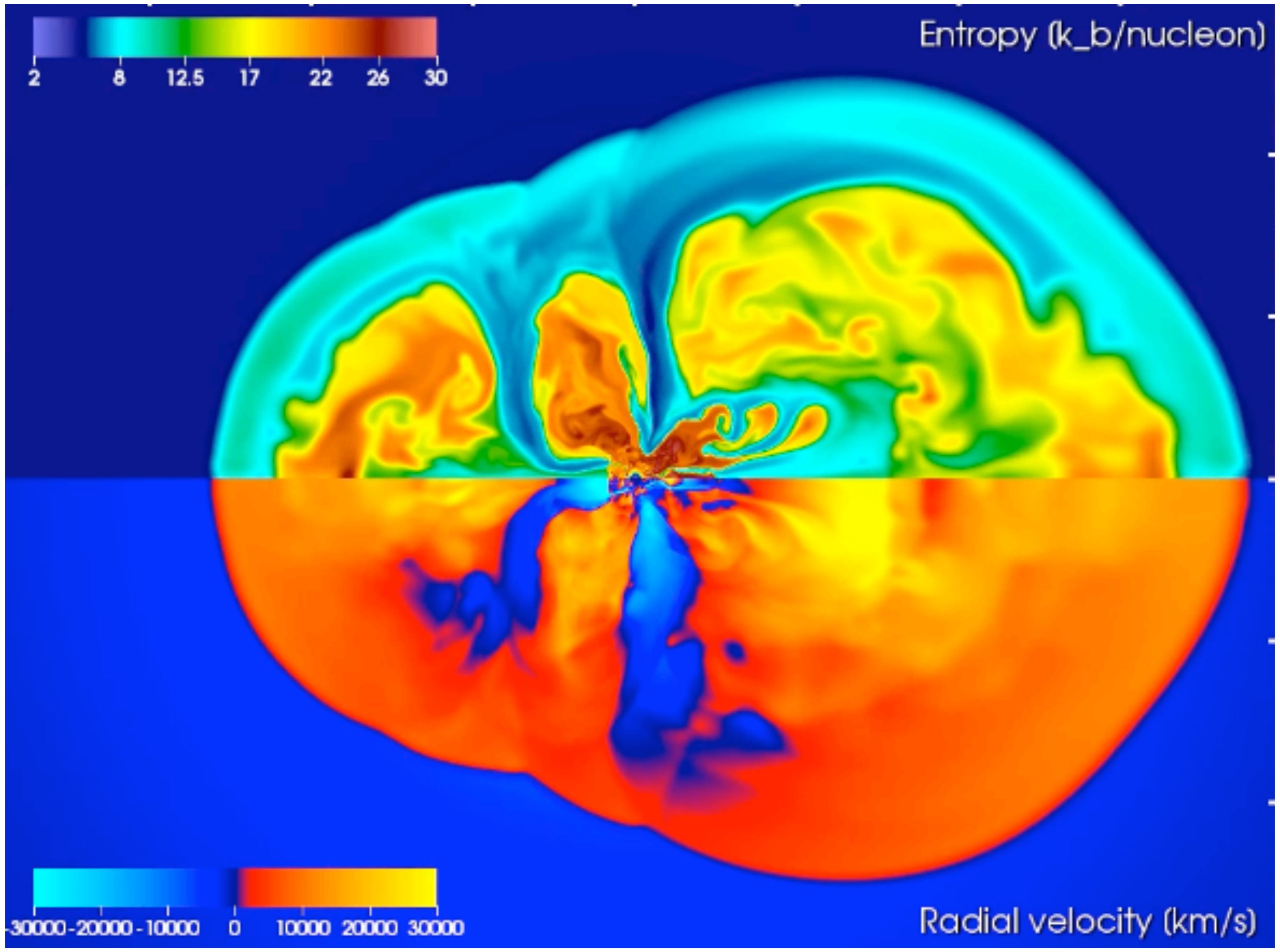
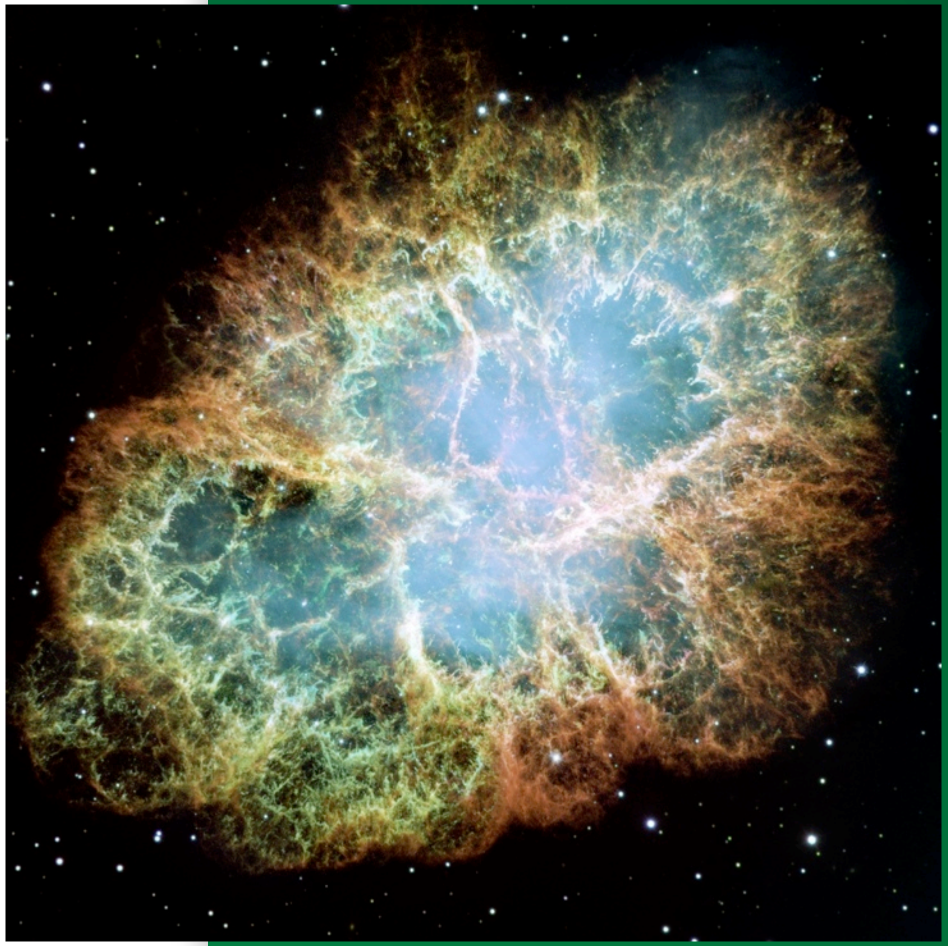
Neutrino Transport In Core-Collapse Supernova Simulations and Connections to Observations





Bronson Messer

Scientific Computing &
Theoretical Physics Groups
Oak Ridge National Laboratory

Department of Physics &
Astronomy
University of Tennessee

ORNL is managed by UT-Battelle
for the US Department of Energy

INT Program INT-15-2a:
Neutrino Astrophysics and Fundamental Properties
Workshop: June 15-19

CHIMERA collaboration

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

OAK RIDGE National Laboratory

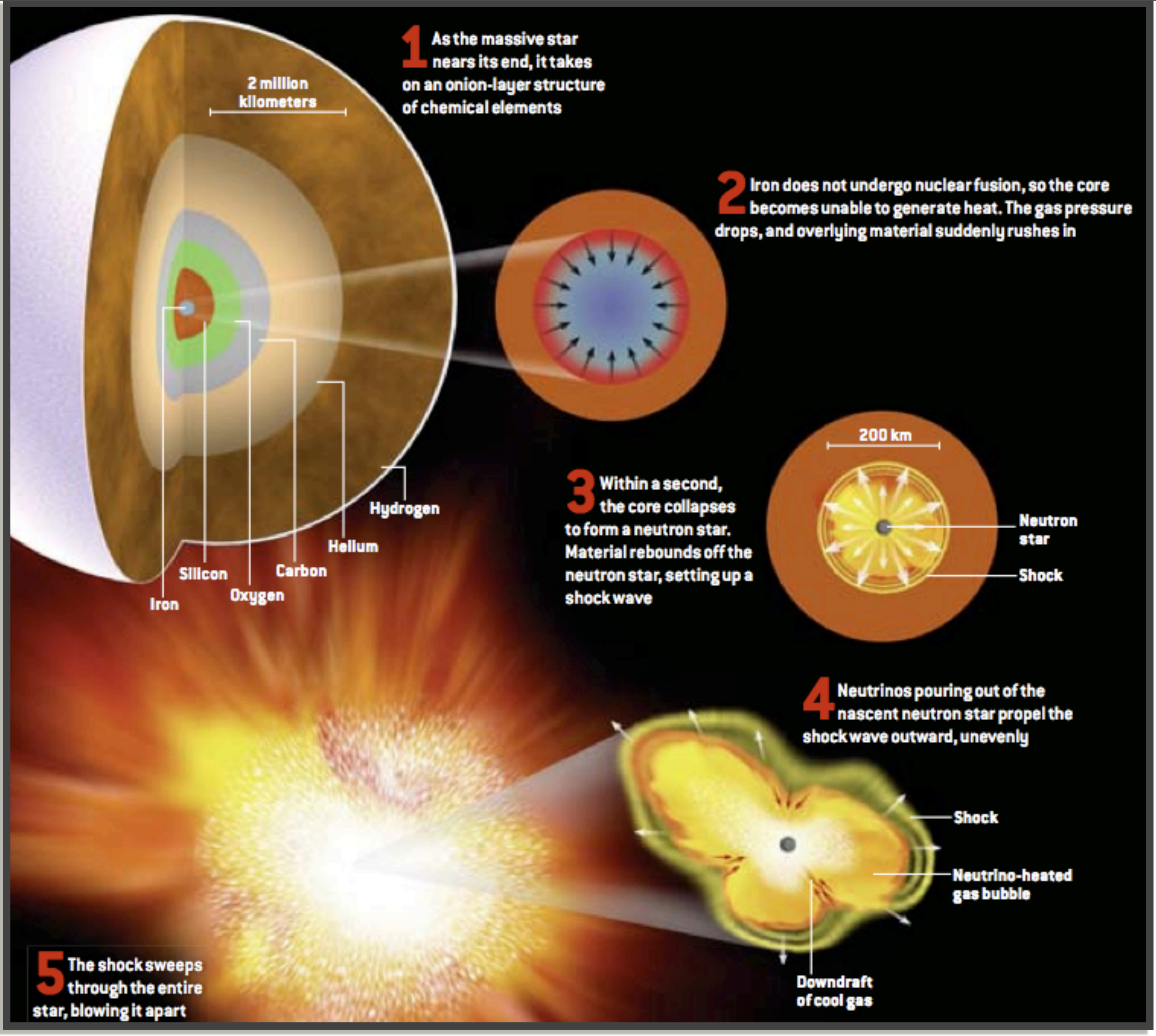
U.S. DEPARTMENT OF ENERGY | Office of Science

NSF NATIONAL SCIENCE FOUNDATION

NASA

The research and activities described in this presentation were performed using the resources of the Oak Ridge Leadership Computing Facility at Oak Ridge National Laboratory, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC0500OR22725.

OAK RIDGE National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY



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

Hillebrandt & Janka 2006 (Sci Am)

Neutrino trapping

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

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

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

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

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

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

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

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

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.

