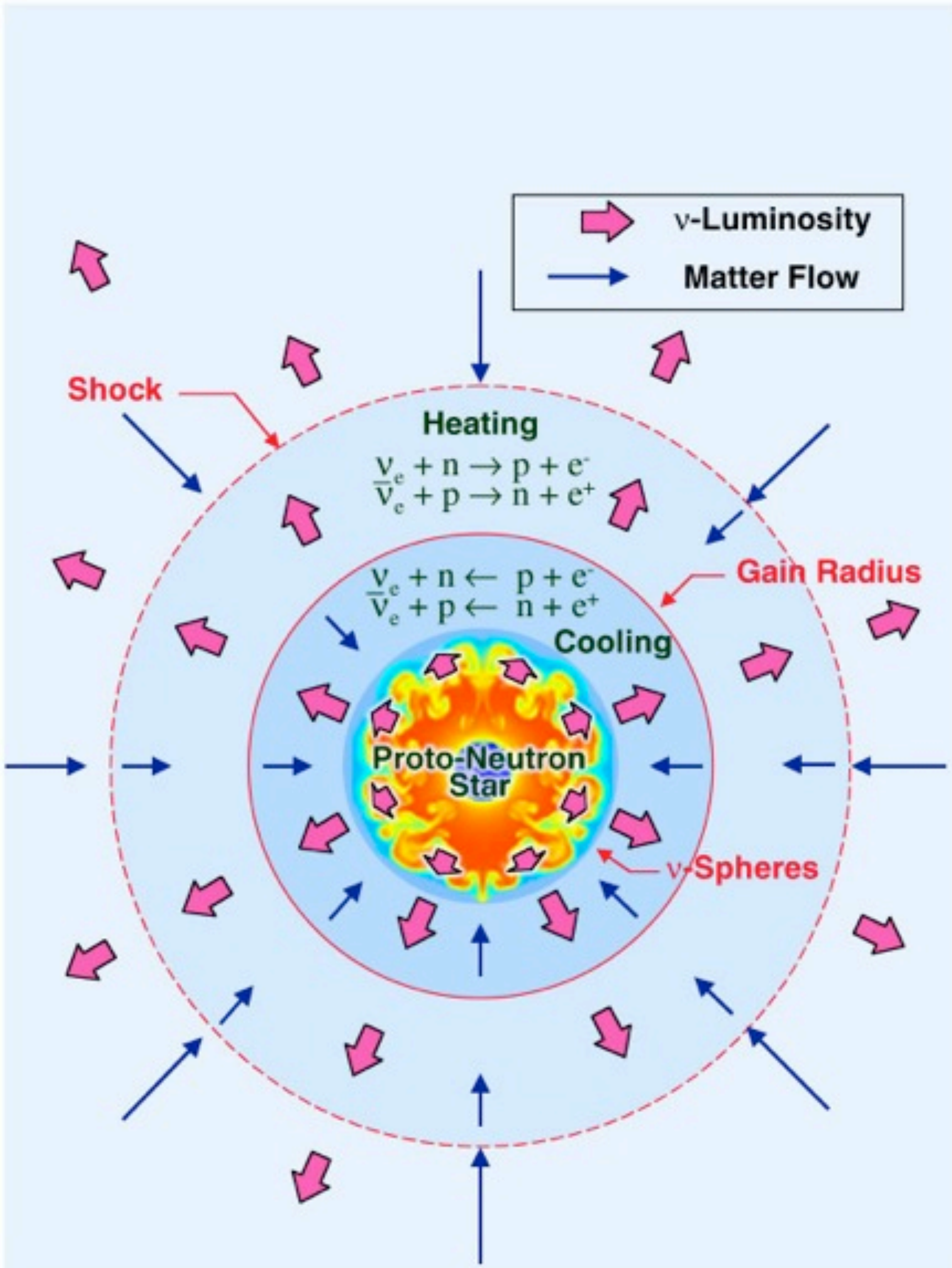

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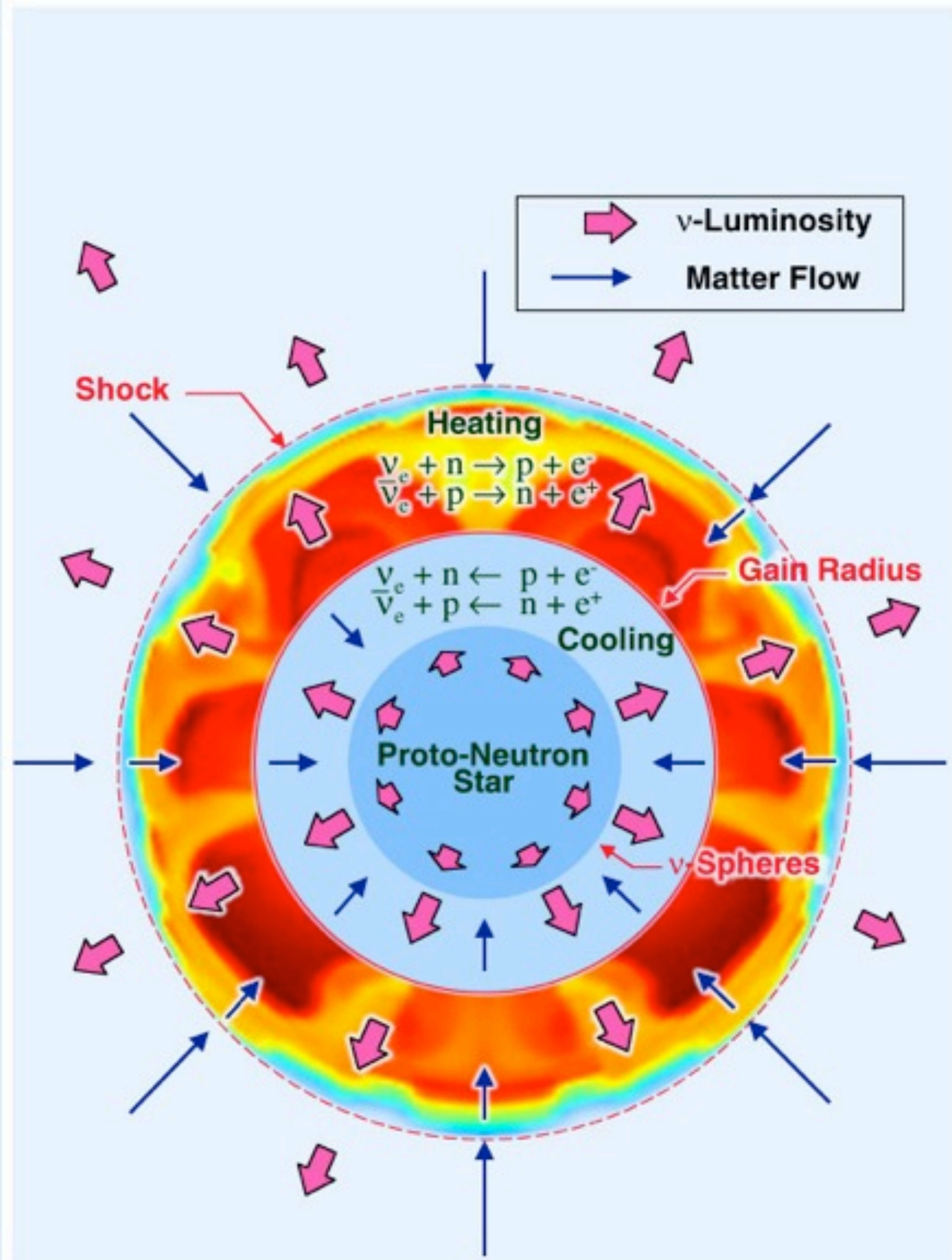

