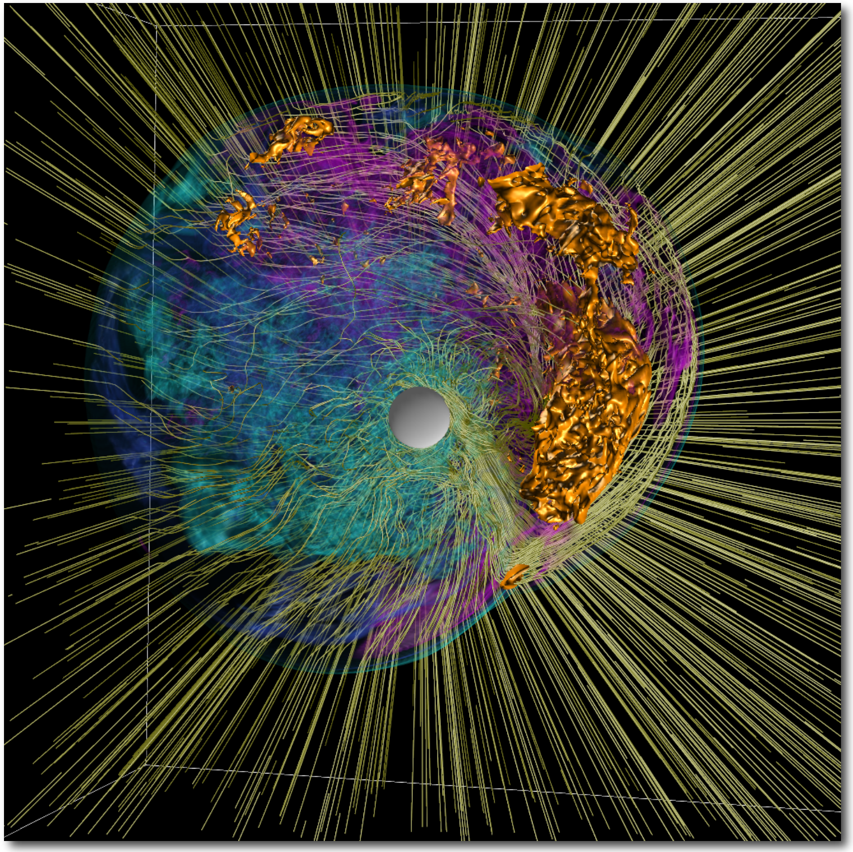
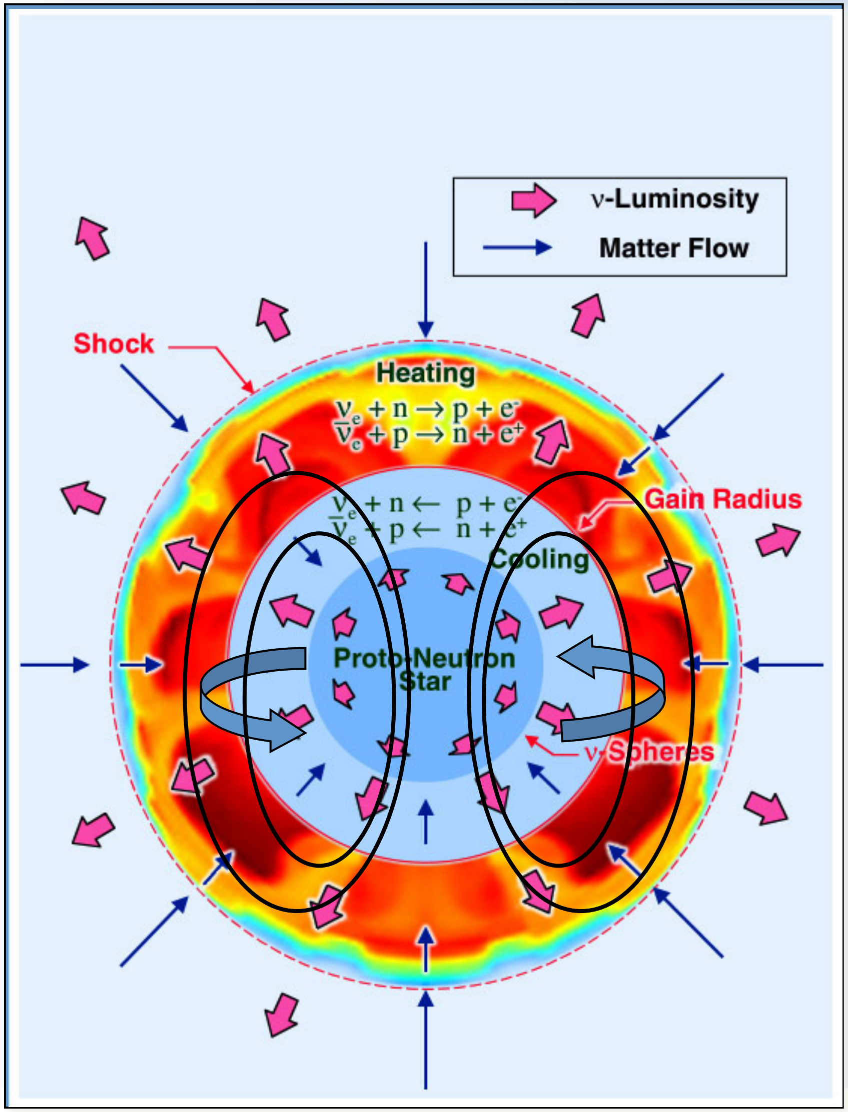
(CORE COLLAPSE) SUPERNOVA SIMULATIONS



