Core Collapse Supernova Modeling at the Crossroads

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Supernova Neutrinos at the Crossroads: Astrophysics, Oscillations, and Detection
ECT, Trento, Italy

The Complete Picture

Each has its own challenges.

The overlap (“crossroads”) may be a nightmare!

My focus will largely be here, although I will touch on other parts of the pipeline.

A Brief History of Supernova Models

Would be consistent with the expected development of our "instruments" over the next decade.

35 years

1966 – 2001

1D

Colgate and White Ap.J. 143, 626 (1966)
Liebendoerfer et al. et al. PRD 63, 103004 (2001)

25 years

1994 – 2018

2D

Herant et al. *Ap.J.* **435**, 339 (1994)
O'Connor and Couch, *Ap.J*. **854**, 63 (2018)
Vartanyan et al. MNRAS **477**, 3091 (2018)

15 years?

2013 –

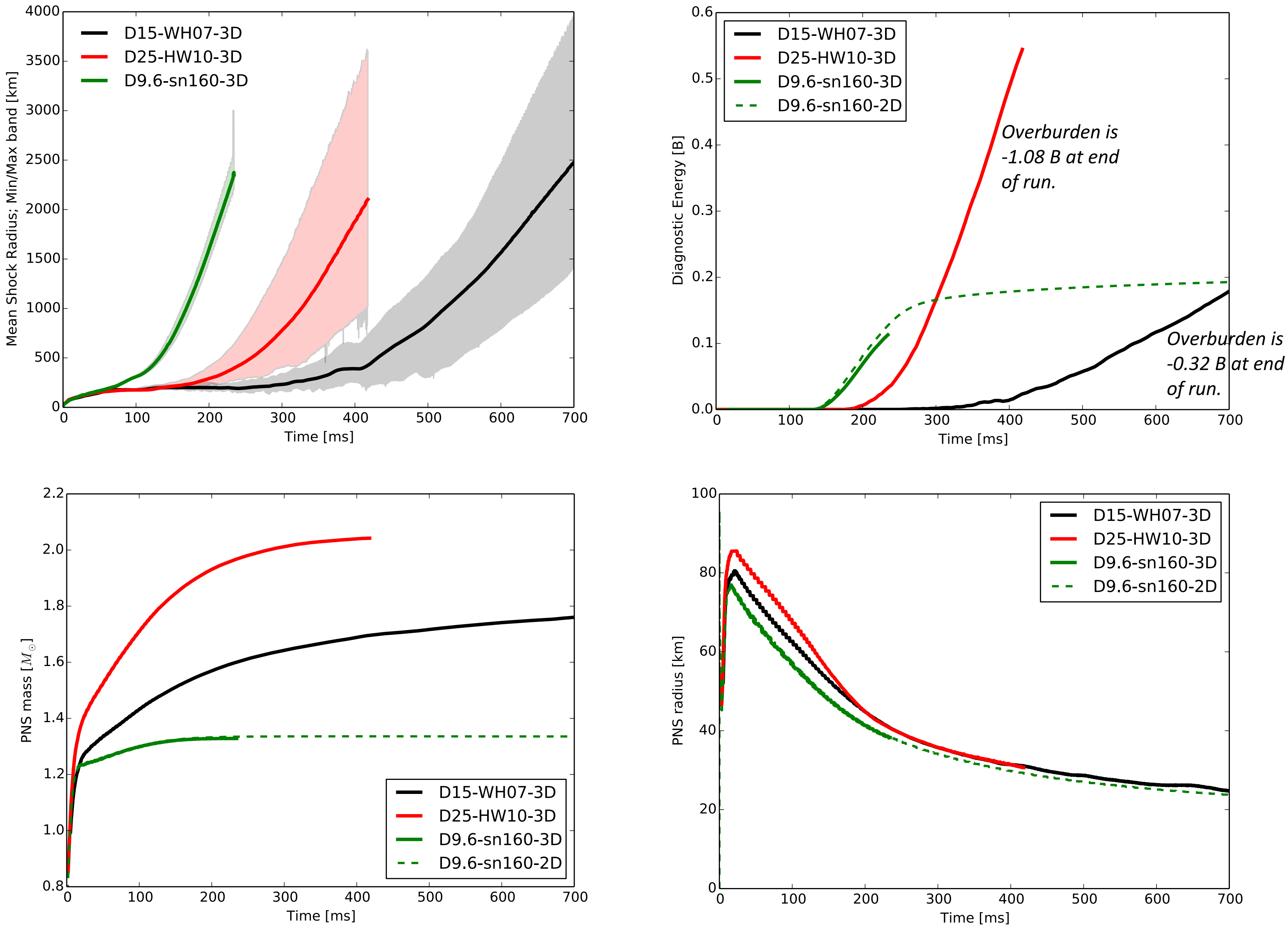
3D

Hanke et al. *Ap.J*. **770**, 66 (2013)
…

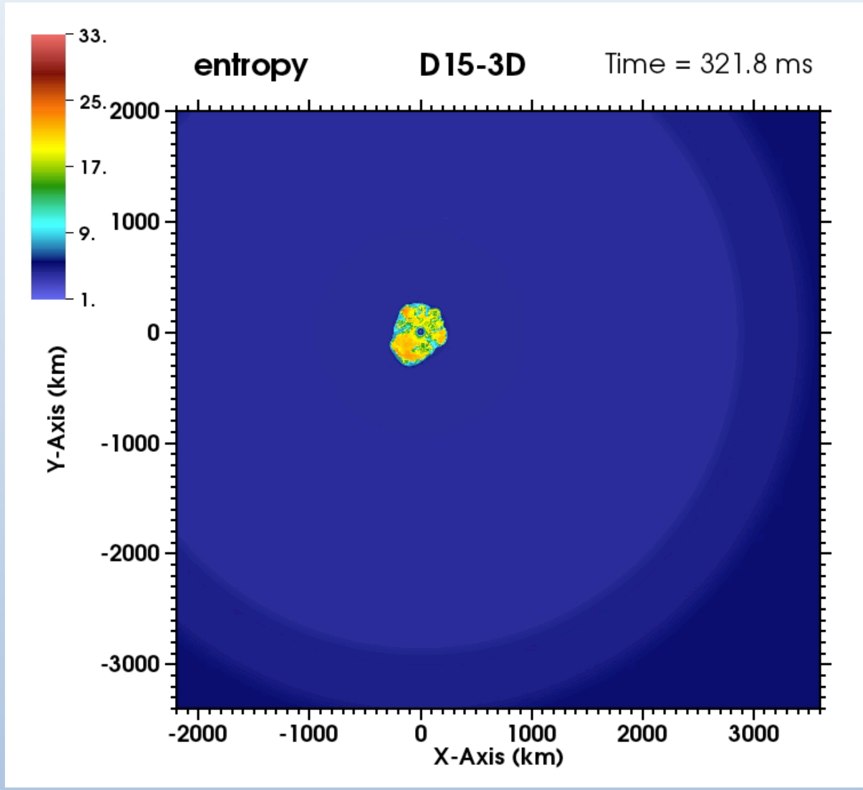
Progress has been accelerating.