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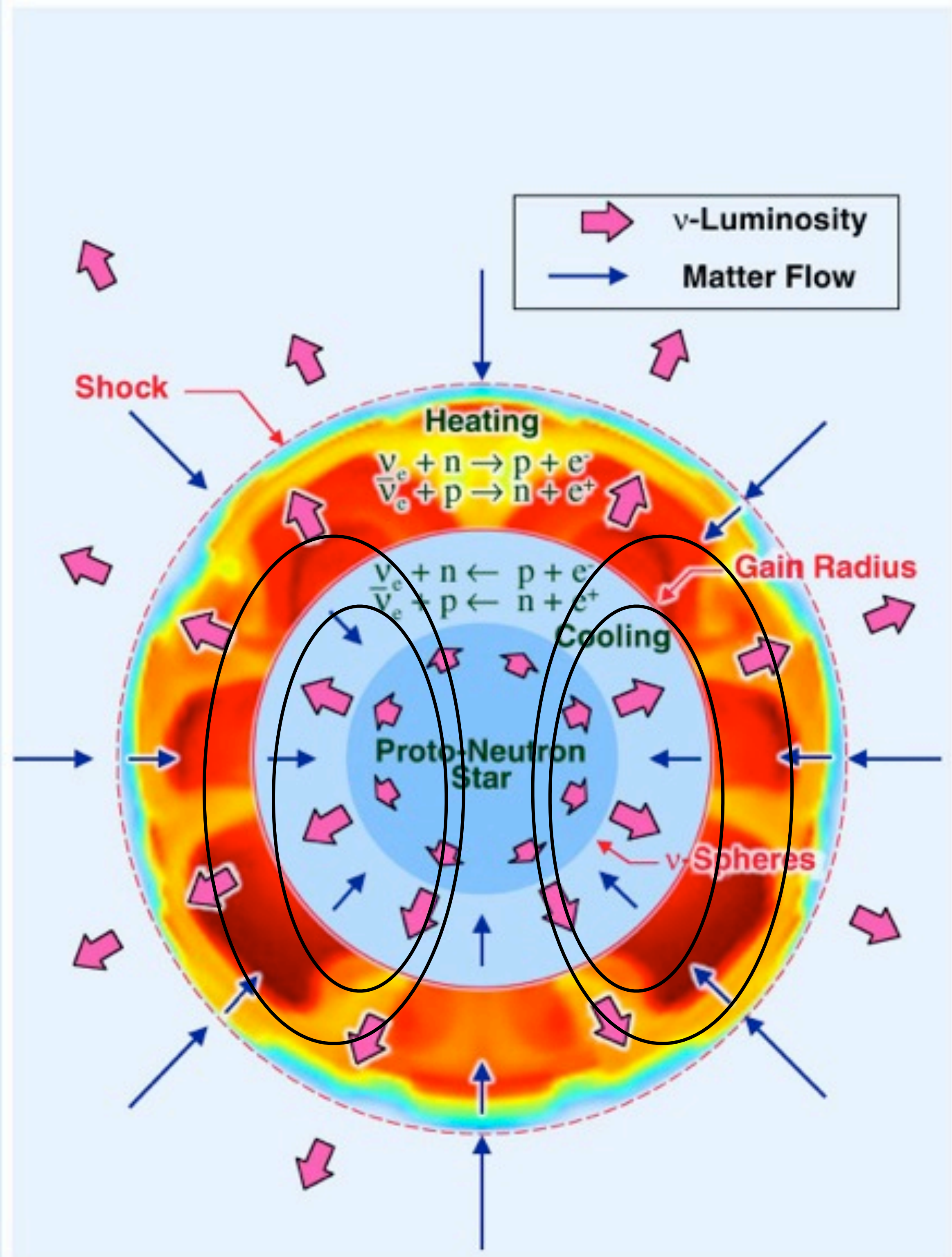

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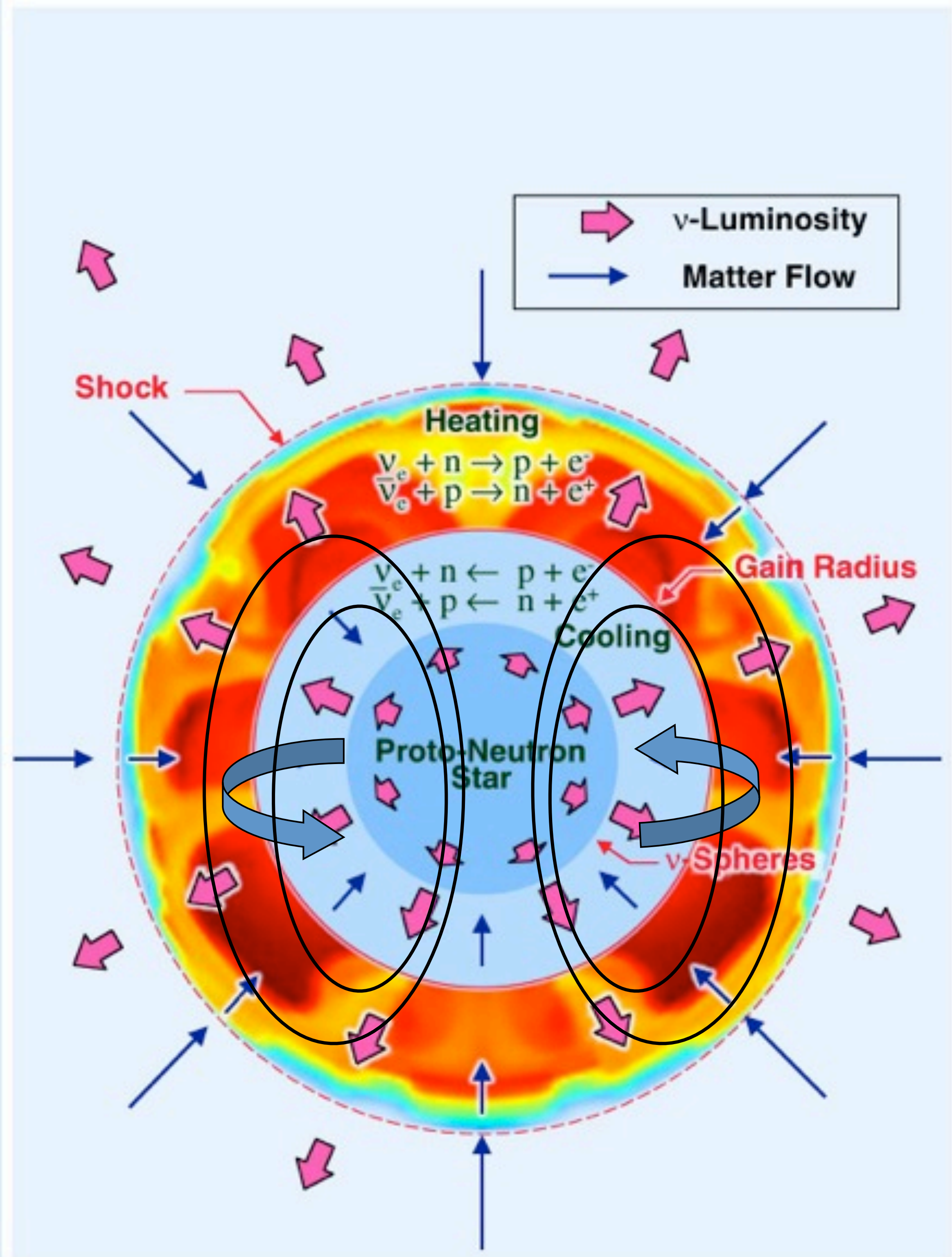

