Moving Supernova Simulations Towards Quantitative Observable Outcomes

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Takeaways

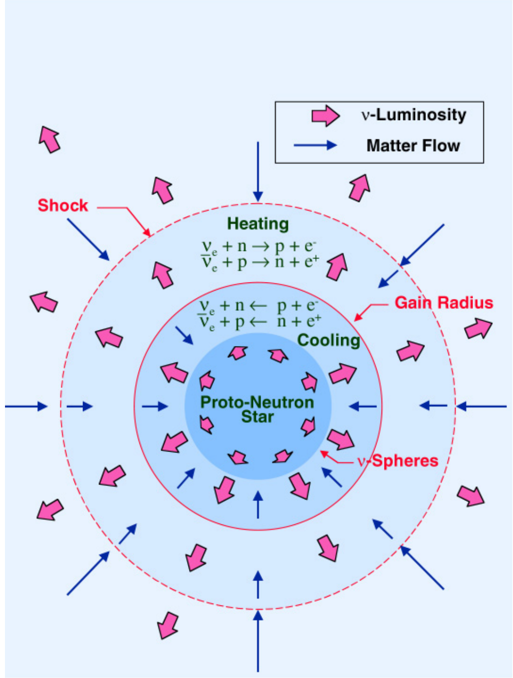
- **Core-collapse supernova models in 3D with sophisticated νRHD explode consistently, reasonably, and in various ways. The next frontier is establishing a quantitative understanding of all multi-messenger observables over much longer timescales.**

- Our current understanding of neutrino emission (and, maybe, nucleosynthesis) over the first few seconds of CCSNe **explosions** is qualitatively OK if you ignore some known physics (e.g., collective flavor oscillations).
  - Prediction is, of course, dependent on understanding this physics, but will also require an *in situ* treatment in RHD simulations.

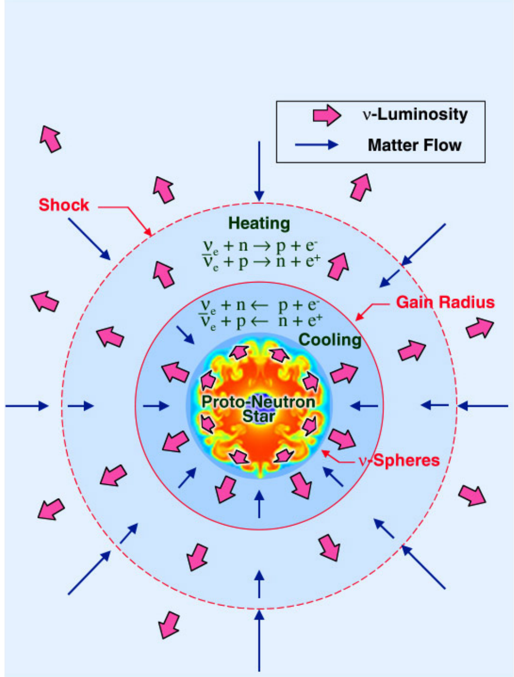
- **But, the details of this emission is tightly coupled to explosion dynamics, depending strongly on progenitor structure in a variety of ways.**

- Aside from neutrino flavor oscillation physics-–a frontier that will require considerably more computational intensity than we have brought to bear to this point—there are other pieces of physics that require more-or-less immediate attention
  - **Including heavy lepton degrees of freedom "everywhere" (every-how) in simulations**

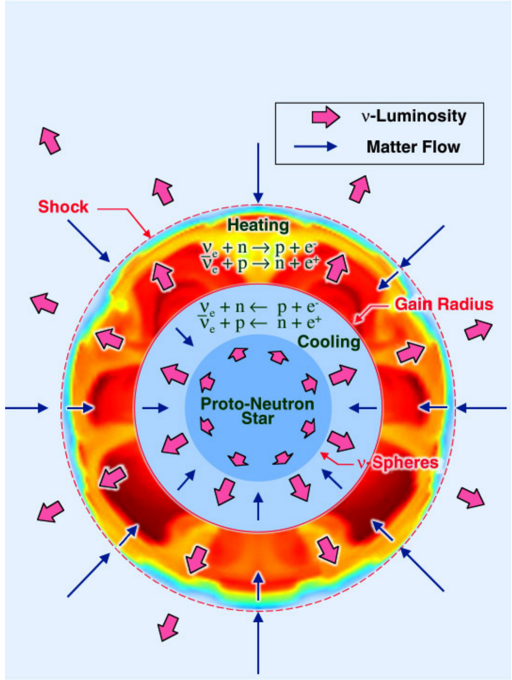
Ingredients of a core-collapse supernova explosion



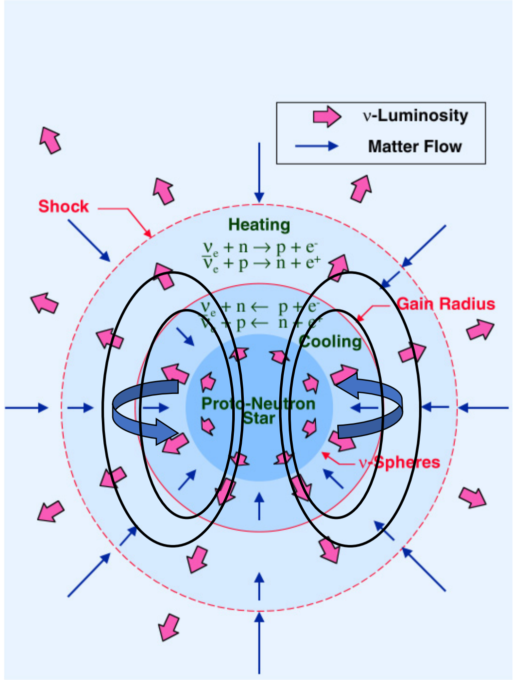
Neutrino Heating



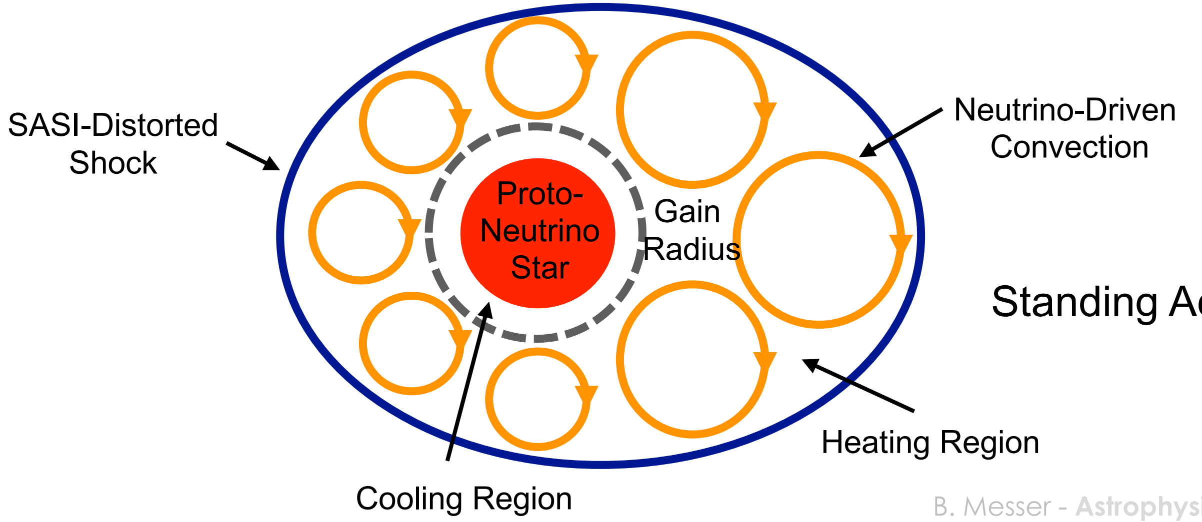
Proto-Neutron Star Instabilities



Neutrino-Driven Turbulent Convection



Rotation
and
Turbulence-Amplified Magnetic Fields

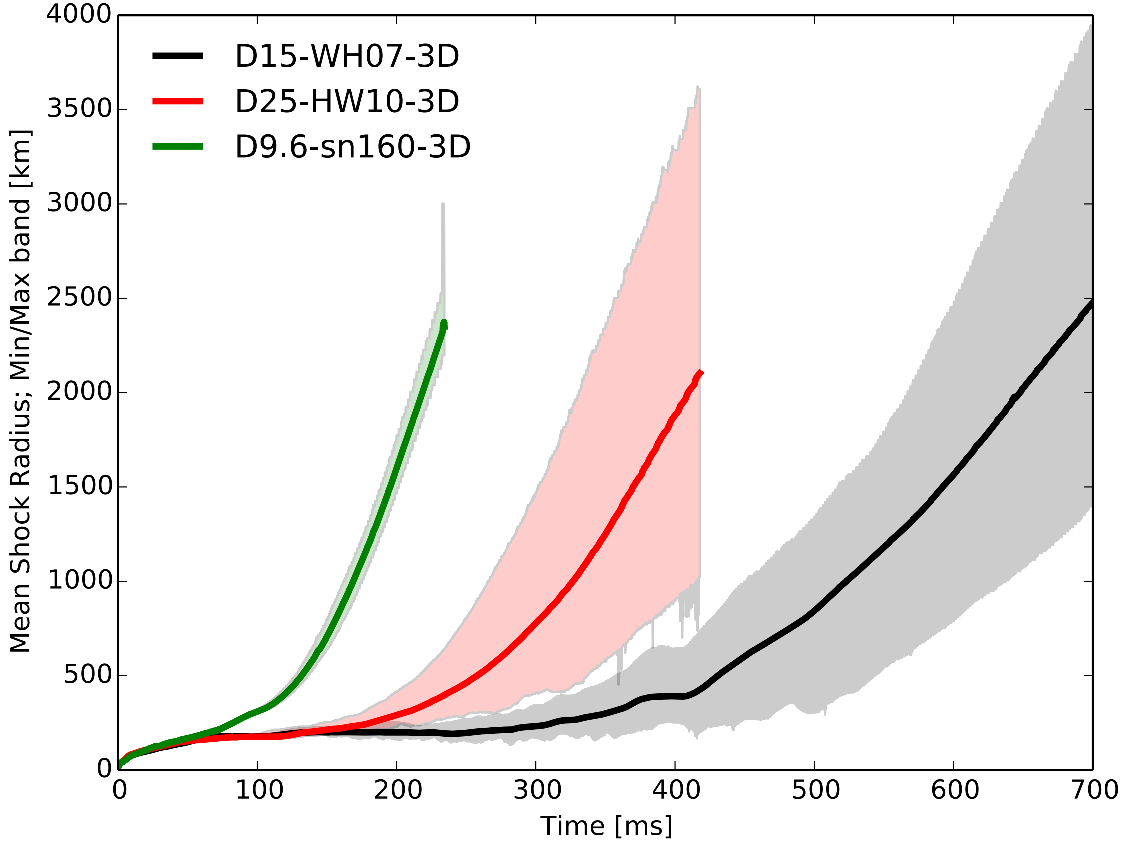


Standing Accretion Shock Instability (SASI)

We are at the beginning of an era where confronting observables via simulation can be/must be quantitative

- 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)
- Mezzacappa, Endeve, Messer, and Bruenn, Liv. Rev. Comp. Astr. 6:4 (2020)
- Burrows and Vartanyan, Nature 589, 29 (2021)



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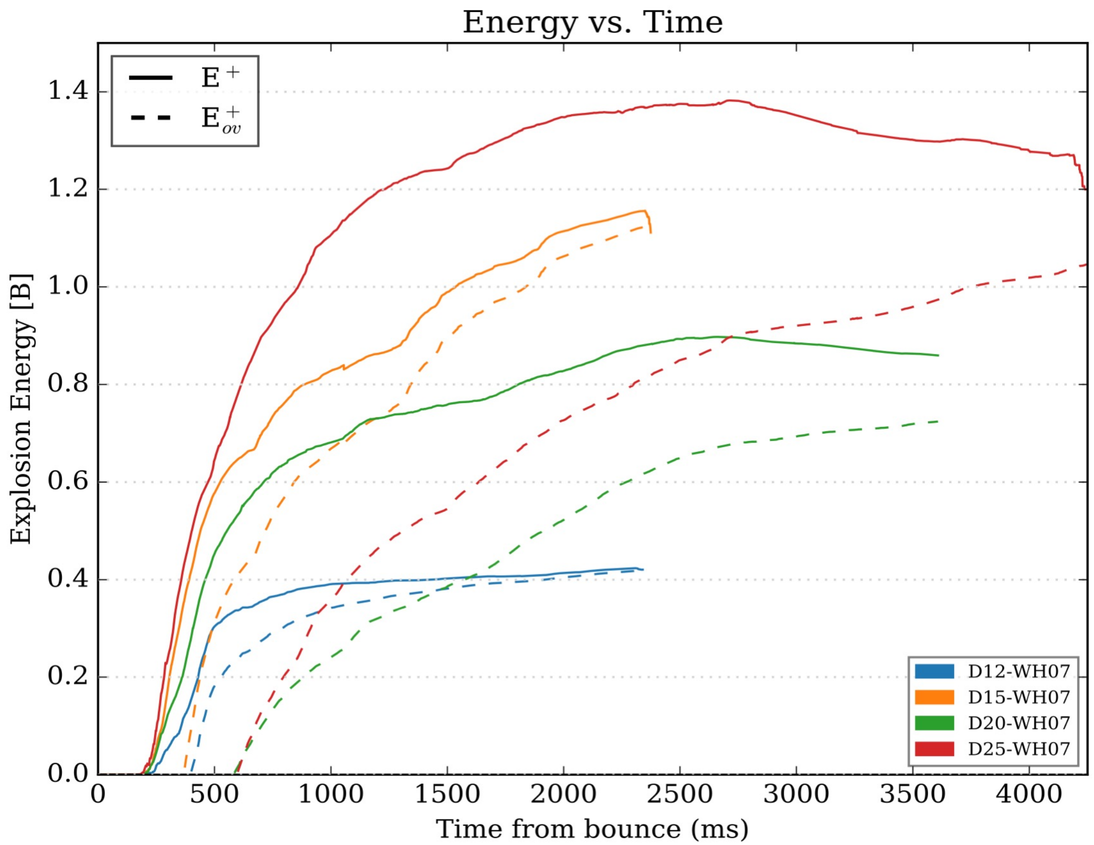
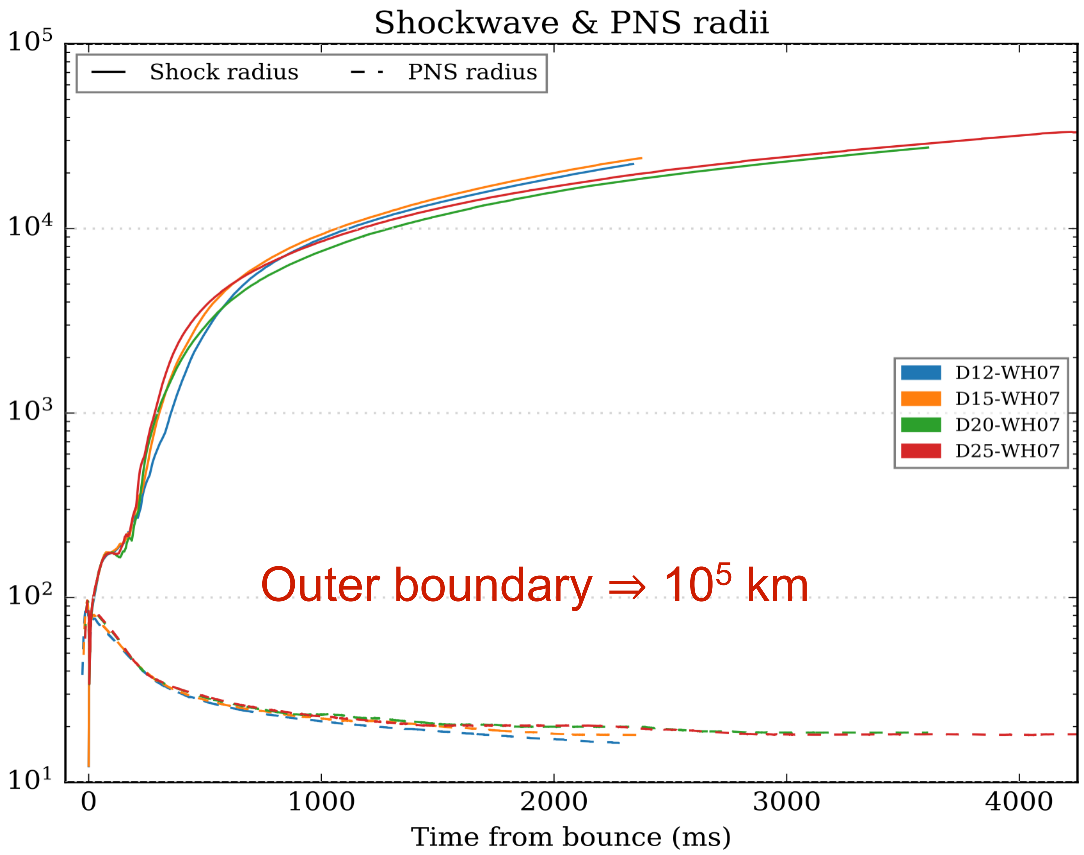
Finishing the explosion

