

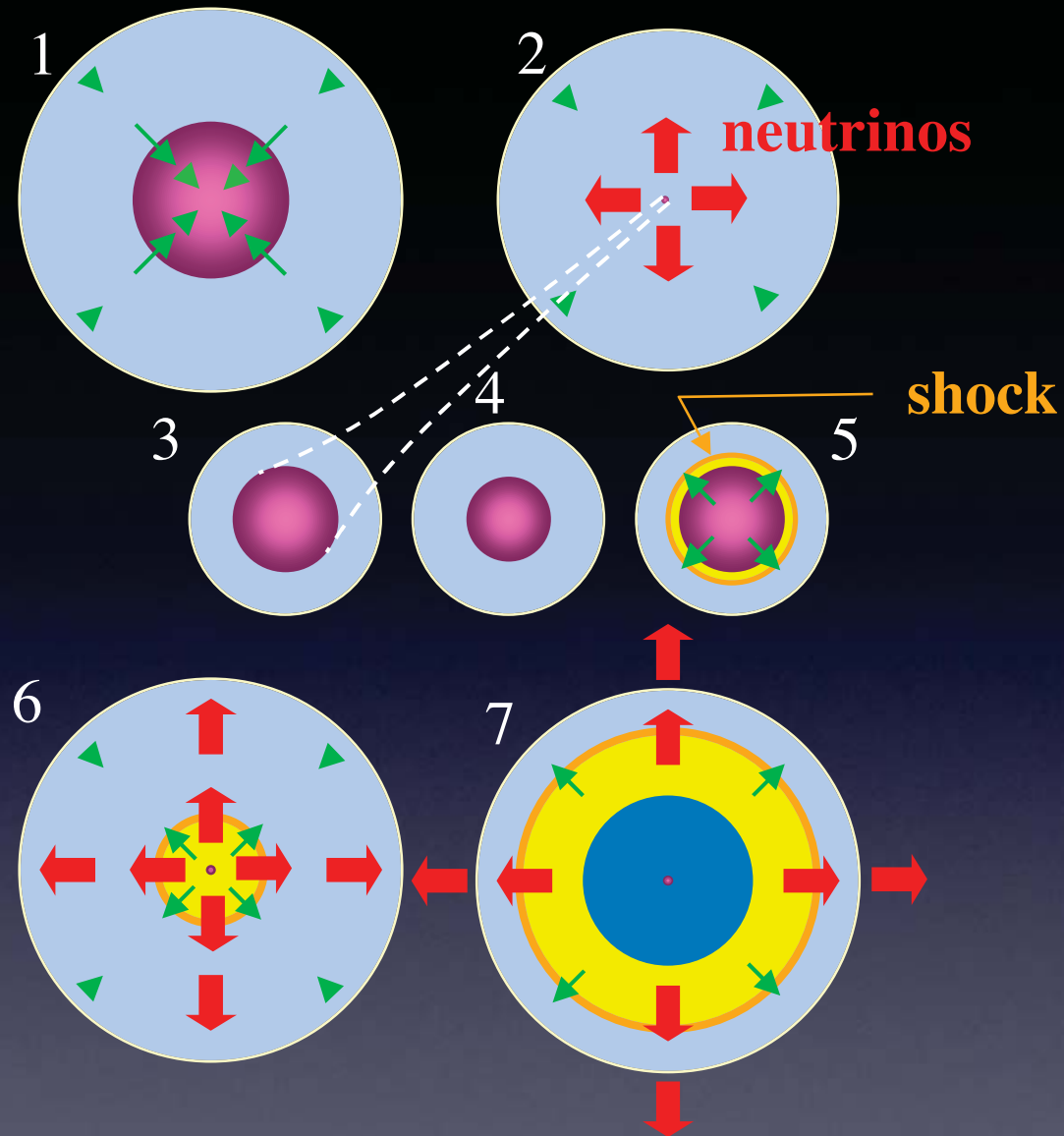
Recent 2D/3D Core-Collapse Supernovae Simulations Results Obtained with the CHIMERA Code



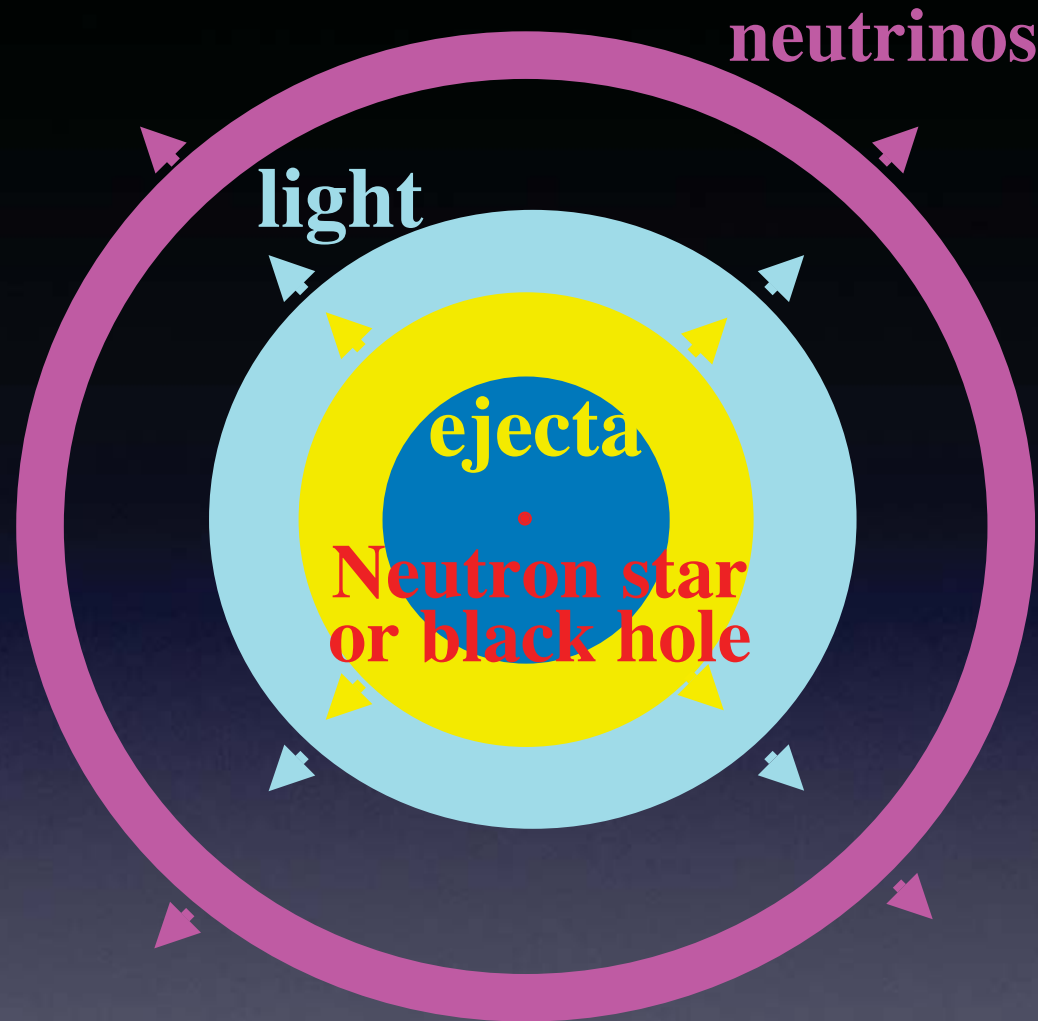
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Santa Fe WorkShop, July 10, 09

Core Collapse Supernovae 101



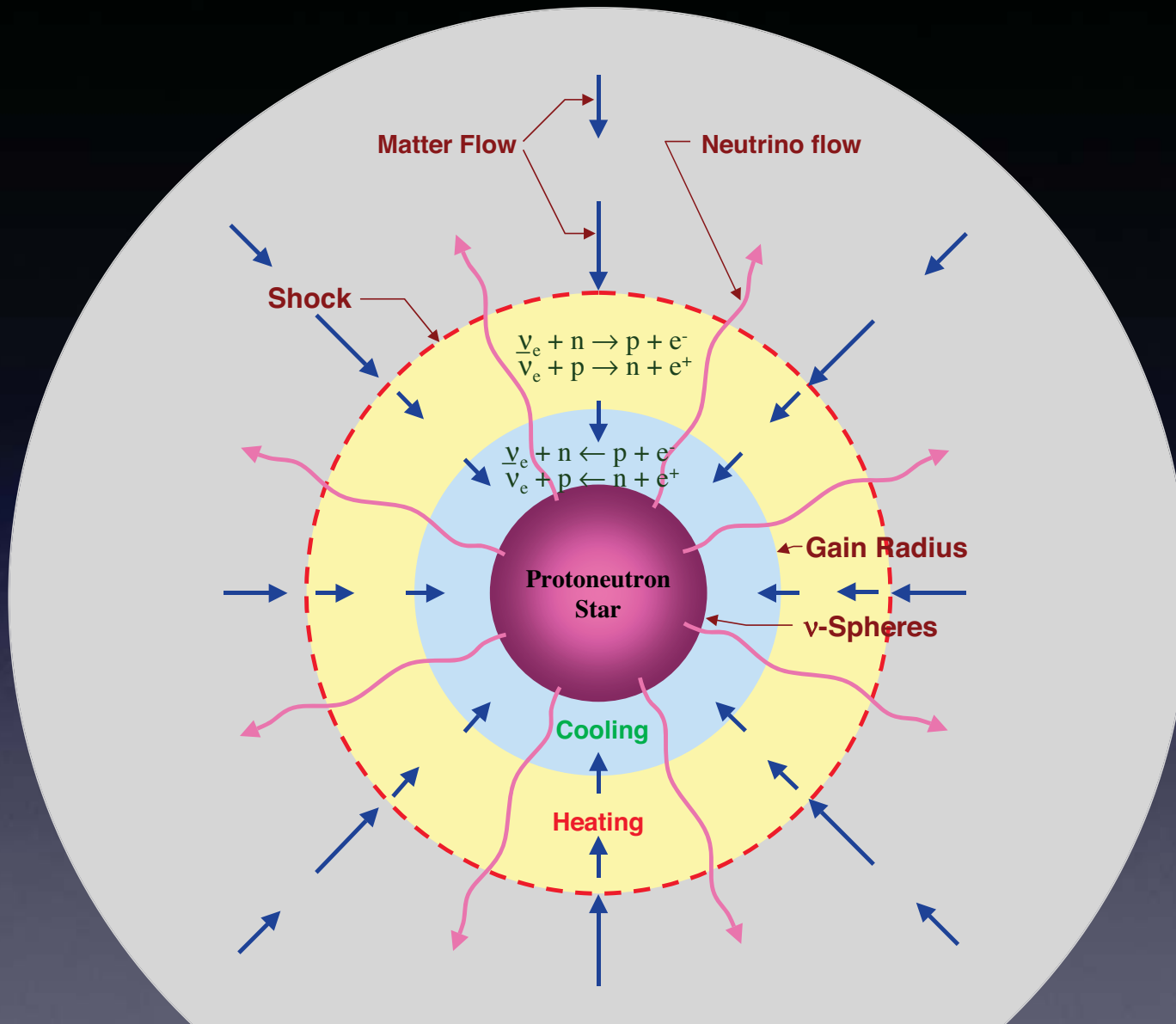
Core Collapse Supernovae 101



Core Collapse Supernova Energetics

- Photons $\sim 10^{49}$ ergs
- Ejecta Kinetic energy $\sim 10^{50} - 10^{52}$ ergs
- Neutrinos $\sim 3 \times 10^{53}$ ergs

The Spherically Symmetric Cul de Sac



Core Collapse Supernova Asymmetries

- Polarization
 - Core collapse SN are polarized at $\sim 1\%$ level
 - Degree of polarization increases with decreasing envelope mass
 - Degree of polarization generally increases after optical maximum
- Outward mixing of Ni in SNI987 A & Cas A
- Axisymmetric ejecta of SNI987A
- Early Emission of x-rays and gamma-rays from SNI987A

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 Mechanism

- 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

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

- Predicted rotational rates of newly formed neutron stars

- 3 - 15 ms (Heger, Woosley & Spruit, 2005)

