The Core Collapse Supernova Mechanism: How Close Are We?

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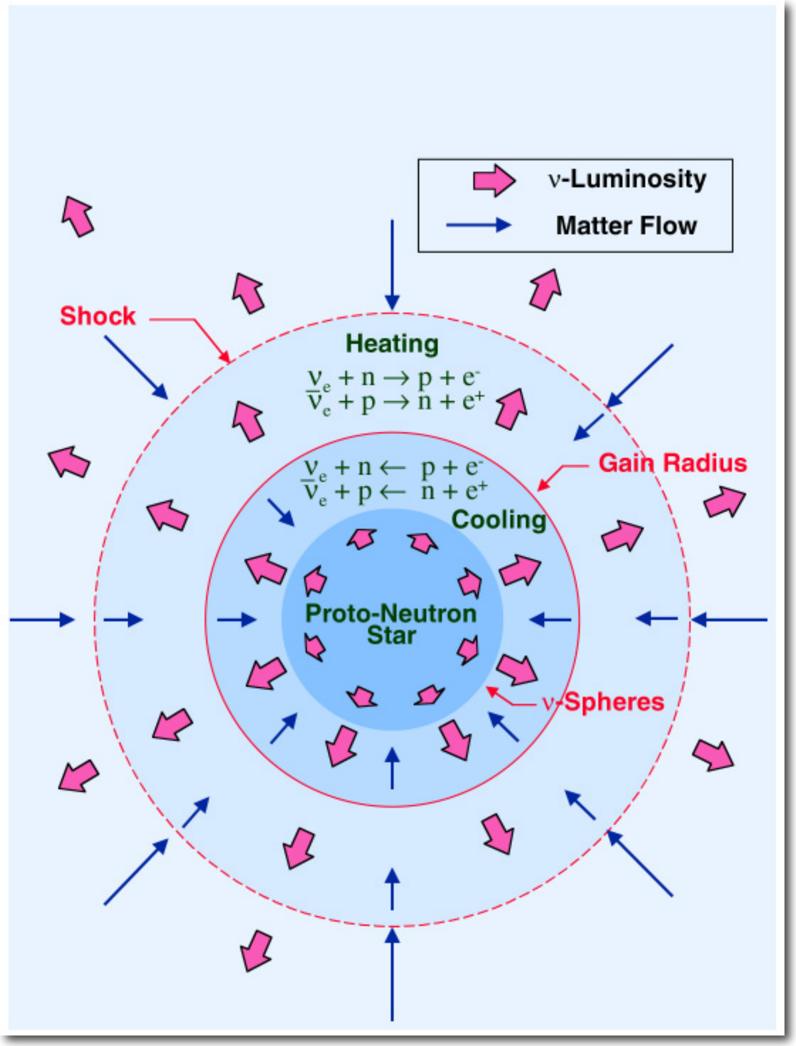
The Heart of the Matter



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

$$\dot{\epsilon} = \frac{X_n}{\lambda_0^a}\frac{L_{\nu_e}}{4\pi r^2}\langle E_{\nu_e}^2\rangle\langle\frac{1}{\mathcal{F}}\rangle + \frac{X_p}{\bar{\lambda}_0^a}\frac{L_{\bar{\nu}_e}}{4\pi r^2}\langle E_{\bar{\nu}_e}^2\rangle\langle\frac{1}{\bar{\mathcal{F}}}\rangle$$

Neutrino heating is sensitive to all three (most sensitive to neutrino spectra).
⇨ Must compute neutrino distributions.

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

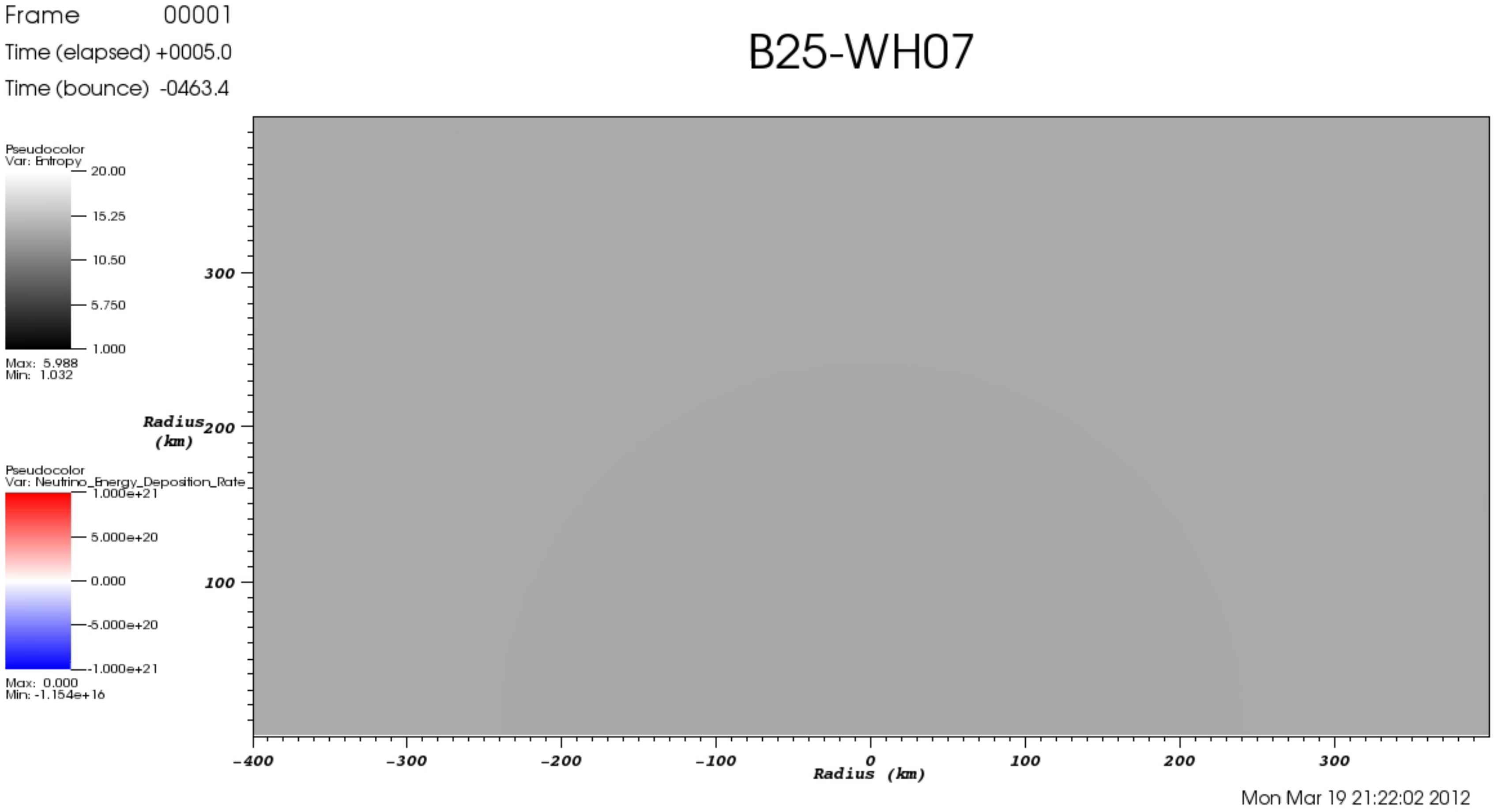
Multifrequency
Multiangle

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

Multifrequency
(*solve for multifrequency angular moments*)

