Core Collapse Supernova (Neutrino) Modeling: Assessing Progress, Future Challenges

What can we say about core collapse supernova neutrinos?

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Outline

What will it take to model core collapse supernova neutrinos?

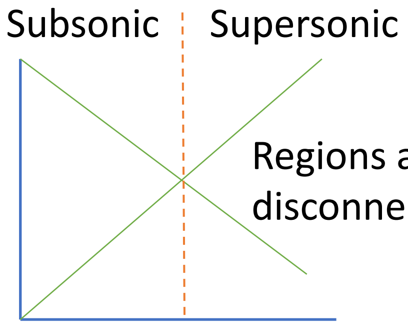
Where do these modeling efforts stand?

What implications does this have for what we can say about them now?

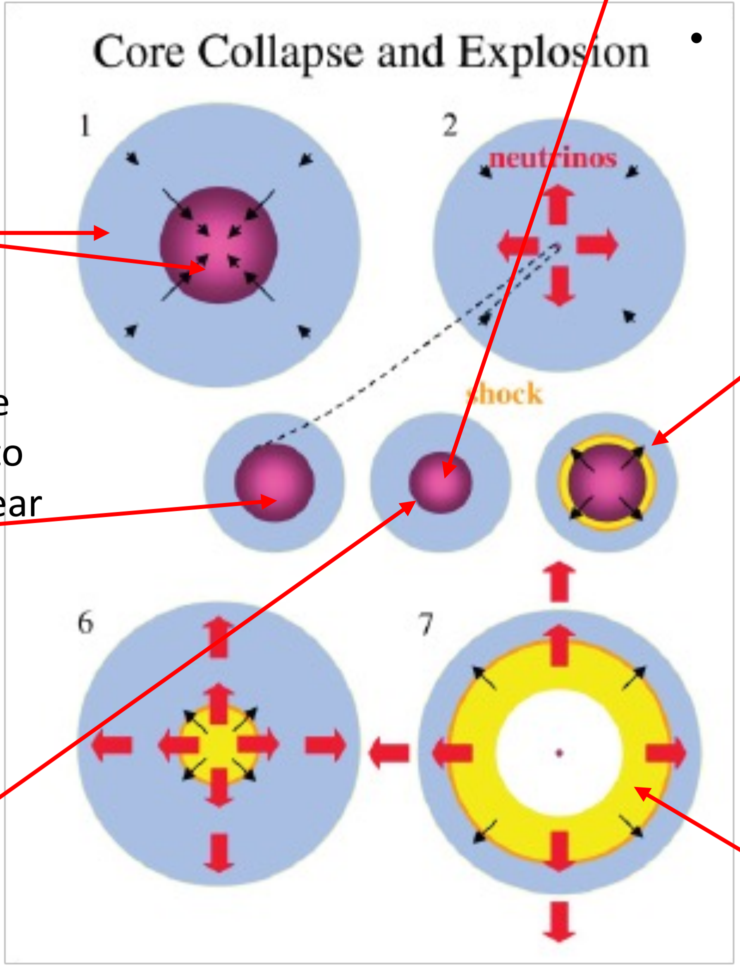
What's lies ahead?

Core Collapse Supernova Paradigm and Problem Description

- Sound speed decreases with radius (density).
- Infall velocity increases with radius.

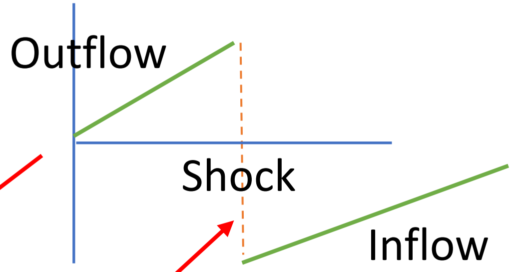


Regions are sonically disconnected.



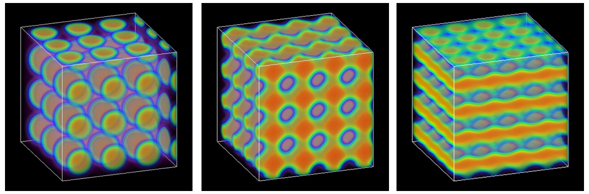
Maximum scrunch.

- Fermi-Dirac Statistics
- Nucleon – nucleon interaction potential’s hard core.



Shock propagation dictated by shock “jump conditions.”

Phase transition from nuclei (dense phase) and nucleons (light phase) to bulk nuclear matter through “nuclear pasta” phases.



$$e^- + p \rightarrow \nu_e + n$$
$$e^- + A \rightarrow \nu_e + A'$$

Electron capture dictates inner-core size.

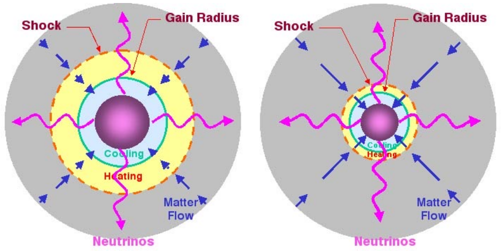
Shock stalls due to neutrino and nuclear dissociation losses.

