Advances in Computational Nuclear Physics: Recent Important Progress on Ascertaining the Core Collapse Supernova Explosion Mechanism

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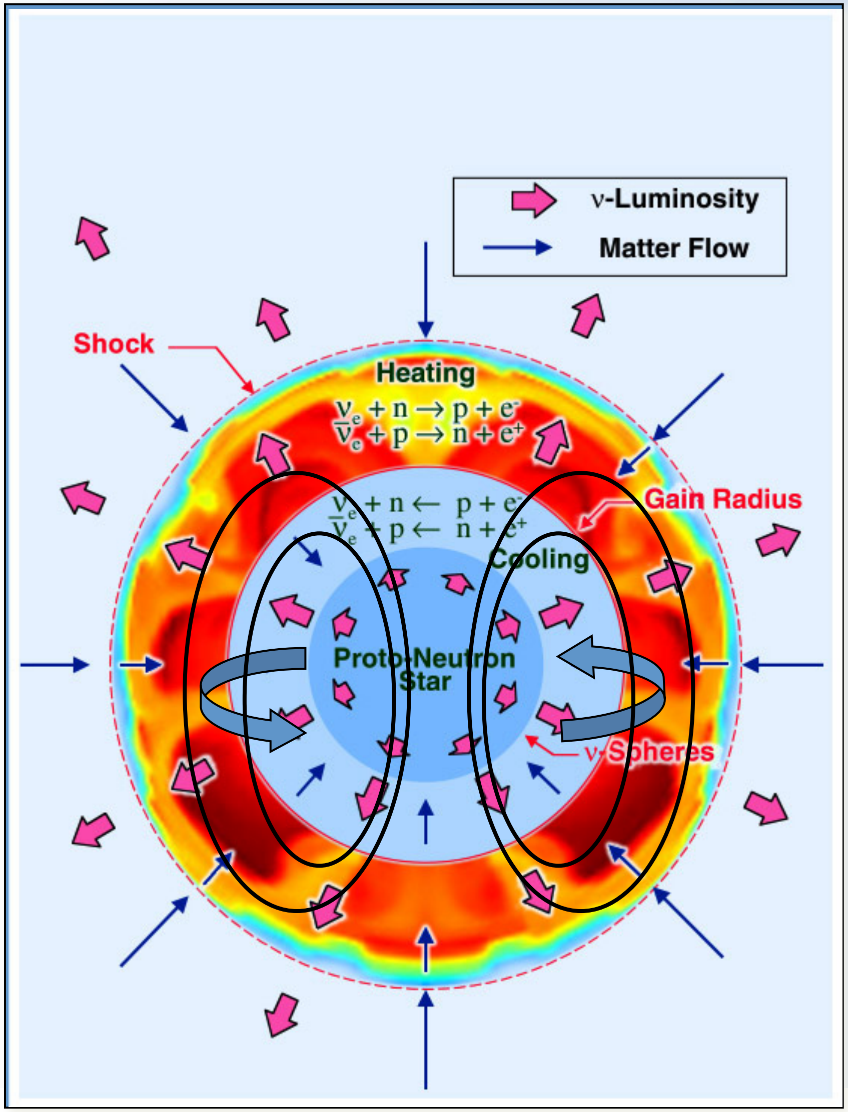
How is the supernova shock wave revived?