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

Gray
(*solve for angular moments, parameterize spectra*)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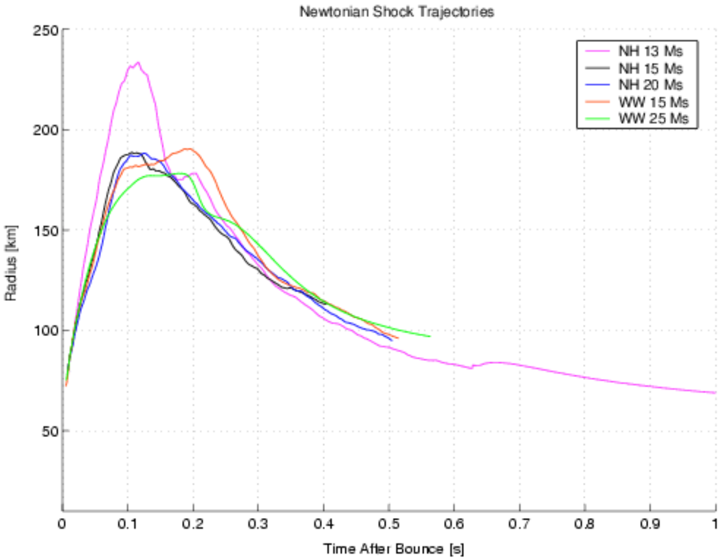
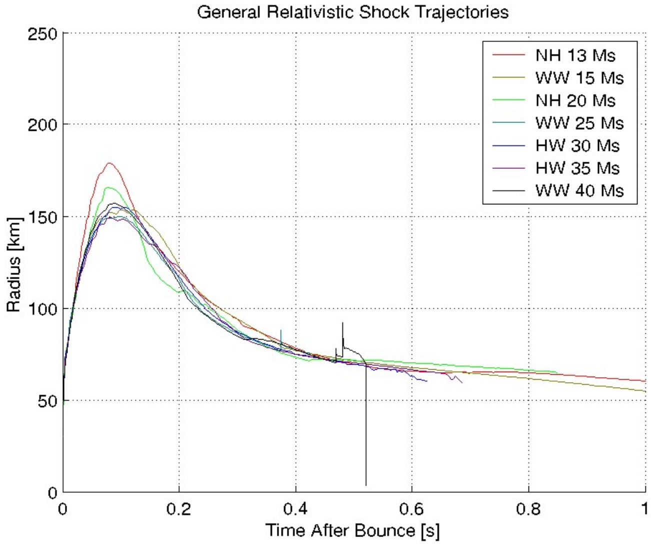
Time (elapsed) +0005.0
Time (bounce) -0463.4
B25-WH07
Pseudocolor
Var: Entropy
20.00
15.25
10.50
5.750
1.000
Max: 5.988
Min: 1.032
Pseudocolor
Var: Neutrino_Energy_Deposition_Rate
1.000e+21
5.000e+20
0.000
-5.000e+20
-1.000e+21
Max: 0.000
Min: -1.154e+16
Radius (km)
300
200
100
-400
-300
-200
-100
0
100
200
300
Radius (km)
Mon Mar 19 21:22:02 2012

Completed: Spherical Models with Boltzmann Transport

Newtonian

General Relativistic





Mezzacappa et al., PRL, **86**, 1935 (2001)

Liebendoerfer et al., PRD, **63**, 103004 (2001)

The simulation of core collapse supernovae with fully general relativistic, multi-angle, multi-frequency, Boltzmann neutrino transport has been achieved for spherically symmetric cases.

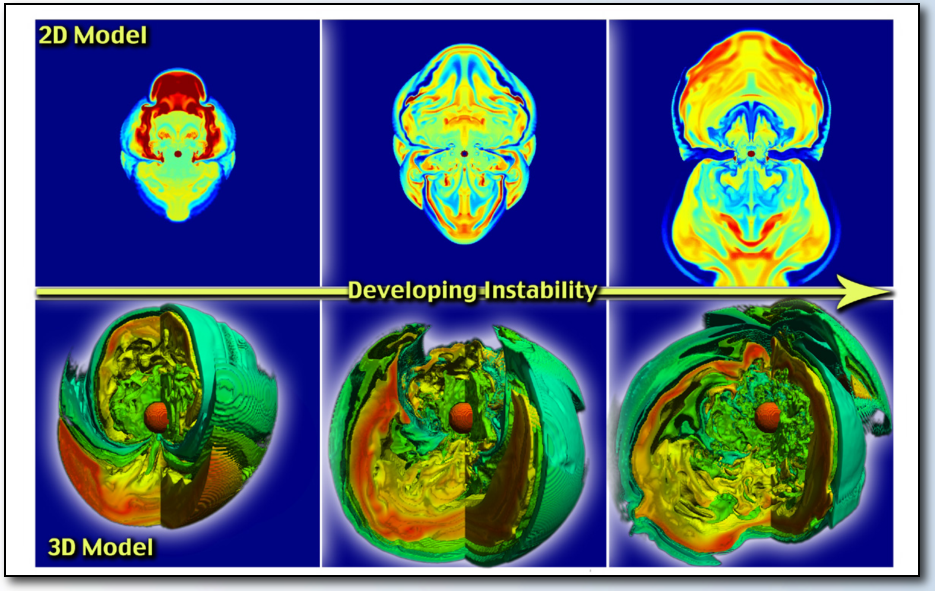
⇨ What's missing?

- Multi-D Effects
- ?

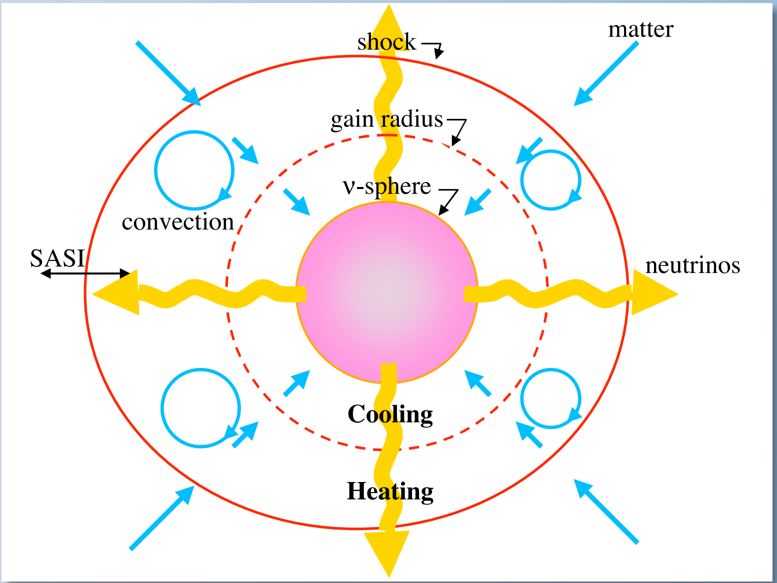
Agile-BOLTZTRAN

See also Lentz et al. 2012. *Ap.J.* **747**, 73.

Stationary Accretion Shock Instability (SASI)



Blondin, Mezzacappa, & DeMarino, *Ap.J.* **584**, 971 (2003)



Shock wave unstable to non-radial perturbations.

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

- Blondin and Mezzacappa, *Ap.J.* **642**, 401 (2006)
- Blondin and Shaw, *Ap.J.* **656**, 366 (2007)
- Blondin and Mezzacappa, *Nature* **445**, 58 (2007)

- Near prolate axis:
  - Decreases advection velocity in gain region.
  - Increases time in the gain region.
  - Increases size of gain region.
  - Moves shock toward silicon/oxygen layer.
- Opposite effect orthogonal to prolate axis.
- Seed convection.

e.g., see Marek and Janka, *Ap.J.* **694**, 664 (2009)

General Relativistic Boltzmann Equation

$$p^{\hat{\mu}} \mathcal{L}^{\mu}{}_{\hat{\mu}} \frac{\partial f}{\partial x^{\mu}} + \left(eF^{\hat{j}}{}_{\hat{\nu}} p^{\hat{\nu}} - \Gamma^{\hat{j}}{}_{\hat{\nu}\hat{\rho}} p^{\hat{\nu}} p^{\hat{\rho}}\right) \frac{\partial u^{\hat{i}}}{\partial p^{\hat{j}}} \frac{\partial f}{\partial u^{\hat{i}}} = \mathbb{C}[f]$$

1. Geometric Effects
2. Special Relativistic Effects
3. General Relativistic Effects

E.G.: Describes increase in neutrino Fermi energy in trapped regions as density increases.

	Spatial Dimensions	**Netwonian or GR**	**1**	**2**	**3**	**Partial Weak Interactions (Thompson et al. (2003))**	**Complete Weak Interactions**	**Label**
Liebendoerfer et al. (2004)Lentz et al. (2012)	1	GR	X	X	X		X	Full GR
Ott et al. (2008)	2	Newtonian	X			X		No-Observer-Correctons Newtonian

Bruenn (1985) – NES + Bremsstrahlung

Important Neutrino Emissivities/Opacities

“Standard” Emissivities/Opacities

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

- Nucleons in nucleus independent.
- No energy exchange in nucleonic scattering.

★ $e^{-(+)} + p(n), A \leftrightarrow \nu_e(\bar{\nu}_e) + n(p), A'$

Langanke et al. PRL, **90**, 241102 (2003)

- Include correlations between nucleons in nuclei.

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

★ $\nu + n,p,A \rightarrow \nu + n,p,A$

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

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.