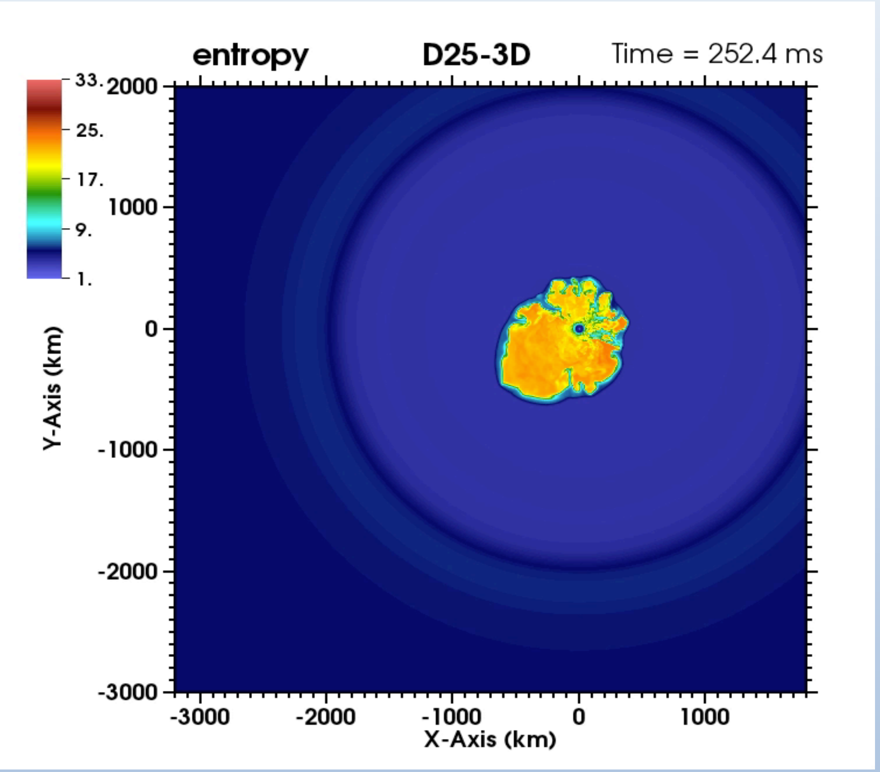
Authors	Progenitor Mass (Solar Masses)	Rotating/Perturbed	Progenitor Family/Metallicity/High-Density EOS	Explosion	Post-bounce Time (ms)
Hanke et al. (2013)	27	N/N	Woosley, Heger, and Weaver (2002)/Solar Metallicity/LS220	N	400
Takiwaki et al. (2014)	11.2	N/N	Woosley, Heger, and Weaver (2002)/Solar Metallicity/LS180	Y	369
Melson et al. (2015)	9.6	N/N	Woosley and Heger (2015)/Zero Metallicity/LS220	Y	400
Lentz et al. (2015)	15	N/N	Woosley and Heger (2007)/Solar Metallicity/LS220	Y	685
Takiwaki et al. (2016)	11.2, 27	Y/N	Woosley, Heger, and Weaver (2002)/Solar Metallicity/LS220	Y for 11.2 N for 27 (except for rapid rotation)	260 275
Roberts et al. (2016)	27	N/N	Woosley, Heger, and Weaver (2002)/Solar Metallicity/LS220	Y	380
Mueller et al. (2017)	18	N/Y	Woosley, Heger, and Weaver (2002)/Solar Metallicity/LS220	Y	2350
Summa et al. (2018)	15	Y/N	Heger, Woosley, and Spruit (2005)/Solar Metallicity/LS220	N (except for rapid rotation)	460
Chan et al. (2018)	40	N/N	Heger and Woosley (2010)/Zero Metallicity/LS220	Y	
Ott et al. (2018)	12, 15, 20, 27, 40	N/N	Woosley and Heger (2007)/Solar Metallicity/SFHo	Y (except for 12)	527, 597, 384, 392, 323
O’Connor and Couch (2018)	20	N/Y	Farmer, Fields, Petermann et al. (2016)/Solar Metallicity/SFHo	N	500
Vartanyan et al. (2019)	16	N/Y	Woosley and Heger (2007)/Solar Metallicity/SFHo	Y	677
Burrows et al. (2019)	9, 10, 11, 12, 13	N/N	Sukhbold, Ertl, Woosley et al. (2016)/Solar Metallicity/SFHo	Y (except for 13)	1042, 767, 568, 694, 674

Authors	Progenitor Mass (Solar Masses)	Rotating/Perturbed	Progenitor Family/Metallicity/High-Density EOS	Explosion/ Shock Radius (km)	Post-bounce Time (ms)/ Explosion Energy (B)
Lentz et al. (2019), in preparation	9.6	N/N	Woosley and Heger (2015)/Zero Metallicity/LS220	Y/9467	467/0.167
	10	N/N	SEWBJ16/Solar Metallicity/LS220	?/300	265
	10.6	N/N	Heger and Woosley (2010)/Zero Metallicity/LS220	?/200	115
	15	N/N	Woosley and Heger (2007)/Solar Metallicity/LS220	Y/ 1600	685
	25	N/N	Heger and Woosley (2010)/Zero Metallicity/LS220	Y/ 2200	405