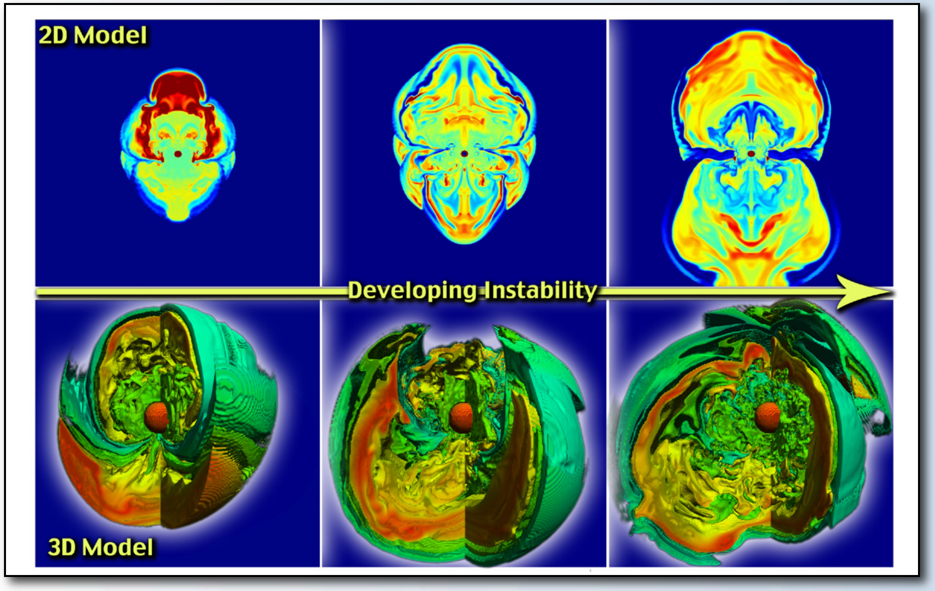


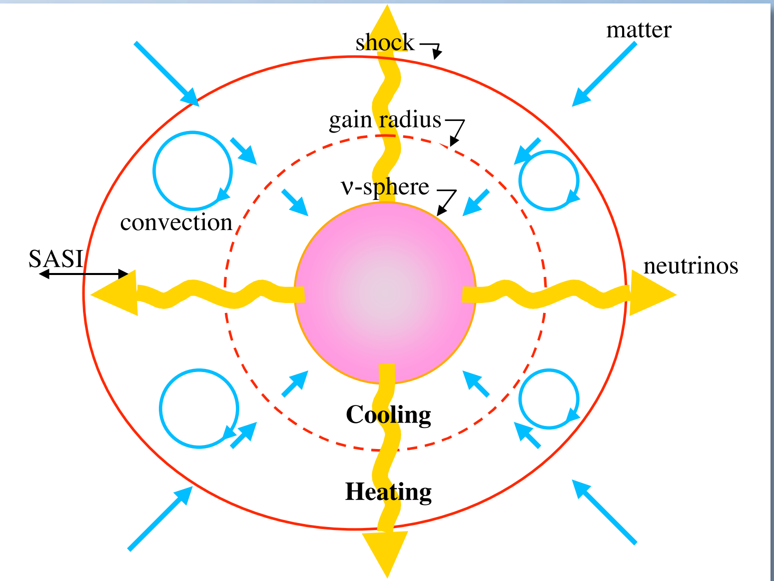
The most fundamental question in supernova theory

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

**New Ingredient*

Stationary Accretion Shock Instability (SASI)





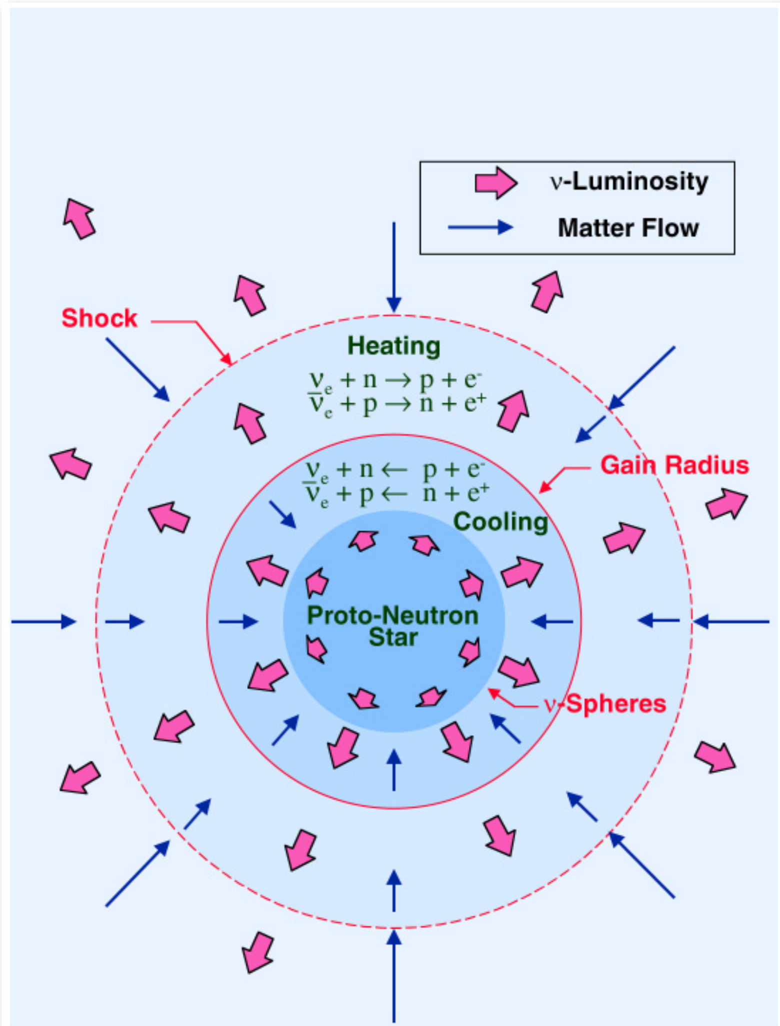
Blondin, Mezzacappa, & DeMarino, *Ap.J.* **584**, 971 (2003)

Shock wave unstable to non-radial perturbations.

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

– Blondin and Mezzacappa, *Ap.J.* **642**, 401 (2006)
– Blondin and Shaw, *Ap.J.* **656**, 366 (2007)

The Heart of the Matter



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

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

➠ *Must compute neutrino distribution functions.*

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

Multifrequency
Multiangle

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

$$F_R^i(t,r,\theta,\phi,E) = \int d\theta_p\, d\phi_p\, n^i f$$

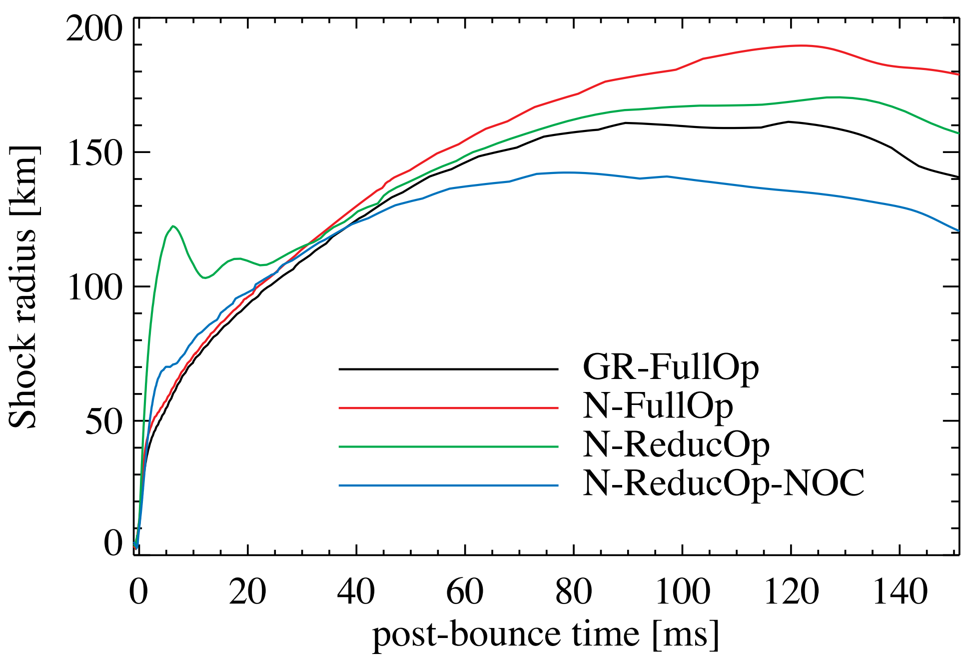
Multifrequency (*solve for lowest-order multifrequency angular moments: energy and momentum density/frequency*)