- Extrapolated periods of newly formed pulsars

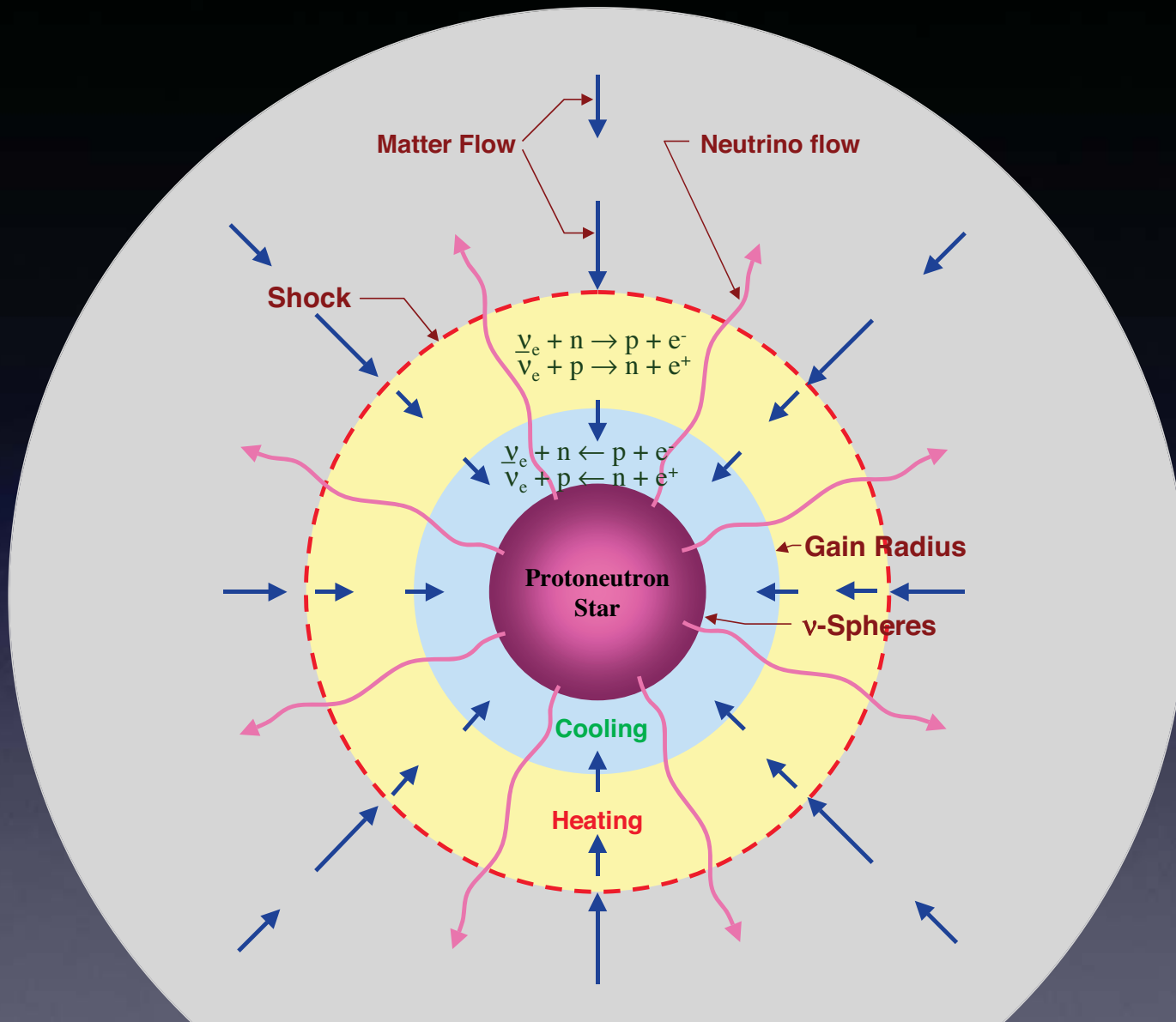
- Crab: 21 ms
- PSR J0537-6910 10 ms
- PSR B0540-69 39 ms
- PSR B1509-58 20 ms

- Problem: Need rapid rotation (not observed or predicted)

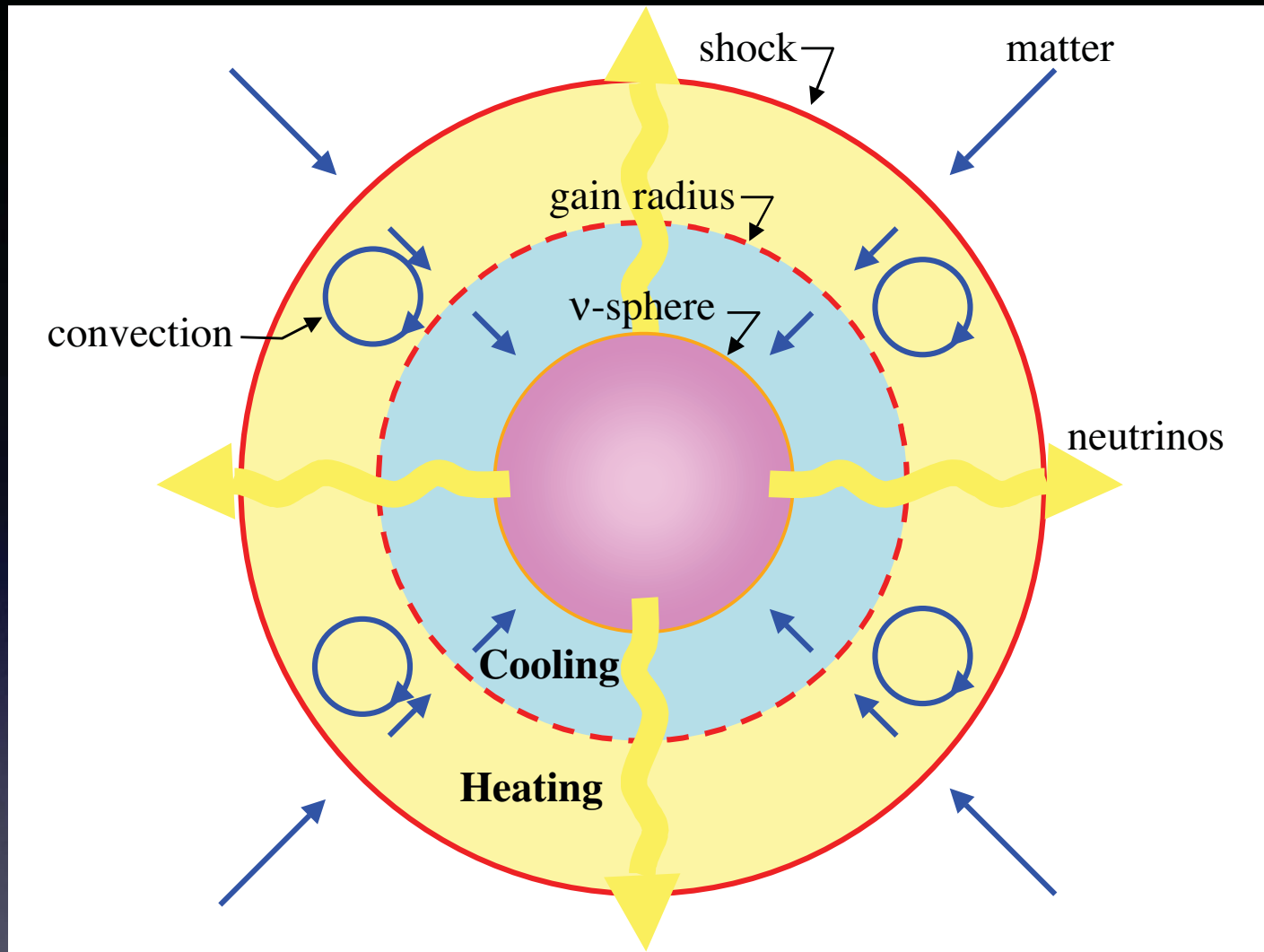
Acoustic Mechanism

- 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

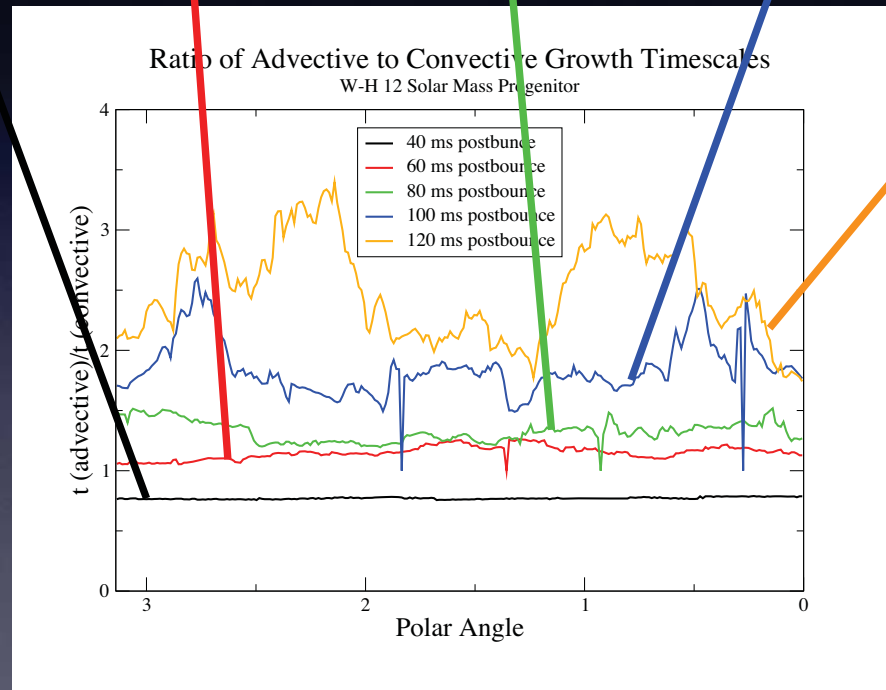
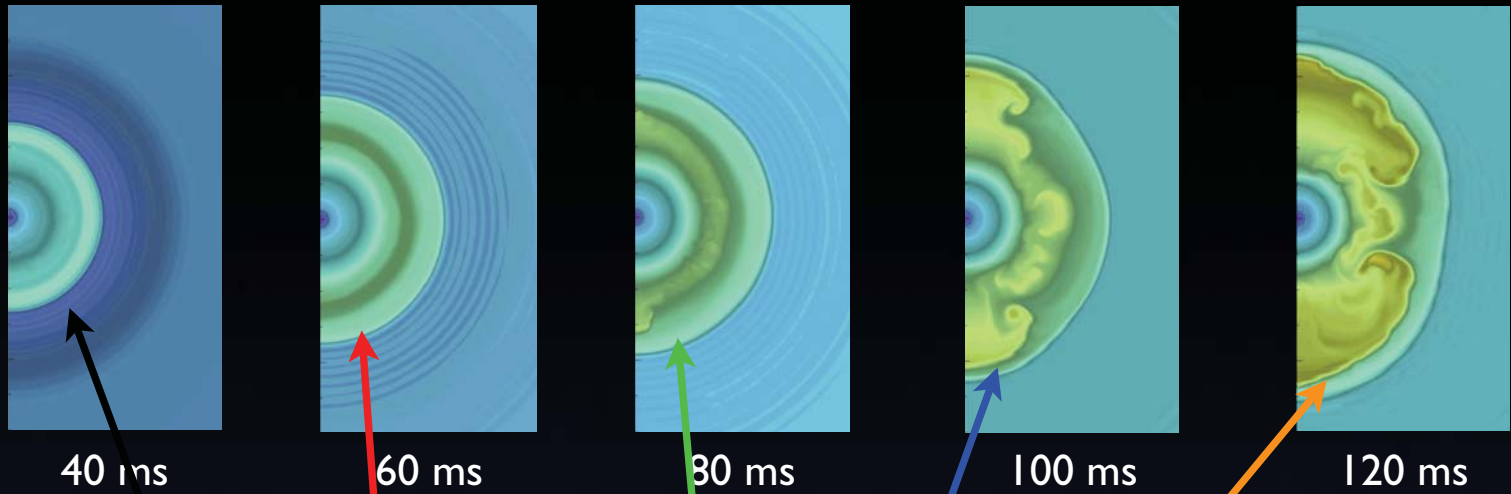
Neutrino Transport Mechanism



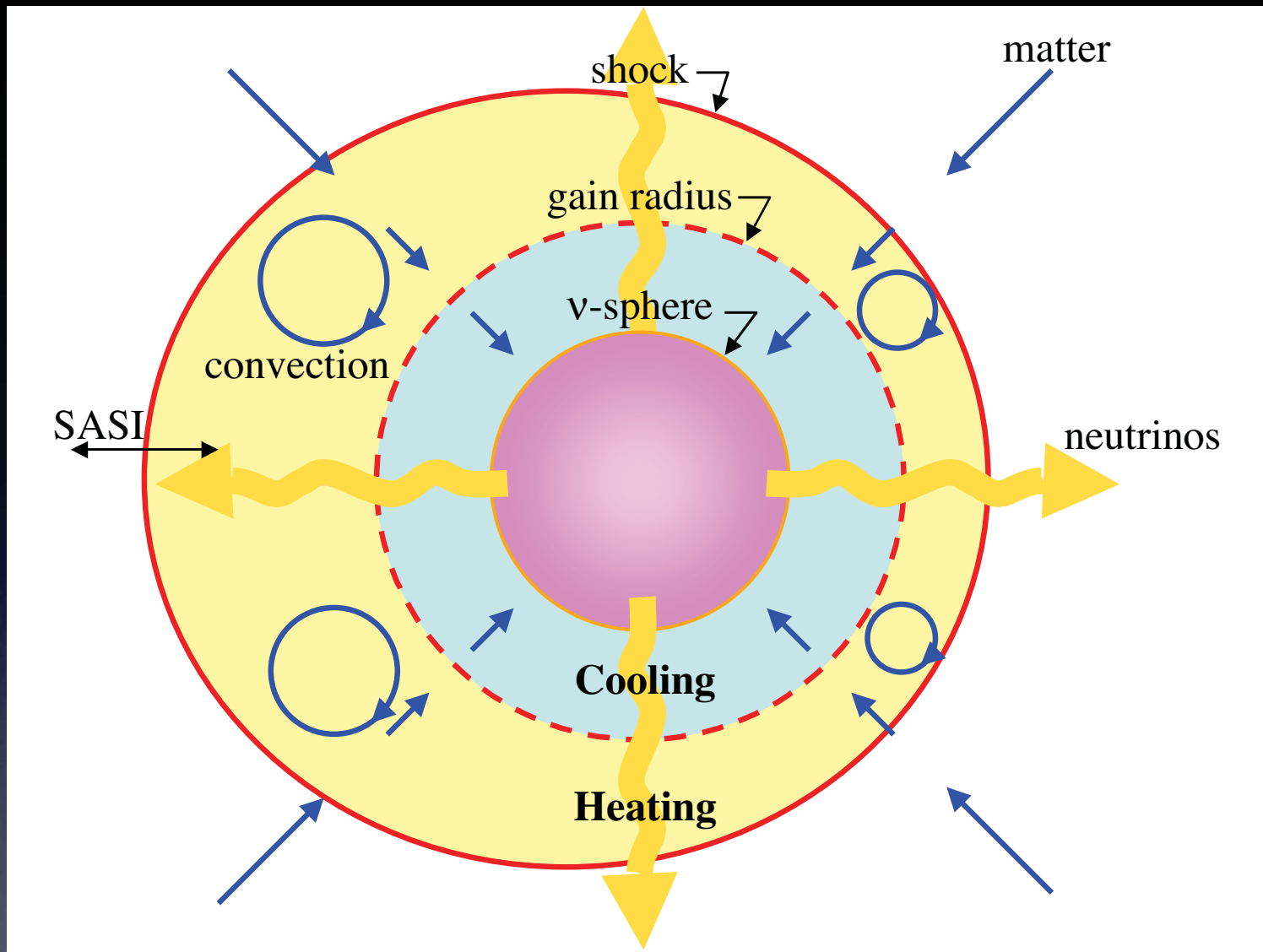
Onset of Neutrino Driven Convection



Onset of Neutrino Driven Convection (12 M_o Progenitor)



