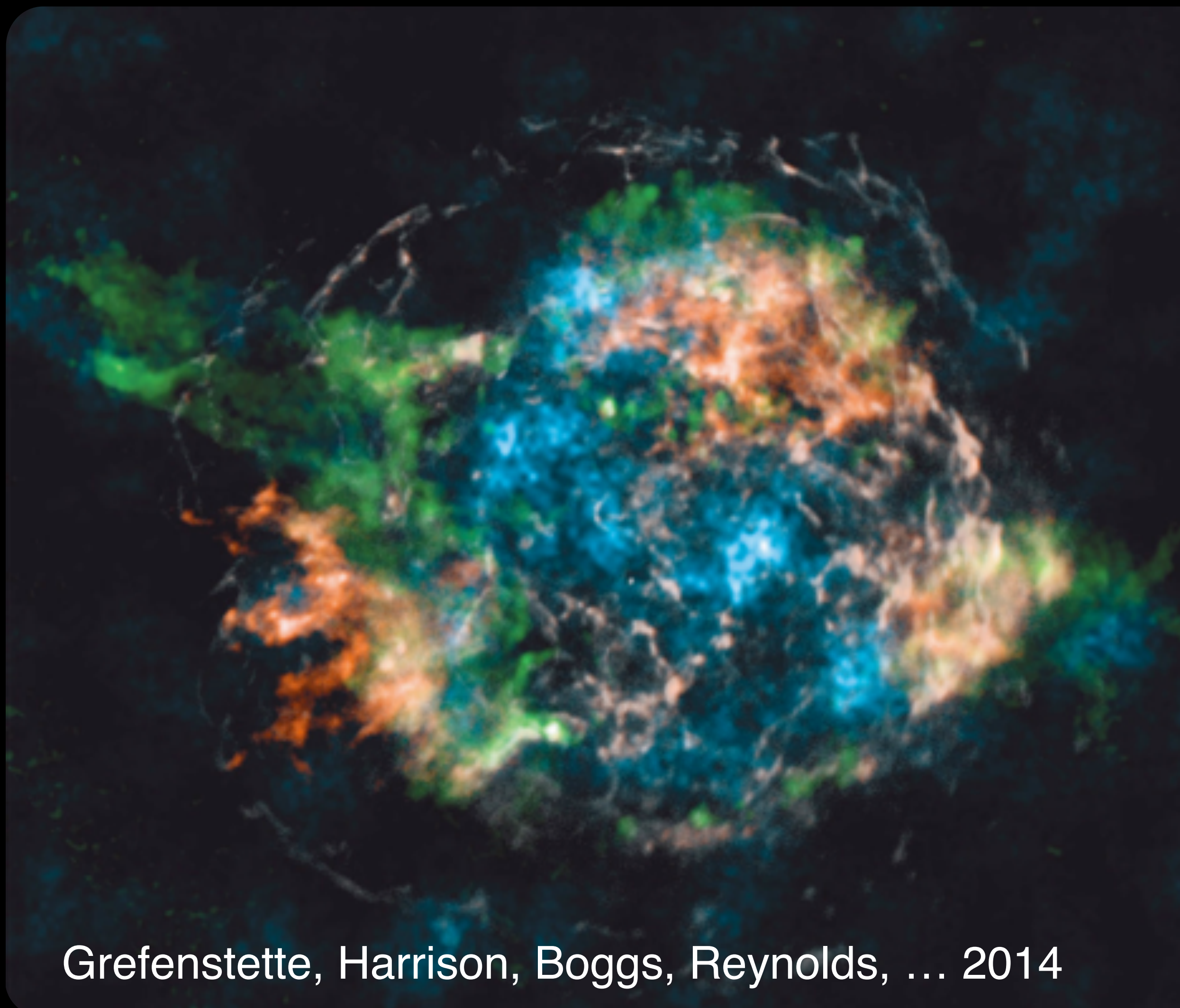
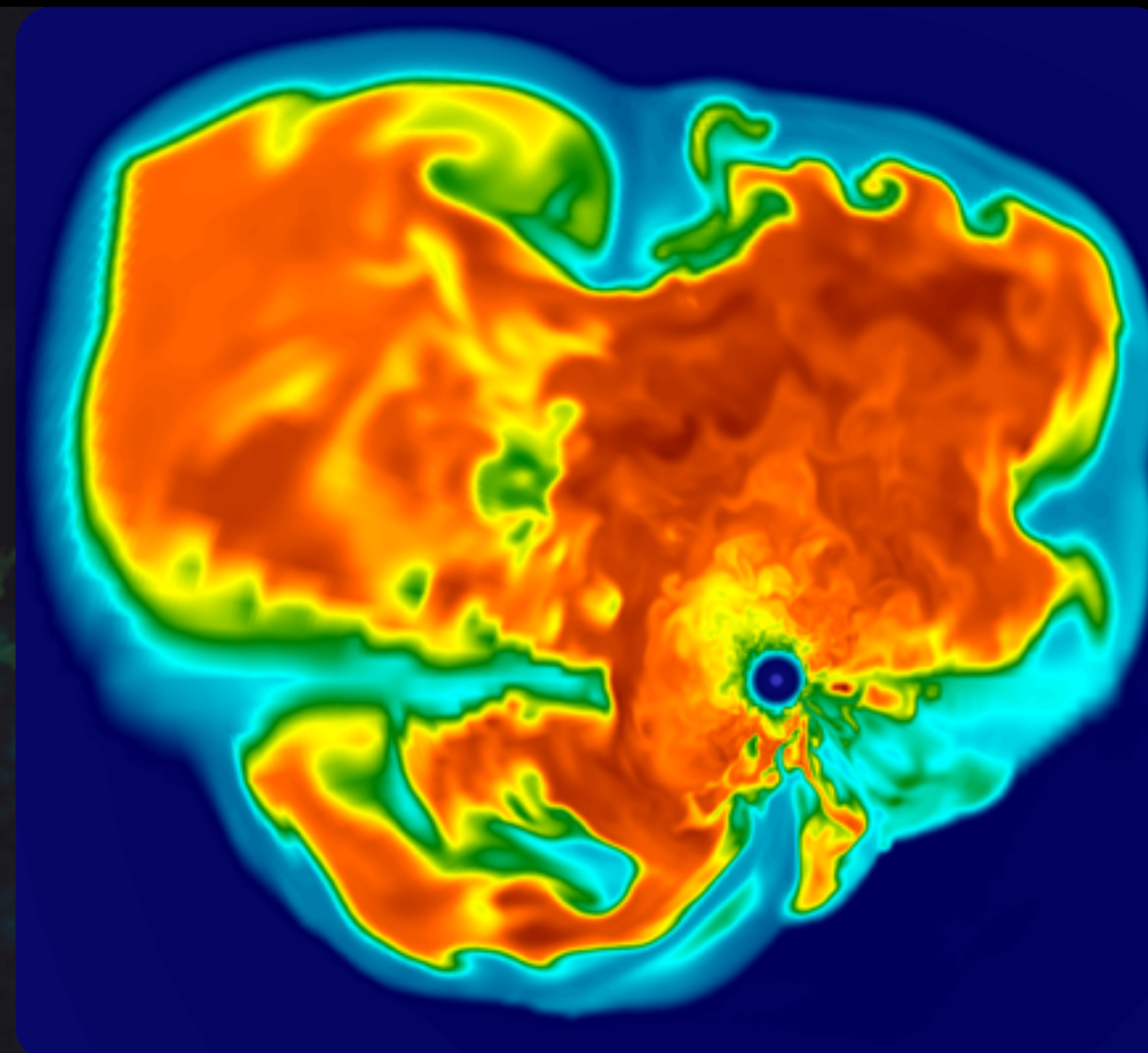
Lessons on Nucleosynthesis from





Multi-dimensional Supernova models

William Raphael Hix (ORNL/U. Tennessee)

Blondin, Bruenn, Endeve, Fröhlich, Harris, Lentz, Marronetti, Messer, Mezzacappa & Yakunin (Florida Atlantic U., NC State U., ORNL, UT, LBL)

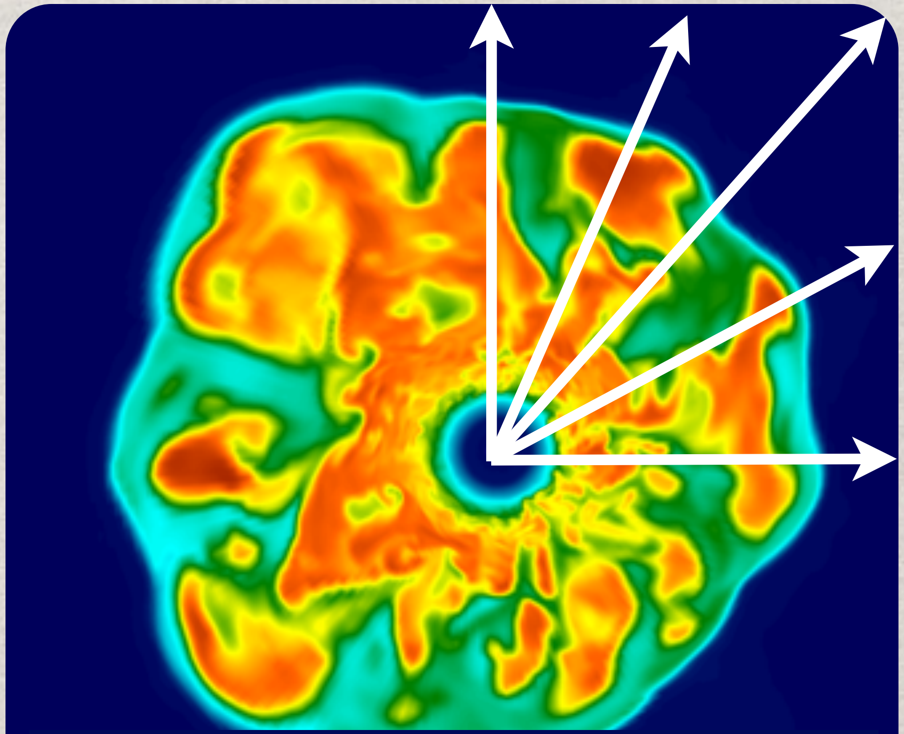
CHIMERA

CHIMERA has 3 “heads”

- Spectral Neutrino Transport (MGFLD-TRANS, Bruenn) in Ray-by-Ray Approximation
- Shock-capturing Hydrodynamics (VH1, Blondin)
- Nuclear Kinetics (XNet, Hix & Thielemann)
- Plus Realistic Equations of State, Newtonian Gravity with Spherical GR Corrections.

Models use a variety of approximations

- Self-consistent (*ab initio*) models use full physics to the center.
- Leakage & IDSA models simplify the transport.
- Parameterized models replace the core with a specified neutrino luminosity.

