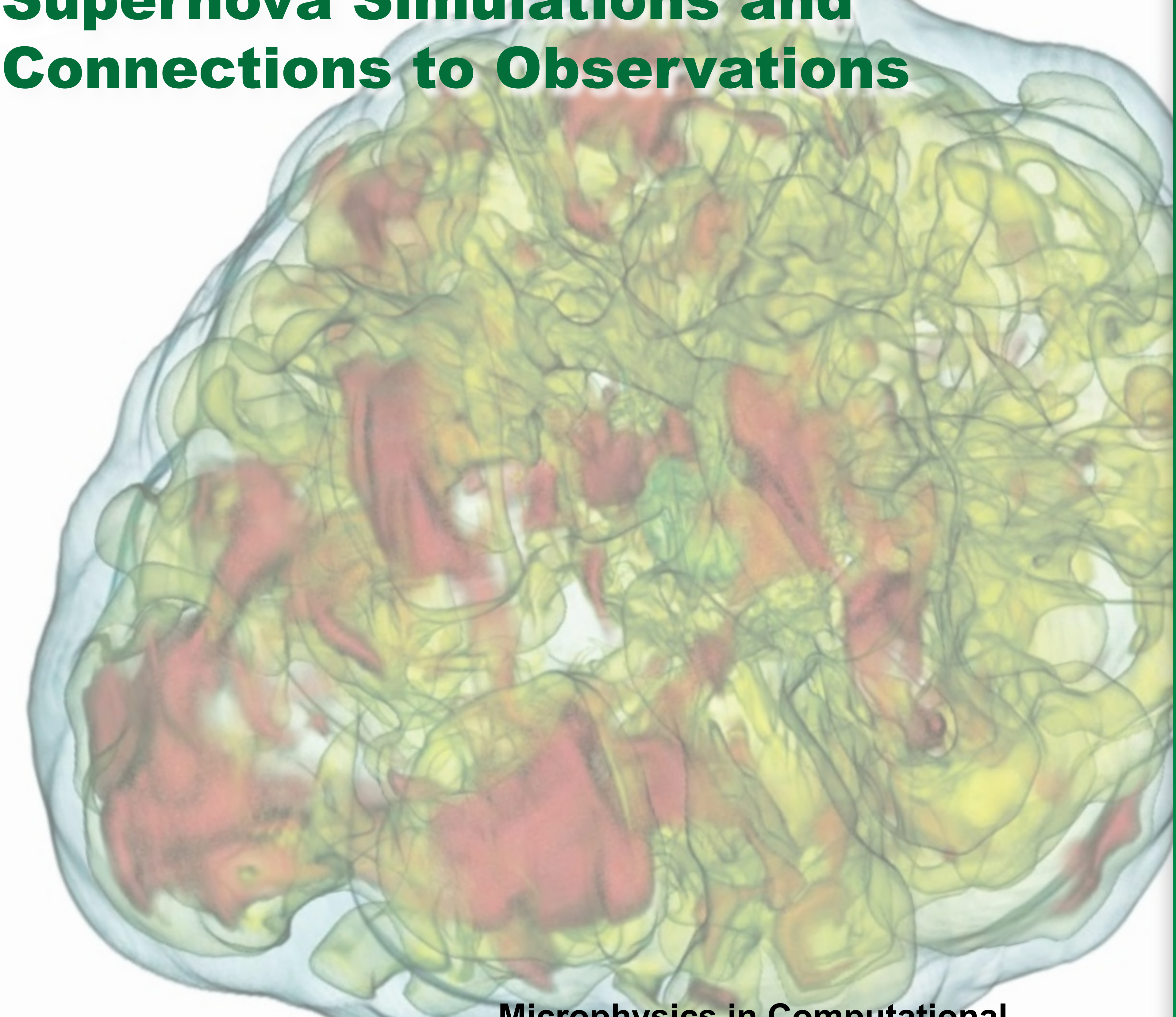
Neutrino Transport In Core-Collapse Supernova Simulations and Connections to Observations



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Microphysics in Computational Relativistic Astrophysics (MICRA)
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CHIMERA collaboration

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

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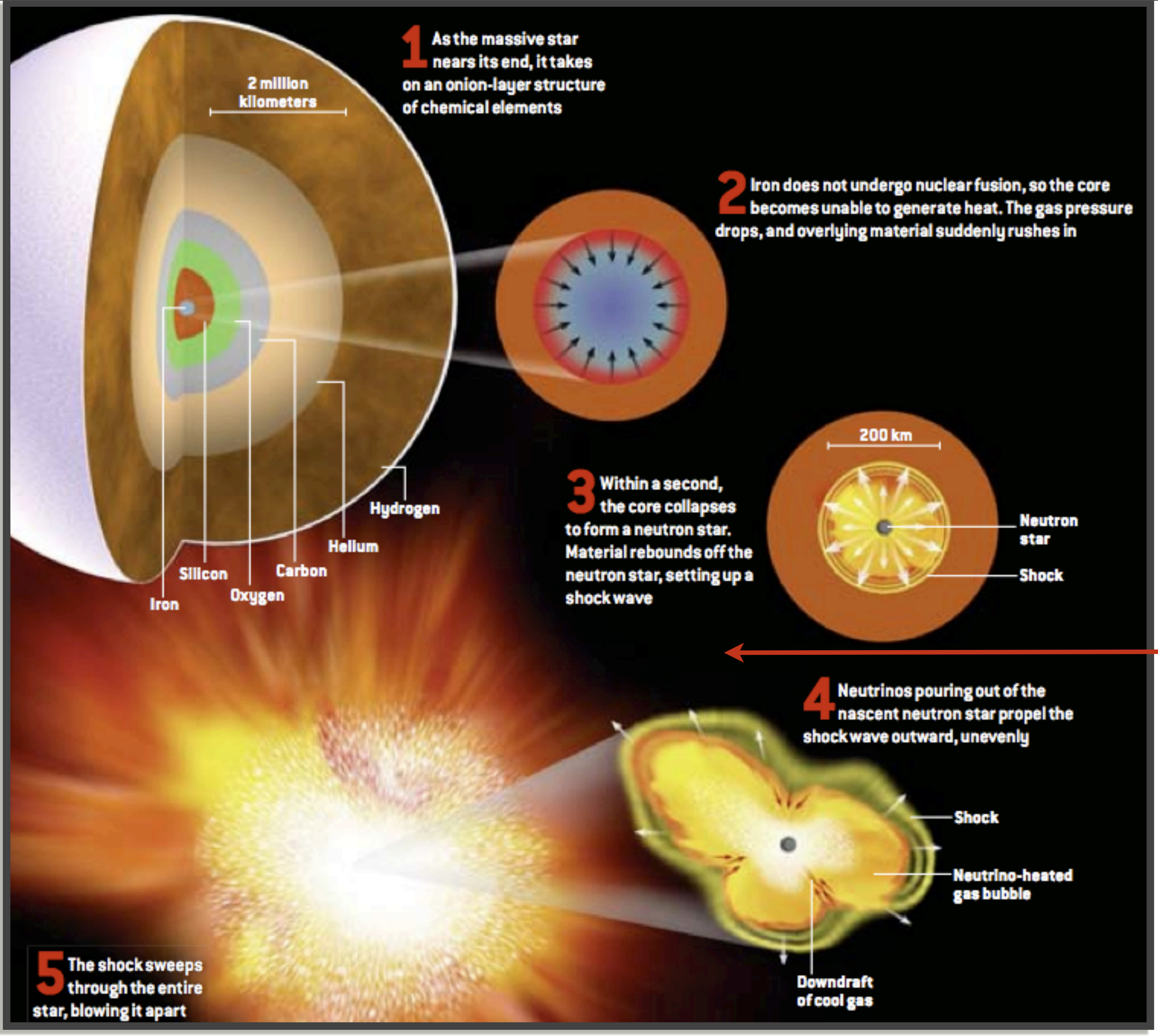


1 As the massive star nears its end, it takes on an onion-layer structure of chemical elements

2 Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in

3 Within a second, the core collapses to form a neutron star. Material rebounds off the neutron star, setting up a shock wave

4 Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly

5 The shock sweeps through the entire star, blowing it apart

3.5

Hillebrandt & Janka 2006 (Sci Am)

Neutrino trapping

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

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

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

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

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

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

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

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

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

Degenerate electron-neutrino Fermi sea develops (E_F > 100 MeV)

Important neutrino emissivities/opacities

Bruenn, *Ap.J. Suppl*. (1985)

- Nucleons in nucleus independent. (N>40 --> e capture quenched)
- No energy exchange in nucleonic scattering.

“Standard” Emissivities/Opacities

$e^- + p,A \leftrightarrow \nu_e + n,A'$

Langanke, ..., Messer, 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.

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

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

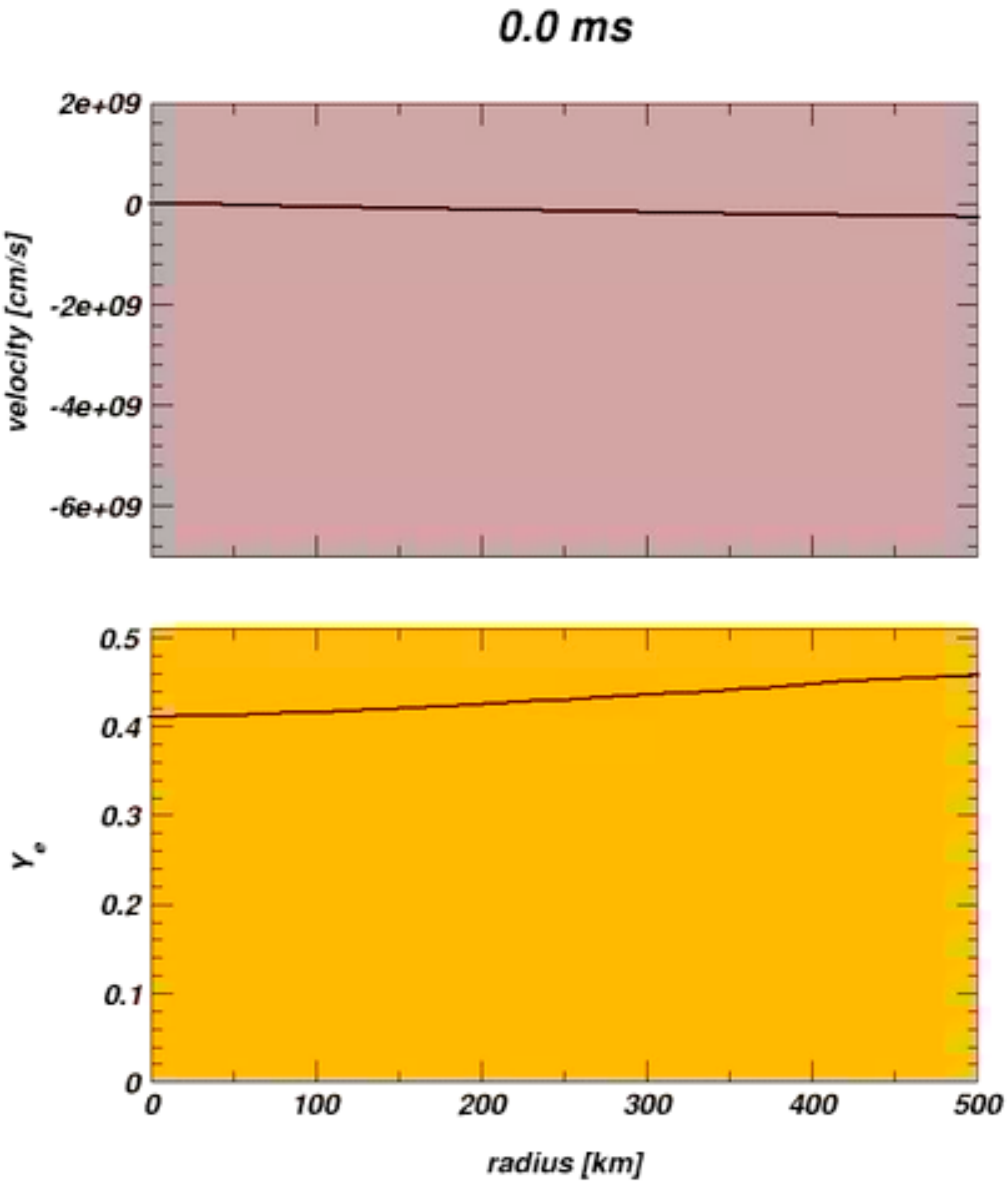
Hannestad and Raffelt, *Ap.J.* **507**, 339 (1998)
Hanhart, Phillips, and Reddy, *Phys. Lett. B*, **499**, 9 (2001)