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

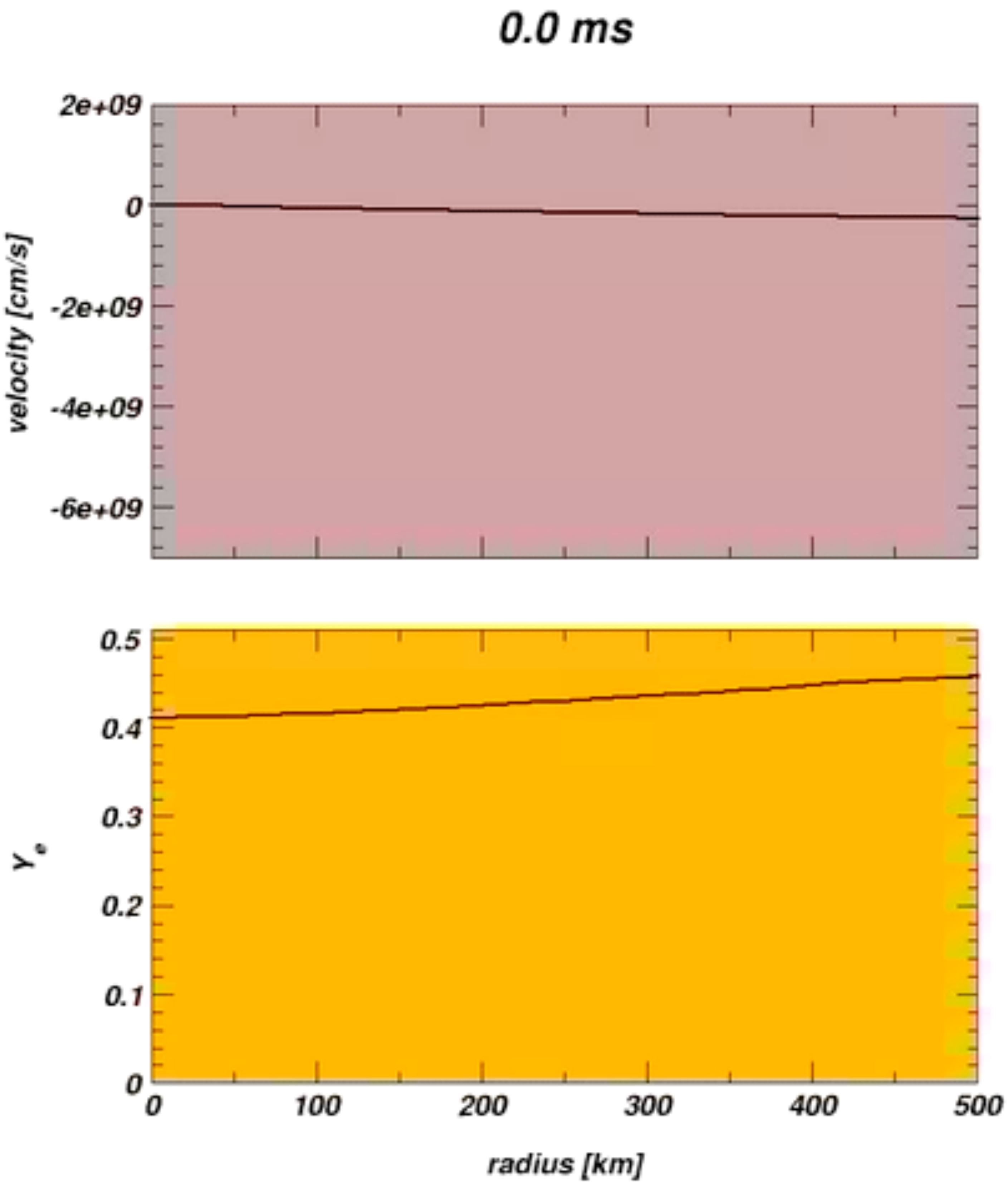
✶ $$N + N \leftrightarrow N + N + \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$$

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

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

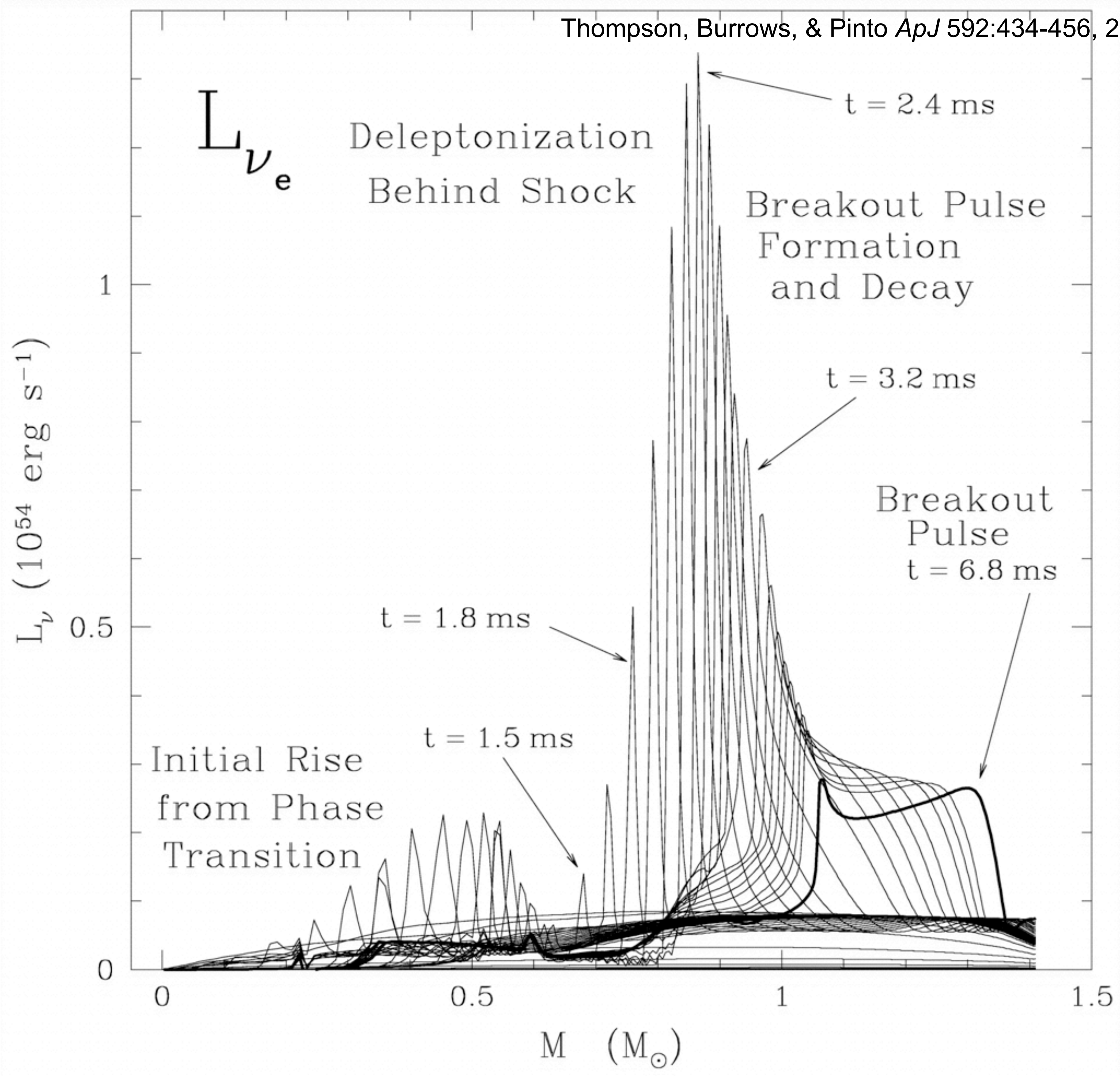
Janka et al. PRL, **76**, 2621 (1996)
Buras et al. *Ap.J.*, **587**, 320 (2003)

Spherically symmetric collapse

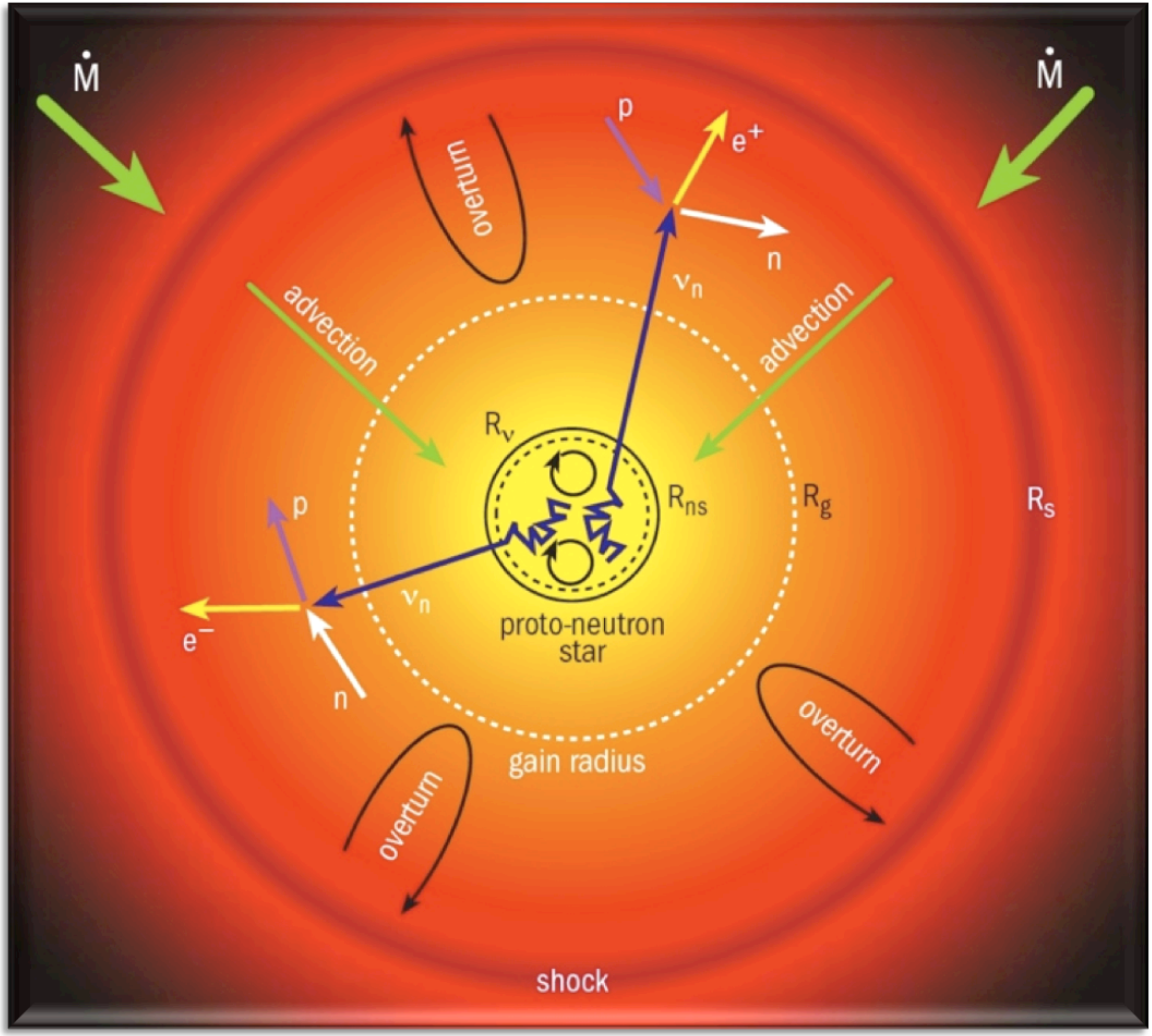


Messer(2000)

