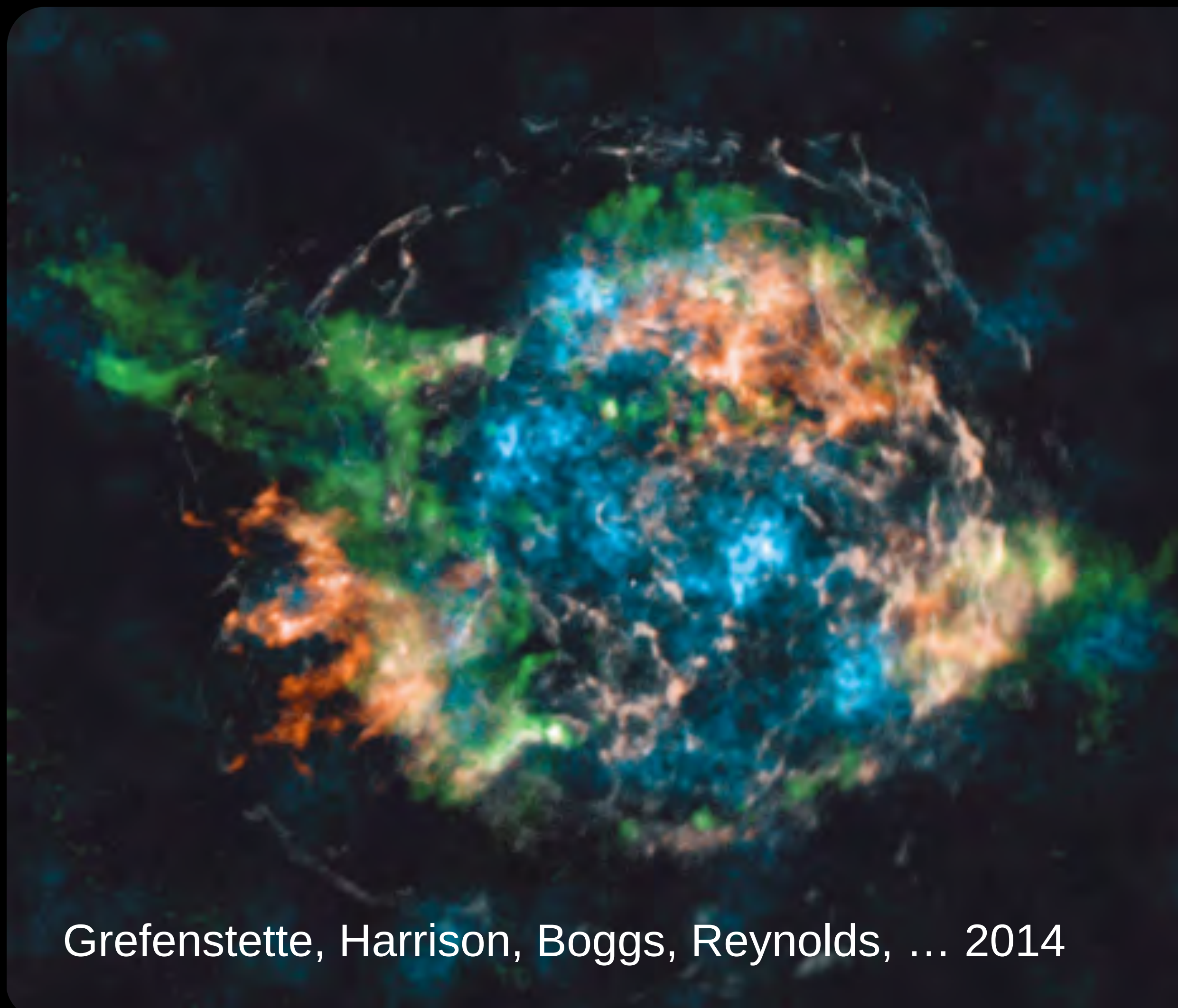
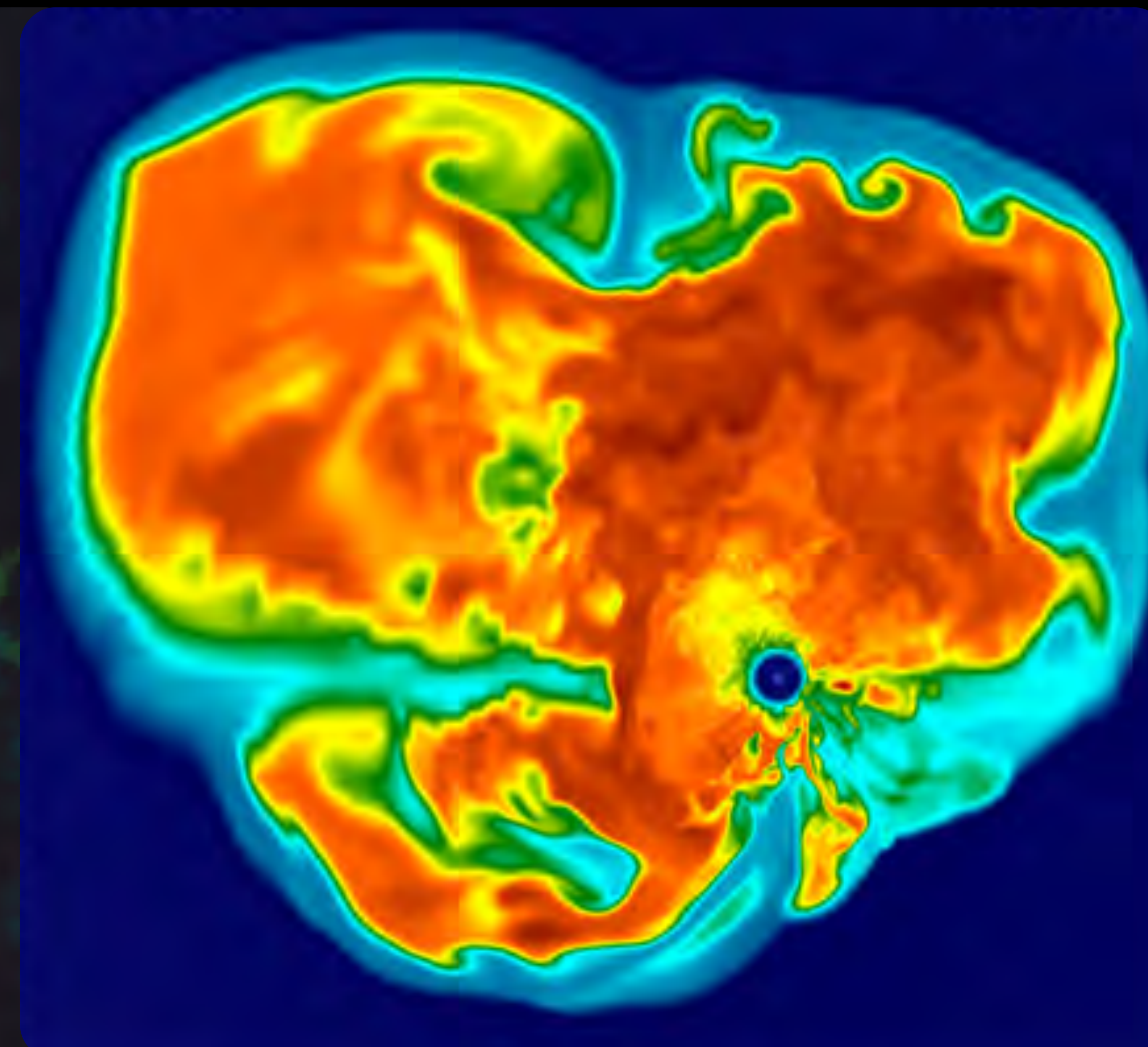
Multidimensional Simulations of Core-Collapse Supernovae



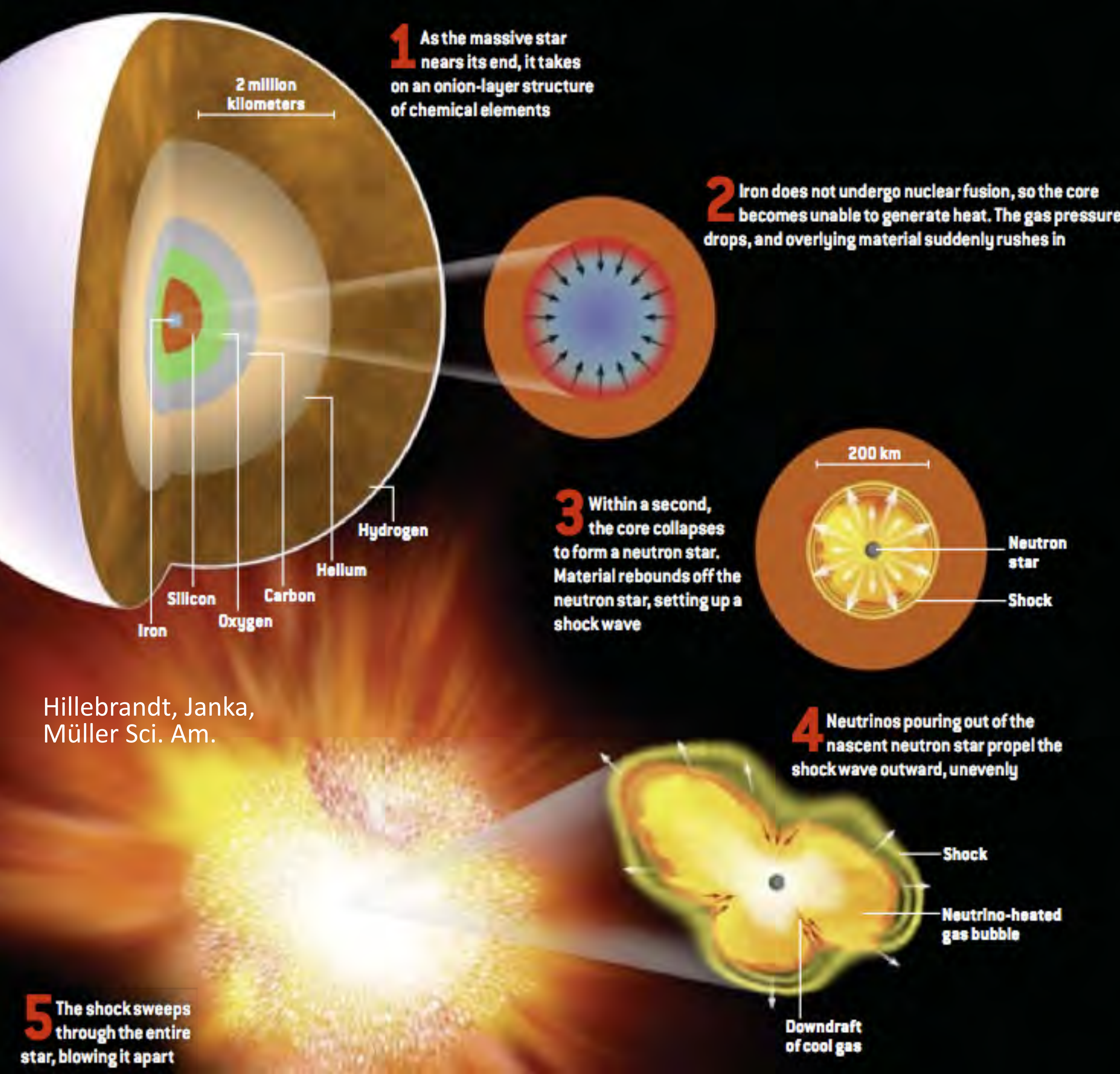


& their Impact on SN Nucleosynthesis

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)

Textbook Supernova



A Core-Collapse Supernova is the inevitable death knell of a massive star (~10+ $M_{\odot}$).

The explosion enriches the interstellar medium with elements from Oxygen to Nickel and potentially the r-process elements as well.

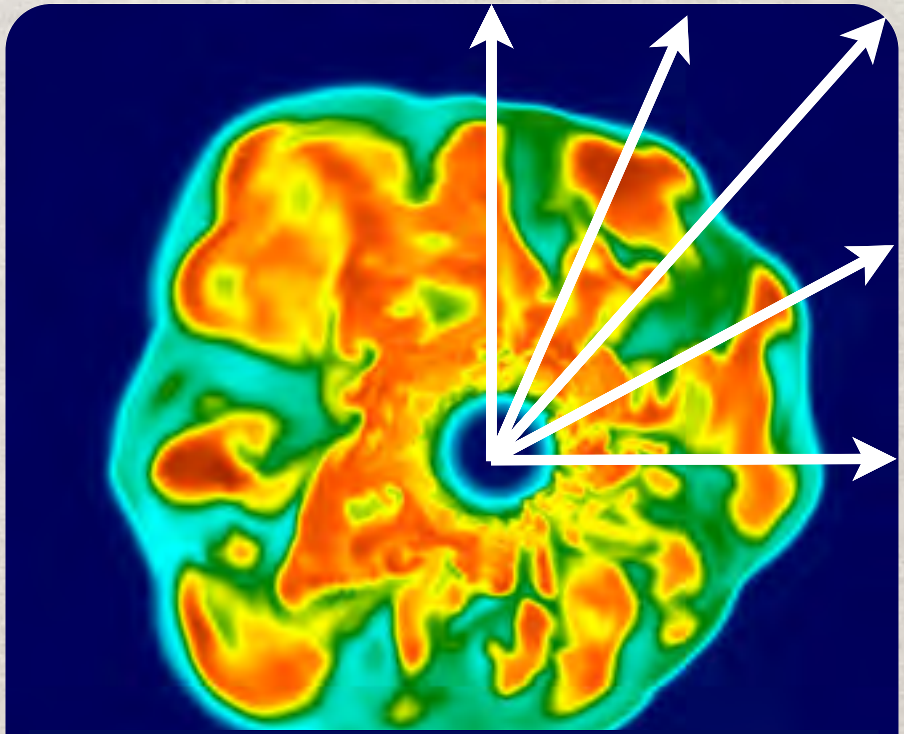
CHIMERA

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.

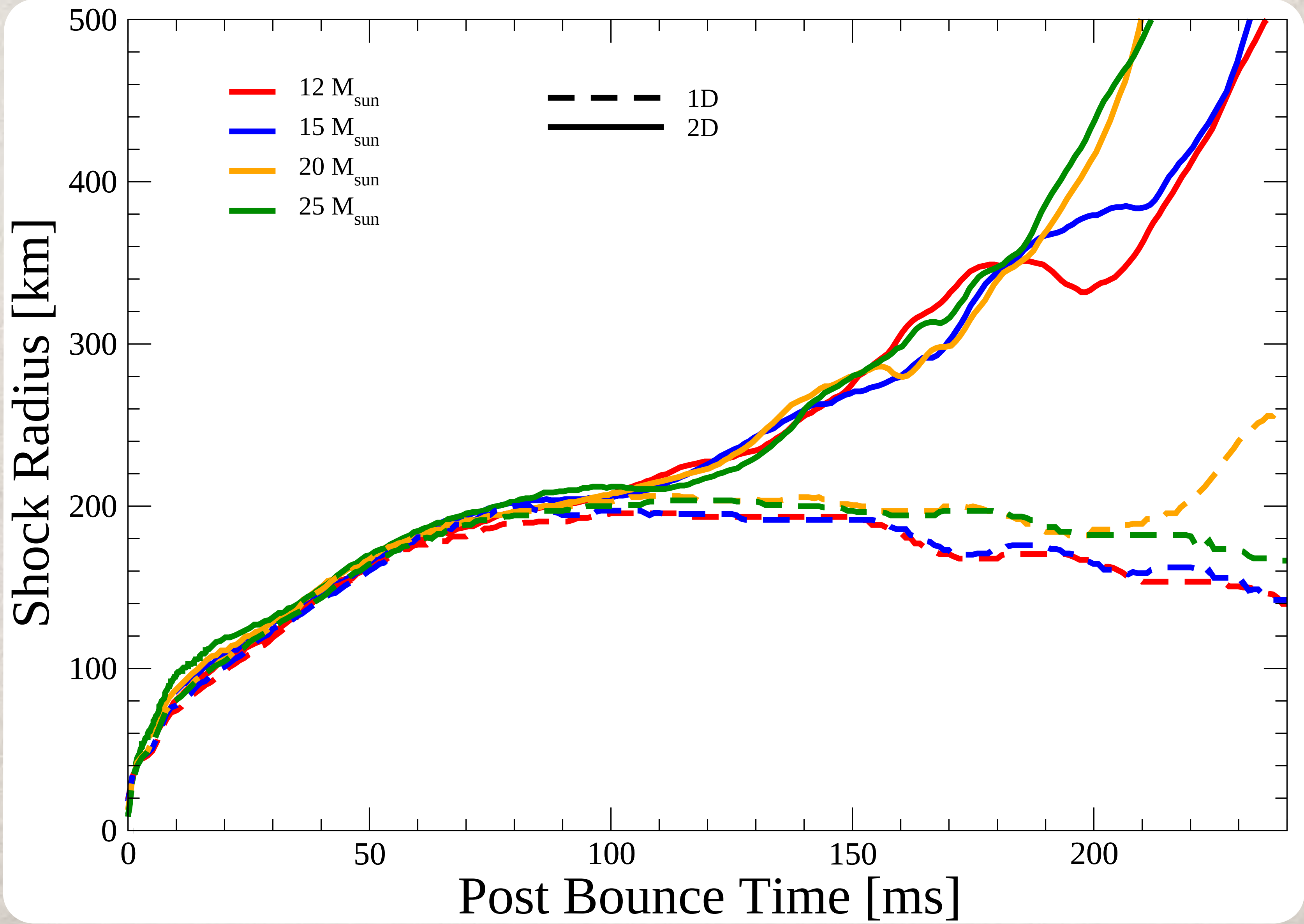


Ray-by-Ray Approximation

The Early Phase

For the first ~0.1 s after bounce, the supernova shock is essentially spherical, with 1D models identical to 2D models.

In multi-dimensions, fluid instabilities begin to deform the shock and gradually push it outwards.



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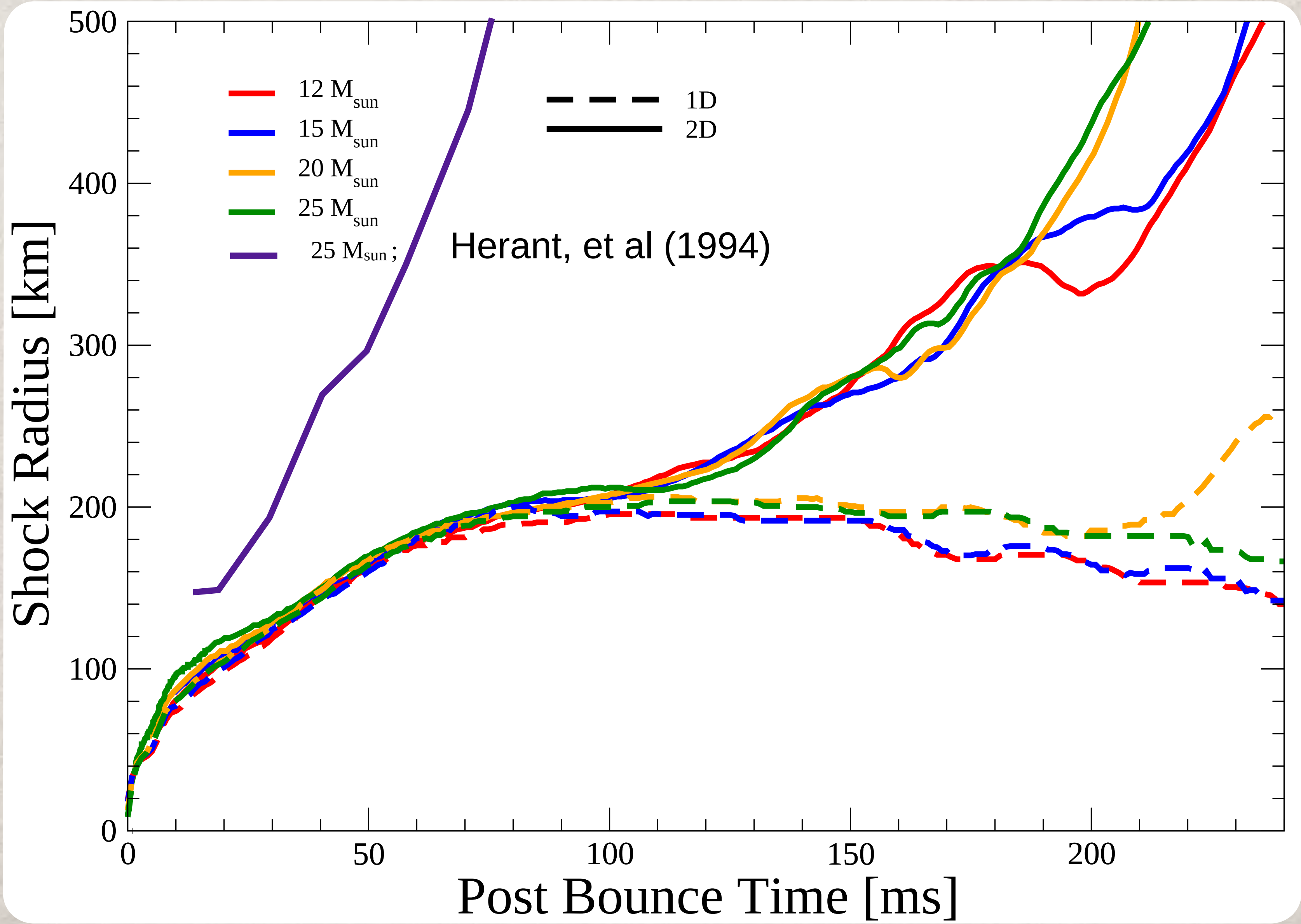

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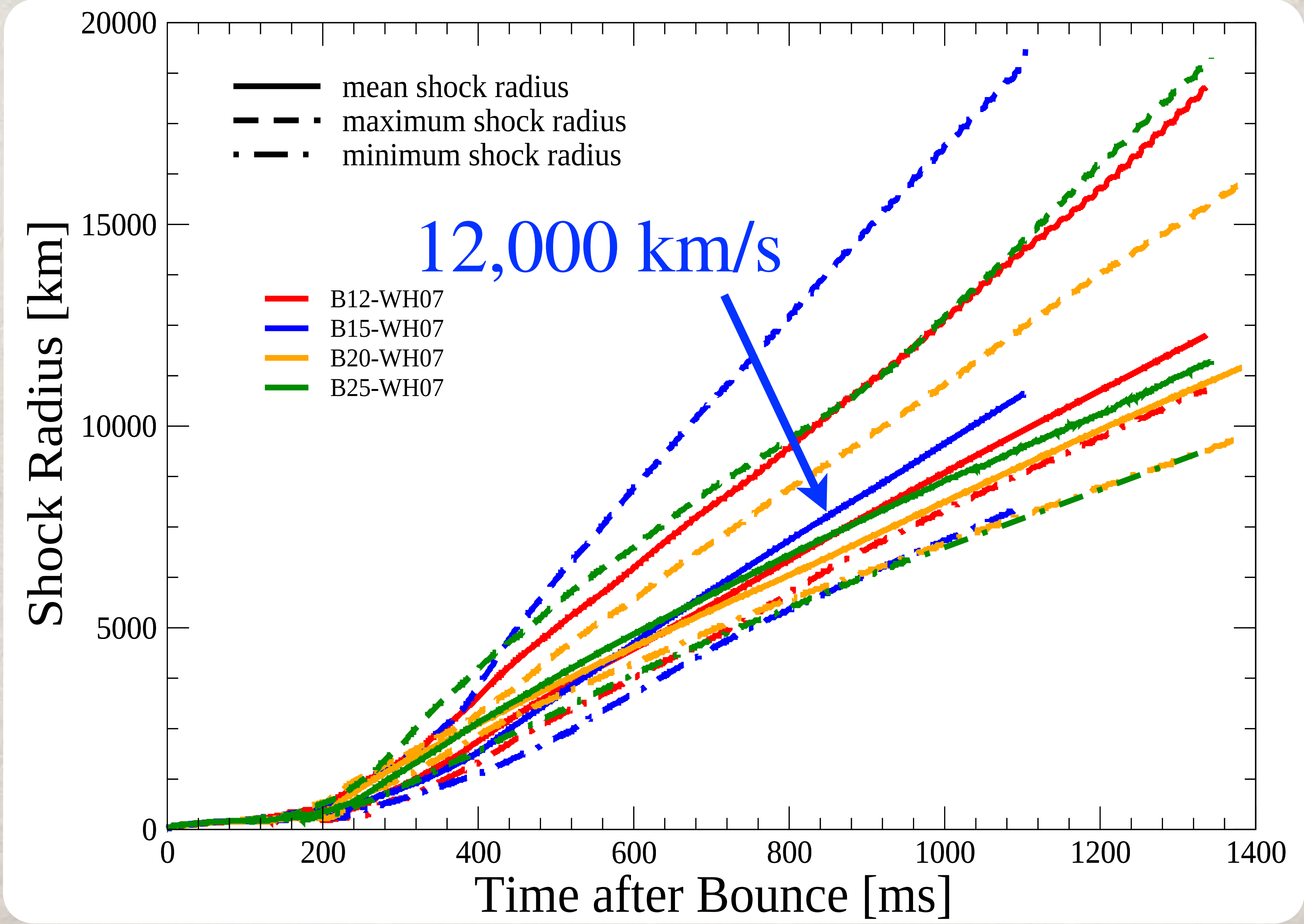