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

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

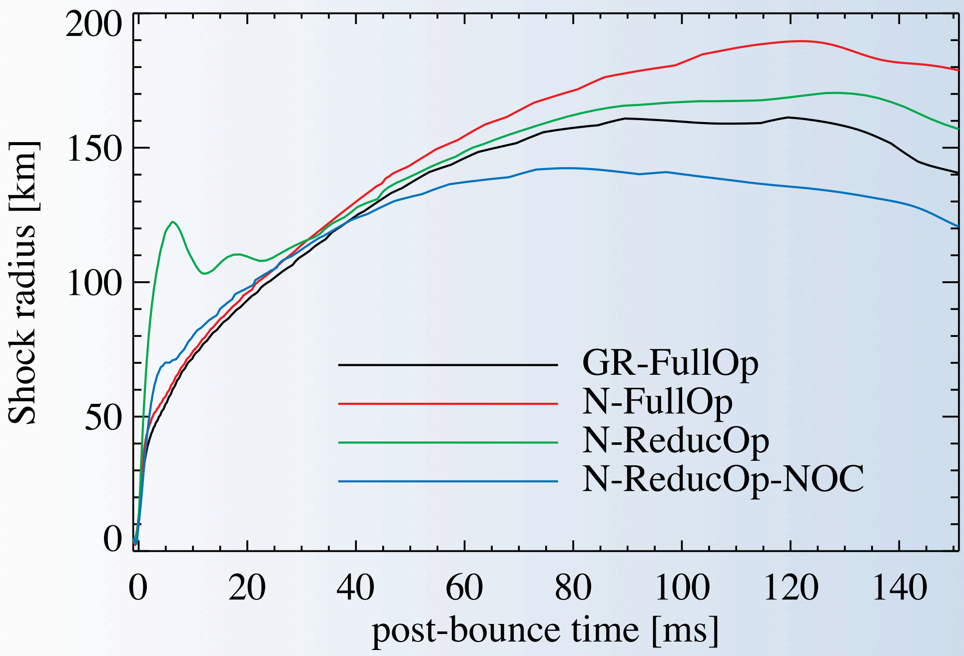
- New source of neutrino-antineutrino pairs.

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

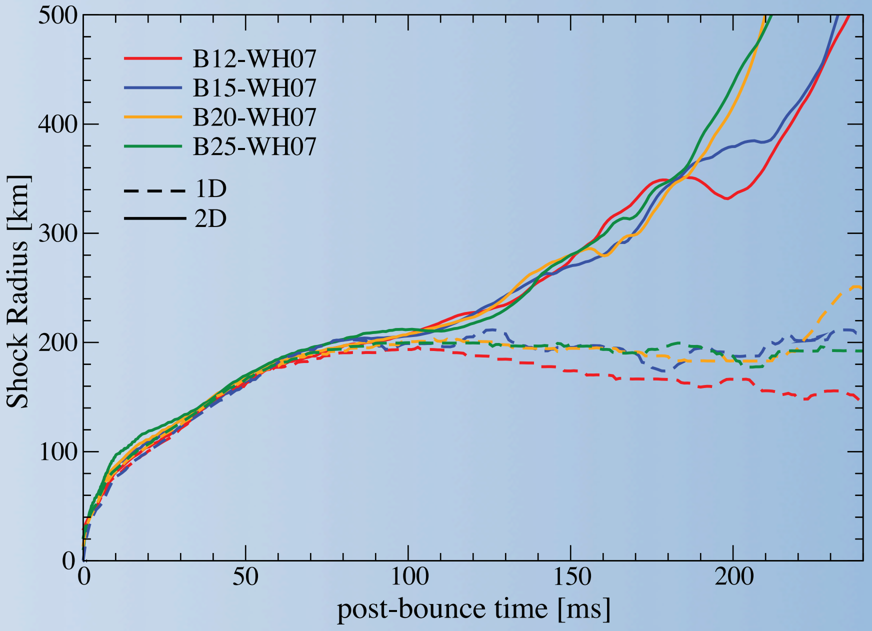
Janka et al. PRL, **76**, 2621 (1996)
Buras et al. *Ap.J.*, **587**, 320 (2003)

Peeling Away the Physics

ReducOp = Bruenn (1985) – NES + Bremsstrahlung



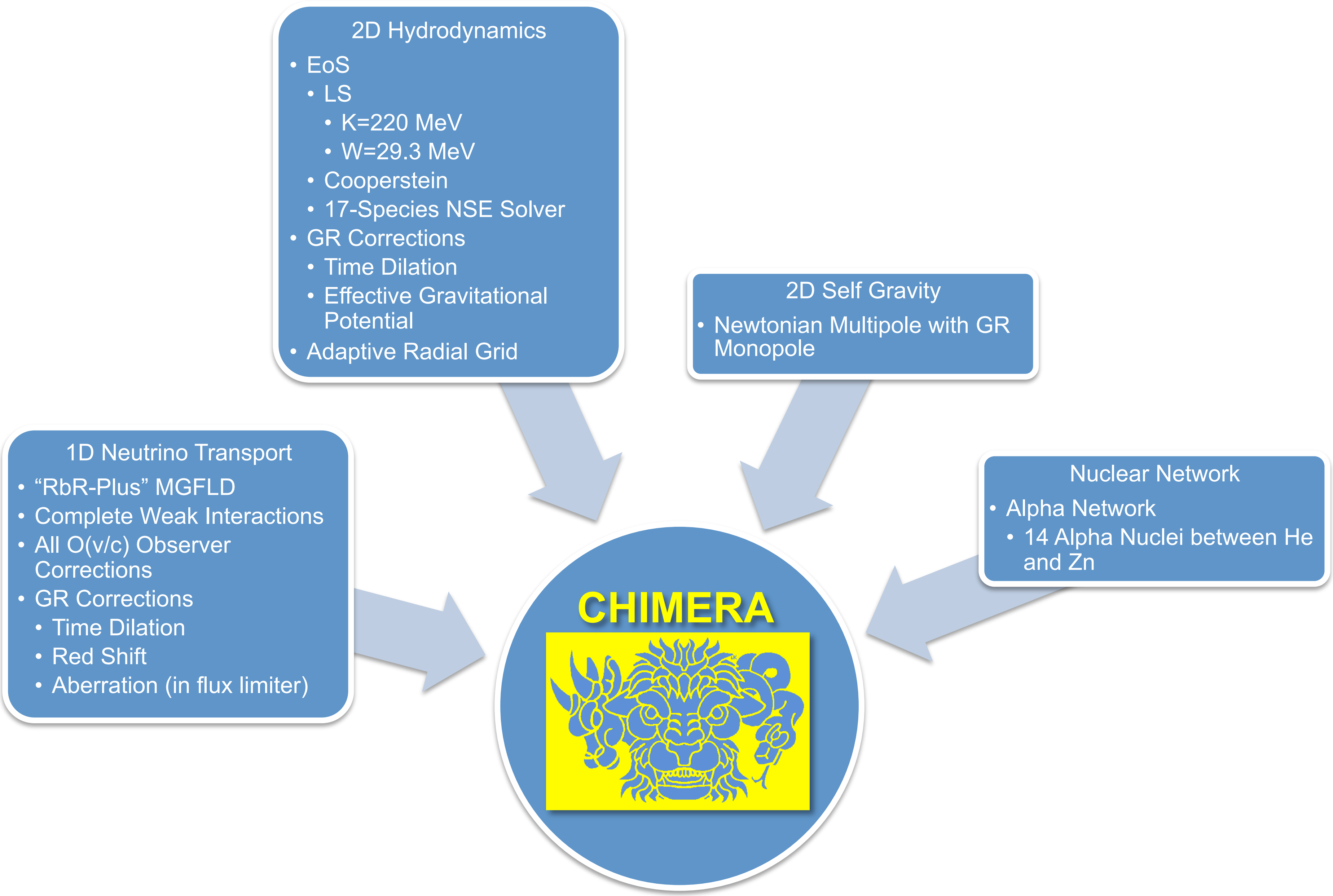
Lentz et al. *Ap.J.* **747**, 73 (2012)



Bruenn et al. *Ap.J. Lett*. **767**, L6 (2013)

Agile-BOLTZTRAN

CHIMERA



2D Hydrodynamics

- EoS
  - LS
    - K=220 MeV
    - W=29.3 MeV
  - Cooperstein
  - 17-Species NSE Solver
- GR Corrections
  - Time Dilation
  - Effective Gravitational Potential
- Adaptive Radial Grid