- “softer” source of neutrino-antineutrino pairs vs. e^+e^-

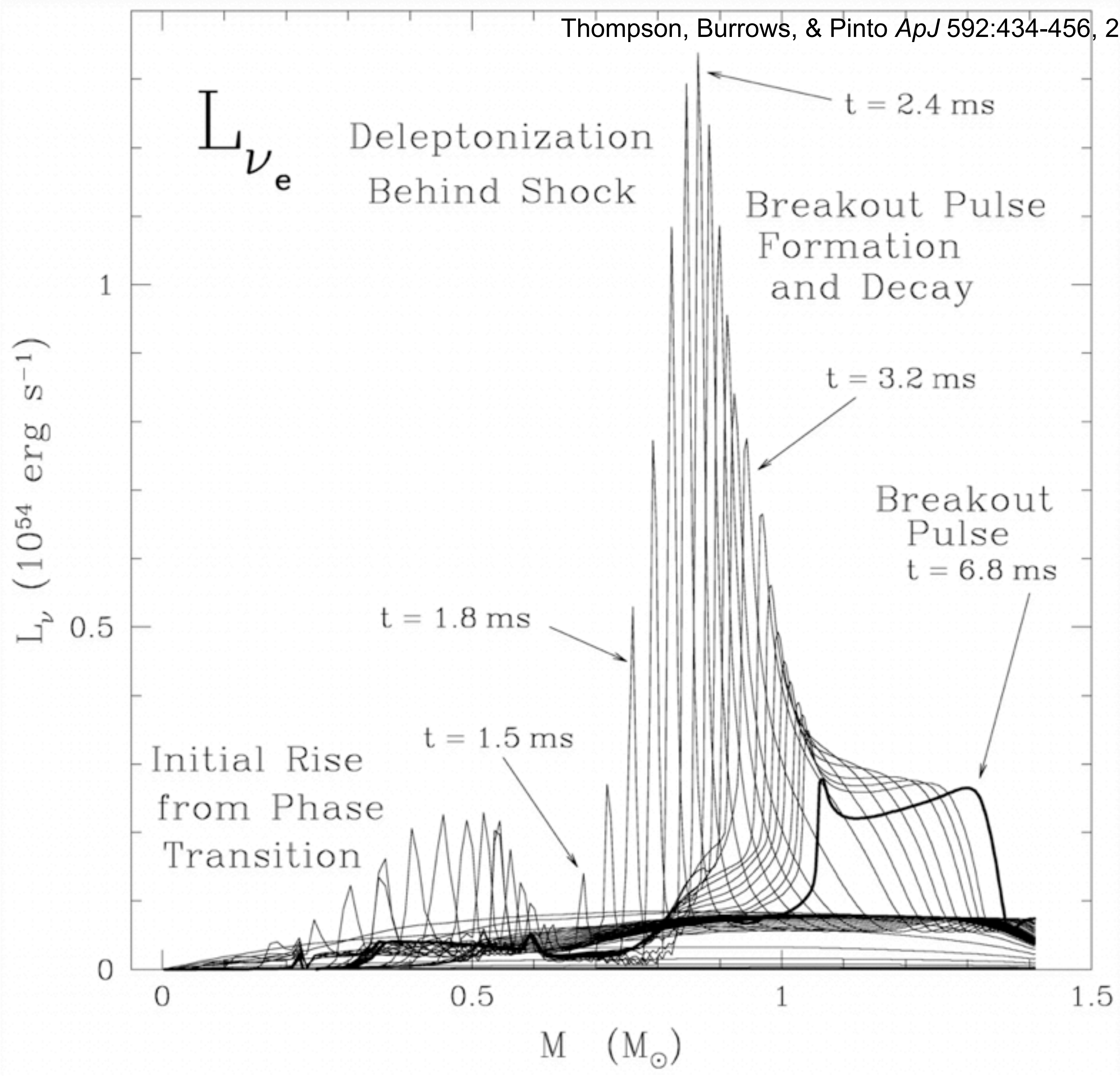
$\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

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

Spherically symmetric collapse with Boltzmann transport

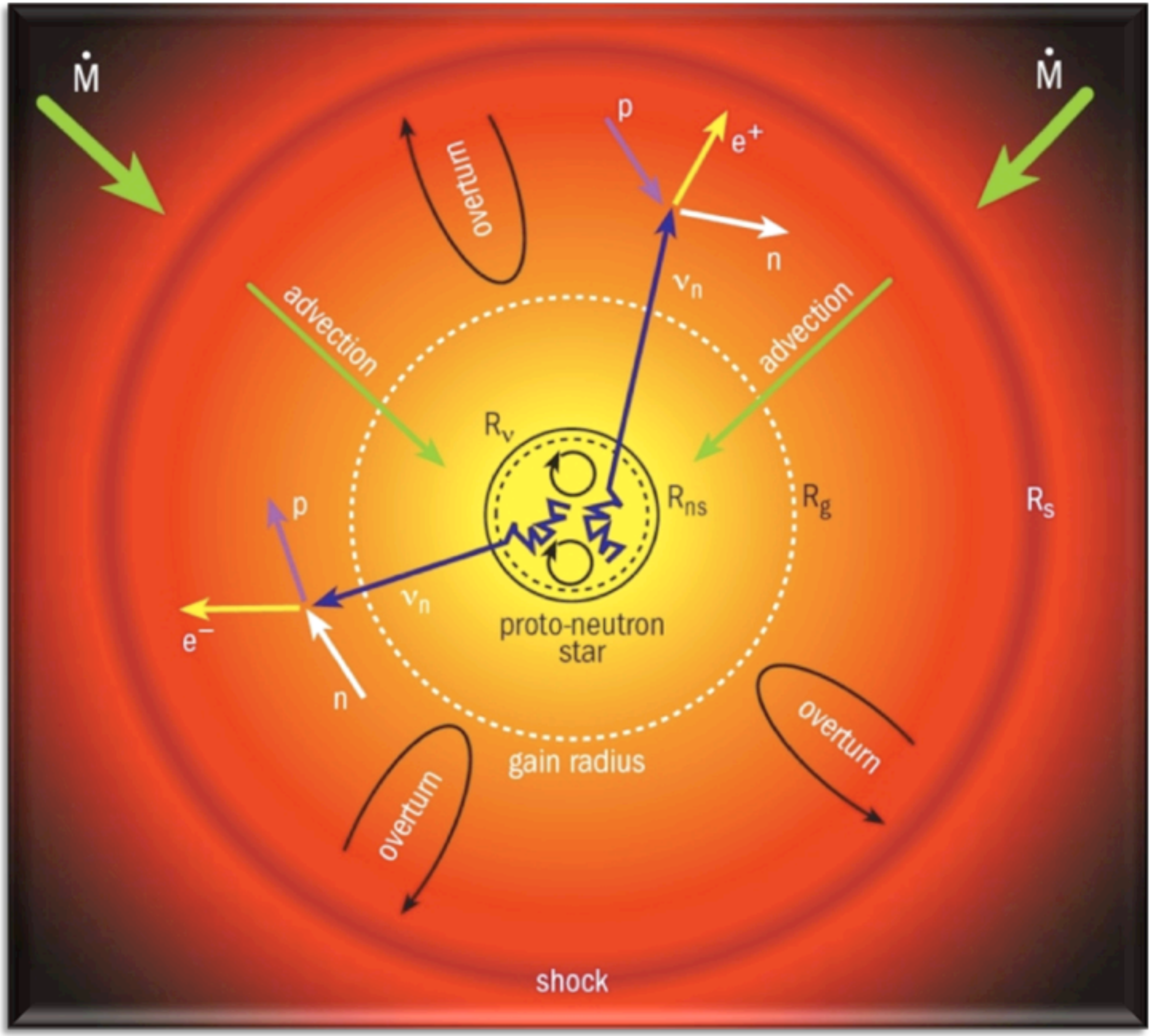


Messer(2000)



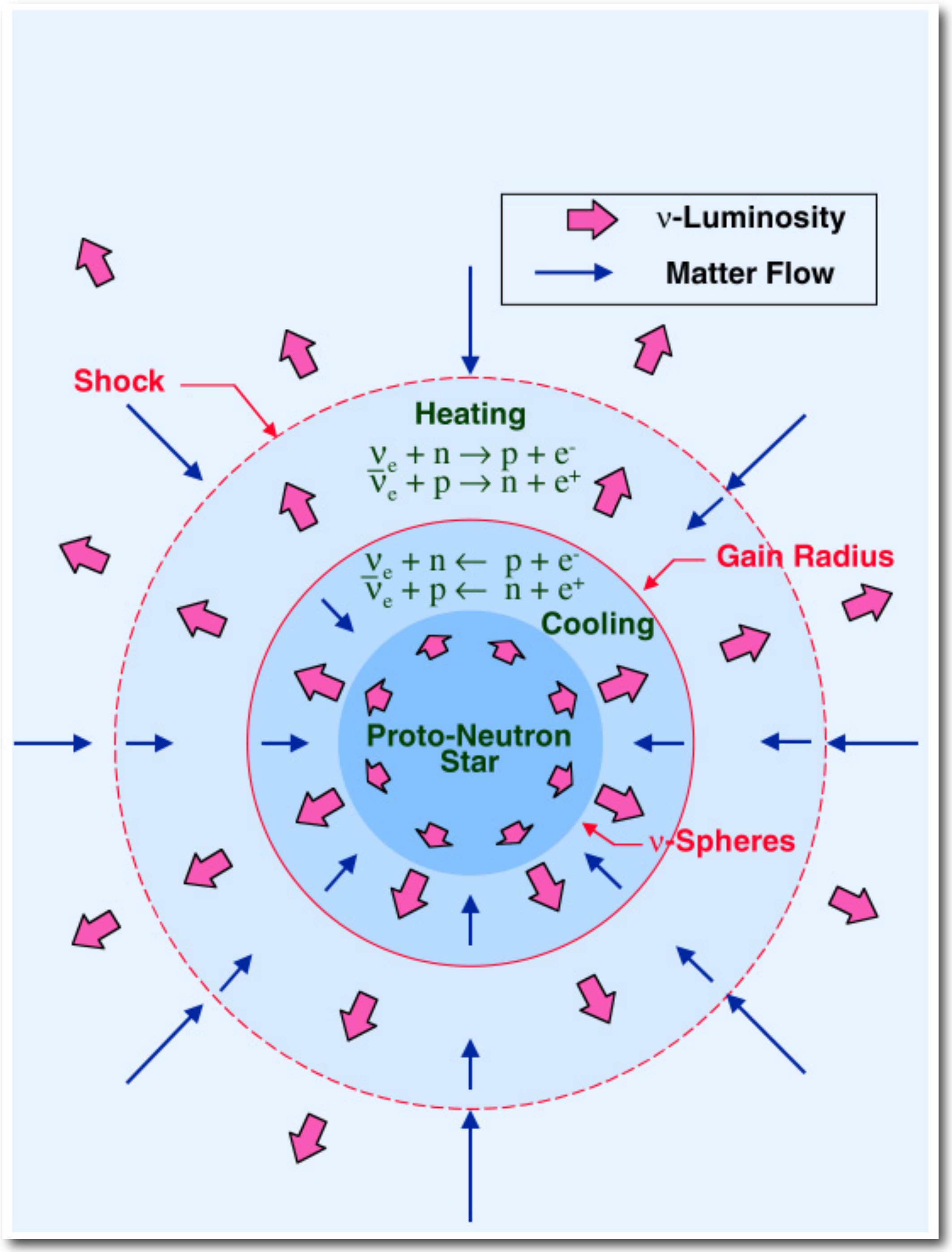
Thompson, Burrows, & Pinto *ApJ* 592:434-456, 2003

Post-bounce profile



Hillebrandt & Janka 2006 (Sci Am)

CCSNe are neutrino events



Neutrino heating depends on neutrino luminosities, spectra, and angular distributions.

$$\dot{\epsilon} = \frac{X_n}{\lambda_0^a}\frac{L_{\nu_e}}{4\pi r^2}\langle E_{\nu_e}^2\rangle\langle\frac{1}{\mathcal{F}}\rangle + \frac{X_p}{\lambda_0^a}\frac{L_{\bar{\nu}_e}}{4\pi r^2}\langle E_{\bar{\nu}_e}^2\rangle\langle\frac{1}{\mathcal{F}}\rangle$$

➠ *Must compute neutrino distribution functions.*

$$f(t,r,\theta,\phi,E,\theta_p,\phi_p)$$

Multifrequency
Multiangle

$$E_R(t,r,\theta,\phi,E) = \int d\theta_p\, d\phi_p\, f$$

$$F_R^i(t,r,\theta,\phi,E) = \int d\theta_p\, d\phi_p\, n^i f$$

Multifrequency
(*solve for lowest-order multifrequency angular moments: energy and momentum density/frequency*)

Requires a closure prescription:

- MGFLD
- MGVEF/MGVET

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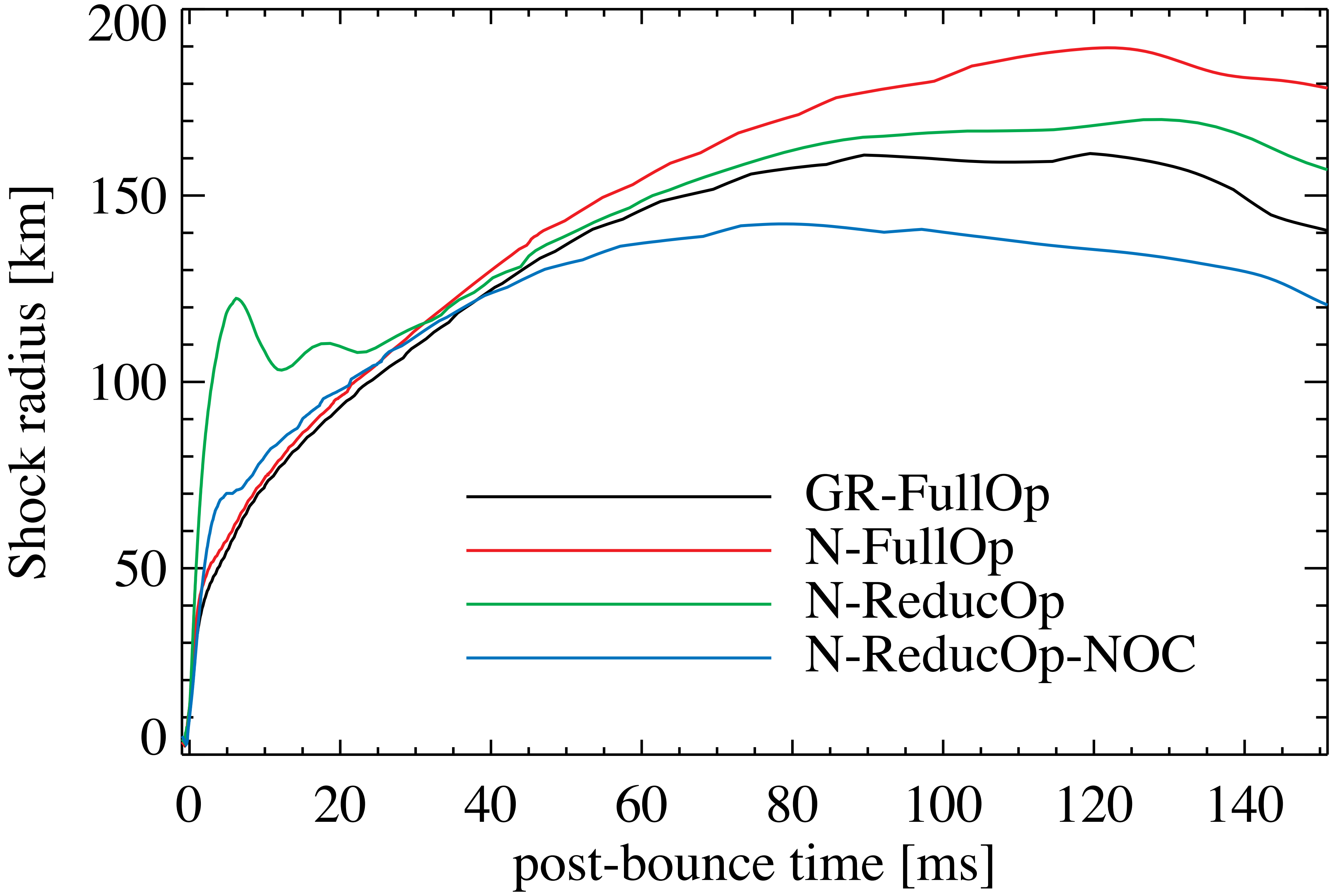
Essential physical realism in neutrino transport

