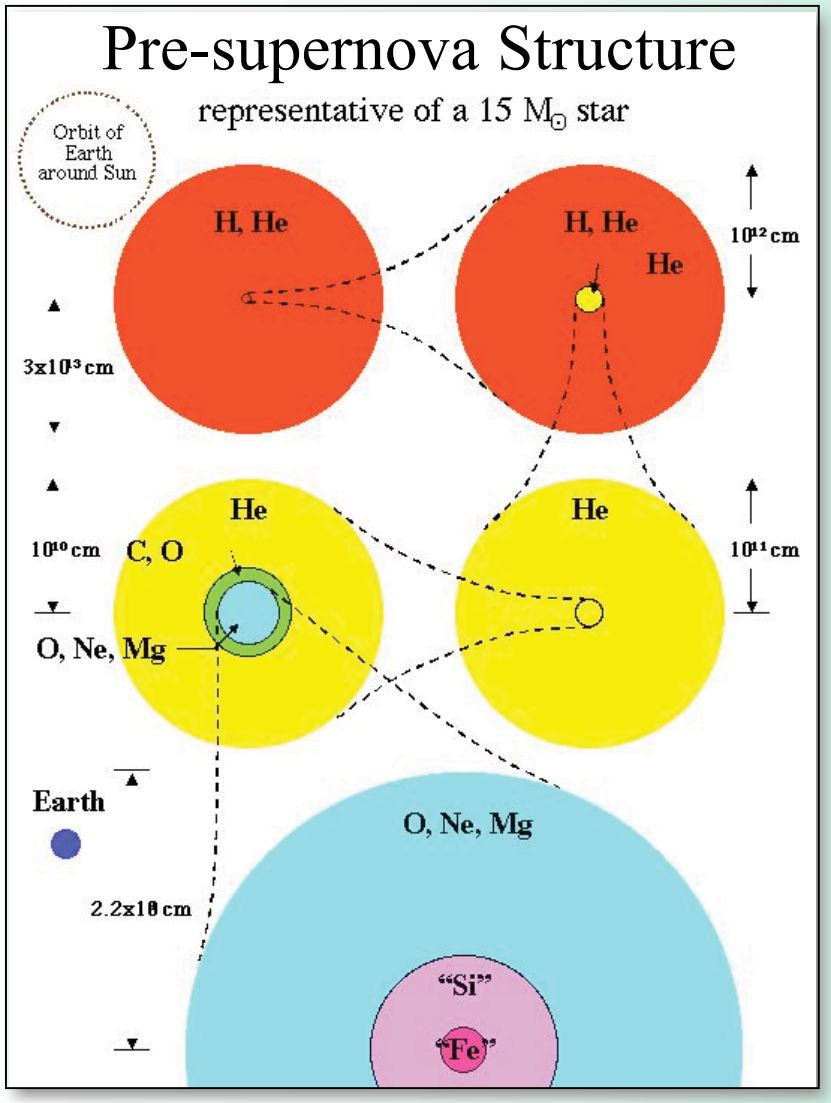
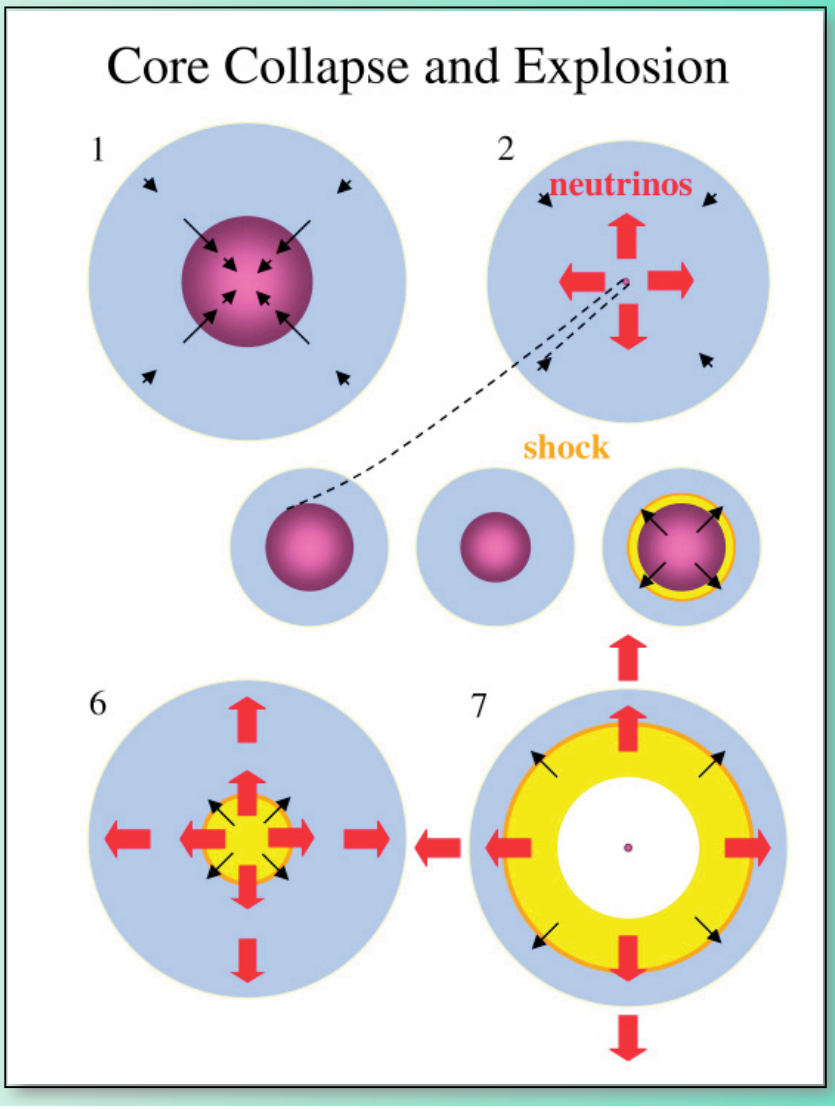
