# Core Collapse Supernova Neutrinos: Progress, Challenges, and Opportunities

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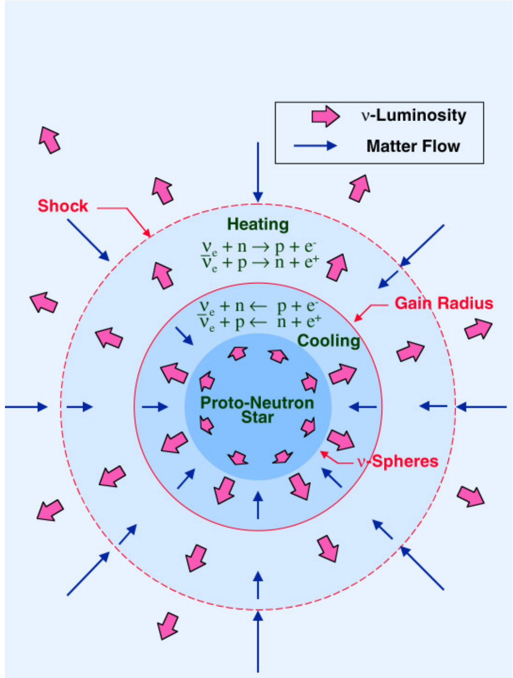
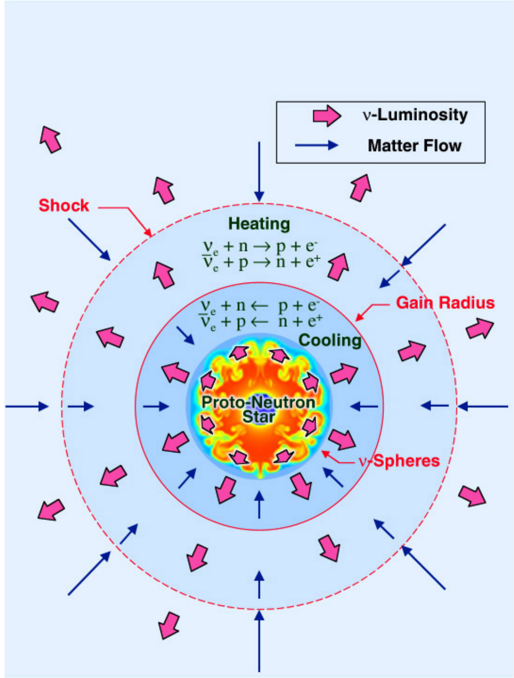
Seattle, WA
July 24 – 28, 2023

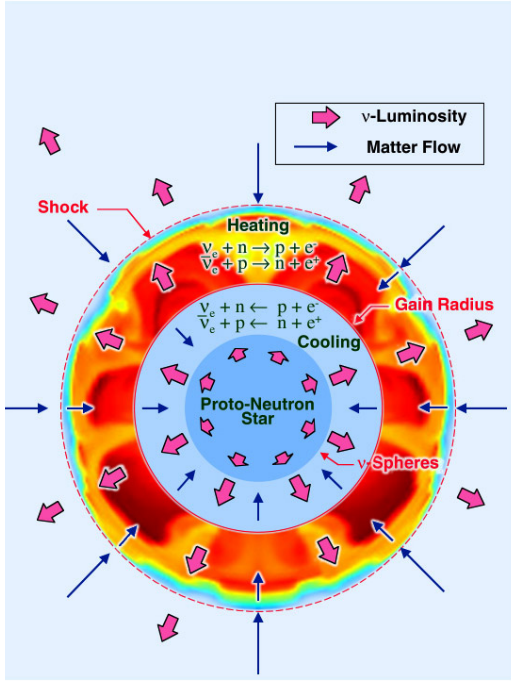
# Ingredients of a Neutrino-Driven Core Collapse Supernova Explosion



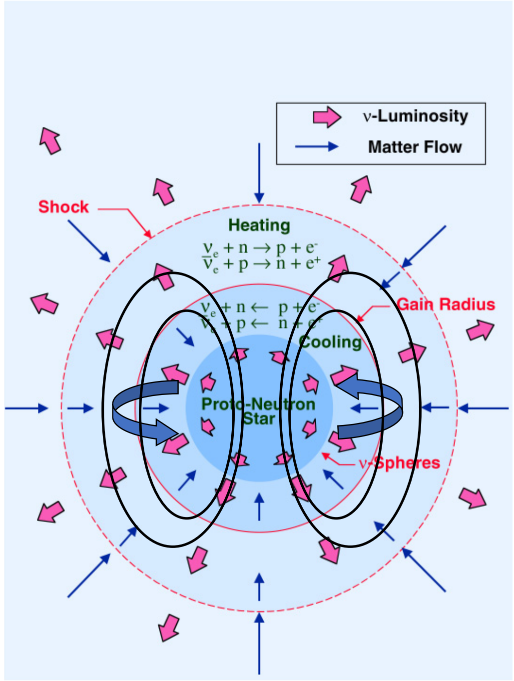
Neutrino Heating



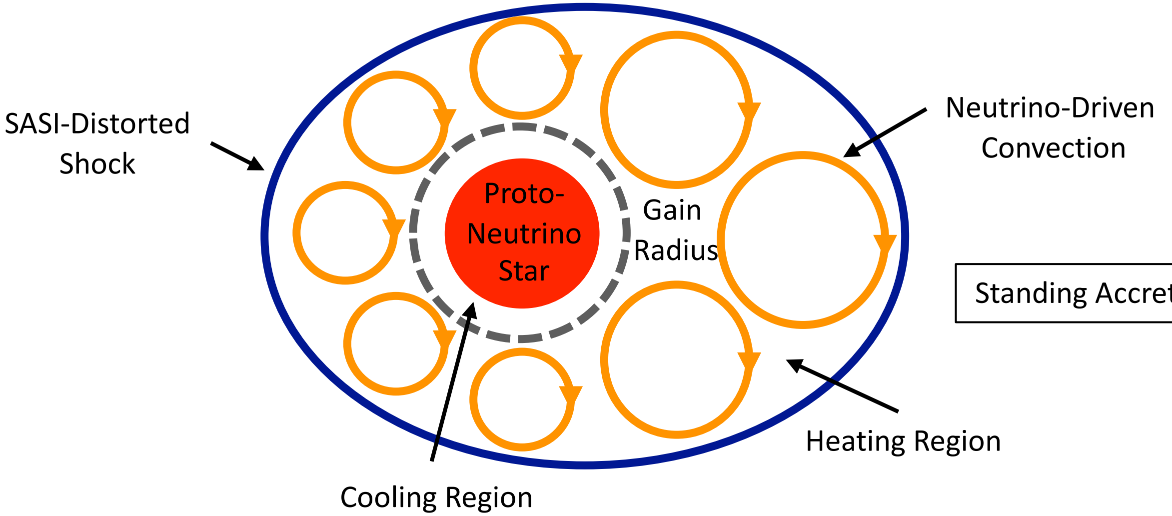
Proto-Neutron Star Instabilities



Neutrino-Driven Turbulent Convection



Rotation and Magnetic Fields



Standing Accretion Shock Instability (SASI)

# Progress

# Progress to Date

*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). Nonetheless, significant challenges remain. For recent reviews, see:*

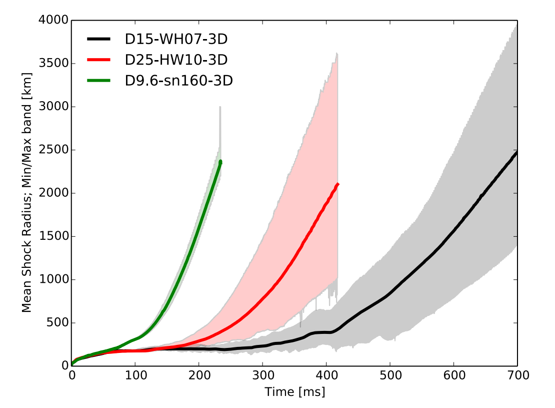
- Janka, Melson, and Summa, *Ann. Rev. Nucl. Part. Sci.* **66** 341 (2016)
- Mueller, *Liv. Rev. Comp. Astr.* **6**:3 (2020)
- AM, Endeve, Messer, and Bruenn, *Liv. Rev. Comp. Astr*. **6**:4 (2020)
- Burrows and Vartanyan, *Nature* **589**, 29 (2021)

*Among the first two 3D sophisticated CCSN explosion models, which ushered in contemporary CCSN modeling and theory.*
w/ Melson et al. *Ap.J. Lett*. **801**, L24 (2015)