Lentz et al. *Ap.J.* **747**, 73 (2012)



ReducOp = Bruenn (1985) – NES + Bremsstrahlung (no neutrino energy scattering, IPM for nuclei)

See also B. Mueller et al. 2012. Ap.J. ***756****, 84 for a comparison in the context of 2D models, with similar conclusions.*

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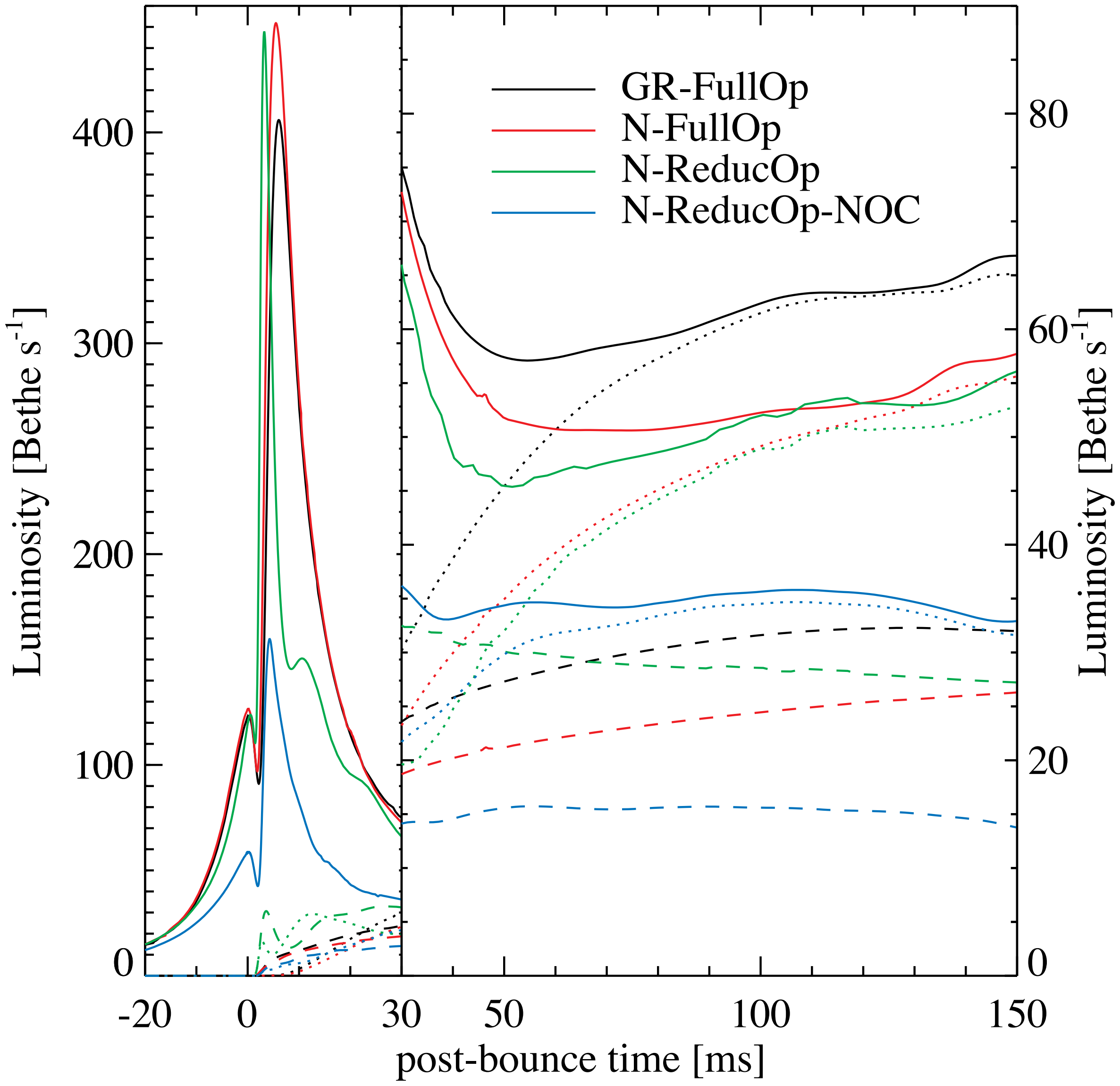
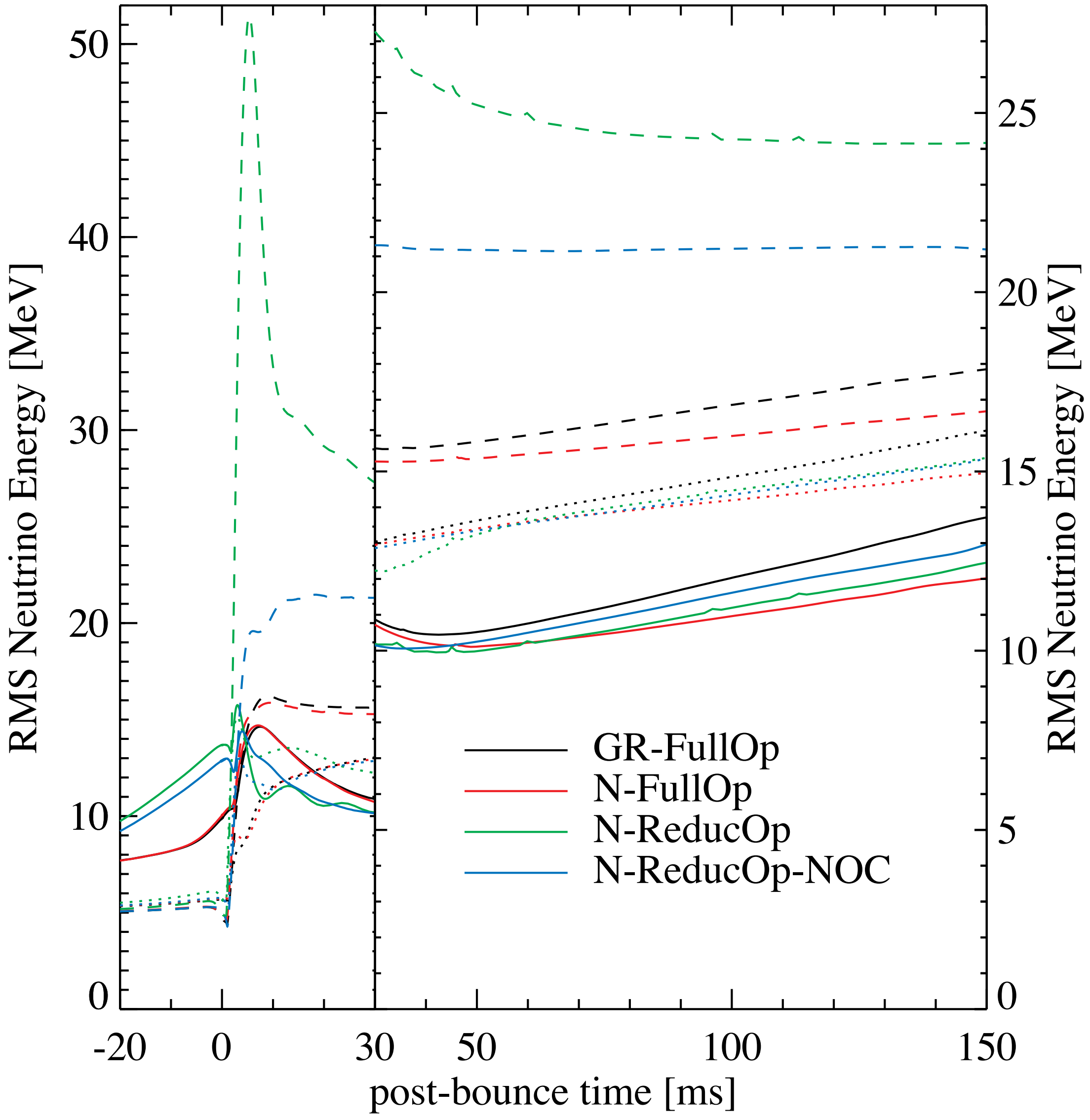
Luminosity



Solid: ν_e
Dotted: $\bar{\nu}_e$
Dashed: $\nu_{\mu\tau}$

RMS Energy



Lentz et al. (2012) ApJ, 760, 94

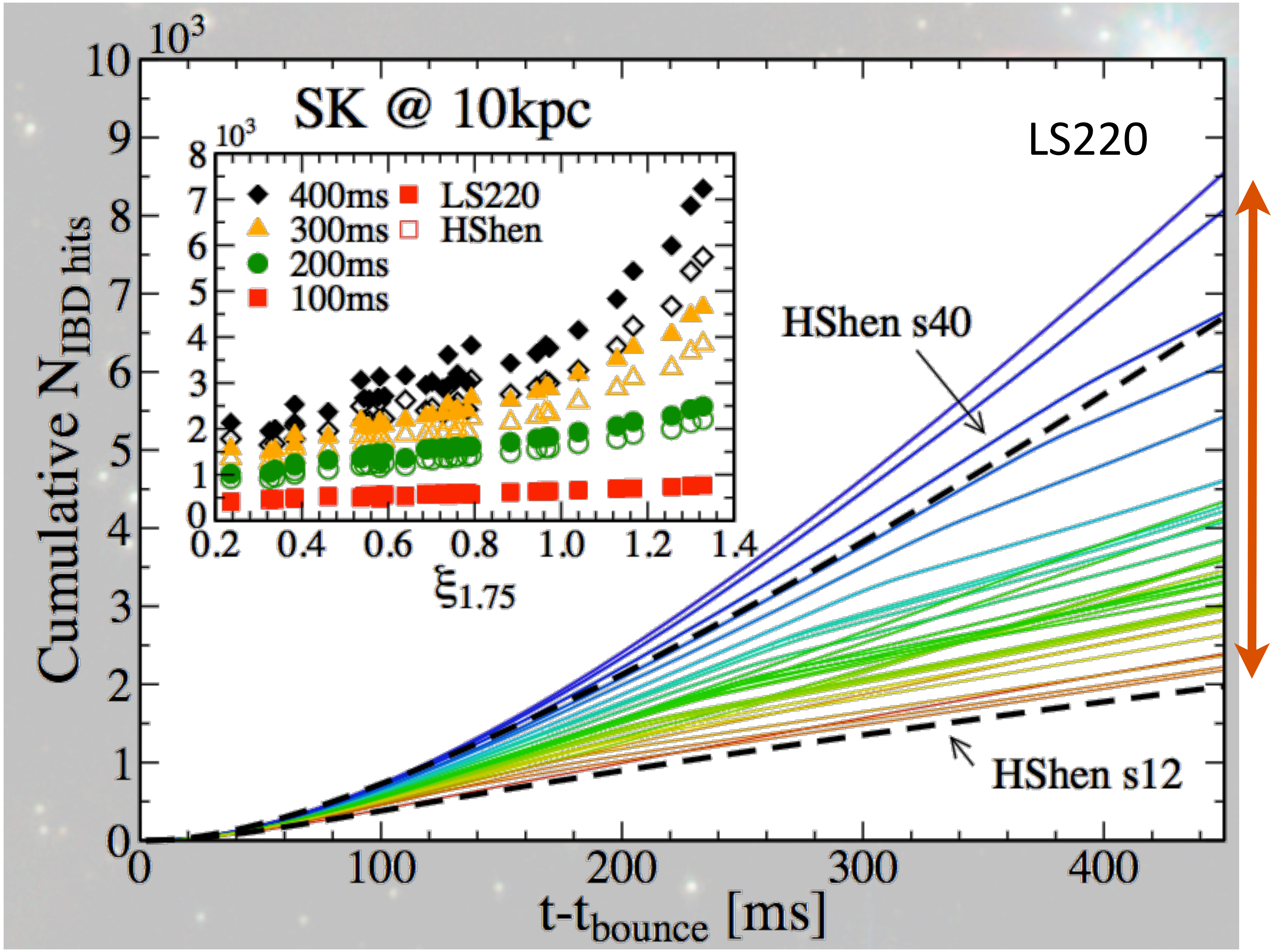
GR: Higher luminosity, harder spectrum

ReducOp opacities: Narrower breakout burst

No Observer Corrections: **Greatly reduced breakout burst and luminosity in accretion phase**