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

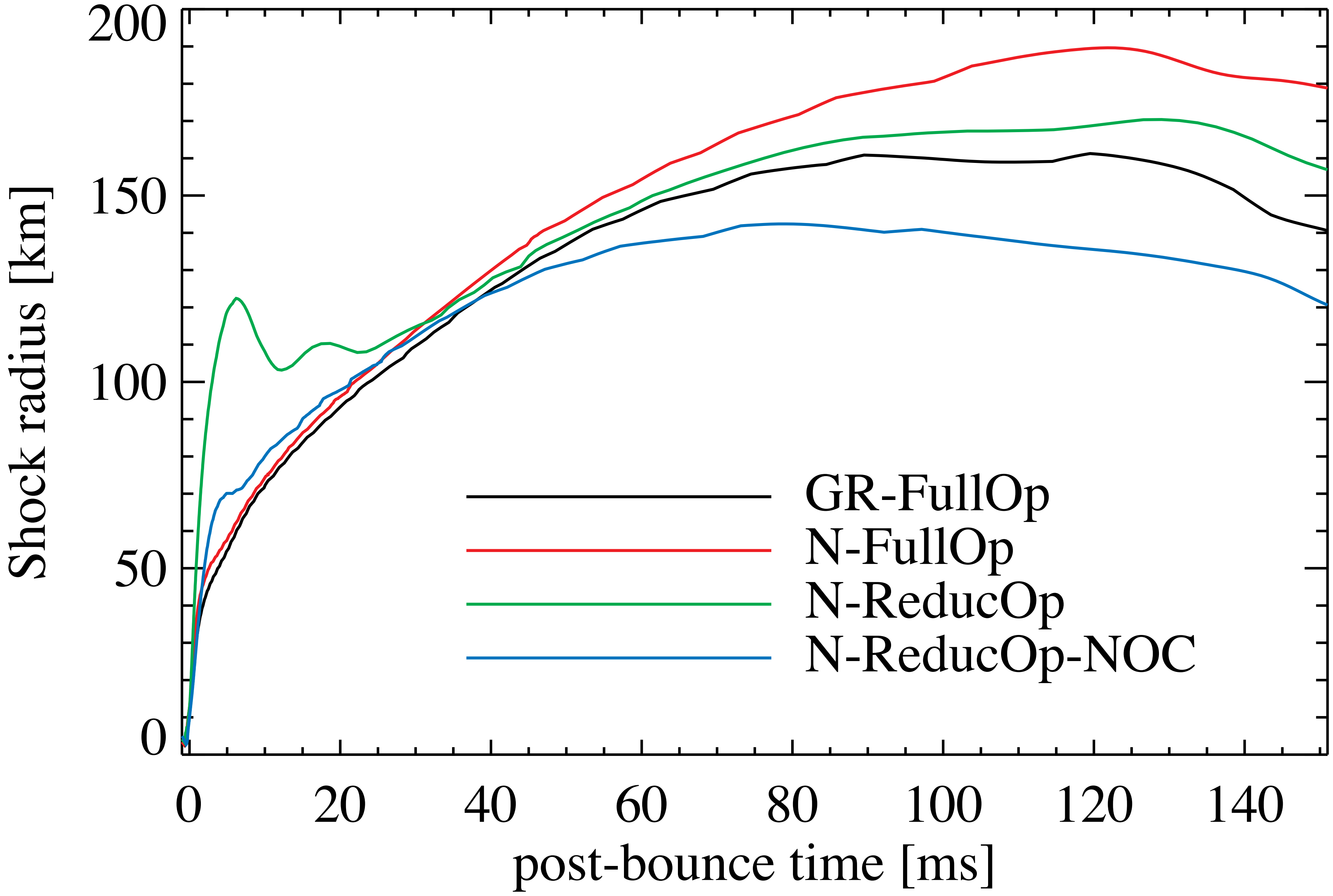


Post-bounce profile



Essential physical realism in neutrino transport

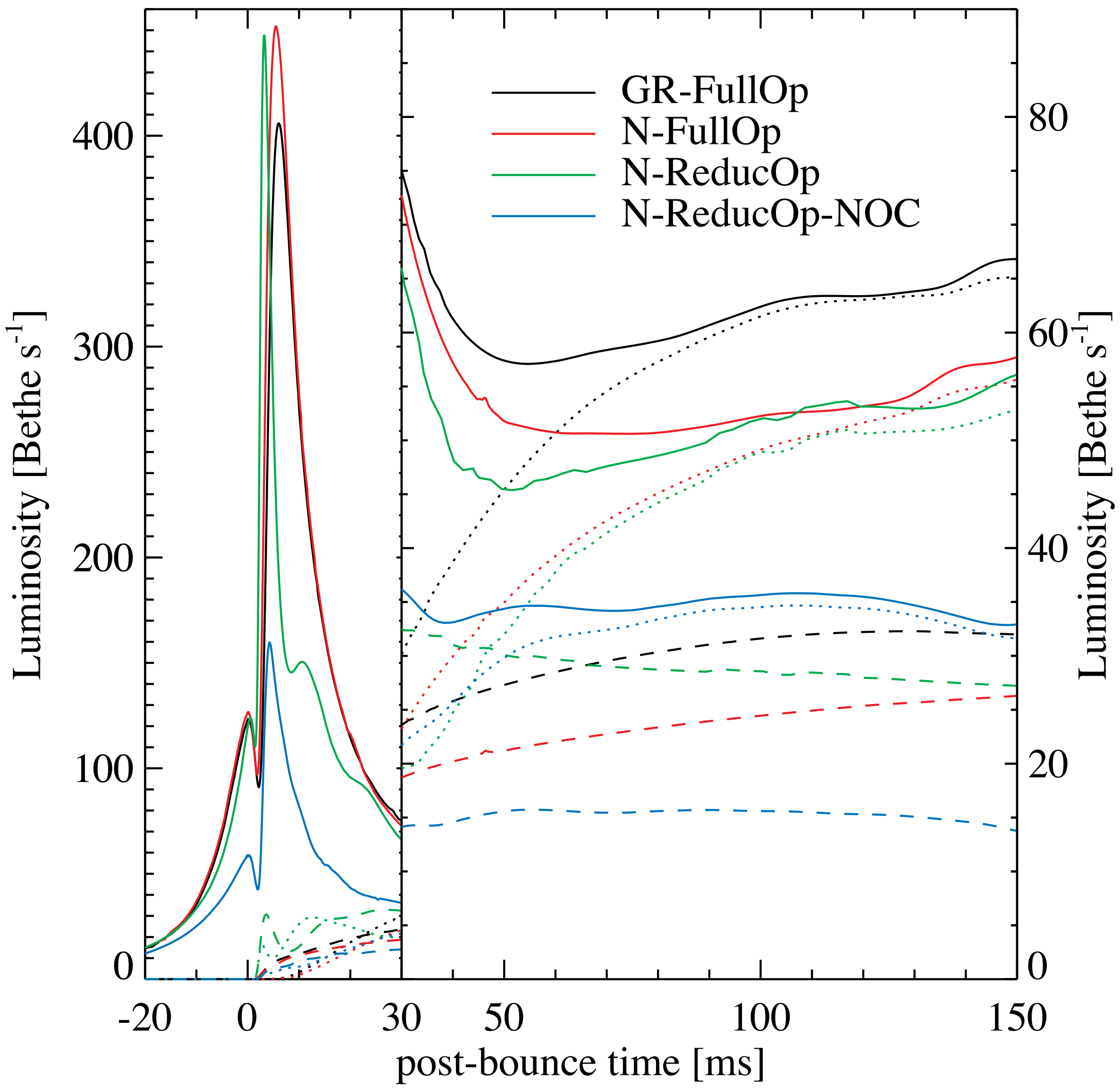
Lentz et al. *Ap.J.* **747**, 73 (2012)



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

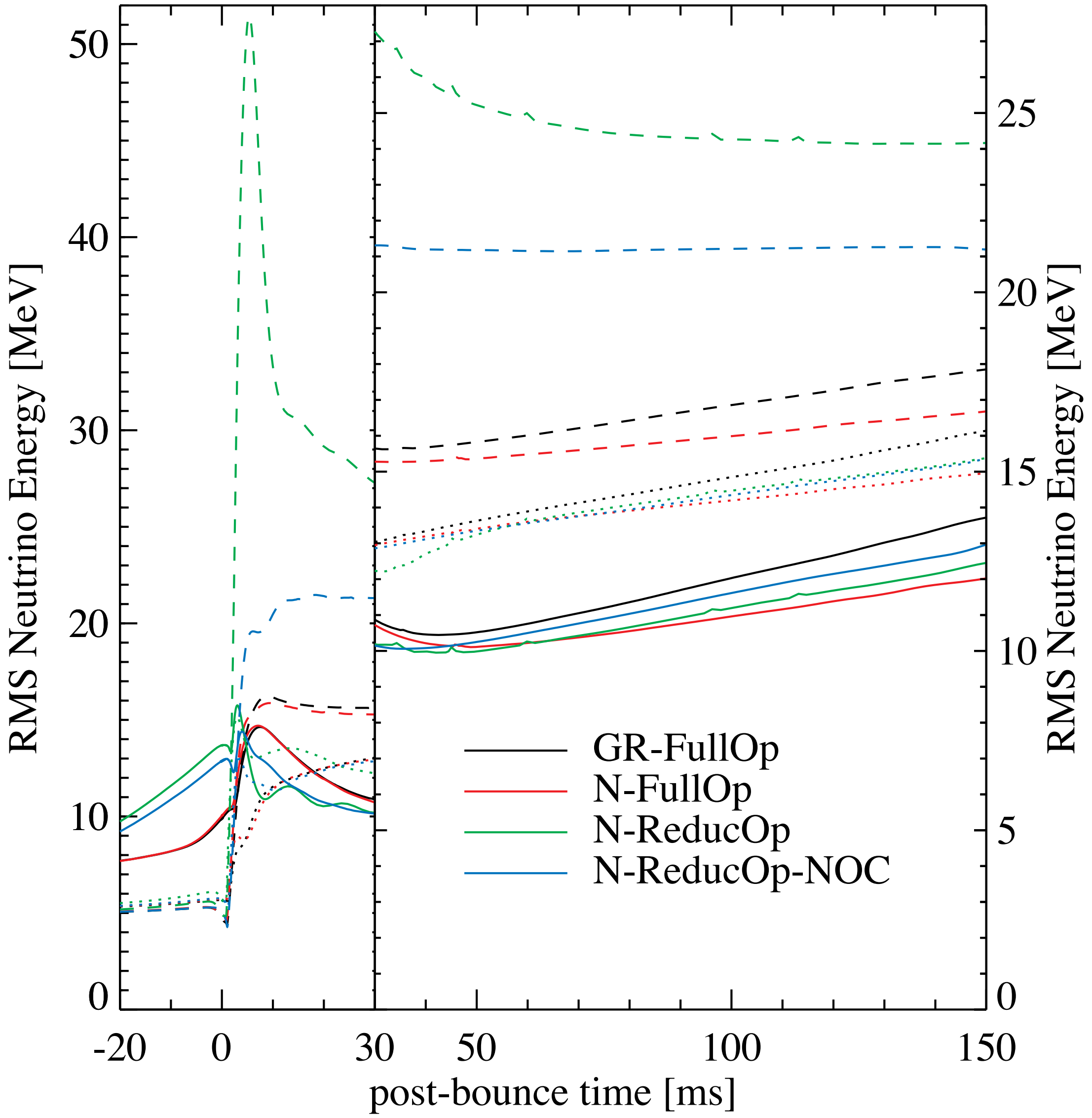
See also B. Mueller et al. 2012. Ap.J. ***756****, 84 for a comparison in the context of 2D models, with similar conclusions.*