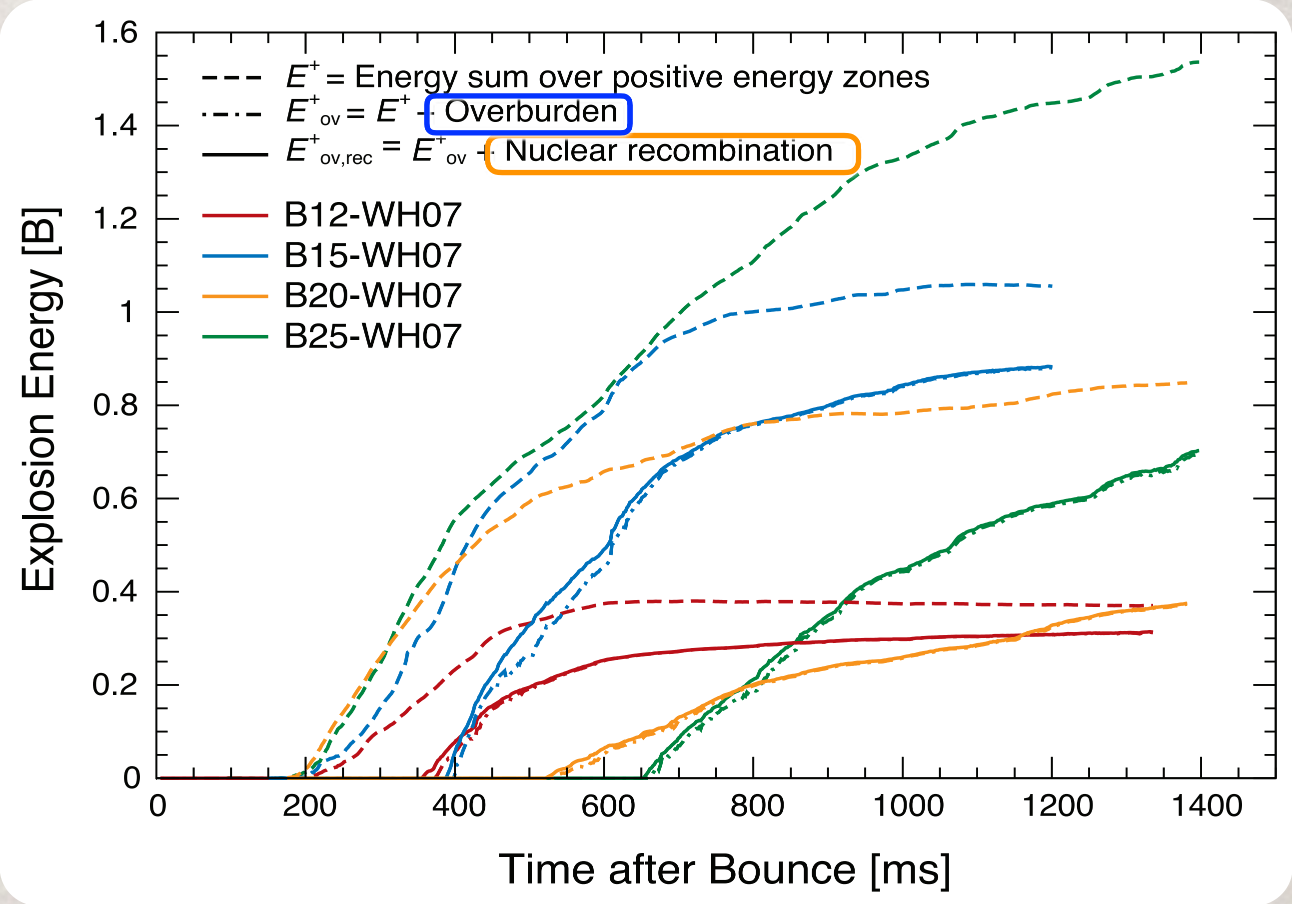


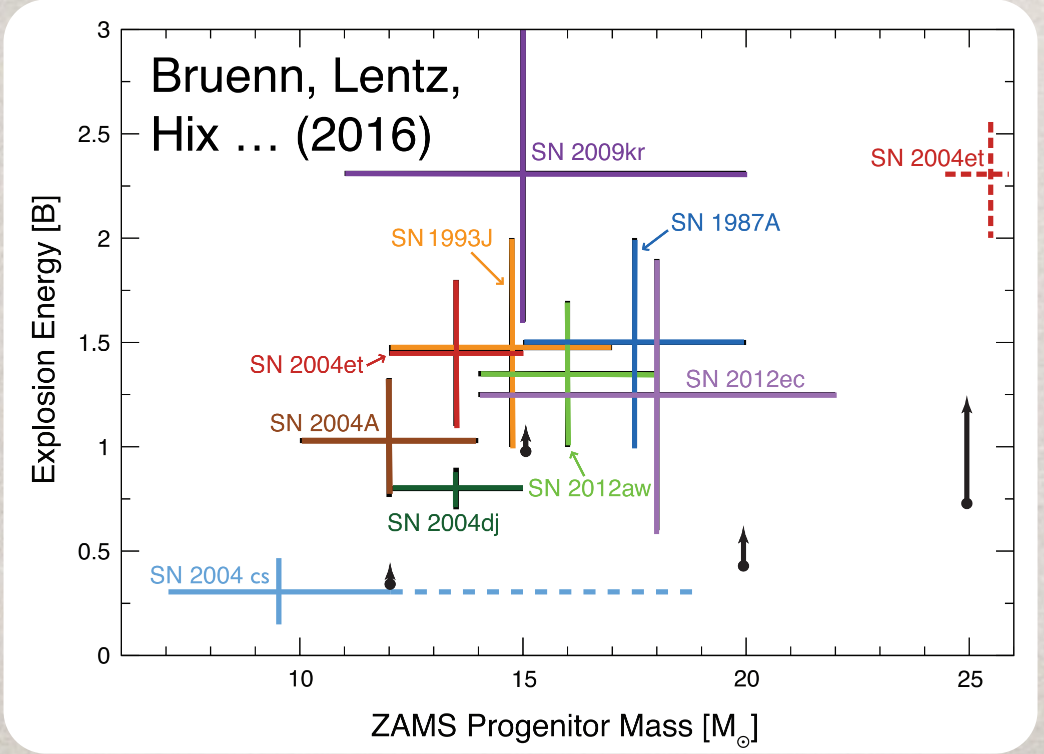
Ray-by-Ray Approximation

Explosion Energies

We must compare models against the myriad of other potential observations. Foremost is the kinetic energy of the explosion.

Unfortunately, models are still in the stage where internal energy dominates, so we must estimate the explosion energy by assuming efficient conversion of $E_i \Rightarrow E_k$.



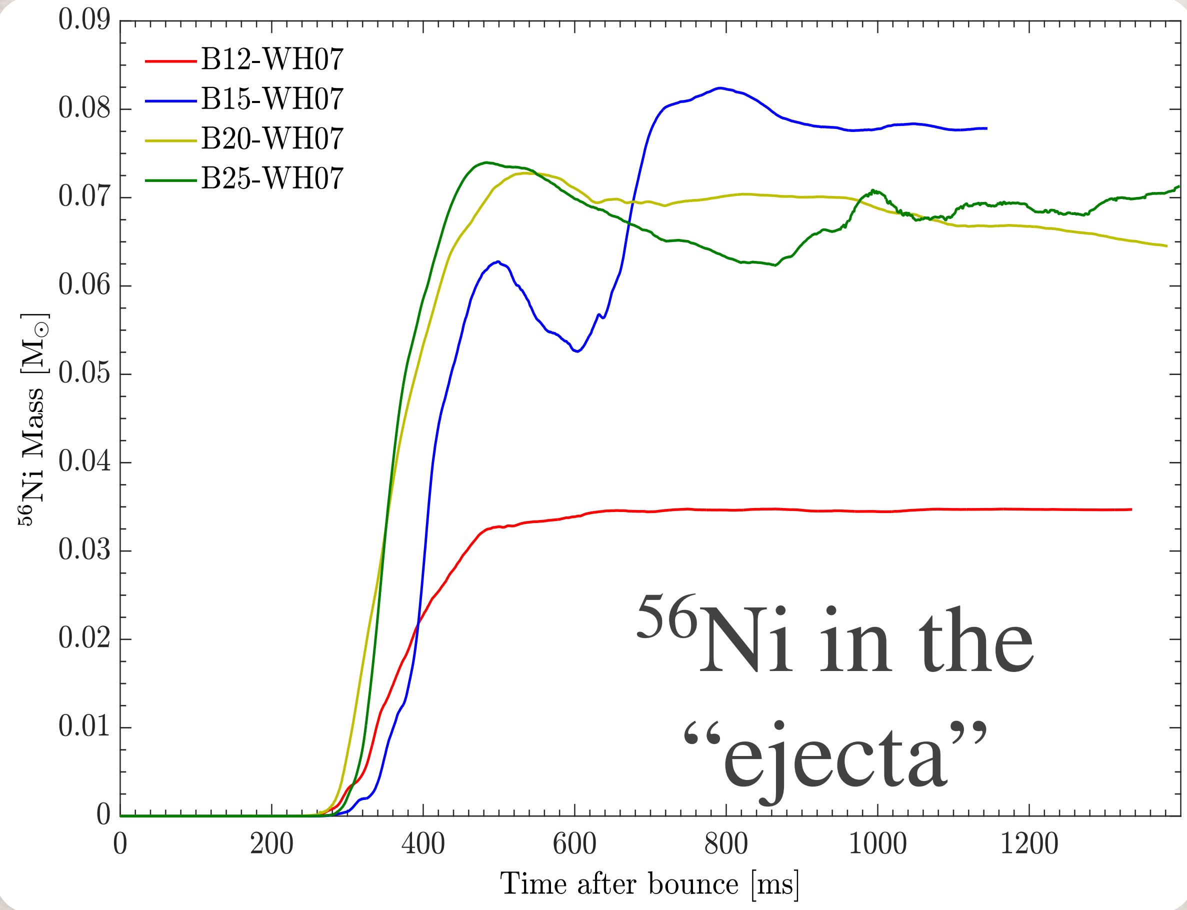


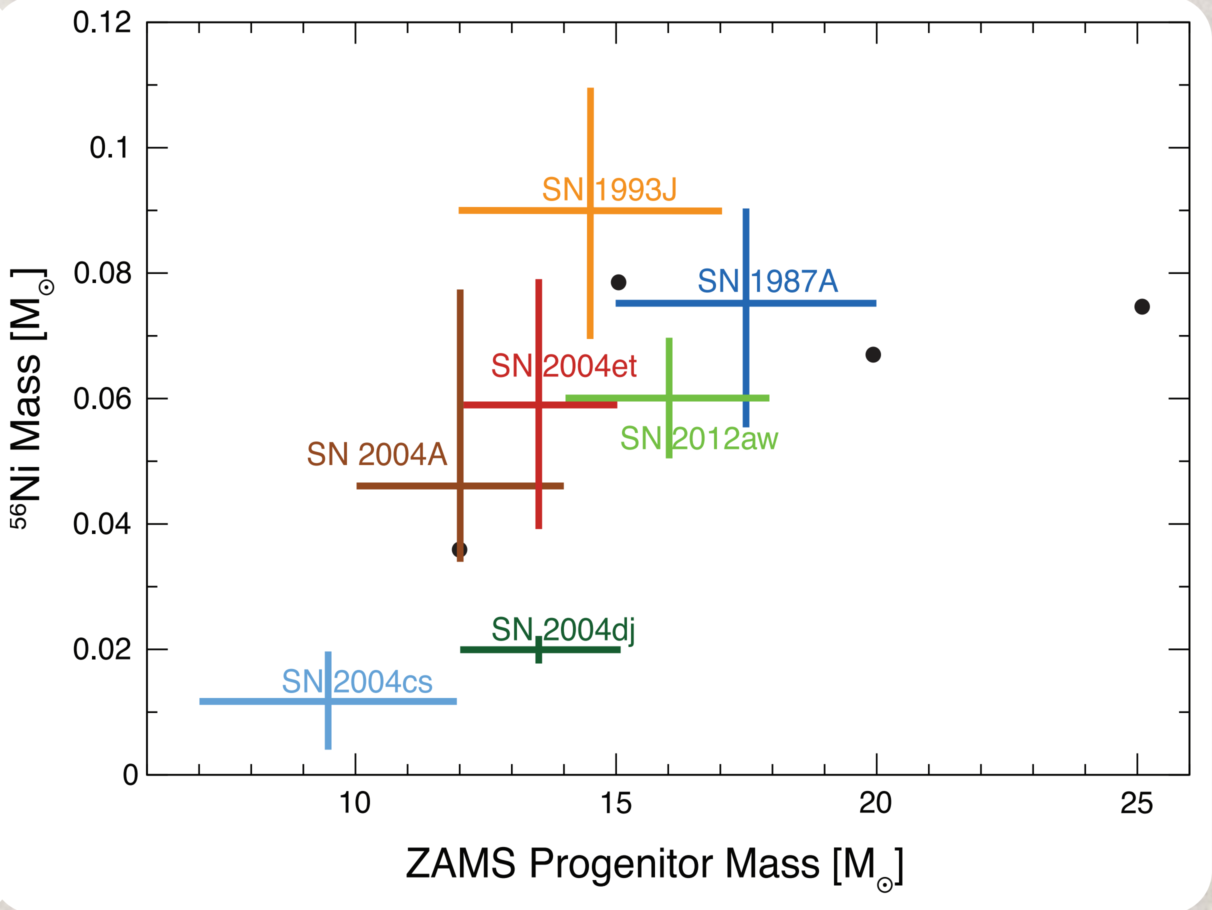
One can construct a "diagnostic" energy, $E^{+} = E_i + E_g + E_k$, summed over zones where $E^{+} > 0$.

Also contributions from nuclear recombination and removing the envelope.

Nickel Mass

Beyond the explosion energy, perhaps the most important observable is the mass of ^{56}Ni, because of its relation to the light curve.





The ejected ^{56}Ni mass saturates in time with the explosion energy.

Results are reasonable, when compared to observations.

