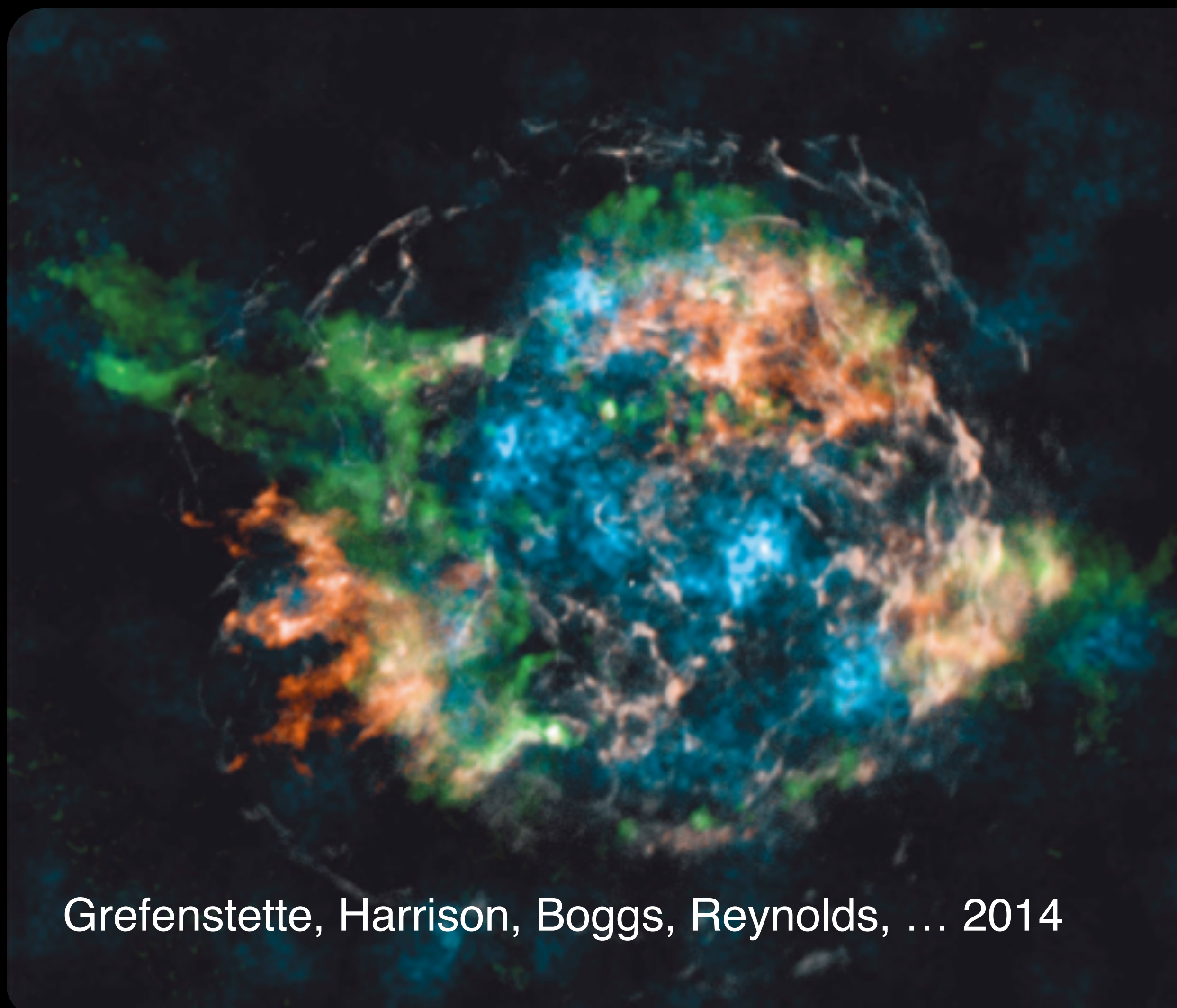
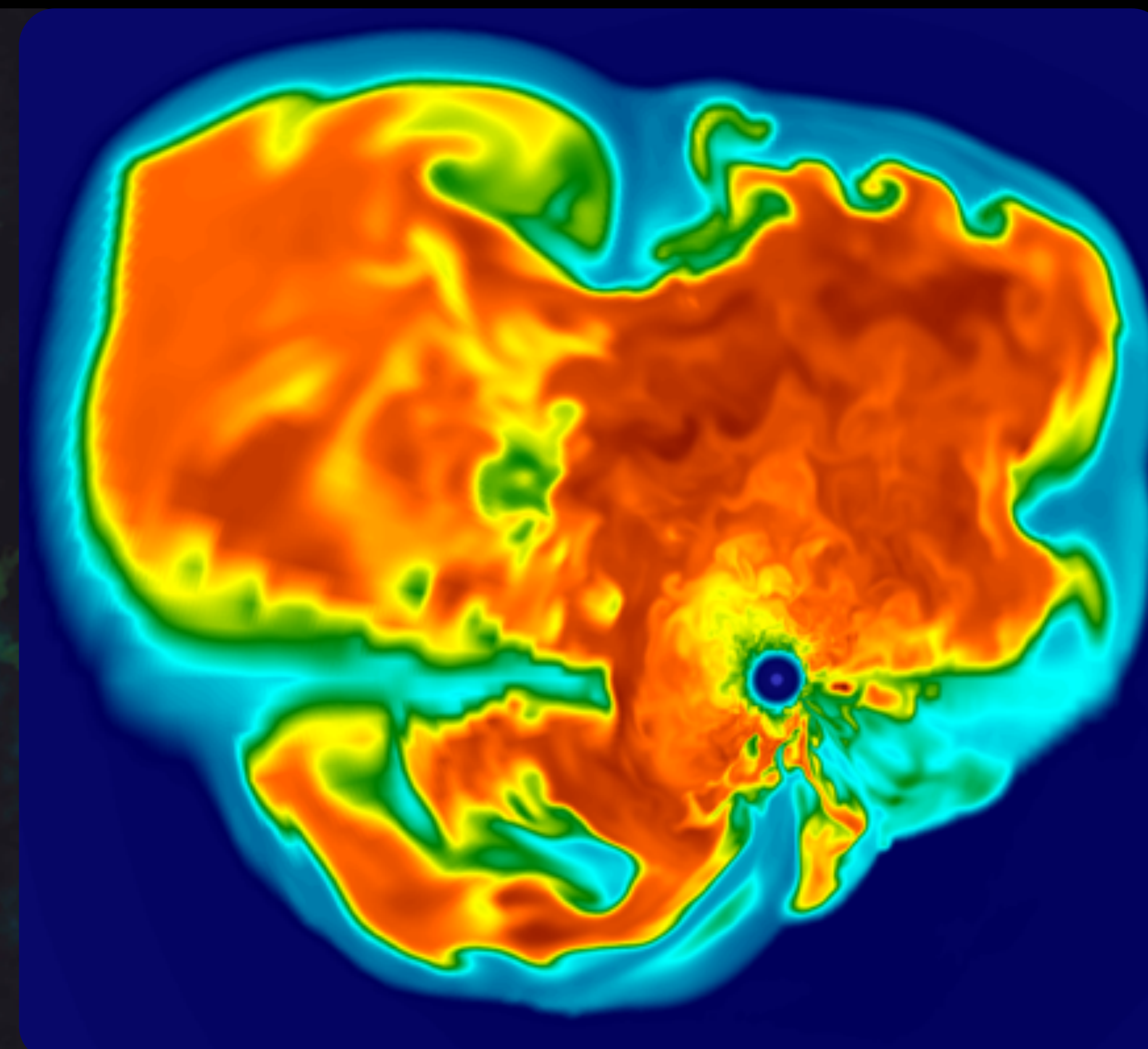
Questions about Core-Collapse Supernovae





