Core-Collapse Supernovae: Striving for Simulations to Confront Observations

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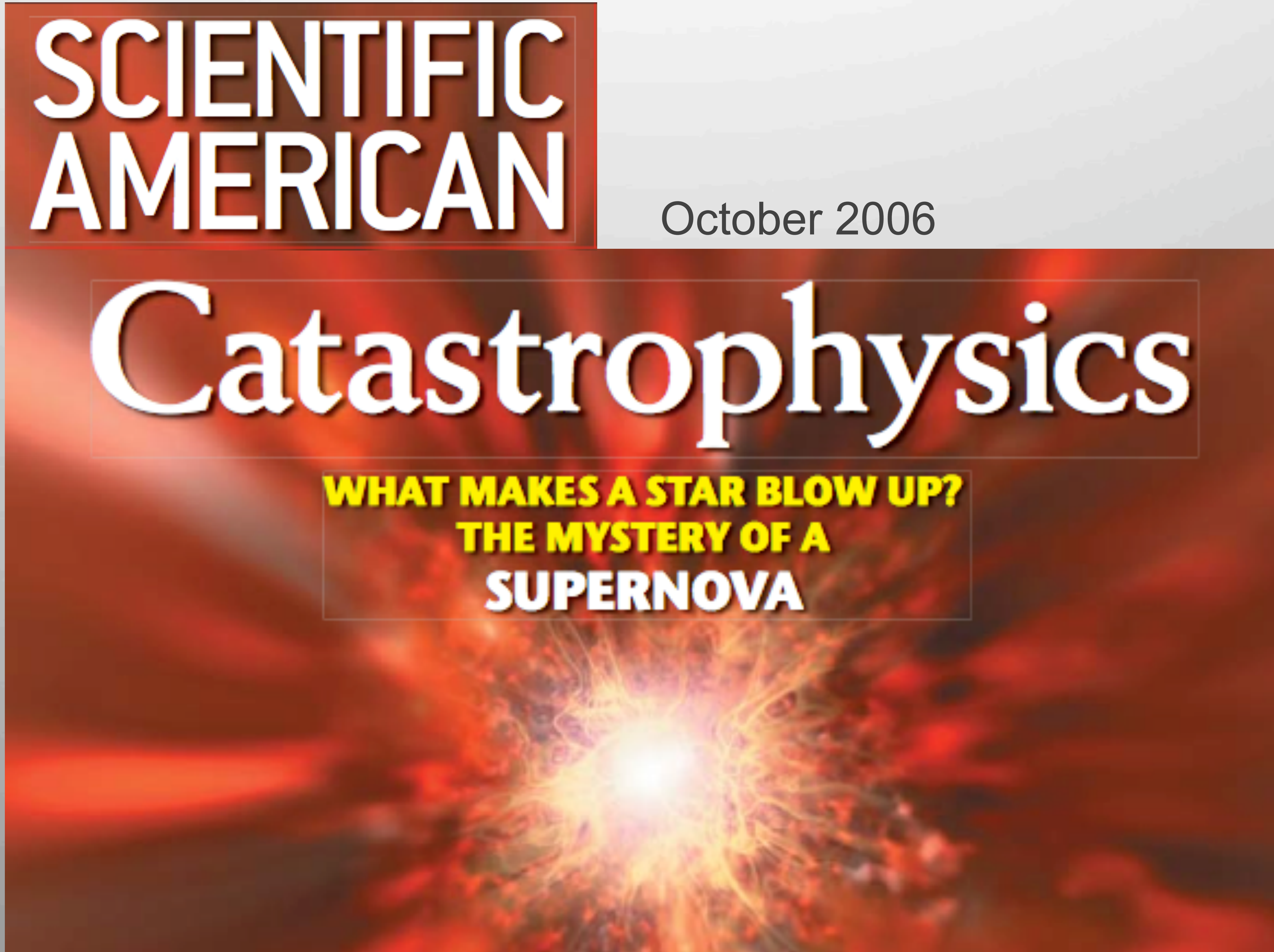
OAK RIDGE National Laboratory

Outline

- Some basics
- Some lesser-known details
- Current simulations from Oak Ridge
- Observables from CC SNe
- Summary



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 (*blue, 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.

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How to Blow Up a Star

By Wolfgang Hillebrandt, Hans-Thomas Janka and Ewald Müller

It is not as easy as you would think.

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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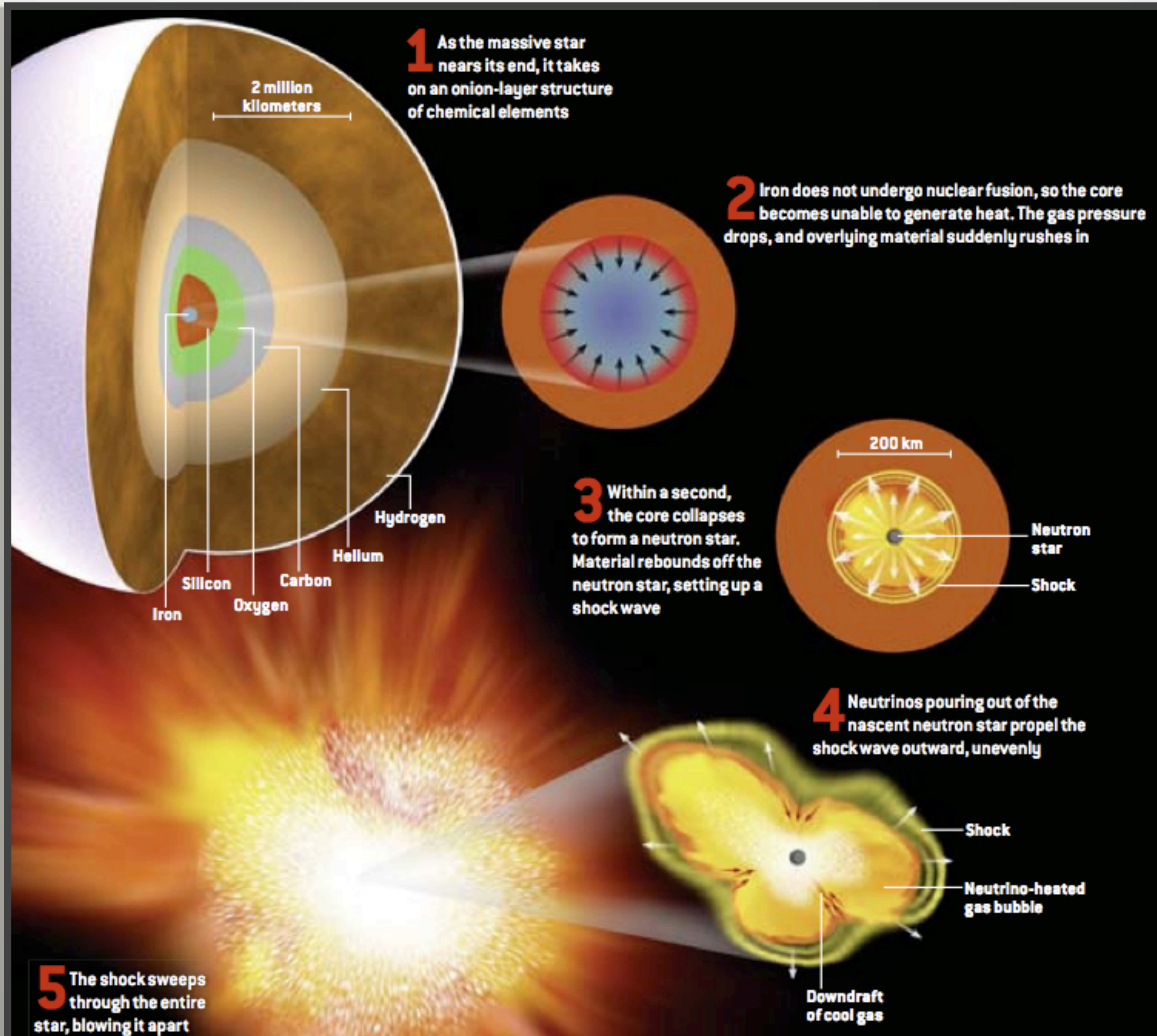


Hillebrandt & Janka 2006 (Sci Am)

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)

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

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

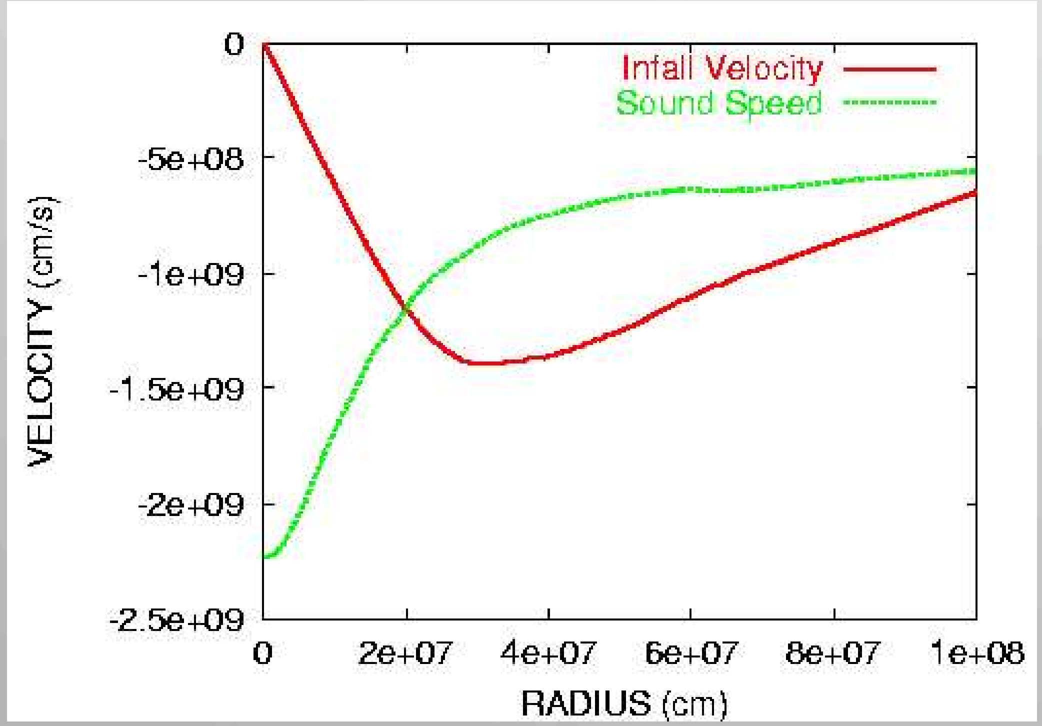
Arnett, ApJ **218**, 815 (1977)

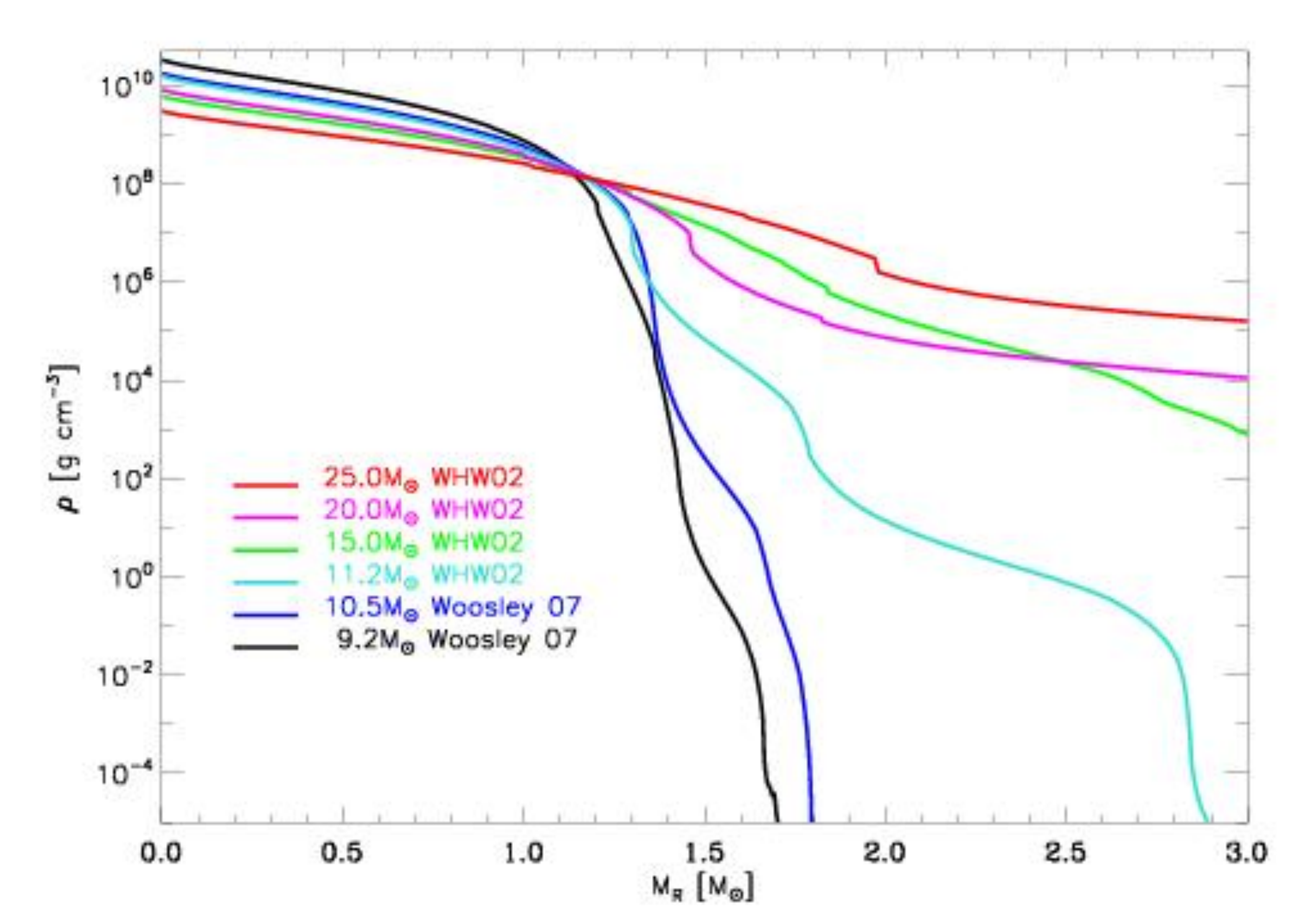
Electron-neutrino mean free path decreases much more rapidly with density than core size, and the neutrinos become trapped in the core.