2D Self Gravity

- Newtonian Multipole with GR Monopole

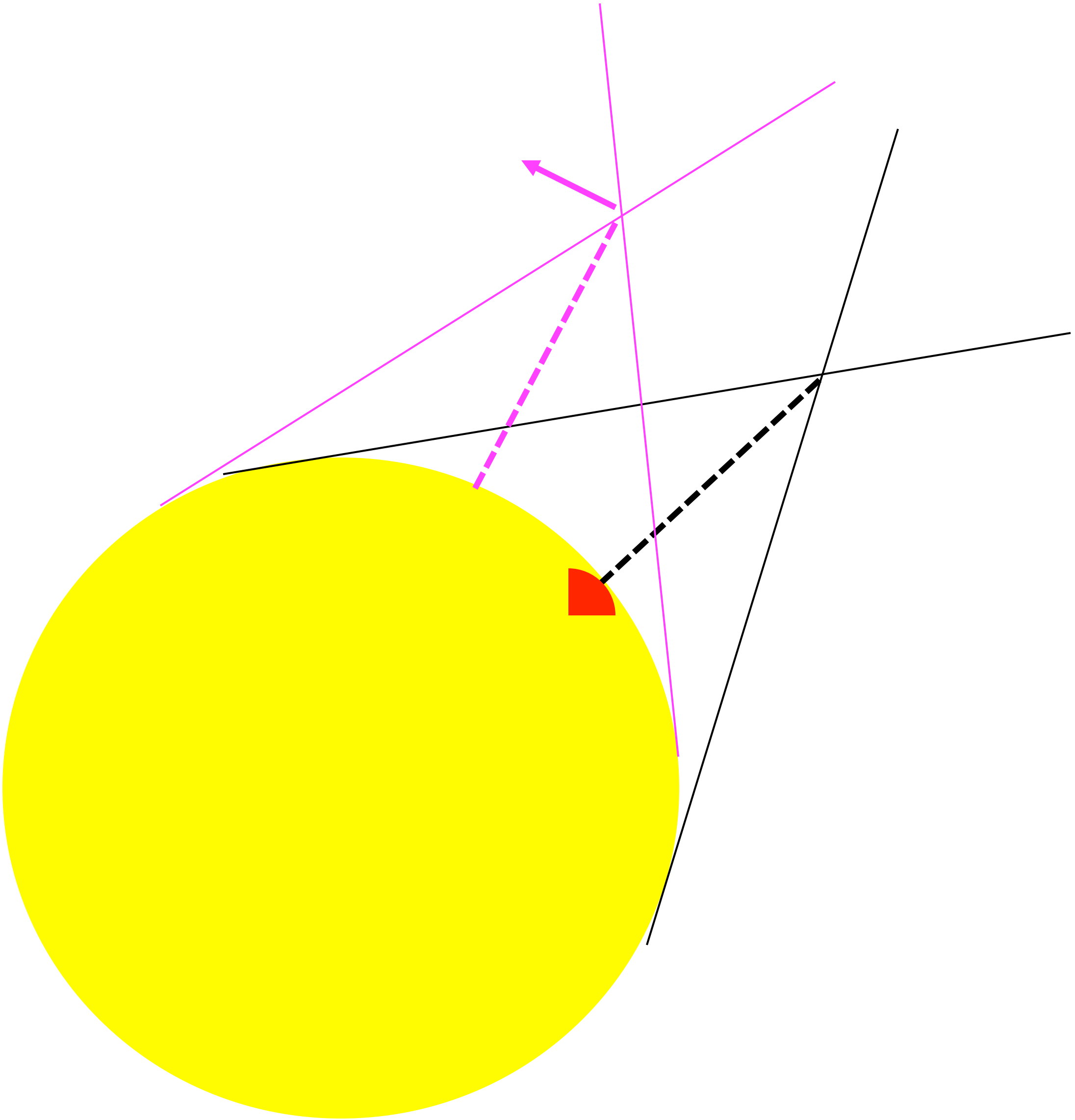
1D Neutrino Transport

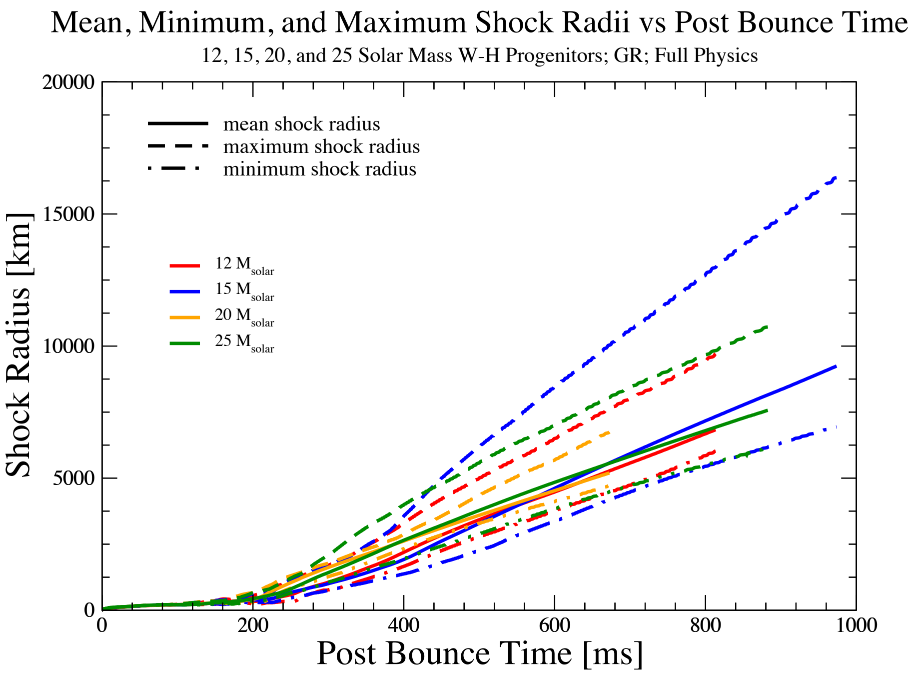
- “RbR-Plus” MGFLD
- Complete Weak Interactions
- All O(v/c) Observer Corrections
- GR Corrections
  - Time Dilation
  - Red Shift
  - Aberration (in flux limiter)

Nuclear Network

- Alpha Network
  - 14 Alpha Nuclei between He and Zn

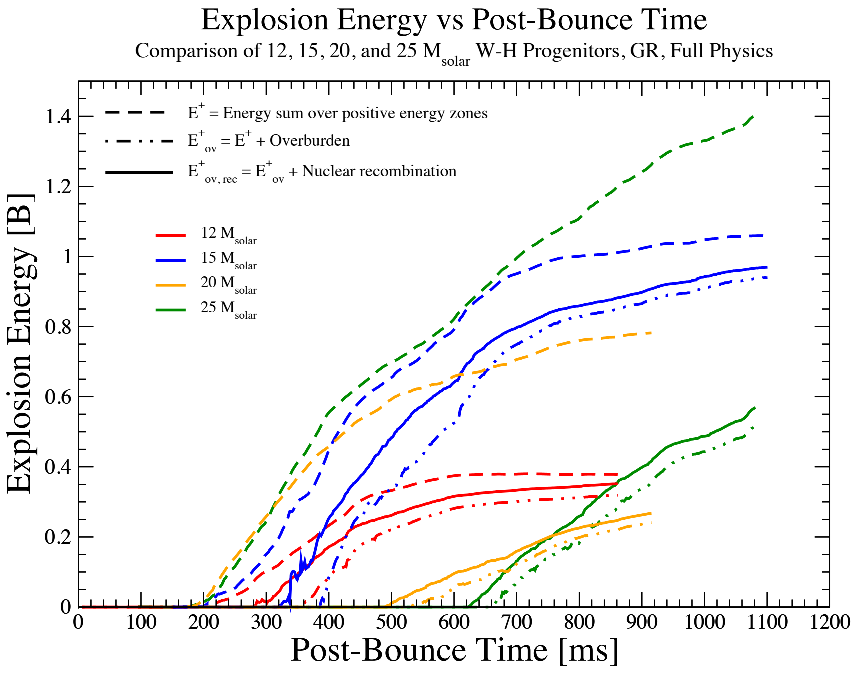
CHIMERA





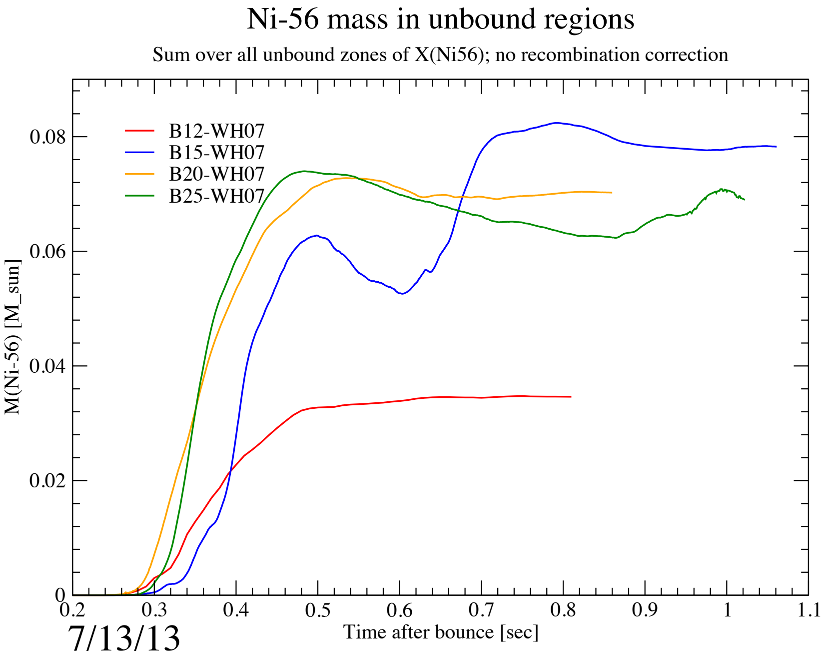
Mean, Minimum, and Maximum Shock Radii vs Post Bounce Time