& their Nucleosynthesis

William Raphael Hix (ORNL/U. Tennessee)

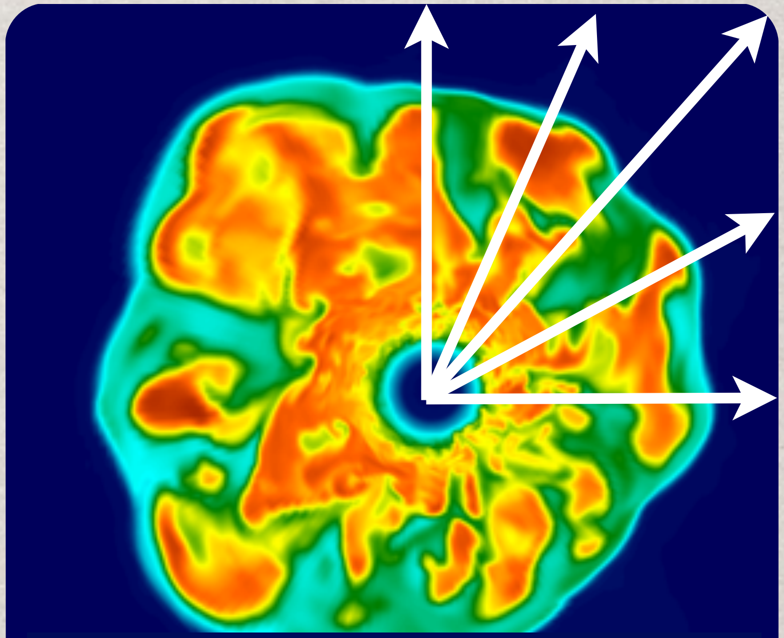
What is a CCSN model?

Our code, CHIMERA, has

- 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.