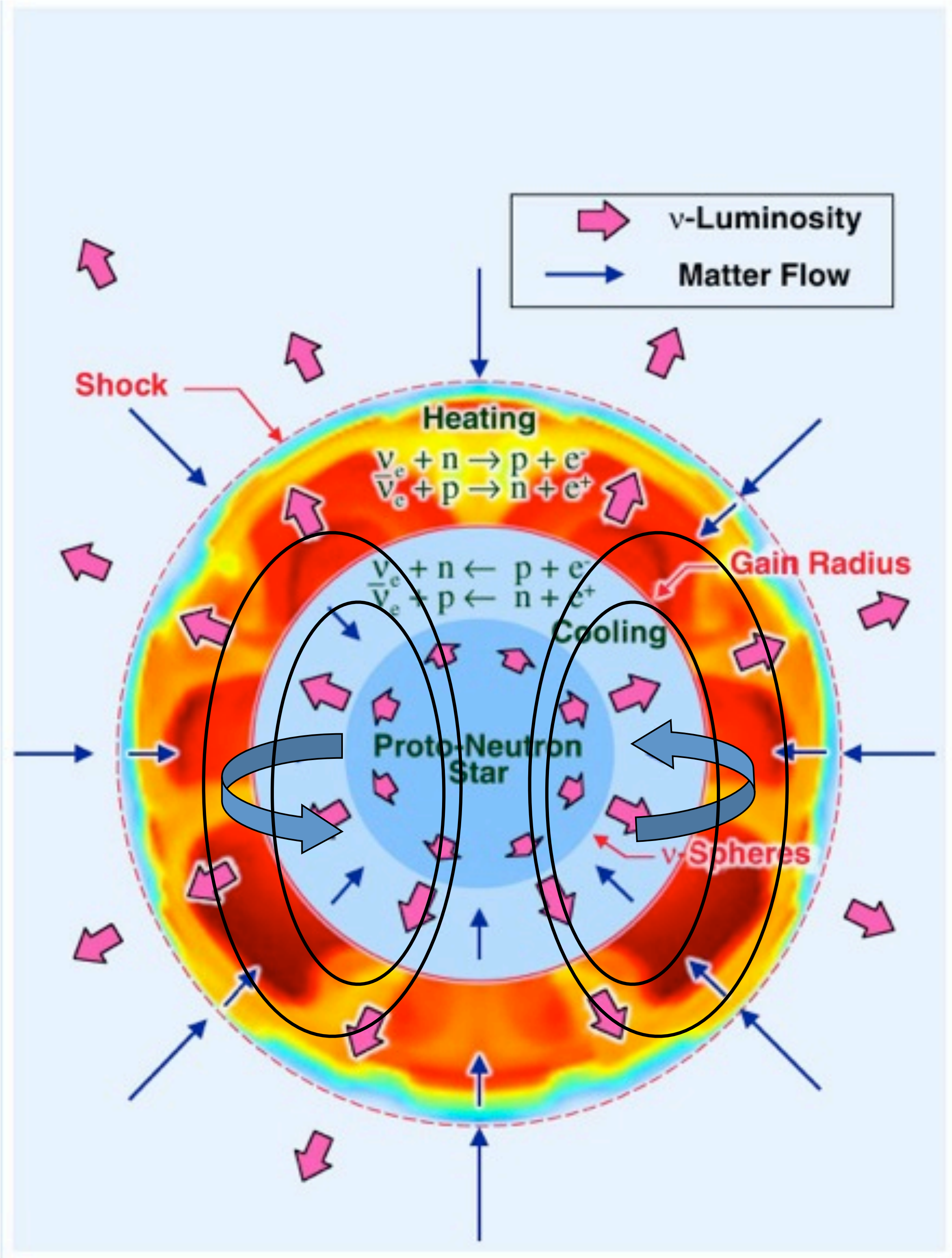
Late-time signal dependent on progenitor structure

- O’Connor & Ott *ApJ* 730, 70 (2011)



- Non-exploding 1D models - ν emission relates inner stellar structure and composition

How is the supernova shock revived?

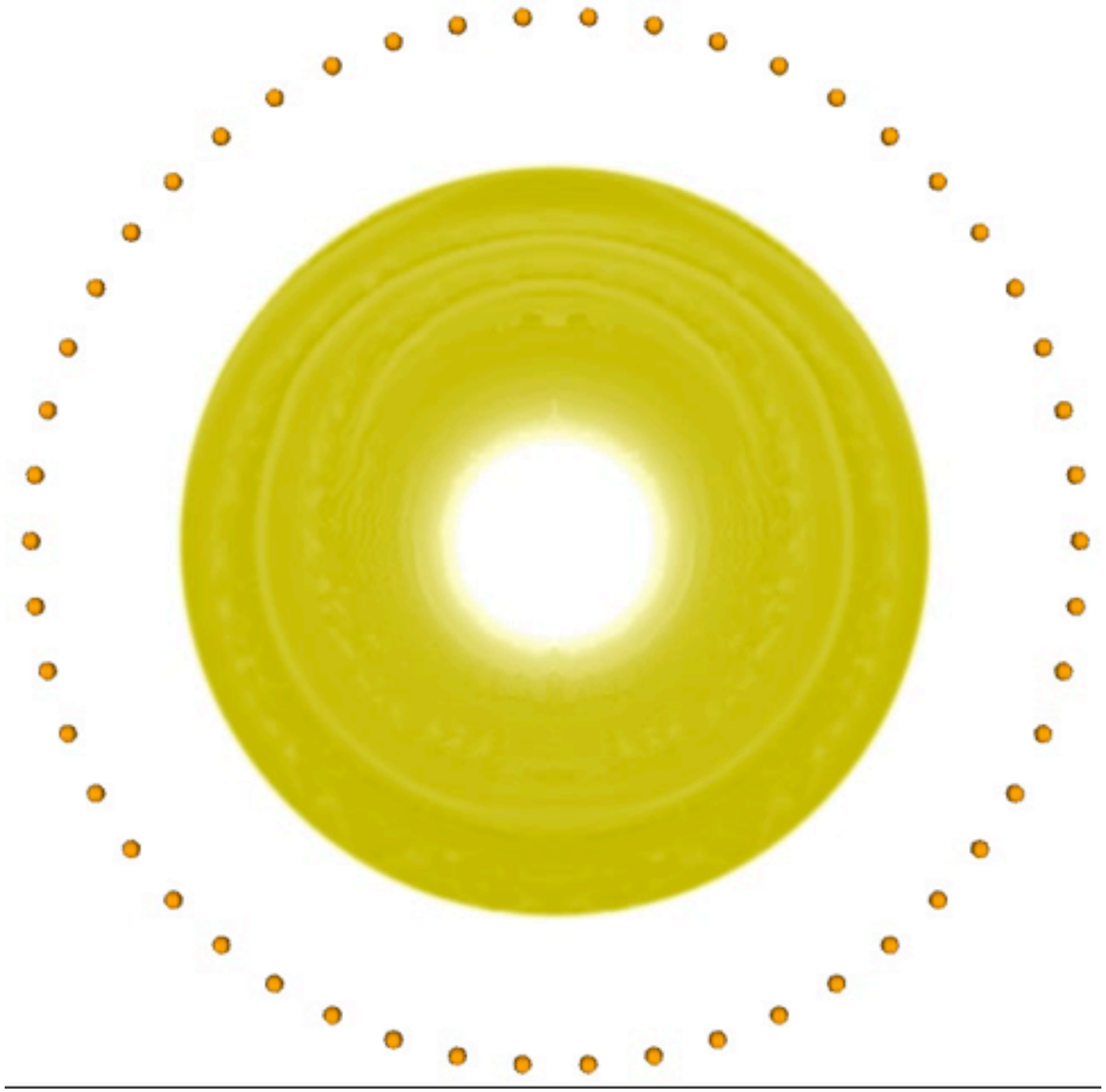


Known, Potentially Important Ingredients

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

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

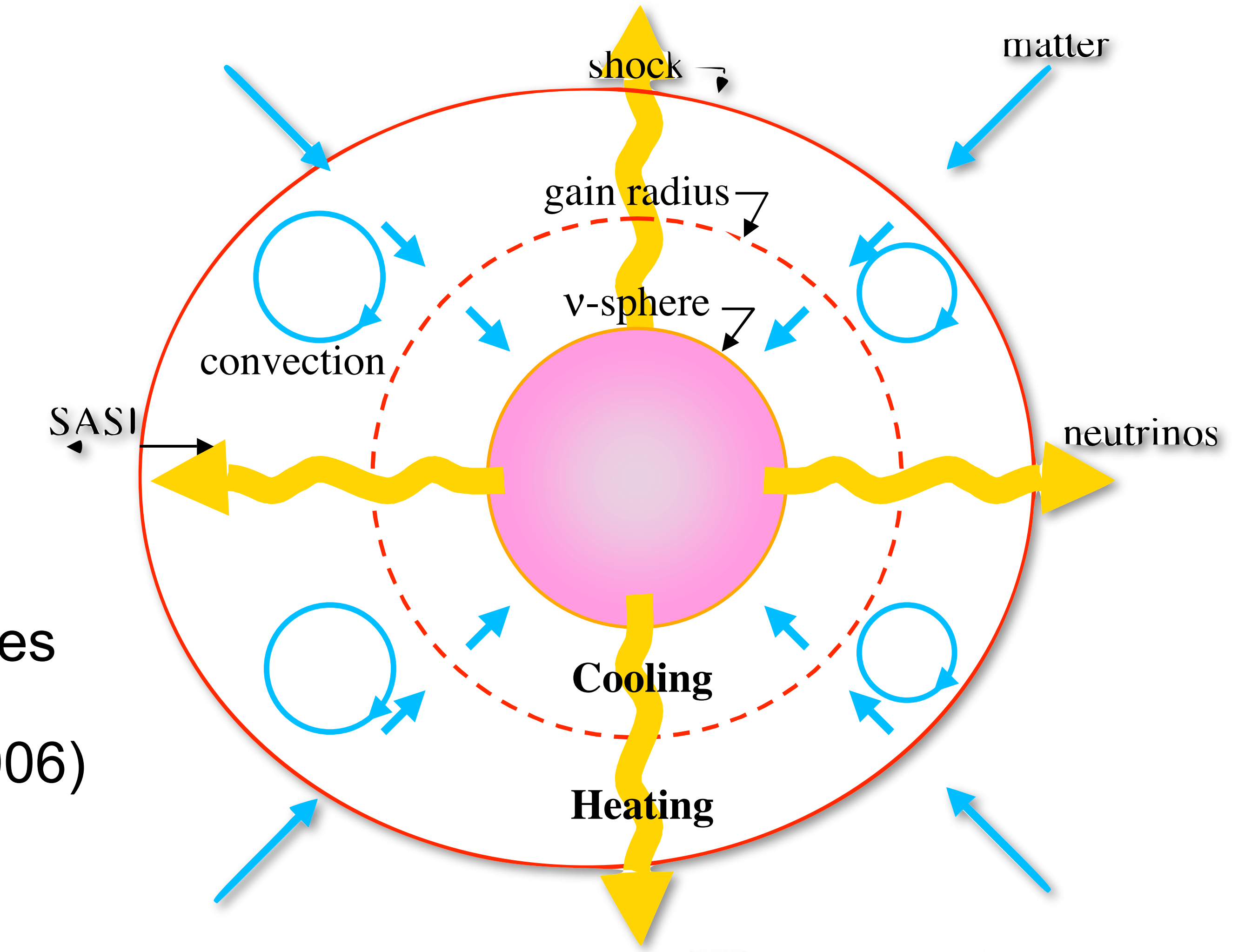
Stationary Accretion Shock Instability



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



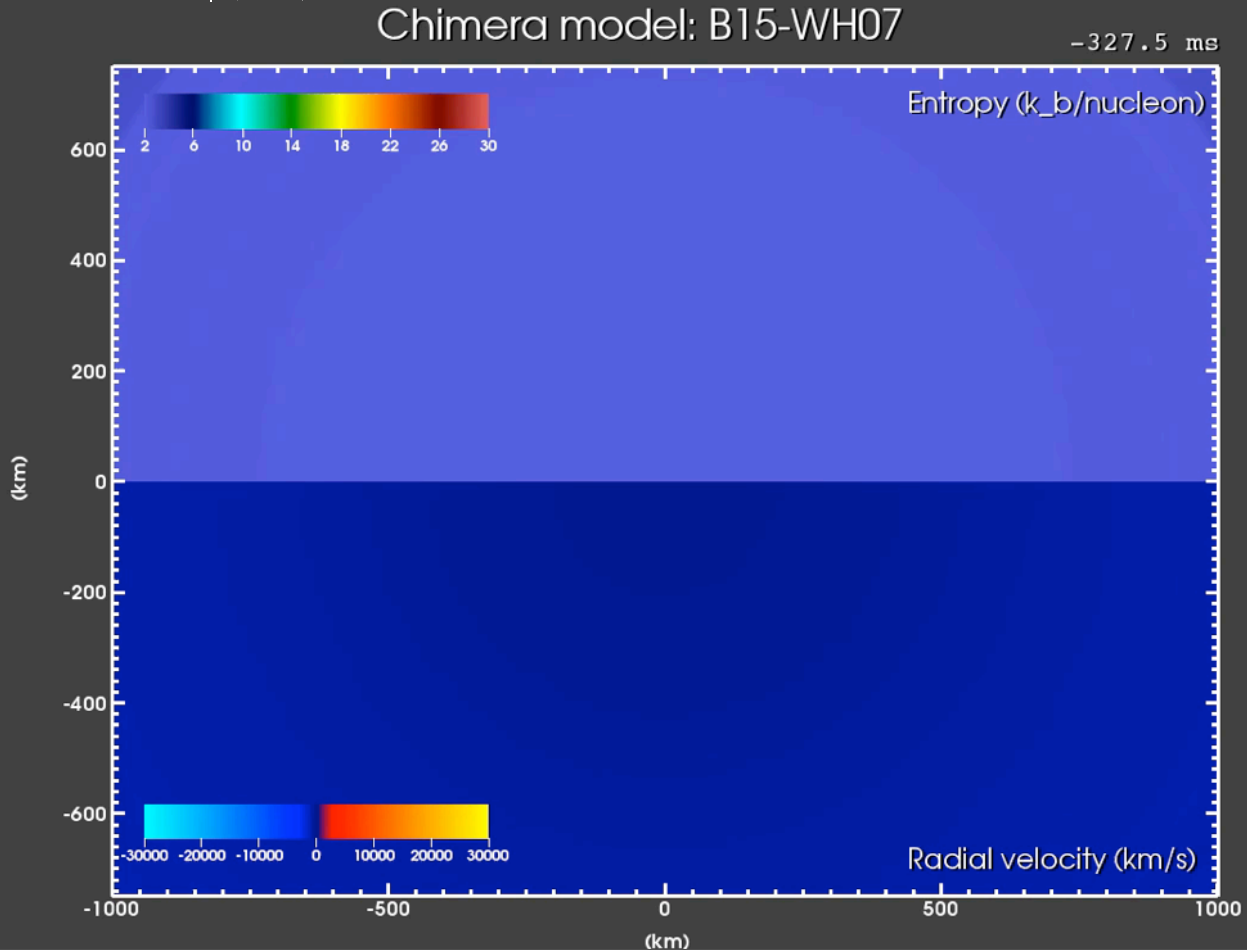
SASI has *axisymmetric and nonaxisymmetric* modes that are both linearly unstable!