The Standing Accretion Shock Instability (SASI)



CHIMERA Code 1D, 2D, and 3D

Hydrodynamics

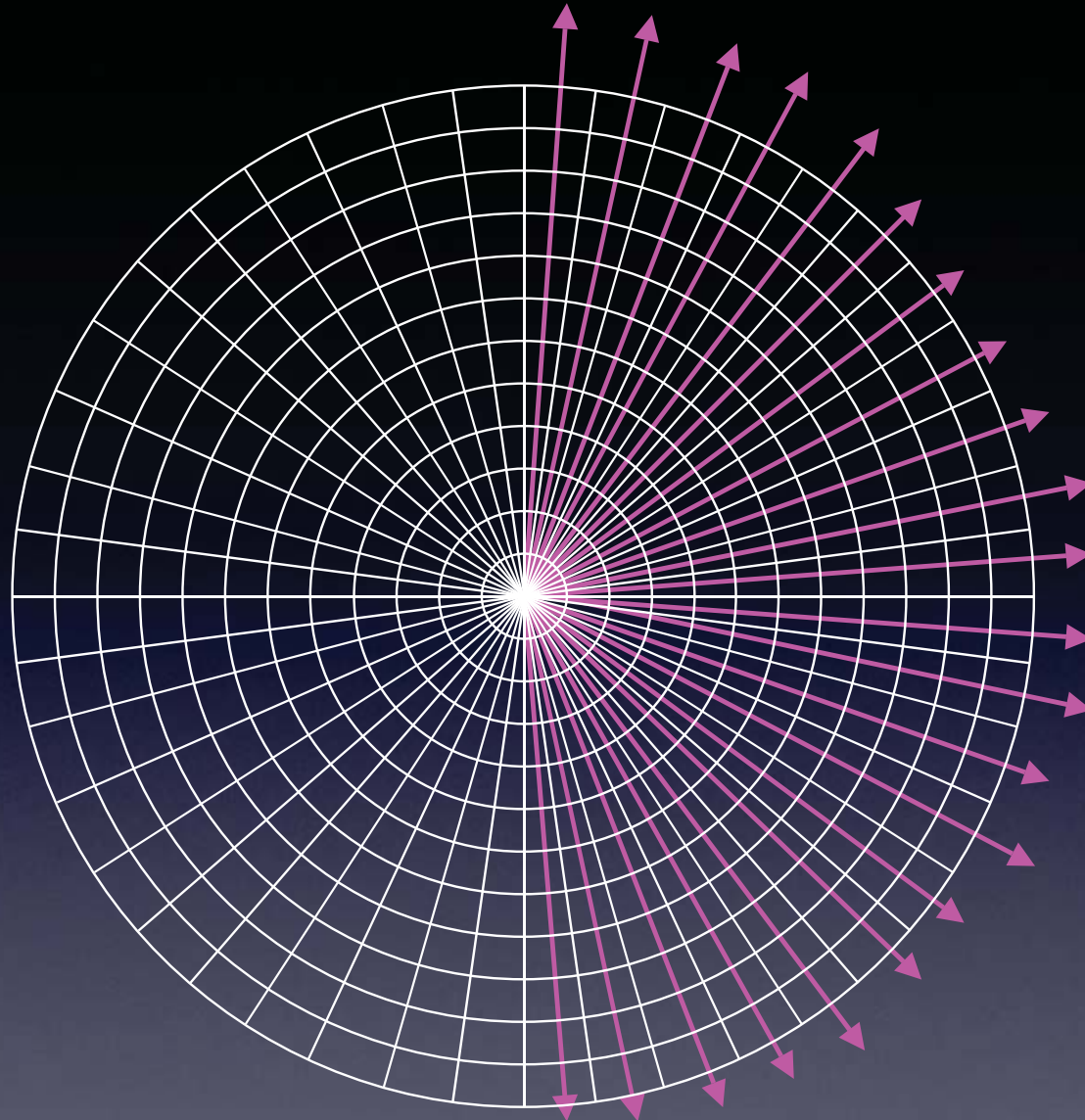
Nuclear Reactions

Equation
of State

Neutrino
Transport

Gravity
Solver

Multi-D Hydro with Radial Ray Transport



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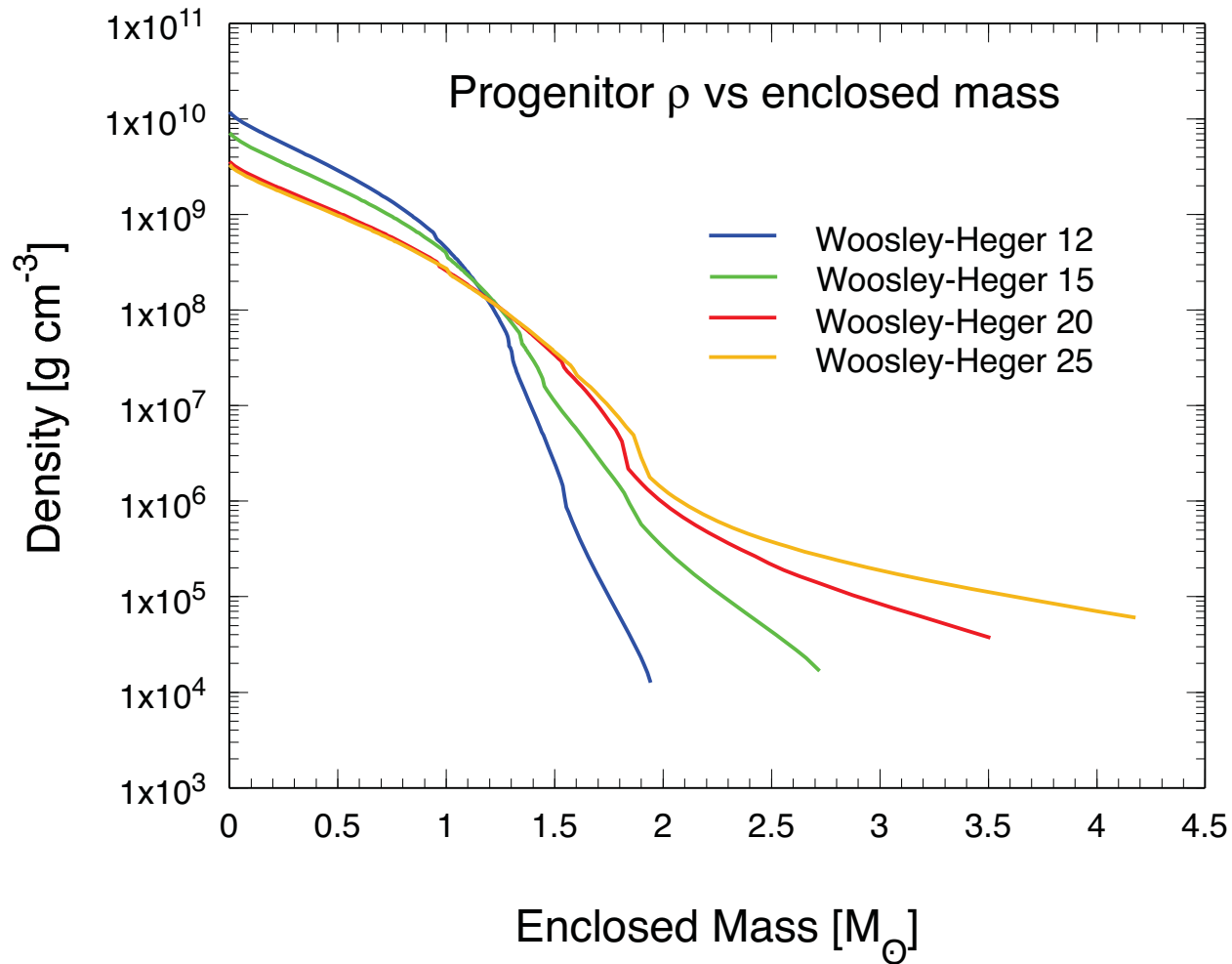
CHIMERA Collaboration

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

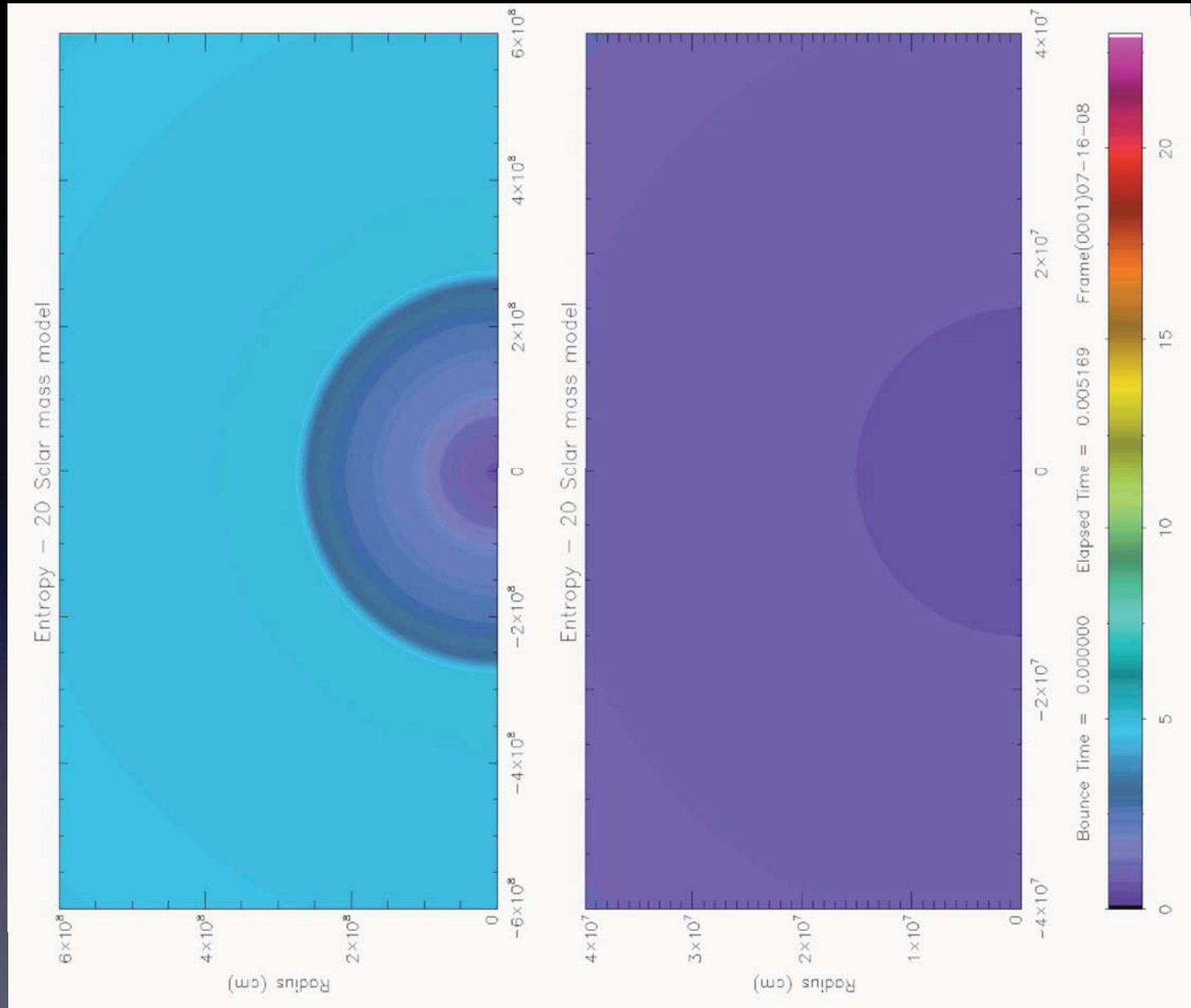
Progenitor Series

- 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 rotational profiles (planned)

