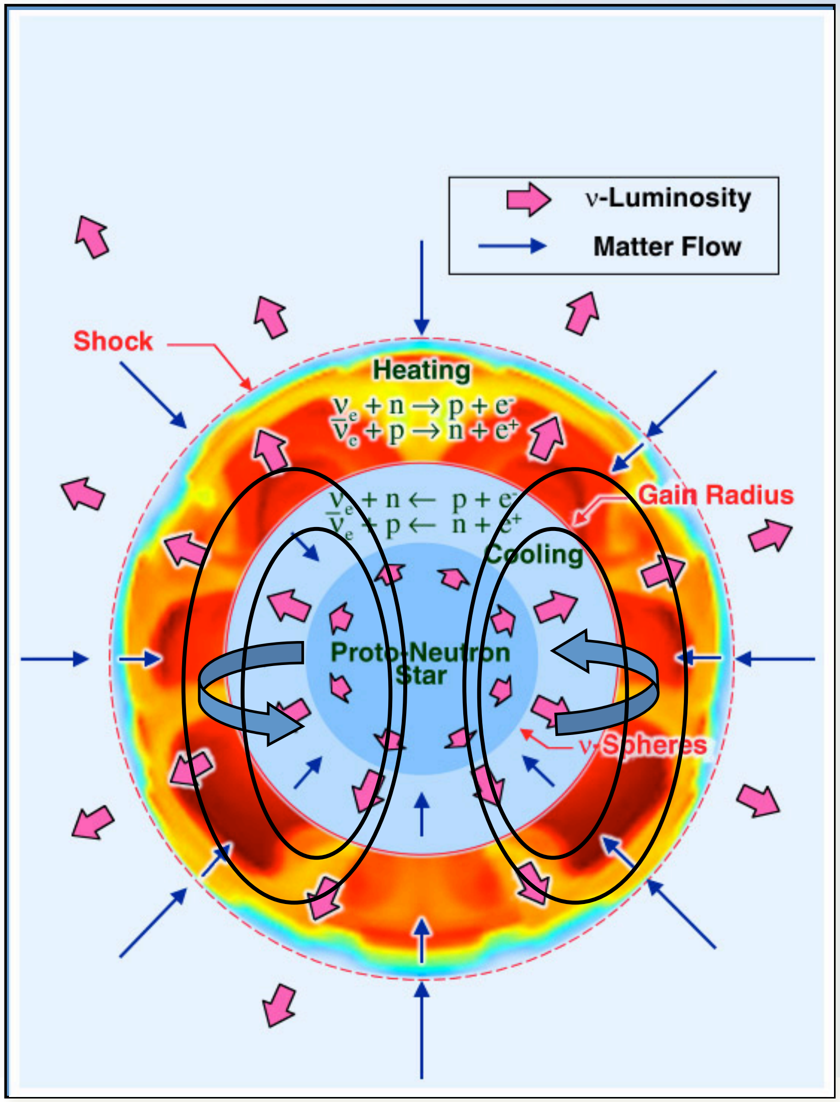
Status of Neutrino Driven Explosions

How is the supernova shock wave revived?

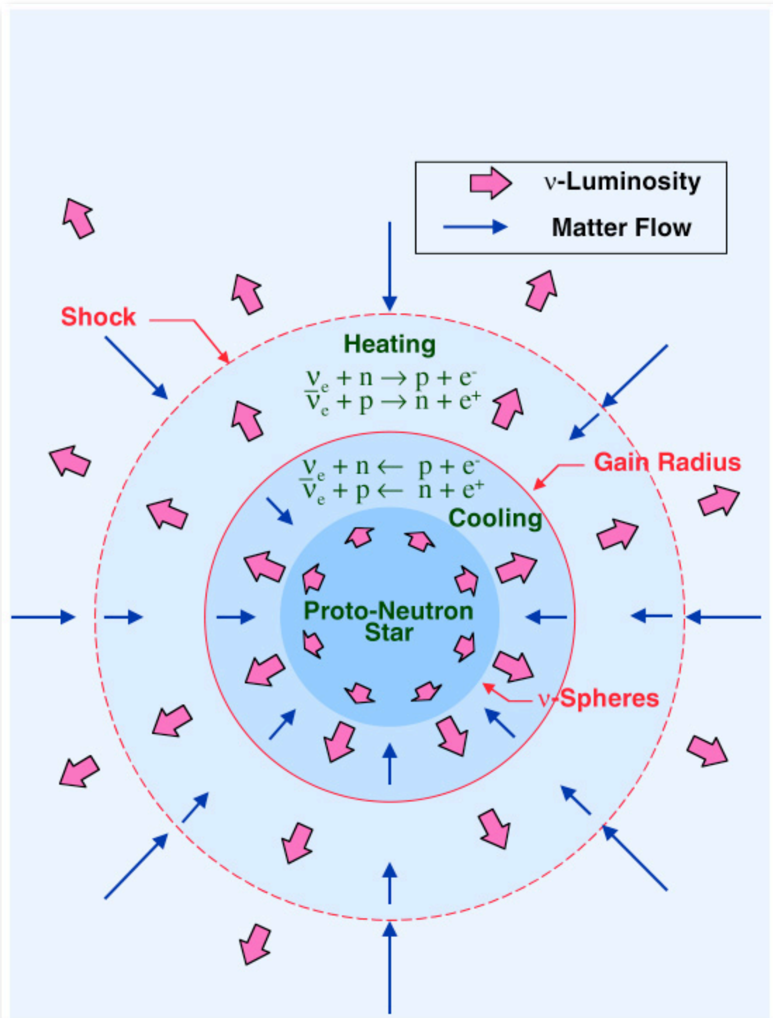


Known, Potentially Important Ingredients

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

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

Neutrino Heating



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

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

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

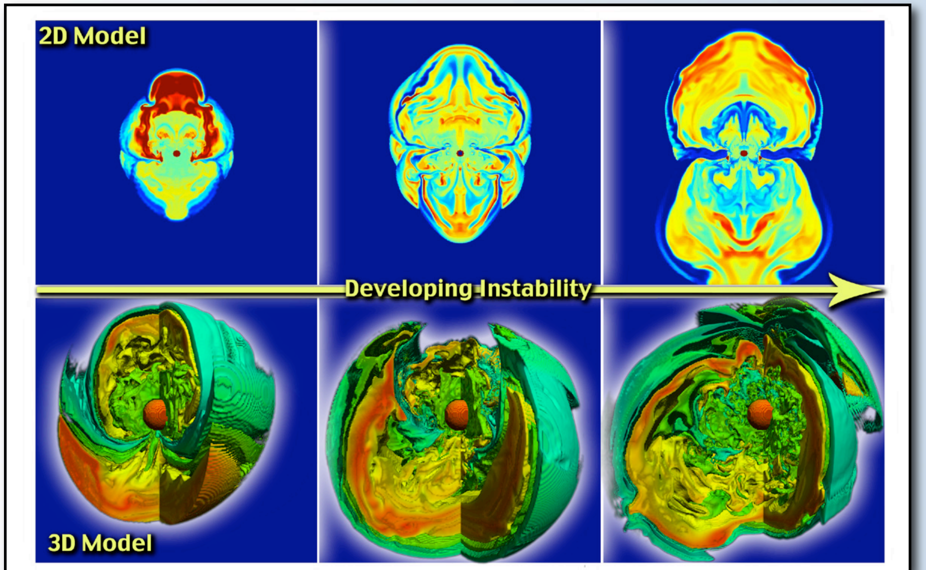
$$E_R(t,r,\theta,\phi,E) = \int d\theta_p\, d\phi_p\, f$$

Multifrequency (*Parameterize Isotropy*)

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

Gray (*Parameterize Isotropy and Spectra*)

Stationary Accretion Shock Instability (SASI)



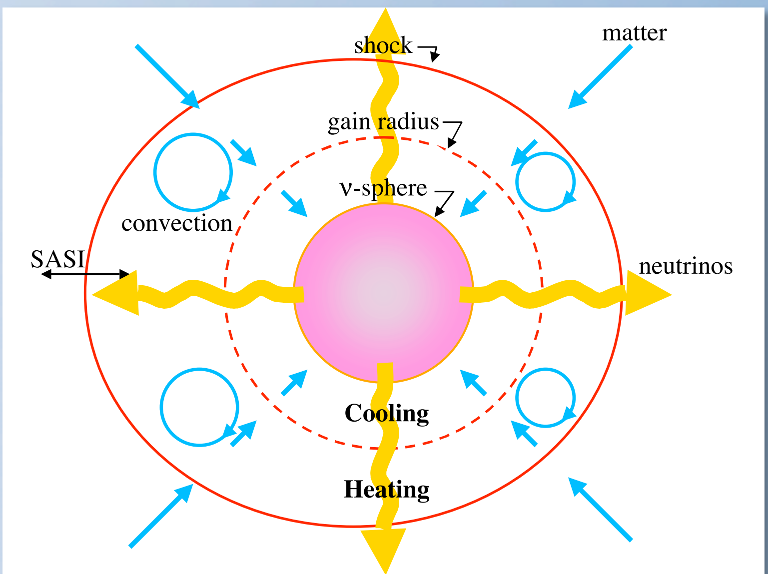
<ins>Blondin, Mezzacappa, & DeMarino, *Ap.J.* **584**, 971 (2003)</ins>

Shock wave unstable to non-radial perturbations.

