Ascertaining the Core Collapse Supernova Explosion Mechanism: A Status Report

(with an eye toward predictions of neutrino signatures)

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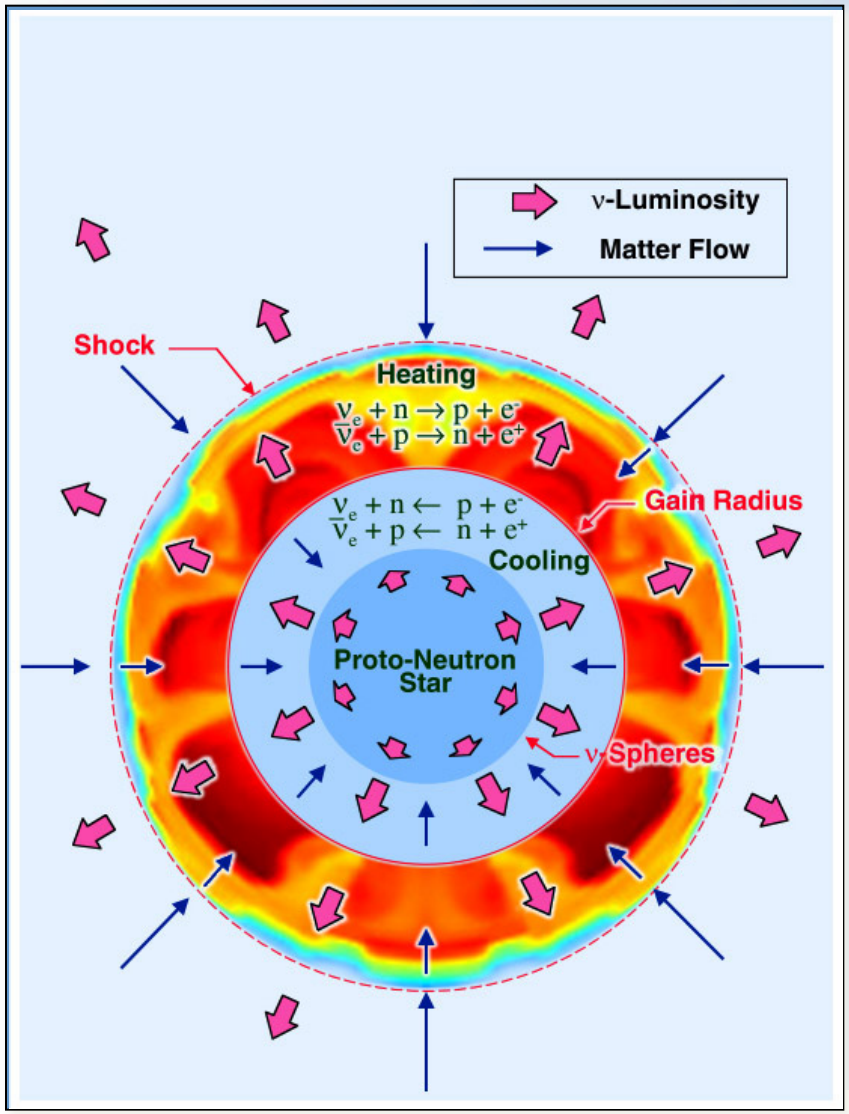
Elements of Neutrino Shock Reheating

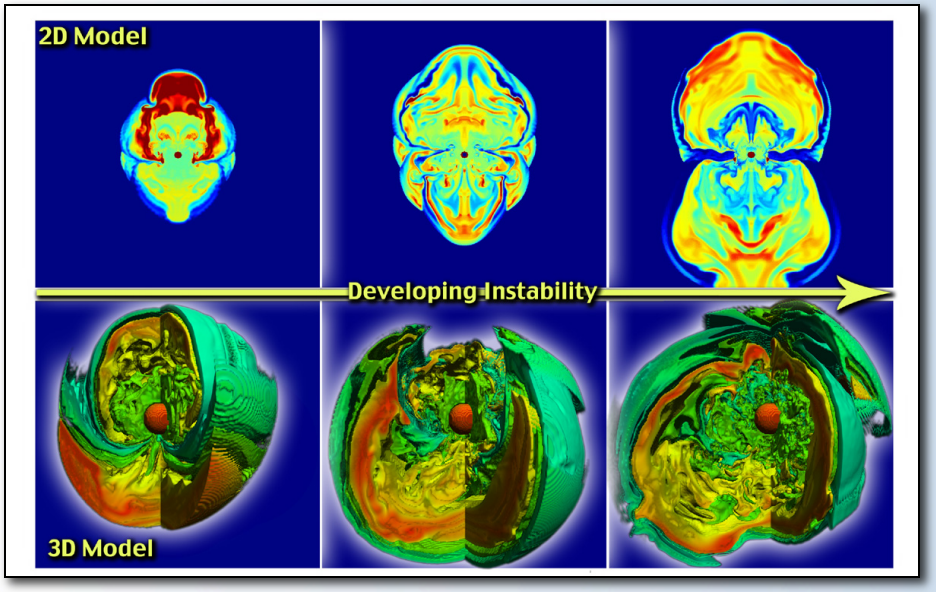


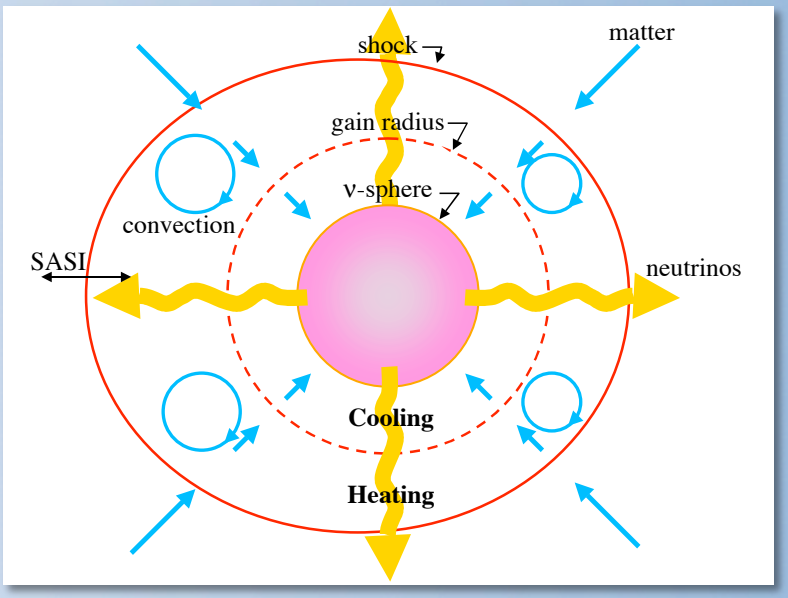
Fundamental Building Blocks

- Neutrino Heating
- Convection
- SASI

- Nuclear Burning
- Rotation
- Magnetic Fields

Stationary Accretion Shock Instability (SASI)





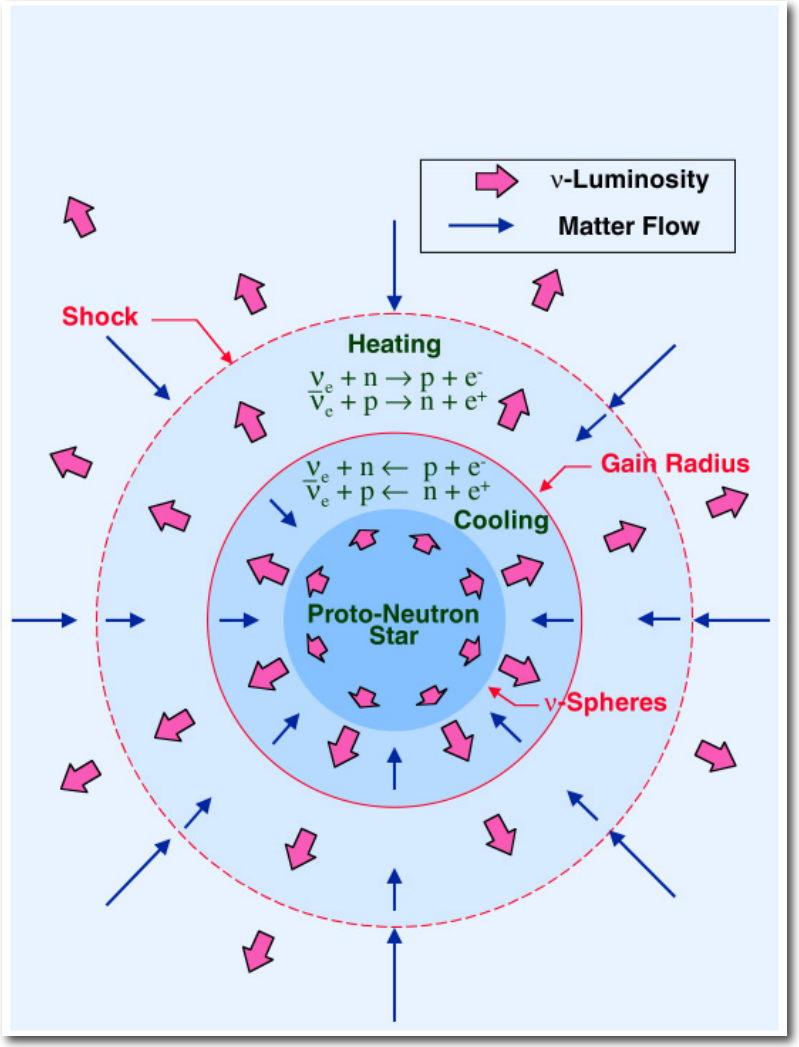
Blondin, Mezzacappa, & DeMarino, *Ap.J.* **584**, 971 (2003)

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

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.