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*

Equations To Be Solved

Components of a Supernova Model

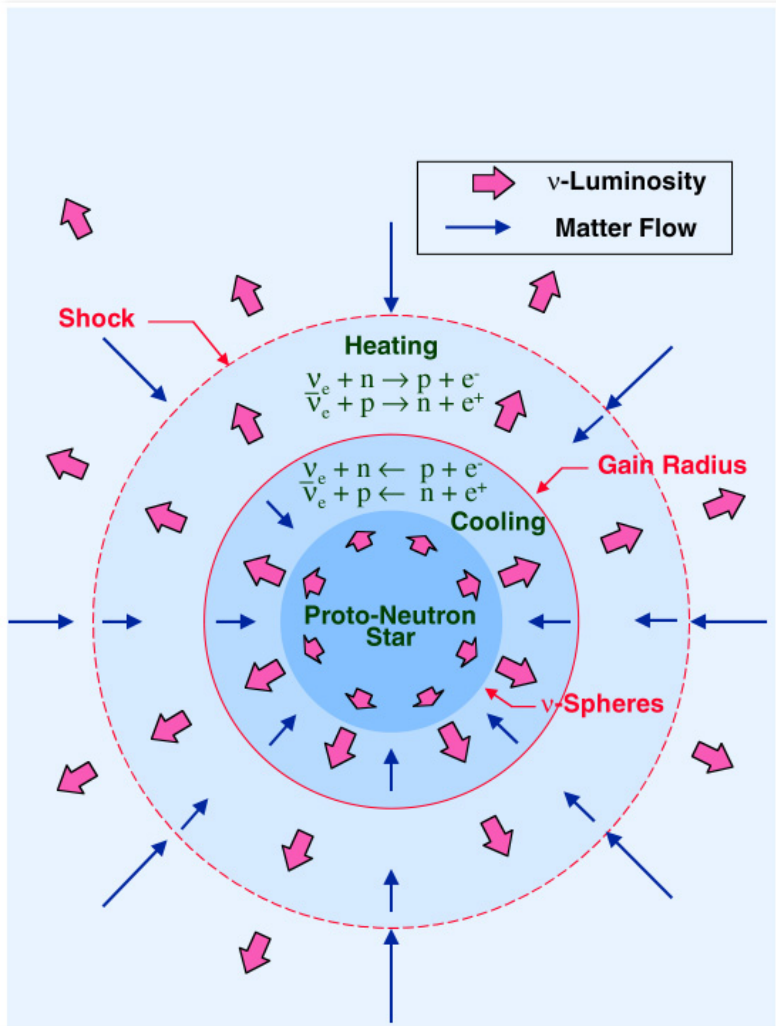
- Neutrino Transport
- Fluid Instabilities
- Rotation
- Magnetic Fields
- Weak Interactions
- Equation of State
- Gravity

Boltzmann Kinetic/Moment Equations

Magnetohydrodynamics Equations

Poisson or Einstein Equations

The Heart of the Matter



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

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

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

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

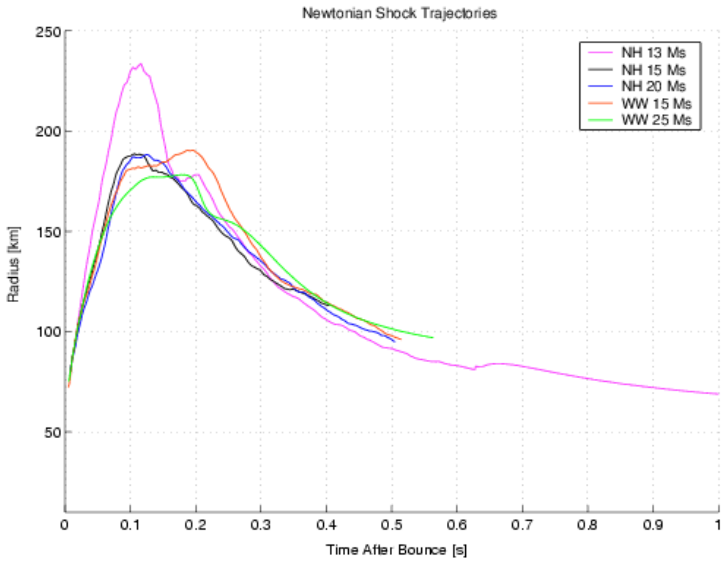
Multifrequency
(MGFLD, MGVET)

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

Gray

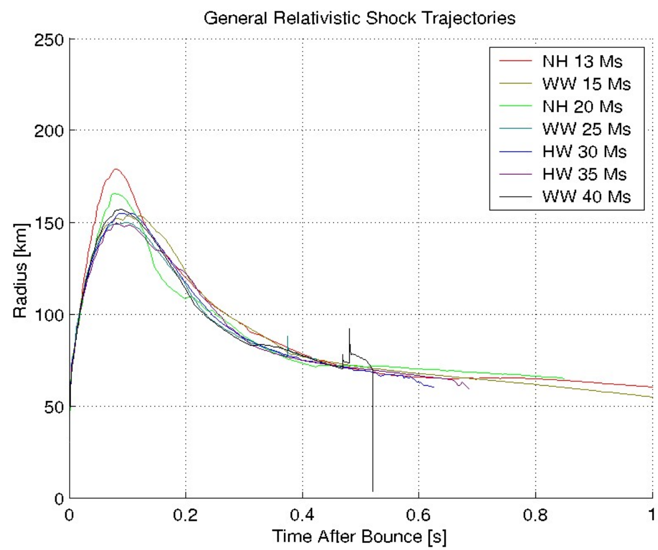
Completed: Spherical Models with Boltzmann Transport

Newtonian



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

General Relativistic



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?

- Better weak interaction physics?
- Better EOS?
- Neutrino mixing?
- Multi-D effects.

