A Status Report on Core Collapse Supernova Modeling: Successes to Date and What Lies Ahead

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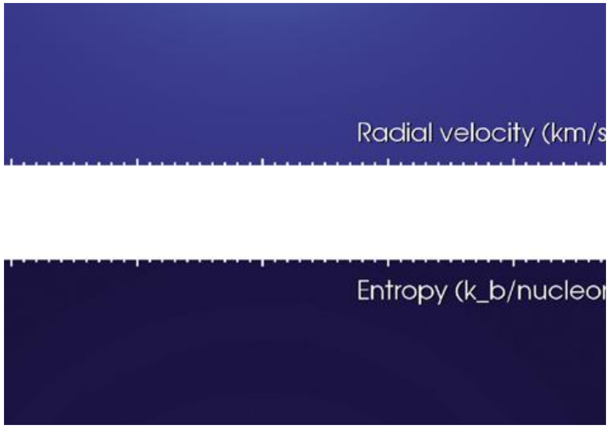
8th Symposium on Large TPCs for Low-Energy Rare Event Detection
Paris Diderot University

Proposed Explosion Mechanisms

Neutrino-Driven CCSNe
(Today's Focus)

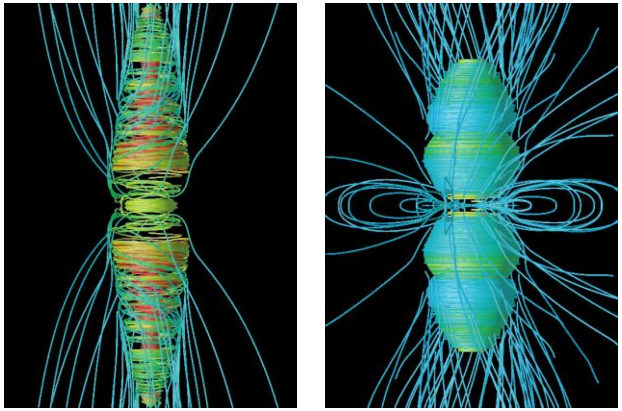


Bruenn et al. 2016, *Ap.J.* **818**, 123

Magnetorotationally-Driven CCSNe

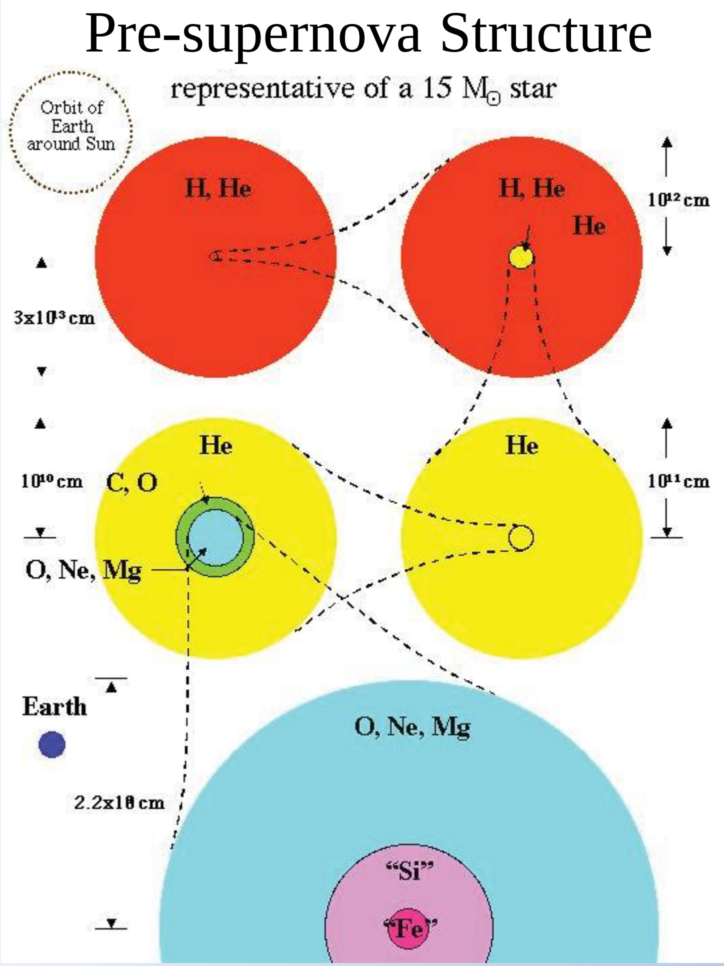
Extreme rotation required to amplify and collimate magnetic towers capable of driving and collimating outflows.

Thought to play a role in rare events – e.g., peculiar Type Ic supernovae.



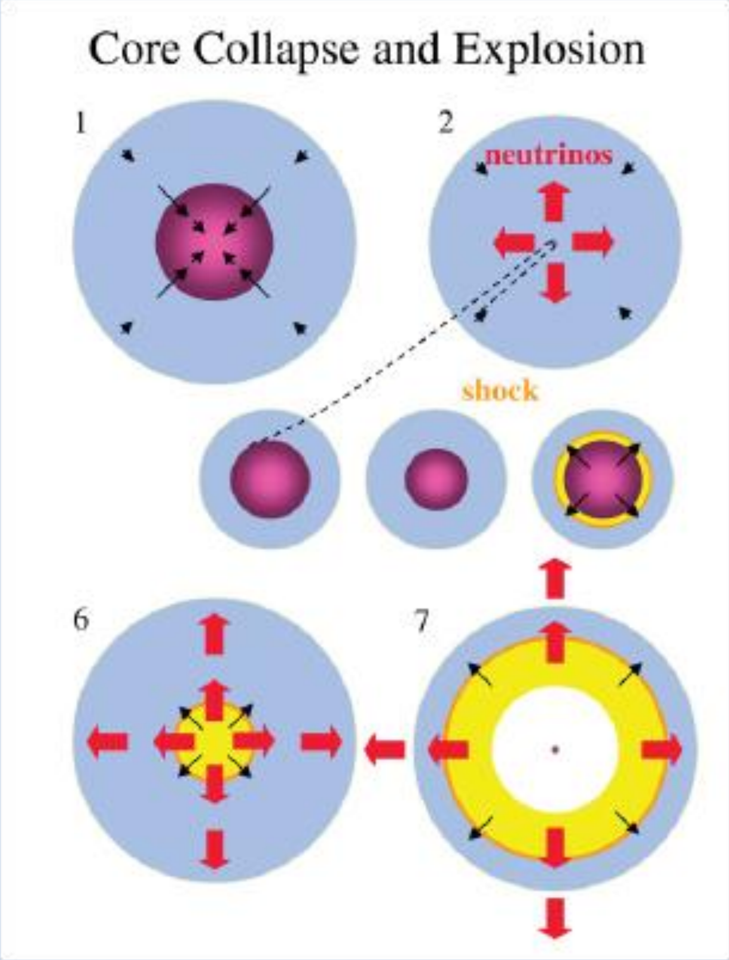
Burrows et al. 2007, *Ap.J.* **664**, 416

Core Collapse Supernova Paradigm and Problem Description



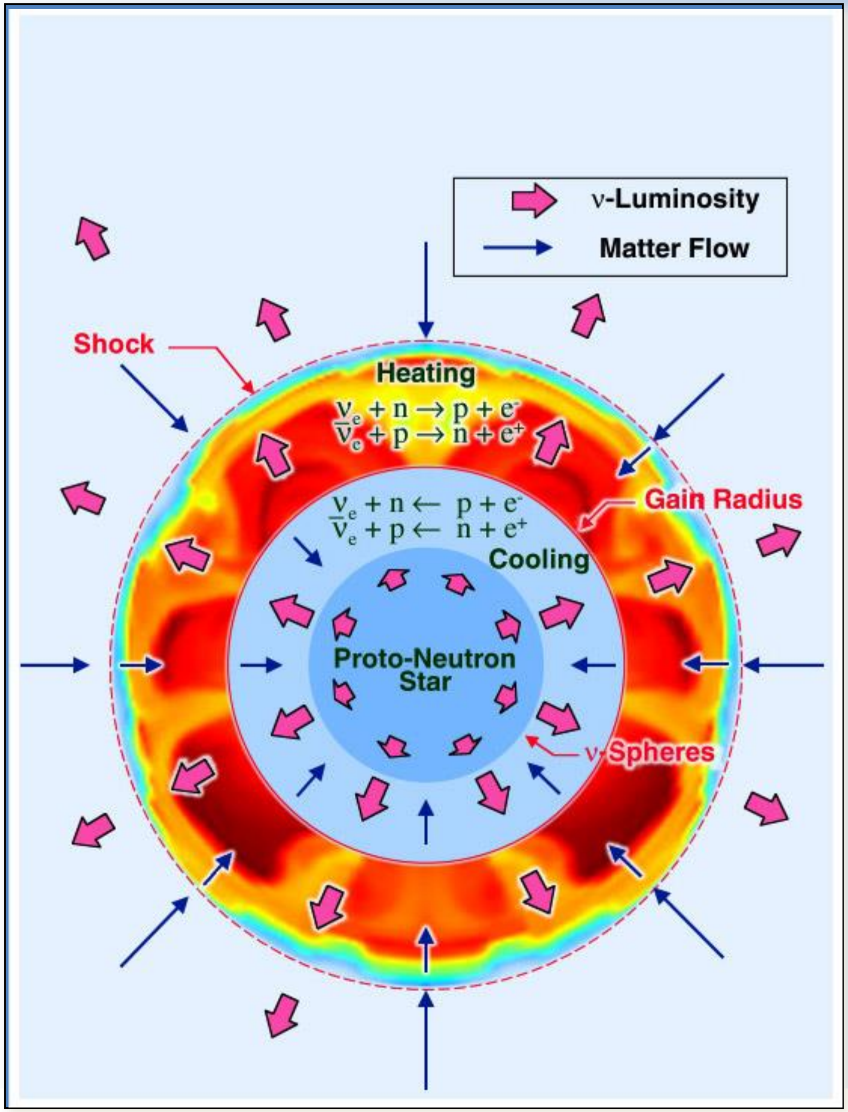
Pre-supernova Structure

representative of a 15 $M_\odot$ star



Core Collapse and Explosion

How is the supernova shock wave revived?



the most fundamental question in supernova theory

Leading Roles

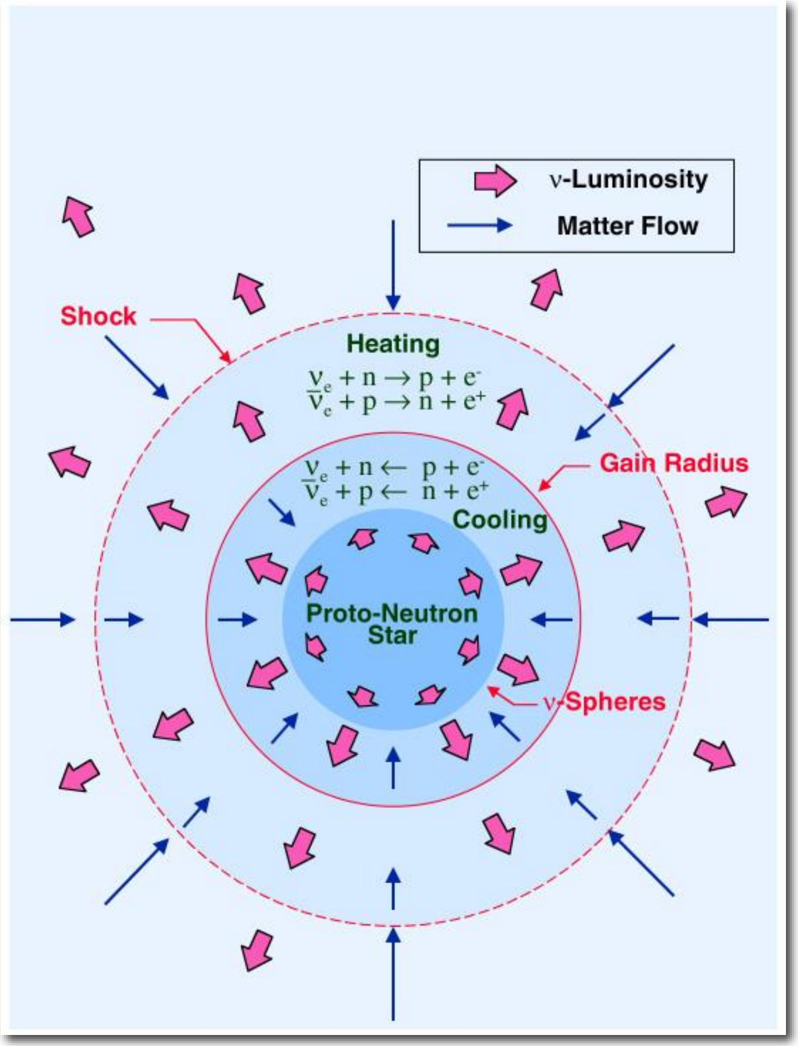
- Gravity
- Neutrinos
- Neutrino-Driven Convection
- Standing Accretion Shock Instability (SASI)

Supporting Roles

- Nuclear Burning
- Rotation
- Magnetic Fields

Where are we today?