Necessary Model Components

Three-Dimensional General Relativistic Gravity

Newtonian General Relativistic

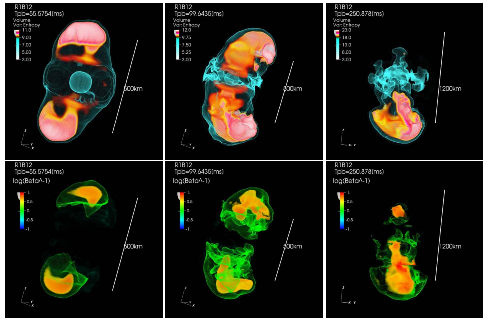
25 M Model



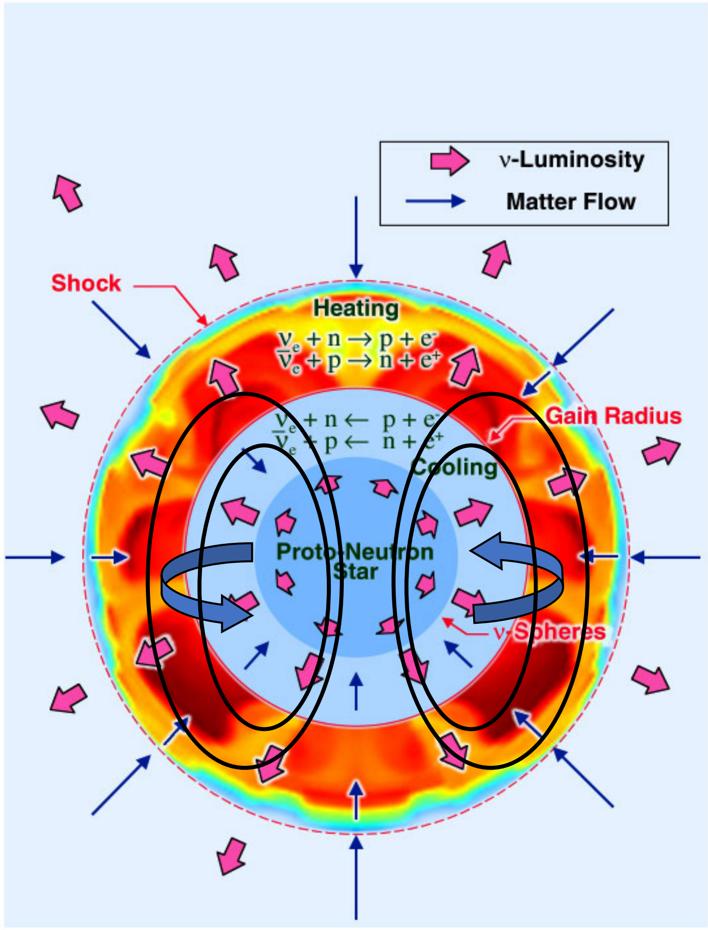
Bruenn, DeNisco, and Mezzacappa, *Ap.J.* **560**, 326 (2001)

Three-Dimensional General Relativistic Magnetohydrodynamics

- Turbulent Convection
- Standing Accretion Shock Instability
- Slow to Rapid Progenitor Rotation
- Magnetic Isotropic Pressure and other MHD Stresses



Kuroda, Arcones, Takiwaki, and Kotake *Ap.J.* **896**, 102 (2020)



Microphysics

Extensive Set of Weak Interactions
State-of-the-Art Implementations of Them

Suitably Constrained Nuclear Equation of State

Three-Dimensional General Relativistic Neutrino Kinetics

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

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

$f(t, r, \theta, \varphi, \varepsilon, \theta_p, \varphi_p)$ Required

$\{I, \boldsymbol{H}\}(t, \boldsymbol{z}) = \int f(t, \boldsymbol{z}, \omega)\{1, \boldsymbol{\ell}\}d\omega$ Feasible

Requires a closure prescription. Closure must be realizable.

$$\boldsymbol{K}(\boldsymbol{z}, t) = \int f(t, \boldsymbol{z}, \omega)\boldsymbol{\ell}\otimes\boldsymbol{\ell}\,d\omega$$

$$\boldsymbol{k} = \frac{1}{2}[(1-\chi)\mathrm{I} + (3\chi - 1)\boldsymbol{h}\otimes\boldsymbol{h}]$$

Eddington Factor

$$\boldsymbol{k} = \frac{\boldsymbol{K}}{I}, \boldsymbol{h} = \boldsymbol{\mathcal{H}}/|\boldsymbol{\mathcal{H}}|$$

Require conservation of lepton number and energy.

Mezzacappa, Endeve, et al. *Liv. Rev. Comp. Astr.* **6**, 4 (2020)

Relevant Neutrino Interactions

Beta processes:	• $e^- + p \rightleftharpoons n + \nu_e$ • $e^+ + n \rightleftharpoons p + \bar{\nu}_e$ • $e^- + A \rightleftharpoons \nu_e + A^*$
Neutrino scattering:	• $\nu + n, p \rightleftharpoons \nu + n, p$ • $\nu + A \rightleftharpoons \nu + A$ • $\nu + e^\pm \rightleftharpoons \nu + e^\pm$
Thermal pair processes:	• $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$ • $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$
Neutrino-neutrino reactions:	• $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$ $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{ or } \bar{\nu}_\tau)$ • $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Janka et al. *Prog. Theor. Exp. Phys.* **2012**, 01A309

+

TABLE I. Neutrino reactions with muons.

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

Bollig et al. PRL **119**, 242702 (2017)

What I will mean by “Full Weak Physics” in a later slide:

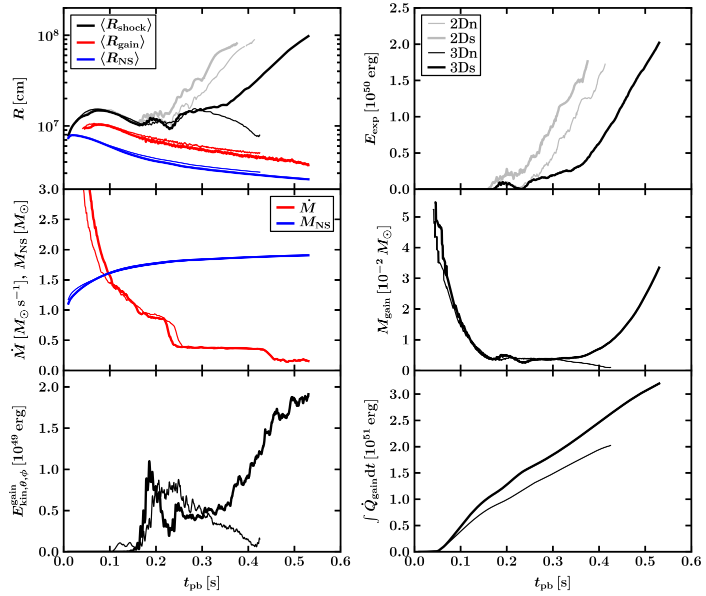
- Inclusion of all of the above weak interactions absent the neutrino–muon interactions.
- Use of state of the art rates for these interactions.

The computational cost is driven by the weak interactions included and how they are treated.

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.



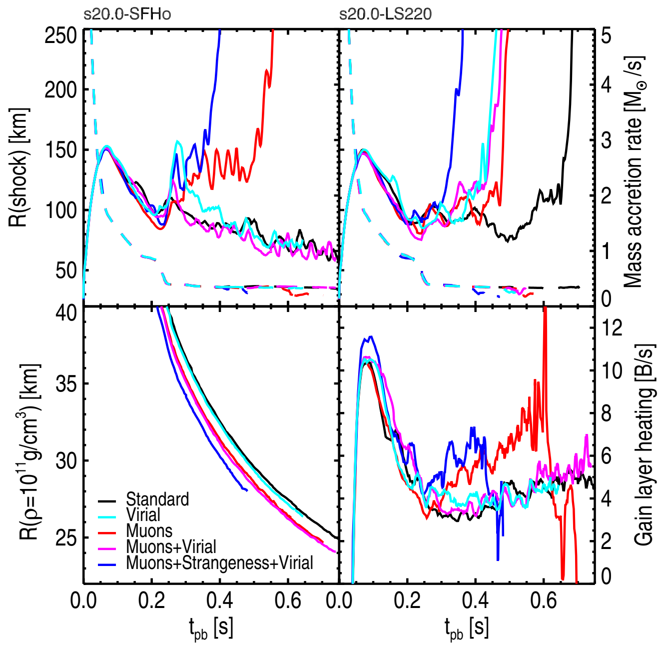
Melson, Janka, Bollig, et al. 2015 *Ap.J. Lett.* **808**, L42

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.