Agile-BOLTZTRAN

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

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)

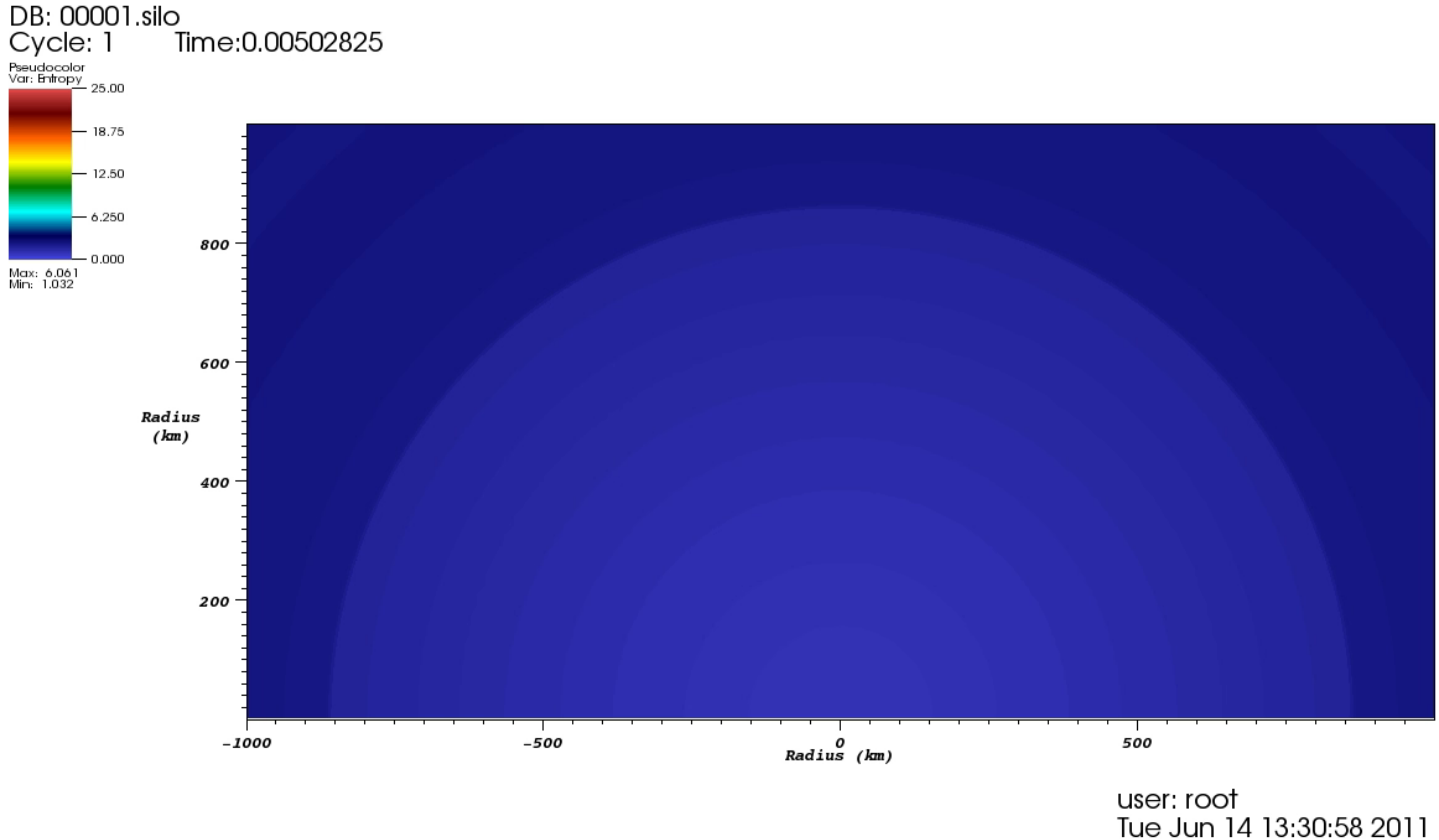
State-of-the-Art Weak Physics and EOS

Cell-by-Cell AMR

SELECT MILESTONES IN CORE COLLAPSE SUPERNOVA THEORY

Publication	Milestone
Colgate and White (1966) Ap.J. 143, 626 Arnett (1966) Can. J. Phys. 44, 2553 Wilson (1971) Ap.J. 163, 209 Wilson (1974) PRL 32, 849	Core collapse supernovae can be neutrino driven! First numerical models.
Wilson (1985), in Numerical Astrophysics, eds. Centrella, LeBlanc, and Bowers Bethe and Wilson (1985) Ap.J. 295 14	Discovery of delayed-shock mechanism. Framed contemporary core collapse supernova theory.
Herant, Benz, and Colgate (1992) Ap.J. 395 642 Herant et al. (1994) Ap.J. 435 339 Burrows, Hayes, and Fryxell (1995) Ap.J. 450 830 Janka and Mueller (1996) A&A 306 167 Mezzacappa et al. (1998) Ap.J. 495 911	First 2D models. Revolutionized core collapse supernova theory.
Mezzacappa and Bruenn Ap.J. 410, 740 (1993) Liebendoerfer et al. (2001) PRD 63 3004 Thompson, Burrows, and Pinto (2003) Ap.J. 592 434 Liebendoerfer et al. (2005) Ap.J. 620 840 Kitaura, Janka, and Hillebrandt (2006) A&A 450 345	First (1+2)D models – i.e., 1D models with Boltzmann neutrino transport.
Blondin, Mezzacappa, and DeMarino (2003) Ap.J. 584 971	SASI discovery. Missing link.
Fryer and Warren (2004) Ap.J. 601 391	First 3D models.
Bruenn et al. (2006) Journ. Phys. Conf. Ser. 46 393 Buras et al. (2006) A&A 457 281 Bruenn et al. (2009) Journ. Phys. Conf. Ser. 180 012018 Marek and Janka (2009) Ap.J. 694 664 Suwa et al. (2010) Publ. Astron. Soc. Japan 62 L49	First (2+1)D models – i.e., 2D models with multi-frequency neutrino transport. Neutrino-driven explosions aided by the SASI obtained across range of progenitors.