Other models use a variety of approximations

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

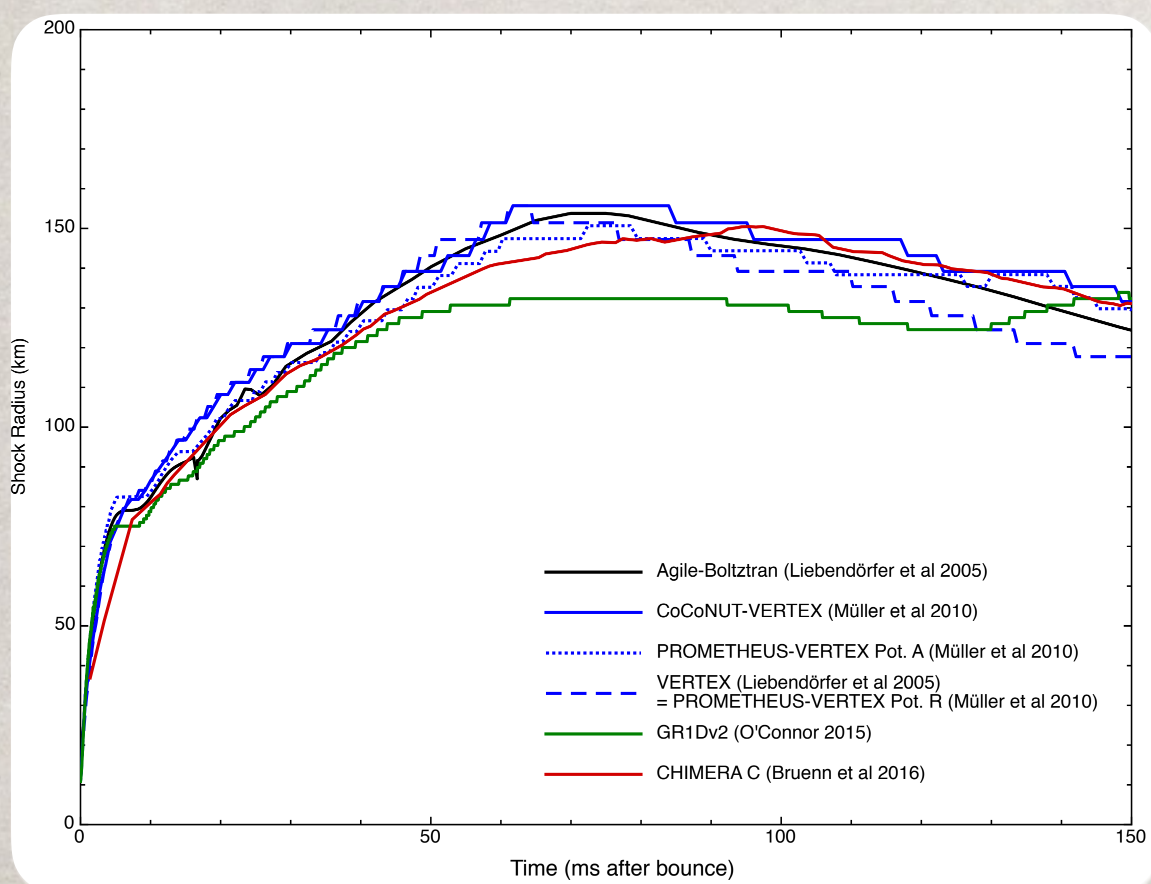

Ray-by-Ray Approximation

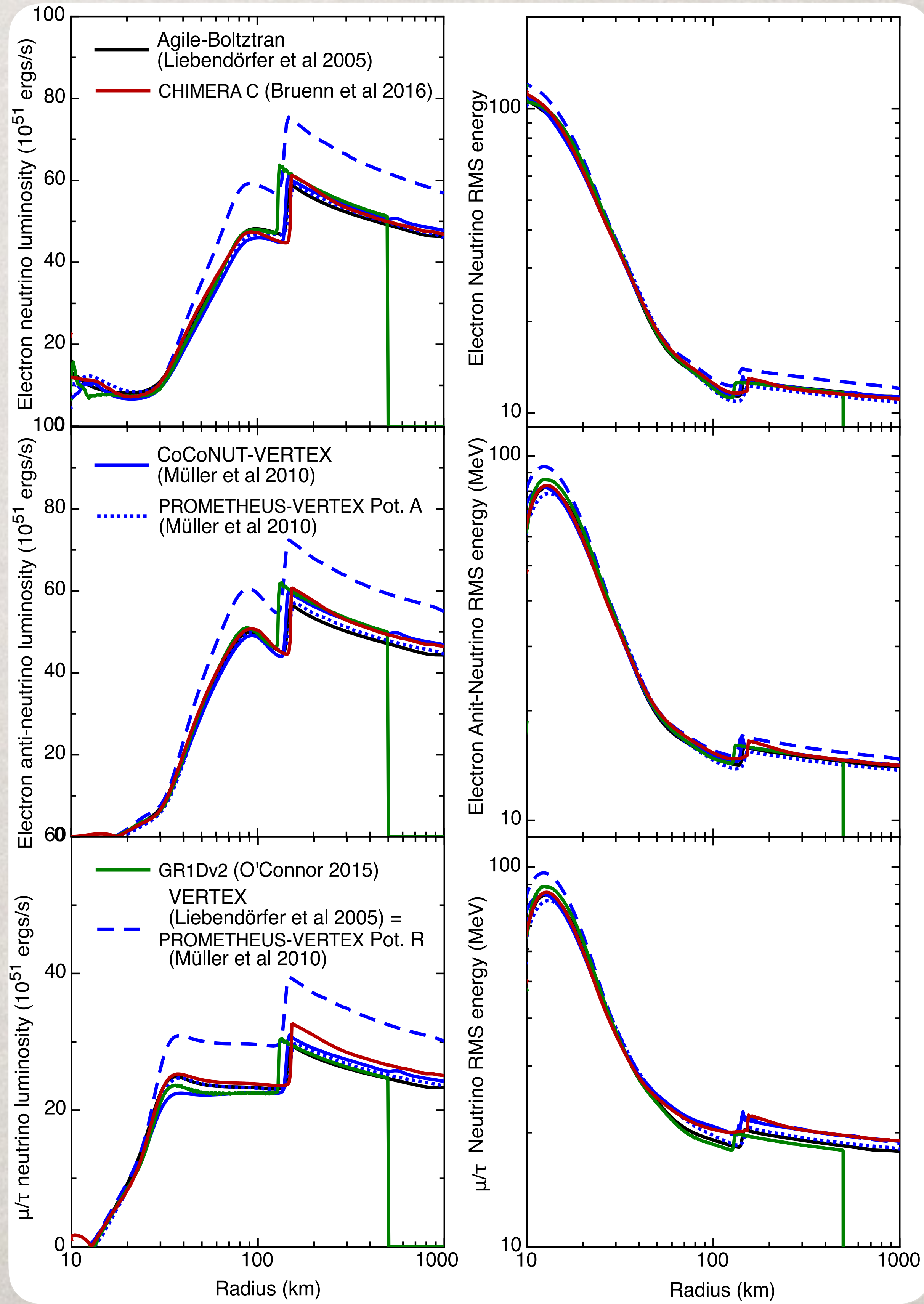
Can we agree on anything?

Self-Consistent Models using Discrete Ordinates, VTEF, M1 and MGFLD can produce quite similar results when used

in one dimension

with limited opacities & EOS.





What is a Completed Model?

