Structure of Proto-Neutron Star

Large positron population.
Neutrino production via:

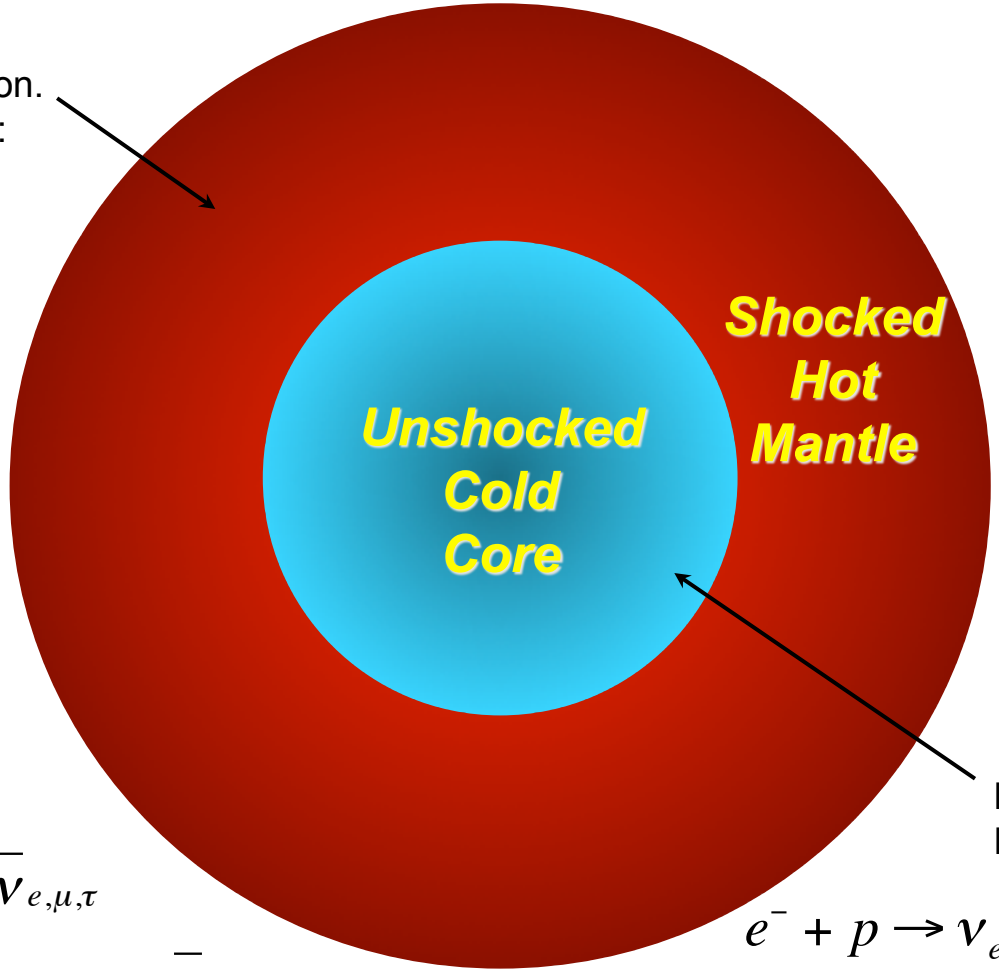
$$e^- + p \rightarrow \nu_e + n$$

$$e^+ + n \rightarrow \bar{\nu}_e + p$$

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

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

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



Low positron population.
Neutrino production via:

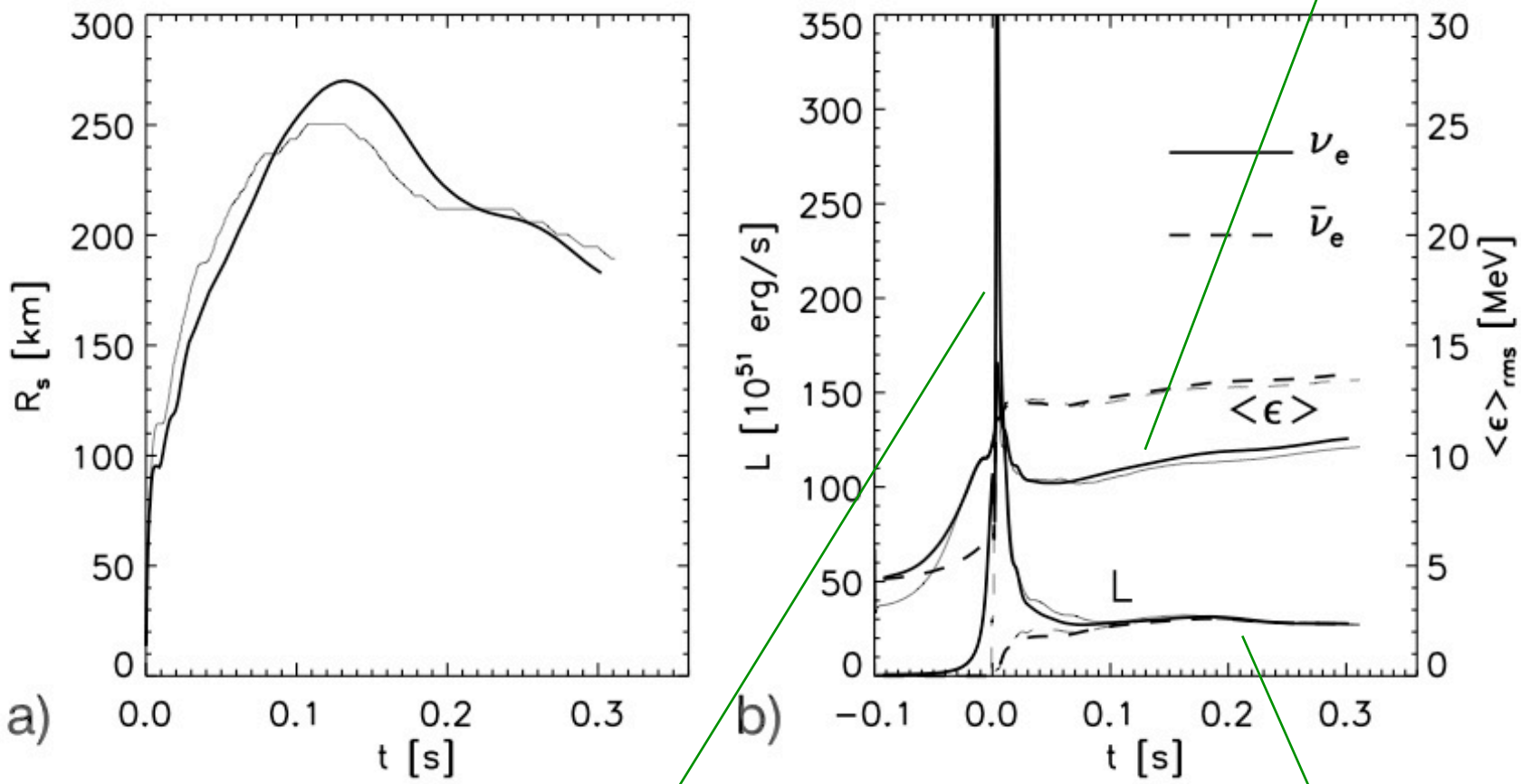
$$e^- + p \rightarrow \nu_e + n$$

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

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

Anatomy of Neutrino Luminosities

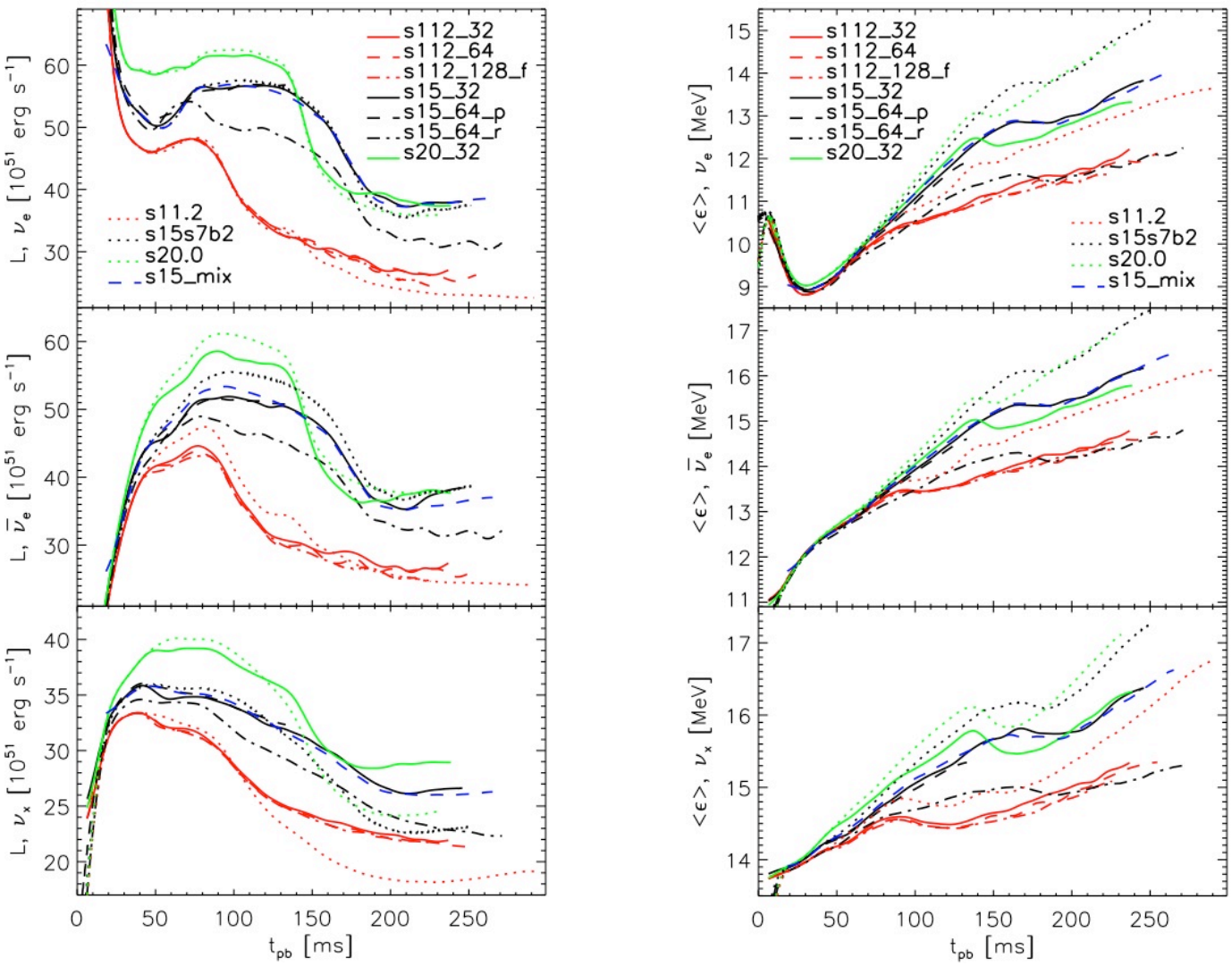
Increase in neutrino rms energies as PNS initially contracts.



Electron-Neutrino Burst

Accretion Luminosity

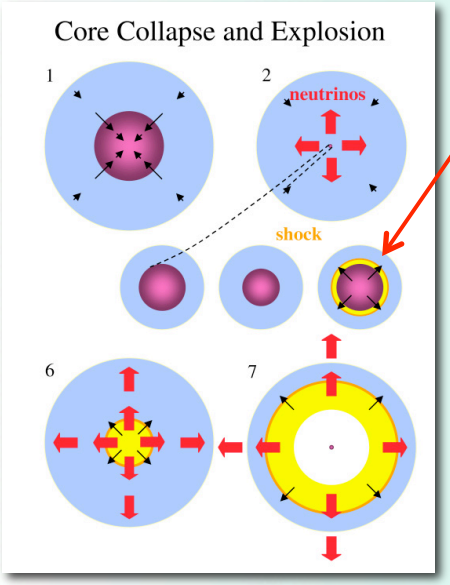
Three-Flavor Neutrino Luminosities and Mean Energies



Buras et al., A&A **457**, 281 (2006)

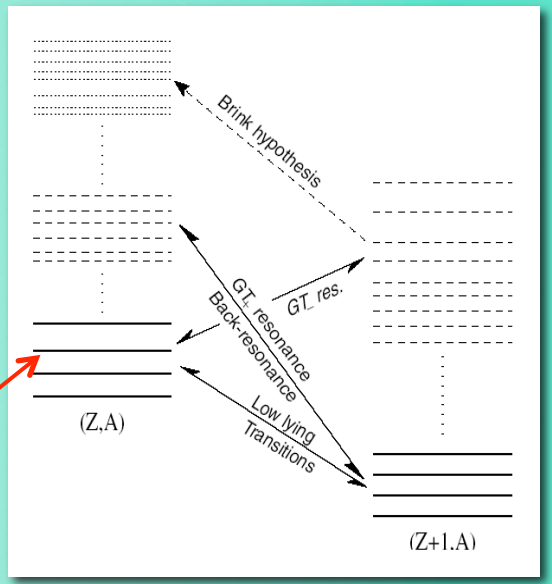
When Micro and Macro Worlds Collide

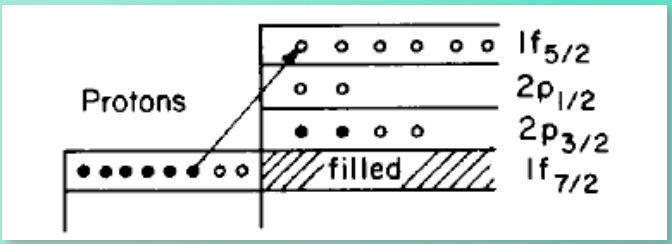
$$e^- + p,A \leftrightarrow \nu_e + n,A'$$



Initial shock location/strength depend on amount of electron capture on nuclei (and protons) during stellar core collapse.

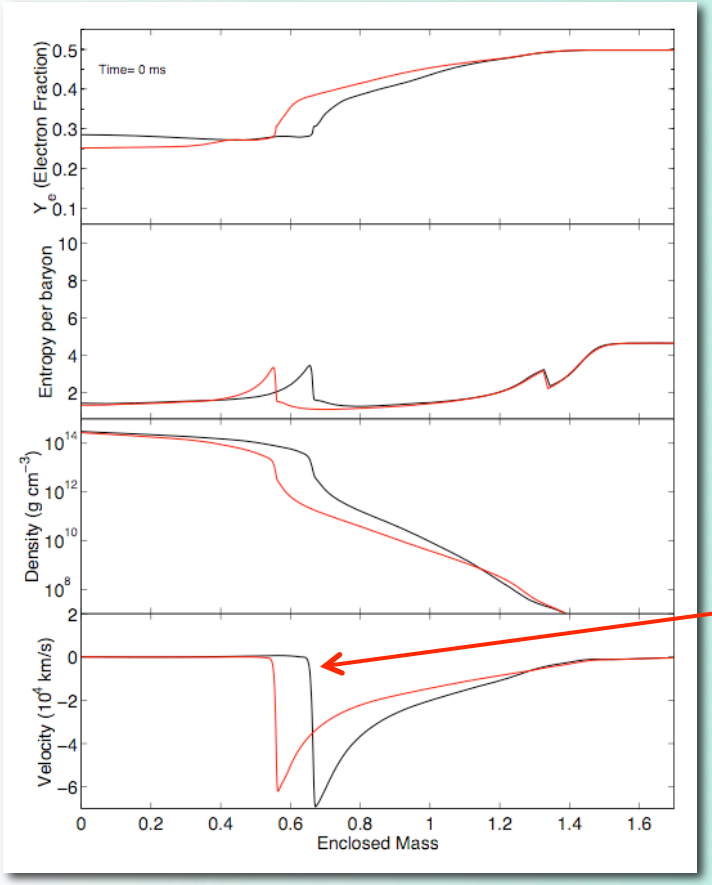
Electron capture on stellar core nuclei depends on energy levels in the nucleus and how the nucleons populate them.