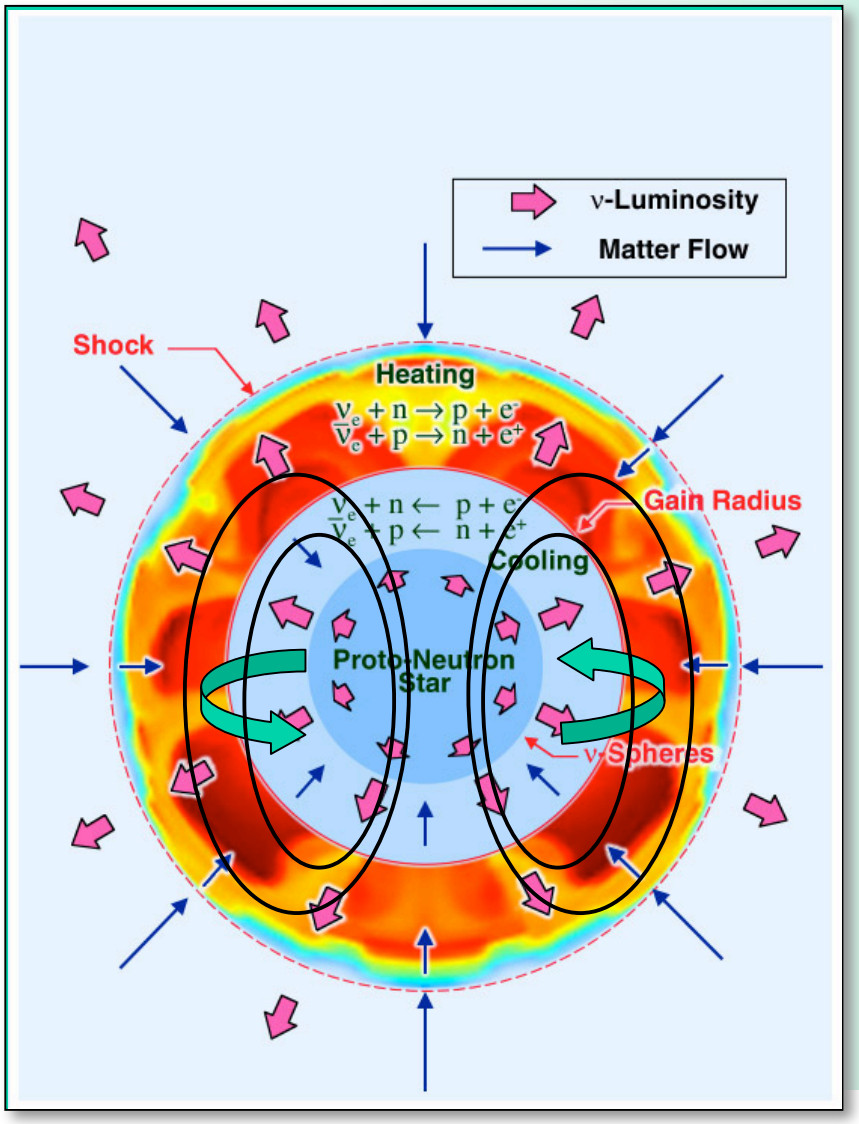
When Micro and Macro Worlds Meet: Modeling Core Collapse Supernovae