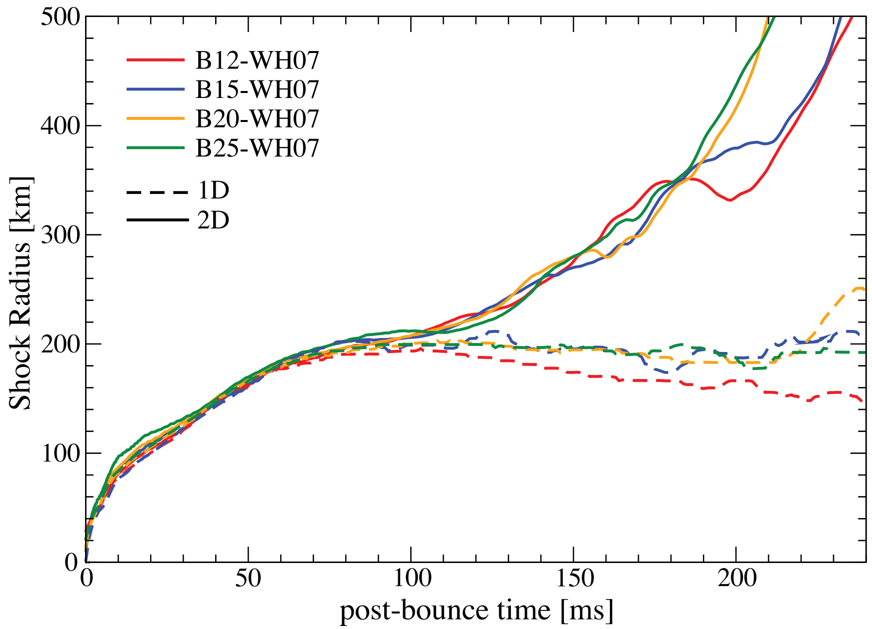
Requires a closure prescription:

- MGFLD
- MGVEF/MGVET

Peeling Away the Physics

ReducOp = Bruenn (1985) – NES + Bremsstrahlung (*no neutrino energy scattering, IPM for nuclei*)





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

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

Agile-BOLTZTRAN

CHIMERA

See also B. Mueller et al. 2012. Ap.J. ***756****, 84 for a comparison in the context of 2D models, with similar conclusions.*

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

+150 Isotope Network

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

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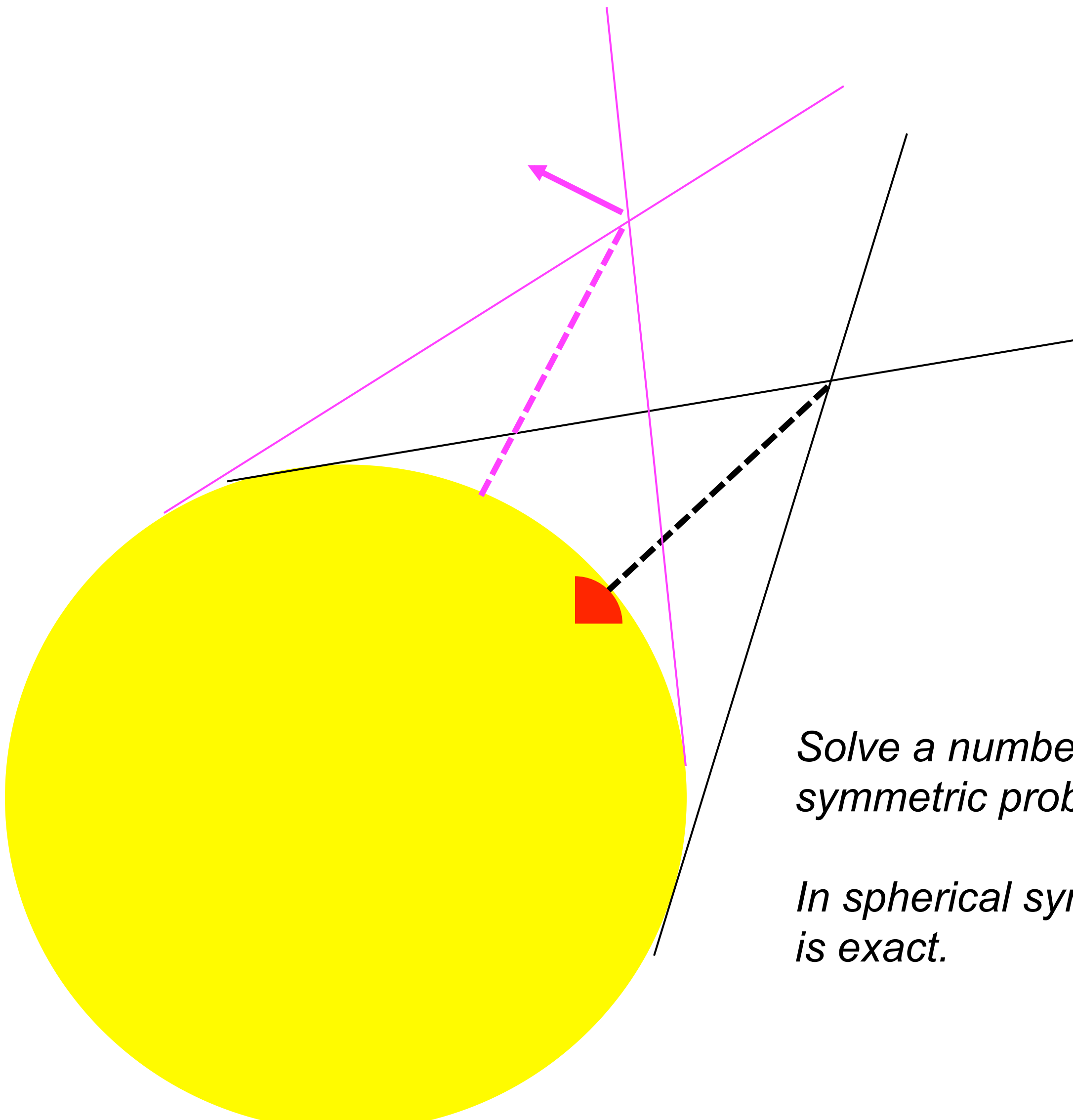
2D and 3D models include the same physics.