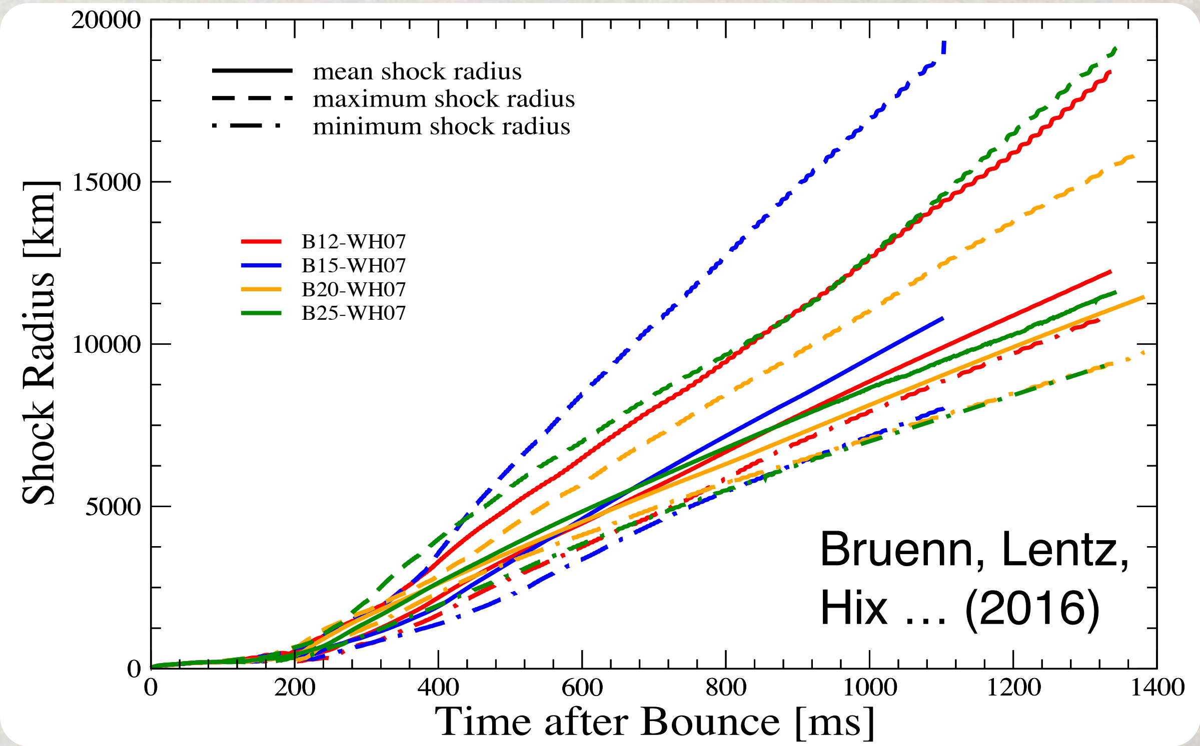
Success should be determined by comparison to observations, but at what level of completion?

