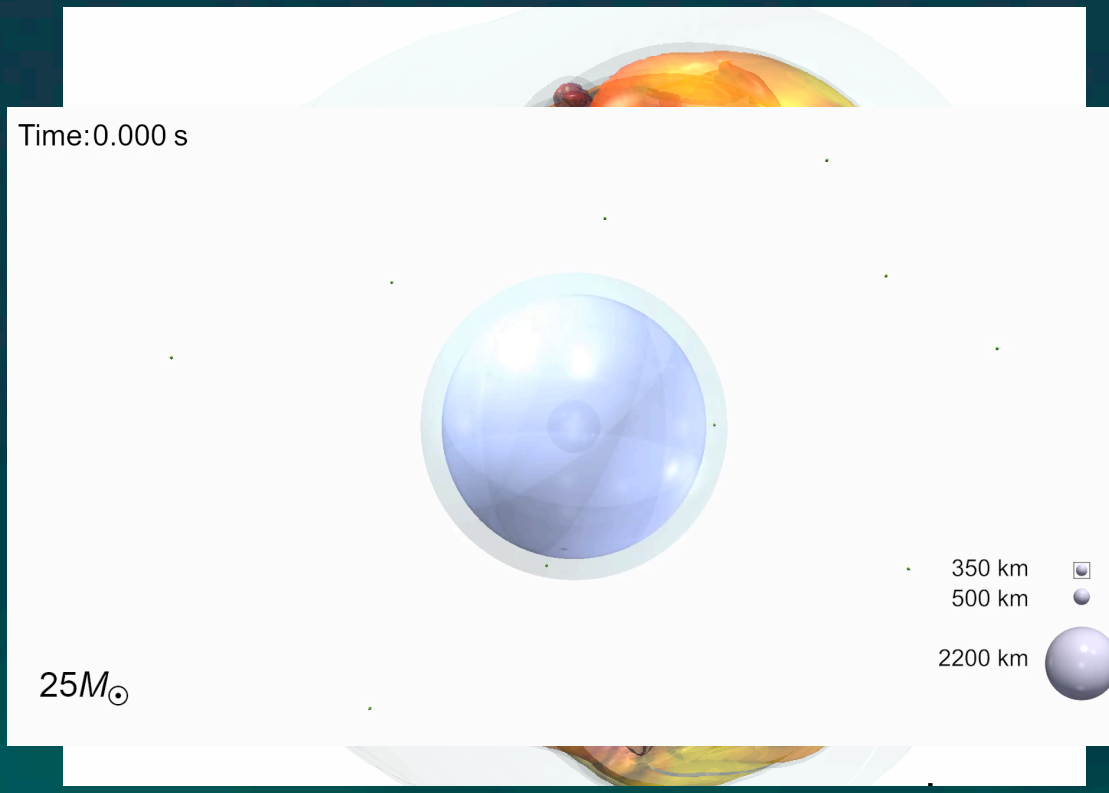
Core-Collapse Supernovae: Bounce to Breakout

NASA Hubble Symposium
Caltech,
09/19/2024



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NASA Hubble Fellow
Carnegie Observatories

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Tianshu Wang (Princeton-> Berkeley), Adam Burrows (Princeton)
Lizzy Teryoshin (UCSD - CASSI), Lyla Choi (Princeton)

Neutrino-Driven Supernovae Simulations
Power Robust Explosions

Many (~2 dozen)

Late-time (~10 s)

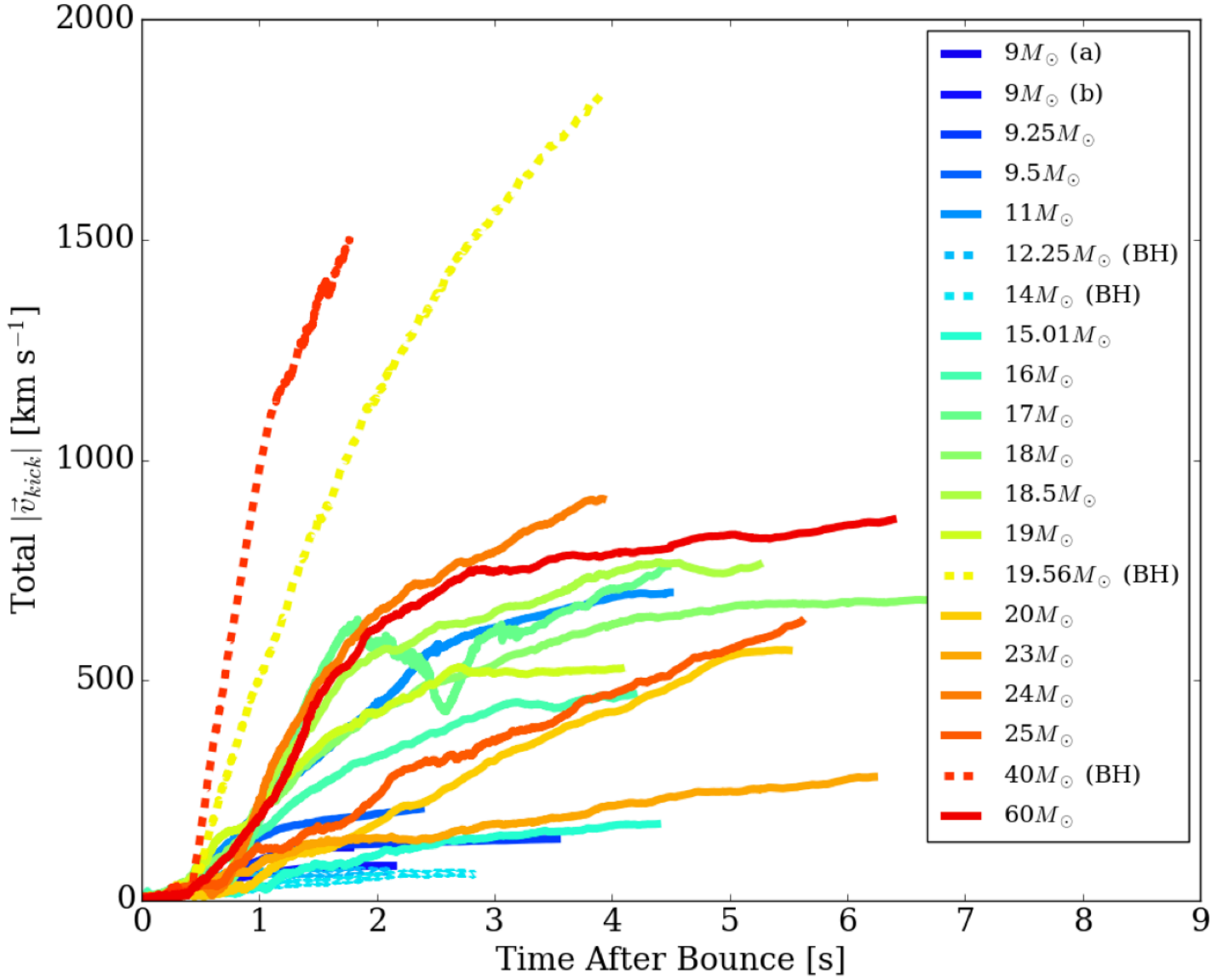
Explosive (0.1-2 B)