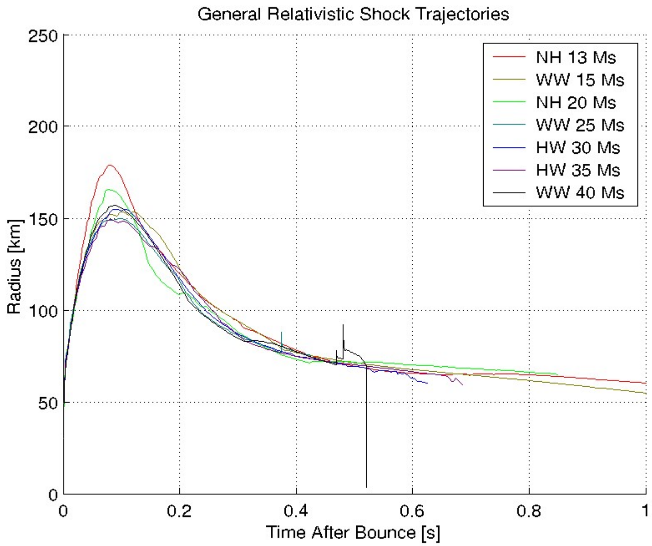
Ray-by-Ray Approximation



Solve a number of spherically symmetric problems.

In spherical symmetry, RbR is exact.

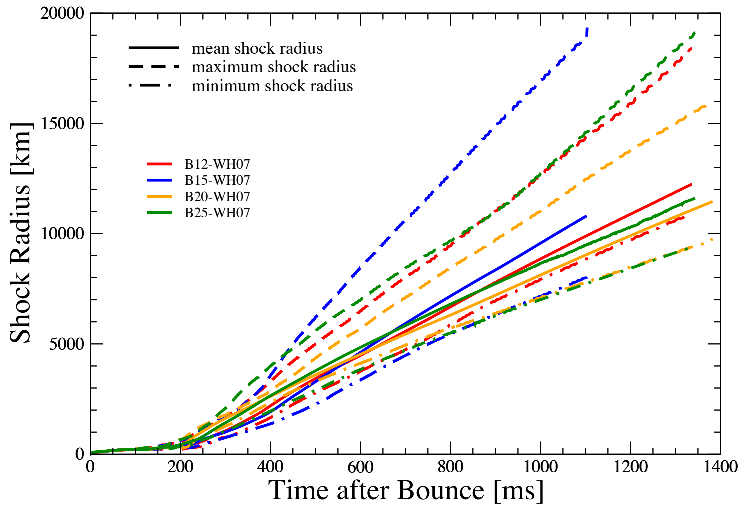
What a Difference a Dimension Makes

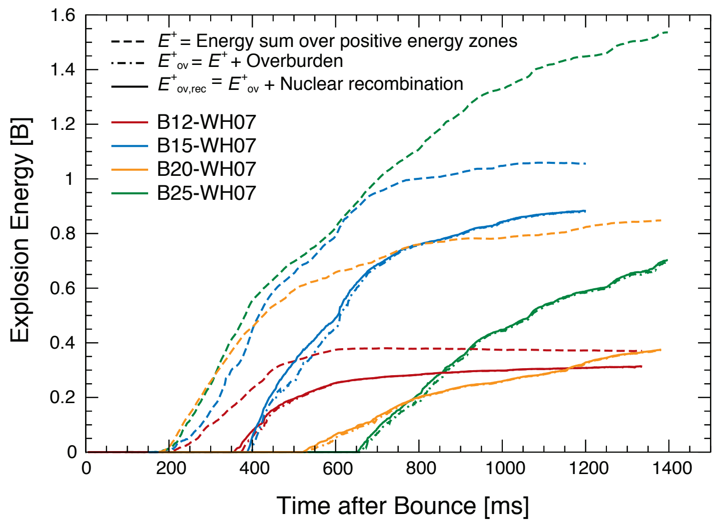


Liebendoerfer et al., PRD, **63**, 103004 (2001)

