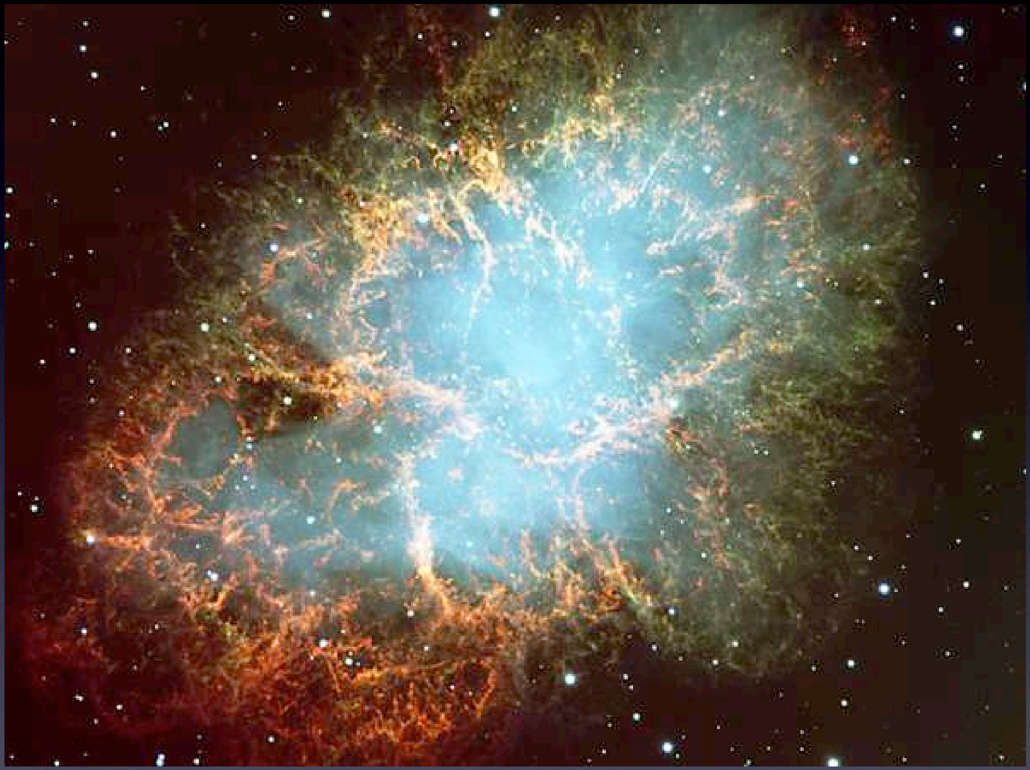
New 2D/3D CHIMERA Simulations of Core Collapse Supernovae



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IPMU - Focus Week on Messengers of Supernova Explosions, November 17-21

Core Collapse Supernova Energetics

- Photons ~ 10^{49} ergs
- Ejecta Kinetic energy ~ 10^{50} - 10^{52} ergs
- Neutrinos ~ 3×10^{53} ergs

Core Collapse Supernova Asymmetries

- Polarization
  - Core collapse SN are polarized at ~1% level
  - Degree of polarization increases with decreasing envelope mass
  - Degree of polarization generally increases after optical maximum
- Outward mixing of Ni in SN1987 A & Cas A
- Axisymmetric ejecta of SN1987A
- Early Emission of x-rays and gamma-rays from SN1987A

The Core Collapse Supernova Mechanism: A Computational Challenge

- Inherently multi-dimensional
- Variety of complex physical processes that need to be accurately modeled
- Extremely nonlinear with many feedbacks
- Explosions are marginal

Core-Collapse Supernova Mechanisms

Magnetic Field Mechanism

- Burrows, Dessart, Livne, Ott, & Murphy, ApJ, 644, 416, 2007 (2D RMHD)
- Shibata Liu, Shapiro, & Stephens, Phys. Rev. D 74, 104026 (2D MHD, High res)
- Dessart, Burrows, Livne, & Ott, ApJ, 669, 585, 2007 (2D RMHD)
- Sawai, Kotake, & Yamada, ApJ, 672, 465, 2008 (2D MHD, offset dipole)
- Mikami, Sato, Matsumoto, & Hanawa, ApJ, 683, 357, 2008 (3D MHD, rotated dipole)

Acoustic Mechansim

- Burrows, Livne, Dessart, Ott, & Murphy, ApJ, 640, 878, 2007; ApJ, 655, 416, 2007

Neutrino Transport Mechanism

- Buras, Janka, Rampp, & Kifonidis, A&A, 447, 1049, 2006; A&A 457, 281, 2006 (2D ray-by-ray plus)
- Bruenn, Dirk, Mezzacappa, Hayes, Blondin, Hix, Messer, SciDAC 2006 (2D ray-by-ray plus)
- Ott, Burrows, Dessart, & Livne, Ap. J. 685, 1069, 2008 (MGFLD, SN, isoenergetic)

Magnetic Field Mechanism

- Taps free energy of differential rotation

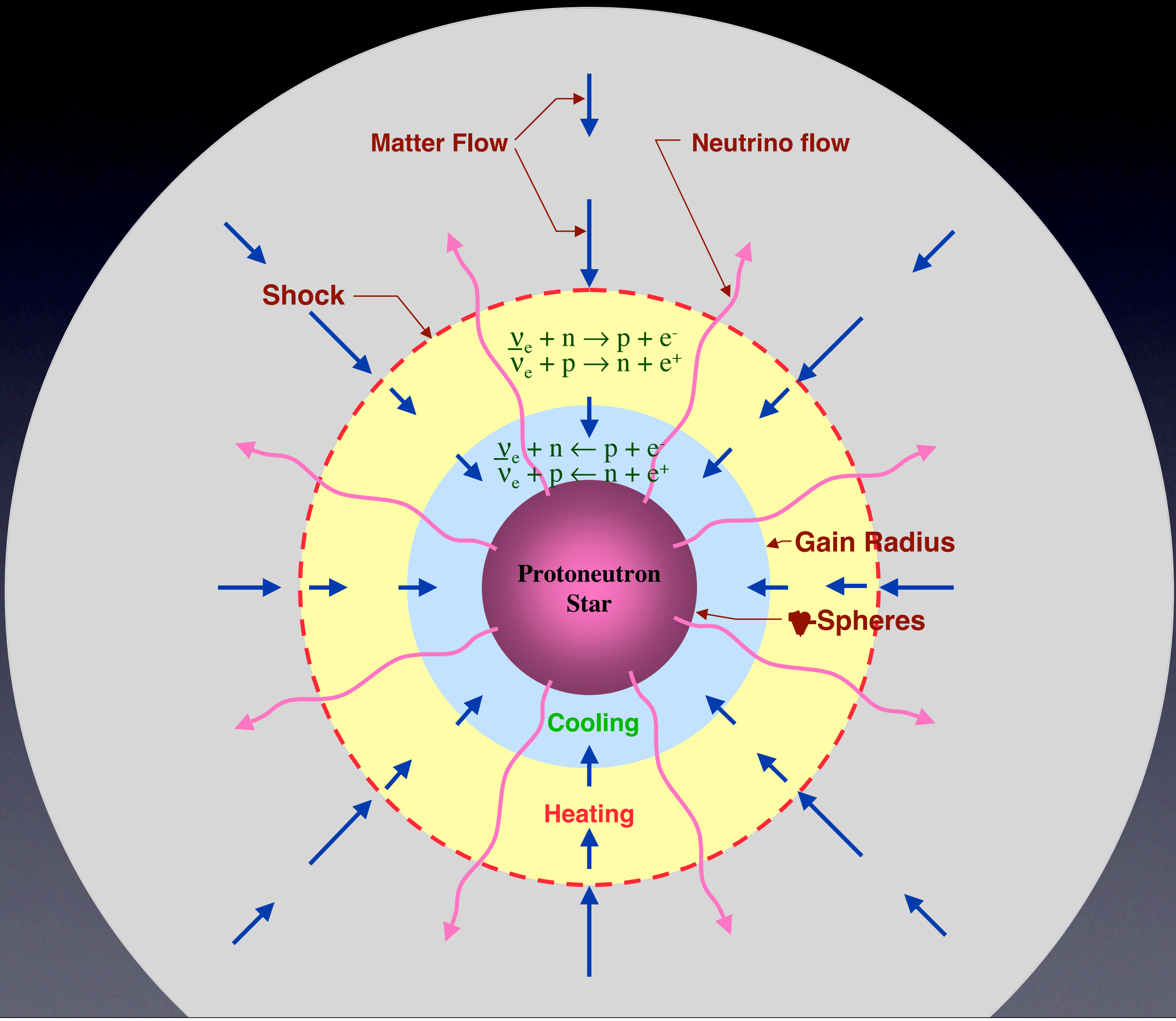
$$T_{\rm rot} = 4\left(\frac{\kappa_I}{0.3}\right)\left(\frac{M}{1.4M_\odot}\right)\left(\frac{R}{10\ {\rm km}}\right)^2\left(\frac{P_{\rm rot}}{2\ {\rm ms}}\right)^{-2}\ {\rm B} \qquad 1\ {\rm B} = 10^{51}\ {\rm ergs}$$

- Predicted rotational rates of newly formed neutron stars
  - 3 - 15 ms (Heger, Woosley & Spruit, 2005)
- Extrapolated periods of newly formed pulsars
  - Crab: 21 ms
  - PSR J0537-6910 10 ms
  - PSR B0540-69 39 ms
  - PSR B1509-58 20 ms
- Problem: Need rapid rotation (not observed or predicted)

Acoustic Mechanism

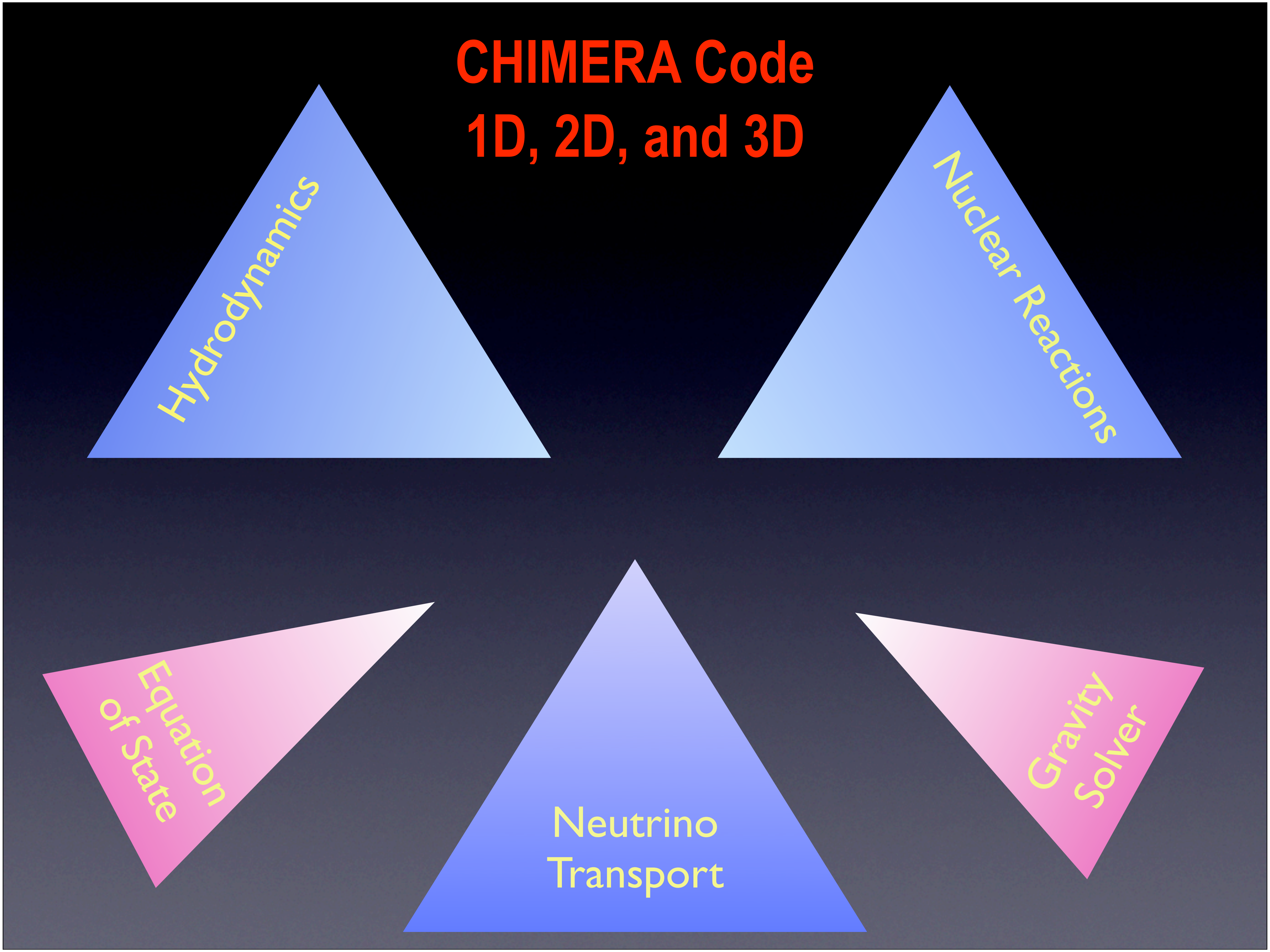
- Anisotropic accretion onto inner core over time excites core g-modes
- Core eigenmodes (mainly L = 1) grow to large amplitudes and radiate sound
- Sound pulses steepen into shocks and deposit energy and momentum in the shocked mantle powering an explosion
- Problem: Occurs late (many hundreds of milliseconds to seconds post bounce), and only one group has seen it