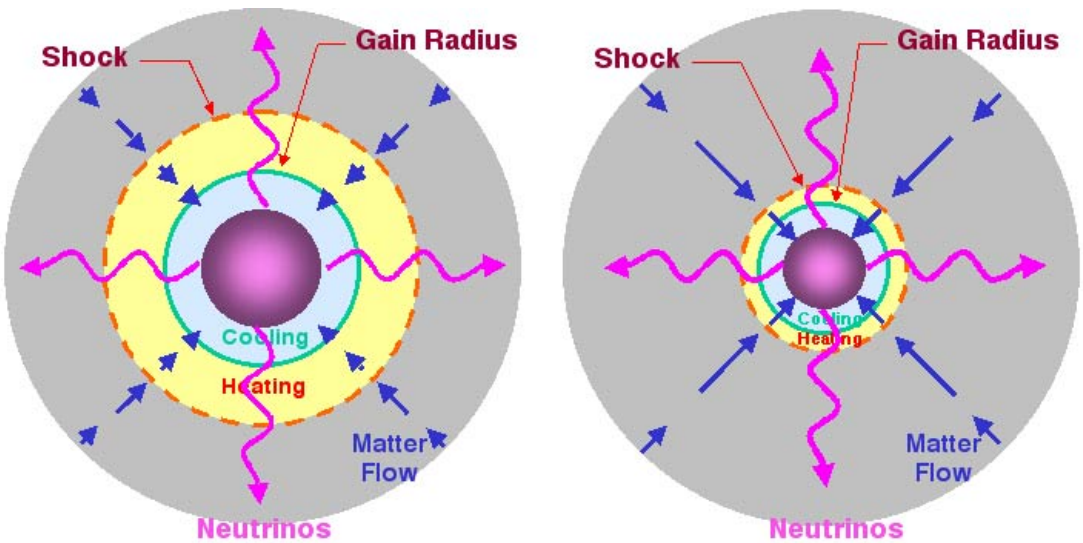
★ $N + N \leftrightarrow N + N + \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$

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

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)

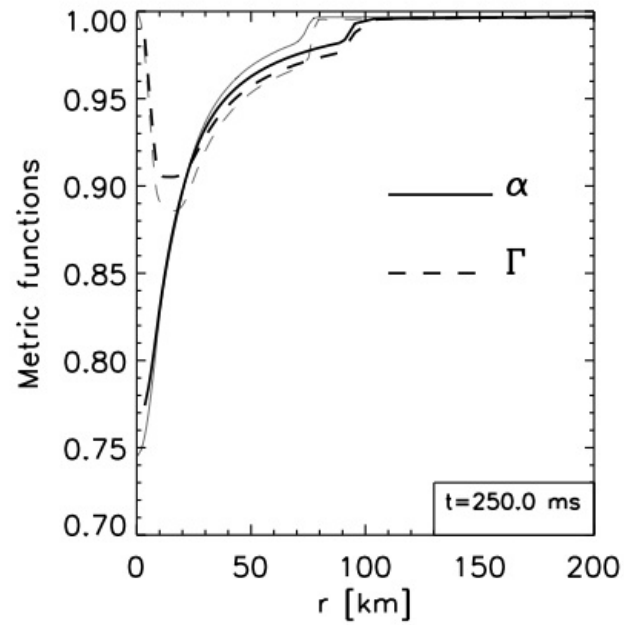
Newtonian versus GR



25 M Model

15 M Model

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



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

General Relativistic Boltzmann Equation

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

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

Conservative treatment presents a significant challenge.

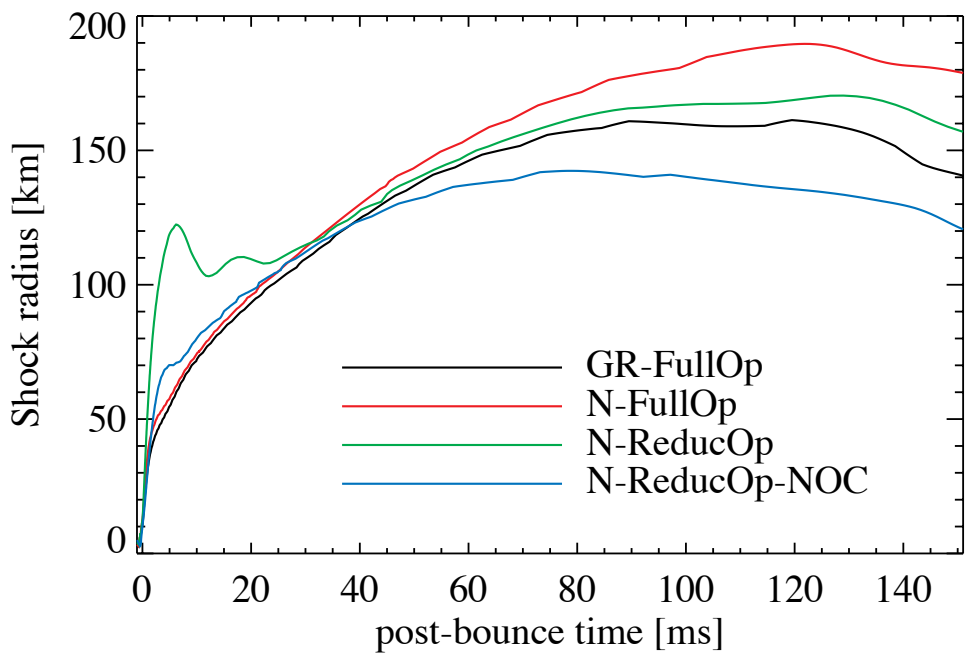
- *Liebendoerfer et al. 2004. ApJ Suppl. 150 263*
- *Cardall & Mezzacappa 2003 PRD 68 023006*
- *Cardall, Endeve, & Mezzacappa 2013 PRD 87 103004*
- *Cardall, Endeve, & Mezzacappa 2013 PRD 88 023011*

1. *What equations to use for the neutrino radiation hydrodynamics is nontrivial.*
2. *Discretizations must be chosen to ensure number and energy conservation simultaneously.*

	Spatial Dimensions	Newtonian or GR	1	2	3	Partial Weak Interactions (Thompson et al. (2003))	Complete Weak Interactions	Label
Lentz et al. (2012)	1	GR	X	X	X		X	GR-Full Op
Ott et al. (2008)	2	Newtonian	X			X		
Sumiyoshi and Yamada (2012)	3	Newtonian	X			X		

Peeling Away the Physics

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

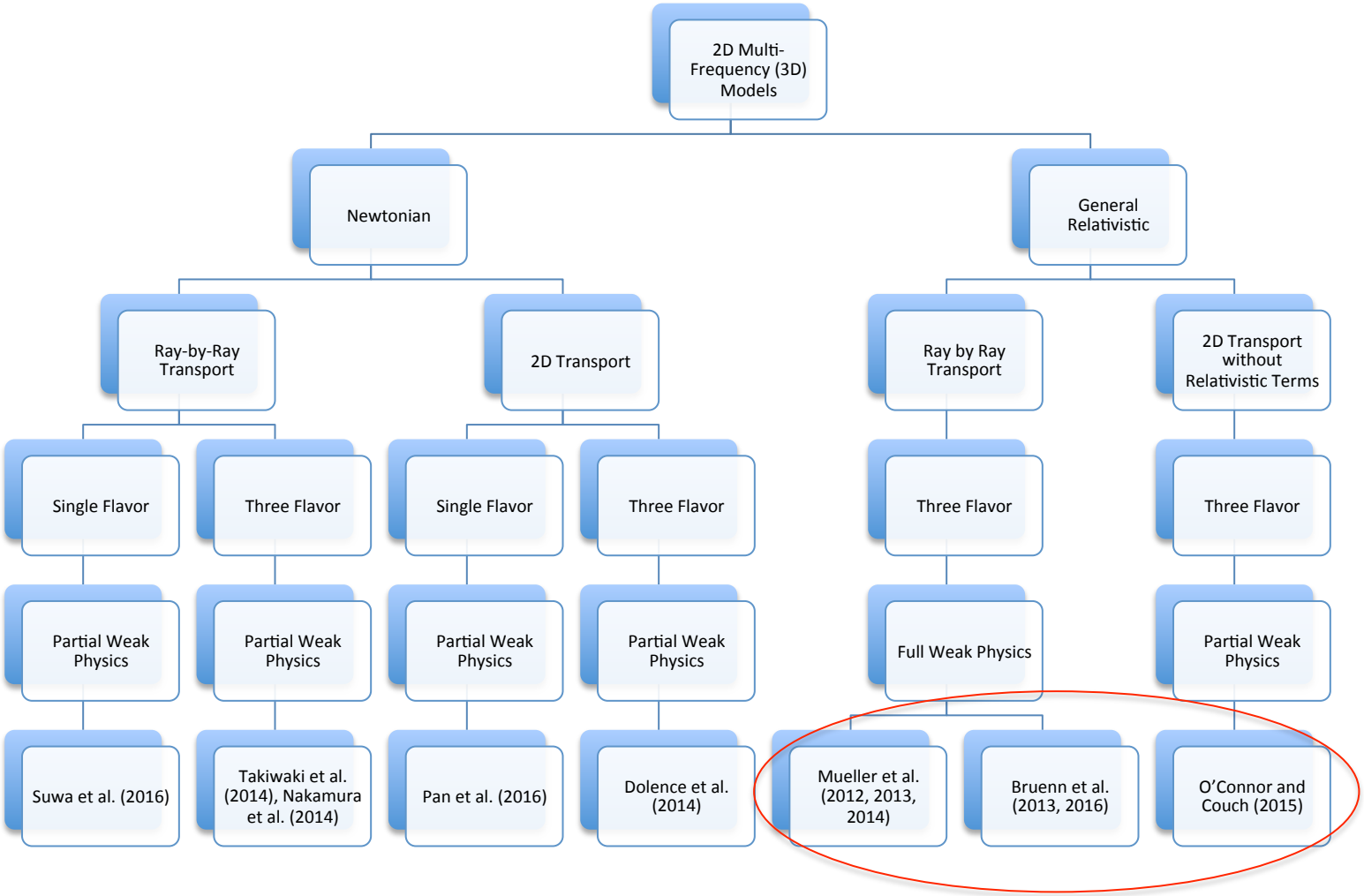


Lentz et al. *Ap.J.* **747**, 73 (2012)

Agile-BOLTZTRAN

See also B. Mueller et al. 2012. Ap.J. ***756****, 84 and O'Connor and Couch (2015) for a comparison in the context of 2D models, with similar conclusions.*

Grand Scheme of Things (2D)



Grand Scheme of Things (3D)