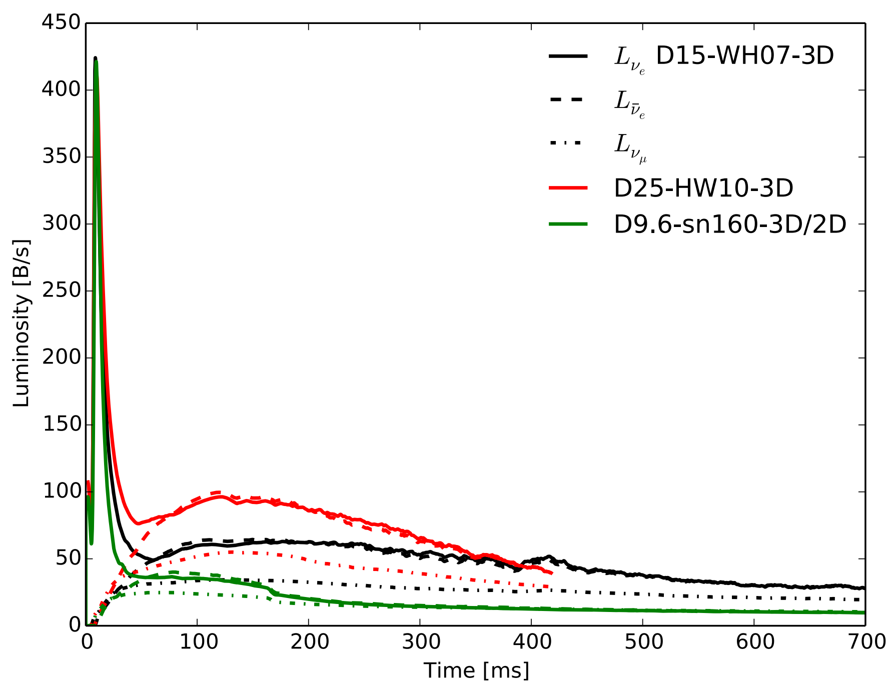


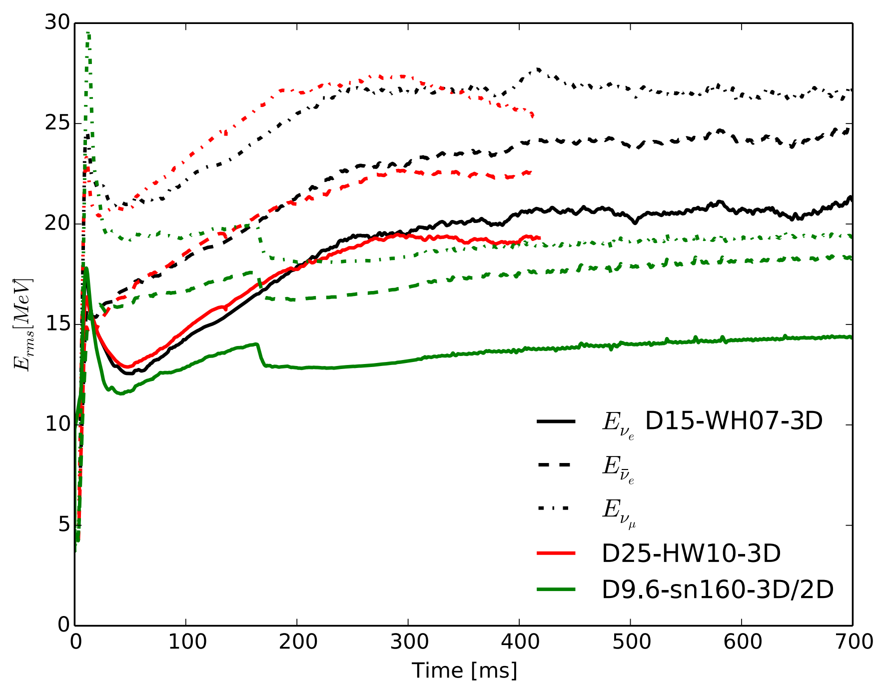
Lentz et al. (2019), in preparation



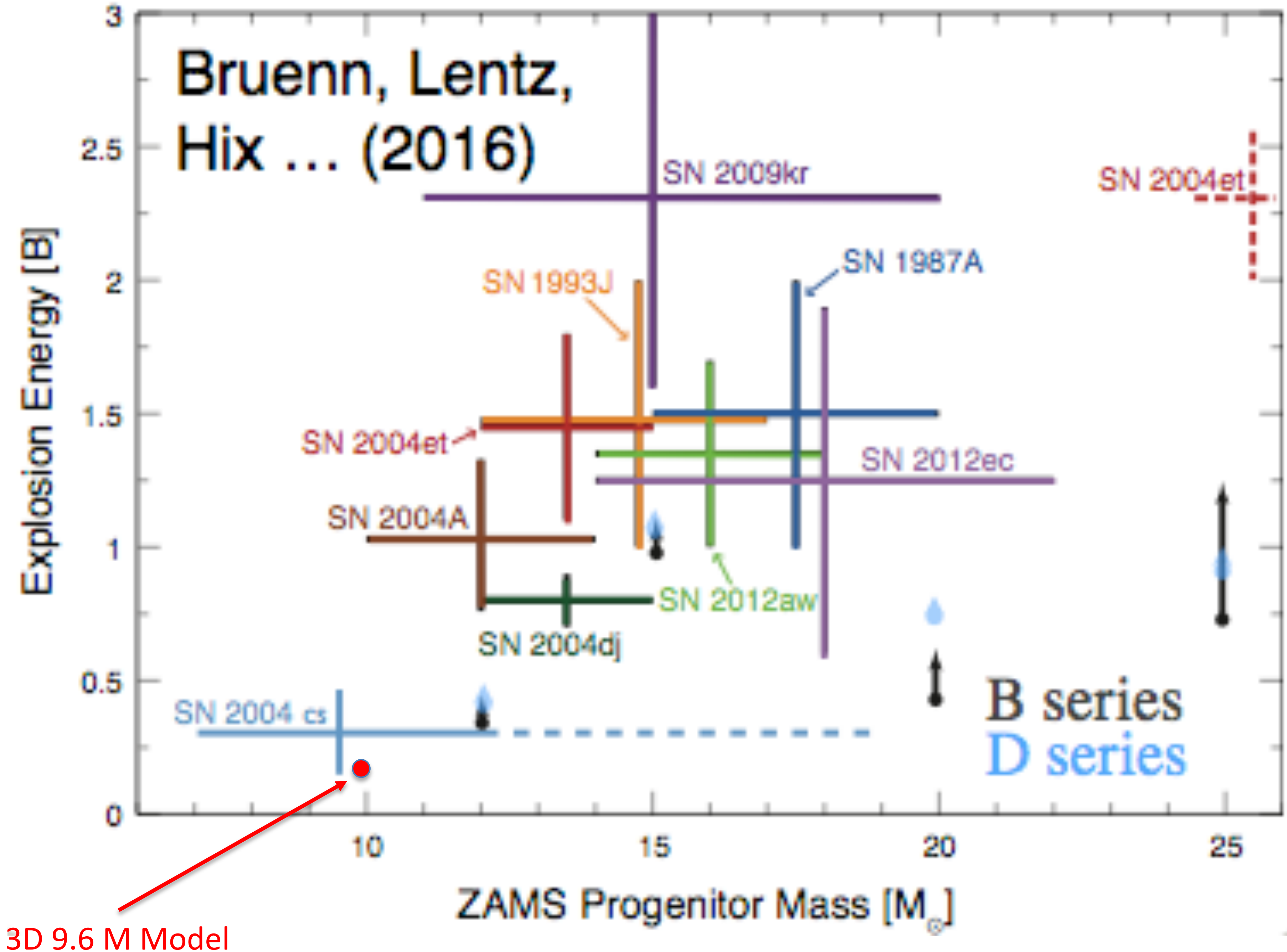


Lentz et al. 2015, *Ap.J. Lett.* **807**, L31; Lentz et al. 2019, in preparation





Lentz et al. (2019), in preparation



Bruenn, Lentz, Hix … (2016)
SN 2009kr
SN 2004et
SN 1987A
SN 1993J
SN 2004et
SN 2012ec
SN 2004A
SN 2012aw
SN 2004dj
SN 2004 cs
B series
D series
3D 9.6 M Model
Explosion Energy [B]
ZAMS Progenitor Mass [M$_\odot$]

Significant progress has been made, but are we fast approaching the base of El Capitan?

Convergence of efforts to include Full Physics in 3D General Relativistic Codes and efforts to include General Relativity in Full Physics Codes

Meeting the Demands illuminated by 2D Models in the Context of 3D Models

Desired Simulation

Keeping Pace with the Weak Interaction Physics and Managing the Uncertainty in the Cross Sections

Bracing for the Clash between Classical Kinetics and Quantum Kinetics of Neutrinos

<u>Each</u> of these things becomes very difficult in 3D, let alone the confluence of them.