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

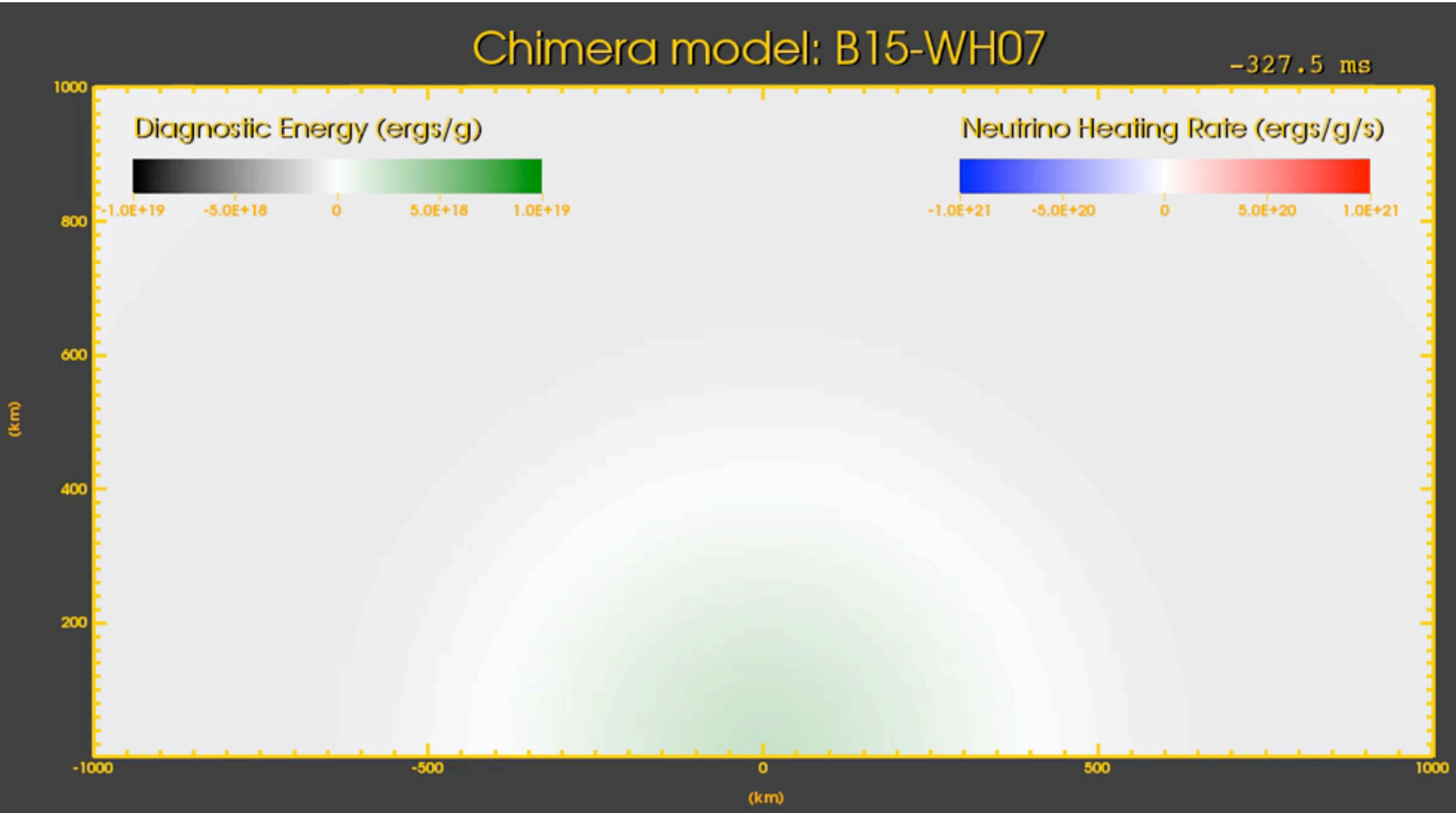
CHIMERA

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

Bruenn et al. 2013. *ApJ*, **767L**, 6B.



Explosion energy & neutrino heating/cooling



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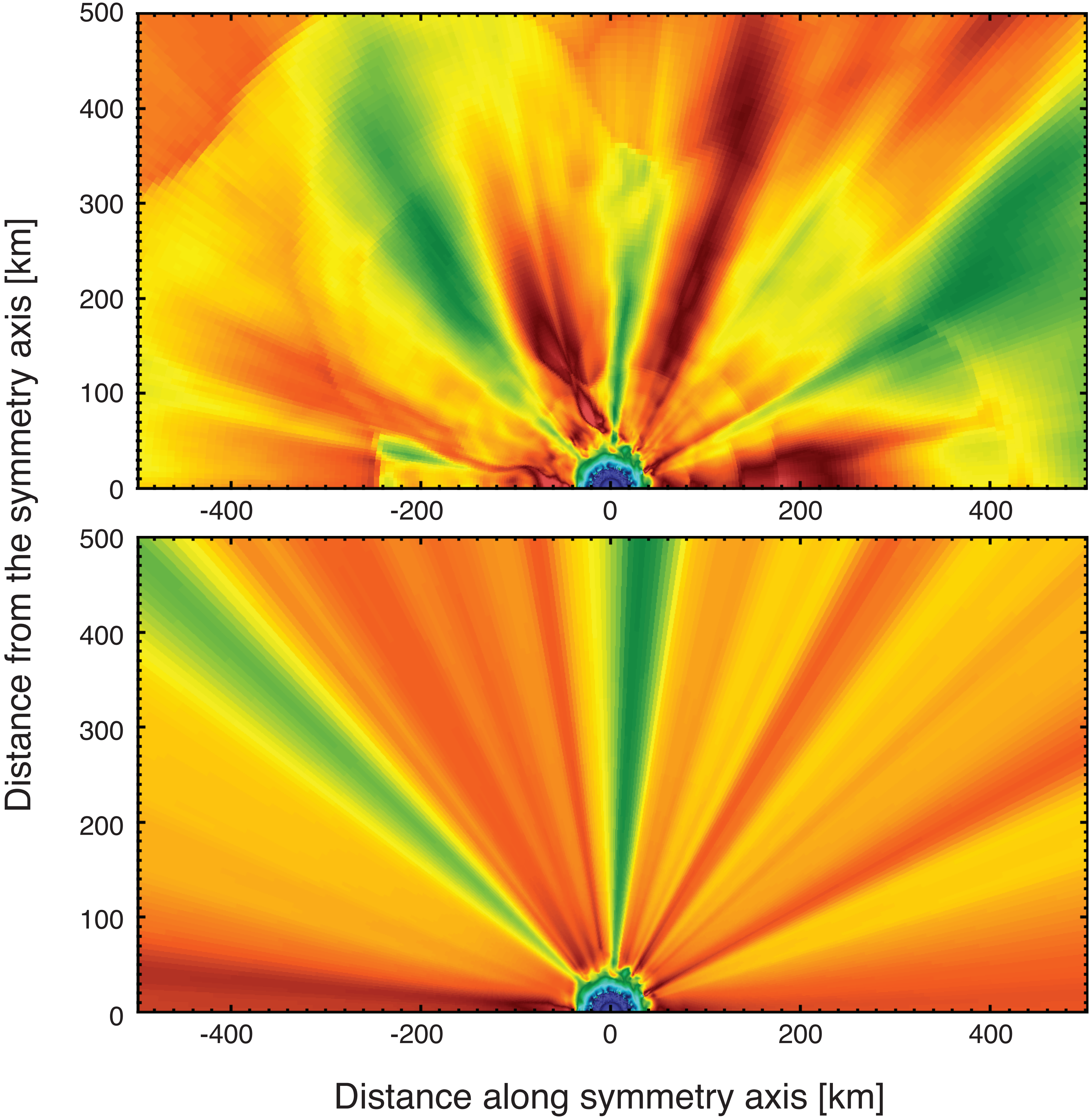
Ray-by-ray - how important are ray effects?



Dynamic snapshot
@ 262 ms pb

$4\pi r^2 F(r,\theta_i)$ for ν_e

Stationary state
solution from
timestep @262ms
post-bounce

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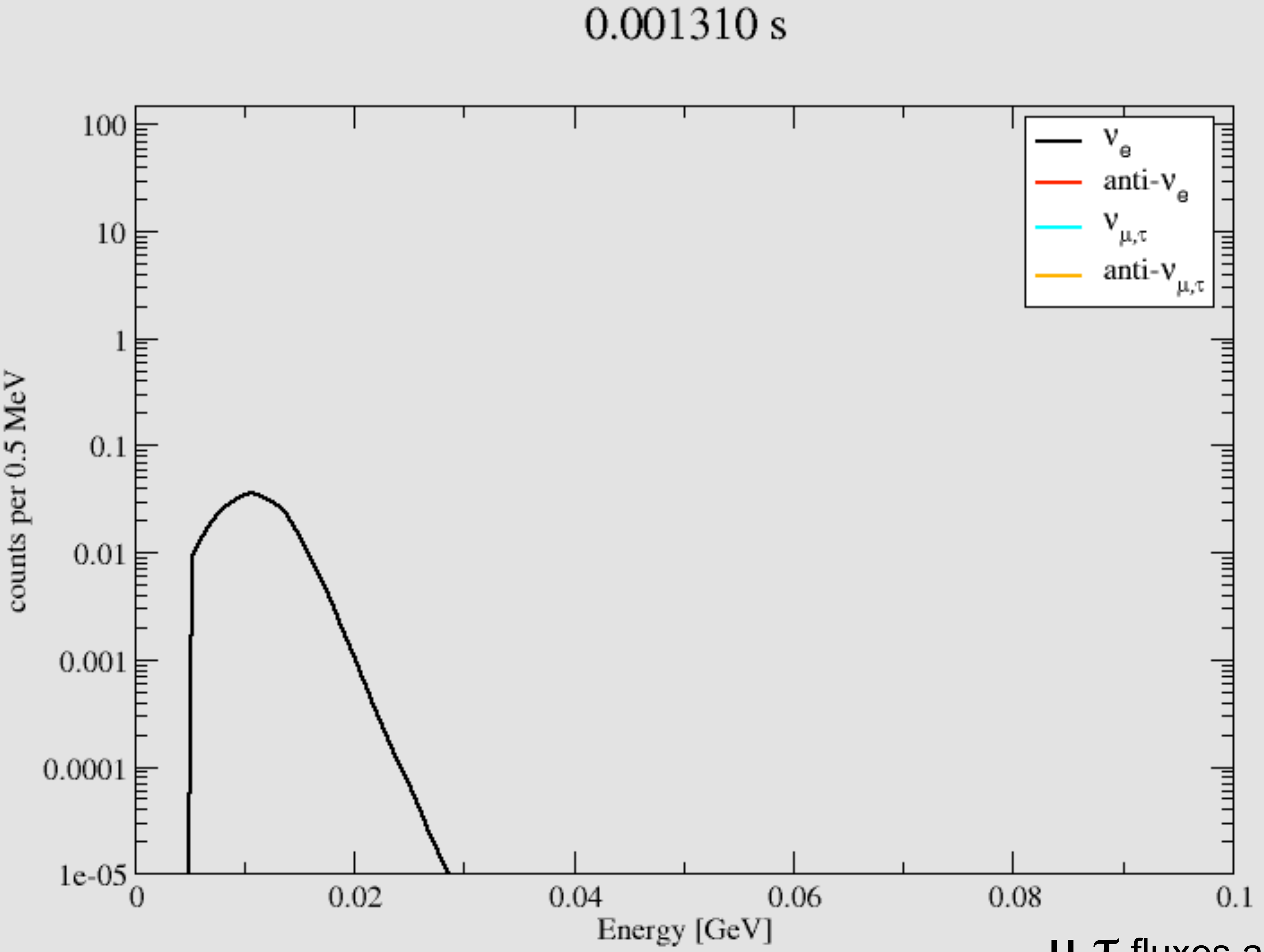
Multi-flavor detection

Messer, Devotie, et al. 2015. In prep.