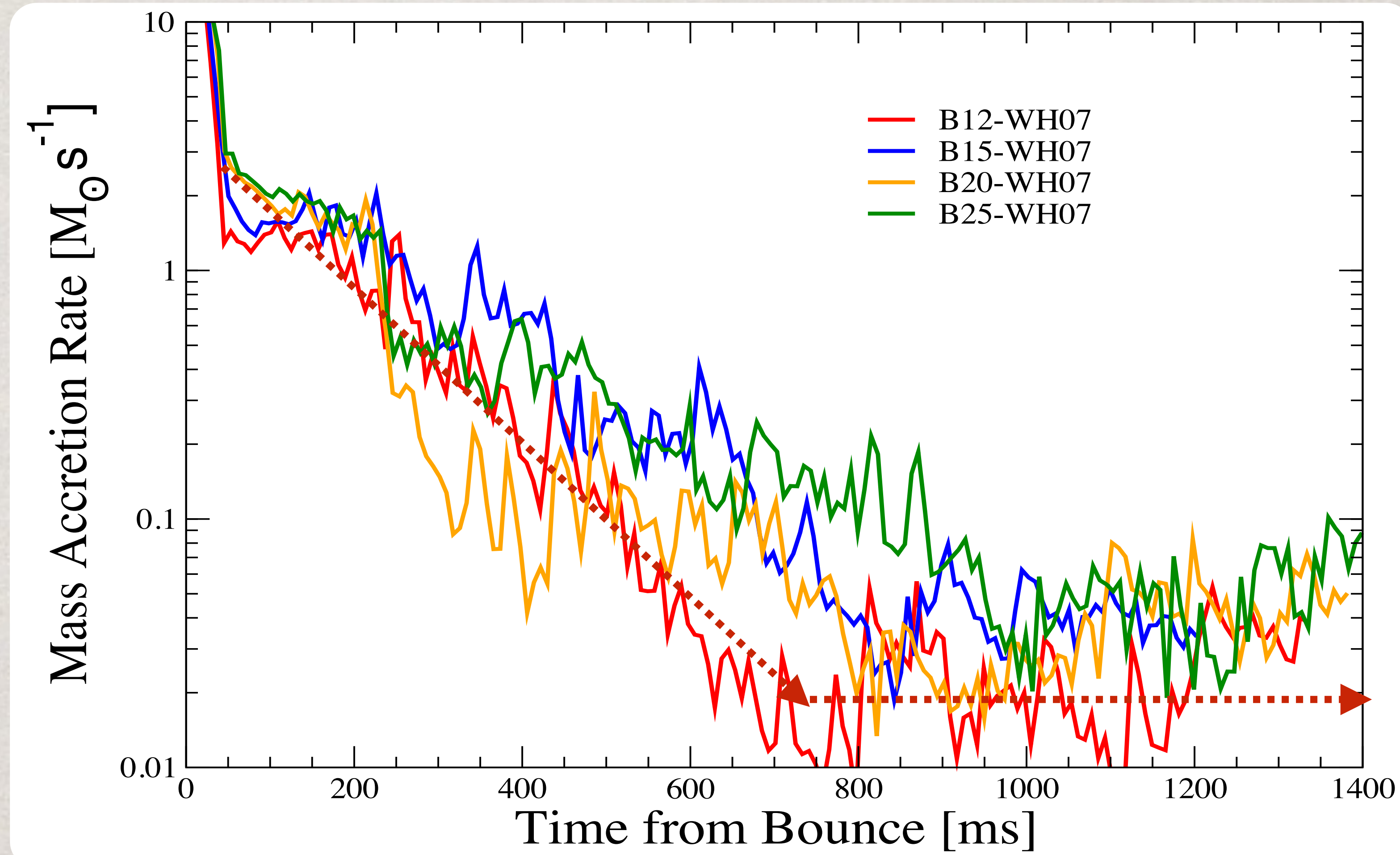
Fallback over longer timescales is uncertain. Recent studies are finding differing results on fallback and ^{56}Ni has higher velocity.

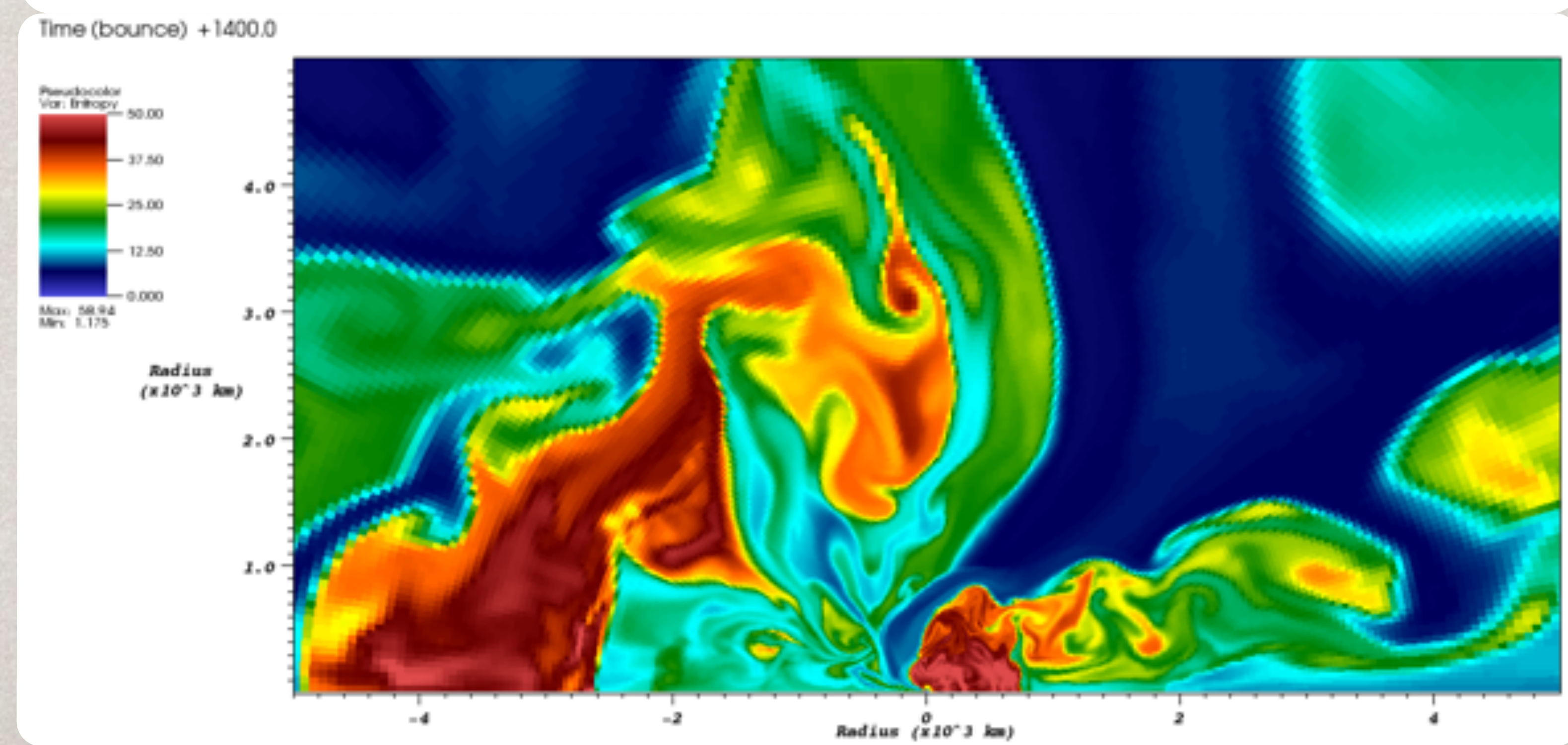
End of the Explosion?

Even in our most fully developed model, the explosion energy has not leveled off 1.3 seconds after bounce.

The reason is that accretion continues at an appreciable rate, showing no sign of abating.

This extends the “hot bubble” phase and suppresses the development of the PNS wind.



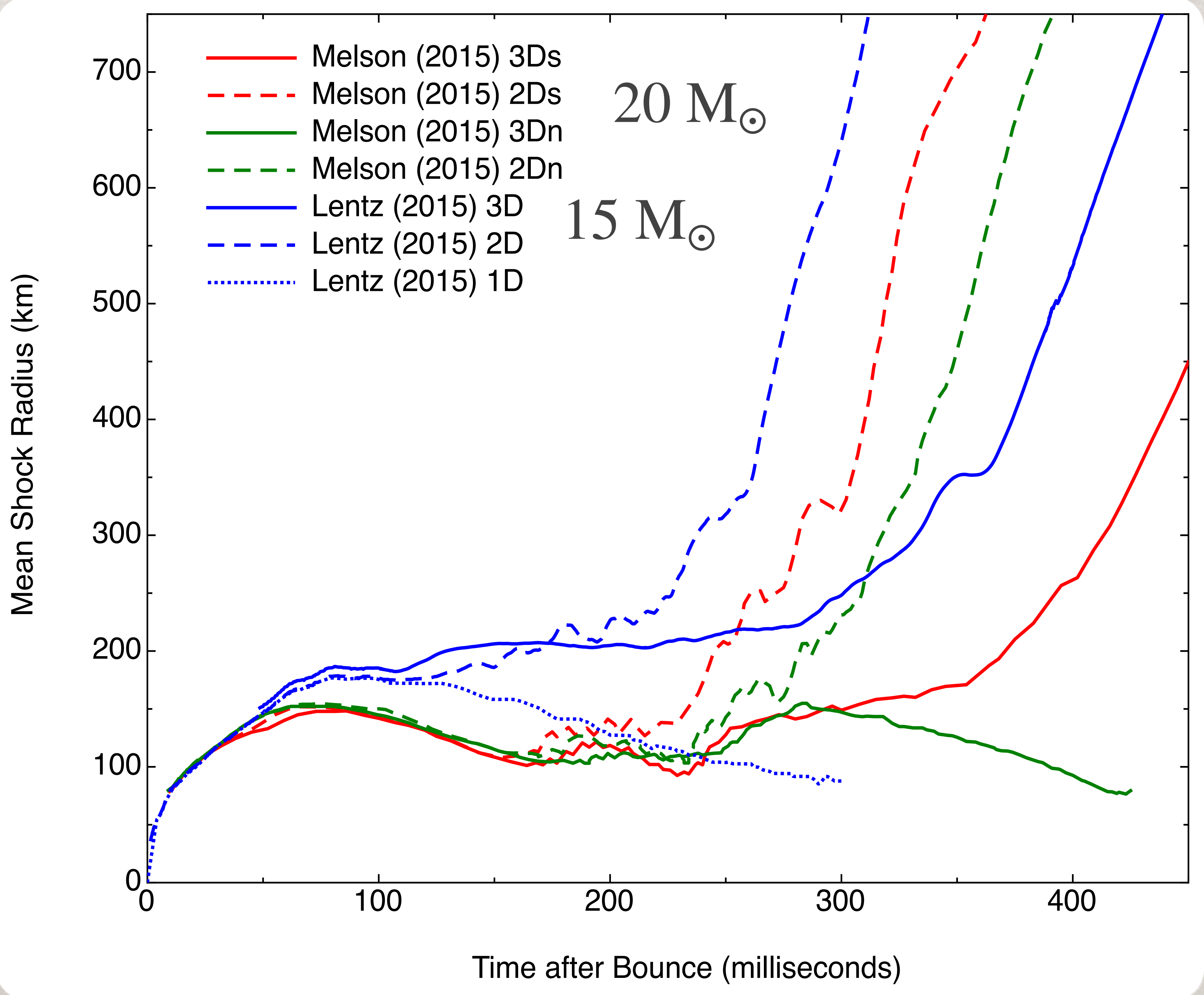


What is 2D good for?

In both 2D and 3D, explosions are preceded by the development of large scale convective flows that span the heating region.

However, in 2D the convective plumes develop too rapidly, leading to an earlier onset of explosion.

What can these accelerated, but much cheaper, models teach us about CCSN?