The Neutrino Transport Mechanism



Current State-of-the-Art Neutrino Transport Supernova Modeling

- 1D
  - Fully GR
  - Boltzmann neutrino transport
  - Sophisticated weak interaction physics
- 2D
  - Ray-by-Ray-Plus Neutrino Transport
    - Post-Newtonian spherical gravity with Newtonian nonspherical components
    - MGFLD or variable Eddington neutrino transport
    - Sophisticated weak interaction physics
  - Fully 2D MGFLD, SN Neutrino Transport
    - Newtonian gravity
    - In-group weak interaction physics
- 3D
  - Hydrodynamic or Magnetohydrodynamic only
  - Smooth particle hydro with grey transport
  - Ray-by-Ray-Plus (as 2D above)


CHIMERA Code
1D, 2D, and 3D
Hydrodynamics
Nuclear Reactions
Equation of State
Neutrino Transport
Gravity Solver

CHIMERA Collaboration

Stephen W. Bruenn	Florida Atlantic U.	Code Architect, Neutrino Transport
Anthony Mezzacappa	Oak Ridge National Lab	Project Leader & Science Advisor
John M. Blondin	North Carolina State	2D & 3D Hydro
W. Raph Hix	Oak Ridge National Lab	Nuclear Physics & Nuclear Network
O. E. Bronson Messer	Oak Ridge National Lab	Systems Advisor, Data Management
Pedro Marronette	Florida Atlantic U.	Gravity, Elliptic Solvers, GR Waves
Konstantin Yakunin	Florida Atlantic U.	Gravity, Elliptic Solvers, GR Waves
Charlotte Dirk	Florida Atlantic U.	Visualization
Ross Toedte	Oak Ridge National Lab	Visualization

Hydrodynamics

- Lagrangian PPM with Remap implementation of a Godunov scheme
- Newtonian spectral Poisson solver with effective GR radial potential
- Spherical polar grid
- Moving radial grid option during infall, sliding adaptive below shock after shock generation

Nuclear Network

- ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca, ^{44}Ti, ^{48}Cr, ^{52}Fe, ^{56}Ni, ^{60}Zn
- n, p, Fe-like tracers
- Advection of material into and out of NSE
- Flashing and freeze-out of zones

Neutrino Transport

- Multigroup, flux-limited diffusion tuned to Boltzmann transport
- Ray-by-ray plus approximation
- Full flavor implicit solve
- All O(v/c) velocity corrections, red shift and time dilation effects included

Neutrino Interactions

Emission and Absorption of ν_e's

$$e^- + p, A(Z, N) \rightleftharpoons \nu_e + p, A(Z-1, N+1)$$

Emission and Absorption of $\bar{\nu}_e$'s

$$e^+ + n, A(Z, N) \rightleftharpoons \bar{\nu}_e + p, A(Z+1, N-1)$$

Neutrino-Electron, Neutrino-Positron Scattering

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

Neutrino Scattering on Nucleons and Nuclei

$$\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau} + n, p, A \rightleftharpoons \nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau} + n, p, A$$

Electron-Positron Pair Annihilation

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

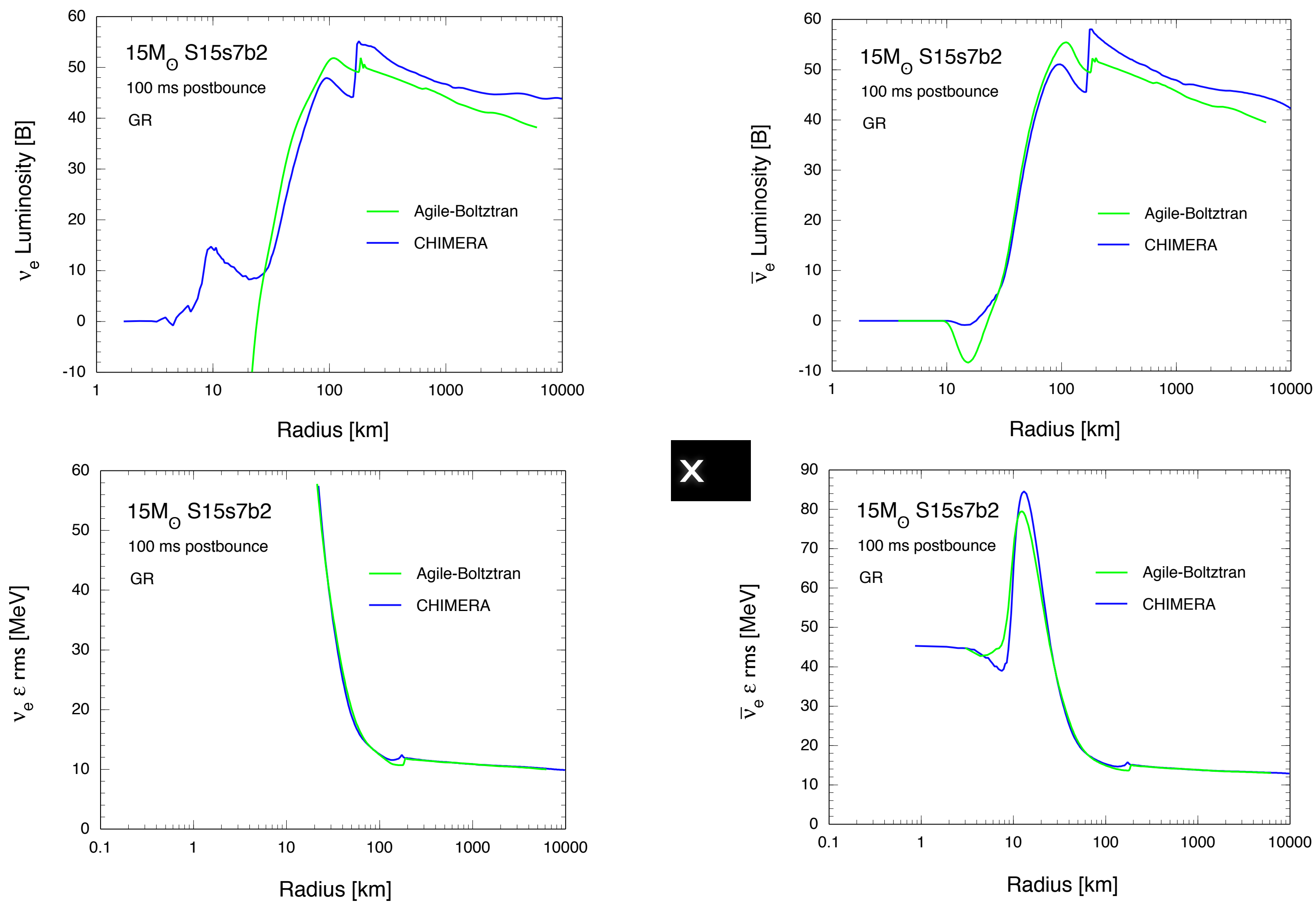
Nucleon-Nucleon Bremsstrahlung

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

Neutrino-Neutrino Scattering

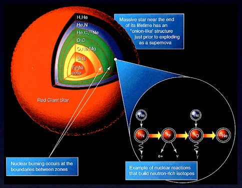
$$\nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau} \rightleftharpoons \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$$

CHIMERA vs Agile-Boltztran

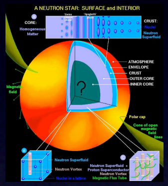


Supernova Connections

Nucleosynthesis



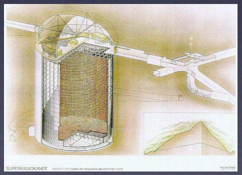
Neutron Stars



Supernovae

Black Holes

Neutrino Signatures



Gravitational Waves

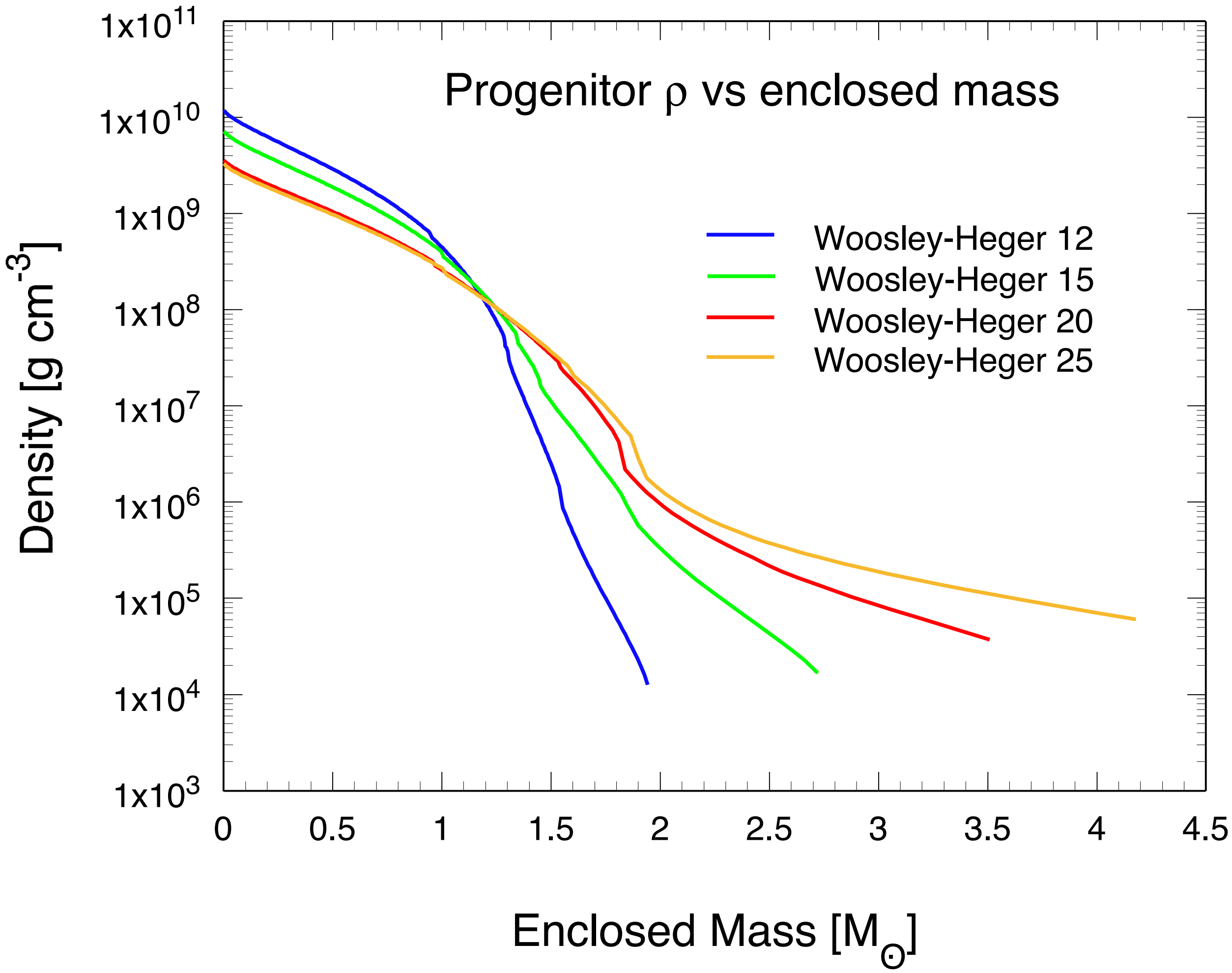
Nucleosynthesis

- 4000 - 8000 Lagrangian tracer particles in each model (Lee & Hix)
- Records thermodynamic state and spectral neutrino history along its trajectory
- Each tracer particle can be post-processed by a full nuclear network