Degenerate electron-neutrino Fermi sea develops

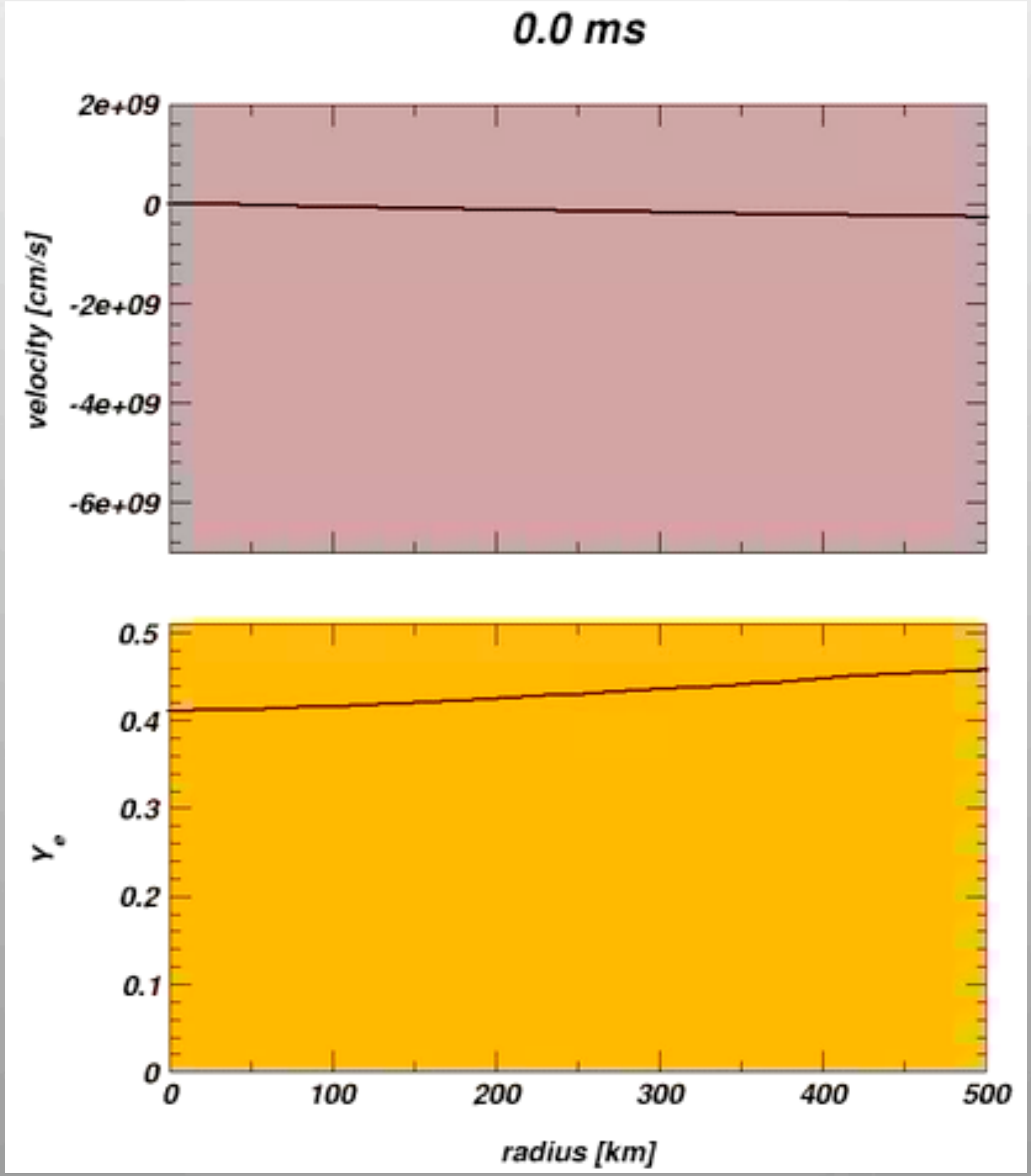
Homologous collapse

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



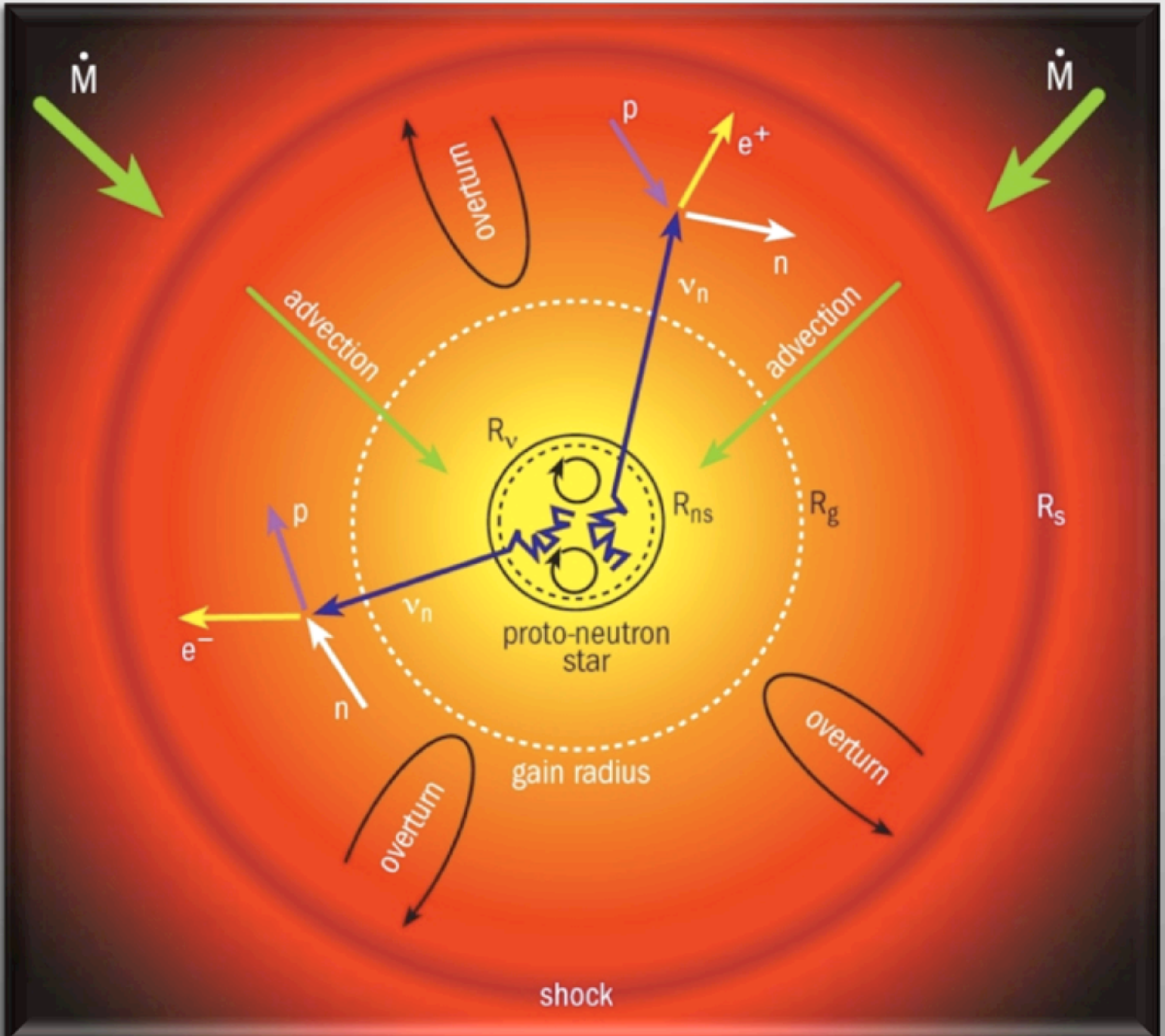


Spherically symmetric collapse



Messer(2000)

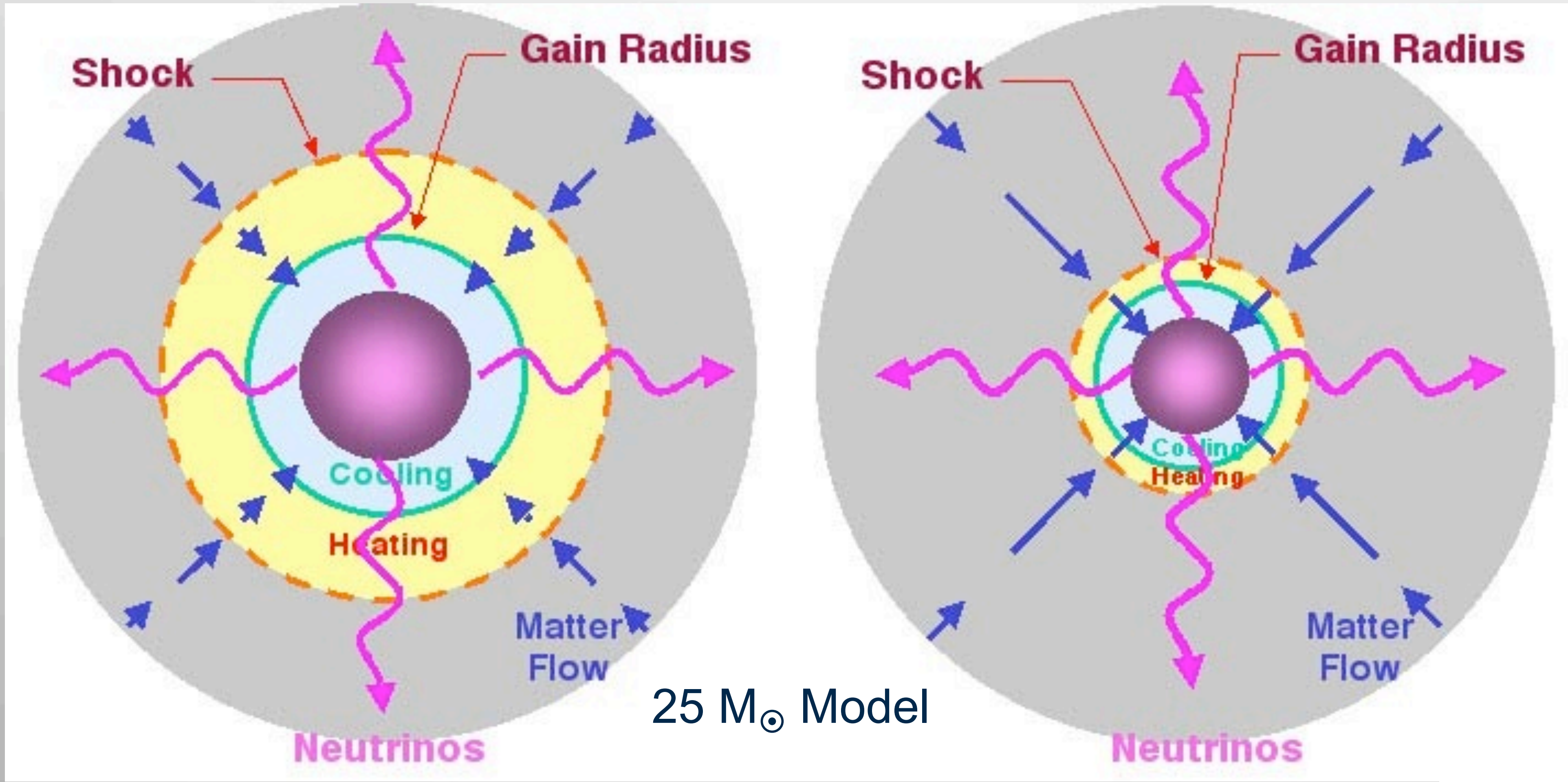
Post-bounce profile



Hillebrandt & Janka 2006 (Sci Am)

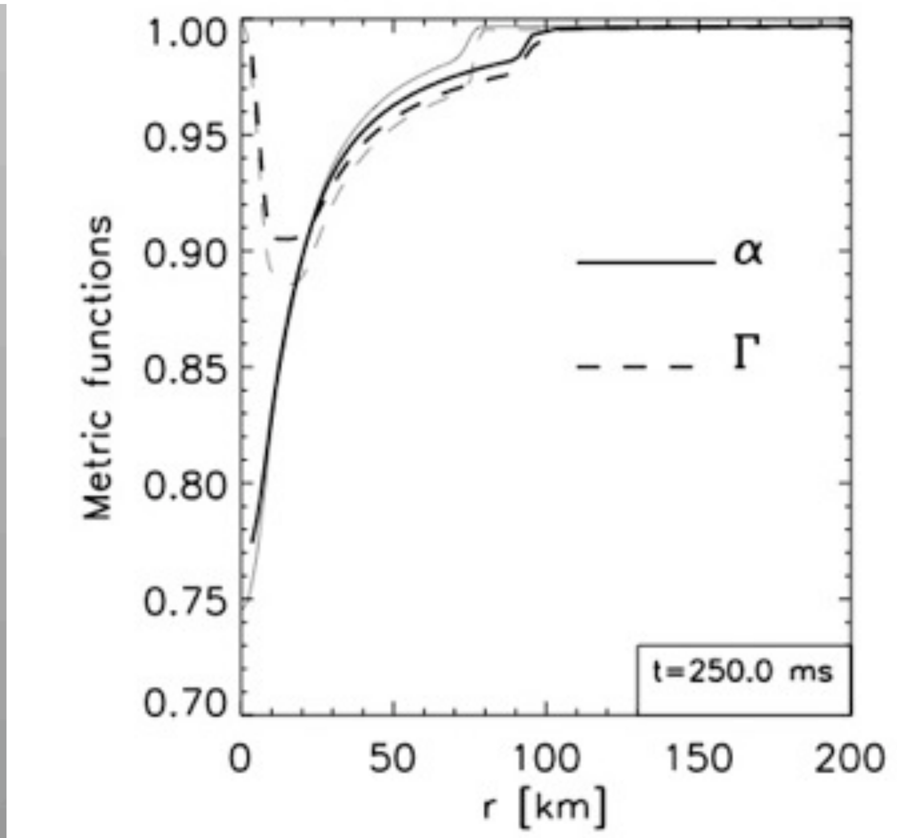
Newtonian versus GR

Bruenn, DeNisco, and Mezzacappa, Ap.J. 560, 326 (2001)
Liebendoerfer et al. Ap.J. 620, 840 (2005)