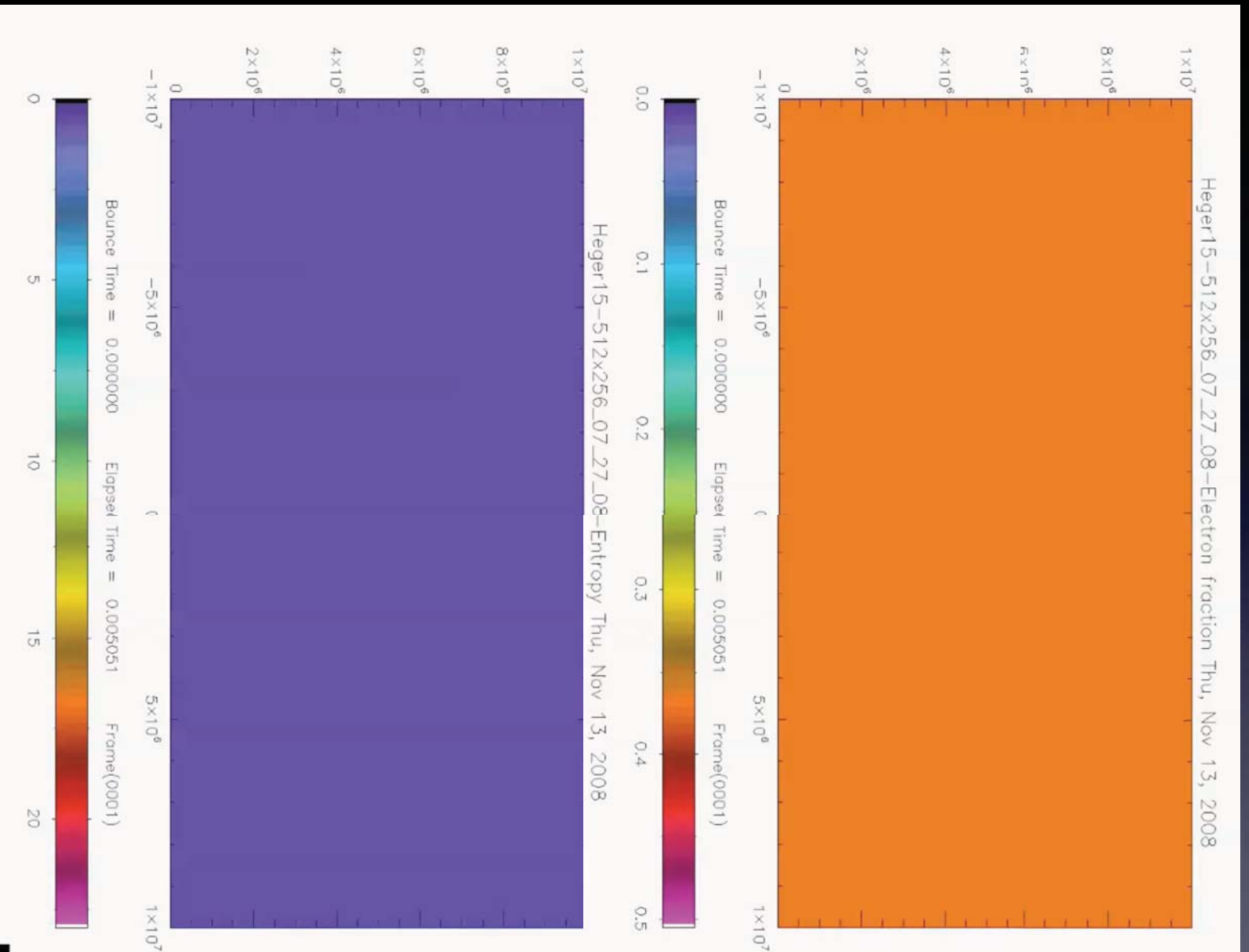
Progenitor Structure



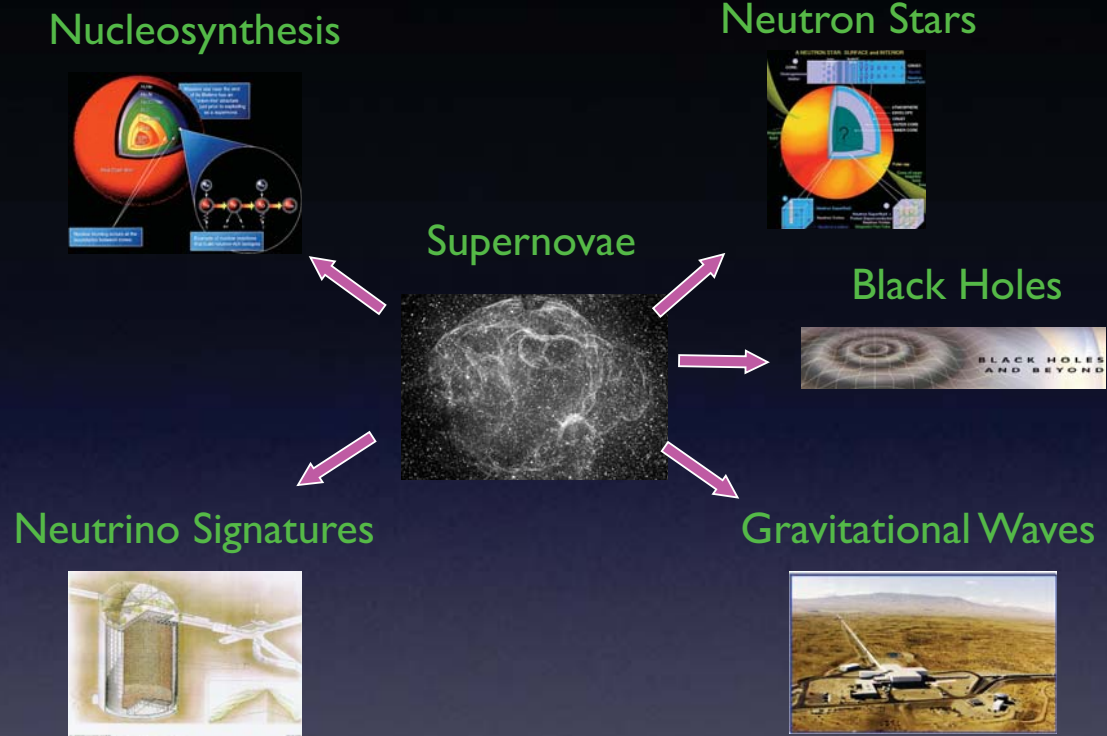
20 M_⊙ 2D Simulation 256x256



15 M_⊙ 2D Simulation 512x256



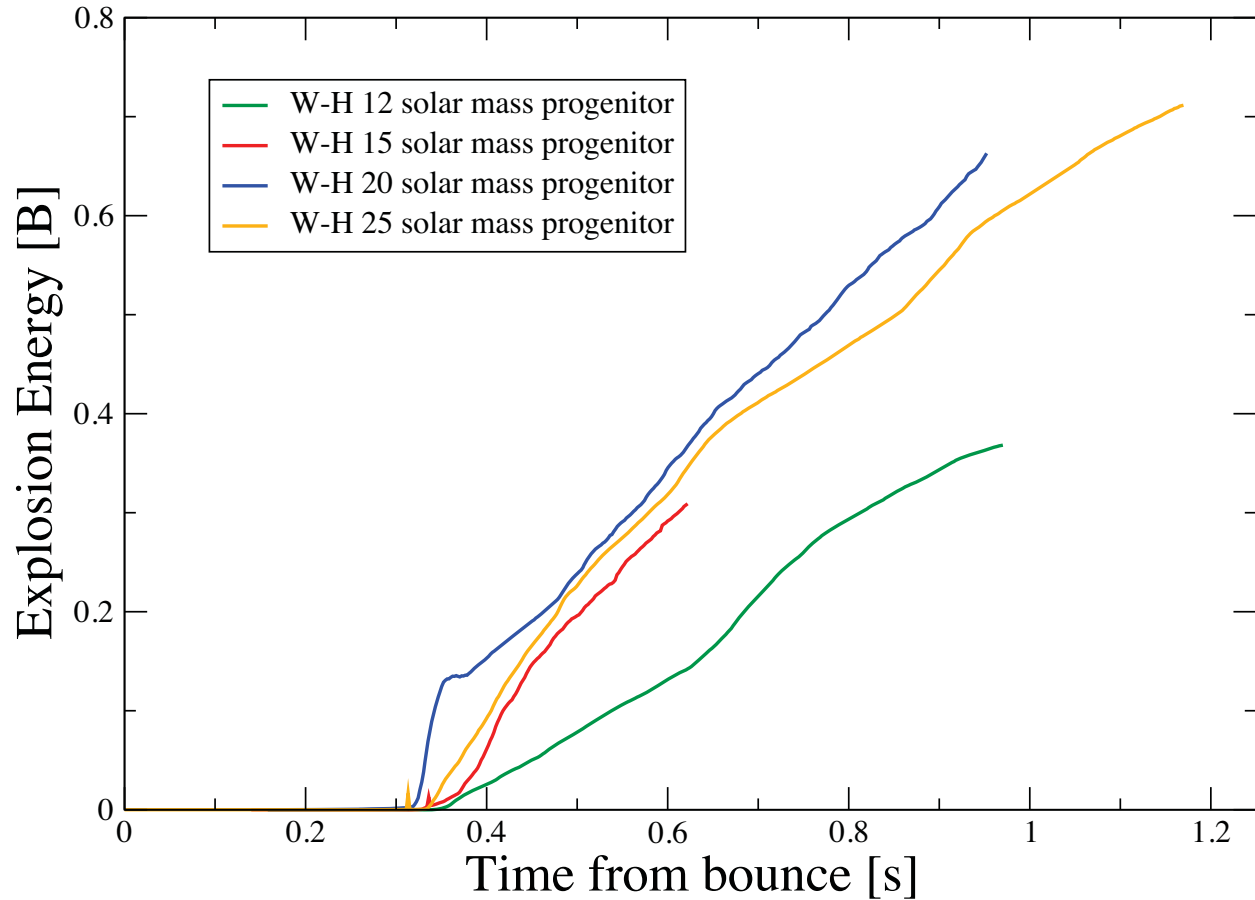
Supernova Connections



Explosion Energy vs Initial MS Mass

Explosion Energy versus Progenitor Mass

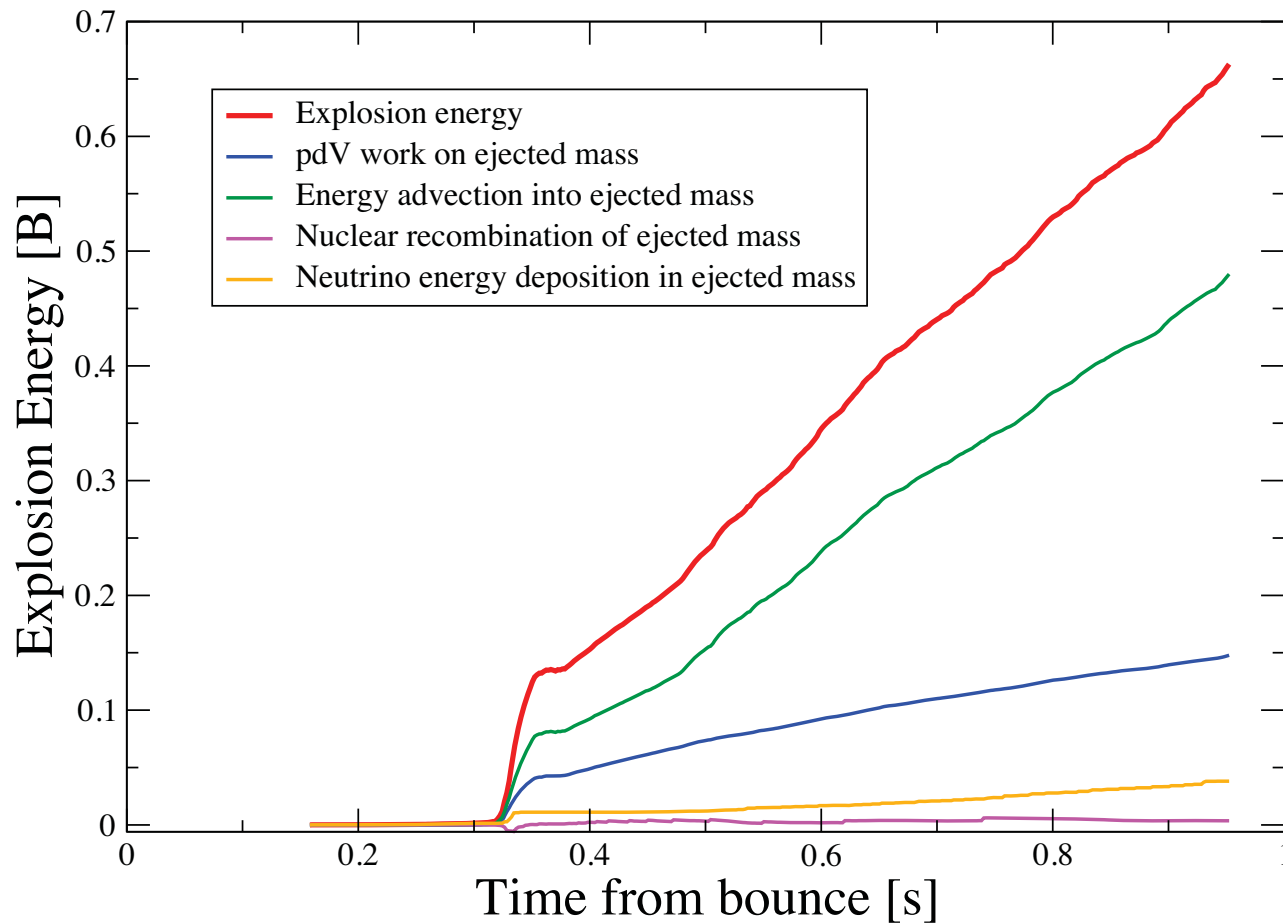
Wossley-Heger 12, 15, 20, 25 Solar Mass Nonrotating Progenitors; 256 x 256 Spatial Resolution