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)



- Decreases advection velocity in gain region.
- Increases time in the gain region.
- Moves shock toward silicon/oxygen layers.
- Generates convection.

⇒ Marek and Janka, *Ap.J.* **694**, 664 (2009)

Important Neutrino Emissivities/Opacities

"Standard" Emissivities/Opacities

Bruenn, *Ap.J. Suppl*. (1985)
- Nucleons in nucleus independent.
- No energy exchange in nucleonic scattering.

$e^- + p, A \leftrightarrow \nu_e + n, A'$ — Langanke et al. PRL, **90**, 241102 (2003)
- Include correlations between nucleons in nuclei.

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

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

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

★ $N + N \leftrightarrow N + N + \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$ — Hannestadt and Raffelt, *Ap.J.* **507**, 339 (1998)
Hanhart, Phillips, and Reddy, *Phys. Lett. B*, **499**, 9 (2001)
- New source of neutrino-antineutrino pairs.

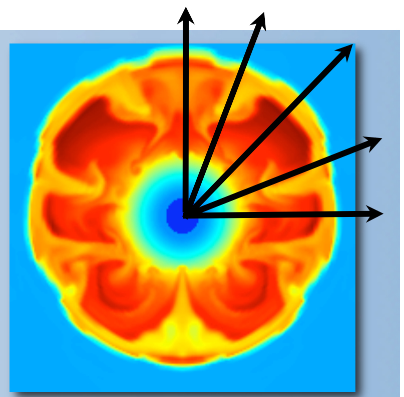
$\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

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

Ongoing 2D Multi-Physics Supernova Models

<u>Simulation Building Blocks</u>

- *"RbR-Plus" MGFLD Neutrino Transport*
  - *O(v/c), GR time dilation and redshift, GR aberration (in flux limiter)*
- *2D PPM Hydrodynamics*
  - *GR time dilation, effective gravitational potential, adaptive radial grid*
- *Lattimer-Swesty EOS*
  - *180 MeV (nuclear compressibility), 29.3 MeV (symmetry energy)*
- *Nuclear (Alpha) Network*
  - *14 alpha nuclei between helium and zinc*
- *2D Effective Gravitational Potential*
  - Marek et al. *A&A*, **445**, 273 (2006)
- *Neutrino Emissivities/Opacities*
  - *"Standard" + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung*

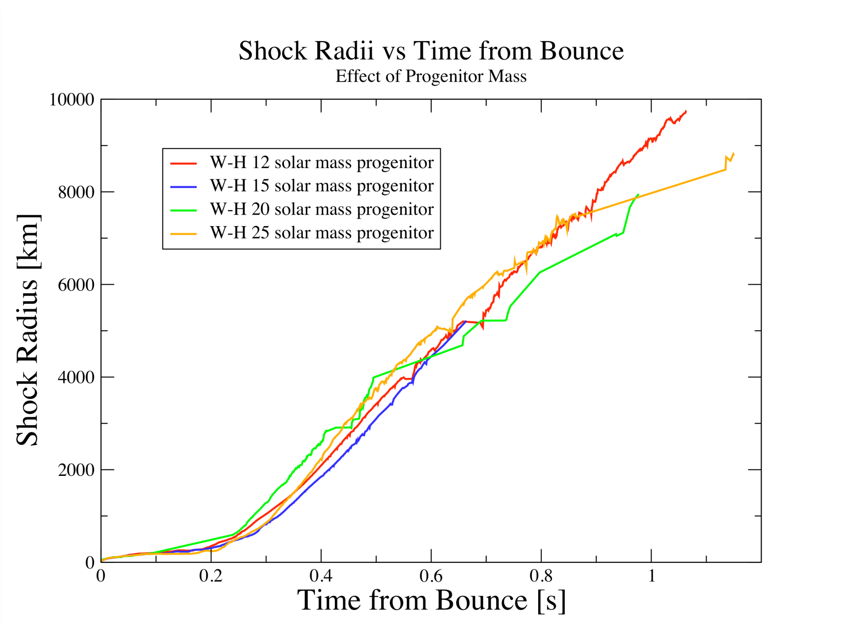


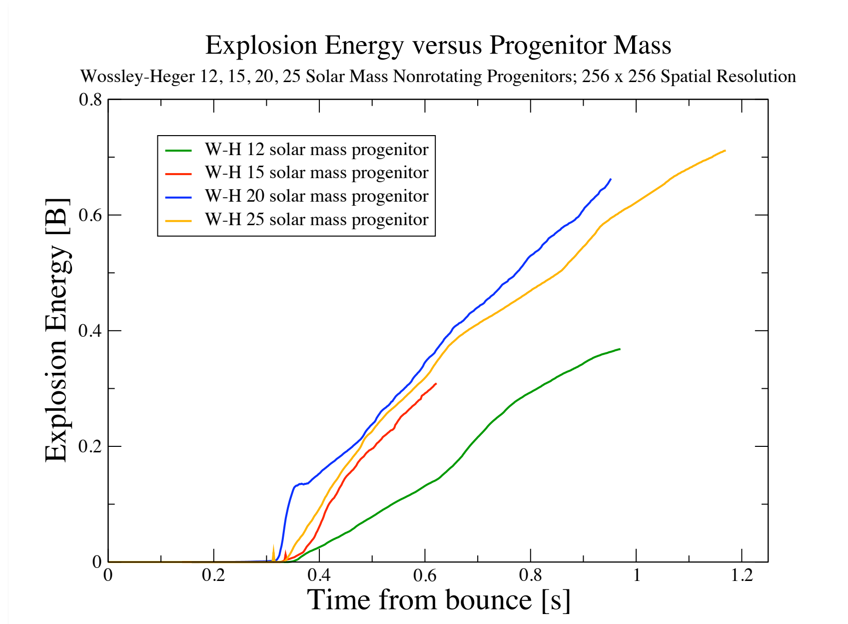
"Ray-by-Ray-Plus" Approximation

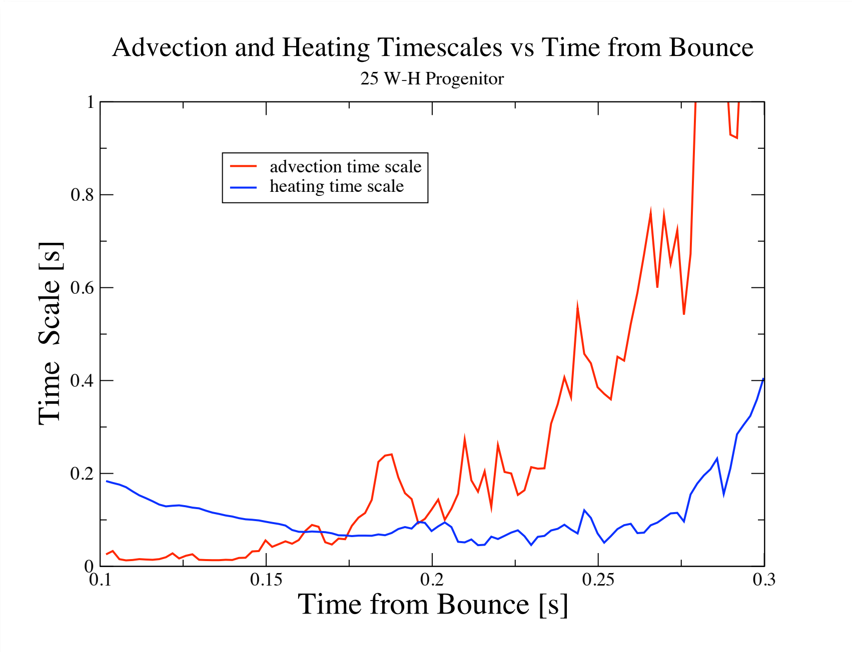
- Radial transport allowed.
- Lateral transport suppressed.