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*)

This requires a prescription relating higher moments to these lower moments. This “closure” can impact simulation outcomes.

Proto-Neutron Star

44 key weak interactions

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

$e^+ + n \rightarrow \overline{n}_e + p$

$e^- + e^+ \rightarrow n_{e,mt} + \overline{n}_{e,mt}$

$N + N \rightarrow N + N + n_{e,mt} + \overline{n}_{e,mt}$

$n_e + \overline{n}_e \rightarrow n_{mt} + \overline{n}_{mt}$

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

$\overline{n}_e + p \rightarrow e^+ + n$

$n_{e,mt} + \overline{n}_{e,mt} \rightarrow e^- + e^+$

$N + N + n_{e,mt} + \overline{n}_{e,mt} \rightarrow N + N$

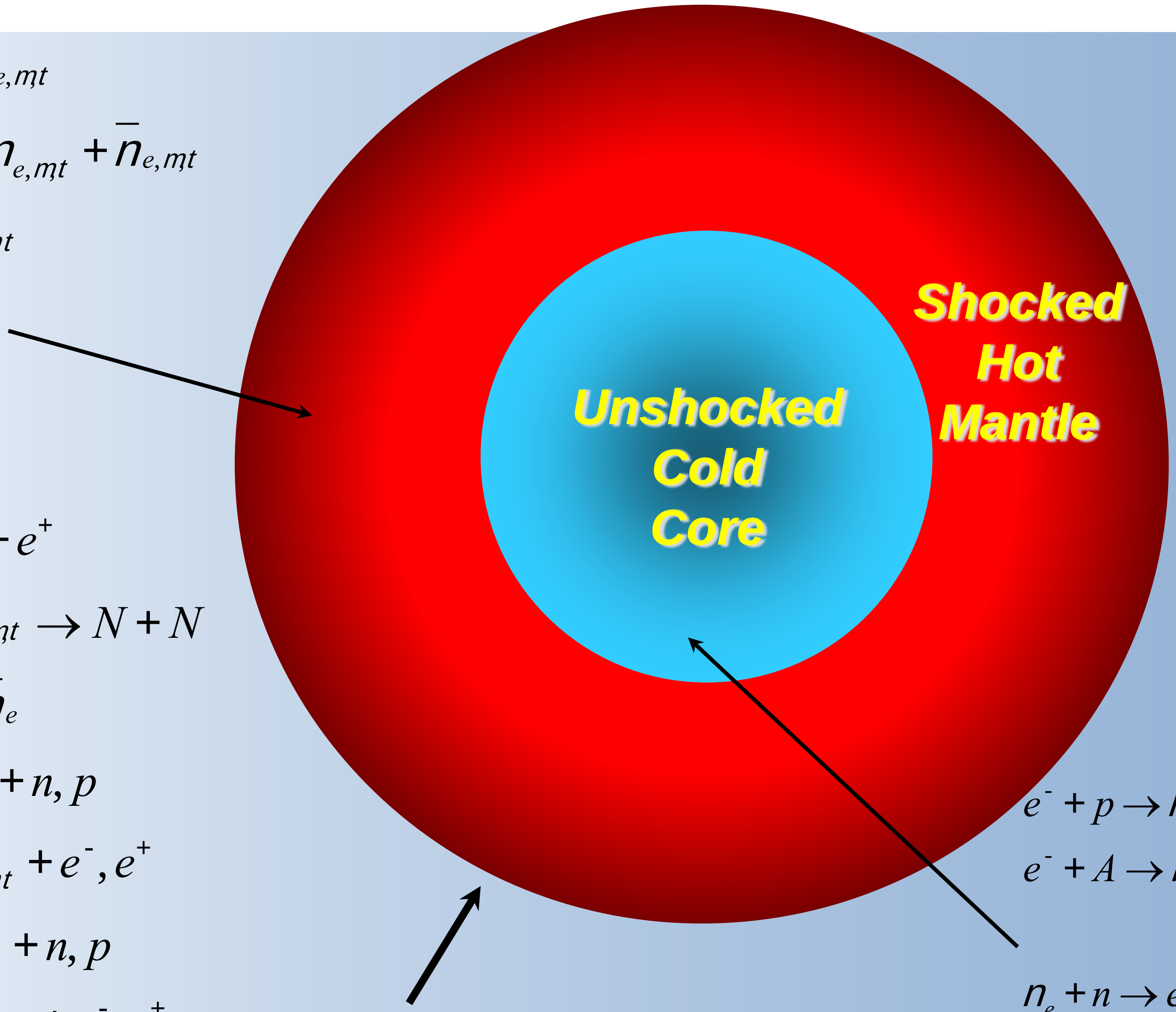
$n_{mt} + \overline{n}_{mt} \rightarrow n_e + \overline{n}_e$

$v_{e,mt} + n, p \rightarrow v_{e,mt} + n, p$

$v_{e,mt} + e^-, e^+ \rightarrow v_{e,mt} + e^-, e^+$

$\overline{n}_{e,mt} + n, p \rightarrow \overline{n}_{e,mt} + n, p$

$\overline{n}_{e,mt} + e^-, e^+ \rightarrow \overline{n}_{e,mt} + e^-, e^+$



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

$e^- + A \rightarrow n_e + A'$

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

$n_e + A' \rightarrow e^- + A$

$v_e + n, p, A \rightarrow v_e + n, p, A$

$v_e + e^- \rightarrow v_e + e^-$

8 key weak interactions

Weak interactions are ignored or approximated for computational expediency.

Important Neutrino Emissivities/Opacities

"Standard" Emissivities/Opacities

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

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

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)

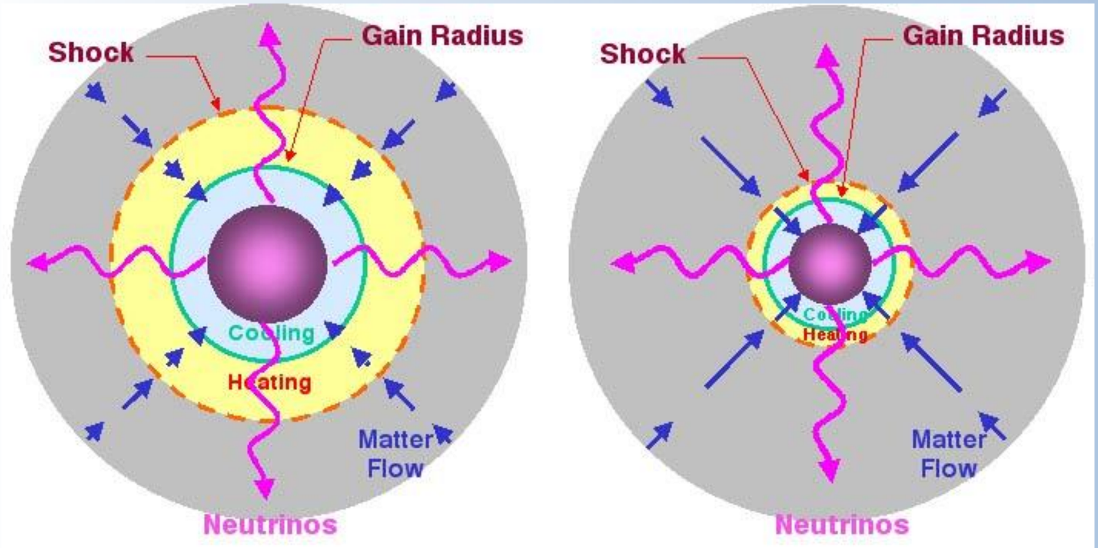
"Partial Weak Physics": Bruenn (1985)
- *Weak interactions above black line sans added realism noted in red.*
- *Sans weak interactions below black line.*

Newtonian vs. GR

25 M Model

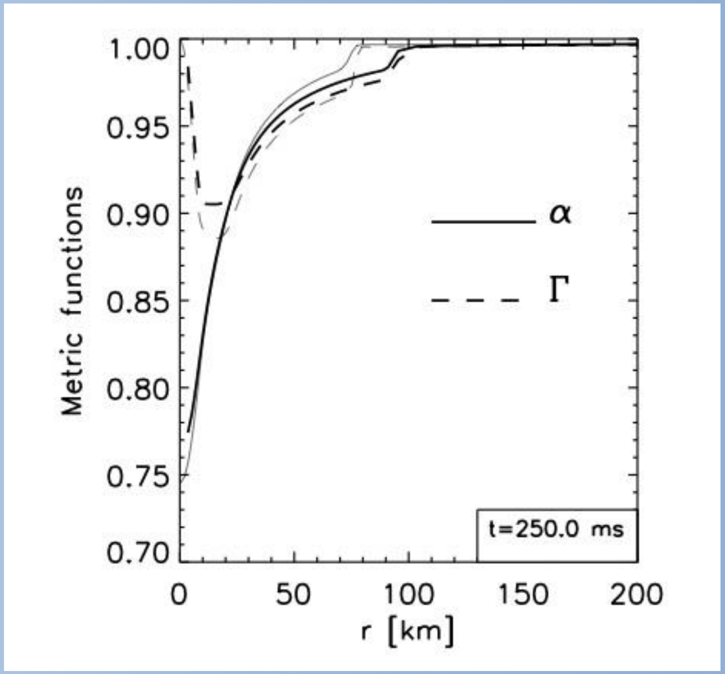
15 M Model

$$ds^2 = -\alpha^2 dt^2 + \left(\frac{r'}{\Gamma}\right)^2 da^2 + r^2\left(d\theta^2 + \sin^2\theta\, d\varphi^2\right)$$



Newtonian

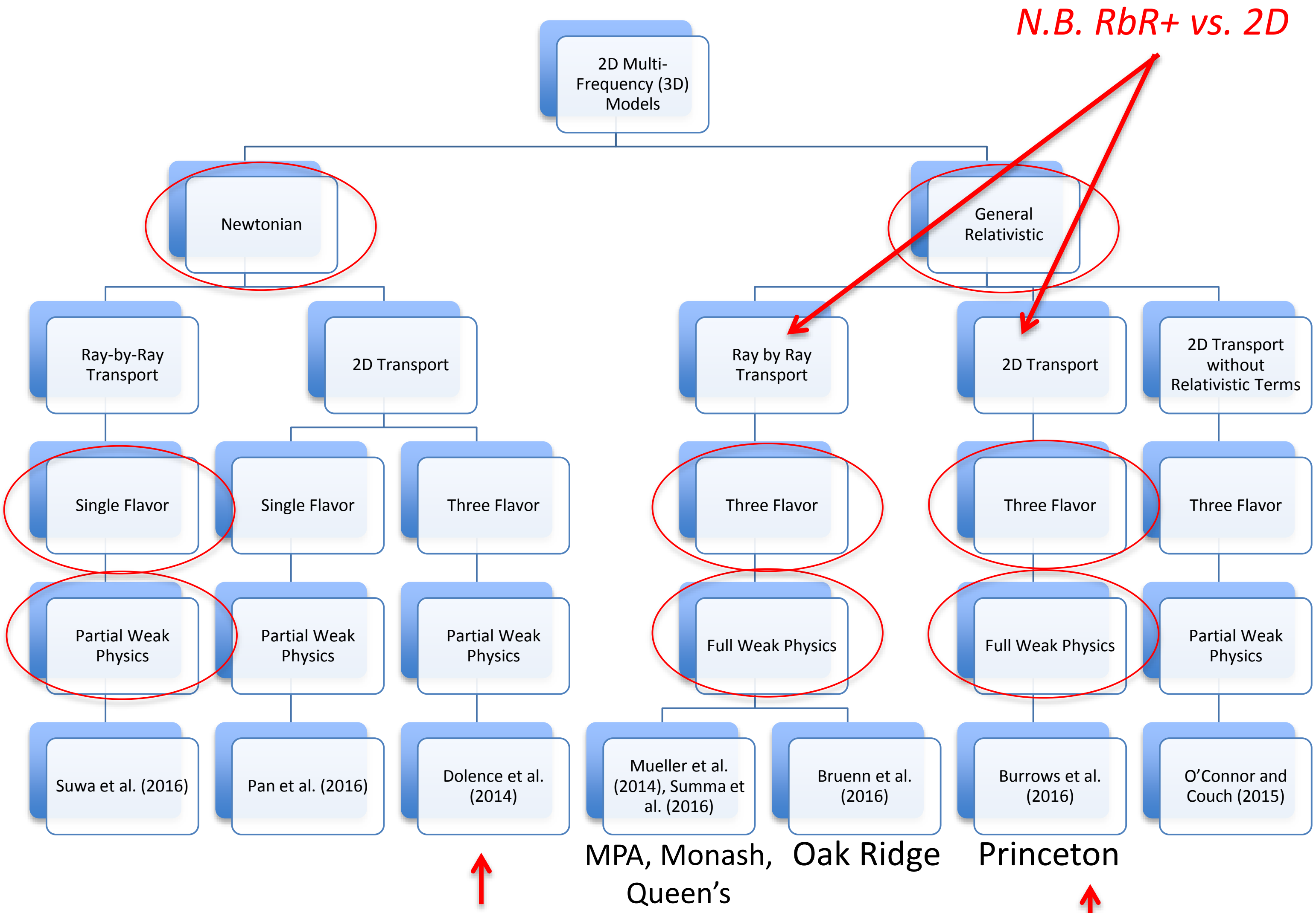
GR



Bruenn, DeNisco, and Mezzacappa, *Ap.J.* **560**, 326 (2001)
Liebendoerfer et al. *Ap.J.* **620**, 840 (2005)

The above outcomes demonstrate the need for general relativistic gravity.