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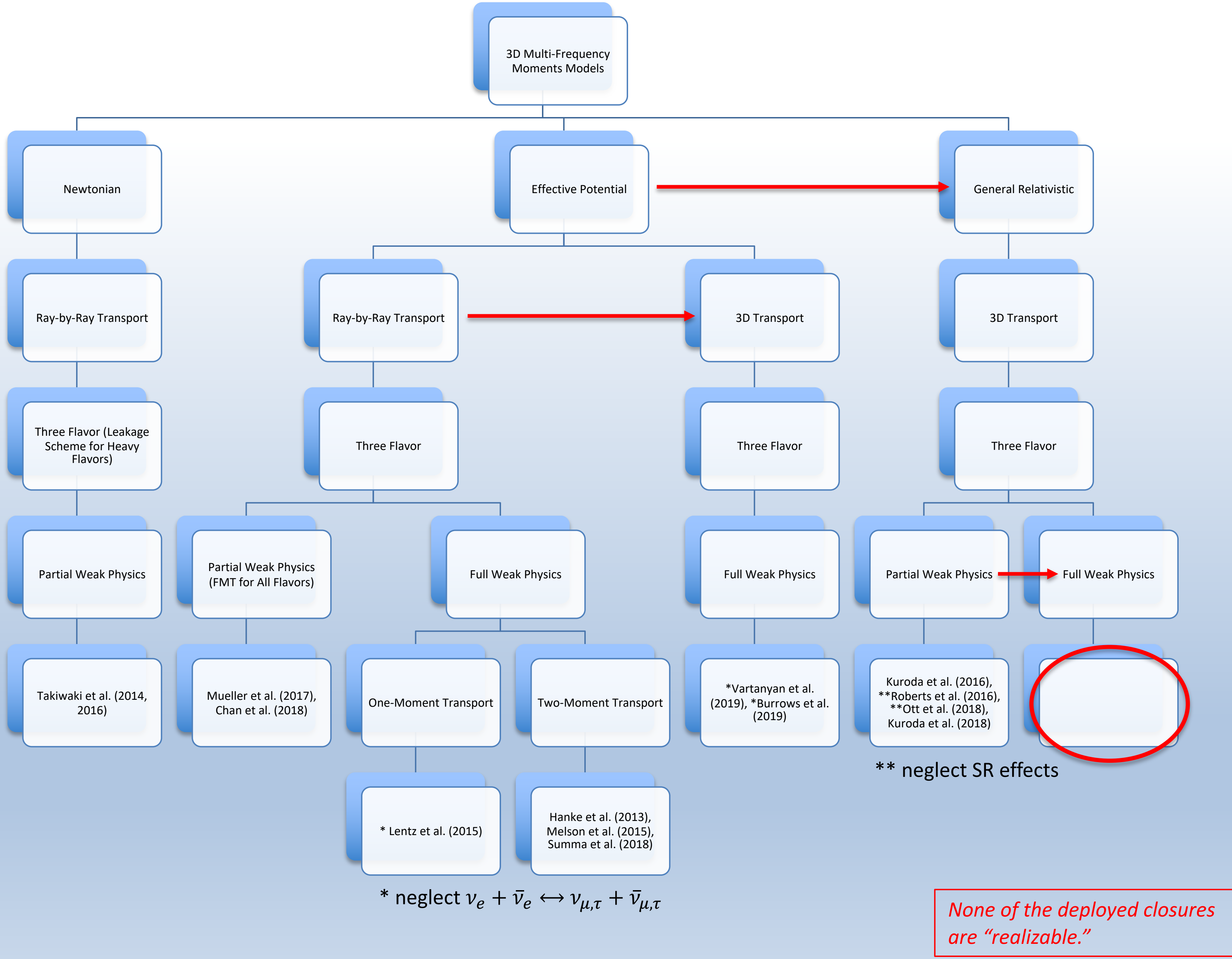
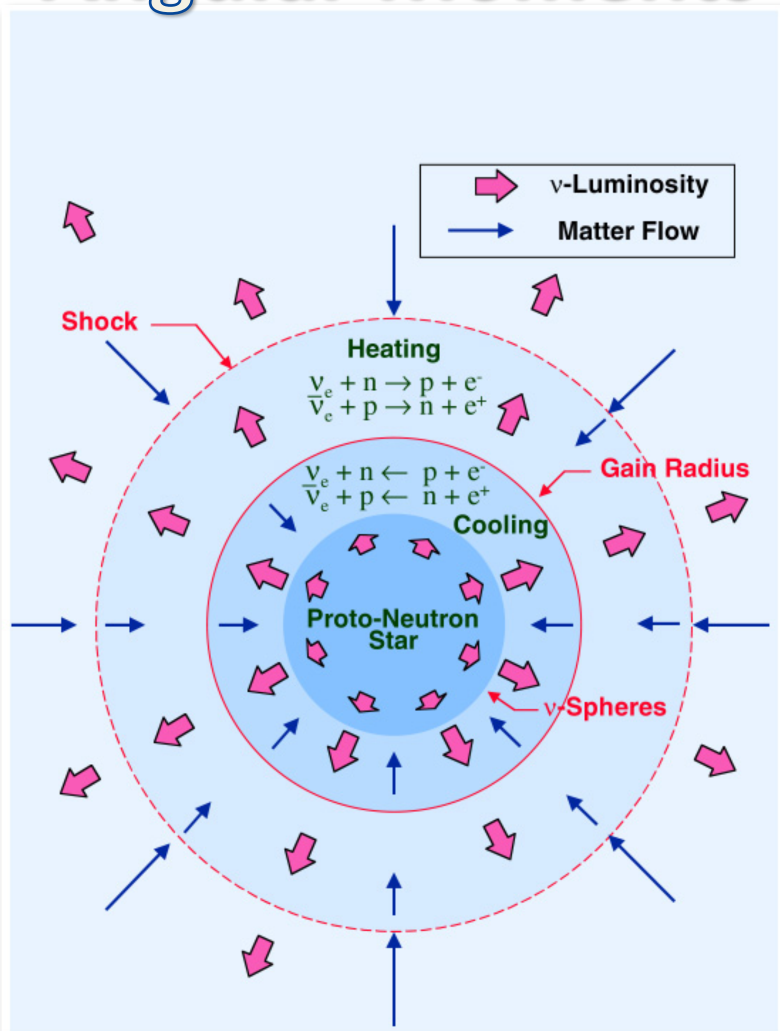

3D Multi-Frequency Moments Models
Newtonian
Effective Potential
General Relativistic
Ray-by-Ray Transport
Ray-by-Ray Transport
3D Transport
3D Transport
Three Flavor (Leakage Scheme for Heavy Flavors)
Three Flavor
Three Flavor
Three Flavor
Partial Weak Physics
Partial Weak Physics (FMT for All Flavors)
Full Weak Physics
Full Weak Physics
Partial Weak Physics
Full Weak Physics
Takiwaki et al. (2014, 2016)
Mueller et al. (2017), Chan et al. (2018)
One-Moment Transport
Two-Moment Transport
*Vartanyan et al. (2019), *Burrows et al. (2019)
Kuroda et al. (2016), **Roberts et al. (2016), **Ott et al. (2018), Kuroda et al. (2018)
** neglect SR effects
* Lentz et al. (2015)
Hanke et al. (2013), Melson et al. (2015), Summa et al. (2018)
* neglect $\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$
None of the deployed closures are "realizable."

The Neutrino Angular Moments



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

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

➠ Should 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:

- 1-Moment (MGFLD)
- 2-Moment (MGVET)

Closure must be “realizable”
- i.e., it must obey Fermi–Dirac statistics.

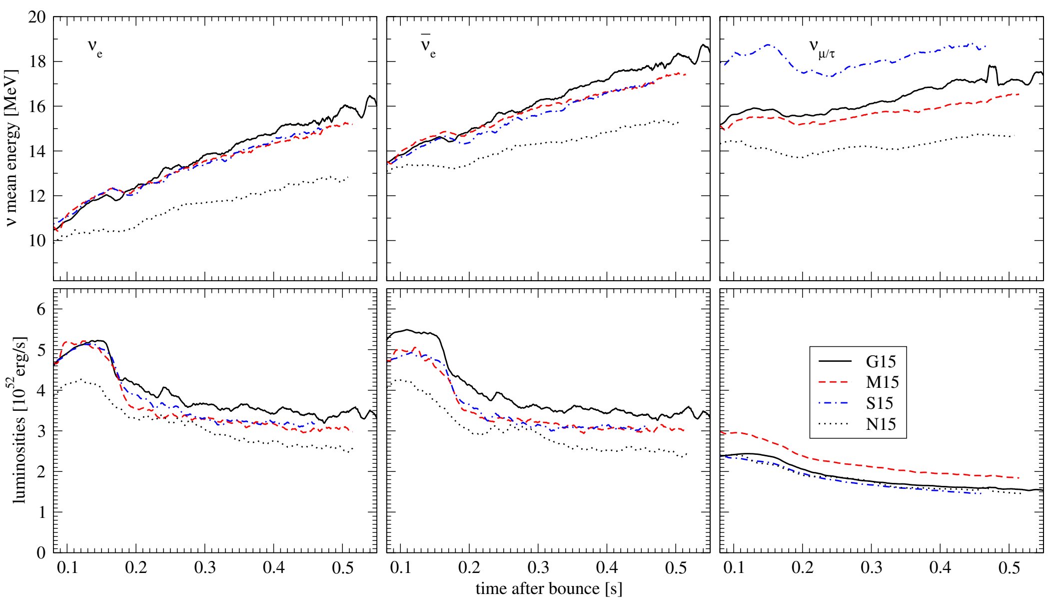
An "Effective" Potential

Comparison of Newtonian and TOV equations for hydrostatic equilibrium suggests a GR correction to the monopole term of the Newtonian potential's multipole expansion.