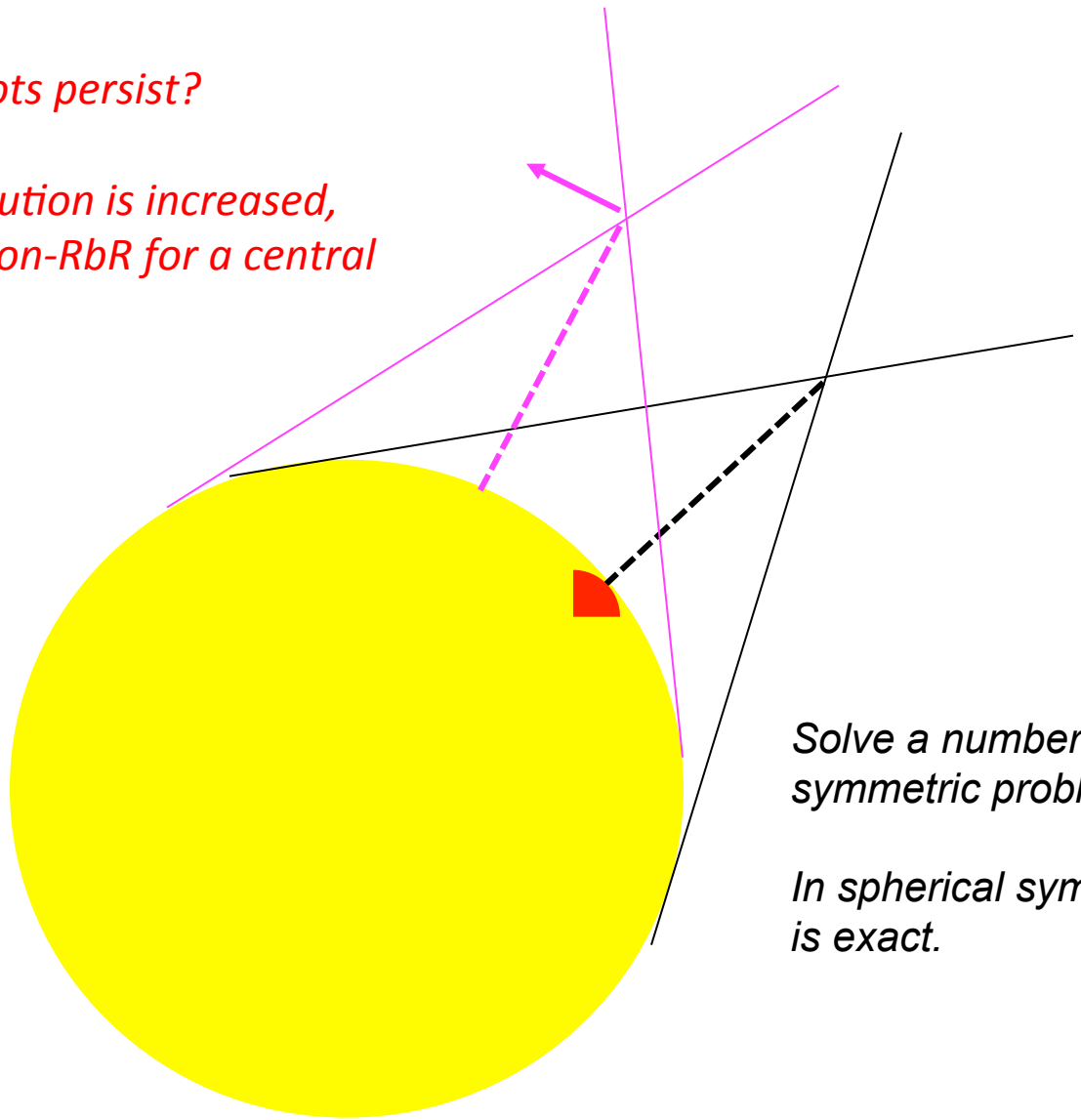
<u>Progenitor Masses Used</u>

- *Takiwaki et al. 11.2 M*
- *Lentz et al. 15 M*
- *Hanke, Tamborra, Melson et al. 9.6, 11.2, 20, 27 M*

Ray-by-Ray Approximation

Do accretion hot spots persist?

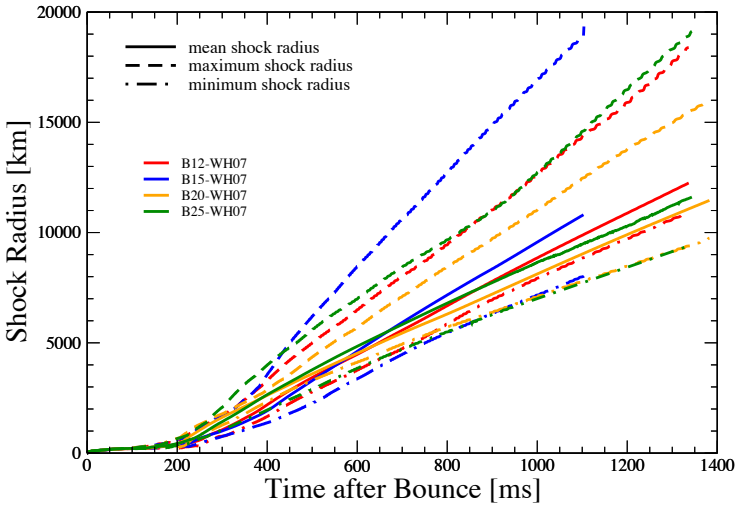
As the angular resolution is increased, RbR will approach non-RbR for a central source.

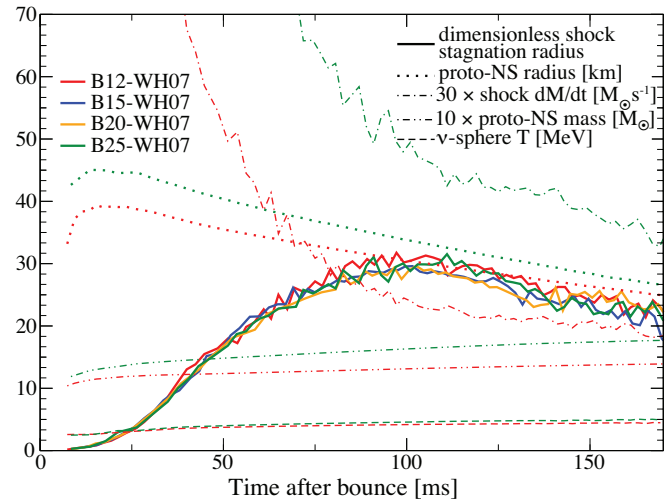


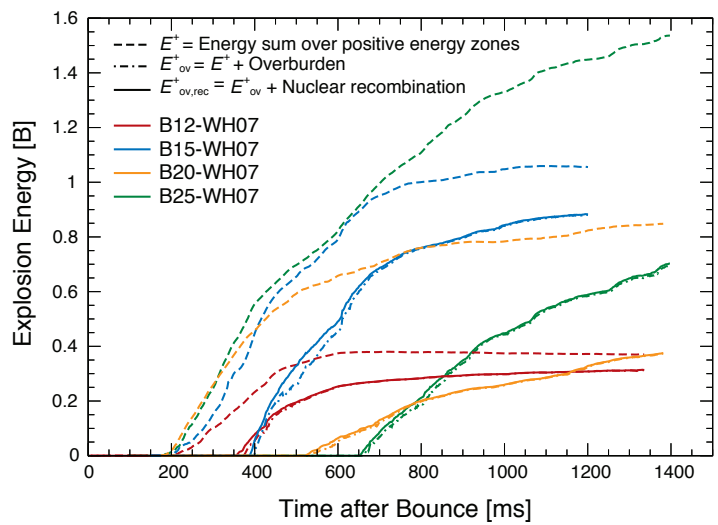
Solve a number of spherically symmetric problems.

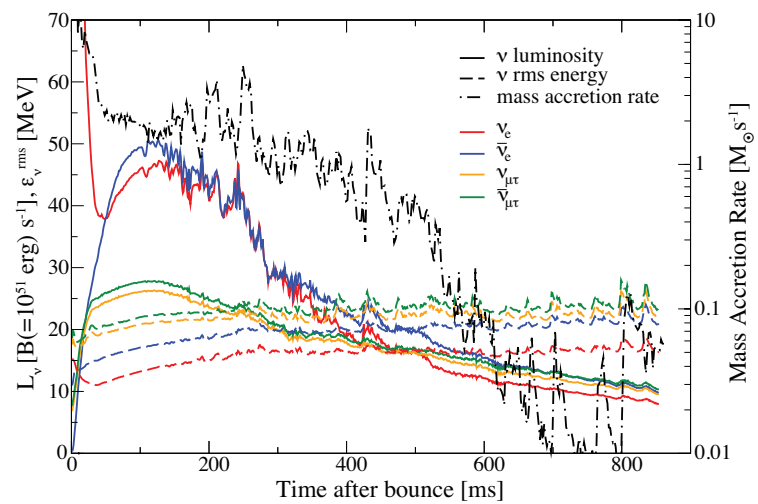
In spherical symmetry, RbR is exact.