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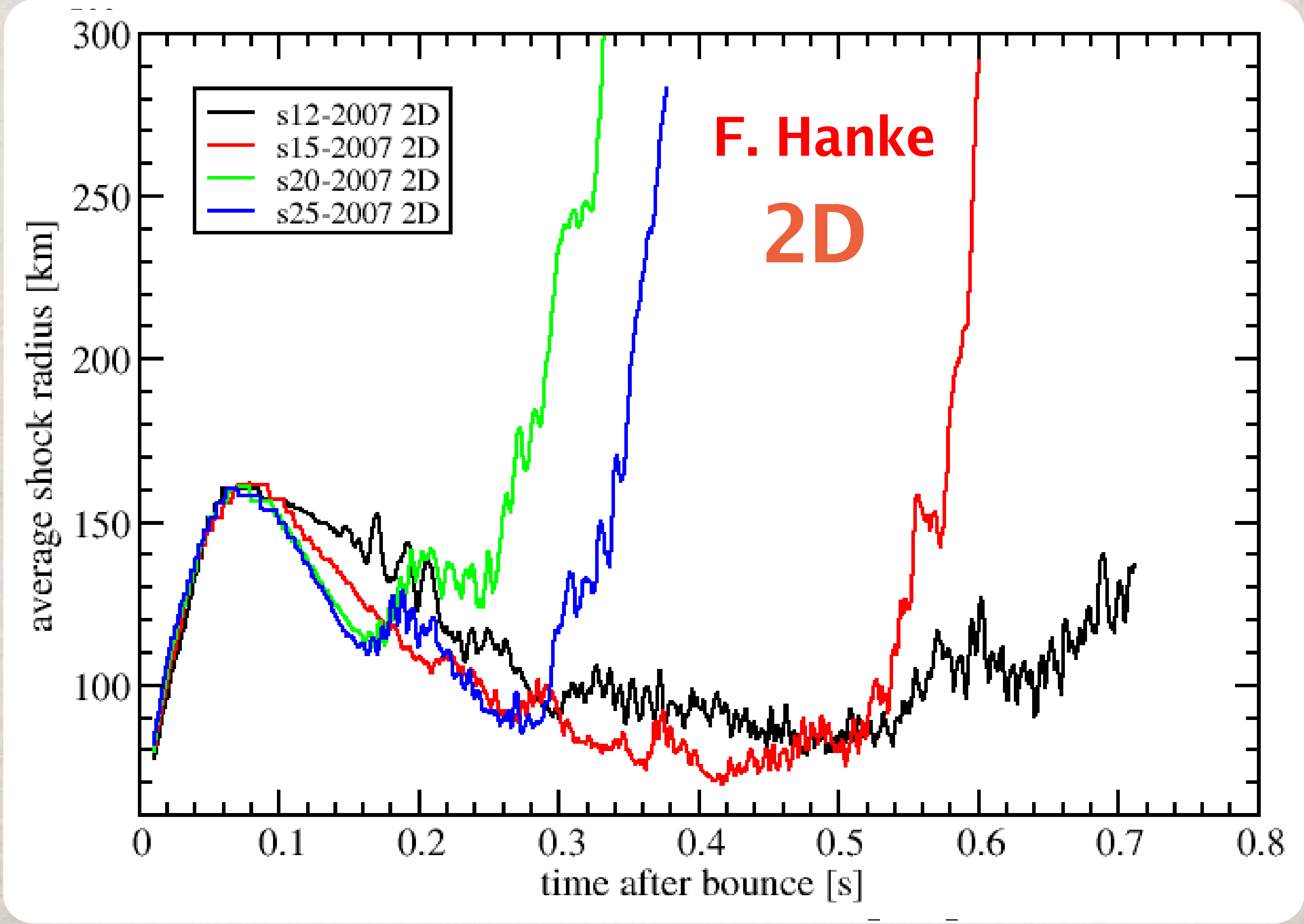
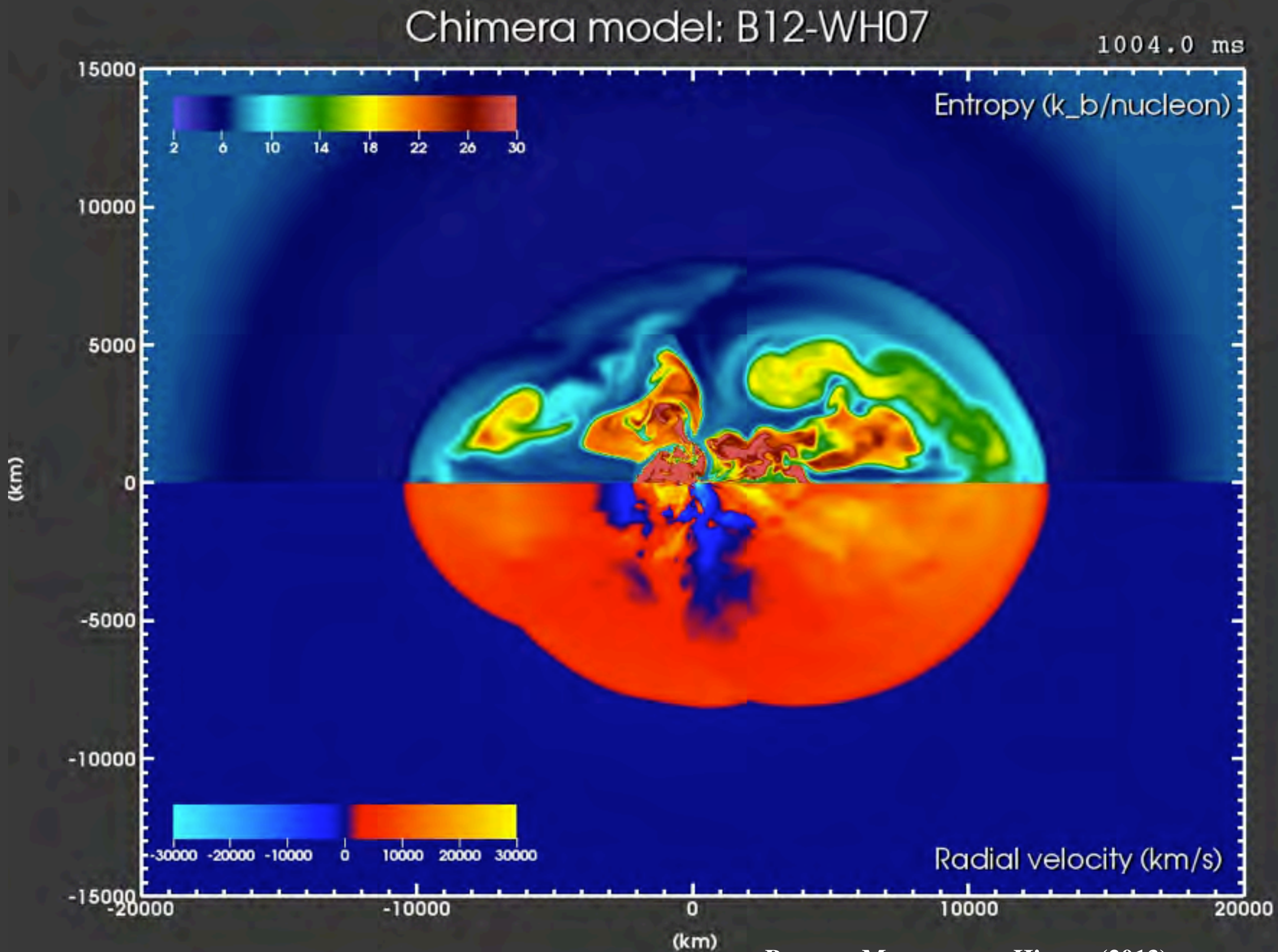
Shock accelerates to free expansion.

Competitive models exhibit even longer delays.



Supernova: the Movie



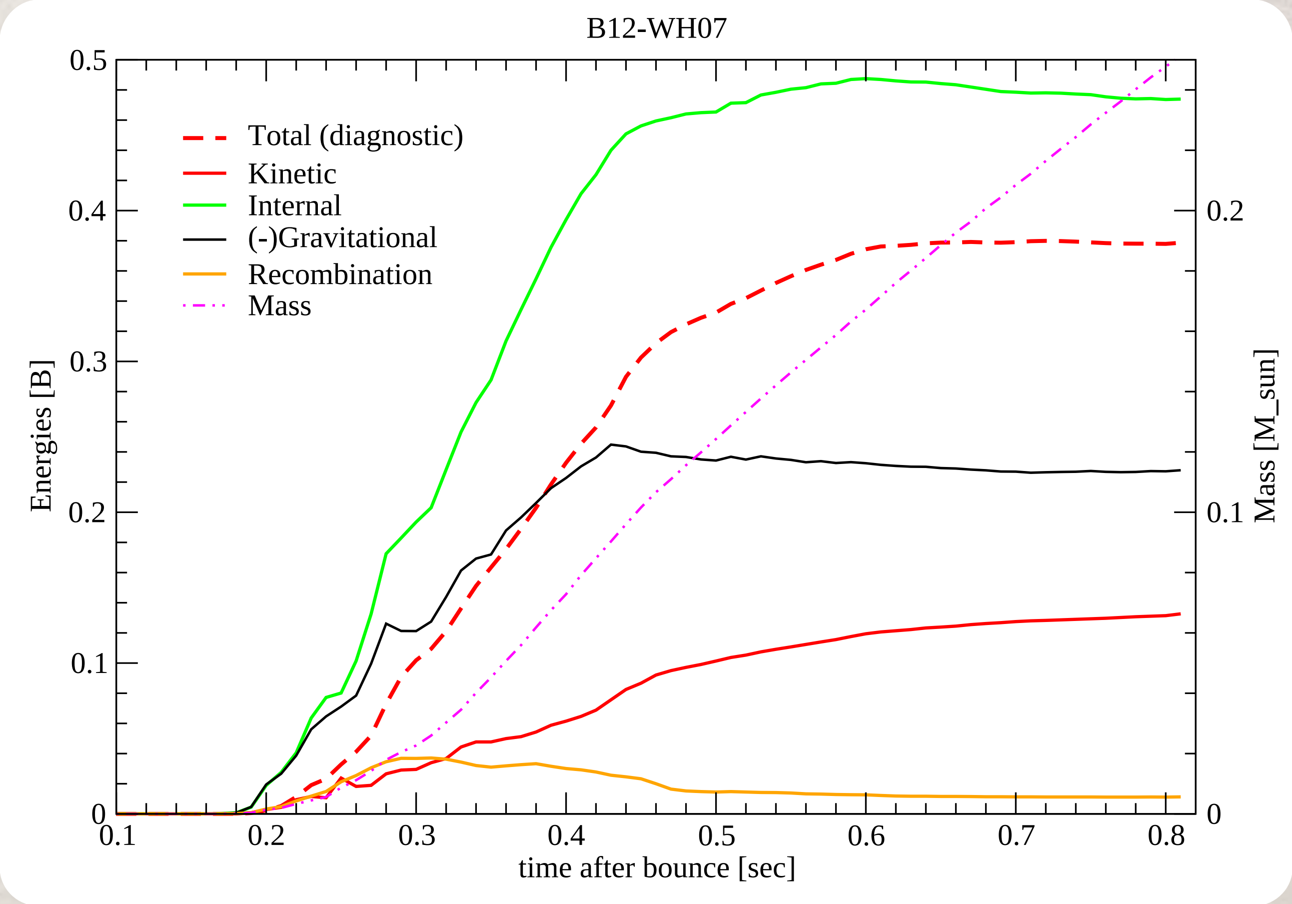
Bruenn, Mezzacappa, Hix, … (2013)

Explosion Energies

Once we achieve the most basic observable, an explosion, we can begin to compare to 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 $E_i \Rightarrow E_k$.



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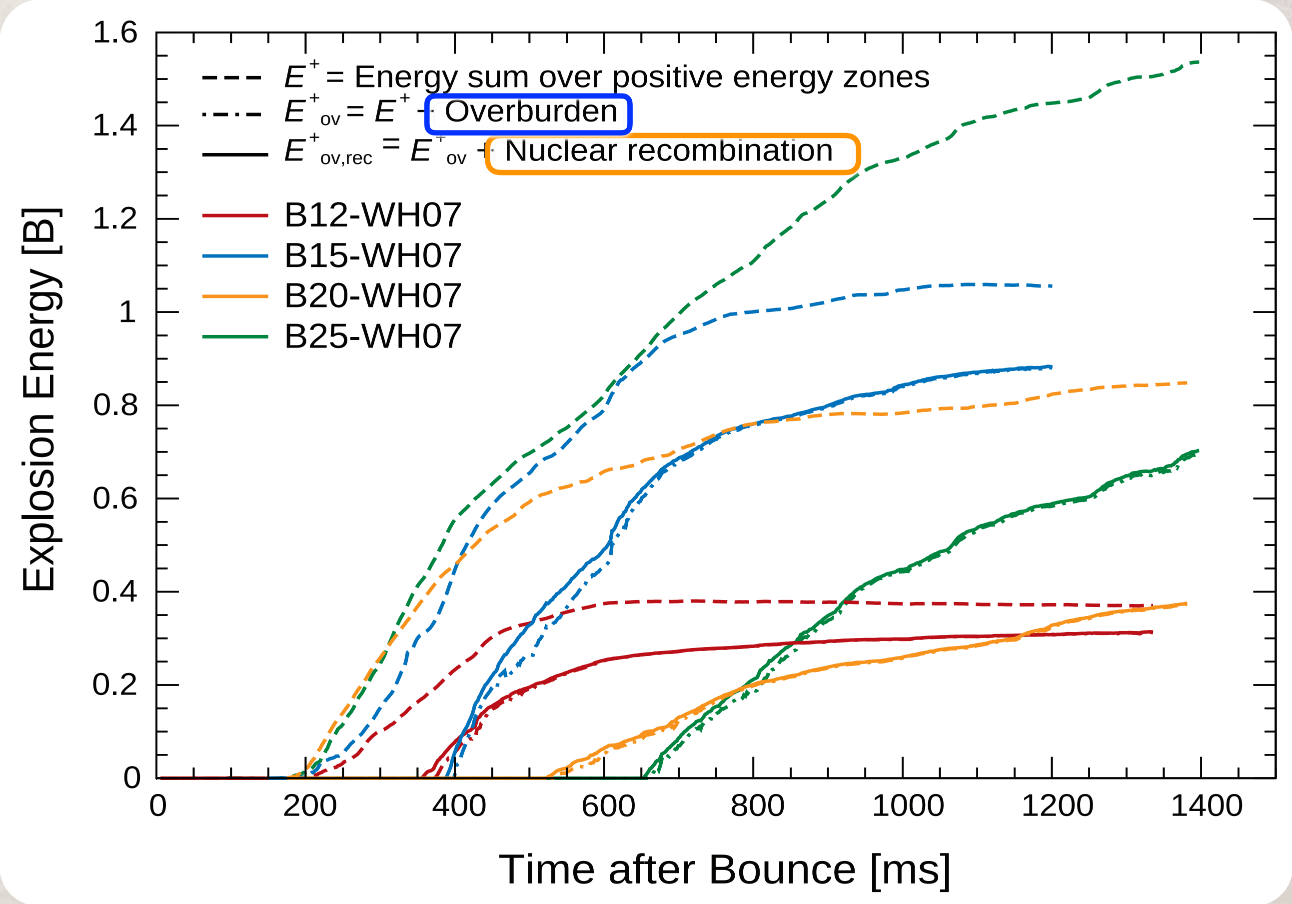

One can construct a "diagnostic" energy, $E^+ = E_i + E_g + E_k$, summed over zones where $E^+ > 0$.

To this we add contributions from nuclear recombination and removing the envelope.

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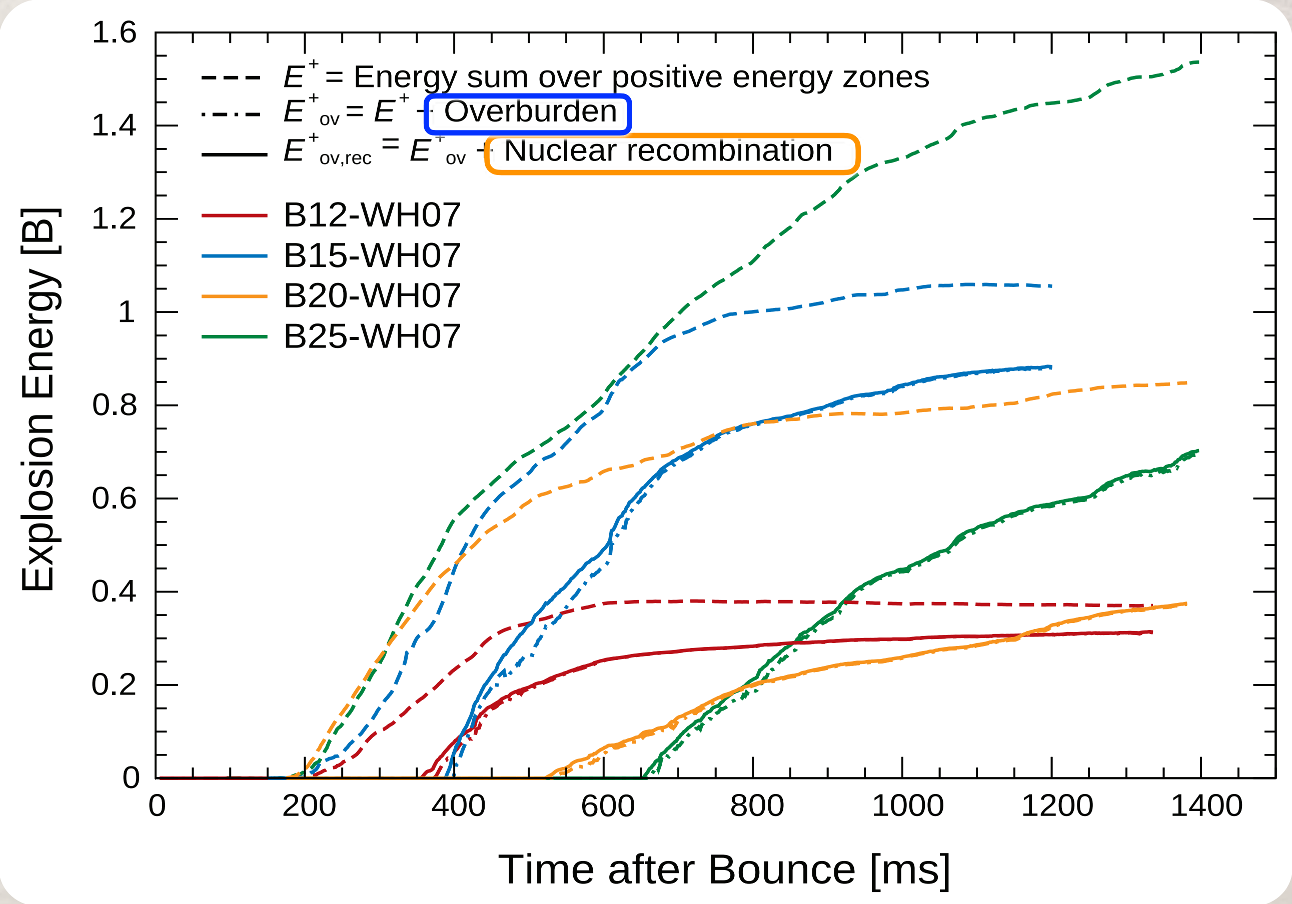

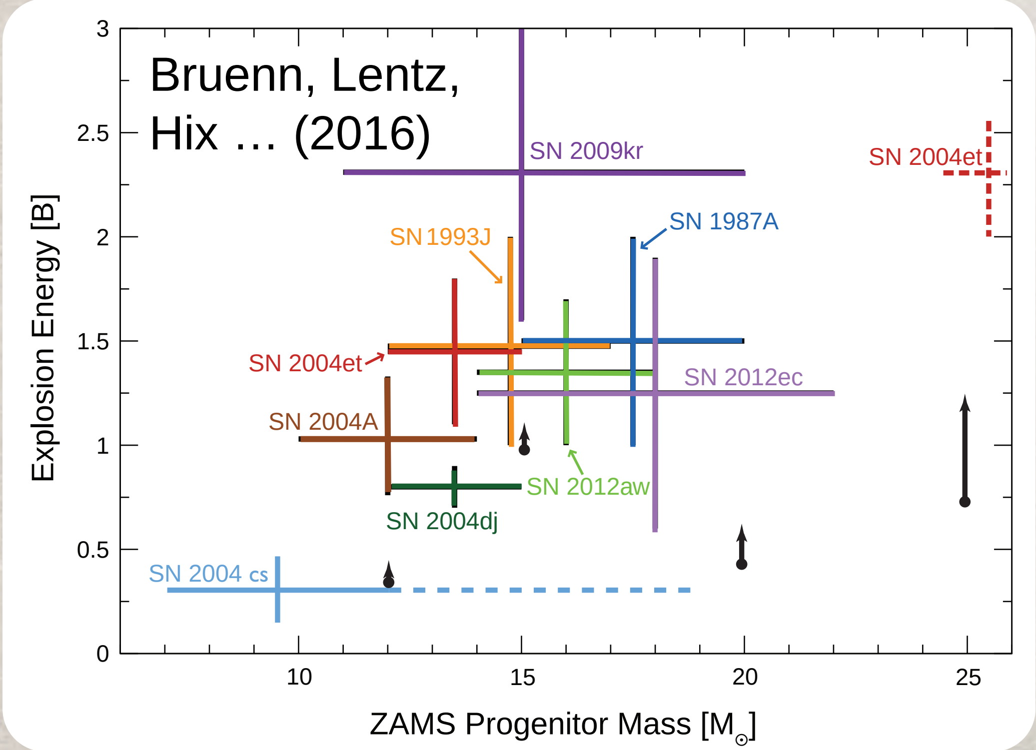

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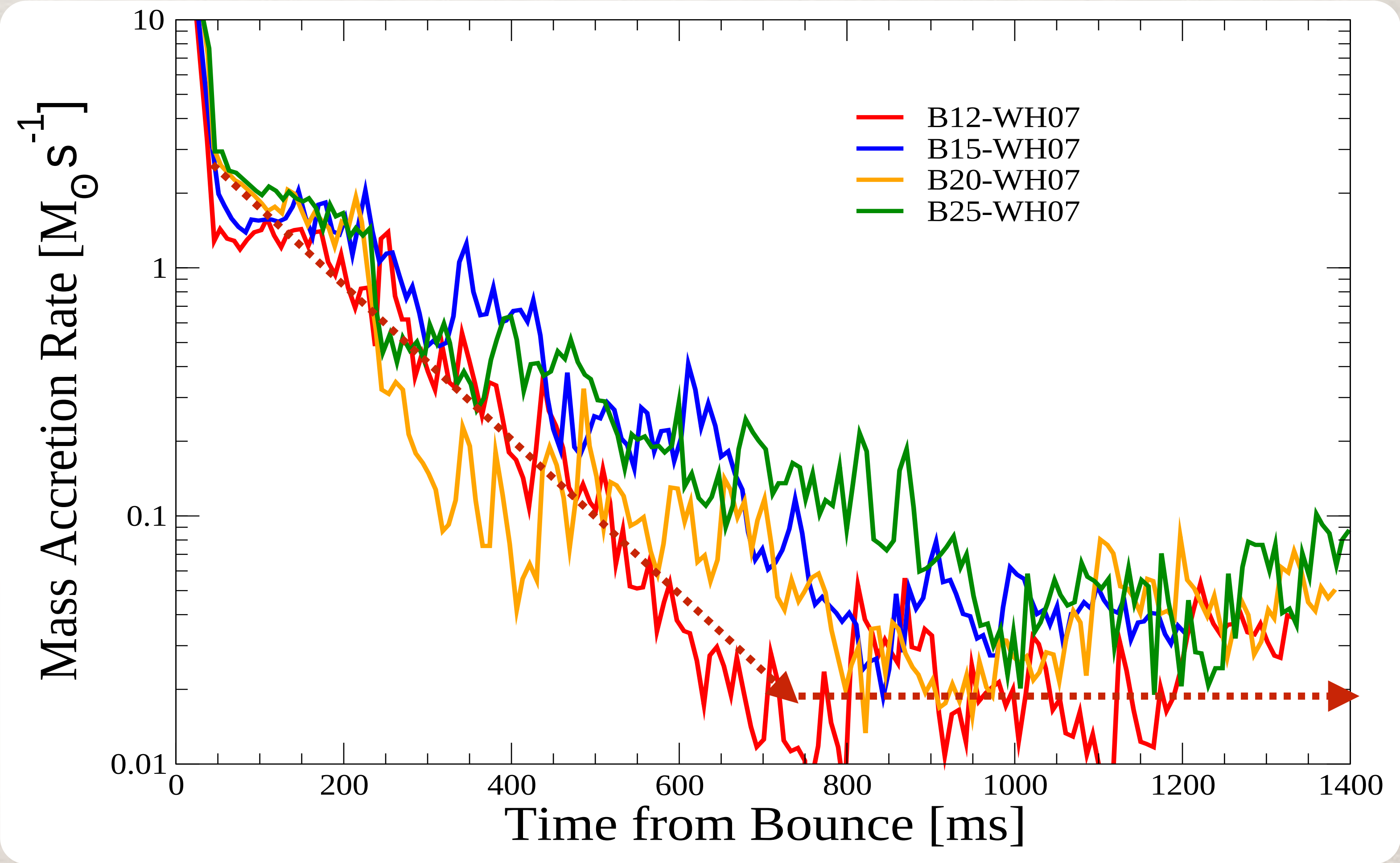
End of the Explosion?

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.



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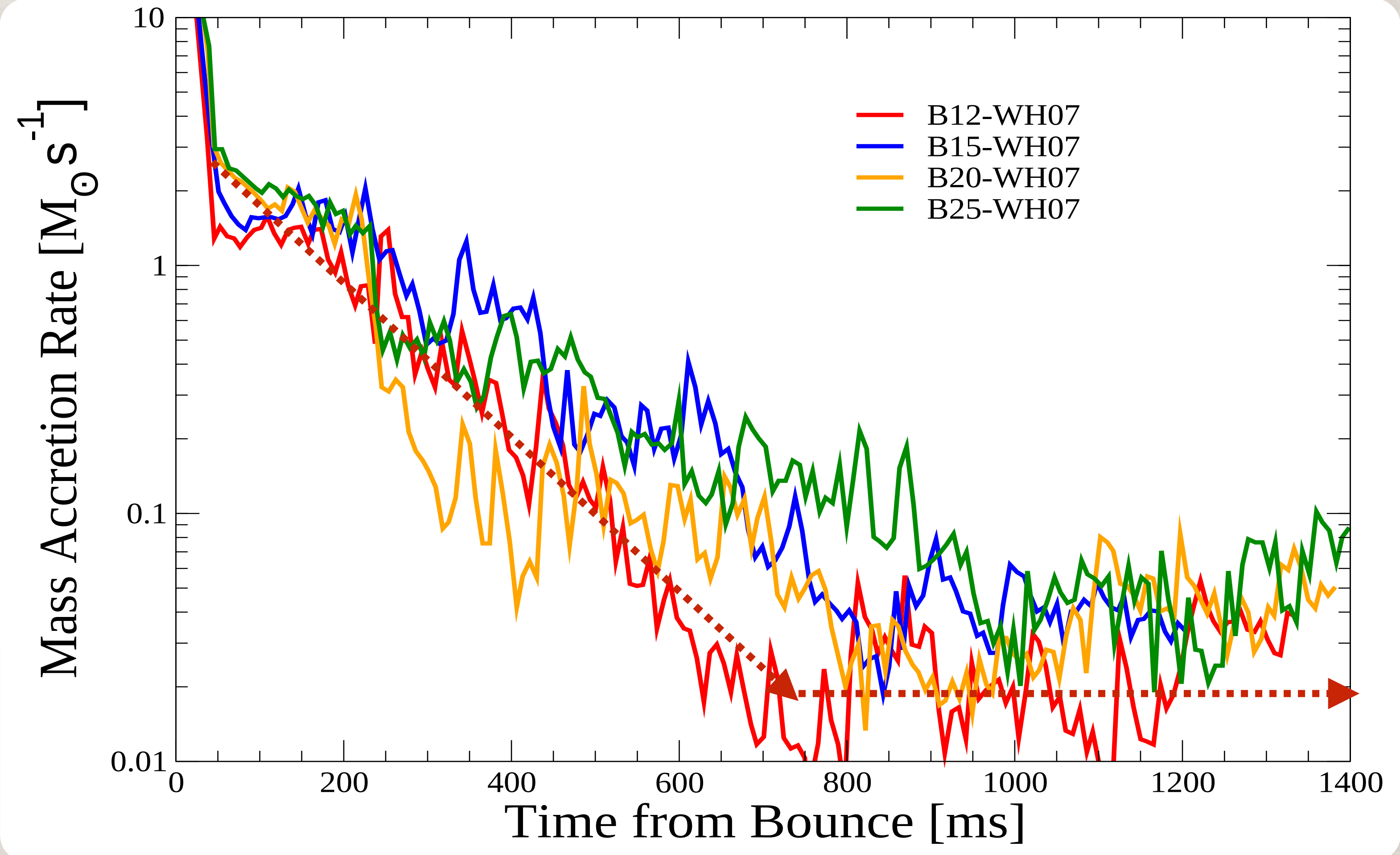