⇨ *Zeroth-order shell model (nucleons independent), electron capture on nuclei is blocked for N>40.*

When Micro and Macro Worlds Collide



No correlations.

With correlations.

Significant change in shock formation mass.

Hix et al. *Phys. Rev. Lett.* 91 201102 (2003)

Shell Model Deployed: “Hybrid Model” [Langanke et al. *Phys. Rev. Lett*. **91**, 241102 (2003)]

Multigroup Flux-Limited Diffusion

The Boltzmann equation contains the same information as an infinite hierarchy of equations for the angular "moments" of the neutrino distribution function:

$$\int d\mu \left[\frac{\partial f}{\partial t} = L[f] \right] \Rightarrow \frac{\partial \psi^0}{\partial t} = \ldots \qquad \psi^0 \equiv \frac{1}{2} \int d\mu \, f$$

$$\int d\mu \mu \left[\frac{\partial f}{\partial t} = L[f] \right] \Rightarrow \frac{\partial \psi^1}{\partial t} = \ldots \qquad \psi^1 \equiv \frac{1}{2} \int d\mu \, \mu \, f$$

$$\ldots \qquad \ldots$$

<u>Approximation:</u>

- Truncate hierarchy at the level of the "zeroth" moment (neutrino energy density).
- Closure: Relate the first moment (momentum density/flux) to the energy density so as to satisfy known limits:

$$\psi^1 = -\Lambda \left(\frac{\partial \psi^0}{\partial r} \right) \qquad \Lambda \equiv \frac{1}{\frac{3}{\lambda} - \frac{1}{\psi^0} \frac{\partial \psi^0}{\partial r}}$$

Diffusion Limit: Fick's Law $\quad \psi^1 \to -\frac{\lambda}{3} \frac{\partial \psi^0}{\partial r}$

Free Streaming Limit $\quad \psi^1 \to \psi^0$

Multigroup Variable Eddington Factor/Tensor Method

The Boltzmann equation contains the same information as an infinite hierarchy of equations for the angular "moments" of the neutrino distribution function:

$$\int d\mu \left[\frac{\partial f}{\partial t} = L[f] \right] \Rightarrow \frac{\partial \psi^0}{\partial t} = \ldots \qquad \psi^0 \equiv \frac{1}{2} \int d\mu \, f$$

$$\psi^1 \equiv \frac{1}{2} \int d\mu \, \mu \, f$$

$$\int d\mu \mu \left[\frac{\partial f}{\partial t} = L[f] \right] \Rightarrow \frac{\partial \psi^1}{\partial t} = \ldots \qquad \ldots$$

$$\ldots$$

<u>Approximation:</u>

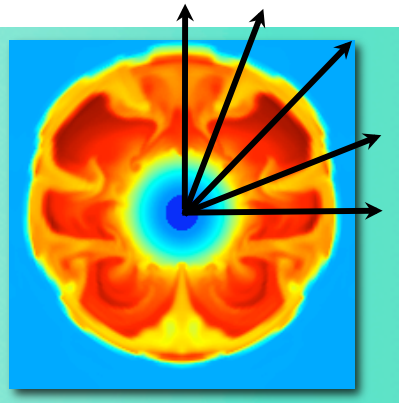
- Truncate hierarchy at level of "first" moment (neutrino momentum density).
- Closure: Relate the second (and third) moments to the zeroth moment using "Eddington factors," which are the ratio of these higher moments to the zeroth moment.

Eddington factors can be computed at different levels of approximation:

- "Prescribed" closure (e.g., maximum entropy closure).
- Approximate Boltzmann solution.
- Exact Boltzmann solution.

Ongoing 2D Multi-Physics Supernova Models

Simulation Building Blocks



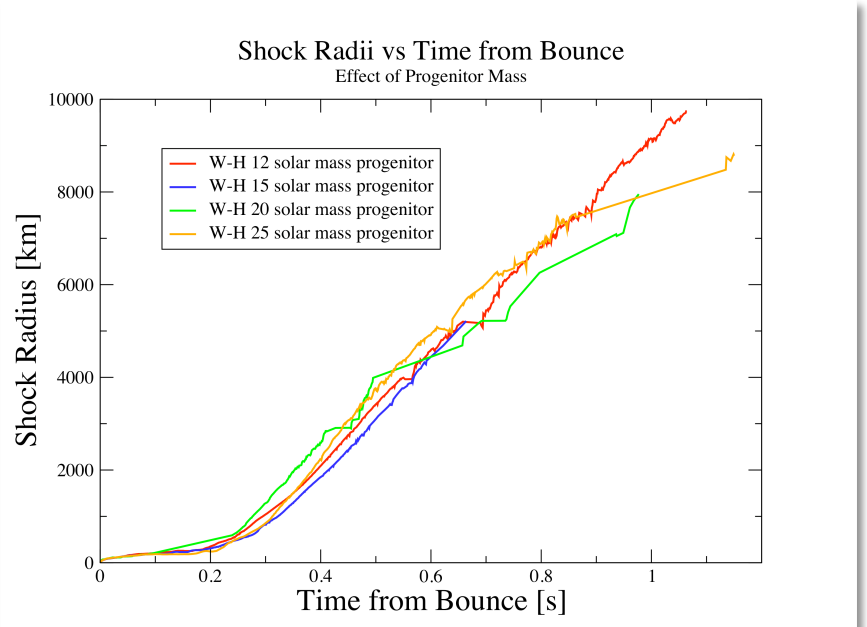
- *"RbR-Plus" MGFLD Neutrino Transport*
  - *O(v/c), GR time dilation and redshift, GR aberration (in flux limiter)*
- *2D PPM Hydrodynamics*
  - *GR time dilation, effective gravitational potential, adaptive radial grid*
- *Lattimer-Swesty EOS*
  - *180 MeV (nuclear compressibility), 29.3 MeV (symmetry 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*