See Li+ (2023) – arxiv 2306.08024!!

We must continue to run with full physics until the explosion is fully developed, until the explosion energy approaches its asymptotic value.

We approximate the asymptotic kinetic energy of the explosion with a "diagnostic" energy, $E^+ = E_{thermal} + E_{grav} + E_{kinetic}$, summed over zones where $E^+ > 0$.





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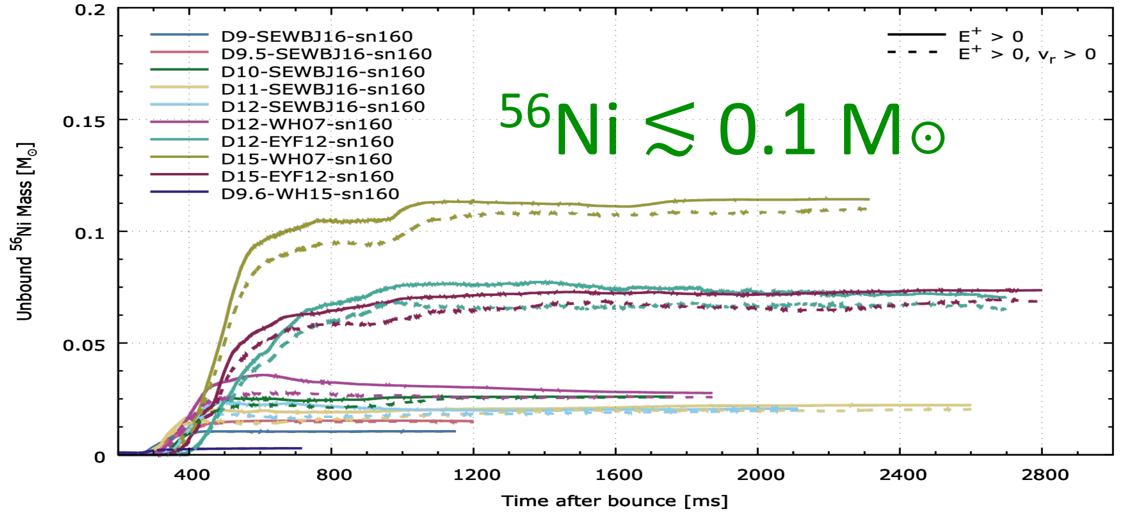
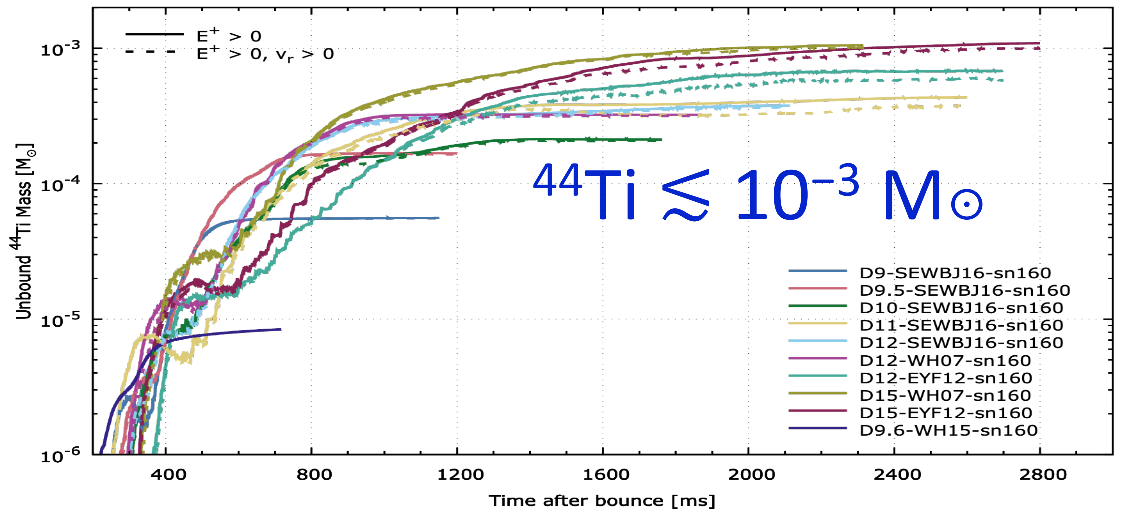
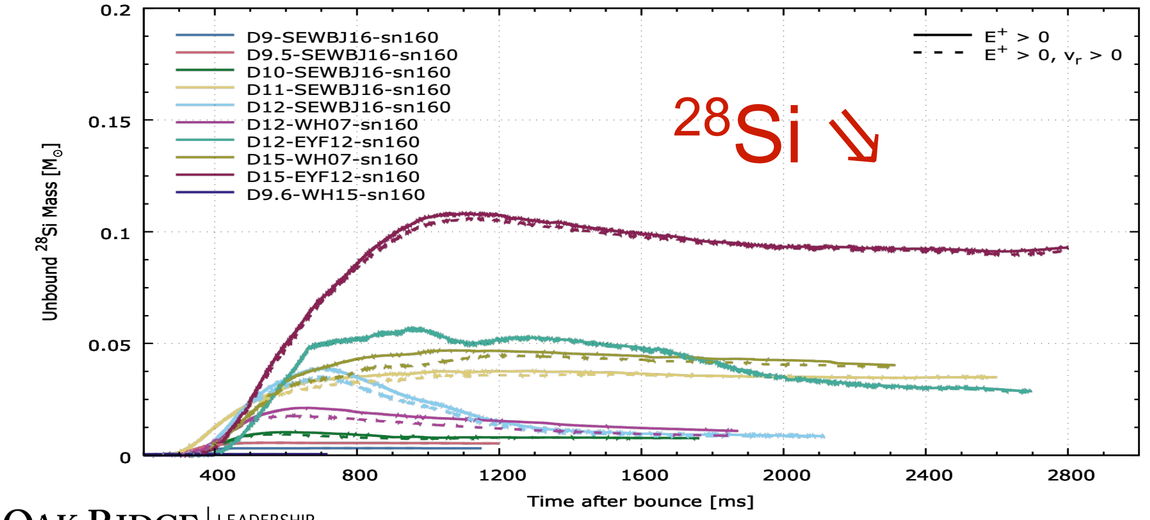
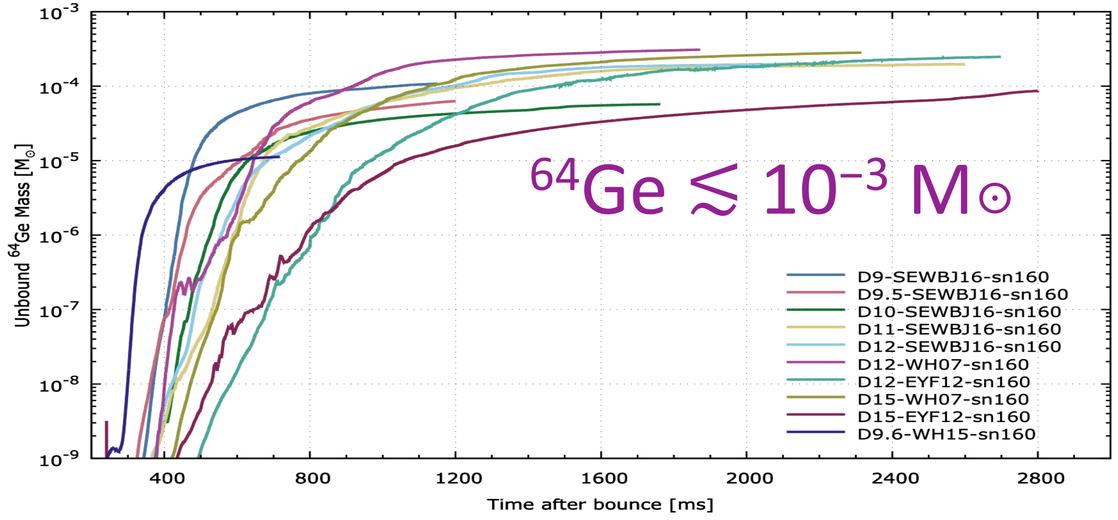
Finishing the nucleosynthesis

Not only to we need the explosion to be fully developed, we need the nucleosynthesis to be completed, at least for the major species of interest.





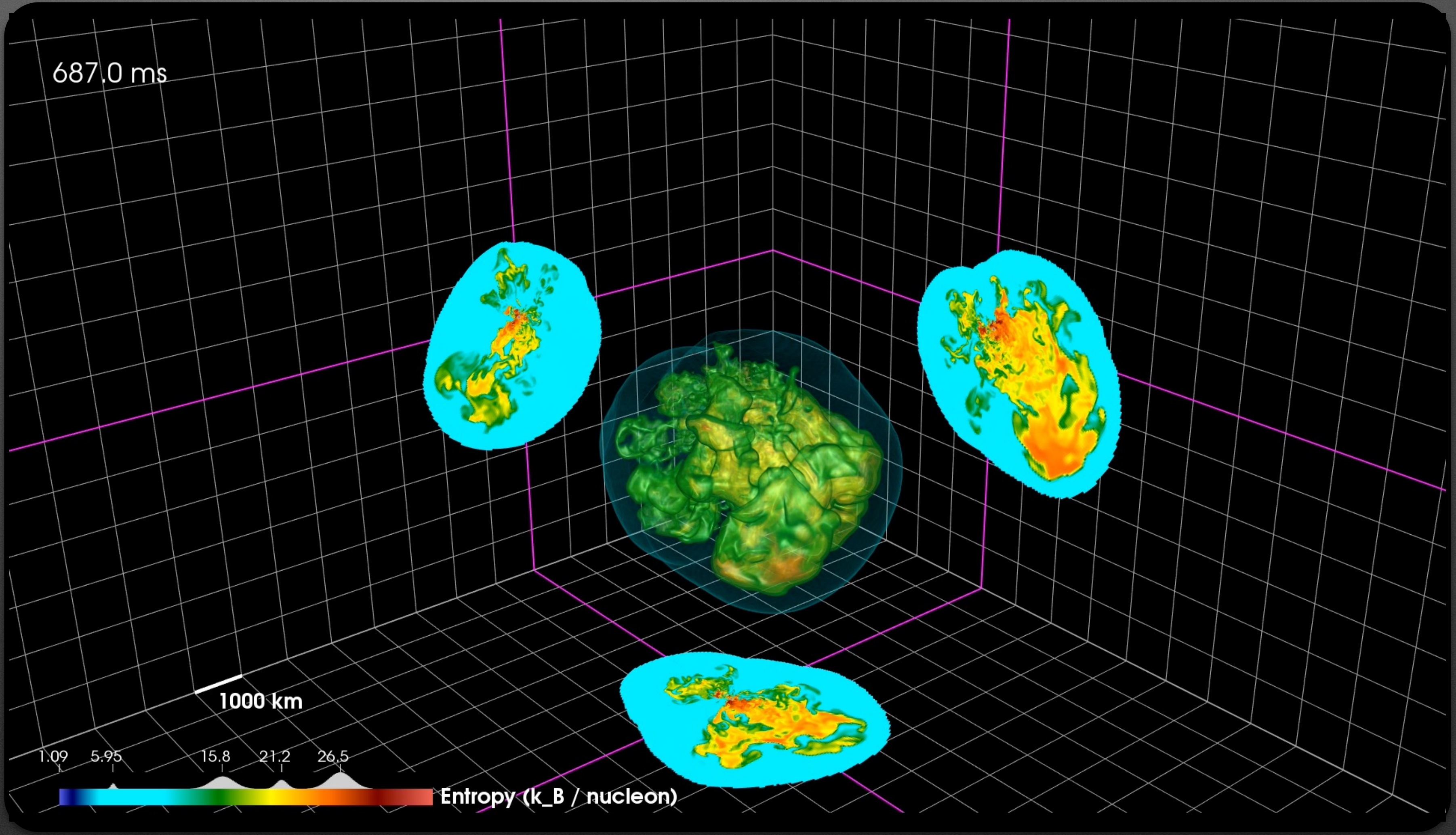




Asymmetries from the Mechanism

Nearly 30 years ago, we concluded that the mechanism imprints strong asymmetries on the inner ejecta, and to a lesser extent on the shock.