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

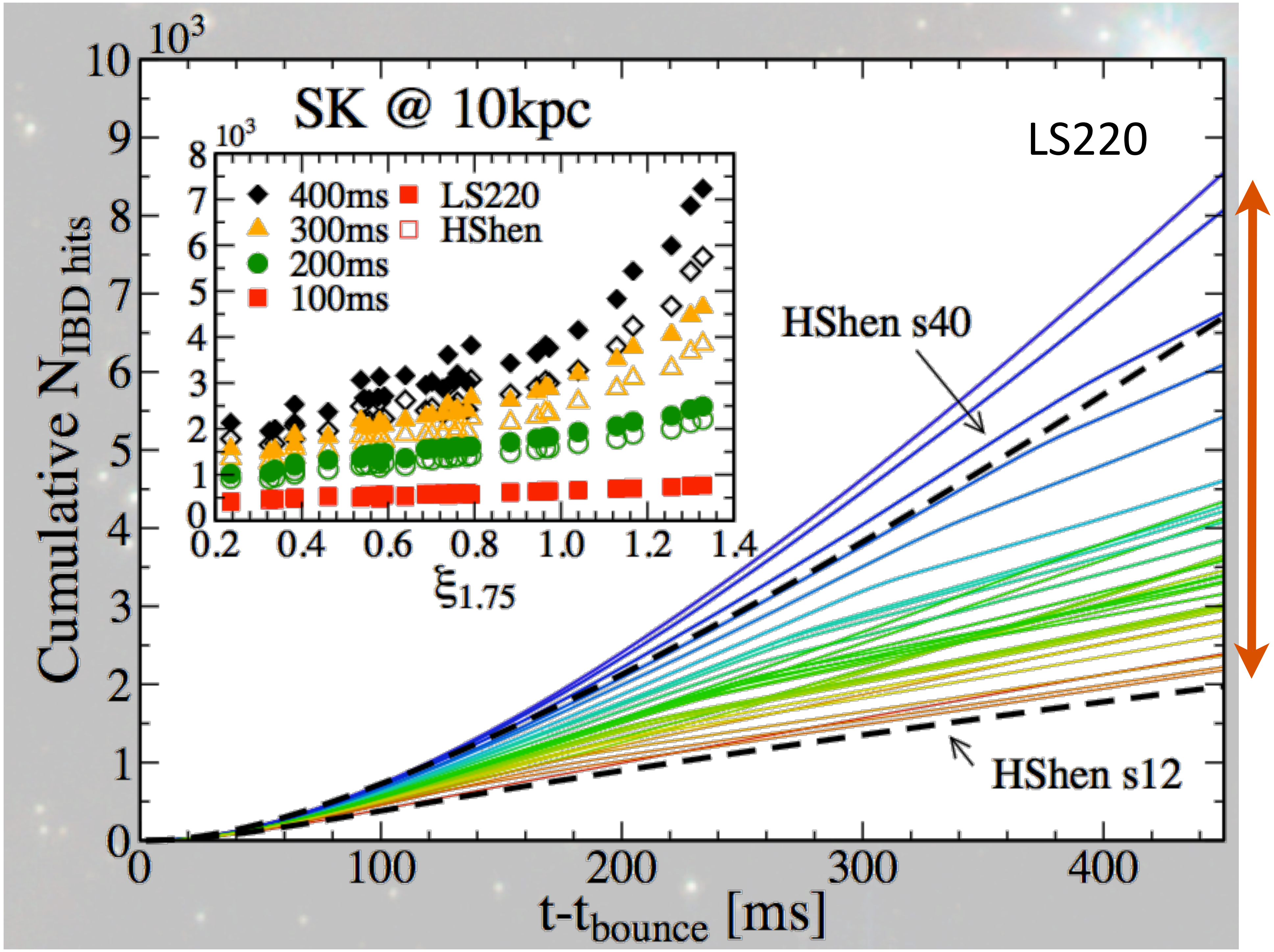
ReducOp opacities: Narrower breakout burst

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

OAK RIDGE National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY

Late-time signal dependent on progenitor structure

- O'Connor & Ott *ApJ* 730, 70 (2011)



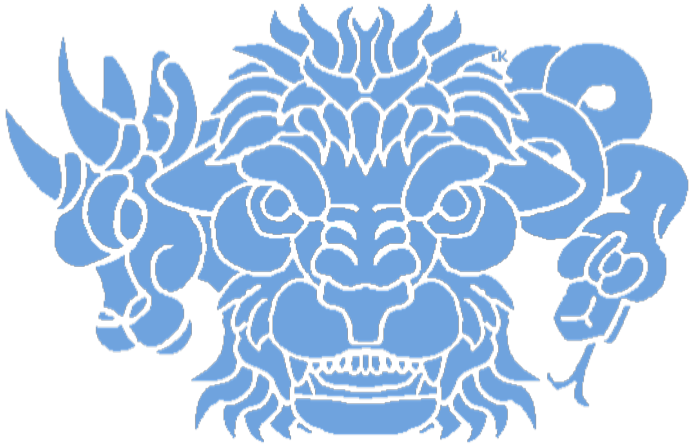
LS220

12 -120 $M_{\odot}$

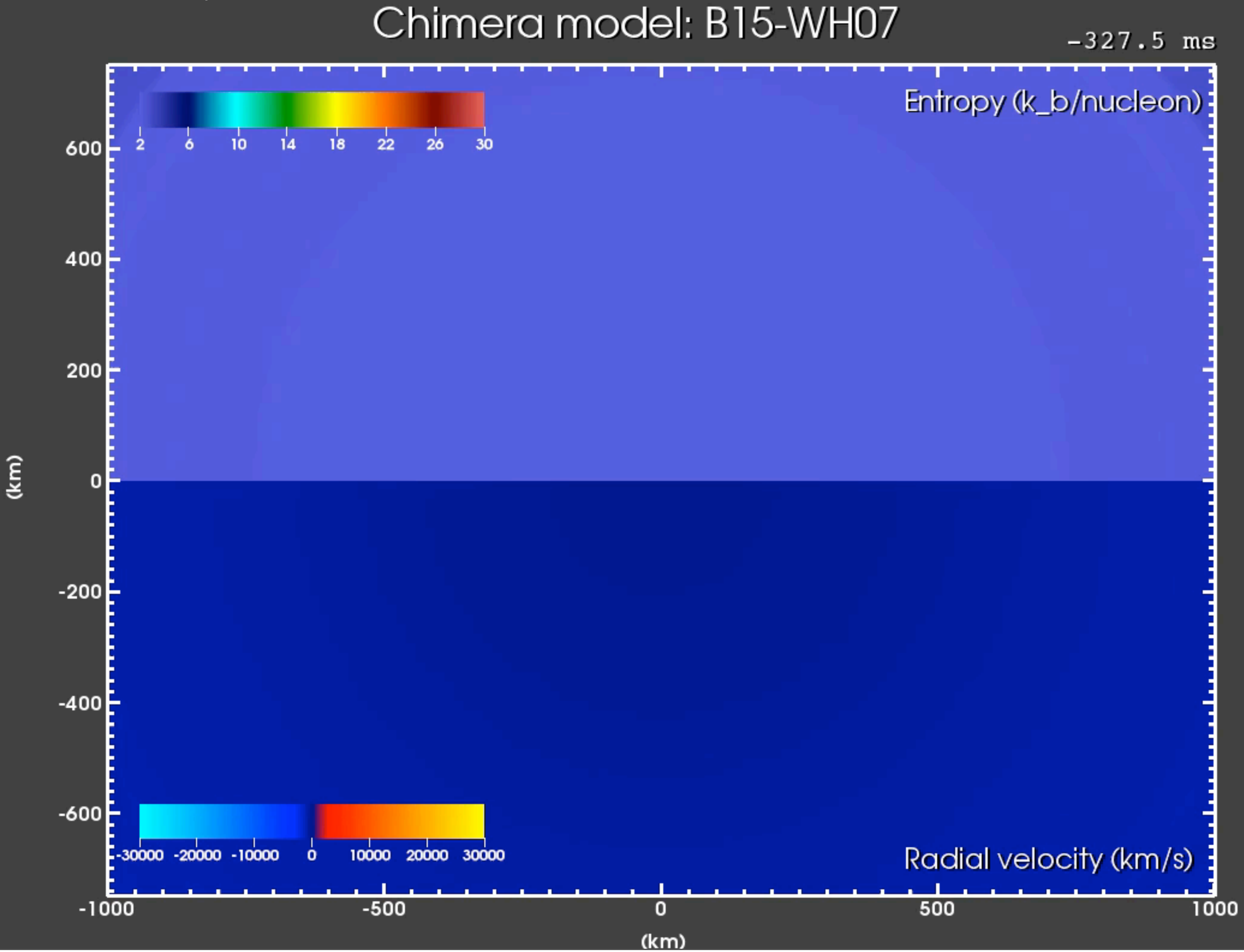
- Non-exploding 1D models - ν emission relates inner stellar structure and composition

CHIMERA

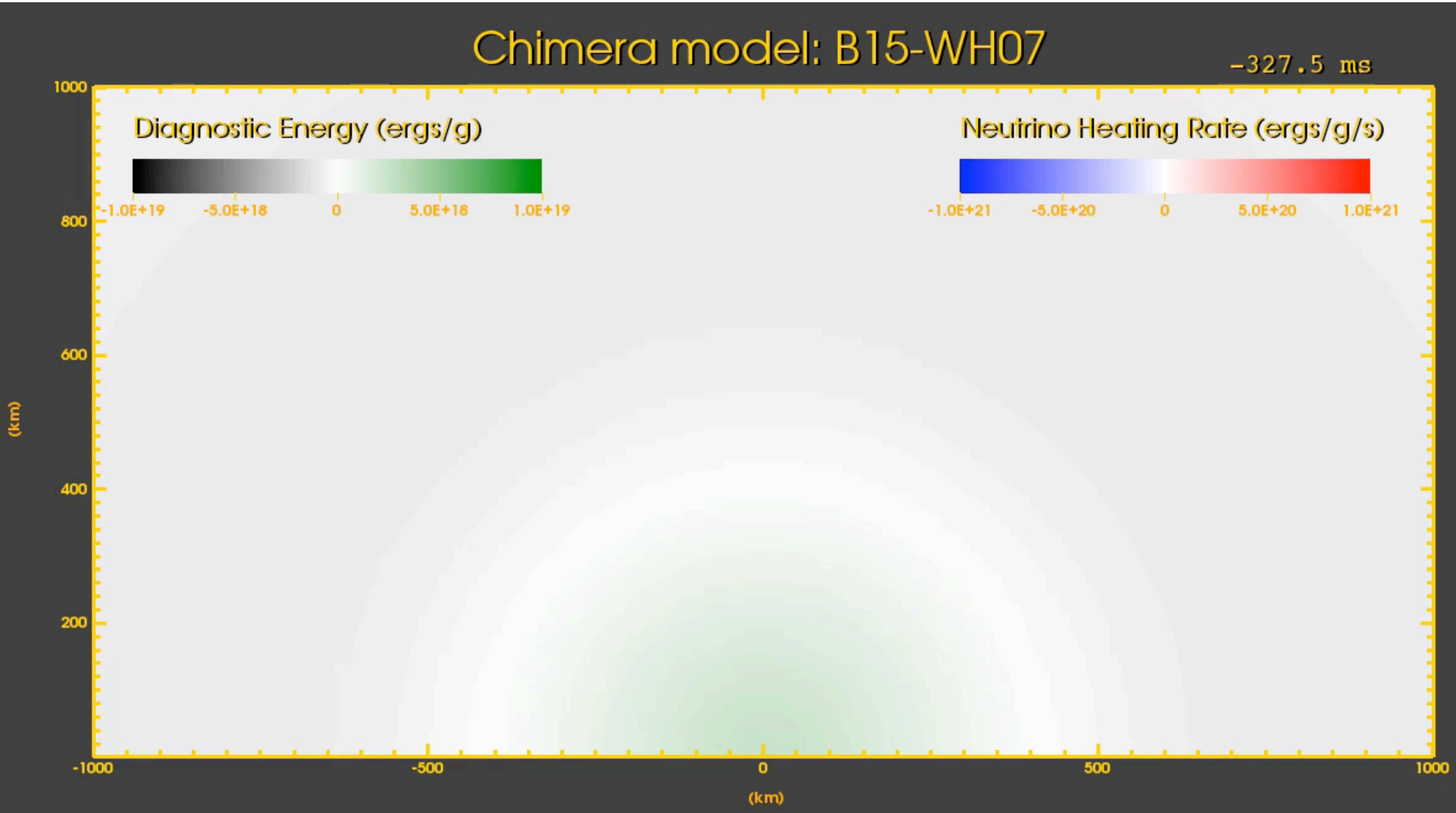
- “Ray-by-ray-Plus” MGFLD Neutrino Transport
  - O(v/c), GR time dilation and redshift, GR aberration
- PPM Hydrodynamics (finite-volume)
  - GR time dilation, effective gravitational potential
  - adaptive radial grid
- Lattimer-Swesty EOS + low-density BCK EOS
  - K=220 MeV
  - low-density EOS (BCK+NSE 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.