Core Collapse Supernova Paradigm





How is the supernova shock wave revived?

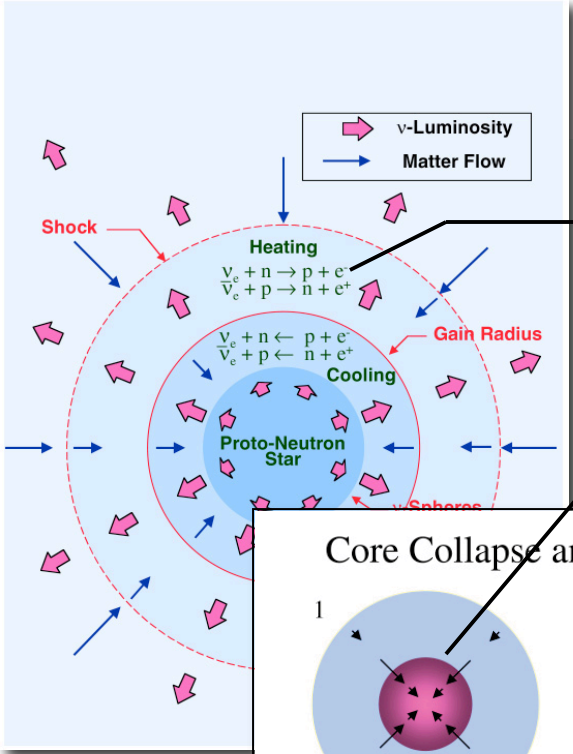


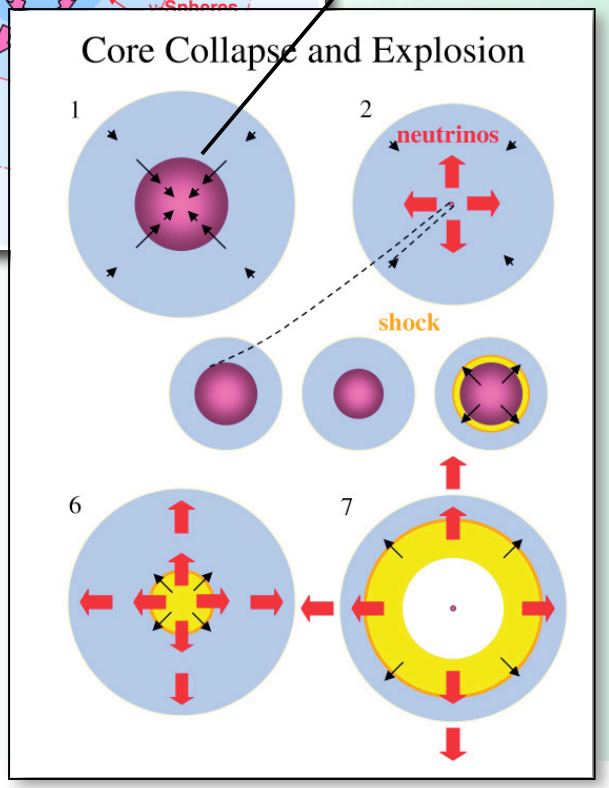
The most fundamental question in supernova theory