## Chimera Models

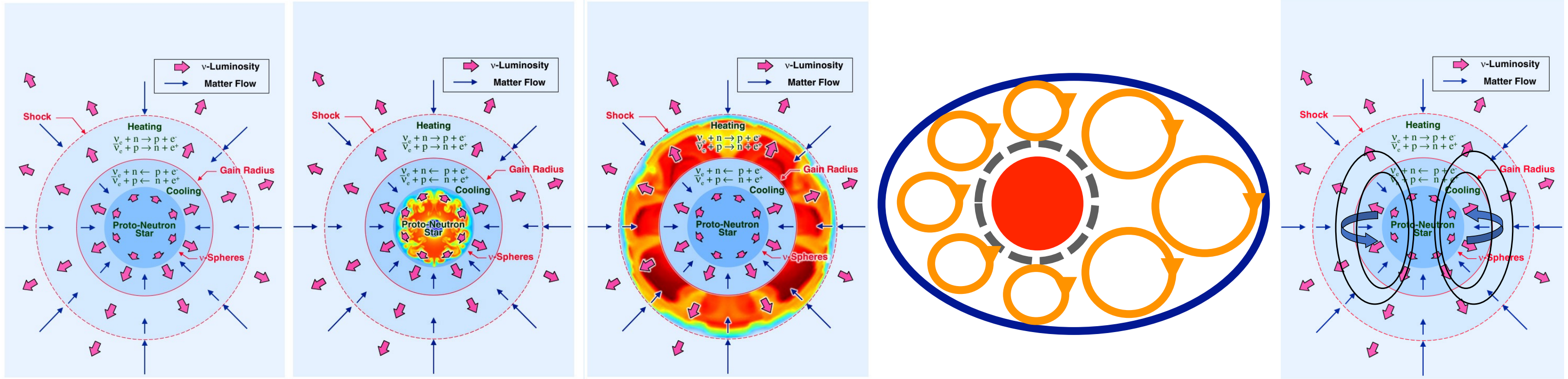
First 3D Chimera Model: Lentz et al. *Ap.J Lett.* **807** L31 (2015)

| Progenitor Mass (Solar Masses) | Metallicity | Rotation | B Fields | Progenitor Family/High-Density EOS | Explosion/ Shock Radius (km) | Post-bounce Time (ms)/ Explosion Energy (B) |
|---|---|---|---|---|---|---|
| 9.6 | Zero | N | N | Woosley and Heger (2015)/LS220 | Y/9467 | 467/0.167 |
| 15 | Solar | N | N | Woosley and Heger (2007)/LS220 | Y/1600 | 750+/? |
| 25 | Zero | N | N | Heger and Woosley (2010)/LS220 | Y/2200 | 500+/? |



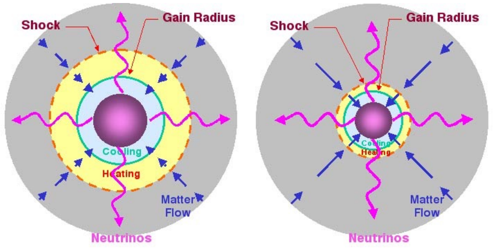
Lentz et al. (2023ab), in preparation
AM, Marronetti, Landfield, Lentz, et al. PRD **107**, 043008 (2023)

# Challenges



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

25 M
Model

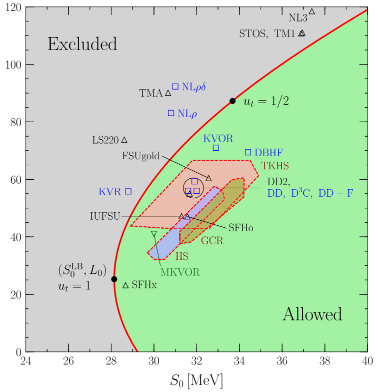


Newtonian GR

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

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

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



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

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)

Need:

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

$$\frac{1}{\sqrt{-g}} \frac{\partial}{\partial x^\mu} \left( \sqrt{-g} \mathscr{L}^{\mu}{}_{\hat{\mu}} p^{\hat{\mu}} f \right)$$
$$- E(\mathbf{p}) \left\| \det \left[ \frac{\partial \mathbf{p}}{\partial \mathbf{u}} \right] \right\|^{-1} \frac{\partial}{\partial u^{\hat{i}}} \left( \frac{1}{E(\mathbf{p})} \left\| \det \left[ \frac{\partial \mathbf{p}}{\partial \mathbf{u}} \right] \right\| \Gamma^{\hat{j}}{}_{\hat{\nu}\hat{\rho}} p^{\hat{\nu}} p^{\hat{\rho}} \frac{\partial u^{\hat{i}}}{\partial p^{\hat{j}}} f \right)$$
$$= \mathscr{C}[f],$$

Instead:

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

Requires a closure prescription.

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

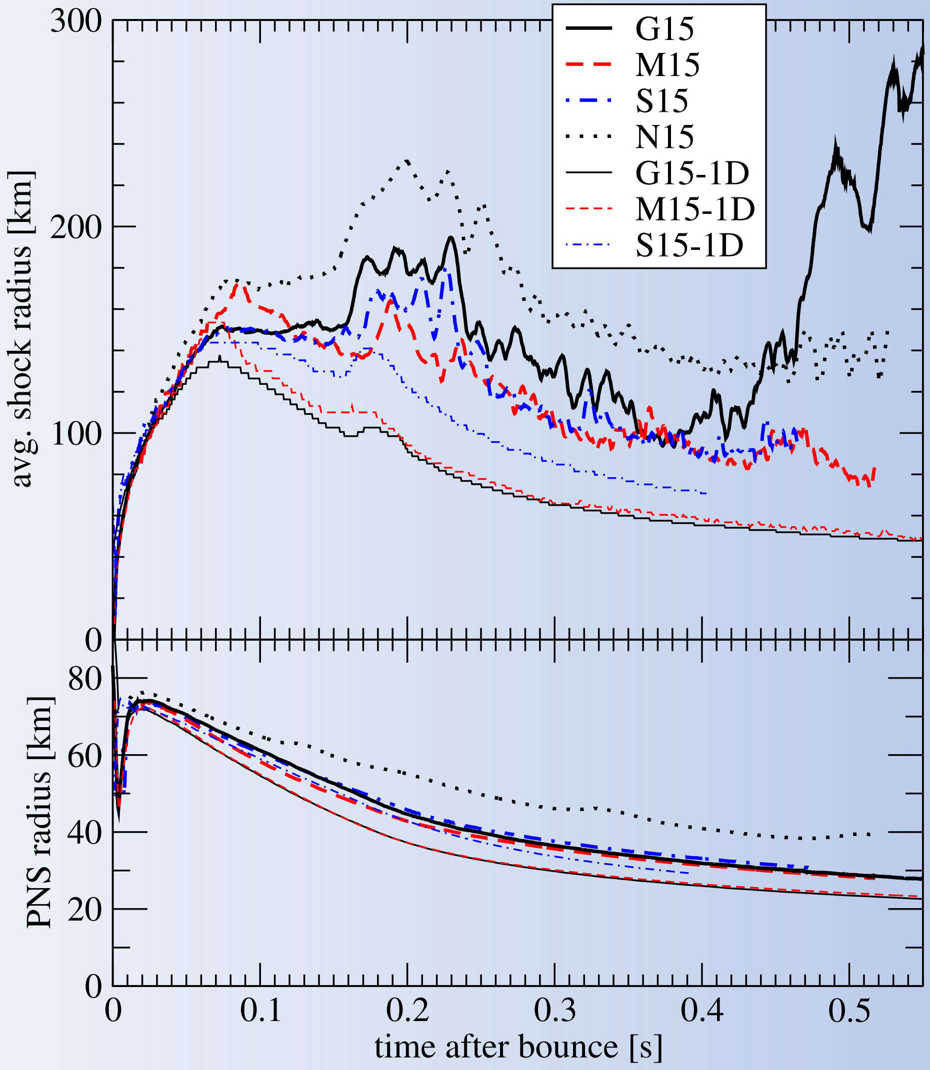
*Eddington Factor*

$$\boldsymbol{K} = \boldsymbol{K}(I, \boldsymbol{H}): \;\; \boldsymbol{k} = \frac{1}{2}[(1 - \underset{\downarrow}{\chi})\mathrm{I} + (3\chi - 1)\boldsymbol{h} \otimes \boldsymbol{h}]$$

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

*To date, only one three-dimensional, general relativistic, spectral-two-moment model with an extensive suite of up-to-date weak interactions and an allowed EOS has been published:) Kuroda Ap.J.* ***906****, 128 (2021).*