Grand Scheme of Things (2D)



N.B. RbR+ vs. 2D

- 2D Multi-Frequency (3D) Models
  - Newtonian
    - Ray-by-Ray Transport
      - Single Flavor
        - Partial Weak Physics
          - Suwa et al. (2016)
    - 2D Transport
      - Single Flavor
        - Partial Weak Physics
          - Pan et al. (2016)
      - Three Flavor
        - Partial Weak Physics
          - Dolence et al. (2014)
  - General Relativistic
    - Ray by Ray Transport
      - Three Flavor
        - Full Weak Physics
          - Mueller et al. (2014), Summa et al. (2016)
          - Bruenn et al. (2016)
    - 2D Transport
      - Three Flavor
        - Full Weak Physics
          - Burrows et al. (2016)
    - 2D Transport without Relativistic Terms
      - Three Flavor
        - Partial Weak Physics
          - O'Connor and Couch (2015)

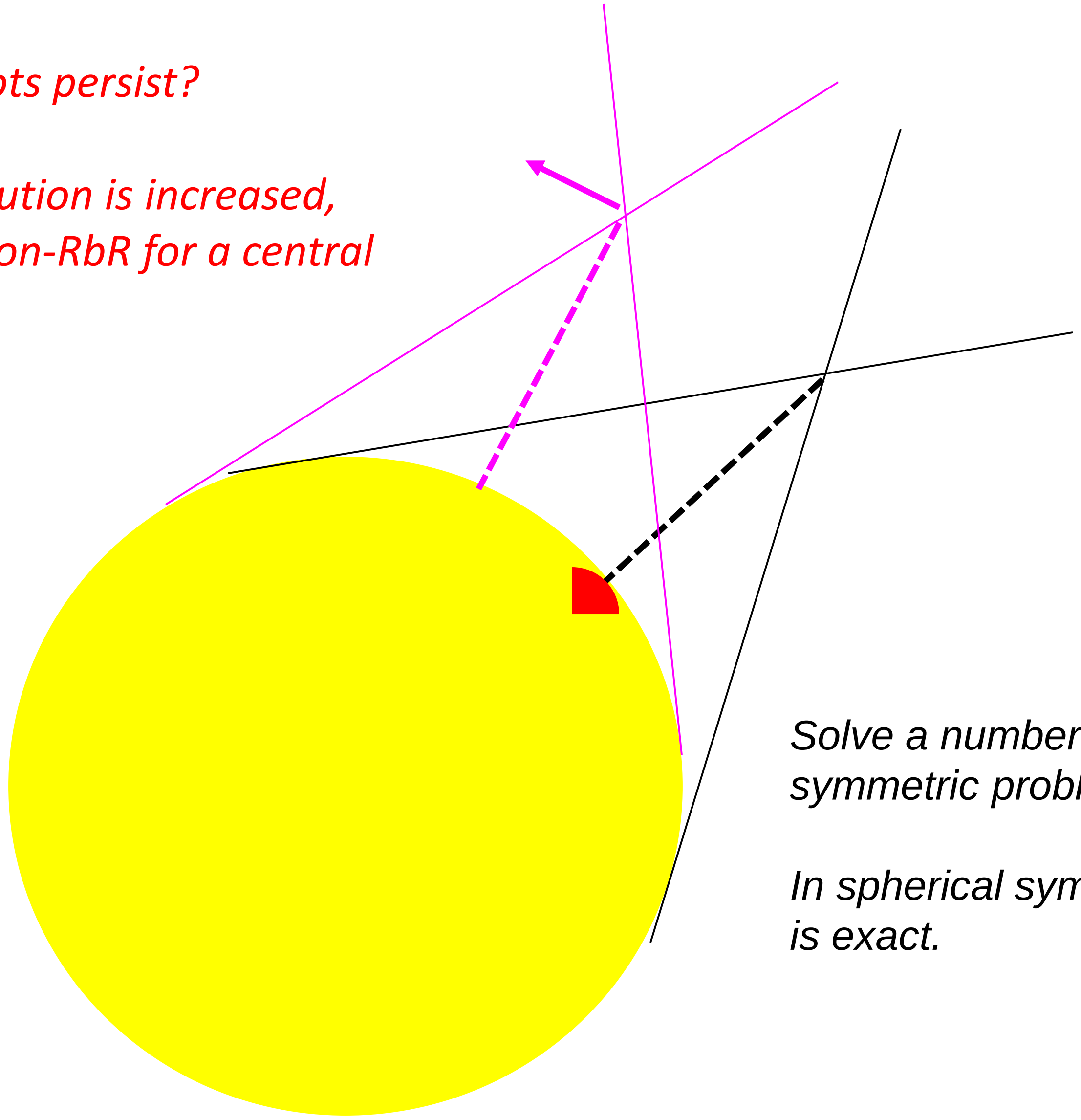
MPA, Monash, Queen's

Oak Ridge

Princeton

The Princeton group obtained no explosions with Newtonian gravity and partial weak interaction physics. With GR included and a full weak interaction set, like MPA and Oak Ridge they now obtain explosions.

Ray-by-Ray Approximation



Do accretion hot spots persist?

As the angular resolution is increased, RbR will approach non-RbR for a central source.

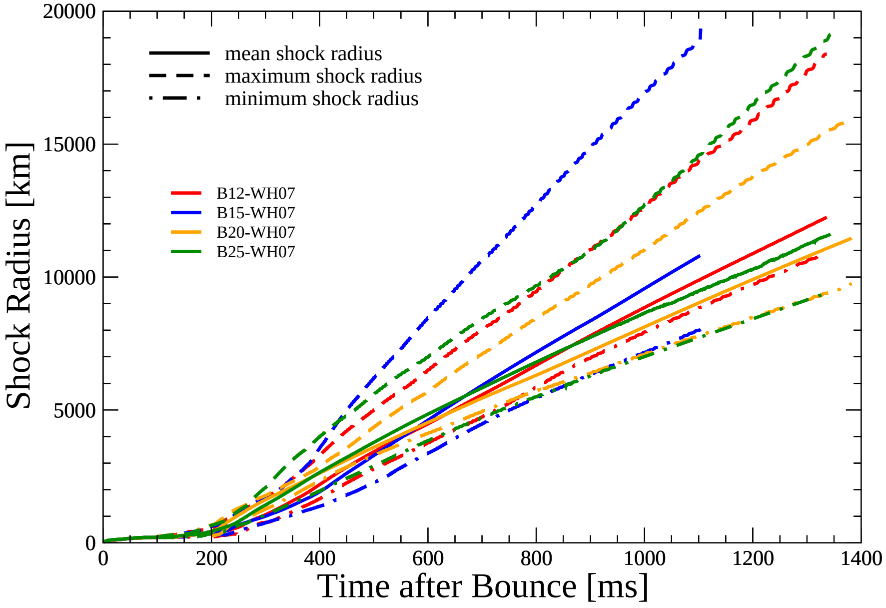
Solve a number of spherically symmetric problems.

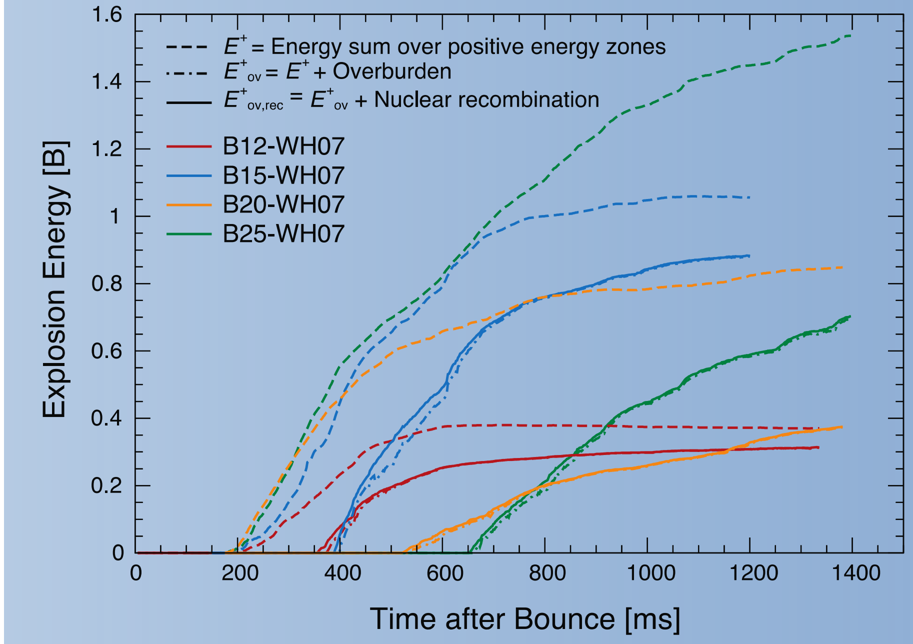
In spherical symmetry, RbR is exact.

The “Oak Ridge” Models

Bruenn et al. 2016. *Ap.J.* **818**, 123.

Oak Ridge 2D Models

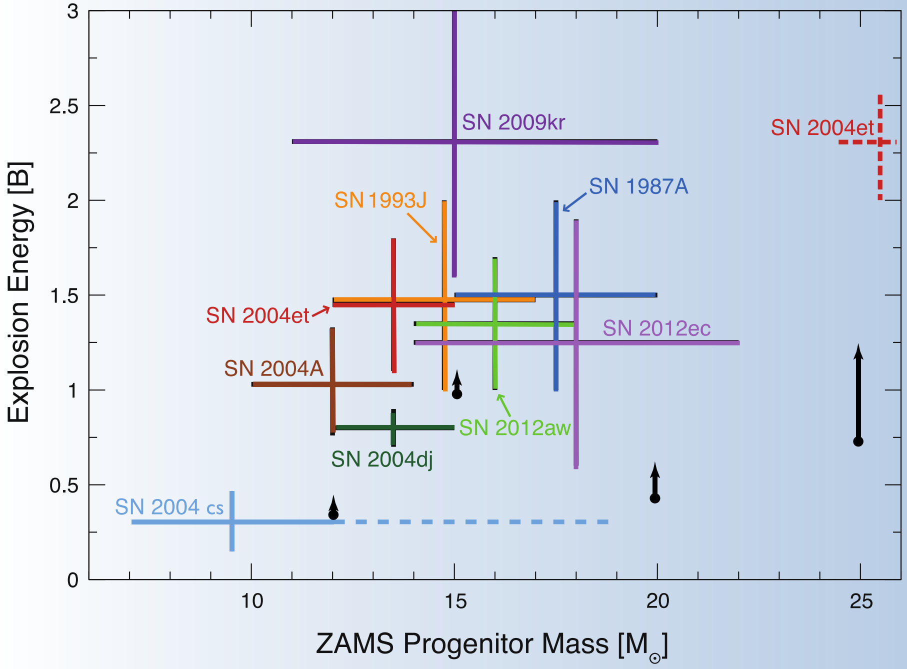


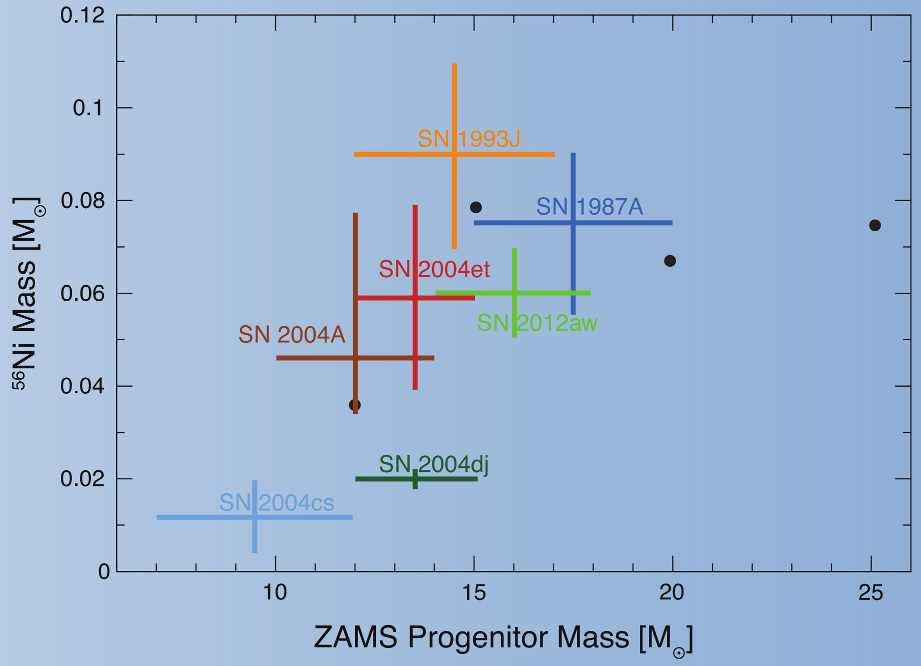


Bruenn et al. 2013. *Ap.J.* **767**, L6.
Bruenn et al. 2016. *Ap.J.* **818**, 123.