Oak Ridge 2D Models



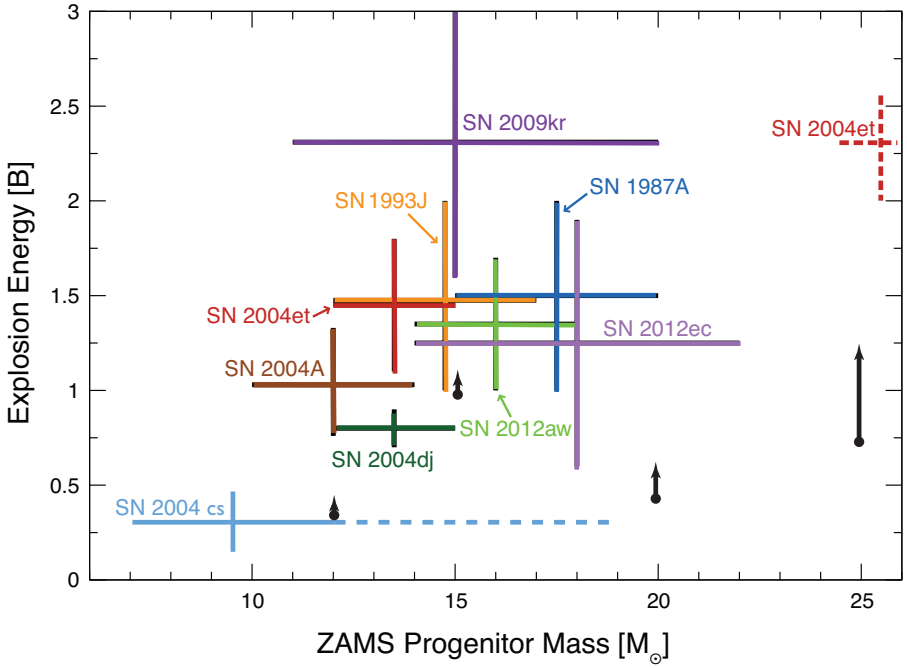


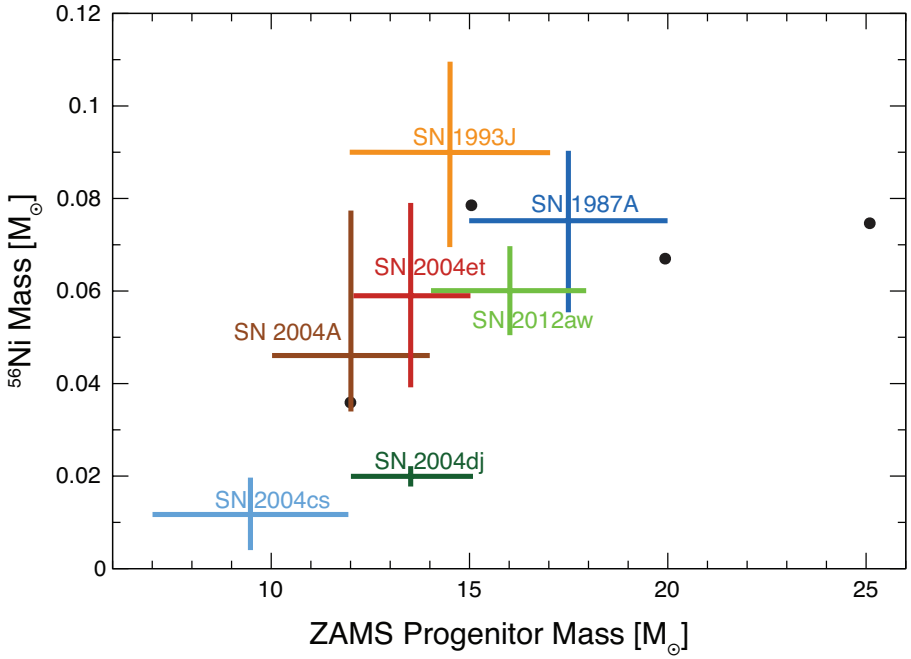




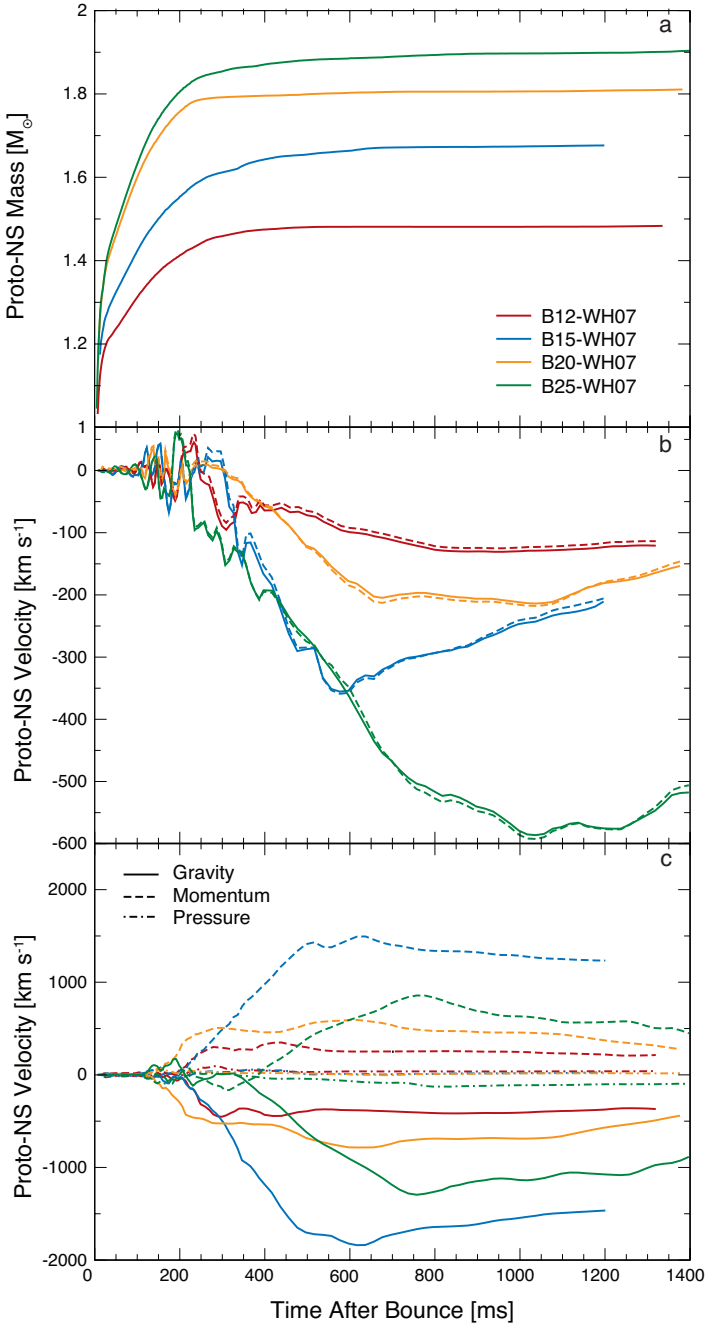
Bruenn et al. 2013. *Ap.J.* **767**, L6.
Bruenn et al. 2016. *Ap.J.* **818**, 123.

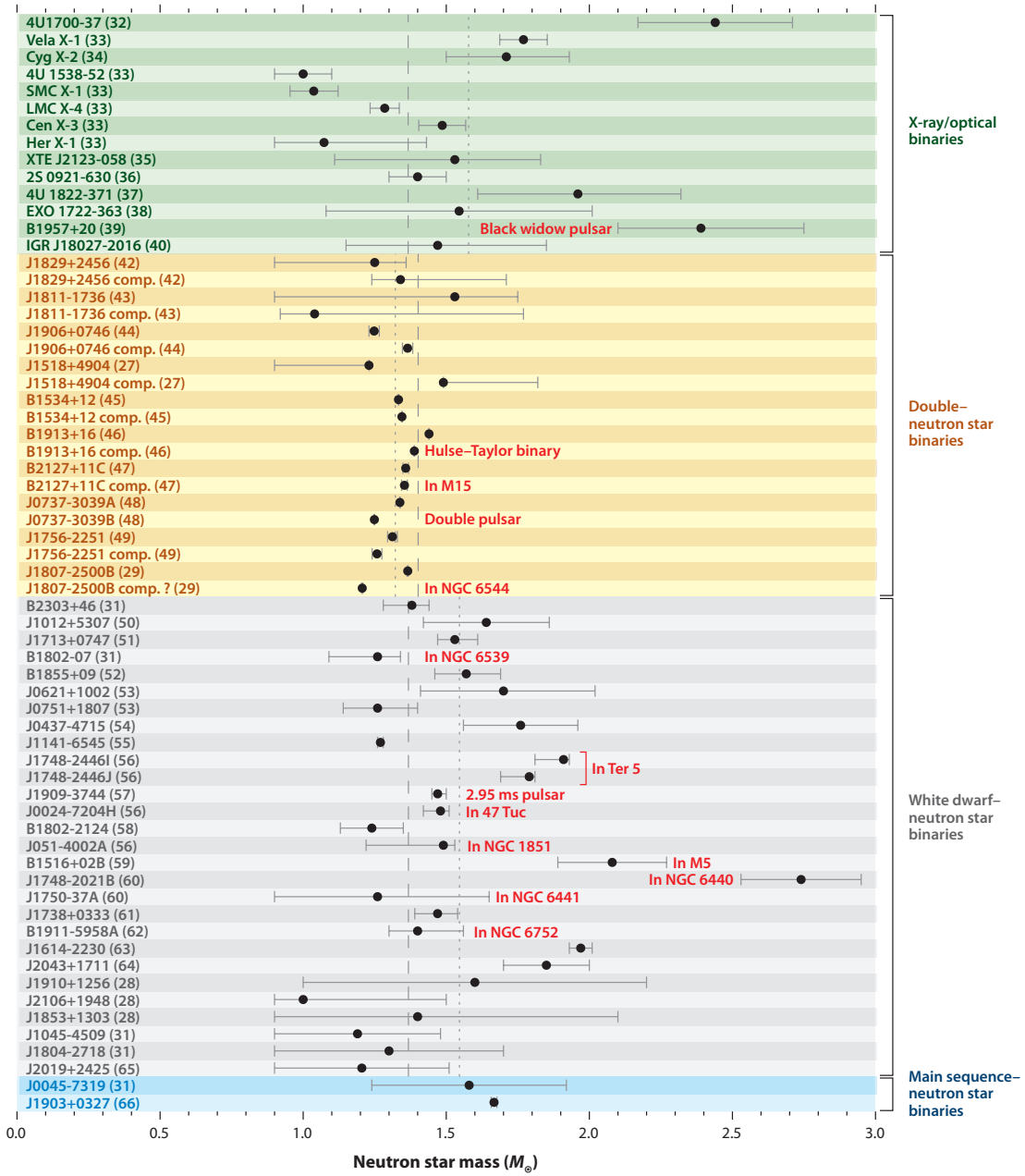
Comparison with Observations





Bruenn et al. 2014. arXiv:1409.5779v1





Lattimer, ARNPS 62 485 (2012)