Progenitor Series

- A suite of progenitor masses (12,15, 20, and 25 $M_{\odot}$) (Woosley and Heger, 2007 PhR) (ongoing)
- Progenitors of given mass evolved with different equations of state (planned)
- Progenitors of given mass evolved by different groups (planned)
- Progenitors of given mass with different

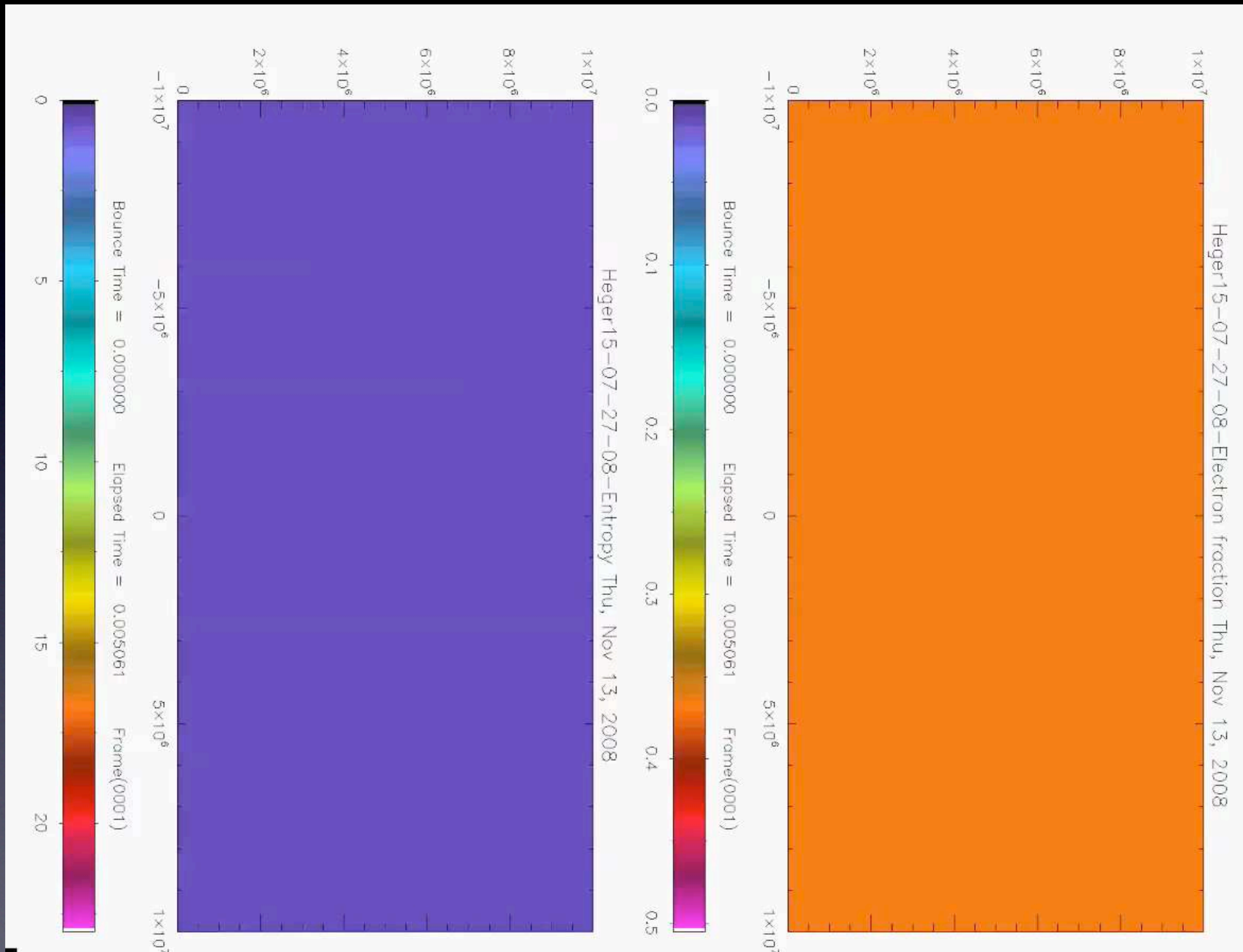
Progenitor Structure



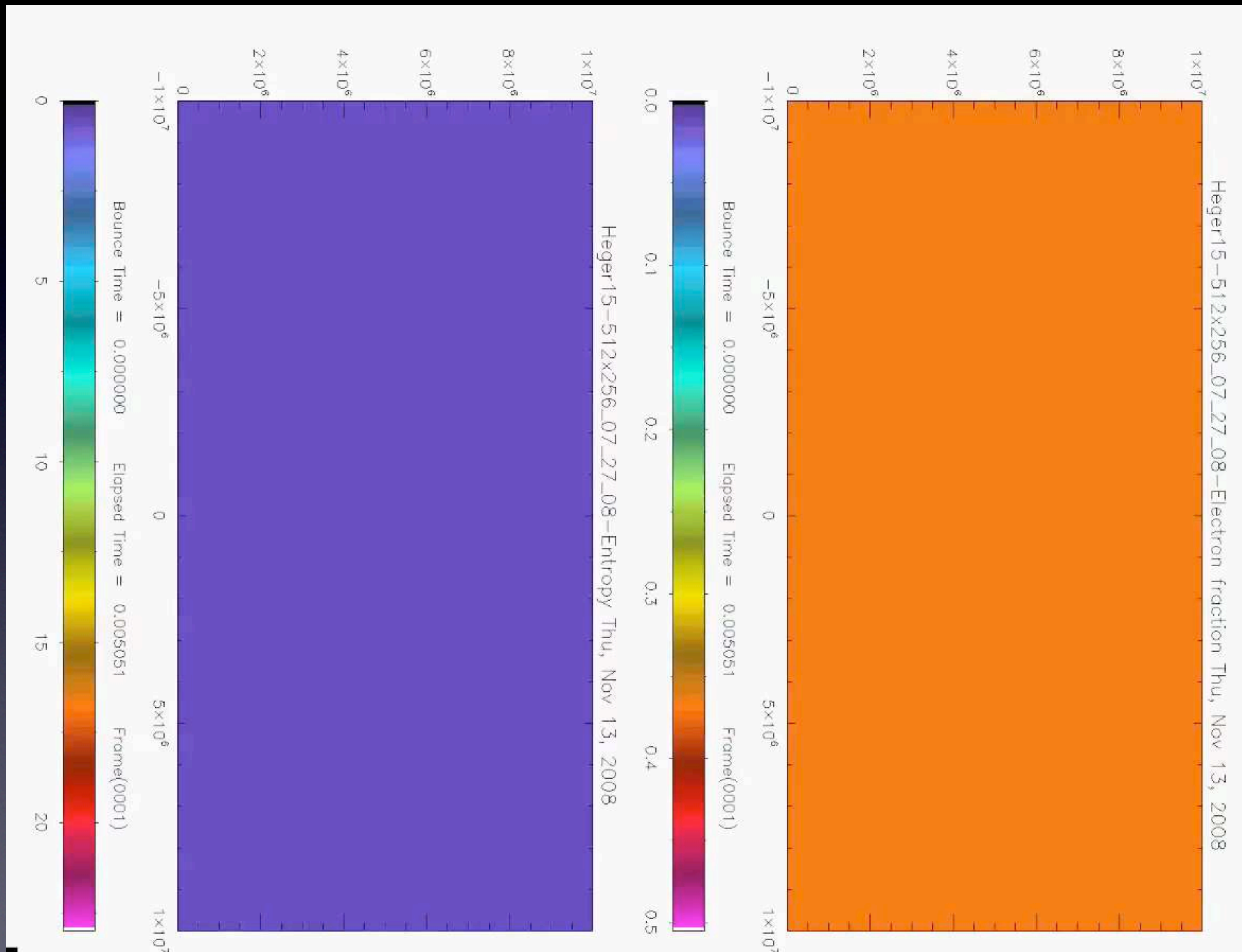
2D Model Grid and EOS

- 256 nonuniformly spaced radial zones out to 2000 km
- 256 evenly spaced angular zones from 0 to 180 degrees
- Lattimer-Swesty EOS for NSE; 17 nuclei network coupled for non-NSE; electron-positron-photon EOS everywhere
- 4 neutrino flavors, 20 energy zones from 4 to 400 MEV for each flavor