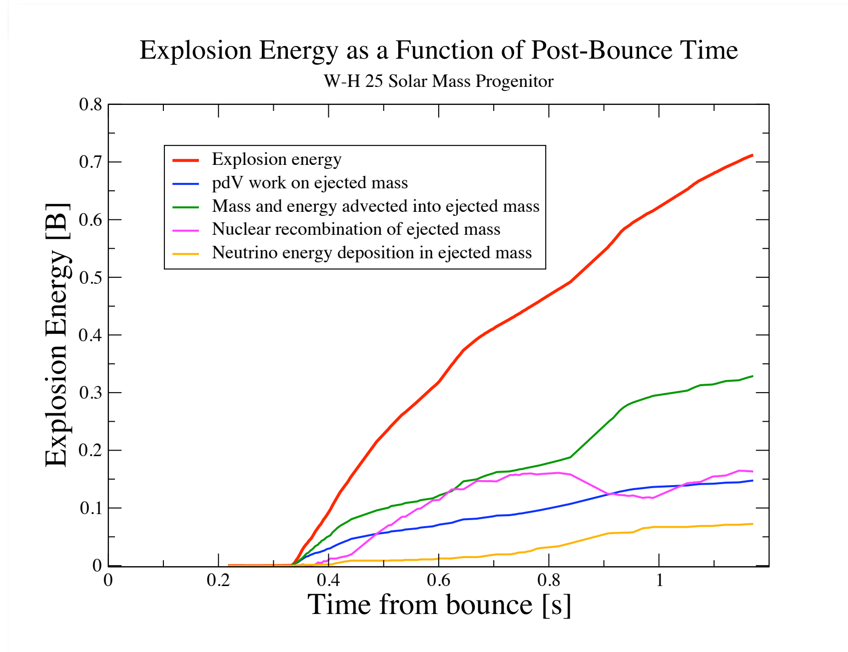
– Buras et al. *A&A*, **447**, 1049 (2003)

CHIMERA

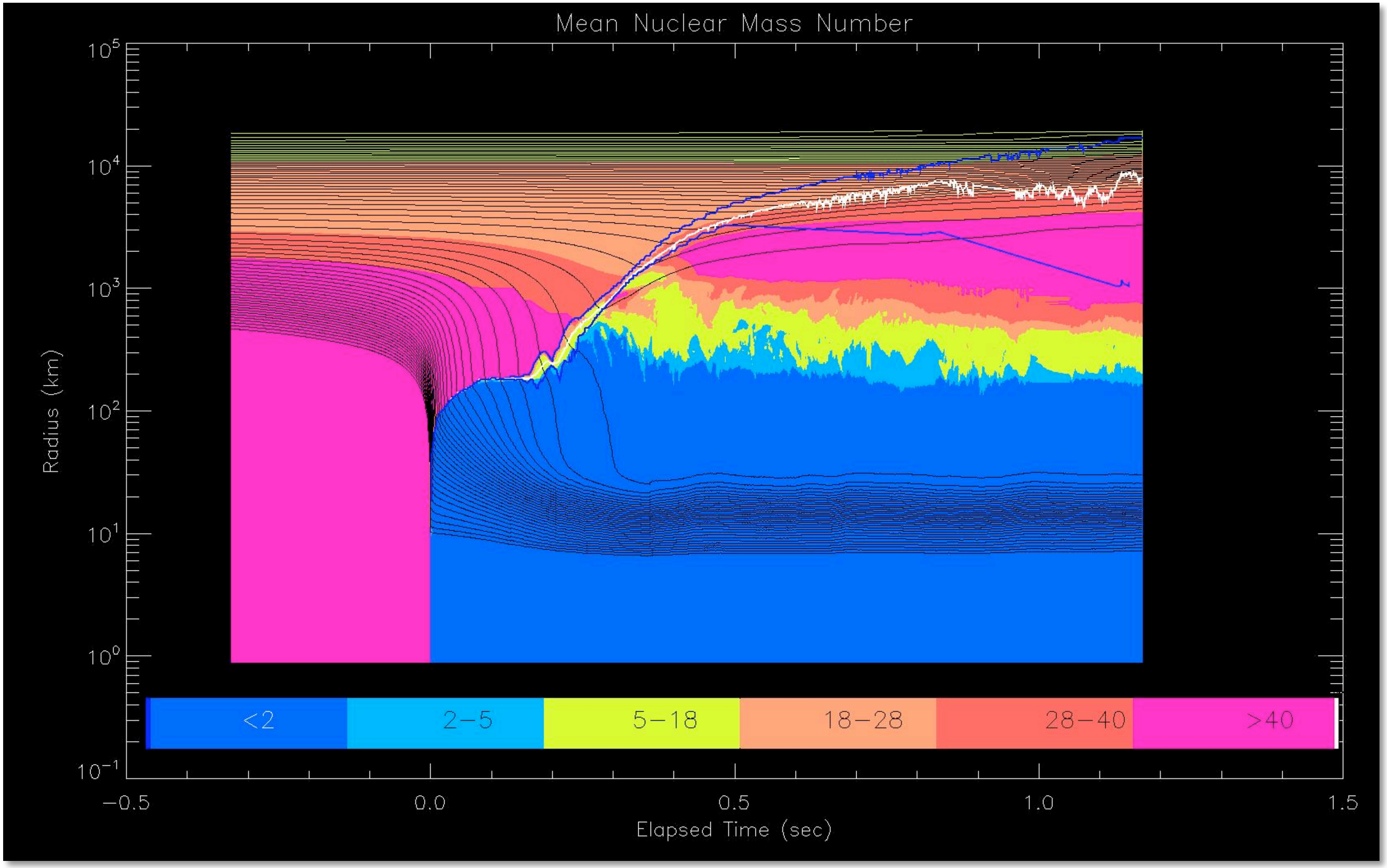

Shock Radii vs Time from Bounce
Effect of Progenitor Mass
W-H 12 solar mass progenitor
W-H 15 solar mass progenitor
W-H 20 solar mass progenitor
W-H 25 solar mass progenitor
Shock Radius [km]
Time from Bounce [s]

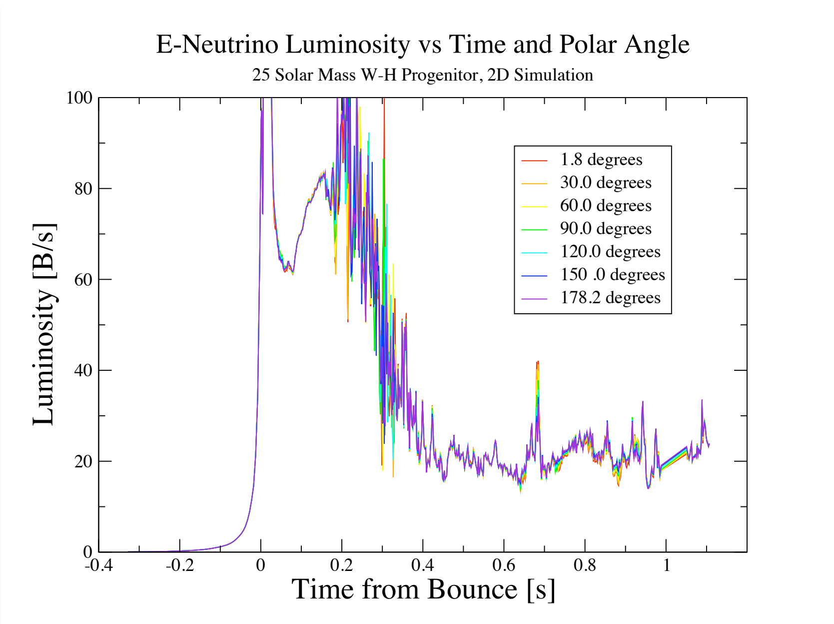

Explosion Energy versus Progenitor Mass
Wossley-Heger 12, 15, 20, 25 Solar Mass Nonrotating Progenitors; 256 x 256 Spatial Resolution
W-H 12 solar mass progenitor
W-H 15 solar mass progenitor
W-H 20 solar mass progenitor
W-H 25 solar mass progenitor
Explosion Energy [B]
Time from bounce [s]