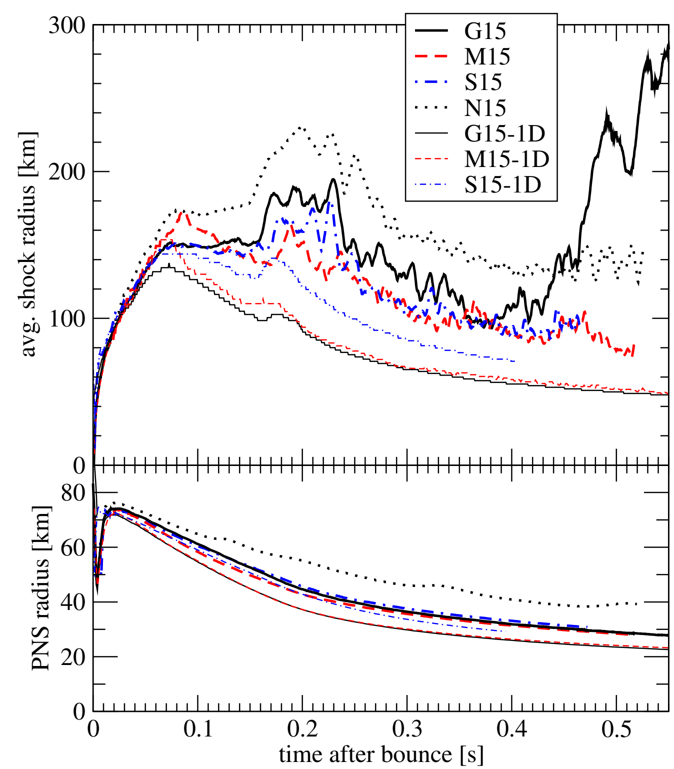
$$\Phi^{\rm GR}(r) = G \int_{\infty}^{r} \mathrm{d}r' \, \frac{1}{r'^2} \left(m + \frac{4\pi r'^3 (p + P)}{c^2} \right) \frac{1}{\Gamma^2} \left(\frac{\rho_{\rm tot} c^2 + p}{\rho c^2} \right)$$

Rampp and Janka 2002 *A&A* **396**, 361

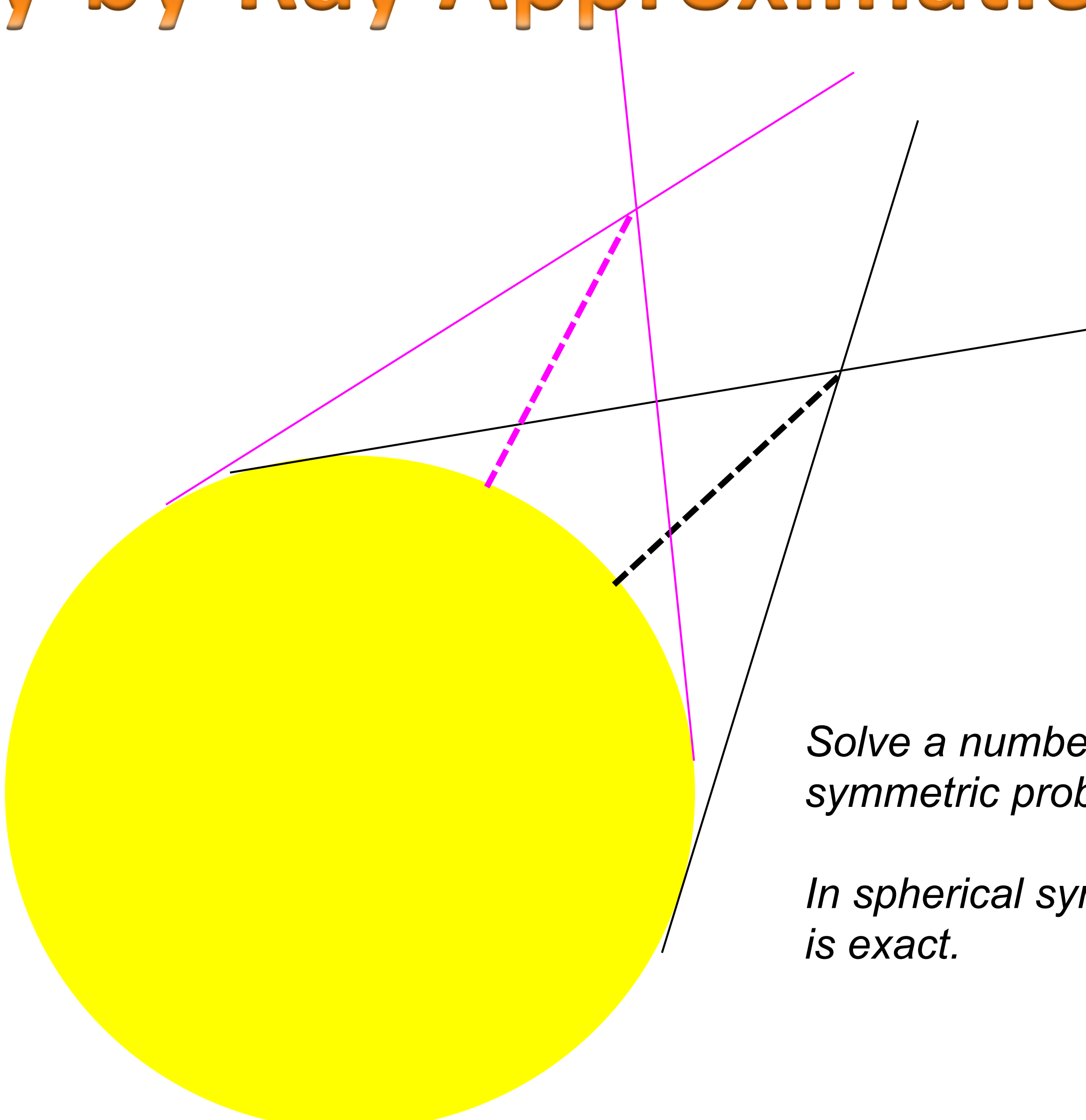
Comparisons of this and a CFA approach demonstrate that an effective potential approach is not sufficient.



Mueller, Janka, and Marek 2012 *Ap.J.* **756**, 84



Ray-by-Ray Approximation



Solve a number of spherically symmetric problems.

In spherical symmetry, RbR is exact.

see Skinner, Burrows, and Dolence 2016, *Ap.J.* **831**, 81 for a comparison with 2D transport
see Glas, Just, Janka, and Obergaulinger 2019 *Ap.J.* **873**, 45 for a comparison with 3D transport

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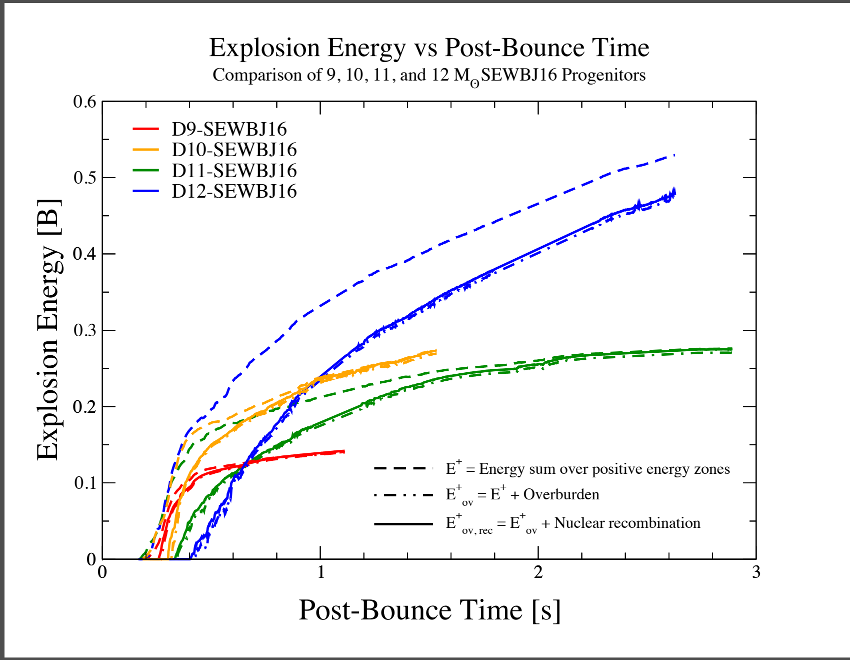
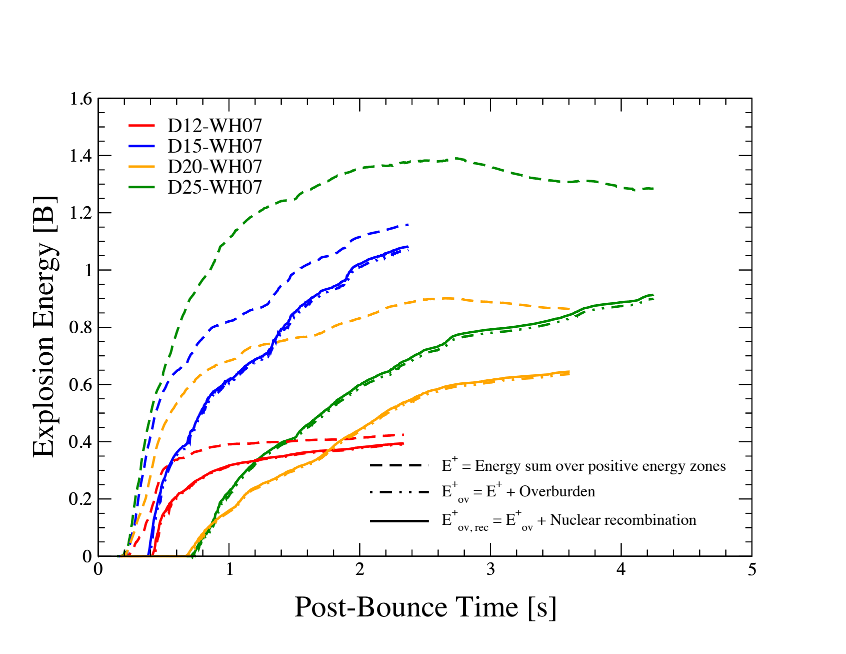
The Time Scale Challenge