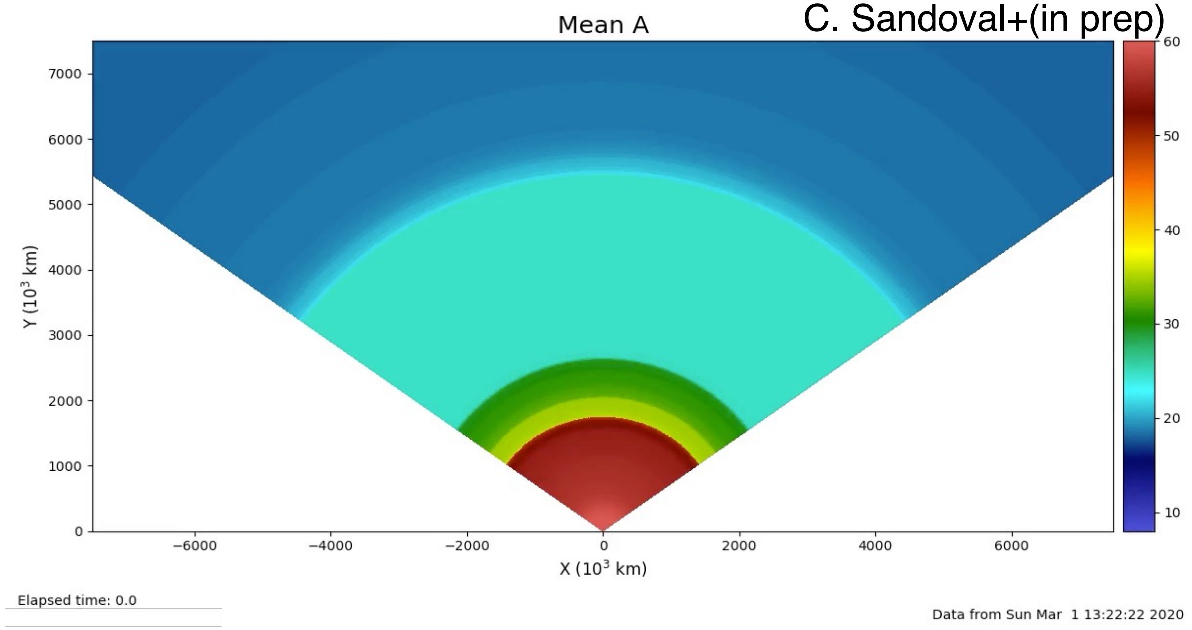
Since the 90s, it has been argued that these early asymmetries are necessary to match observations of heavy element velocity distributions, etc.



Progenitor asymmetries

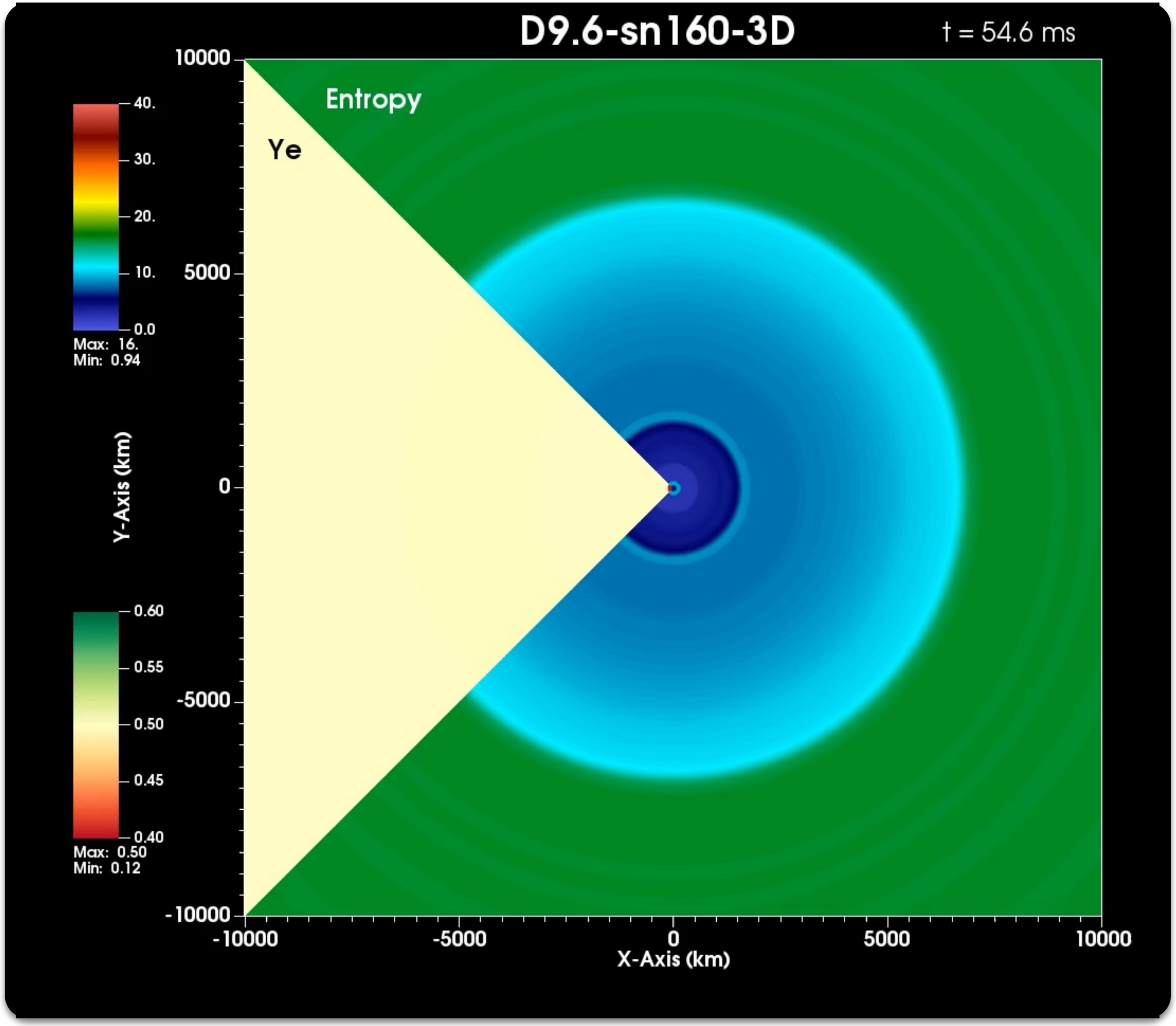
- When discussing asymmetries, as with all other aspects of CCSN, it is important to remember that the collapse of the core is just the final act of a massive star's life.
- Asymmetry late in the evolution, primarily on the silicon and oxygen layers that are reaching the shock as the explosion powers up, can accelerate the development of asymmetry in shocked material.
- Even larger effects are possible, if, for example, convection affects the growth of the iron core.

C. Sandoval+(in prep)



D9.6-sn160-3D

- 9.6 M⊙ zero-metallicity progenitor from Heger (p.c.)
- Same progenitor as Melson+(2015) and Stockinger+(2020)
- Very light envelope alters the explosion mechanism
- Shock doesn't stall for long, like ECSN, neutron-rich material from just above the PNS is entrained in the ejecta
- Explosion is quite spherical



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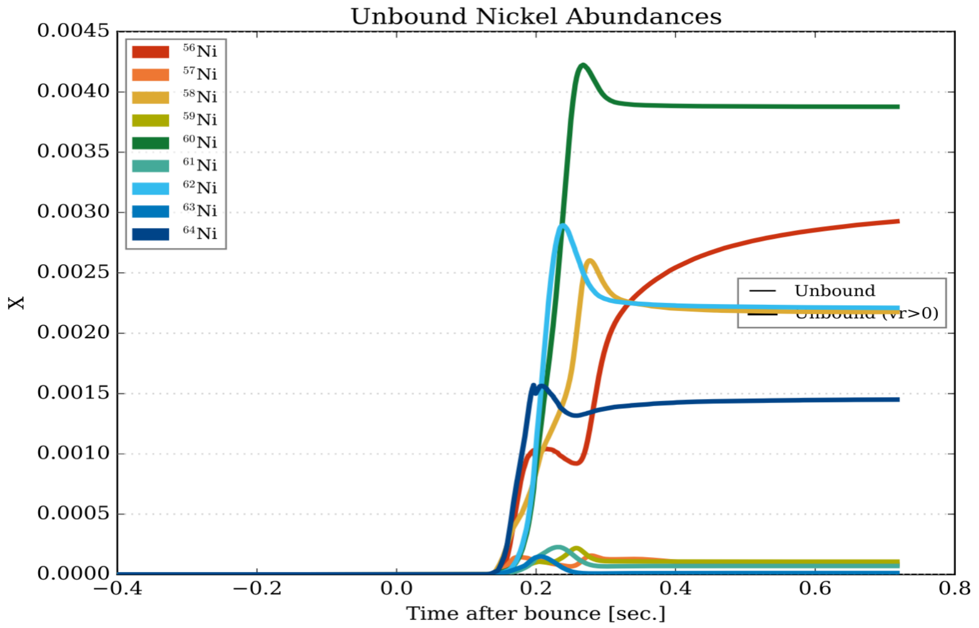
ECSN mimicry

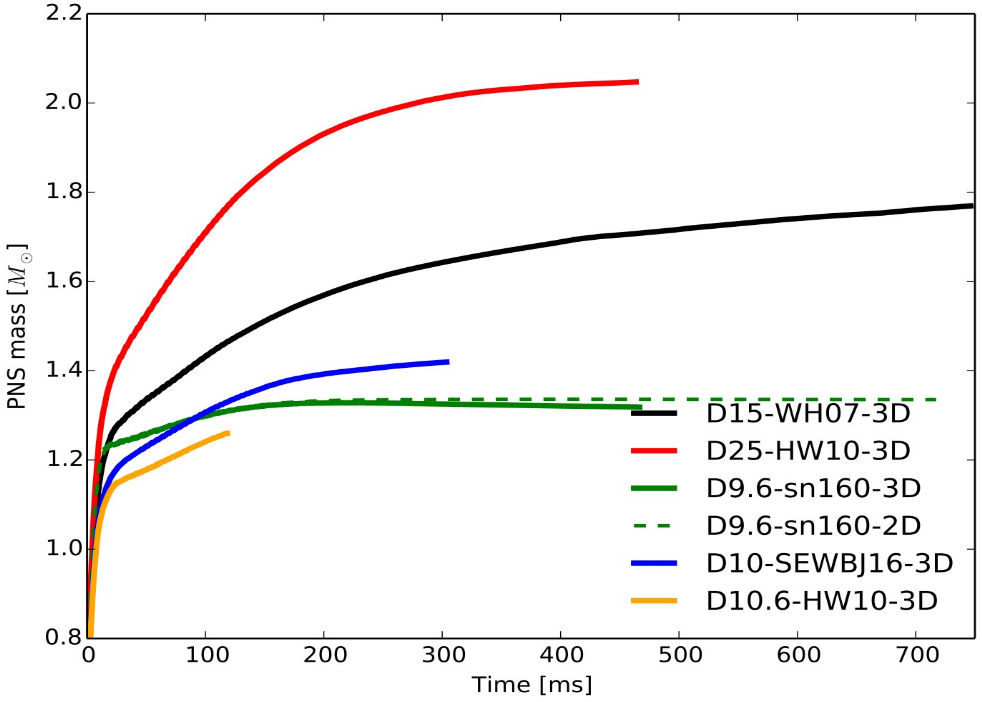
- With the rapid development of the explosion of this relatively low mass iron-cored star, the explosion of the D9.6 model shares many features with ECSN models.
  - Explosion Energy ~ .2 B
  - ^{56}Ni ejected ~ 3 × 10^{-3} M⊙

    with large amounts of neutron-rich ejecta

    (cf. Hiramatsu+ 2021)

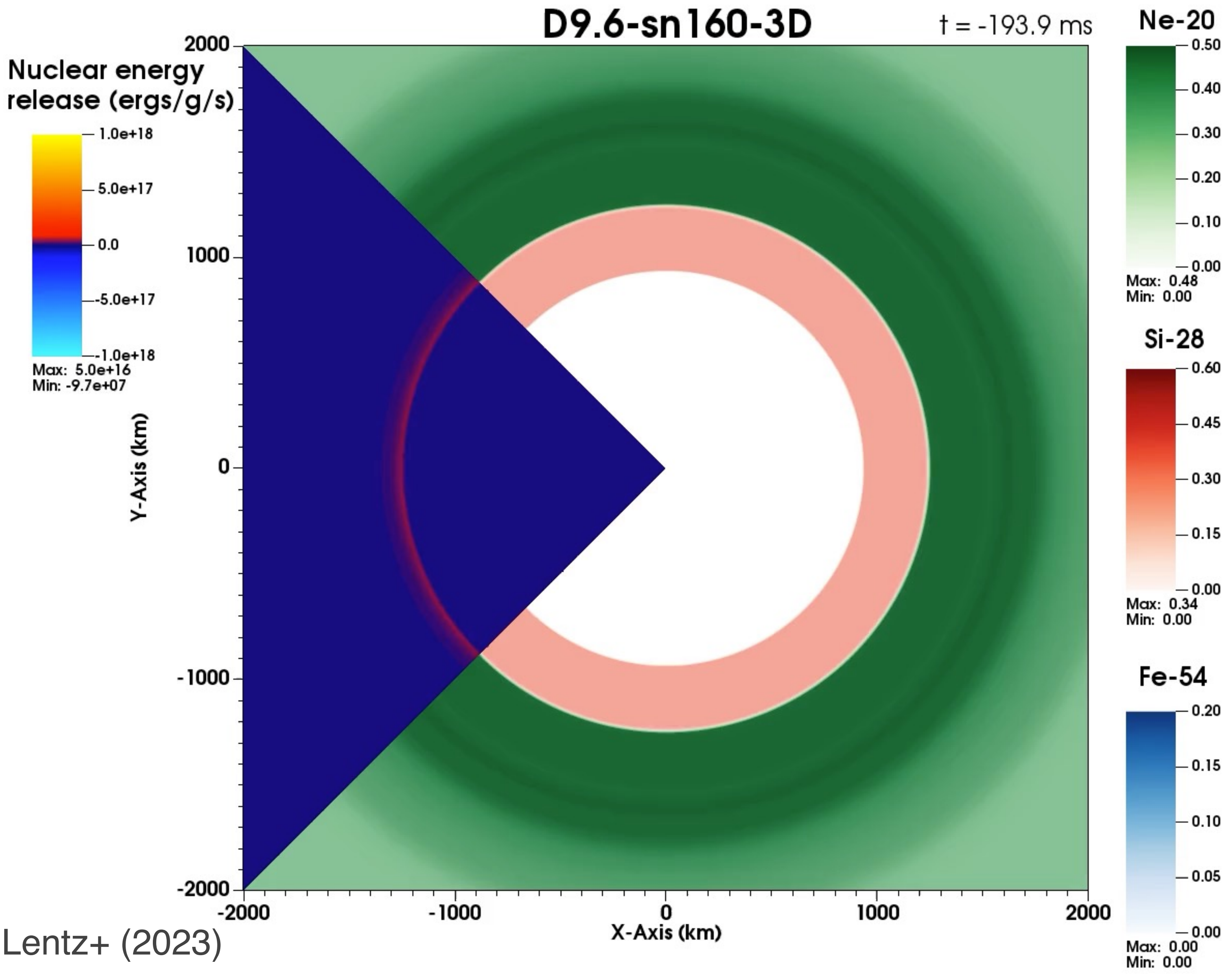
- Remnant neutron star masses are also small, with a baryonic mass of ~ 1.3 M⊙ and an ultimate gravitational mass of ~ 1.2 M⊙.
- Given the uncertainties in modeling SAGB and massive stars and the uncertainties in supernova models, it is hard to distinguish ECSN and low mass CCSN.