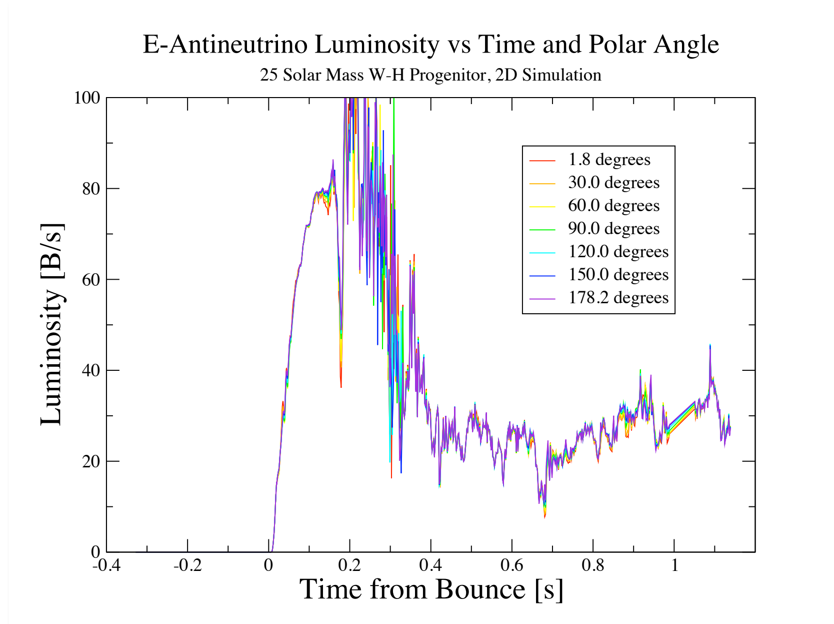

Advection and Heating Timescales vs Time from Bounce
25 W-H Progenitor
advection time scale
heating time scale
Time Scale [s]
Time from Bounce [s]

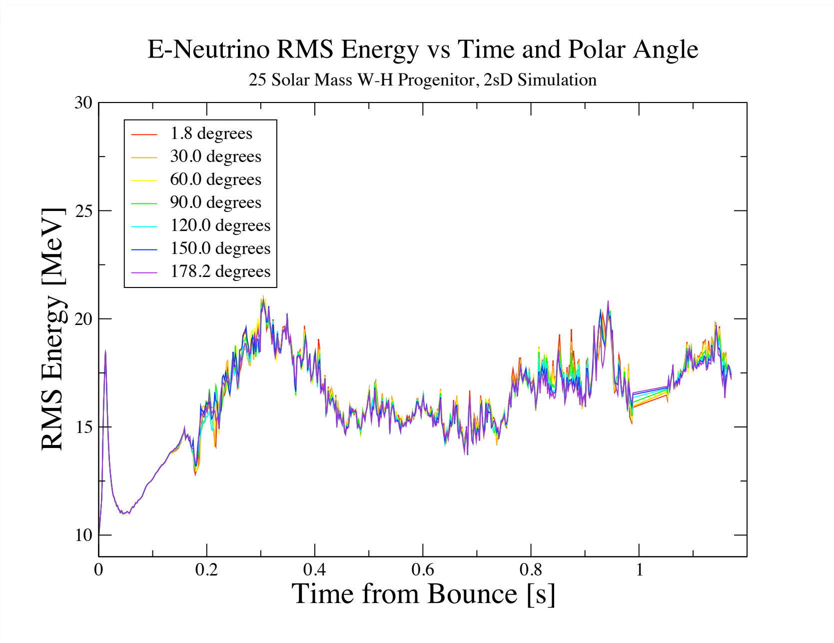

Explosion Energy as a Function of Post-Bounce Time
W-H 25 Solar Mass Progenitor
Explosion energy
pdV work on ejected mass
Mass and energy advected into ejected mass
Nuclear recombination of ejected mass
Neutrino energy deposition in ejected mass
Explosion Energy [B]
Time from bounce [s]

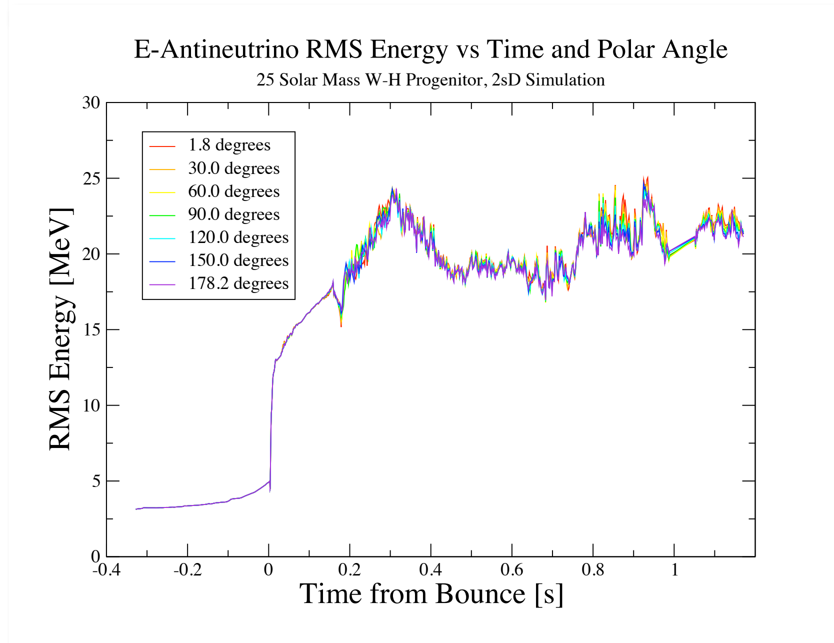
25 M: Mass Shell Trajectories

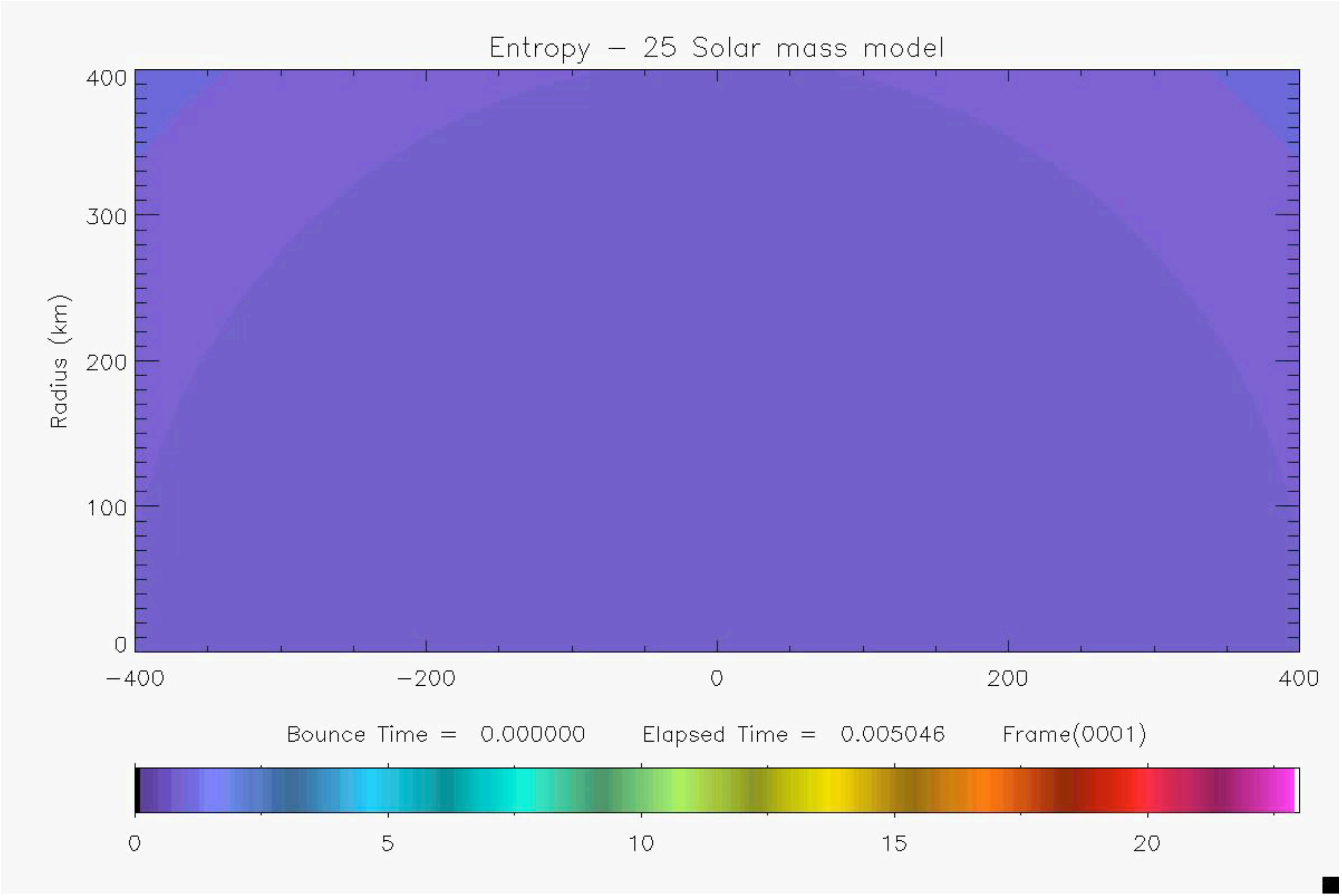



E-Neutrino Luminosity vs Time and Polar Angle
25 Solar Mass W-H Progenitor, 2D Simulation
Luminosity [B/s]
Time from Bounce [s]
1.8 degrees
30.0 degrees
60.0 degrees
90.0 degrees
120.0 degrees
150 .0 degrees
178.2 degrees
0
20
40
60
80
100
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