# Effective Potential vs. General Relativity



GR Model

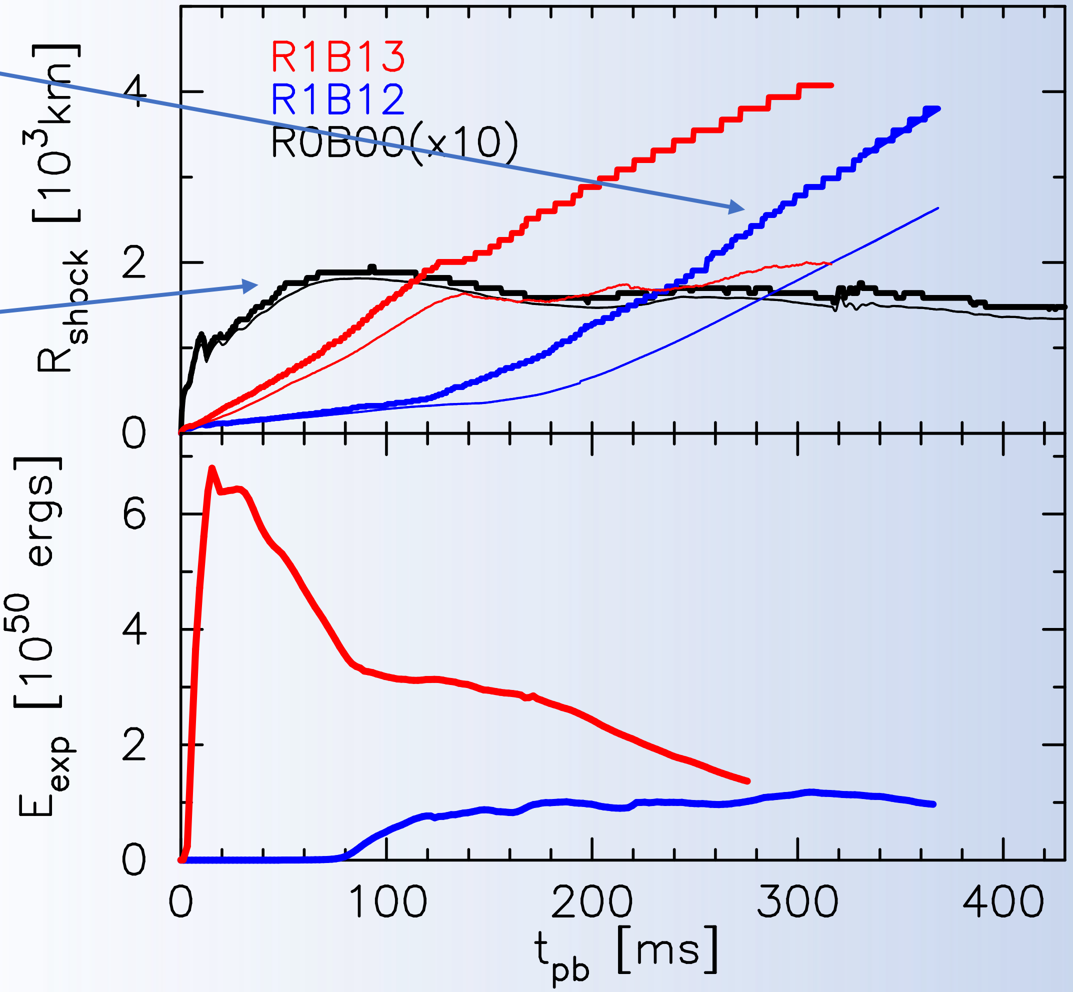
Pseudo-Newtonian Model

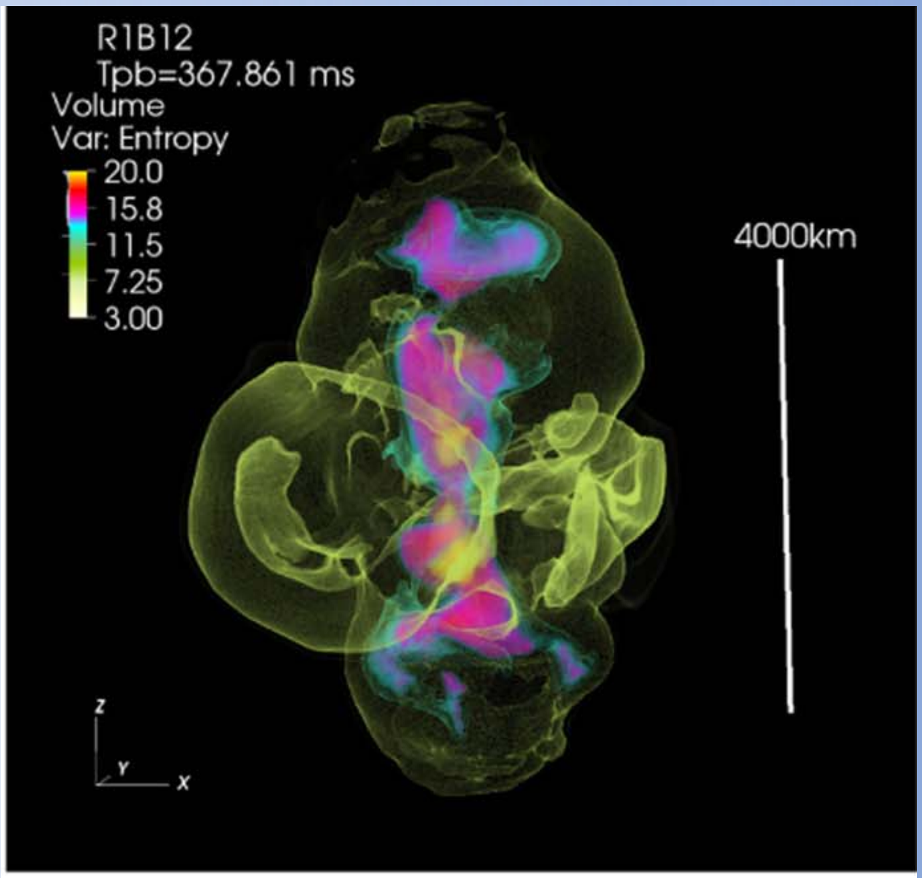
Mueller, Janka, and Marek 2012 *Ap.J.* **756**, 84

# with and without Rotation and Magnetic Fields

rotation,
magnetic fields

no rotation,
no magnetic fields





Kuroda, Ap.J. 906, 128 (2021)

$20\ M_\odot$ (WH07) $\Omega_0 = 1\ \mathrm{rad\ s}^{-1}$ $B = 10^{12}$ G

# Quantum Kinetics: It’s still all about the angular distributions!

*Length and Time Scales Severe*

- *length scale is O(1 cm) and typical CCSN radial resolution is O(100 m) – differ by O($10^4$)*
- *time scale is O(1 ns) and typical CCSN temporal resolution is O(1 μs) – differ by O($10^3$)*

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

$R_\nu$ 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

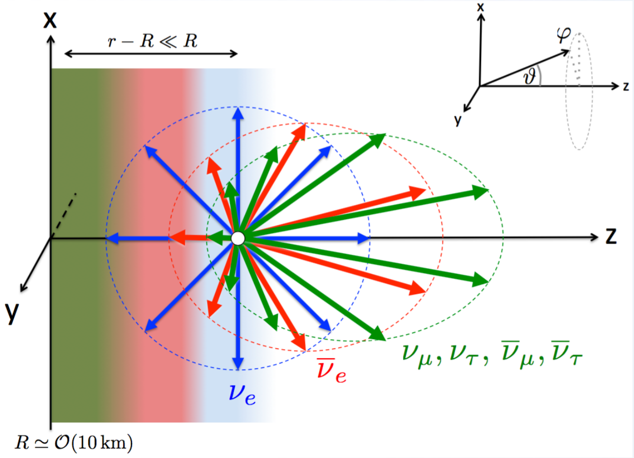
- Duan, H., Fuller, G. M., & Qian, Y.-Z. 2010, ARNPS **60**, 569