μ,τ fluxes are 0.5x

C15-2D, angle-averaged, SNOwGLoBES Ar17kt, 10 kpc

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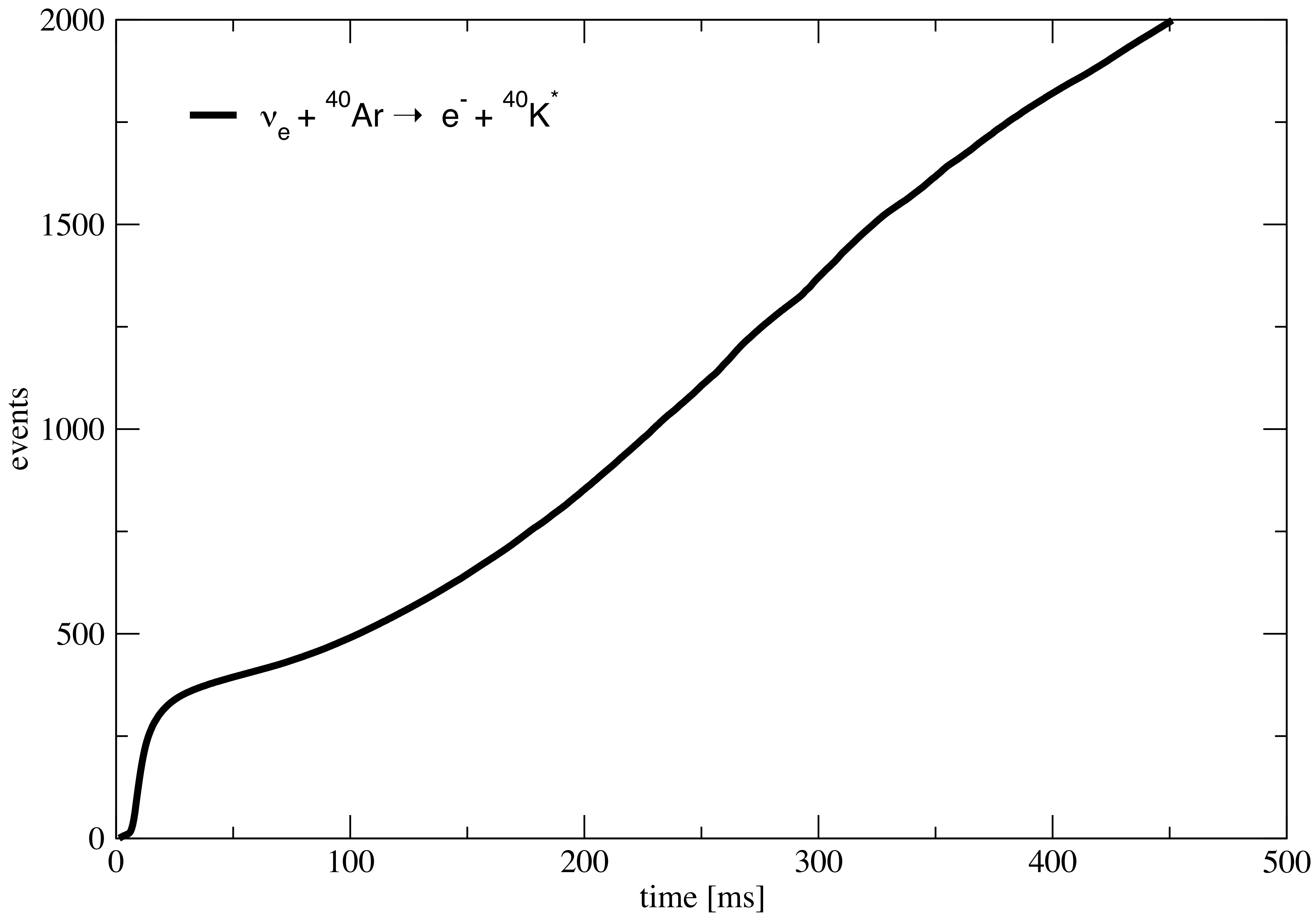
2D - ν_e Total counts vs. time Ar 17kt detector



C15-2D, angle-averaged, SNOwGLoBES Ar17kt, 10 kpc

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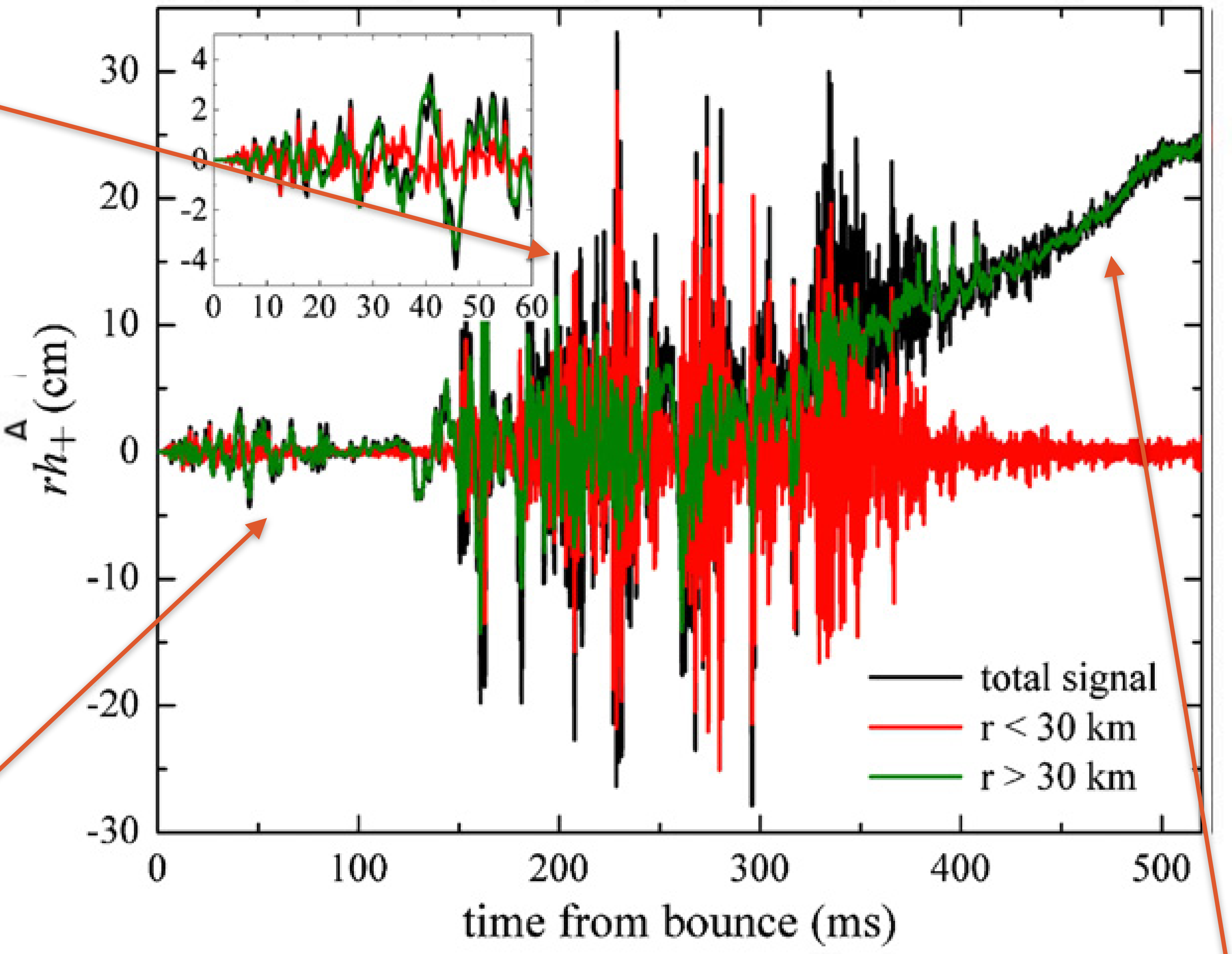
Example of observables: Anatomy of a GW signature

Yakunin, ..., Messer, et al. 2010. *Class. Quantum Grav.* **27,**194005**.**
see also arXiv:1505.05824 (Yakunin et al. 2015)

- Lower-Frequency Envelope: SASI-Induced Shock Excursions

- Higher-Frequency Variations: Impingement of Downflows on PNS from Neutrino-Driven Convection and SASI

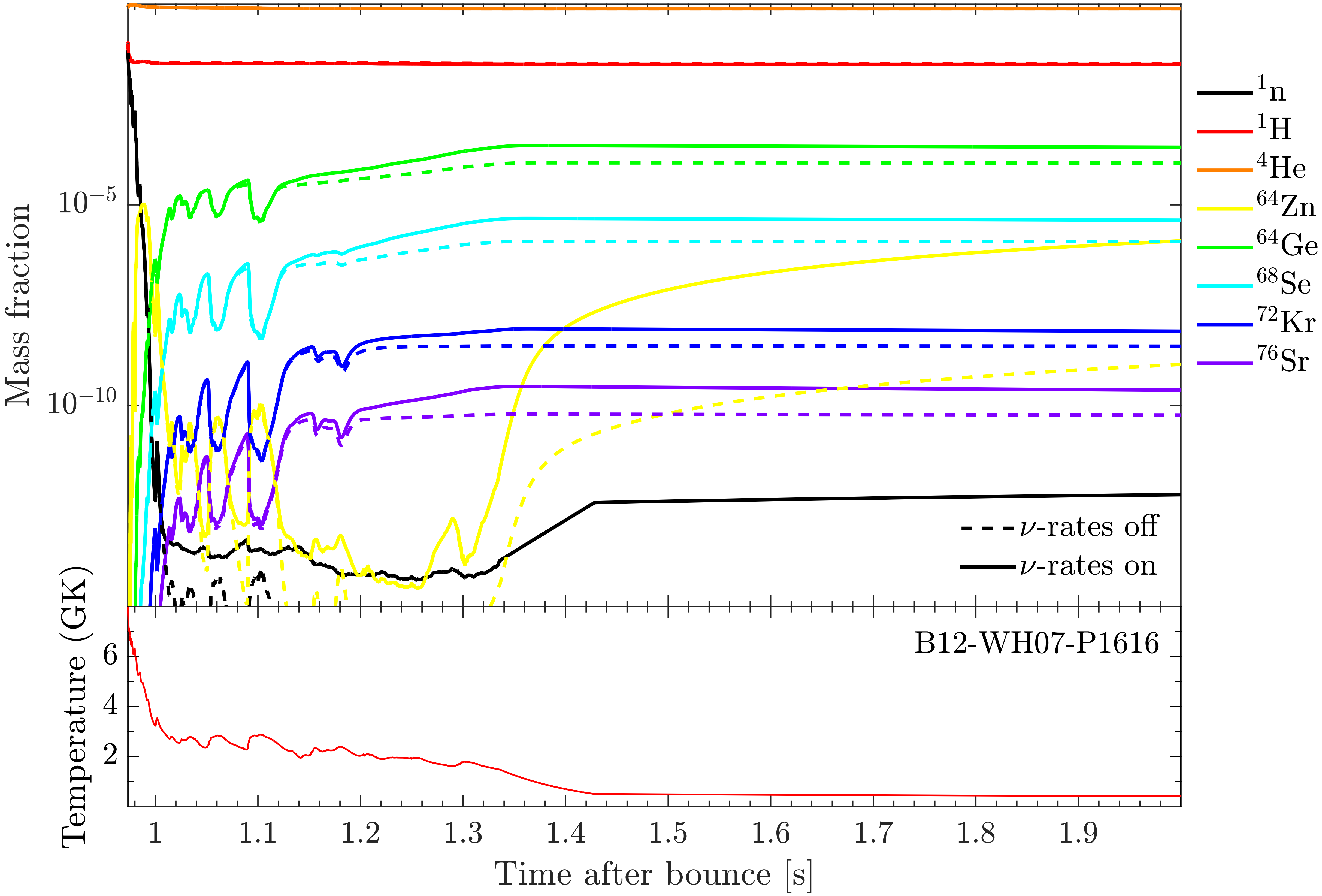
Gravitational Wave Signal (S15 LS EoS 256x256)