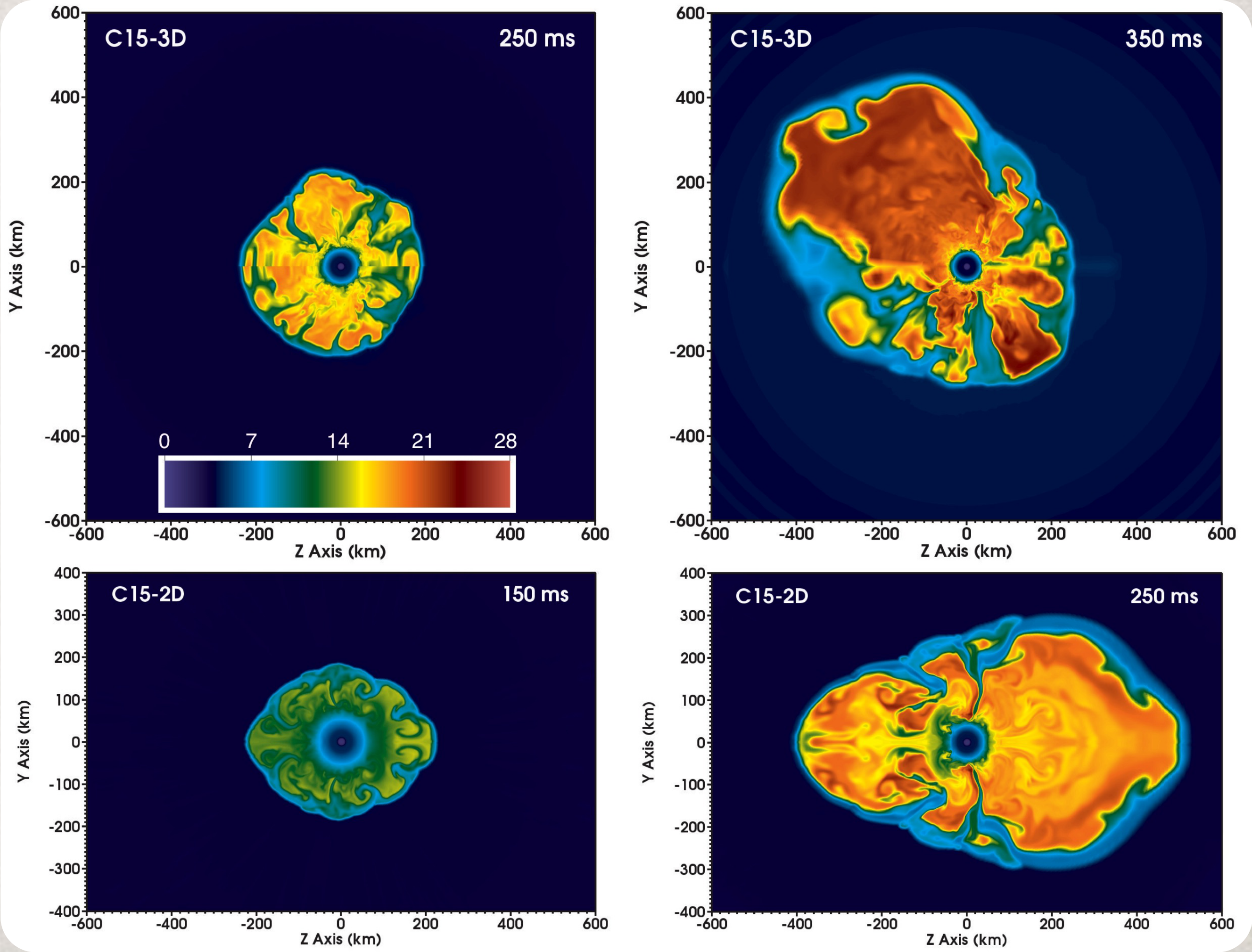


Is 2D Turning down the heat?

The Rayleigh-Taylor Instability, driven in CCSN by neutrino heating, favors large scale plumes, regardless of dimensionality.

In 2D, the turbulent cascade also favors organizing small scale motion into larger scale flows.

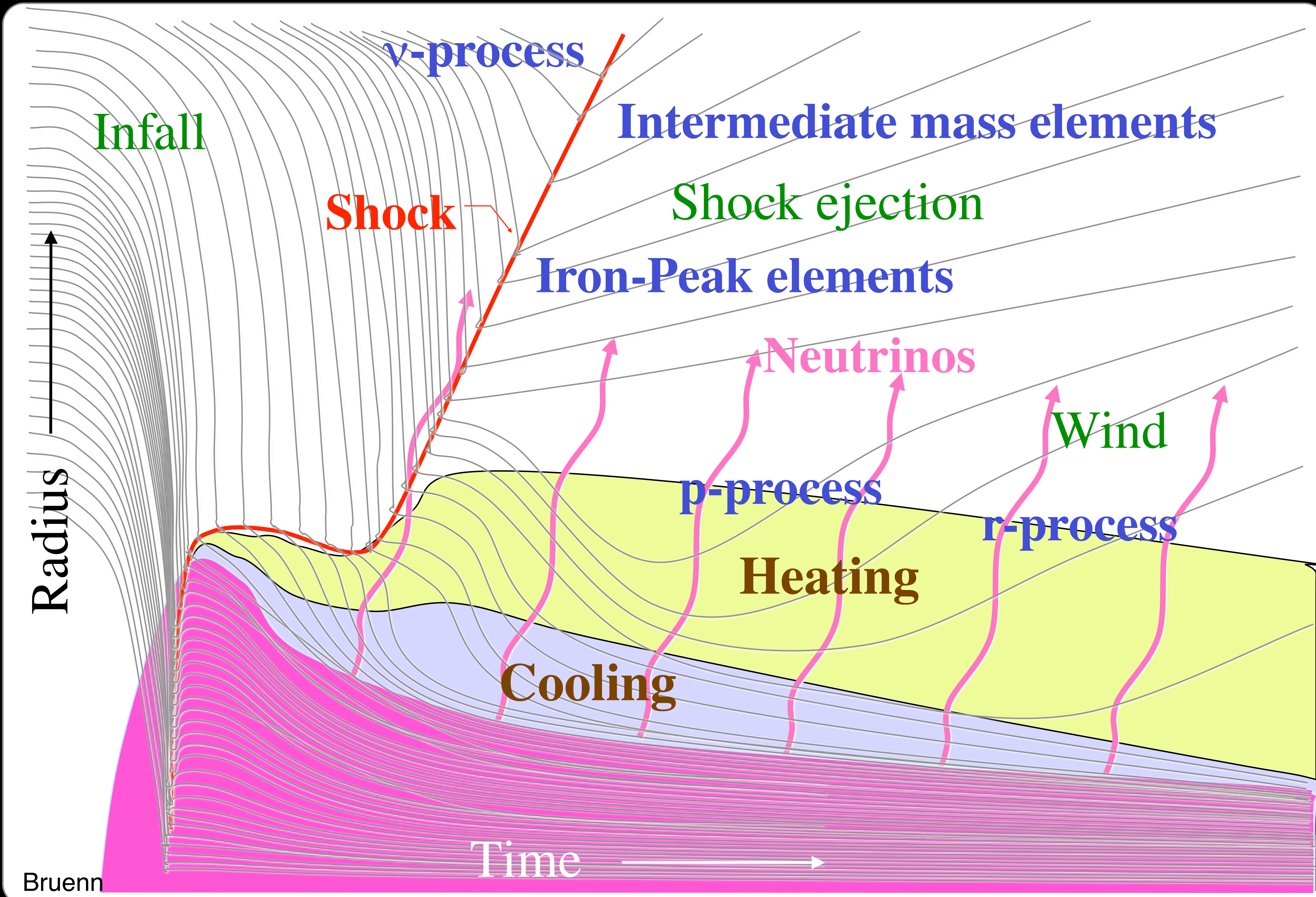
However, in 3D, the cascade favors tearing apart large scale flows. Thus in 3D, R-T requires more time and more heating to develop.



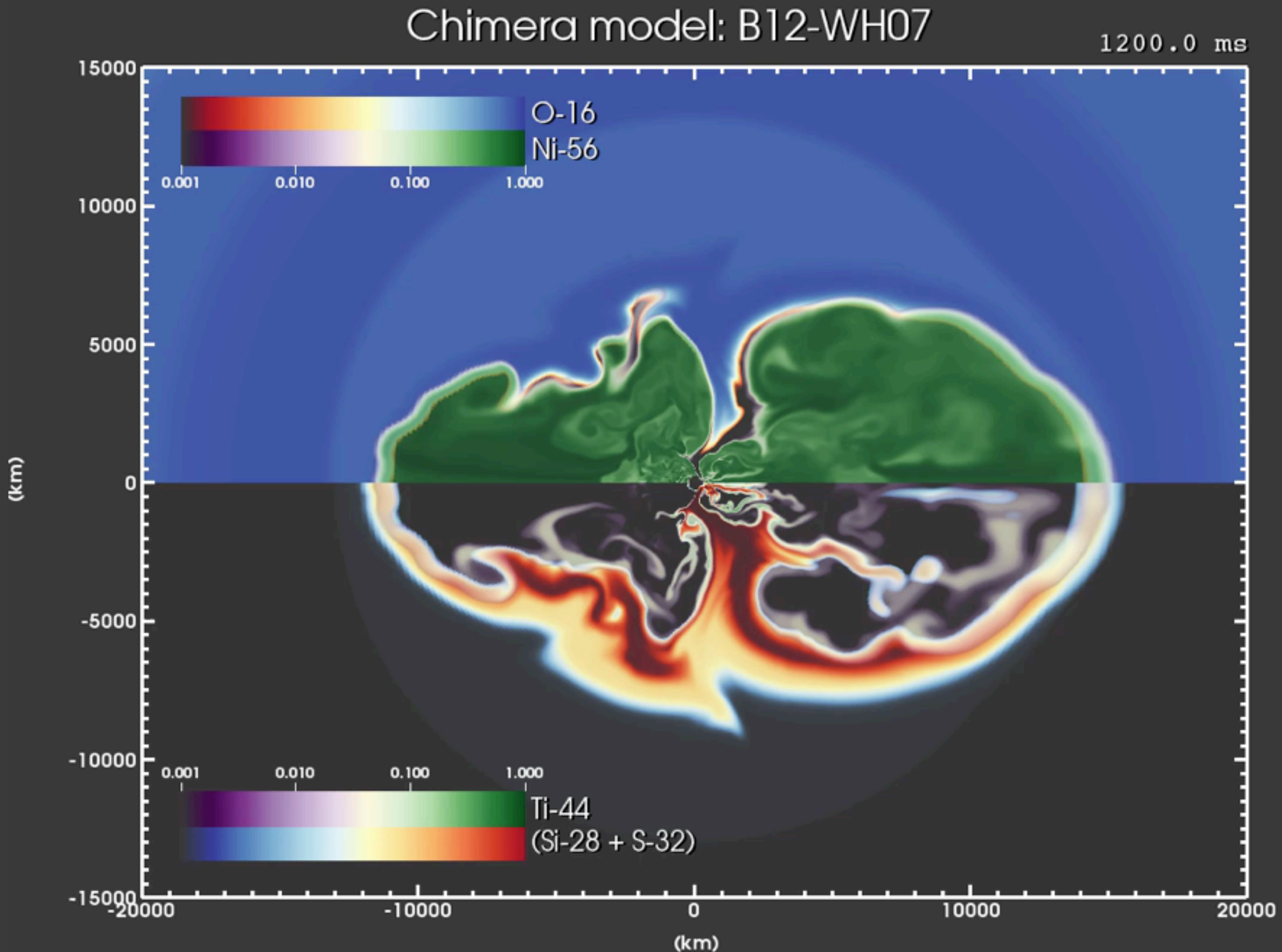
This implies that successful 2D models will tend to have lower entropy in the heating regions.

This likely impacts the degree of alpha-richness in the ejecta.