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

**New Ingredient*

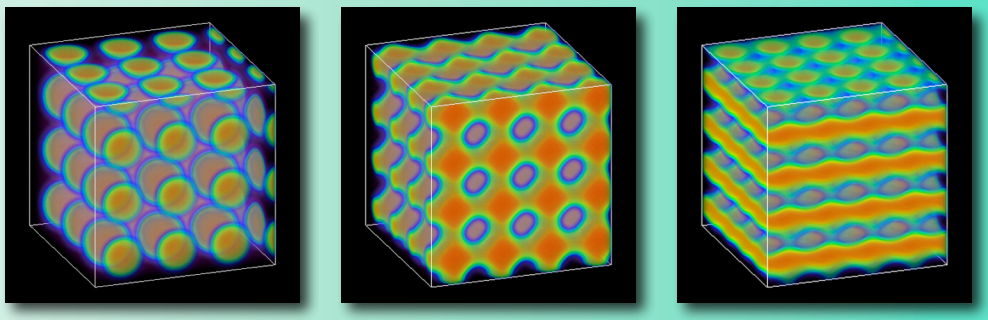
Microscopic Physics





Neutrino Emissivities/Opacities

Equation of State
- ⇨ Nuclear
- ⇨ Leptonic
- ⇨ Photonic



Evolution of nuclei during collapse.

Newton et al. (2006)

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.

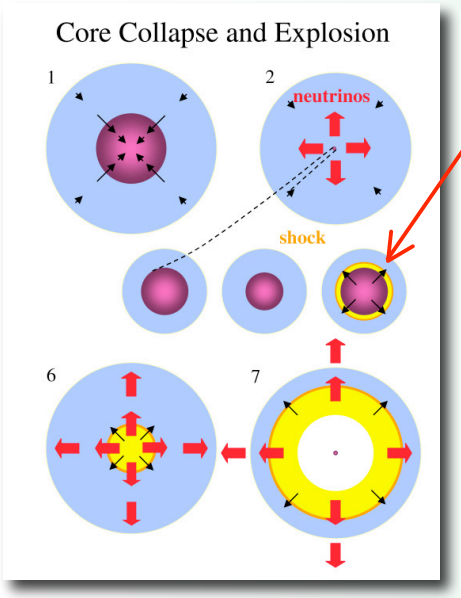
$\nu + e^-, e^+ \rightarrow \nu + e^-, e^+$