Simulations must be carried out to 1-2 s after core bounce before explosion energies defined.

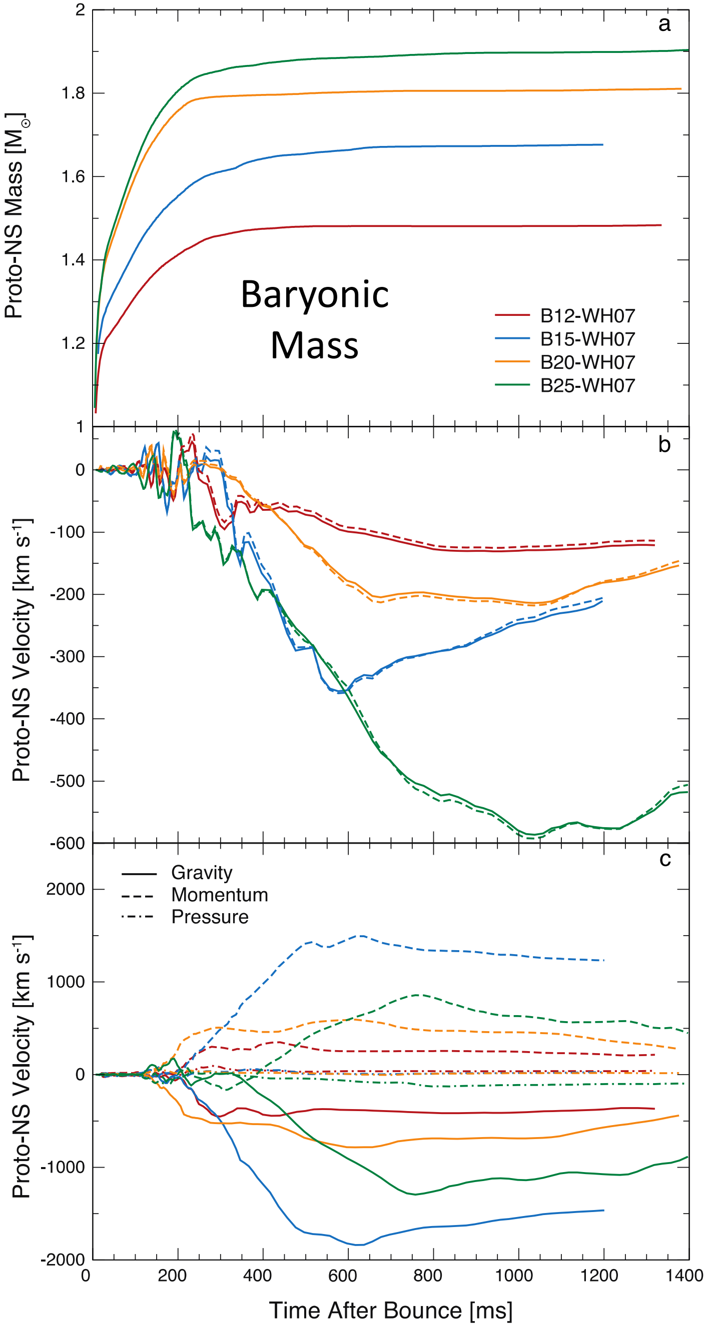
Comparison with Observations



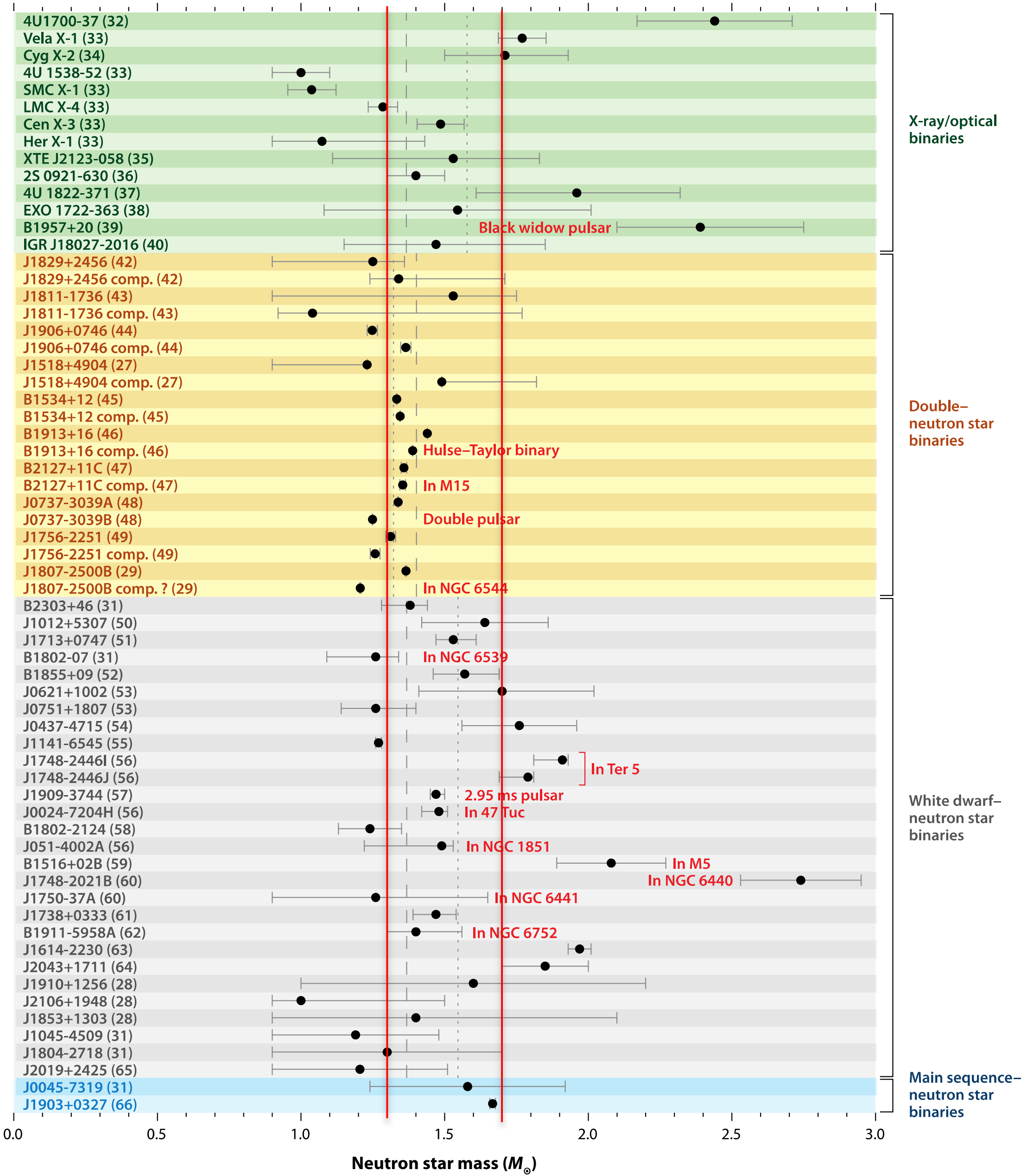


Bruenn et al. 2016. *Ap.J.* **818**, 123

Explosion energies and nickel production in reasonable agreement with observations.



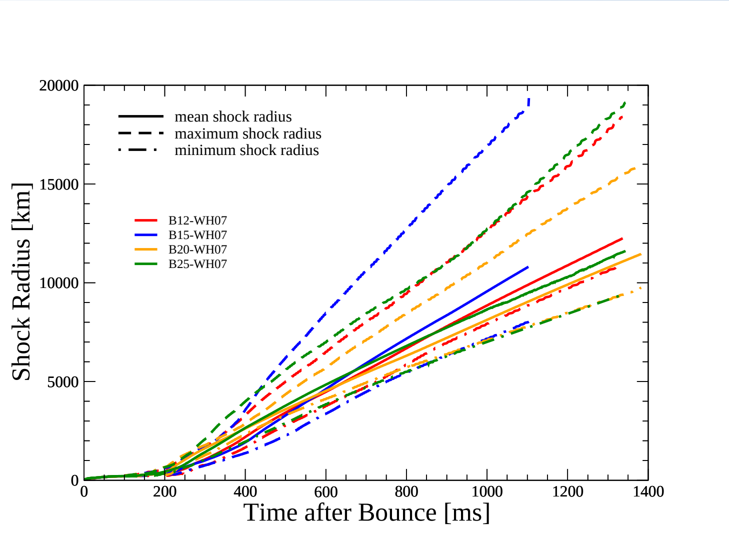
Bruenn et al. 2016. *Ap.J.* **818**, 123.



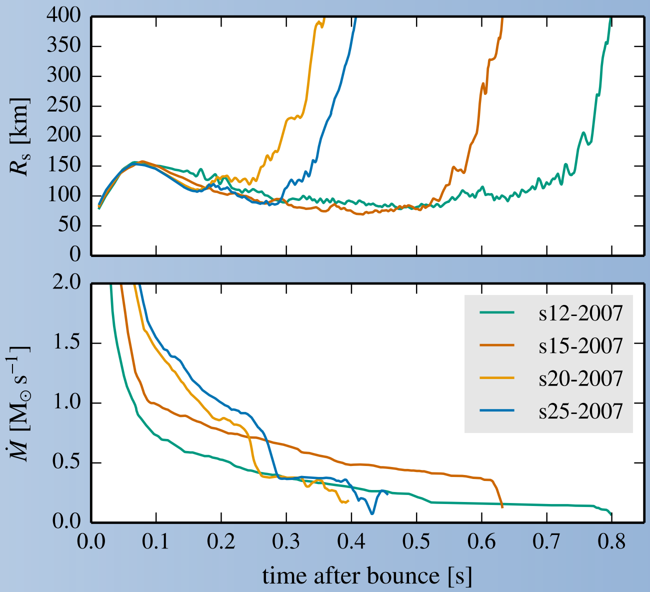
Lattimer, ARNPS **62**, 485 (2012)

Predicted neutron star gravitational masses are within the range delineated by the vertical lines.

Comparing Oak Ridge and MPA Models



Shock expansion occurs at similar post-bounce times.

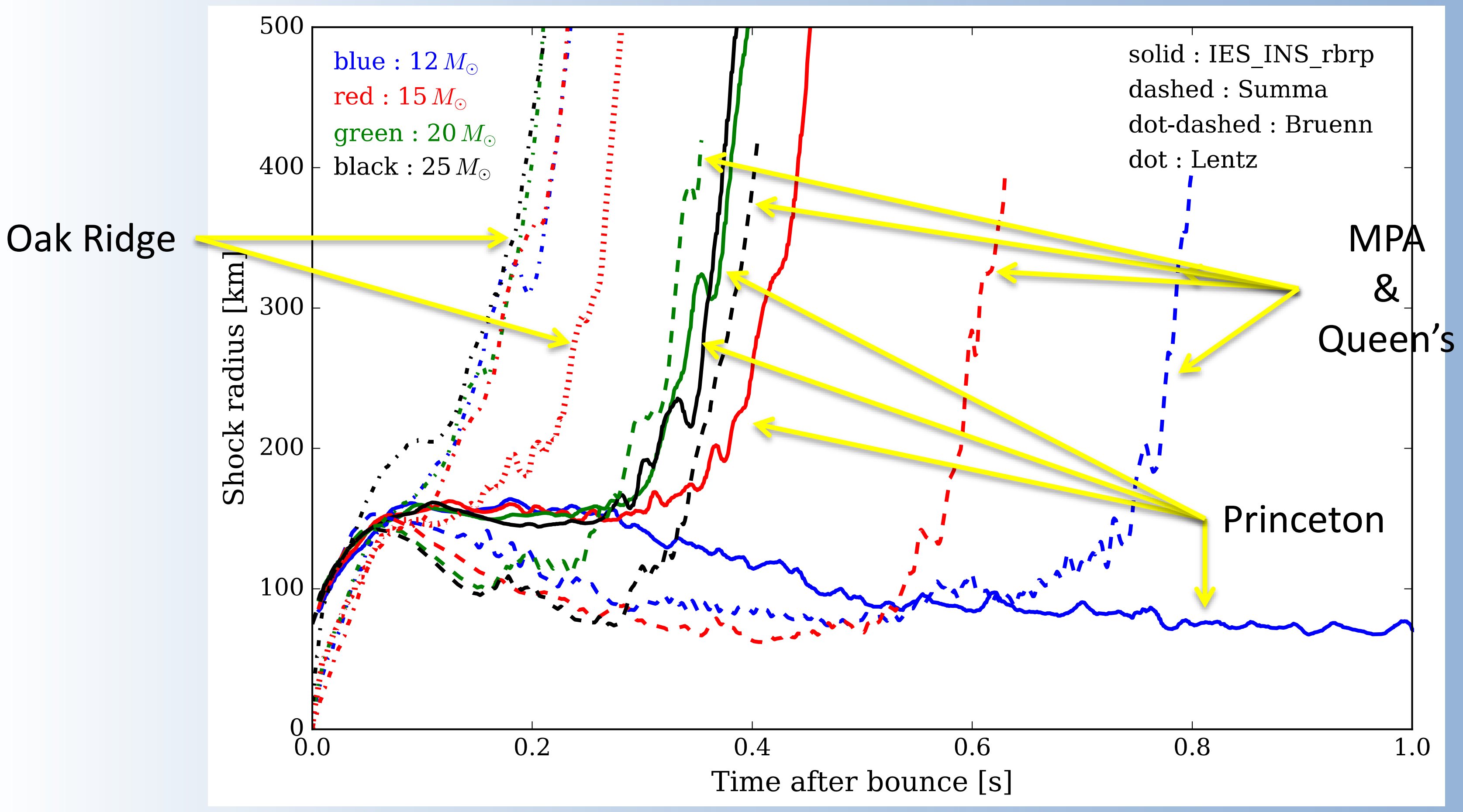


Summa et al. 2016 *Ap.J.* **825**, 6

Shock expansion occurs at Si/O interface for all models.