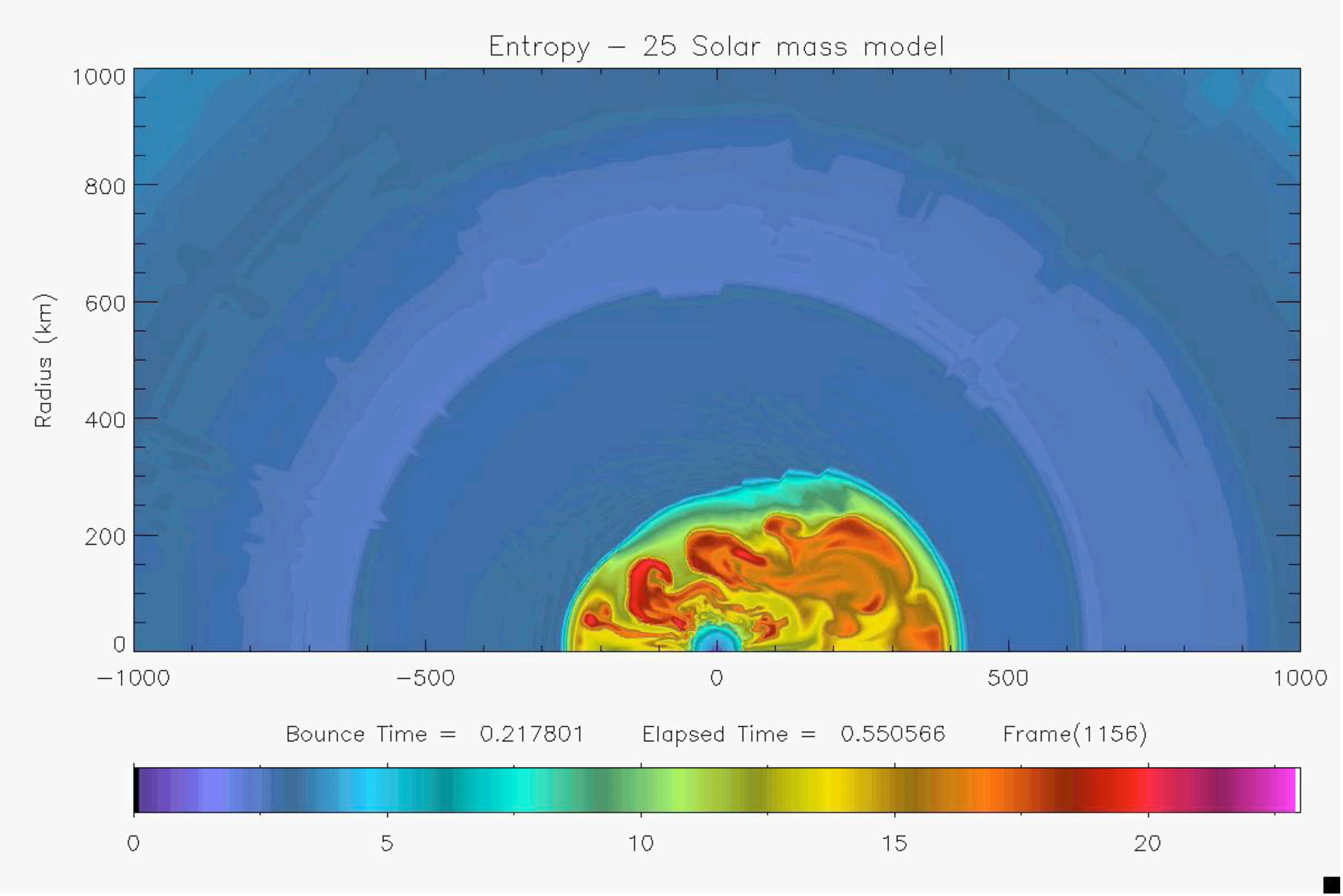

E-Antineutrino Luminosity vs Time and Polar Angle
25 Solar Mass W-H Progenitor, 2D Simulation
Luminosity [B/s]
Time from Bounce [s]
1.8 degrees
30.0 degrees
60.0 degrees
90.0 degrees
120.0 degrees
150.0 degrees
178.2 degrees
0
20
40
60
80
100
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

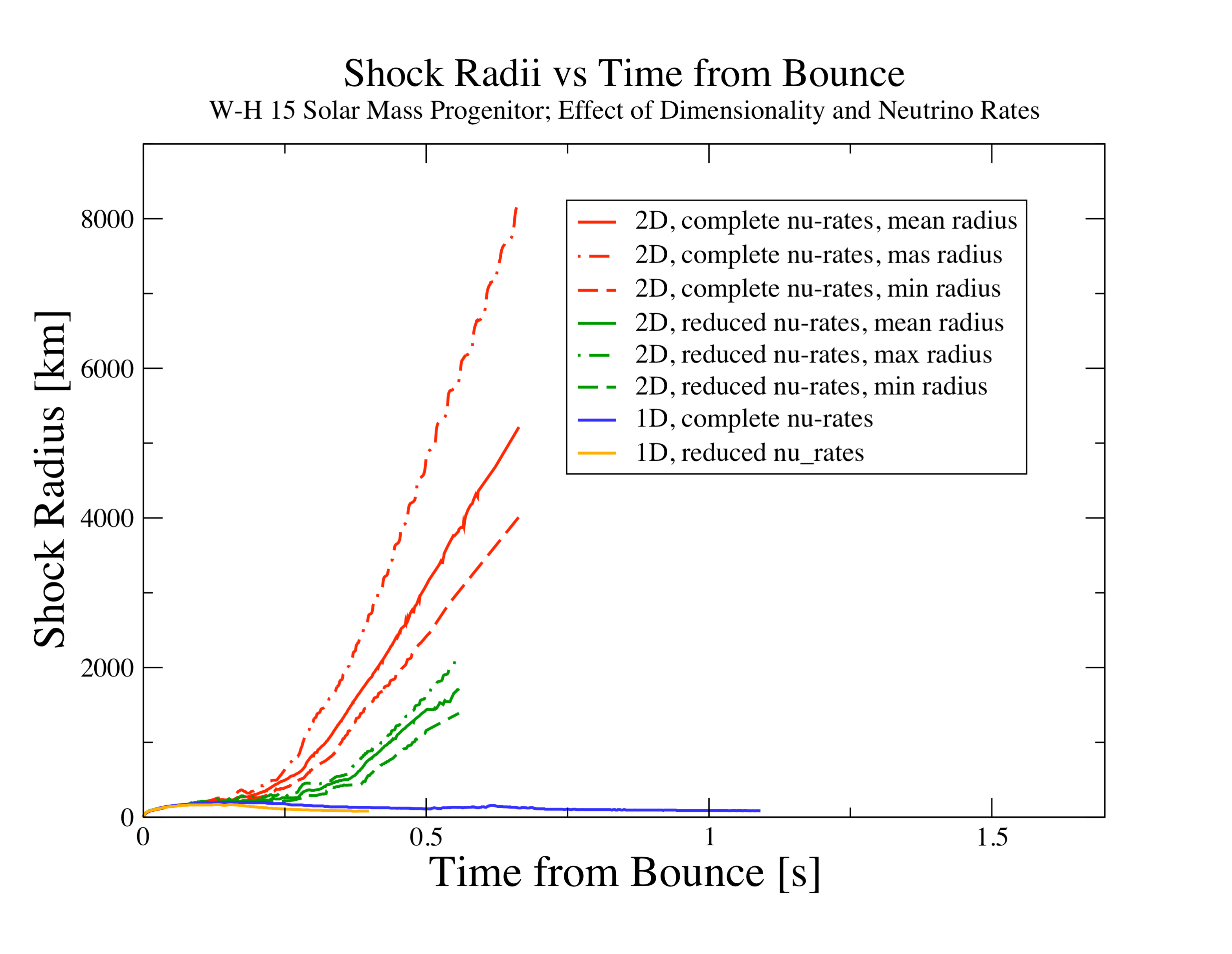

E-Neutrino RMS Energy vs Time and Polar Angle
25 Solar Mass W-H Progenitor, 2sD Simulation
RMS Energy [MeV]
Time from Bounce [s]
1.8 degrees
30.0 degrees
60.0 degrees
90.0 degrees
120.0 degrees
150.0 degrees
178.2 degrees
10
15
20
25
30
0
0.2
0.4
0.6
0.8
1