Diverse Remnants

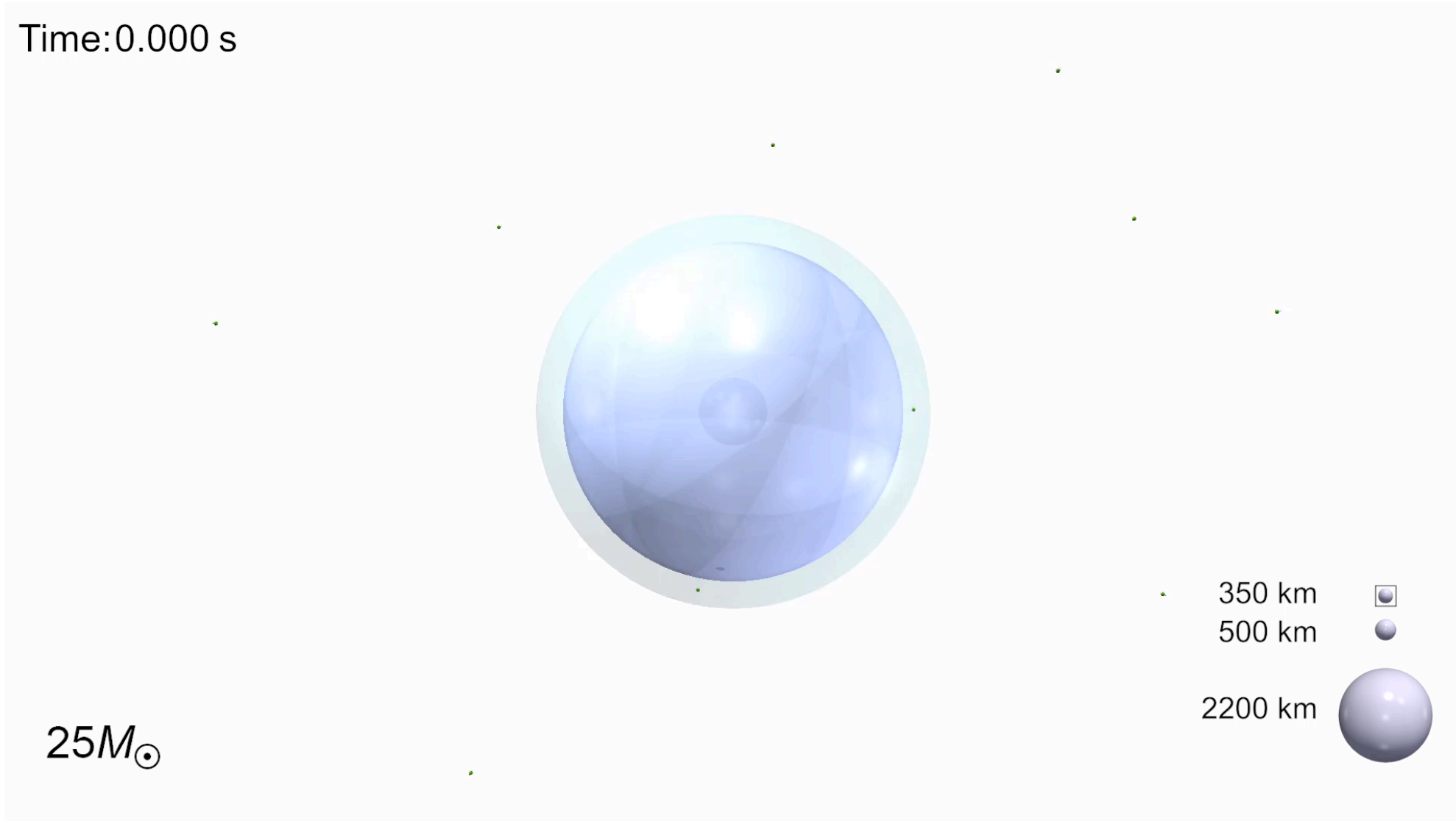
Spread of kick/spins

Ni56 Yields

And templates …



Burrows & Vartanyan, 2020 Nat
Tsang et al. 2022
Vartanyan et al. 2023
Wang et al. 2023
Burrows et al. 2023


Time:0.000 s
350 km
500 km
2200 km
25$M_\odot$

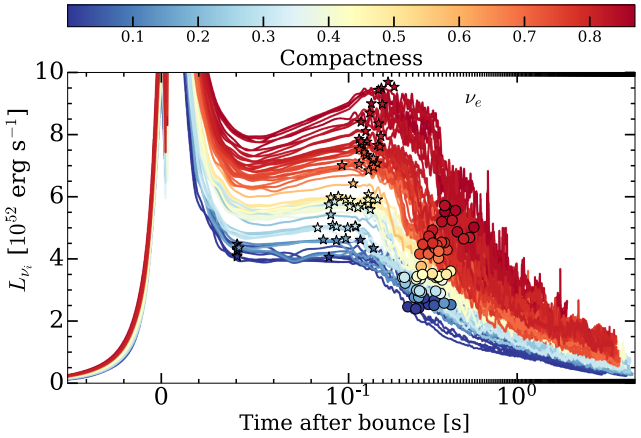
Neutrinos in CCSNe

https://dvartany.github.io/data/

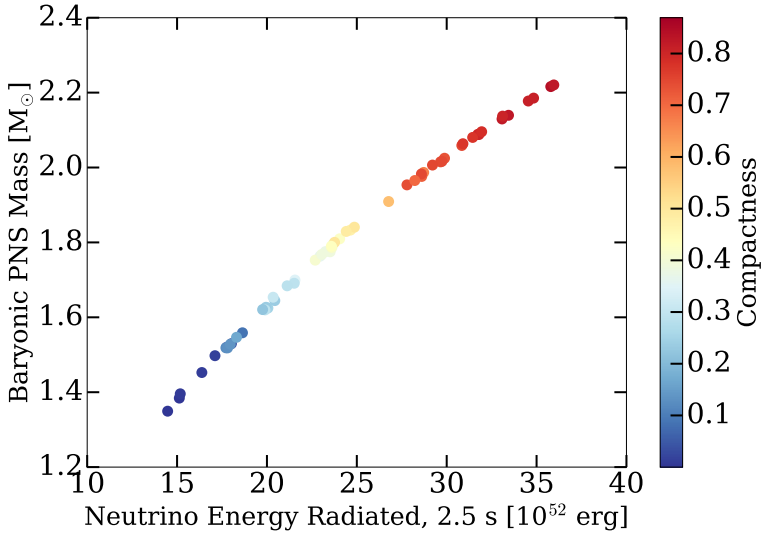
Vartanyan & Burrows, 2023
Seadrow et al. 2018