Prompt Convection
Early Shock Deceleration

Later Rise: Prolate Explosion/Deceleration at Shock

Consistent ν transport affects nucleosynthesis

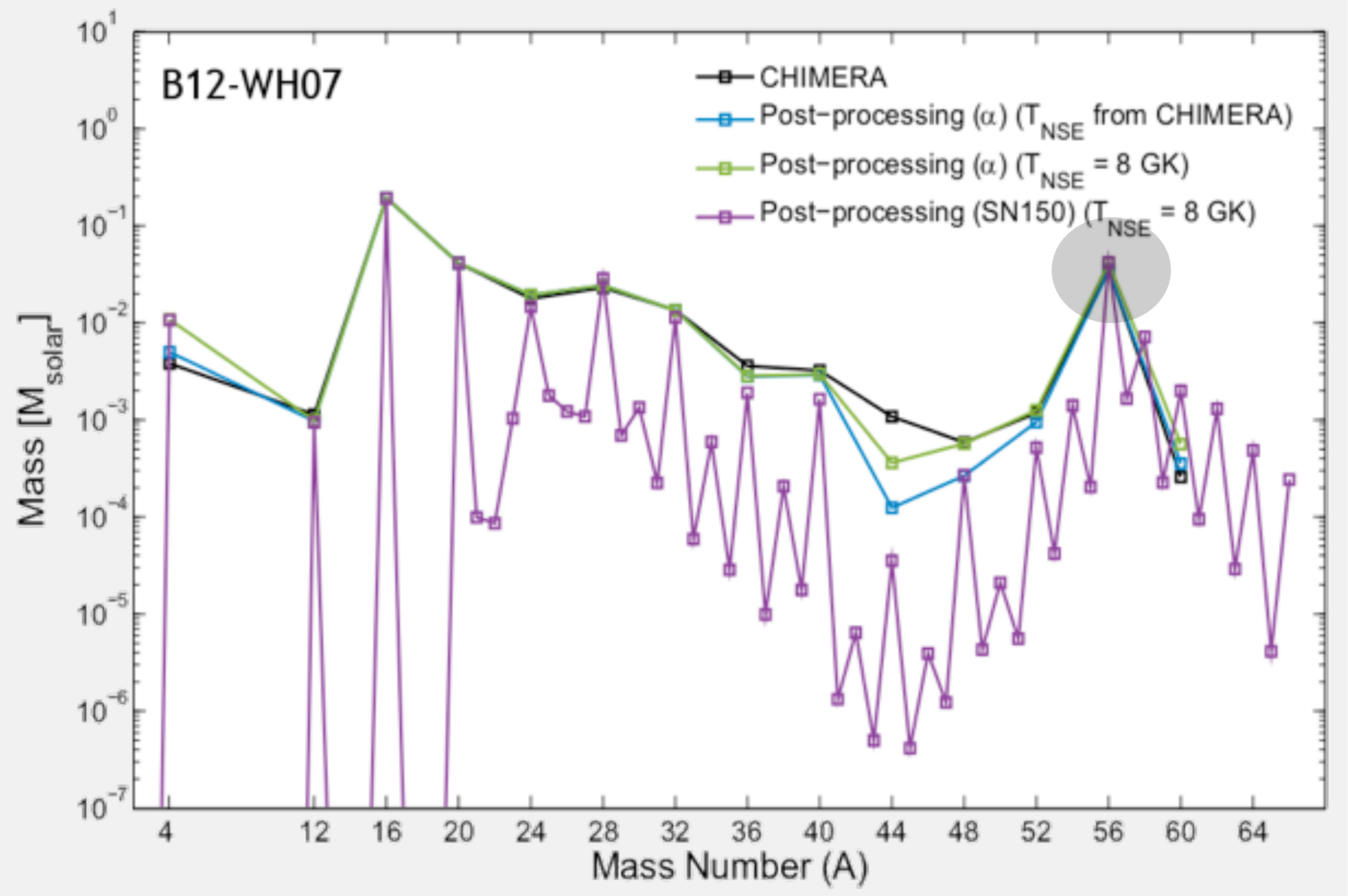


Harris et al. 2015. In prep.

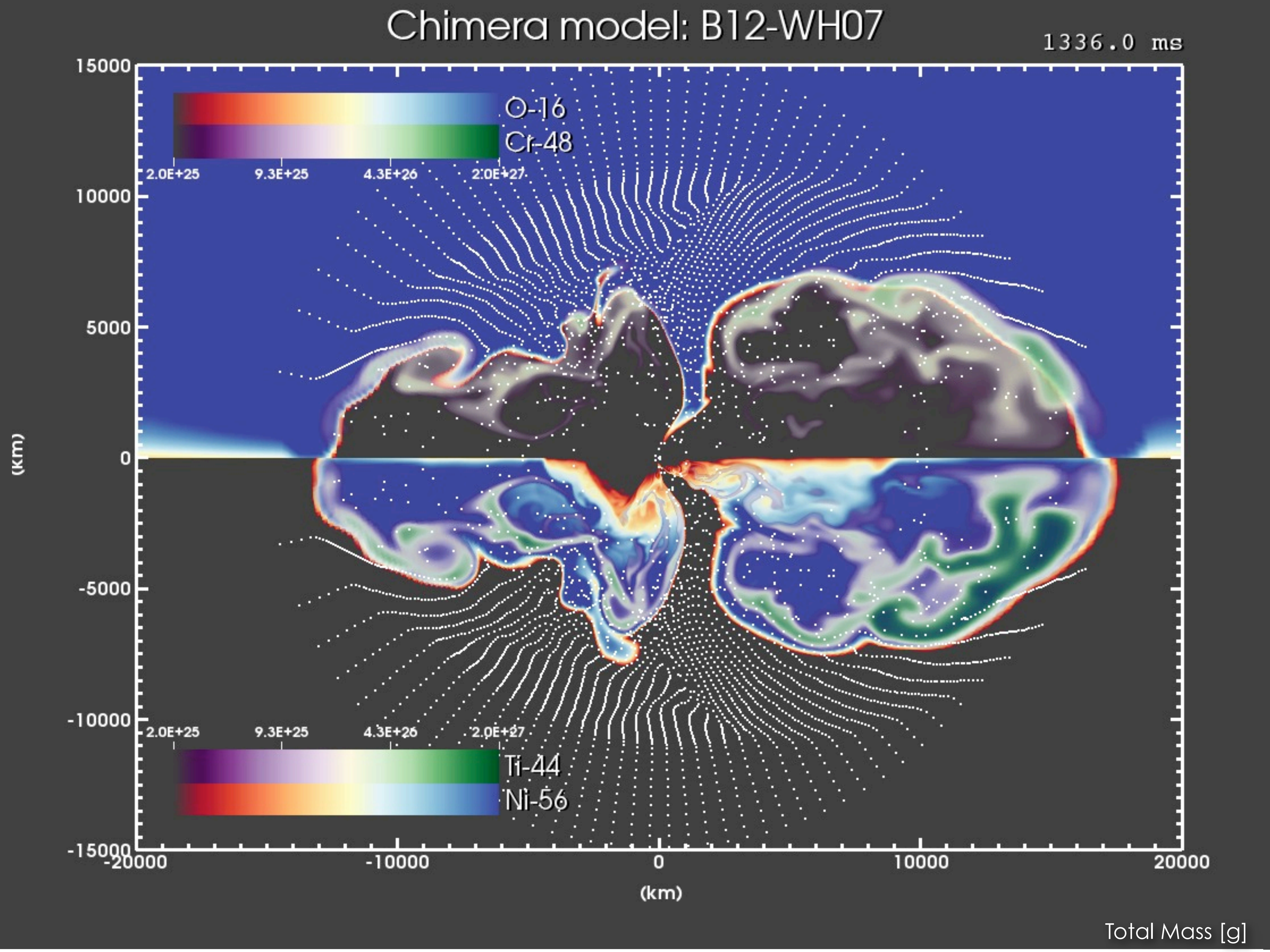
Nucleosynthesis in ejecta

Harris, et al., in prep

- Does post-processing tracer particles produce the same answer as *in situ* network calculation? (“The Commutator Problem”) (black vs. blue)
    - No extrapolation
    - α-network
    - Same NSE criteria
- Higher NSE transition temperature (blue vs. green)
- More realistic network (green vs. purple)



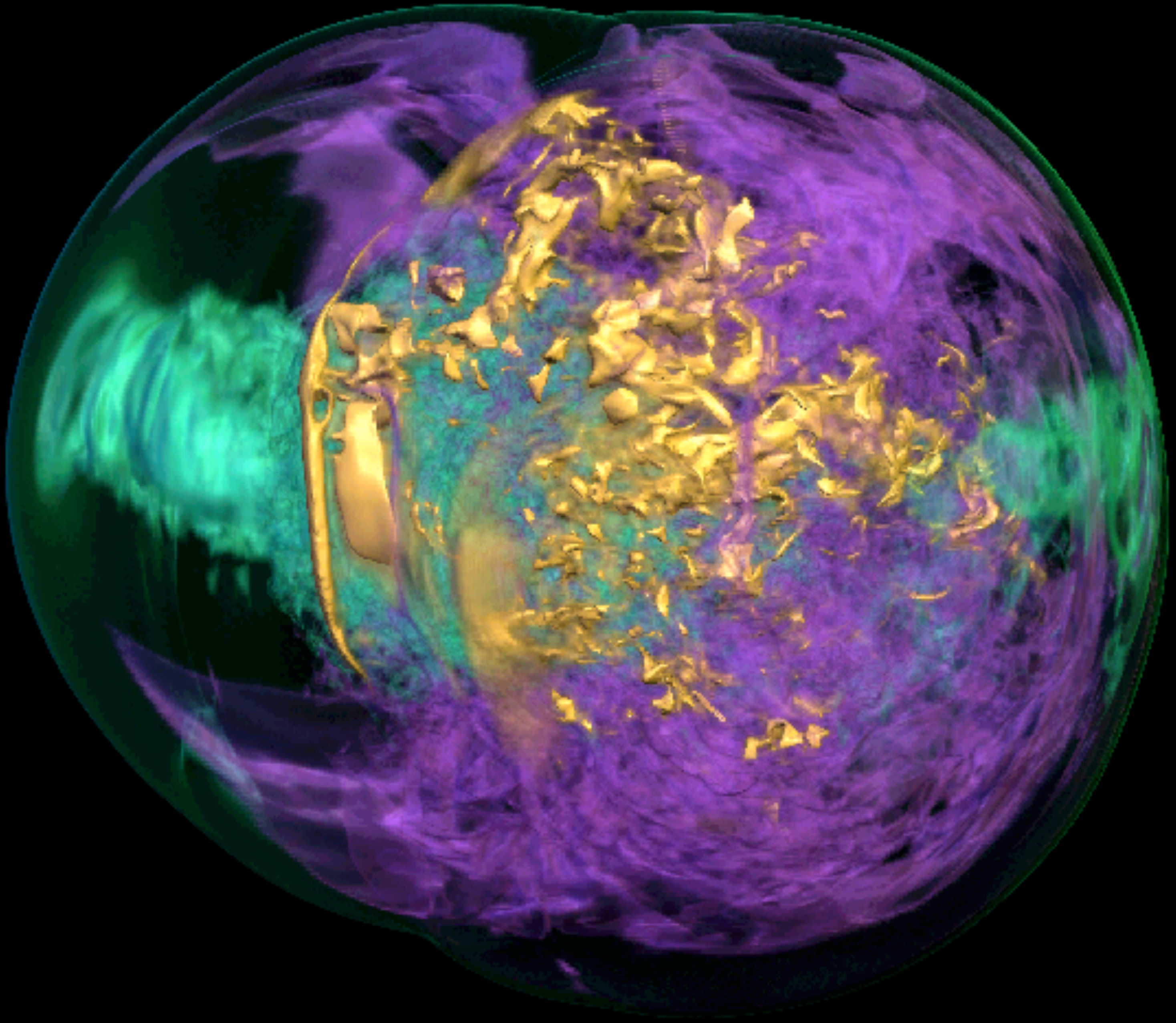
- Nickel mass relatively unaffected by particle resolution, but is affected by T_{NSE} (~20%) (0.03472 $M_\odot$, 0.03439 $M_\odot$, 0.04142 $M_\odot$, 0.4189 $M_\odot$)



- Rapid expansion creates ^{44}Ti-rich “clumps” via α-rich freezeout
- Tracer particles under-sample these low-density regions
- Effect is also noticeable in ^{48}Cr, but not as severe, as the “clumpiness” is a bit less localized

Harris, et al., in prep

SASI in 3D



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

15 solar mass 3D run

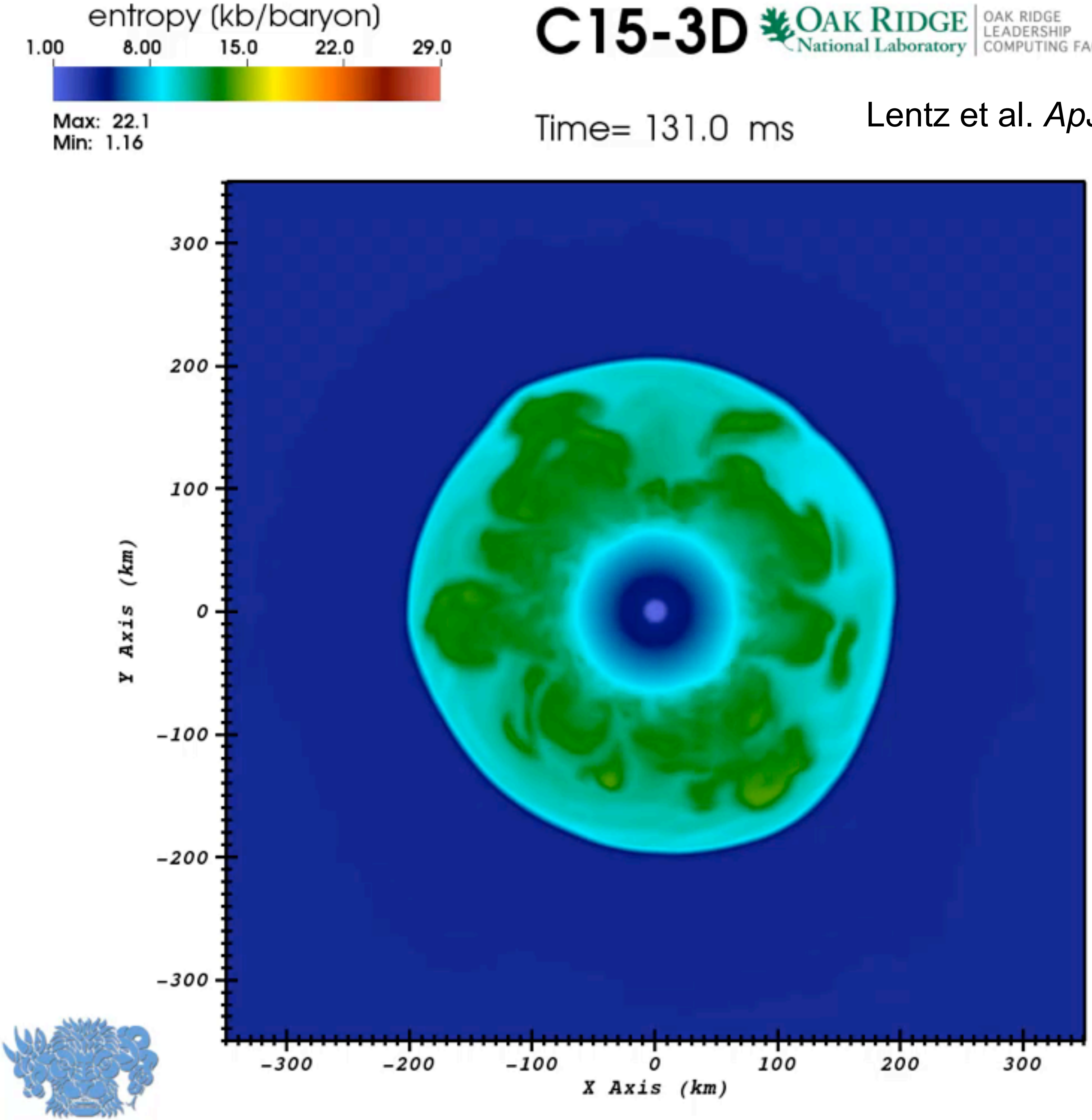
~6 months on ~48,000 cores

- 15 solar mass WH07 progenitor
- 540 radial zones covering inner 11000 km
- 180 phi zones (2 degree resolution)
- 180 theta zones in "constant mu" grid, from 2/3 degree at equator to one 8.5 degree zone at pole.
- “Full” opacities
- 0.1% density perturbations (10-30 km) applied at 1.3 ms after bounce in transition from 1D.