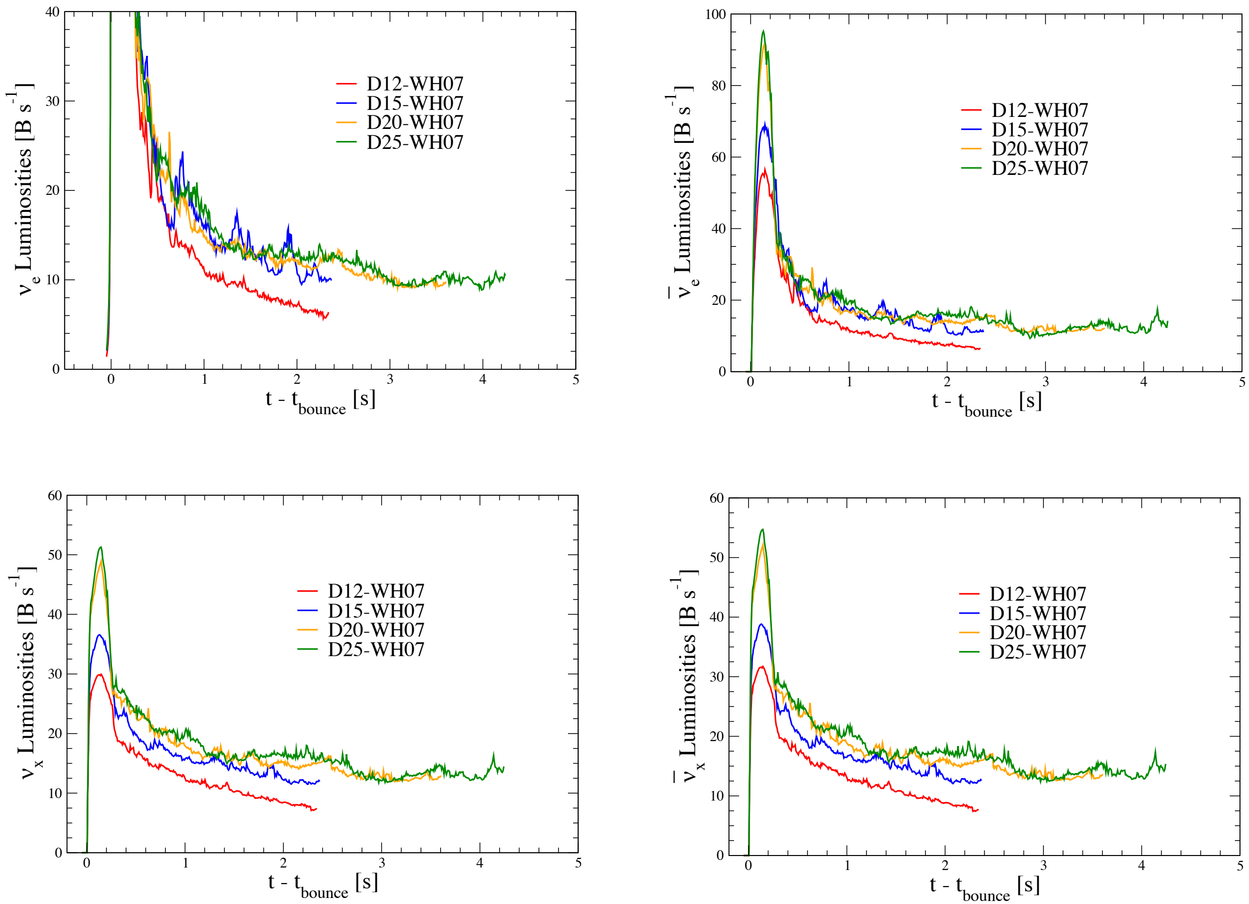


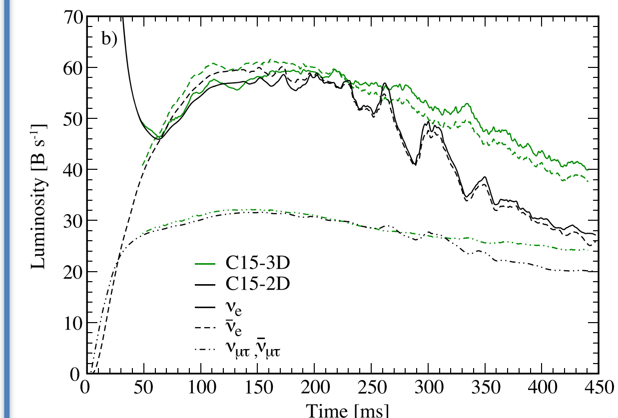
Bruenn et al. (2019), in preparation

Pushing to Late Times in the Context of Multi-Physics Simulations

What can we learn from 2D (self-consistent) explosion models about the late-time neutrino signature evolution?

Bruenn et al. (2019), in preparation





Lentz et al. (2015)