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

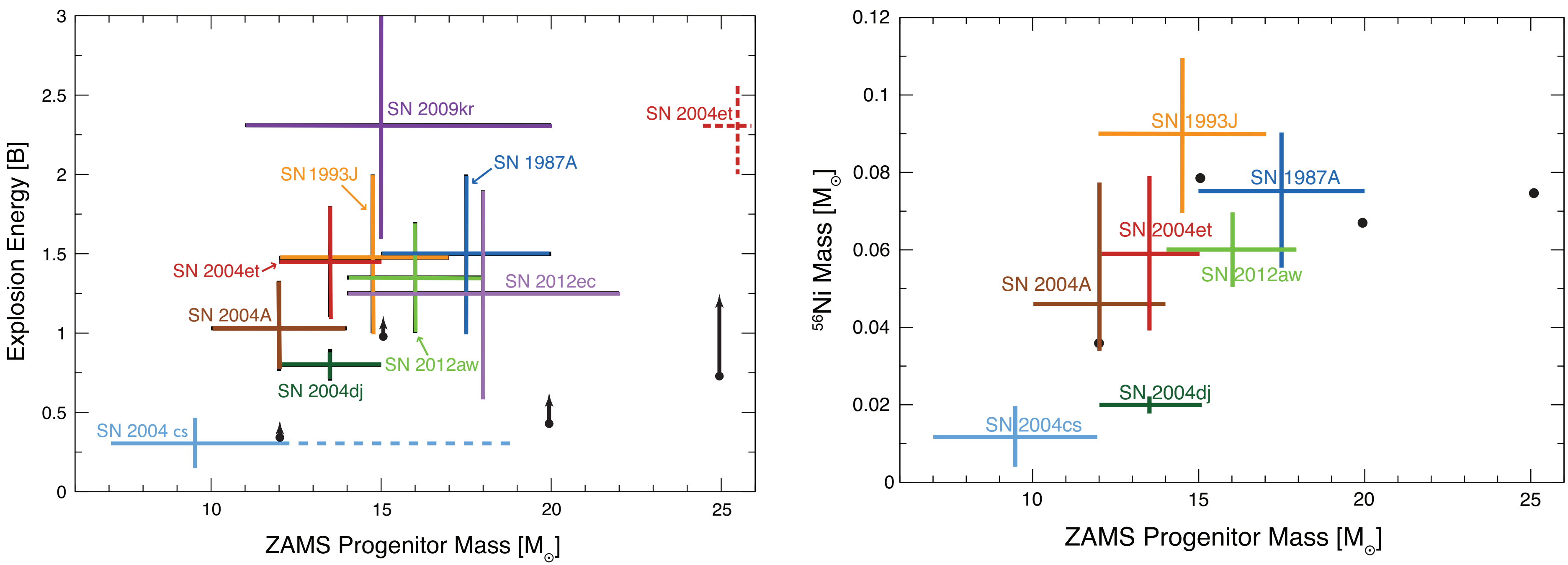
Agile-BOLTZTRAN



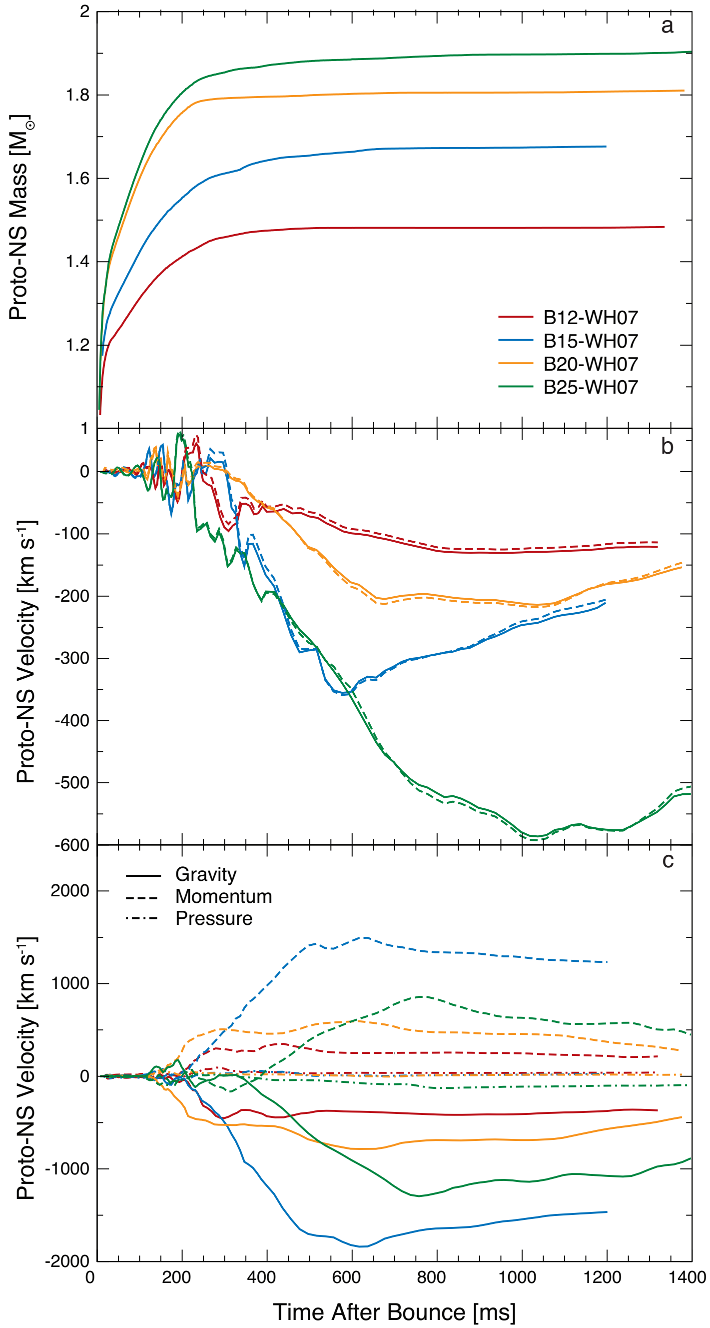