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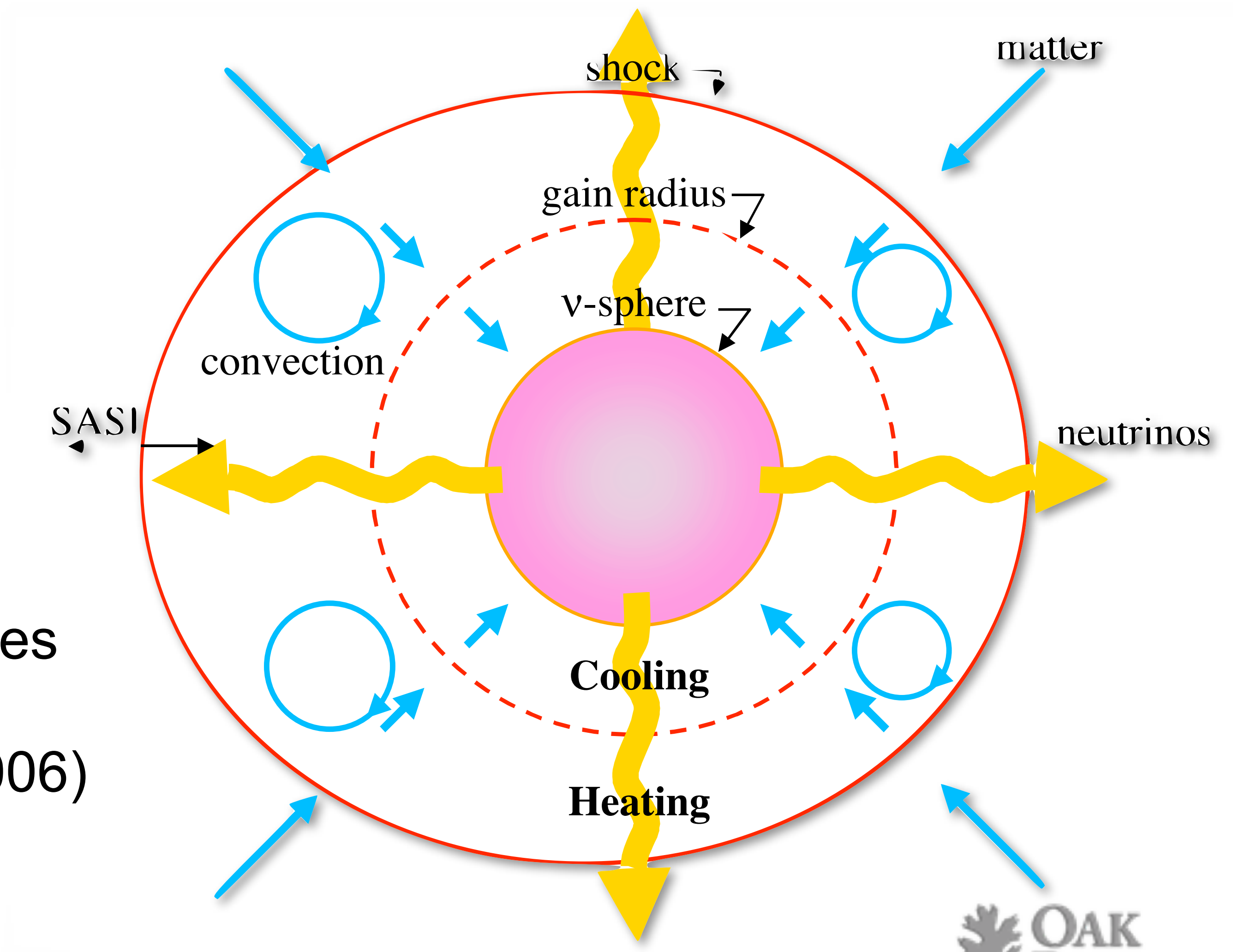
Stationary Accretion Shock Instability

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)

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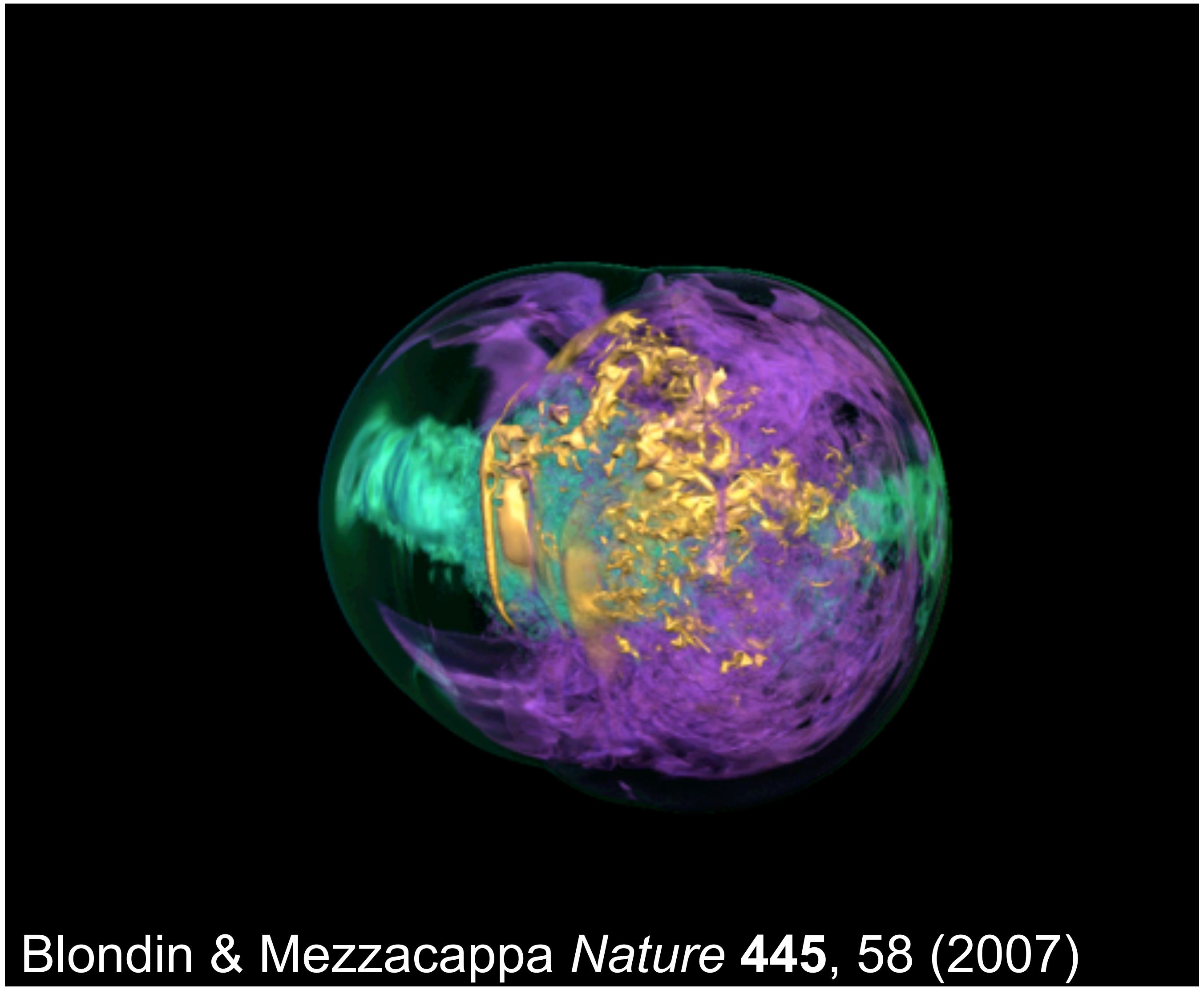