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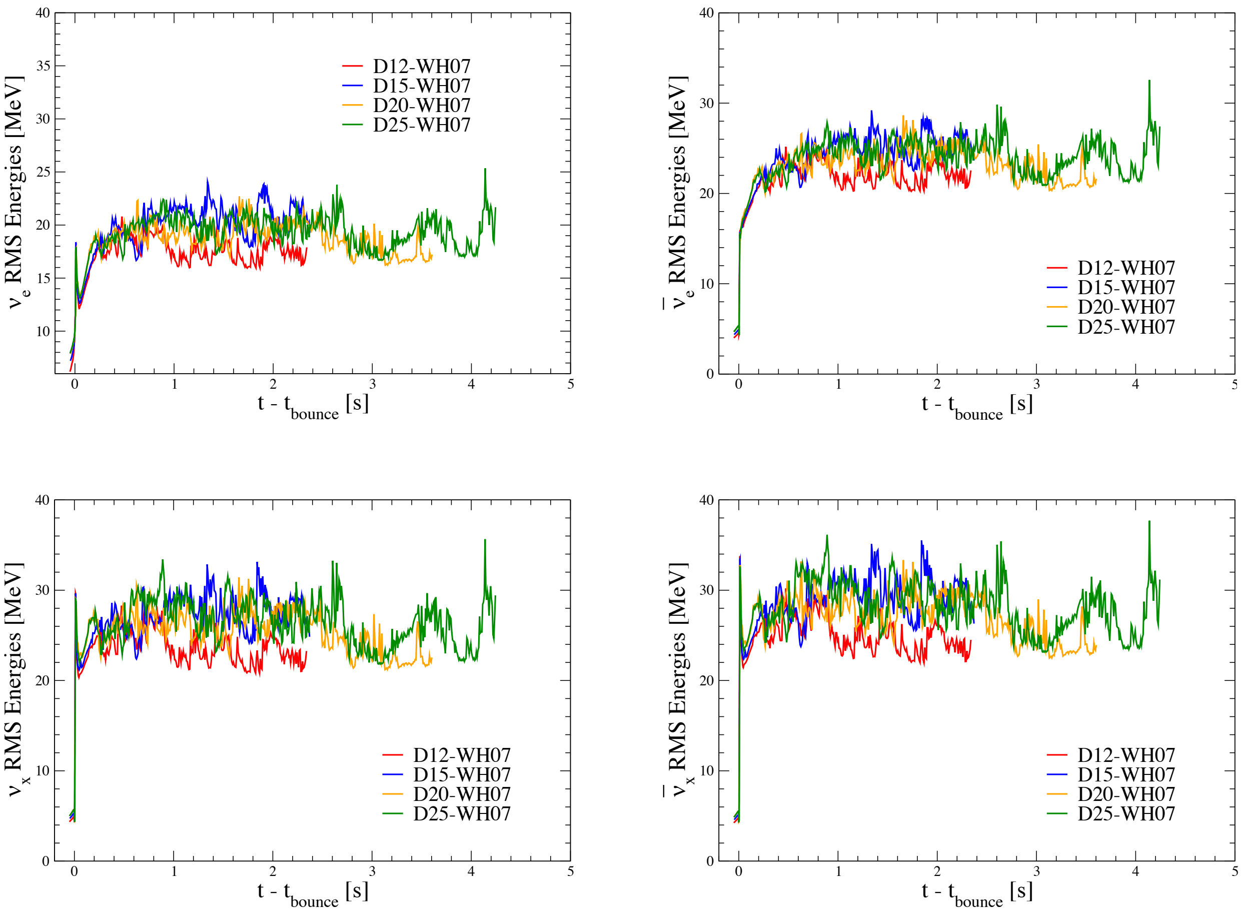

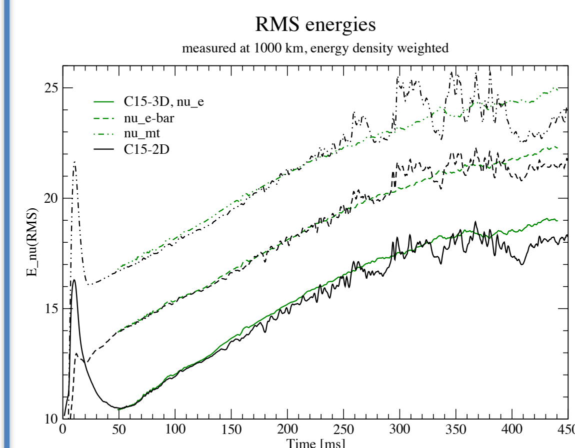

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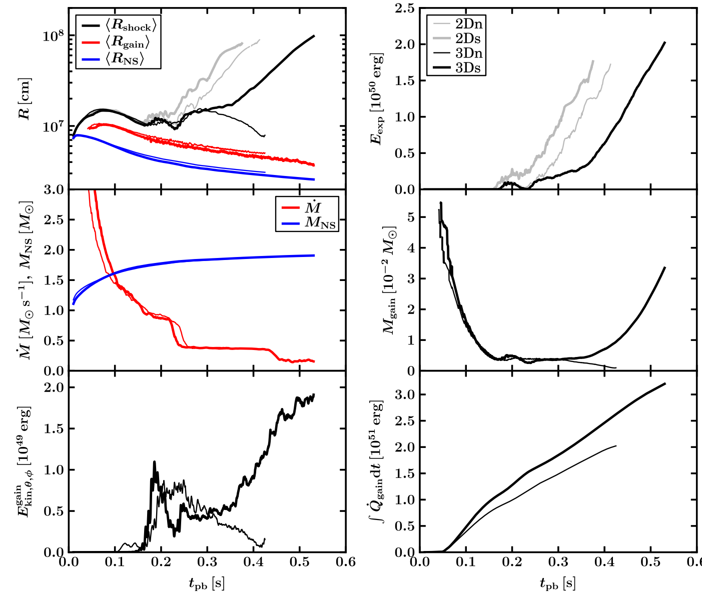
Keeping Pace with the Weak Interactions

Uncertainty: Uncertainty in things included in the models.

A 10% correction in the neutrino–nucleon scattering cross section consistent with the uncertainty in the strangeness content of the nucleon led to explosion in a model that otherwise failed to explode.



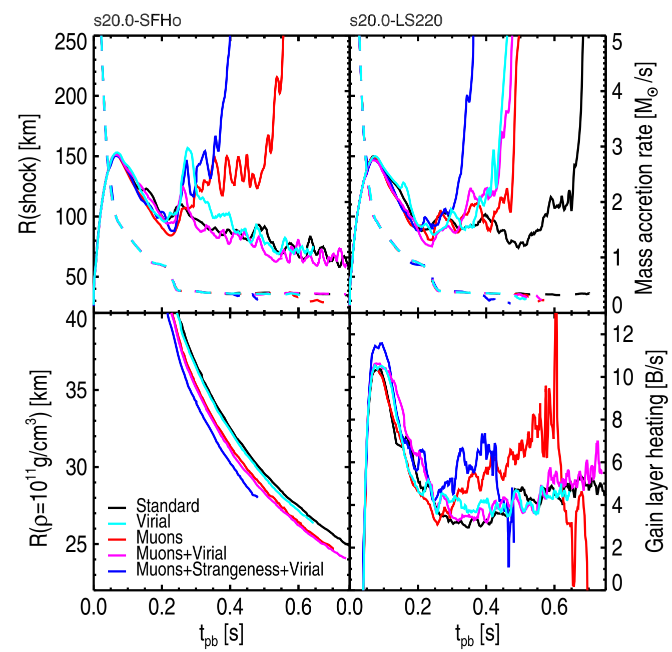
Melson, Janka, Bollig, et al. 2015 *Ap.J. Lett.* **808**, L42

Limitation: Model limitations due to things not yet included.

TABLE I. Neutrino reactions with muons.

$\nu + \mu^- \rightleftarrows \nu' + \mu^{-\prime}$	$\nu + \mu^+ \rightleftarrows \nu' + \mu^{+\prime}$
$\nu_\mu + e^- \rightleftarrows \nu_e + \mu^-$	$\bar{\nu}_\mu + e^+ \rightleftarrows \bar{\nu}_e + \mu^+$
$\nu_\mu + \bar{\nu}_e + e^- \rightleftarrows \mu^-$	$\bar{\nu}_\mu + \nu_e + e^+ \rightleftarrows \mu^+$
$\bar{\nu}_e + e^- \rightleftarrows \bar{\nu}_\mu + \mu^-$	$\nu_e + e^+ \rightleftarrows \nu_\mu + \mu^+$
$\nu_\mu + n \rightleftarrows p + \mu^-$	$\bar{\nu}_\mu + p \rightleftarrows n + \mu^+$