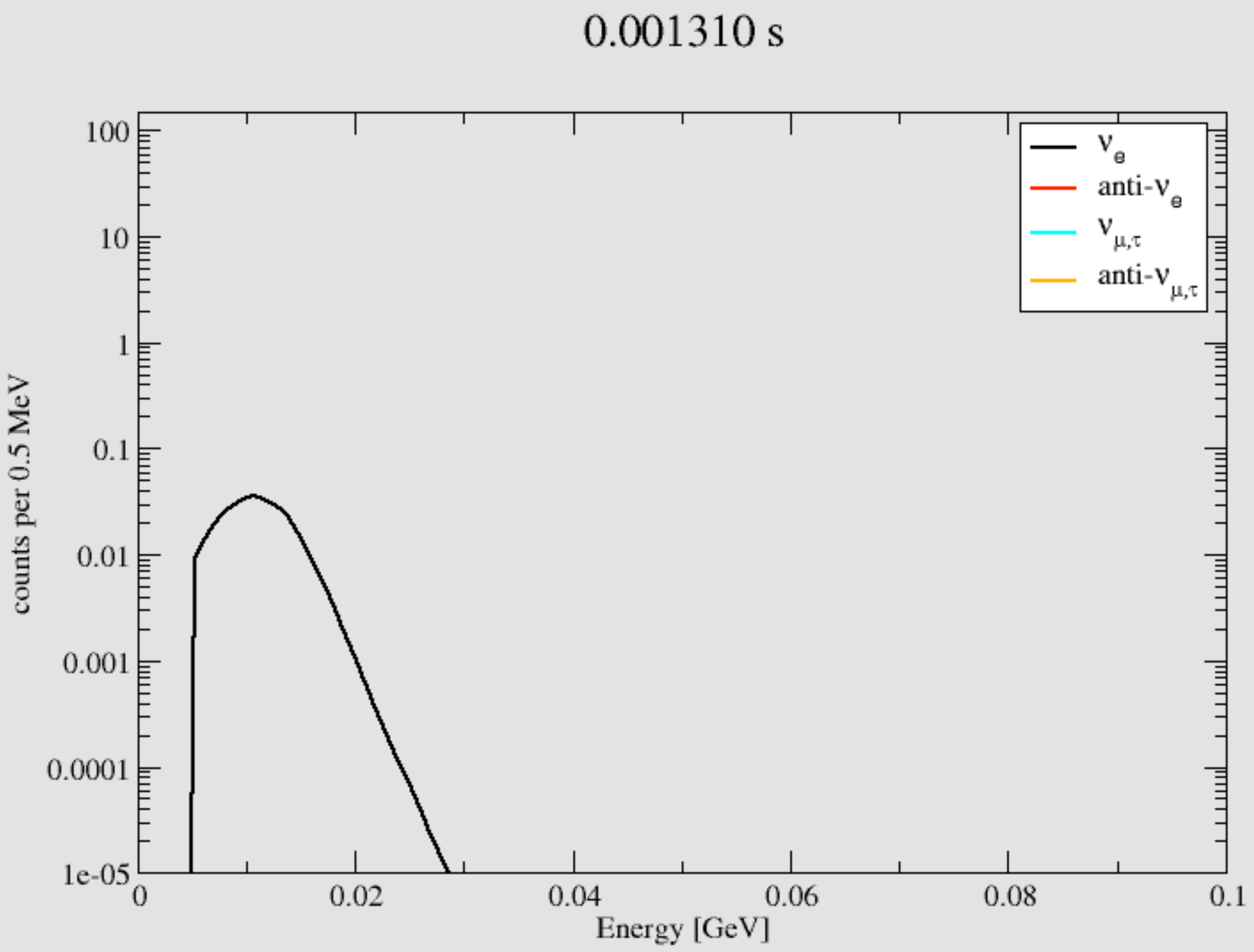
Explosion energy & neutrino heating/cooling



OAK RIDGE National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY

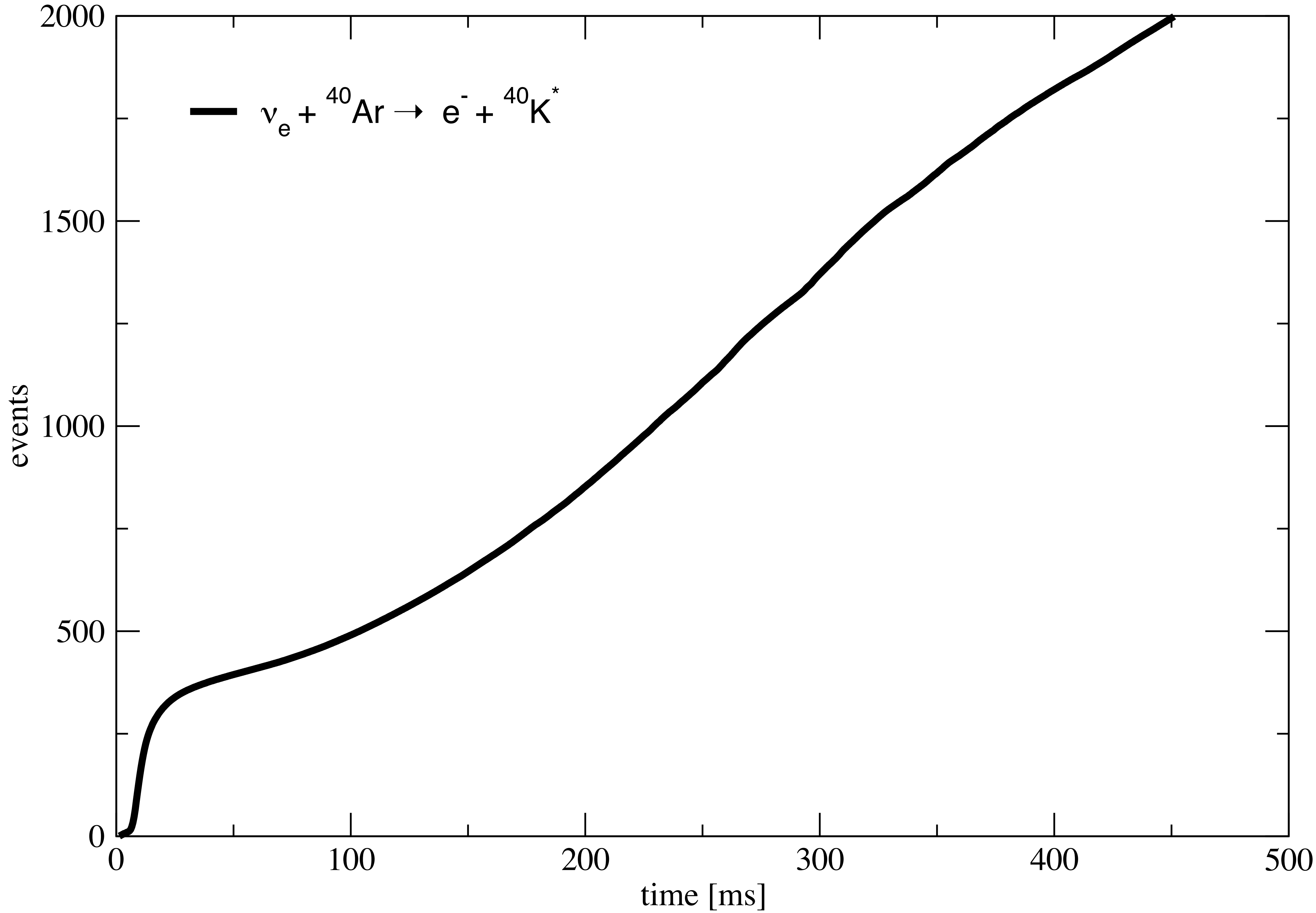
Multi-flavor detection

μ,τ fluxes are 0.5x



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

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



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

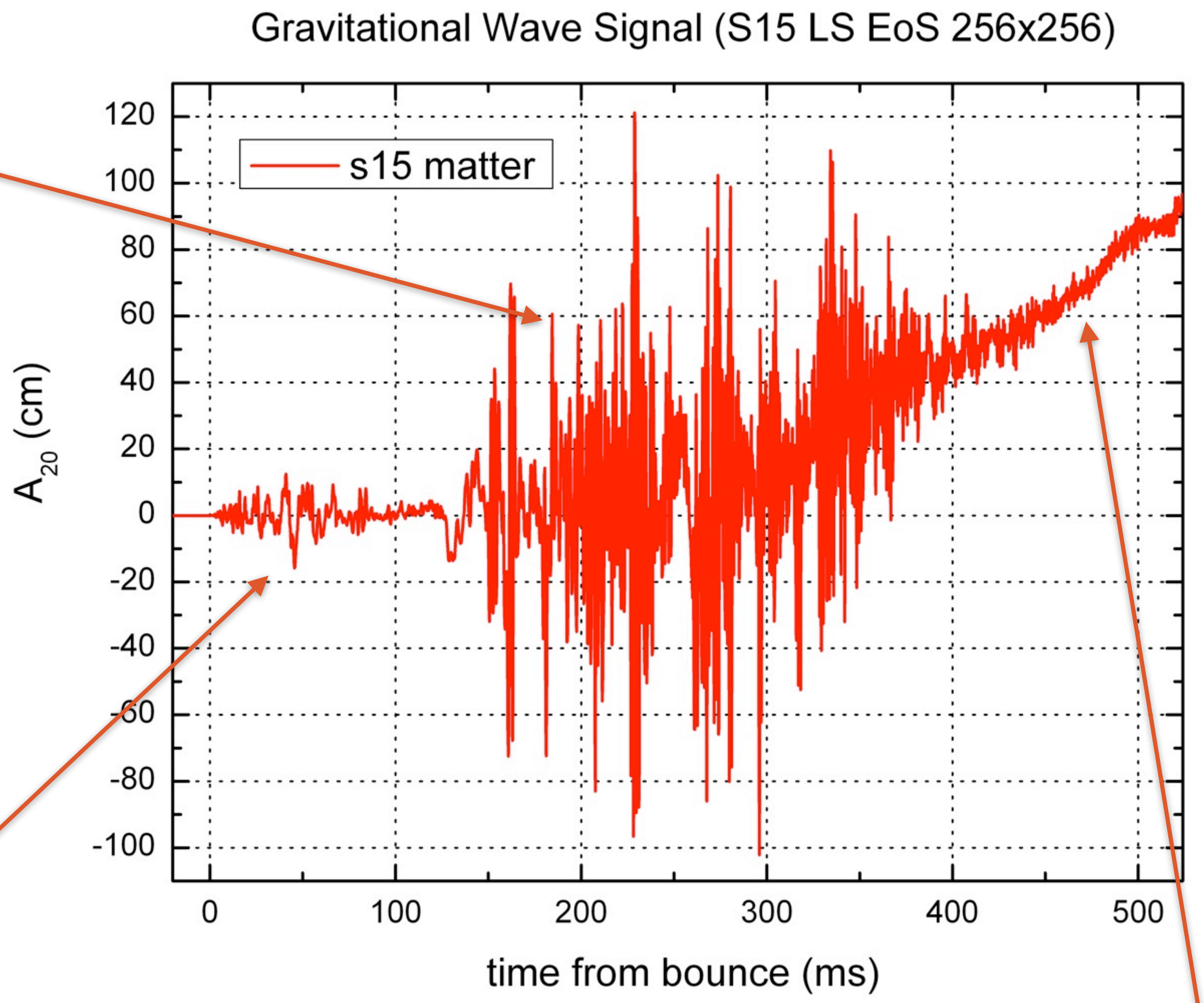
OAK RIDGE National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY

Example of observables: Anatomy of a GW signature

Yakunin, ..., Messer, et al. 2010. *Class. Quantum Grav.* **27,**194005**.**

- Lower-Frequency Envelope: SASI-Induced Shock Excursions

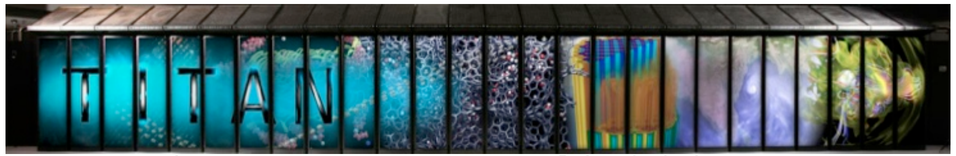
- Higher-Frequency Variations: Impingement of Downflows on PNS from Neutrino-Driven Convection and SASI



Prompt Convection
Early Shock Deceleration

Later Rise: Prolate Explosion/Deceleration at Shock

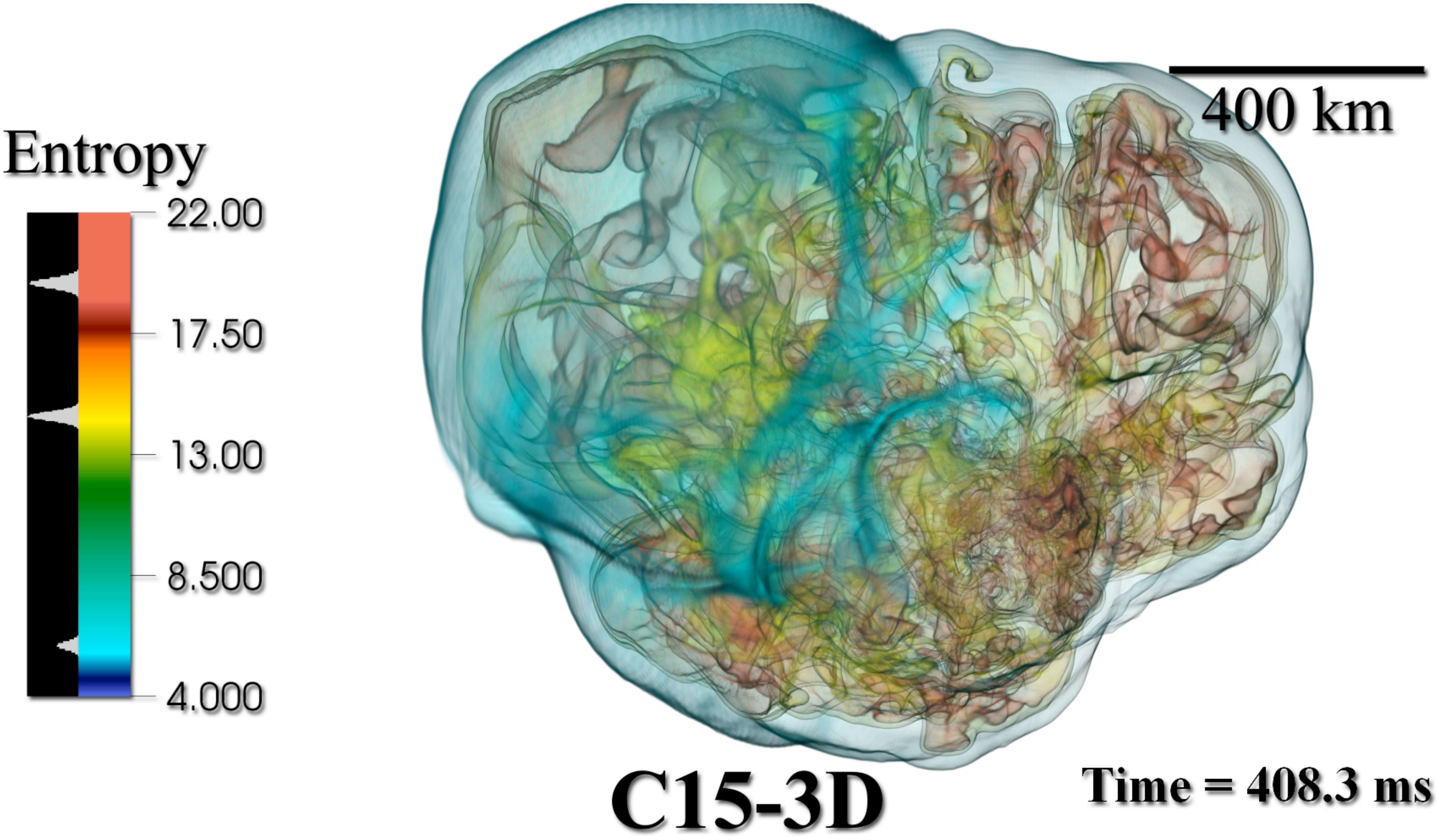
15 solar mass 3D run



~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.

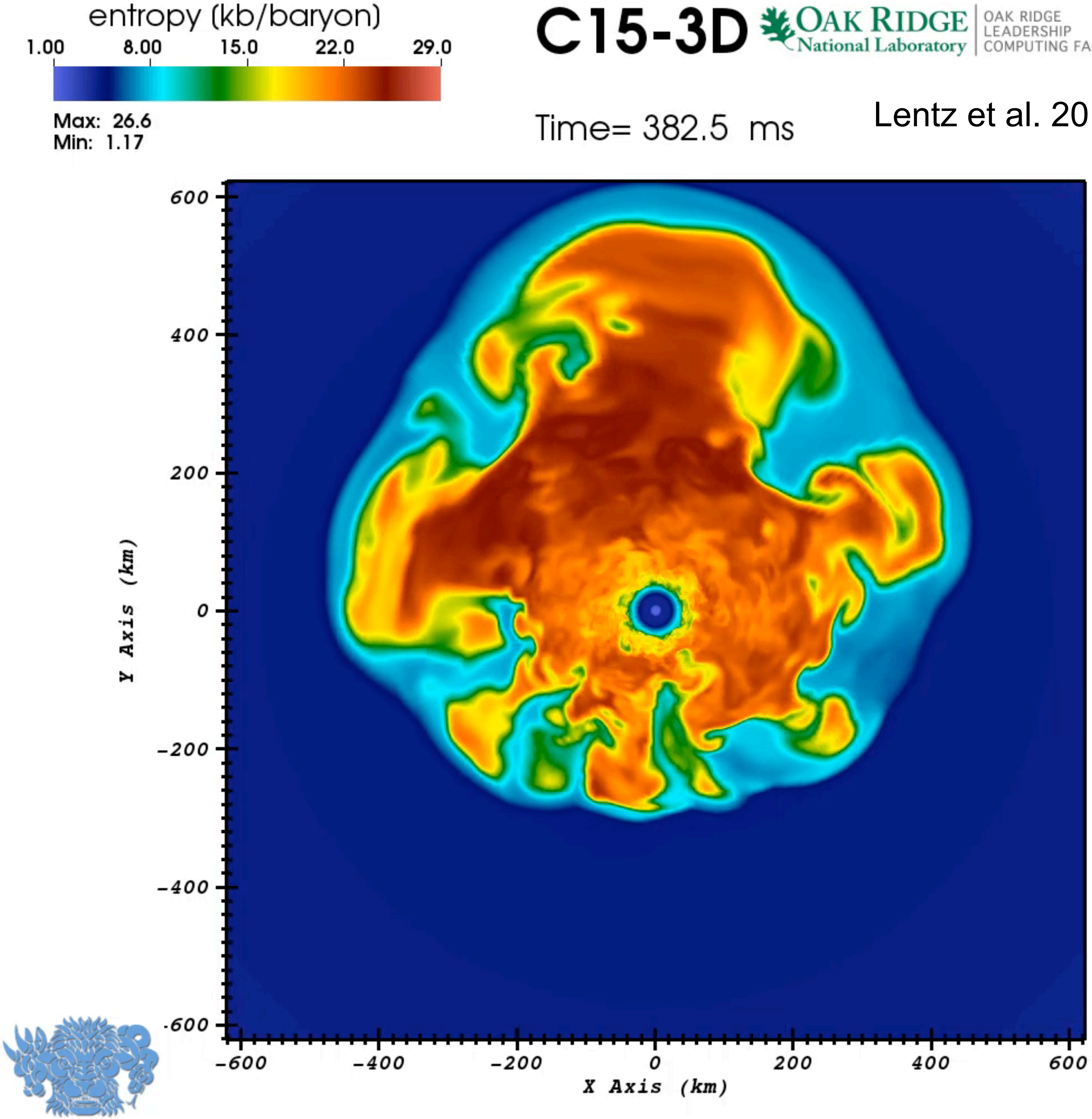
Lentz et al. 2015. In press, *ApJL*



C15-3D

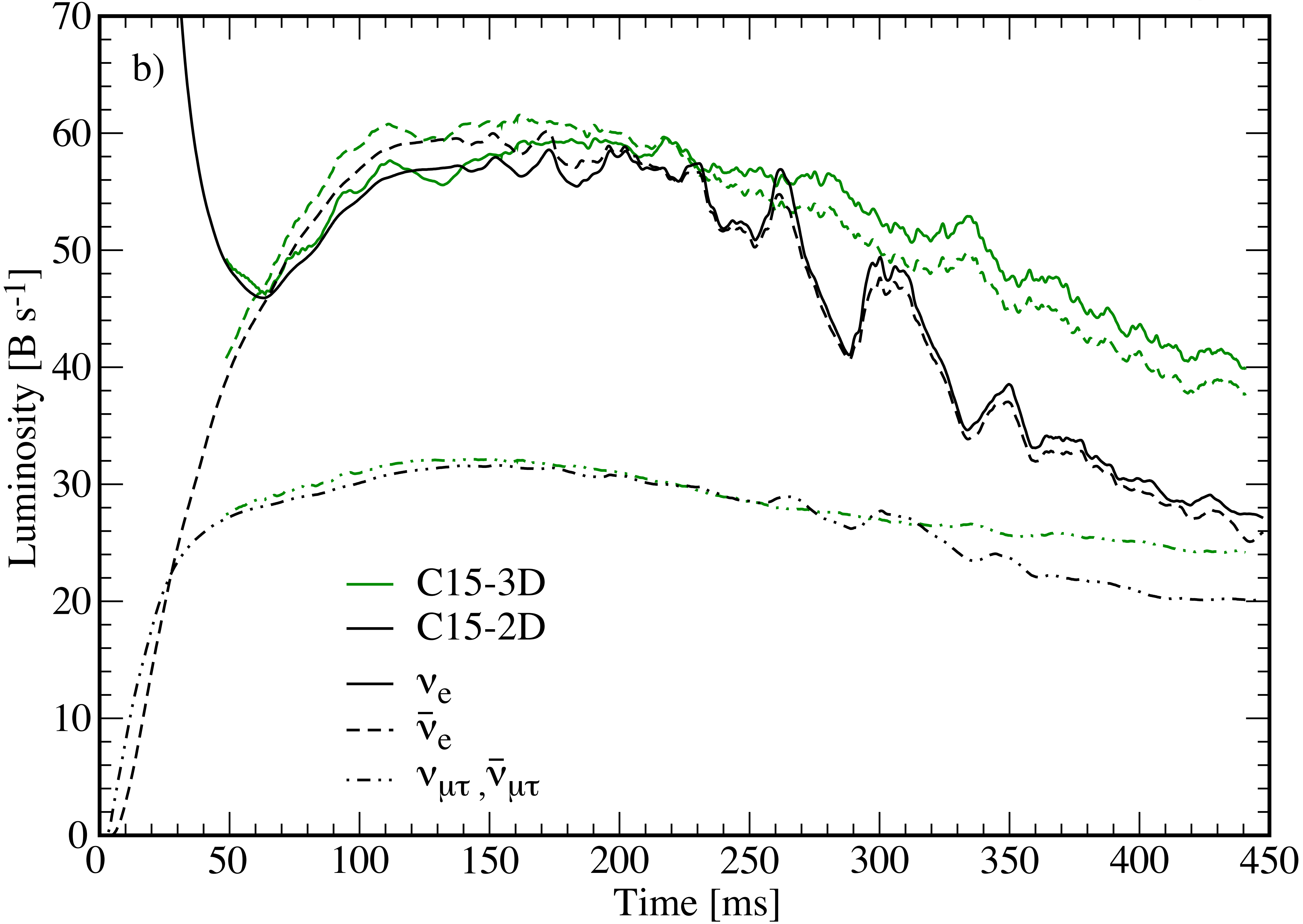
Oak Ridge National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY