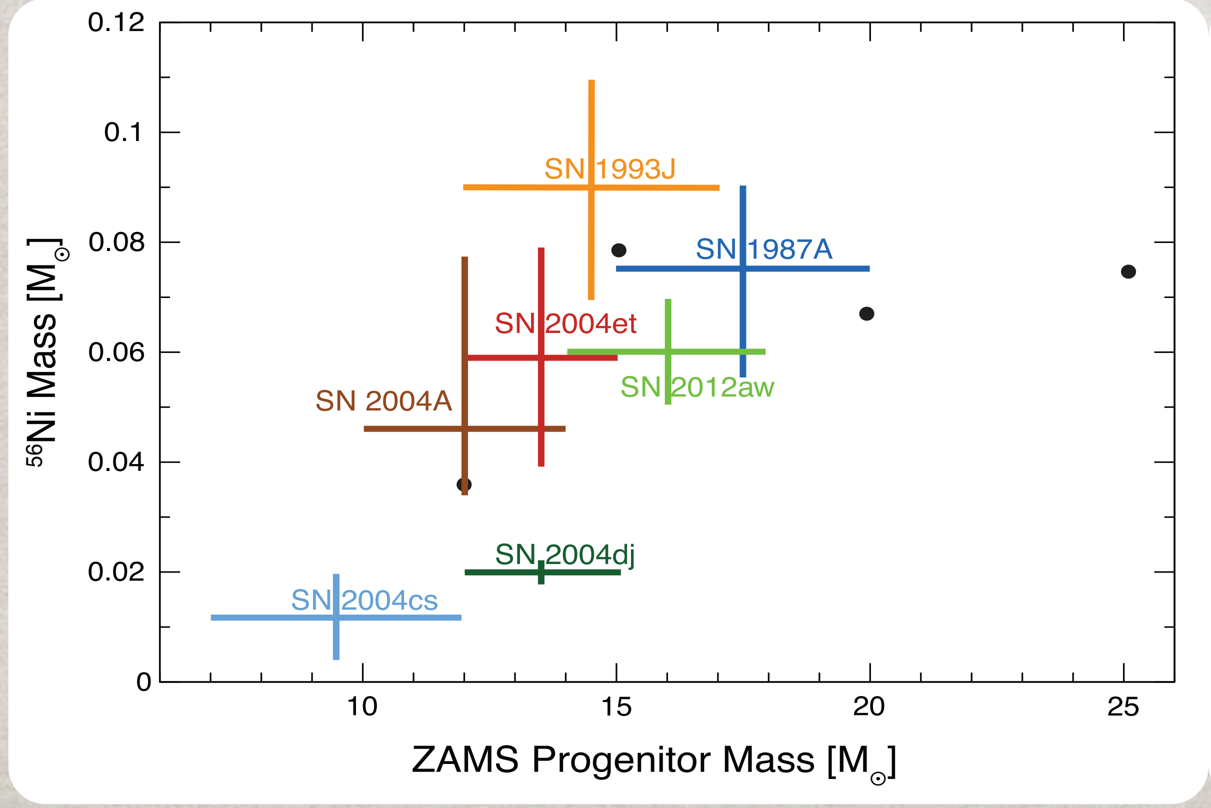
Shock velocity reaching 10^5 km/s?

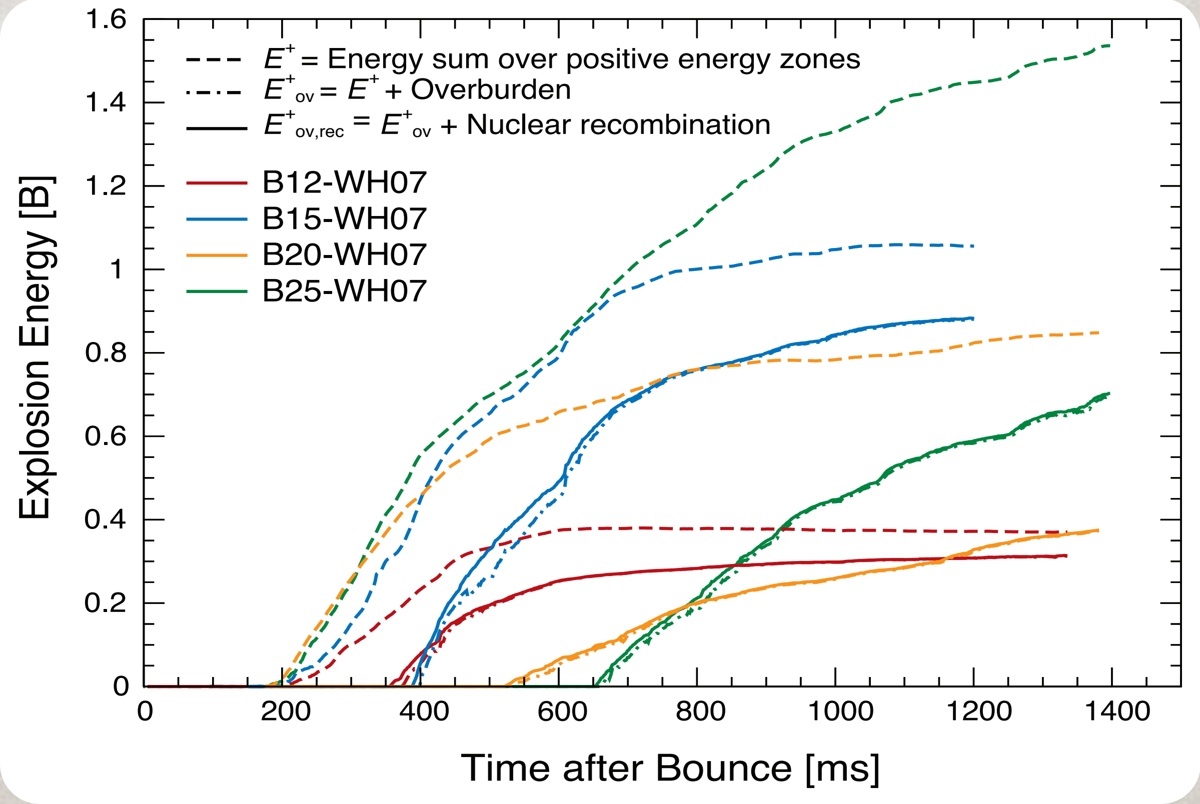
Explosion energy (or surrogate) reaching ~1B?