(3+1)D awaits! **(3+2)D looms!**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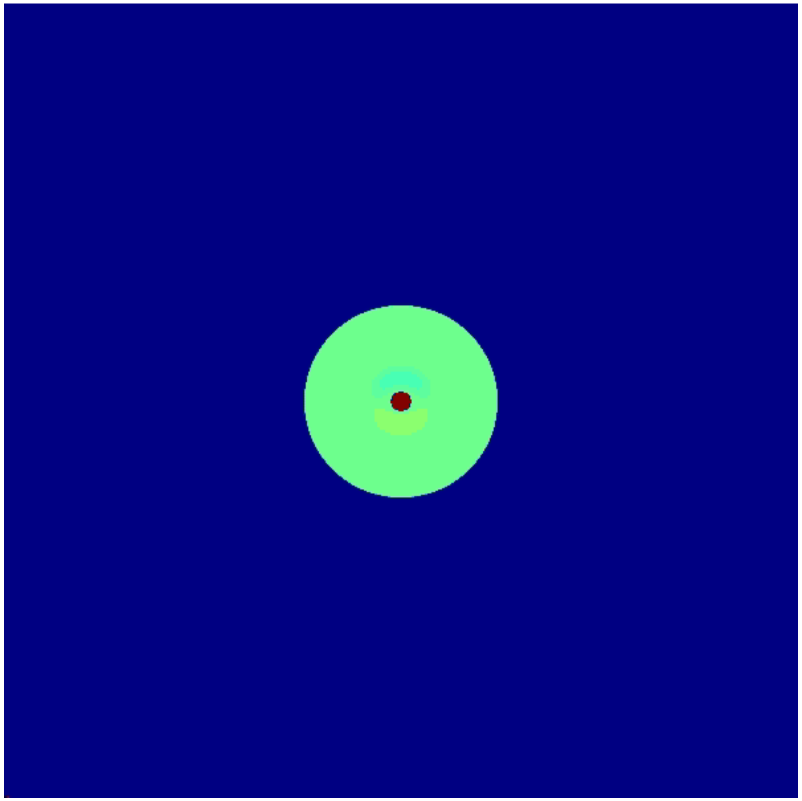
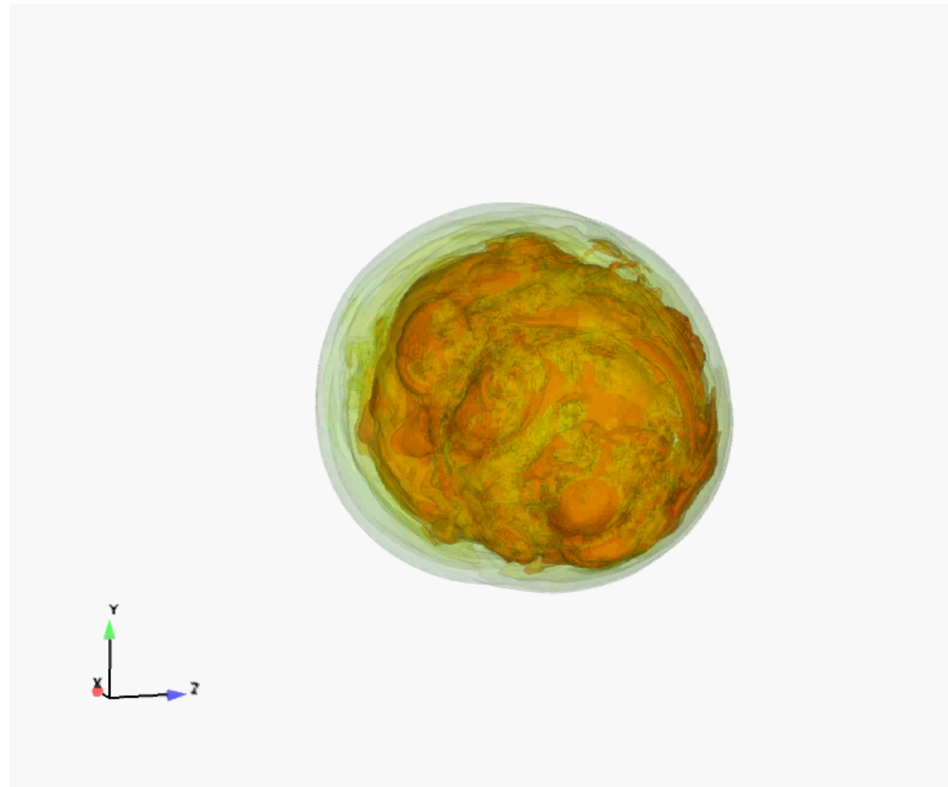
What can we expect from 3D?



Blondin, Mezzacappa, and DeMarino 2003 *ApJ* **584,** 971



Blondin and Mezzacappa 2007 *Nature* **445,** 58

General Relativistic Boltzmann Equation

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

Cardall and Mezzacappa PRD **68** 023006 (2003)

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

	Spatial Dimensions	Netwonian or GR	1	2	3	Partial Weak Interactions	Complete Weak Interactions	Label
Liebendoerfer et al. (2004)	1	GR	X	X	X		X	Full GR
Ott et al. (2008)	2	Newtonian	X			X		1D Counterpart: No-Observer-Correctons Newtonian

Partial Weak Interactions:

(1) No electron capture on nuclei.

(2) Scattering is assumed isotropic and isoenergetic.