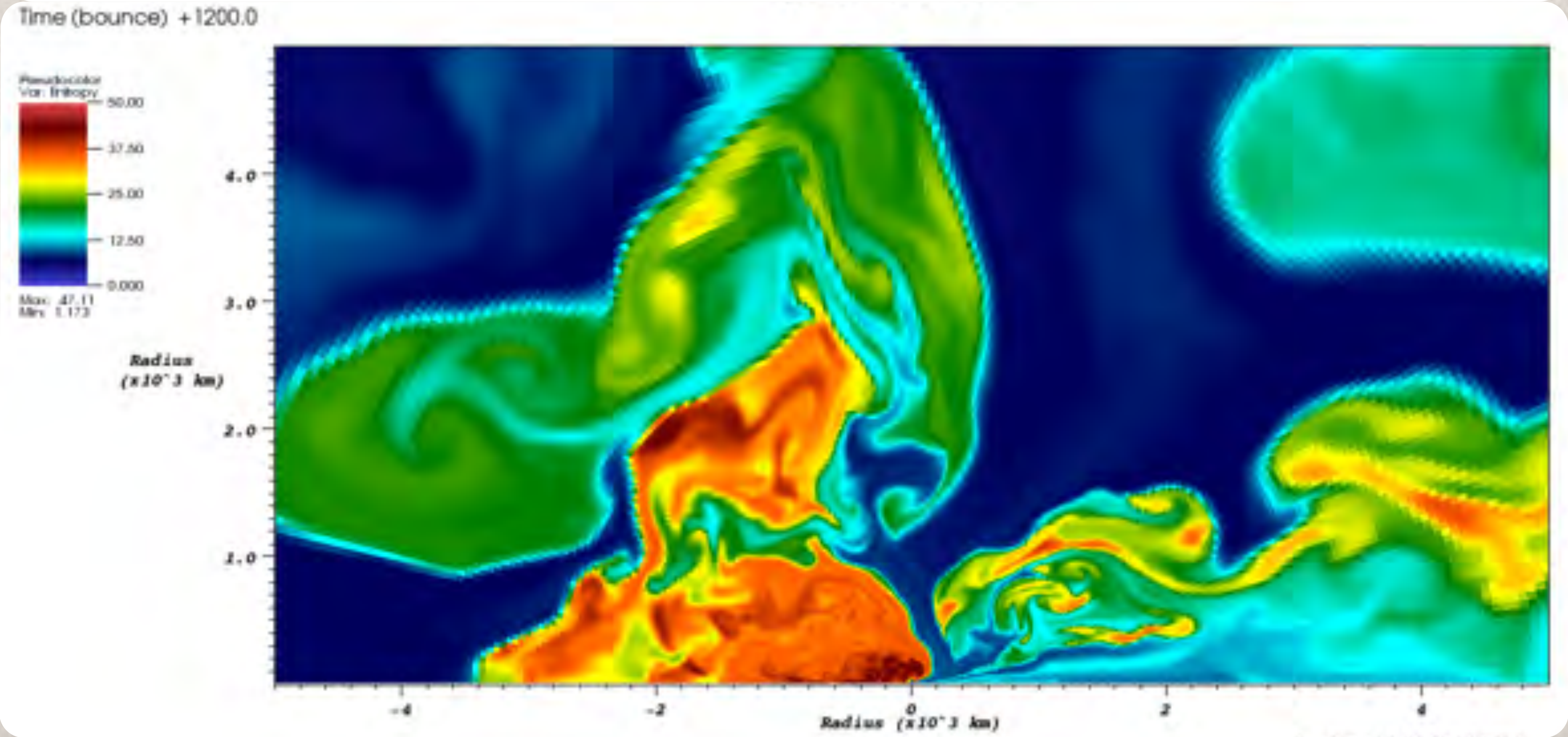

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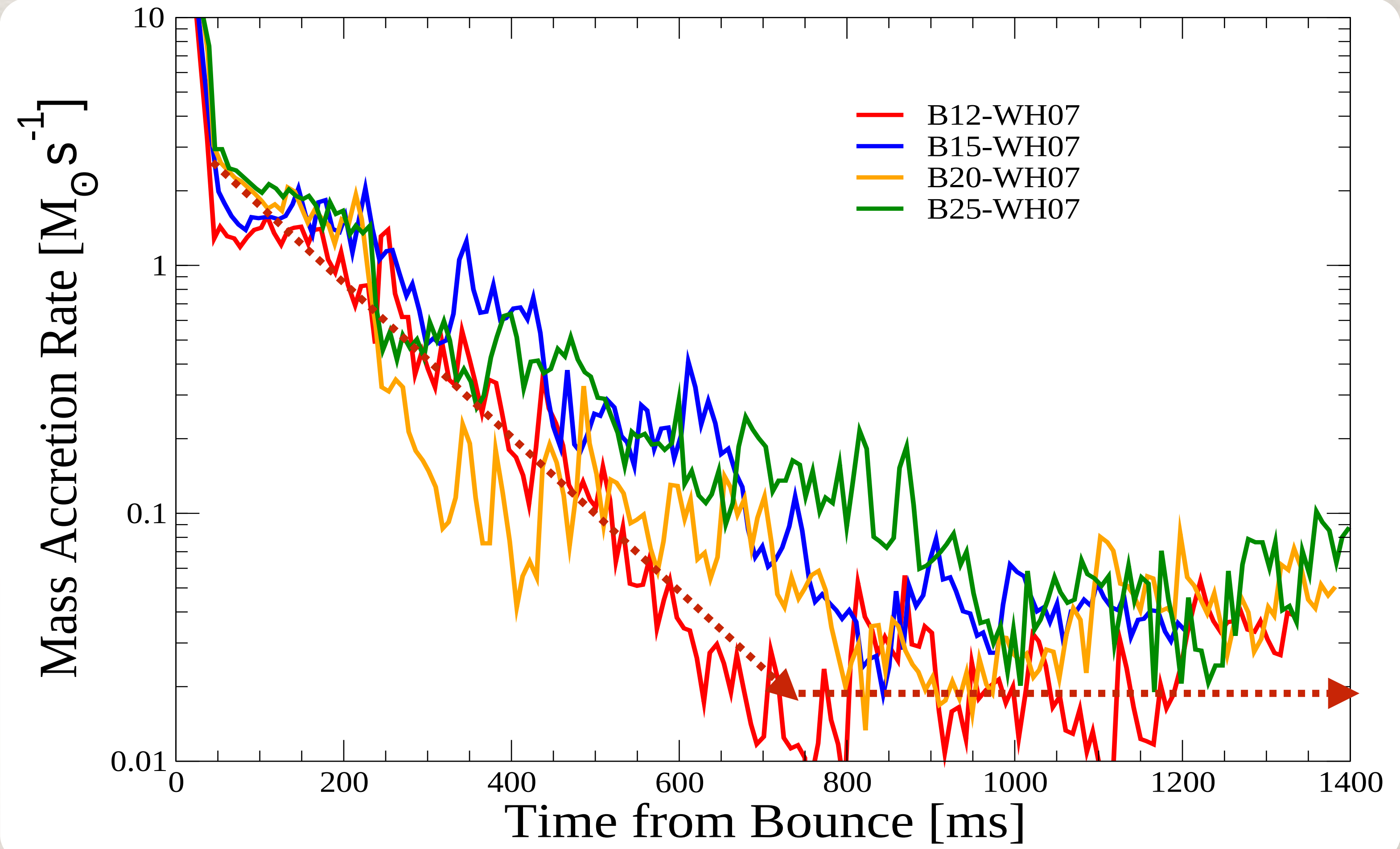
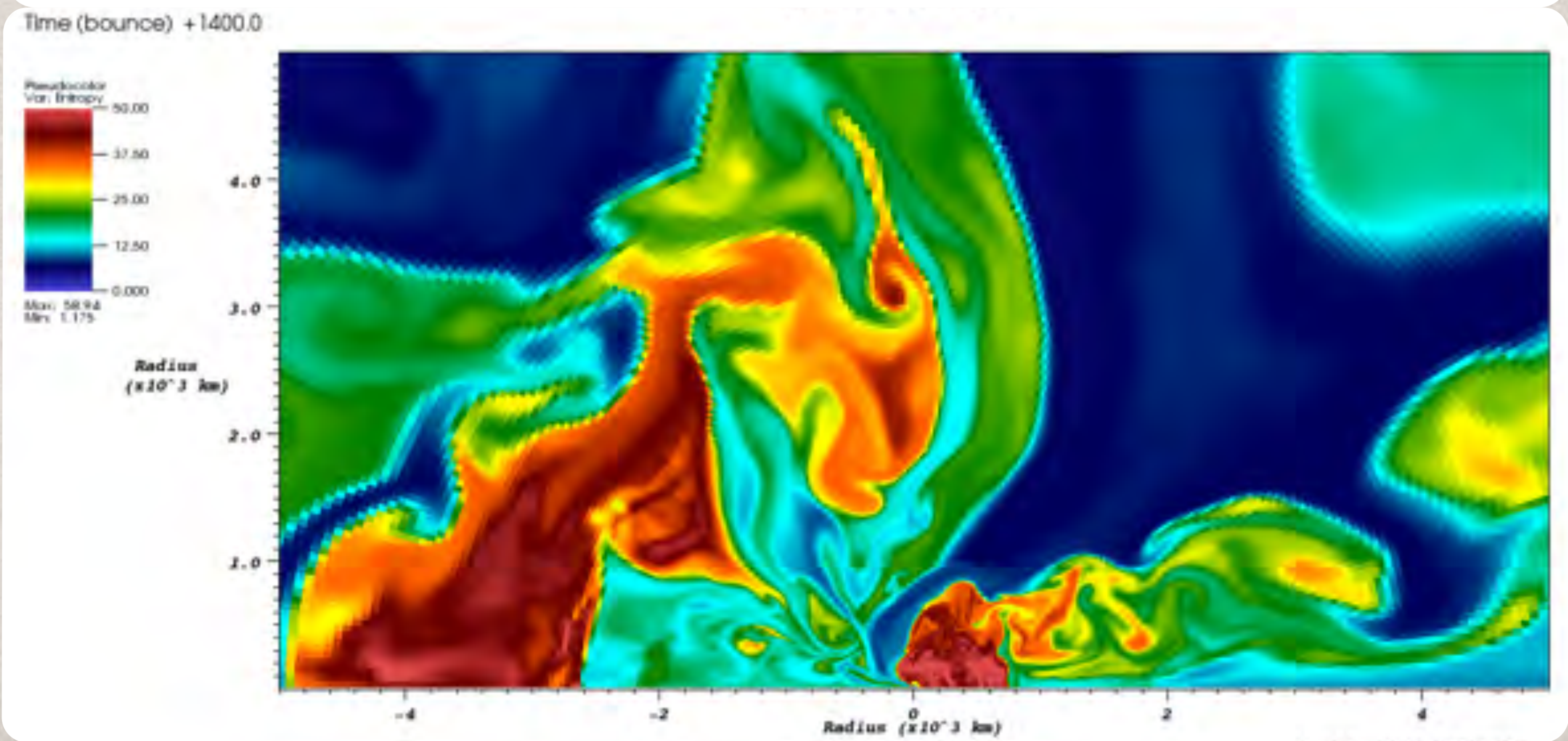
This extends the "hot bubble" phase and suppresses the development of the PNS wind.

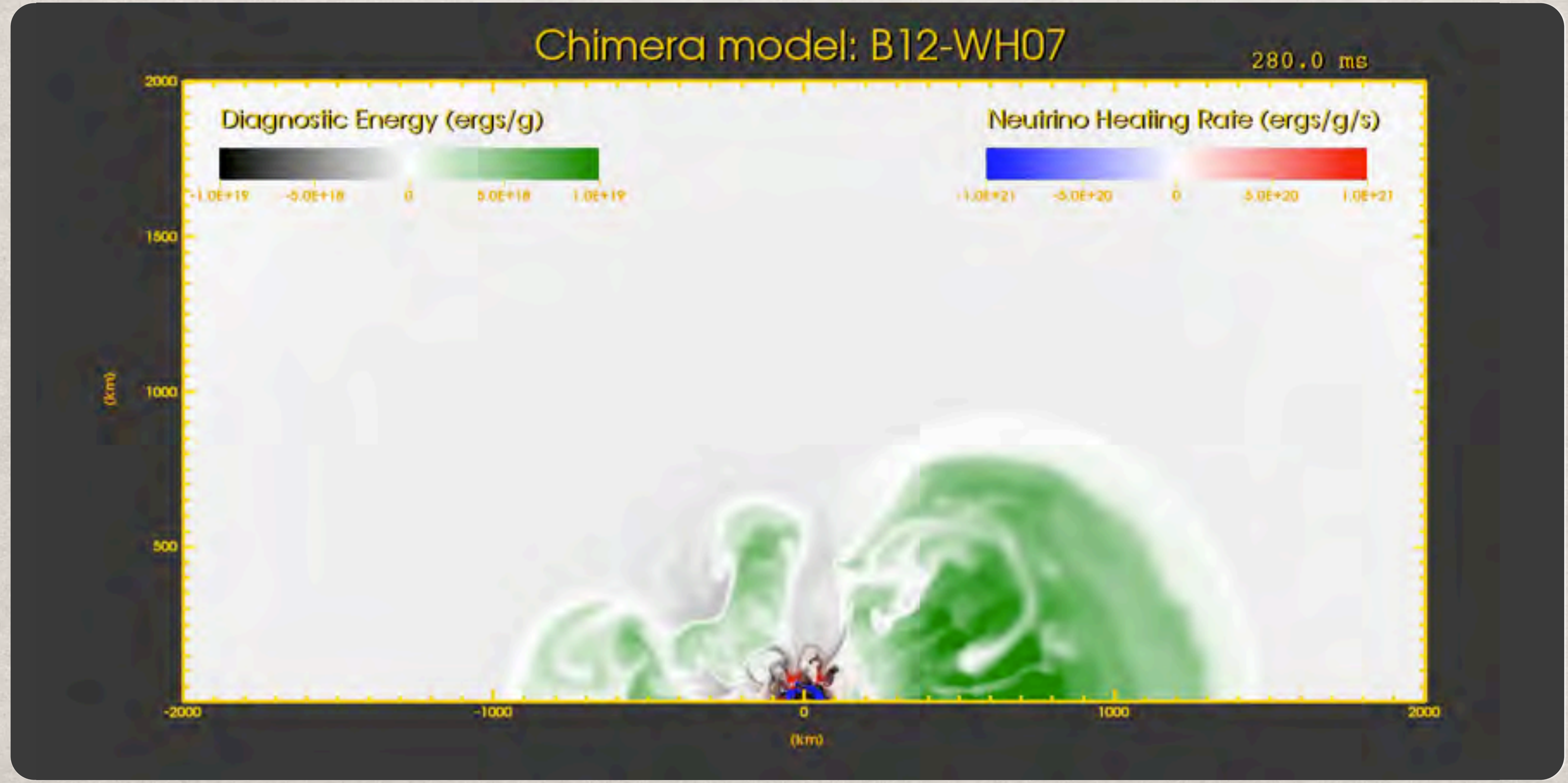




The Problem of Fallback

Some of the infalling matter at late times is making its first approach to the PNS, but much of the matter has been here before, having expended energy lifting the remainder of the star.

This continued accretion & heating impacts the nucleosynthesis.



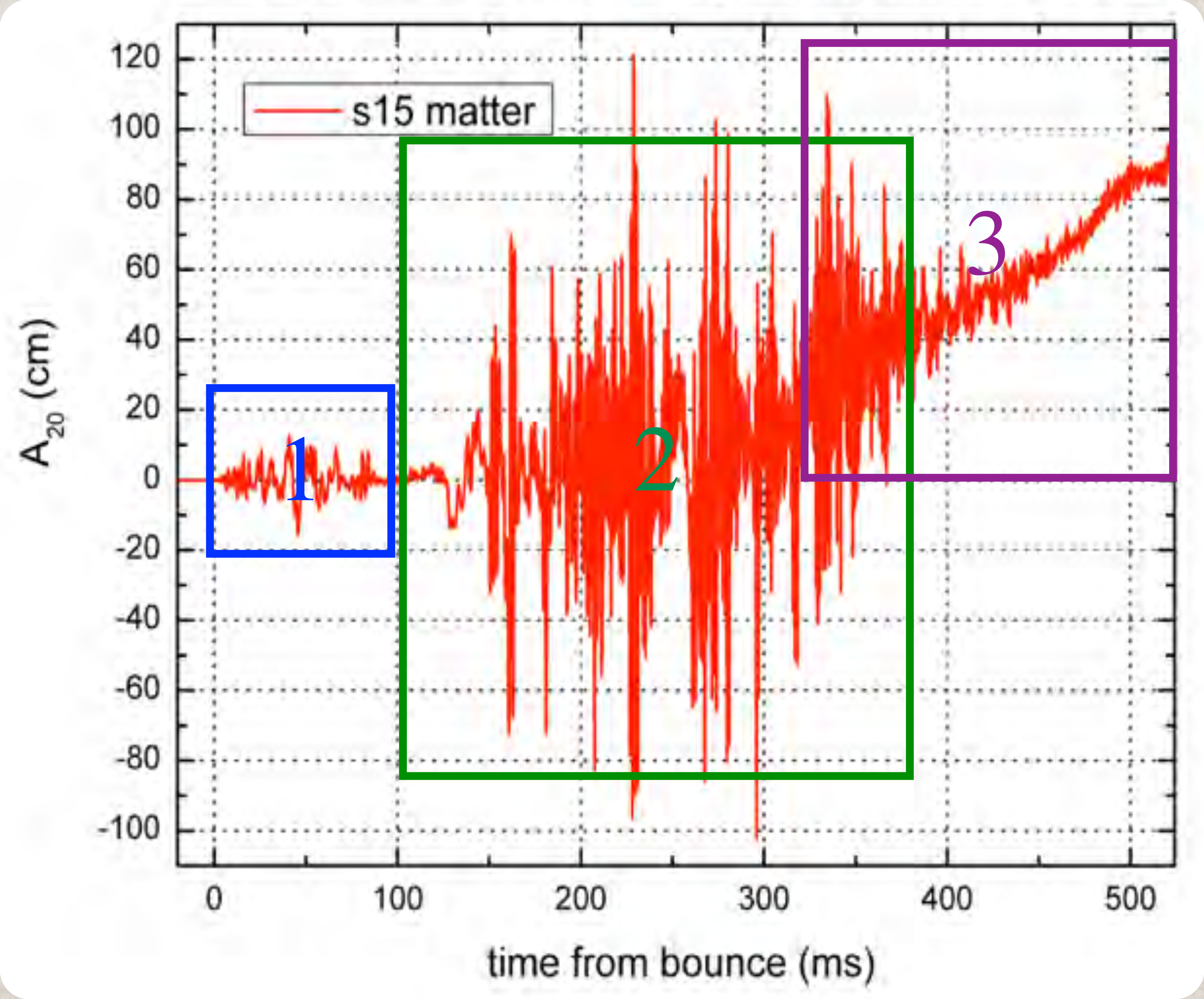
Anatomy of a GW Signal

Gravity Wave signal shows 3 separate phases

1) Prompt Convection & Early Shock Deceleration

2a) Shock Motions lead to lower-frequency envelope.

2b) Impingement of downflows on the PNS, leads to higher-frequency variations.

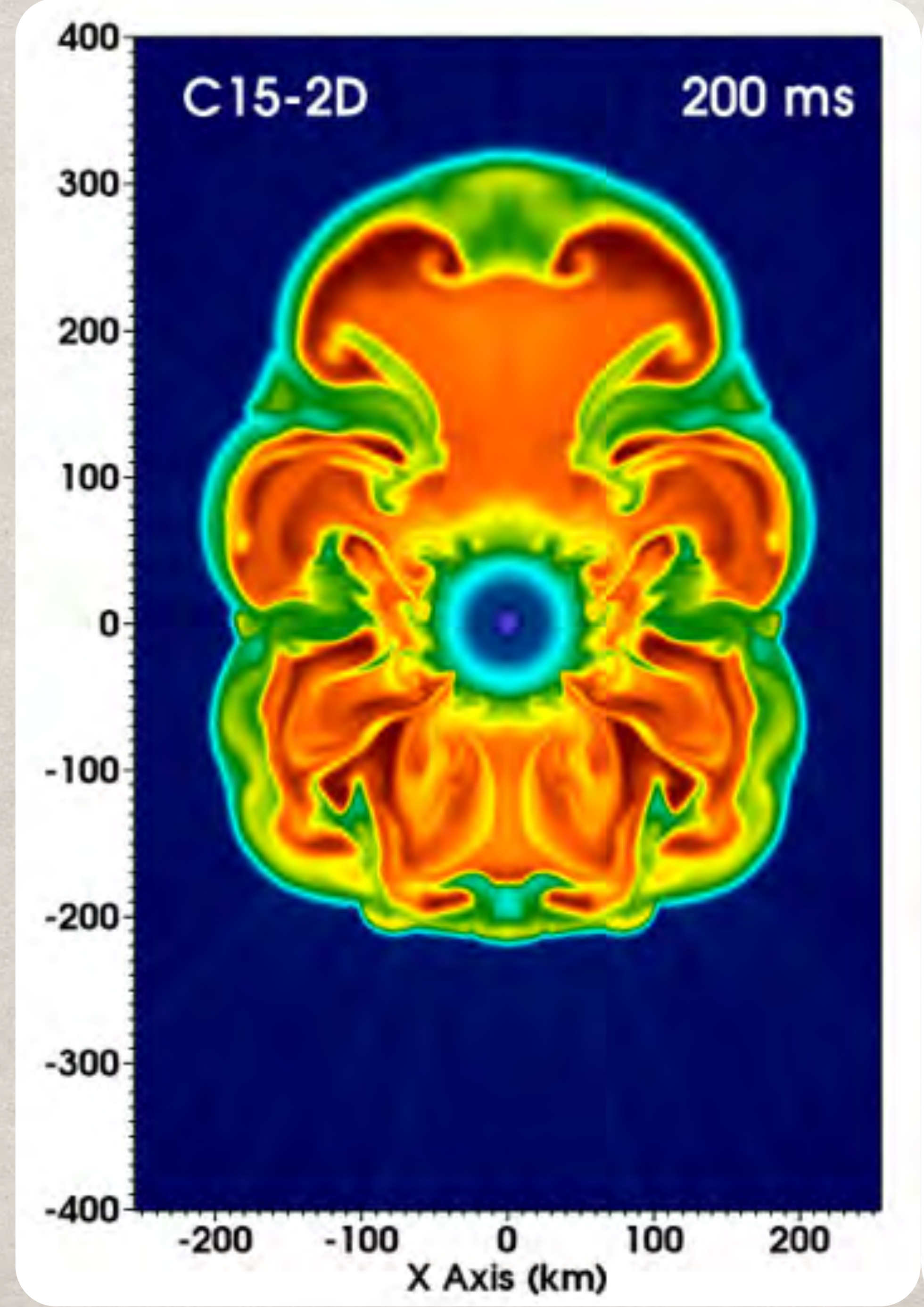


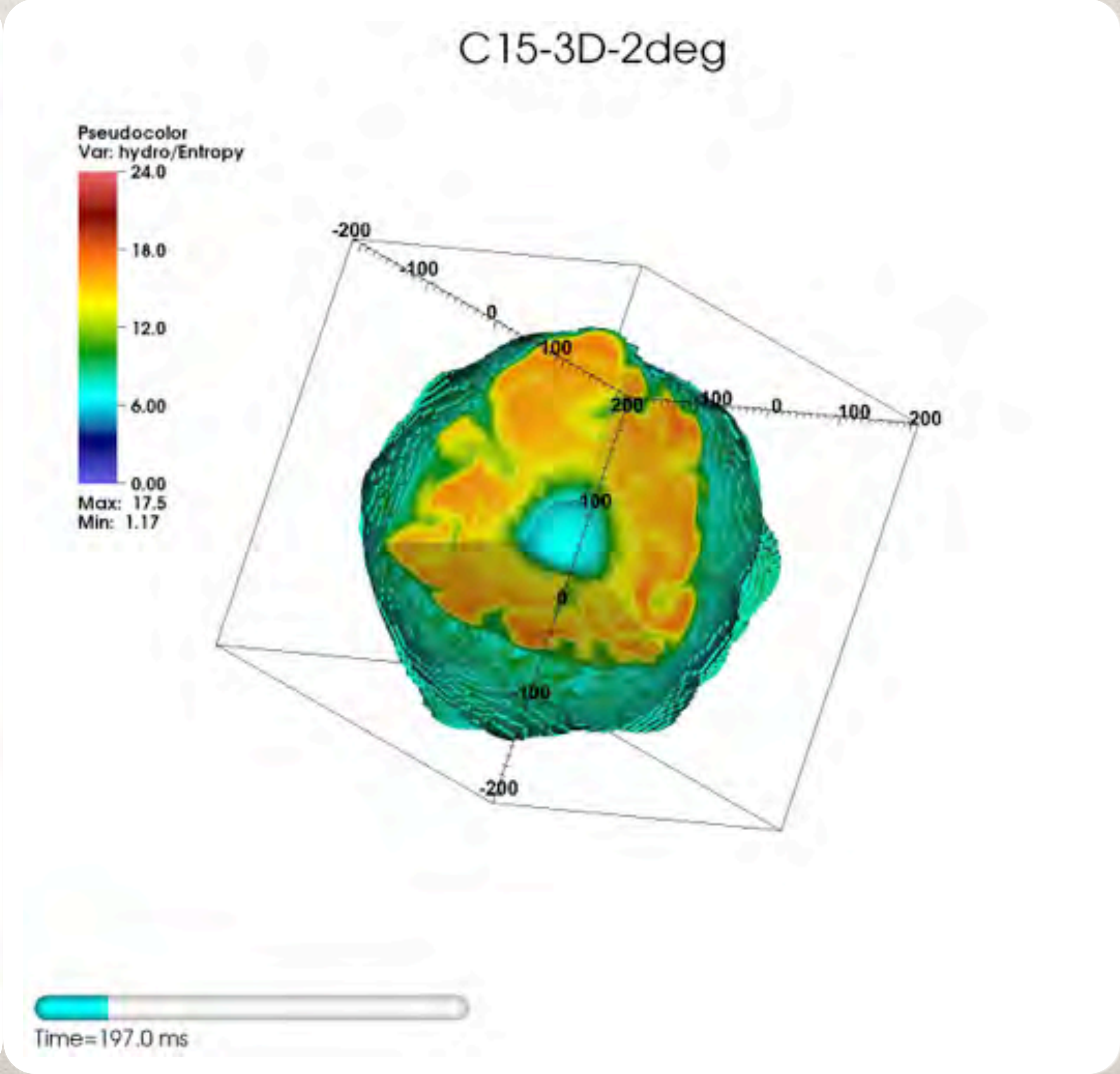
3) Prolate Explosion/Deceleration at Shock

How does 3D compare?

2D models tend to explode preferentially along the symmetry axis.

This tendency alone points to the need for 3D models, .



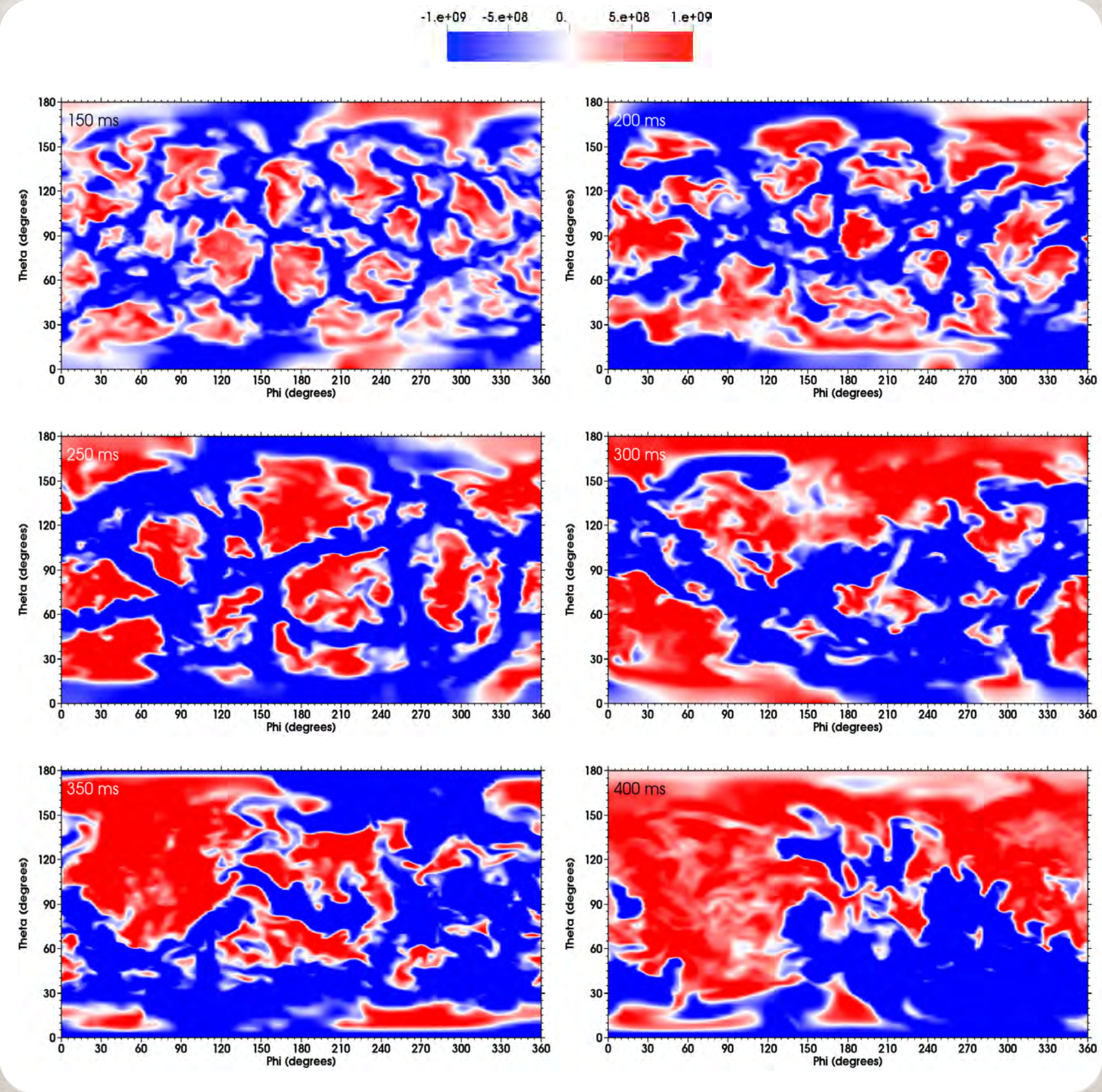


Growing Plumes

The explosion in 3D (as well as 2D) is preceded by the progress to fewer, larger plumes, see Fernandez (2015).