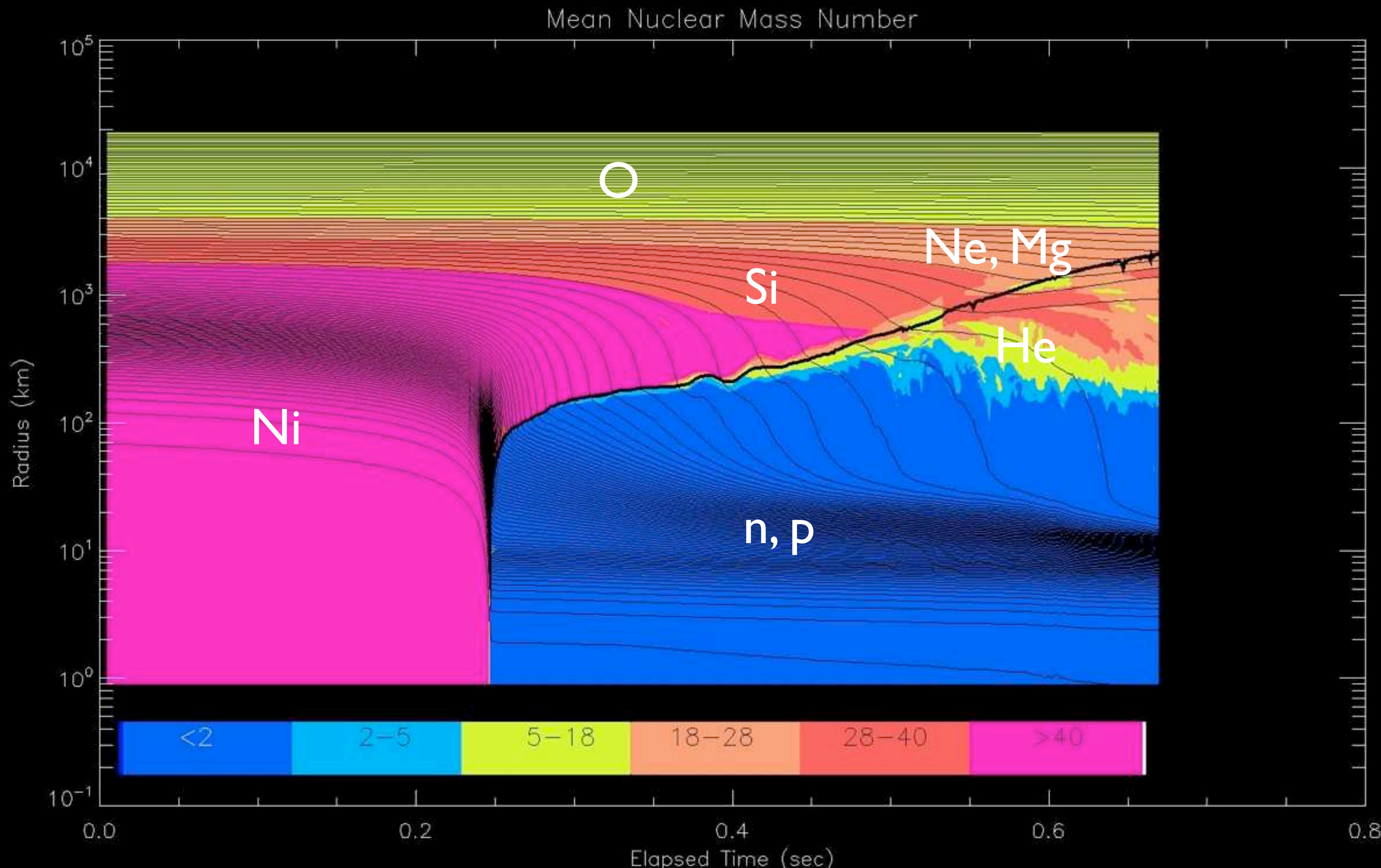
15 $M_\odot$ 2D Simulation 256x256



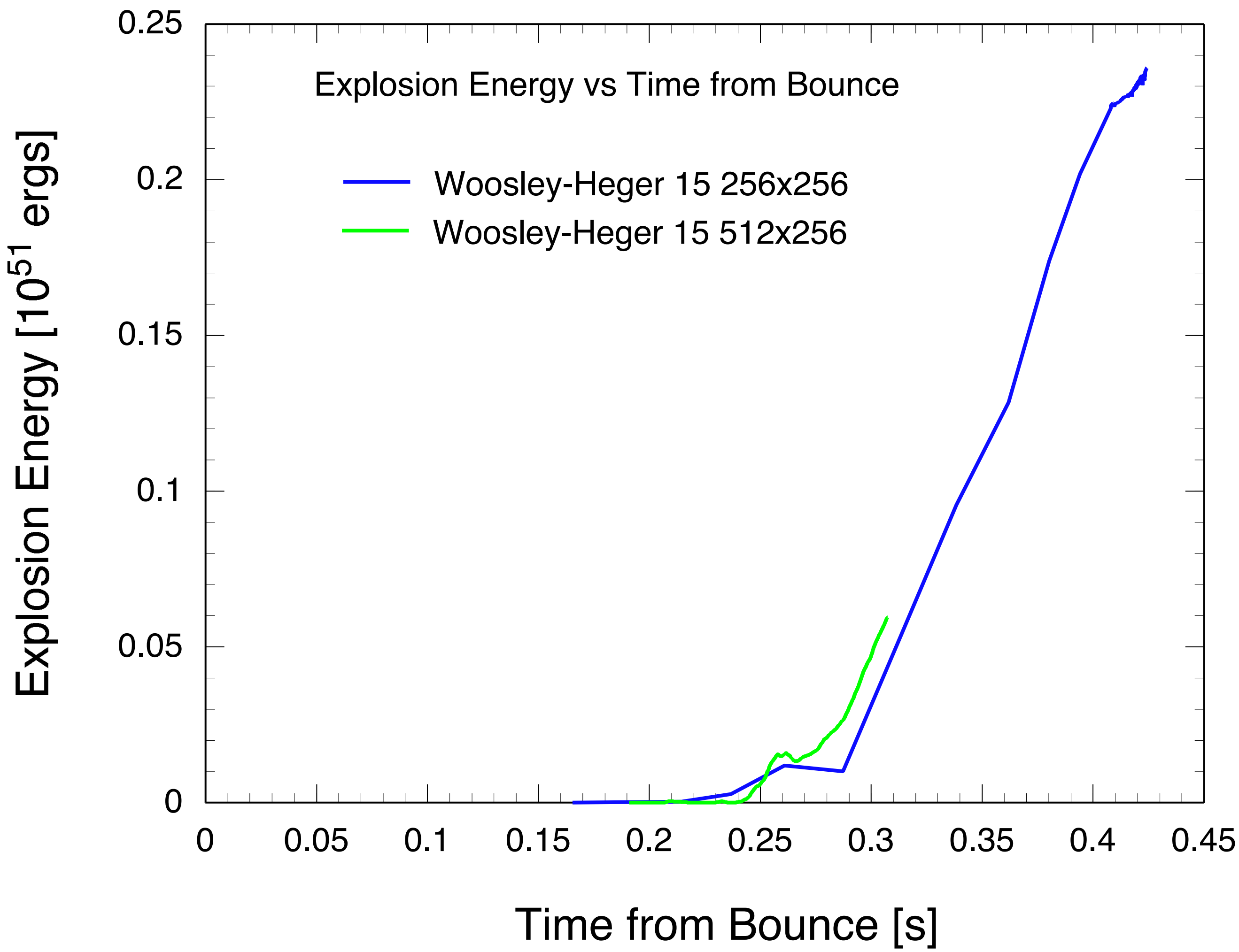
15 M☉ 2D Simulation 512x256



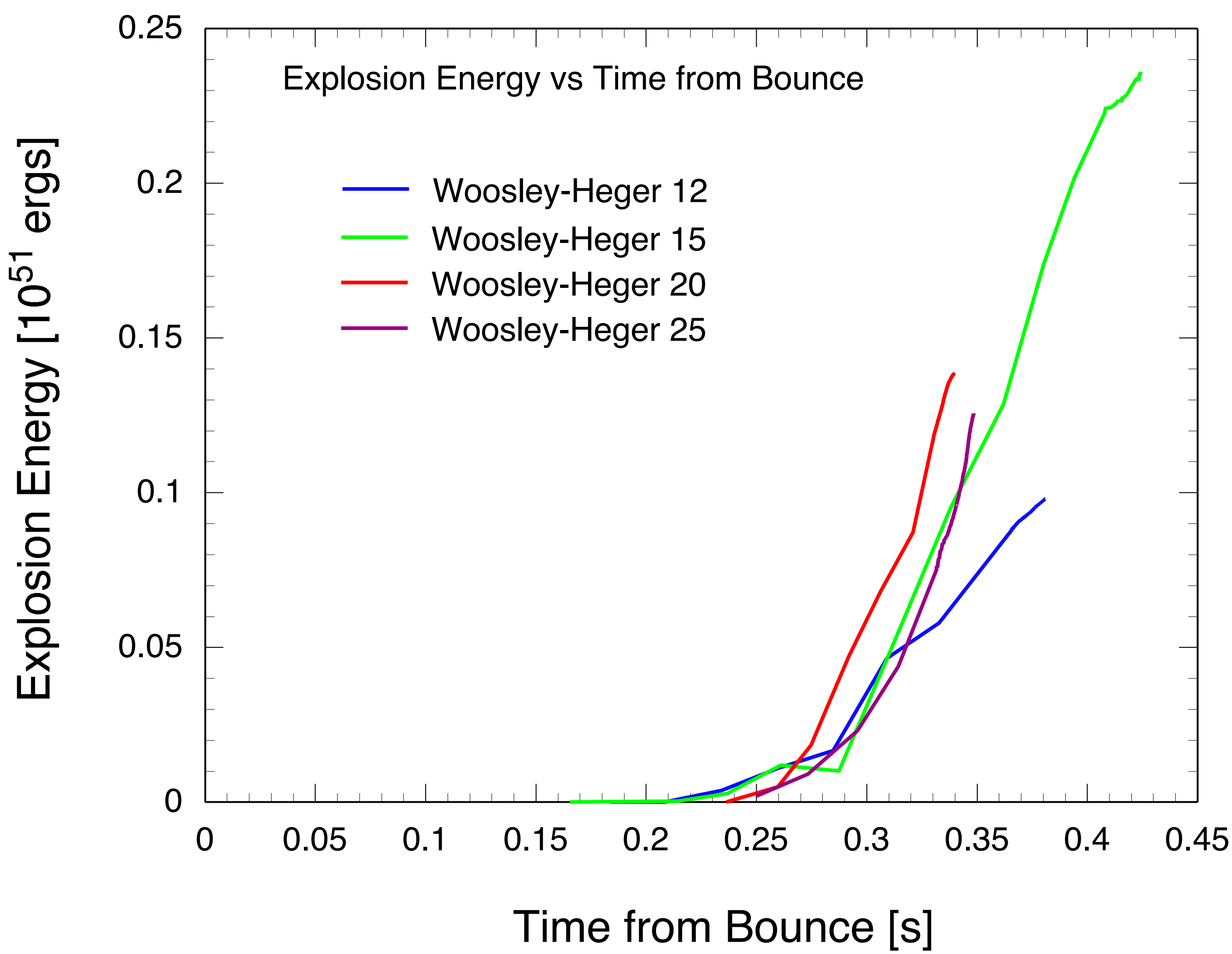
Lagrangian and Shock Trajectories



Explosion Energy vs Grid Resolution



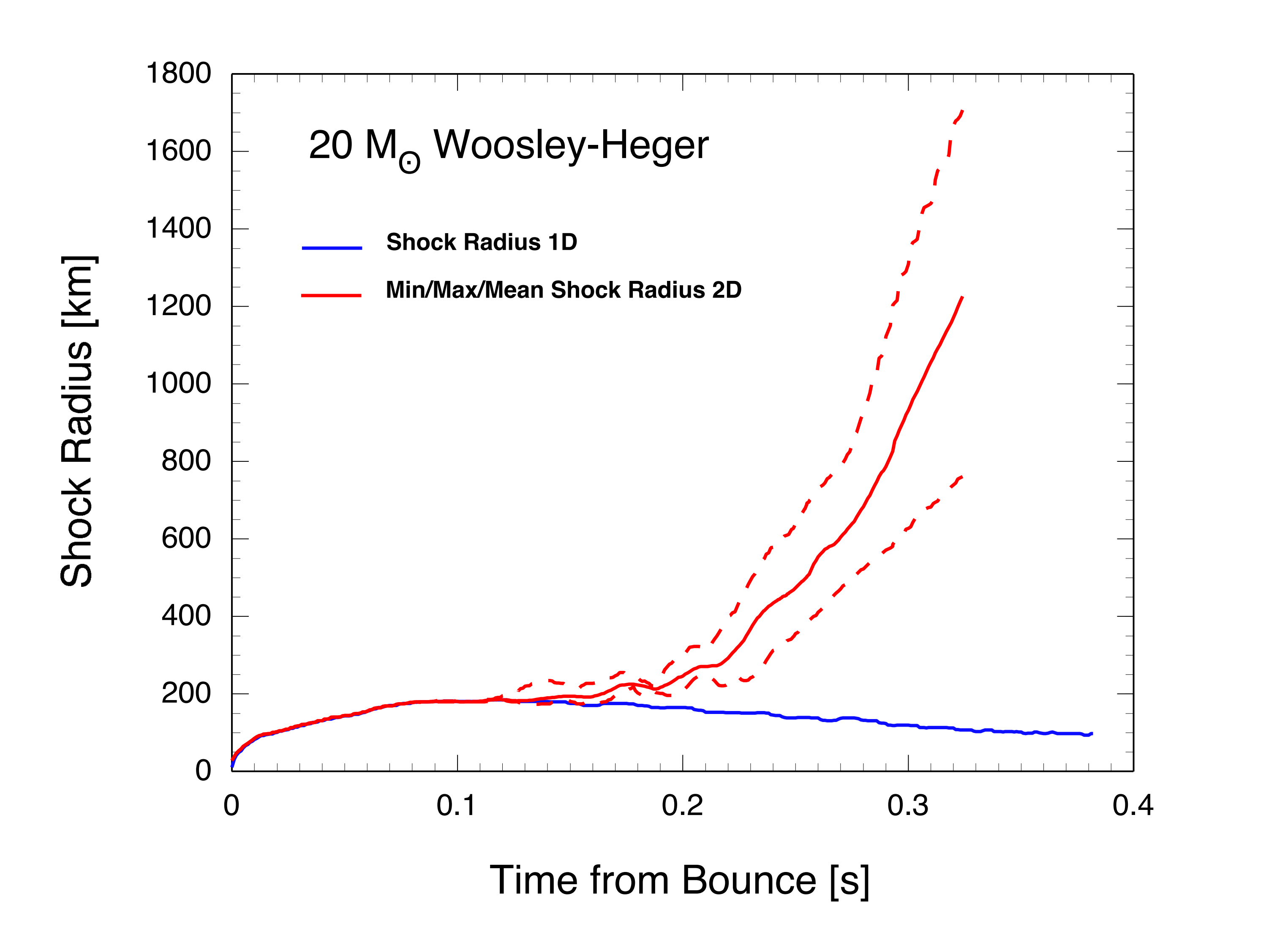
Explosion Energy vs Initial MS Mass

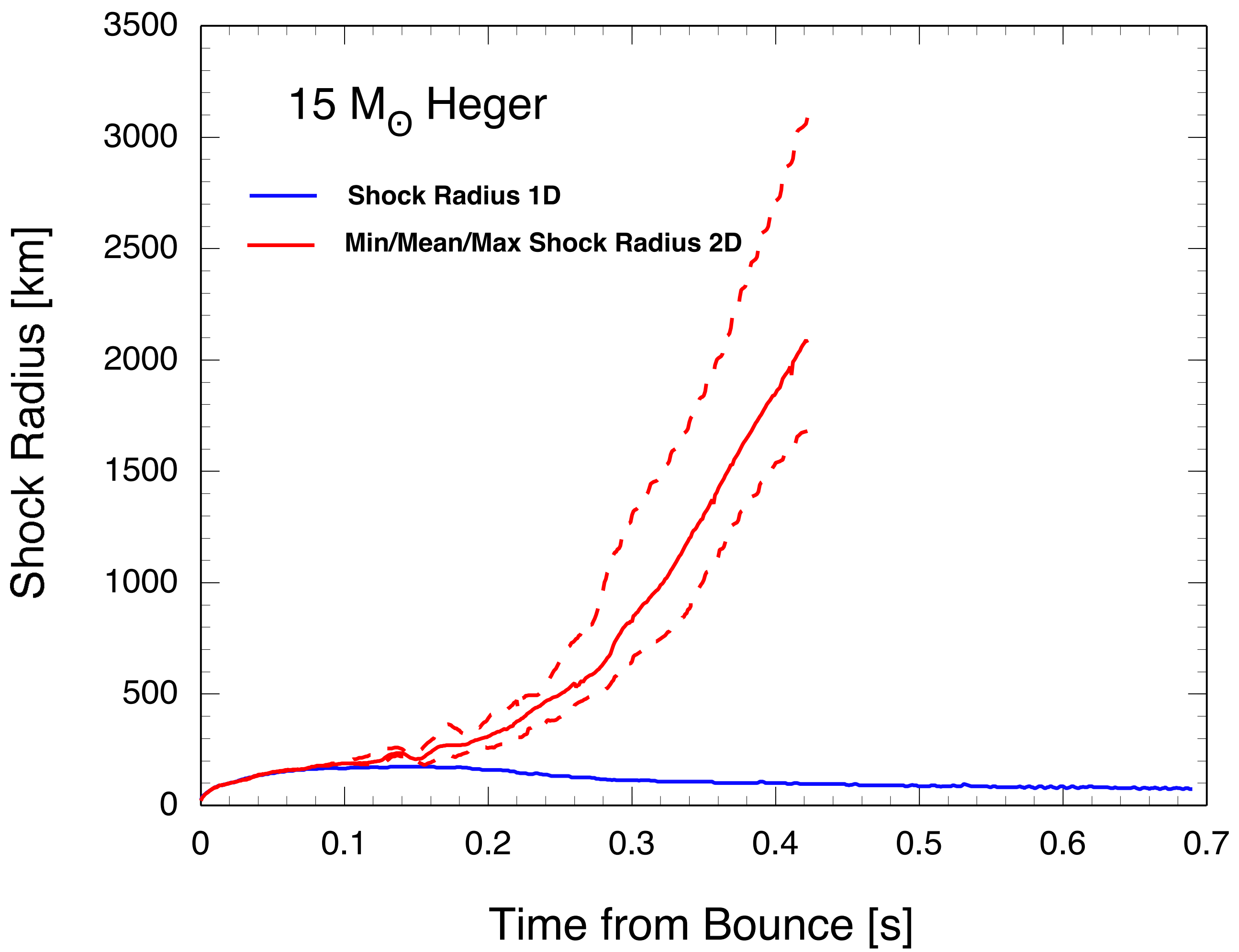


Why Are We Getting Explosions?

- Dimensional Effects:
  - Convection driven by neutrino heating
  - SASI (Standing Accretion Shock Instability)
- Improved neutrino rates
- Energy deposition by nuclear reactions

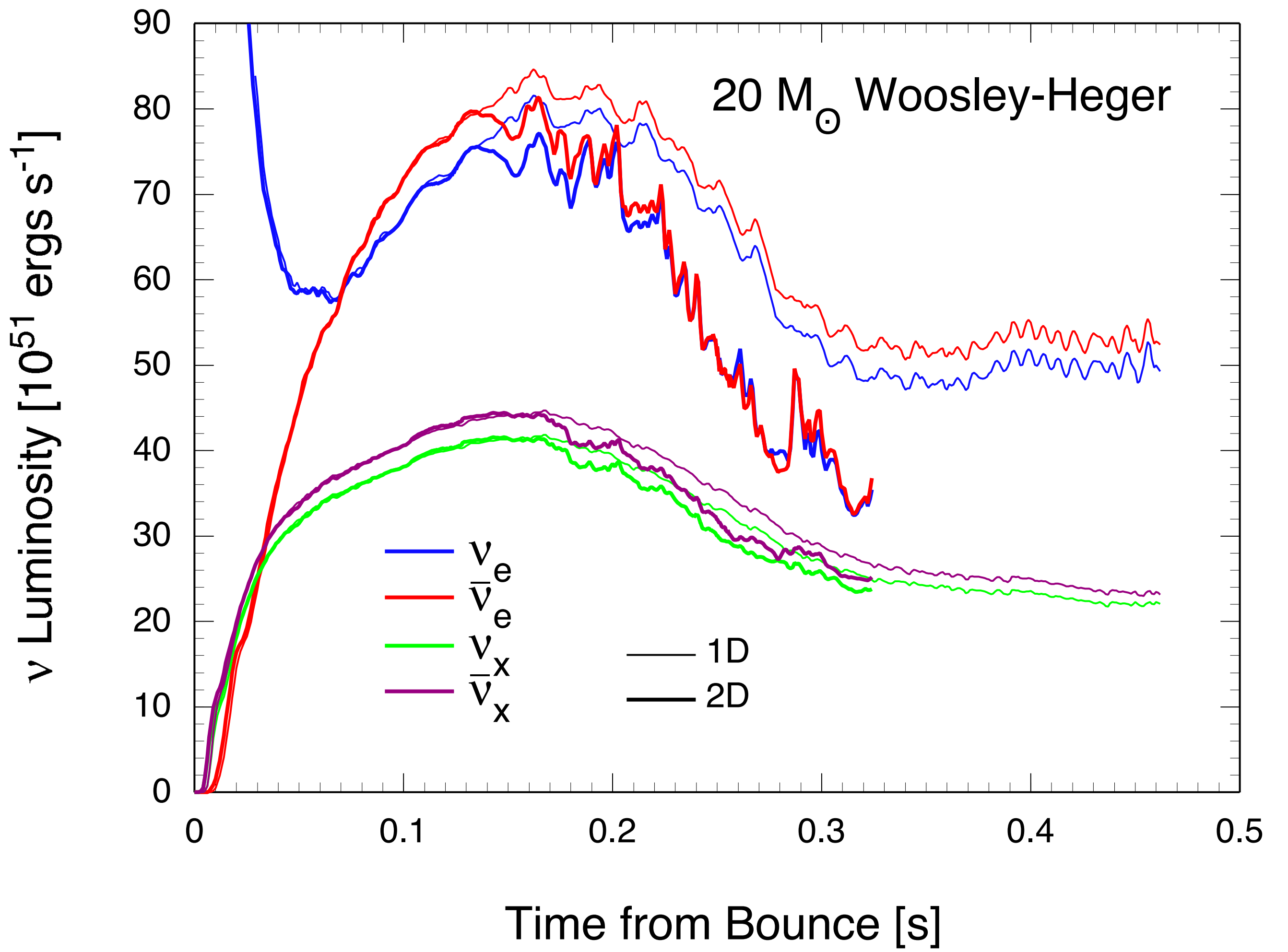
Dimensional Effects on Shock Propagation

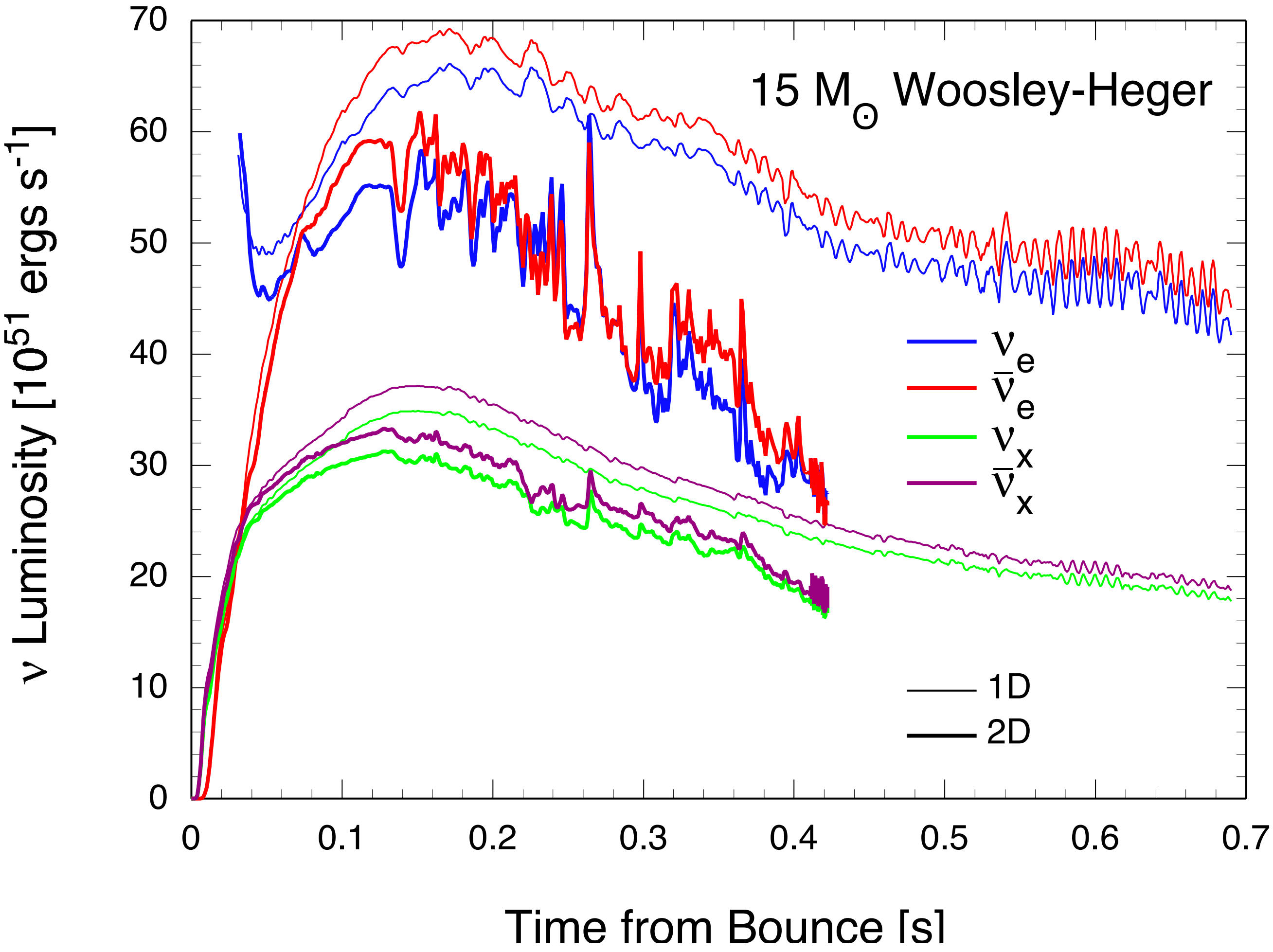




15 M$_\odot$ Heger
Shock Radius 1D
Min/Mean/Max Shock Radius 2D
Shock Radius [km]
Time from Bounce [s]
0
500
1000
1500
2000
2500
3000
3500
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