Supernova Nucleosynthesis

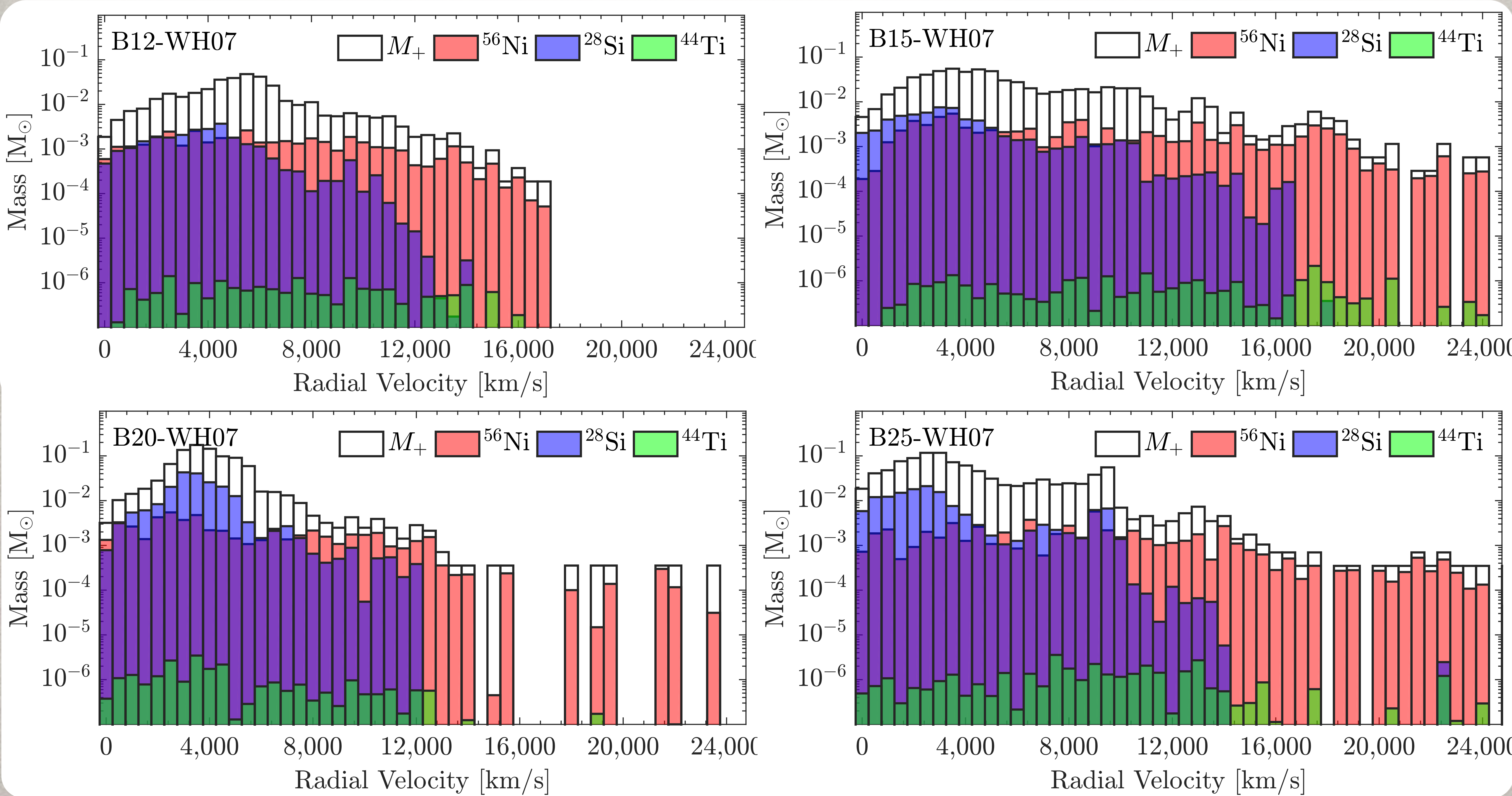


Nucleosynthesis: the Movie



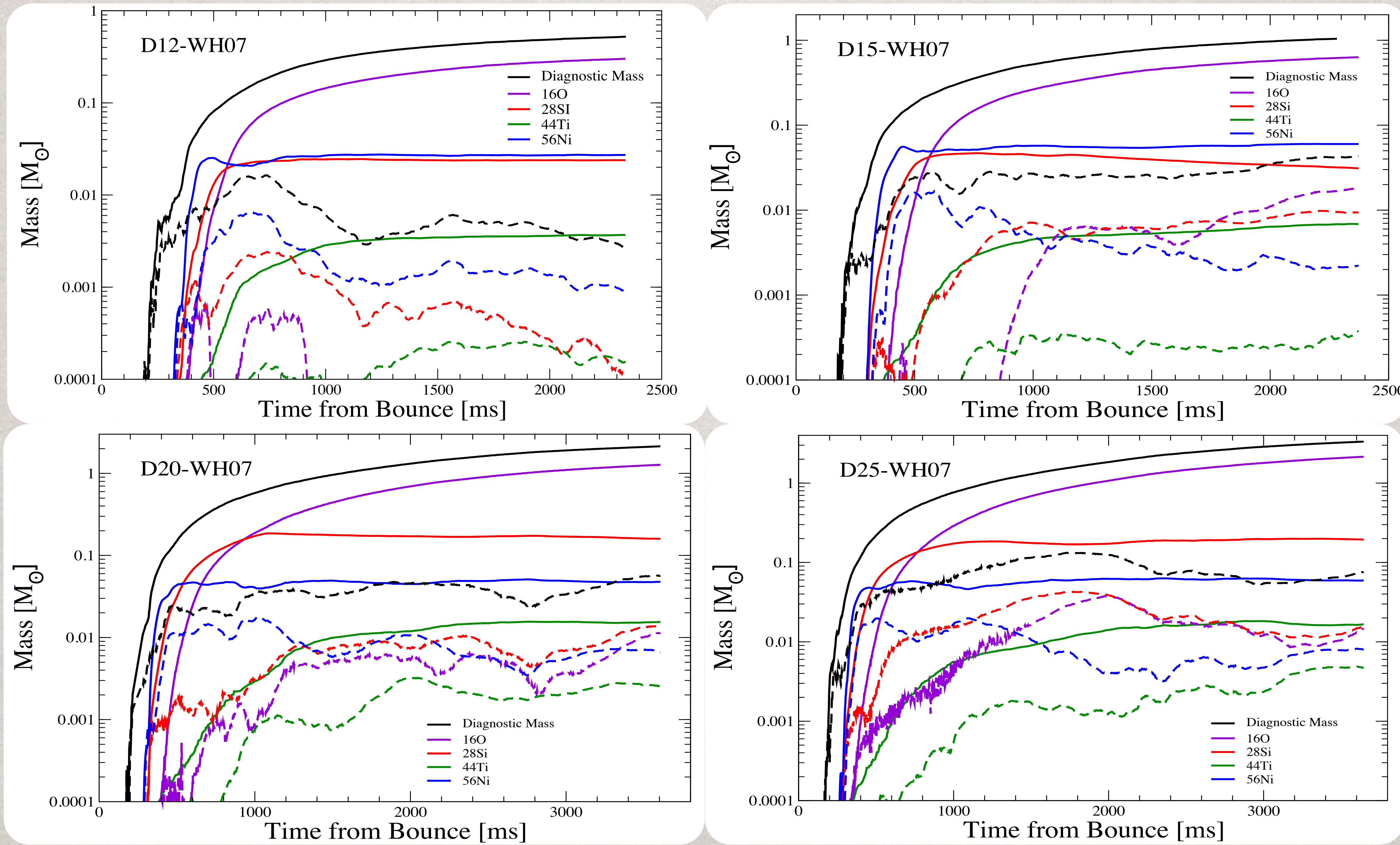
Velocity Distribution

Unlike 1D, Nickel and Titanium have higher velocities than Silicon and Oxygen, thus they are not preferentially sensitive to fallback.



Evacuating the Hot Bubble

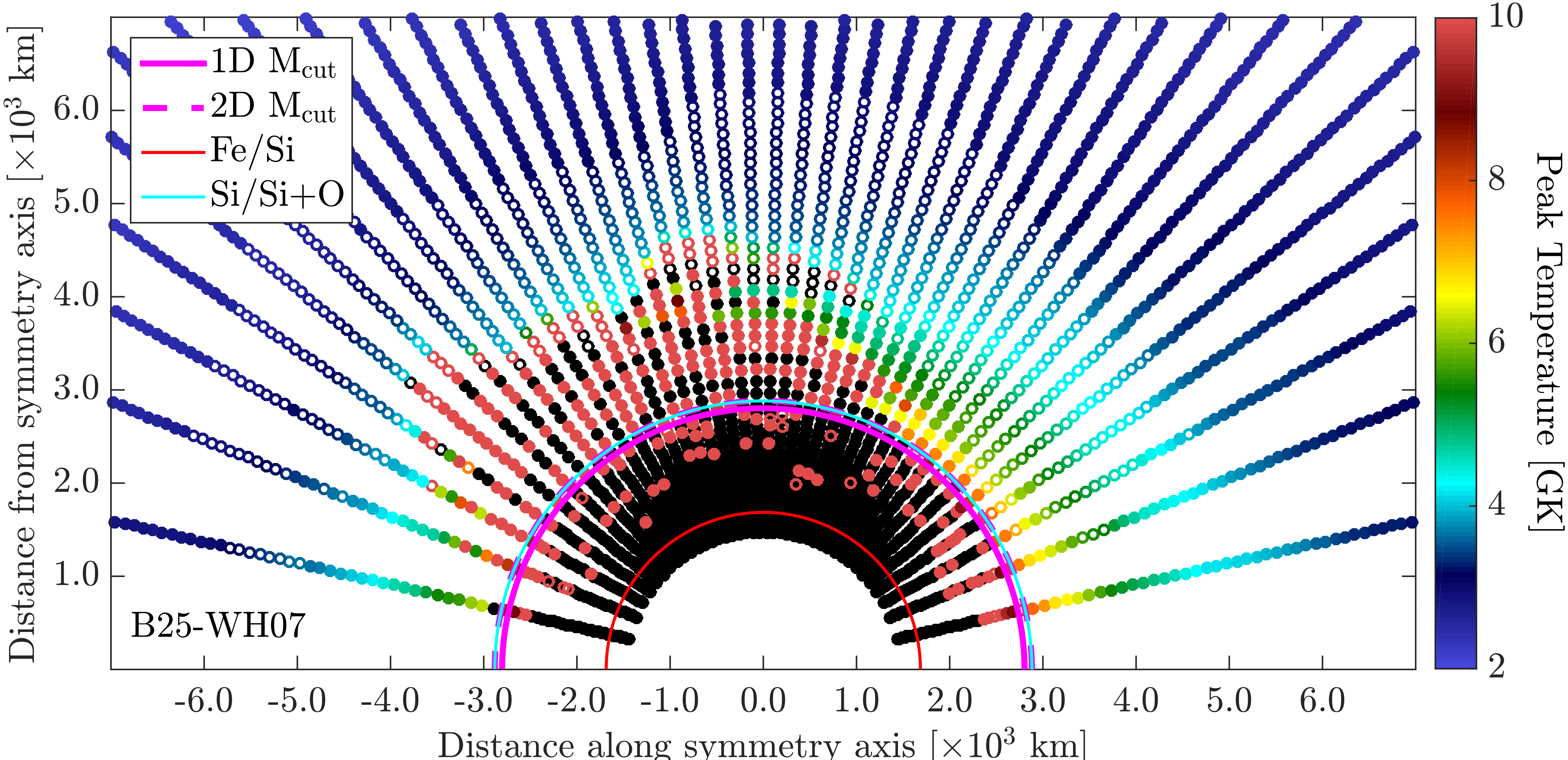
Even more than 2 seconds after bounce, nearly 0.1 $M_\odot$ remains in the Hot Bubble, except the 12 $M_\odot$ model where bubble begins to clear.



Tracing the Mass Cut

Post-processing of tracer particles is required for nucleosynthesis predictions beyond the built-in network, α-network or otherwise.

Their Lagrangian view also reveals the complexity of the mass cut.