25 $M_\odot$ Model

15 $M_\odot$ Model



$$ds^2 = -\alpha^2 dt^2 + \left(\frac{r'}{\Gamma}\right)^2 da^2 + r^2\left(d\theta^2 + \sin^2\theta d\varphi^2\right)$$

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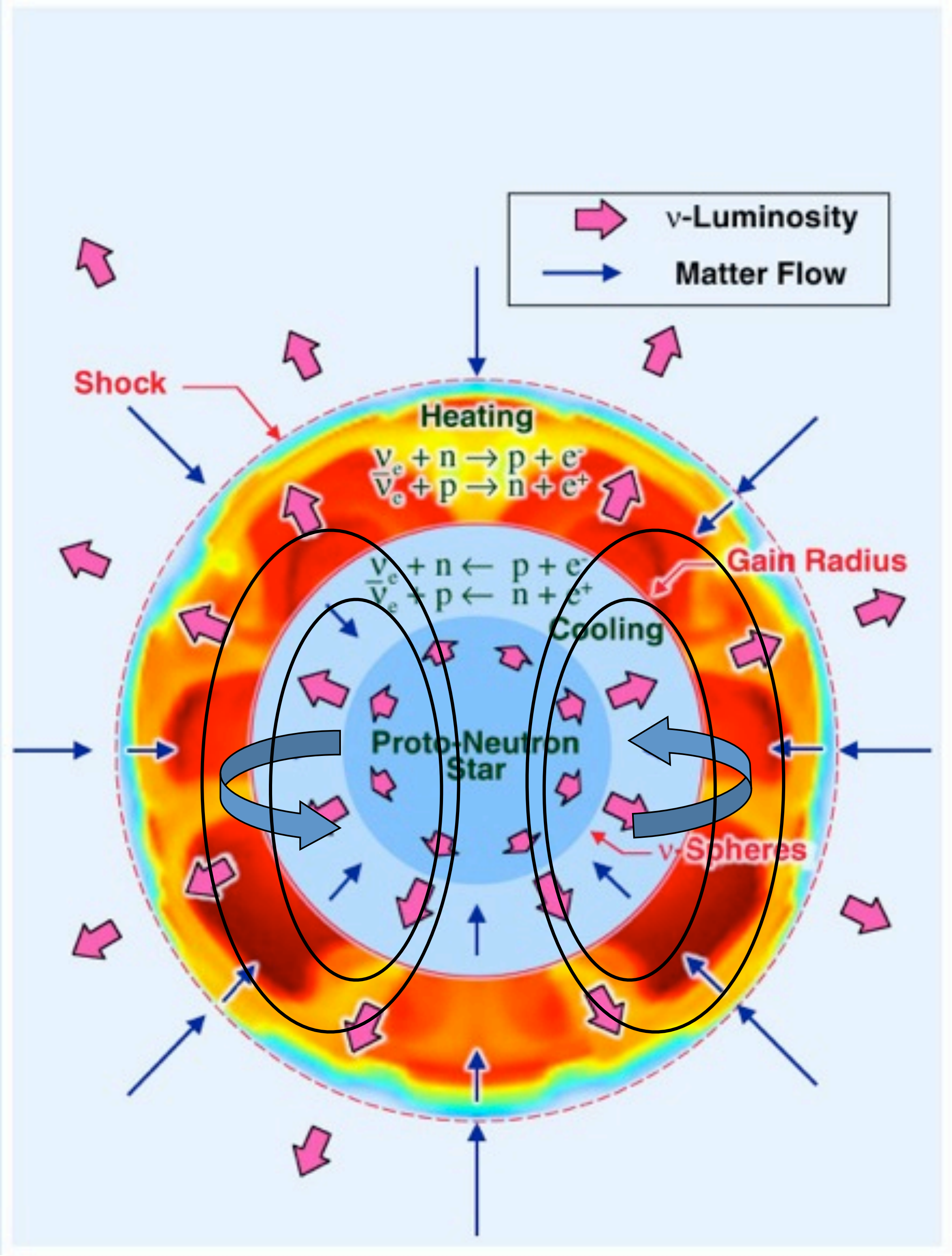
How is the supernova shock revived?