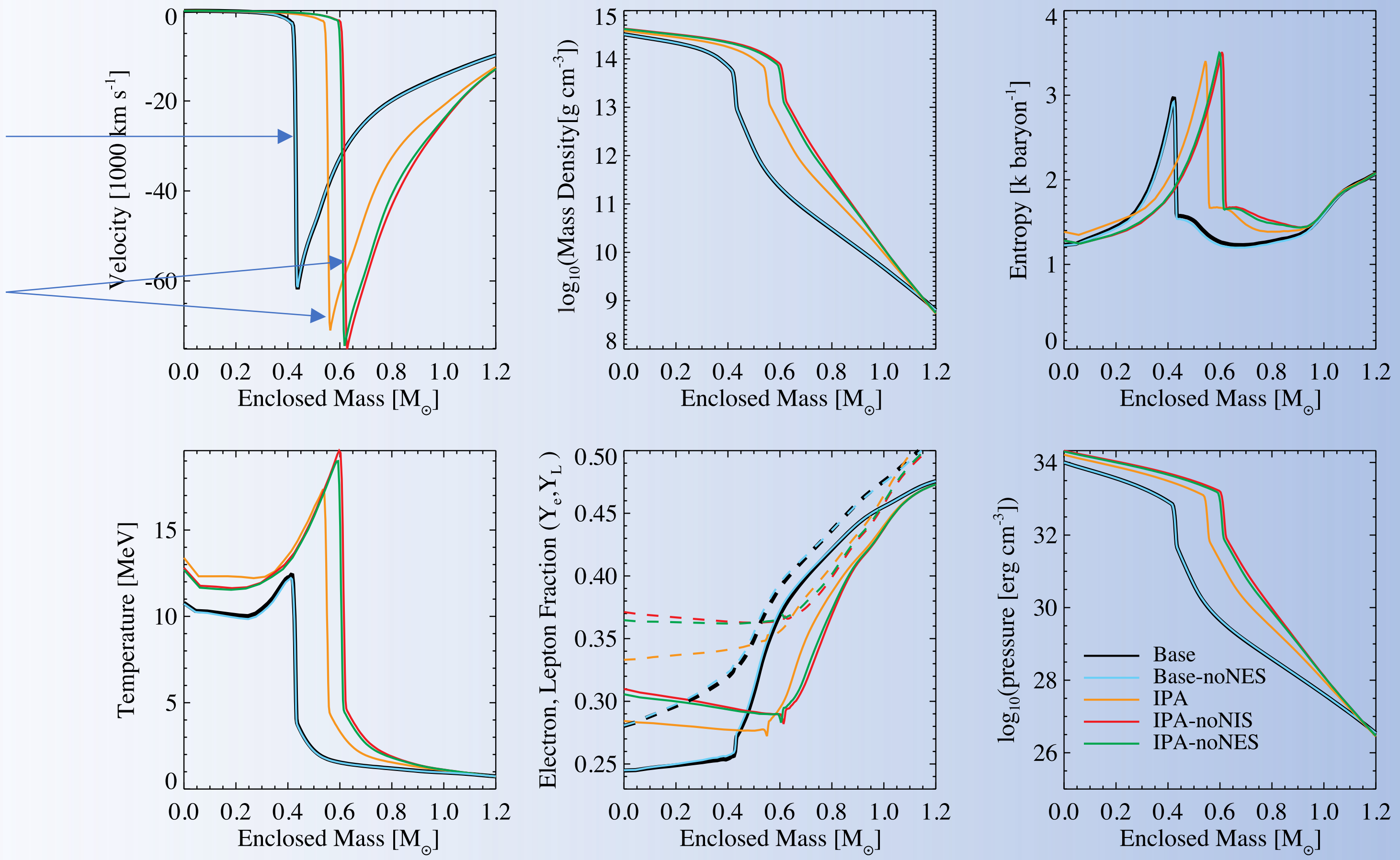


Bollig, Janka, et al. 2017 PRL **119**, 242702

The Interplay of Neutrino Opacities

NES vs. no-NES Hybrid Model

NES vs. no-NES IPA Model



Lentz et al. *Ap.J.* **760**, 94 (2012)

The interplay between opacity improvements is complex. Calls into question the efficacy of varying a single opacity.