However, in 2D this progress is very rapid.

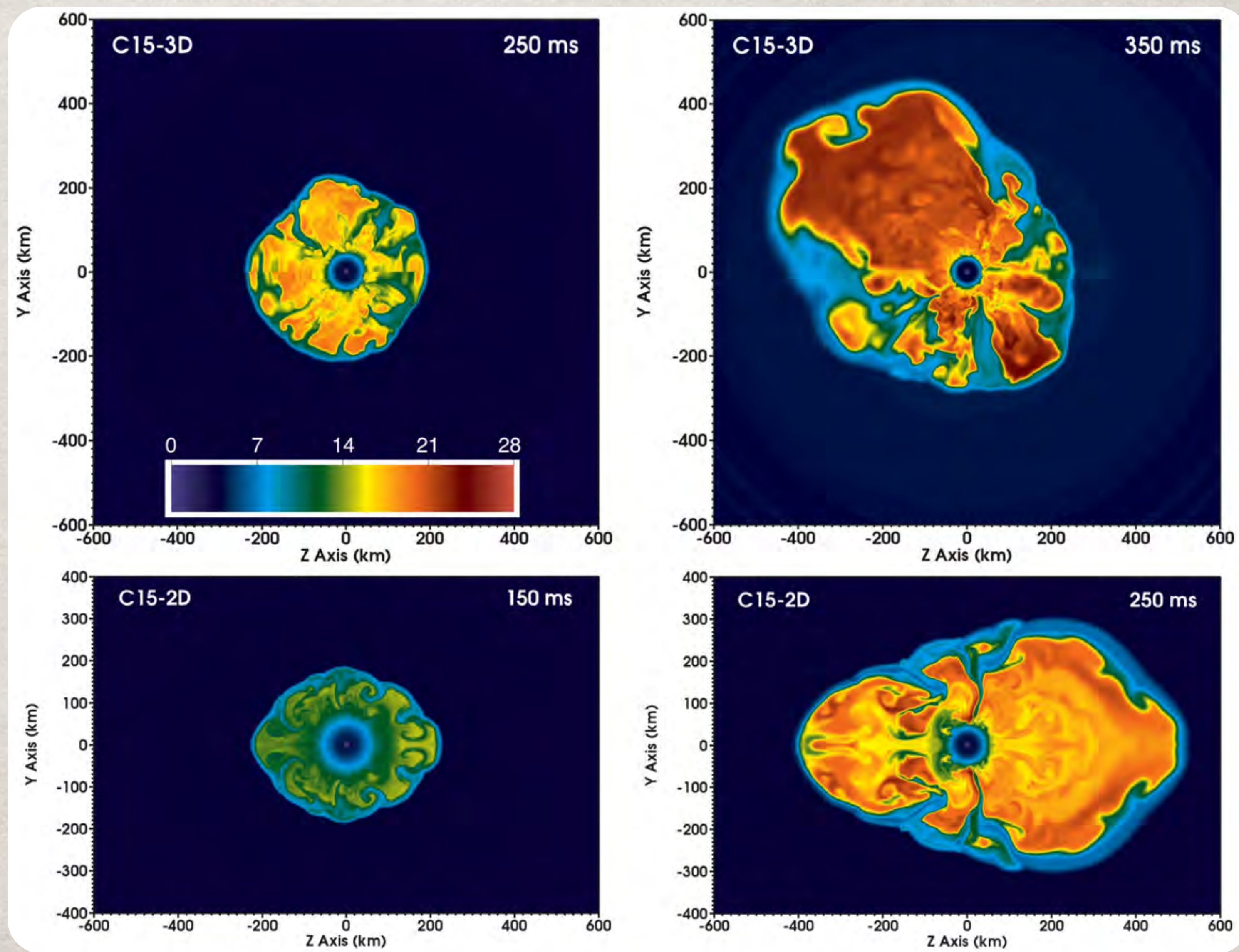
These larger plumes allow neutrino heating to do work on the shock.



Rayleigh-Taylor vs Turbulence

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.

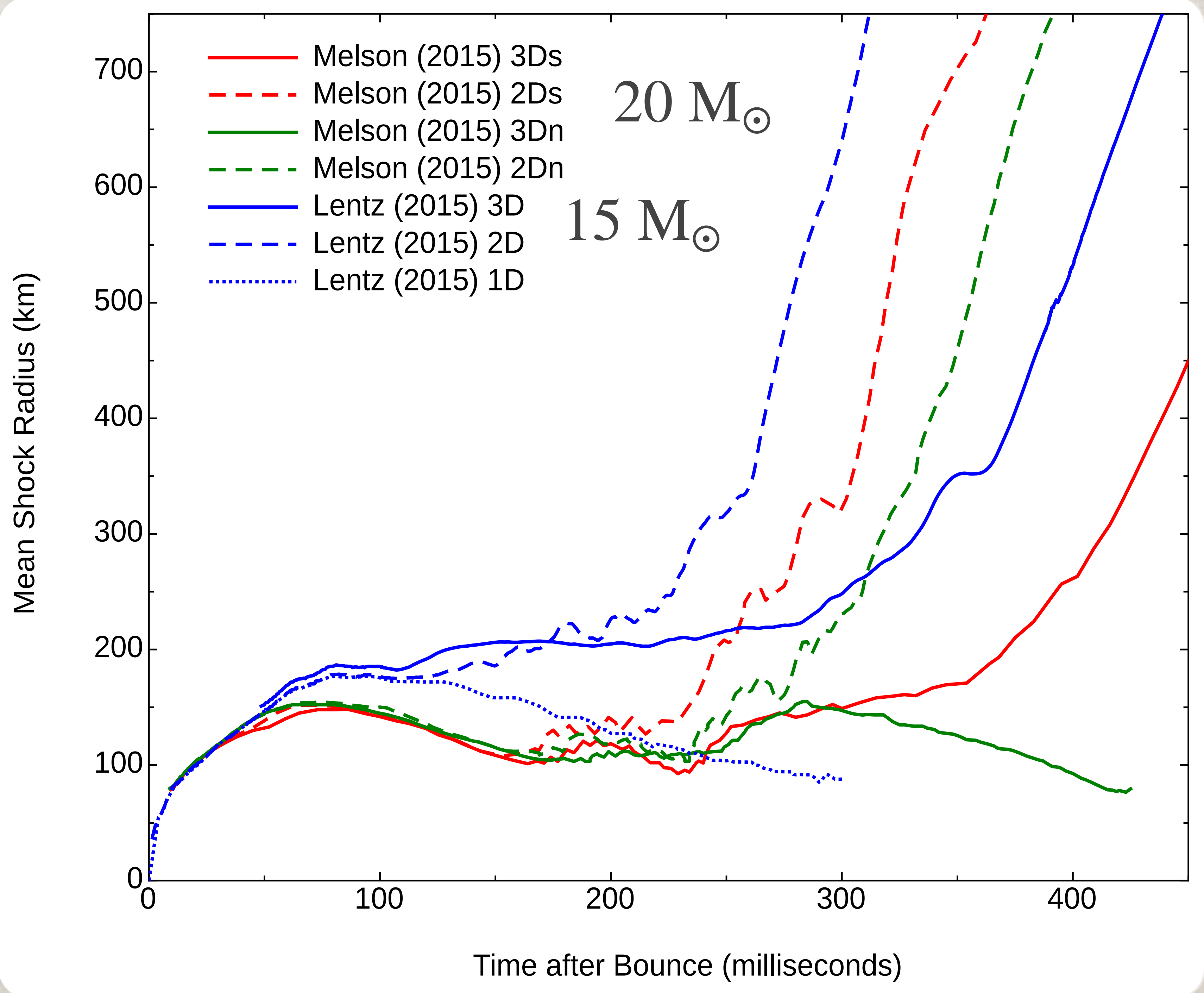
Thus in 3D, without the assistance of the cascade, R-T requires more heating, and hence more time, to develop.

3D Delays

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

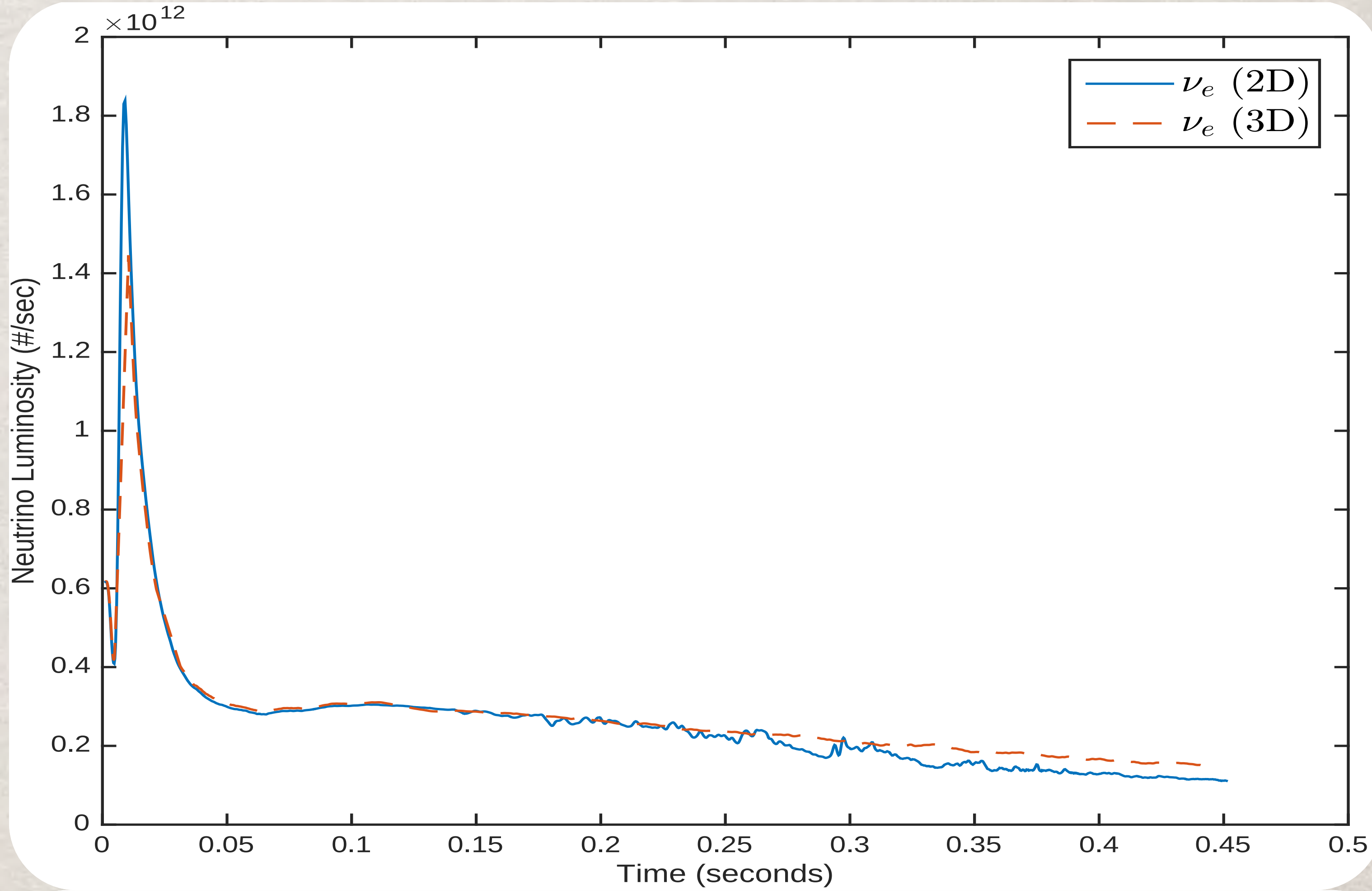
Consensus is that in 2D models the convective plumes develop too rapidly, leading to an earlier onset of explosion.

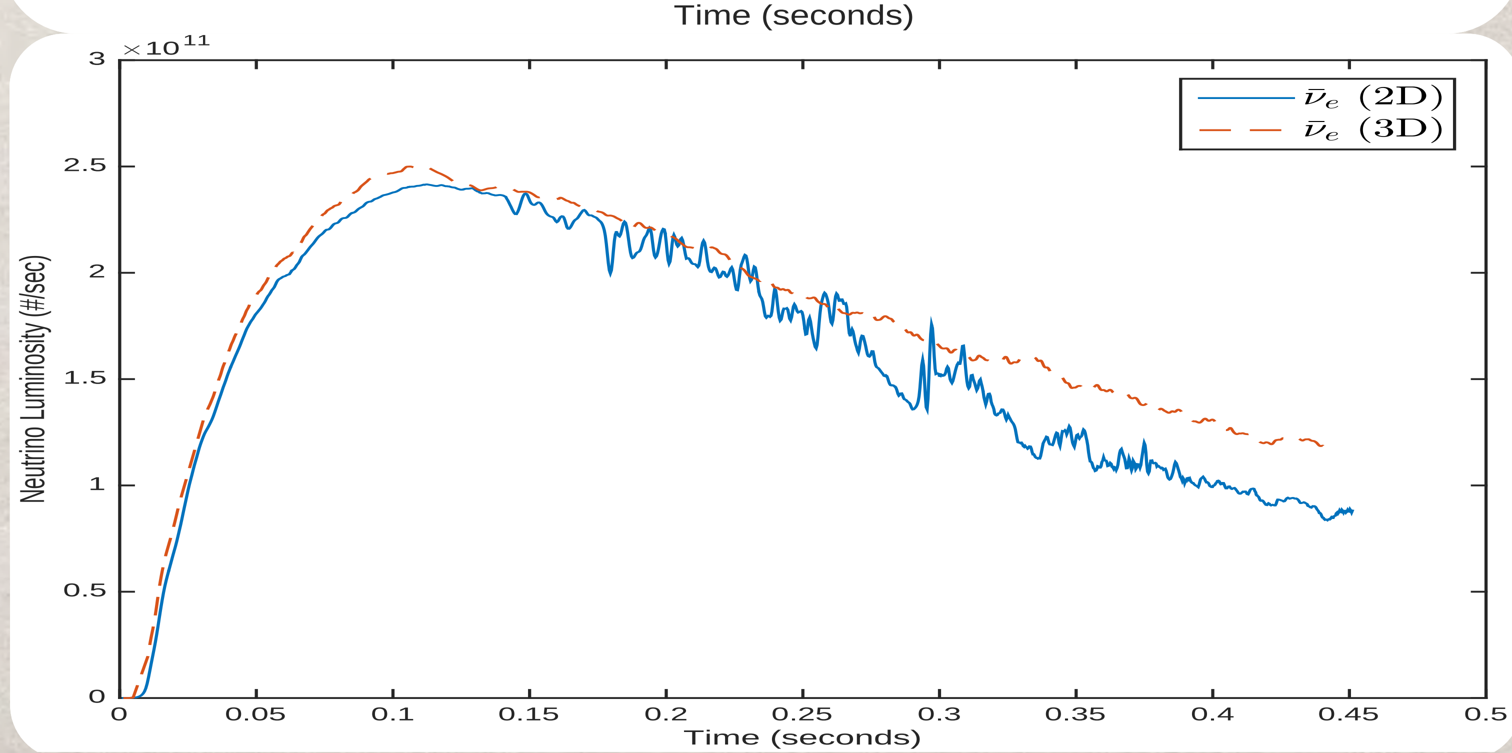
Understanding the complete effects of 3D will require models that exceed a second in supernova time.



3D (In)Variability

One fascinating difference between 2D and 3D is the strong reduction in variability in the 3D models.





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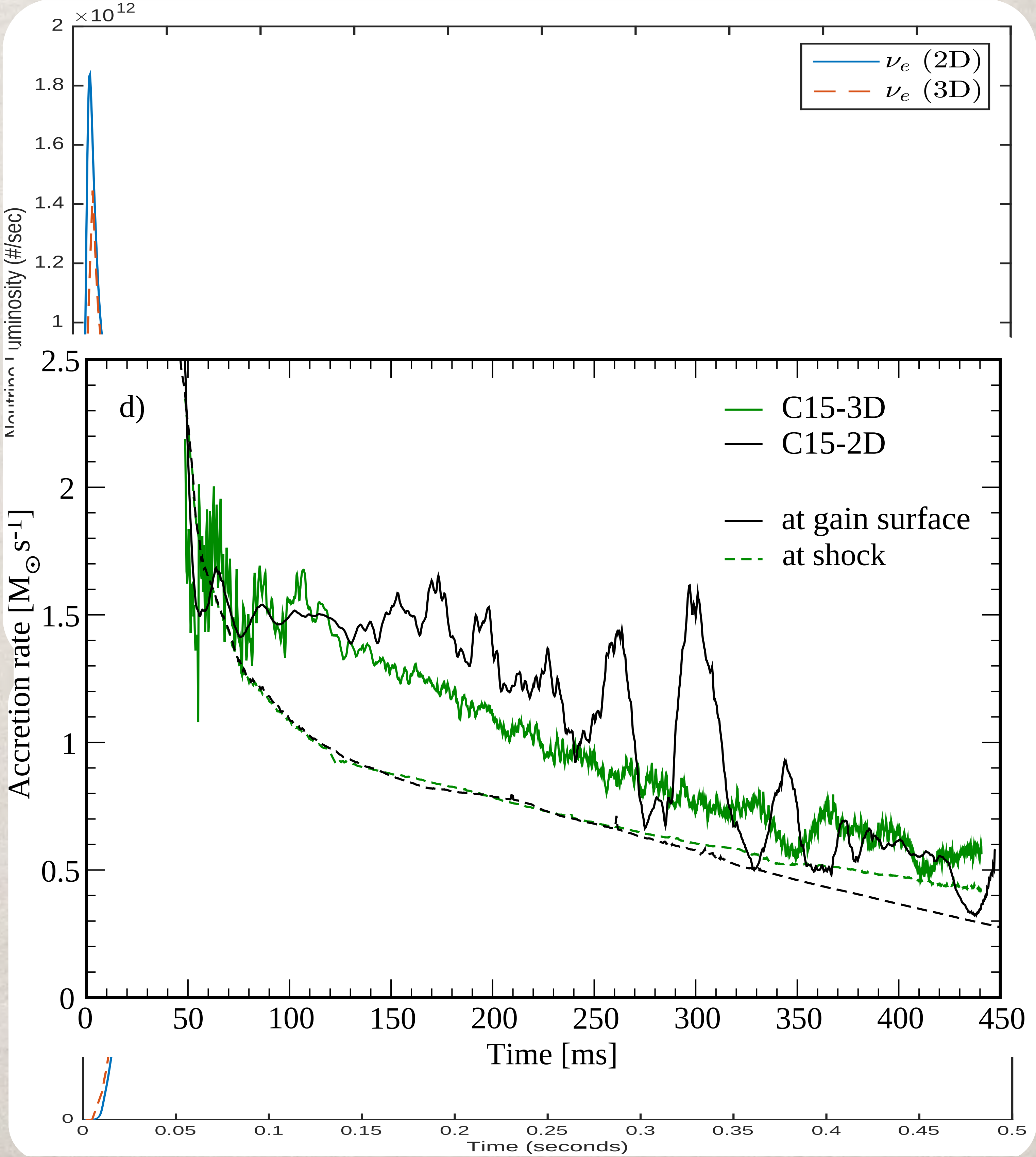
In place of the single downflow often seen in 2D, accretion in 3D flows more paths and is therefore steadier.



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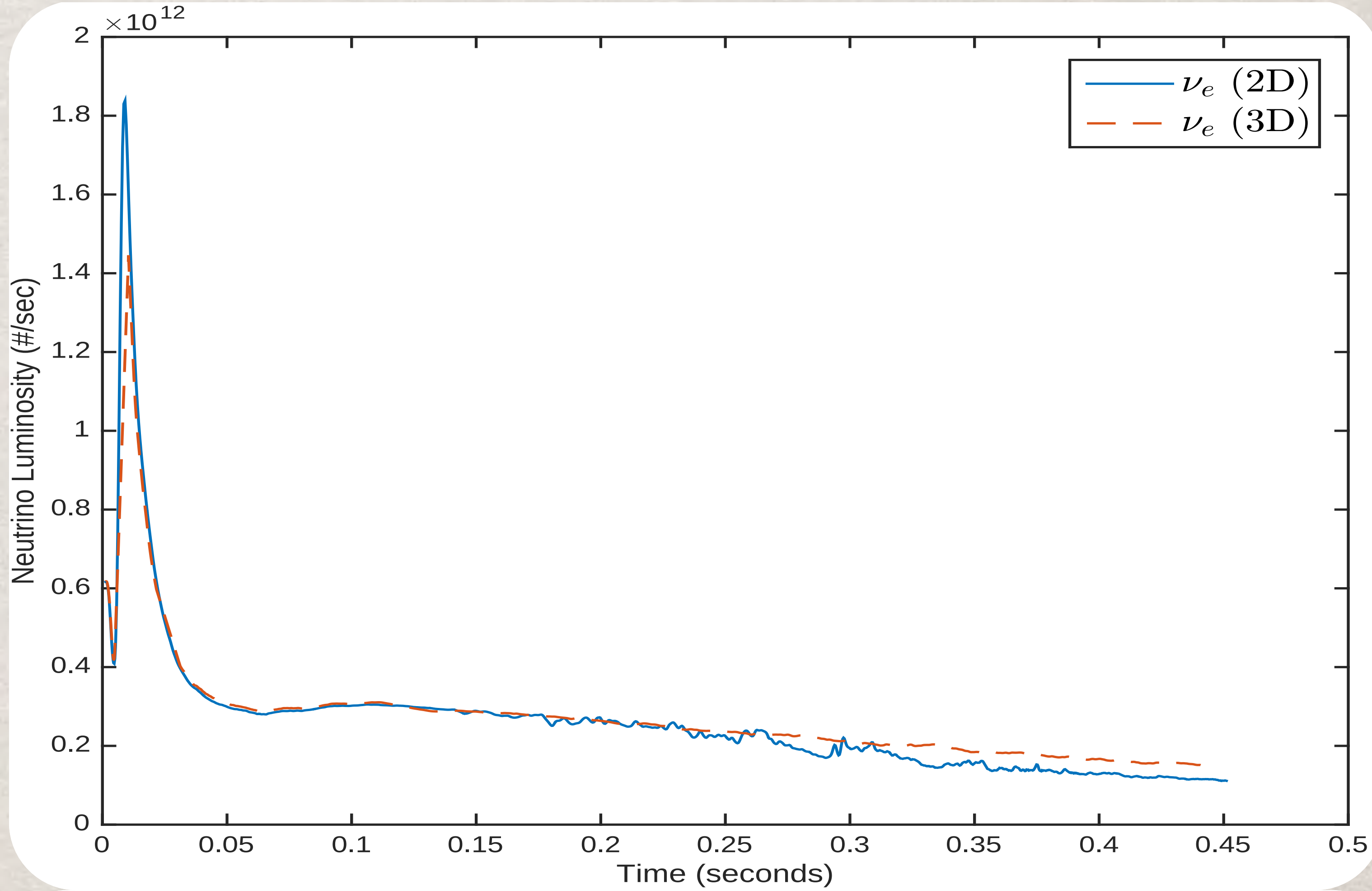
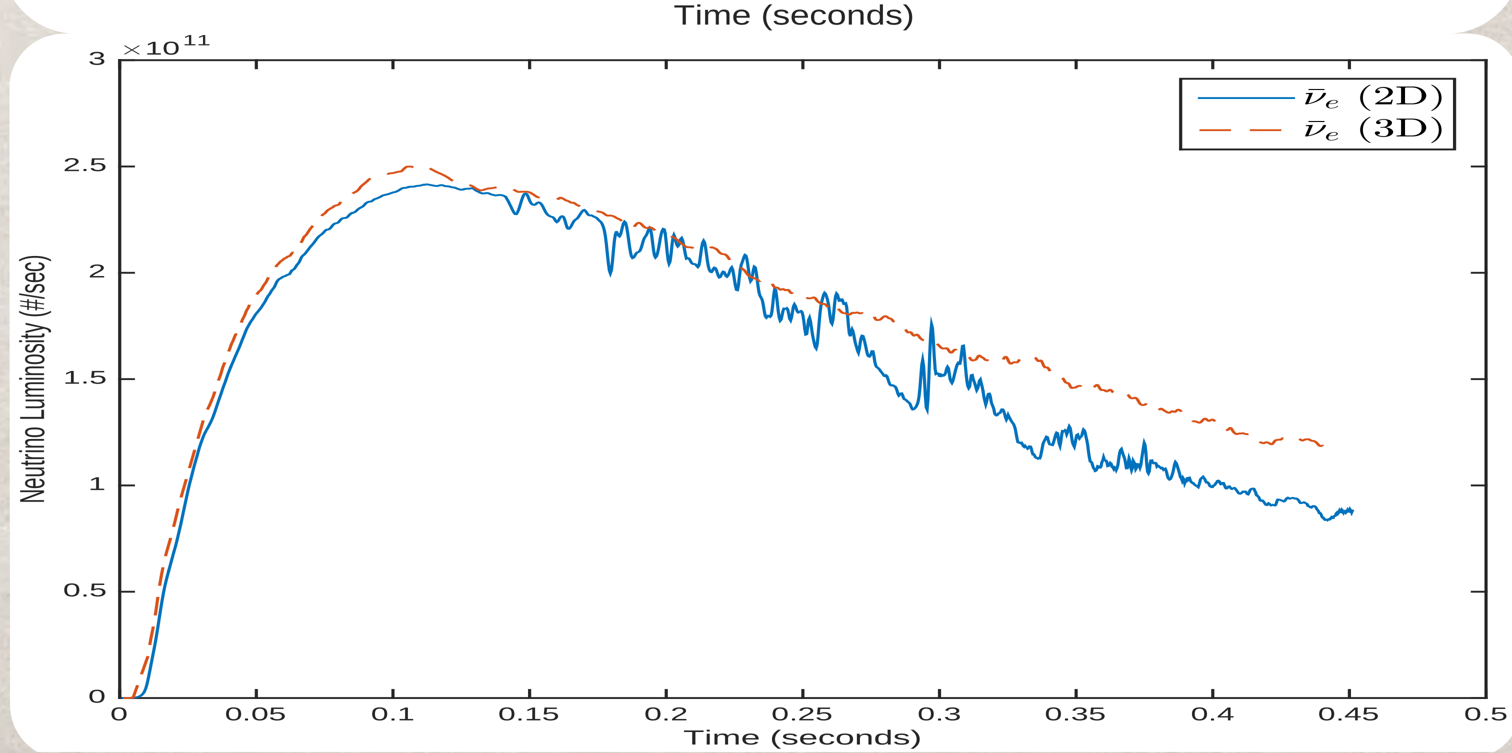
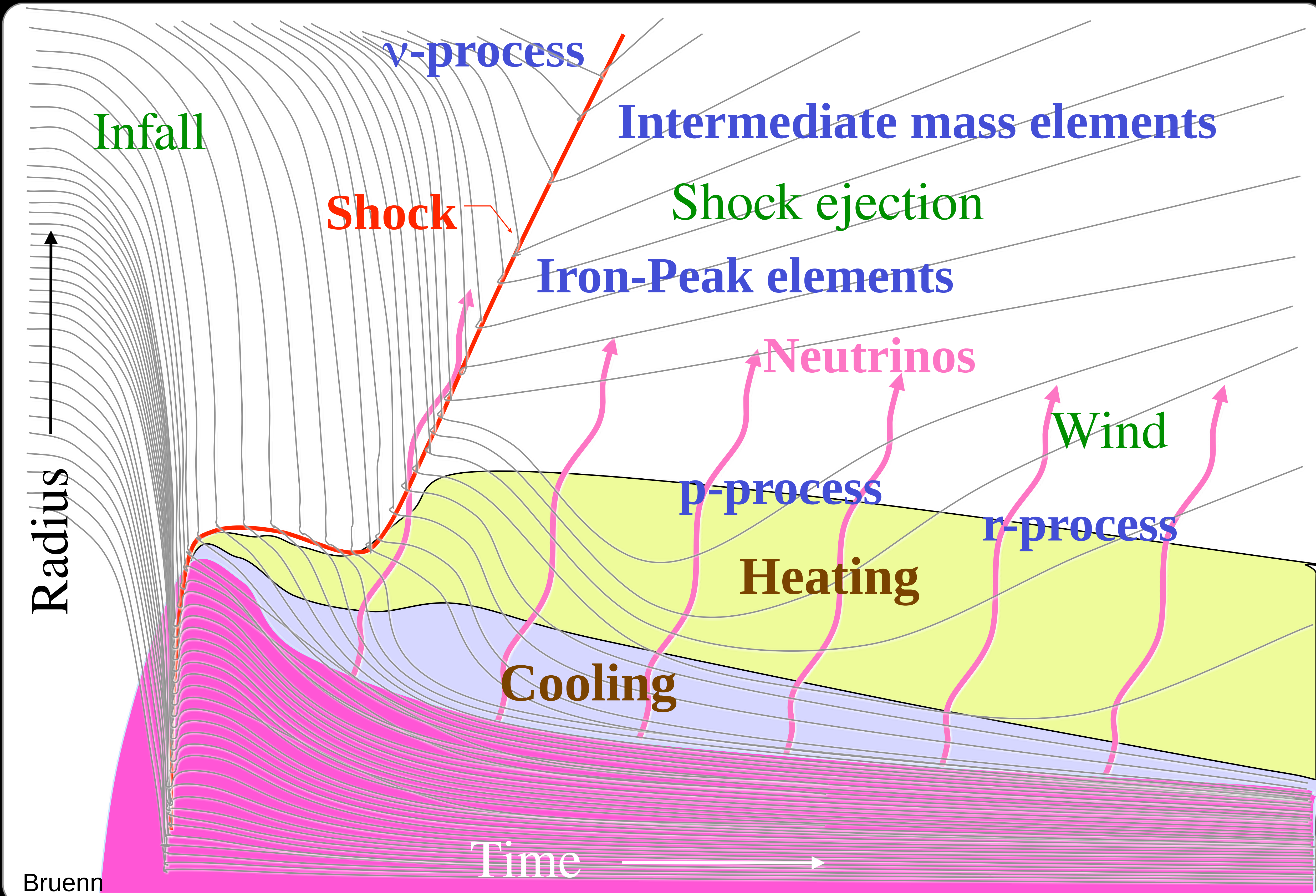
Timing of explosion is also evident in the 2D model, but less so (at least thus far) in the 3D model.