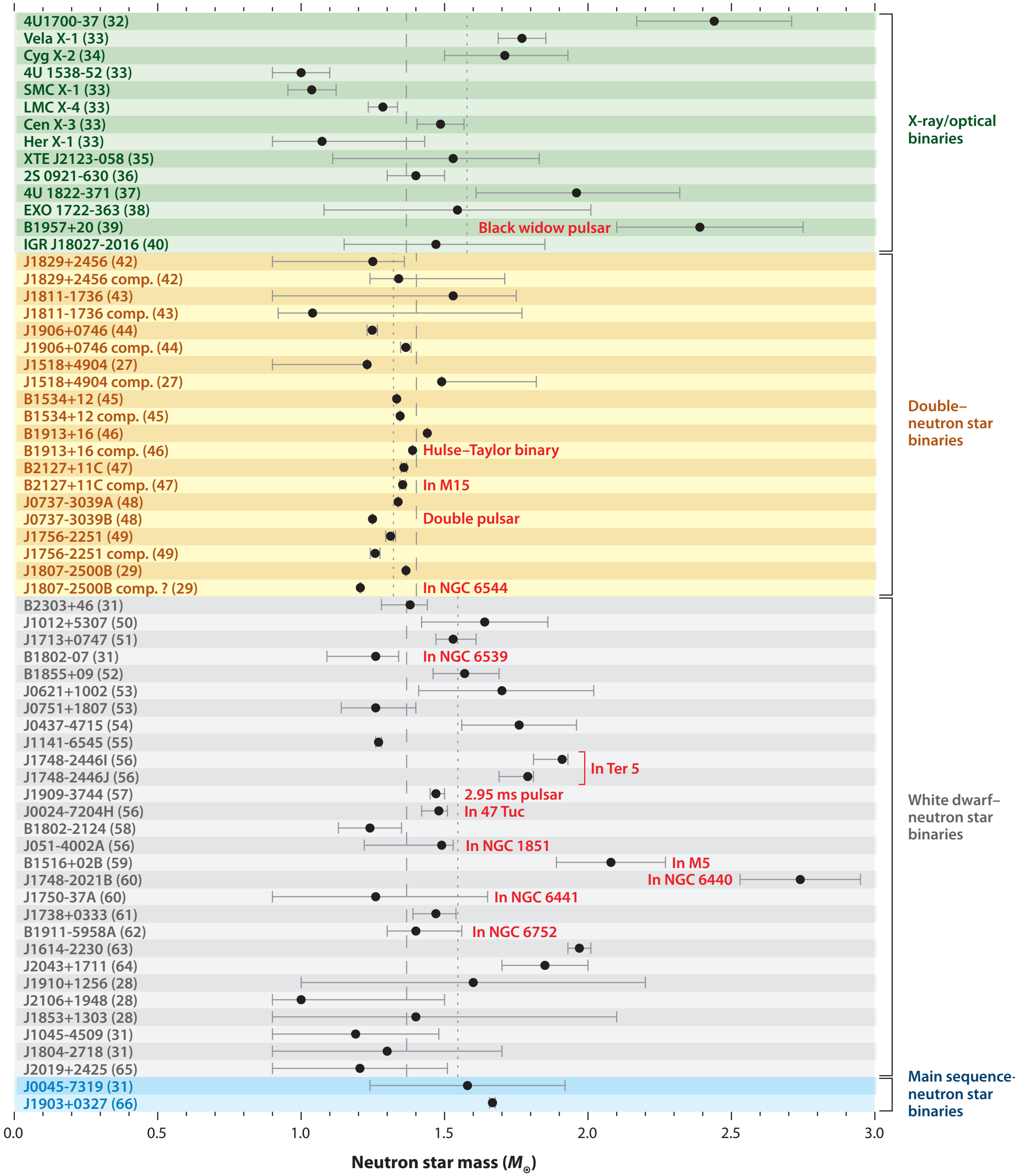
Bruenn et al. 2013. *Ap.J.* **767**, L6.
Bruenn et al. 2014. arXiv:1409.5779v1