flavor mixing due to
neutrino forward scattering
on electrons
MSW

$R_{\text{star}}$

not as well understood

well understood



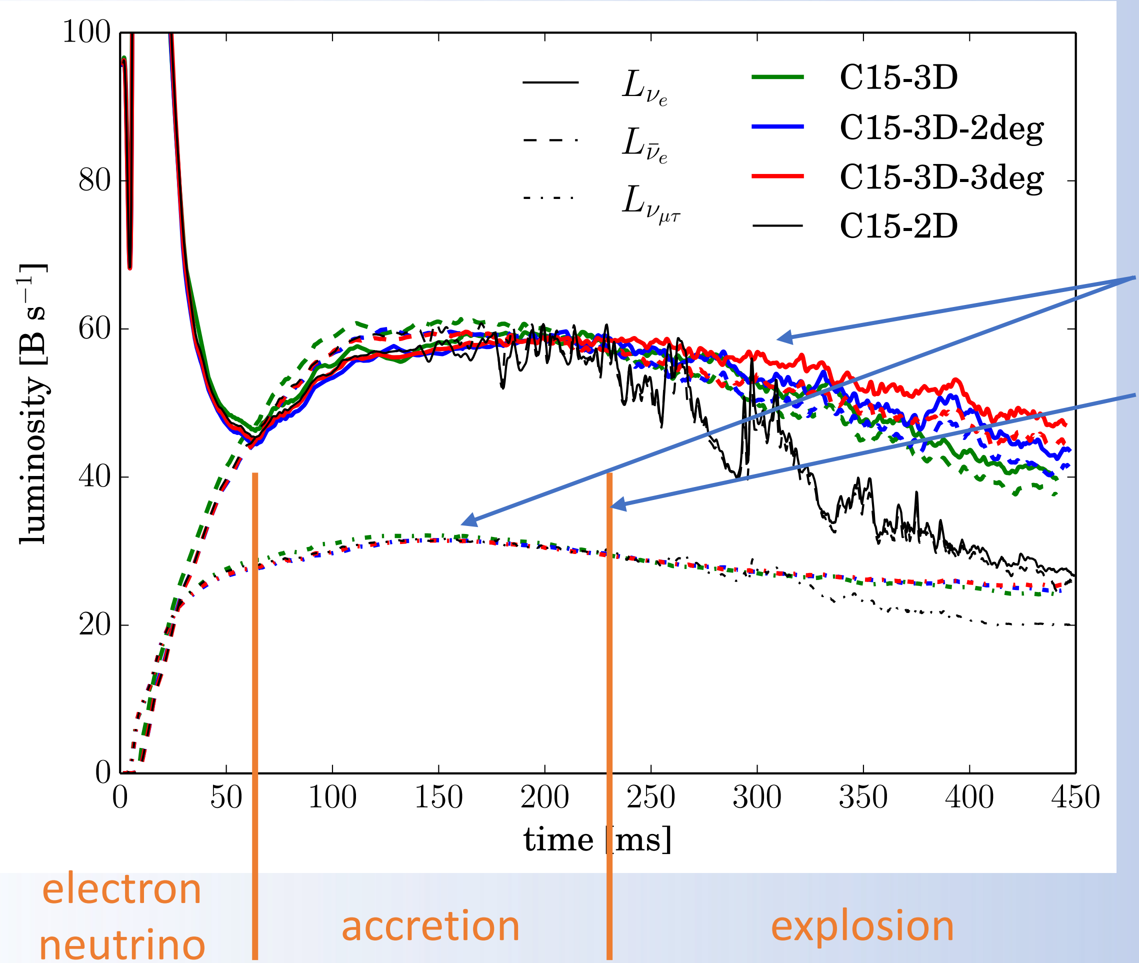
Dasgupta, Mirizzi, and Sen, JCAP 1702, 019 (2017)

Do we know the QKE?

- Mean field versus many-body approaches (Volpe, arXiv: 2301.11814)?
- Moments approaches?

# The Anatomy of a Core Collapse Supernova Neutrino “Light Curve”

Lentz et al. *Ap.J. Lett.* **807**, 31 (2015)



Will we get the right amplitudes?

Will we get the right accretion phase duration?

electron neutrino burst

accretion phase

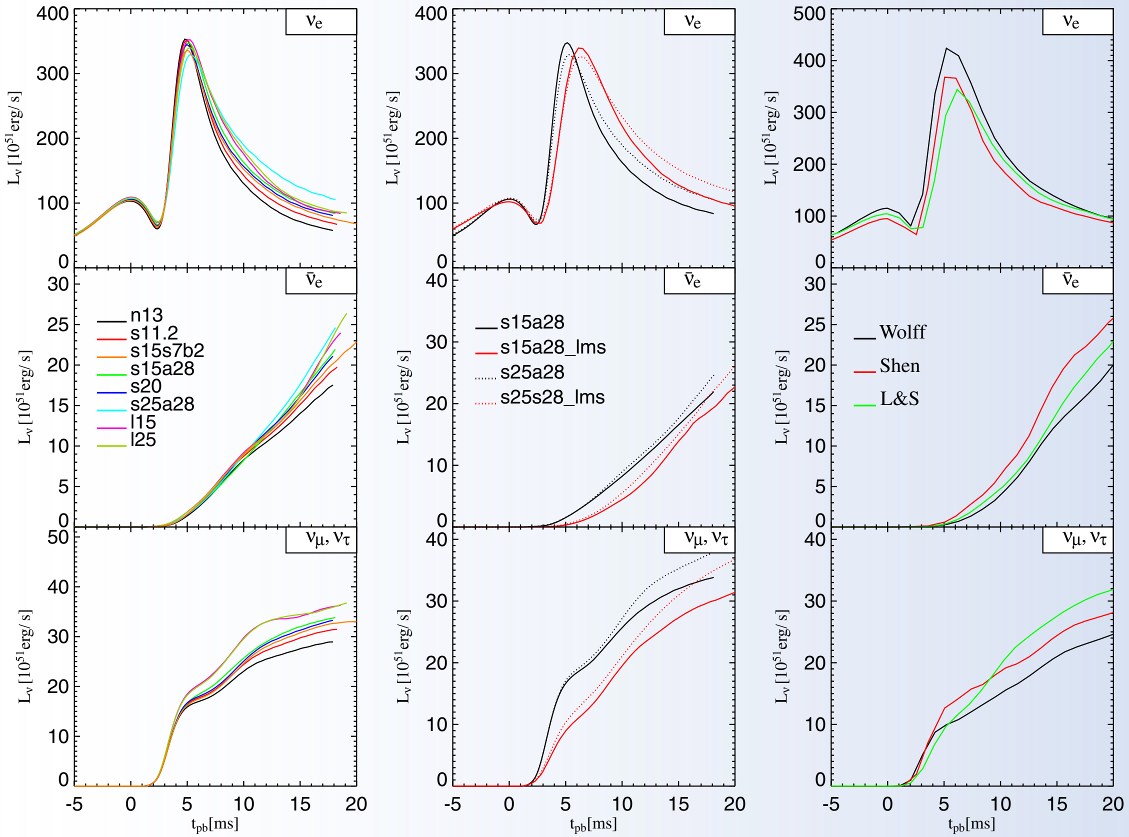
explosion phase

(for the 2D case)

# Opportunities

# Opportunities: Electron Neutrino Burst

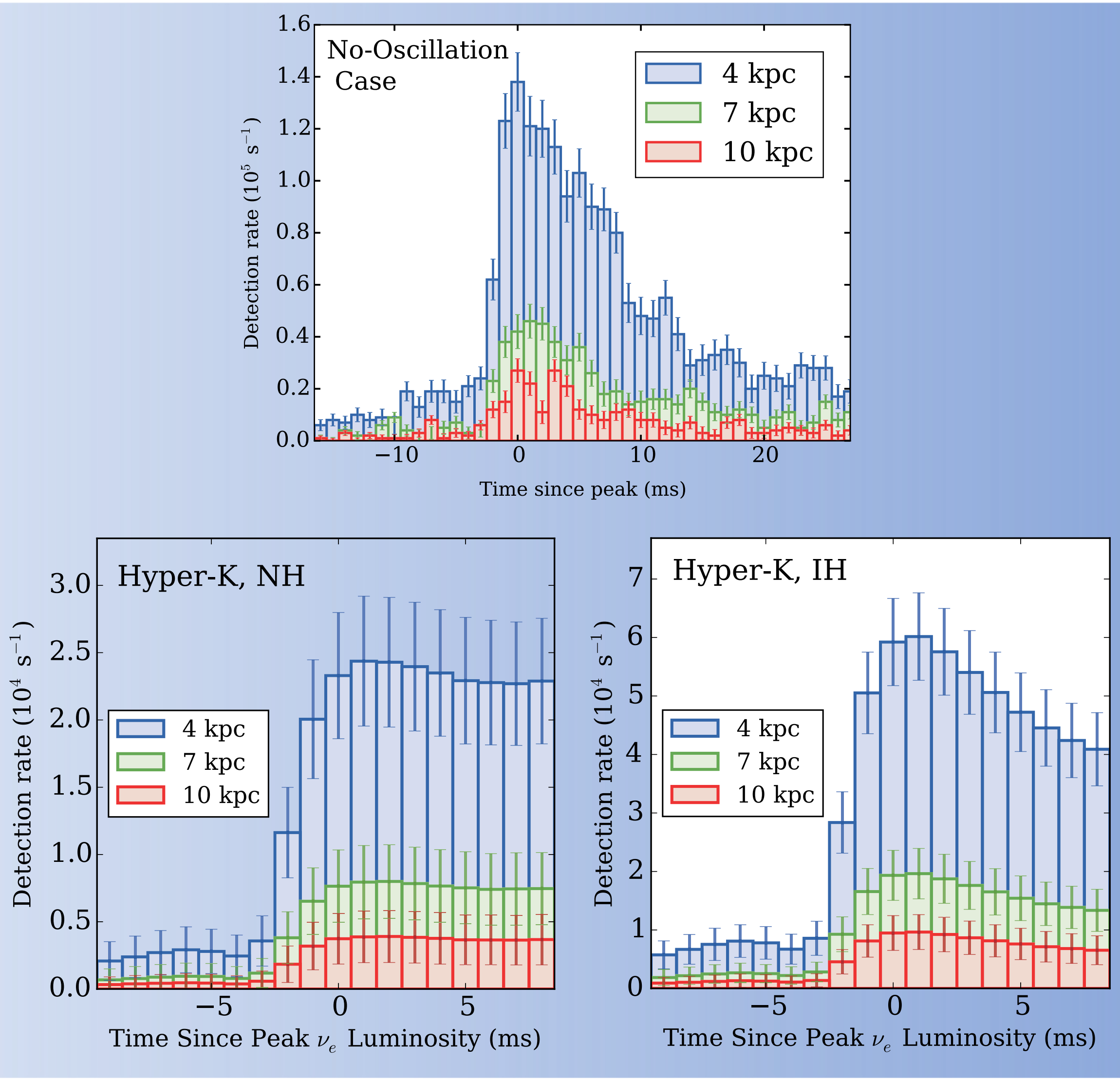
Kachelreiss et al. PRD **71**, 063003 (2005)