Bruenn et al. 2014. arXiv:1409.5779v1

Table 1
Model Setup

Model	Progenitor	Neutrino Opacities	Treatment of Relativity	Simulated Post-bounce Time	Angular Resolution	Explosion Obtained	Time of Explosion[a]	EOS
G8.1	u8.1	Full set	GR hydro + xCFC	325 ms	1°.4	Yes	175 ms	LS180
G9.6	z9.6	Full set	GR hydro + xCFC	735 ms	1°.4	Yes	125 ms	LS220
G11.2	s11.2	Full set	GR hydro + xCFC	950 ms	2°.8	Yes	213 ms	LS180
G15	s15s7b2	Full set	GR hydro + xCFC	775 ms	2°.8	Yes	569 ms	LS180
S15	s15s7b2	Reduced set	GR hydro + xCFC	474 ms	2°.8	No	...	LS180
M15	s15s7b2	Full set	Newtonian + modified potential	517 ms	2°.8	No	...	LS180
N15	s15s7b2	Full set	Newtonian (purely)	525 ms	1°.4	No	...	LS180
G25	s25.0	Full set	GR hydro + xCFC	440 ms	1°.4	No	...	LS220
G27	s27.0	Full set	GR hydro + xCFC	765 ms	1°.4	Yes	209 ms	LS220

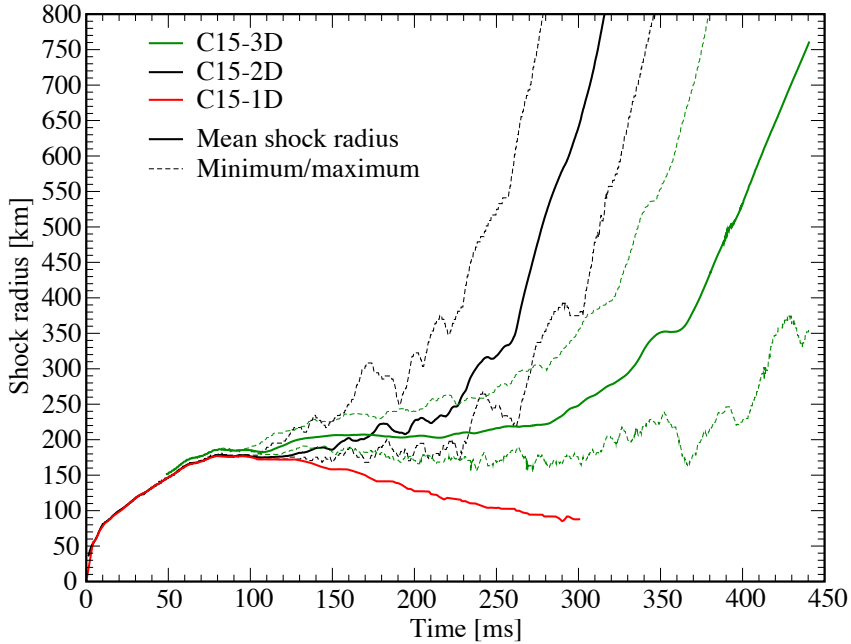
Note. [a] Defined as the point in time when the average shock radius $\langle r_{\rm sh} \rangle$ reaches 400 km.

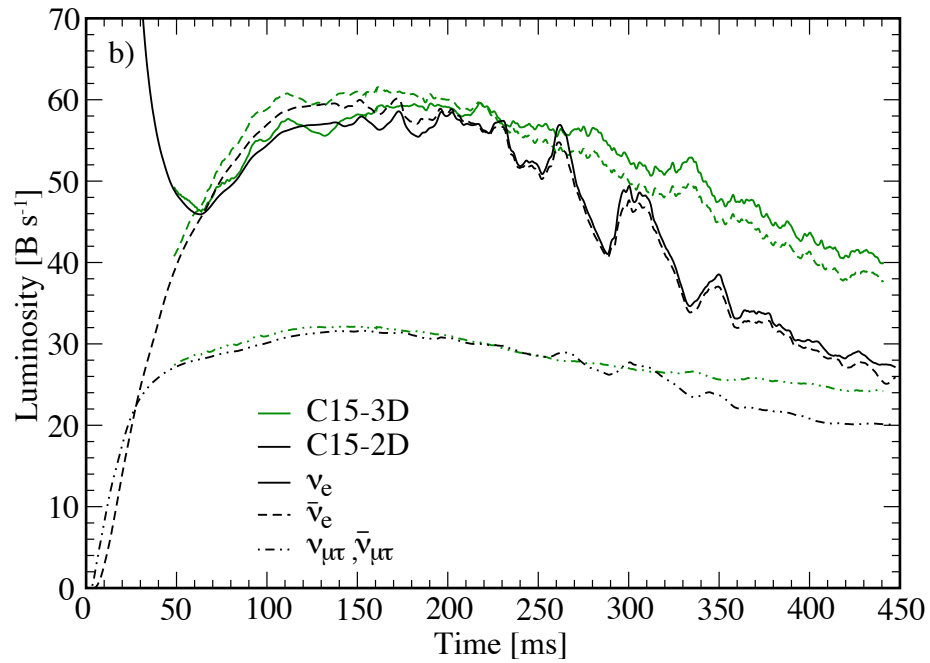
Table 1

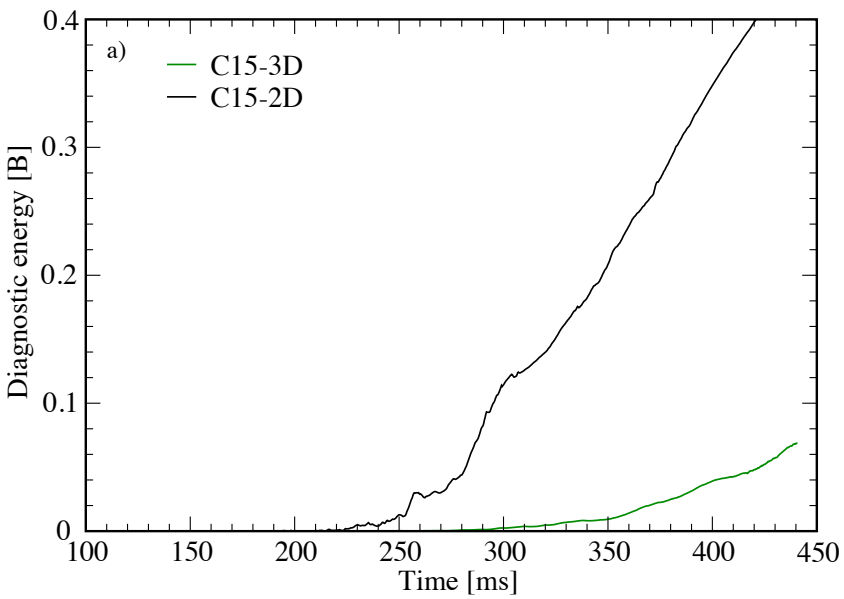
Reference	Gravity	EOS	Grid	ν Treatment	s12		s15		s20		s25	
					Exp?	$t_{\rm exp}$ [s]	Exp?	$t_{\rm exp}$ [s]	Exp?	$t_{\rm exp}$ [s]	Exp?	$t_{\rm exp}$ [s]
Bruenn et al. (2013)	GREP	LS220	Spherical	MGFLD RxR+	Yes	0.236	Yes	0.233	Yes	0.208	Yes	0.212
Hanke (2014)	GREP	LS220	Spherical	VEF RxR+	Yes	0.79	Yes	0.62	Yes	0.32	Yes	0.40
this work	GREP	LS220	Cylindrical	MG M1	No	–	Yes	0.737	Yes	0.396	Yes	0.350
Dolence et al. (2015)	NW	H. Shen	Cylindrical	MGFLD	No	–	No	–	No	–	No	–
Suwa et al. (2014)	NW	LS220	Spherical	IDSA RxR	Yes	0.425	No	–	No	–	N/A	N/A
this work	NW	LS220	Cylindrical	MG M1	No	–	No	–	No	–	No	–