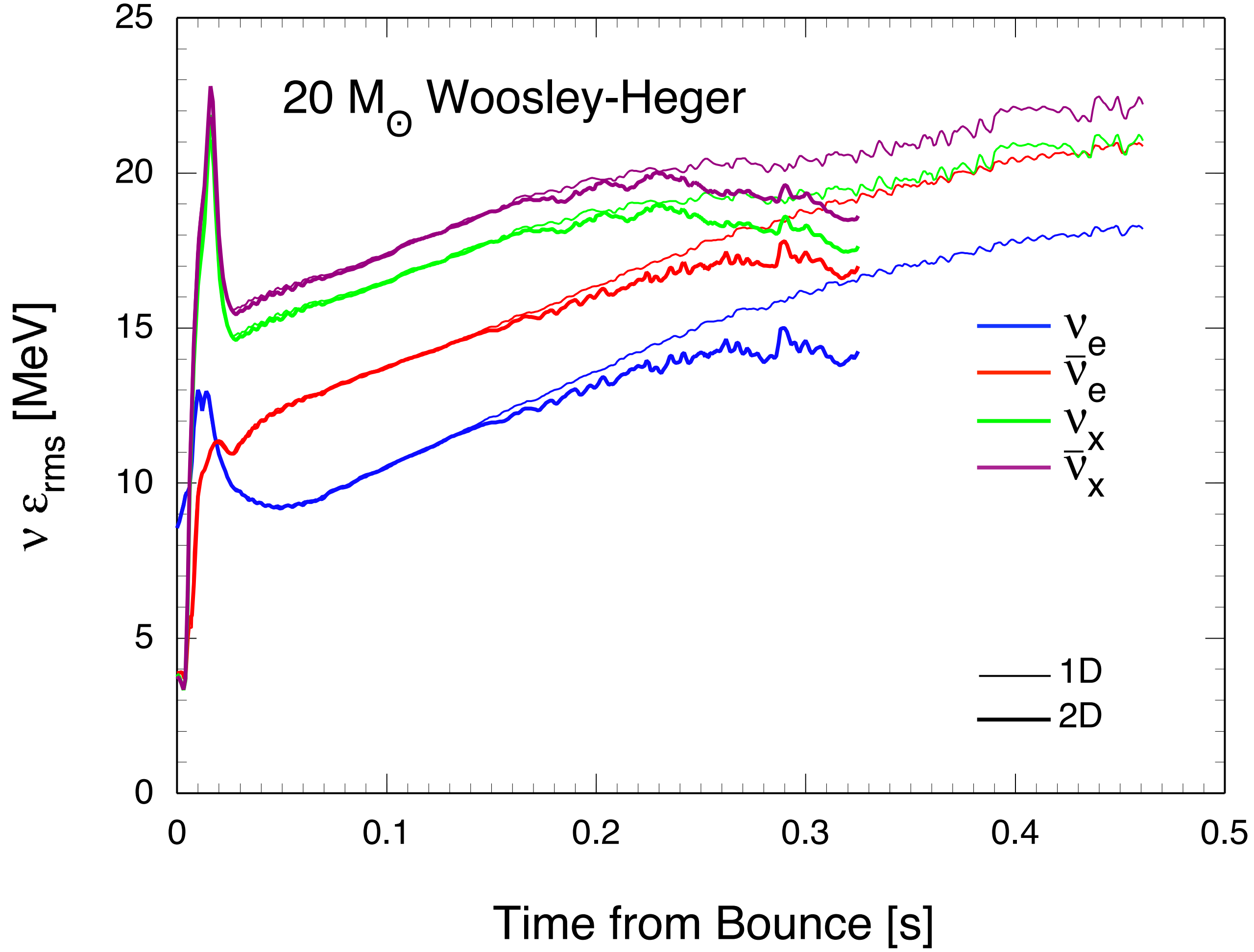
Dimensional Effects on Neutrino Luminosities

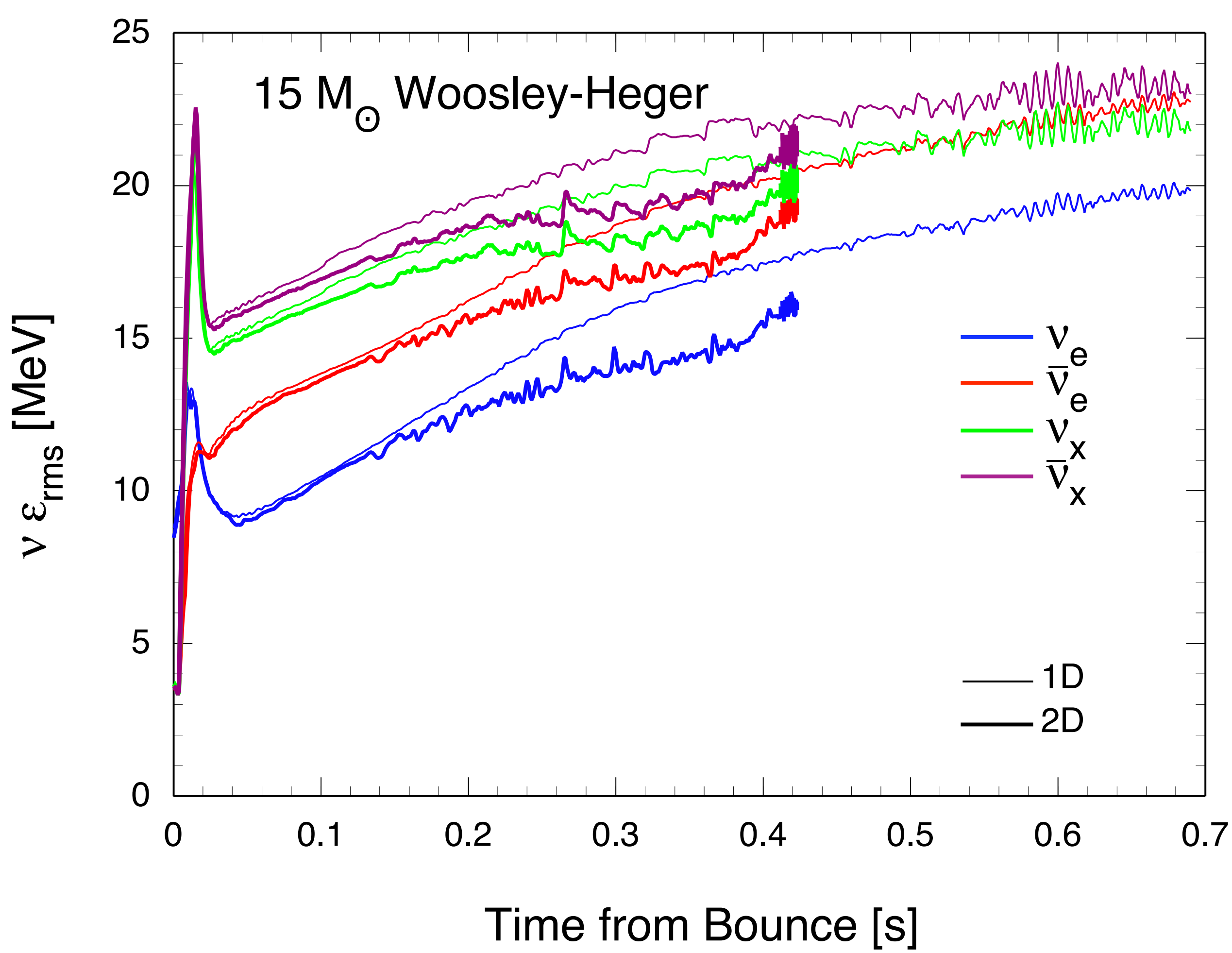




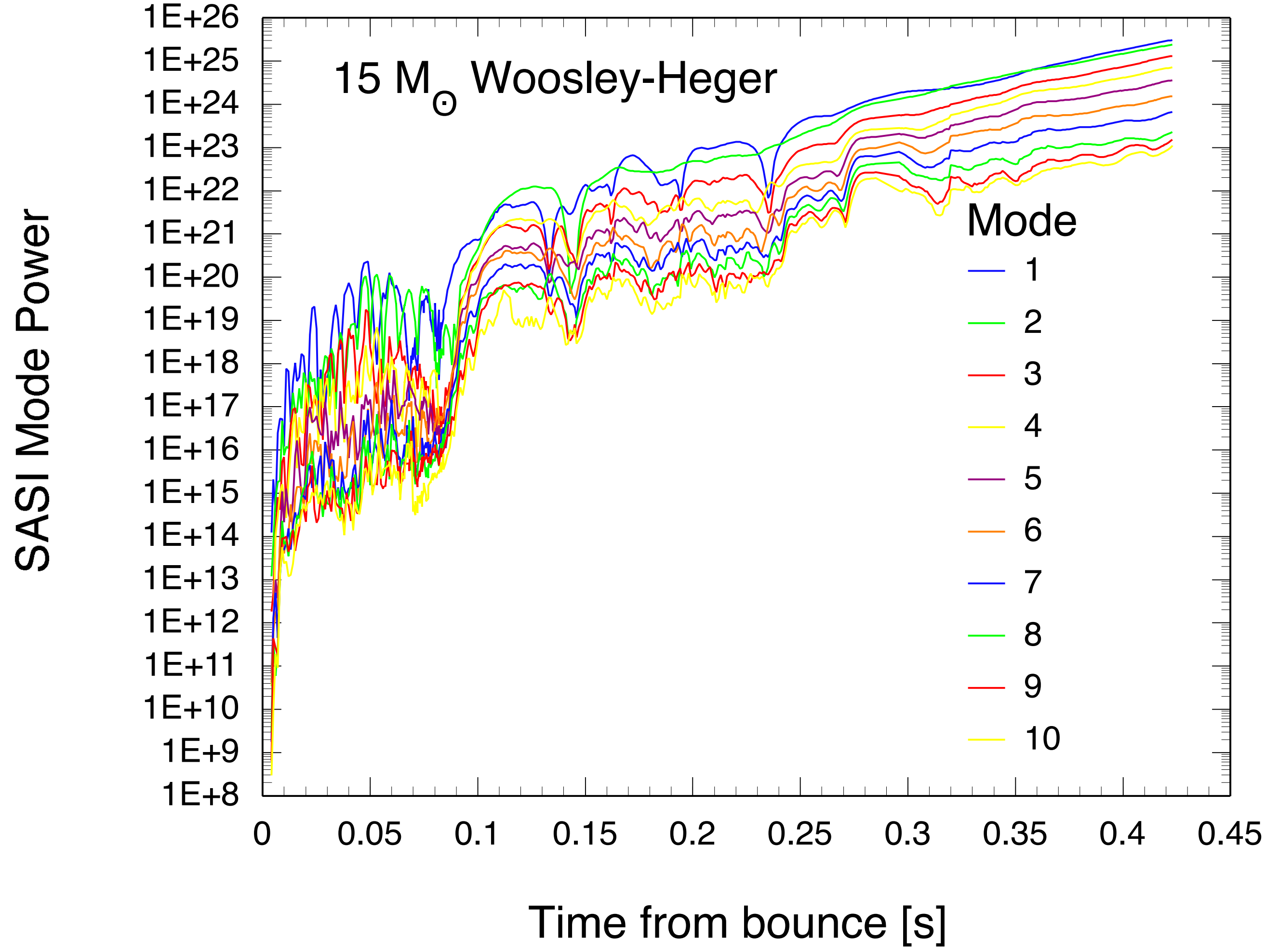
15 M⊙ Woosley-Heger
ν Luminosity [10^51 ergs s^-1]
Time from Bounce [s]
νe
ν̄e
νx
ν̄x
1D
2D
0
10
20
30
40
50
60
70
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

Dimensional Effects on Neutrino rms Energies

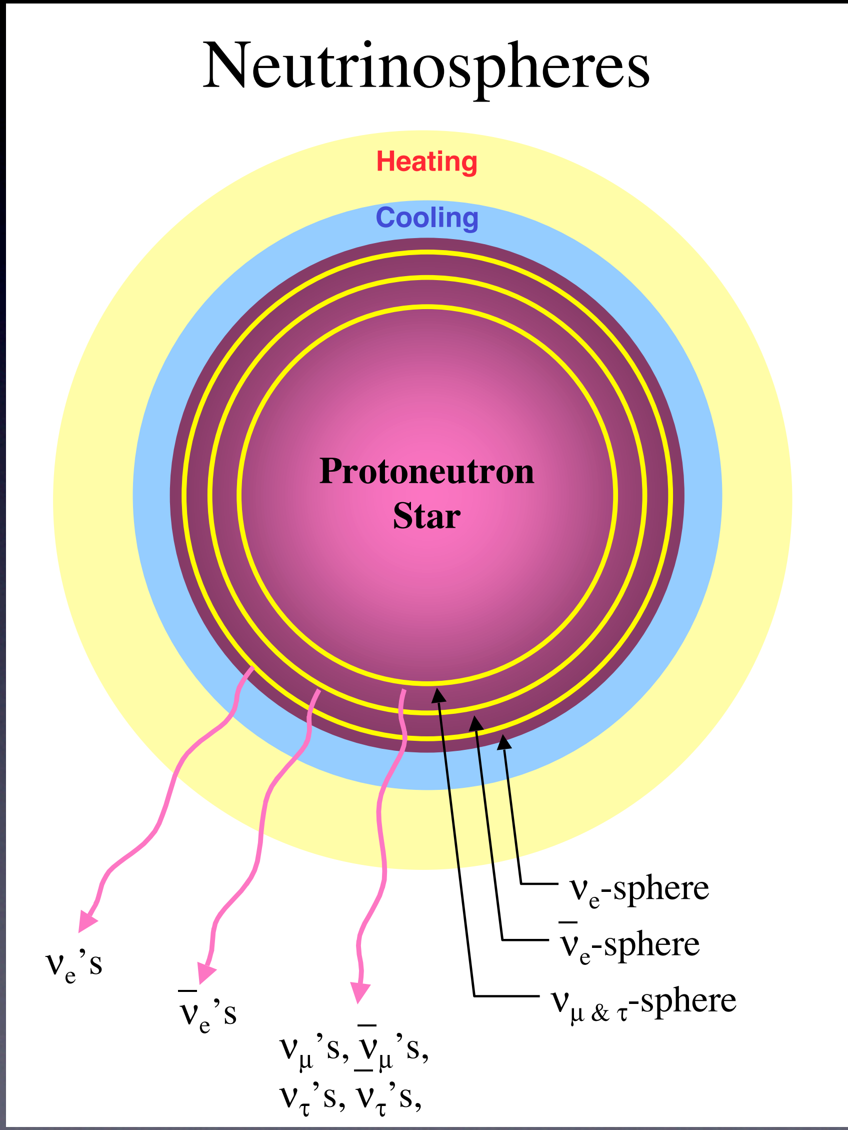



15 M☉ Woosley-Heger
ν ε_rms [MeV]
Time from Bounce [s]
0
5
10
15
20
25
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ν_e
$\bar{\nu}_e$
ν_x
$\bar{\nu}_x$
1D
2D