Weak Progenitor Mass Dependence

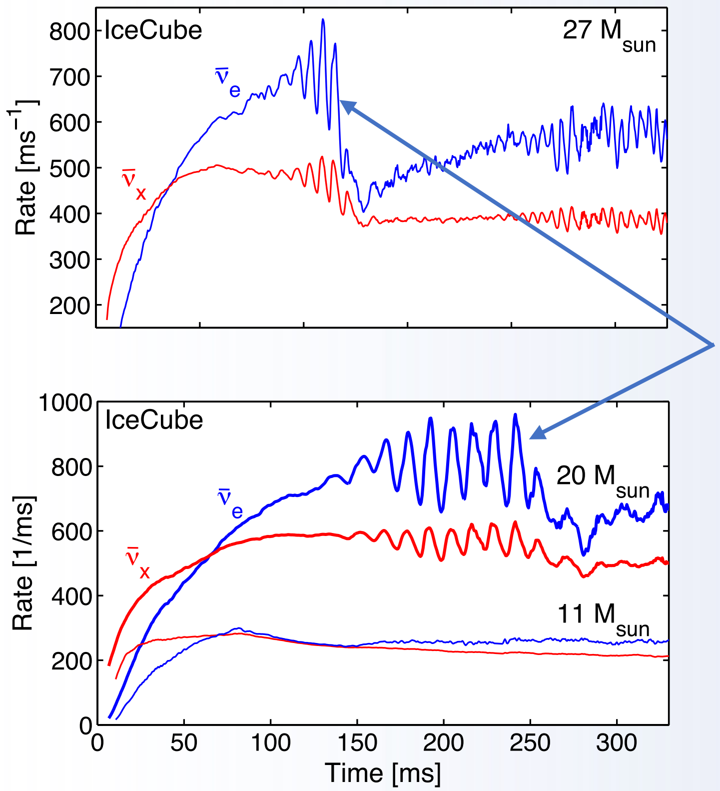
Some Model Dependence

EOS Dependence

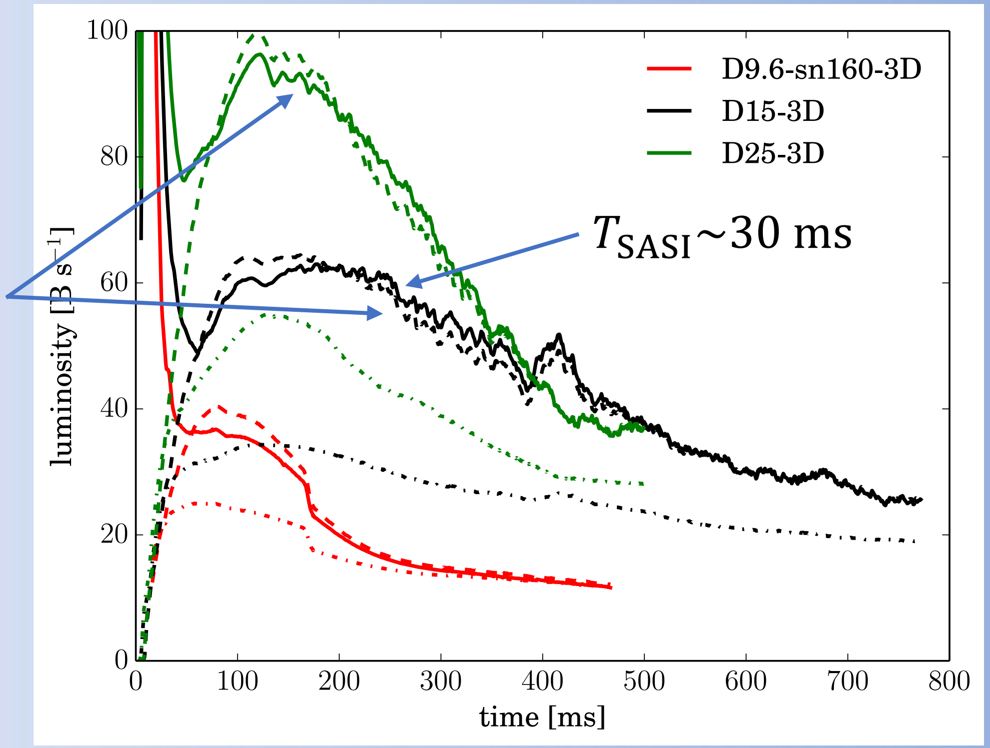


Wallace, Burrows, and Dolence, *Ap.J.* **817**, 182 (2016)

# Opportunities: Accretion Phase



SASI-induced oscillations.



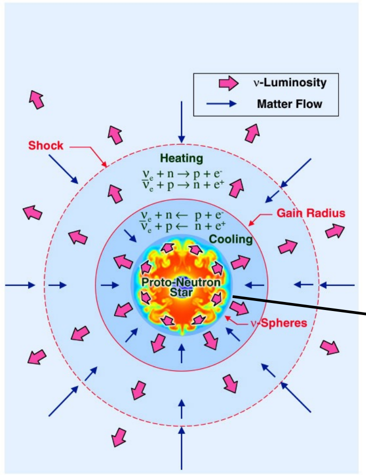
Tamborra et al. PRL **111**, 121104 (2013)

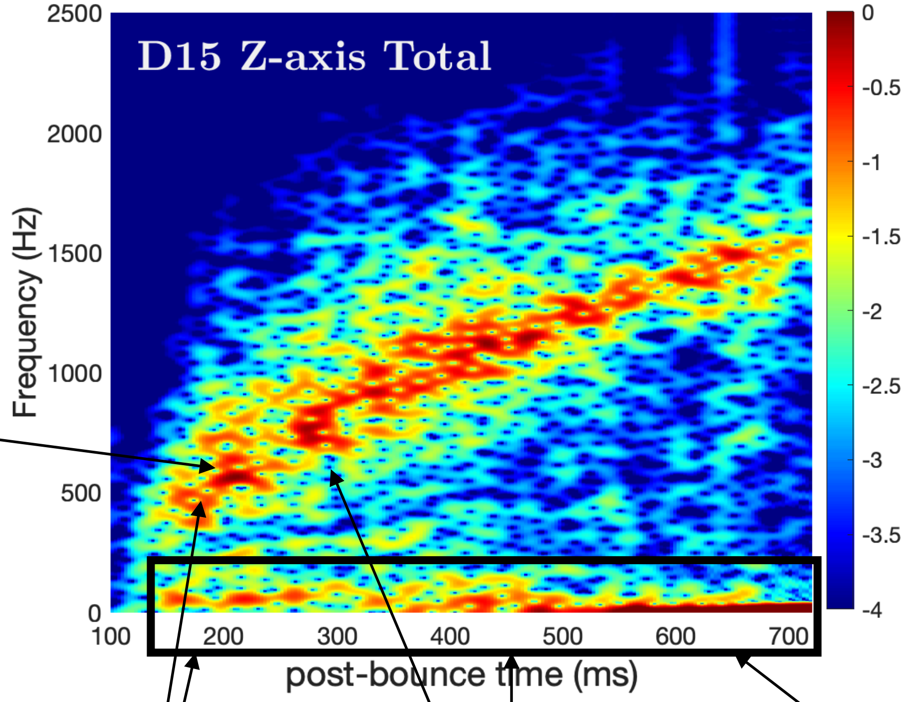
For an optimal viewing angle, the "SASI can be detected throughout the Galaxy."

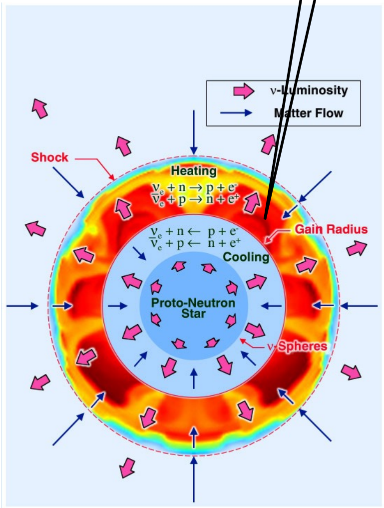
"SASI Meter": "The SASI frequency and amplitude can be reconstructed if D $\lesssim$ 5 kpc for Hyper-K (D $\lesssim$ 10 kpc for IceCube)."