Lentz et al. 2015. In press, *ApJL*



3D vs 2D luminosities

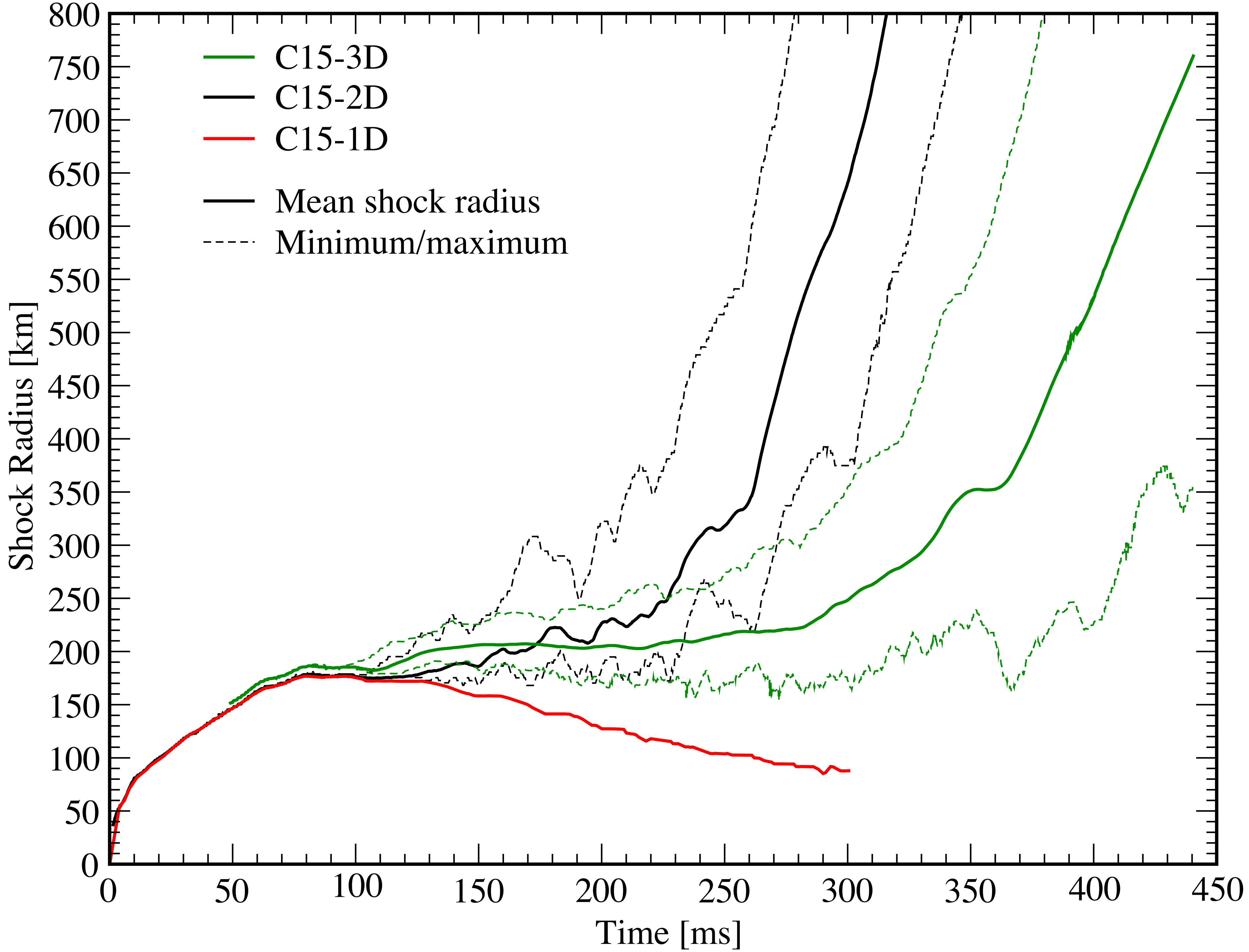
Lentz et al. 2015. In press, *ApJL*



OAK RIDGE National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY

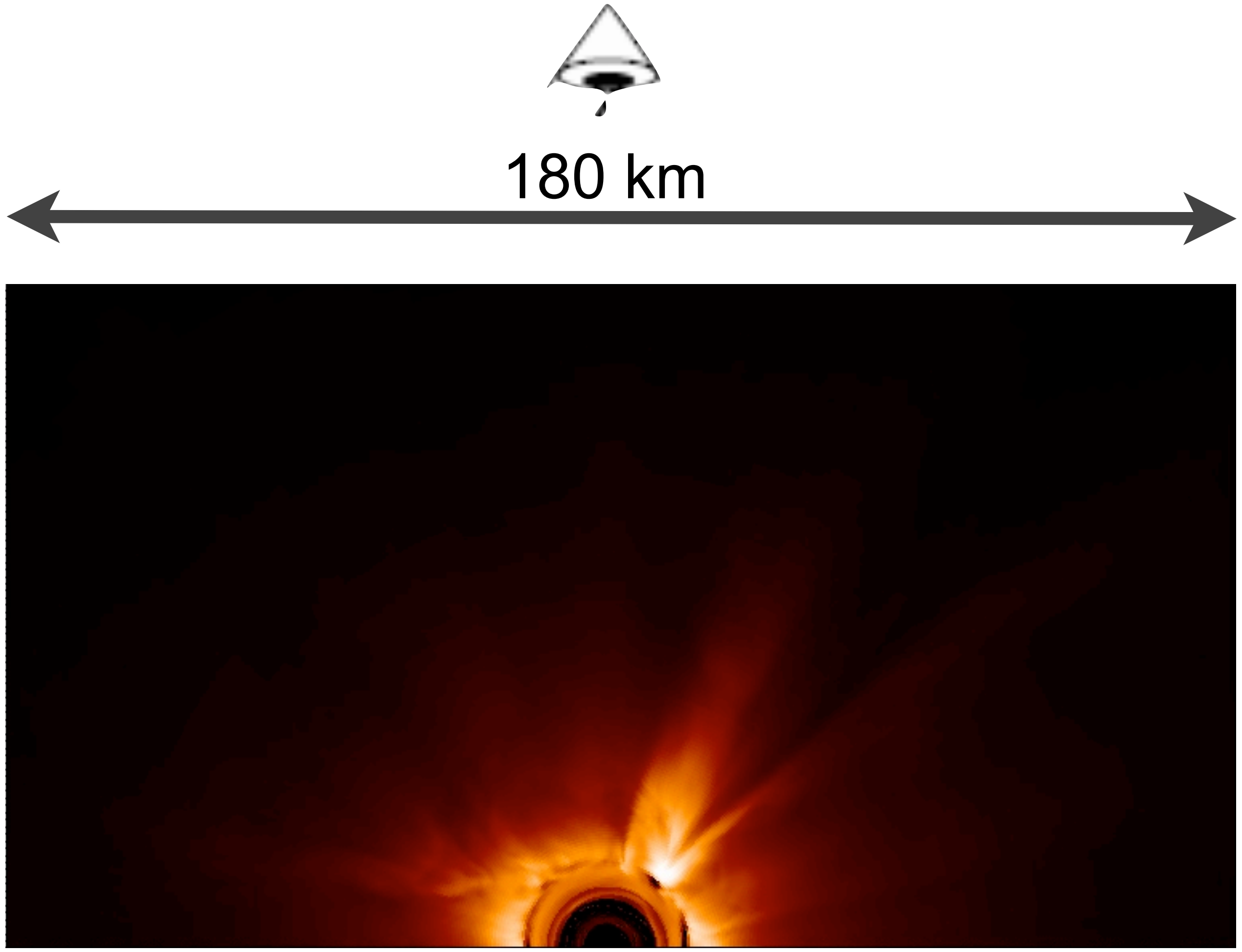
1D vs. 2D vs. 3D

Lentz et al. 2015. In press, *ApJL*

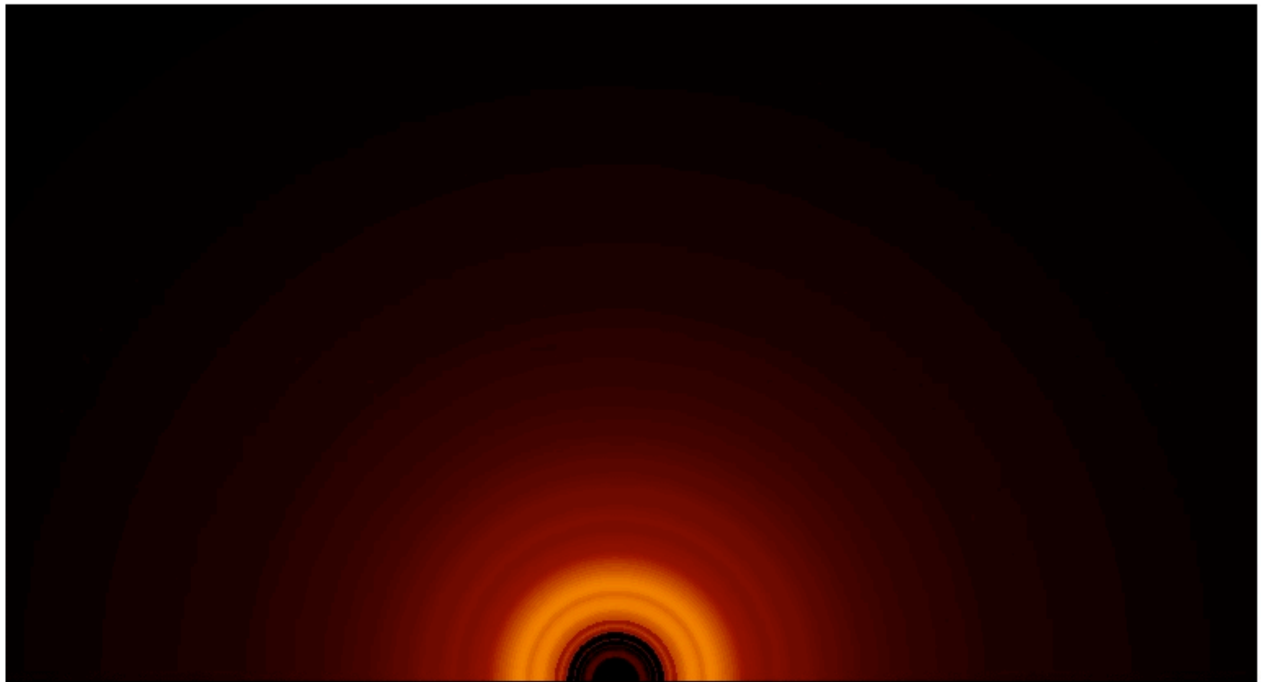


OAK RIDGE National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY

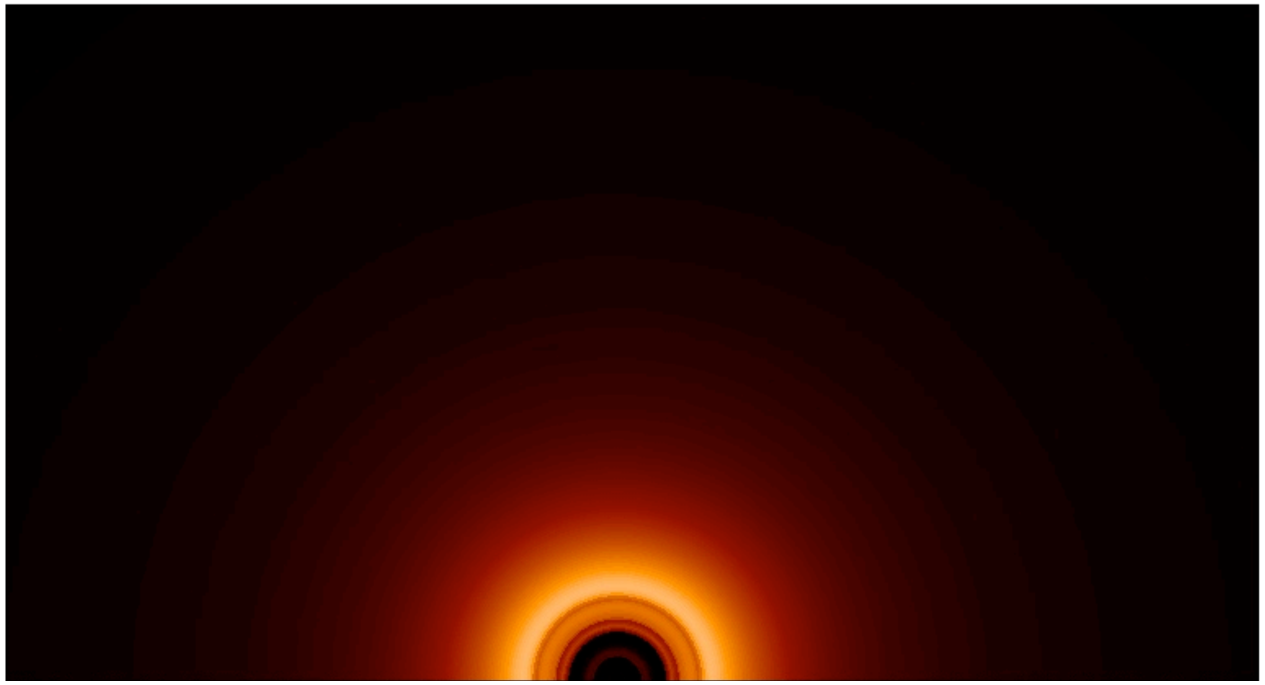
Recovering “realistic” ν fluxes from RbR simulations



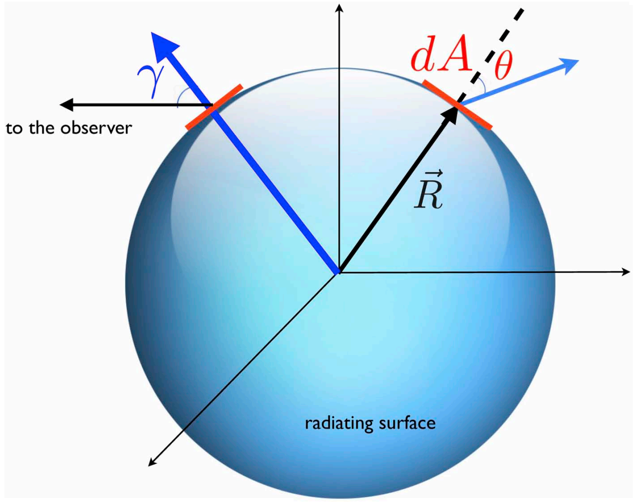
raw



1 polar ray



average