Lentz et al. *ApJL* **807**, L31 (2015)

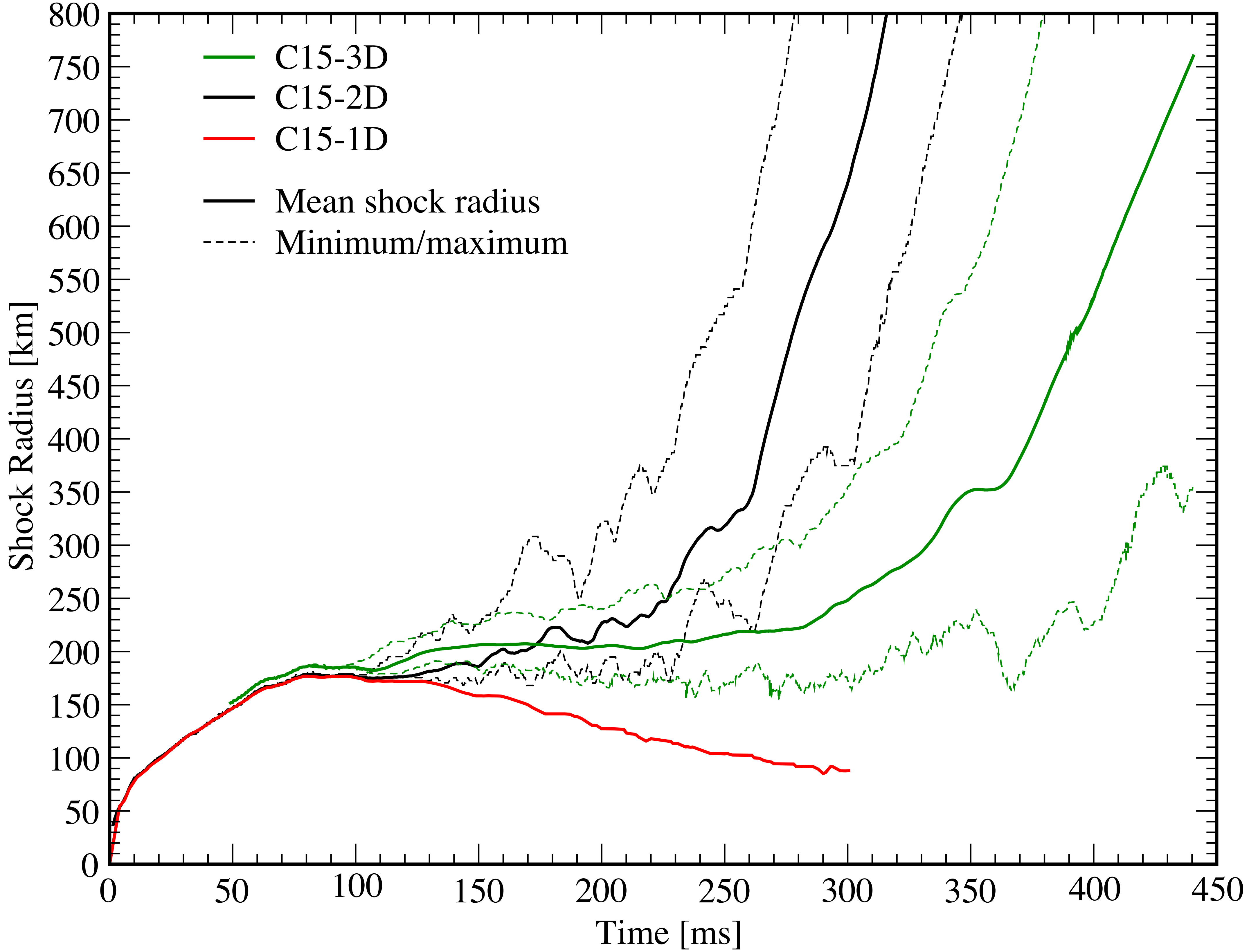
C15-3D

Lentz et al. *ApJL* **807**, L31 (2015)



1D vs. 2D vs. 3D

Lentz et al. *ApJL* **807**, L31 (2015)



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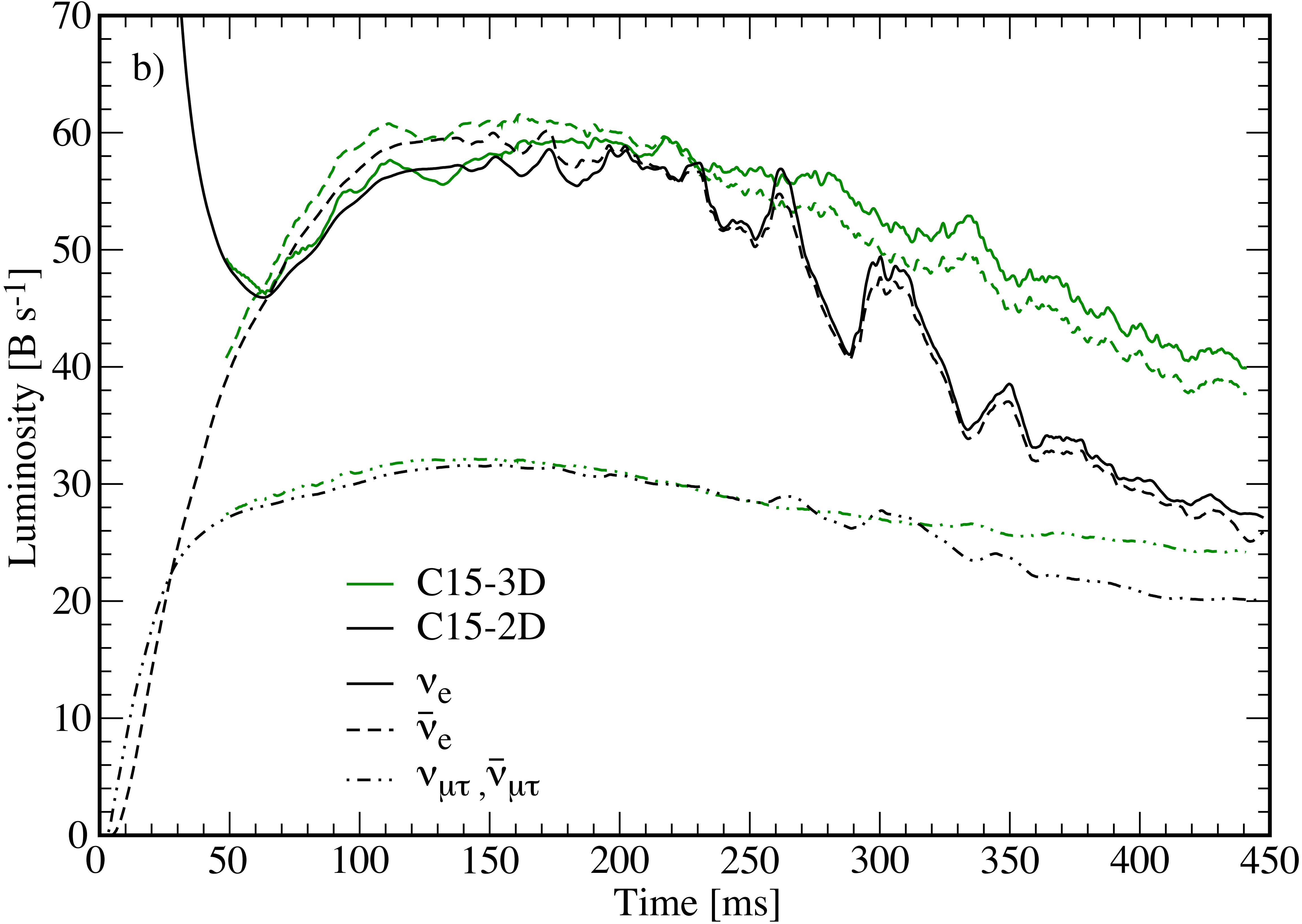
3D vs 2D luminosities

Lentz et al. *ApJL* **807**, L31 (2015)



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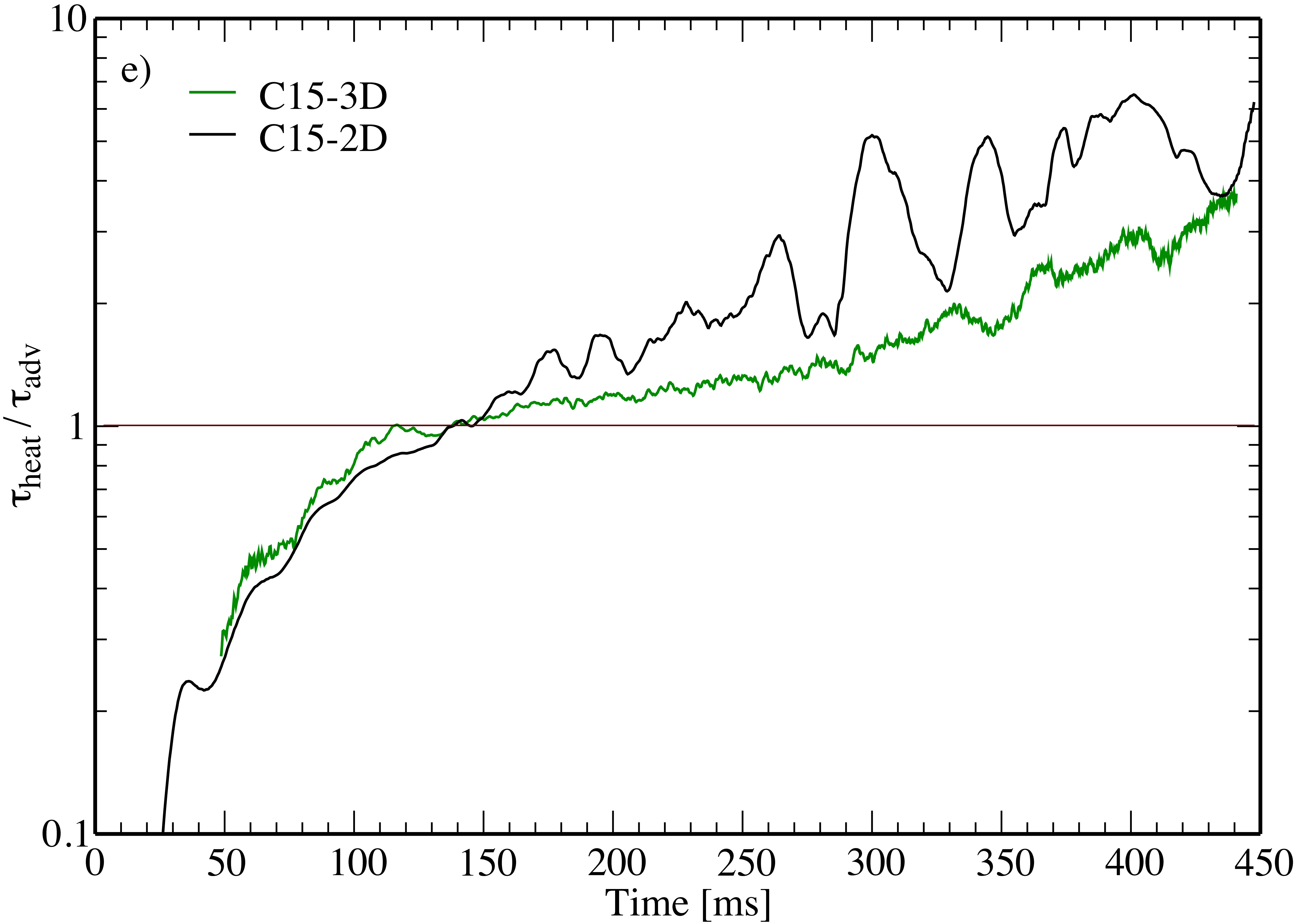
Heating/advection time scales



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Summary

- There is evidence that sufficiently realistic, multidimensional CC SNe simulations can produce explosions that match observations in several multi-messenger channels.
- Necessary realism for CCSNe simulation: Multifrequency neutrino transport with relativistic effects, a state-of-the-art weak interaction set, and general relativity
- Self-consistent CHIMERA simulations point to a successful neutrino-reheating mechanism, with the explosion delayed by 300 ms or more after bounce and with outcomes consistent with observations, in 2D.
- A three-dimensional simulation for a 15 $M_\odot$ progenitor also produces a neutrino-driven explosion, but delayed relative to 2D.