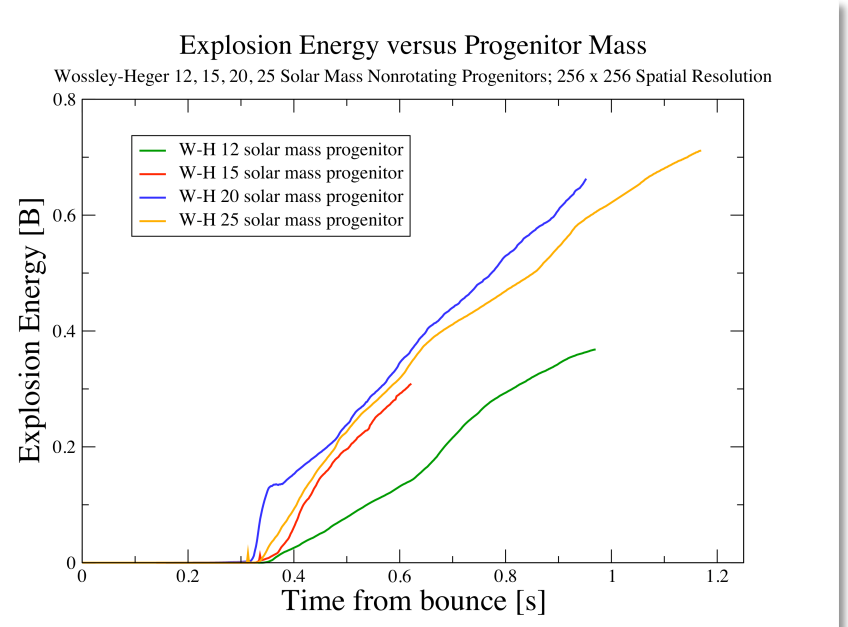
"Ray-by-Ray-Plus" Approximation

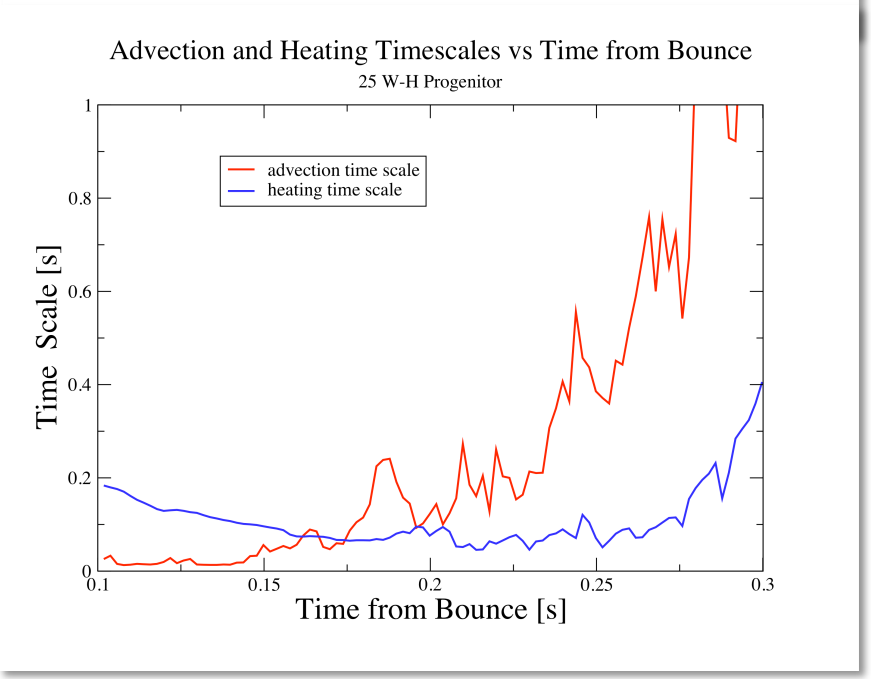
- Radial transport allowed.
- Lateral transport suppressed.

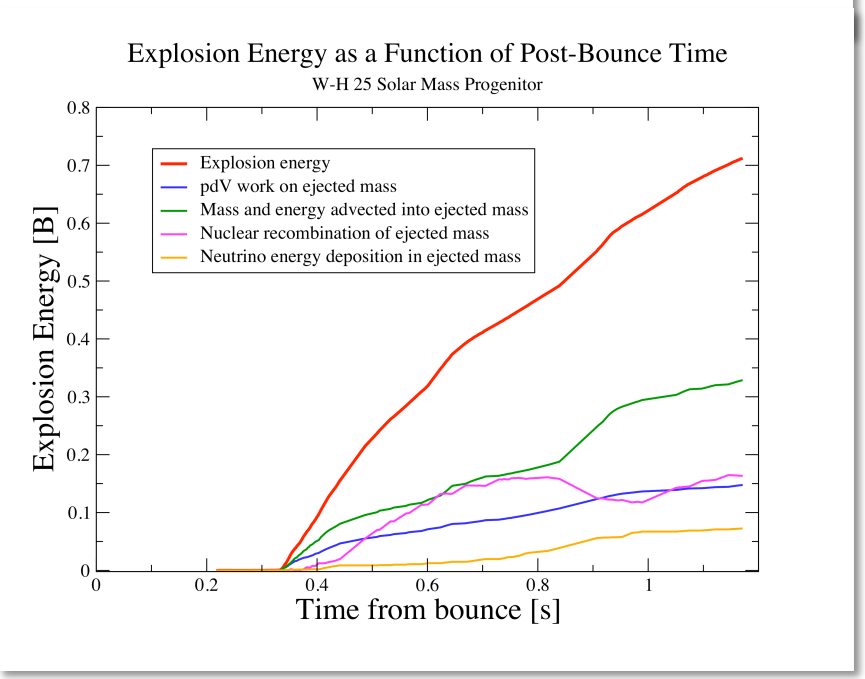
– Buras et al. *A&A*, **447**, 1049 (2003)

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]

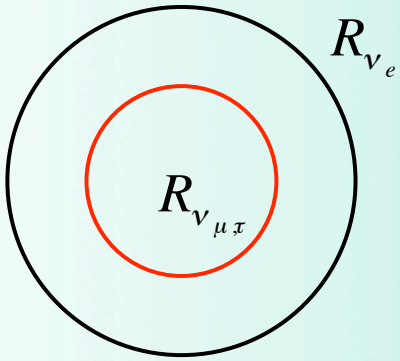

Explosion Energy versus Progenitor Mass
Wossley-Heger 12, 15, 20, 25 Solar Mass Nonrotating Progenitors; 256 x 256 Spatial Resolution
W-H 12 solar mass progenitor
W-H 15 solar mass progenitor
W-H 20 solar mass progenitor
W-H 25 solar mass progenitor
Explosion Energy [B]
Time from bounce [s]

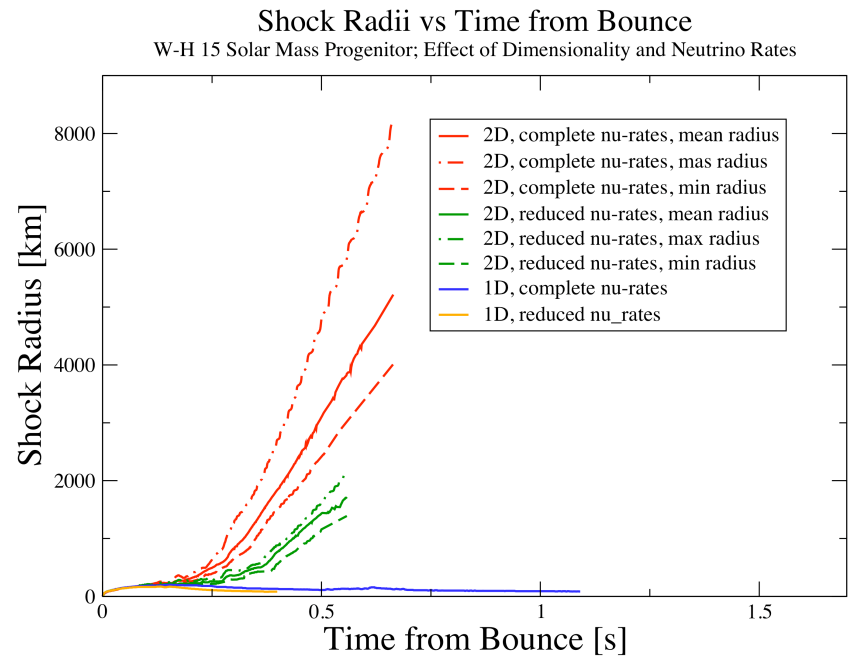

Advection and Heating Timescales vs Time from Bounce
25 W-H Progenitor
advection time scale
heating time scale
Time Scale [s]
Time from Bounce [s]


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]