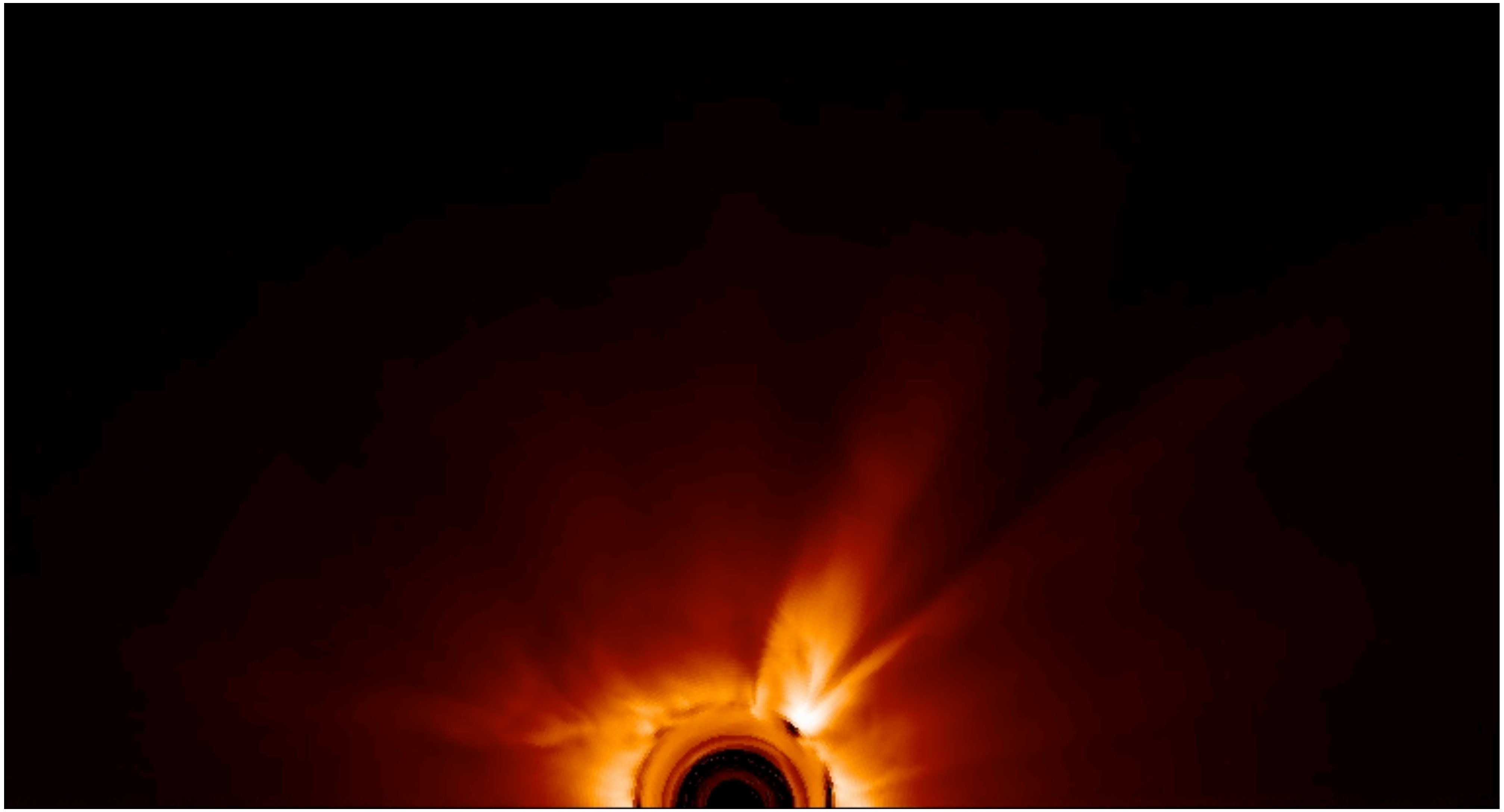


Tamborra, et al.
Phys.Rev. **D90** (2014) 045032

“In principle, I(R,θ) can be extracted from the numerical results, but would require a vast amount of post-processing of huge data files. Instead, we fall back on a simple approximation...”

Recovering “realistic” ν fluxes from RbR simulations

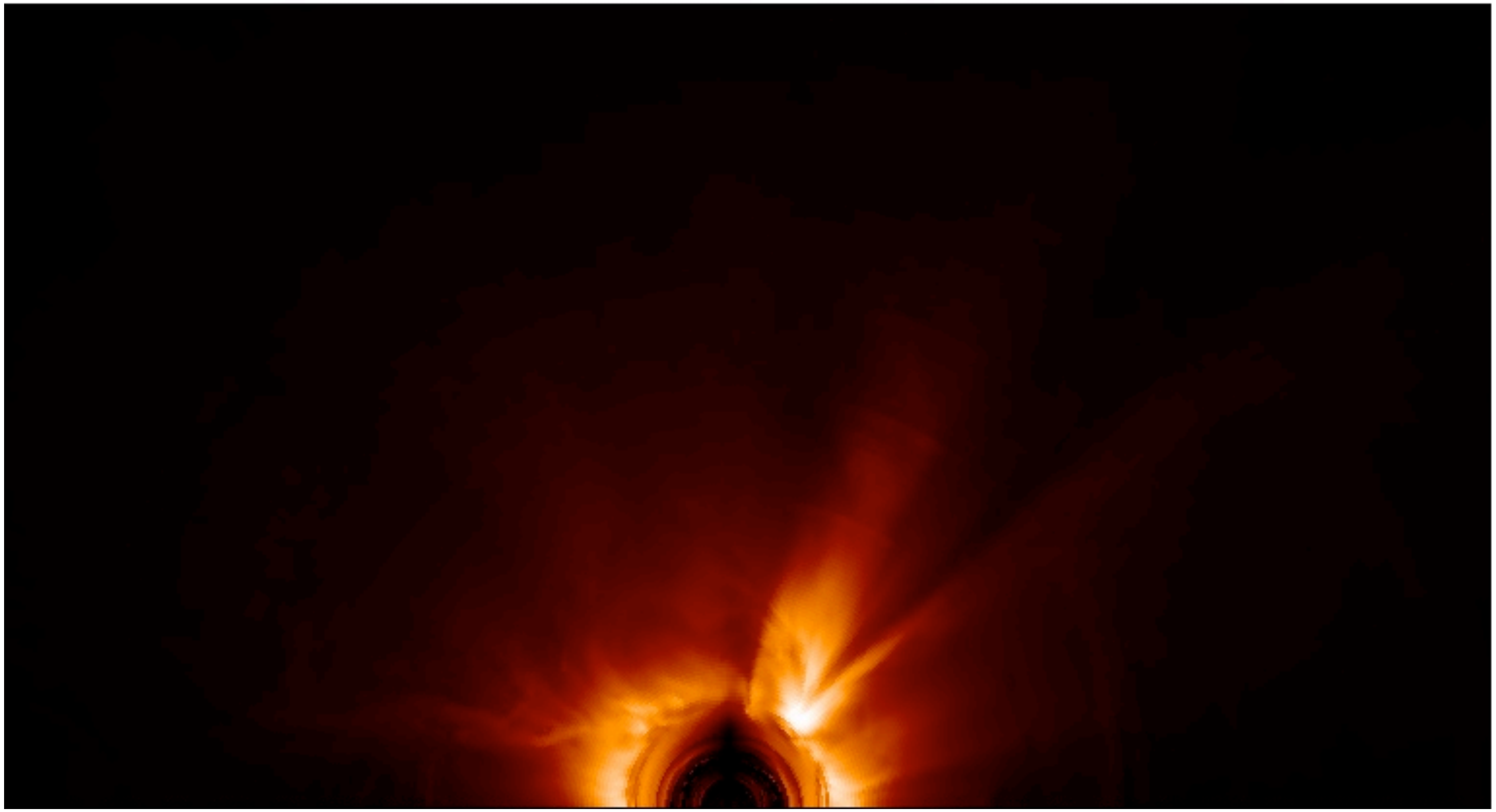
raw



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

Recovering “realistic” ν fluxes from RbR simulations

limb-darkened



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

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.