Sources of the Explosion Energy

Explosion Energy as a Function of Post-Bounce Time

W-H 20 Solar Mass Progenitor



Progenitor Fe Core, Neutron Star, and ^{56}Ni Masses

Progenitor ¹	Fe Core ¹	N Star ¹	N Star ²	^{56}Ni ¹
12 M_{\odot}	1.31	1.46	1.31	0.028
15 M_{\odot}	1.42	1.57	1.42	< 0.01
20 M_{\odot}	1.59	1.84	1.61	< 0.01
25 M_{\odot}	1.71	1.87	1.63	0.077

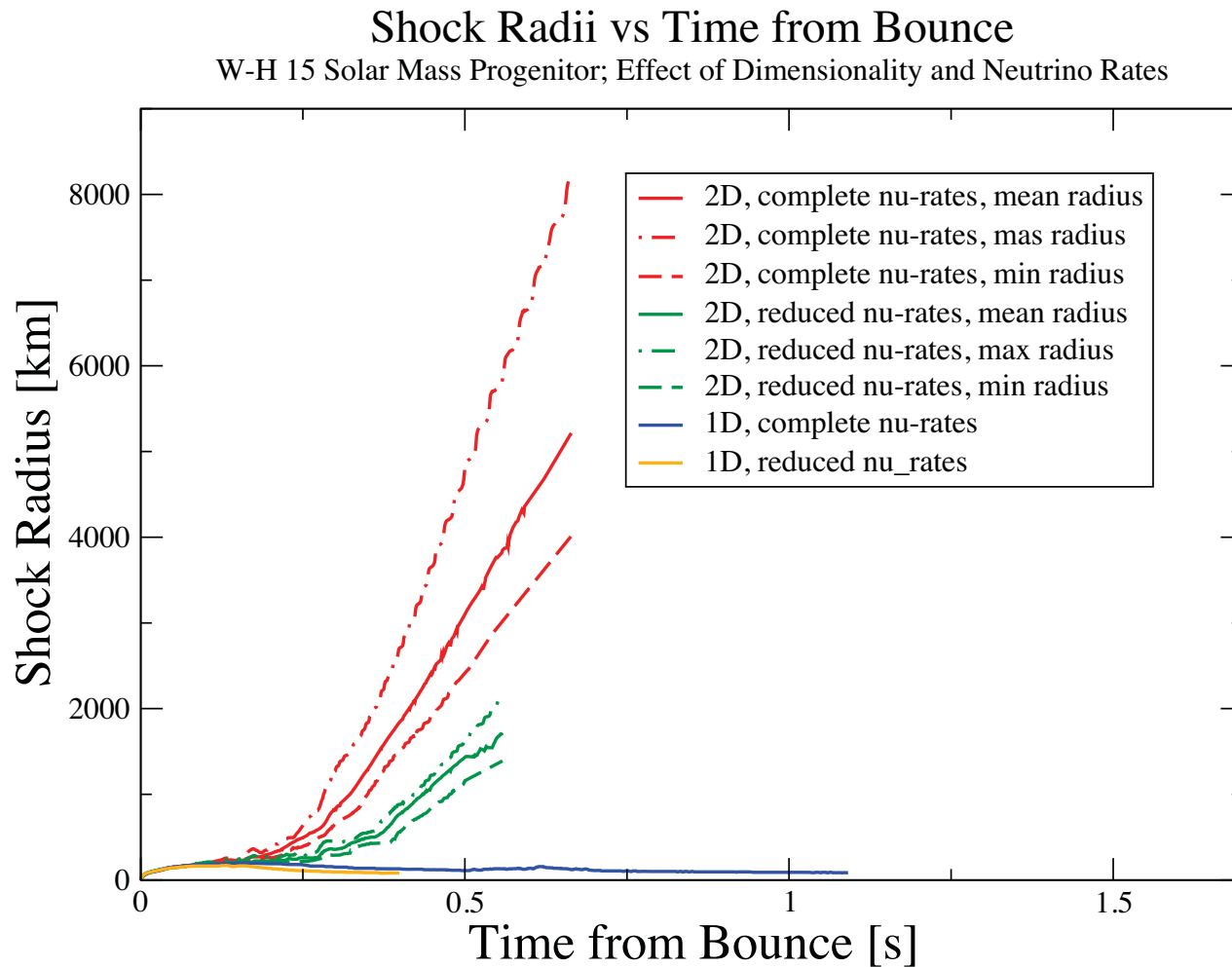
¹ Rest mass

² Gravitational mass

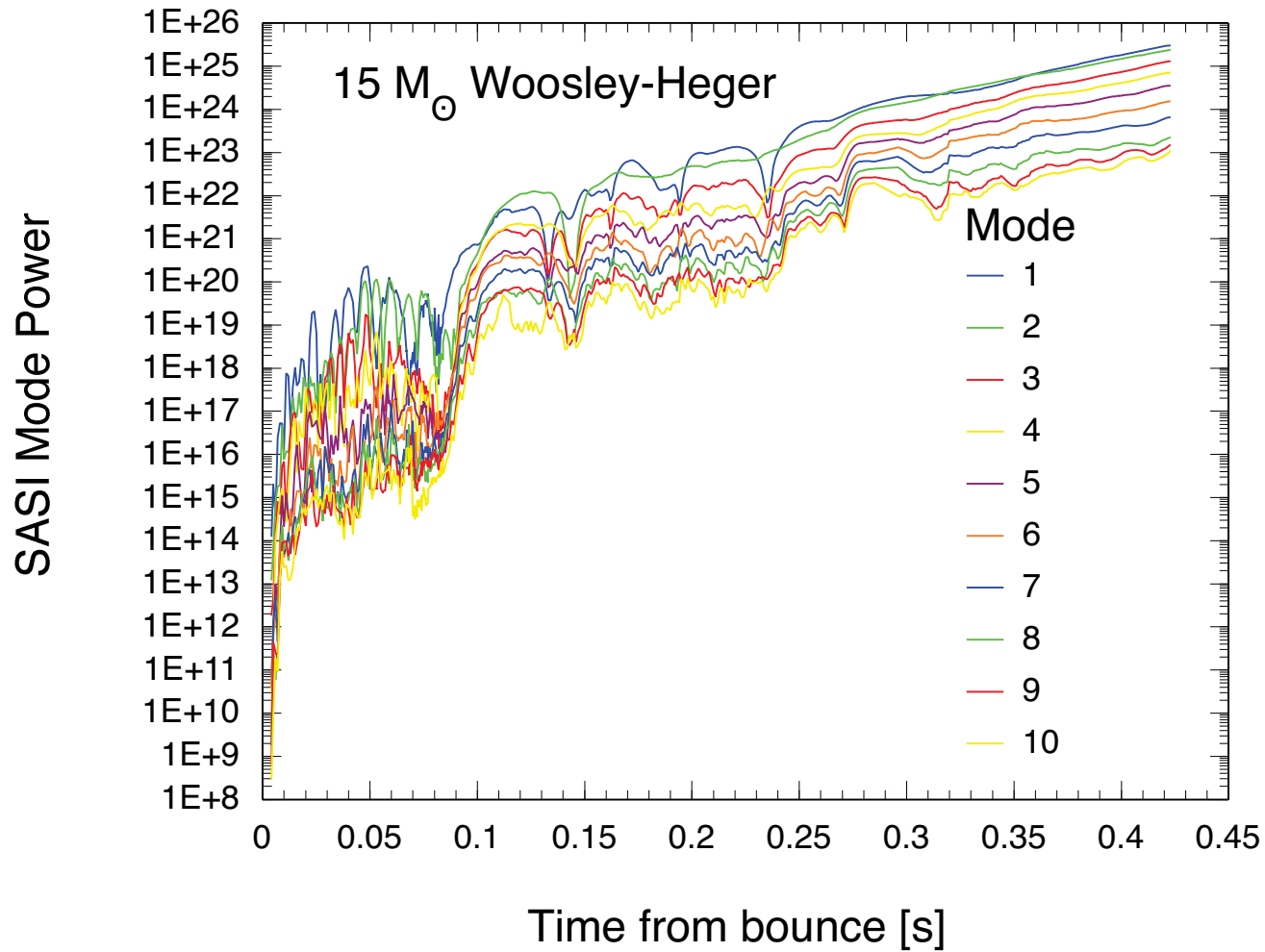
Why Are We Getting Explosions?