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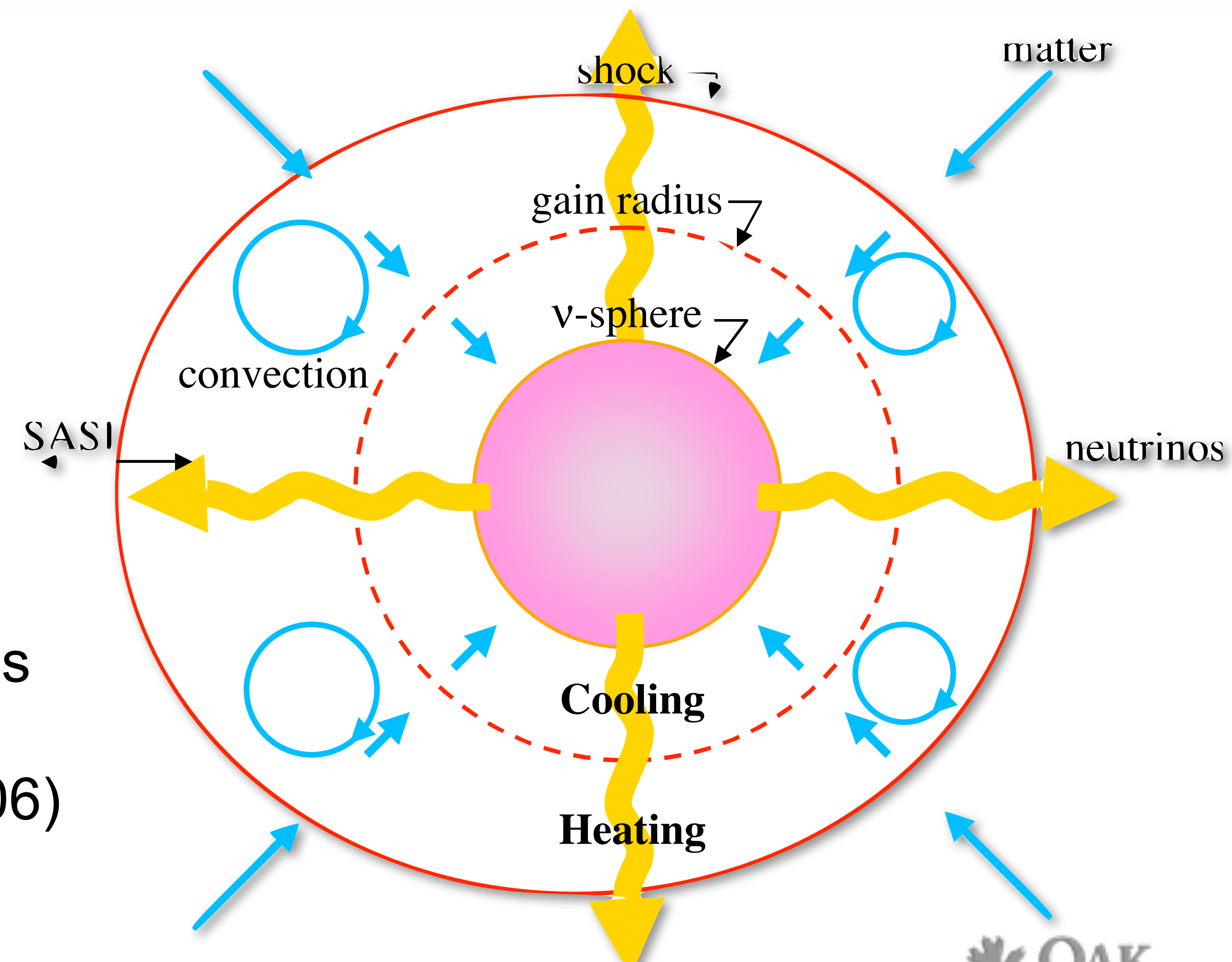

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CHIMERA

- "RbR-Plus" MGFLD Neutrino Transport
  - O(v/c), GR time dilation and redshift, GR aberration (in flux limiter)
- 2D 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
  - 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

cf. Buras et al. *A&A,* **447***,* 1049 (2003)

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.