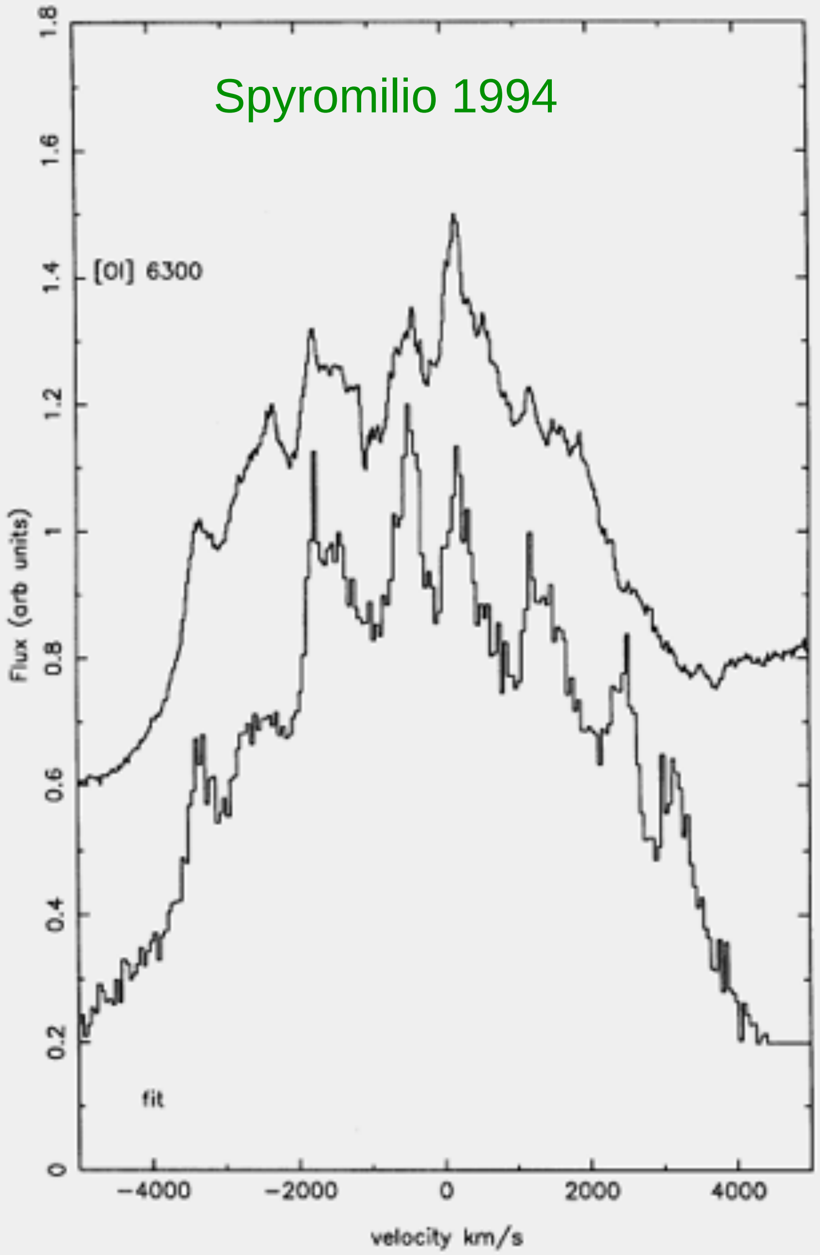


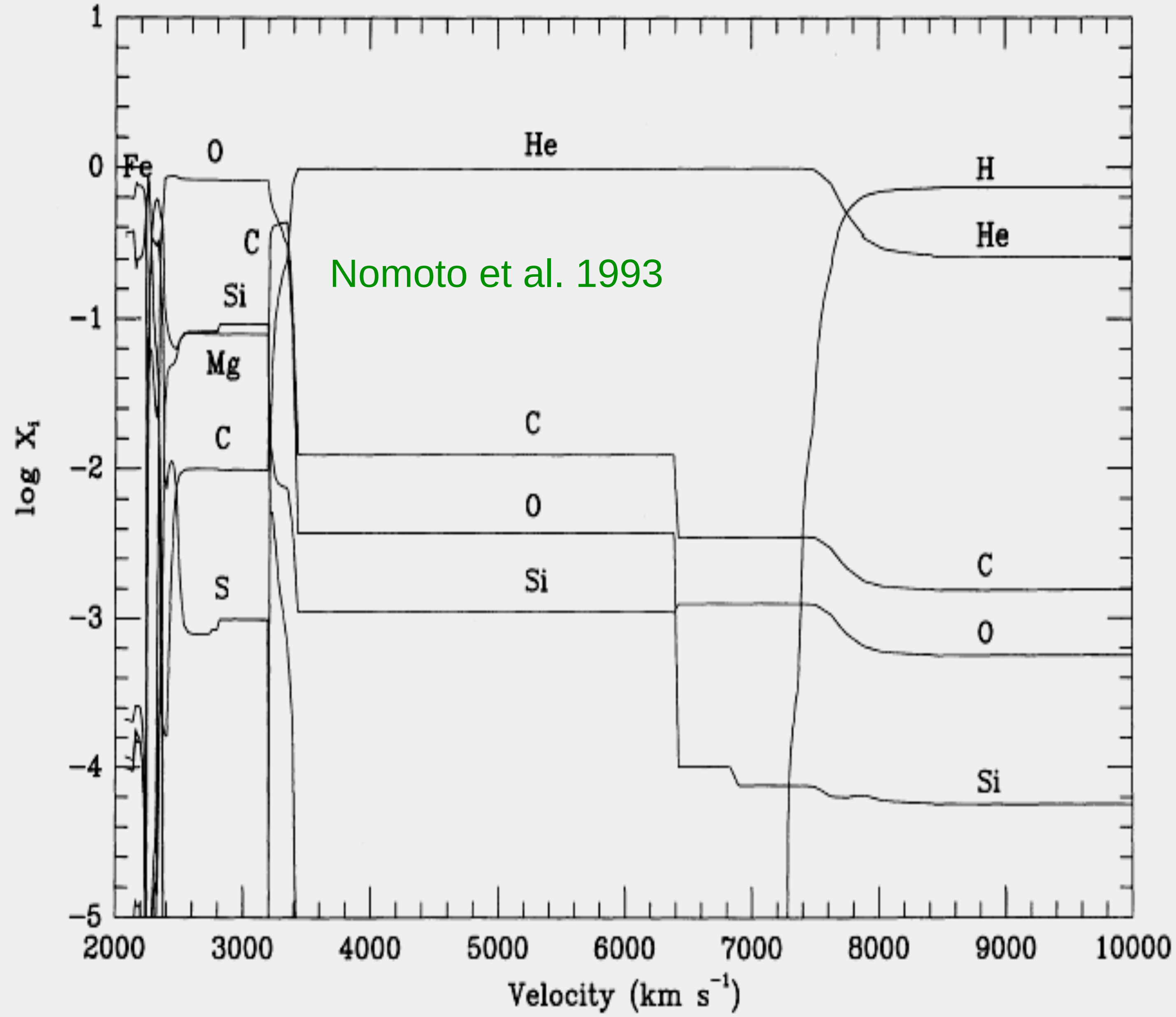


Supernova Nucleosynthesis



Tuning the Explosion





In parameterized nucleosynthesis models, 2 parameters, the Bomb/Piston energy and the mass cut, are constrained by observations of explosion energy and mass of ^{56}Ni ejected.

Unlearn the Onion

Observations tell us that the explosion, and the ejected elements, are asymmetric. Yet we rely on spherically symmetric models to understand supernova nucleosynthesis.

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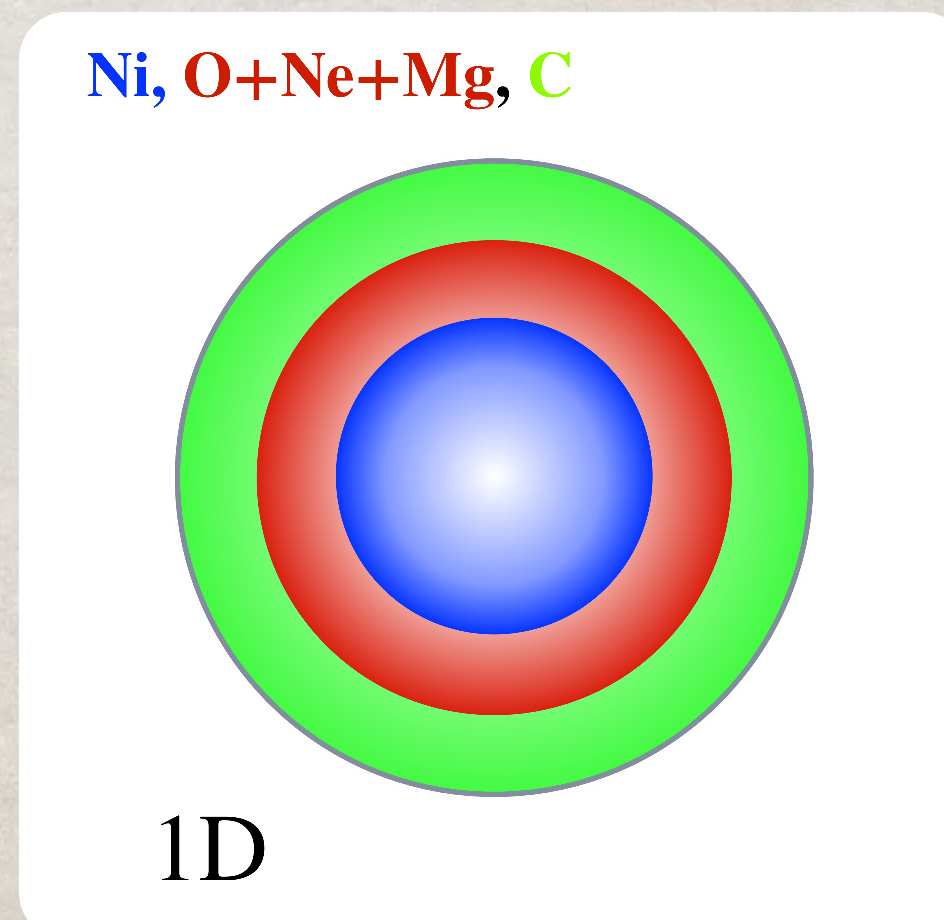

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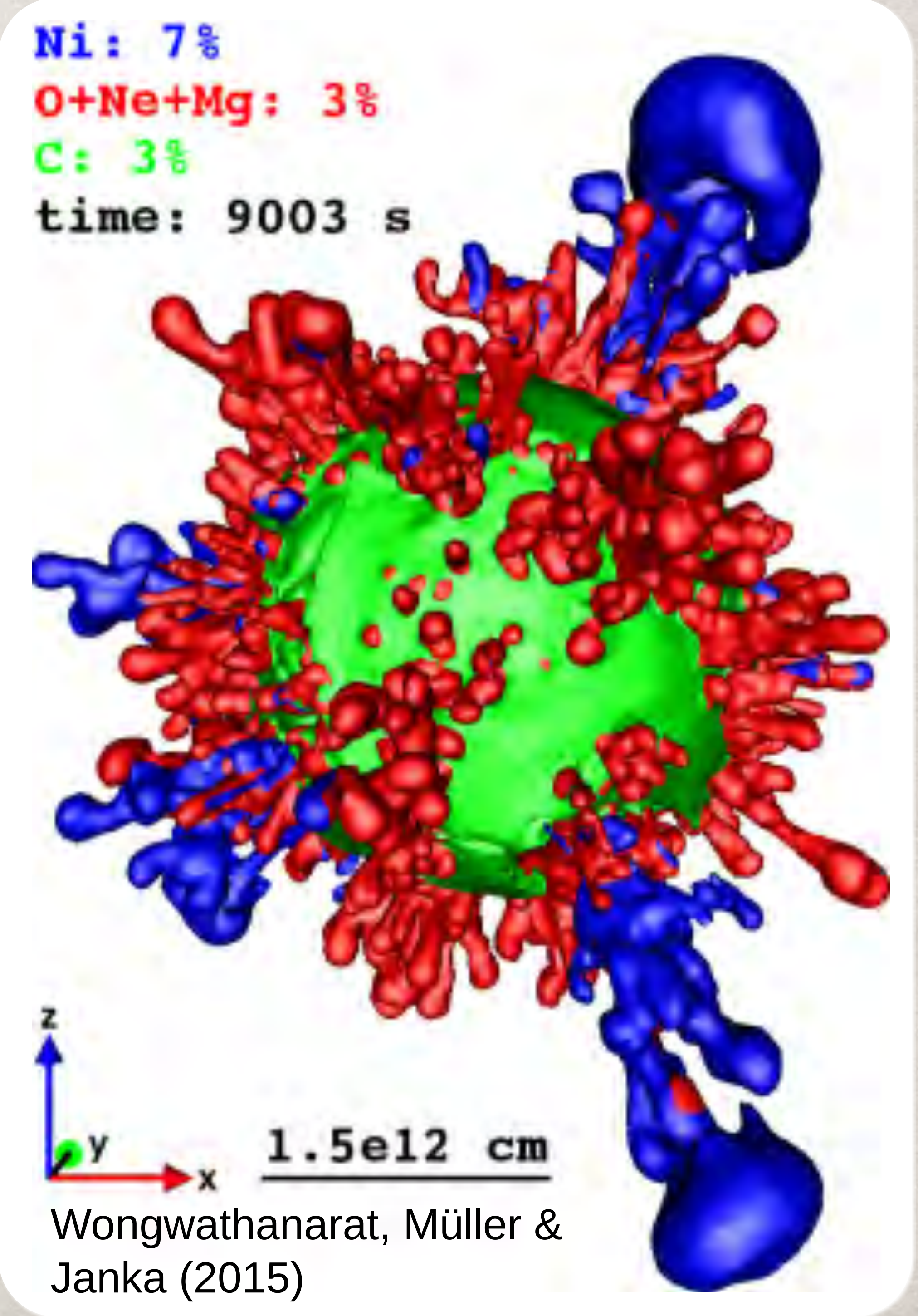
This colors our discussion, for example the notion that the matter created closest to the neutron star is most sensitive to the "mass cut".

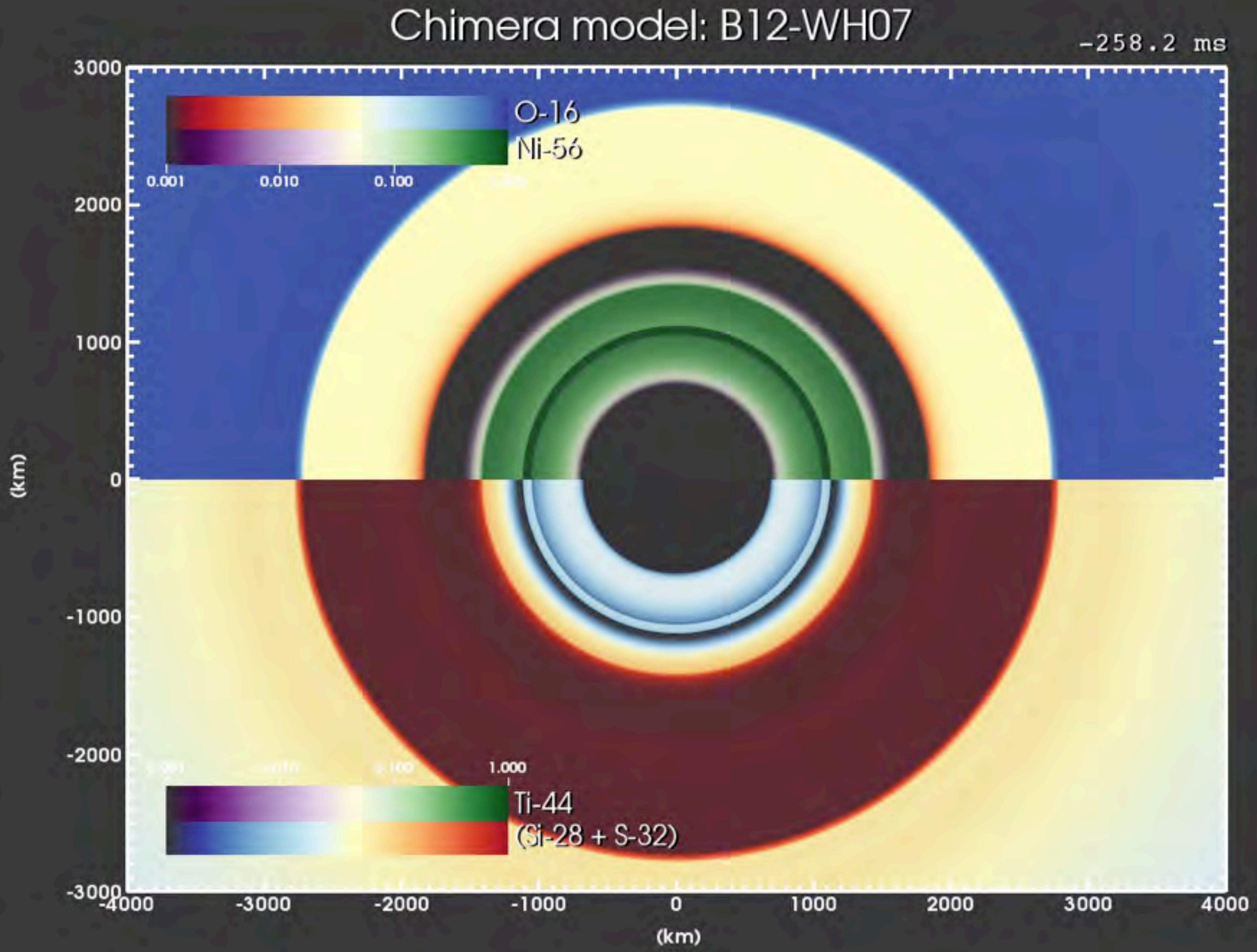
Hughes, Rakowski, Burrows & Slane 2000

? =



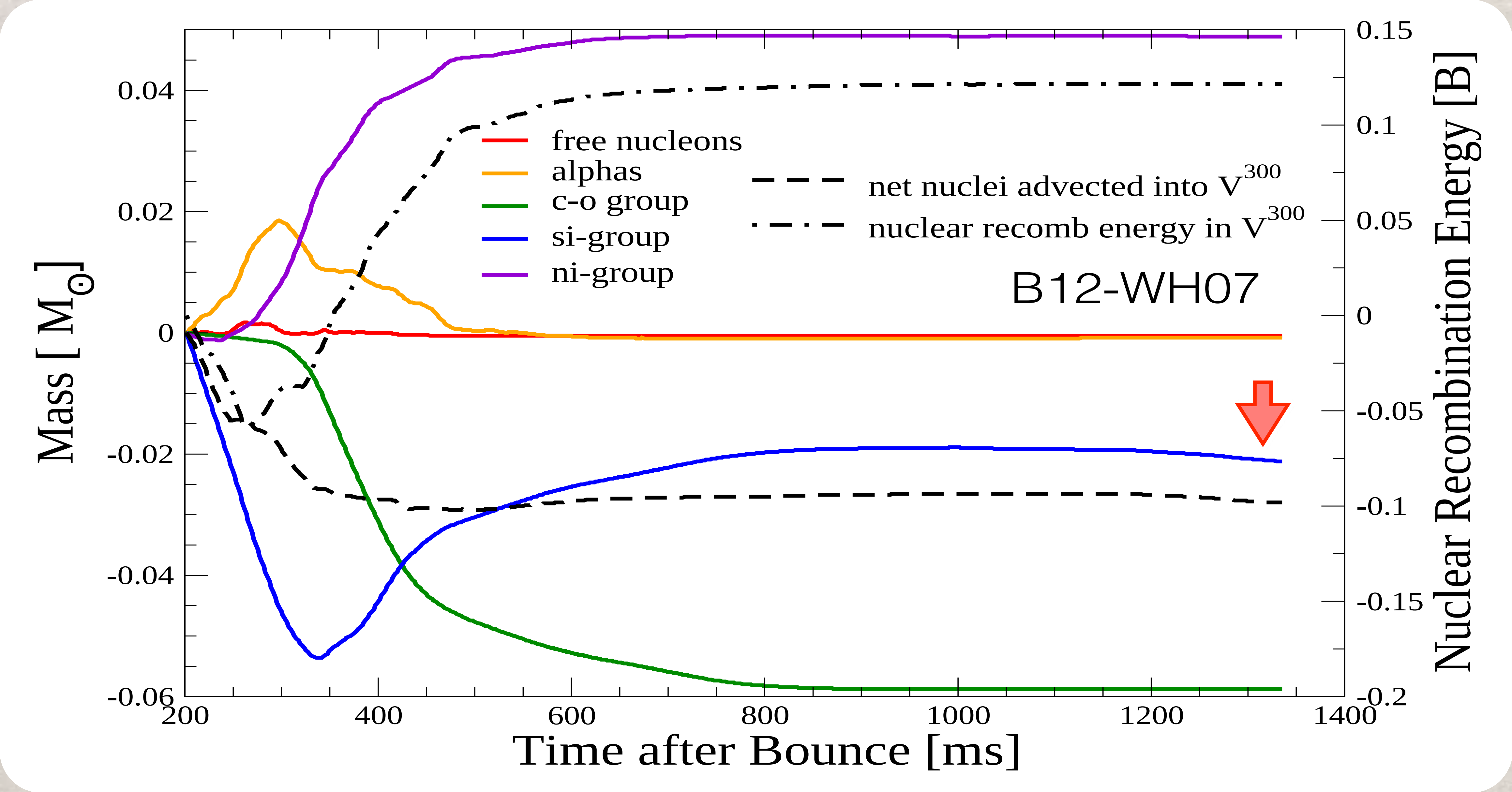
Wongwathanarat, Müller & Janka (2015)

Nucleosynthesis: the Movie



Finished Cooking?

By 800–900 ms after bounce, shock burning in the 12 $M_\odot$ model is nearly complete with shock temperature ~ 2 GK.



Matter continues to fall inward of 300 km beyond one second, predominantly from cut-off down flows.

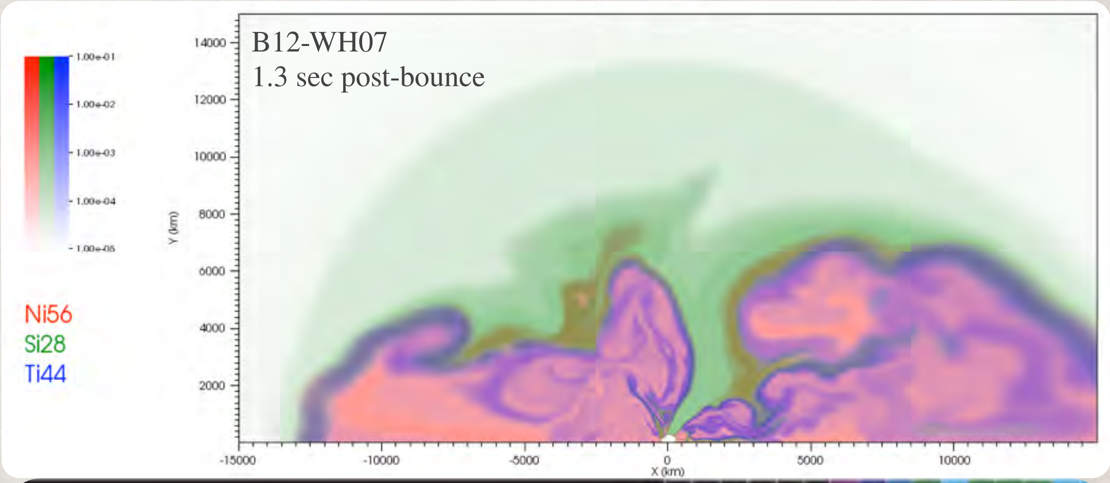
Nucleosynthesis Limits

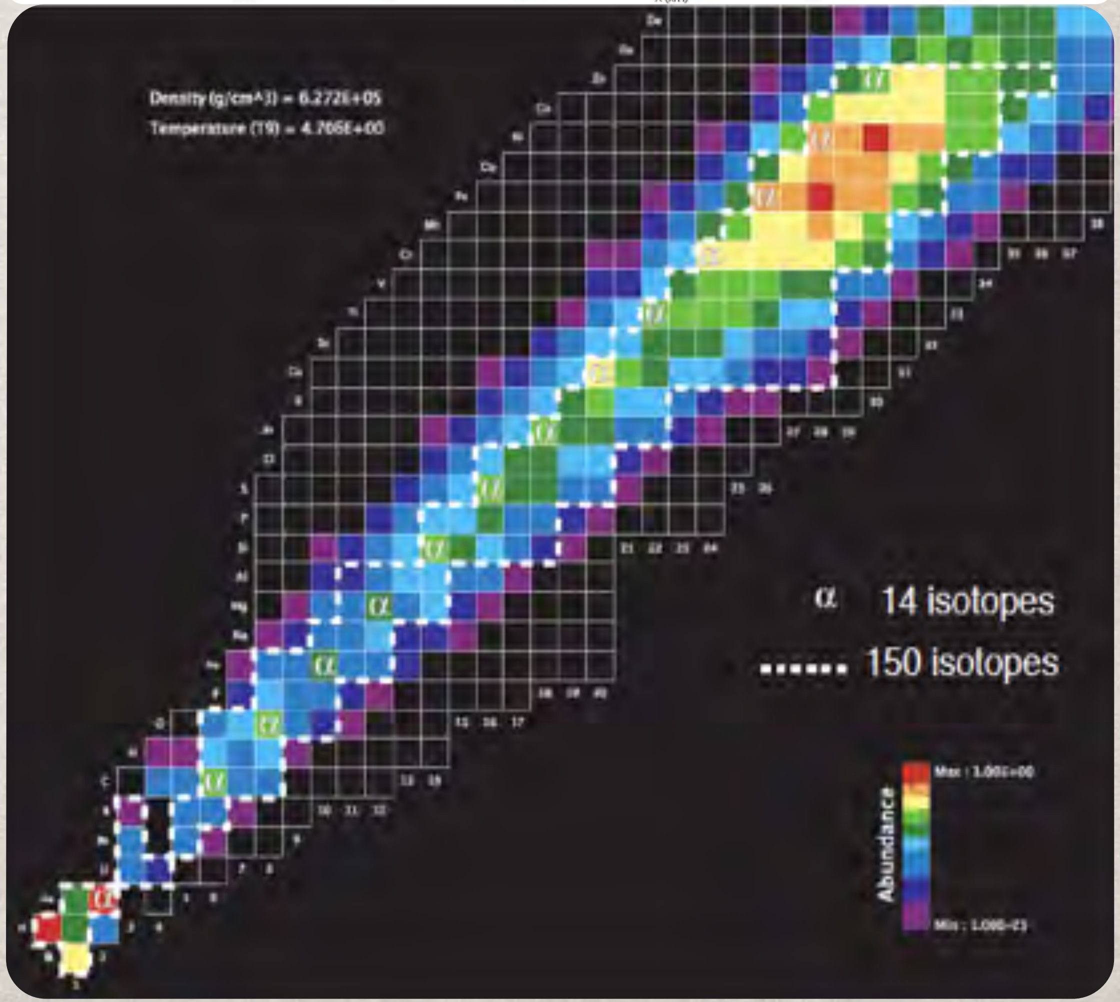
We can calculate nucleosynthesis directly with the α-network (plus neutrons, protons and auxiliary heavy) in CHIMERA.