Ejecting ~0.1 $M_\odot$ of Nickel?

Looking like Cas A?



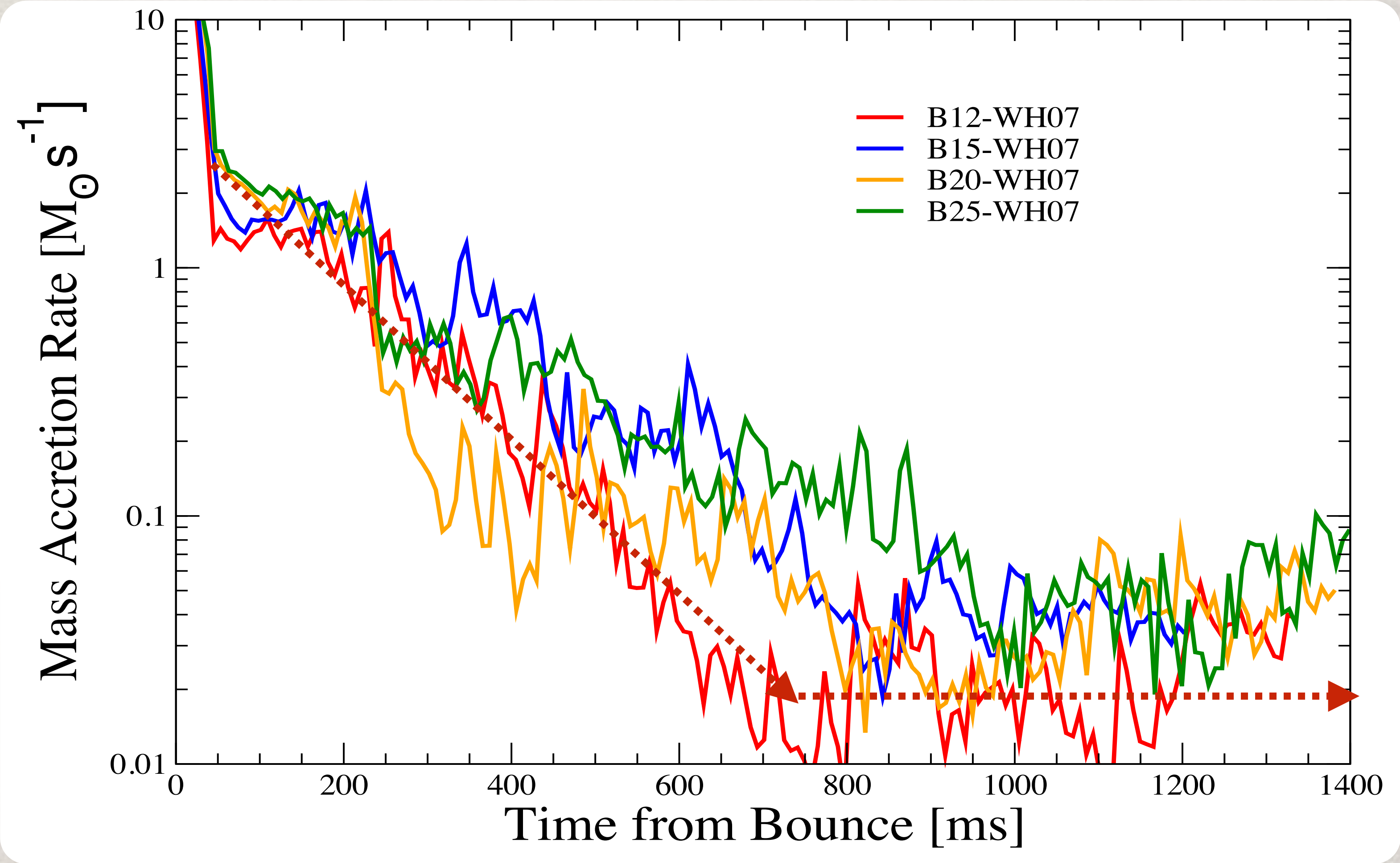




When does the Explosion End?