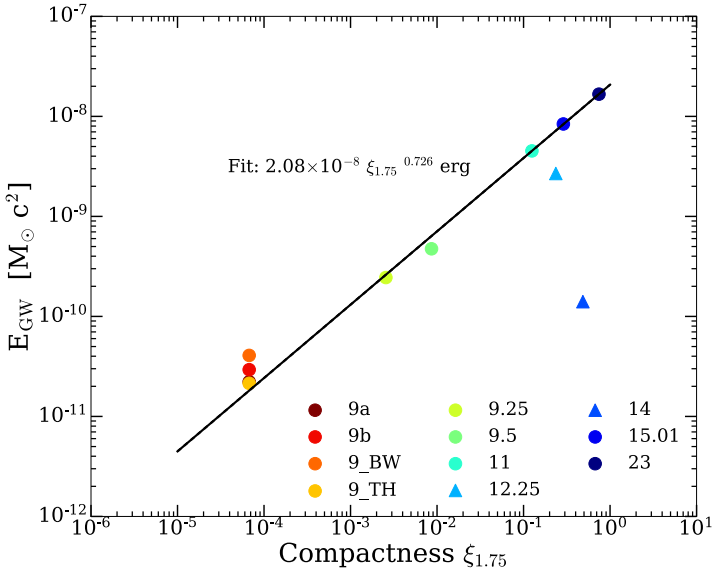
Core compactness (Couch, O'Connor 2014):

$$\xi = \frac{M}{R}$$



Neutrino loss correlated:
core compactness
& PNS mass
& plateau duration
...
& GWs





Gravitational Waves in CCSNe

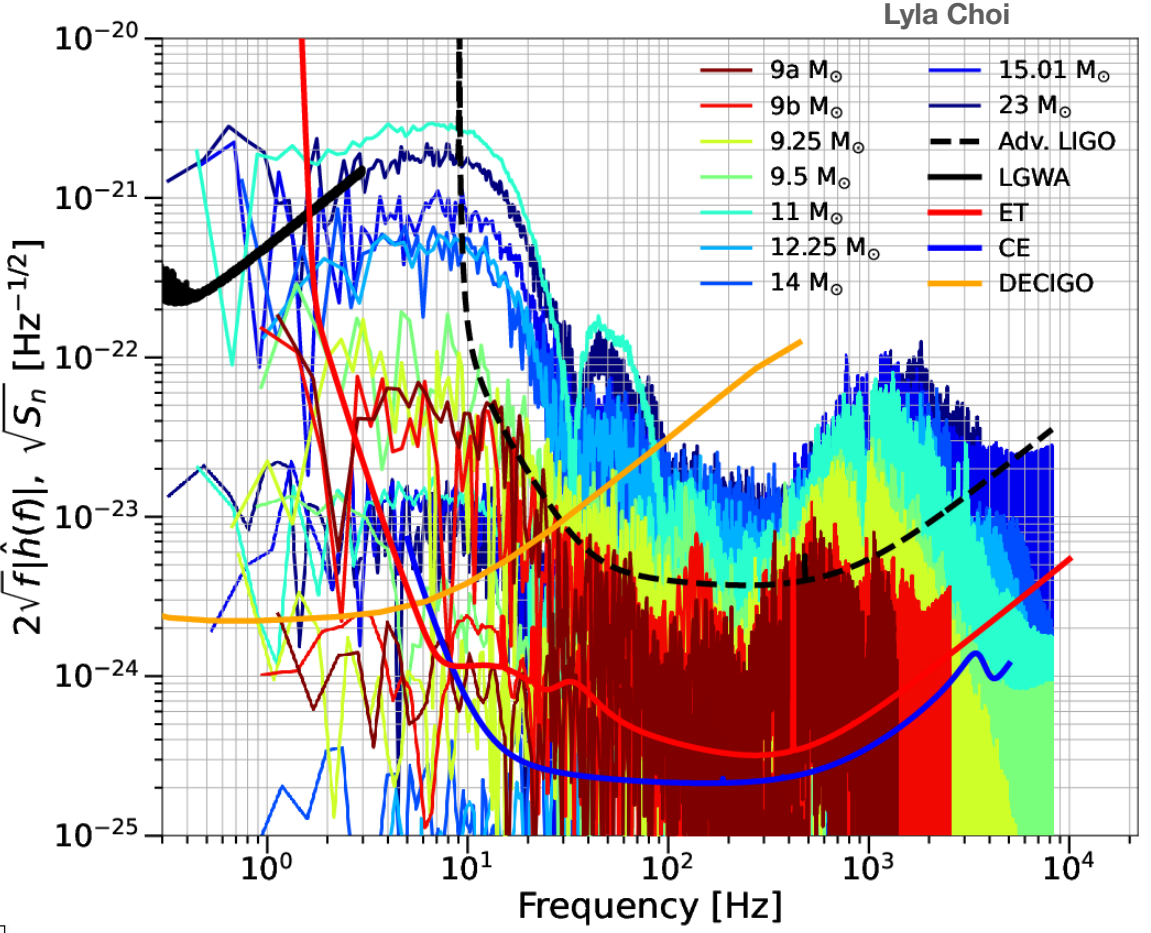
https://dvartany.github.io/data/

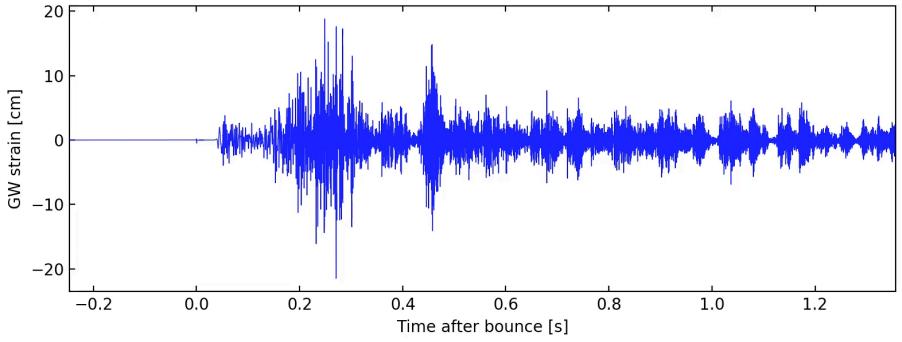
Vartanyan et al. 2023
Choi, Burrows, Vartanyan 2024