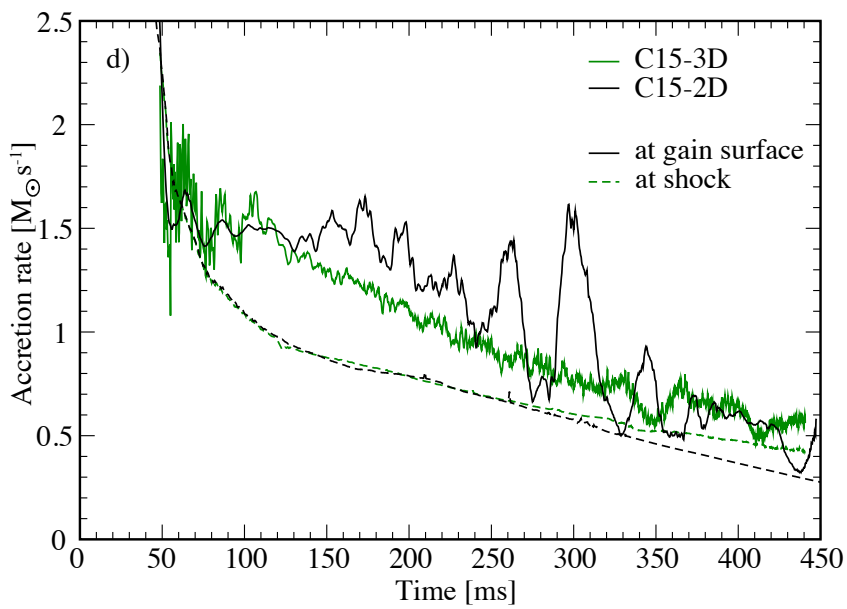
Oak Ridge 3D Models

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



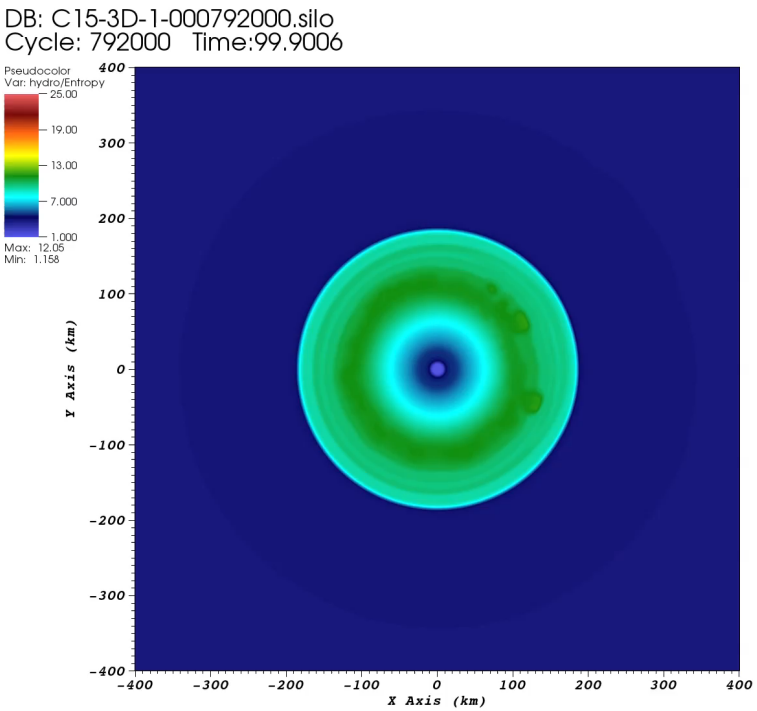


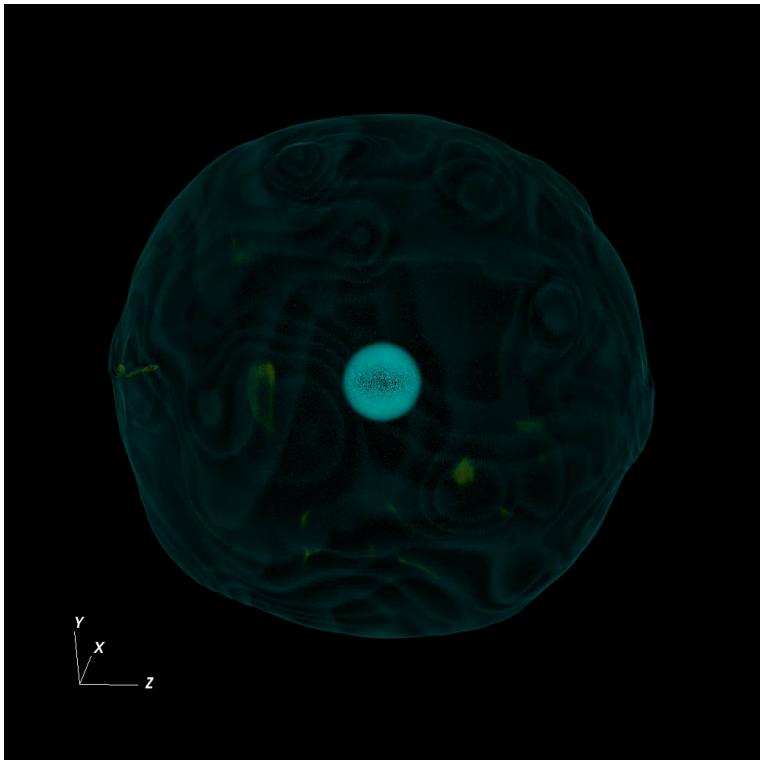




15 M
LS (220)

3D Counterpart Models



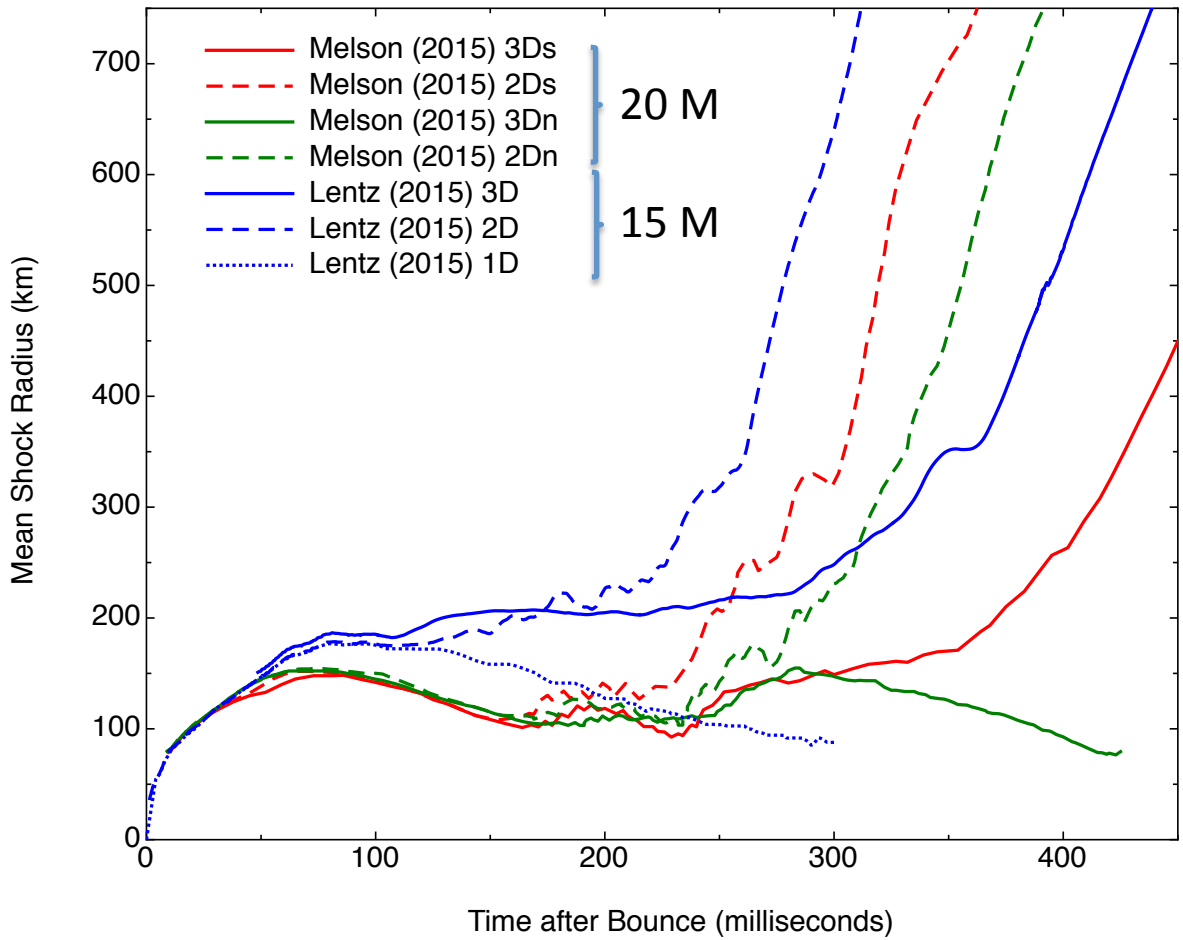


Lentz et al. 2015. *Ap.J. Lett.* **807**, L31.

<u>Simulation Stats</u>

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

Comparing Qualitative Behavior



Similarities in the qualitative behavior of 2D models, and 3D models, obtained by the MPA and Oak Ridge groups is evident in the above graph.

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.

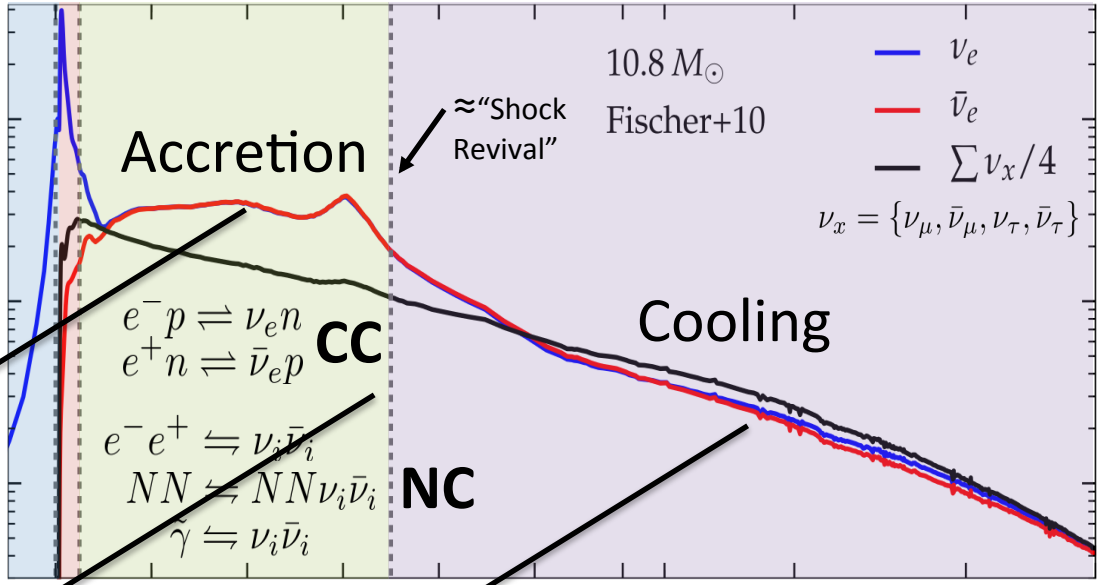
~4000X more computationally intensive.

Will there be enough memory?

Replace 3D Boltzmann Transport with 3D Quantum Kinetics

?

CCSN Neutrino Signatures

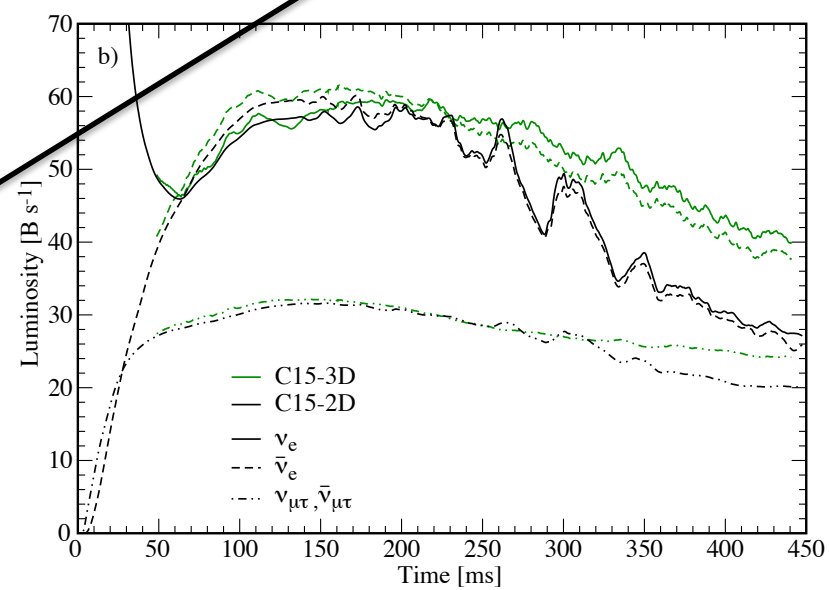


What are the amplitudes, variations, and time scales of the accretion signatures?