As the mass cut resolves, we can examine the nucleosynthesis with increasing accuracy.

But parameterized models consider hundreds (or even thousands) of species within the supernova simulation.

Doing the same in CHIMERA requires post-processing of Lagrangian tracer particles, or using a larger network within the supernova models.

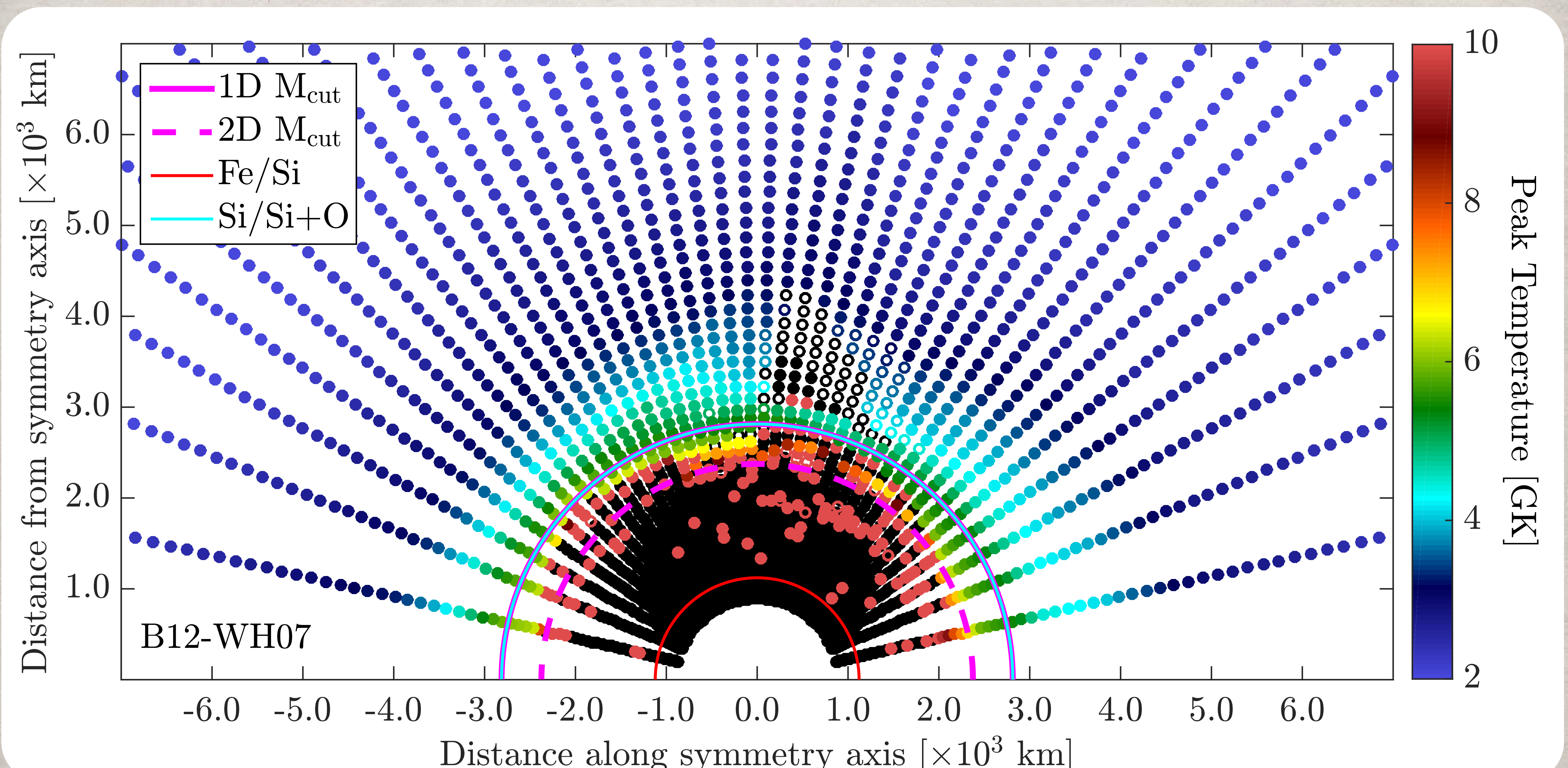




Tracing the Mass Cut

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.



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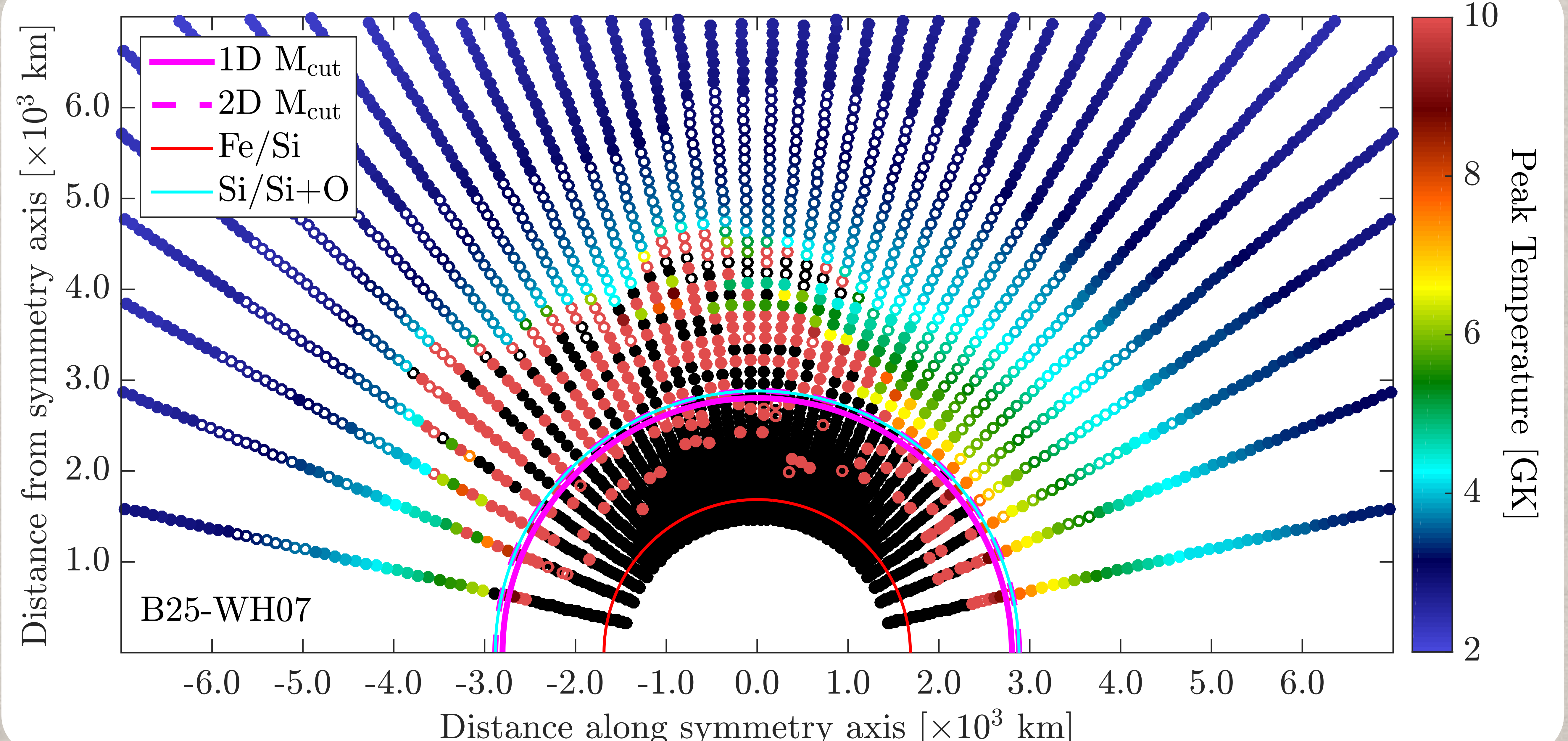
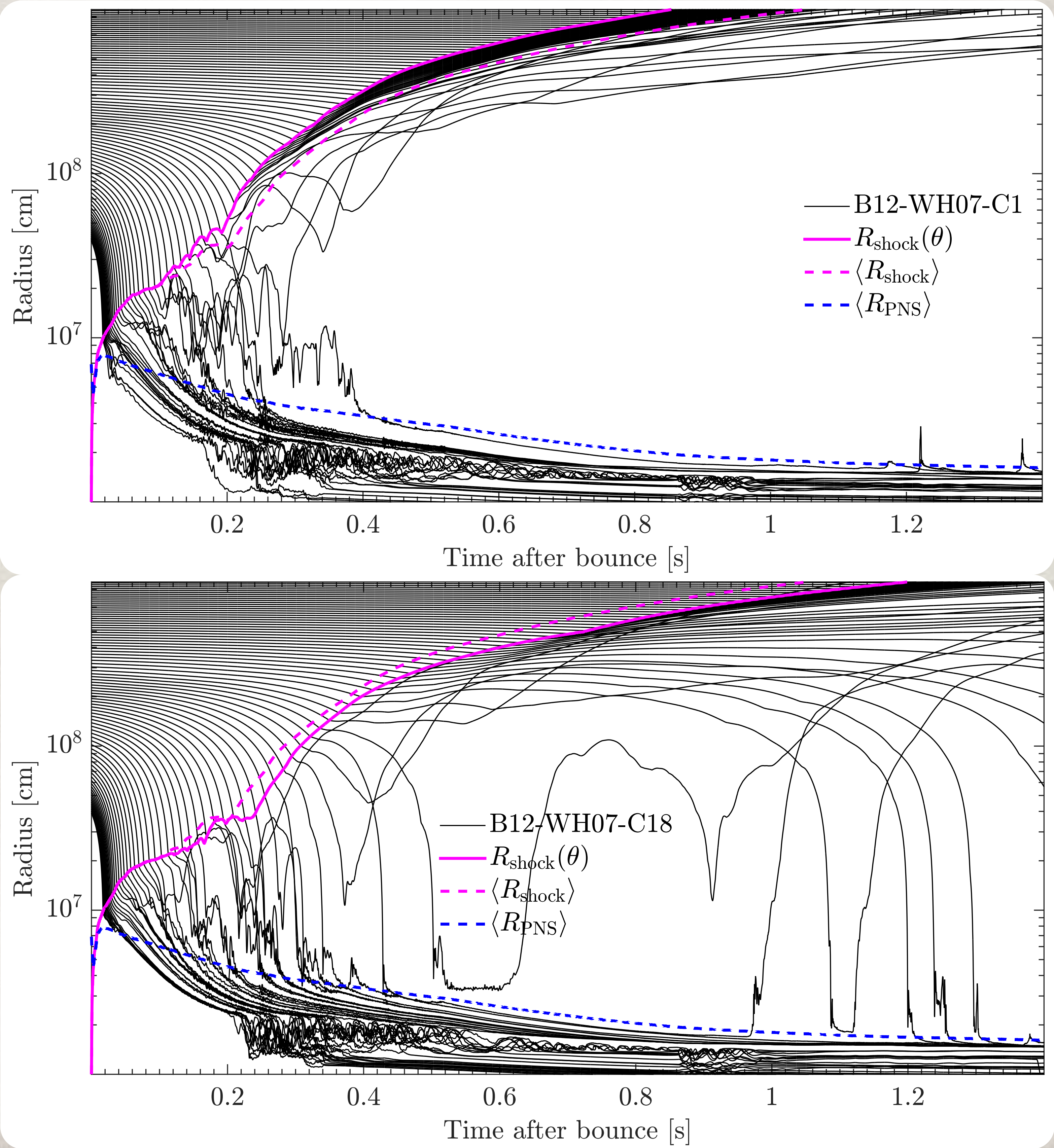


Latitude Dependence

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

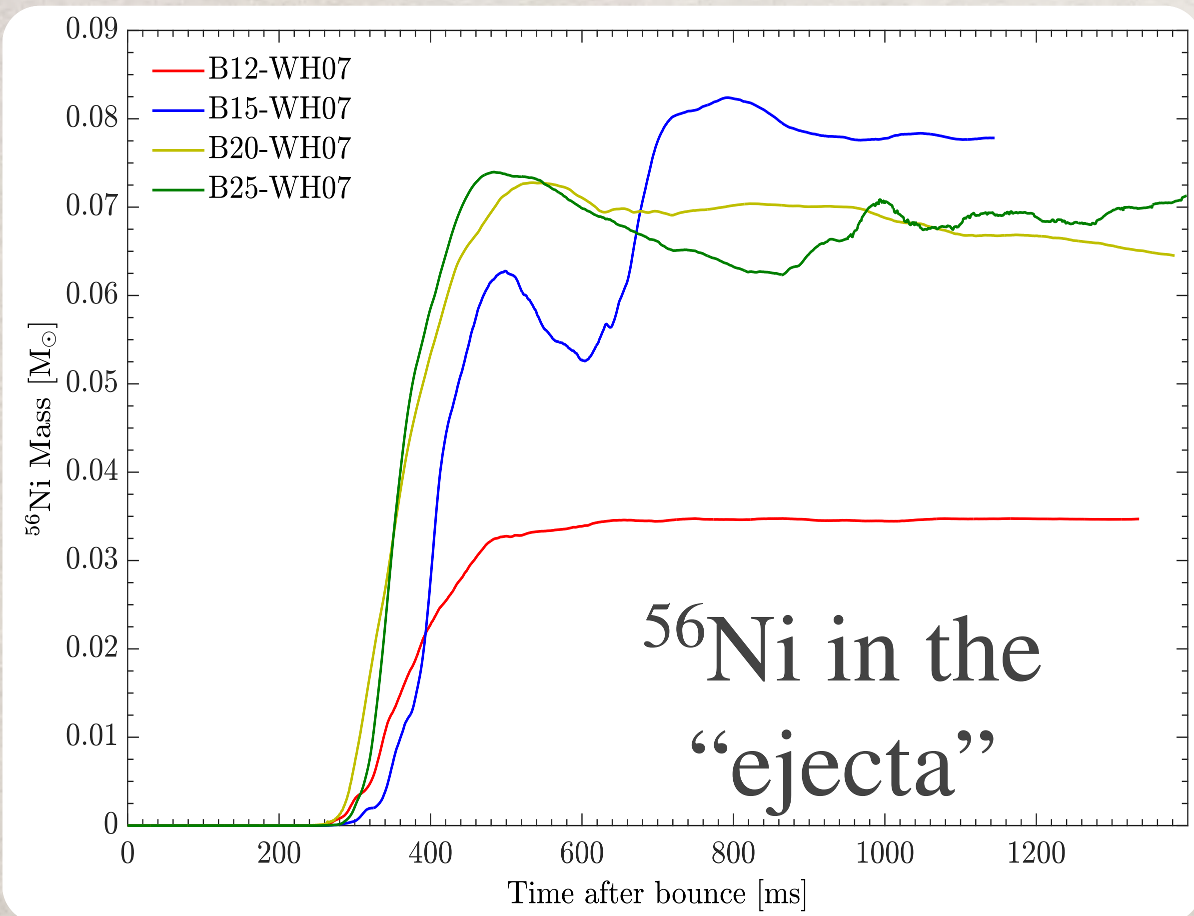
Near the pole, separation between ejecta and PNS develops rapidly and robustly.

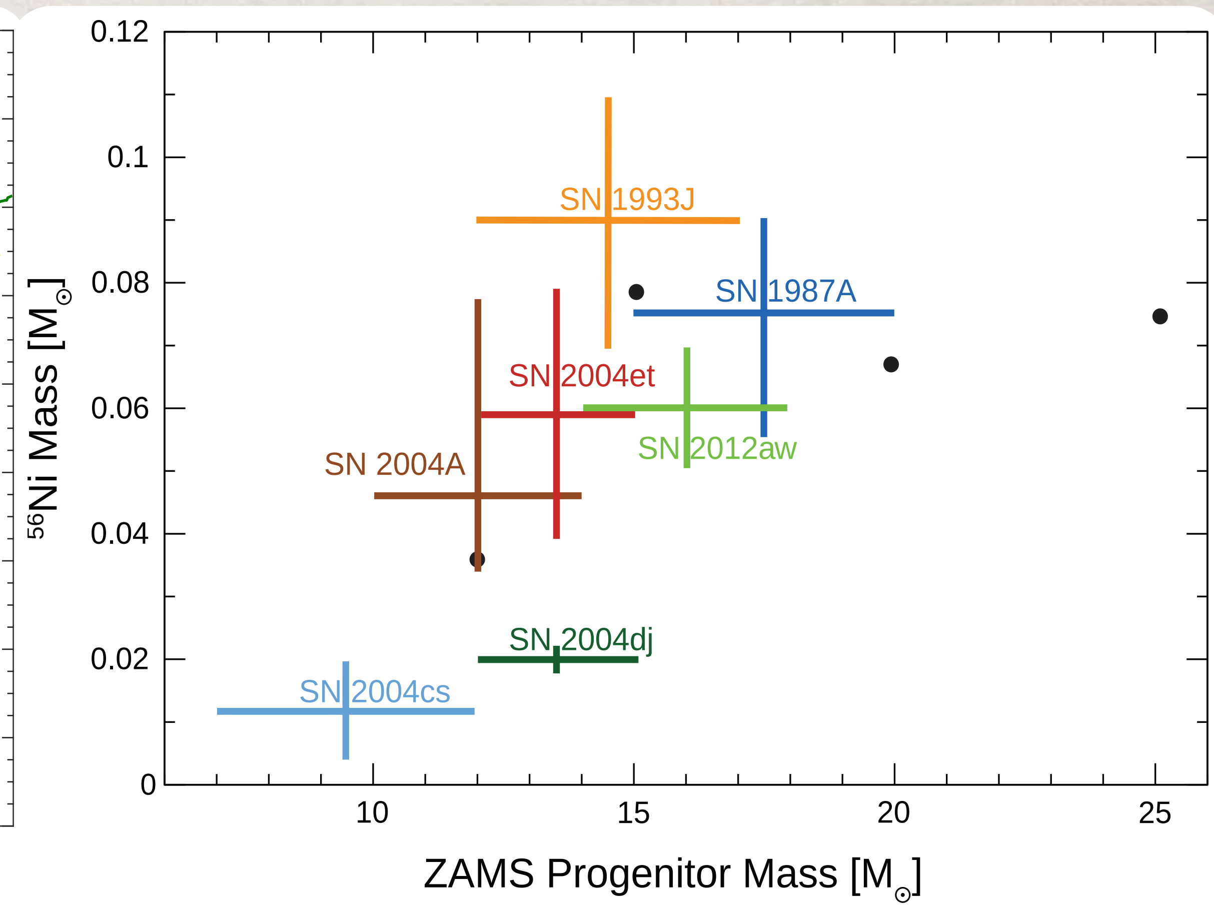
Matter from near the equator continues to accrete and be ejected through the end of the simulations.



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.





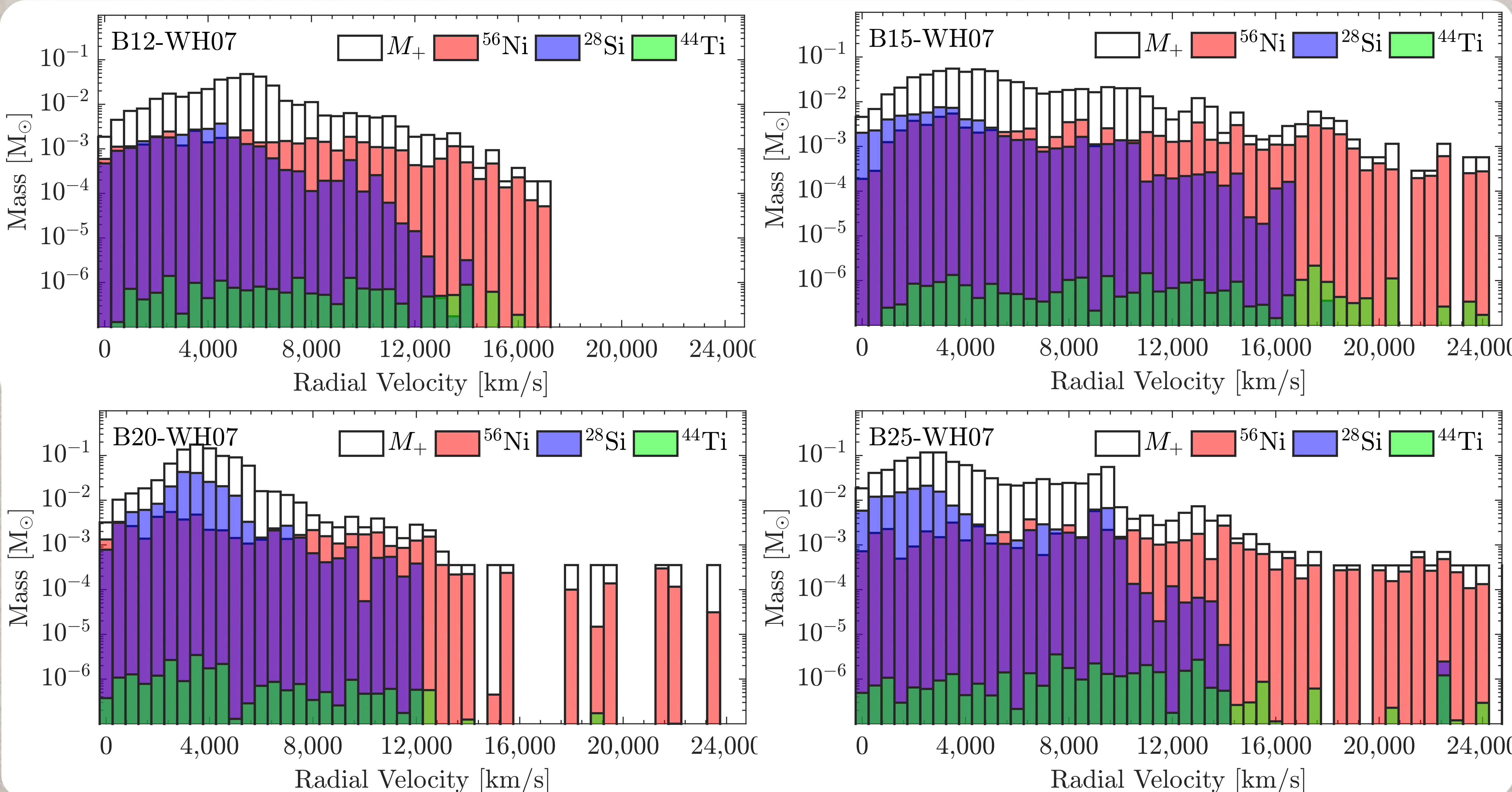
The ejected ^{56}Ni mass saturates in time with the explosion energy.

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.

Velocity Distribution

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

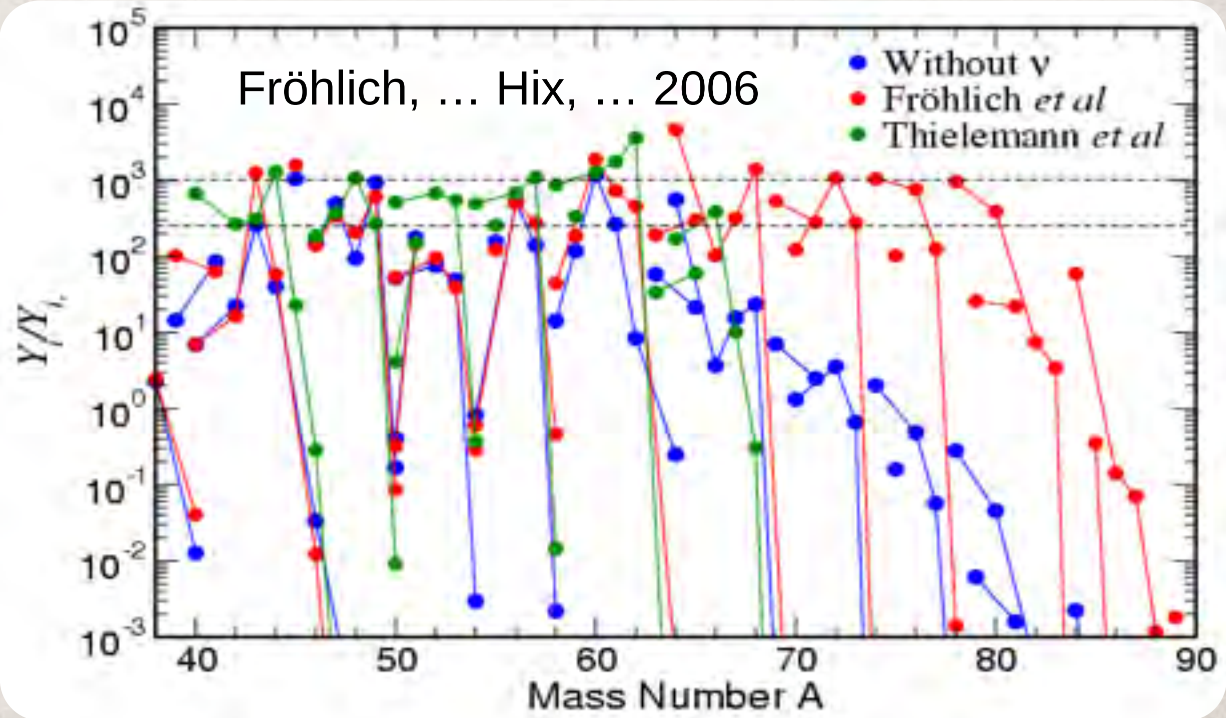


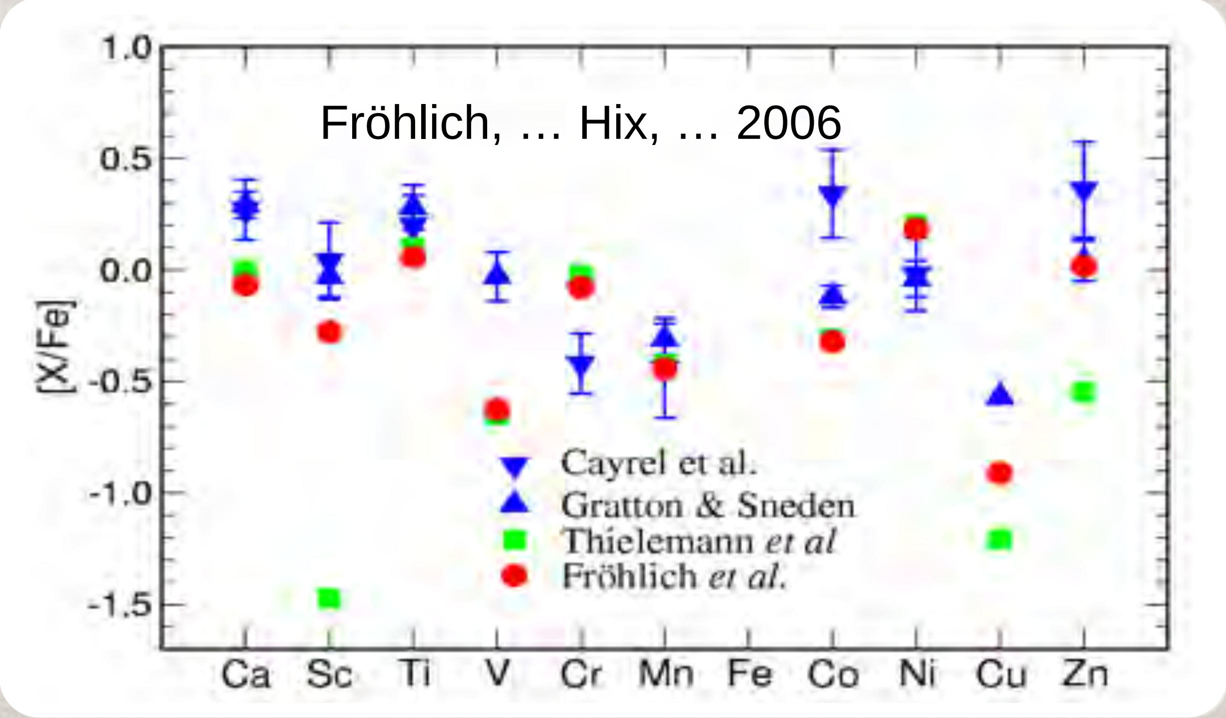
Neutrinos & Nucleosynthesis

Despite the perceived importance of neutrinos to the core collapse mechanism, models of the nucleosynthesis have largely ignored this important effect.