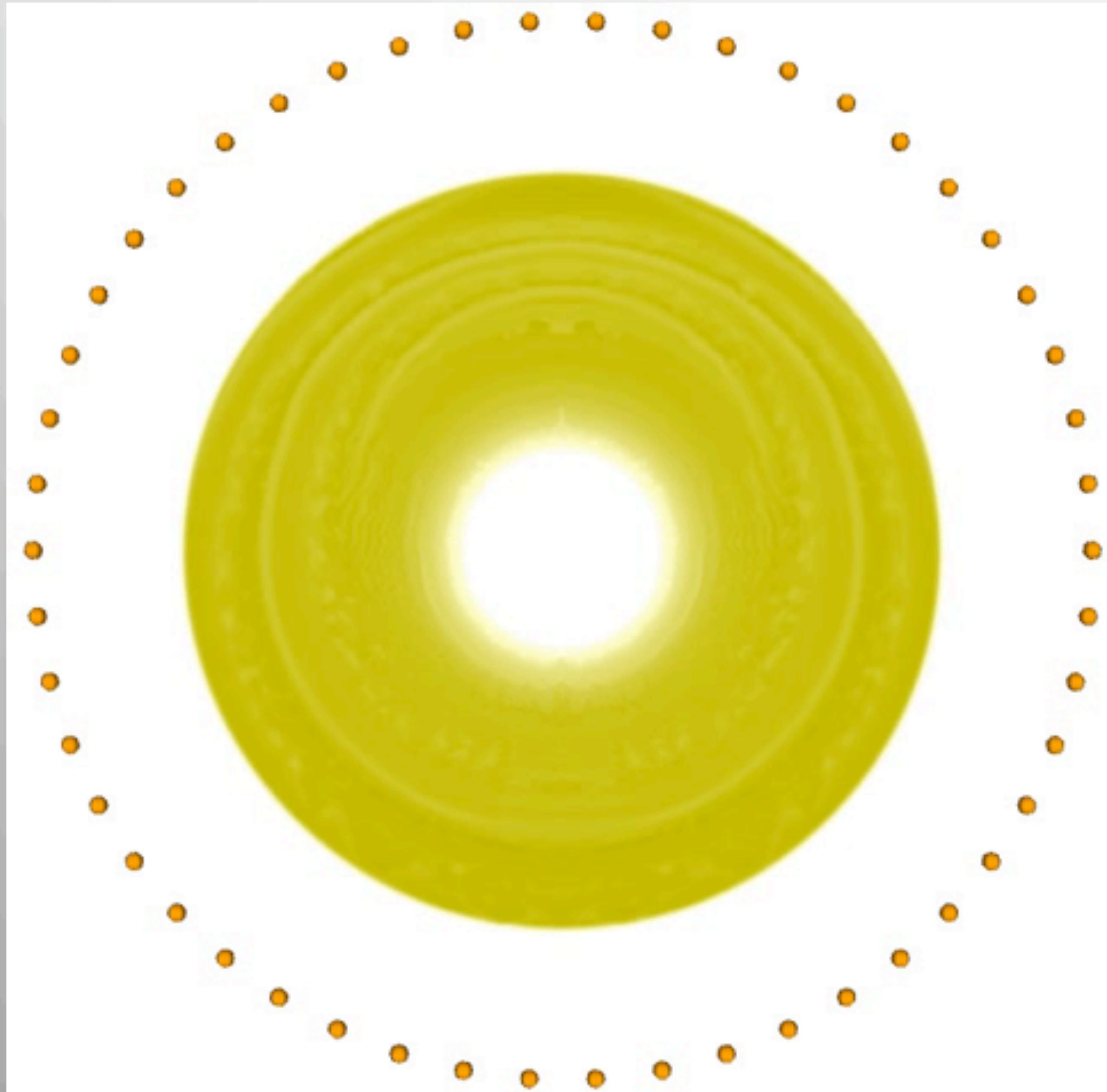


Known, Potentially Important Ingredients

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

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

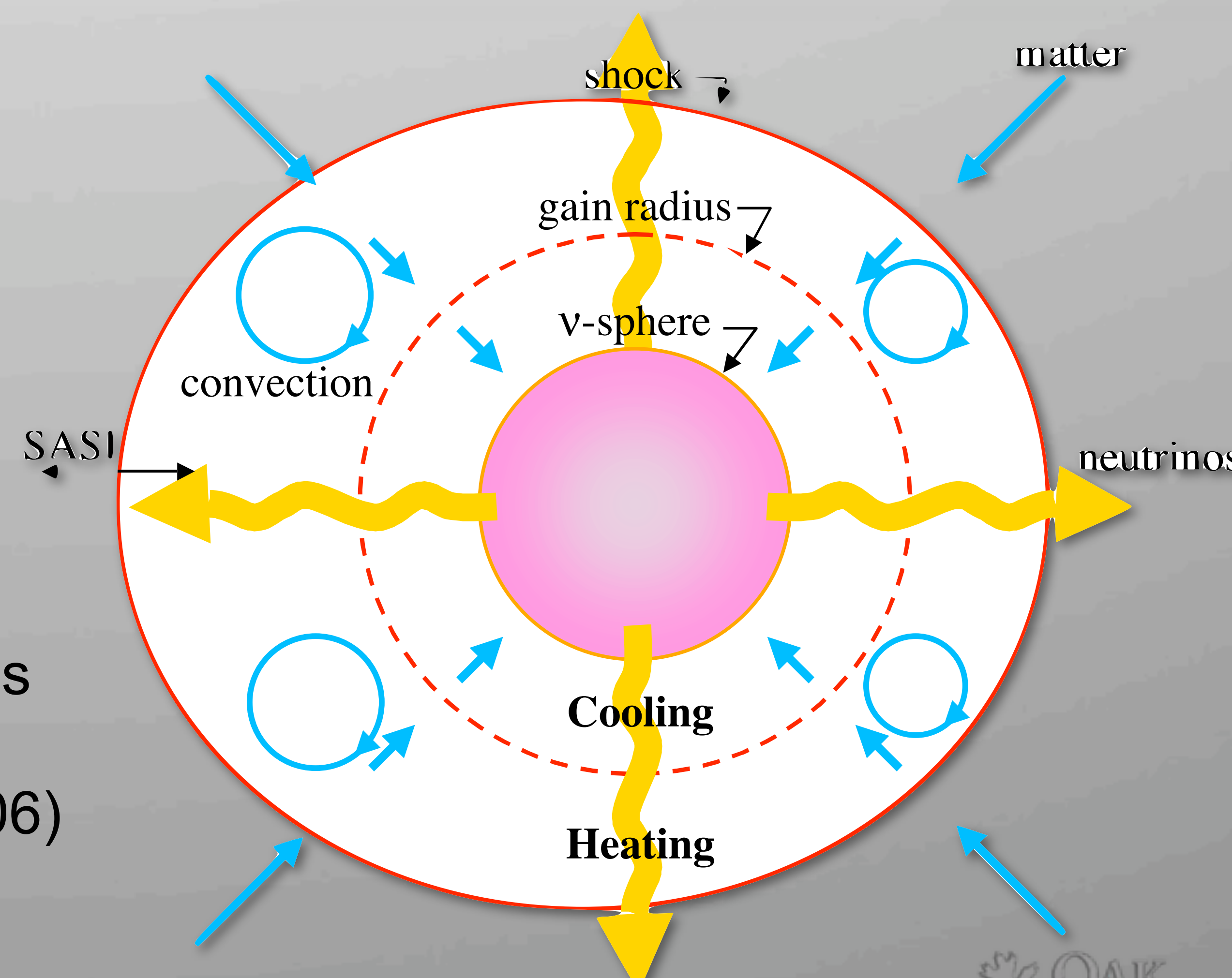
Stationary Accretion Shock Instability



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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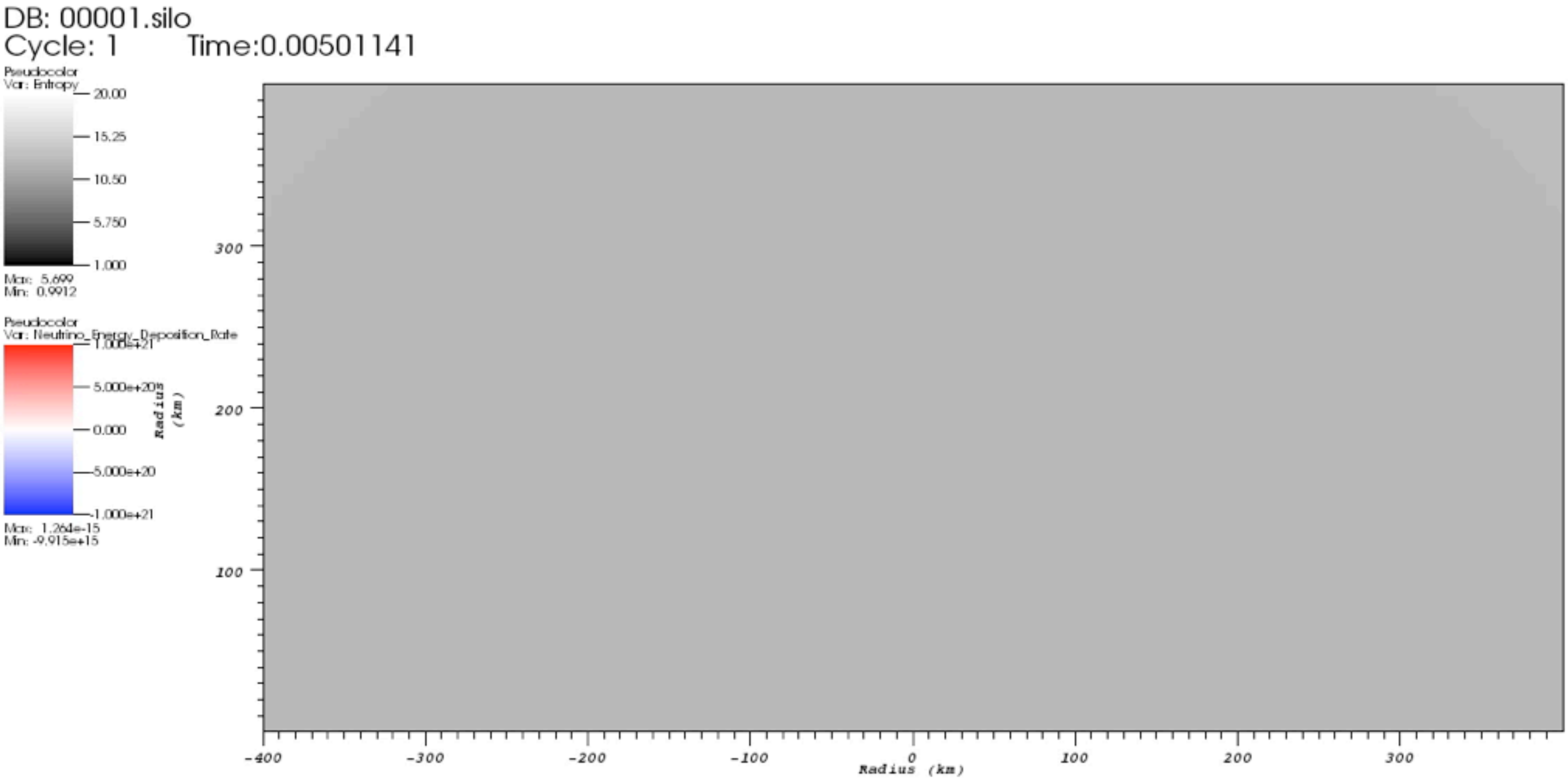
- “RbR-Plus” MGFLD Neutrino Transport
  - O(v/c), GR time dilation and redshift, GR aberration
- 2D PPM Hydrodynamics
  - GR time dilation, effective gravitational potential,
  - adaptive radial grid
- Lattimer-Swesty EOS
- Nuclear (Alpha) Network
  - 14 alpha nuclei between helium and zinc
- 2D Effective Gravitational Potential
  - Marek et al. A&A, 445, 273 (2006)
- Neutrino Emissivities/Opacities
  - “Standard” + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung

2D simulations

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)



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)

Determining what's important to include...

observer corrections

$$\frac{\partial F}{\alpha c \partial t} + \frac{\partial\left(4\pi r^2 \alpha\rho\mu F\right)}{\alpha \partial m} + \Gamma\left(\frac{1}{r} - \frac{\partial \alpha}{\alpha \partial r}\right)\frac{\partial\left[\left(1-\mu^2\right)F\right]}{\partial\mu}$$

$$+ \left(\frac{\partial \ln\rho}{\alpha c \partial t} + \frac{3u}{r c}\right)\frac{\partial\left[\mu\left(1-\mu^2\right)F\right]}{\partial\mu}$$

$$+ \left[\mu^2\left(\frac{\partial \ln\rho}{\alpha c \partial t} + \frac{3u}{r c}\right) - \frac{1}{r}\frac{u}{c} - \mu\Gamma\frac{\partial\alpha}{\alpha\partial r}\right]\frac{1}{E^2}\frac{\partial\left(E^3 F\right)}{\partial E}$$

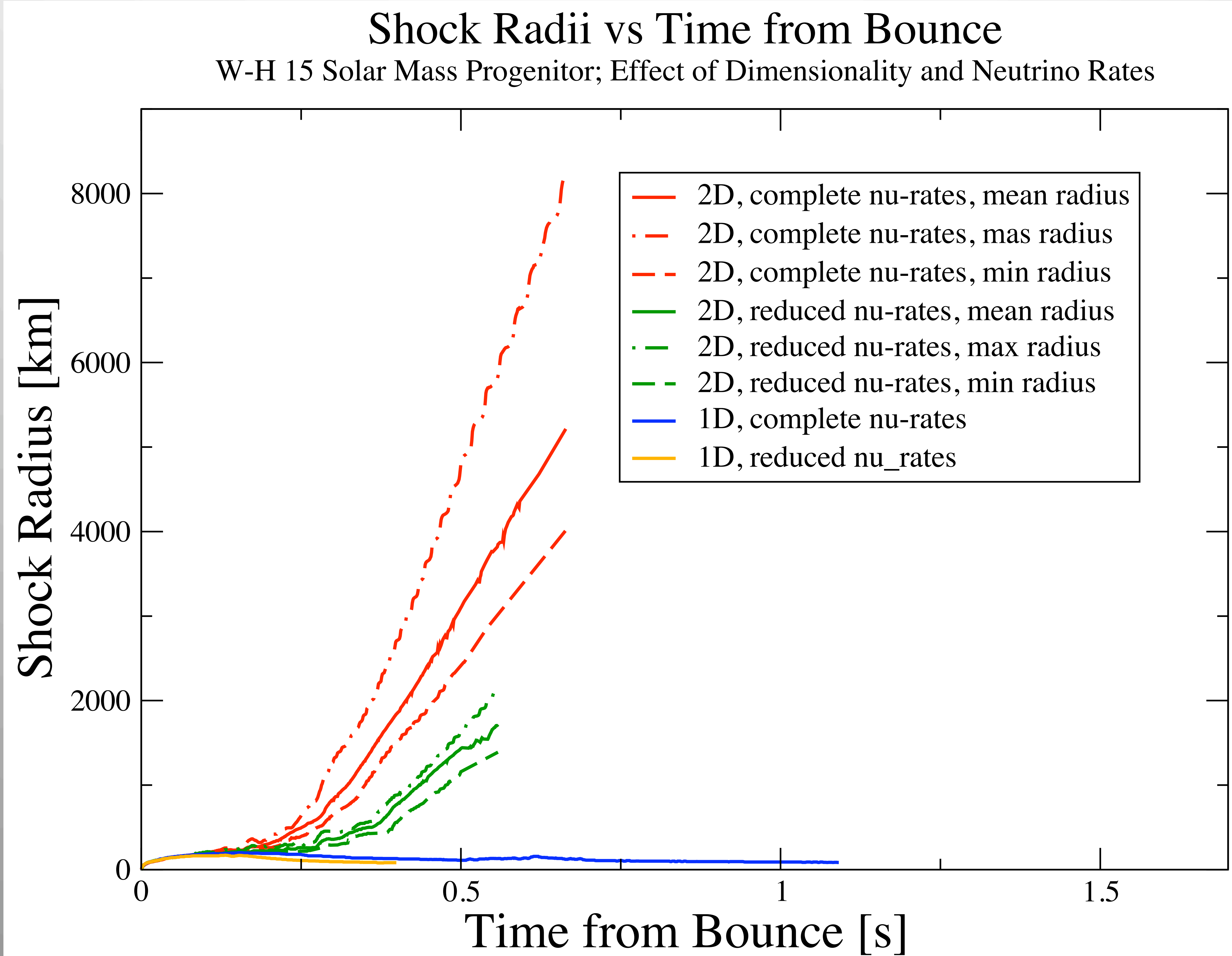
$$= \frac{j}{\rho} - \tilde{\chi}F + \frac{1}{h^3c^4}E^2\int d\mu' R_{is}\left(\mu,\mu',E\right)F\left(\mu',E\right)$$

$$- \frac{1}{h^3c^4}E^2F\int d\mu' R_{is}\left(\mu,\mu',E\right)$$

$$+ \frac{1}{h^3c^4}\left[\frac{1}{\rho} - F\left(\mu,E\right)\right]\int E'^2 dE' d\mu' \tilde{R}^{in}_{nes}\left(\mu,\mu',E,E'\right)F\left(\mu',E\right)$$

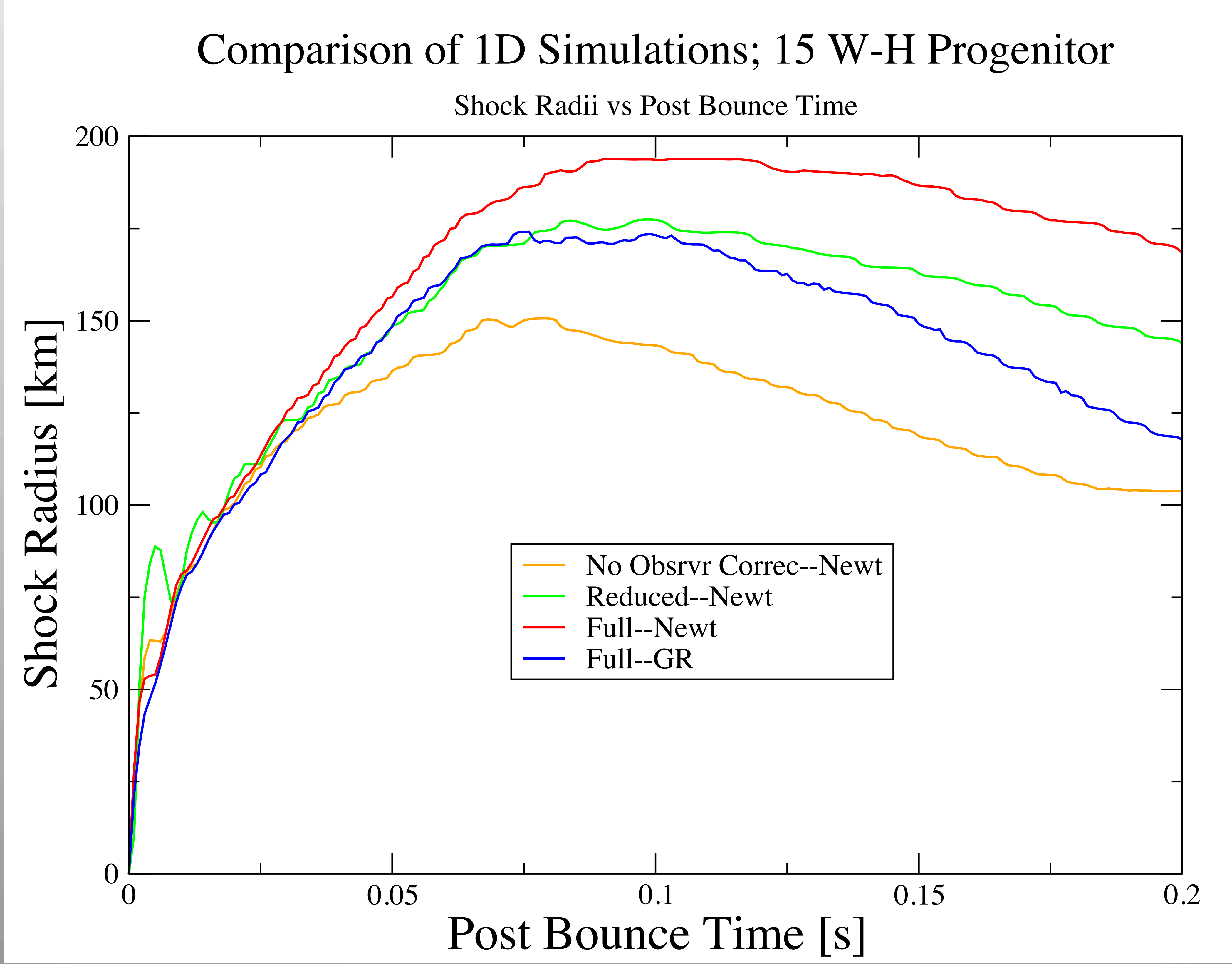
$$- \frac{1}{h^3c^4}F\left(\mu,E\right)\int E'^2 dE' d\mu' \tilde{R}^{out}_{nes}\left(\mu,\mu',E,E'\right)\left[\frac{1}{\rho} - F\left(\mu',E'\right)\right]$$