Comparison with Observations



Bruenn et al. 2014. arXiv:1409.5779v1

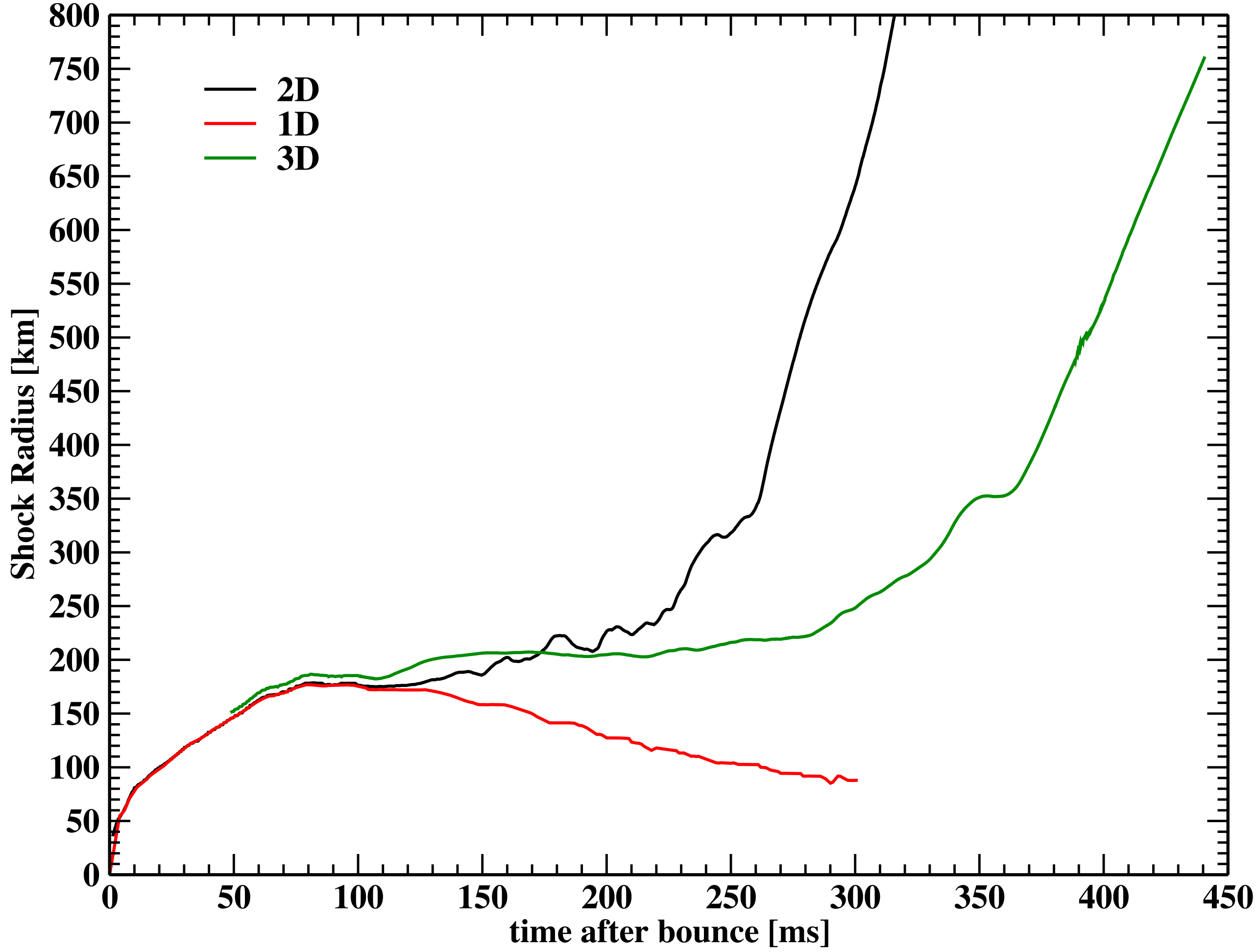




Lattimer, ARNPS 62 485 (2012)

Bruenn et al. 2014. arXiv:1409.5779v1

1D vs. 2D vs. 3D



Lentz et al. 2014. In preparation.