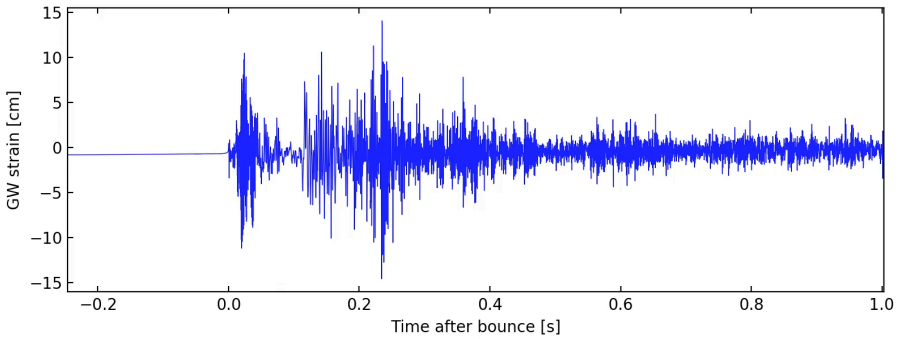
Lyla Choi

Galactic SN are detectable across 5 decades in frequency

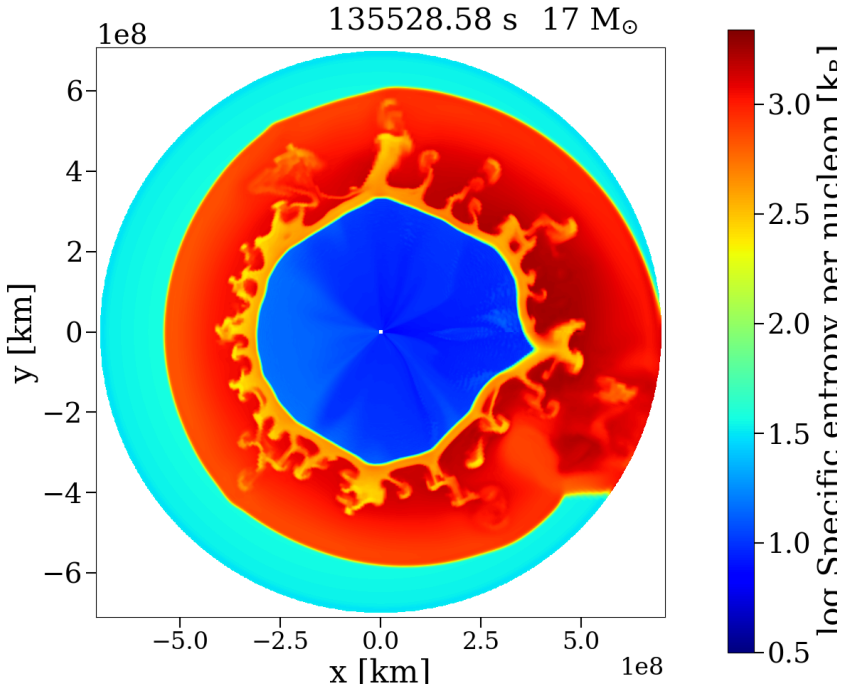
- With Current & Next-Gen detectors
- For all masses
- Including Matter- & neutrino-memory GWs