energy-exchanging processes

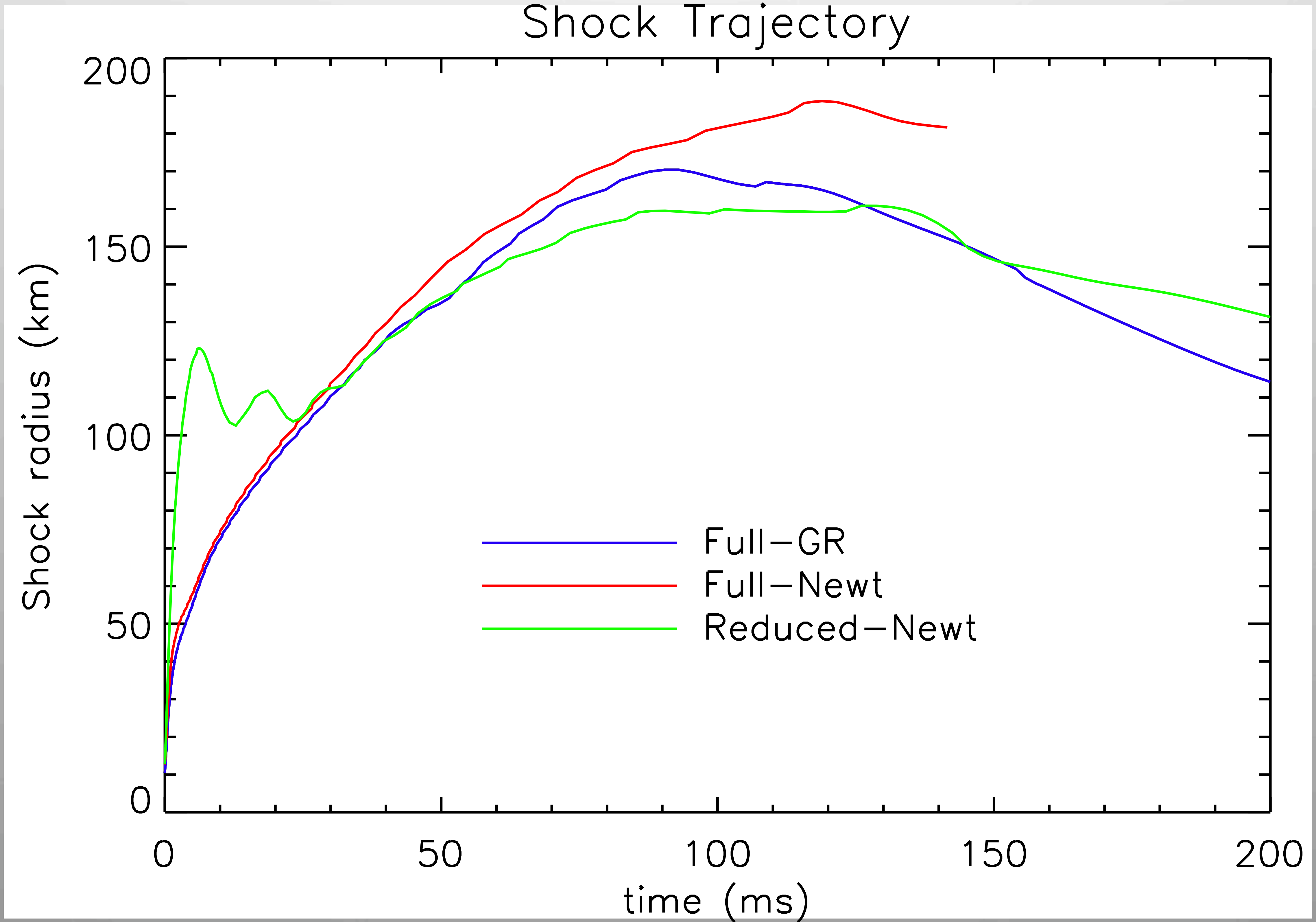


Shock Radii vs Time from Bounce
W-H 15 Solar Mass Progenitor; Effect of Dimensionality and Neutrino Rates
Shock Radius [km]
Time from Bounce [s]
0
2000
4000
6000
8000
0
0.5
1
1.5
2D, complete nu-rates, mean radius
2D, complete nu-rates, mas radius
2D, complete nu-rates, min radius
2D, reduced nu-rates, mean radius
2D, reduced nu-rates, max radius
2D, reduced nu-rates, min radius
1D, complete nu-rates
1D, reduced nu_rates

CHIMERA 1D simulations

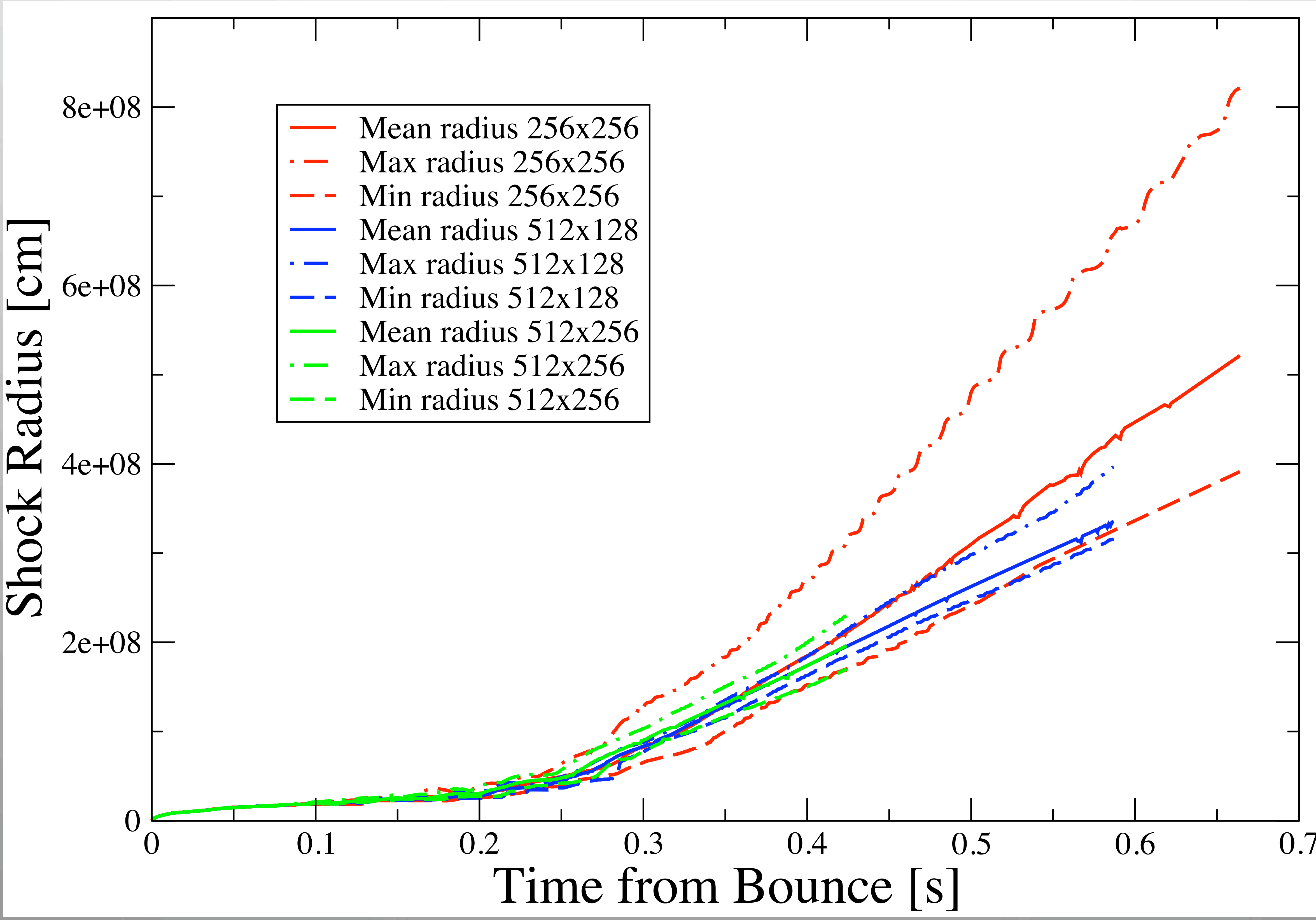


AGILE-Boltztran



Lentz et al. *in prep*

Impact of resolution



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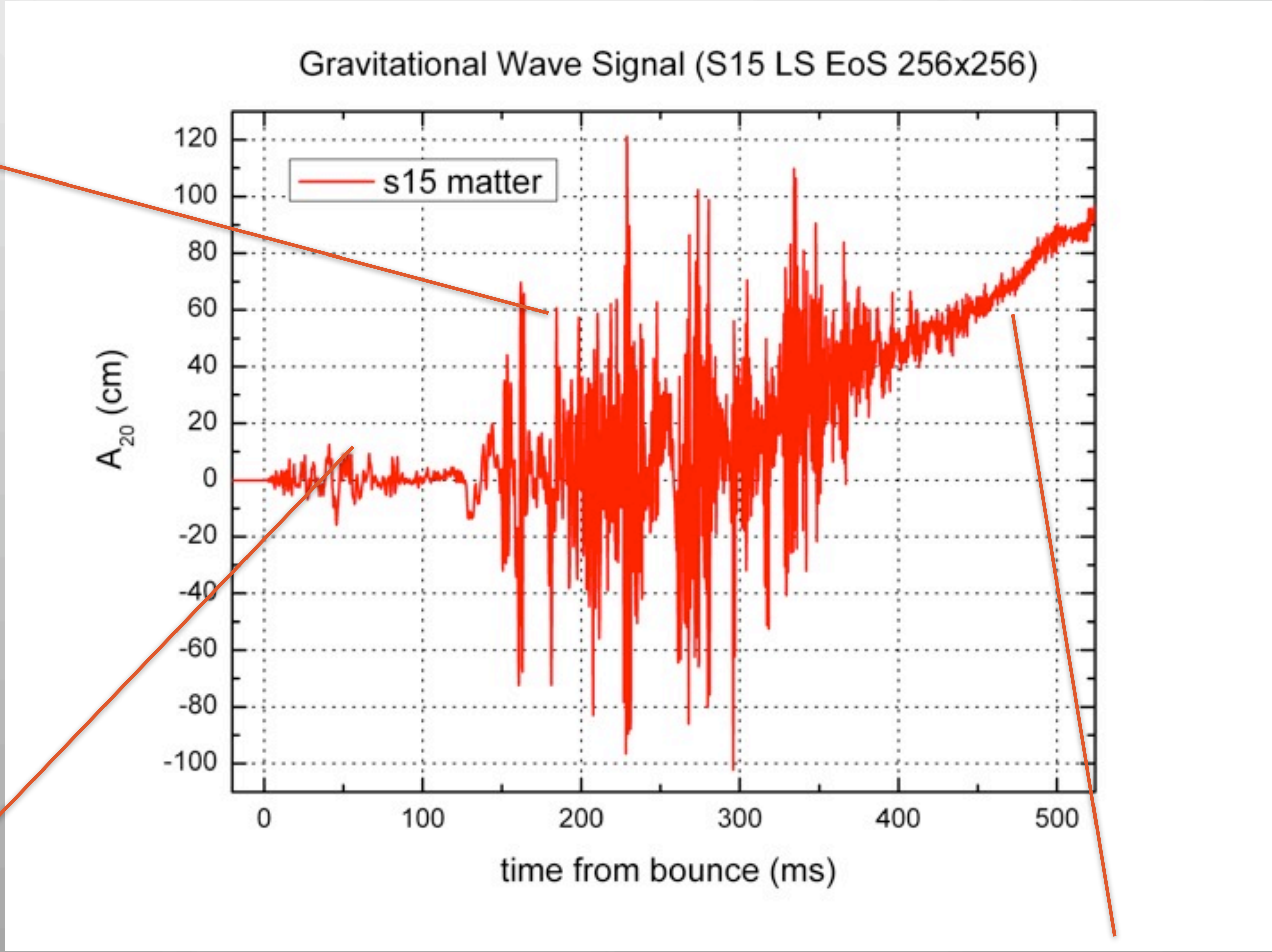
Example of observables: Anatomy of a GW signature