Comparing Oak Ridge, MPA, and Princeton Models

Burrows et al. 2016 arXiv 1611.0589v1



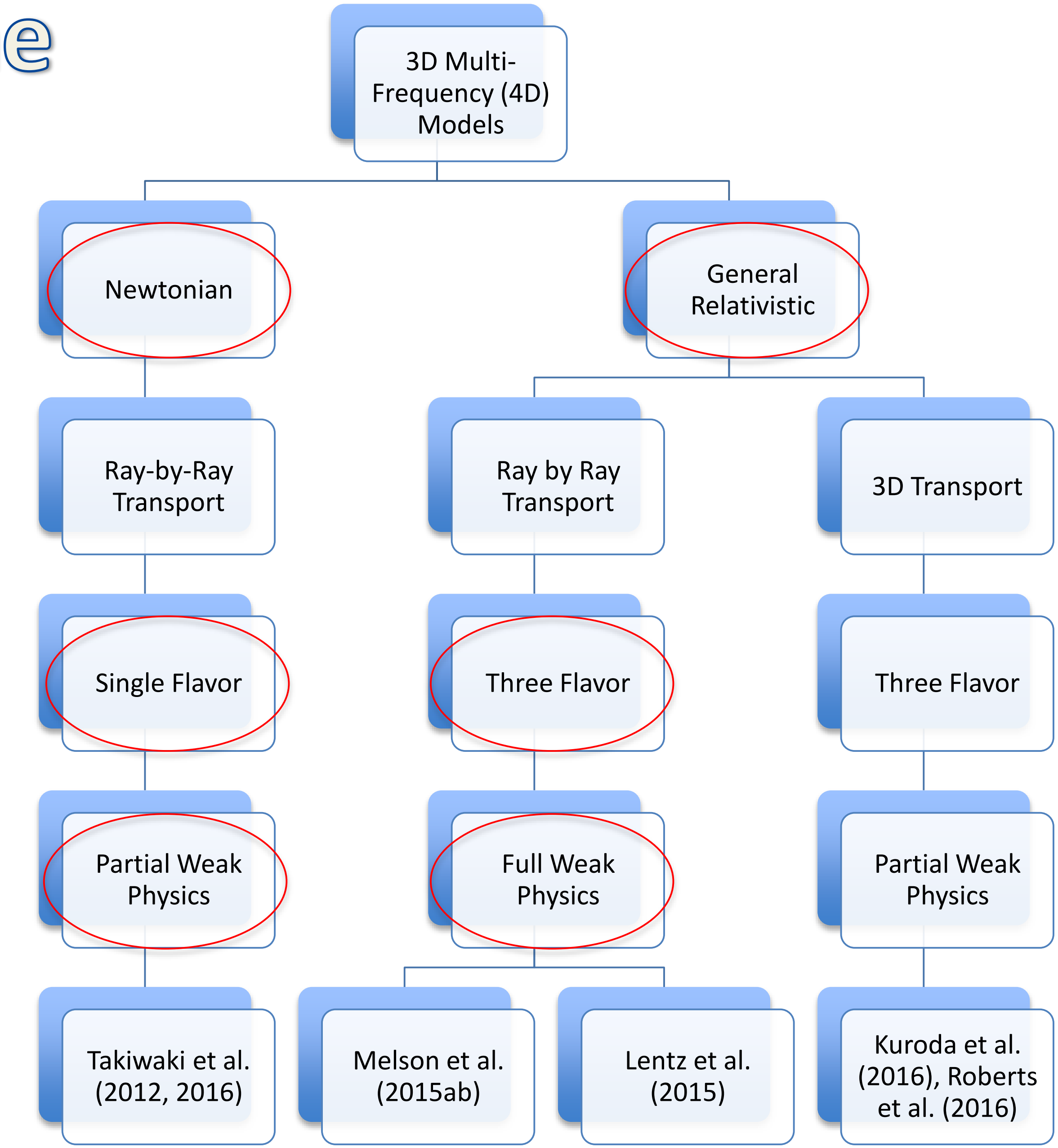
Oak Ridge

MPA & Queen's

Princeton

All 3 groups obtain explosions across the same progenitor set. Task now is to compare outcomes quantitatively. Will require that all simulations be carried out to 1-2 s after bounce (only Oak Ridge models have run that long). Explosion times vary. Explosion energies will vary. Variation in part likely due to the different "closures" used in the neutrino moment equations.

Grand Scheme of Things (3D)



3D Multi-Frequency (4D) Models

Newtonian

General Relativistic

Ray-by-Ray Transport

Ray by Ray Transport

3D Transport

Single Flavor

Three Flavor

Three Flavor

Partial Weak Physics

Full Weak Physics

Partial Weak Physics

Takiwaki et al. (2012, 2016)

Melson et al. (2015ab)

Lentz et al. (2015)

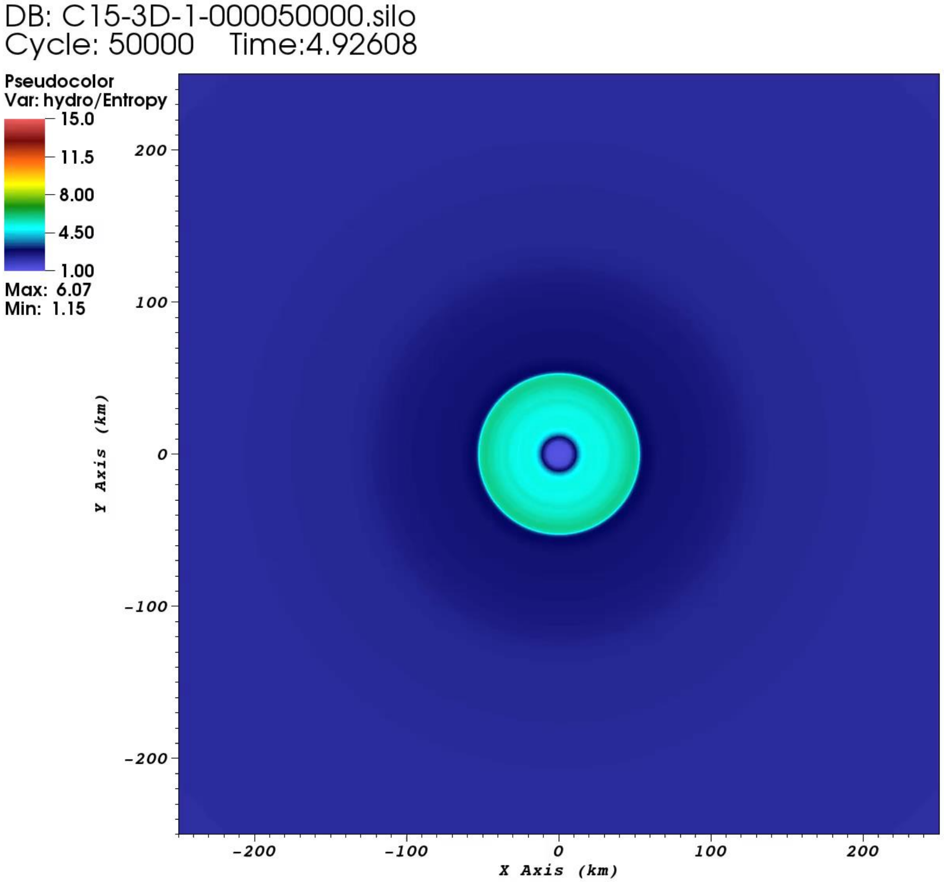
Kuroda et al. (2016), Roberts et al. (2016)

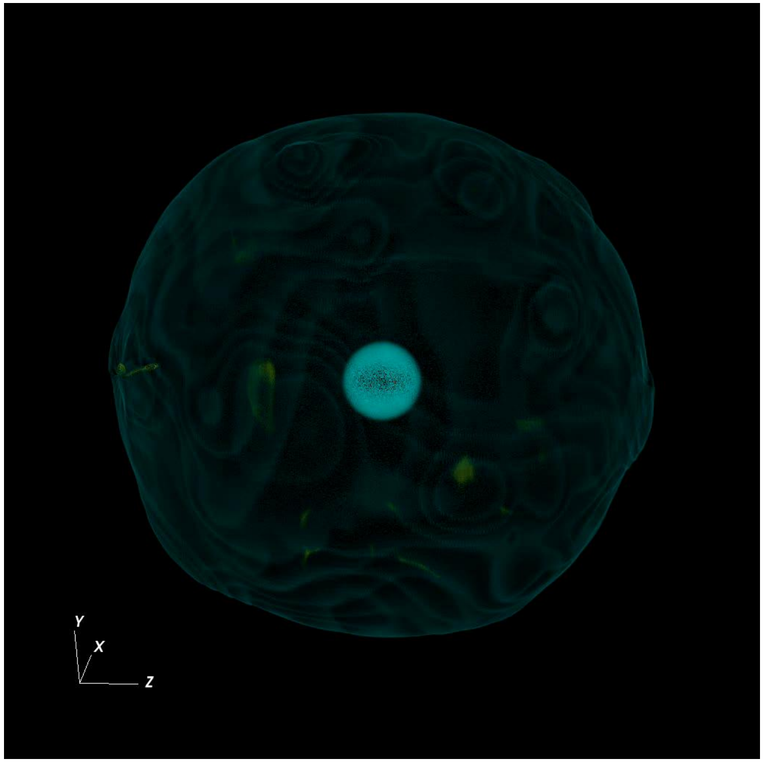
MPA, Monash

Oak Ridge

15 M
LS (220)

3D Counterpart Models



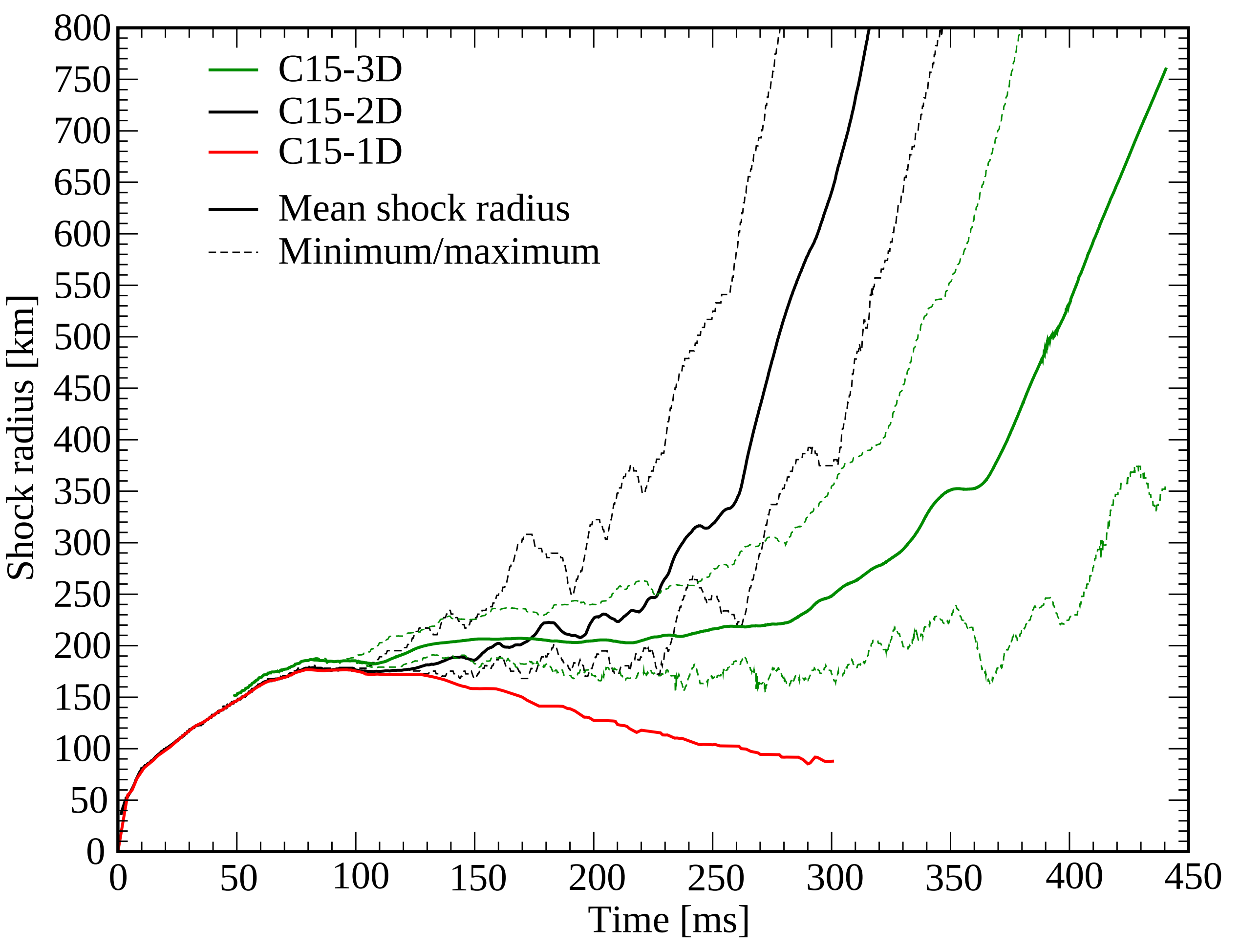


<u>Simulation Stats</u>

Lentz et al. 2015. *Ap.J. Lett.* **807**, L31.