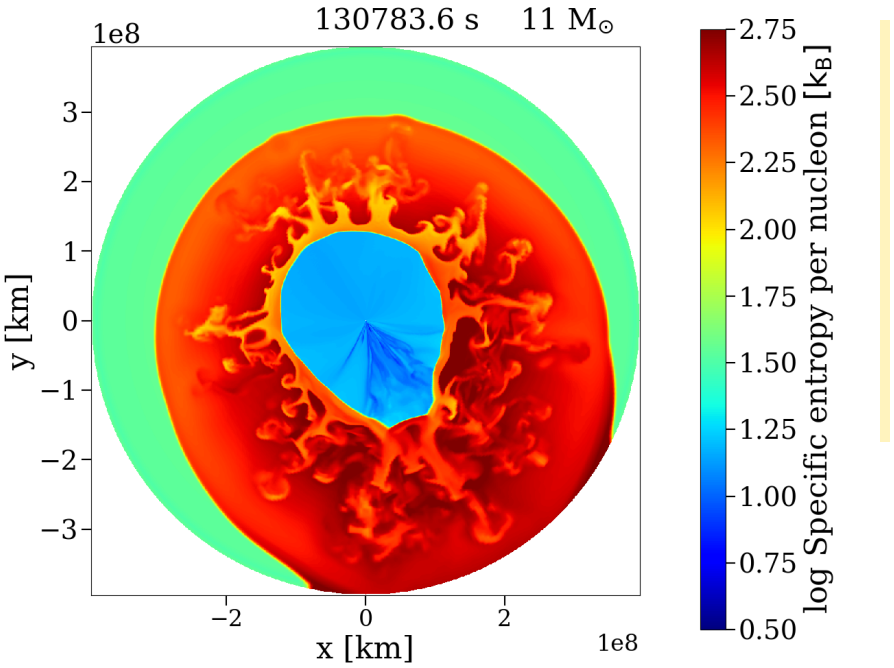


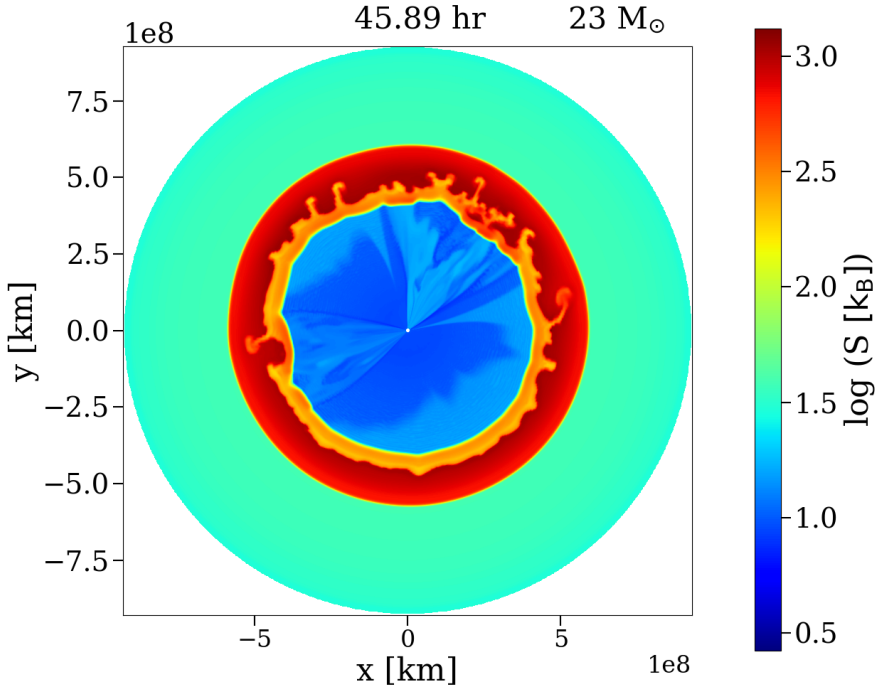


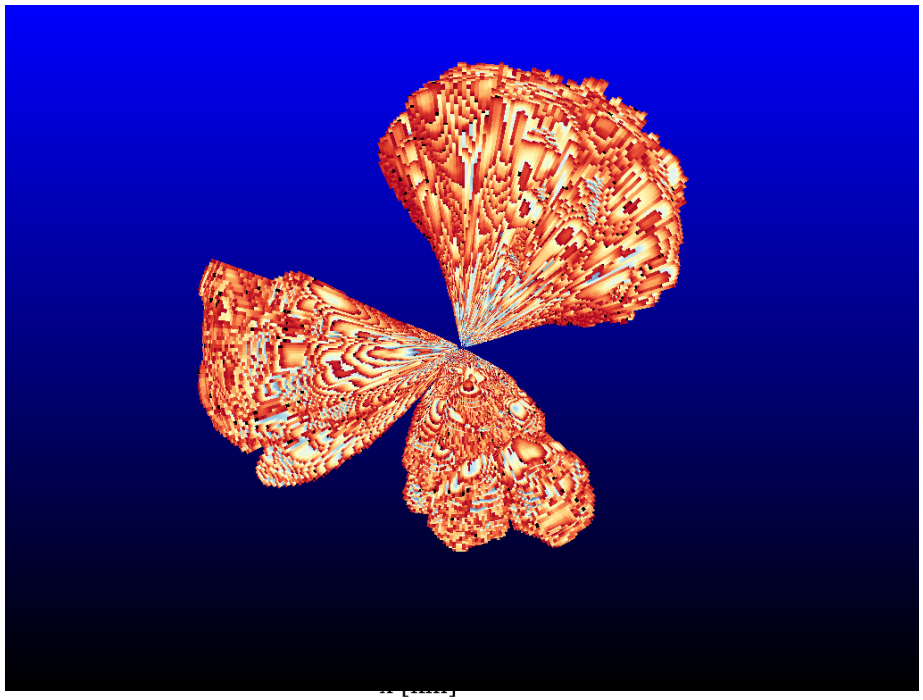


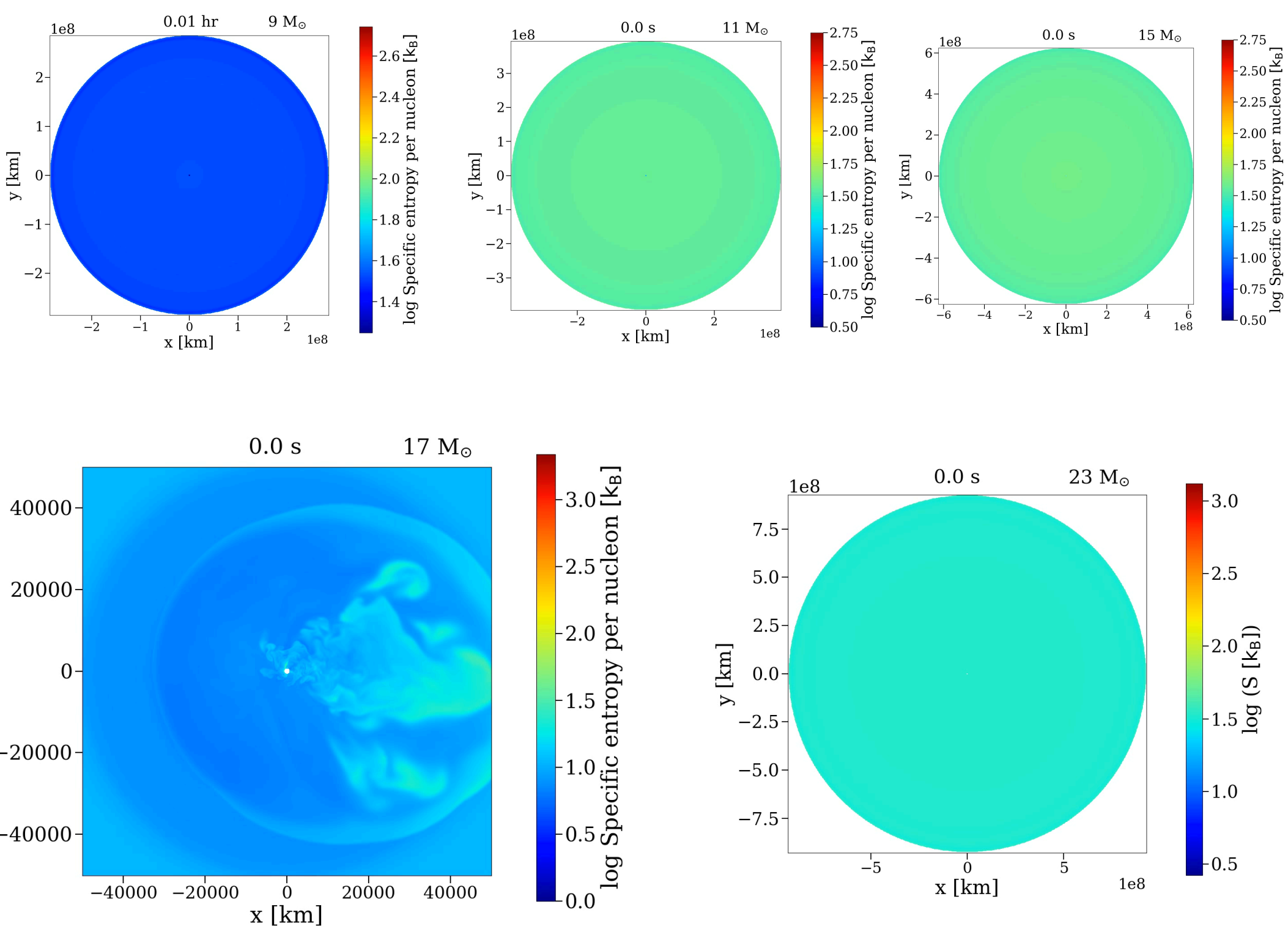
The Next Generation of Breakout Simulations