Silicon Flash during Collapse

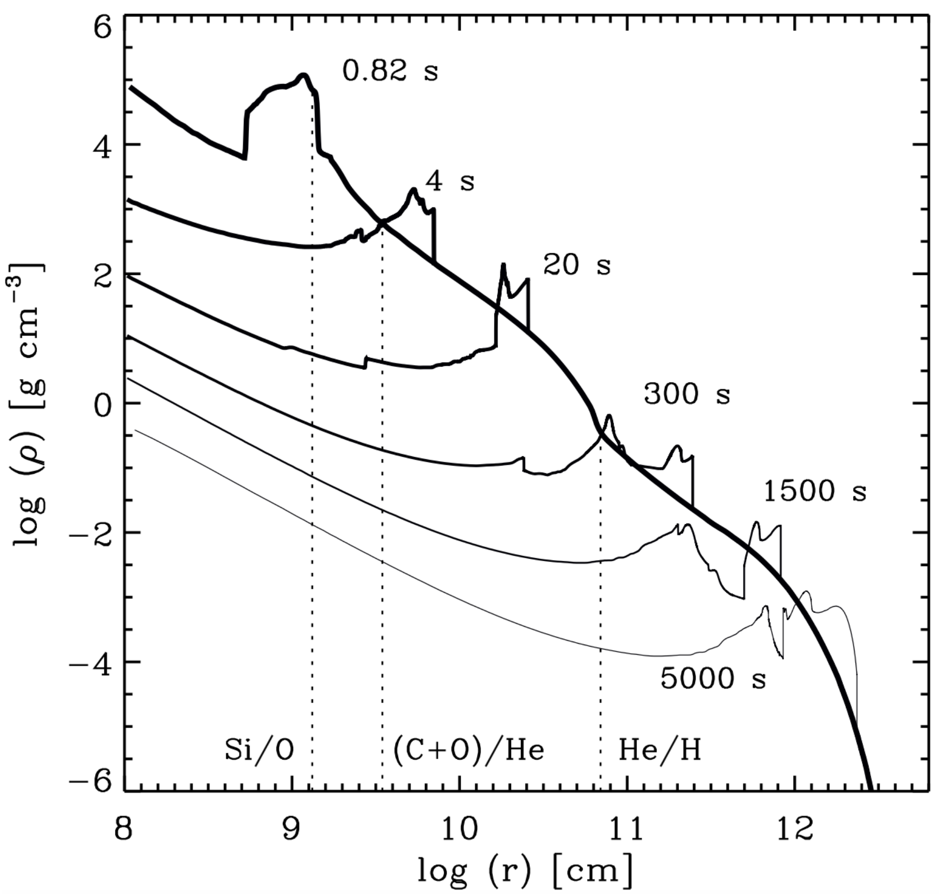
- Stellar evolution models (e.g. Woosley & Heger 2015) for 9-11 M⊙ exhibit flashes starting in the silicon layer.
- Here, compressional heating during collapse leads to accelerated burning in the neon and silicon burning shells.
- This flash propagates to several thousand km before it is caught by the supernova shock.

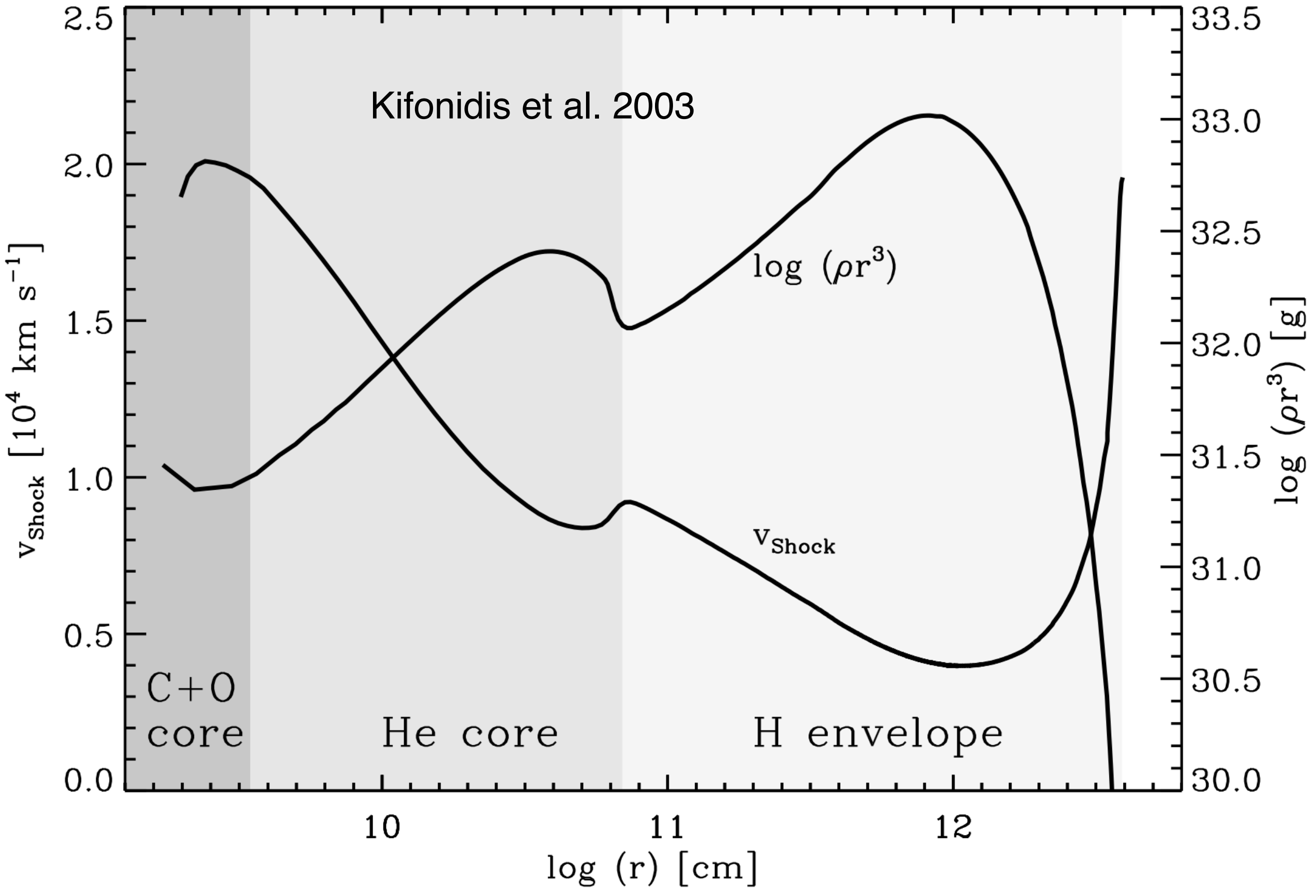


Lentz+ (2023)

Decelerating shocks & developing instabilities

Progress of the shock is generally impeded by the envelope with $a \propto \rho r^3$. Density jumps at shell interfaces also launch reverse shocks and instabilities.





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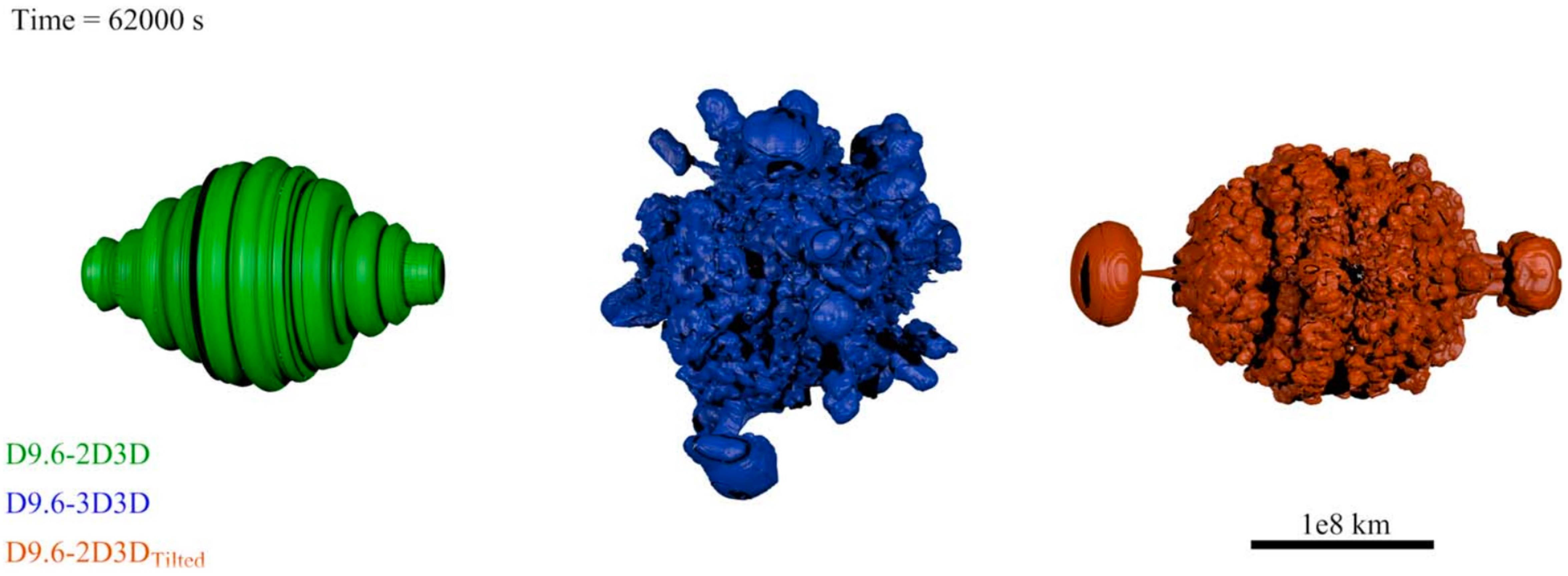
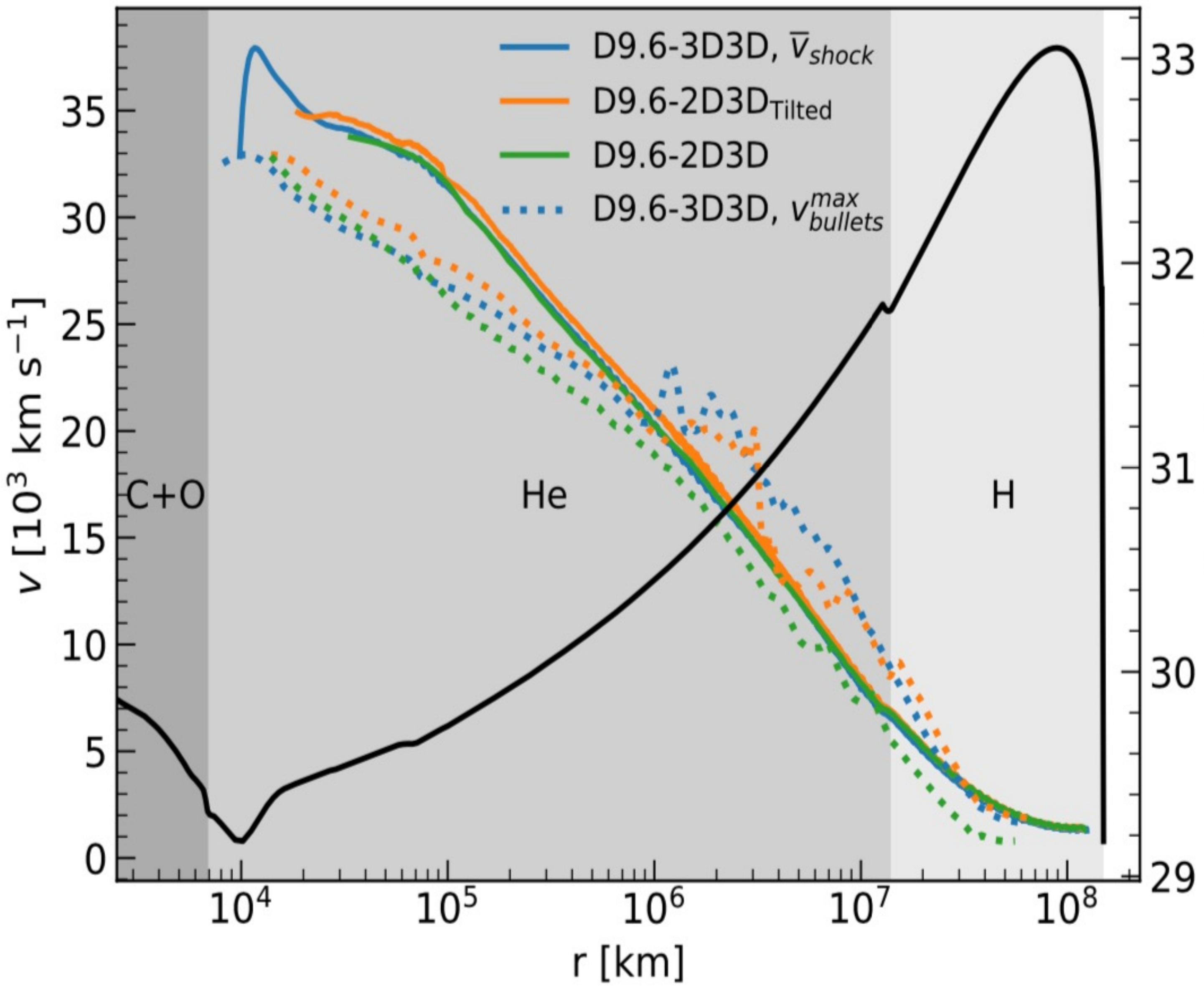
But, the initial morphology at mapping matters as well