Important Neutrino Emissivities/Opacities

"Standard" Emissivities/Opacities

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

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

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

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

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

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

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

- Include correlations between nucleons in nuclei.

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.

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

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

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

- New source of neutrino-antineutrino pairs.

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

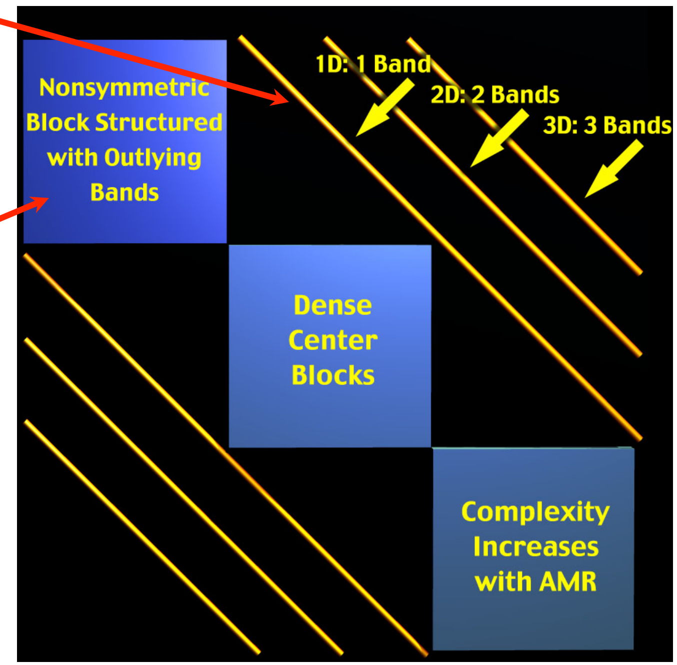
Solving ExaScale Linear Systems

Correspondence between structure of integro-PDE and underlying linear systems...

$$
\begin{aligned}
&\frac{1}{c}\frac{\partial F}{\partial t} + 4\pi\mu_0\frac{\partial(r^2\rho_0F)}{\partial m} \\
&+ \frac{1}{r}\frac{\partial[(1-\mu_0^2)F]}{\partial\mu_0} \\
&+ \frac{1}{c}\left(\frac{\partial ln\rho_0}{\partial t}+\frac{3v}{r}\right)\frac{\partial[\mu_0(1-\mu_0^2)F]}{\partial\mu_0} \\
&+ \frac{1}{c}\left[\mu_0^2\left(\frac{\partial ln\rho_0}{\partial t}+\frac{3v}{r}\right)-\frac{v}{r}\right]\frac{1}{E_0^2}\frac{\partial(E_0^3F)}{\partial E_0} \\
&= \frac{j}{\rho_0} - \tilde{\chi}F \\
&+ \frac{1}{c}\frac{1}{h^3c^3}E_0^2\int d\mu_0' R_{IS}(\mu_0,\mu_0',E_0)F(\mu_0',E_0) \\
&- \frac{1}{c}\frac{1}{h^3c^3}E_0^2F\int d\mu_0' R_{IS}(\mu_0,\mu_0',E_0) \\
&+ \frac{1}{h^3c^4}\left(\frac{1}{\rho_0}-F(\mu_0,E_0)\right)\int dE_0'E_0'^2d\mu_0'\tilde{R}_{NES}^{in}(\mu_0,\mu_0',E_0,E_0')F(\mu_0',E_0') \\
&- \frac{1}{h^3c^4}F(\mu_0,E_0)\int dE_0'E_0'^2d\mu_0'\tilde{R}_{NES}^{out}(\mu_0,\mu_0',E_0,E_0')\left(\frac{1}{\rho_0}-F(\mu_0',E_0')\right)
\end{aligned}
$$

…Leads to Nonlinear Algebraic Equations

- **Linearize**
- **Solve via Multi-D Newton-Raphson Method**
  - **⇨ Solve Exascale Sparse Linear Systems**