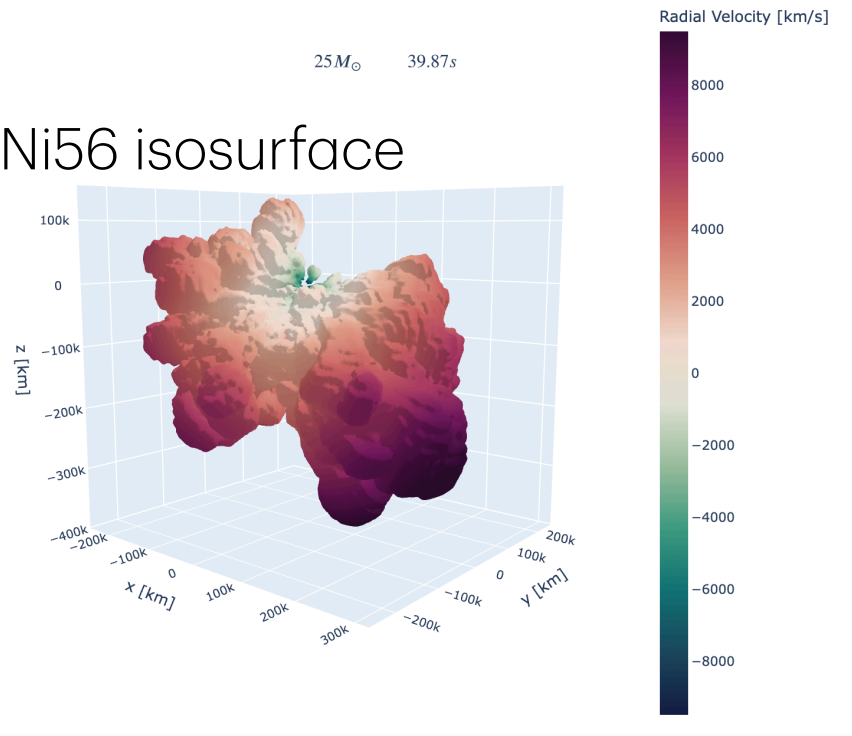


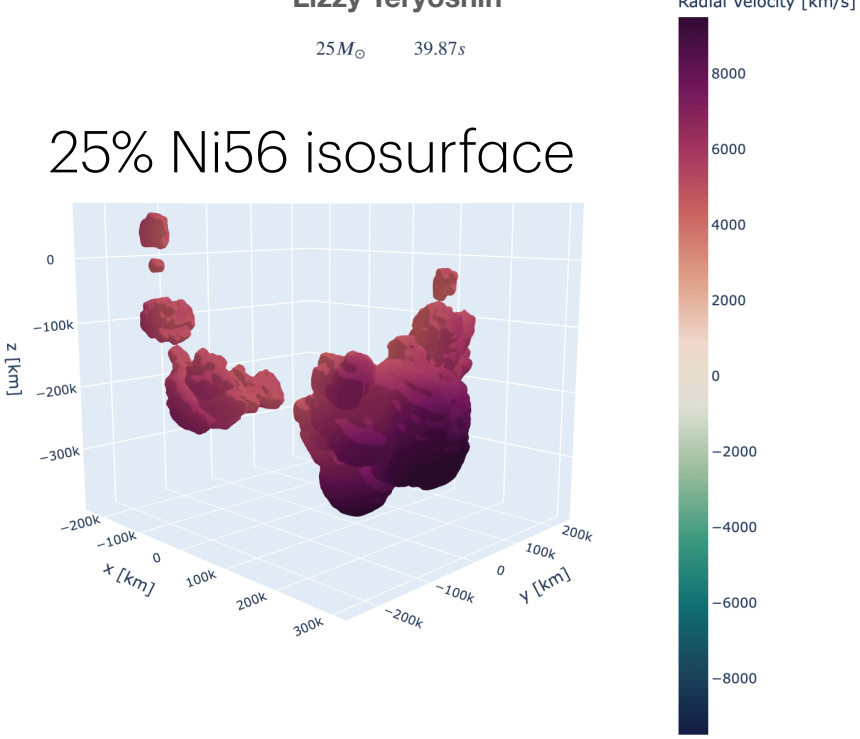



0.01 hr
9 M⊙
1e8
y [km]
x [km]
log Specific entropy per nucleon [kB]
0.0 s
11 M⊙
0.0 s
15 M⊙
0.0 s
17 M⊙
0.0 s
23 M⊙
log (S [kB])

Ni-56 Distributions

Lizzy Teryoshin

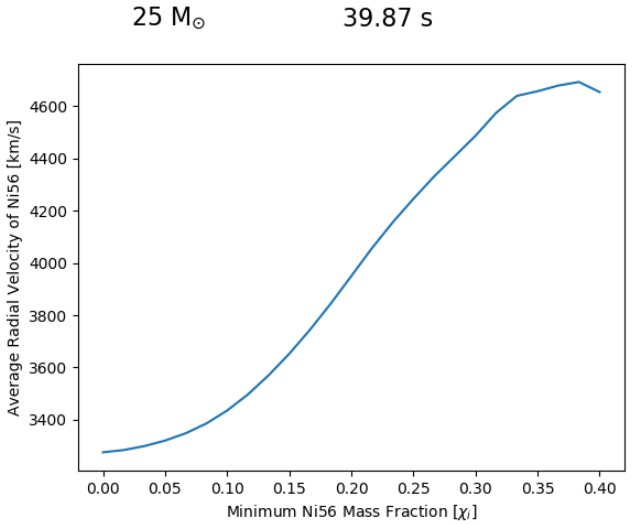




25-solar mass model w/ 1 B energy:

Correlation between Nickel bullet
mass fraction, **velocity**, & **distribution**