Impact of Energy Exchange in Neutrino Scattering on Nucleons

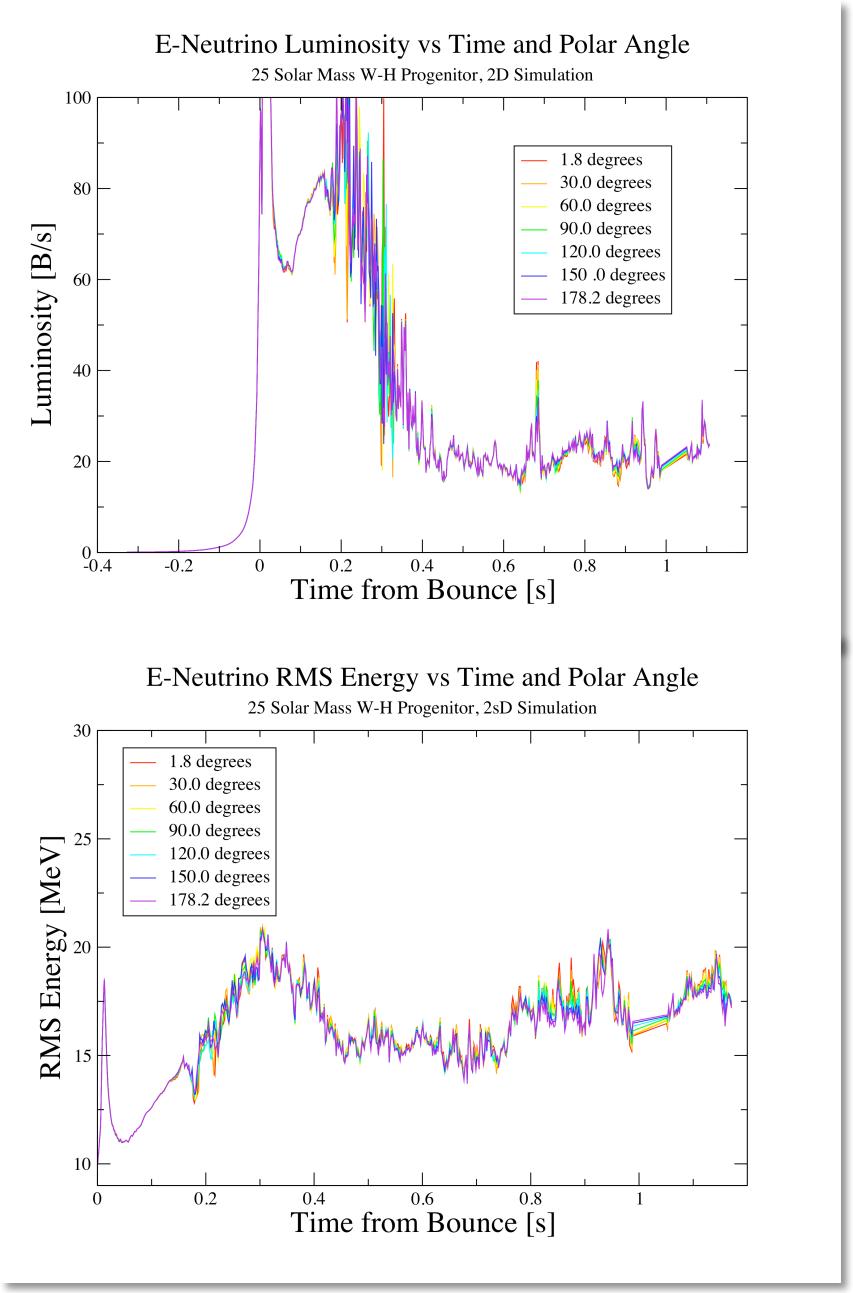
Schematice Layout of Neutrinospheres in PNS

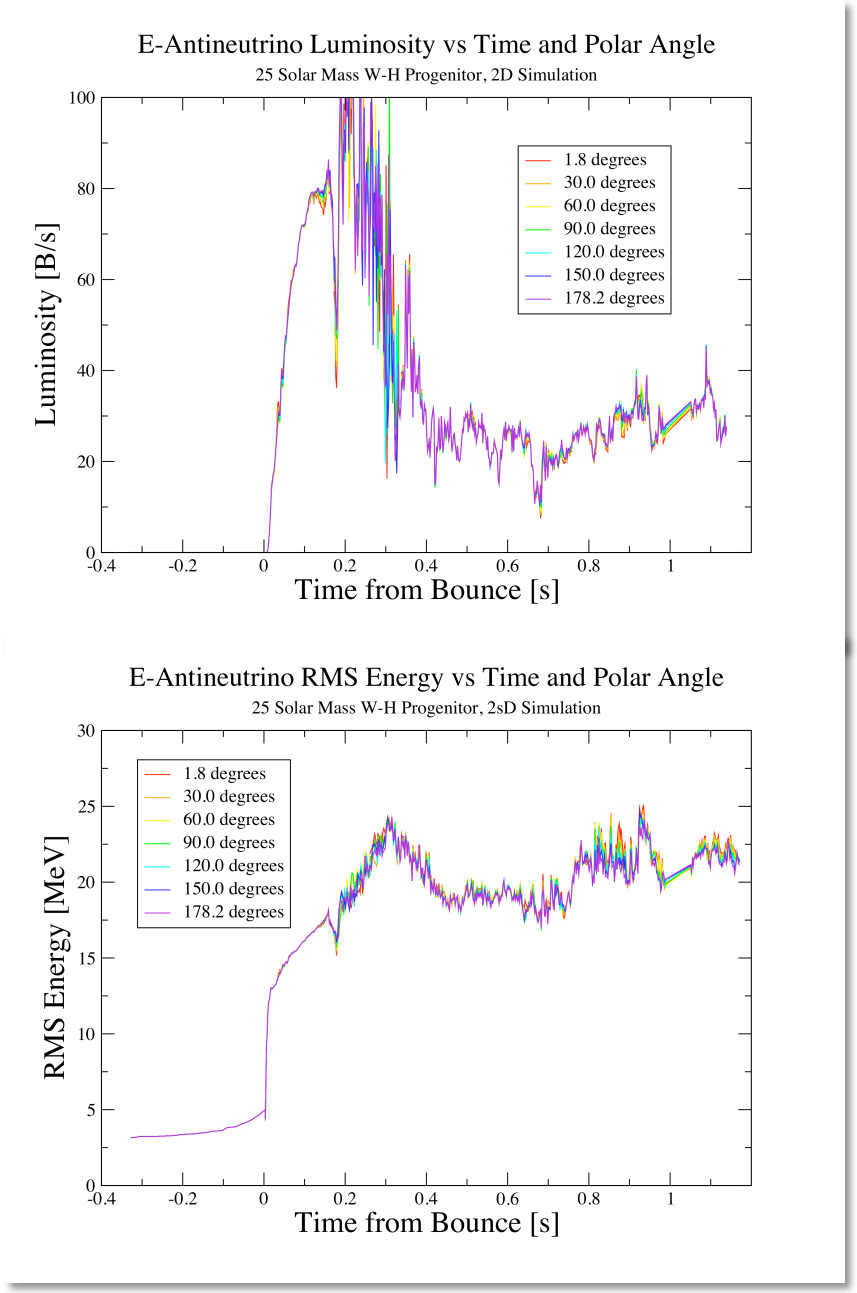




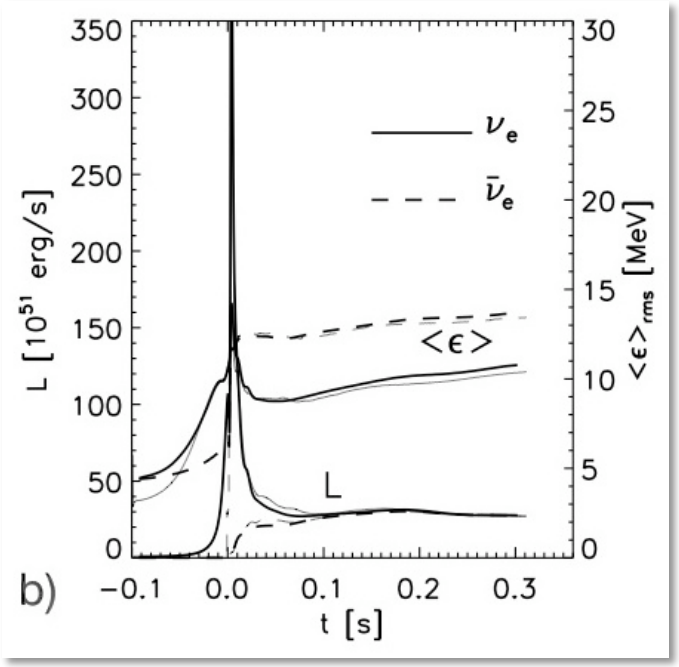
New Weak Interaction Physics and Its Ramifications:

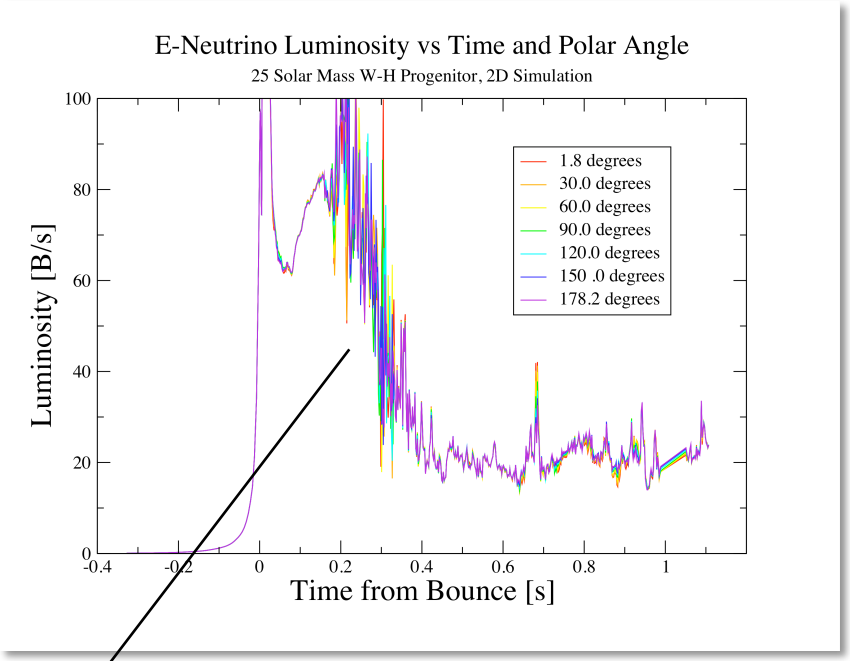
⇨ *Muon/tau neutrino elastic scattering on nucleons leads to heating of electron neutrinospheres.*


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
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


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
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

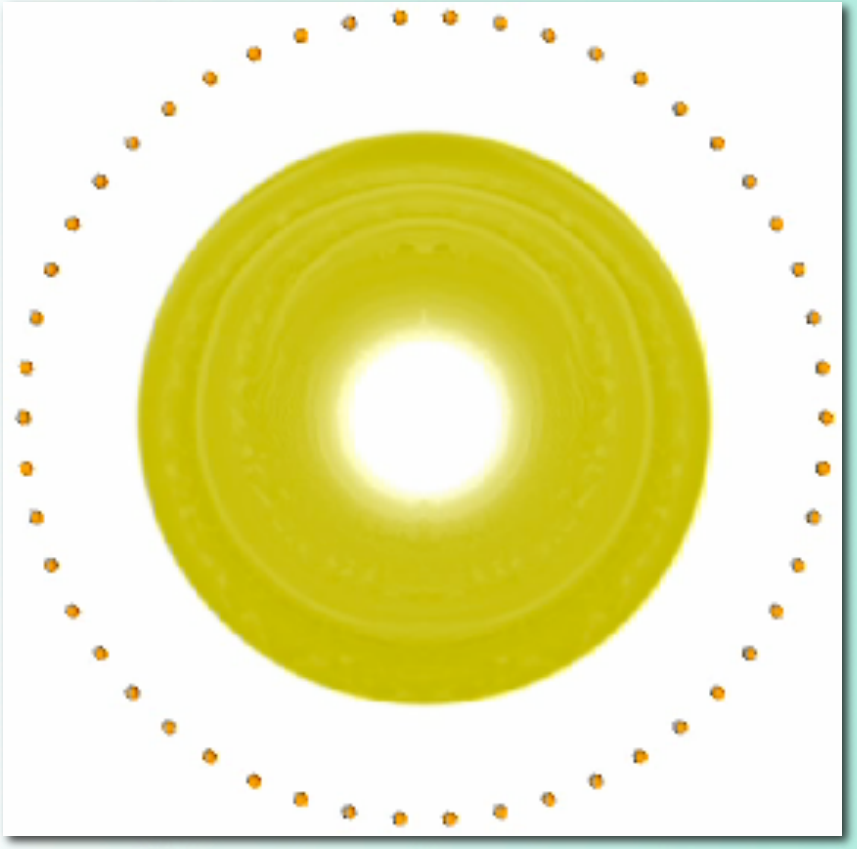
Neutrino Luminosity: 1D vs. 2D

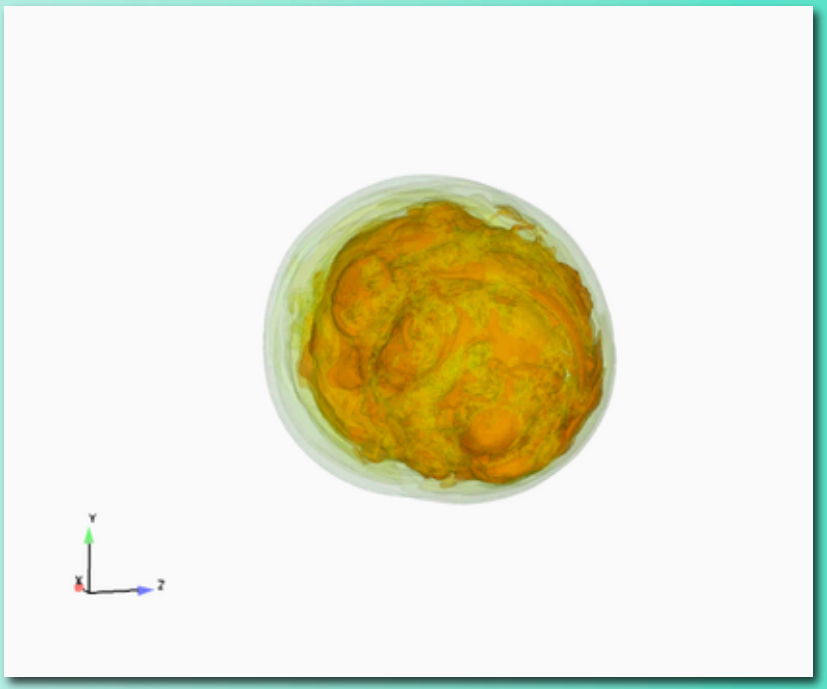




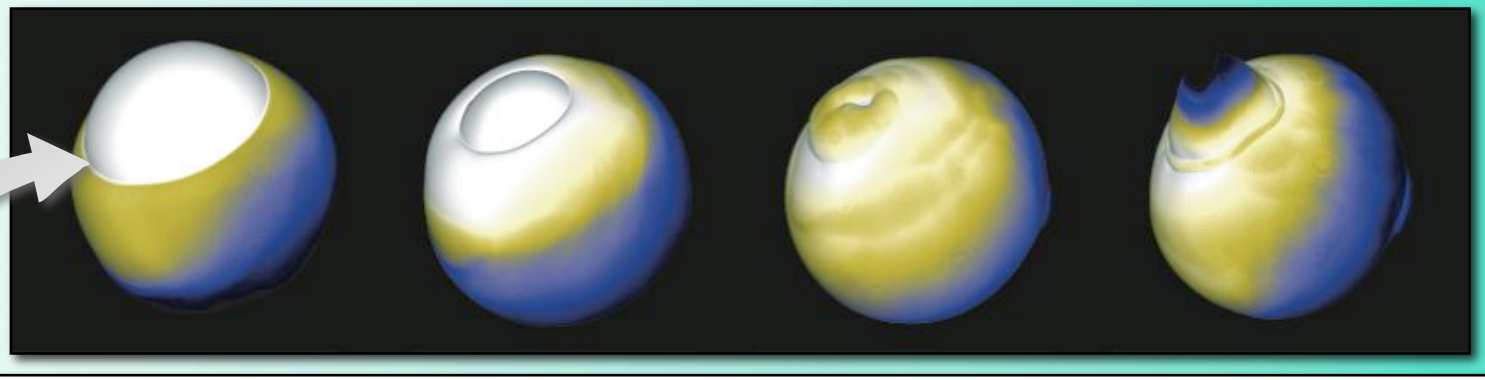
- Variations with angle due to highly nonspherical flow in postshock region, induced by convection and SASI.
- Variations are angle *and* time dependent.