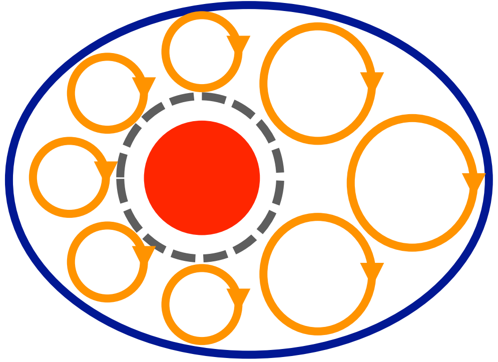
Lin et al. PRD 101 123028 (2020)

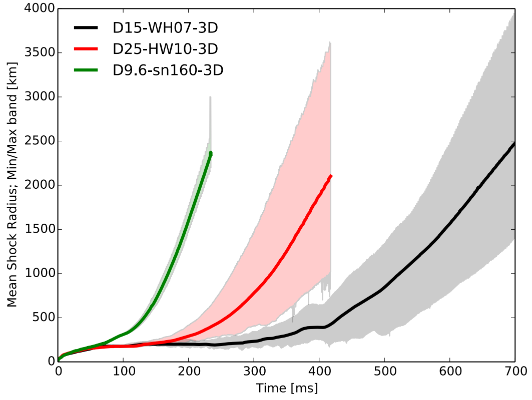
# Sources of CCSN Gravitational Waves











Colter Richardson

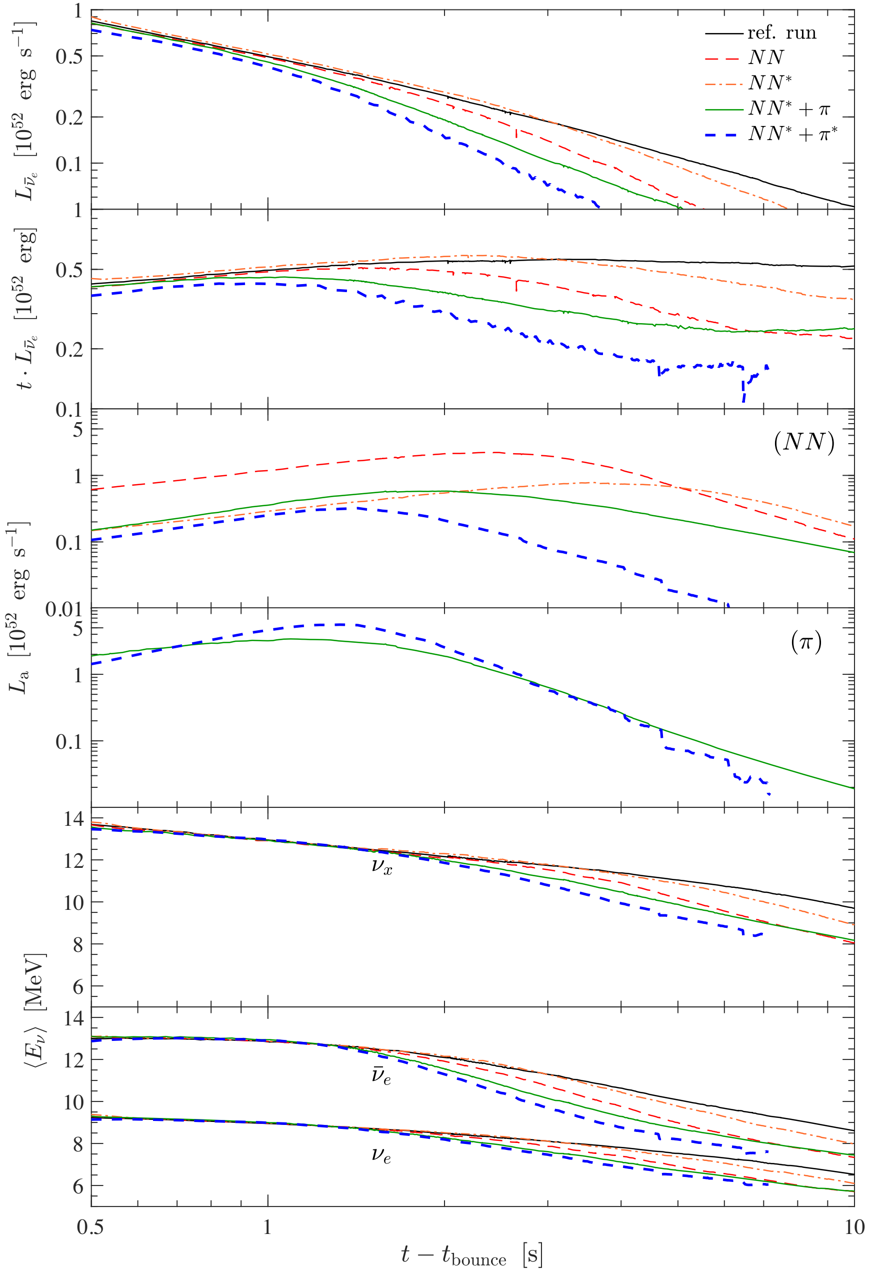
Daniel Murphy

AM, Marronetti, Landfield, Lentz, et al. PRD, **107**, 048003 (2023)

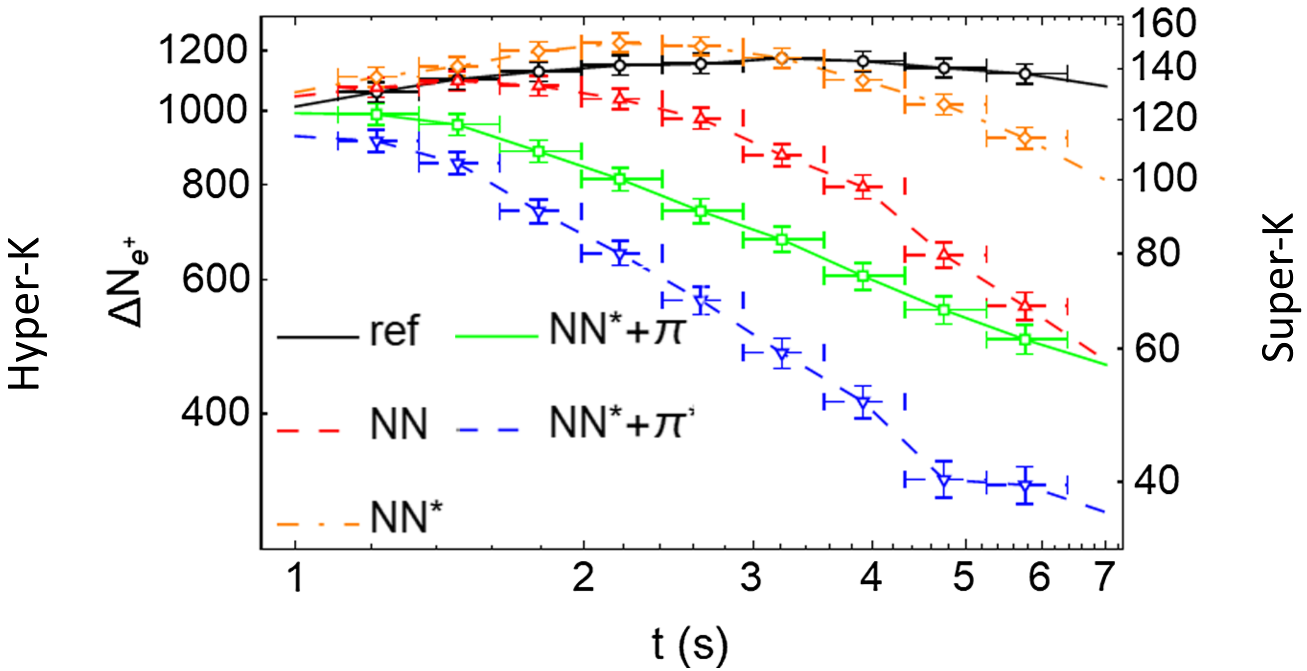
# Impact of Exotica: Axions

$$N + N \longrightarrow N + N + a$$

$$\pi^- + p \longrightarrow n + a$$



Fischer et al. 2021 104 103012 (2021)



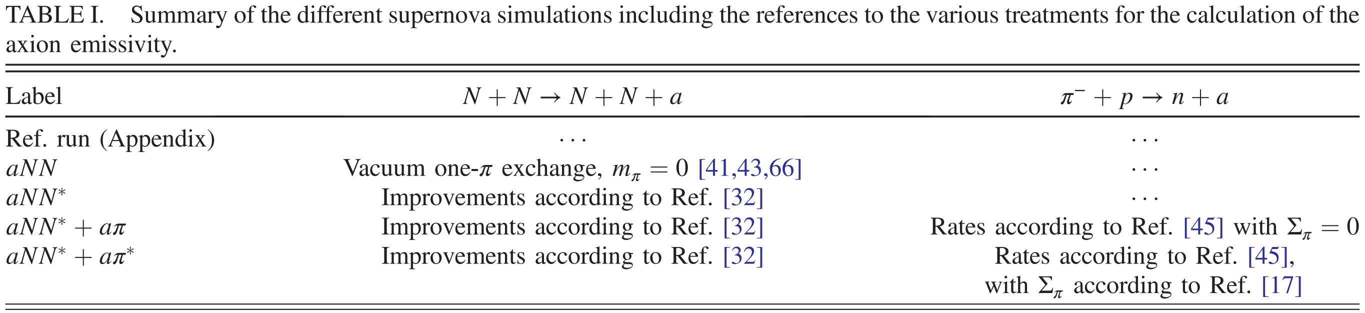
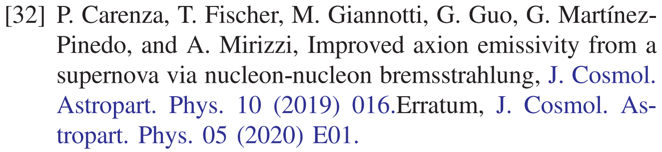


TABLE I. Summary of the different supernova simulations including the references to the various treatments for the calculation of the axion emissivity.