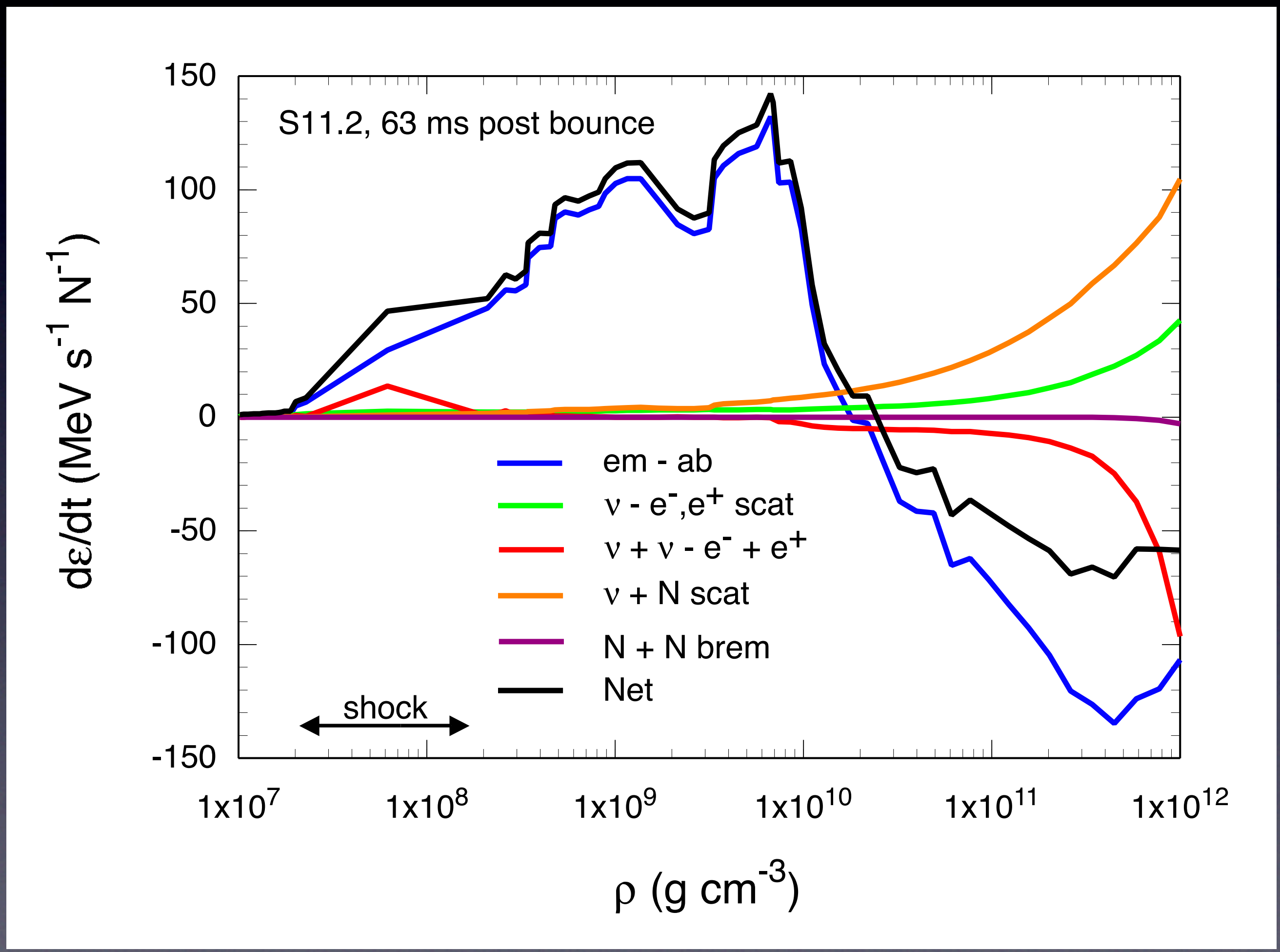
Role of the SASI



Neutrinospheres



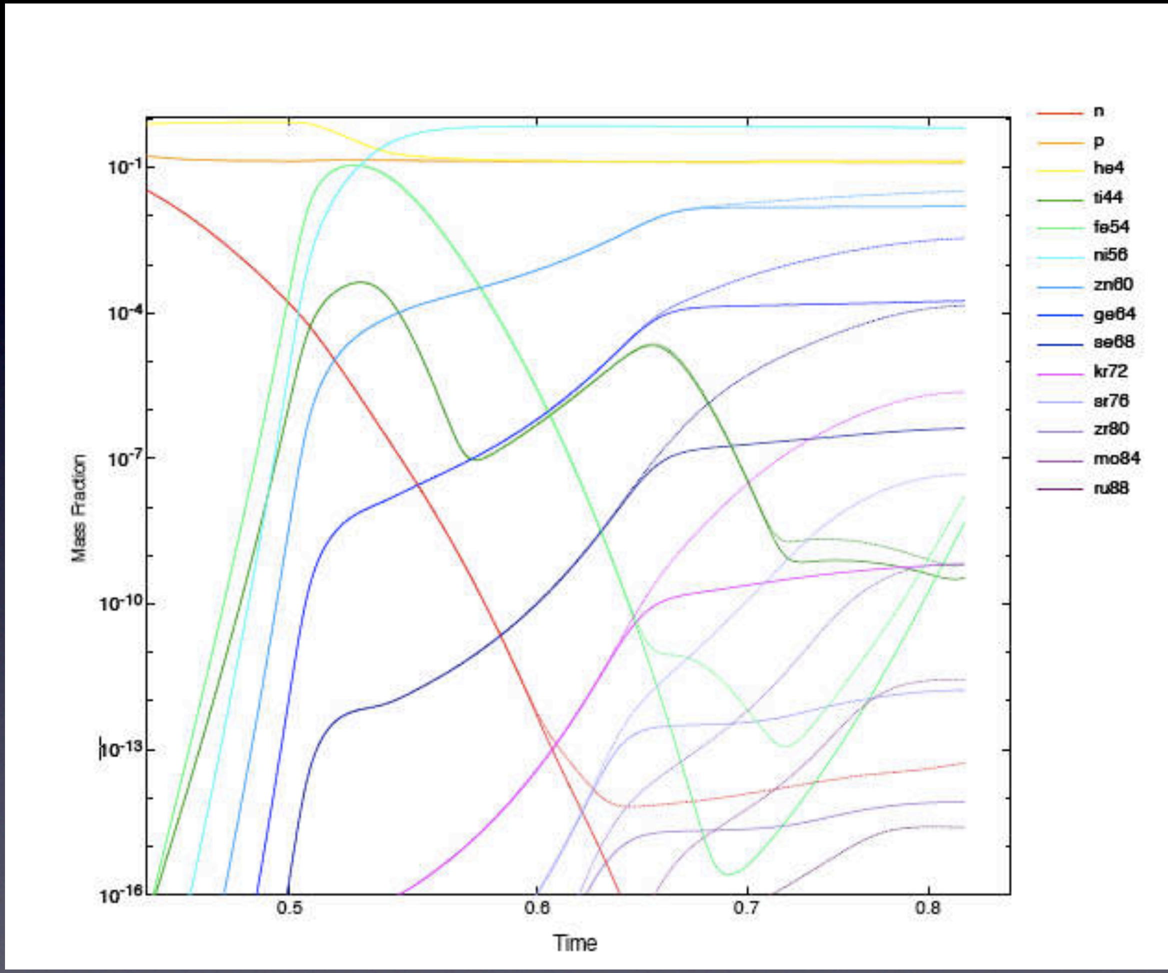
1D Supernova Simulations



ν-p Process

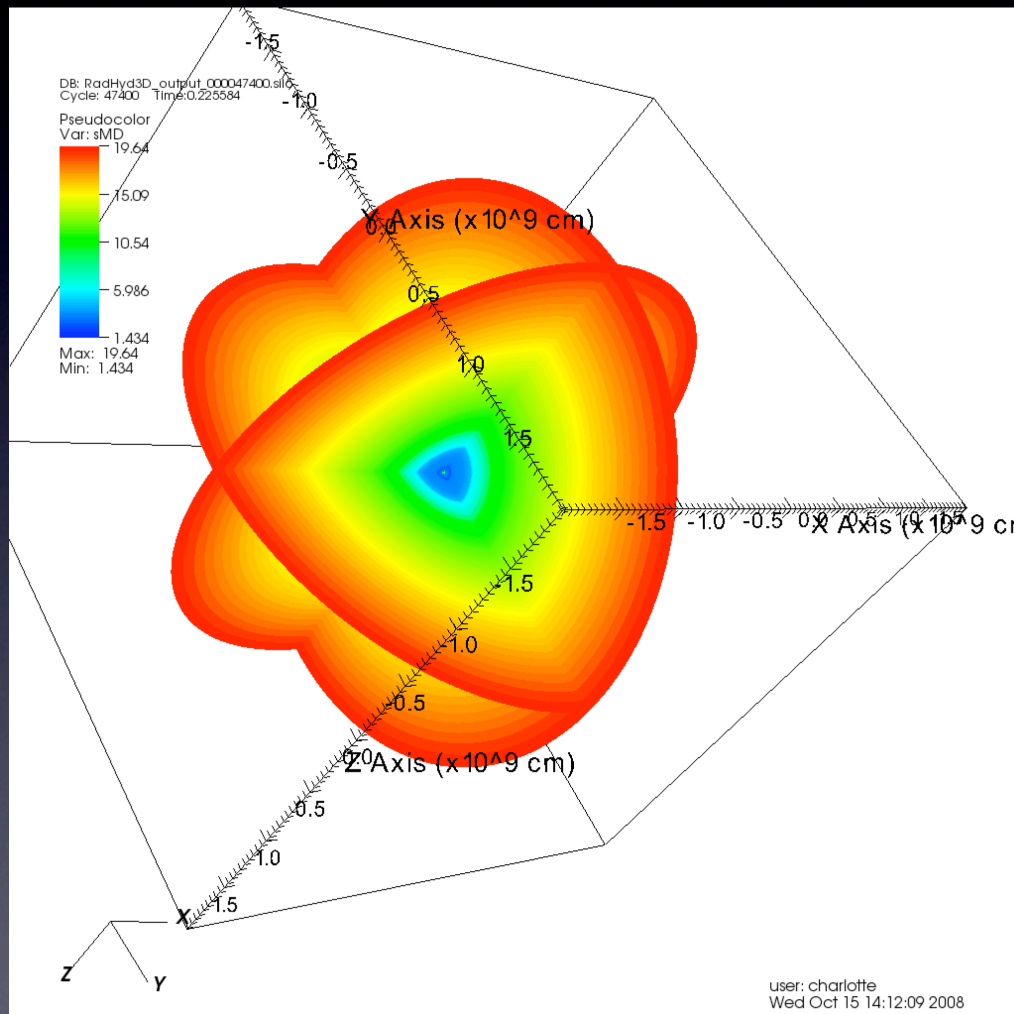
- Inclusion of neutrino interactions during nucleosynthesis opens up a new chain of nuclear reactions
  - Fröhlich, Martínez-Pinedo, Liebendörfer, Thielemann, Bravo, Hix, Langake, Zinner, PRL, 96, 142502, 2006
  - Pruet, Hoffman, Woosley, Janka, Buras, ApJ, 644, 1028, 2006
- Neutrino absorption on proton rich material creates residual neutron abundance [$\bar{\nu}_{\mathrm{e}} + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^{+}$]
- Neutron captures on proton-rich seeds bypasses the ^{64}Ge bottleneck