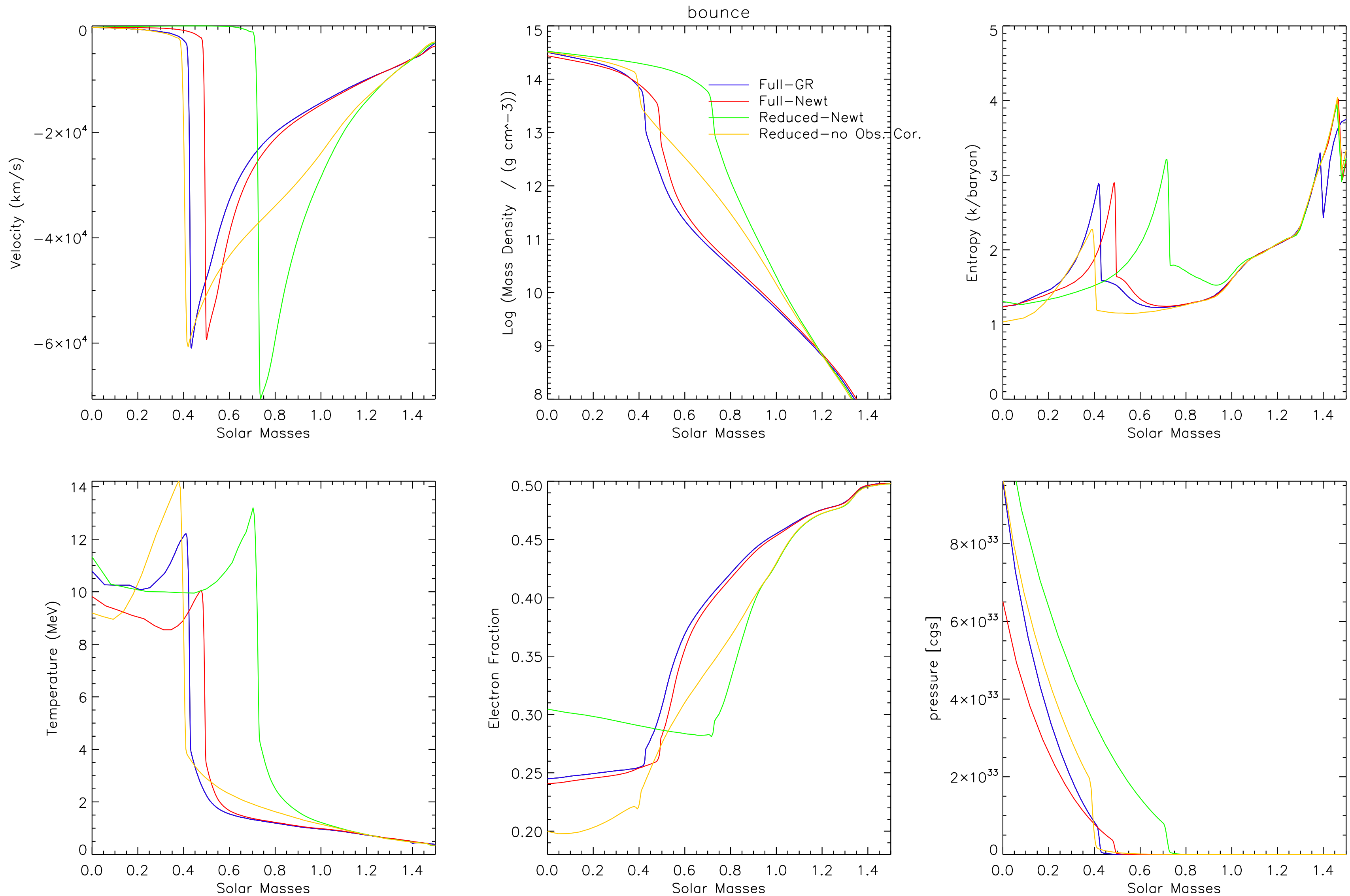


Implicit Time Differencing…

- **Extremely Short Neutrino-Matter Coupling Time Scales**
- **Neutrino-Matter Equilibration**
- **Neutrino Transport Time Scales**

Conservative numerical formulation of these terms is challenging.

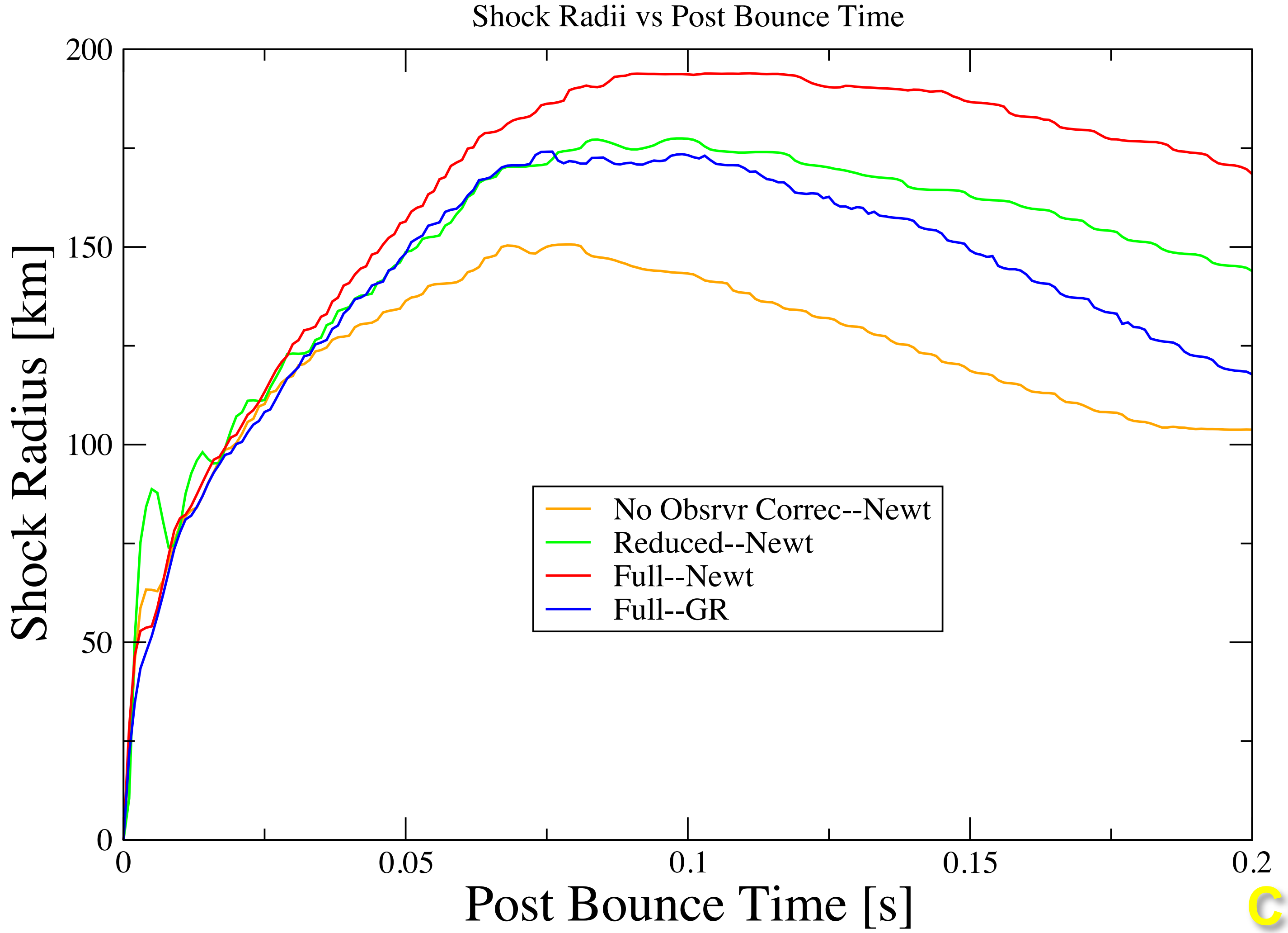
See Liebendoerfer et al. *Ap.J. Suppl*. **150**, 263 (2004) (1D) and Cardall and Mezzacappa PRD **68** 023006 (2003) (Multi-D).