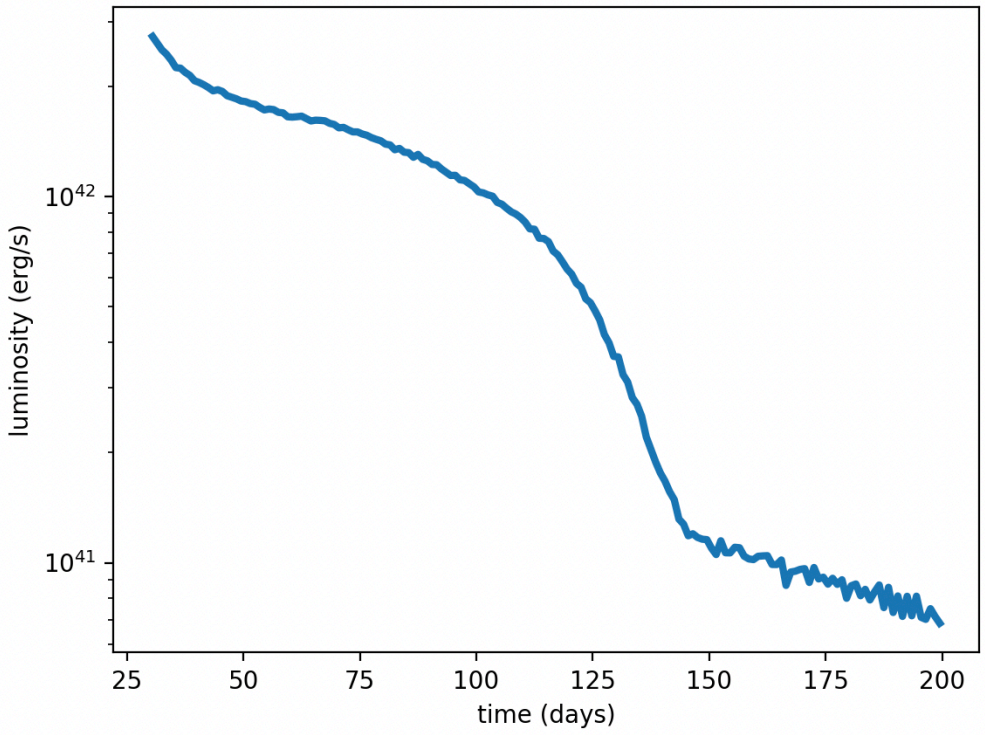
- Bulk Ni56 velocities > 4000 km/s
- Comparable to Cas A, iron-rich ejecta velocities ‘around and above 4000 km/s’ (Milisavljevic et. al. 2024)



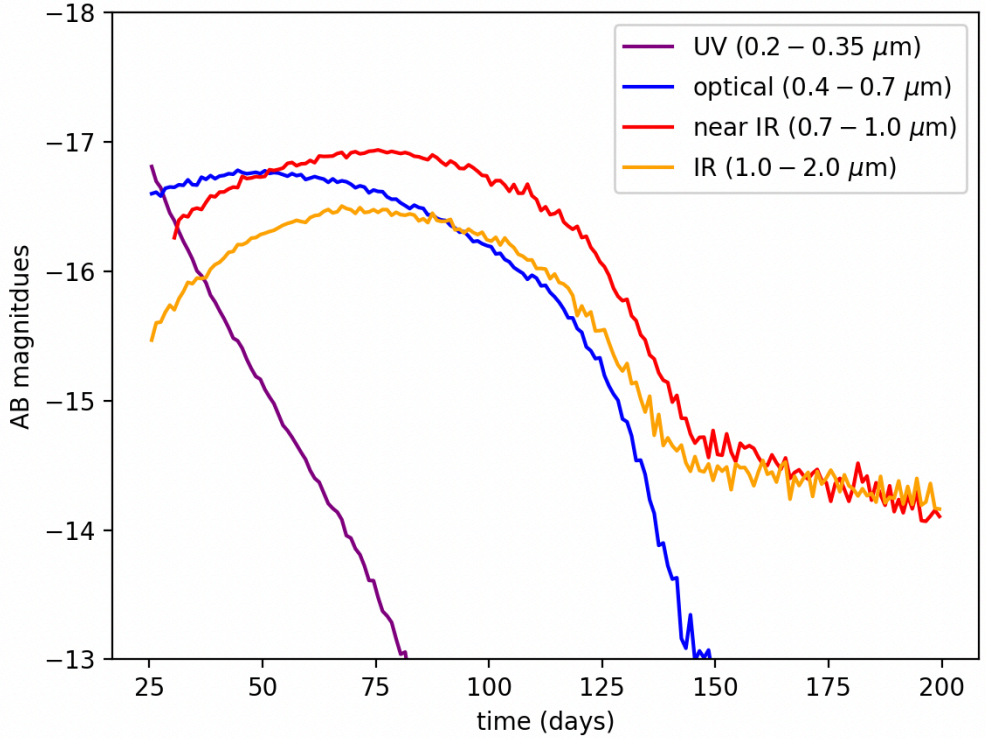
Synthetic Observables, $23\ M_\odot$ RSG progenitor

$M_{\rm ej} = 8.5\ M_\odot$, $E_{\rm K} = 3 - 4 \times 10^{50}$ erg, $M_{\rm ni} = 0.03\ M_\odot$

bolometric light curve
(angle averaged)