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

Oak Ridge 3D Explosion Model

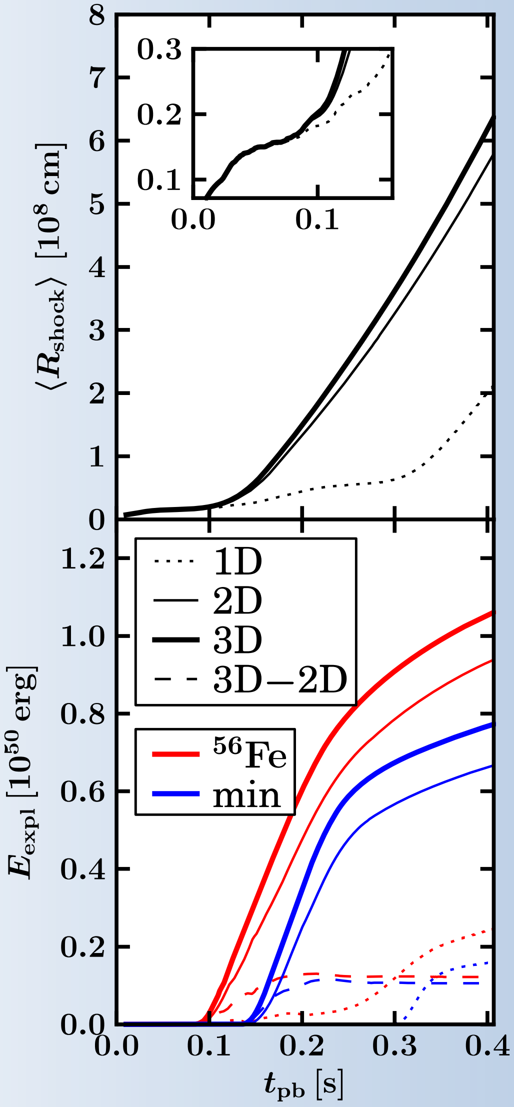


Lentz et al. 2015. *Ap.J. Lett.* **807**, L31.

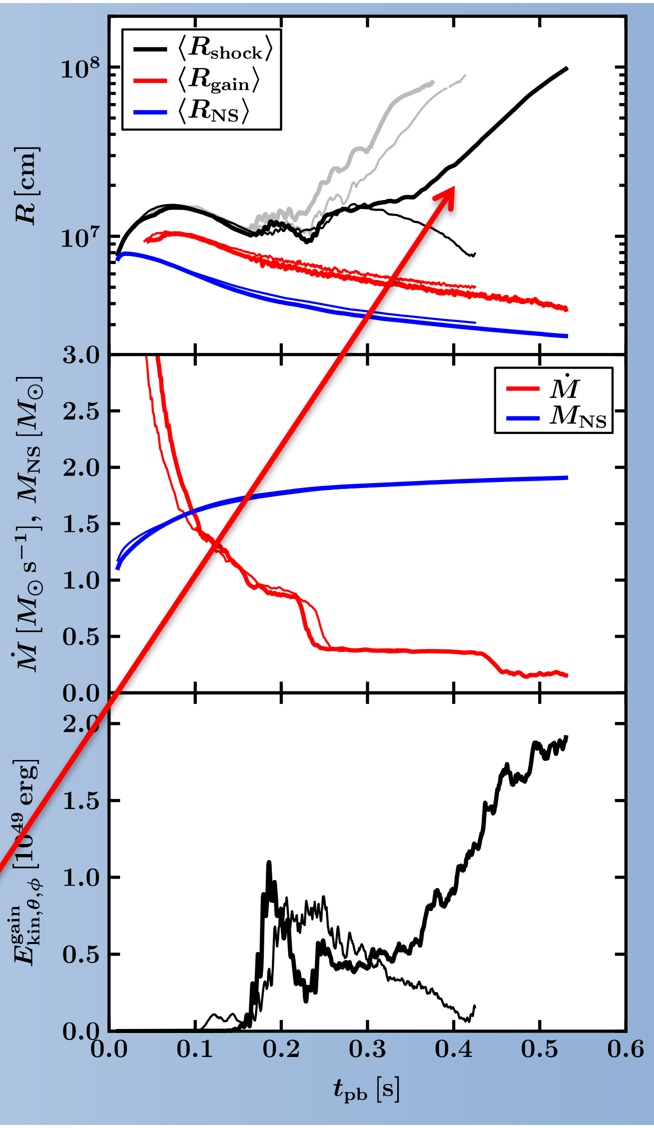
Explosion evident, but model must be run much longer to assess explosion energy and other observables.

MPA 3D Explosion Models

8.9 M



20 M



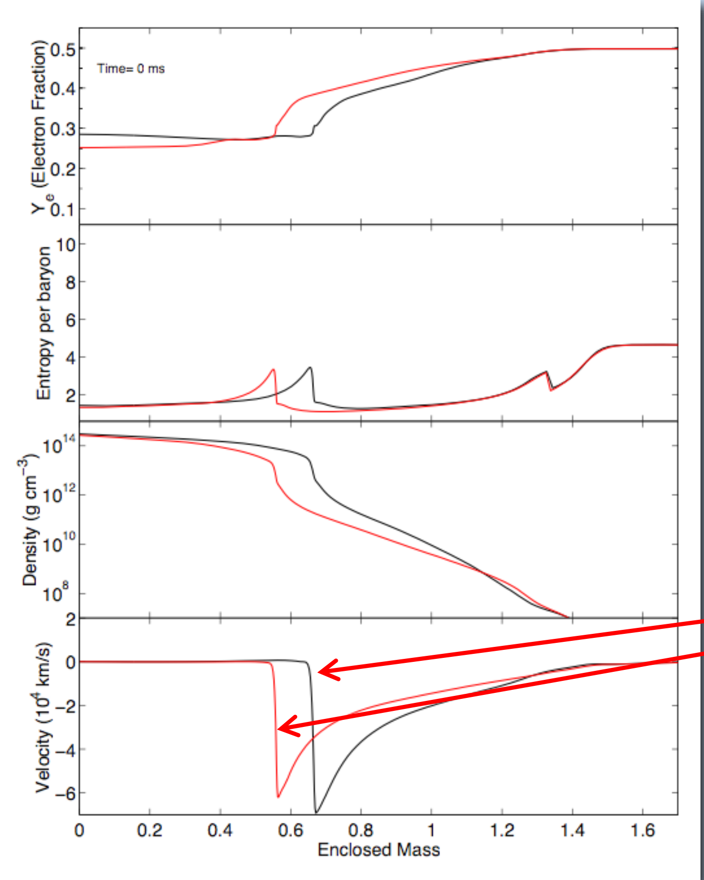
Melson et al. 2015a, *Ap.J. Lett*. **801**, L24.
Melson et al. 2015b, *Ap.J. Lett*. **808**, L42.

O(10%) reduction in axial vector coupling constant for neutrino-nucleon scattering leads to explosion in 3D for the WH07 20 Solar Mass model.

Sensitivity to Weak Interaction Cross Sections

Adding Known Physics

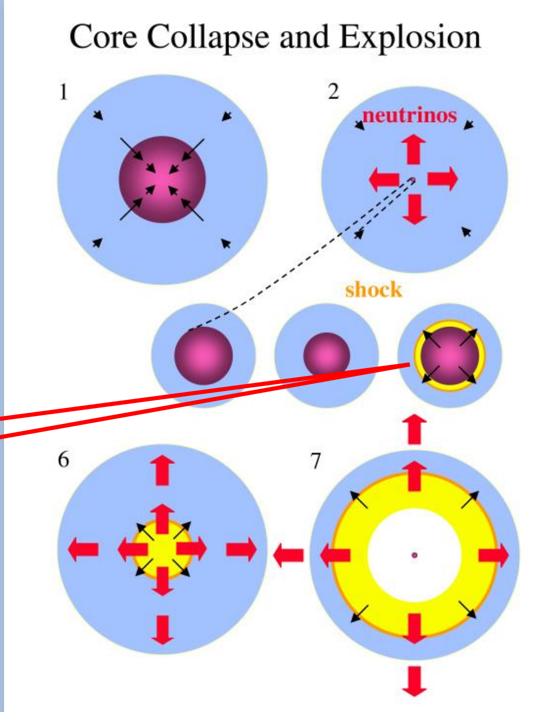
When Micro and Macro Worlds Collide



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

— No correlations.

— With correlations.

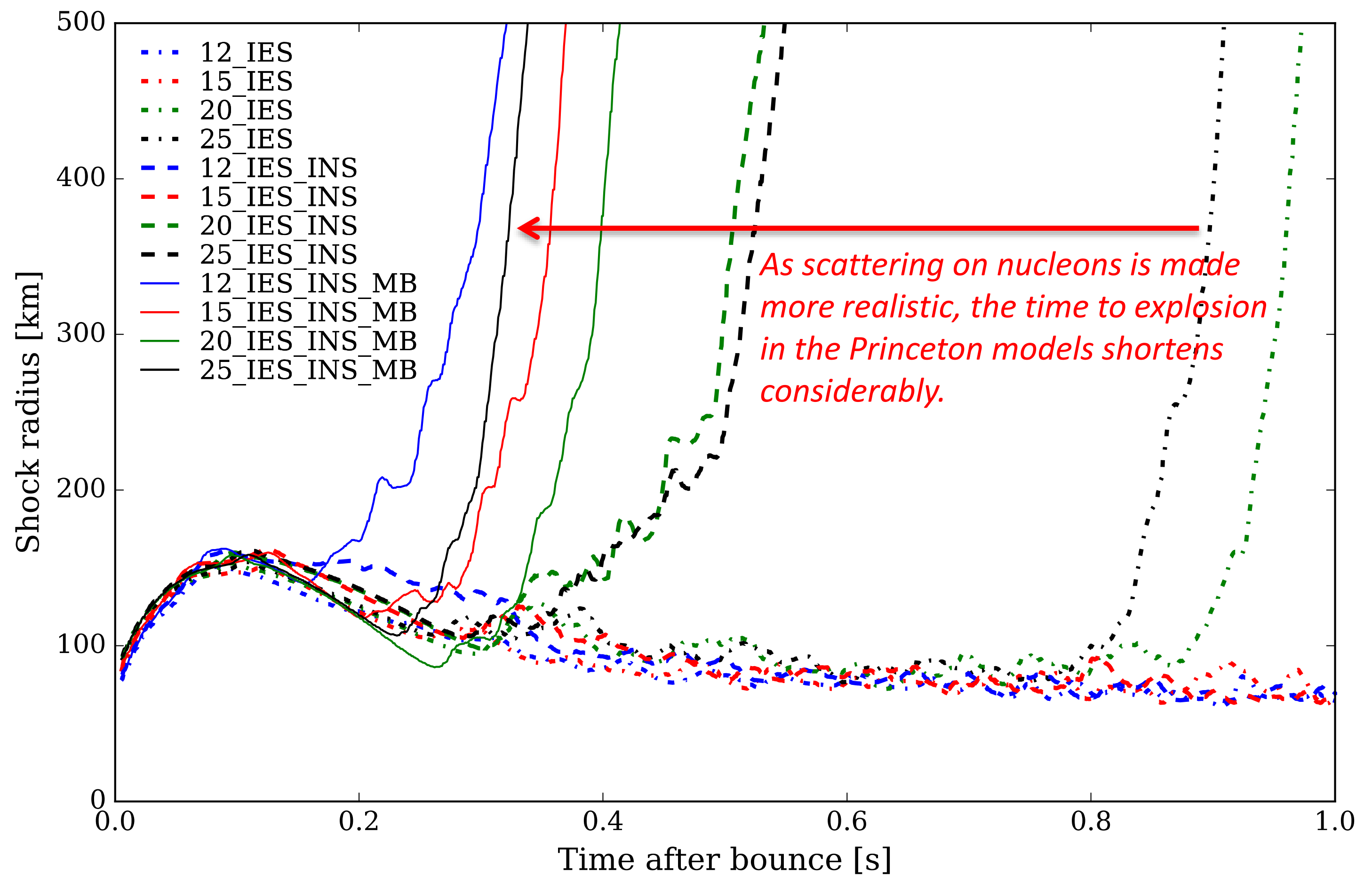


Significant change in shock formation mass.