Agile-BOLTZTRAN

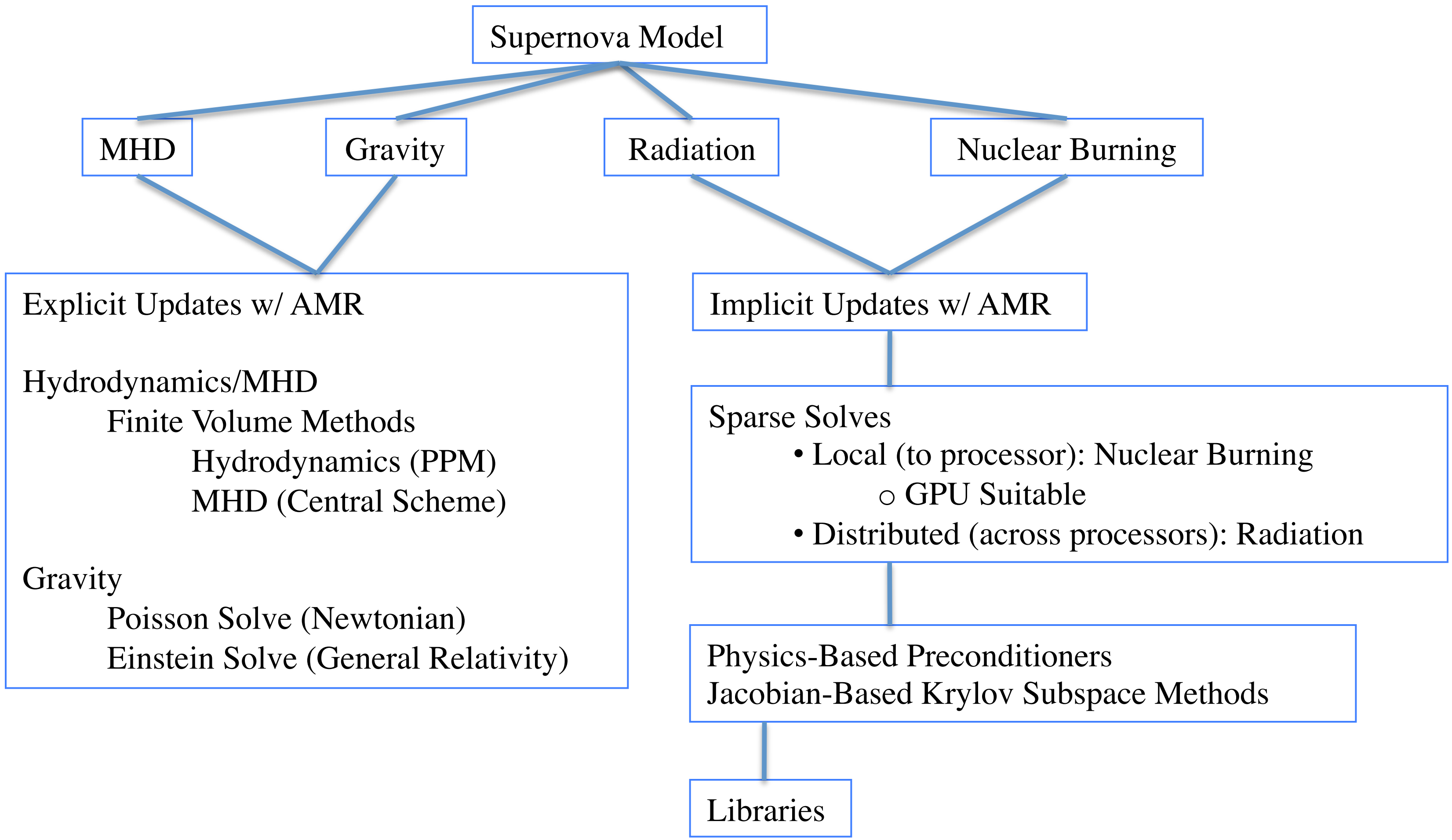
Lentz et al. (2010), in preparation.

Comparison of 1D Simulations; 15 W-H Progenitor



CHIMERA

SCIENCE TO SOLVERS MAPPING



The Need for Exascale Resources

Dominated by preconditioning of dense blocks.