Example ν-p Process

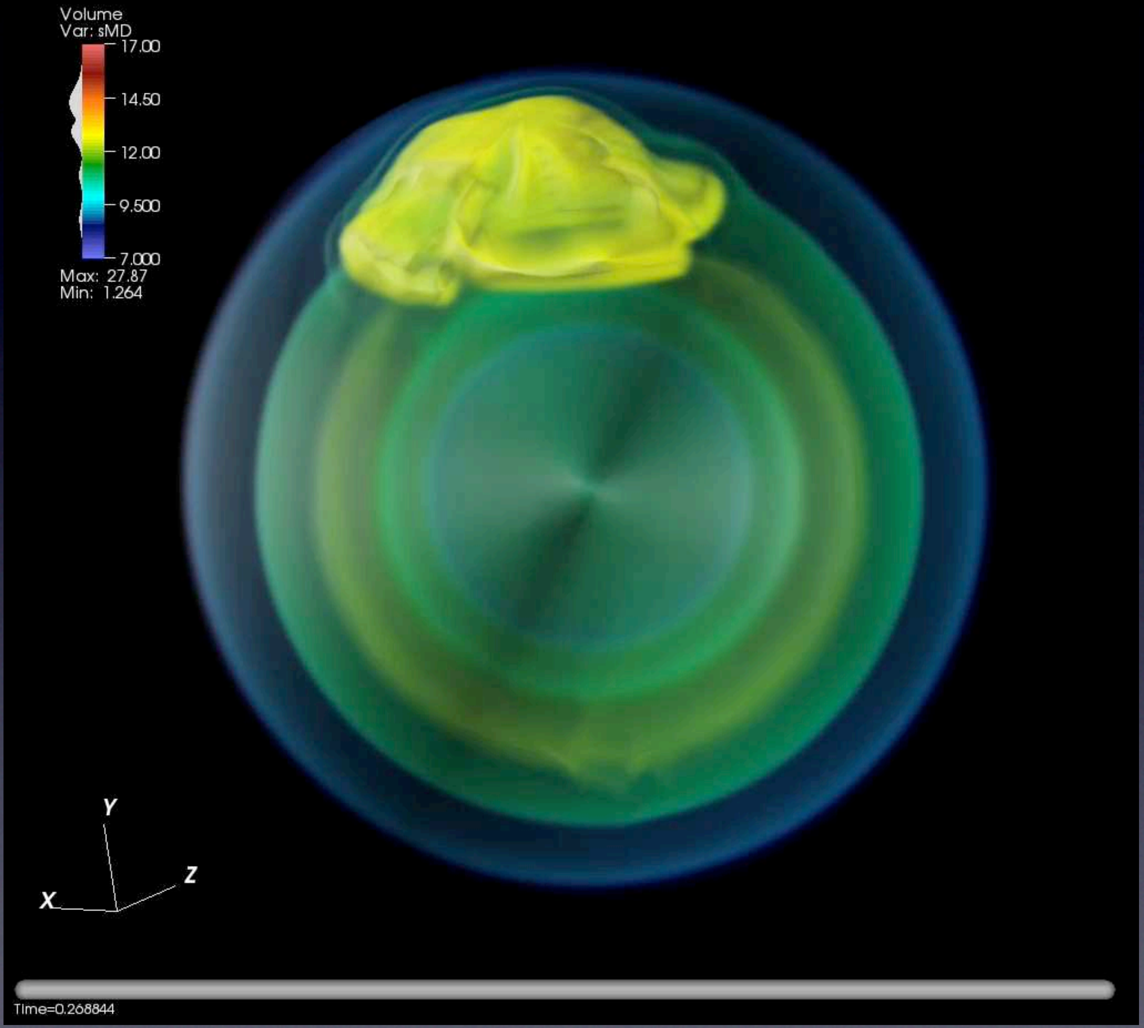


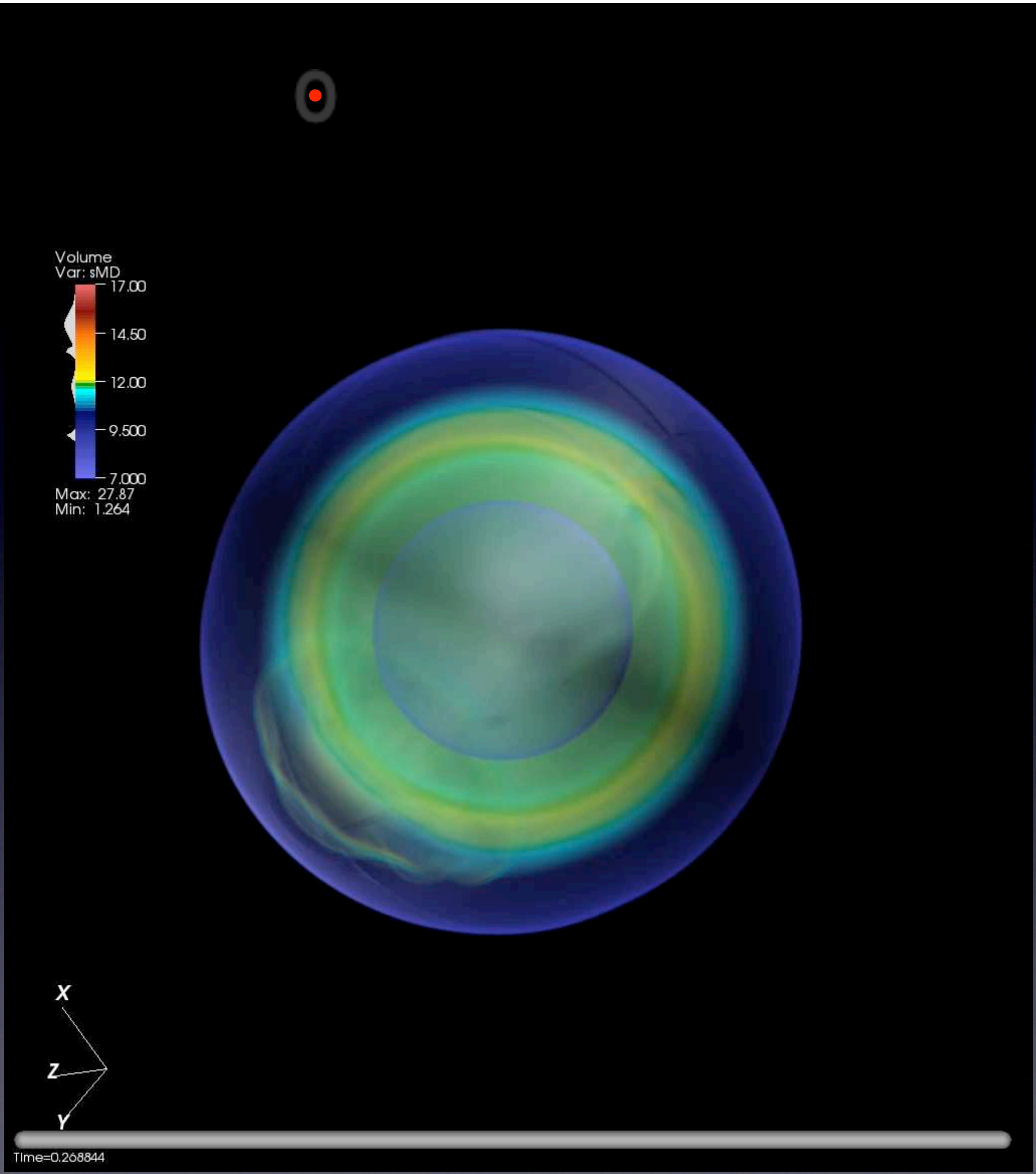
3D 15 $M_\odot$ Model Simulation

- 304 nonuniformly spaced radial zones out to 2000 km
- 78 evenly spaced angular zones from 0 to 180 degrees
- 156 evenly spaced azimuthal zones from 0 to 360 degrees
- 4 neutrino flavors, 20 energy zones from 4 to 400 MEV for each flavor
- Requires 11,552 processors

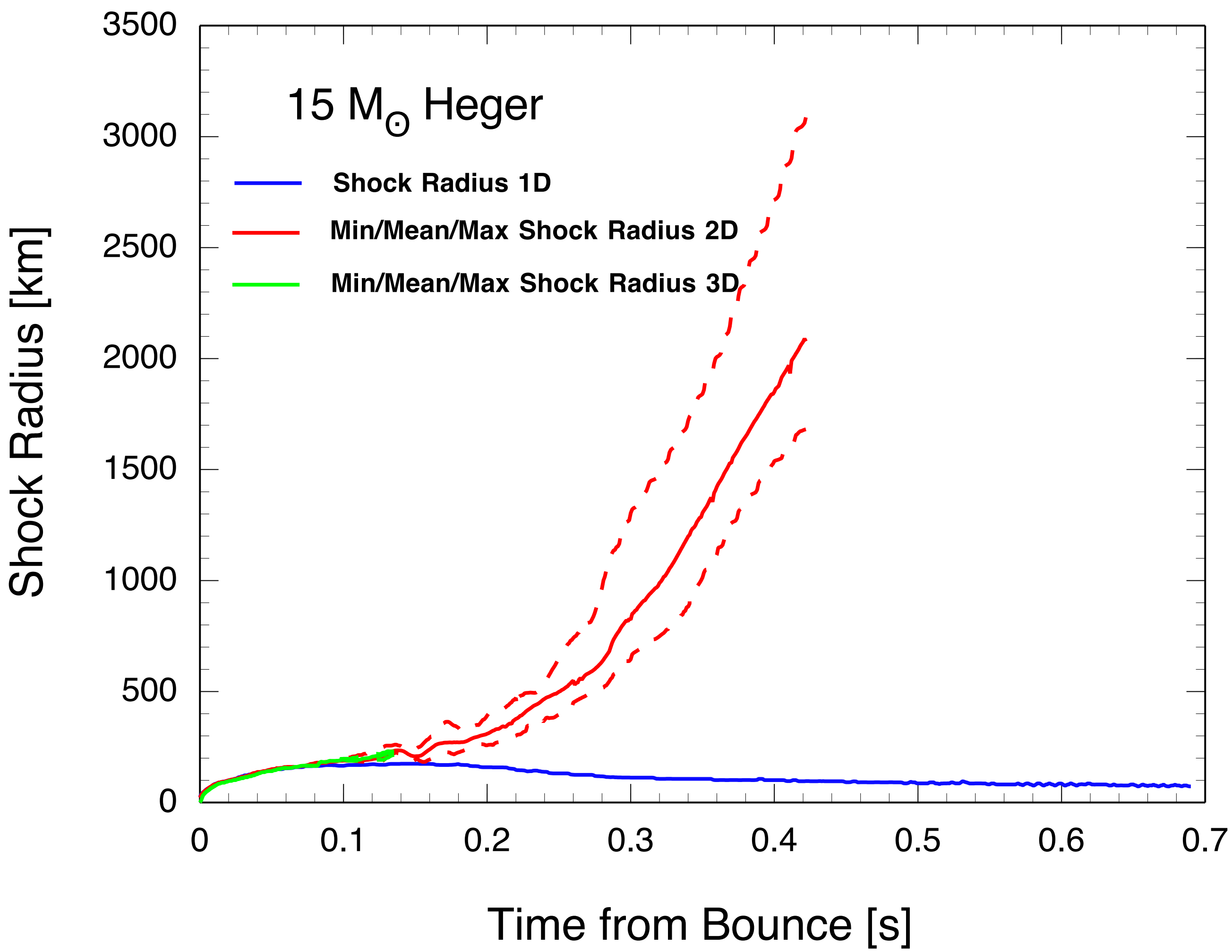

DB: RadHyd3D_output_000047400.silo
Cycle: 47400 Time:0.225584
Pseudocolor
Var: sMD
19.64
15.09
10.54
5.986
1.434
Max: 19.64
Min: 1.434
Y Axis (x 10^9 cm)
X Axis (x 10^9 cm)
Z Axis (x 10^9 cm)
user: charlotte
Wed Oct 15 14:12:09 2008

3D 15 $M_\odot$ Model Simulation




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

Comparison of Shock Trajectories



Conclusions

- 2D simulations with spectral neutrino transport exhibit explosions for each of the Woosley-Heger 12, 15, 20, & 25 solar mass models. 3D simulation in progress.

- The explosion energy may be directly correlated with the mass of the progenitor.

- However, comparisons of the 2D simulations with other groups have yet to show a convergence of results.

Work in Progress

- Investigate the observables of the exploding models---nucleosynthesis, neutrino and gravitational wave signatures, neutron star masses and kick velocities
- Use a singularity-free grid
- Incorporate magnetic fields

The End

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