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

When nucleon correlations are included in nuclear shell model, electron capture on nuclei and, hence, shock formation mass, are notably altered.

When Micro and Macro Worlds Collide

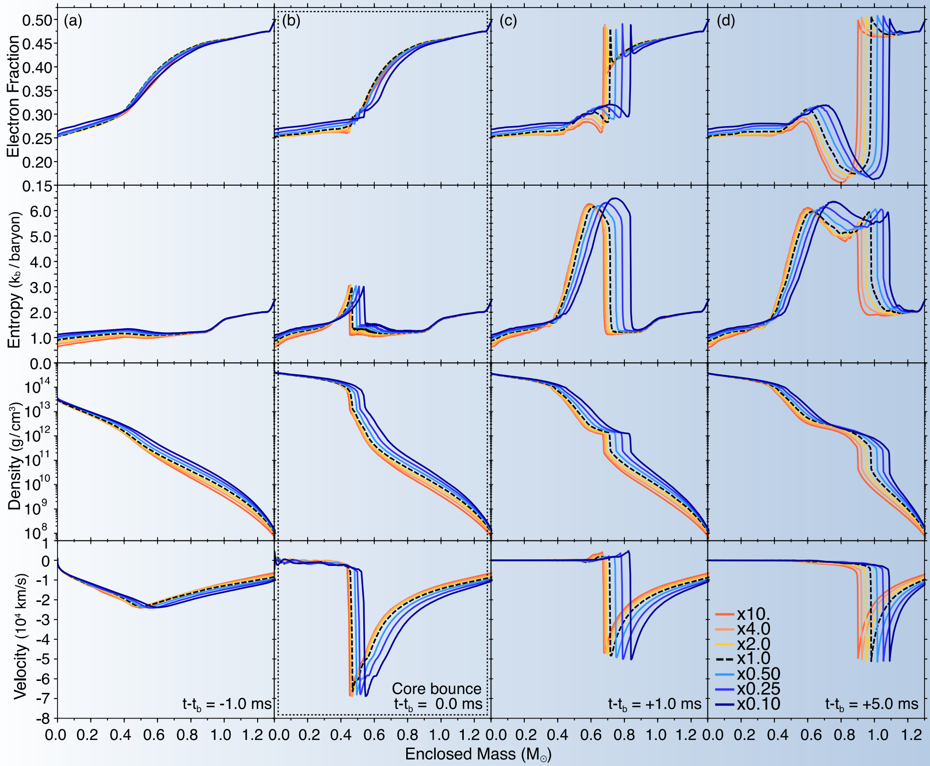


As scattering on nucleons is made more realistic, the time to explosion in the Princeton models shortens considerably.

Burrows et al. 2016 arXiv 1611.0589v1

Sensitivity to Uncertainty in the Cross Sections

When Micro and Macro Worlds Collide



Sullivan et al. *Ap.J.* **816**, 44 (2016)

Similar change in shock formation mass as cross section is varied within its range of uncertainty.

Neutrino Interaction Cross Section Uncertainties

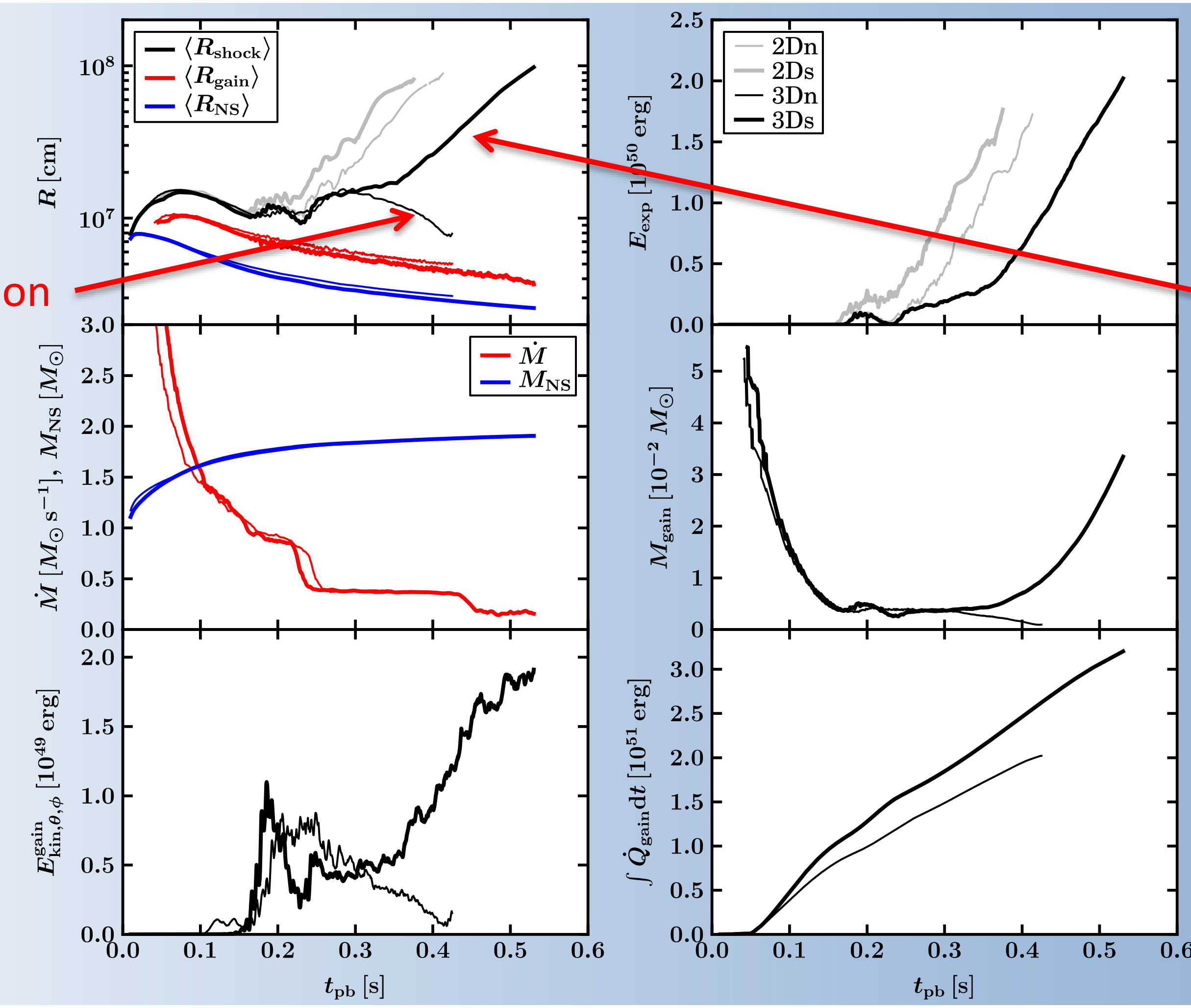
Sensitivity to Uncertainty in Electron Capture on Nuclei

See also (for other cross section studies):

- Bartl et al. PRL **113**, 081101 (2014)
- Rrapaj et al. PRC **91**, 035806 (2015)
- Shen and Reddy PRC **89**, 032802 (2014)

When Micro and Macro Worlds Collide

THE ASTROPHYSICAL JOURNAL LETTERS, 808:L42 (8pp), 2015 August 1 MELSON ET AL.



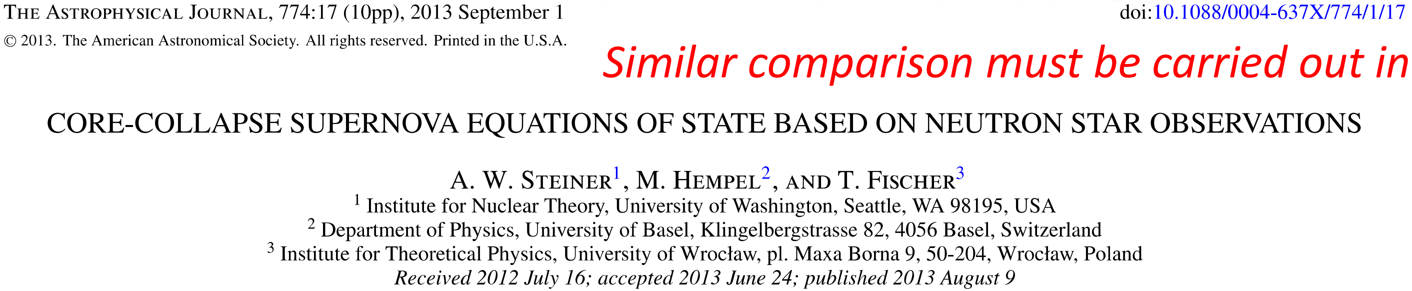
without correction

with correction

O(10%) reduction in axial vector coupling constant for neutrino-nucleon scattering leads to explosion in 3D for the WH07 20 Solar mass model.

Sensitivity to Nuclear Equation of State

When Micro and Macro Worlds Collide



The Astrophysical Journal, 774:17 (10pp), 2013 September 1
doi:10.1088/0004-637X/774/1/17

CORE-COLLAPSE SUPERNOVA EQUATIONS OF STATE BASED ON NEUTRON STAR OBSERVATIONS

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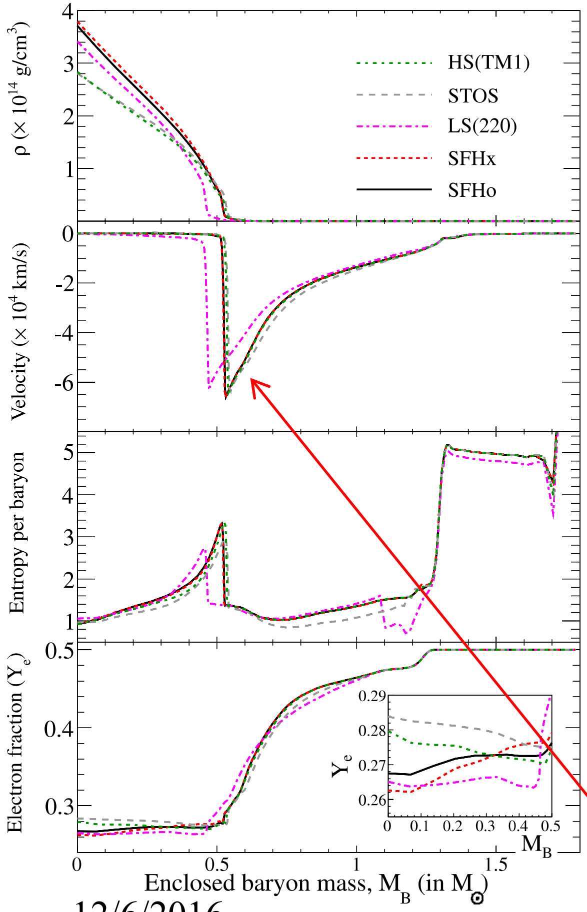
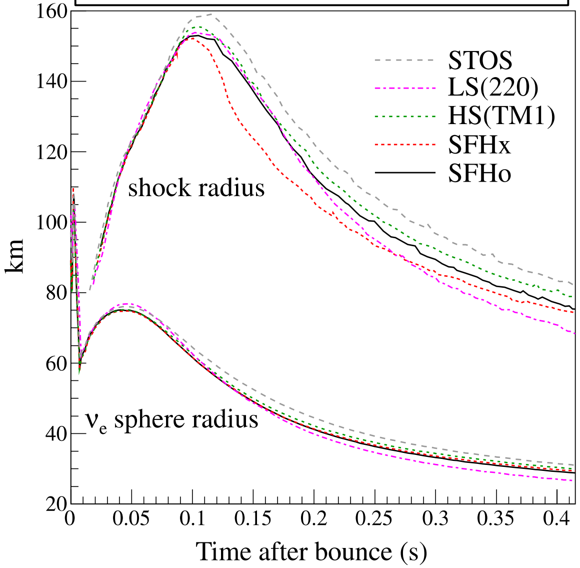
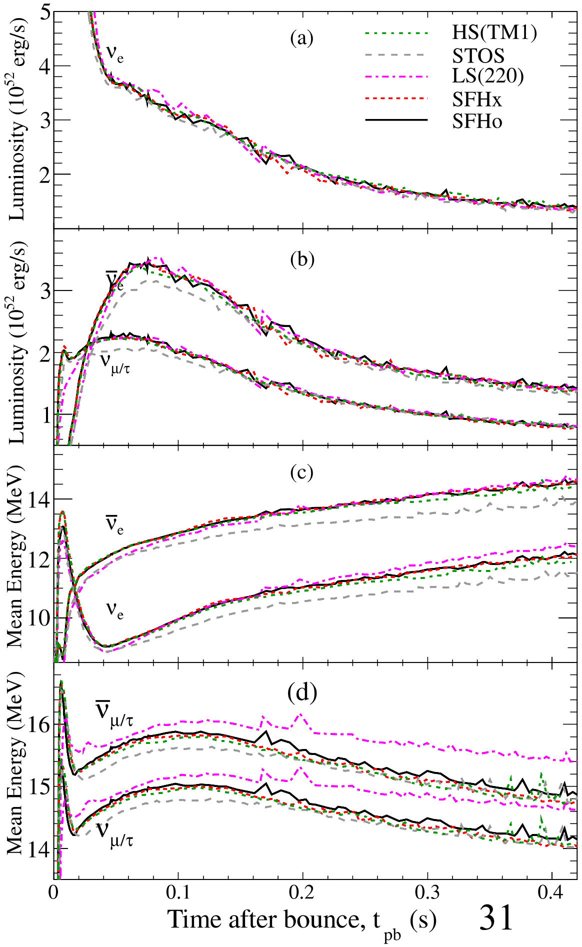
Similar comparison must be carried out in 2- and 3-D.