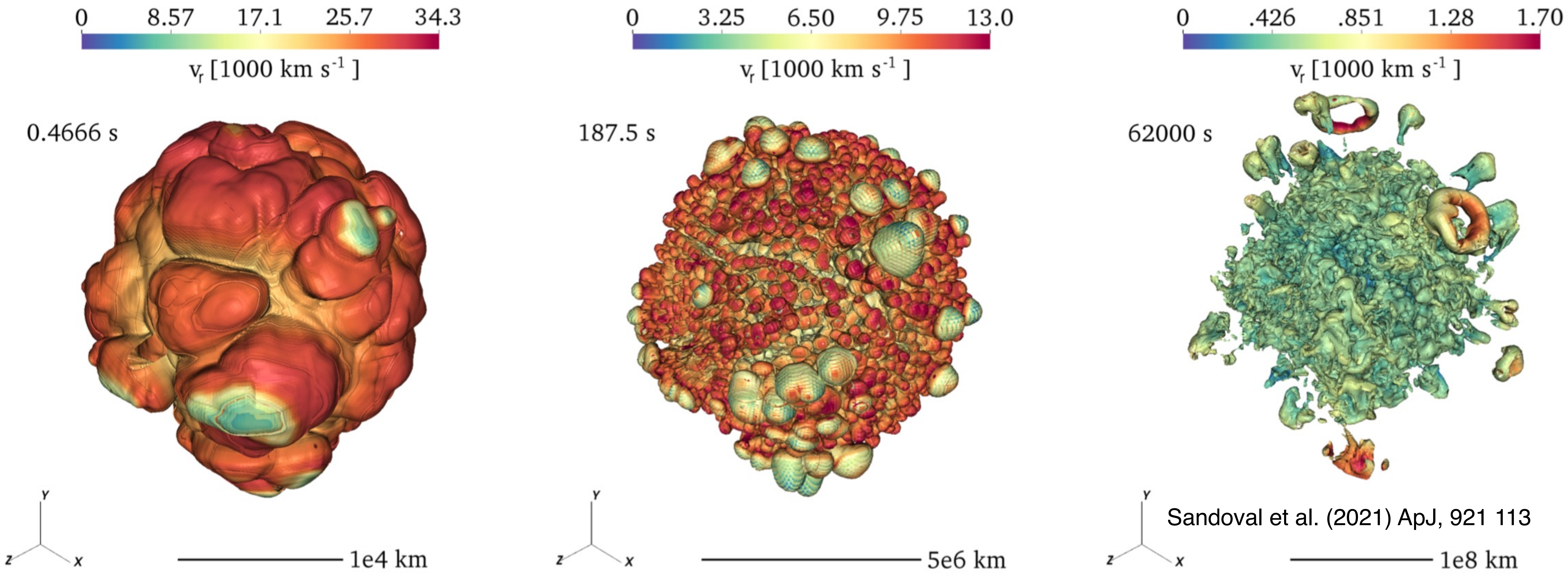
Bullets getting ahead

- While the shock responds to ρr^3, in the D9.6-3D3D (and the D9.6-2D3D$_{Tilted}$) (3D) R-T fingers catch up to the shock and push it outward.
- This does not occur in our D9.6-2D3D run (or the z9.6 model from Stockinger+ (2020)), which prevents the mixing of metals into the outer parts of the star.



D9.6-3D3D: Mushroom view

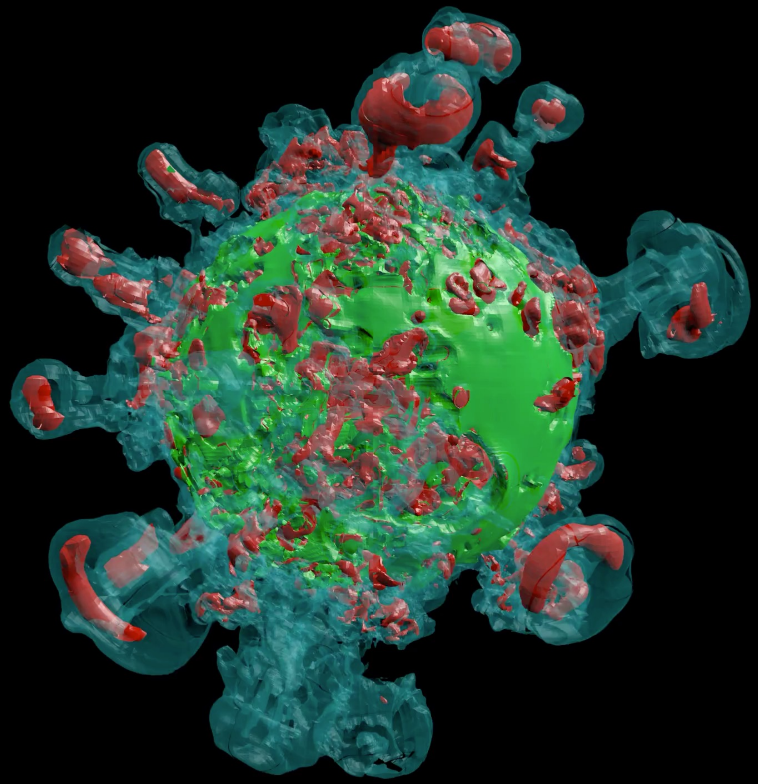
3D view of nickel at mapping, in He shell, and at surface.