What are the explosion time scales - i.e., when does the cooling phase begin for each progenitor?

What are the late-time neutrino signatures - i.e., the signature at O(10) s?

What is the impact of neutrino mixing on all of the above?



Wish List

- *The absolute flux from the neutronization burst.*
  - *Will allow us to discriminate between different EOS.*
- *The ms-scale structure of the emission from the accretion phase (convection vs. SASI).*
  - *We need at least 1 ms timing resolution to discern the feature that precedes the neutronization burst, which depends on the symmetry energy, as well as the neutronization peak.*
  - *We need 1 ms timing to resolve well the O(10 ms) SASI cycle time.*
- *10% energy resolution is sufficient.*
- *Need SnowGlobes to handle neutrino energies above 100 MeV.*

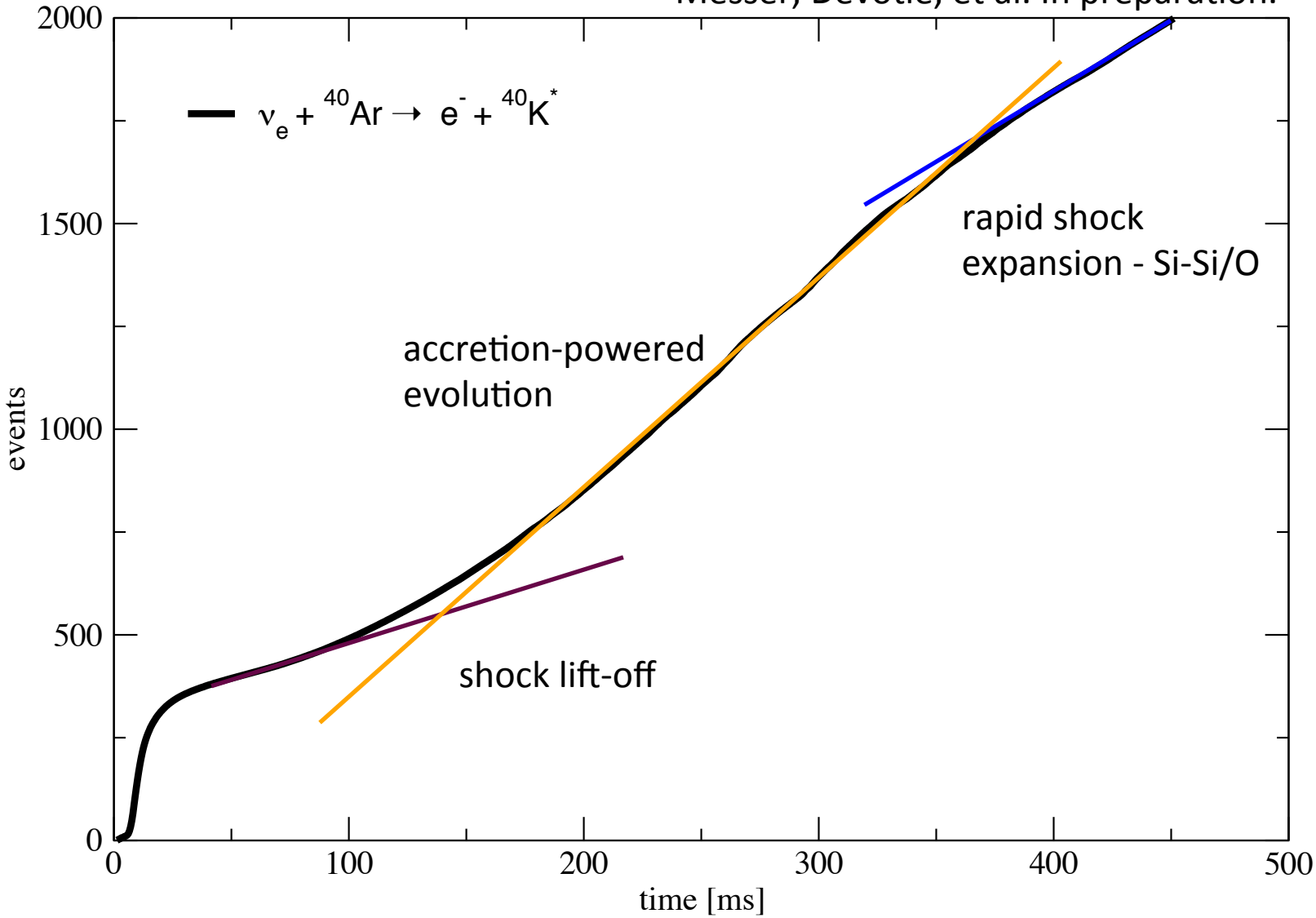
What We Can Provide

We can provide

- *raw luminosity spectra as a function of time,*
- *our output from SnowGlobes,*
- *our alpha fit (2-alpha fit as a function of time).*

Signatures of Supernova Dynamics

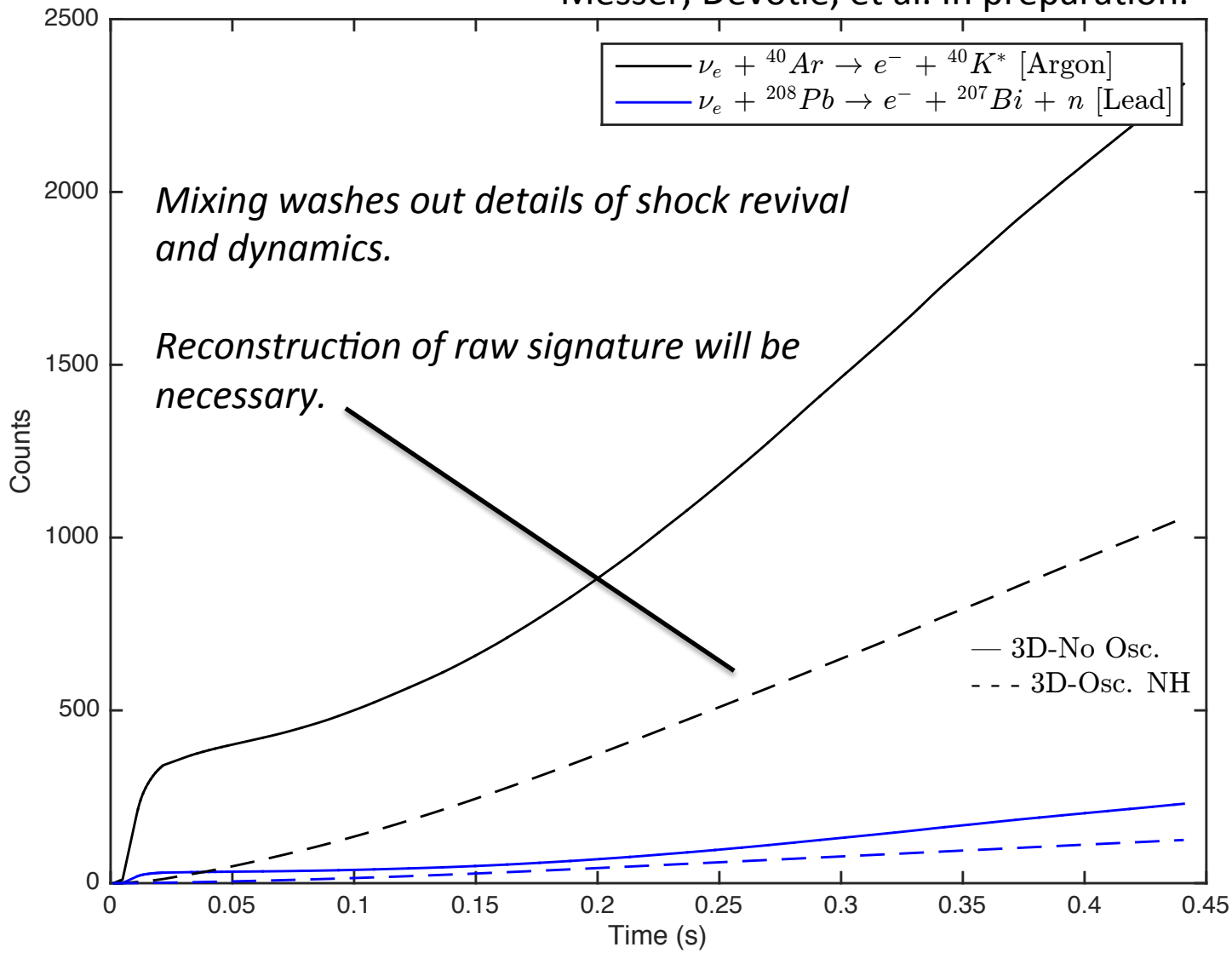
Messer, Devotie, et al. In preparation.