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

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

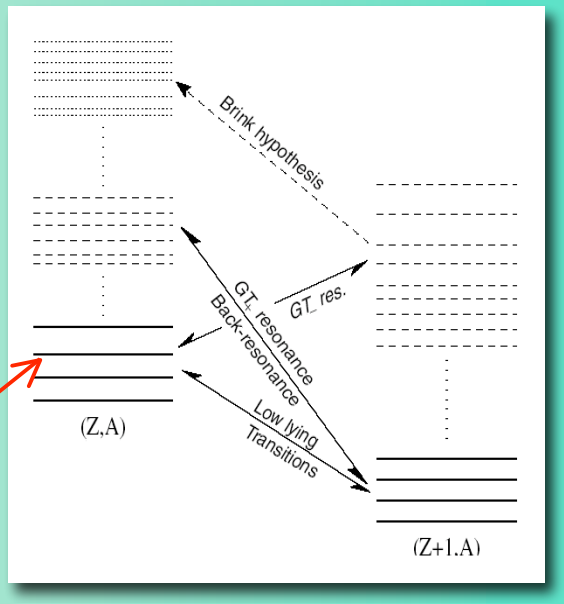
When Micro and Macro Worlds Collide

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



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

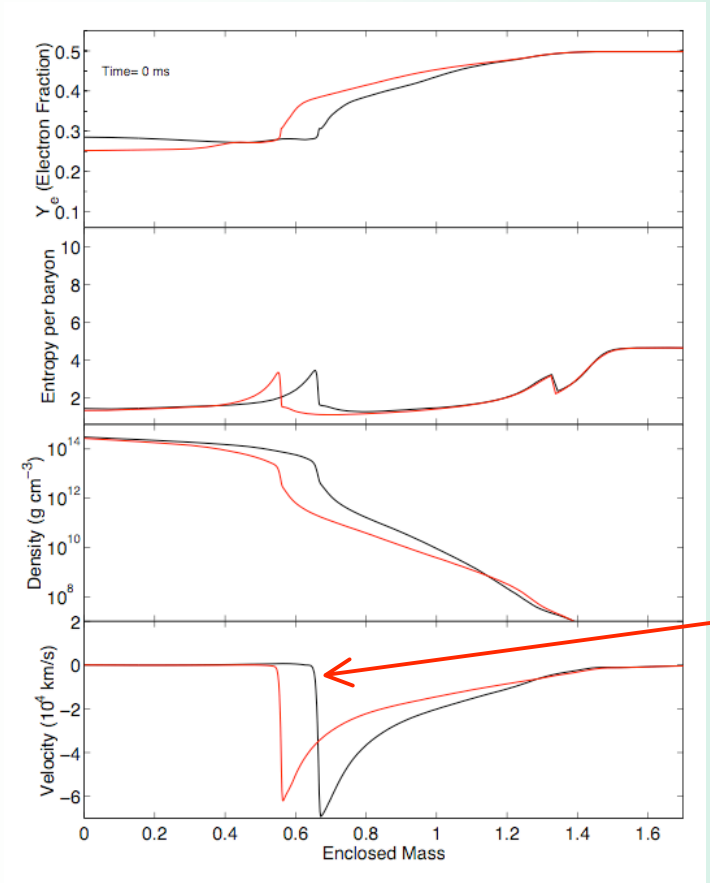
Electron capture on stellar core nuclei depends on their nuclear structure.



⇨ *Independent particle model, electron capture on nuclei is blocked.*
⇨ *With correlations, electron capture on nuclei is not blocked.*

Langanke et al. *Phys. Rev. Lett.* 91 241102 (2003)

When Micro and Macro Worlds Collide



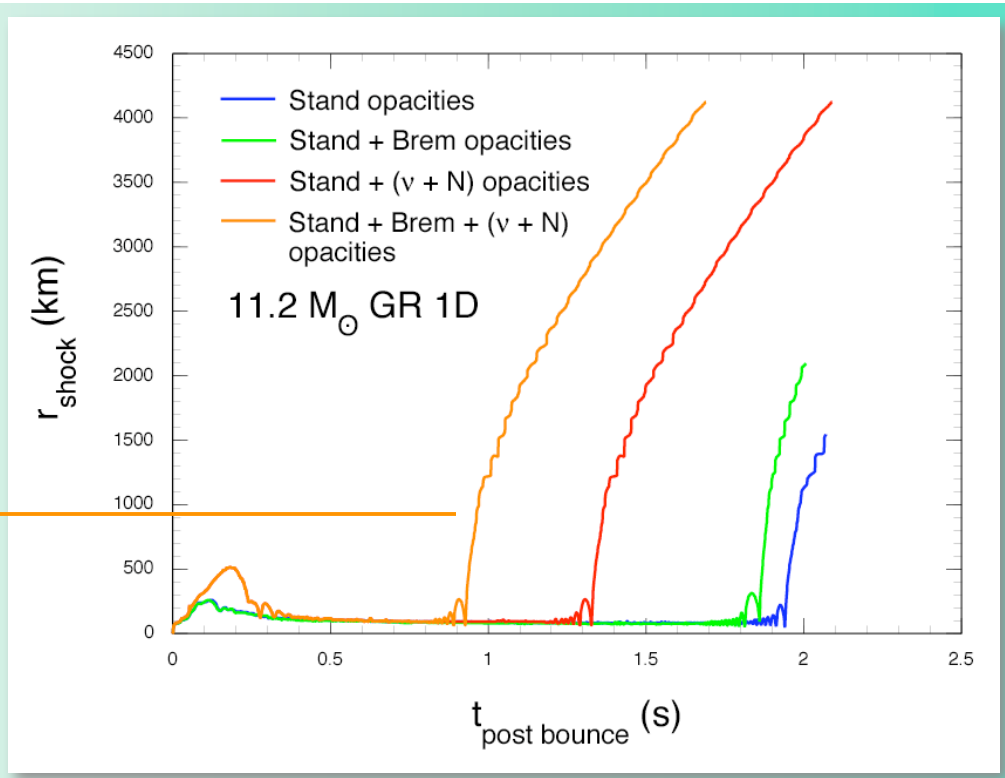
No correlations.