Sandoval et al. (2021) ApJ, 921 113

D9.6-3D3D: Heavy element distribution

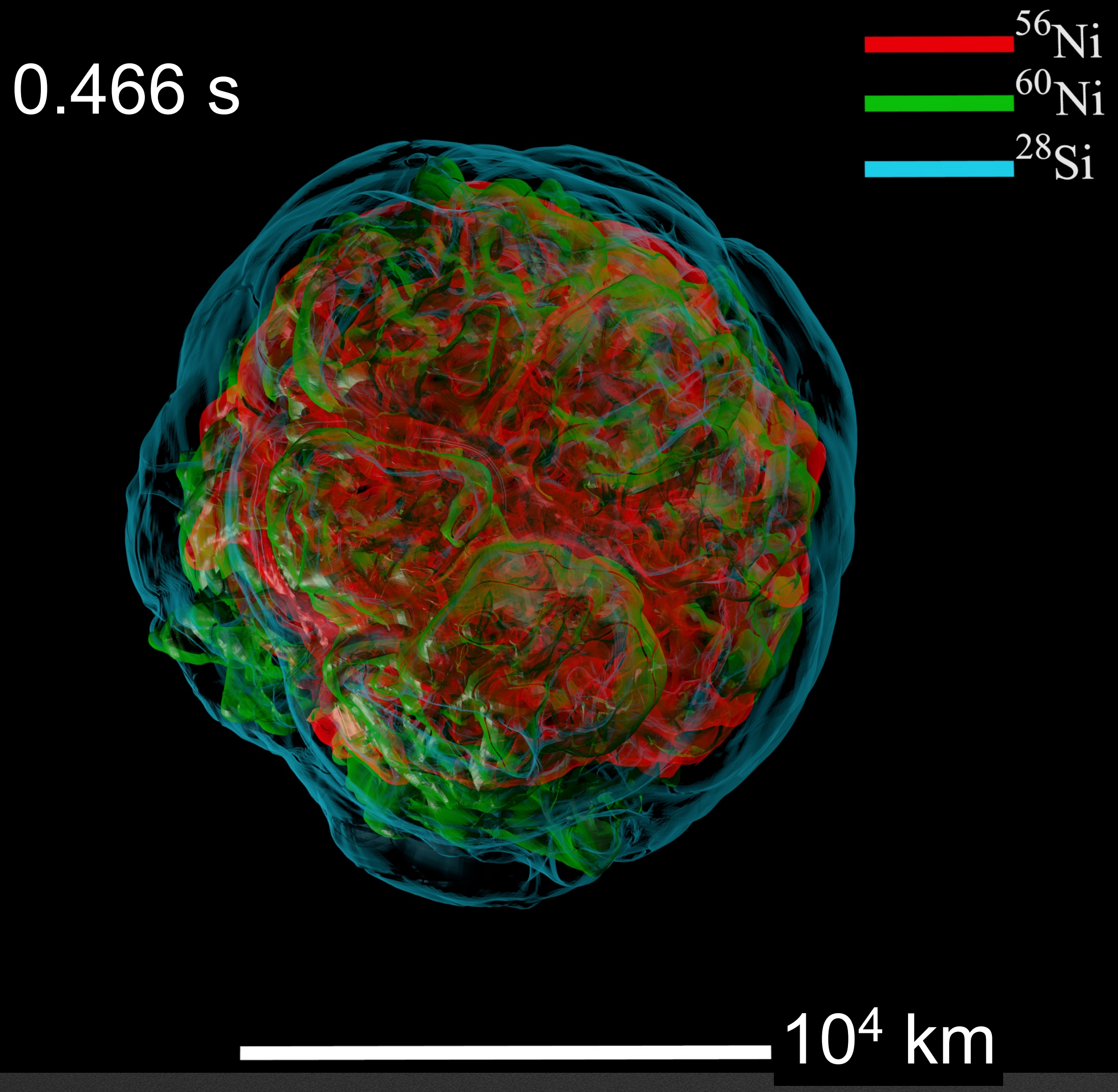
Time=79961.690 s

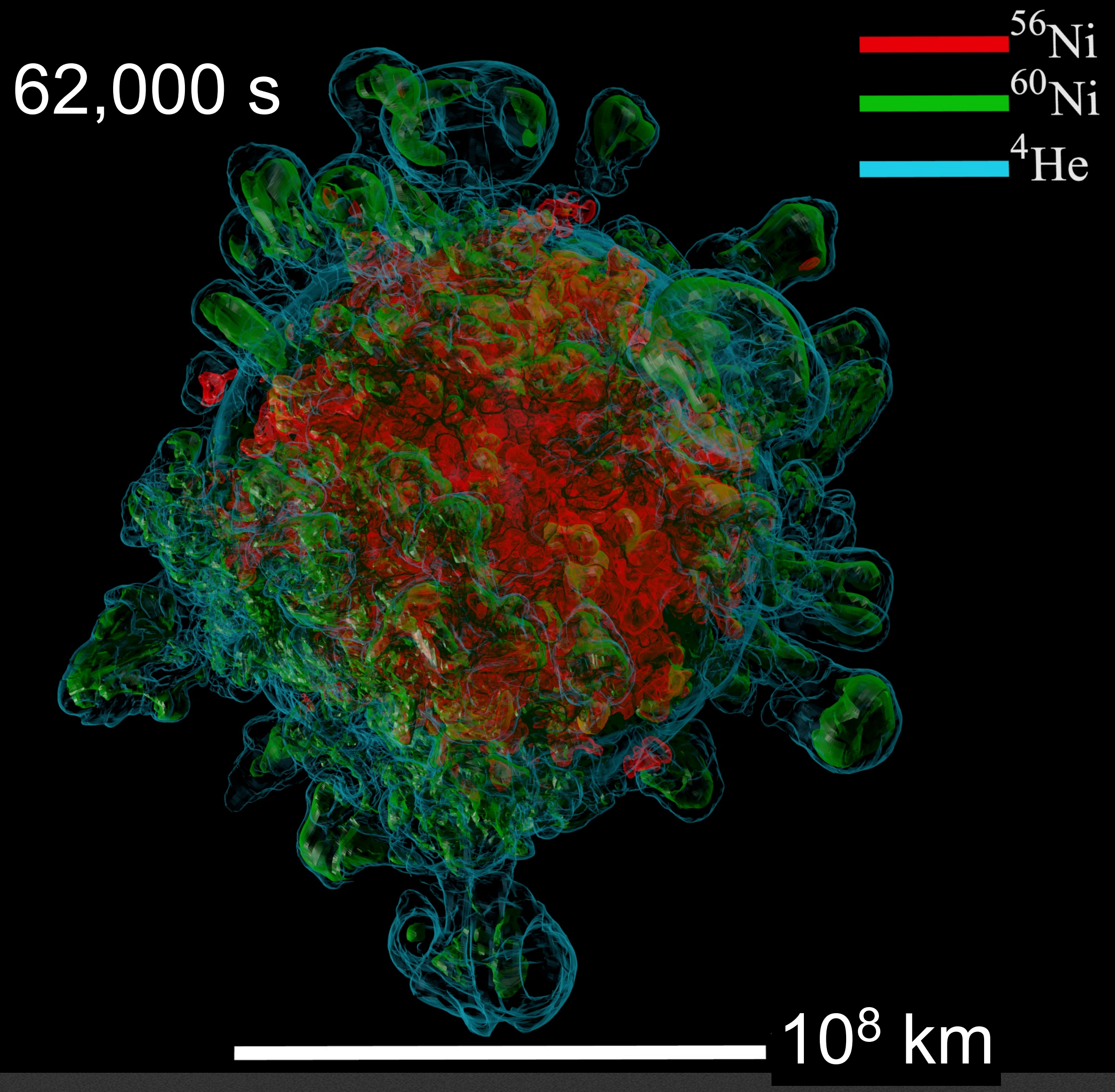


Mass Fraction Isosurfaces

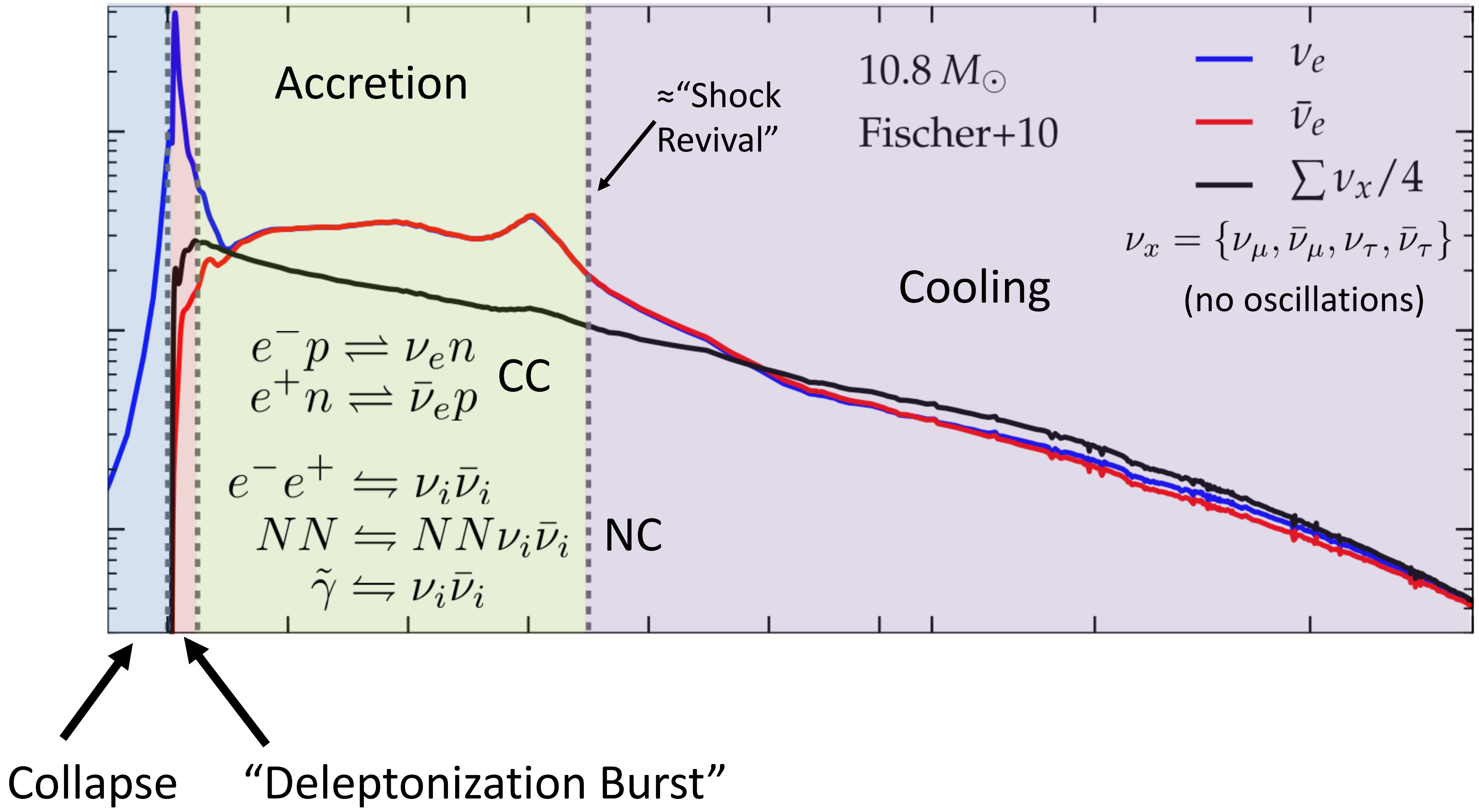
40% ^{4}He
6% ^{12}C
1% ^{60}Ni

Bullet Anatomy: ^{56}Ni and ^{60}Ni



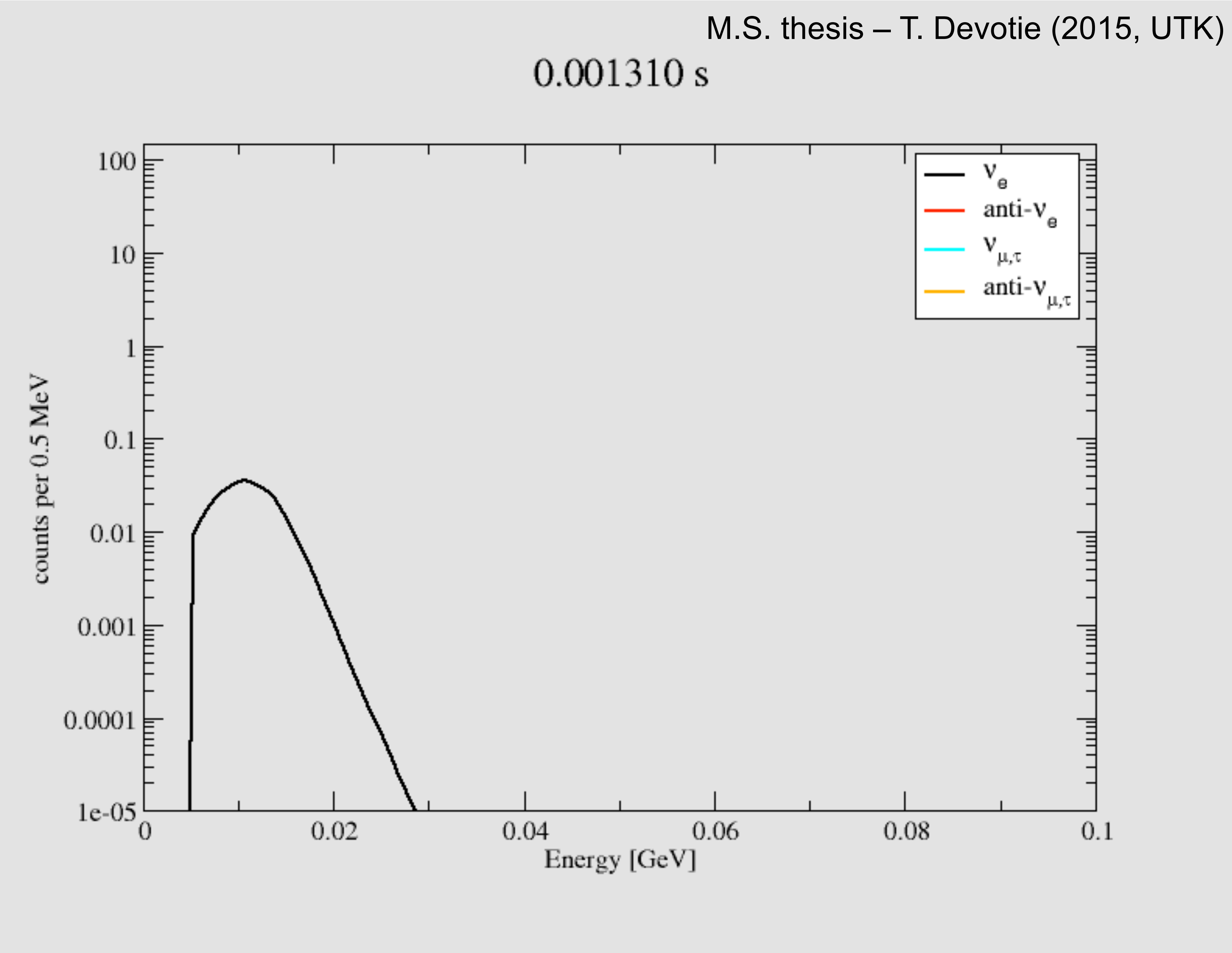


Supernova neutrino "lightcurves"



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

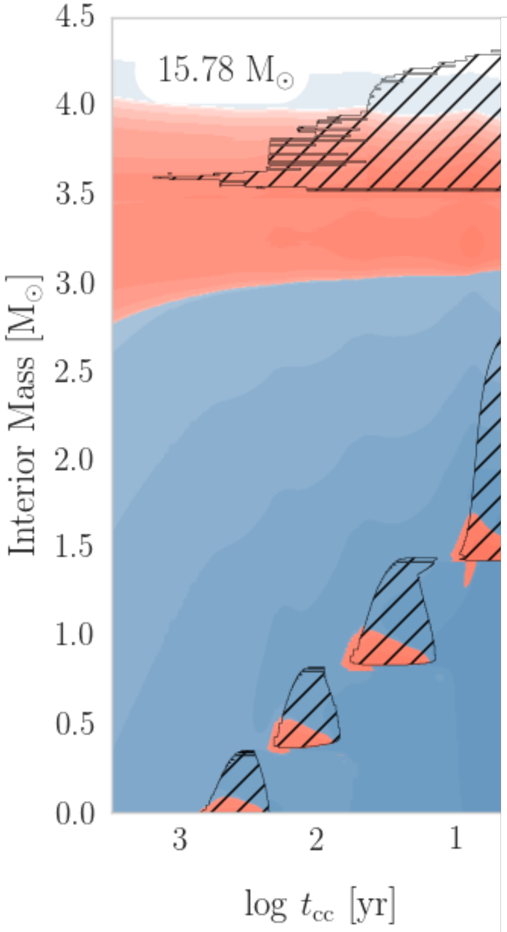
Multi-flavor detection

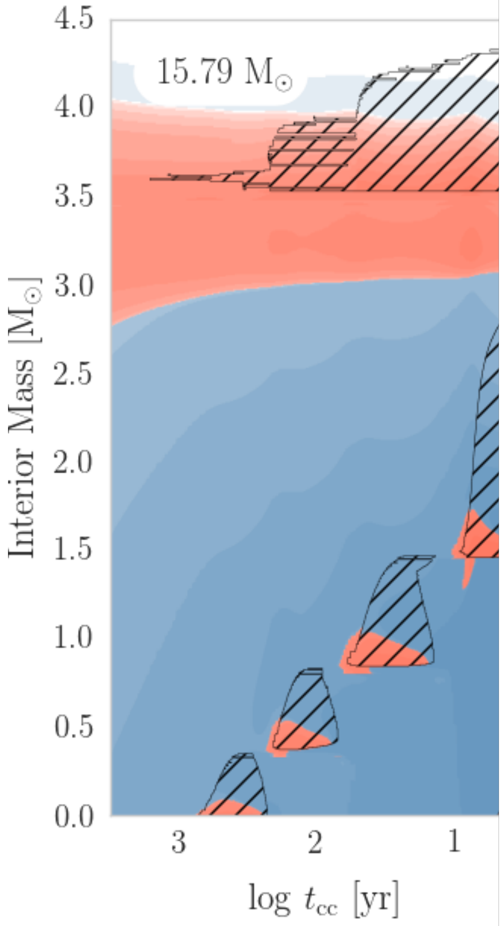


C15-2D, angle-averaged, SNOwGLoBES Ar17kt, 10 kpc

A tale of two “identical” progenitors

15.78 M$_\odot$ versus 15.79 M$_\odot$



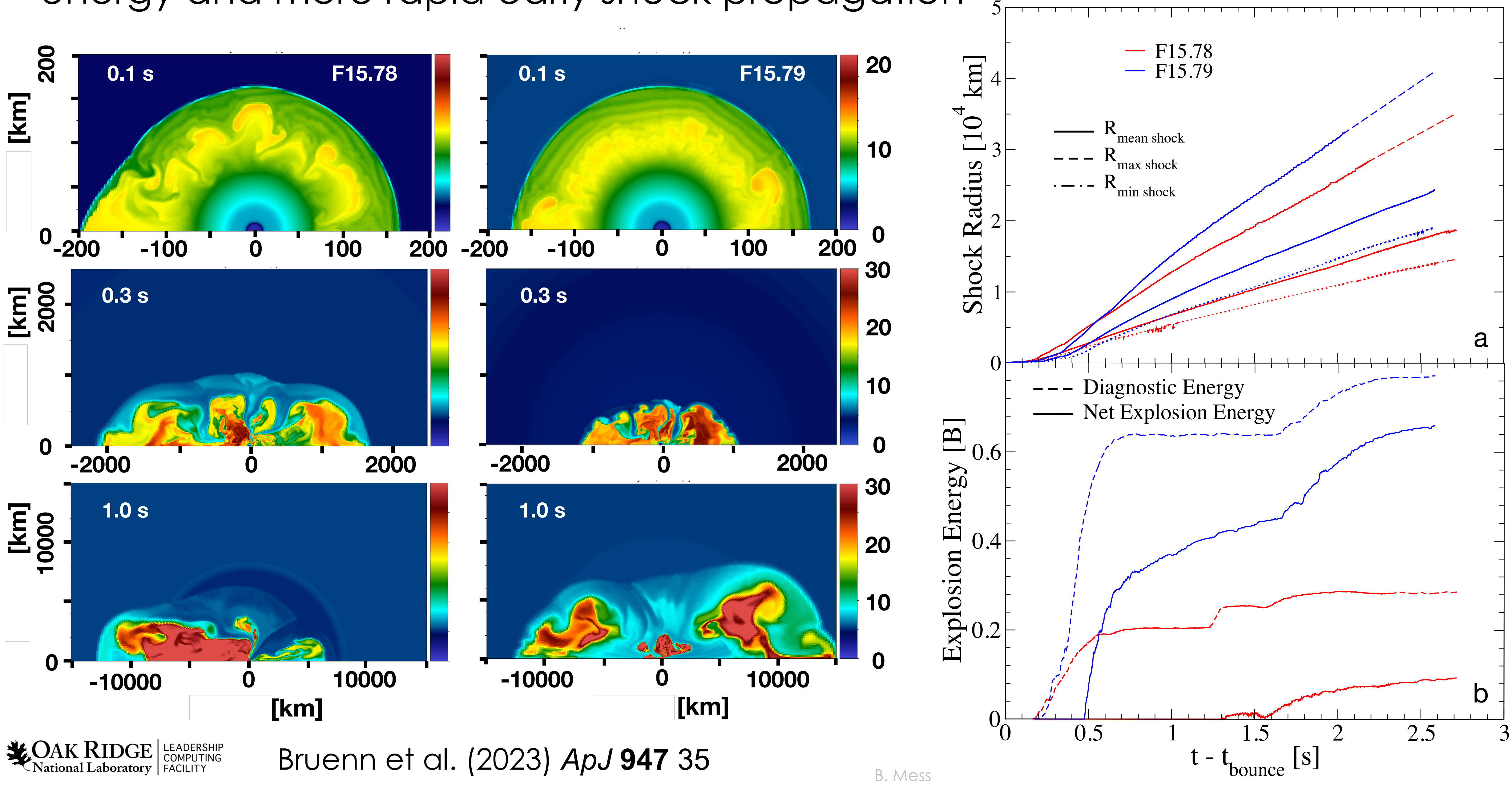


~month

~week

Bruenn et al. (2023) *ApJ* **947** 35

Later start to explosion, but more massive progenitor has higher explosion energy and more rapid early shock propagation