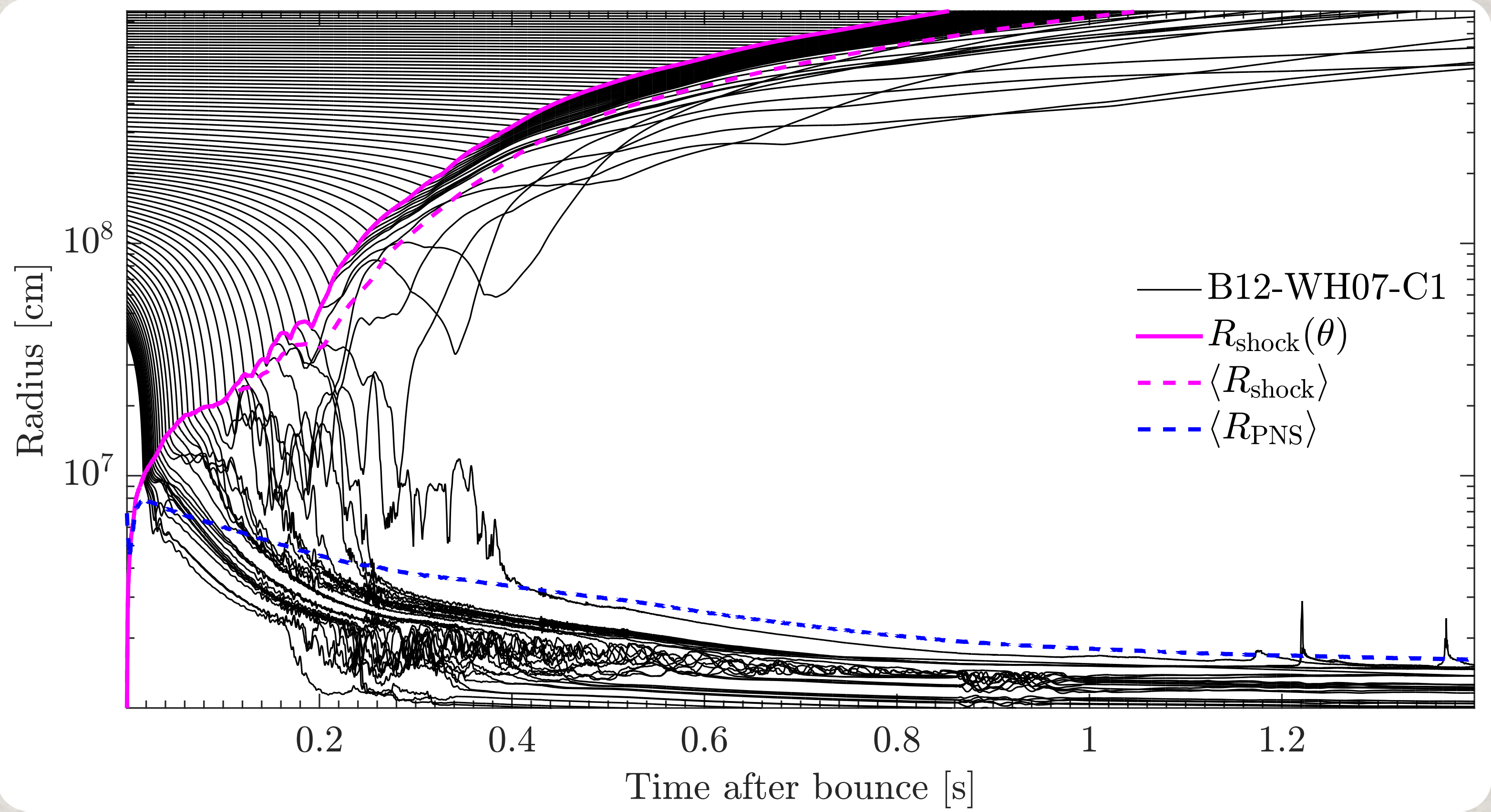


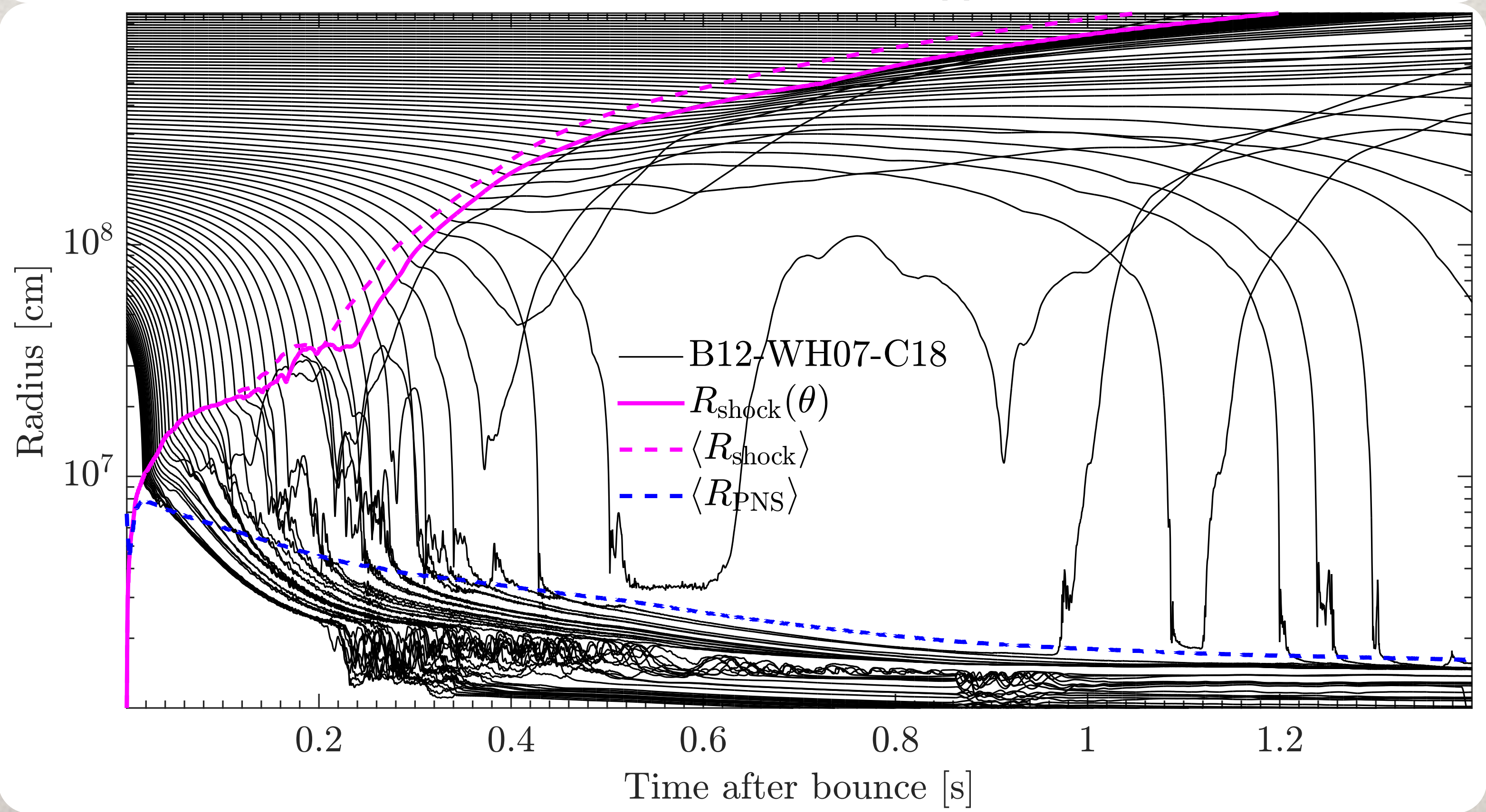
Latitude Dependence

With 40 columns of tracers in each model, we can examine the fate of the star as a function of latitude.

Near the pole, separation between ejecta and PNS develops rapidly and robustly.

Matter from near the equator continues to accrete and be ejected through the end of the simulations.



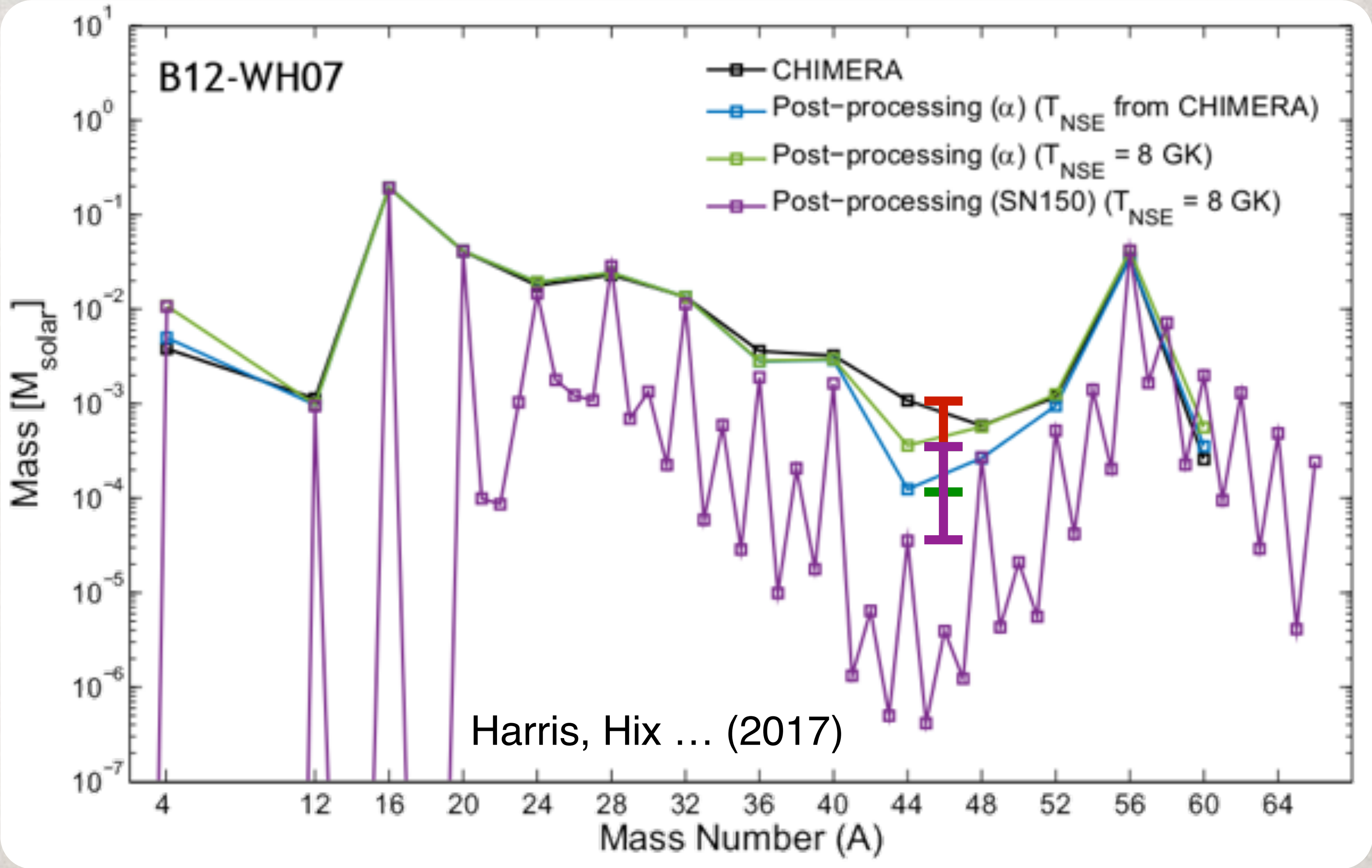


Nucleosynthesis Testing

By computing the post-process nucleosynthesis in the same fashion as that built into CHIMERA, we learn about the limits of the tracers.

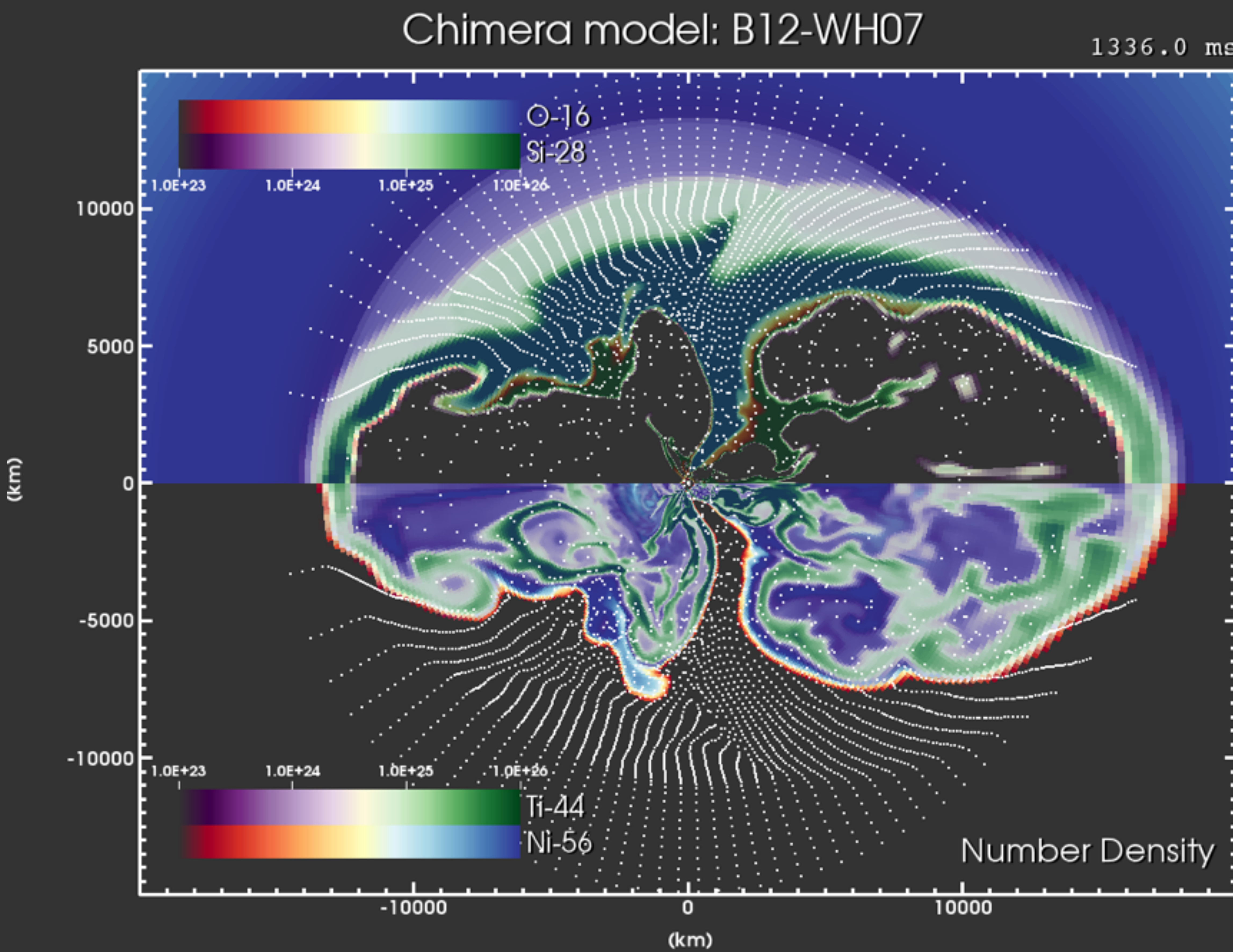
Products of α-rich freezeout are poorly captured by the post-processing.

Accurately capturing the α-rich freezeout also requires transitioning out of NSE at temperatures > 6 GK.