15 M
LS (220)

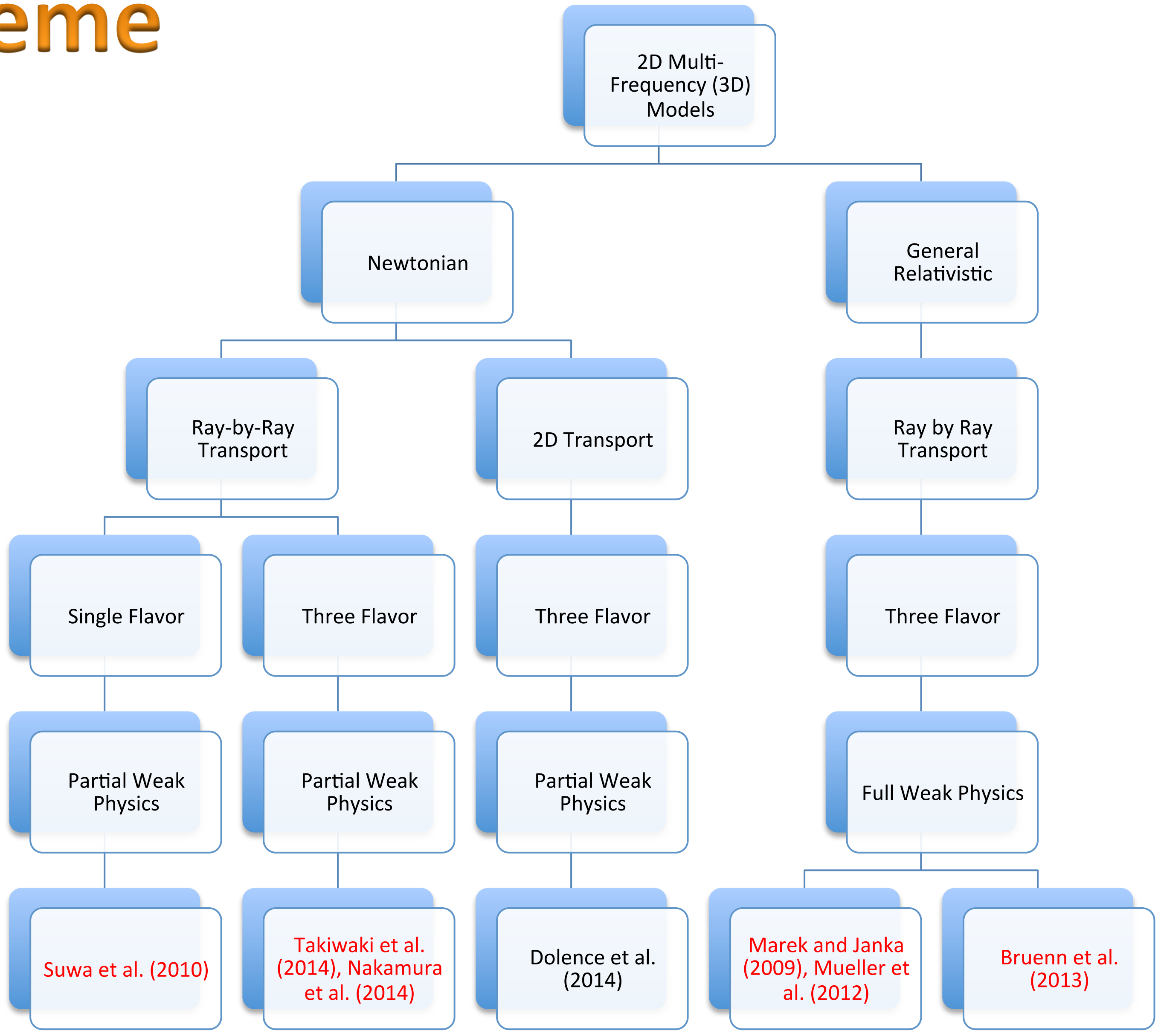
3D Counterpart Models

Lentz et al. 2014. In preparation.

Simulation Stats

- 64,800 cores
- 35 weeks/postbounce second
- 100 M processor-hours/postbounce second

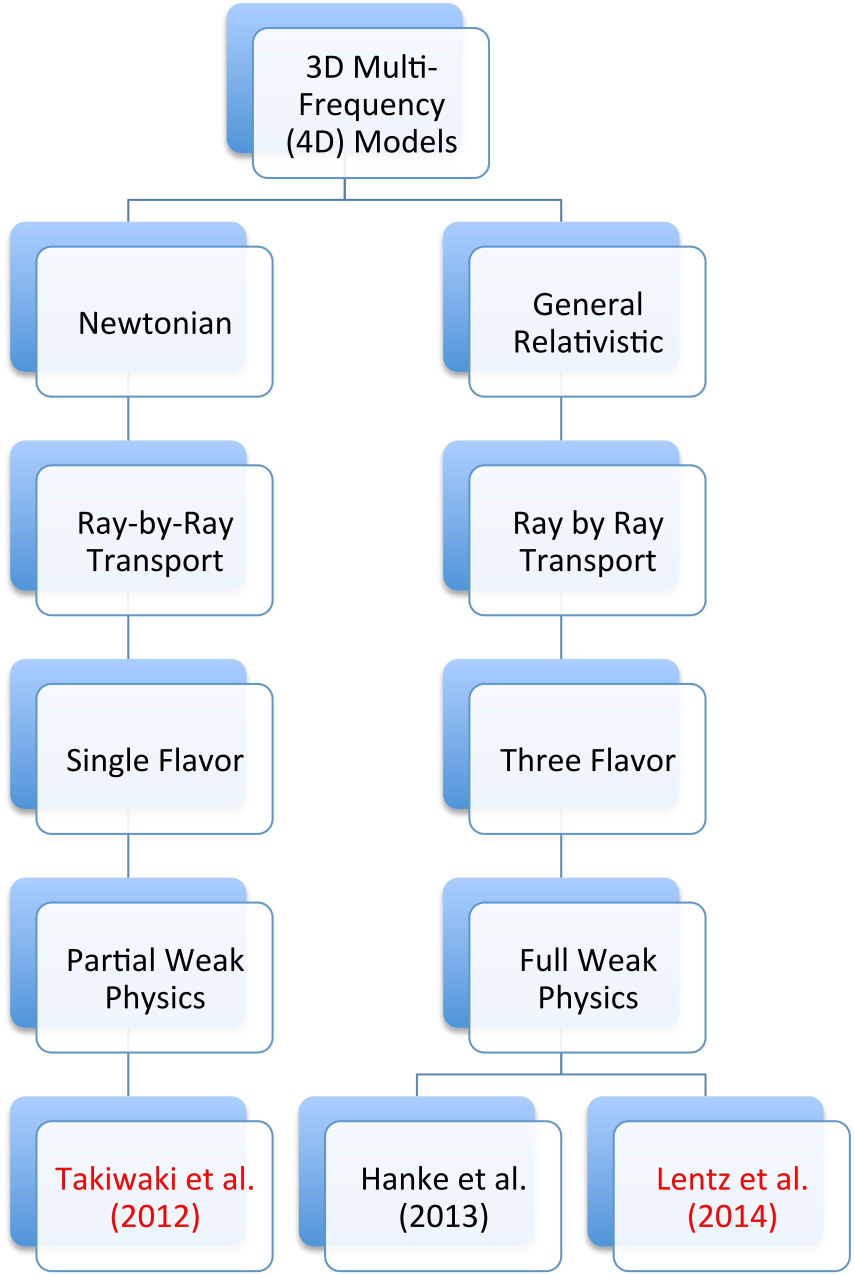
Grand Scheme of Things (2D)



Red indicates explosions obtained for some progenitors.

Most simulations noted above need to be run MUCH longer.

Grand Scheme of Things (3D)



<u>Progenitor Mass Used</u>

- Takiwaki et al. 11.2 M
- Lentz et al. 15 M
- Hanke et al. 27 M

What's Next?

Replace 1D RbR Transport with 3D (Lowest Angular Moments) Transport

Will require ~3 days @ 1 PF sustained.

Strong scaling essential.

Replace GR Monopole Correction with "Full" GR

Replace 3D Moments Transport with 3D Boltzmann Transport

Will require ~12 days @ 1 EF sustained.

~4000X more computationally intensive.

Will there be enough memory?

Replace 3D Boltzmann Transport with 3D Quantum Kinetics

?

CHIMERA Collaboration

Chertkow
Endeve
Harris
Hix
Lentz
Lingerfelt
Messer
Mezzacappa
Parete-Koon
Yakunin

Bruenn
Marronetti

Blondin
Mauney

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