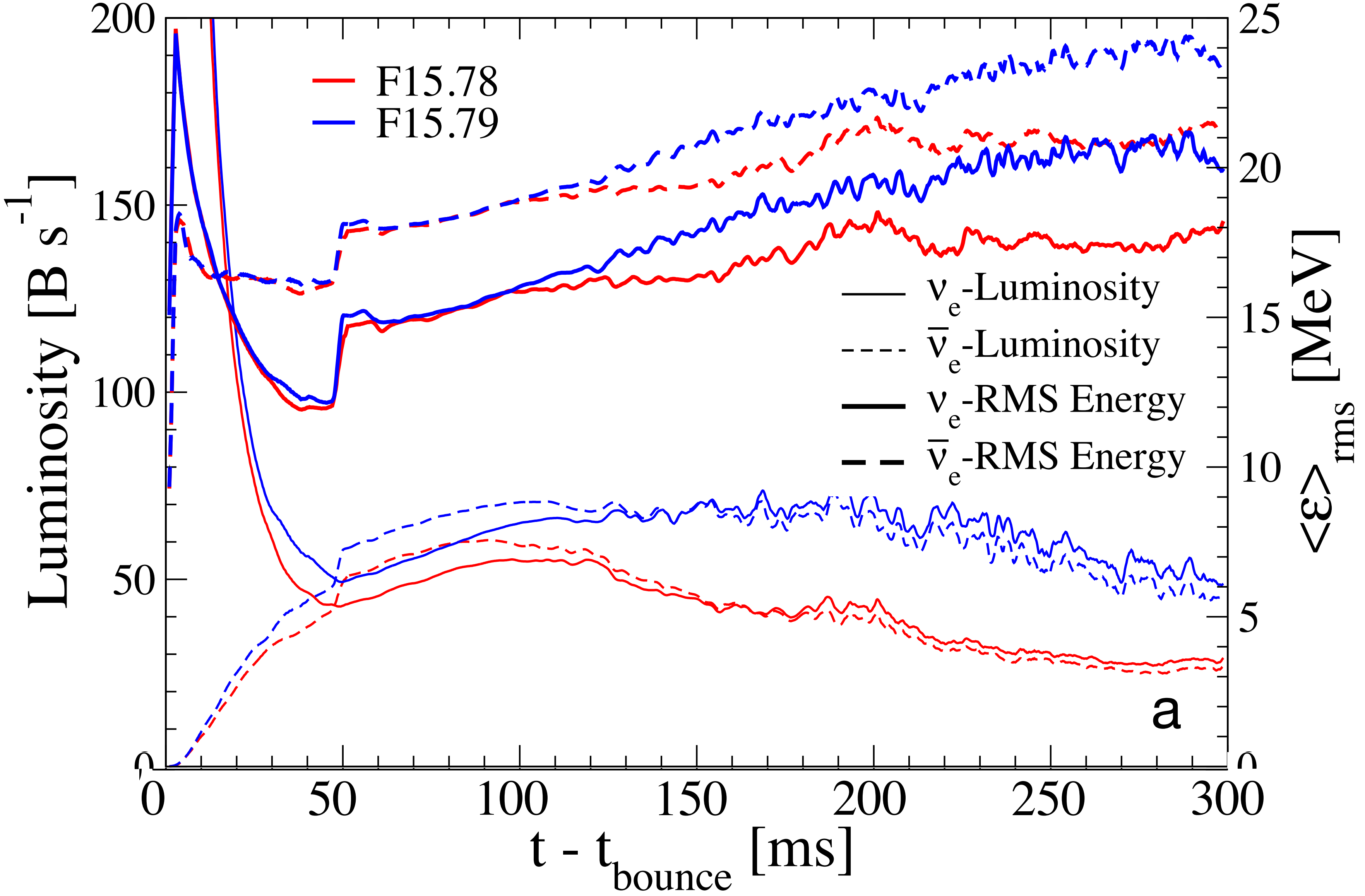
Bruenn et al. (2023) *ApJ* **947** 35

B. Mess

Early RMS energies and luminosities

Bruenn+ (2023)

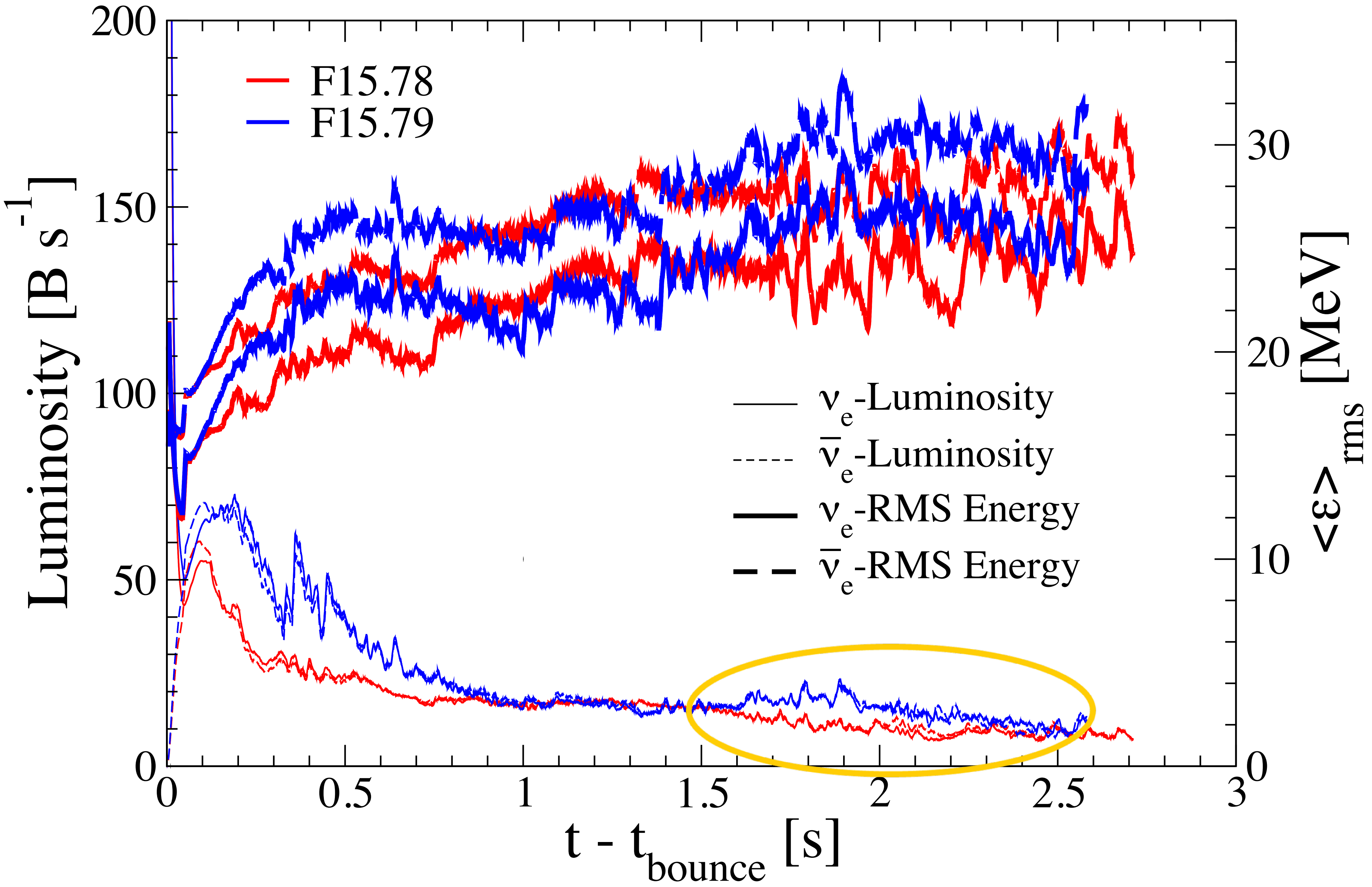
- After explosion starts for F15.78 @ about 150ms
  - ~10% differences in <E>
  - ~40% differences in L



Later energies and luminosities @ gain radius

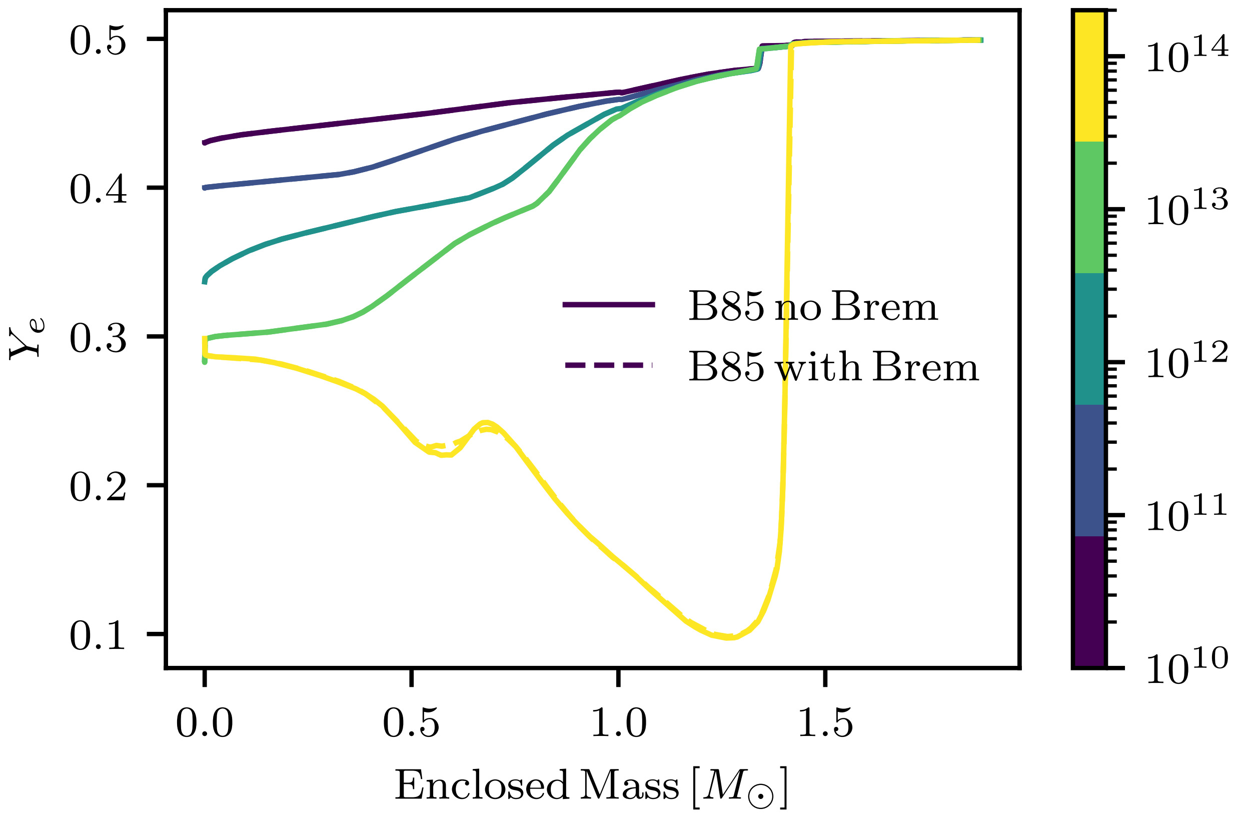
Bruenn+ (2023)

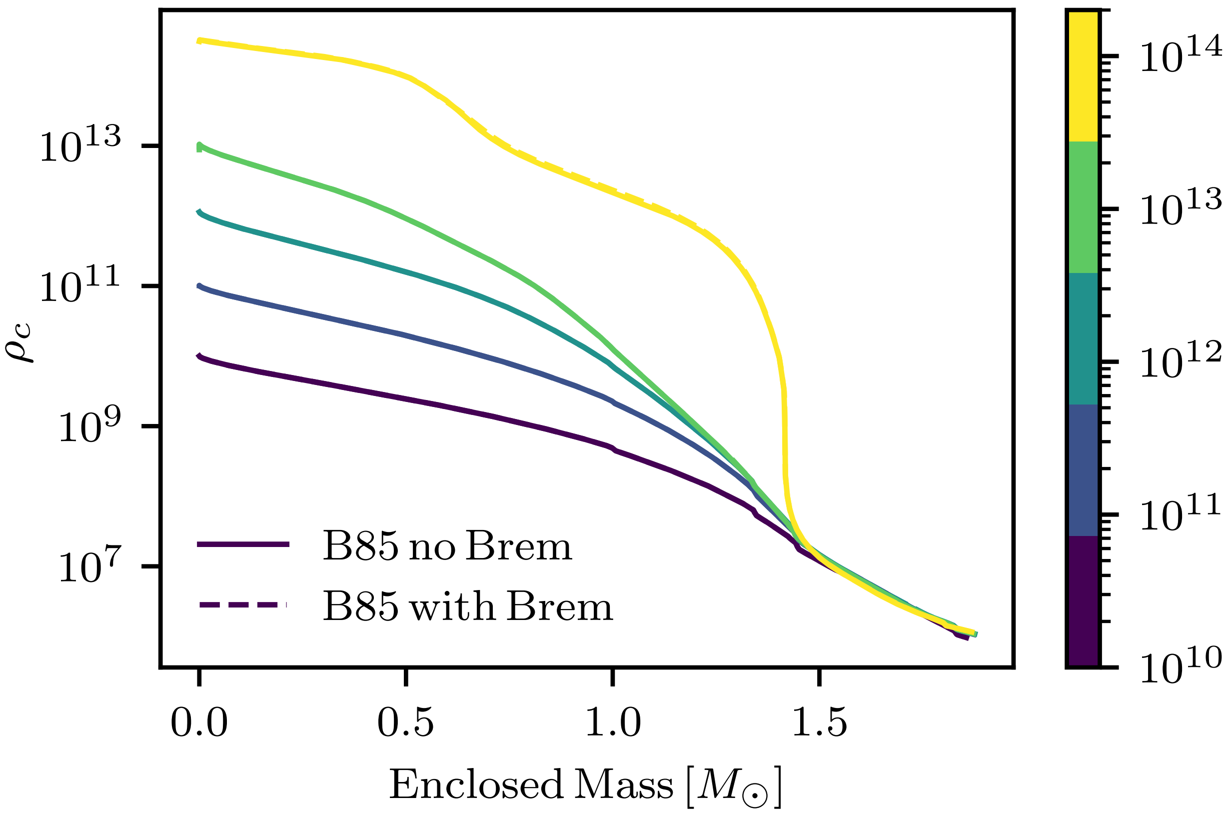
- Later, at ~1.6s to 2.5s
  - ~10% differences in <E>
  - ~40% differences in L