C15-2D, angle-averaged, SNOwGLoBES Ar17kt, 10 kpc

Signatures of Supernova Dynamics

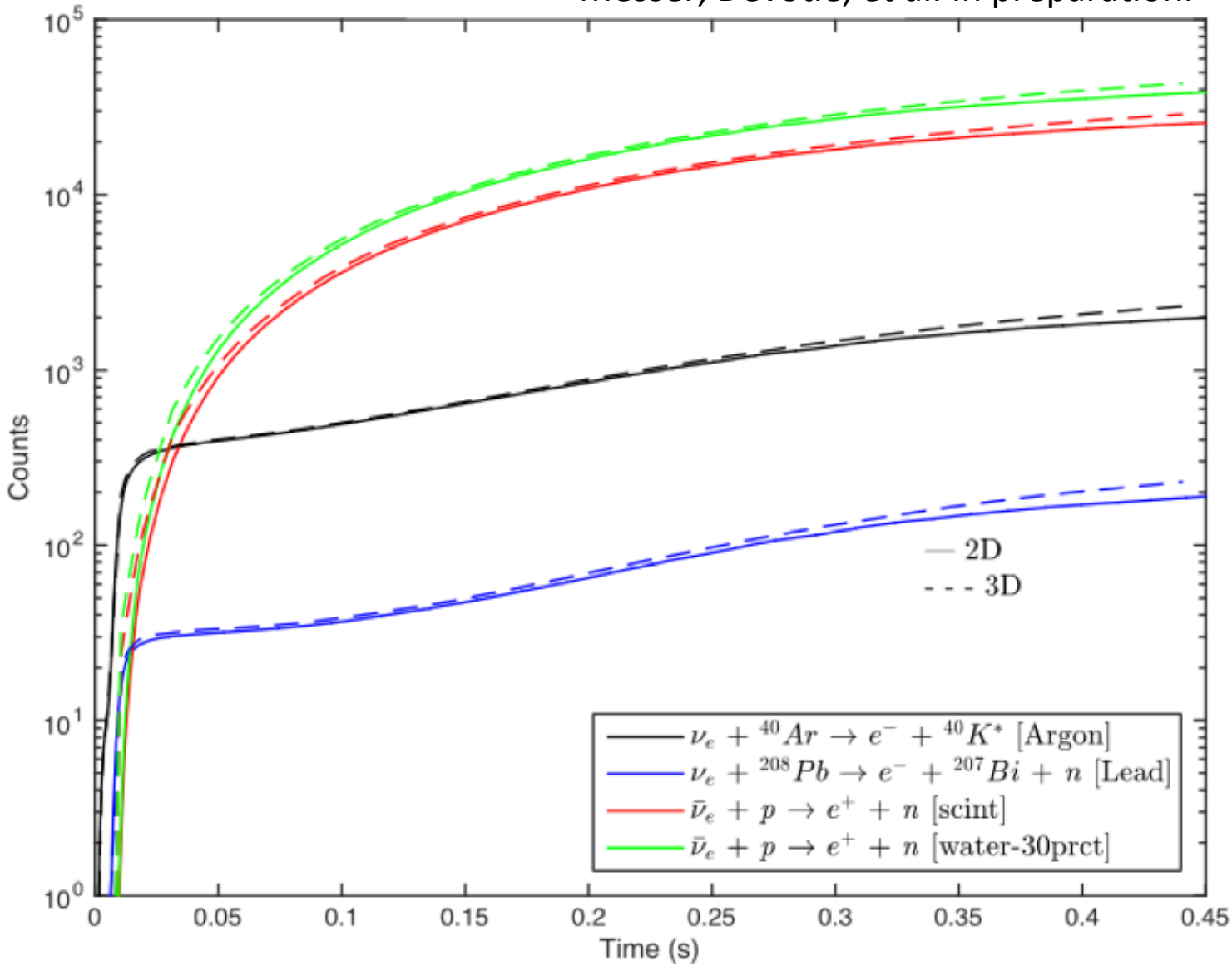
Messer, Devotie, et al. In preparation.



Oak Ridge group evolves both the neutrino and the antineutrino distributions for all 3 flavors.

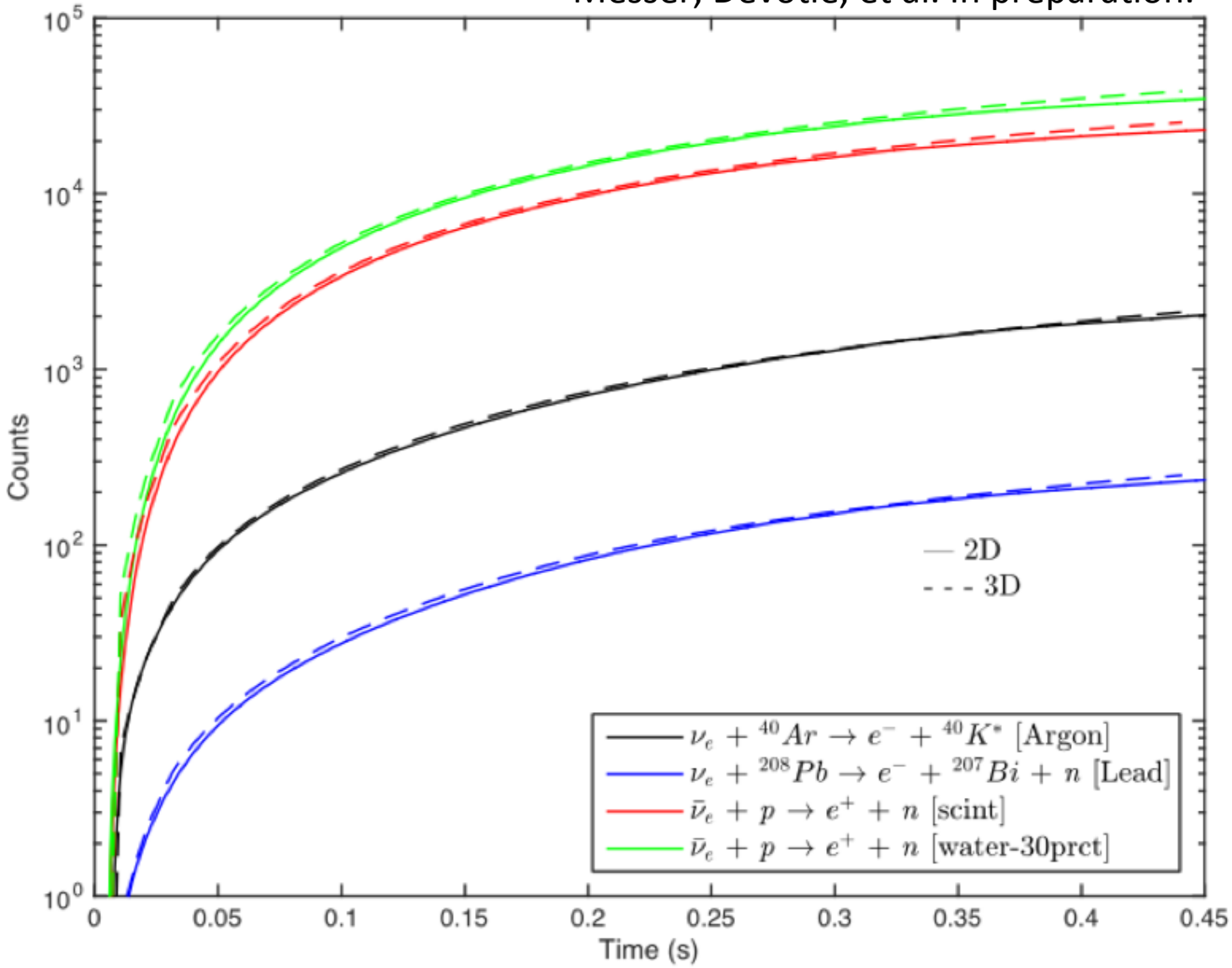
Signatures of the Mass Hierarchy

Messer, Devotie, et al. In preparation.



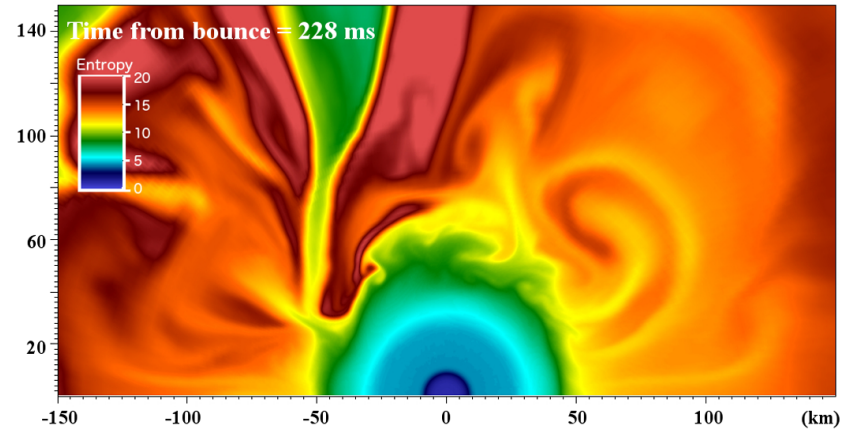
Signatures of the Mass Hierarchy

Messer, Devotie, et al. In preparation.



Letting Space Tell Us About Matter

Yakunin et al. 2015. *Phys. Rev. D* **92**, 084040

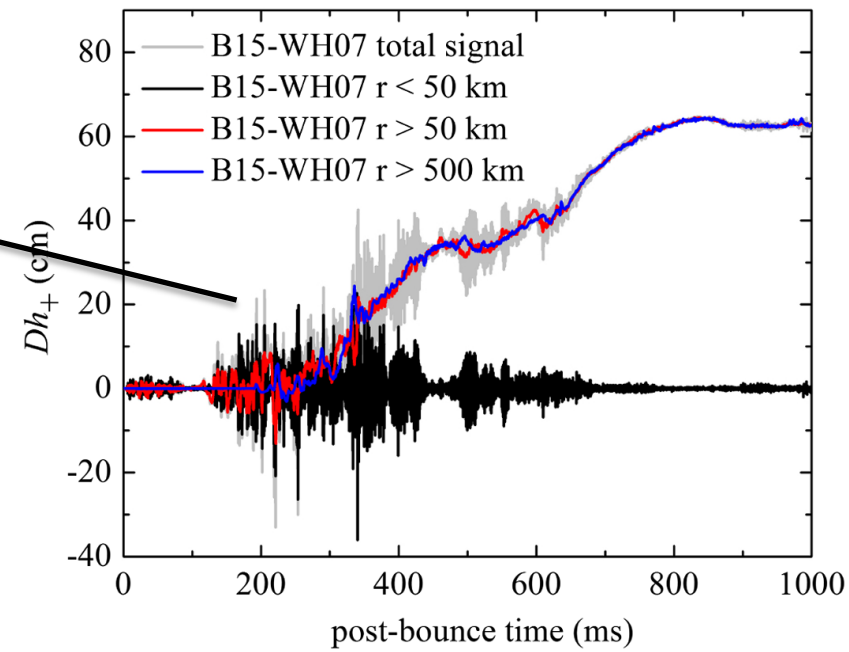


Gravitational wave signal is dominated by the SASI and the SASI-induced accretion flows impinging on the PNS surface.

- Evidence of the SASI.

Explosion is imprinted in the signal as well.

- Explosion time scale.
- Progenitor.



CHIMERA Collaboration

Endeve
Harris
Hix
Landfield
Lentz
Lingerfelt
Messer
Mezzacappa
Yakunin

Bruenn
Marronetti

Blondin

Funded by