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

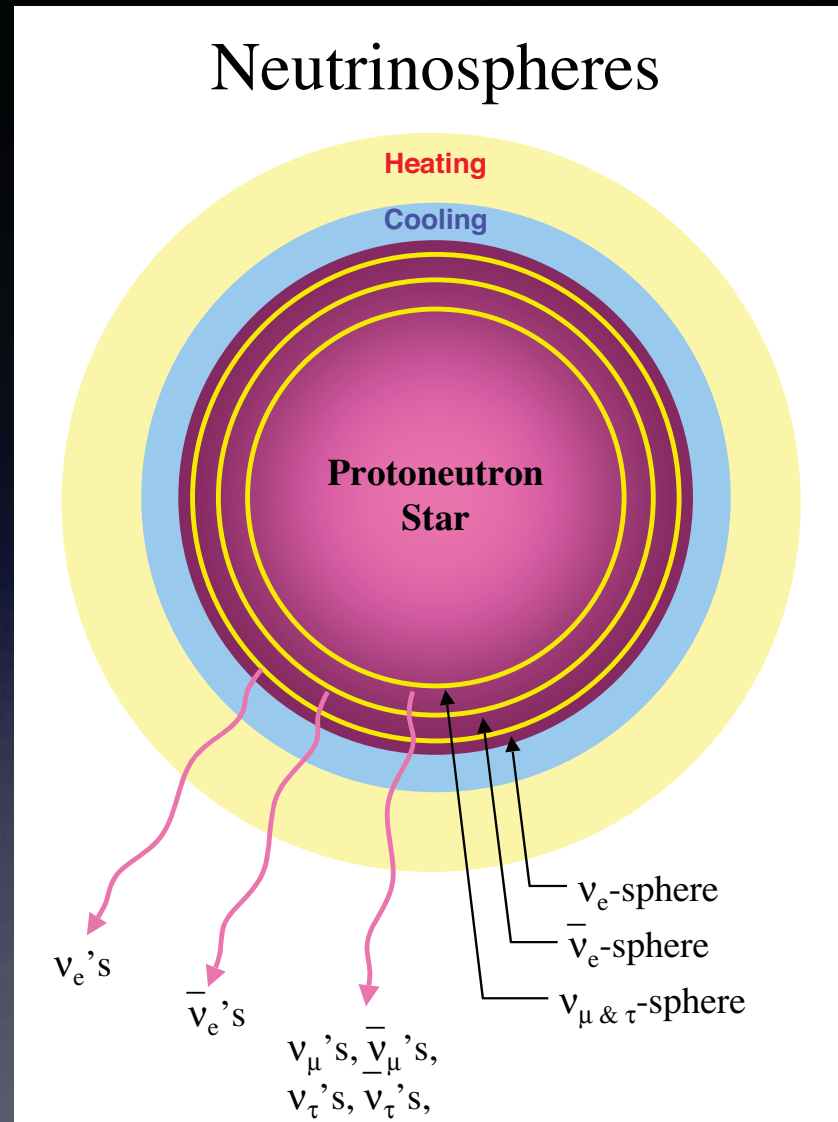
Dimensional and Neutrino Rate Effects



Role of the SASI



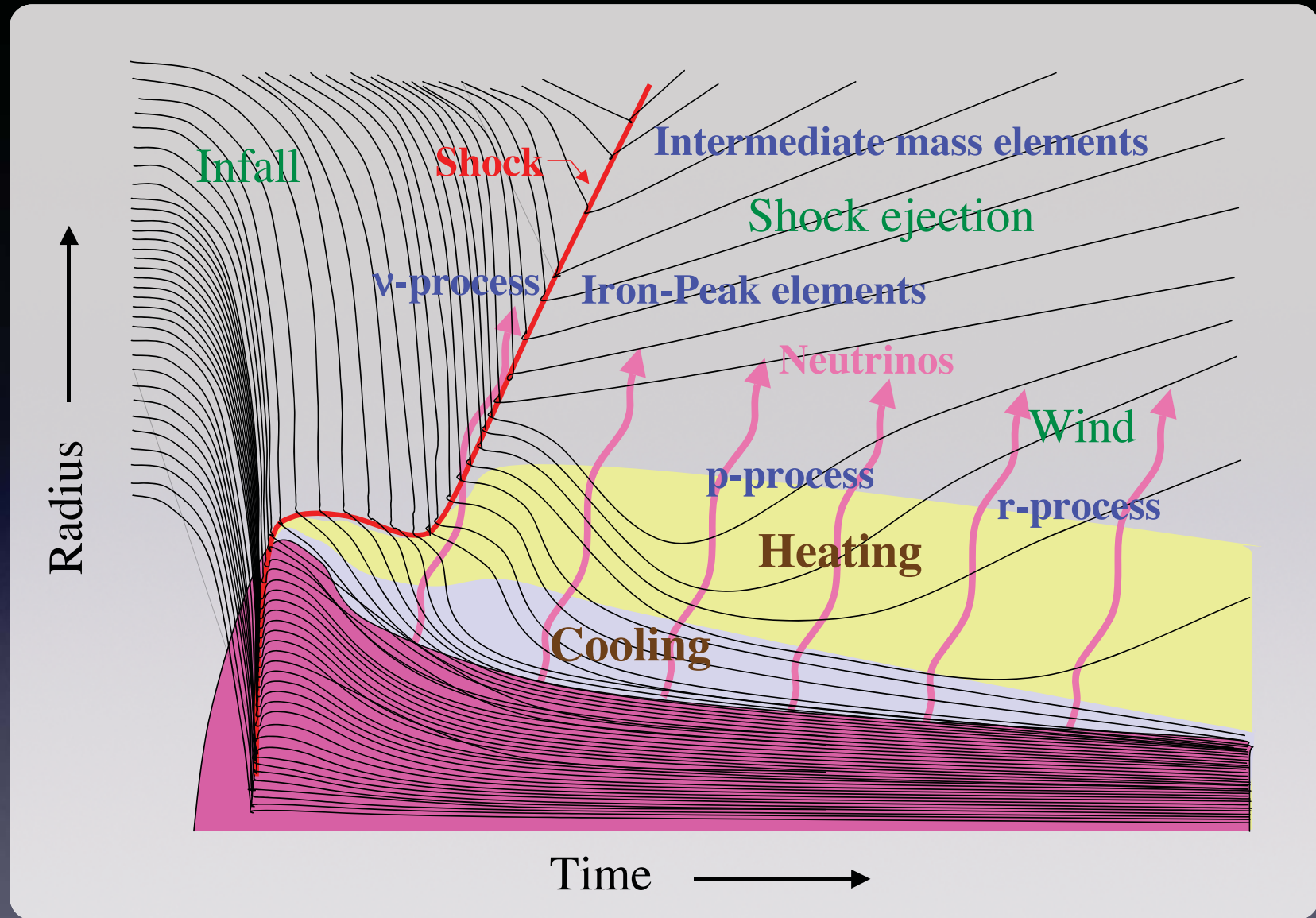
Neutrinospheres



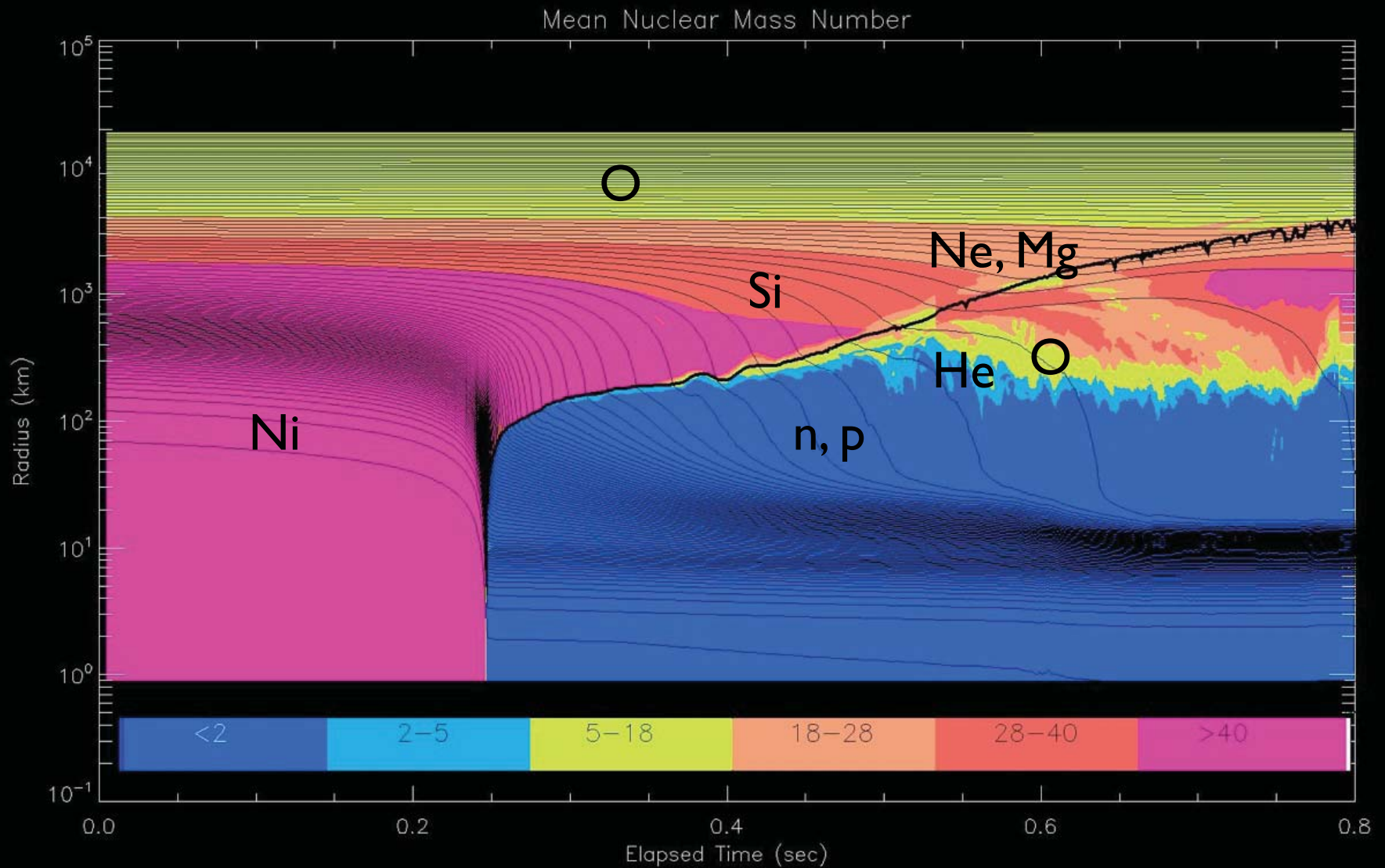
Lagrangian Tracer Particles for Nucleosynthesis

- 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

Core-Collapse Supernova Nucleosynthesis



15 M_⊙ Lagrangian and Shock Trajectories



$\bar{\nu}$ -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 [$\bar{\nu}_e + p \rightarrow n + e^+$]
- Neutron captures on proton-rich seeds bypasses the ^{64}Ge bottleneck

Neutrinos and Nucleosynthesis

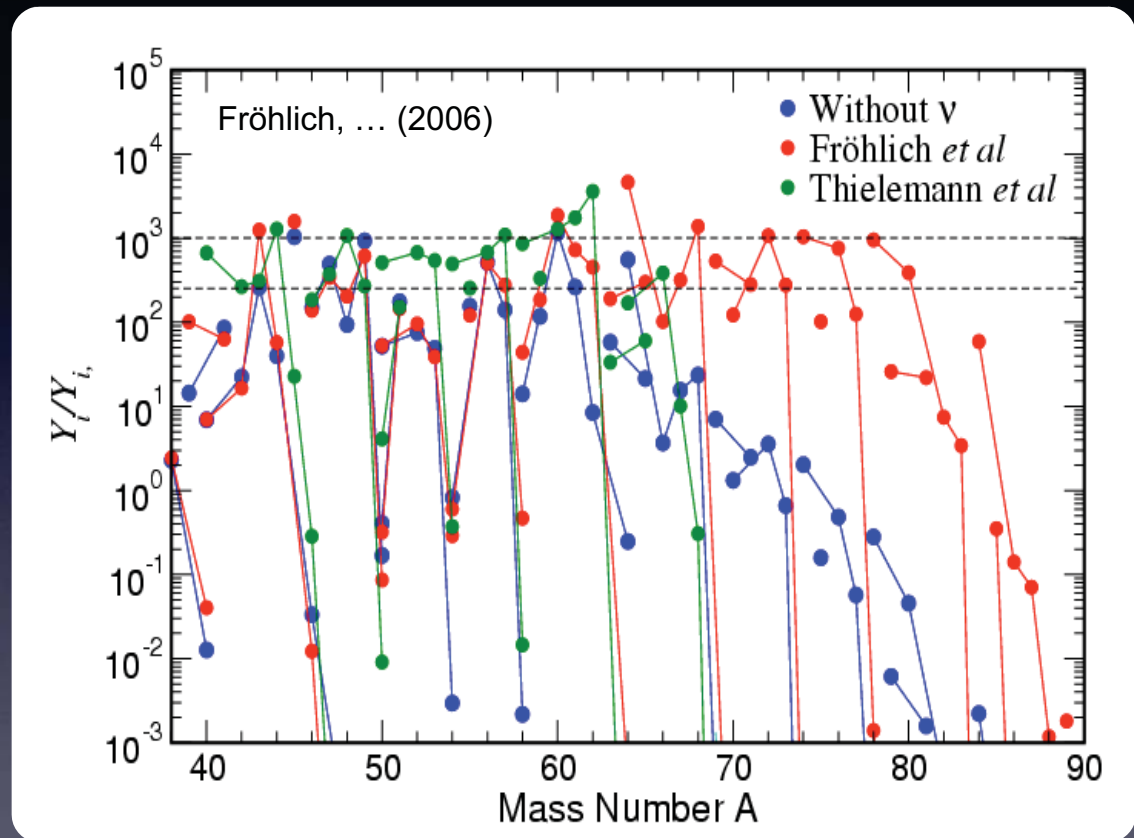
Despite the perceived importance of neutrinos to the core collapse mechanism, models of the nucleosynthesis have largely ignored this important effect.

Nucleosynthesis from parameterized **neutrino-powered supernova** models show several **notable improvements**.

Elemental abundances of **Sc, Cu & Zn** closer to those observed in metal-poor stars.

Over production of **neutron-rich iron and nickel** ($A \sim 62$) reduced.

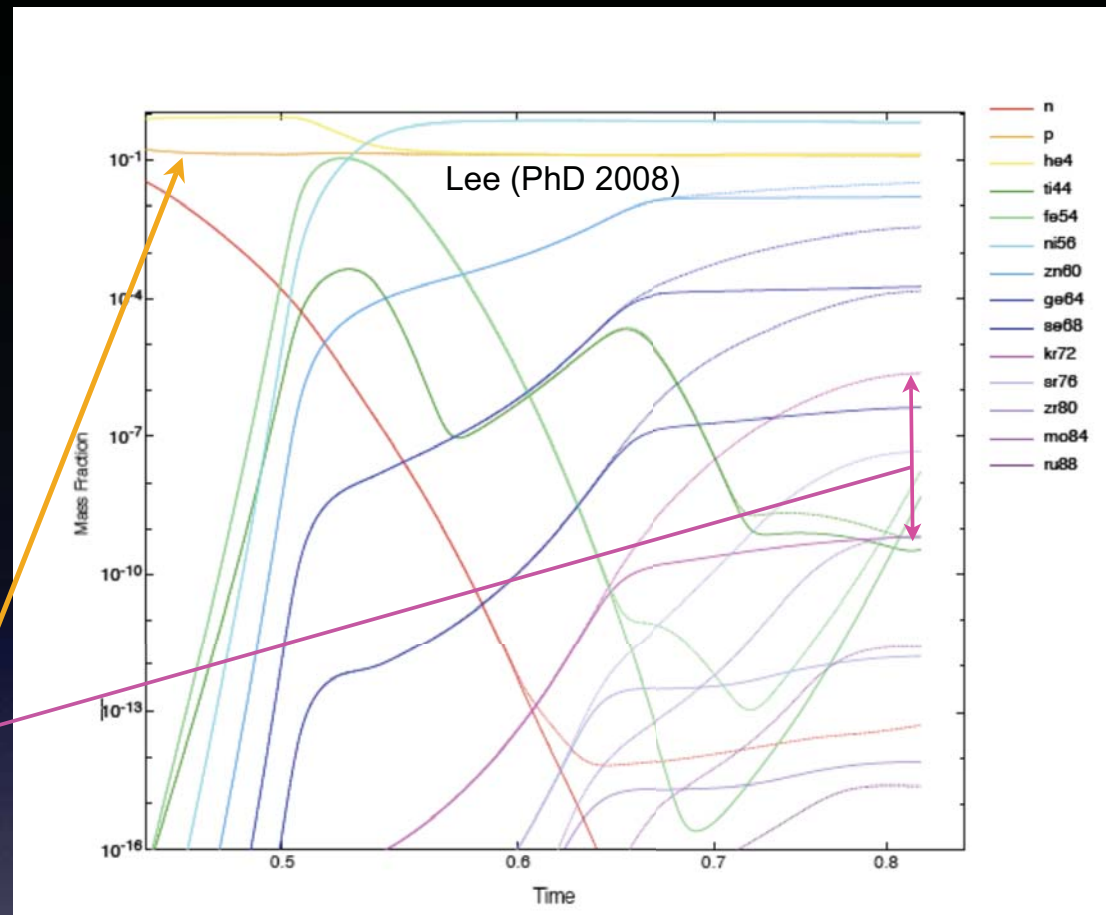
Potential source of **light p-process nuclei** (^{76}Se , ^{80}Kr , ^{84}Sr , $^{92,94}\text{Mo}$, $^{96,98}\text{Ru}$) by the **p-process**.