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

★ $$N + N \leftrightarrow N + N + \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$$

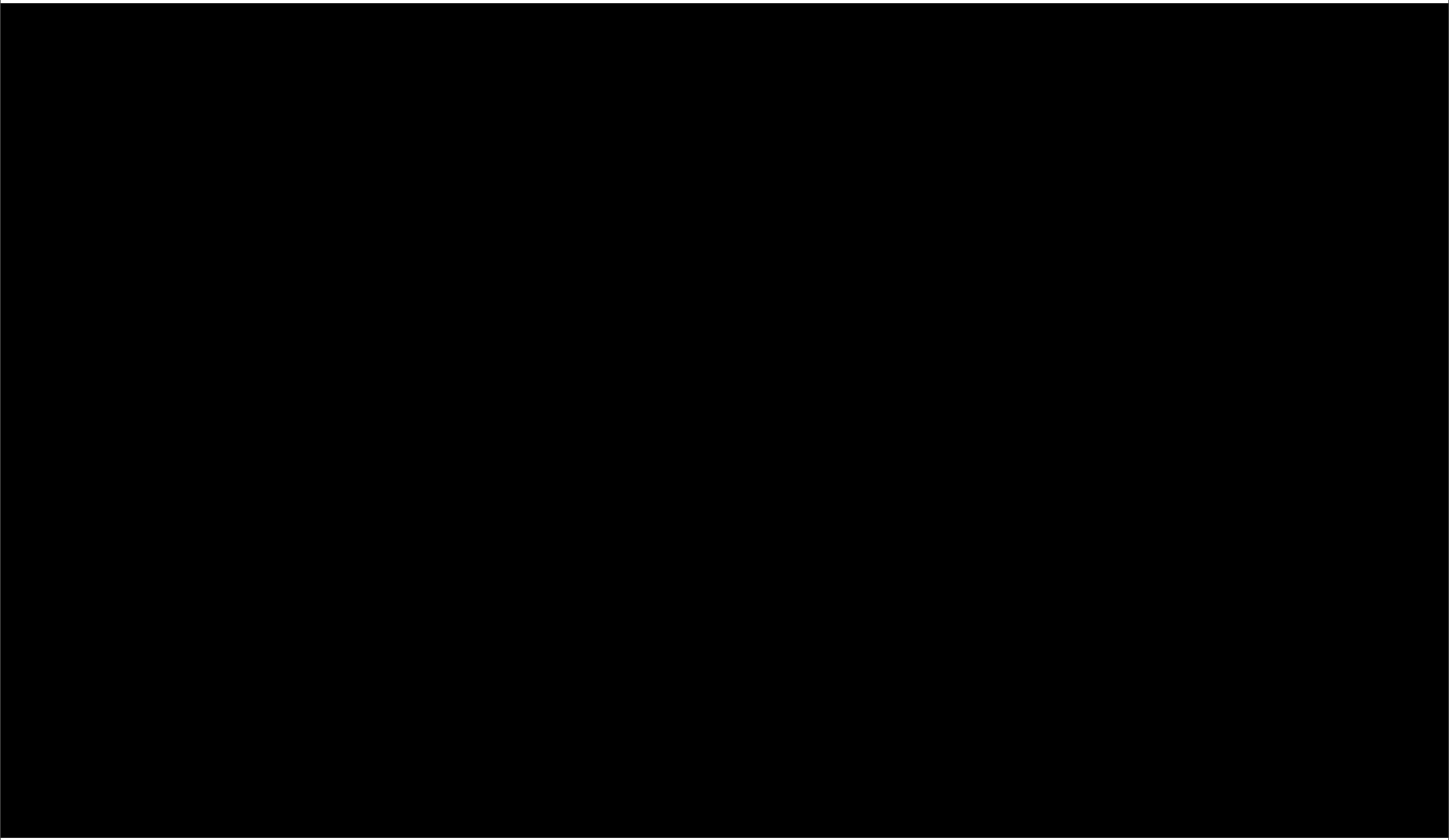
Hannestadt and Raffelt, *Ap.J.* **507**, 339 (1998)
Hanhart, Phillips, and Reddy, *Phys. Lett. B*, **499**, 9 (2001)
- New source of neutrino-antineutrino pairs.

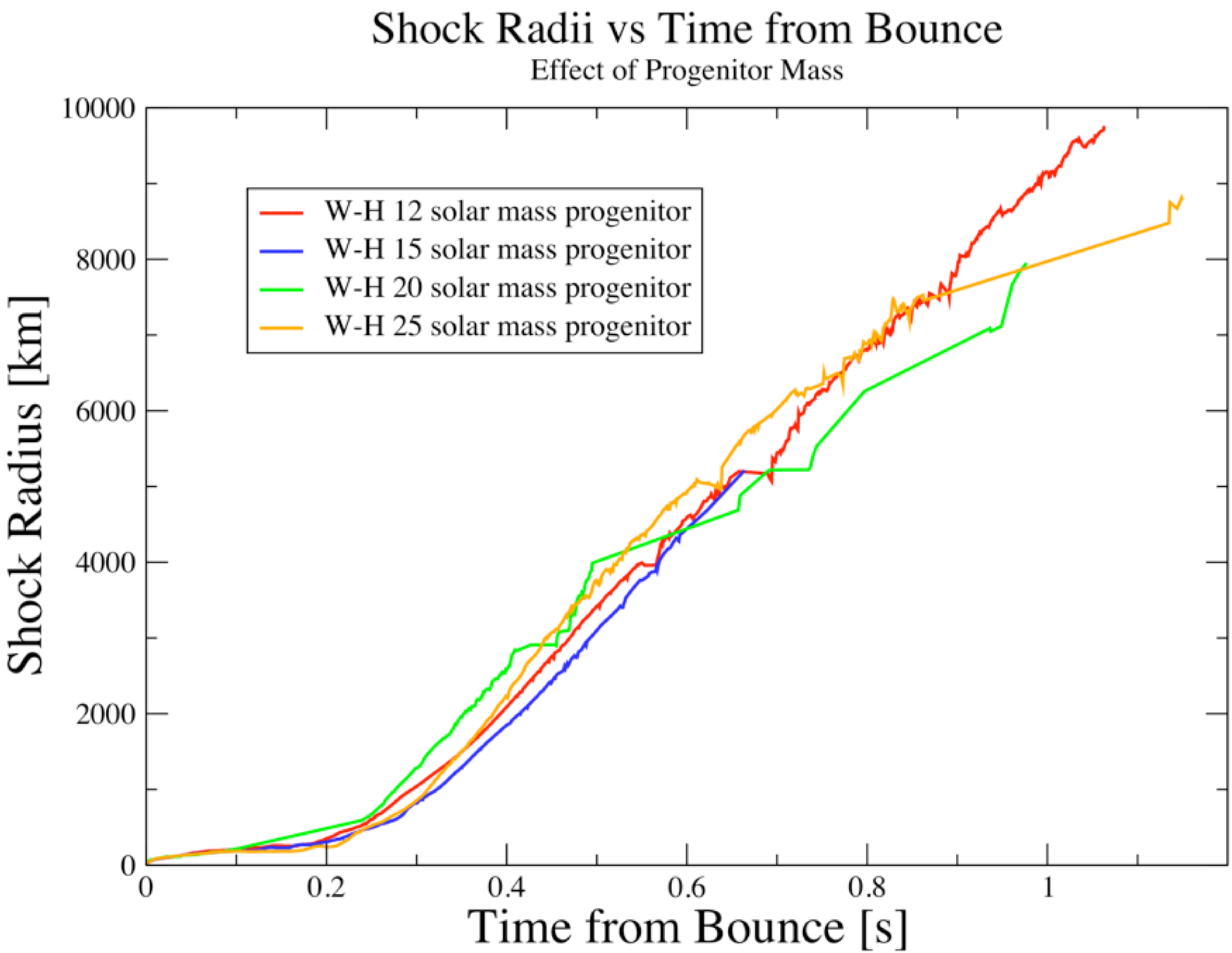
$$\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$