With correlations.

Significant change in shock formation mass.

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

1D Revisited



New Physics:

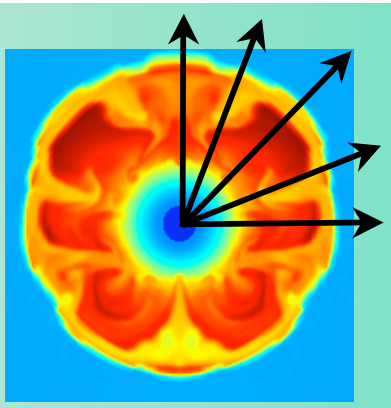
⇨ N.B. Explosions can occur in 1D!
- Generally, explosions occur much later than thought before.

⇨ Improved neutrino emissivities/opacities affect explosion time scale.
- Nucleon bremsstrahlung and neutrino elastic scattering on nucleons lead to heating of the electron neutrino- and antineutrino-spheres.

Ongoing 2D Multi-Physics Supernova Models

Simulation Building Blocks

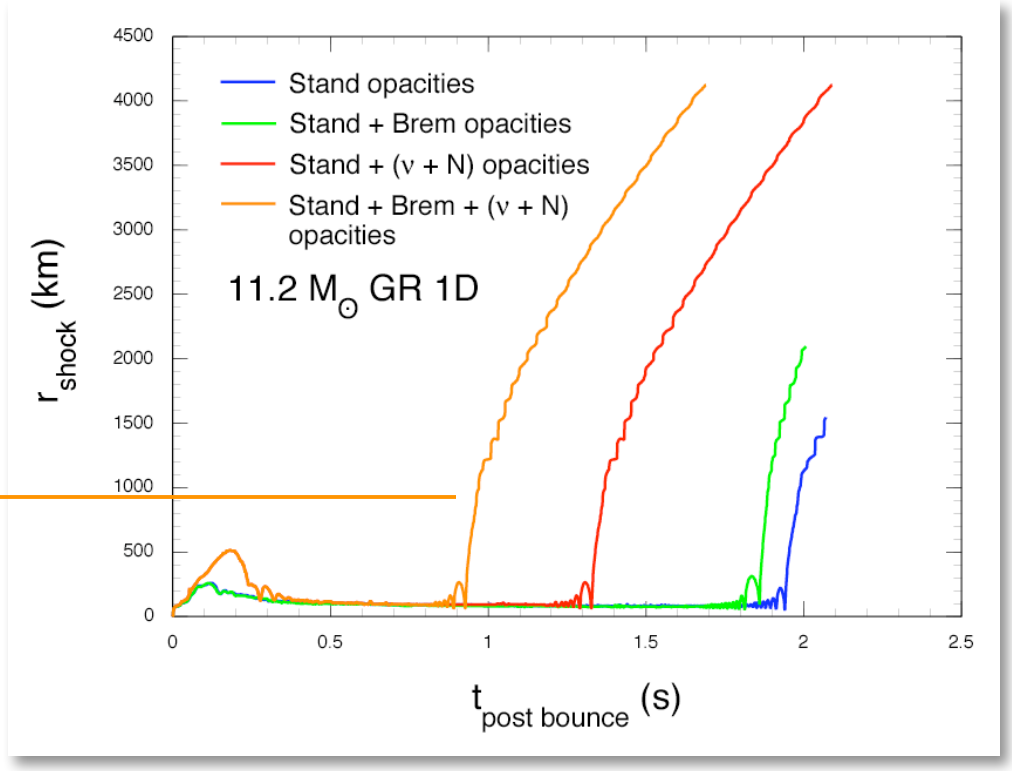
- *"RbR-Plus" MGFLD Neutrino Transport*
- *2D PPM Hydrodynamics*
- *Lattimer-Swesty EOS*
- *Nuclear (Alpha) Network*
- *2D Newtonian Gravity with Spherical GR Corrections*
- *Neutrino Emissivities/Opacities*
  - ➲ *"Standard" + Elastic Scattering on Nucleons*
    + Nucleon–Nucleon Bremsstrahlung