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

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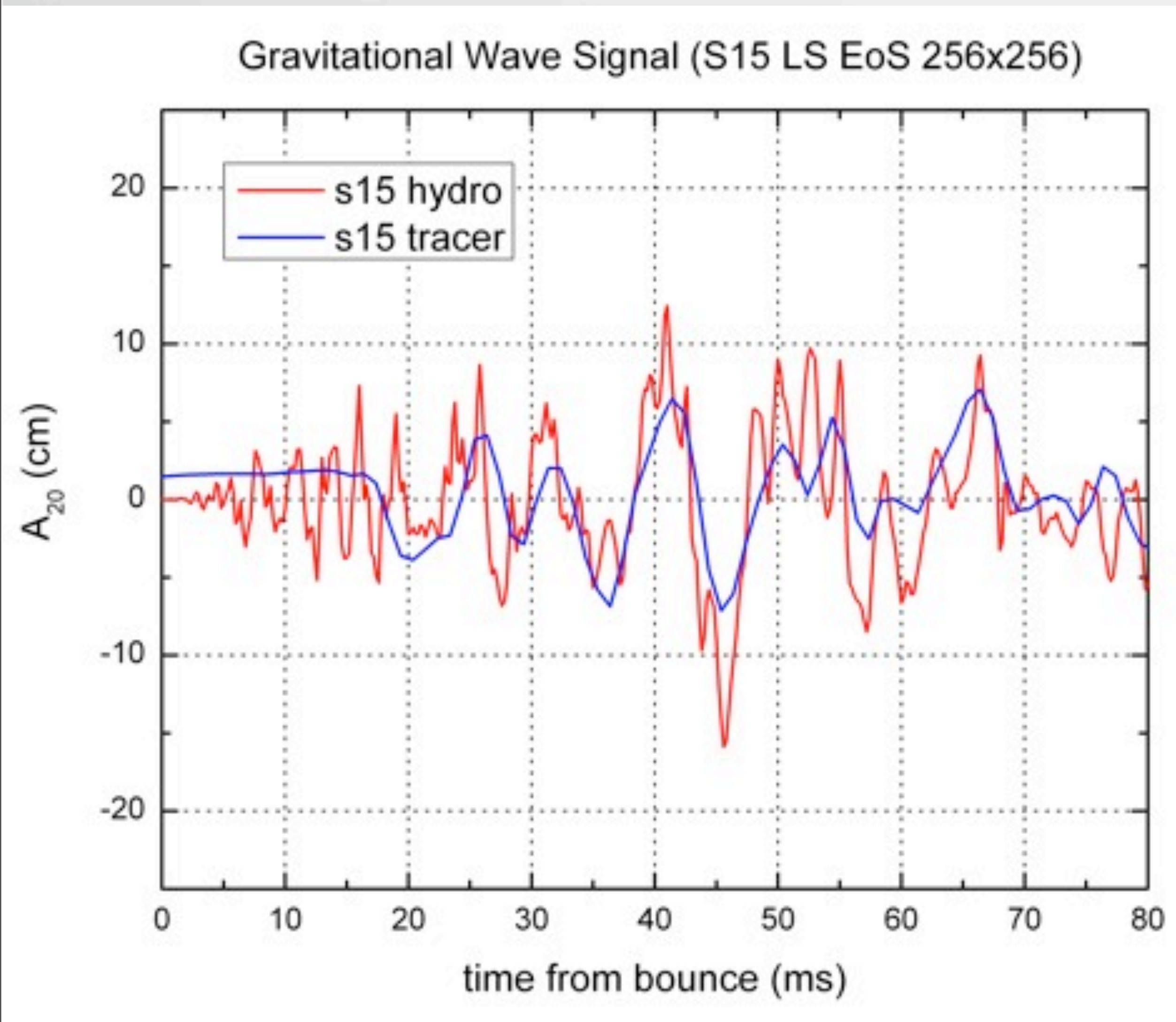
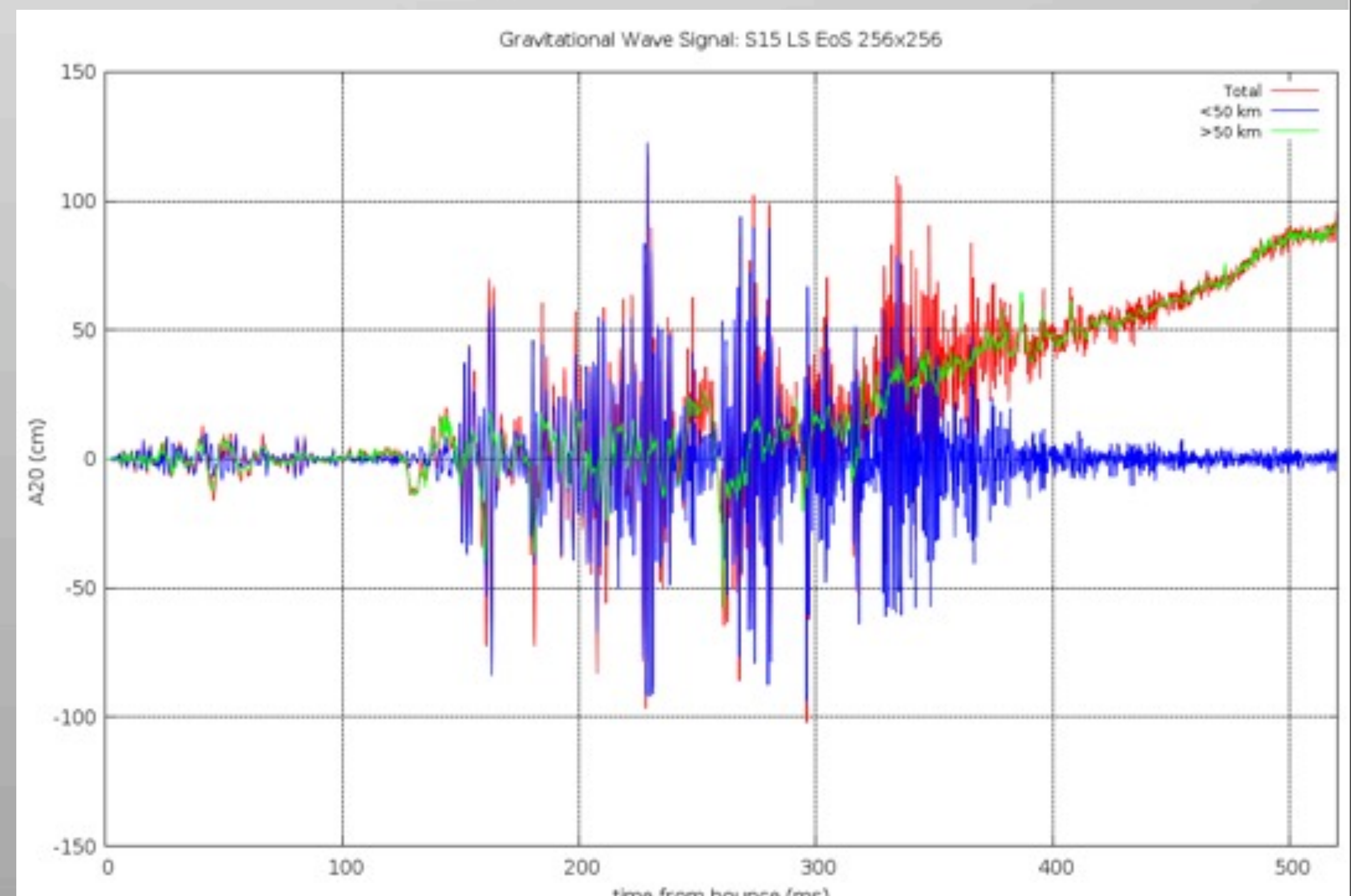
Using Tracers for GW Diagnostics





Yakunin et al. 2010, Class. Quant. Grav. 27, 194005

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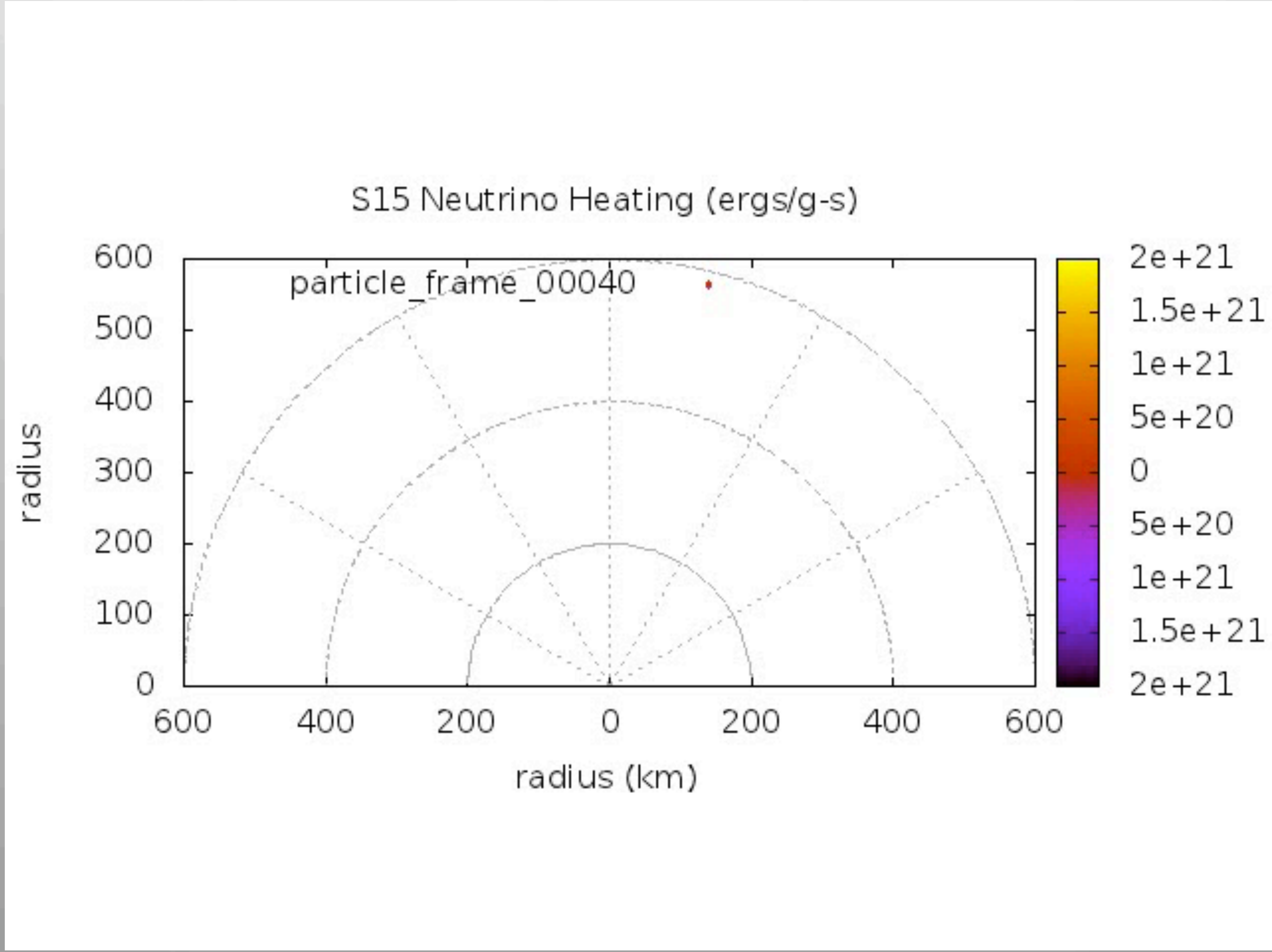
Oak Ridge National Laboratory

Tuesday, July 12, 2011

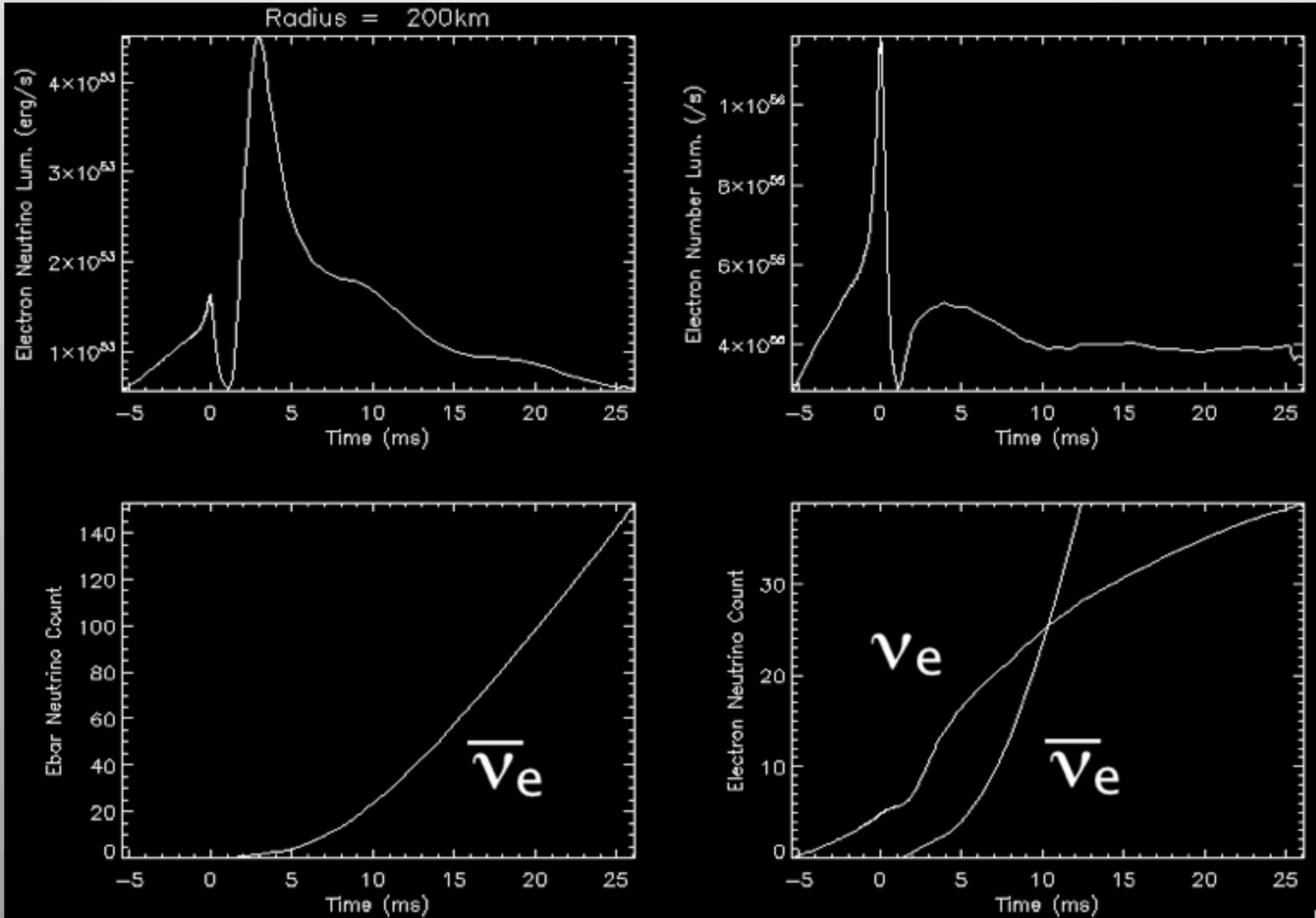
The primary purpose of tracers: nucleosynthetic post-processing



Chertkow, PhD thesis (2011)