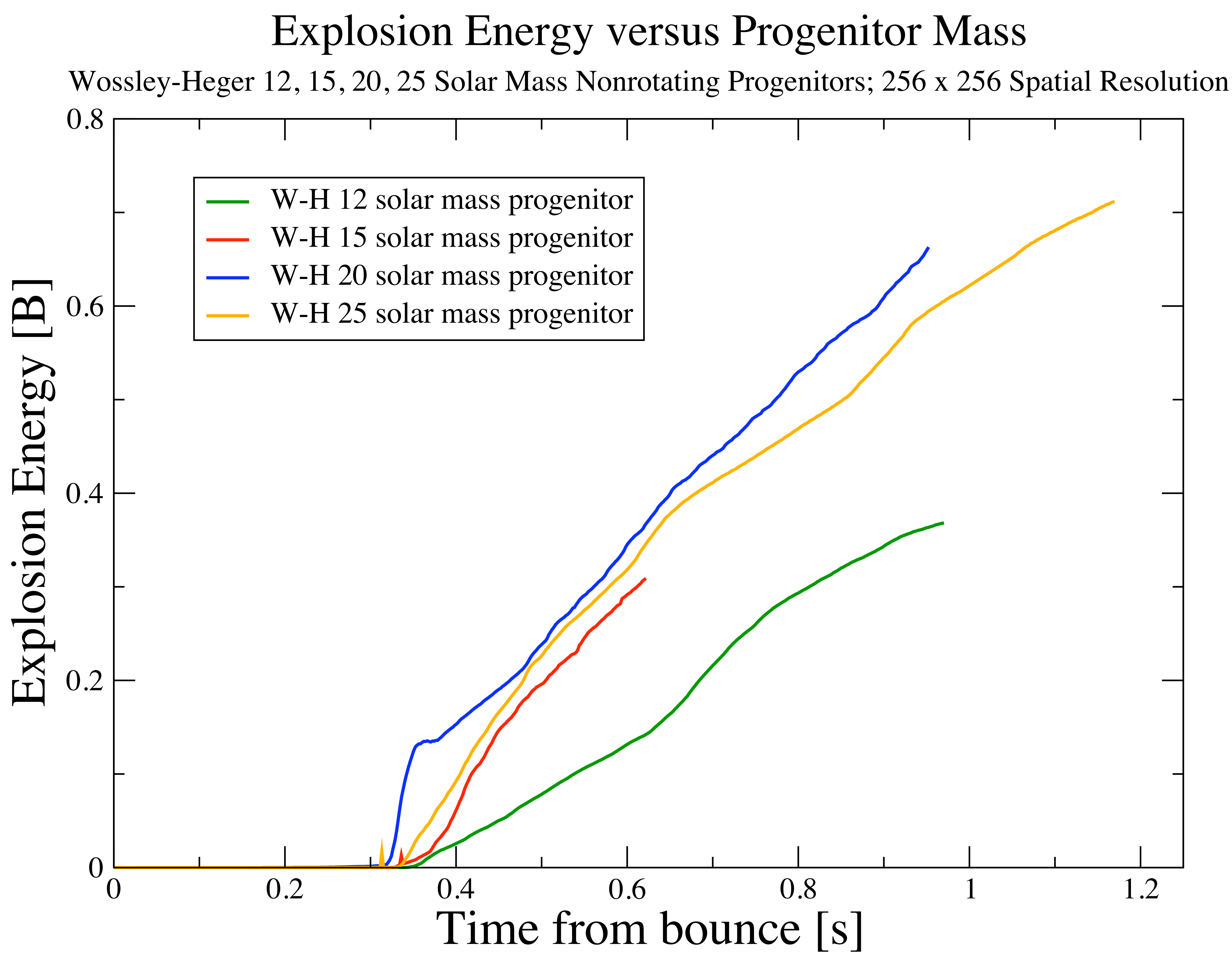
Janka et al. PRL, **76**, 2621 (1996)
Buras et al. *Ap.J.*, **587**, 320 (2003)

More about the impact of many of these (and the EoS):
Poster NIC_XI_379 (E. Lentz)