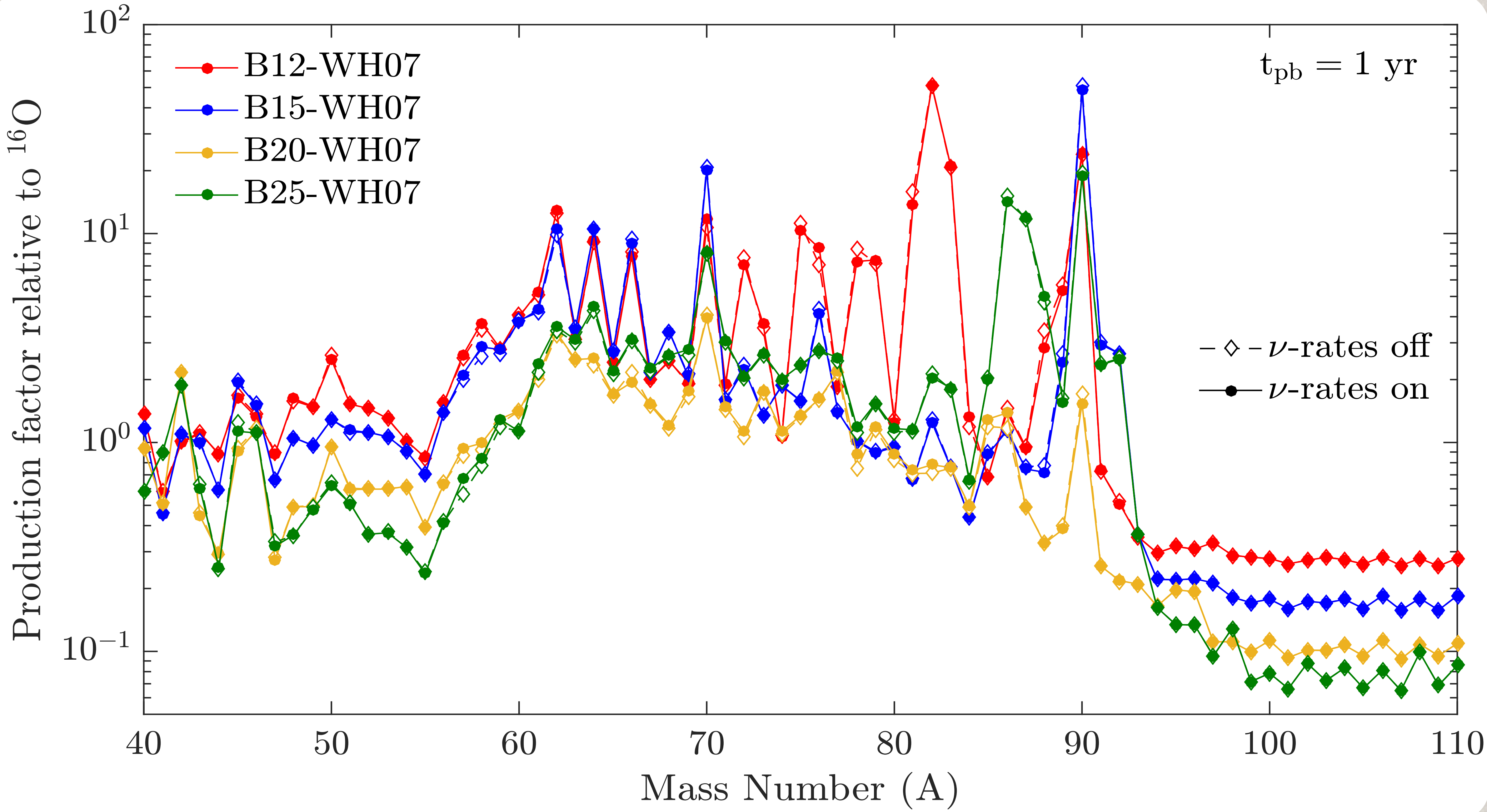
The limitations of the α-network, when compared to a more realistic network, are most evident in the α-rich freezeout and for A > 56.

Tracking Low Density



νP-PROCESS IS MISSING

The νp-process is very weak in these models.

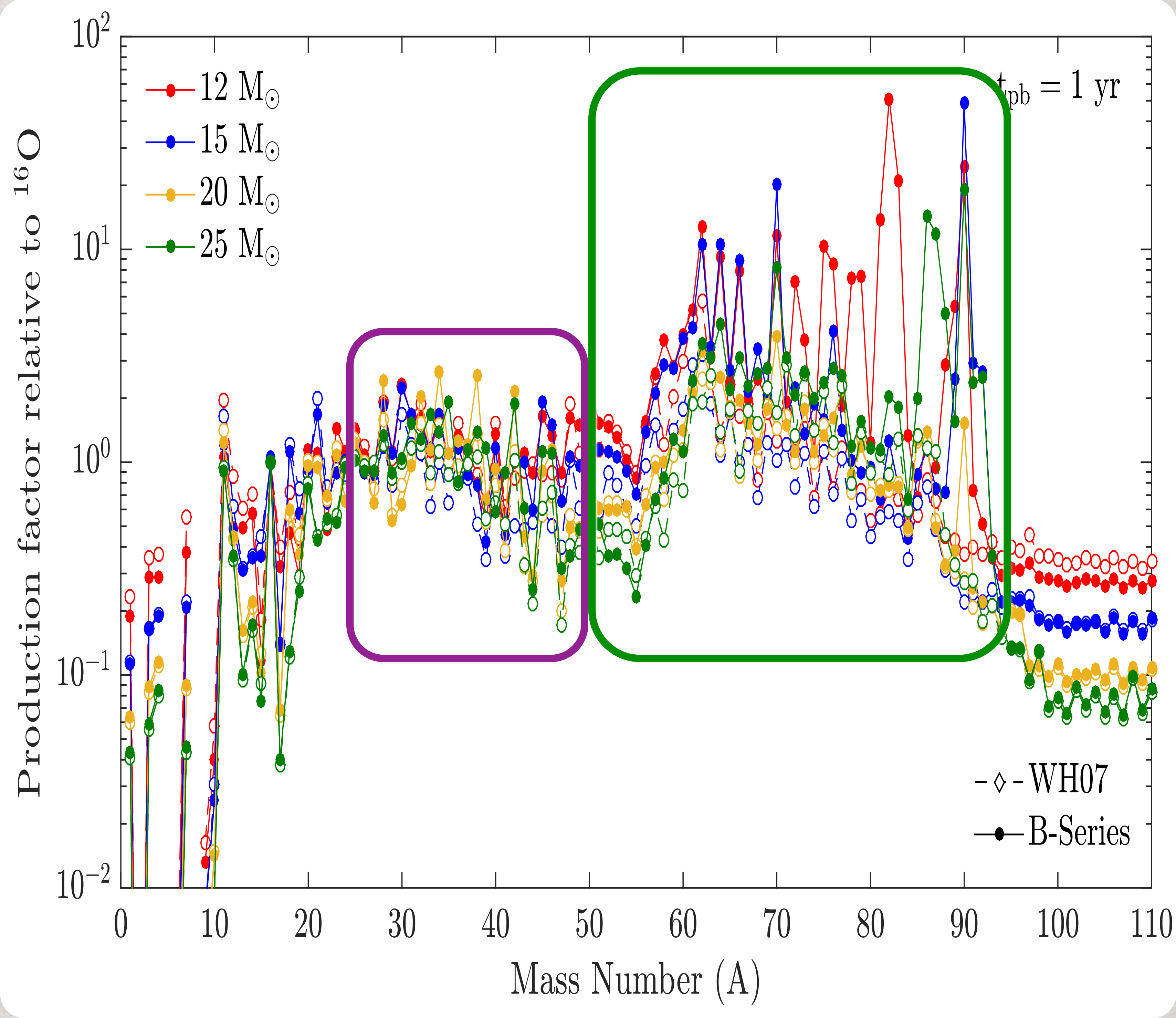


The suppression of the PNS wind is delaying or preventing a strong νp-process from occuring.

Comparing to Standard

Until we can replace 1D CCSN models in all of their applications, we can use the 2D models to identify areas of concern.

Intermediate mass elements, up to A=50, are similar, though significant isotopic differences exist.



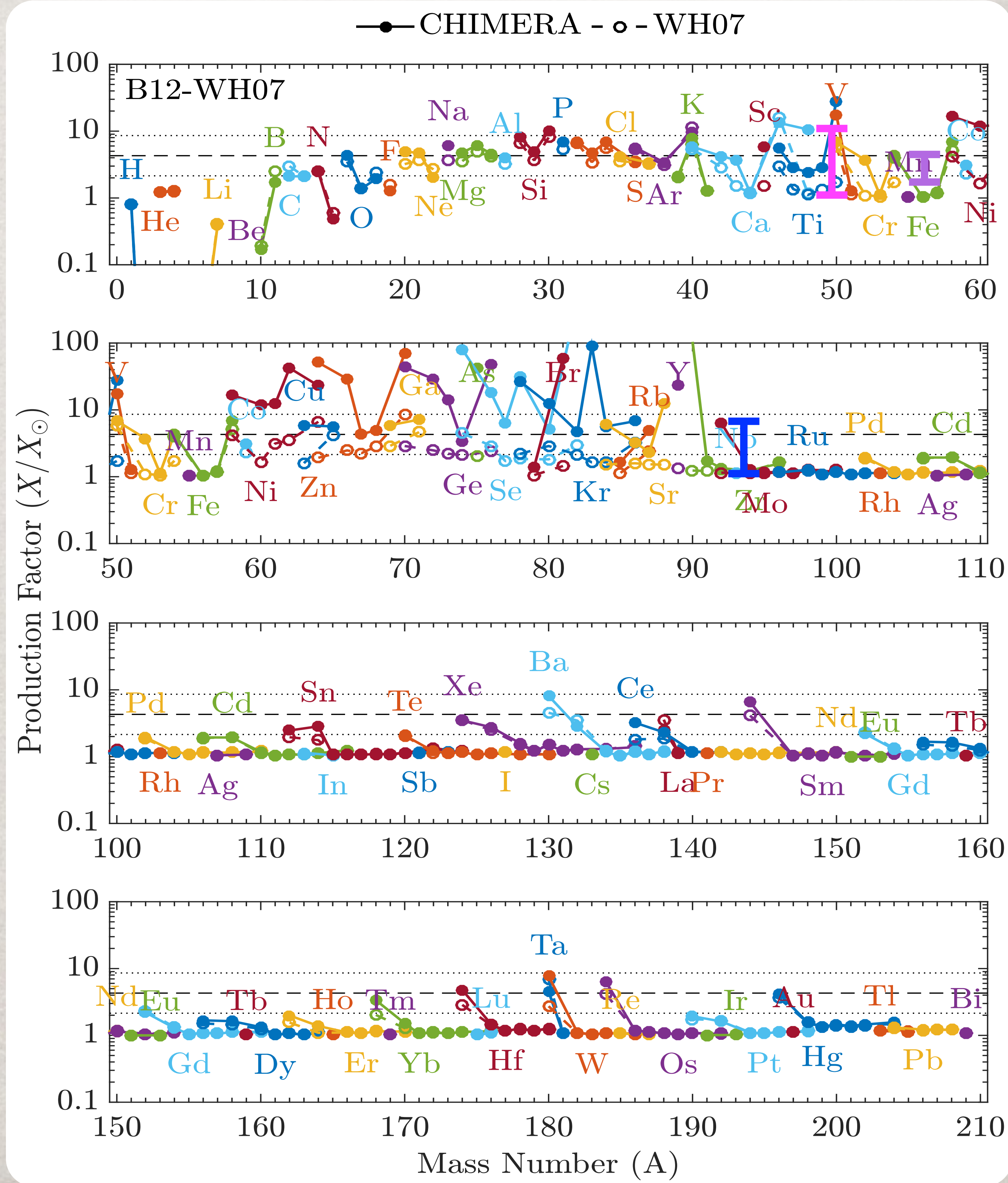
Iron peak and heavier, up to A=90, the differences get larger.

Isotopic Comparison

Isotopic comparisons reveal significant differences from 1D on both the proton-rich and neutron-rich sides.