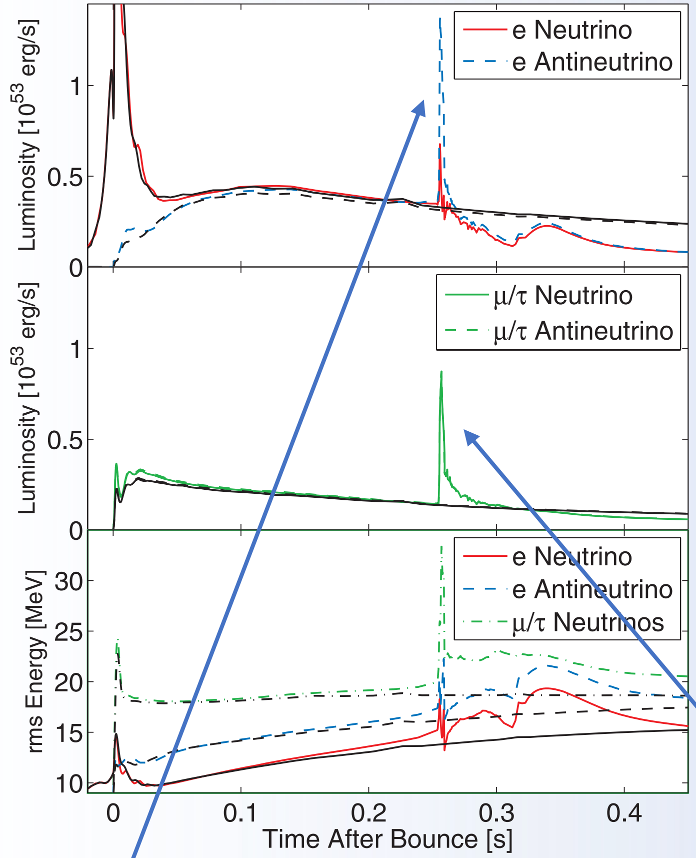
| Label | $N + N \to N + N + a$ | $\pi^- + p \to n + a$ |
|---|---|---|
| Ref. run (Appendix) | ... | ... |
| $aNN$ | Vacuum one-$\pi$ exchange, $m_\pi = 0$ [41,43,66] | ... |
| $aNN^*$ | Improvements according to Ref. [32] | ... |
| $aNN^* + a\pi$ | Improvements according to Ref. [32] | Rates according to Ref. [45] with $\Sigma_\pi = 0$ |
| $aNN^* + a\pi^*$ | Improvements according to Ref. [32] | Rates according to Ref. [45], with $\Sigma_\pi$ according to Ref. [17] |



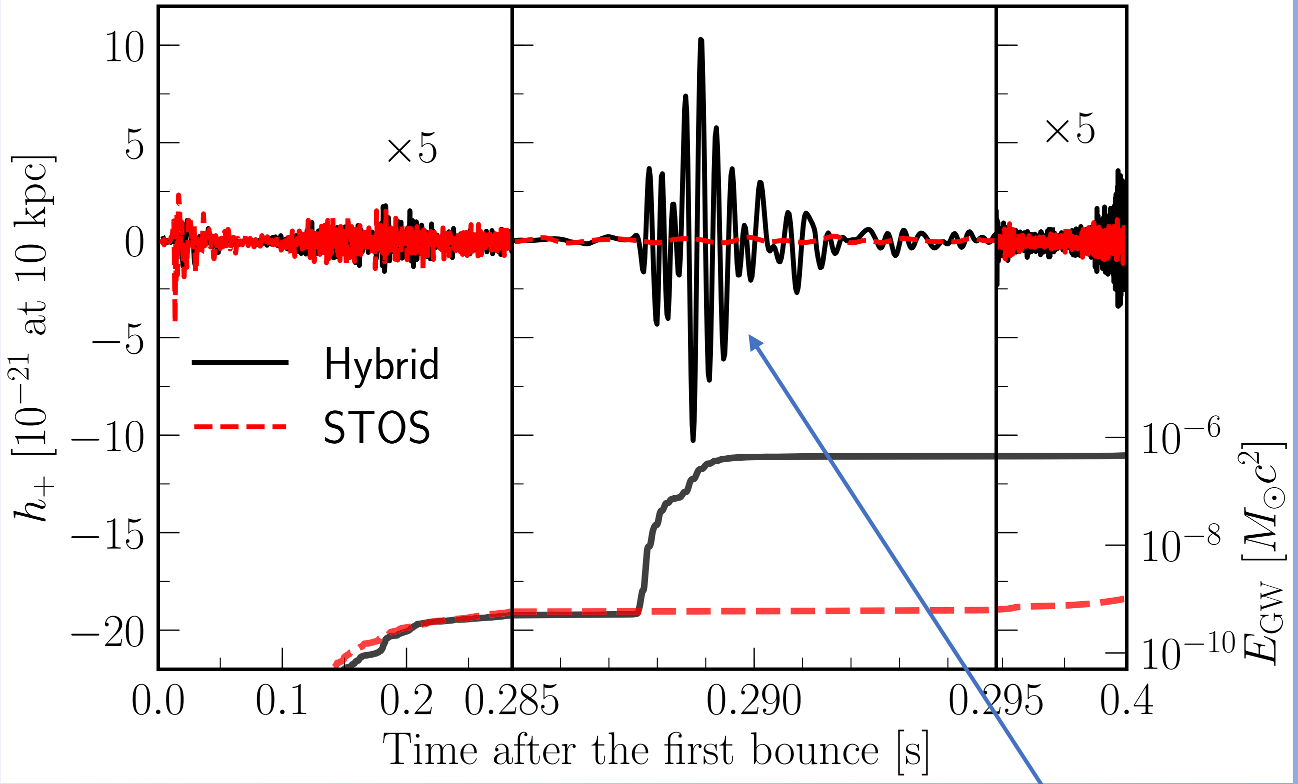
[32] P. Carenza, T. Fischer, M. Giannotti, G. Guo, G. Martínez-Pinedo, and A. Mirizzi, Improved axion emissivity from a supernova via nucleon-nucleon bremsstrahlung, J. Cosmol. Astropart. Phys. 10 (2019) 016.Erratum, J. Cosmol. Astropart. Phys. 05 (2020) E01.

# Impact of Exotica: Quark – Hadron Phase Transitions

Sagert et al. PRL **102**, 081101 (2009)



Zha et al. PRL **125**, 051102 (2020)