12, 15, 20, and 25 Solar Mass W-H Progenitors; GR; Full Physics



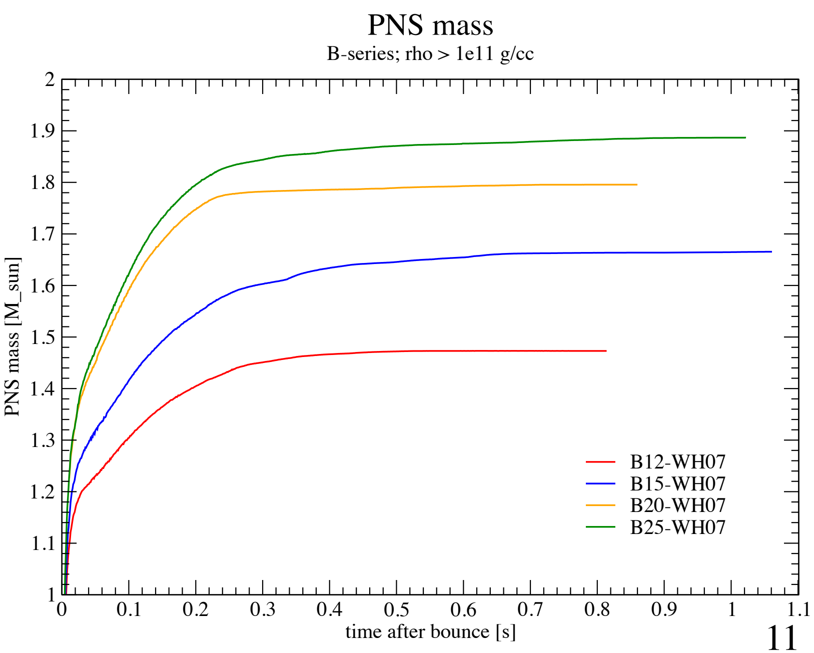
Explosion Energy vs Post-Bounce Time

Comparison of 12, 15, 20, and 25 M_{solar} W-H Progenitors, GR, Full Physics



Ni-56 mass in unbound regions

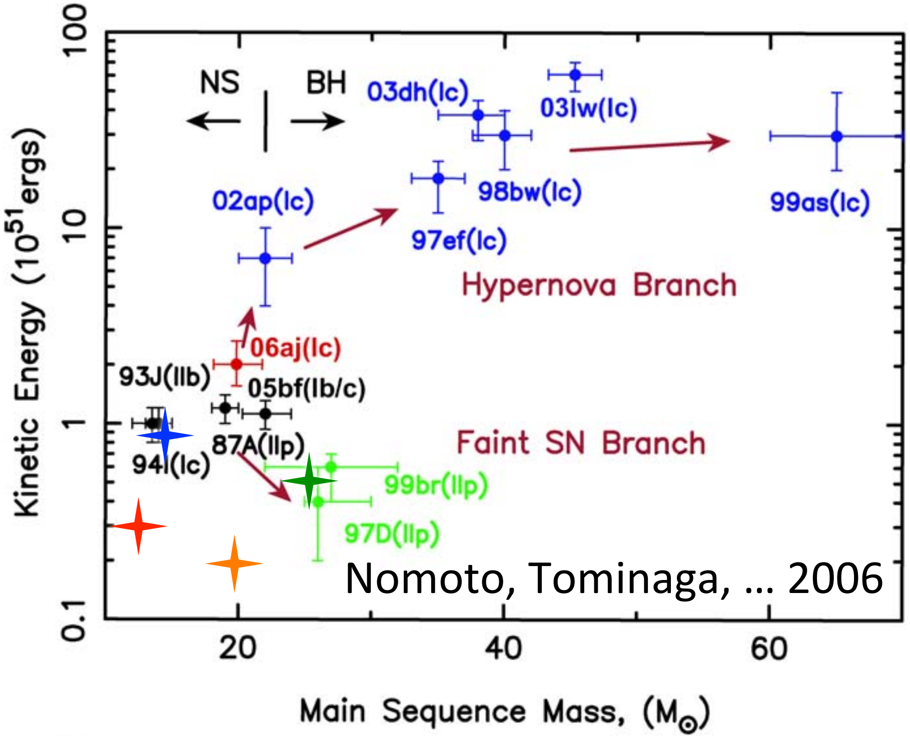
Sum over all unbound zones of X(Ni56); no recombination correction