E-Antineutrino RMS Energy vs Time and Polar Angle
25 Solar Mass W-H Progenitor, 2sD Simulation
RMS Energy [MeV]
Time from Bounce [s]
1.8 degrees
30.0 degrees
60.0 degrees
90.0 degrees
120.0 degrees
150.0 degrees
178.2 degrees
0
5
10
15
20
25
30
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

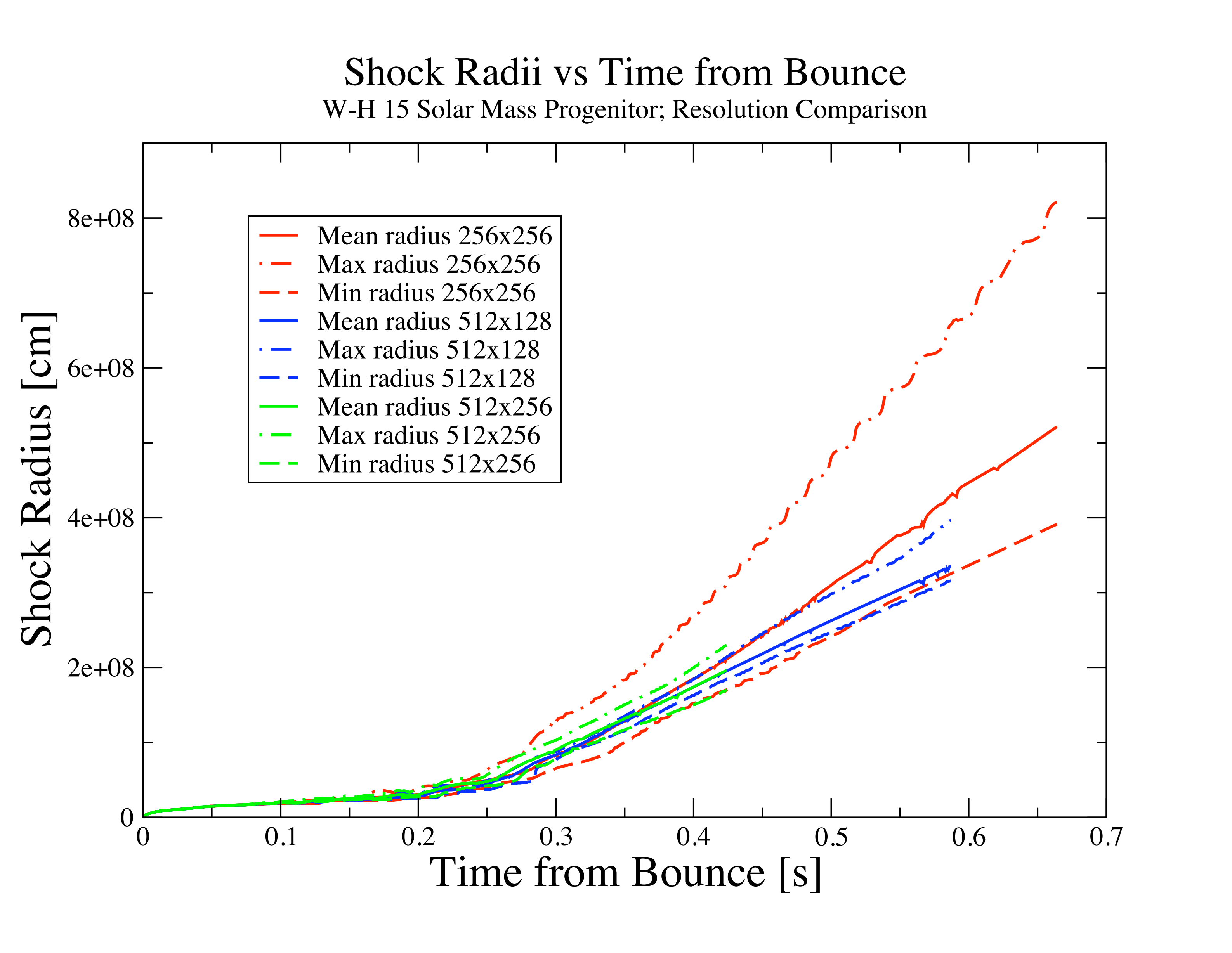


Entropy – 25 Solar mass model
Radius (km)
400
300
200
100
0
–400
–200
0
200
400
Bounce Time = 0.000000
Elapsed Time = 0.005046
Frame(0001)
0
5
10
15
20


Entropy – 25 Solar mass model
1000
800
600
400
200
0
Radius (km)
−1000
−500
0
500
1000
Bounce Time = 0.217801
Elapsed Time = 0.550566
Frame(1156)
0
5
10
15
20



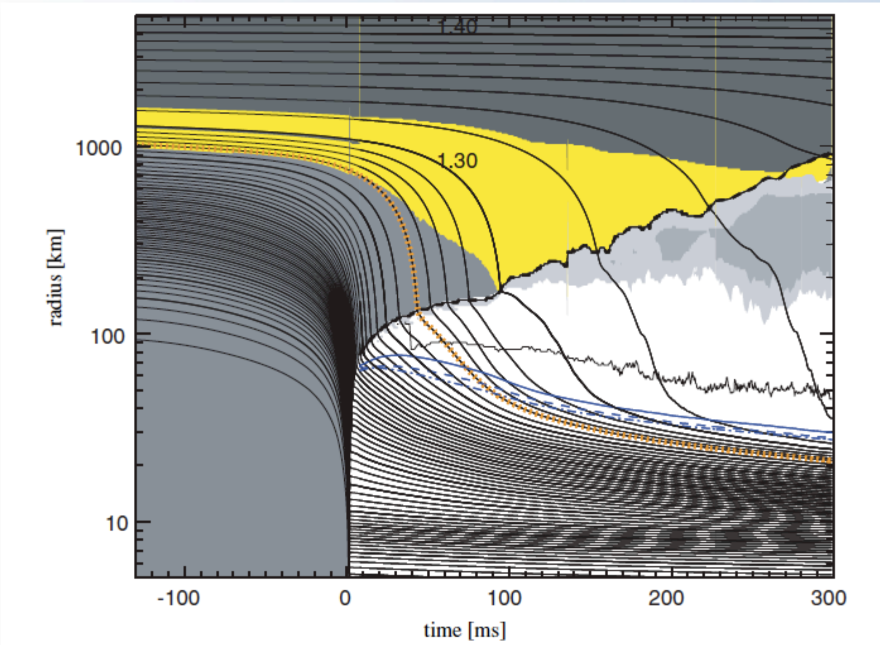
Shock Radii vs Time from Bounce
W-H 15 Solar Mass Progenitor; Effect of Dimensionality and Neutrino Rates
2D, complete nu-rates, mean radius
2D, complete nu-rates, mas radius
2D, complete nu-rates, min radius
2D, reduced nu-rates, mean radius
2D, reduced nu-rates, max radius
2D, reduced nu-rates, min radius
1D, complete nu-rates
1D, reduced nu_rates
Shock Radius [km]
0
2000
4000
6000
8000
0
0.5
1
1.5
Time from Bounce [s]