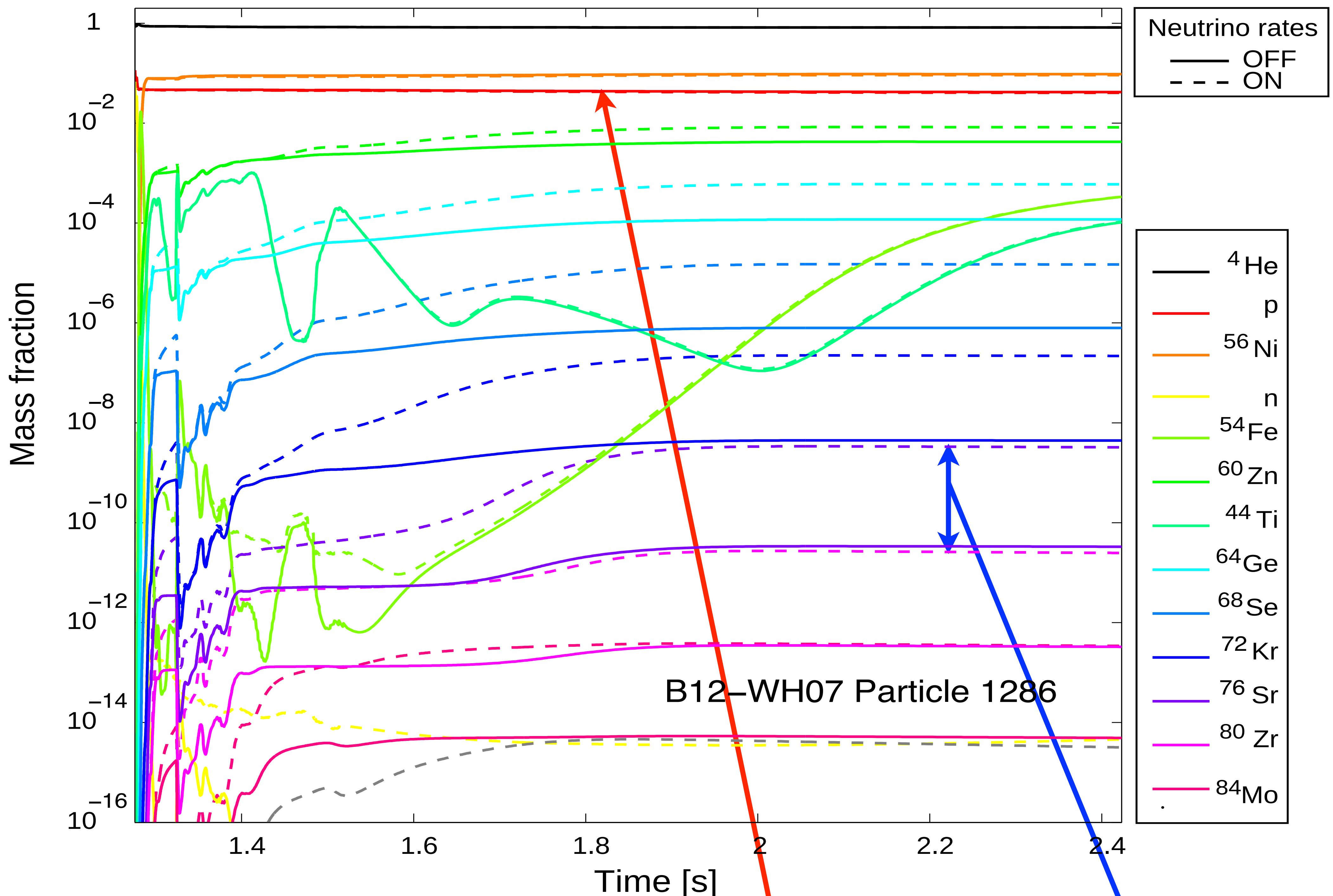
Nucleosynthesis from ν-powered supernova models shows several notable improvements.

1. Over production of neutron-rich iron and nickel reduced.
2. Elemental abundances of Sc, Cu & Zn closer to those observed in metal-poor stars.
3. Potential source of light p-process nuclei (^{76}Se, ^{80}Kr, ^{84}Sr, ^{92,94}Mo, ^{96,98}Ru).





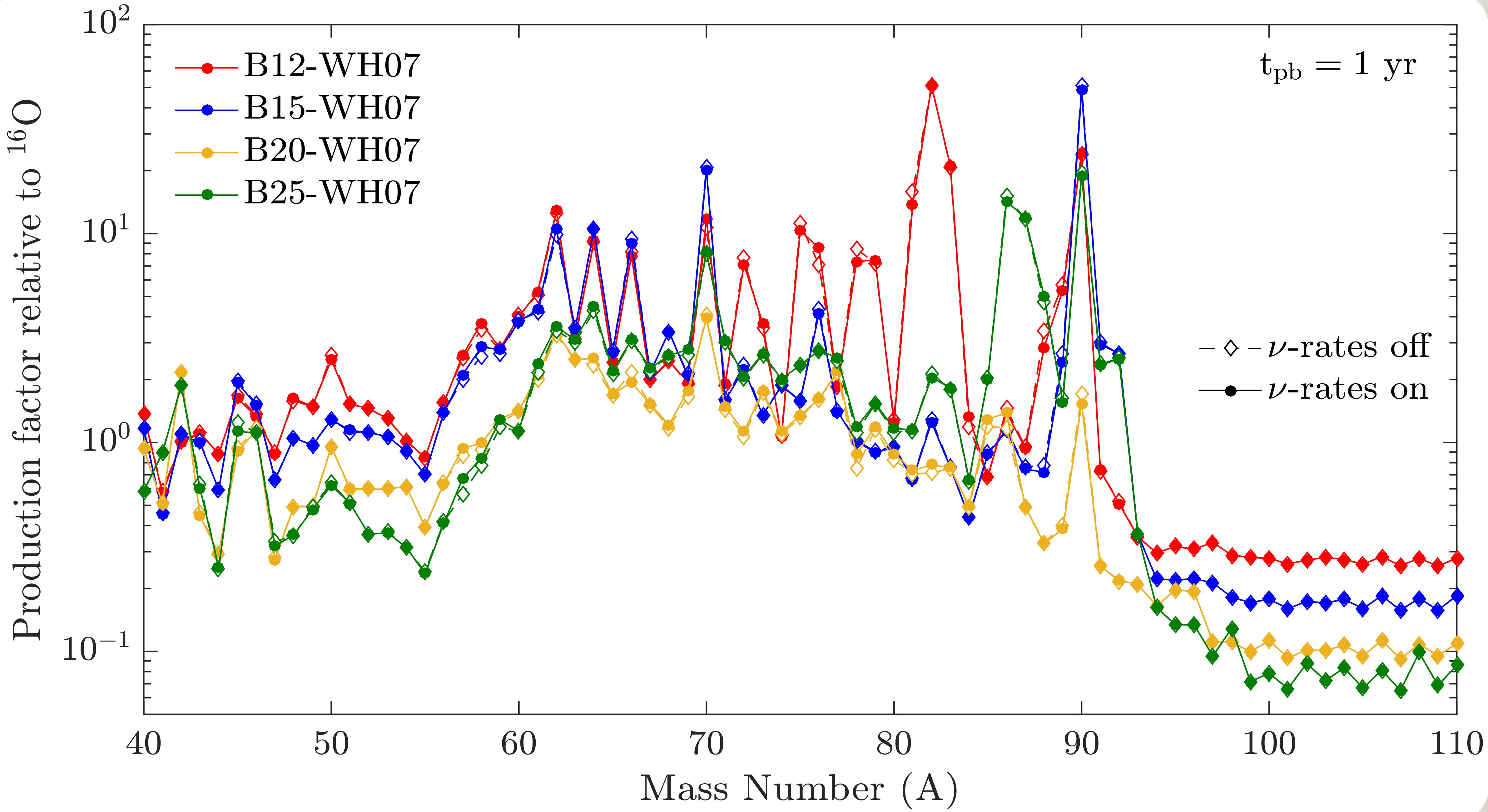
νp-PROCESS …



Our preliminary results show proton-rich ejecta, but the νp-process (dotted lines) occurs for only a handful of particles.

… IS MISSING

The νp-process is very weak in these models.

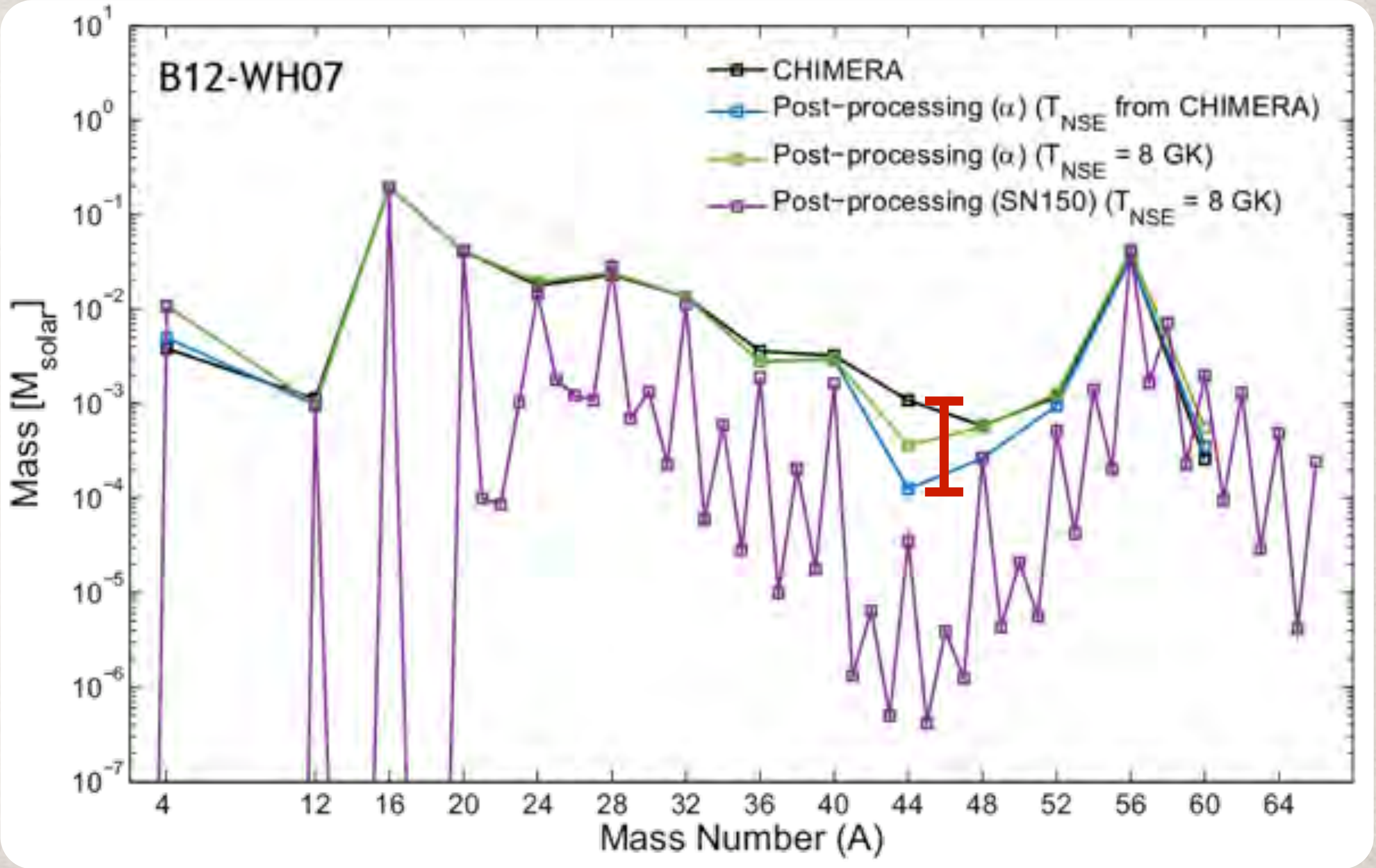


The suppression of the PNS wind is delaying or preventing a strong νp-process from occuring.

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.



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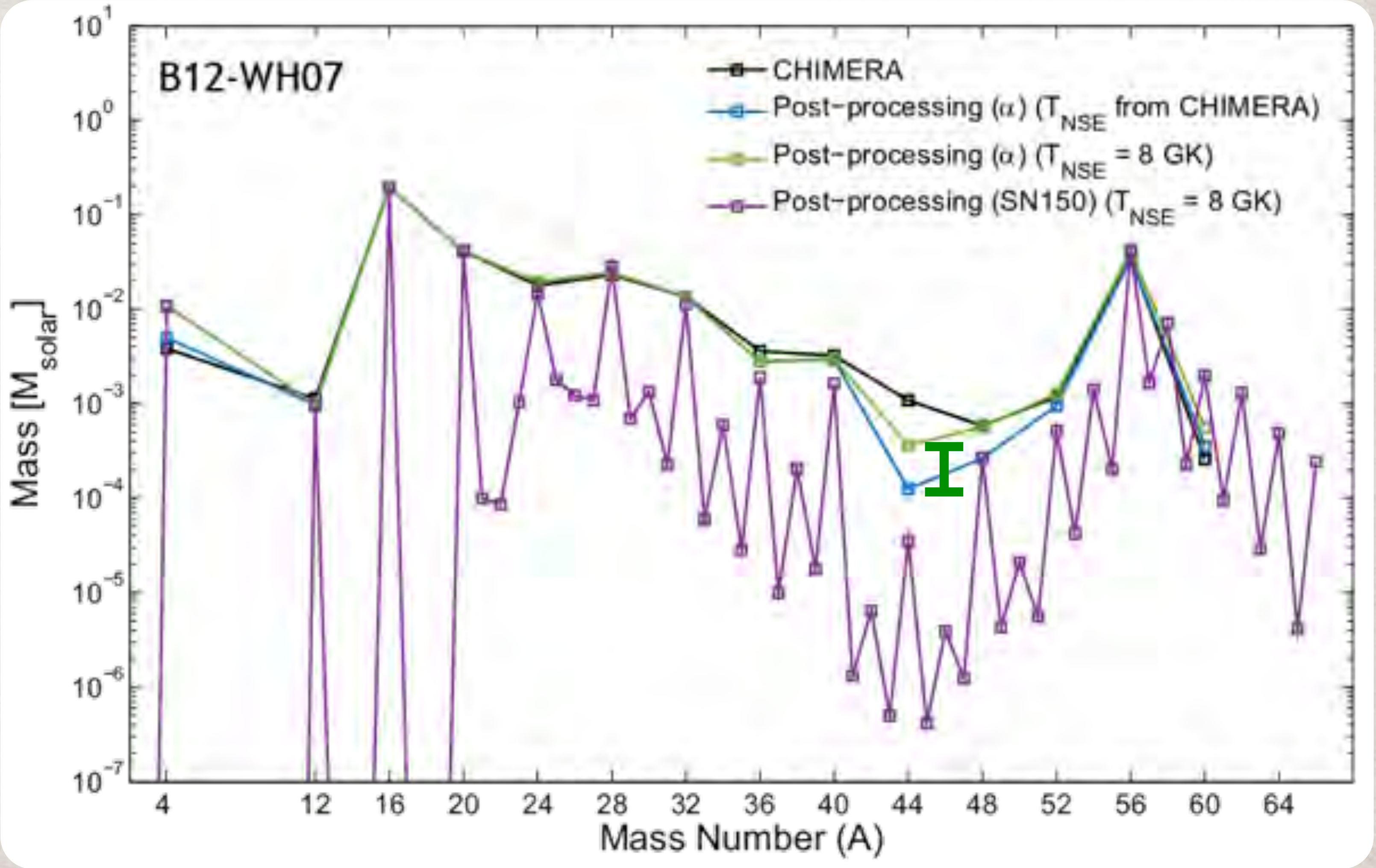
Accurately capturing the α-rich freezeout also requires transitioning out of NSE at temperatures > 6 GK.



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.

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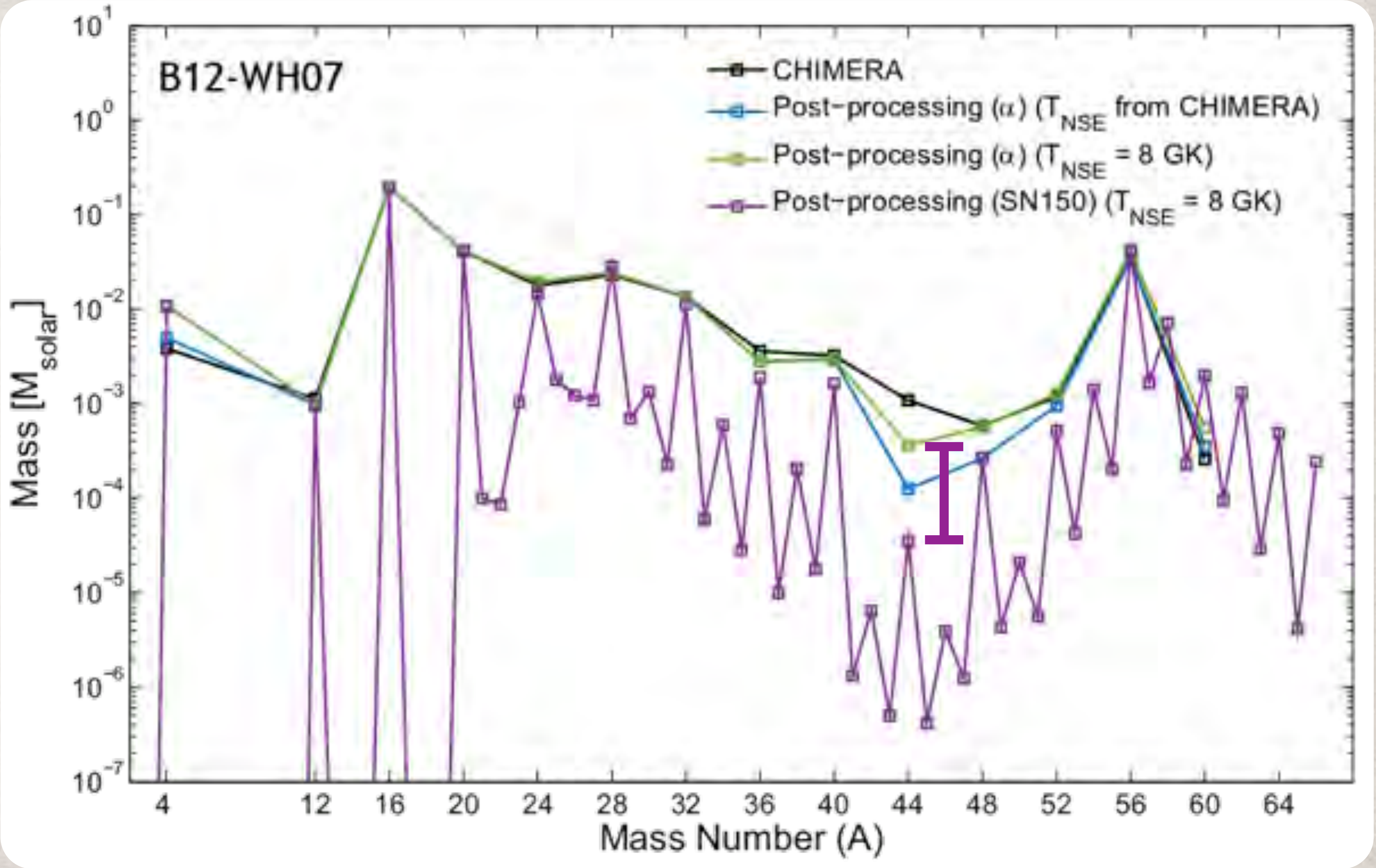
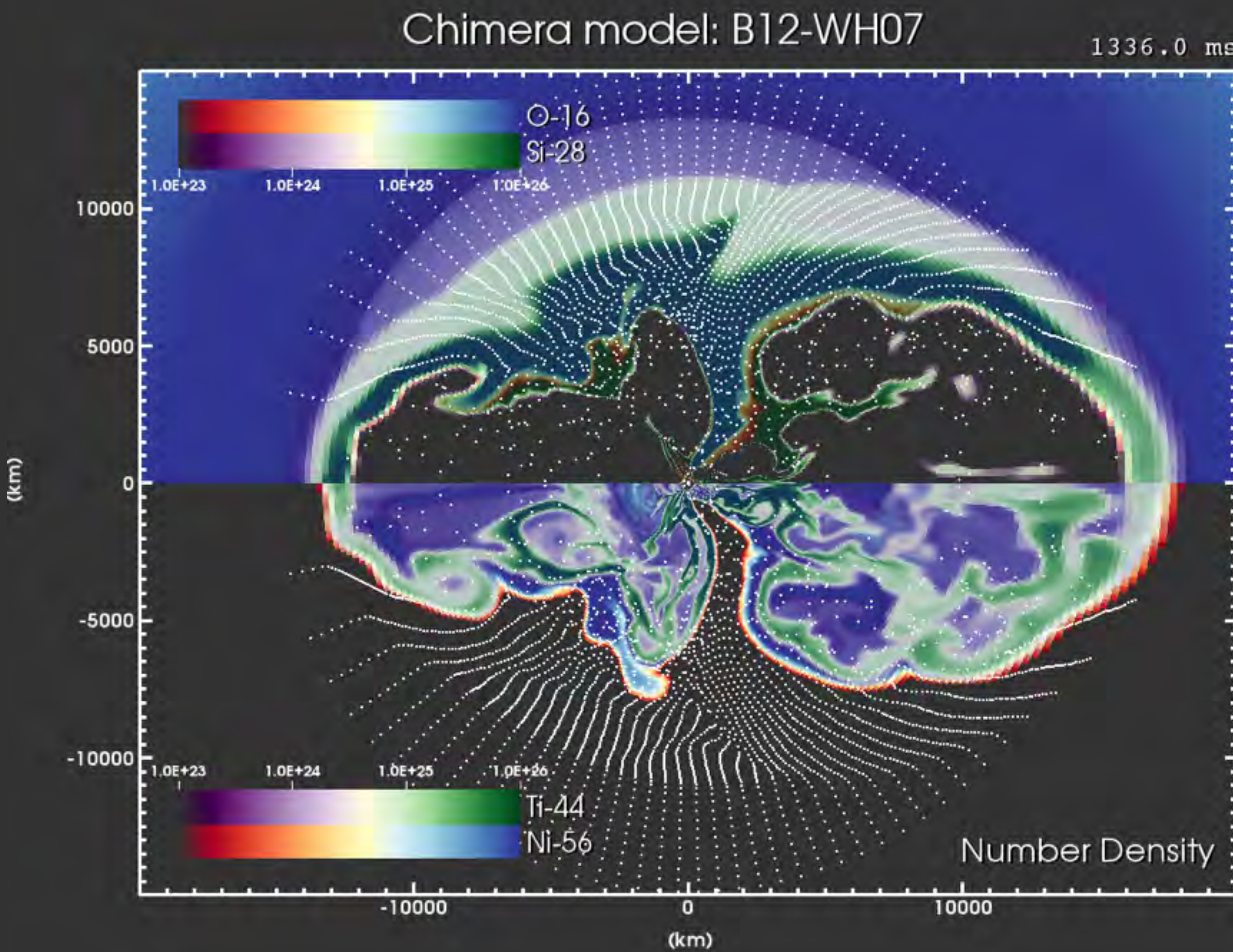


The limitations of the α-network, when compared to a more realistic network, are most evident in the α-rich freezeout and for A > 56.

Tracking Low Density



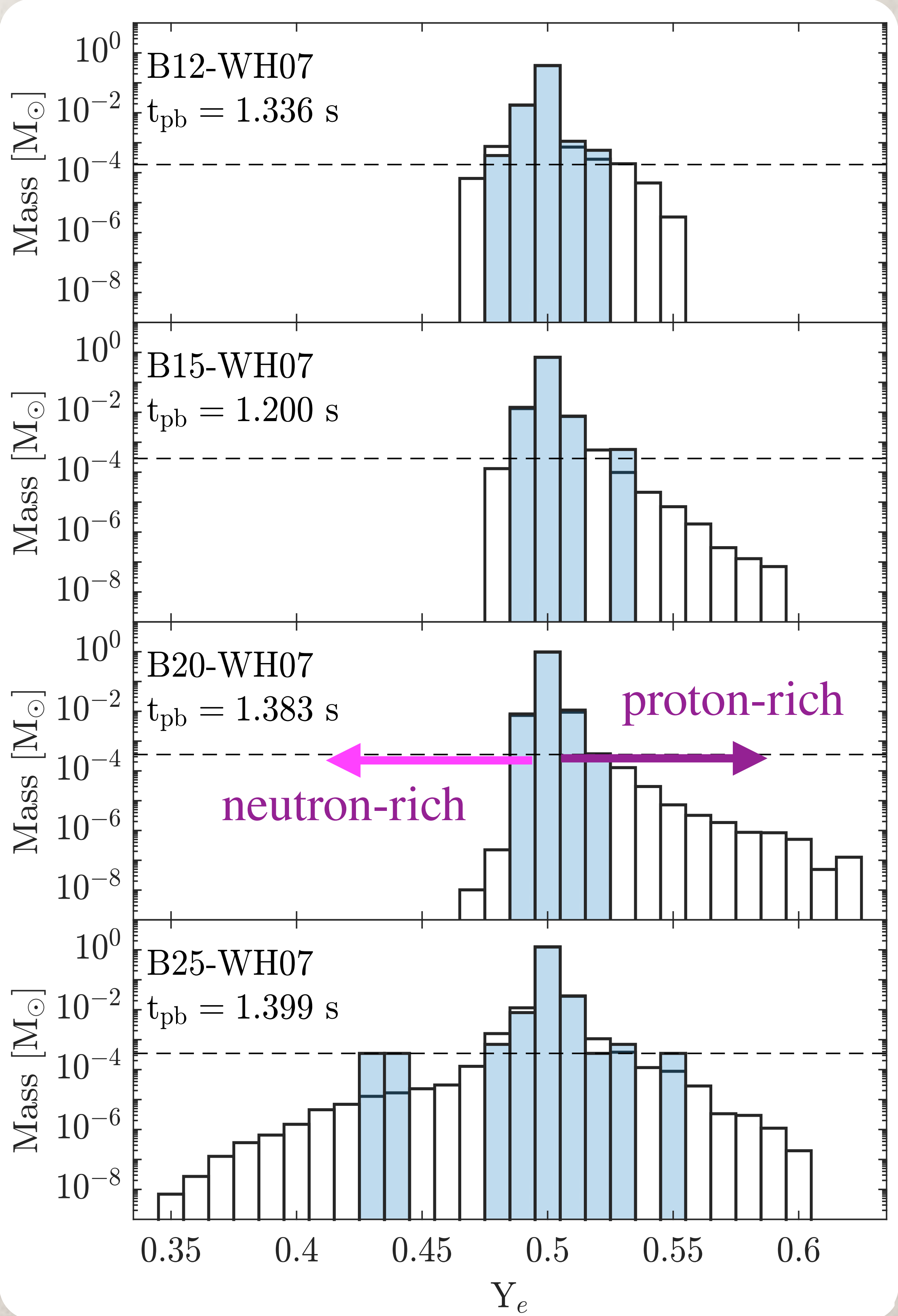
TRACER RESOLUTION

Another view of the limitations of the tracer resolution is the distribution in the electron fraction of the ejecta.