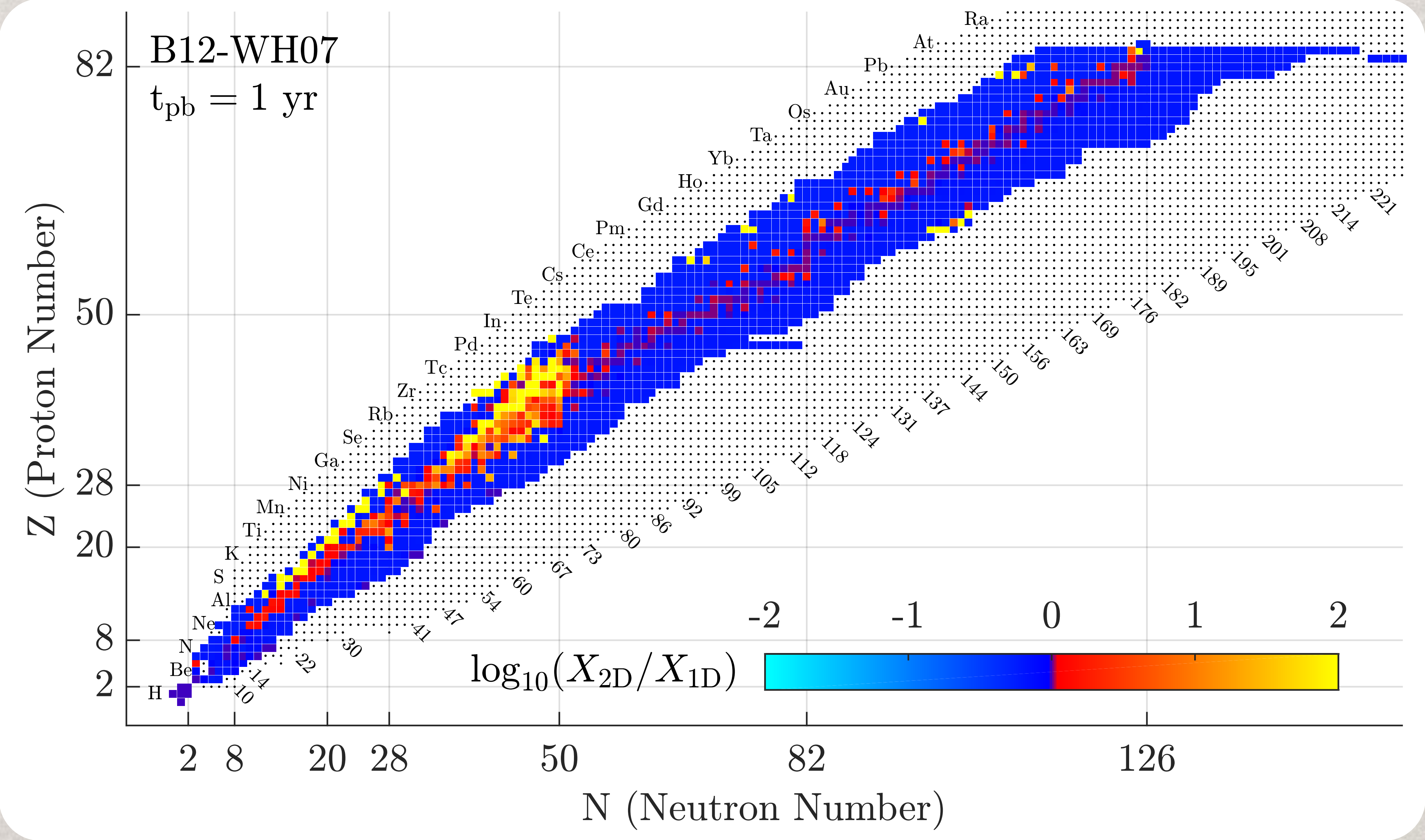
Ejection of small quantities of neutron-rich, (Y_e<0.45), low entropy matter produces significant amounts of neutron-rich intermediate mass isotopes like ^{48}Ca and ^{54}Cr.

Ejecta with somewhat higher Y_e (<0.48) and entropy produces ^{92}Mo.



Thermodynamic Variety

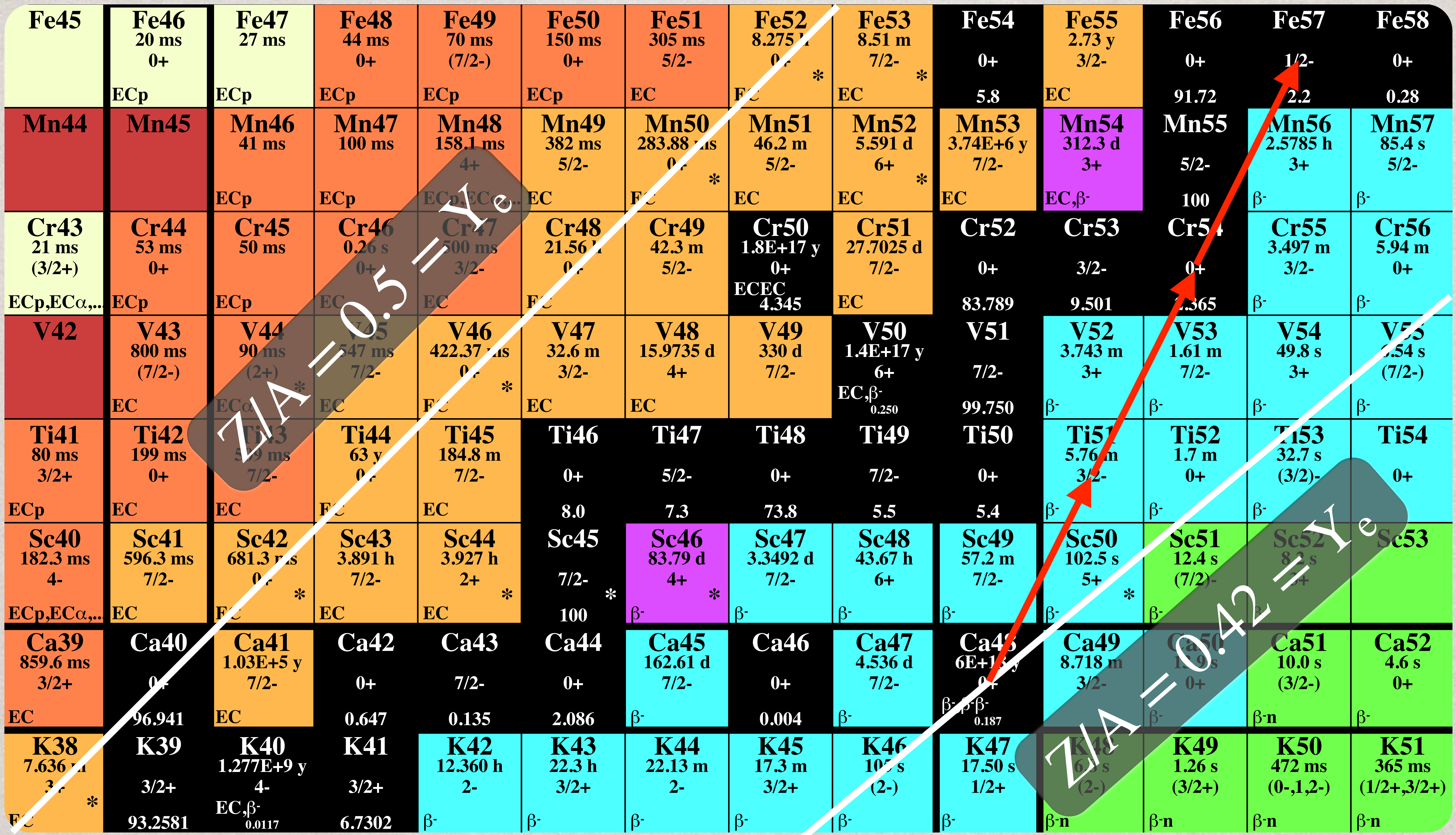
Multi-dimensional dynamics allows the ejecta to experience a wider variety of temperature, density, electron fraction and neutrino exposure.



Deeper Mass Cut and weaker explosion results in modest increase in intermediate mass and iron-group elements.

Magic of ^{48}Ca

^{48}Ca, with 20 protons and 28 neutrons, is a doubly-magic nucleus.



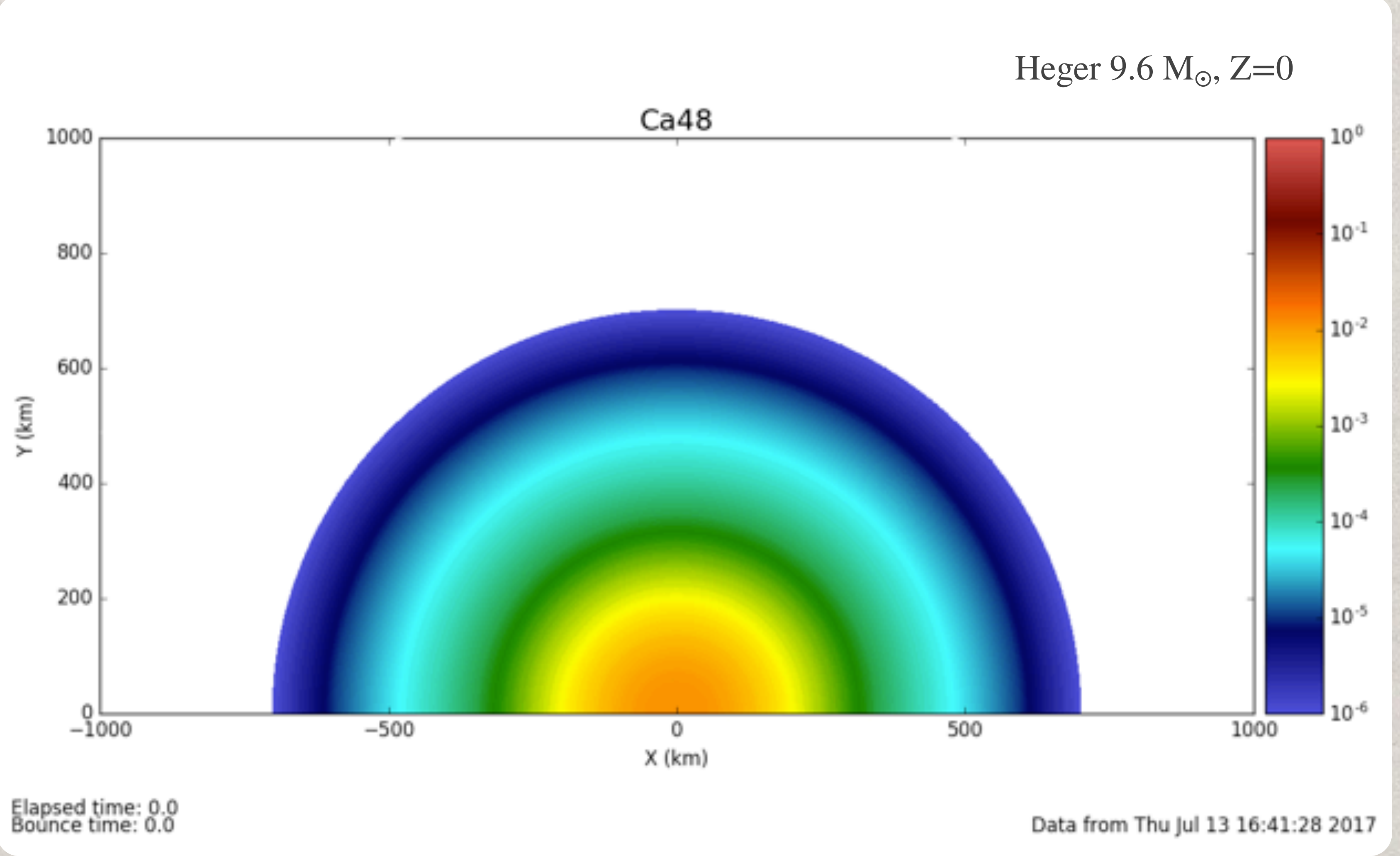
Making ^{48}Ca requires neutron-rich NSE conditions, but if temperature gets too high, α-rich freezeout converts to neutron-rich iron or nickel.

Stripping a Neutron Star

Relatively cold, but neutron-rich, matter is trapped in the neutron star and not ejected in the parameterized spherically symmetric models.

In the self-consistent, multi-dimensional CCSN models, accretion streams occasionally dredge neutron-rich matter off the neutron-star.

If this matter is not strongly heated by subsequent interactions, it can retain ^{48}Ca.



For light Fe cores and ECSN (Wanajo, … 2013), such matter can be lifted directly by shock and convection.

Conclusions

Examining the nucleosynthesis of CCSN with models that self-consistently treat the explosion mechanism requires running the models to times > 1 second after bounce for uncertainties like the mass cut, thermodynamic extrapolation, etc. to become tractable.

Even then, low post-processing resolution is a significant uncertainty.

Differences from 1D models are seen in differing amounts of iron peak and intermediate mass elements as a result of changes in the explosion timing and mass cut.

The ejection of significantly more proton-rich matter as well as small quantities of neutron-rich matter can change the production of individual isotopes by orders of magnitude.

Neutrino-Driven wind is strongly suppressed by accretion.

There is considerable commonality in the production of species from NSE freezeout between lower mass CCSN and ECSN.