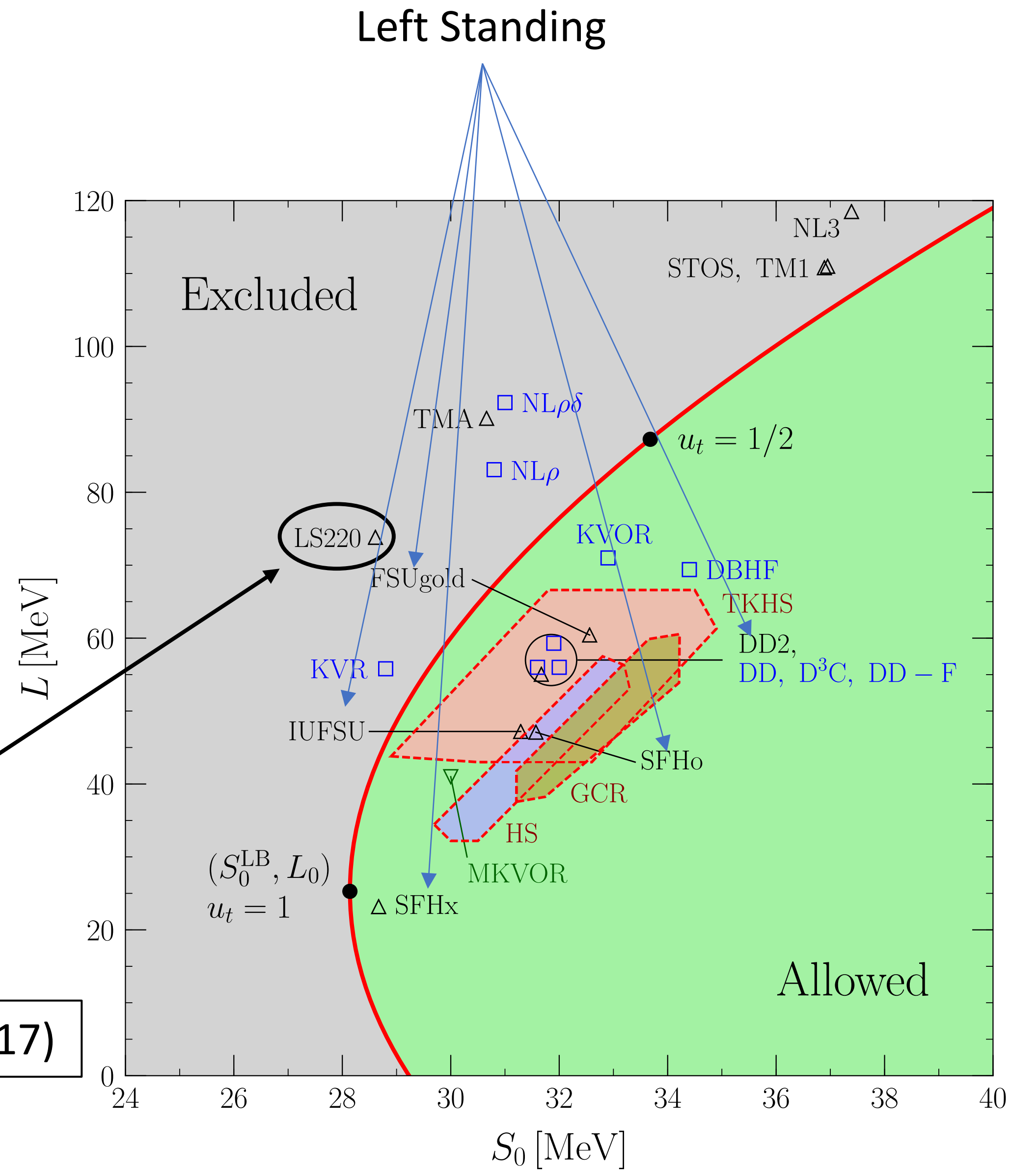
A true sensitivity study in 3D is not possible at this time.

Keeping Pace with the Nuclear Equation of State

The nuclear equation of state is increasingly constrained by

- nuclear experiment,
- relativistic heavy ion collisions,
- measurements of neutron star masses, and
- measurements of neutron star radii.

For a review, see Oertel et al. RMP **89** 015007 (2017).



Some equations of state used in past core collapse supernova simulations have been ruled out.

Tews et al. *Ap.J.* **848**, 105 (2017)

Status Report

The efficacy of the neutrino shock reheating/delayed shock mechanism has now been demonstrated by all leading groups across progenitor characteristics (mass, rotation, and metallicity).

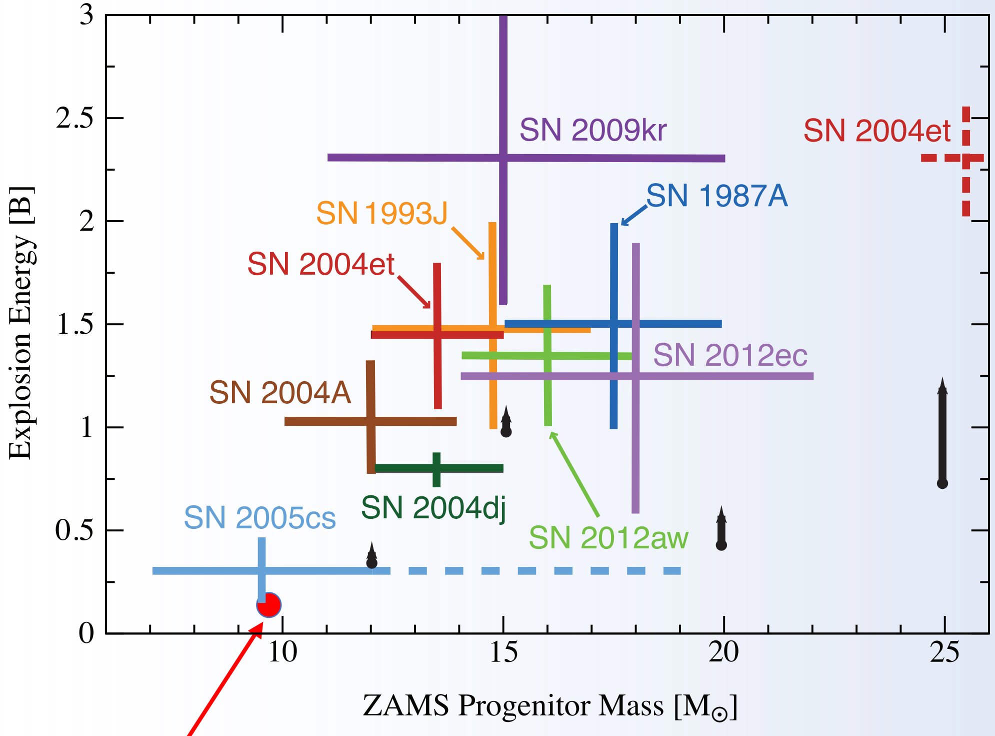
For recent reviews, see:

- Mueller, *Proceedings of the Astronomical Society of Australia* **33** e048 (2016)
- Janka, Melson, and Summa, *Ann. Rev. Nucl. Part. Sci.* **66** 341 (2016)
- Mueller, *Liv. Rev. Comp. Astr.* **6** 3 (2020)
- Mezzacappa, Endeve, Messer, and Bruenn, *Liv. Rev. Comp. Astr*. **6** 4 (2020)

Nonetheless, significant challenges remain.