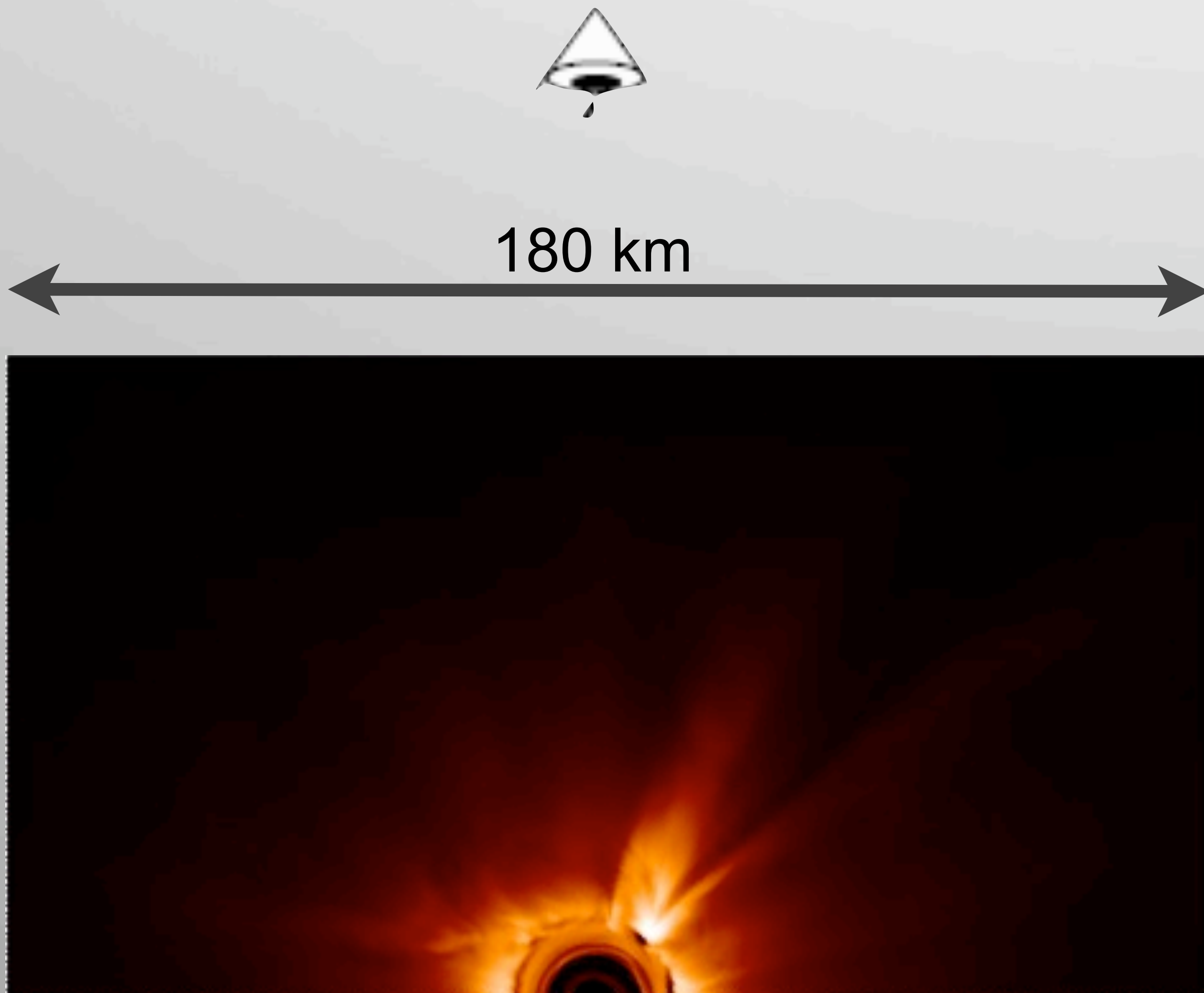
ν signatures in terrestrial detectors

Sanchez, Messer, et al. *in prep.*

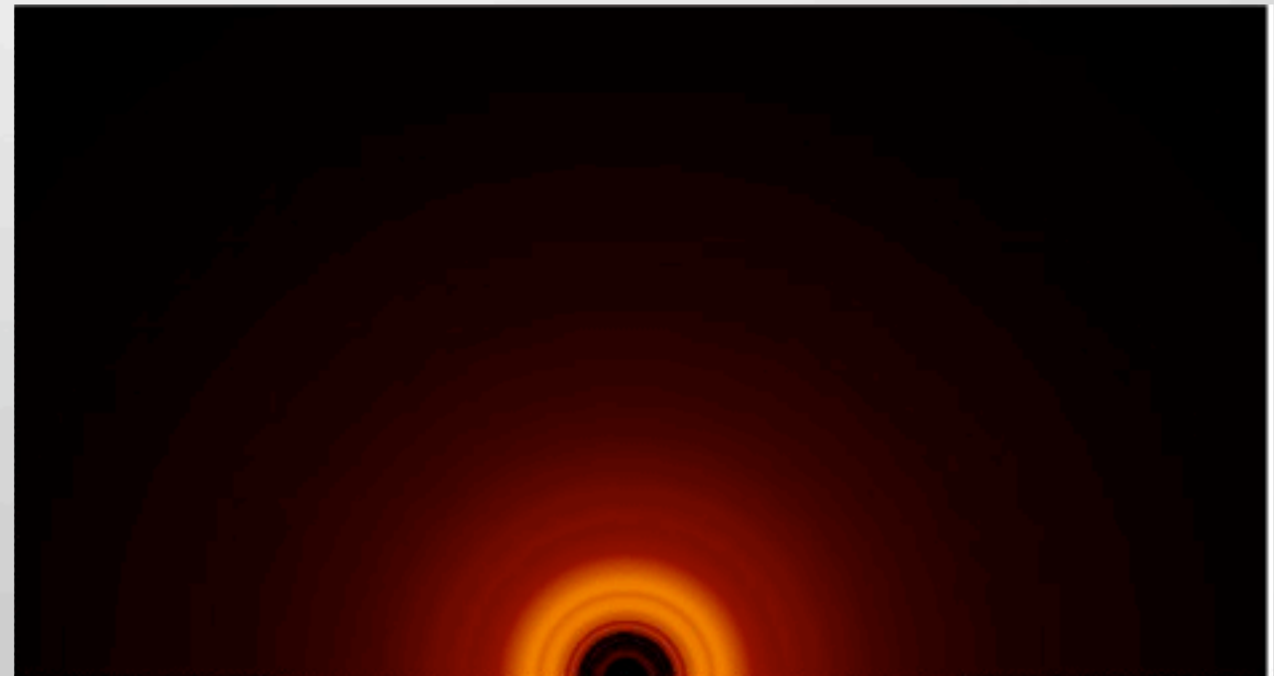


Shock breakout signature in Super Kamiokande 15 $M_{\odot}$ progenitor 10 kpc distance

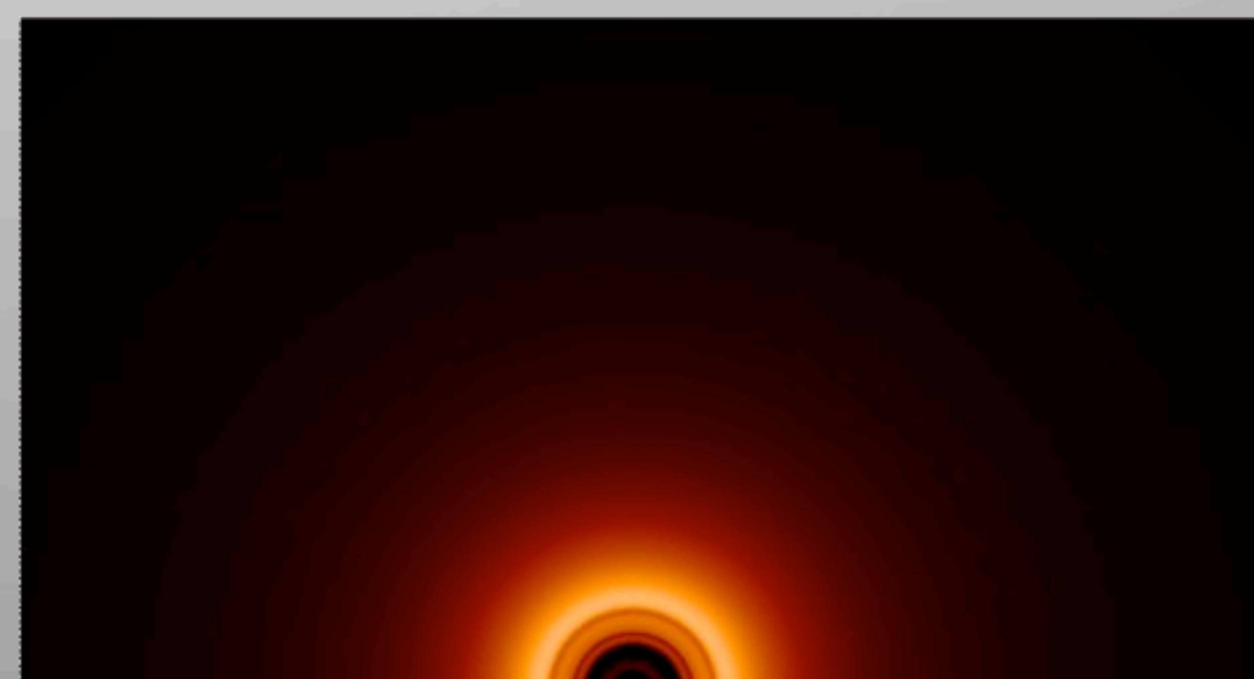
Recovering "realistic" ν fluxes from RbR simulations



raw



1 polar ray

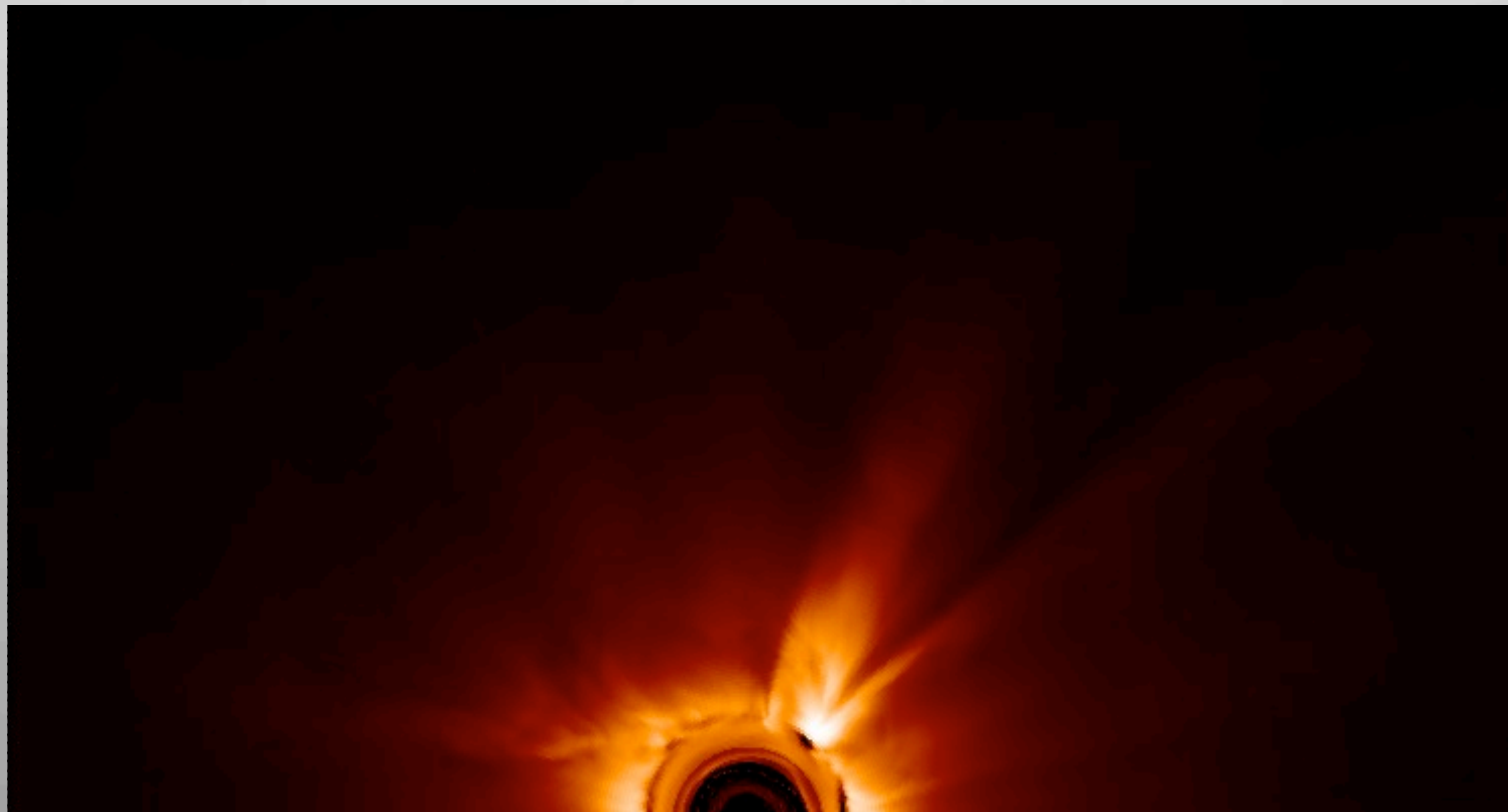


average

Sanchez, Messer, et al. *in prep.*
cf. Lund, et al., *Phys. Rev. D 82, 063007 (2010)*