"Ray-by-Ray" Approximation

- Radial transport allowed.
- Lateral transport suppressed.

1D Results for Reference:



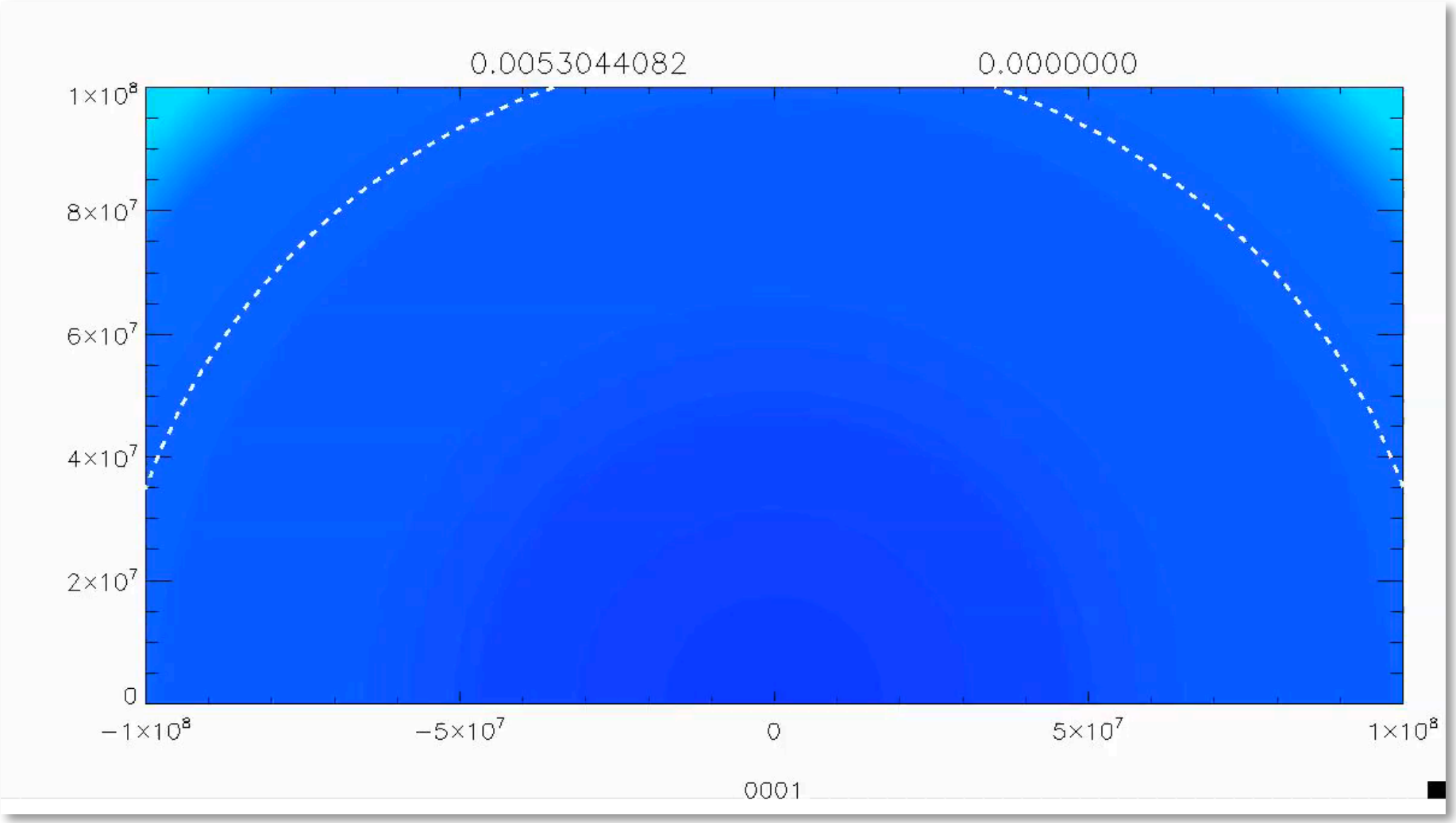
2D Results:

Stellar Mass	Gravity	Opacities	Resolution 20 Groups	t (ms pb)	Explosion	Energy (B)
11	GR	Improved	256 X 256	372	Y	0.30
15	GR	Improved	256 X 256	180		
20	GR	Improved	256 X 256	307	Y	

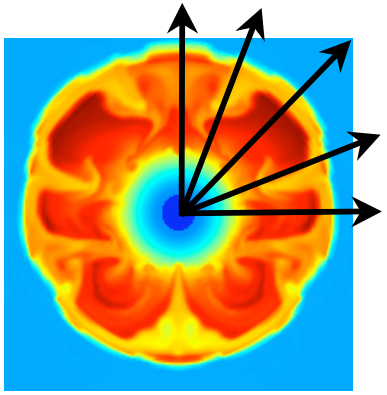
Compare

- Bruenn et al. *Journ. Phys. Conf. Ser.* **46**, 393 (2006)
- Mezzacappa et al. *AIP Conf. Proc.* **924**, 234 (2007)

11 Solar Mass Model



A Quantum Leap in Difficulty



$$N_{\text{cores}} = N_{\text{rays}} = N_{\theta} \times N_{\phi}$$

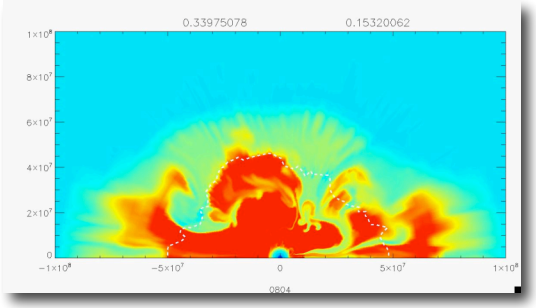
	Number of Cores	Latitudinal Zones	Longitudinal Zones
	12,168 (Current)	78 (2-3 Degree Resolution)	156 (2-3 Degree Resolution)
CY08	32,768 (250 TF)	128 (1-2 Degree Resolution)	256 (1-2 Degree Resolution)
CY09	73,728 (1 PF)	192 (<1 Degree Resolution)	384 (<1 Degree Resolution)

Cannot request "beam time" (cycles) "on the facility" (LCF) unless scaling is demonstrated.

✶ *Significant investment.*

Runtime: ~1/2 -1 month per run at 1 ray per core.

⇨ *Most of ORNL LCF 250 TF platform and 75% of 1 PF platform will be dedicated to each run for ~1/2 - 1 month.*



Summary and Outlook

2D Models

- Explosions for a range of supernova progenitors.
- *Trends are good: 1D to 2D … to 3D?*
- The treatments of the nuclear and weak interaction physics matter considerably.

Ongoing and Planned 3D Multi-Physics Simulations

- First 3D simulations ongoing on the Leadership Computing Facility
- Higher-resolution models will require 32,768 cores and are planned for the 250 TF LCF platform this year

Longer Term

What role will magnetic fields and neutrino mixing play?

Investments made under TSI provided foundation for these and future efforts.

Collaborators

Bruenn
Marronetti

Blondin

Fuller

Cardall
Hix
Messer
Mezzacappa

Funded by

Other Collaborators
Solvers: D'Azevedo
Data Management: Klasky, Meredith, Podhorski
Networking: Beck, Moore, Rao
Visualization: Ahern, Ma, Toedte