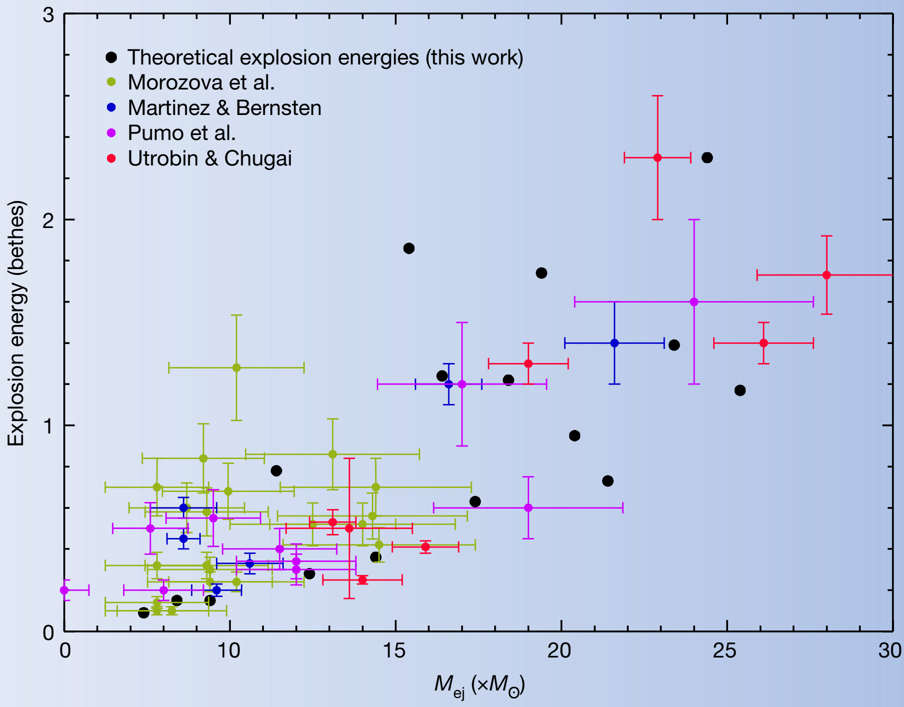
Transitioning to Quantitative Prediction

The following are based on 2D models:

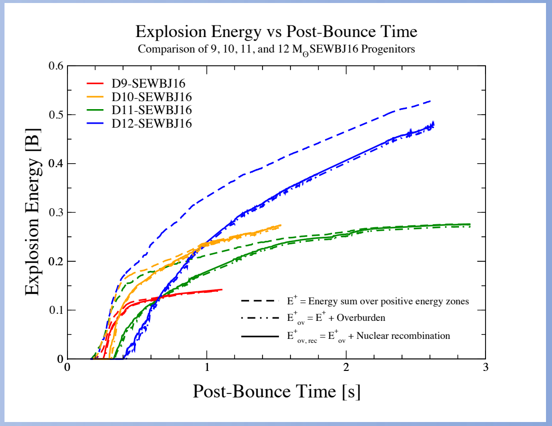


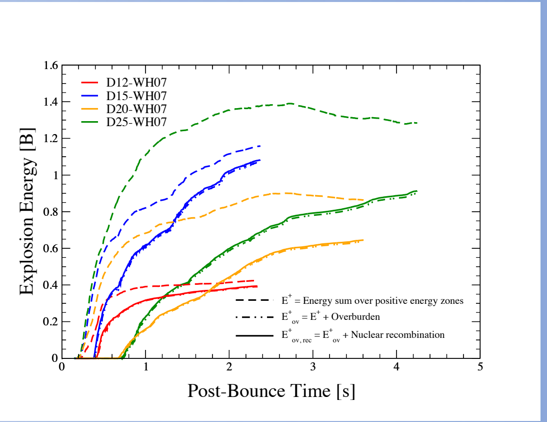
Bruenn et al. *Ap.J.* **818**, 123 (2016)

3D 9.6 M Model, Lentz et al. (2021), in preparation



Burrows and Vartanyan, *Nature*, **589**, 29 (2021)