Shock dynamics does not vary much using different equations of state.





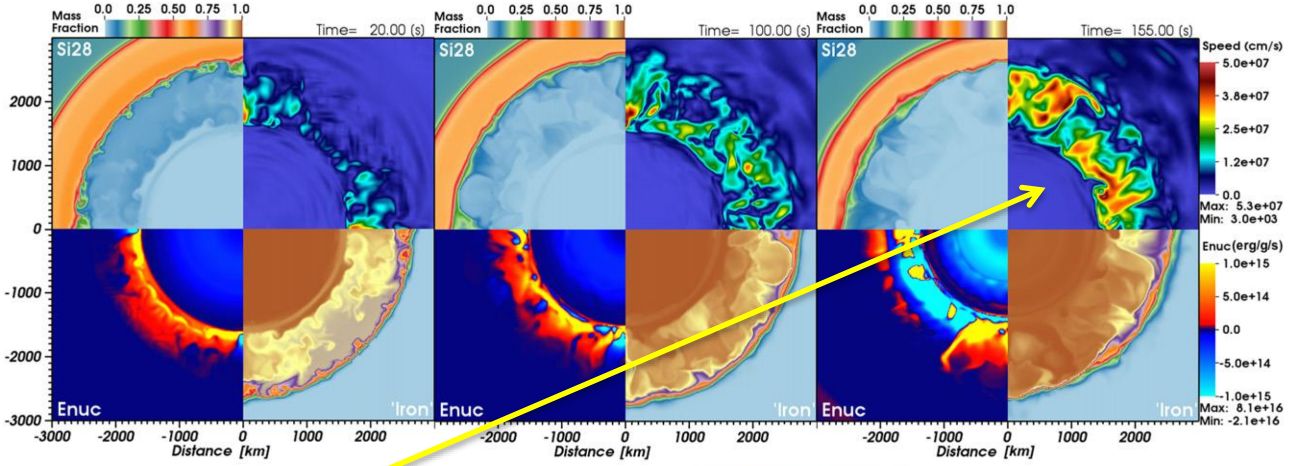


Comparable to the change we saw using an improved model for electron capture on nuclei.

A Look Ahead

3D Progenitors

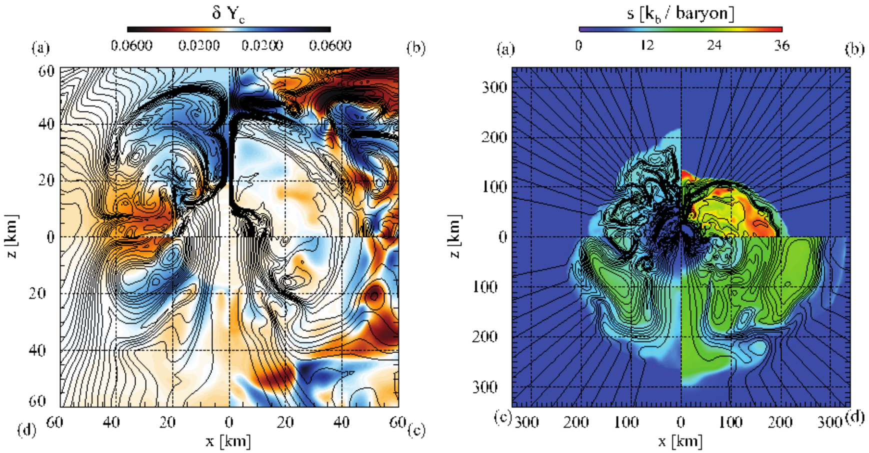
We've been using spherically symmetric progenitors for nearly 50 years!

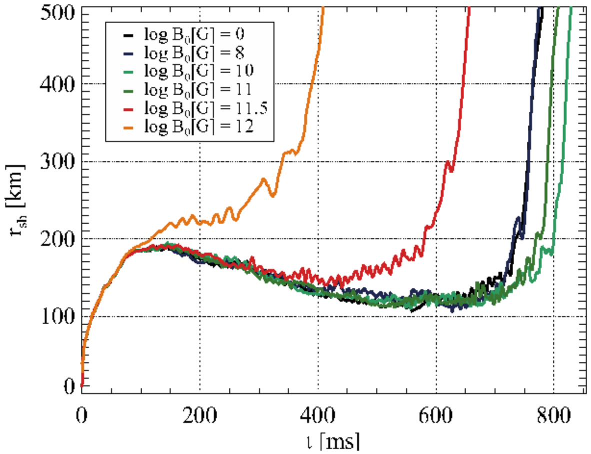


Couch et al. *Ap.J. Lett.* **808**, L21 (2015)
Mueller et al. arXiv: 1605.01393 (2016)

Silicon burning in 3D prior to core collapse results in significant deviations from spherical symmetry that impact the development of multi-D effects in the post-shock region.

Preview of Impact of Magnetic Fields





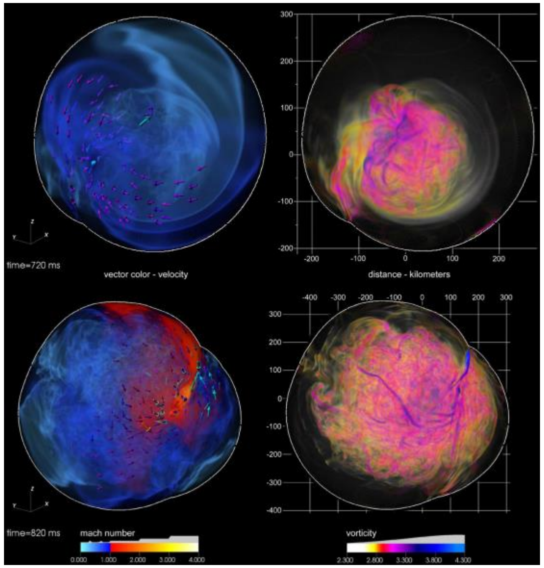
Obergaulinger et al. 2015, *ASP Conf. Ser.* **498**, *Proceedings of ASTRONUM 2014*.

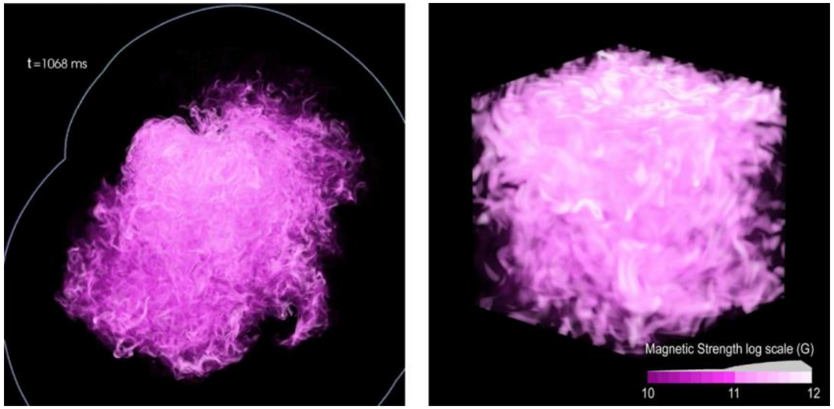
- *Magnetic fields stabilize high-entropy bubbles.*
- *High initial B fields are required to see significant quantitative changes.*

Is increase in B field in 2D case underestimated?

2D

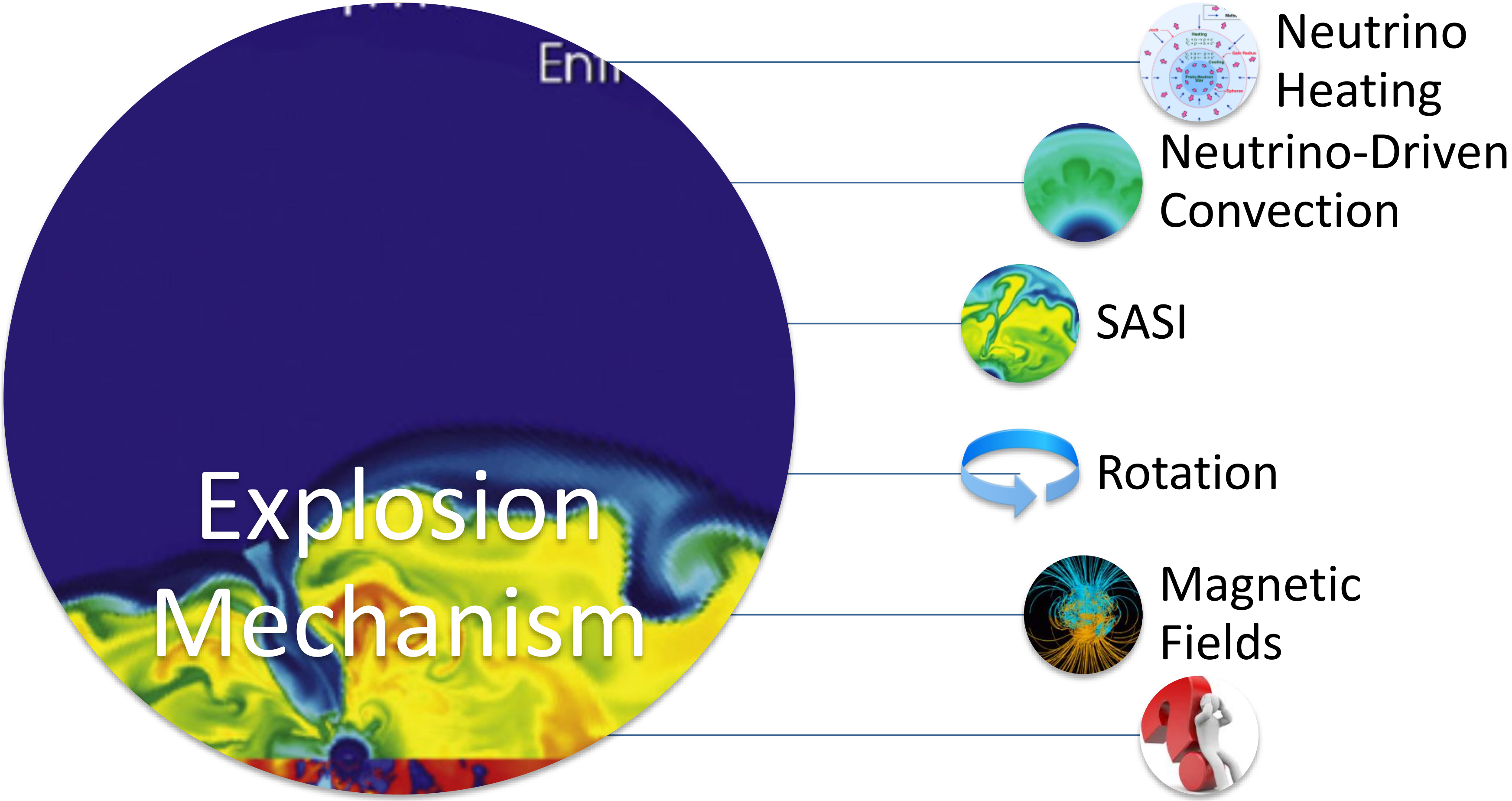
3D





Endeve et al. 2012 *Ap.J.* **751**, 26.

Initial magnetic field strength amplified by SASI-induced turbulence, to neutron star magnetic field strengths.



Explosion Mechanism

Neutrino Heating

Neutrino-Driven Convection

SASI

Rotation

Magnetic Fields

Progress to date in the context of 2D core collapse supernova simulations suggests that when the first five ingredients are included in multi-physics models, and when non-spherical progenitors are used, we may (in the context of 3D simulations) predict explosion energies and other quantities in good agreement with observations, across a range of initial conditions (e.g., progenitor mass) and across simulation groups.

Will 3D simulations bear this out? We have only a few ongoing multi-physics explosion models, but none have yet covered the full window of post-bounce time (~1-2 s), which will enable the community to make quantitative assessments regarding the explosion energies, etc.

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