CHIMERA Nucleosynthesis

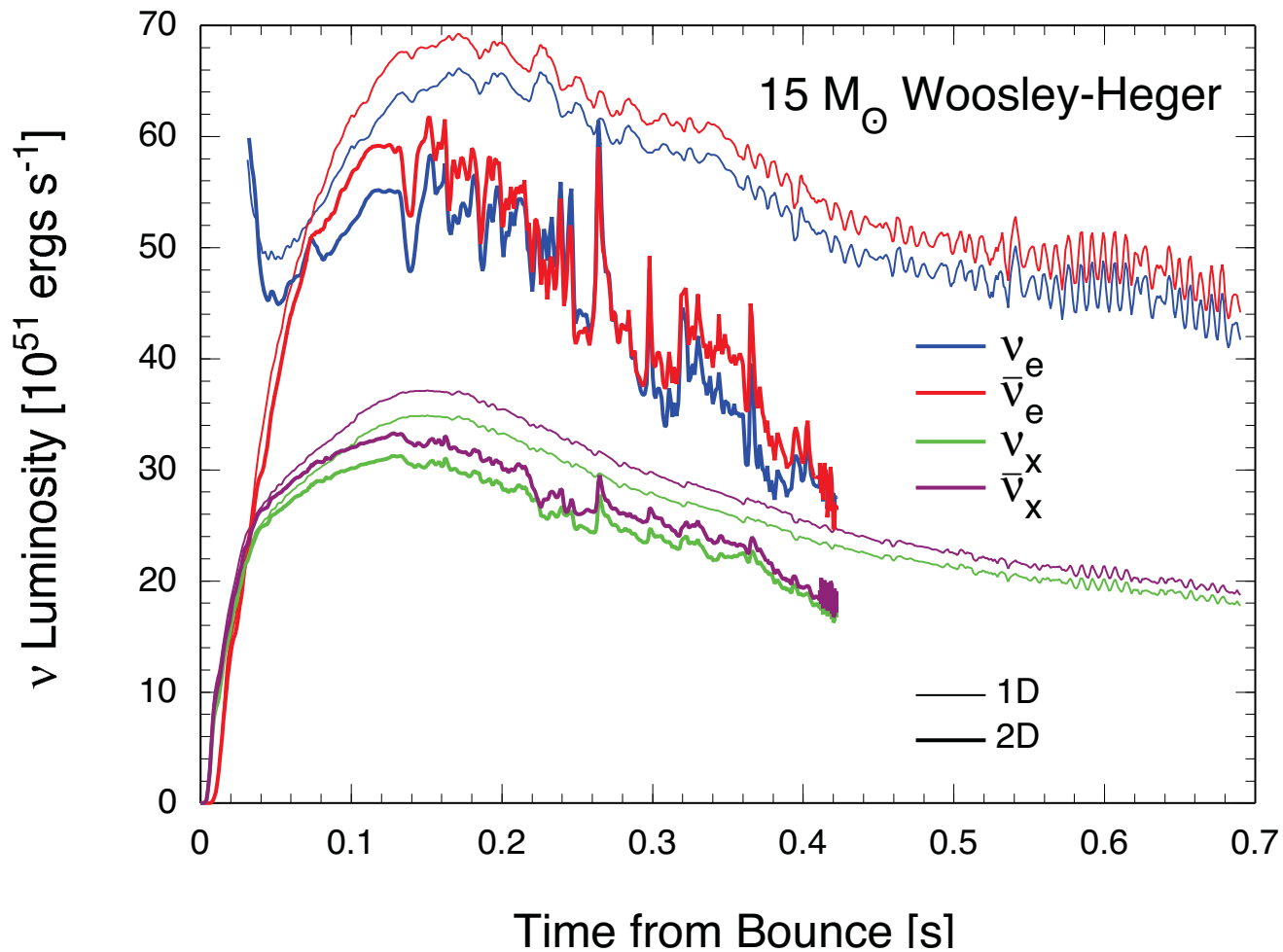
With successful, self-consistent supernova models, we can make better predictions of the nuclear composition and begin to use nucleosynthesis to constrain our models.

Our preliminary post-processing results also show proton-rich ejecta and p -process (dotted lines), but more weakly than previous results.

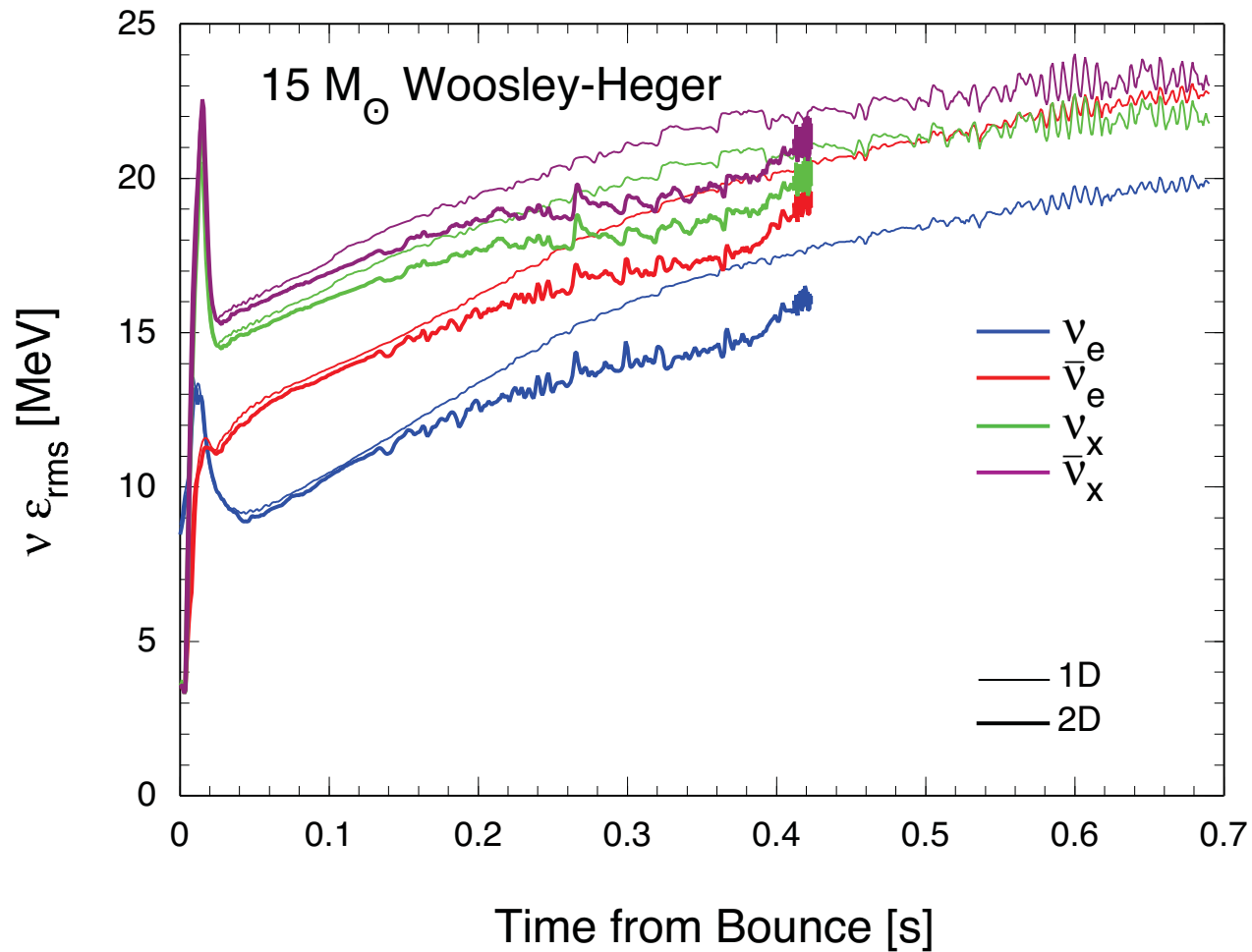


However, strength of the p -process depends on the expansion rate, which is extrapolated in these preliminary calculations.