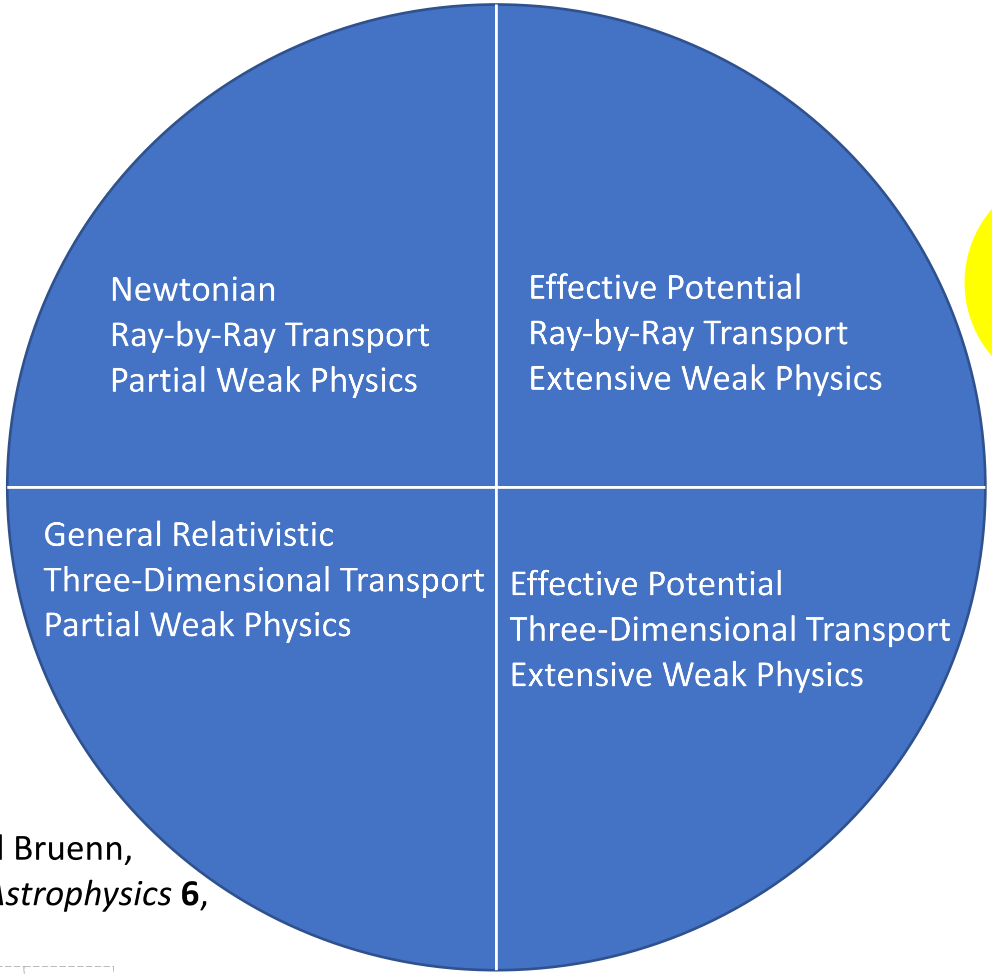


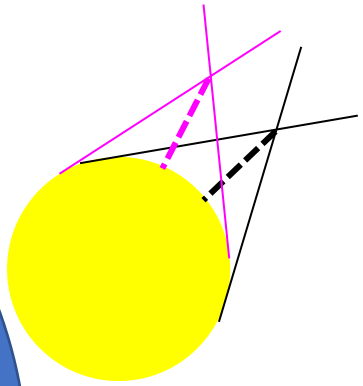


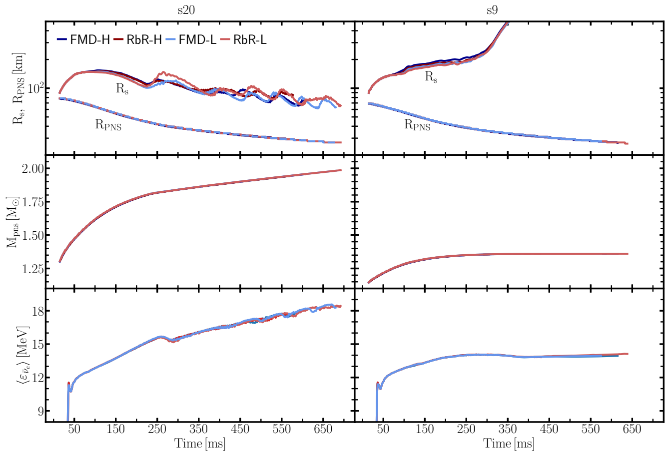
Bruenn et al. (2021), in preparation

Time scale over which explosion develops presents a significant challenge for 3D models.

3D State of the Art

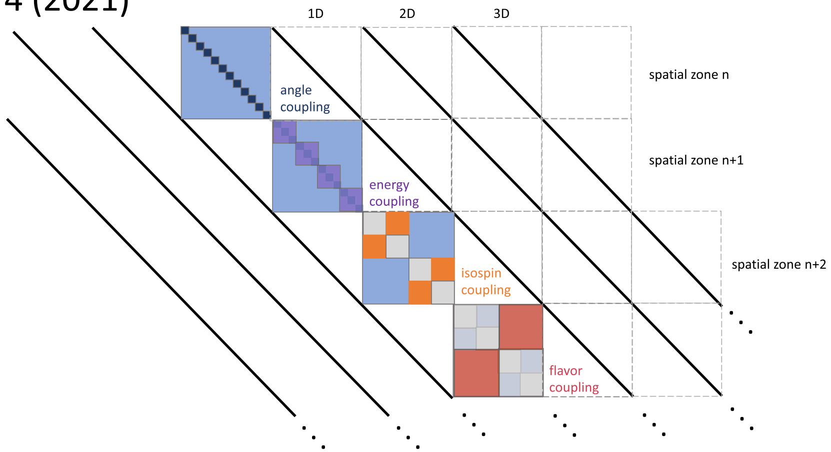






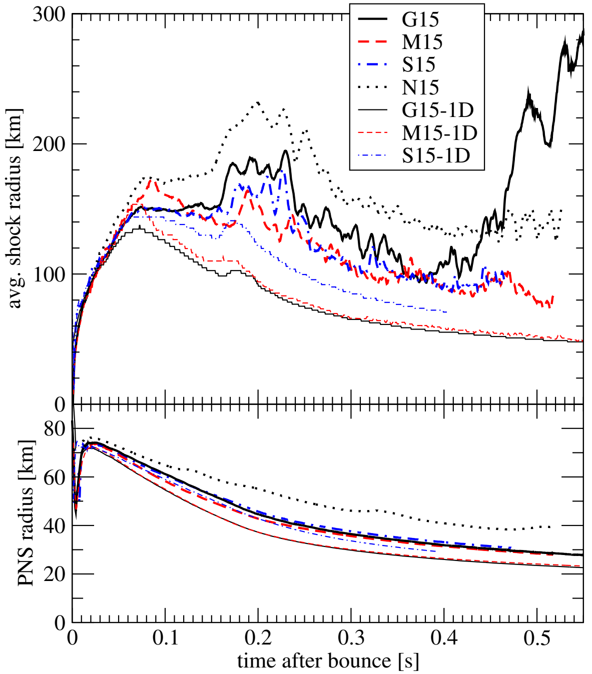
Andresen, Glas, and Janka MNRAS **503**, 3552 (2021)

Mezzacappa, Endeve, Messer, and Bruenn, *Living Reviews in Computational Astrophysics* **6**, 4 (2021)