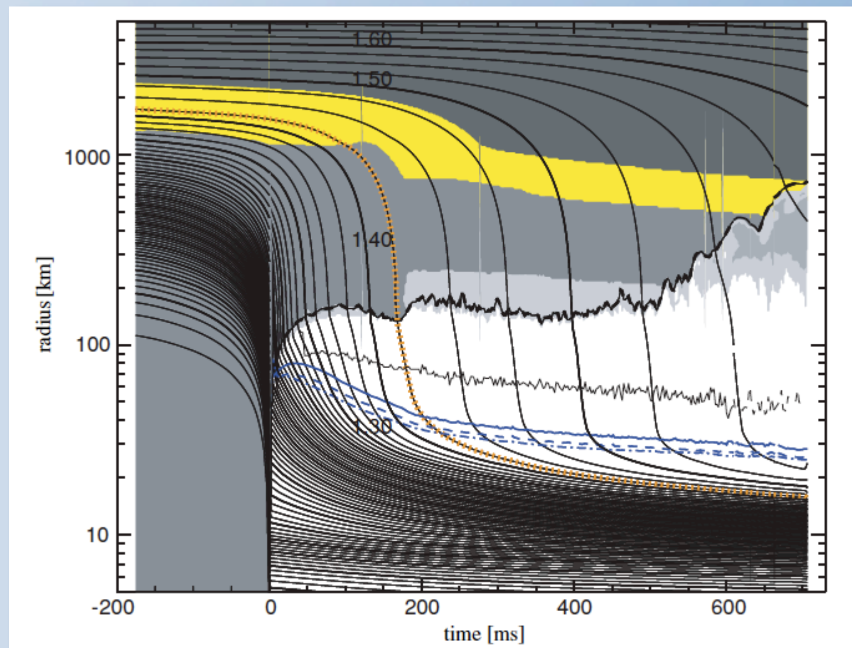
Shock Radii vs Time from Bounce
W-H 15 Solar Mass Progenitor; Resolution Comparison
Mean radius 256x256
Max radius 256x256
Min radius 256x256
Mean radius 512x128
Max radius 512x128
Min radius 512x128
Mean radius 512x256
Max radius 512x256
Min radius 512x256
Shock Radius [cm]
0
2e+08
4e+08
6e+08
8e+08
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Time from Bounce [s]

Neutrino-Driven, SASI-Aided Explosions

11 M



15 M



$t_{\text{explosion}} \sim 200\ \text{ms}$

$t_{\text{explosion}} \sim 600\ \text{ms}$

$E_{\text{explosion}} \sim \text{"several"} \times 10^{50}\ \text{erg}$

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

Neutrino-driven explosions not obtained by Burrows et al. *Ap.J.* **655**, 416 (2007).

Ongoing 3D Multi-Physics Simulations

Simulation Building Blocks

- ➲ *"RbR-Plus" MGFLD Neutrino Transport*
  - *O(v/c), GR time dilation and redshift, GR aberration (in flux limiter)*
- ➲ *3D PPM Hydrodynamics*
  - *GR time dilation, effective gravitational potential, adaptive radial grid*
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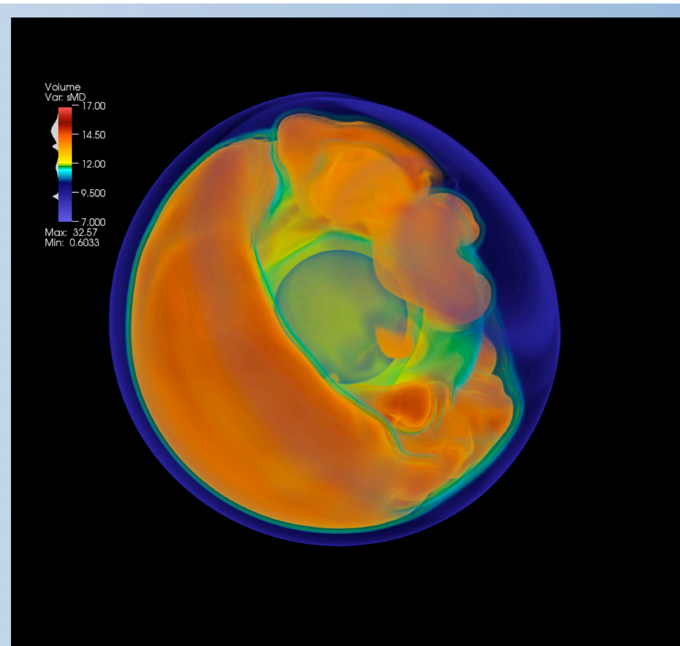
  - *180 MeV (nuclear compressibility), 29.3 MeV (symmetry energy)*
- ➲ *Nuclear (Alpha) Network*
- ➲ *3D Effective Gravitational Potential*
  - Marek et al. *A&A*, **445**, 273 (2006)
- ➲ *Neutrino Emissivities/Opacities*
  - *"Standard" + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung*



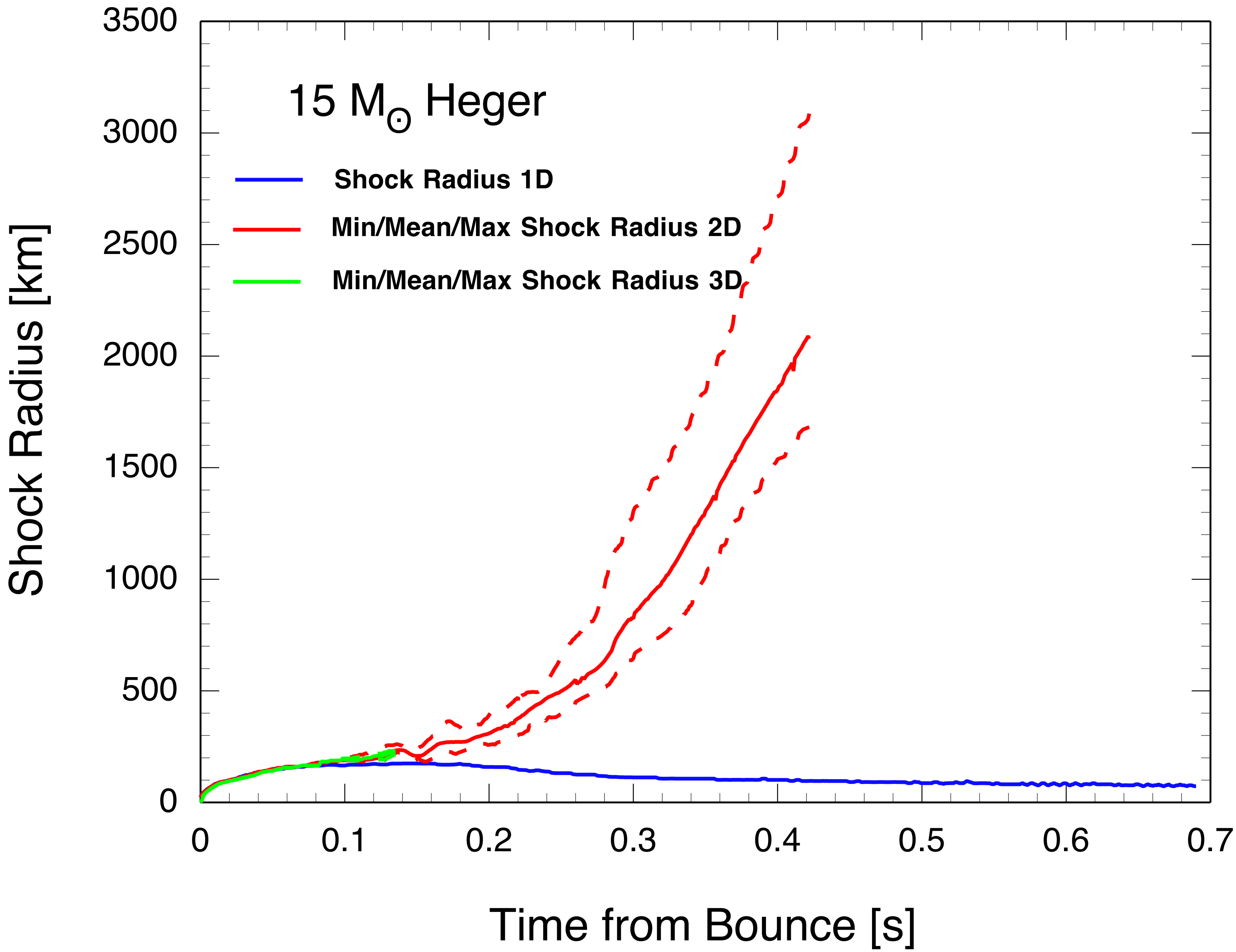
Bruenn et al., *Journ. Phys. Conf. Ser.,* in press (2009)