SASI: A Case Study for 3D

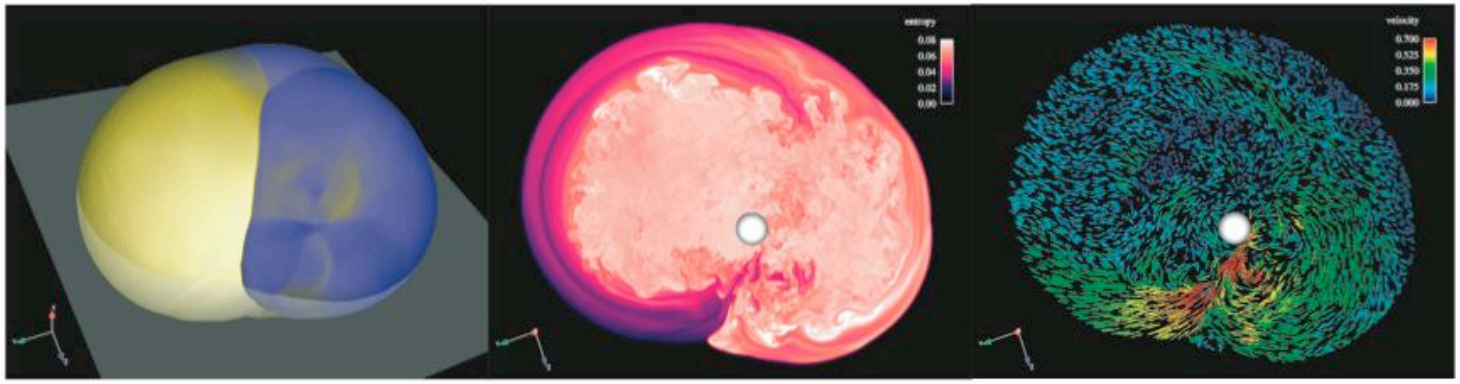




Anatomy of a Mach Reflection



Mach Reflection



- Symmetry of Mach reflection broken in three dimensions.
- Internal shock (orthogonal to supernova shock) leads to two counter-rotating flows.

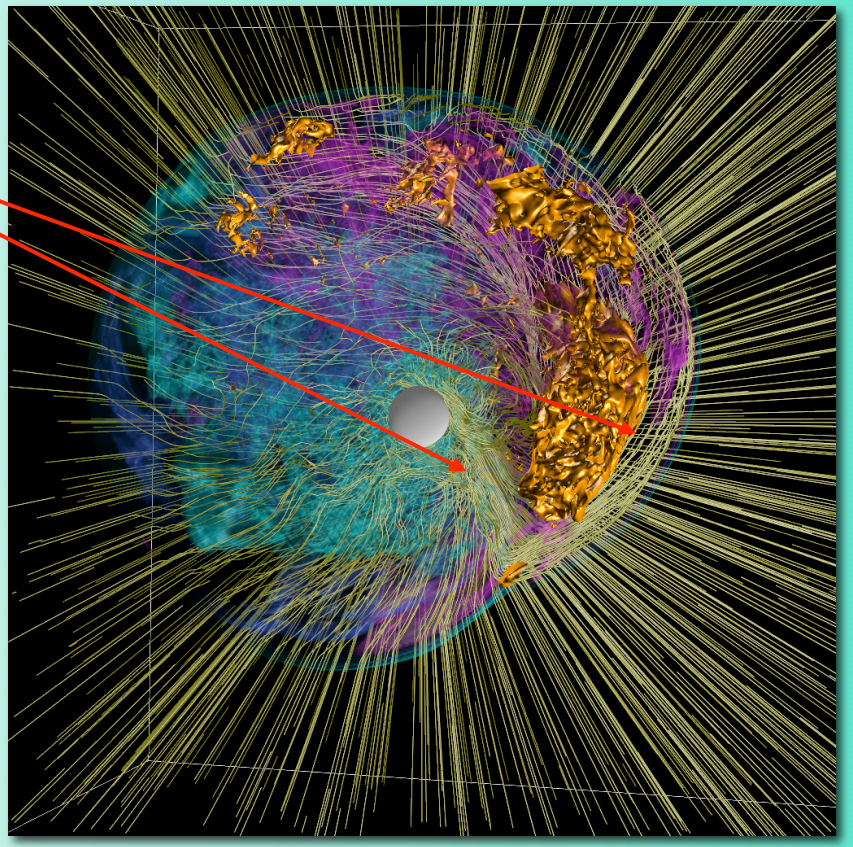
Ramifications...

SASI-induced counter rotating flows.

Inner flow capable of spinning up remnant NS to 50 ms periods, even beginning with spherically symmetric initial conditions.

Implications for

- ⇨ the growth of B fields?
- ⇨ the supernova mechanism?
- ⇨ supernova observables?



Blondin and Mezzacappa, *Nature*, **445**, 58 (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)*
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  - *GR time dilation, effective gravitational potential, adaptive radial grid*
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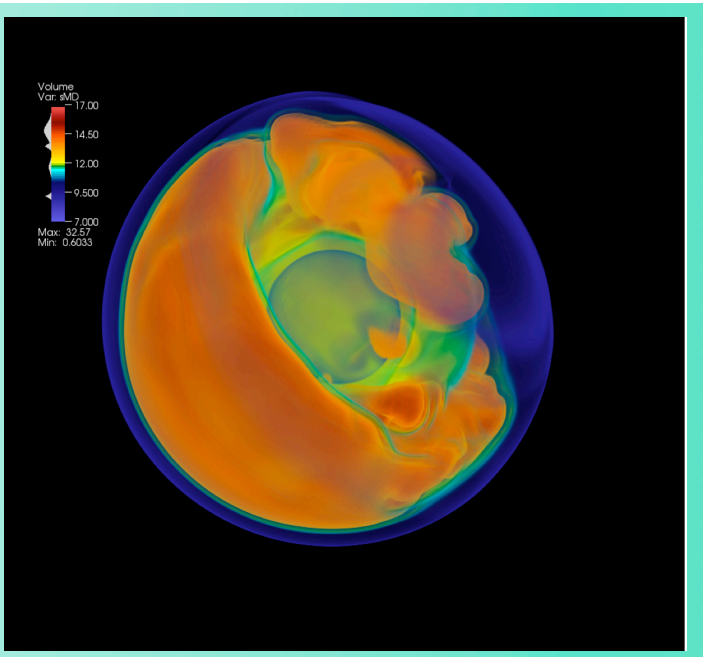
  - Marek et al. *A&A*, **445**, 273 (2006)
- *Neutrino Emissivities/Opacities*
  - *"Standard" + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung*