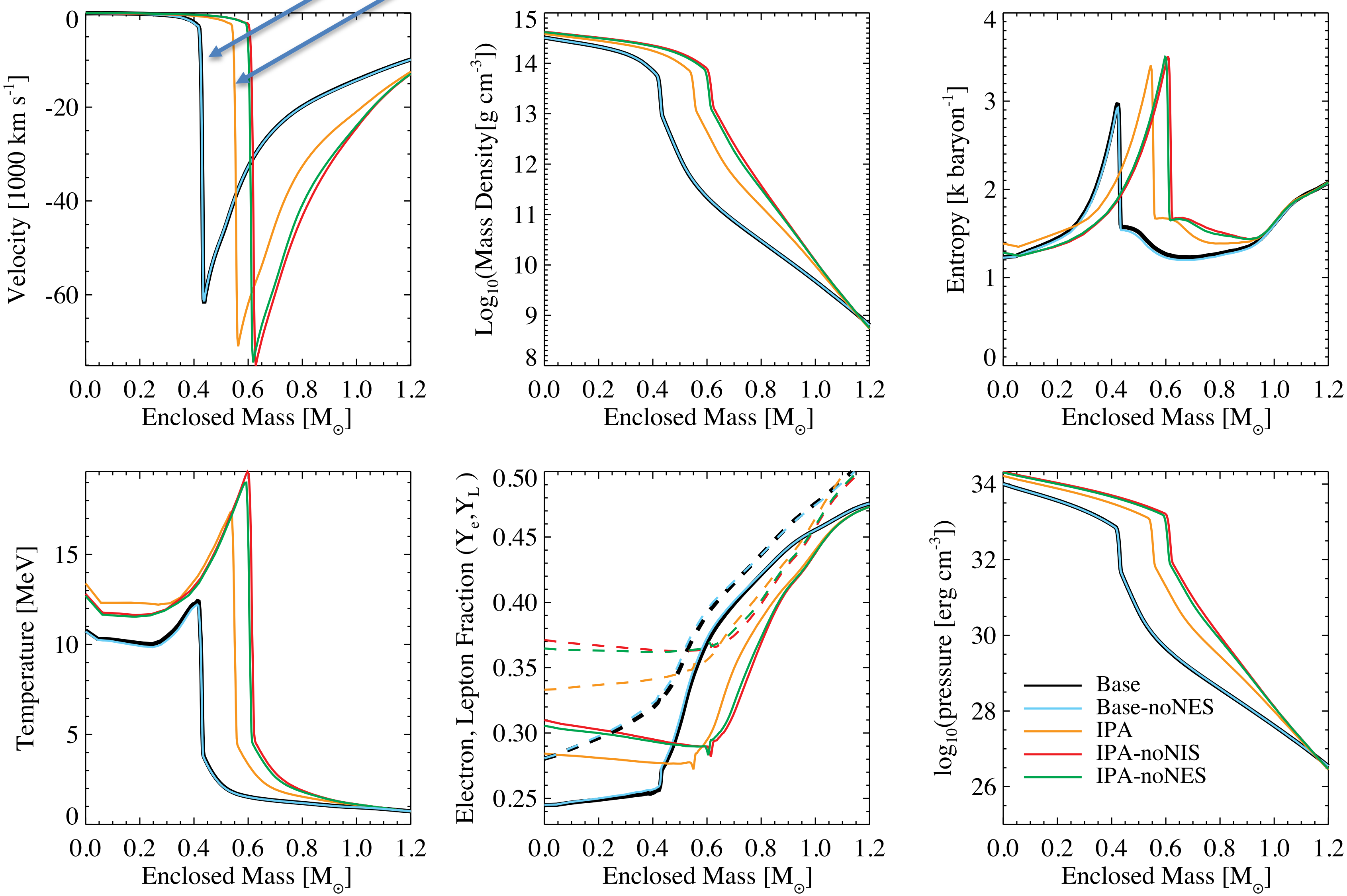
The inclusion of muons led to explosion in a model that otherwise failed to explode.



Bollig, Janka, et al. 2017 PRL **119**, 242702

Lentz, AM, Messer et al. (2012): The interplay between opacity improvements is complex. Calls into question the efficacy of varying a single opacity. A true sensitivity study in 3D would be difficult to conduct.

NES added to model with Langanke et al. (2003) electron capture rates.
NES added to model with Bruenn (1985) electron capture rates.



Lentz, AM, Messer et al. 2012, *Ap.J.* **760**, 94

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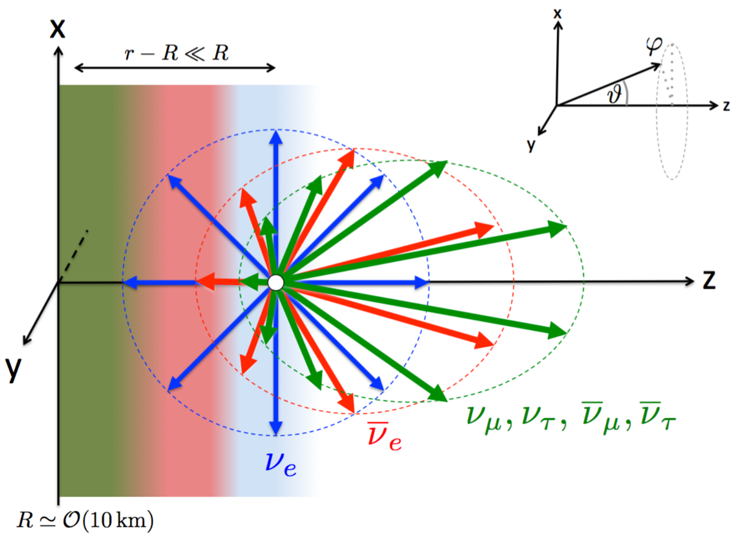
Neutrino Quantum Kinetics

Neutrino flavor evolution is complicated by neutrino–neutrino interactions, which affect all neutrinos at all energies – i.e., the entire ensemble of neutrinos – collectively.

- Duan, H., Fuller, G. M., & Qian, Y.-Z. 2010, ARNPS **60**, 569
- Chakraborty, S., Hansen, R., Izaguirre, I., & Raffelt, G. G. 2016a, NuPhB **908**, 366
- Mirizzi, A., Tamborra, I., Janka, H.-T., et al. 2016, NCimR **39**, 1



Dasgupta, Mirizzi, and Sen, JCAP 1702, 019 (2017)

If ν_e and $\overline{\nu}_e$ angular distributions are sufficiently different, “fast flavor instabilities” in the vicinity – i.e., within *O*(m) – of the neutrinospheres may be triggered.

- Sawyer, R. F. 2005, PRD **72**, 045003

Impact on the explosion mechanism?

Tamborra et al., *Ap.J.* **839**, 132 (2017)
Dasgupta, Mirizzi, and Sen, JCAP **1702**, 019 (2017)
Abbar, Duan, Sumiyoshi, Takiwaki, and Volpe, arXiv:1812.06883v1

Have demonstrated that conditions for fast flavor conversion near the neutrinospheres may in fact exist.

For recent steps in the direction of developing a QKE capability for CCSN simulation and a glimpse at the computational requirements see Richers, McLaughlin, Kneller, and Vlasenko: arXiv:1903.00022v1.

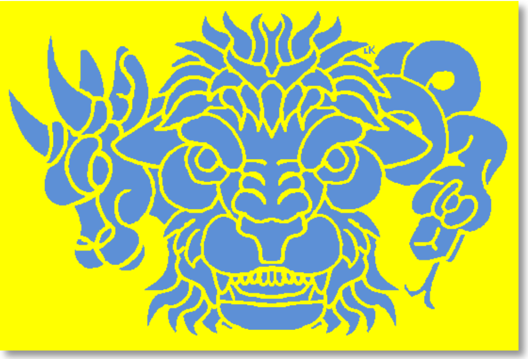
Outlook

- There has been significant progress to date and progress is accelerating. Numerous 3D multi-physics simulations are now being performed.
- The results obtained by the leading groups thus far indicate that neutrino driven explosions are possible. This was an open question for some time. In this sense, there is more agreement than disagreement among the groups.
- Some of the predicted outcomes have been shown to be consistent with observations.
- Full consistency across groups for the same "problem set" is still "under development."
- It will take the next decade or more for 3D modeling to mature.
- It will be difficult to carry out a sufficient number of 3D models spanning progenitor mass, metallicity, rotation, and other characteristics, for sufficiently long periods of time to determine all explosion outcomes quantitatively.
- It will be impossible for some time to perform sensitivity studies in 3D that take into account the nonlinear interplay of neutrino opacities.
- If neutrino quantum kinetics plays a role in the explosion mechanism, it will be some time before we have 3D full-physics models to assess precisely the role it plays.

CHIMERA Collaboration

Oak Ridge National Laboratory

The University of Tennessee Knoxville



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