Resolution

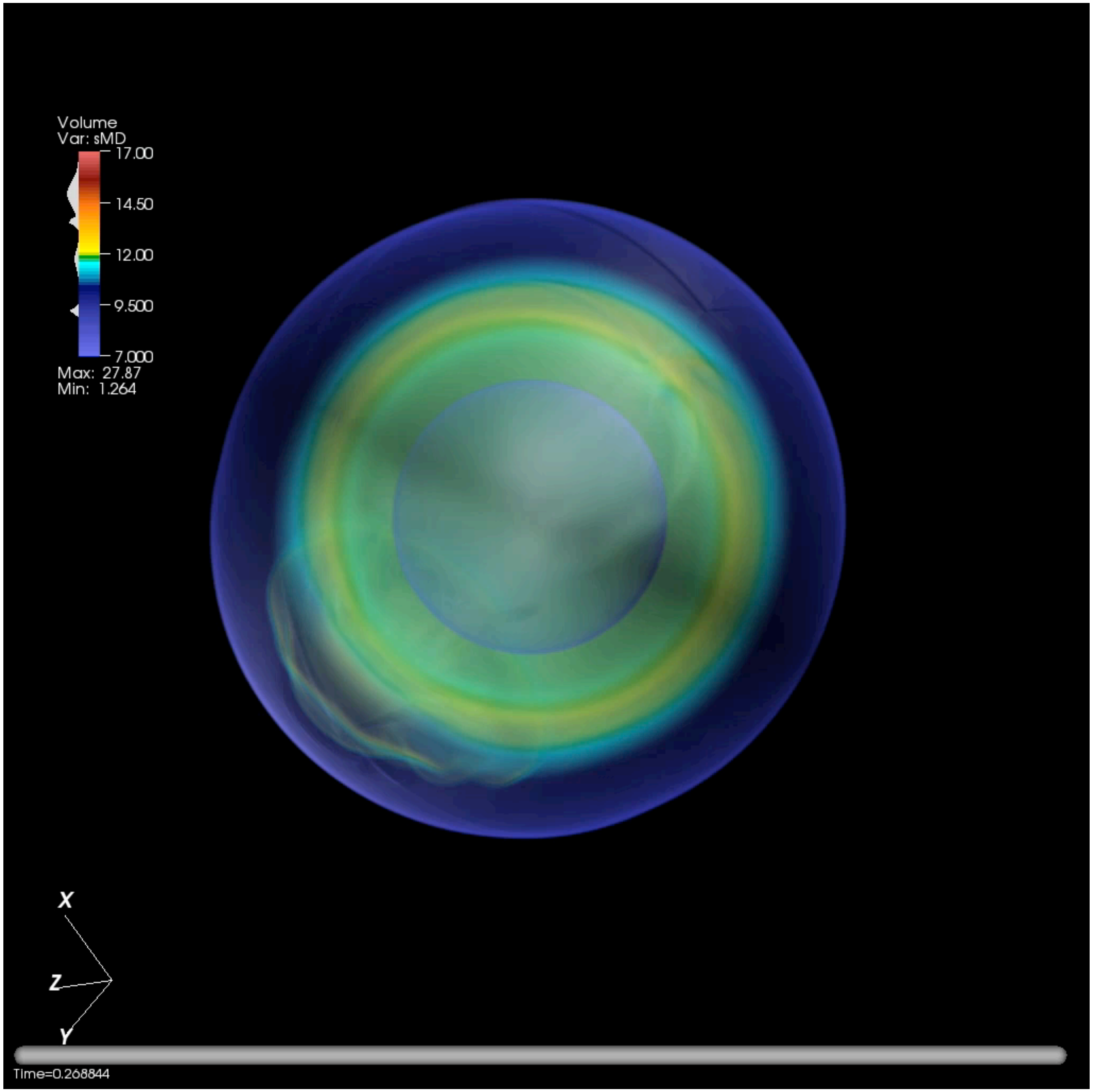
304 X 76 X 152
⇒ 11,552 processors

576 X 96 X 192 (recently launched)
⇒ 18,432 processors

512 X 256 X 512
⇒ 131,072 processors

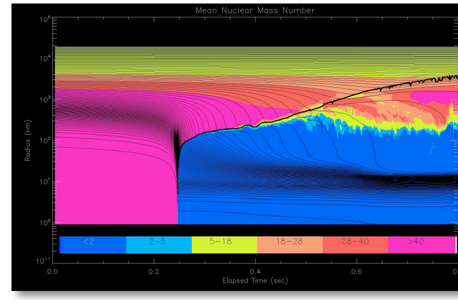


15 M☉ Heger
Shock Radius 1D
Min/Mean/Max Shock Radius 2D
Min/Mean/Max Shock Radius 3D
Shock Radius [km]
Time from Bounce [s]
3500
3000
2500
2000
1500
1000
500
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7


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

Summary and Outlook

★ *In 2D, neutrino-driven explosions have been obtained for a large range of progenitor masses in the context of multi-physics simulations with multi-frequency neutrino transport and approximate GR.*

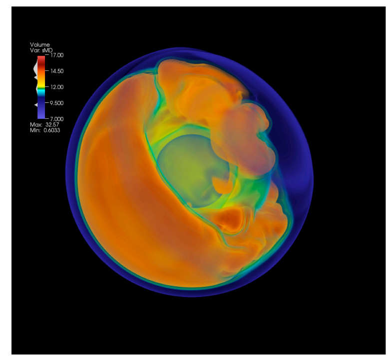


➲ Starting point for cross comparison of results from MPA, ORNL-centered, and Princeton-centered collaborations:
- Begin with identical progenitors and EOS.
- All need to include corrections for GR.

➲ What's next?
- 3D.
  - ⇨ Multi-physics simulations w/ multi-frequency neutrino transport now running on the ORNL LCF.

Our ability to run a number of 2D multi-physics models and now their 3D counterparts is the result of significant algorithm and code development, and code optimization and scaling.

⇒ The CHIMERA code has scaled to >130,000 processors.

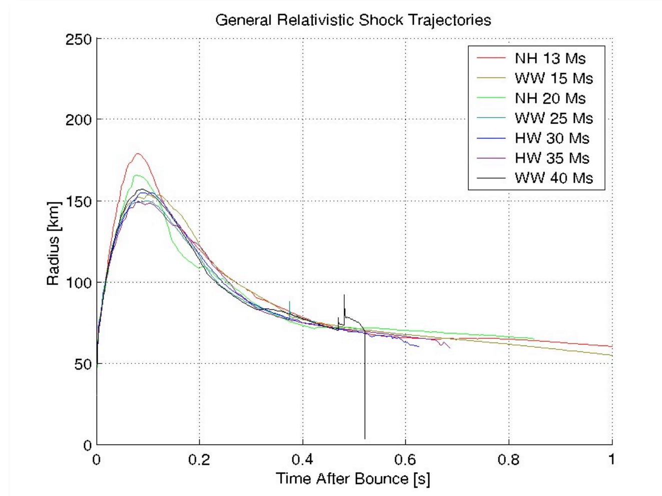


➲ Longer Term
- Replace RbR transport with 2D/3D multi-angle, multi-frequency transport.
- Implement full general relativity.
- Larger nuclear network (> 150 isotopes).
- Include magnetic fields.
- Include neutrino mixing.

➲ Other needs:
- Continued work on neutrino weak interactions and EOS.
- 3D stellar evolution.

Future Requirements

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



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

Method	r	D	r,θ	D	r,θ,φ	D
MGFLD	E	2	E	3	E	4
MGVET	E	2	E	3	E	4
BT	μ,E	3	μ,η,E	5	μ,η,E	6

- Complexity
- Computational Requirements

Theoretical and numerical framework for 2D/3D Boltzmann studies is being laid out:

- Cardall and Mezzacappa, *Phys. Rev. D*, **68**, 023006 (2003)
- Liebendoerfer et al., *Ap.J. Suppl.* **150**, 263-316 (2004)
- Livne et al. *Ap.J.* **609**, 277 (2004)
- Cardall, Lentz, and Mezzacappa, *Phys. Rev. D*, **72**, 043007 (2005)
- Hubeny and Burrows, Ap.J. 659, 1458 (2007)

General relativistic treatments:

- Cardall and Mezzacappa, *Phys. Rev. D*, **68**, 023006 (2003)
- Liebendoerfer et al., *Ap.J. Suppl.* **150**, 263-316 (2004)

GenASiS

Collaborators

Budiardja
Cardall
Endeve
Hix
Lentz
Messer
Mezzacappa
Parete-Koon

Bruenn
Marronetti
Yakunin
Dirk

Blondin
Warren

Fuller

Funded by

Office of Science
U.S. DEPARTMENT OF ENERGY

Collaborators

- *Solvers: D'Azevedo*
- *Data Management: Barreto, Canon, Klasky, Podhorszki*
- *Networking: Beck, Moore, Rao*
- *Visualization: Ahern, Daniel, Ma, Meredith, Pugmire, Toedte*
- *Cray Center of Excellence: Levesque, Wichmann*