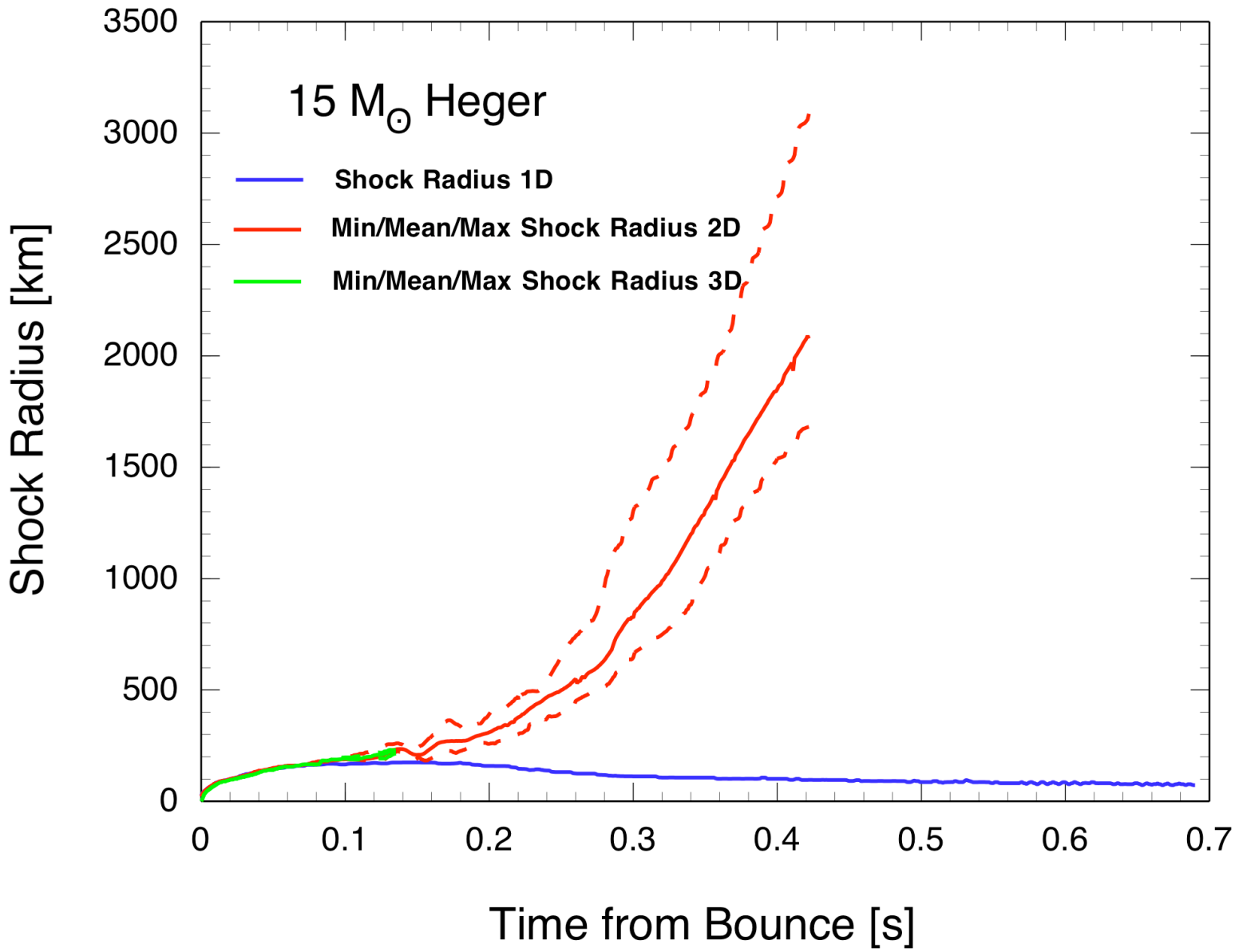
Bruenn et al., *Journ. Phys. Conf. Ser.*, in press (2009)

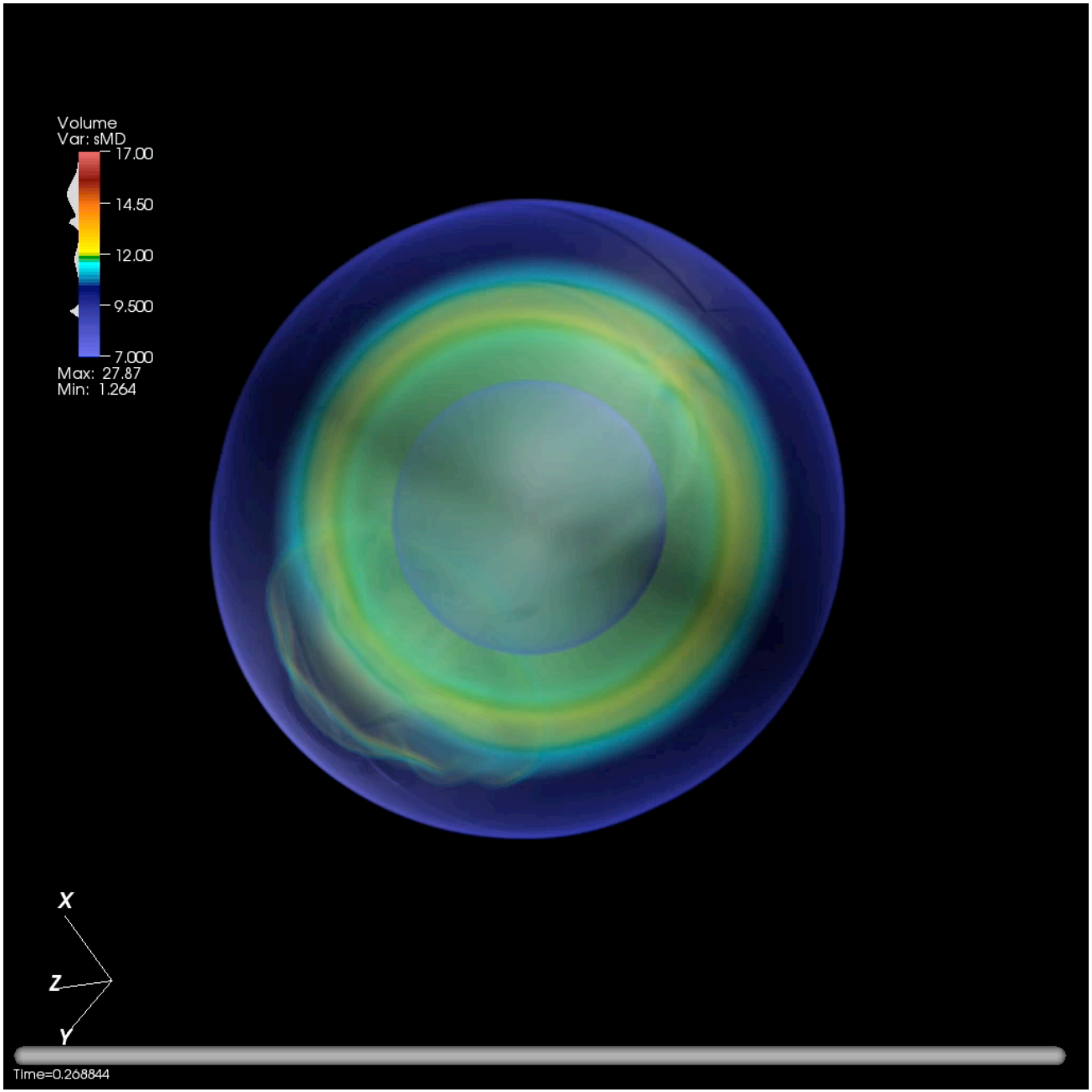
Resolution

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]
0
500
1000
1500
2000
2500
3000
3500
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

PREVIEWS OF COMING DISTRACTIONS

3D Models: Path Forward						
Neutrino Transport Approach	Code	GR	Network	Platform	Time Frame	Target
RbR MGFLD	CHIMERA	Approximate	Alpha, Full	2-20 PF	2010-2015	CCSNe
MGFLD	CHIMERA	Approximate	Alpha, Full	100 PF – 1 EF	2015-2020	CCSNe
MGVET	GenASiS	BSSN	Alpha, Full	100 PF – 1 EF	2015-2020	CCSNe, Hypernovae
Boltzmann	GenASiS	BSSN	Alpha, Full	> 10 EF	> 2020	CCSNe, Hypernovae