The inclusion of bremsstrahlung has little dynamic impact

Yellow == 300ms PB

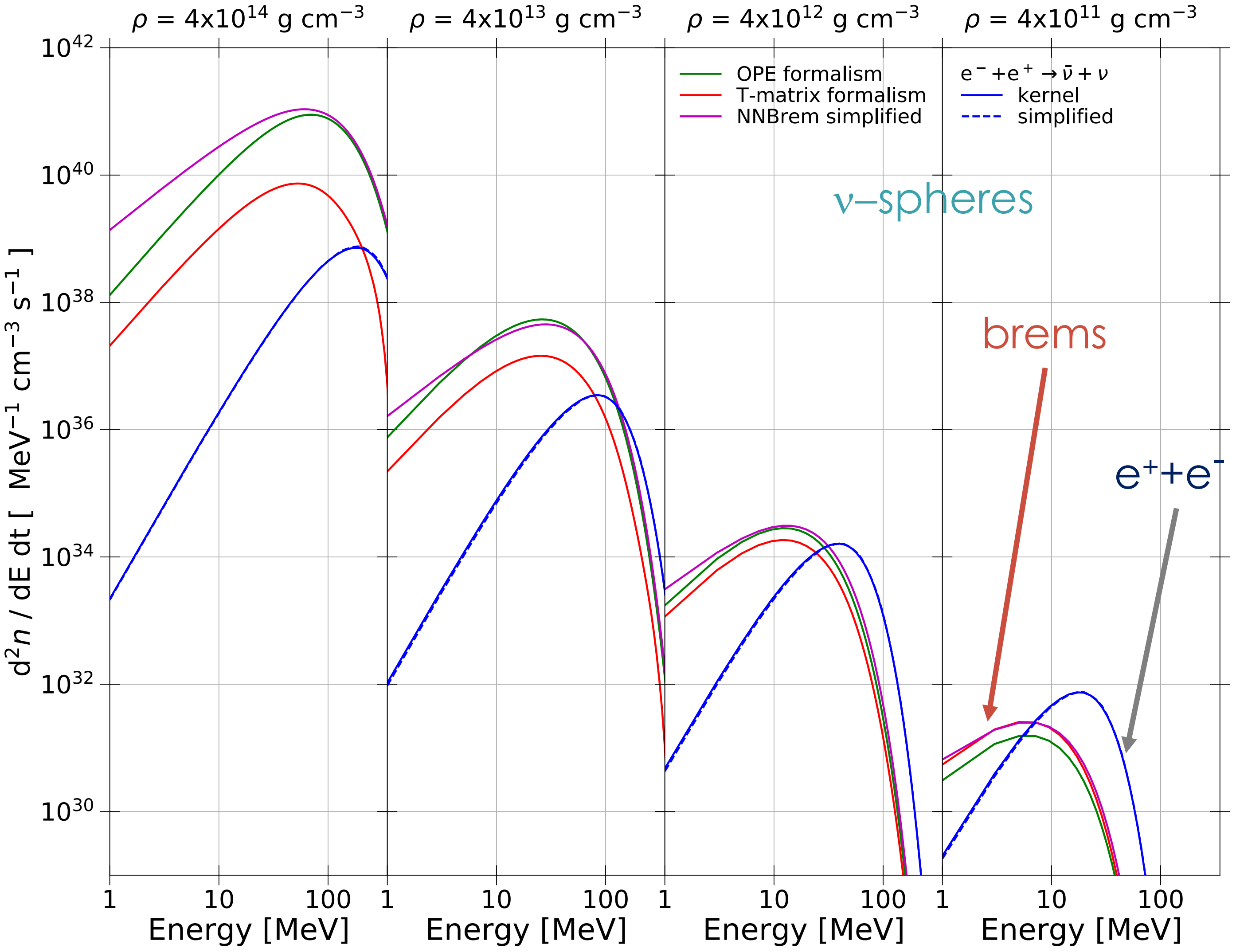




1D with Flash-X (V. Mewes, ORNL)

Impact of bremsstrahlung on heavy-lepton-flavor neutrino spectra

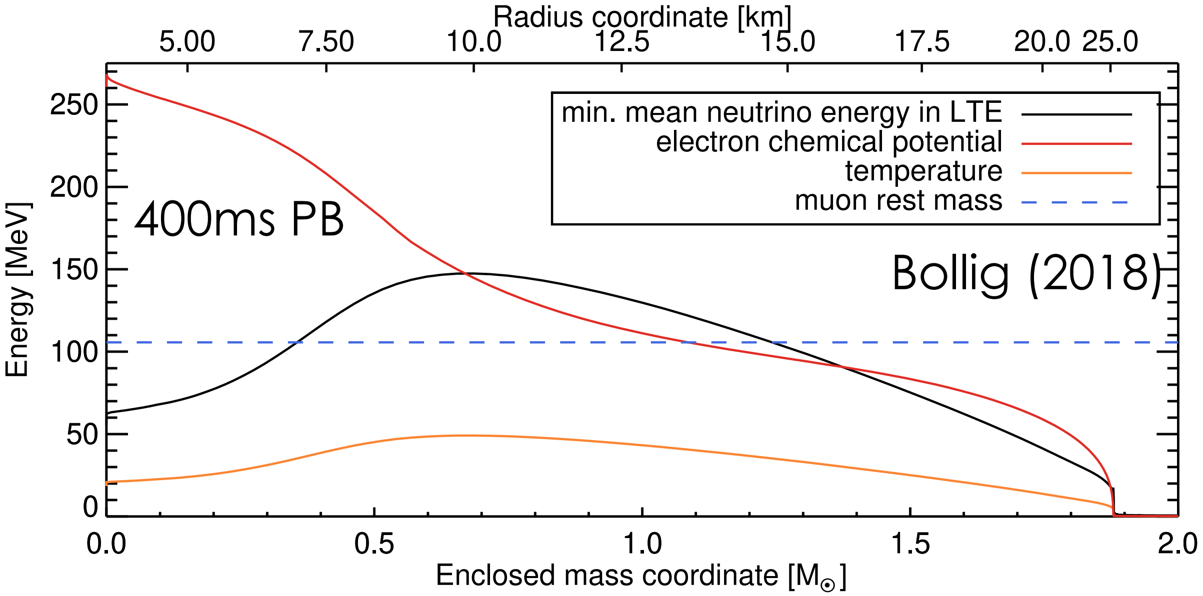
Significantly softer neutrino spectra formed in and around the neutrinospheres.

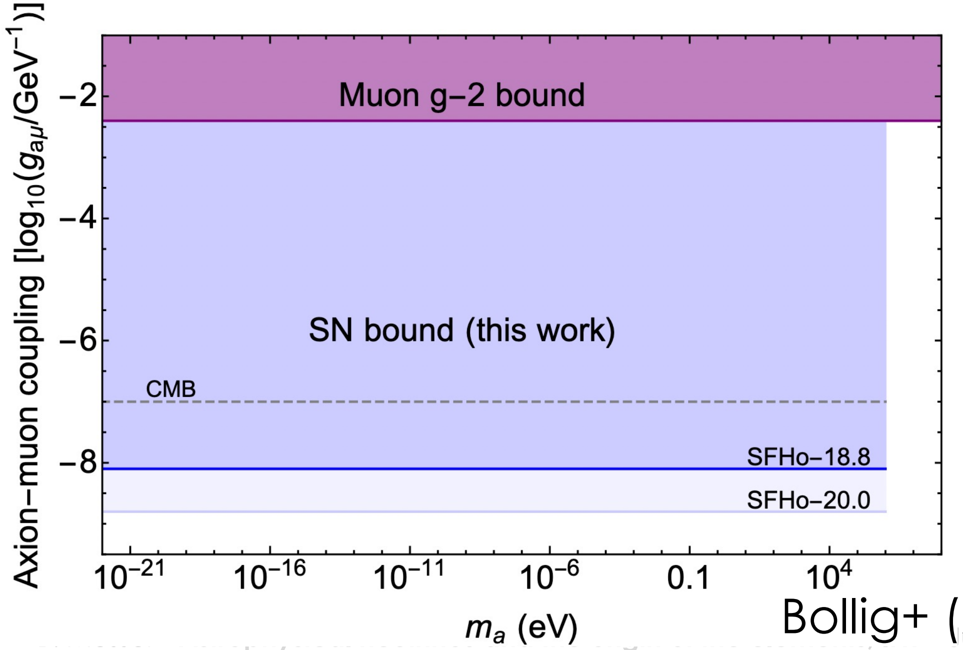


Betranhandy & O'Connor
Phys. Rev. D 102, 123015 (2020)

Muons and the total neutrino flux budget

- Inclusion of muons in RHD simulation codes is a comprehensive change
- Requires changes to
  - EOS
  - RHS of transport equation
  - Transport solver preconditioners
- Changes flux after ~200ms
- Changes total flux → new axion bounds

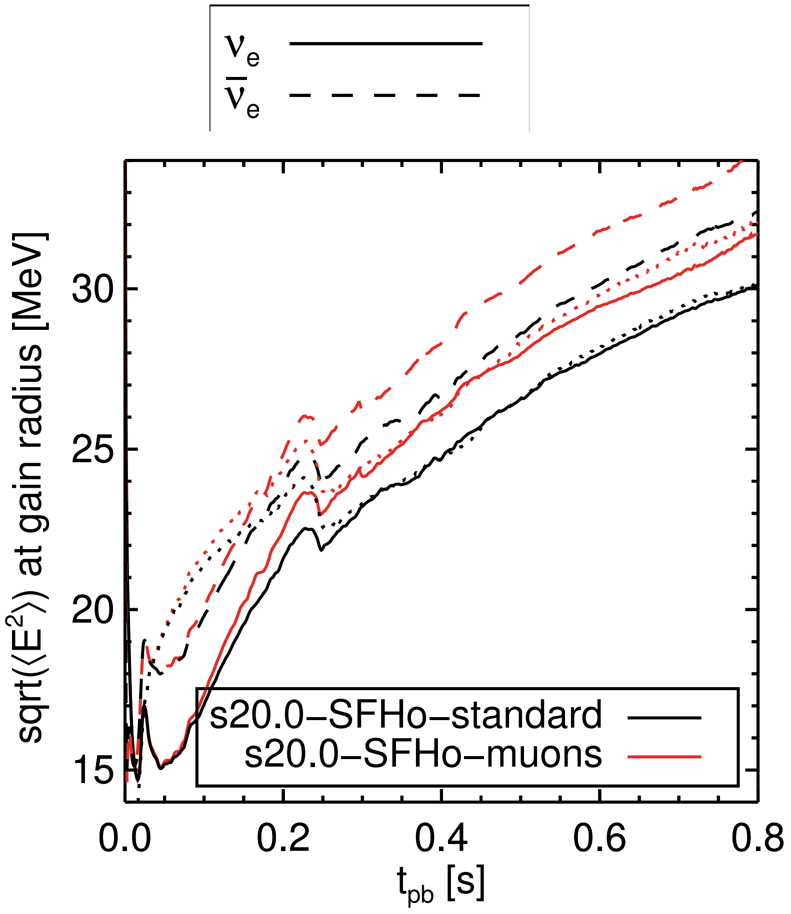


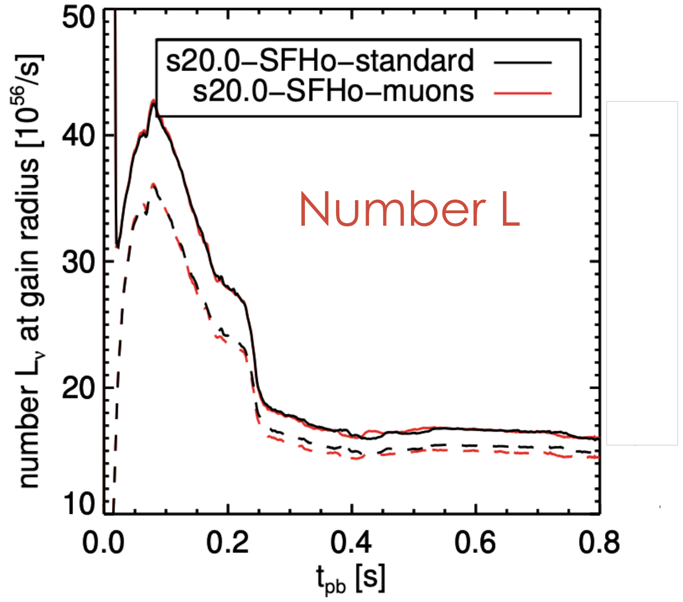


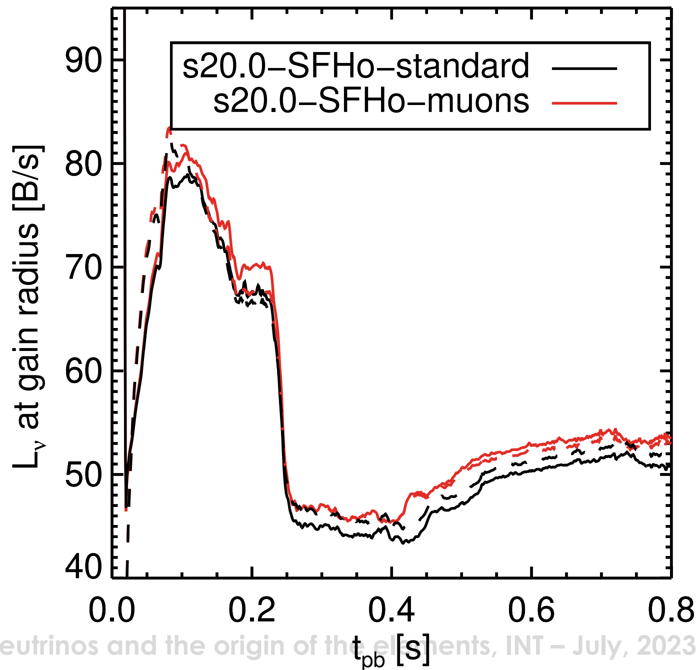
Bollig+ (2020)

Modest dynamic differences, but at interesting times and places

- 1-2km differences in PNS radius at ~1s PB
- ~10% differences in <E> and L at late times, hardening the spectra versus no-muons







R. Bollig (PhD thesis, TUM 2018)

Complete multi-messenger theory of CCSNe will enable astrophysical neutrino science

For true multi-messenger astronomy, we must build a continuous chain of core-collapse supernova/remnant simulations linking the earliest moments of the explosion, when the neutrino & gravitational wave signals originate, to the epochs when the photon signals arise.

- Examine late stellar evolution in multi-dimensions
- Model CCSN mechanism with 3D spectral neutrino radiation hydrodynamics and detailed nucleosynthesis *until the explosion matures and the nucleosynthesis finishes*
- Model progress of the shock and heavy element ejecta through the star
- Model shock breakout and the light curve phase with (3D?) photon radiation hydrodynamics, etc
- Model nebular phase with full chemistry, etc.
- Model supernova remnant phase including cosmic ray generation, etc.

…and connect to NS cooling calculations!

Takeaways redux

- **Core-collapse supernova models in 3D with sophisticated νRHD explode consistently, reasonably, and in various ways. The next frontier is establishing a quantitative understanding of all multi-messenger observables over much longer timescales.**

- Our current understanding of neutrino emission (and, maybe, nucleosynthesis) over the first few seconds of CCSNe **explosions** is qualitatively OK if you ignore some known physics (e.g., collective flavor oscillations).
  - Prediction is, of course, dependent on understanding this physics, but will also require an *in situ* treatment in RHD simulations.

- **But, the details of this emission is tightly coupled to explosion dynamics, depending strongly on progenitor structure in a variety of ways.**

- Aside from neutrino flavor oscillation physics-–a frontier that will require considerably more computational intensity than we have brought to bear to this point—there are other pieces of physics that require more-or-less immediate attention
  - **Including heavy lepton degrees of freedom "everywhere" (every-how) in simulations**

Questions?