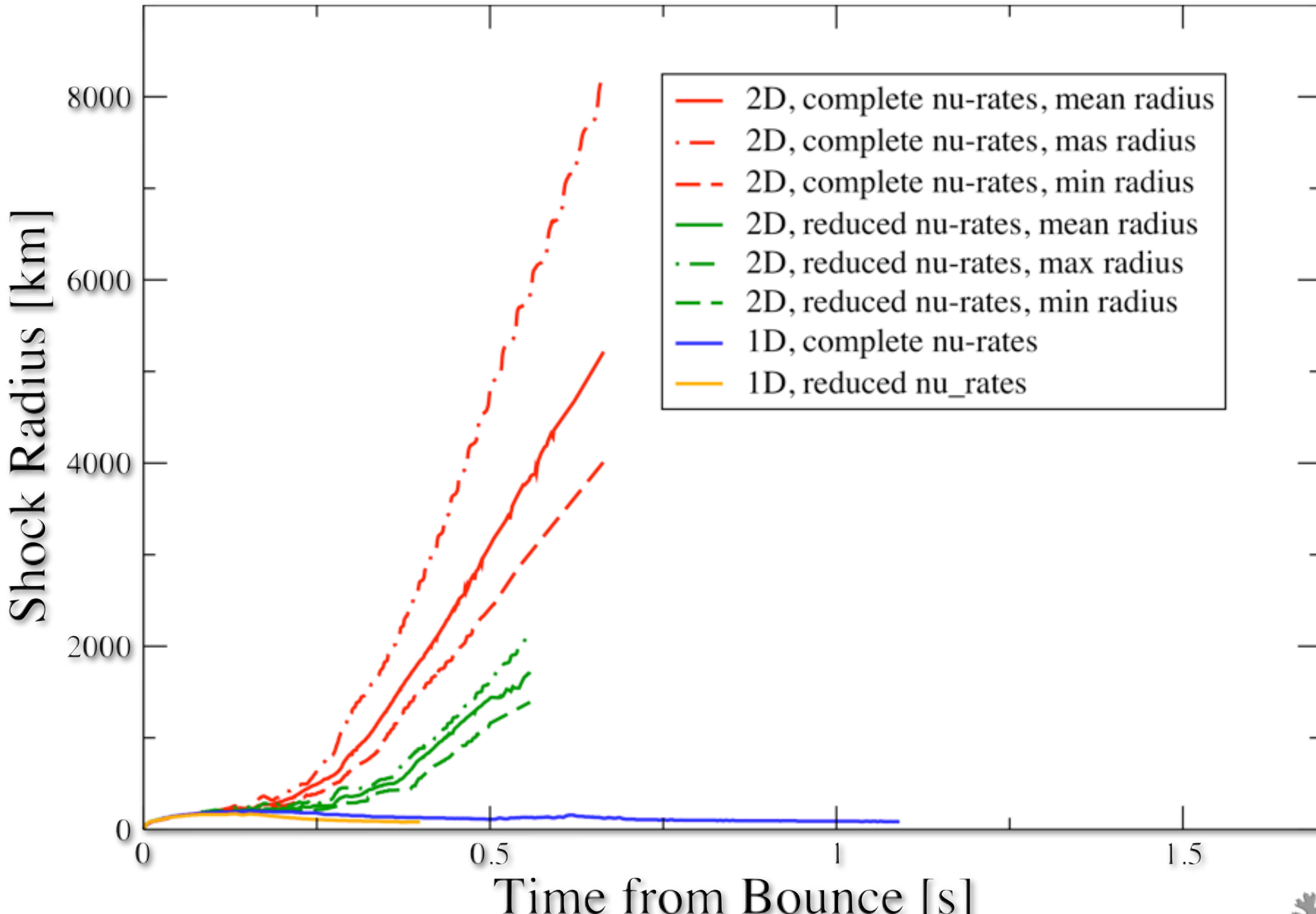
2D simulations



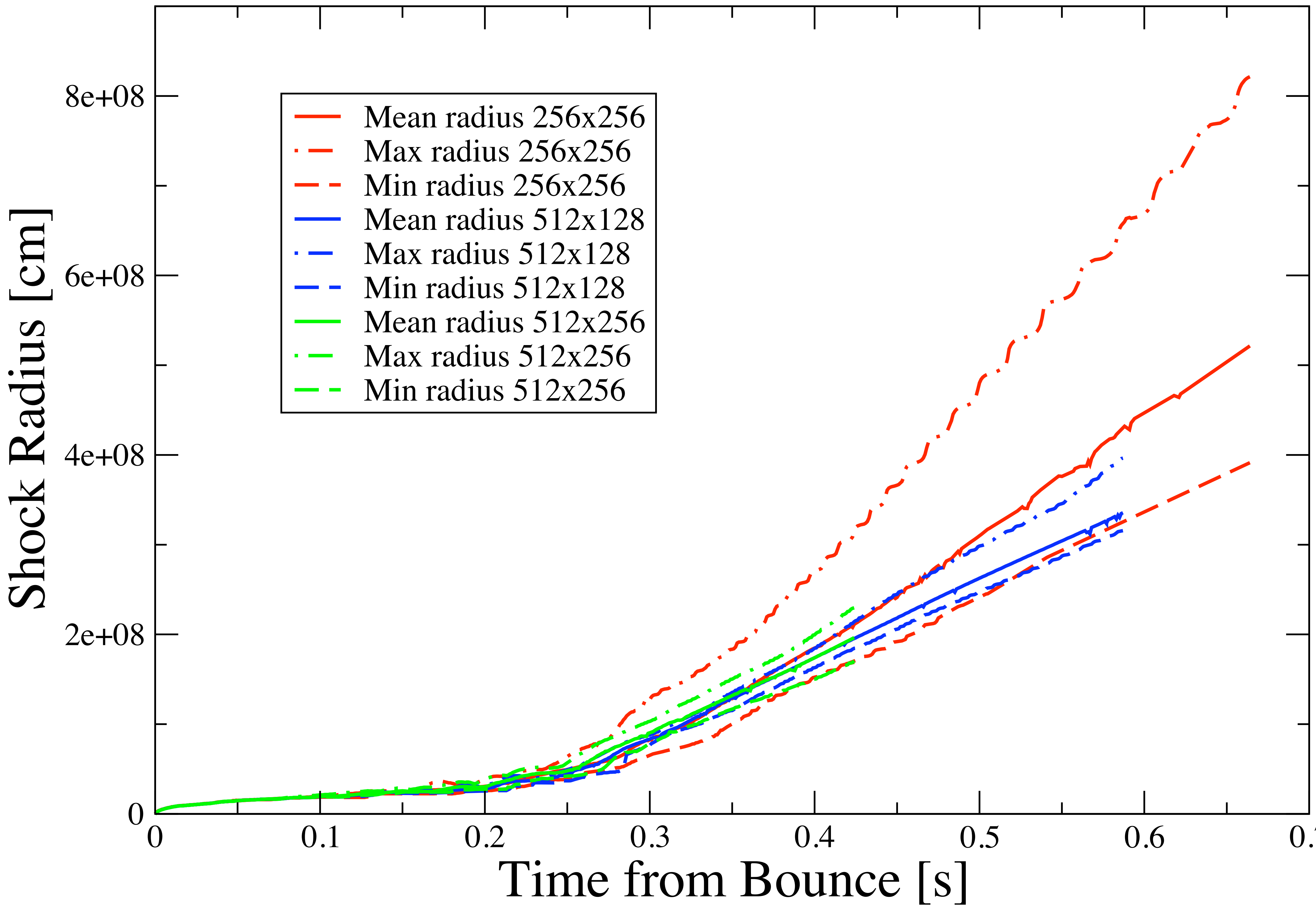

Shock Radii vs Time from Bounce
Effect of Progenitor Mass
10000
8000
6000
4000
2000
0
Shock Radius [km]
W-H 12 solar mass progenitor
W-H 15 solar mass progenitor
W-H 20 solar mass progenitor
W-H 25 solar mass progenitor
0
0.2
0.4
0.6
0.8
1
Time from Bounce [s]


Explosion Energy versus Progenitor Mass
Wossley-Heger 12, 15, 20, 25 Solar Mass Nonrotating Progenitors; 256 x 256 Spatial Resolution
W-H 12 solar mass progenitor
W-H 15 solar mass progenitor
W-H 20 solar mass progenitor
W-H 25 solar mass progenitor
Explosion Energy [B]
Time from bounce [s]
0
0.2
0.4
0.6
0.8
1
1.2