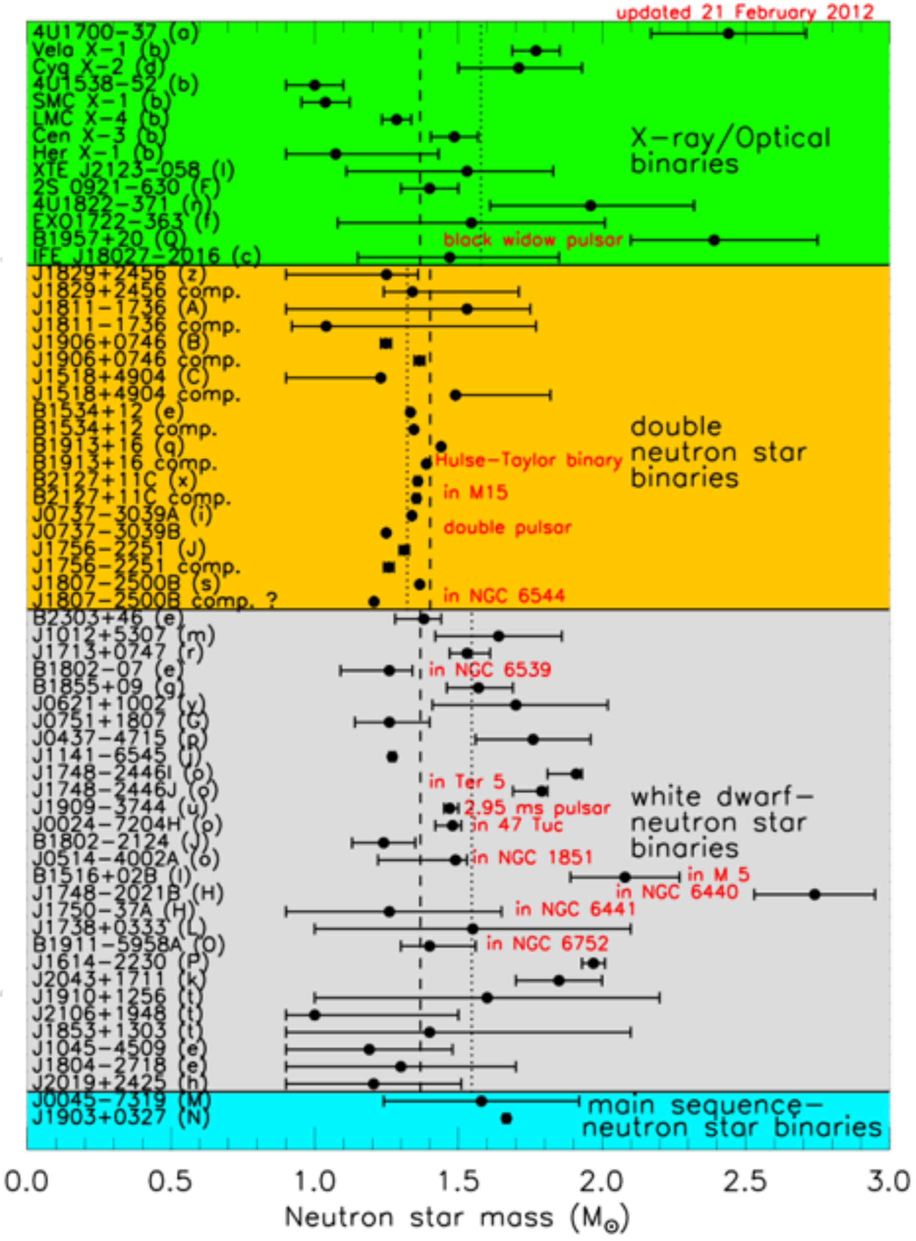
PNS mass

B-series; rho > 1e11 g/cc

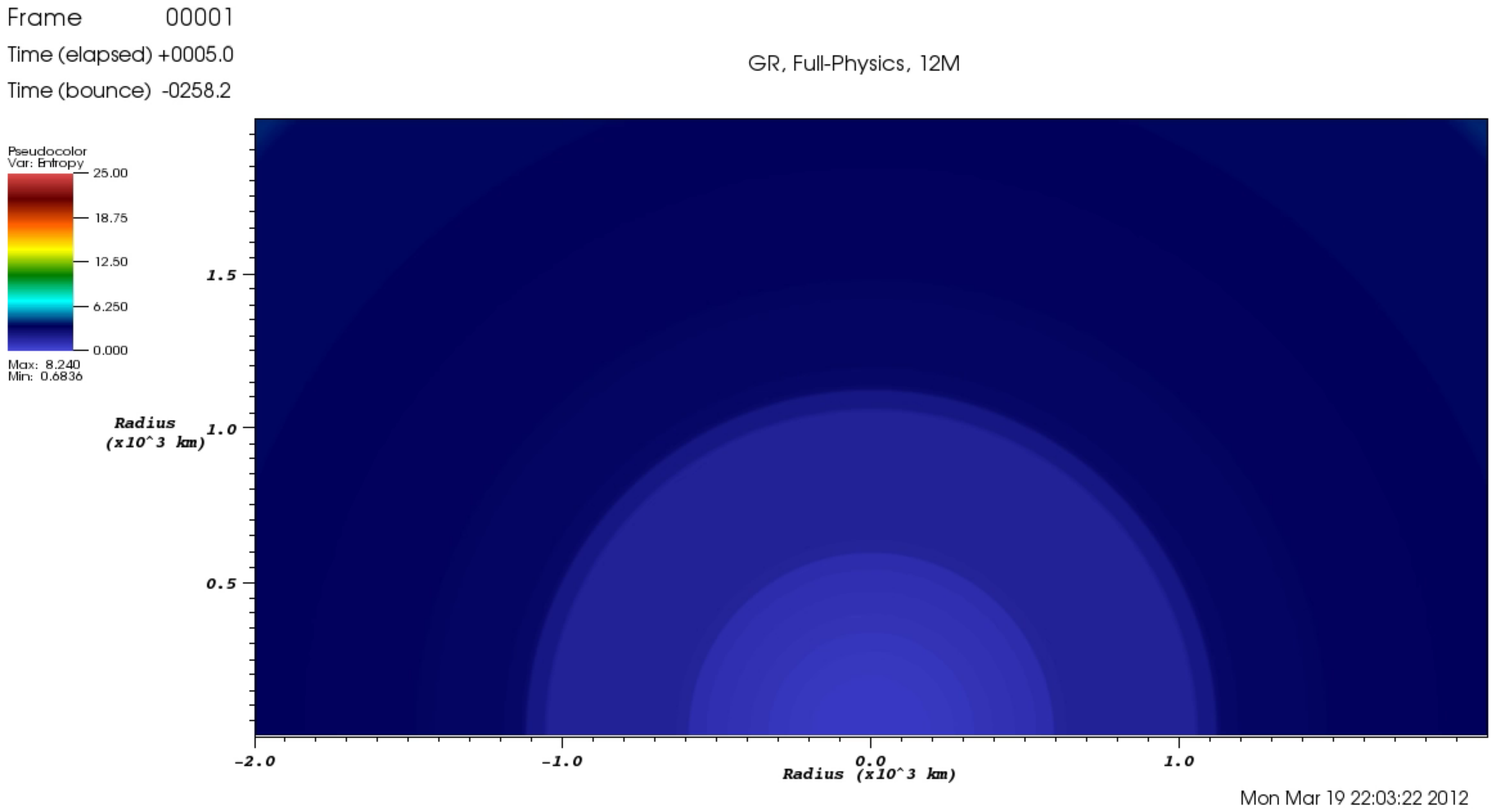
Bruenn et al. 2013. *Ap.J. Lett.* **767**, L6.



Nomoto, Tominaga, … 2006



Lattimer and Prakash (2010)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Time (bounce) -0258.2
GR, Full-Physics, 12M
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Var: Entropy
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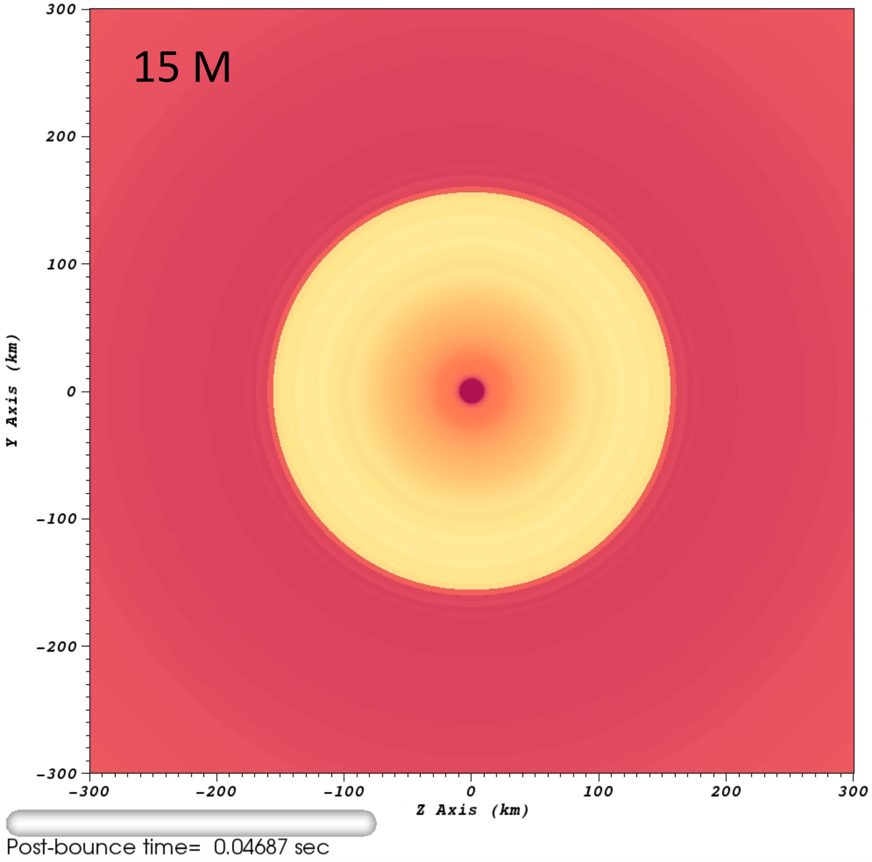
18.75
12.50
6.250
0.000
Max: 8.240
Min: 0.6836
Radius (x10^3 km)
1.5
1.0
0.5
-2.0
-1.0
0.0
1.0
Radius (x10^3 km)
Mon Mar 19 22:03:22 2012