Dimensional Effects on Neutrino Luminosities



Dimensional Effects on Neutrino rms Energies



Gravitational Wave Emission

Source

Amplitude at 10 kpc

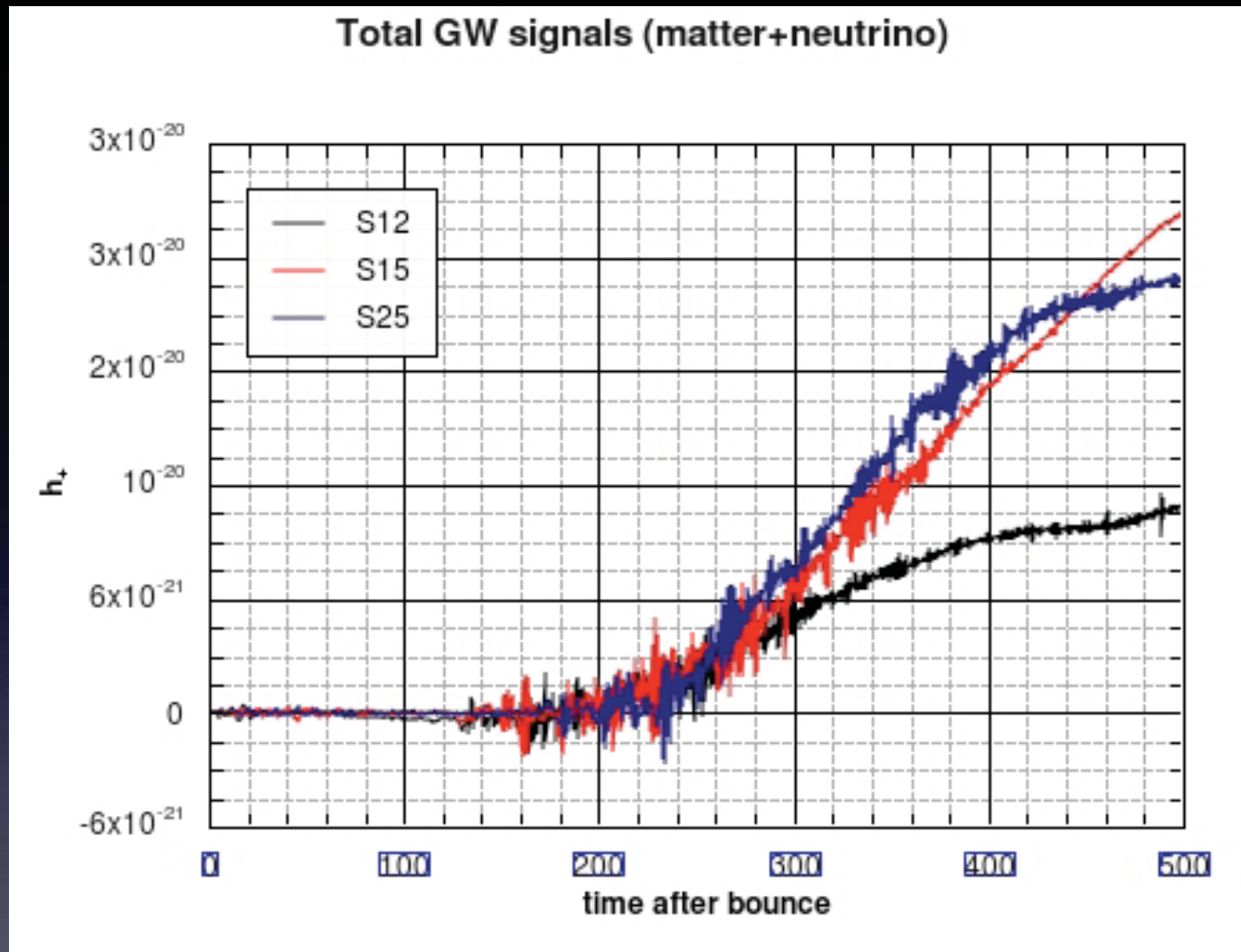
Magnetic

Acoustic

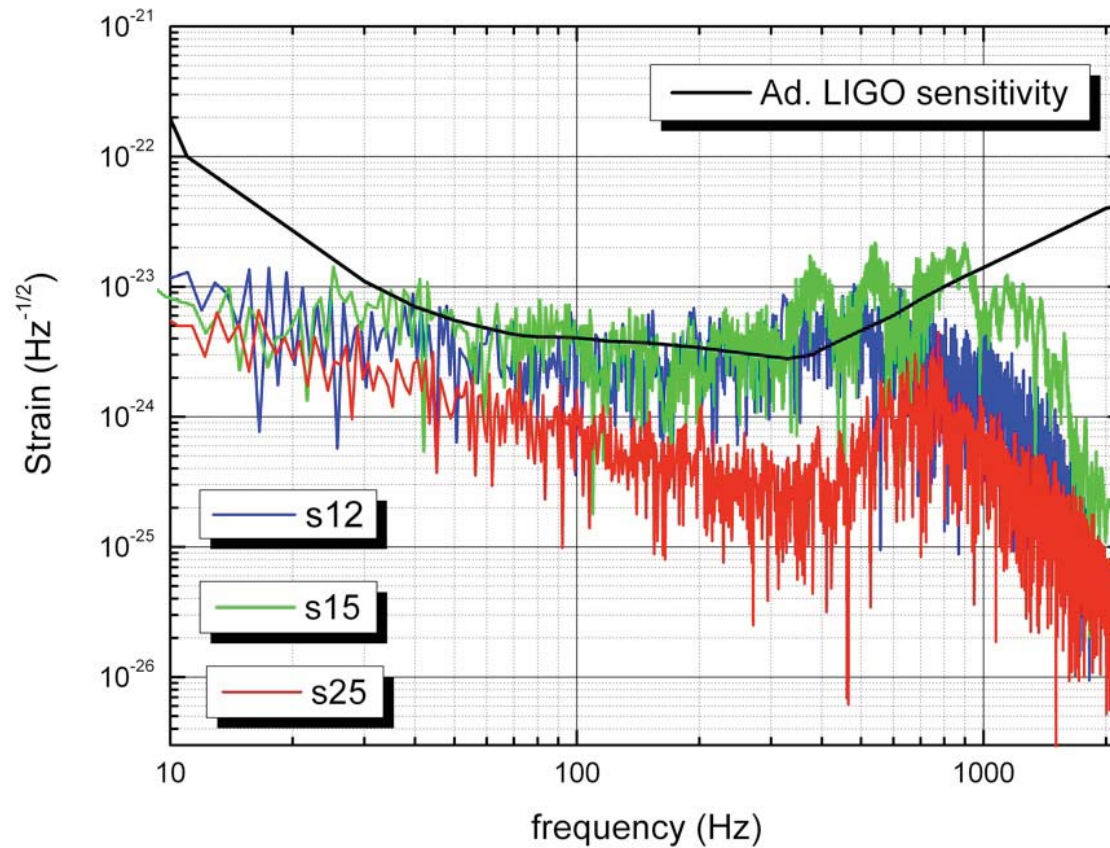
Bounce $\Omega_{\text{Fe core}} < 1 - 1.5 \text{ rad s}^{-1}$	Core bounce dominated by nuclear pressure Small peak GW's $ h_{\text{max}} < 5 \times 10^{-22}$
Bounce $1 - 2 \text{ rad s}^{-1} < \Omega_{\text{Fe core}} < 6 - 13 \text{ rad s}^{-1}$	Core bounce dominated by nuclear pressure Sizable peak GW's $5 \times 10^{-22} < h_{\text{max}} < 2 \times 10^{-20}$
Bounce $6 - 13 \text{ rad s}^{-1} < \Omega_{\text{Fe core}}$	Slow core bounce dominated by centrifugal forces Longer duration $3.5 \times 10^{-21} < h_{\text{max}} < 7.5 \times 10^{-21}$
Rot instability at $\Omega_{\text{Fe core}} < (\Omega_{\text{sec}}, \Omega_{\text{dyn}})$	$1 \times 10^{-21} < h_{\text{max}} < 5 \times 10^{-21}$
Prompt Convection	$1 \times 10^{-22} < h_{\text{max}} < 6 \times 10^{-22}$
PNS Convection	$1 \times 10^{-23} < h_{\text{max}} < 5 \times 10^{-23}$
Neutrino Driven Convection	$1 \times 10^{-23} < h_{\text{max}} < 1 \times 10^{-22}$
Protoneutron Star g-Mode Pulsations	$1 \times 10^{-21} < h_{\text{max}} < 5 \times 10^{-20}$
$\Omega_{\text{Fe core}} \sim 5 \times 10^{-2} \text{ rad s}^{-1}$	Heger, Woosley, Spruit Progenitor (ApJ, 626, 350, 2005)

Ott, C. D. arXiv:0809.0695v2; Dimmelmeier, J. A. et al. Phys. Rev. D., 78, 064056; Ott, C. D. Muller, E. et al. ApJ, 603, 221, 2004; Ott, C. D. et al. Phys. Rev. Lett. 96, 201102; Marek, A. ; Fryer C. L. ApJ 609, 288, 2004; Fryer, C. L. ApJ Lett. 601, L175, 2004.

Gravitational Waves from the CHIMERA Models



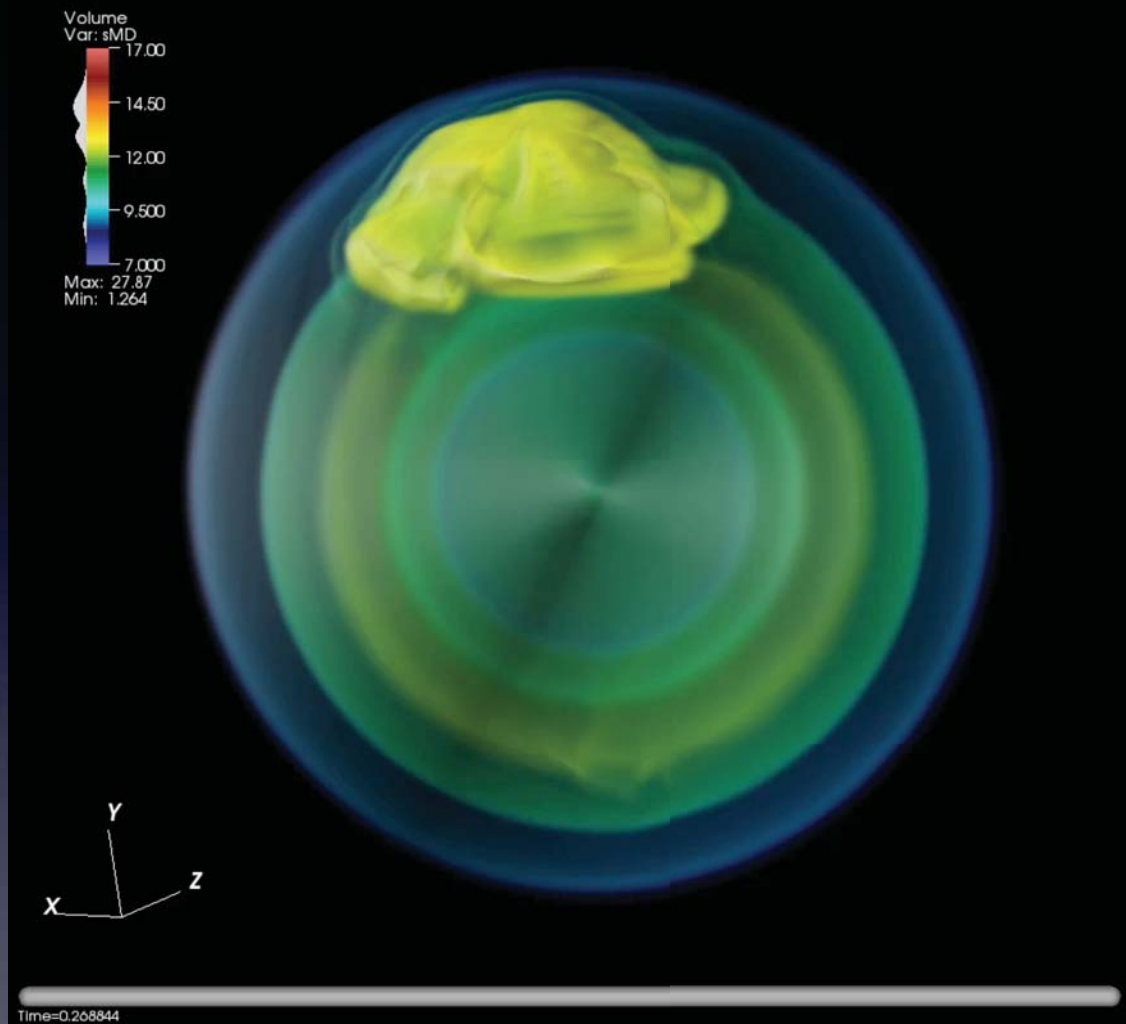
Gravitational Waves from the CHIMERA Models



3D 15 M_{\odot} Model Simulation

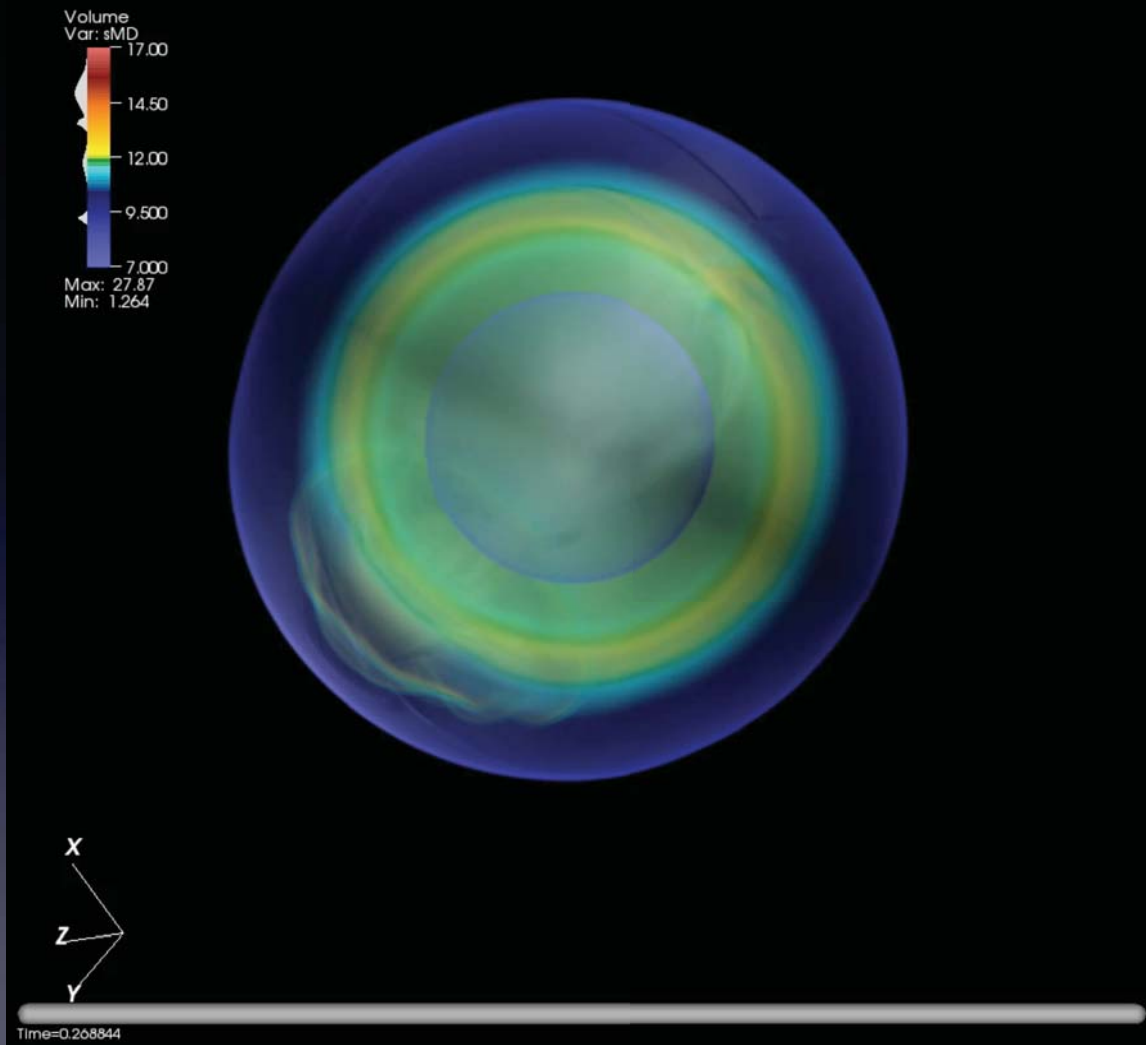
- 304 nonuniformly spaced radial zones out to 2000 km
- 78 evenly spaced angular zones from 0 to 180 degrees
- 156 evenly spaced azimuthal zones from 0 to 360 degrees
- 4 neutrino flavors, 20 energy zones from 4 to 400 MEV for each flavor
- Requires 11,552 processors

3D 15 M_⊙ Model Simulation



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3D 15 M_⊙ Model Simulation



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Status of the Neutrino Transport Model

Arizona-Israeli Group	No explosions	2D MGFLD Transport No energy exchanging neutrino interactions Newtonian Hydro
Munich Group	Explosions at late times for some models	Ray-by-ray plus VEF Transport Approximate GR hydro etc.
Oak-Ridge-FAU-NCState Group	Explosions at earlier times for 12 - 25 M_{\odot}	Ray-by-ray plus MGFLD Transport Approximate GR hydro etc.

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.
- However, comparisons of the 2D simulations with other groups have yet to show a convergence of results.
- But what about neutrino-neutrino flavor changing interactions????

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
- Incorporate flavor changing reactions
- Deploy Genasis

The End

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