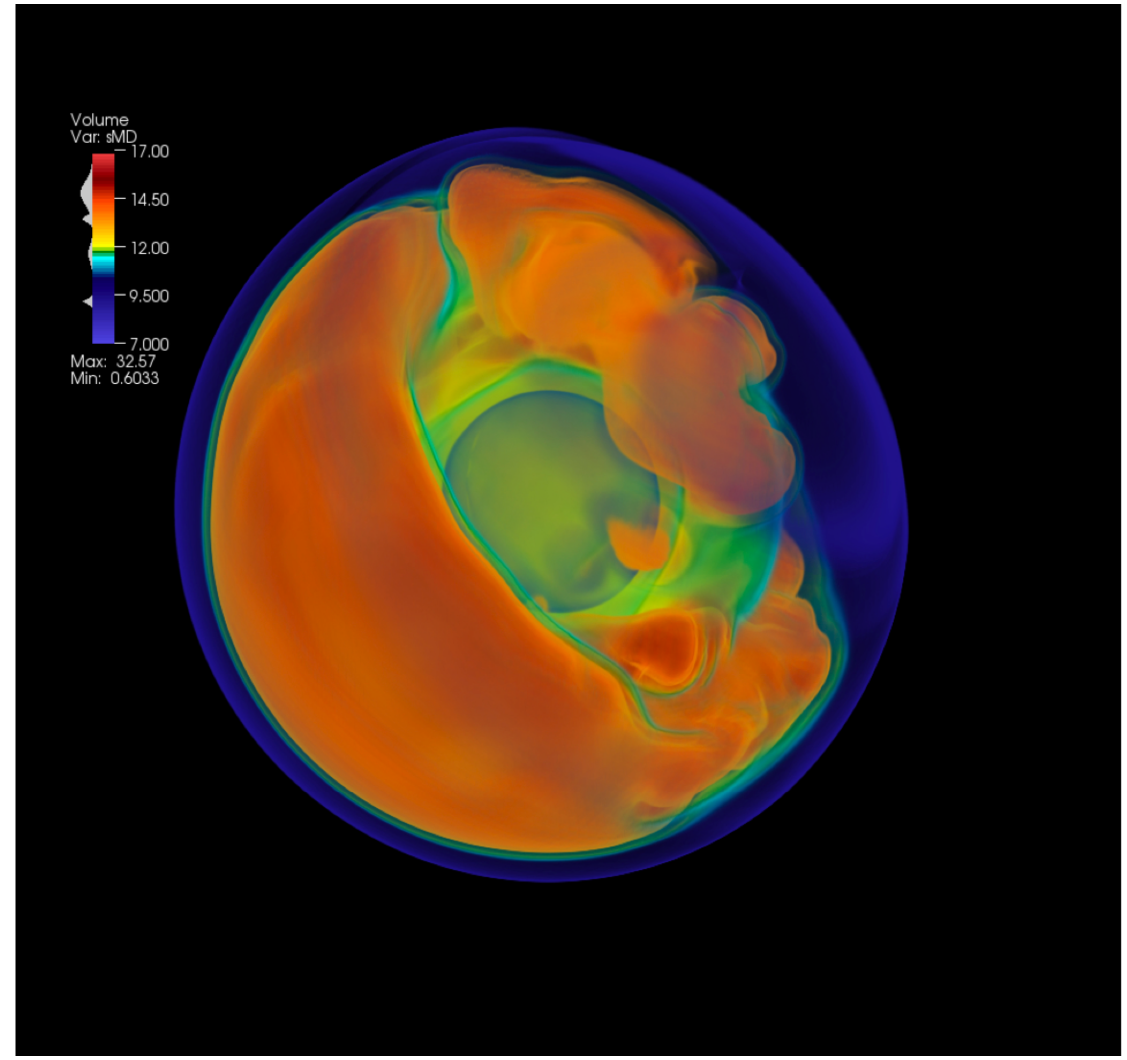
Impact of improved microphysics



Impact of resolution



3D simulations



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<u>Resolution</u>

304 X 76 X 152

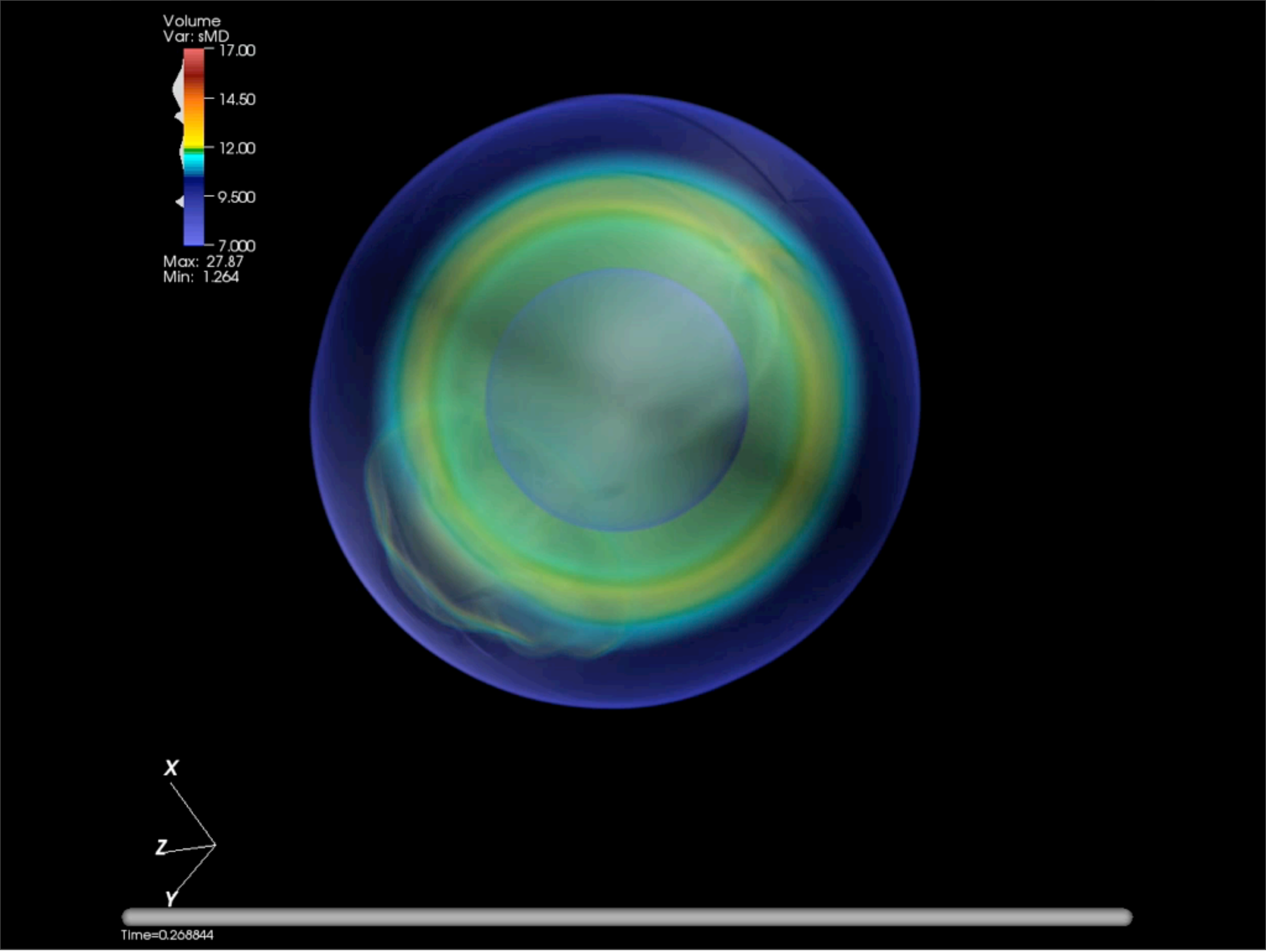
⇒ 11,552 processors

576 X 96 X 192 (current production size)

⇒ 18,432 processors

512 X 256 X 512

⇒ 131,072 processors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Y
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Summary

- In 2D, neutrino-driven explosions have been obtained for a large range of progenitor masses in the context of multi-physics simulations with multi-frequency neutrino transport and approximate GR. 3D simulations are underway.

- Longer Term
  - Replace RbR transport with 2D/3D multi-angle, multi-frequency transport
  - Implement full general relativity
  - Larger nuclear network (> 150 isotopes)
  - Include magnetic fields
  - Include neutrino mixing

- Other needs:
  - Continued work on neutrino weak interactions and EOS
  - 3D stellar evolution