Multi-Physics 3D Models



Lentz et al., in preparation

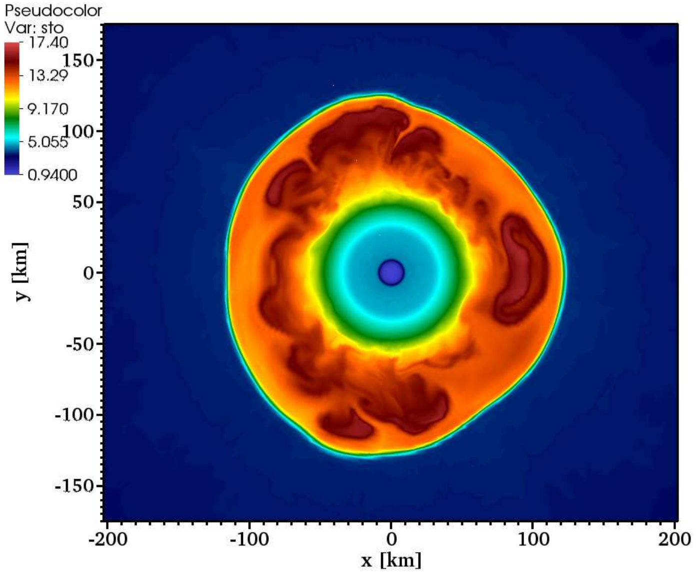
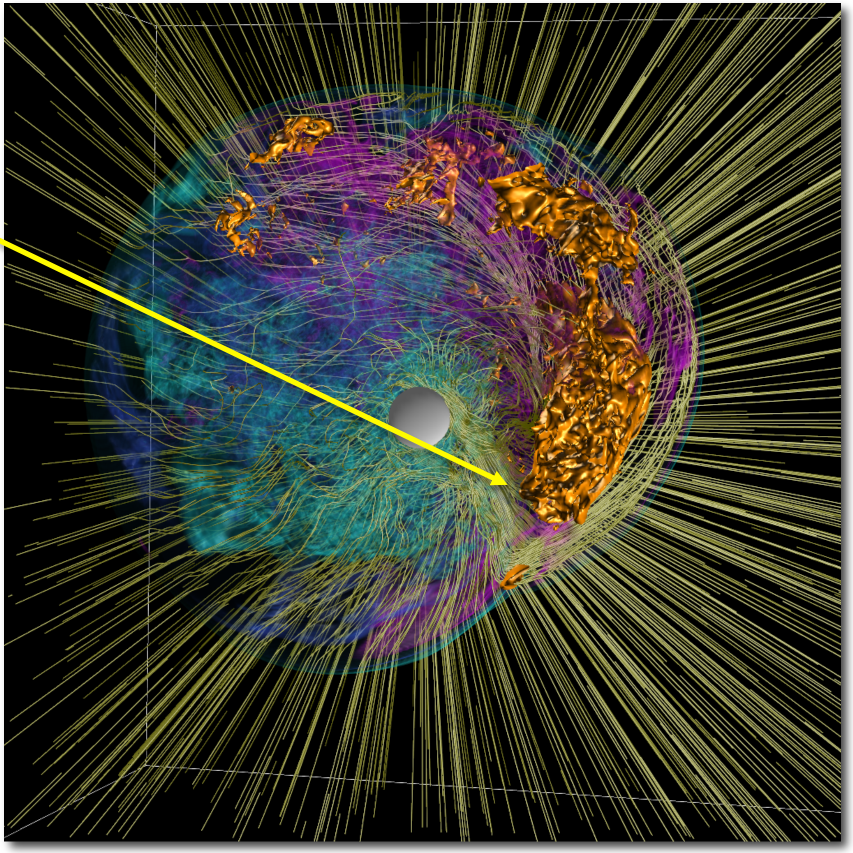


Figure 5. Snapshot of the entropy (color coded according to color bar at the upper left corner, in units of Boltzmann's constant k_b per nucleon) in the plane through the origin normal to the vector $\mathbf{n} = (-0.35, 0.93, 0.12)$ at a post-bounce time of 152 ms in the $27\,M_\odot$ 3D model. The high-entropy plumes with high-order spherical harmonics pattern suggest buoyancy-driven convective overturn of neutrino-heated matter.

Hanke et al. 2013, astro-ph/1303.6269v1

David vs. Goliath: Turbulence vs. SASI



SASI induced shear layer in 3D induces turbulence via secondary instabilities (e.g., Kelvin-Helmholtz).

High-resolution 3D studies suggest that the energy of long-wavelength SASI modes may be sapped by short-wavelength modes via turbulence.

— Endeve et al. 2012. *Ap.J.* **751**, 26.

3D multi-physics simulations will be needed to determine how this plays out.

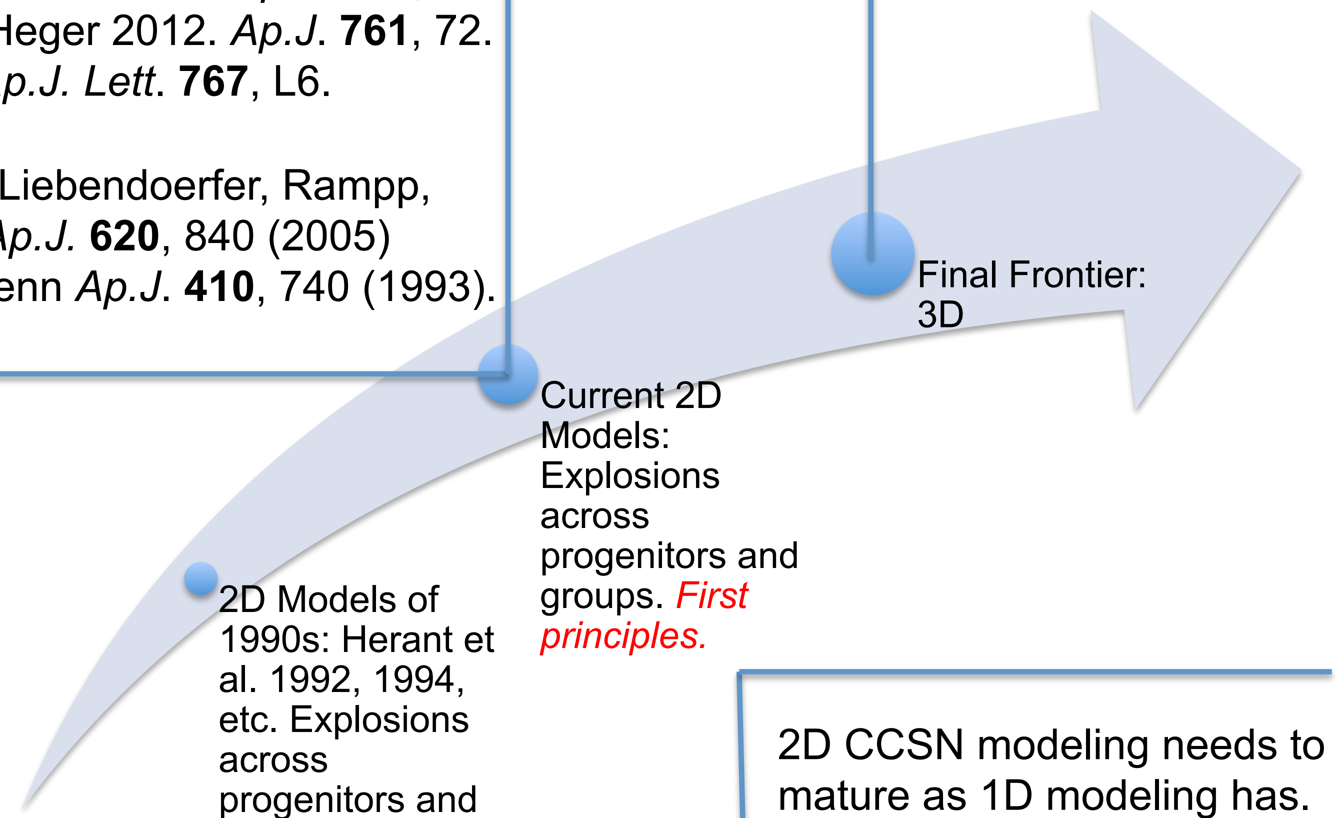
Outlook

Comparative quantitative analyses of 2D models

Mueller, Janka, and Marek 2012. *Ap.J.* **756**, 84.
Mueller, Janka, and Heger 2012. *Ap.J.* **761**, 72.
Bruenn et al. 2013. *Ap.J. Lett.* **767**, L6.

should be performed, ala' Liebendoerfer, Rampp, Janka, and Mezzacappa *Ap.J.* **620**, 840 (2005) and Mezzacappa and Bruenn *Ap.J.* **410**, 740 (1993).

How will SASI and the turbulence it generates interact?



2D Models of 1990s: Herant et al. 1992, 1994, etc. Explosions across progenitors and supernova groups. *Parameterized.*

Current 2D Models: Explosions across progenitors and groups. *First principles.*

Final Frontier: 3D

2D CCSN modeling needs to mature as 1D modeling has.

OAK RIDGE COLLABORATION CODE LINES

Agile-BOLTZTRAN

1D

Boltzmann Neutrino Transport

Exact GR

State-of-the-Art Weak Physics and EOS

CHIMERA

1D/2D/3D

Approximate MGFLD

Approximate GR

State-of-the-Art Weak Physics and EOS

Adaptive (fixed-zone-number) radial mesh.