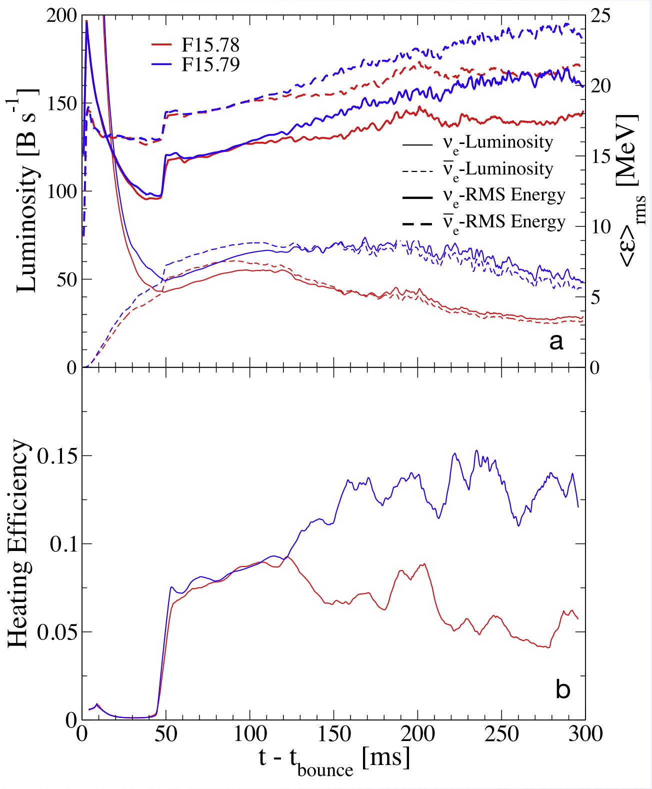
Associated Gravitational Wave Strain

Electron Antineutrino Burst

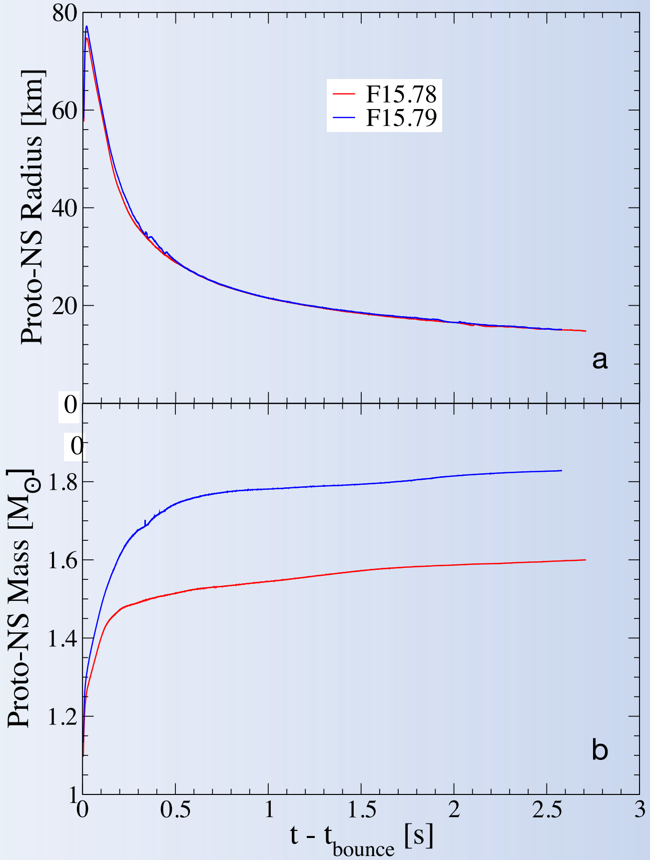
Muon and Tau Neutrino and Antineutrino Bursts

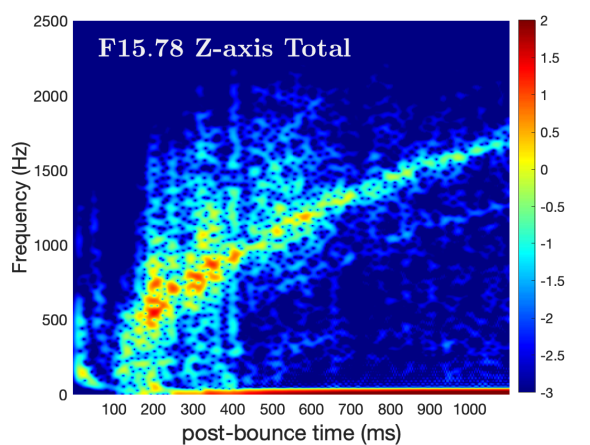
# A Poster Child for Multi-Messenger Astronomy?

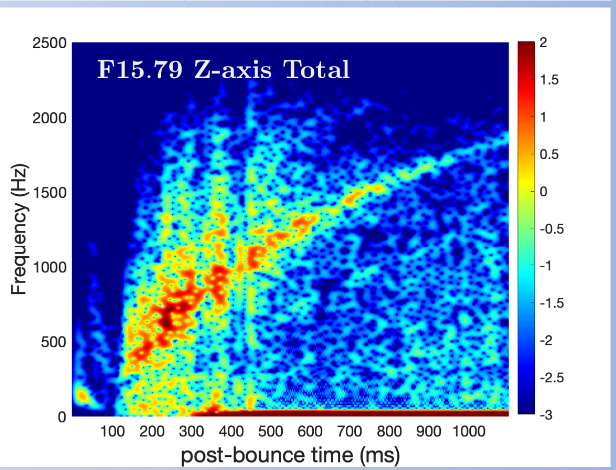
Bruenn et al. *Ap.J.* **947**, 35 (2023)



Murphy, AM, Marronetti, Landfield, and Lentz (2023), in prep.







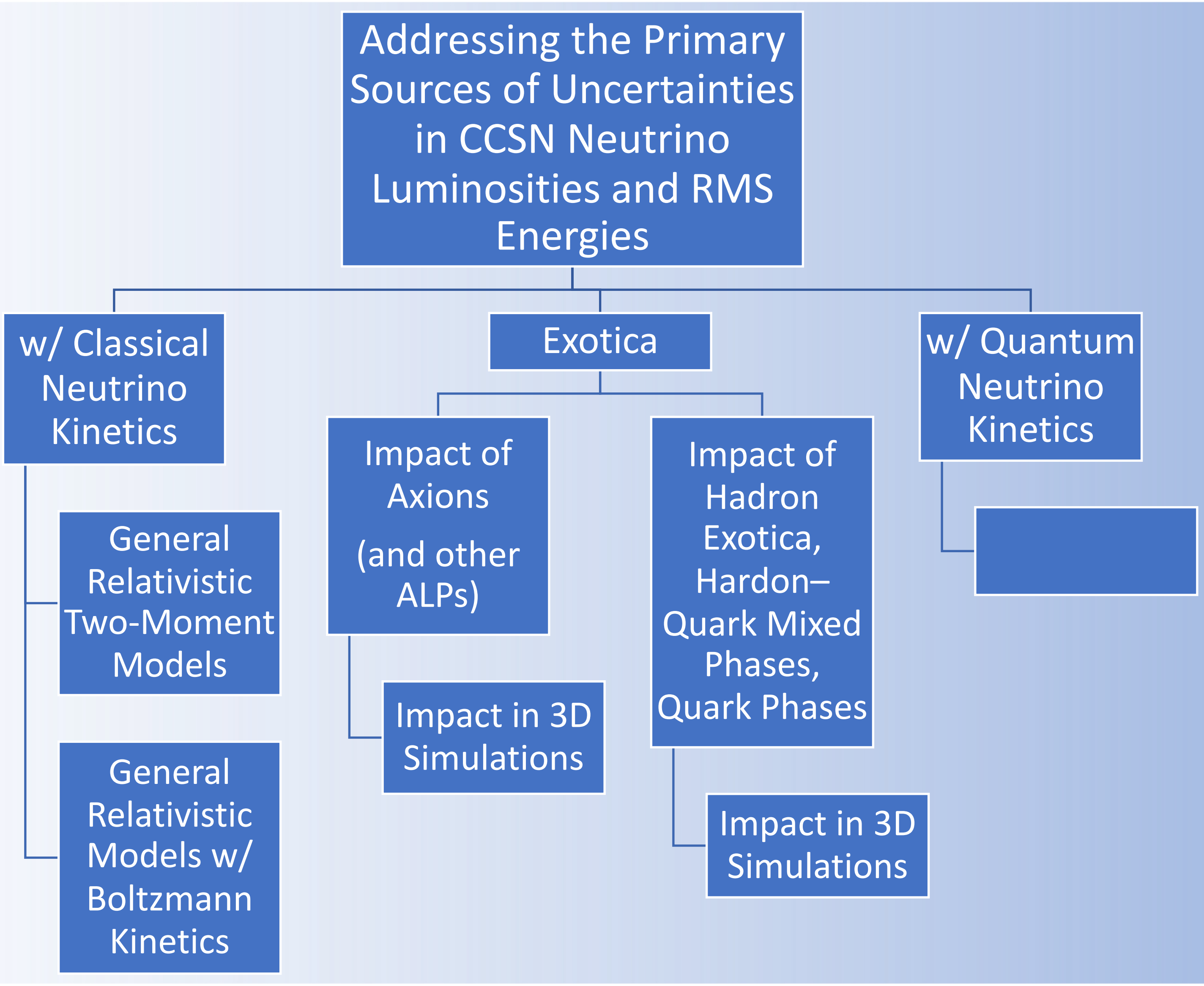
Daniel Murphy

How do we distinguish the progenitors?

Clue: The PNS masses differ.

And the GW spectrograms differ.

# The Road Ahead



- Addressing the Primary Sources of Uncertainties in CCSN Neutrino Luminosities and RMS Energies
  - w/ Classical Neutrino Kinetics
    - General Relativistic Two-Moment Models
    - General Relativistic Models w/ Boltzmann Kinetics
  - Exotica
    - Impact of Axions

      (and other ALPs)
      - Impact in 3D Simulations
    - Impact of Hadron Exotica, Hardon–Quark Mixed Phases, Quark Phases
      - Impact in 3D Simulations
  - w/ Quantum Neutrino Kinetics

# UT–ORNL Supernova Code Lines

Eric Lentz

- Code
  - Chimera
    - Newtonian Gravity with General Relativistic Corrections
    - Ray-by-Ray, O(v/c) Neutrino Kinetics with General Relativistic Corrections
    - Newtonian Hydrodynamics, No B Fields
    - Extensive Weak Physics
  - thornado
    - General Relativistic Gravity (xCFC, CCZ4 Under Development)
    - Three-Dimensional General Relativistic Neutrino Kinetics
    - General Relativistic Hydrodynamics (MHD under Development)
    - Extensive Weak Physics

Eirik Endeve

## Related and Future Developments

- Inclusion of a nuclear network in thornado.
- thornado is a development platform for Flash-X.

Raph Hix

Bronson Messer

Nick Roberts

Zack Elledge

Sam Dunham (Vanderbilt)

Jesse Buffaloe