Recovering “realistic” ν fluxes from RbR simulations

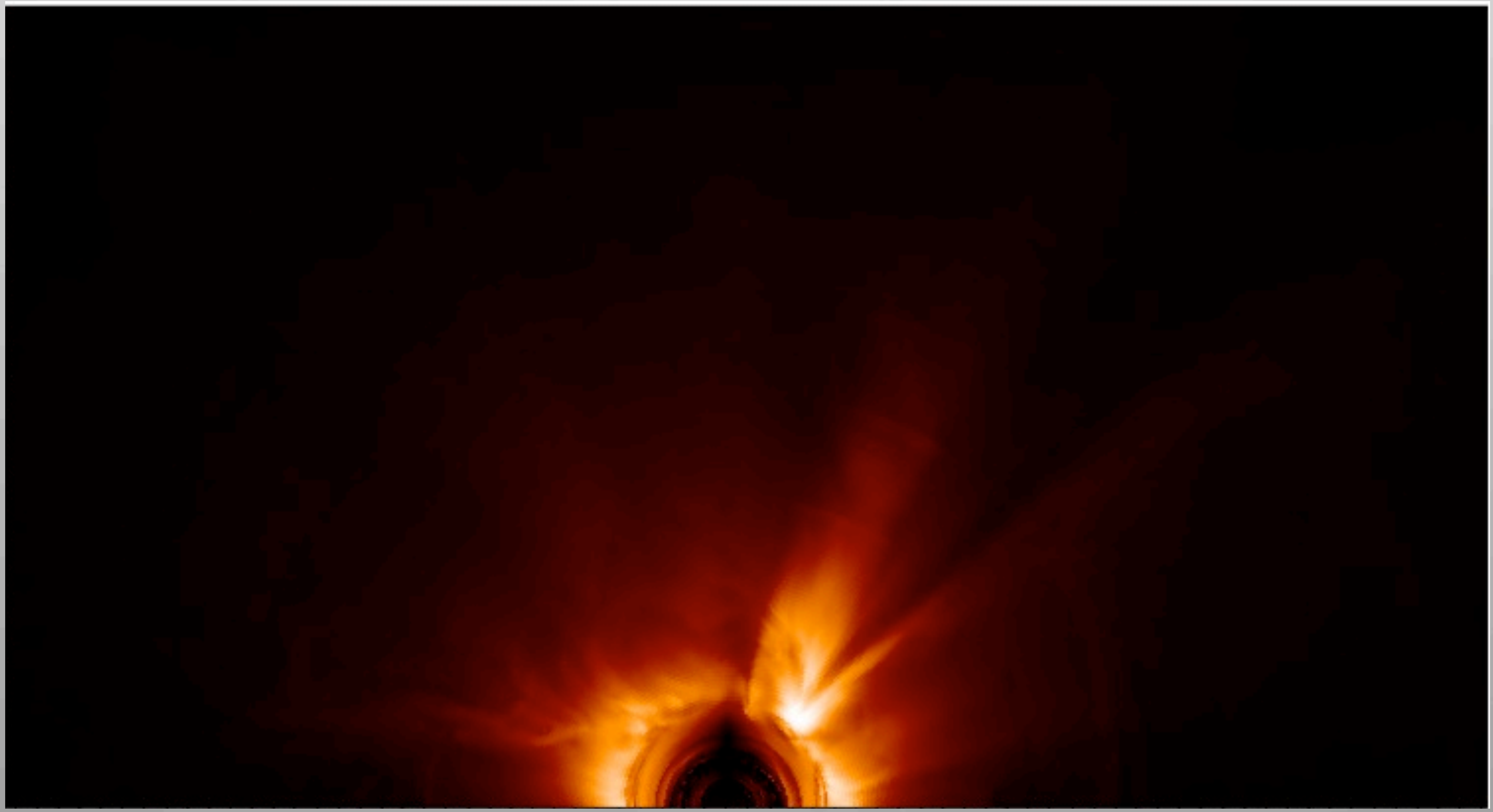
raw



Sanchez, Messer, et al. *in prep.*

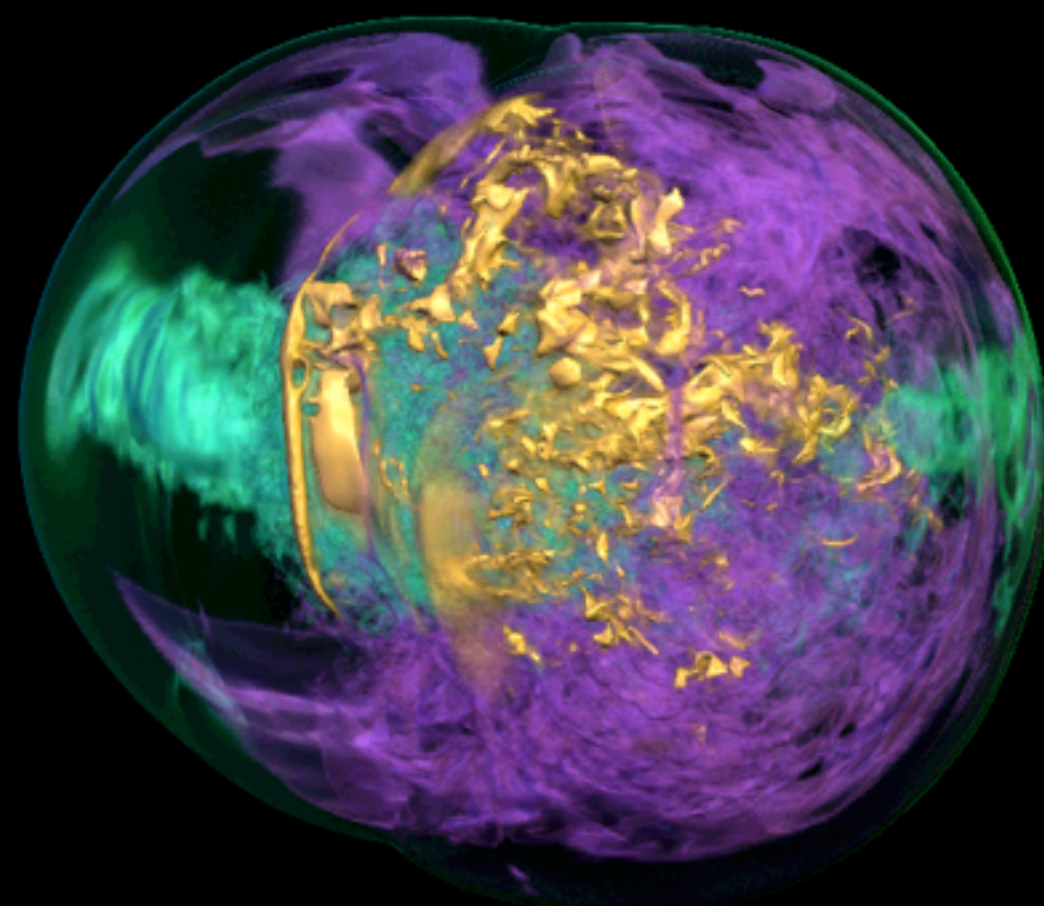
Recovering “realistic” ν fluxes from RbR simulations

limb-darkened



Sanchez, Messer, et al. *in prep.*

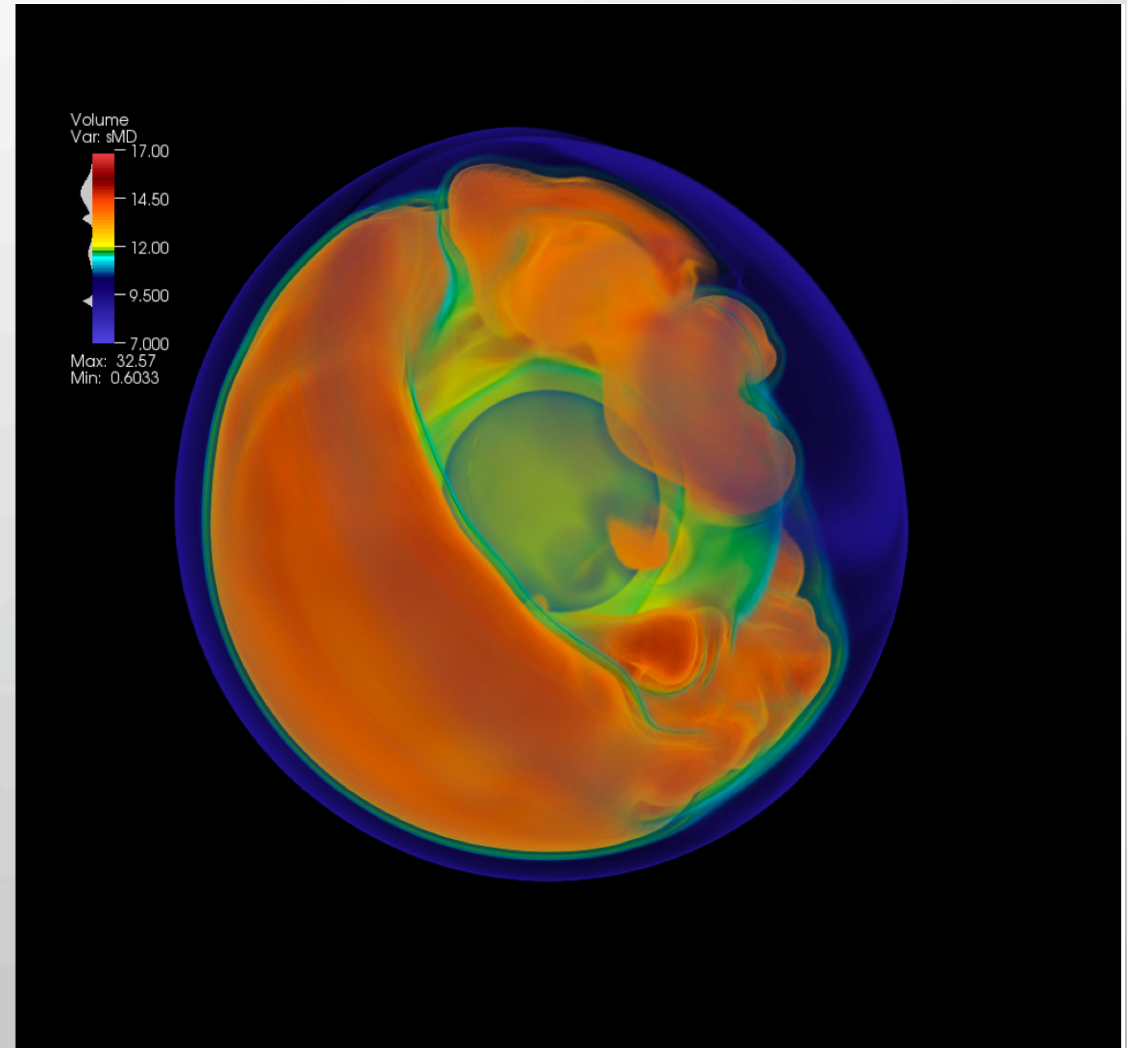
SASI in 3D



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

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*



<u>Resolution</u>

304 X 76 X 152

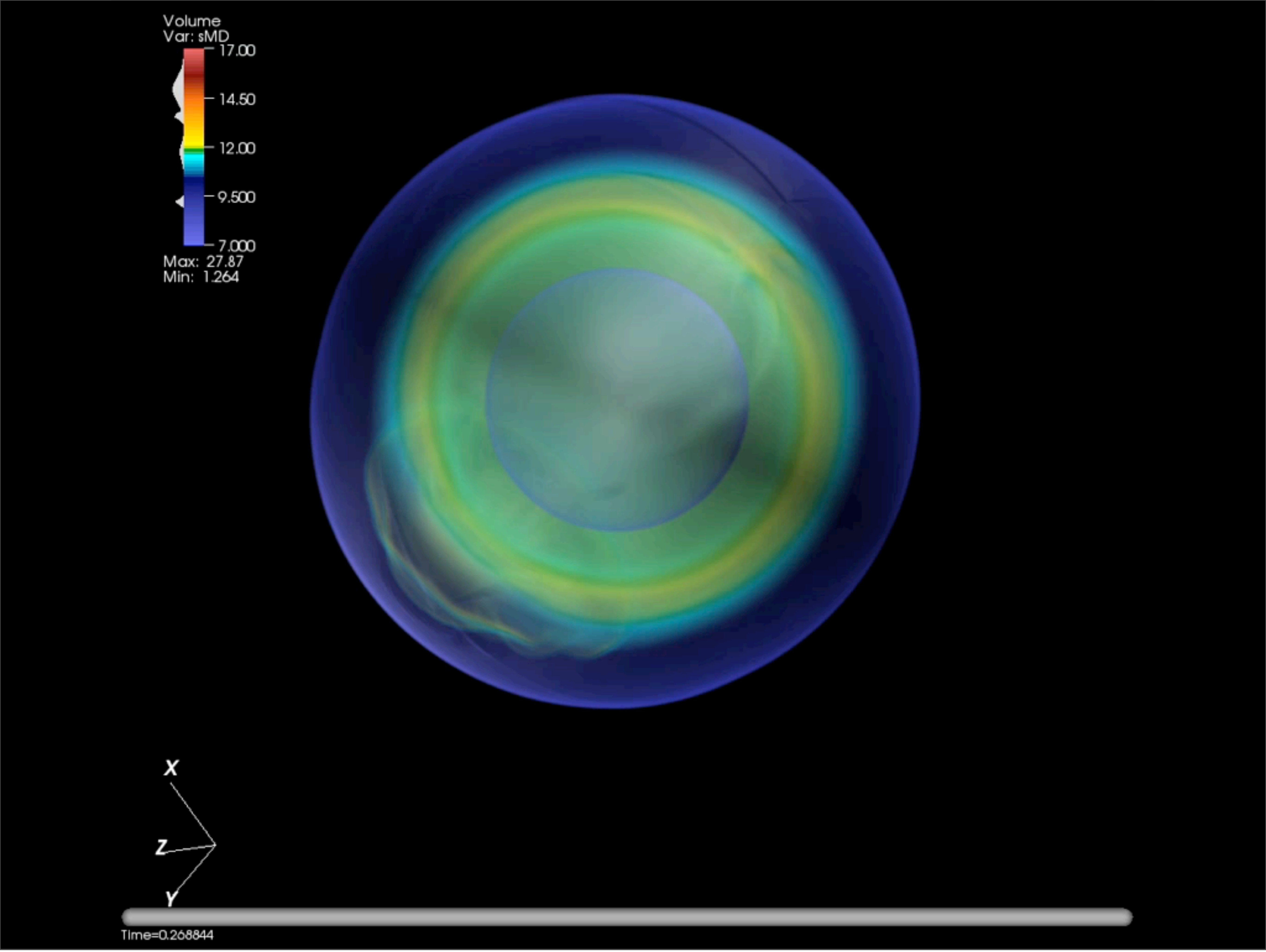
⇒ 11,552 processors

576 X 96 X 192 (current production size)

⇒ 18,432 processors

512 X 256 X 512

⇒ 131,072 processors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12.00
9.500
7.000
Max: 27.87
Min: 1.264
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Y
Time=0.268844

Summary

- Improved neutrino interaction physics + convection + SASI + nuclear burning + sufficient simulation time leads to explosions across a range of stellar progenitor models in 2D simulations.
- The inherently three-dimensional nature of both convection and the SASI demands three-dimensional simulations.
- These simulations produce a raft of multi-messenger observables.

Bellerophon

- Revision control, regression testing, viz, workflow... what else ya got?