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

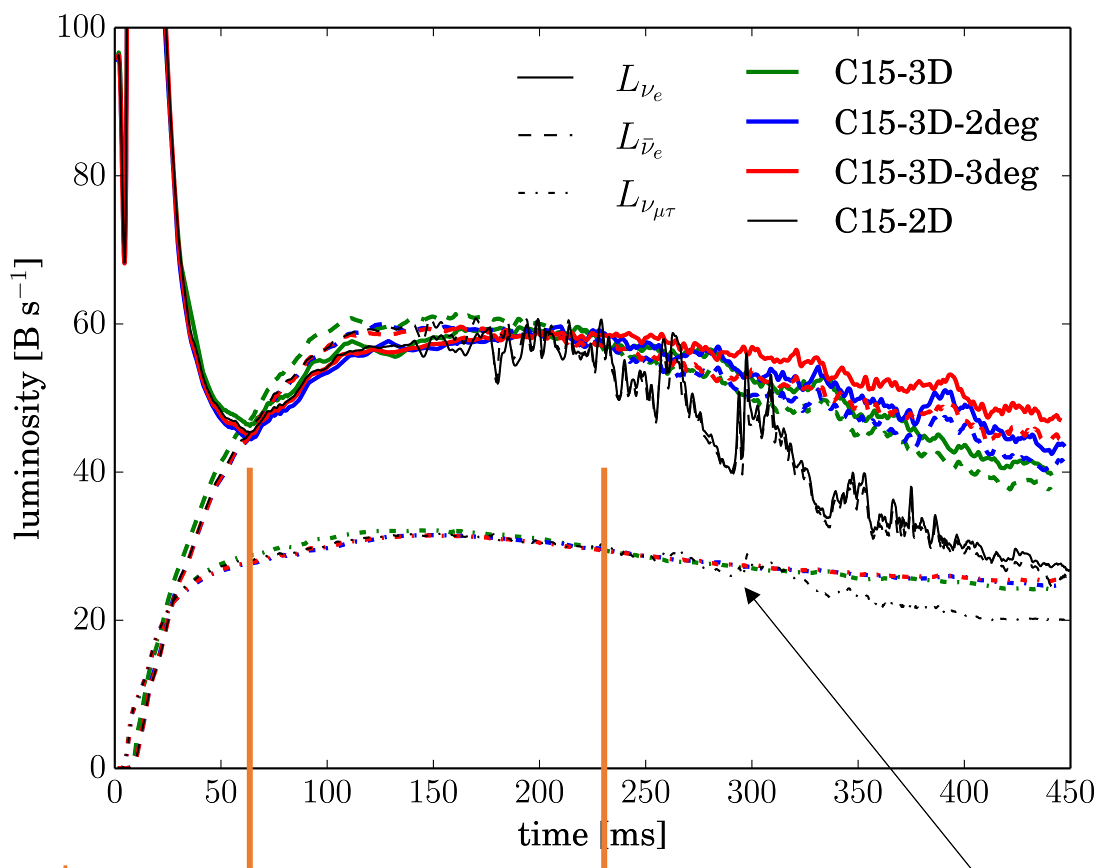
Rampp and Janka 2002 *A&A* **396**, 361



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

The Anatomy of a Core Collapse Supernova Neutrino "Light Curve"

Lentz et al. *Ap.J. Lett.* **807**, 31



electron neutrino burst

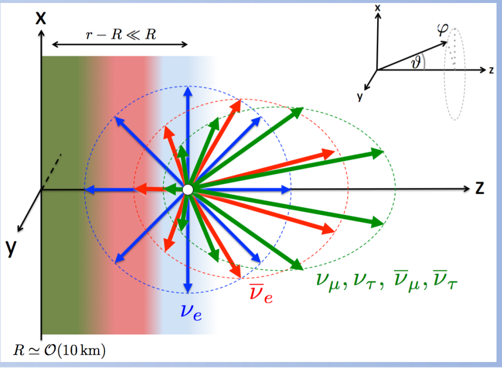
accretion phase

explosion phase

deeper neutrinospheres

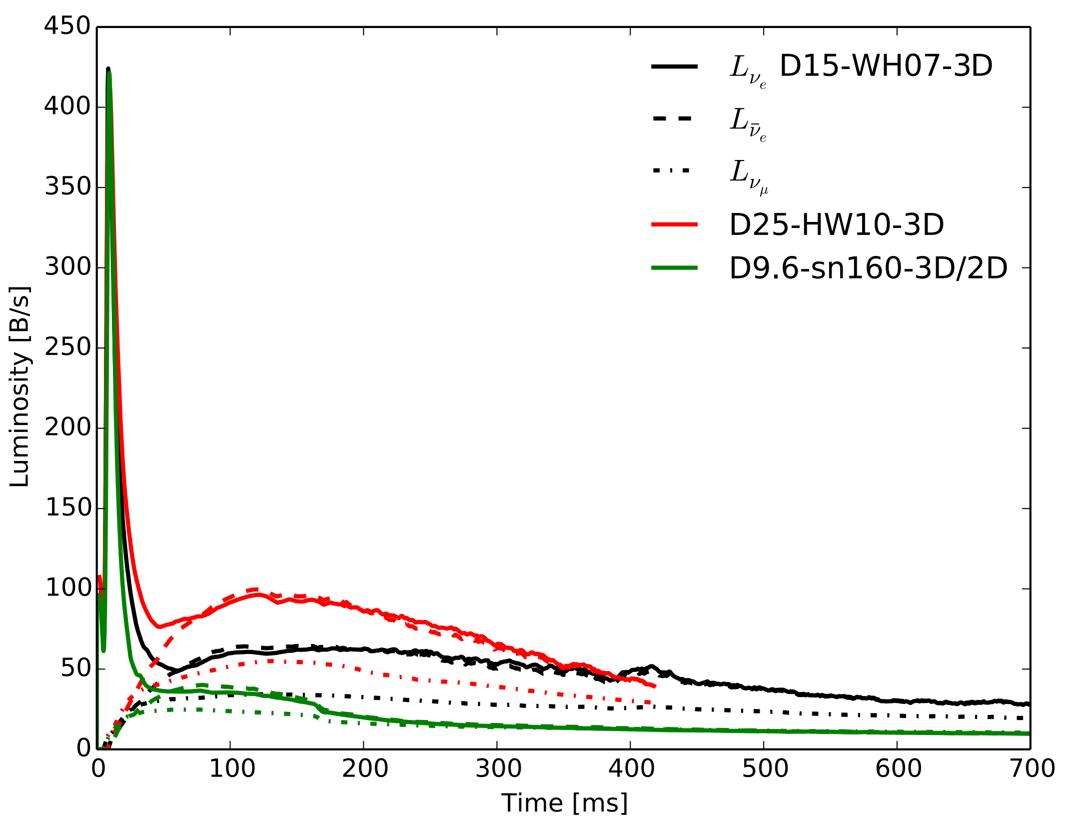
The following depend on the fidelity of the core collapse supernova (classical neutrino kinetics) modeling:

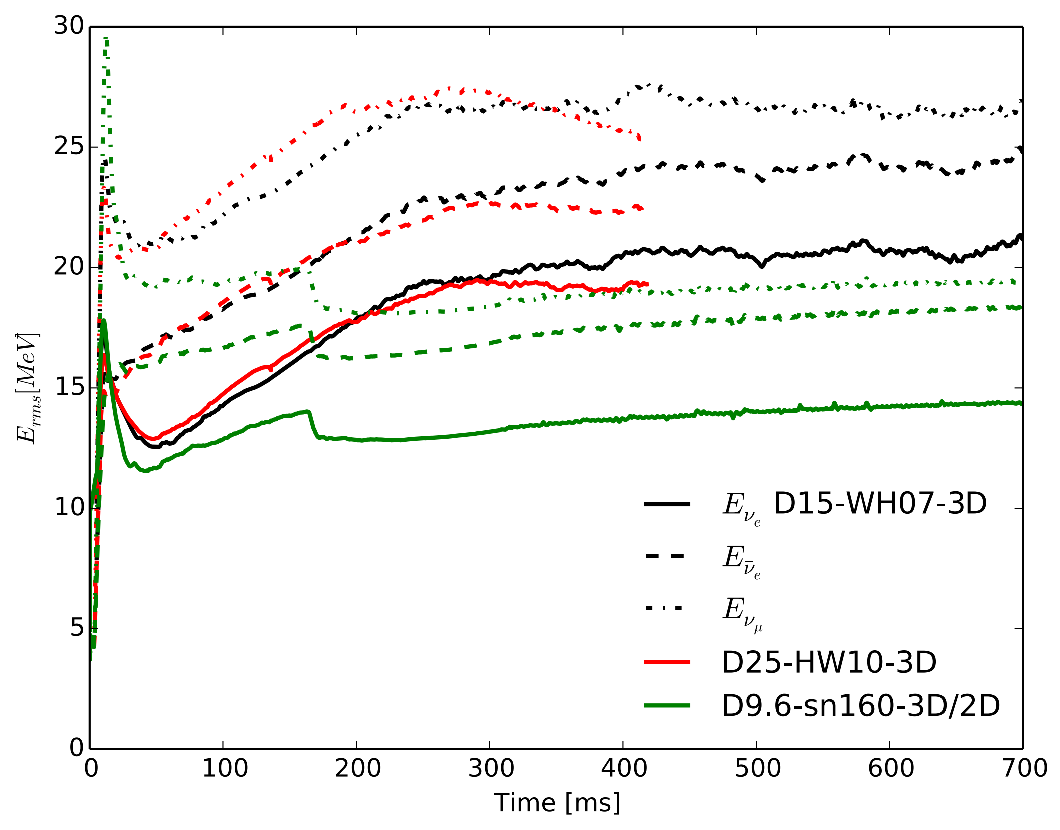
- explosion
- time to explosion
- duration of accretion phase
- neutrino fluence of the accretion phase
- neutrino fluence of the explosion phase
- evolution of the neutrino fluence
- temporal modulation of the neutrino fluence