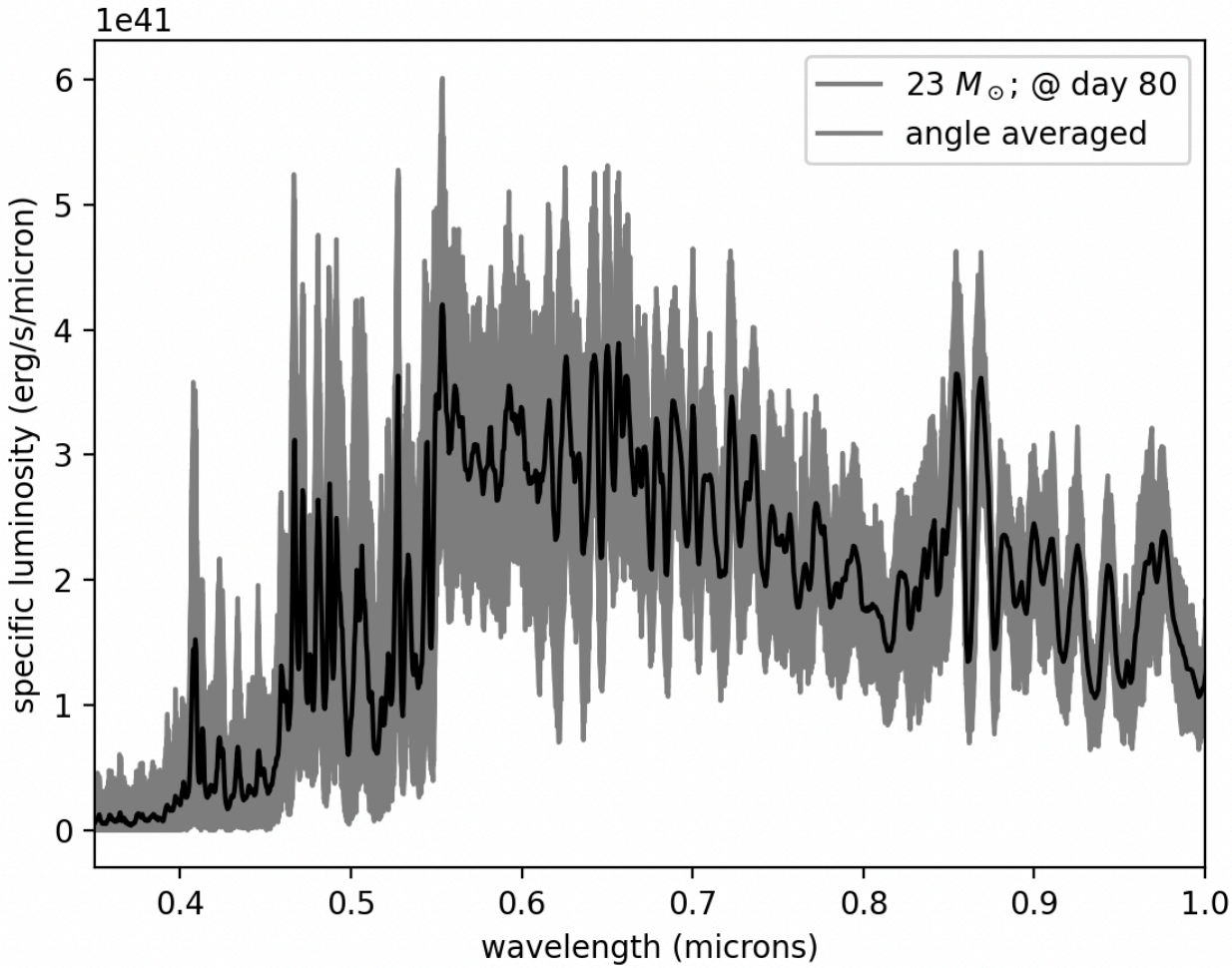


broadband light curves
(angle averaged)



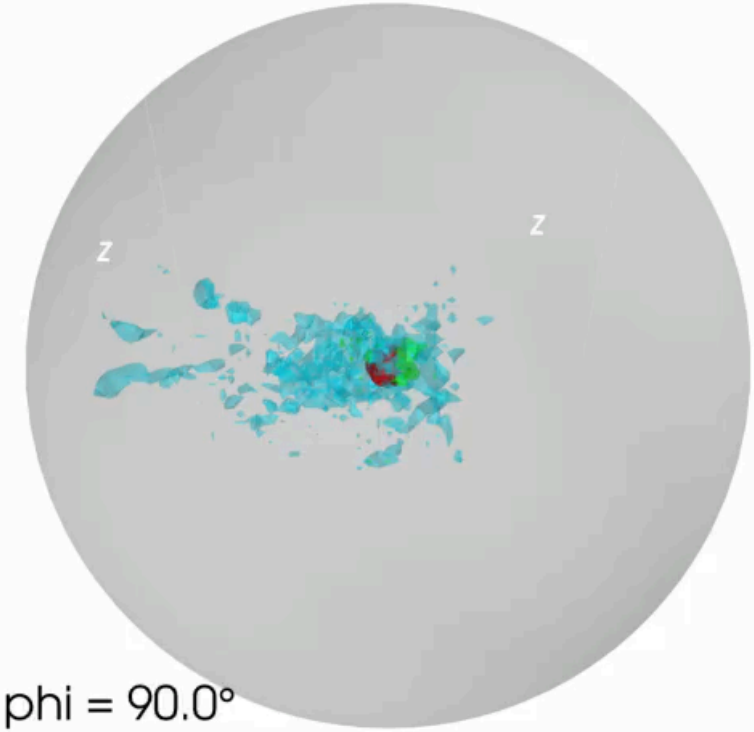
Daniel Kasen

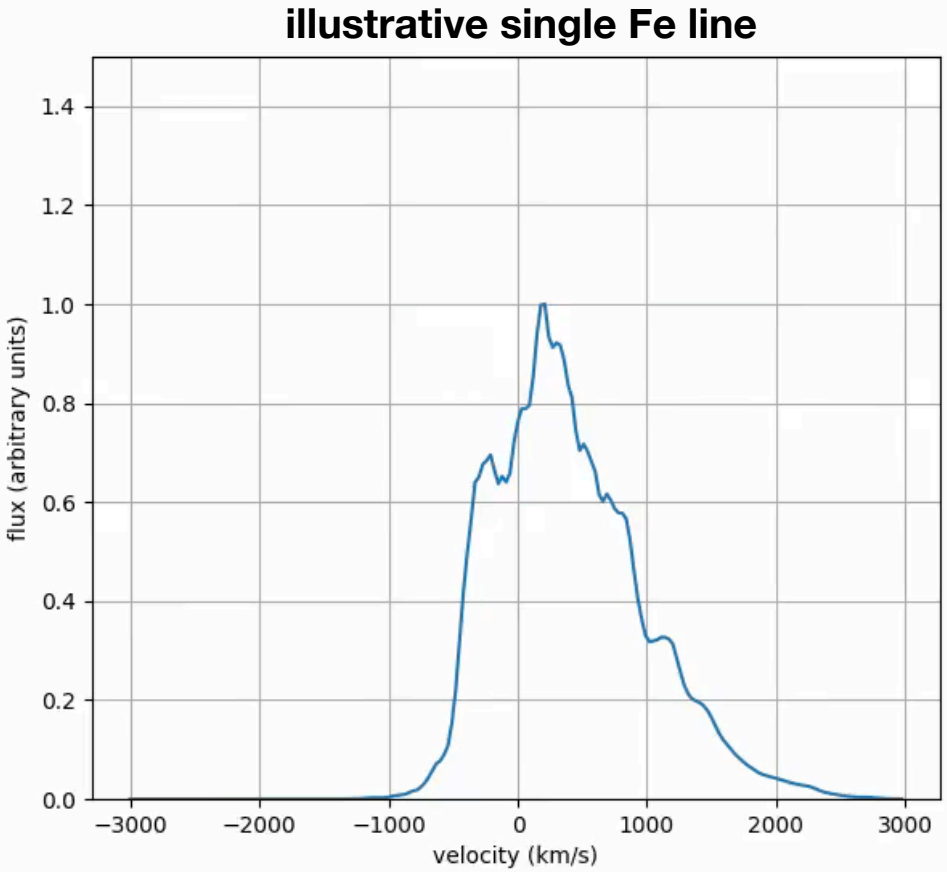
Viewing angle dependent spectra, $23\ M_\odot$ progenitor



3D LTE radiative transfer

Asymmetry and Nebular line Profiles



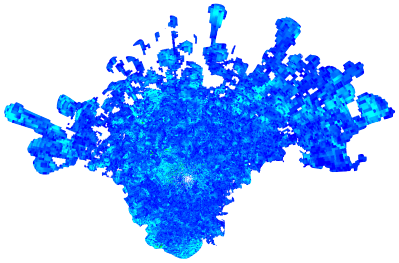


First 3D energetic CCSNe carried out from core-collapse to beyond shock-breakout with consistent neutrino heating

Massive stellar explosions can generically produce:

1. Energies, ejecta yields
2. Ejecta bulk and peak velocities
3. Asymmetric structures:
   - Cavities/voids
   - Bullets/fingers
   - Bochum event
4. ~1 day delay in SBO by LoS
5. Thorough element mixing

Initial asymmetries set final structures!



$M = 9\ M_\odot$