Tracer resolution clearly limits the production of more exotic species.

For the B-series, run to 1.2-1.4 s after bounce, this is the largest uncertainty, though it only affects α-rich freezeout.

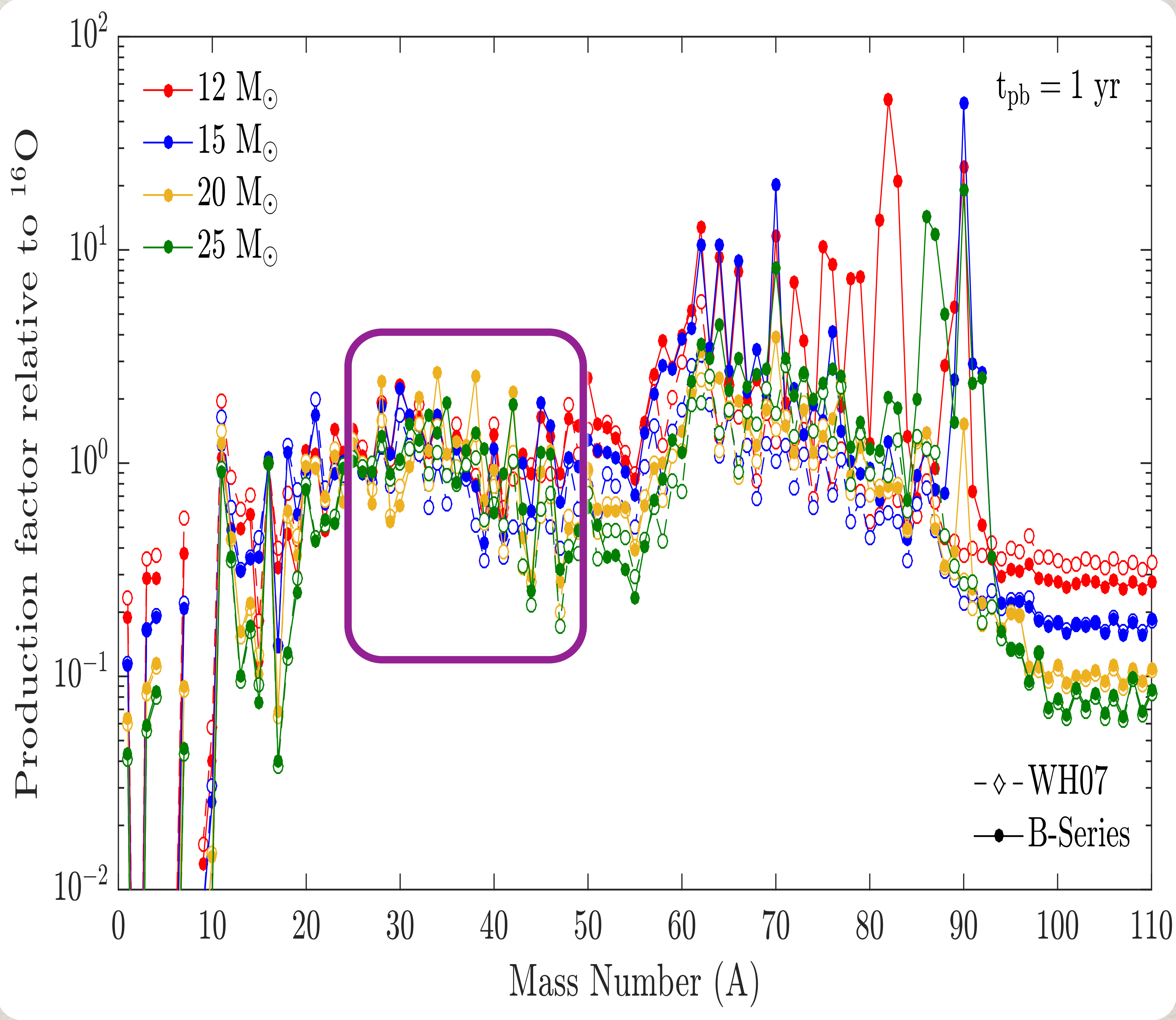
Model	Particles	M_{tracer} [$M_\odot$]
B12-WH07	**4000**	**1.87×10^{-4}**
B15-WH07	**5000**	**2.86×10^{-4}**
B20-WH07	**6000**	**3.55×10^{-4}**
B25-WH07	**8000**	**3.49×10^{-4}**



Comparing to 1D

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.



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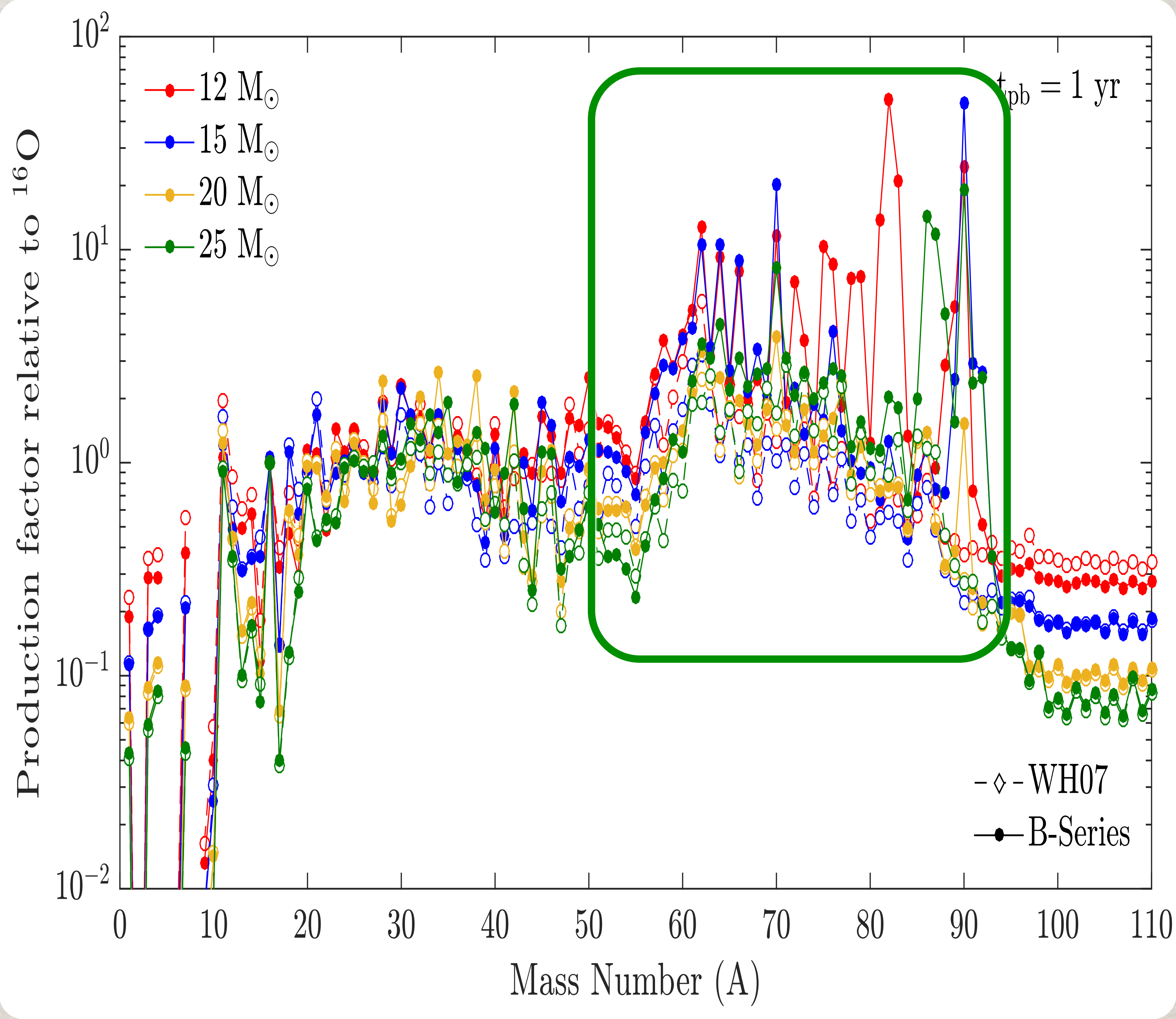


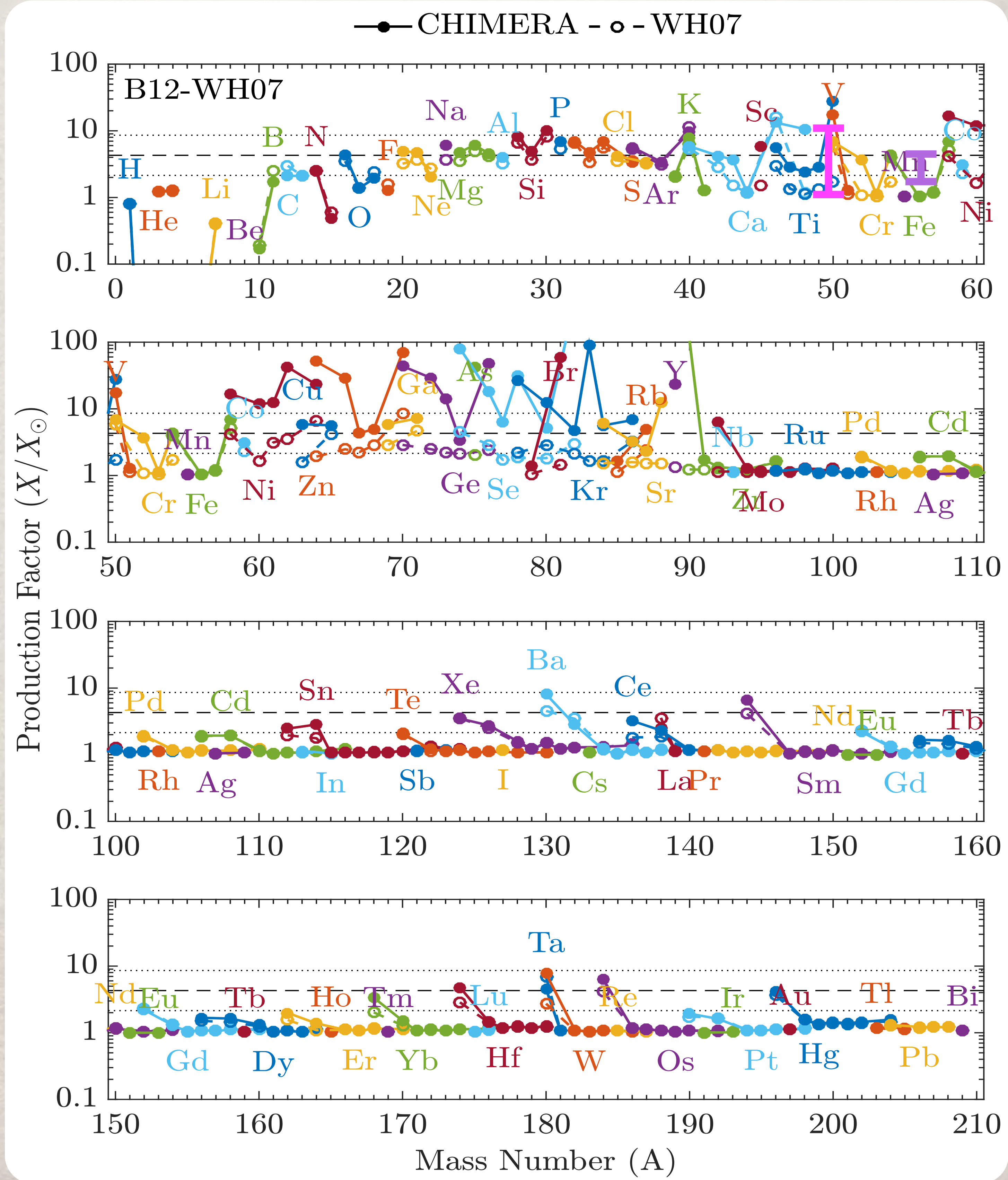
Intermediate mass elements, up to A=50, are similar, though significant isotopic differences exist.

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.



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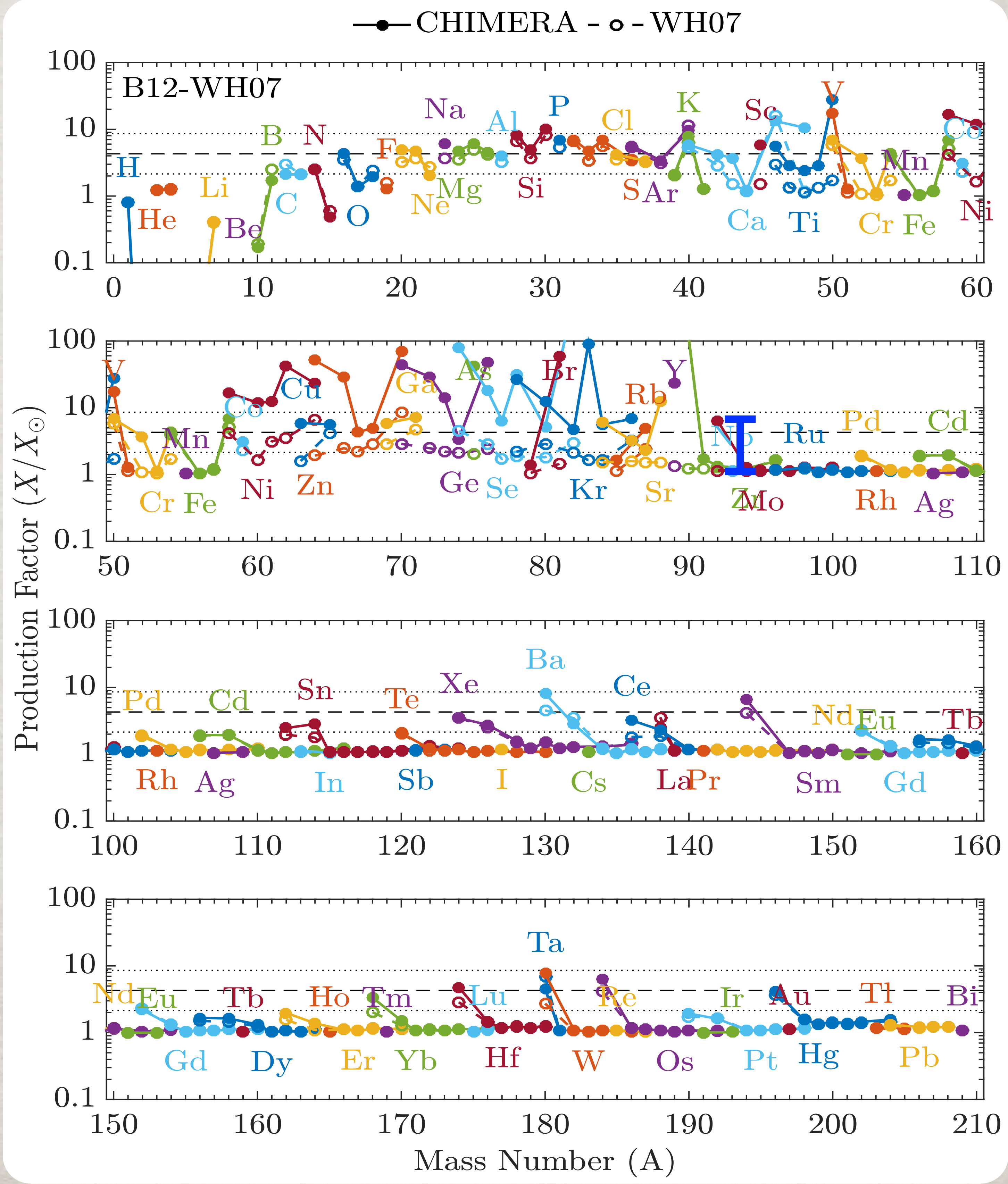
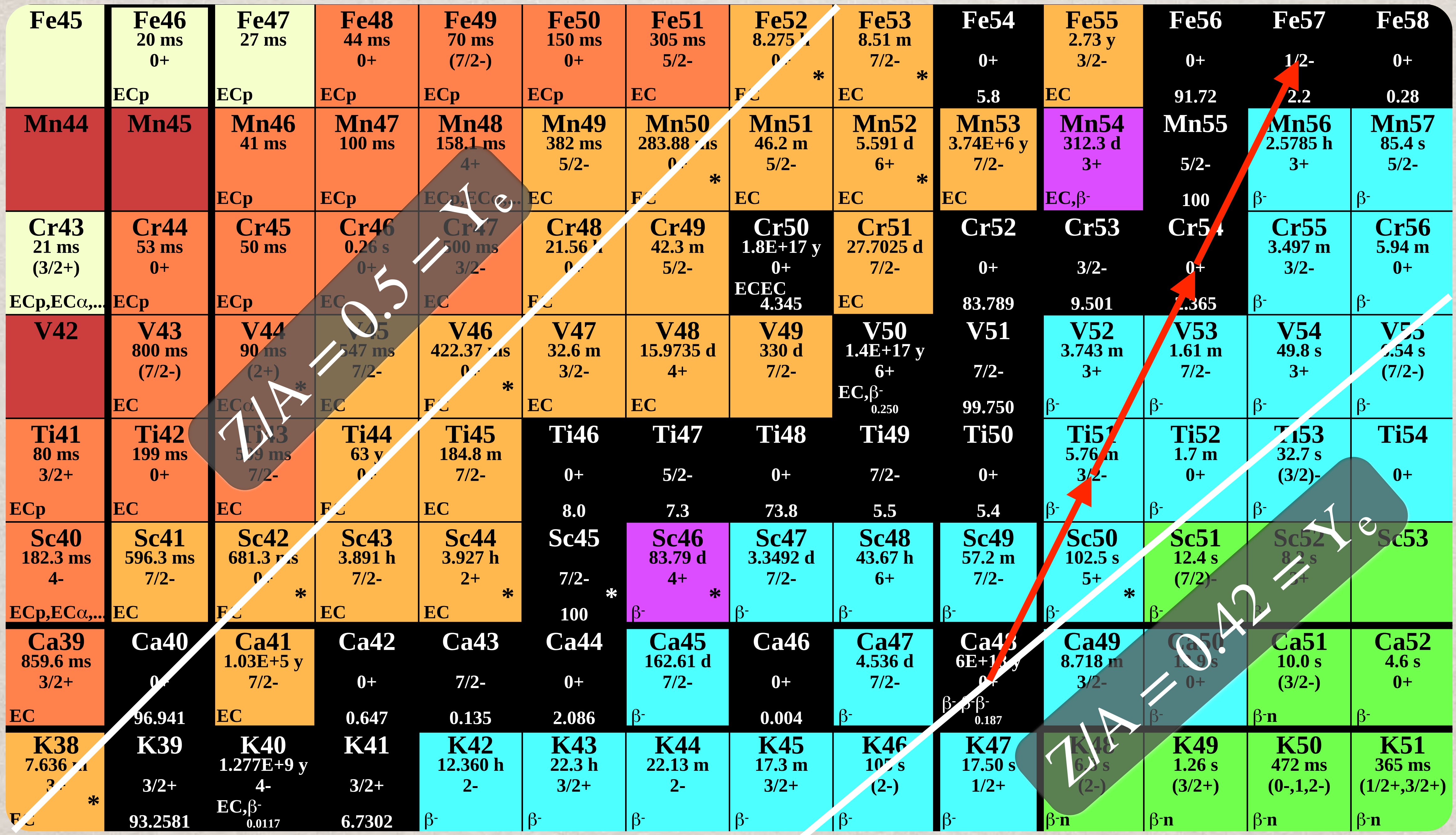
Ejecta with somewhat higher Y_e (<0.48) and entropy produces ^{92}Mo.



Magic of ^{48}Ca

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



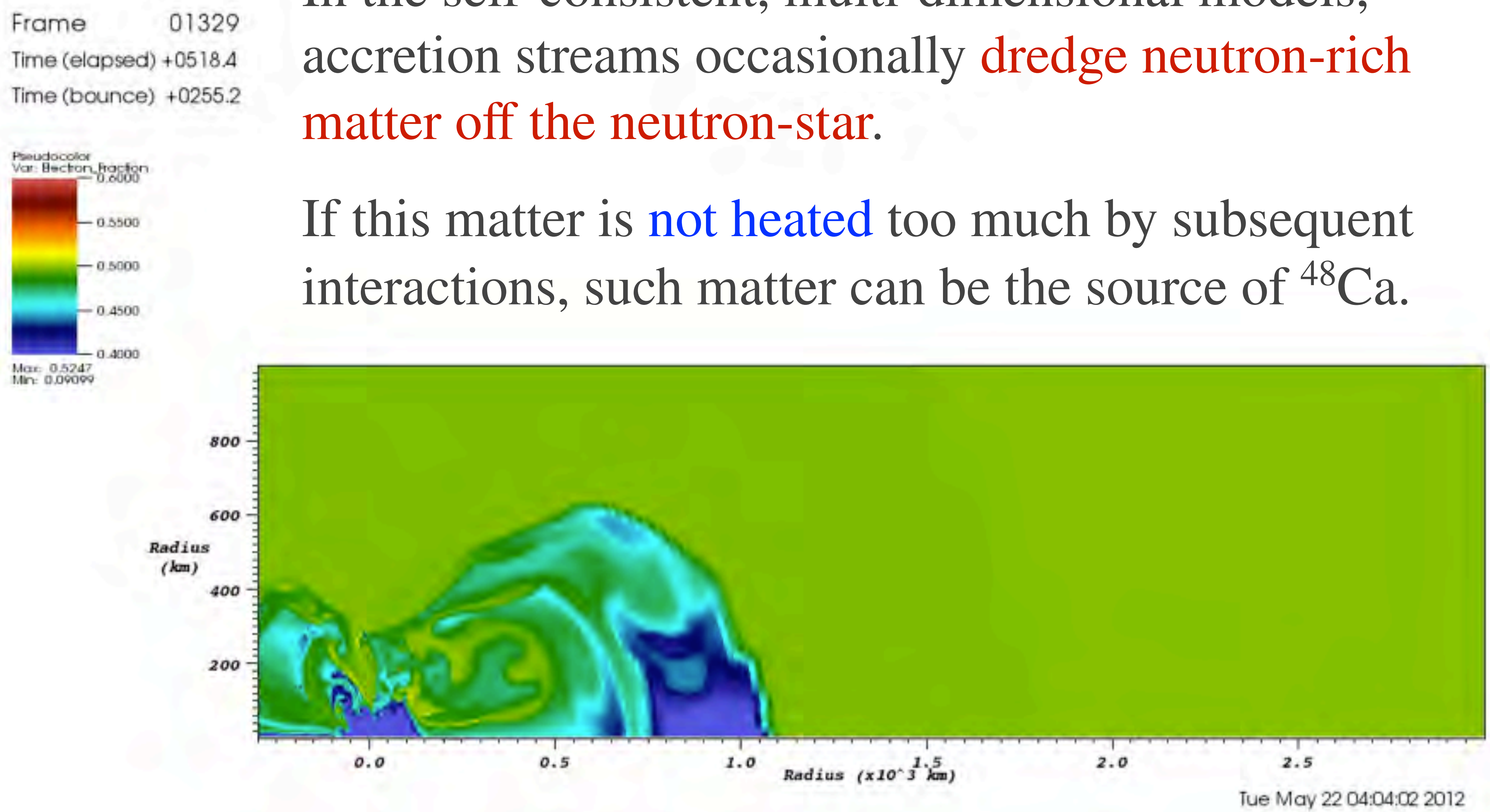
Making ^{48}Ca requires neutron-rich conditions, but if temperature gets too high, it will burn to form neutron-rich iron or nickel.

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.

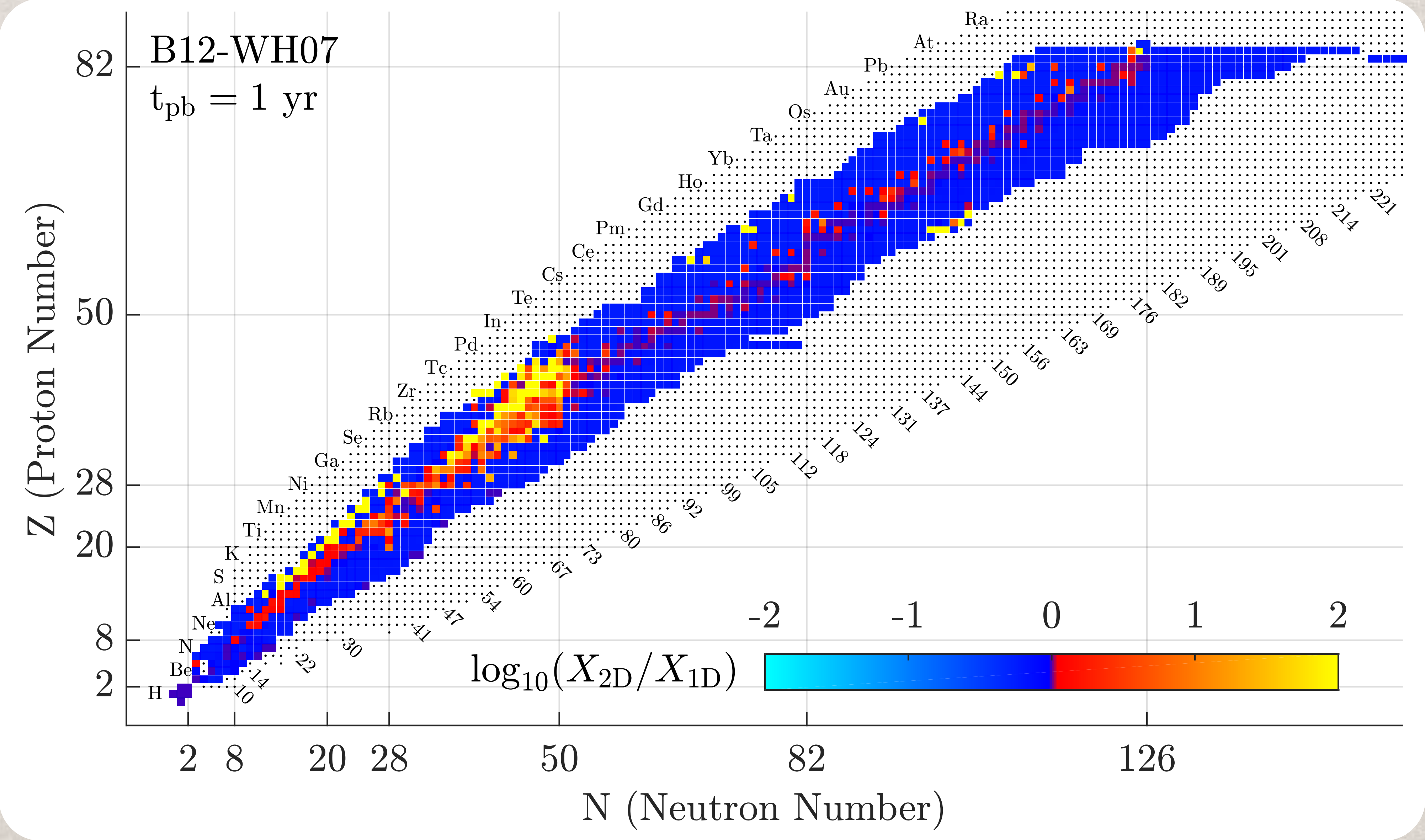
In the self-consistent, multi-dimensional models, accretion streams occasionally dredge neutron-rich matter off the neutron-star.

If this matter is not heated too much by subsequent interactions, such matter can be the source of ^{48}Ca.



Thermodynamic Variety

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



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

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.

Peek at the Future