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

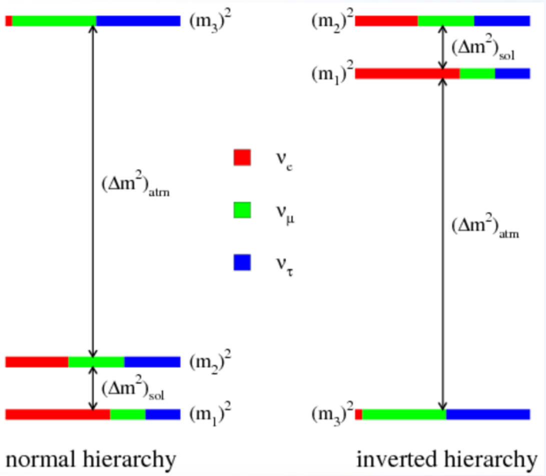
The Evolution of Core Collapse Supernova Neutrino Spectra





Lentz et al. (2022). In preparation.

Enter Neutrino Mass and Mixing



Think of the physics! Think of what we can learn!

Think of the temporal and spatial scales! Think of the resolution requirements! Think of the cost of the computations!

- Neutrinos have mass and can change flavor.
- Shock heating mediated by the electron-flavor neutrinos.
- The spectra are different across neutrino flavor.
- Impact on shock reheating?

$$\begin{matrix} f_{ee} & f_{e\mu} & f_{e\tau} \\ f_{\mu e} & f_{\mu\mu} & f_{\mu\tau} \\ f_{\tau e} & f_{\tau\mu} & f_{\tau\tau} \end{matrix}$$

Quantum Kinetics Equations

$$\begin{cases} p^\mu \dfrac{\partial f}{\partial x^\mu} - \Gamma^\mu_{\alpha\beta} p^\alpha p^\beta \dfrac{\partial f}{\partial p^\mu} = -p^\mu u_\mu \left(C - \dfrac{i}{\hbar c} [H, f] \right) \\ p^\mu \dfrac{\partial \bar{f}}{\partial x^\mu} - \Gamma^\mu_{\alpha\beta} p^\alpha p^\beta \dfrac{\partial \bar{f}}{\partial p^\mu} = -p^\mu u_\mu \left(\bar{C} - \dfrac{i}{\hbar c} [\bar{H}, \bar{f}] \right) \end{cases}$$

Richers, McLaughlin, Kneller, and Vlasenko 2019 PRD **99** 123014

A Common Theme: It's all about the Angular Distributions

Length and Time Scales Severe

e.g., length scale is O(1 cm) and typical CCSN radial resolution is O(100 m)

How do we couple this quantum evolution to the classical evolution?

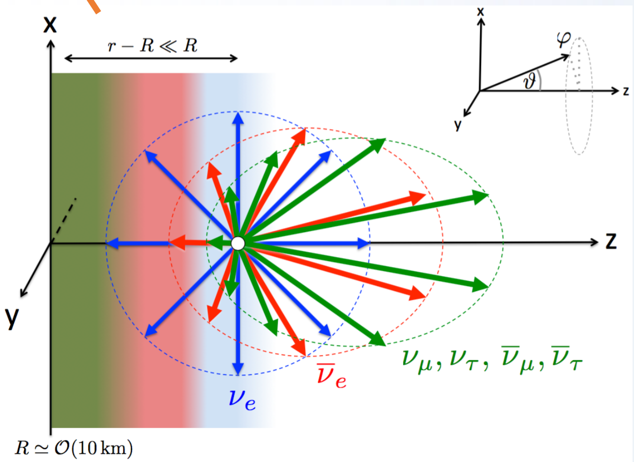
R_ν flavor mixing due to fast flavor instability

- Tamborra I. and Shalgar S. ARNPS 2021 **71**, 165

R_S flavor mixing due to neutrino forward scattering on neutrinos

- Duan, H., Fuller, G. M., & Qian, Y.-Z. 2010, ARNPS **60**, 569

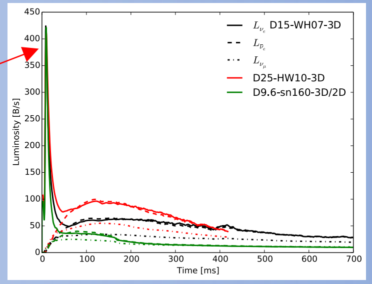
flavor mixing due to neutrino forward scattering on electrons MSW R_{star}



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

not as well understood

well understood



Observation of the electron neutrino burst or lack thereof could convey information about the mass hierarchy.

Takeaways

Recent progress has been great!

Multiple groups have demonstrated the efficacy of the neutrino heating mechanism over a range of progenitor characteristics, in three dimensions.

Current three-dimensional models have allowed us to study associated phenomena such as gravitational wave emission.

There is a great deal of development to be done to arrive at (classical) definitive three-dimensional models.

Full three-dimensionality.
Full general relativity.
Full physics (weak interaction physics, magnetic fields, …).
Full phase space.

And we need to run many models for a sufficiently long time.

Quantum kinetics looms large as a potential requirement, the development of which will occupy our community for some time.

We have a detailed picture for core collapse supernova neutrinos, but that picture can change in quantitative and qualitative ways given one or more considerations listed above.