GenASiS

3D

MGVET/Boltzmann Neutrino Transport

MHD

Exact GR (with Singularity Avoidance)

State-of-the-Art Weak Physics and EOS

Cell-by-Cell AMR

CHIMERA Collaboration

Oak Ridge National Laboratory

The University of Tennessee Knoxville

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Endeve
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NC STATE UNIVERSITY

Blondin
Mauney

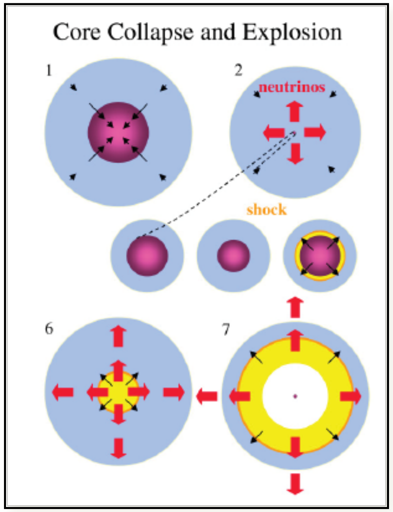
Funded by

Office of Science
U.S. DEPARTMENT OF ENERGY

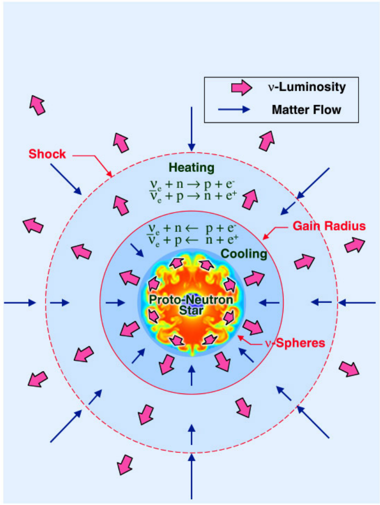
National Science Foundation

National Aeronautics and Space Administration U.S.A.

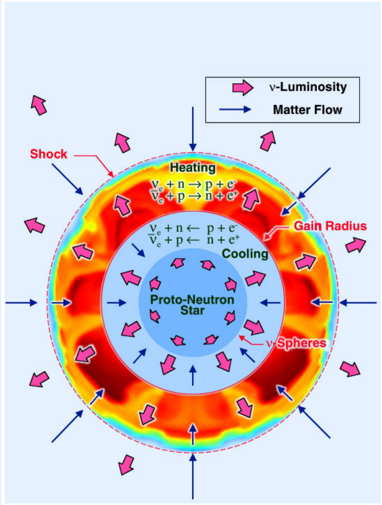
Sources of Gravitational Radiation



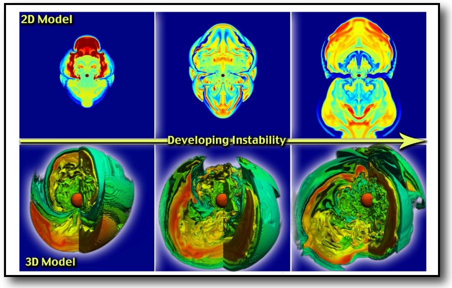
Core Bounce



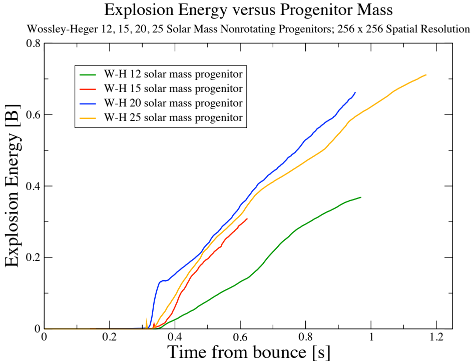
PNS Instabilities



Neutrino-Driven Convection



SASI

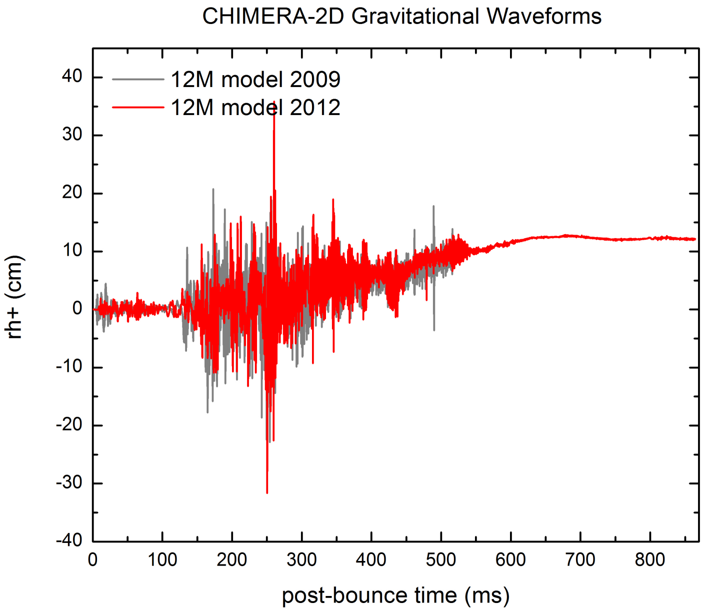


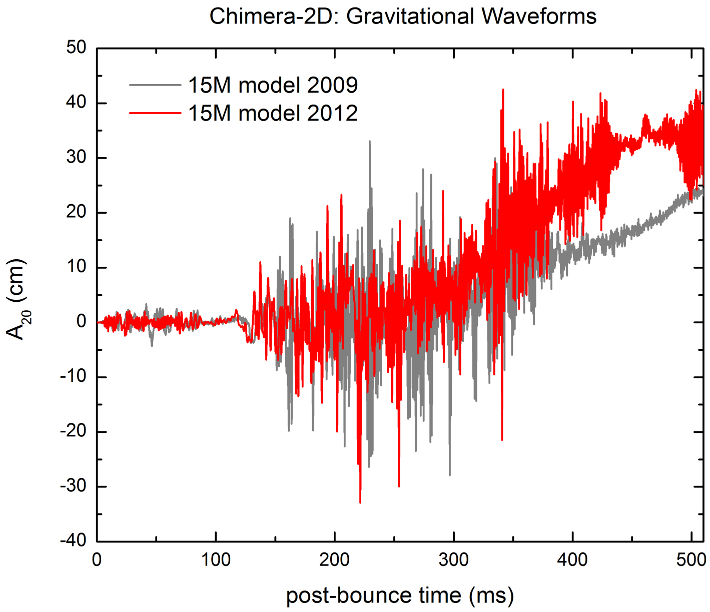
Explosion

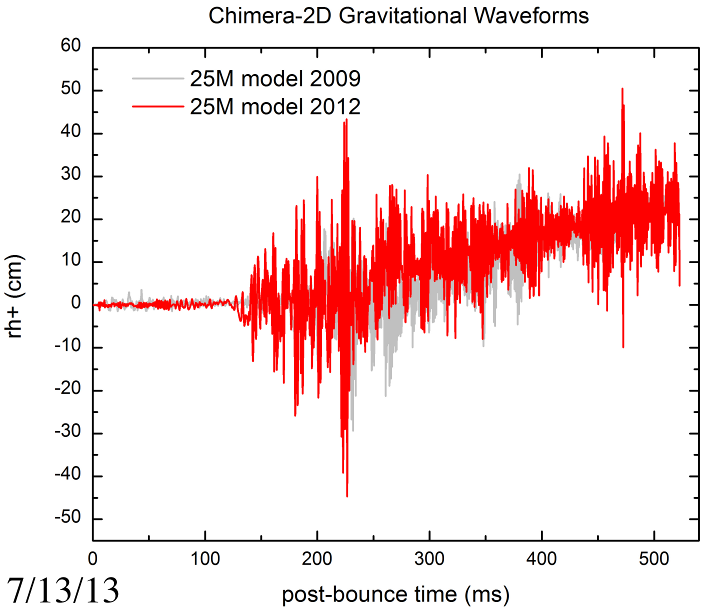
- Core Bounce: Requires realistic (3D) GR electron-neutrino transport.
  1D: Liebendoerfer et al. 2001. PRD **63**, 103004.

- PNS Instabilities: Require realistic 3D GR multiflavor neutrino transport.
  1. Prompt convection.
  2. PNS convection.
  3. Doubly diffusive instabilities - see Bruenn and Dineva 1996, Ap.J. **458**, L71.

- Neutrino-Driven Convection and SASI: Require realistic 3D explosion models.
  2D: Bruenn et al. 2013, *Ap.J. Lett*. **767**, L6; Mueller, Janka, and Marek 2012, *Ap.J.* **756**, 84.


CHIMERA-2D Gravitational Waveforms


Chimera-2D: Gravitational Waveforms


Chimera-2D Gravitational Waveforms

Ab initio – i.e., non-parameterized – explosions allow us to predict more accurately the gravitational wave signatures.

Our signature predictions are being used by the LIGO collaboration to calibrate their analyses.

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