$$\text{FLOPS} \sim N_t N_s N_i f N_m^{\ 2} \sim 3.5 \times 10^{22} f$$

N_t = number of time steps $\sim 1 \times 10^6$

N_s = number of spatial zones $\sim 512 \times 512 \times 512$

N_i = number of iterations per time step ~ 10

N_m = number of neutrino momentum zones

$f \in [1, N_m] = [1, 5120]$

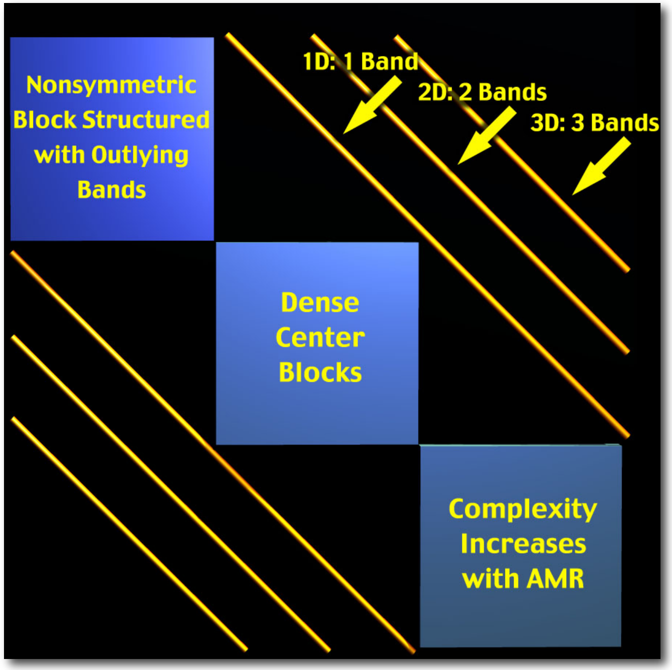
$$N_m = N_\nu \times N_E \times N_p \times N_a$$

$N_\nu = 4$

N_E = number of neutrino energy groups ~ 20

N_p = number of neutrino polar direction angles ~ 8

N_a = number of neutrino azimuthal direction angles ~ 8



Algorithms critical!

Runtime: ~ 4*f* days per run on a 1 EF machine (at 10% of peak).

Memory Footprint: 27 PB

The Need for Exascale Resources

Dominated by preconditioning of dense blocks.

$$\text{FLOPS} \sim N_t N_s N_i f N_m^{\ 2} \sim 3.4 \times 10^{19} f$$

N_t = number of time steps $\sim 1 \times 10^6$

N_s = number of spatial zones $\sim 512 \times 512 \times 512$

N_i = number of iterations per time step ~ 10

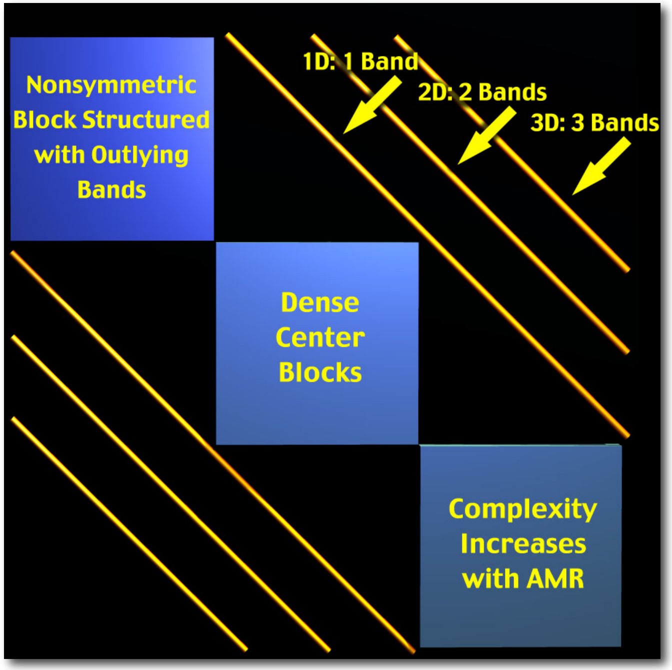
N_m = number of neutrino momentum zones

$f \in [1, N_m] = [1,160]$

$N_m = N_\nu \times N_E$

$N_\nu = 4 \times 2$

N_E = number of neutrino energy groups ~ 20



Algorithms critical!

Runtime: ~ f hours per run on a 1 EF machine (at 10% of peak).

Memory Footprint: 27 TB

CONCLUSIONS AND OUTLOOK

- Recent (2+1)D models show promise. We are on track.
  - Wilson delayed shock mechanism plus SASI yields explosions in models performed by several groups beginning with a range of progenitor masses.
- A great deal remains to be done in (2+1)D and (2+3)D.
  - There are presently very few published explosion models, and even they are incomplete.
- Approximate (3+1)D models with multi-frequency neutrino transport will emerge soon.
- (3+1)D models with GR, full weak interaction physics, and complete transport physics must be performed.
  - Such simulations will require exascale resources.
- Definitive (3+3)D simulations will likely require sustained exascale platforms.

CHALLENGES

- Solvers
  - Communication optimal, reduce data movement, multi-core aware, fault tolerant, …
- AMR (See Martin Berzins' talk.)
  - Will geometric (e.g., space-filling curve) approaches scale?
  - Are task-based approaches a viable alternative?
    - All about the scheduling.
- Programming Models (See Brad Chamberlain's talk.)
  - Maximize the use of extant code.
  - Facilitate a task-based approach.
- Compilers (See Rich Graham's talk.)
  - Translation support for Chapel/MPI/OpenMP/Fortran/… with user hints to specify task dependencies.
- Debuggers (See Rich Graham's talk.)
  - Debugging at 10^5-10^6 cores.
- Data Analytics (See Scott Klasky's talk.)
  - High-performance I/O.
  - *In situ* and post-processed visualization of multi-D scalar, vector, and tensor data.

ORNL-FAU-NCSU-UCSD COLLABORATION

Multi-institution, multi-investigator, multi-disciplinary effort.

Budiardja
Cardall
Chertkow
Endeve
Hix
Lentz
Messer
Mezzacappa
Parete-Koon

Bruenn
Marronetti
Tsatsin
Yakunin

Blondin
Mauney

Fuller
Vlasenko

Applied Math/CS Collaborators

- *Closures, Preconditioners/Solvers: Hauck, D'Azevedo*
- *I/O, Data Management: Klasky, Shipman*
- *Compilers/Debuggers: Graham*
- *Visualization: Ahern, Meredith, Pugmire, Toedte*
- *Cray Center of Excellence: Wichmann*

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