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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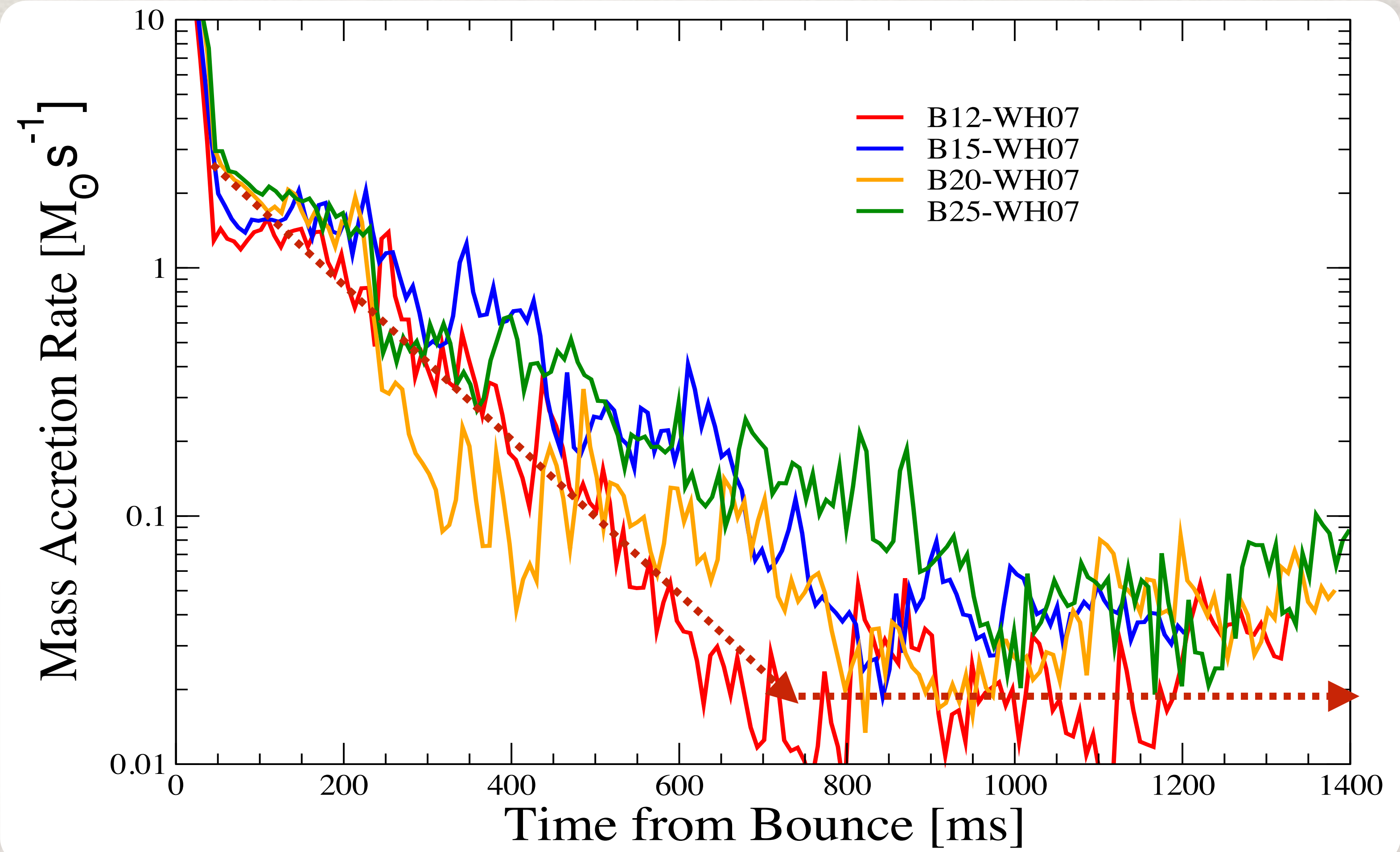

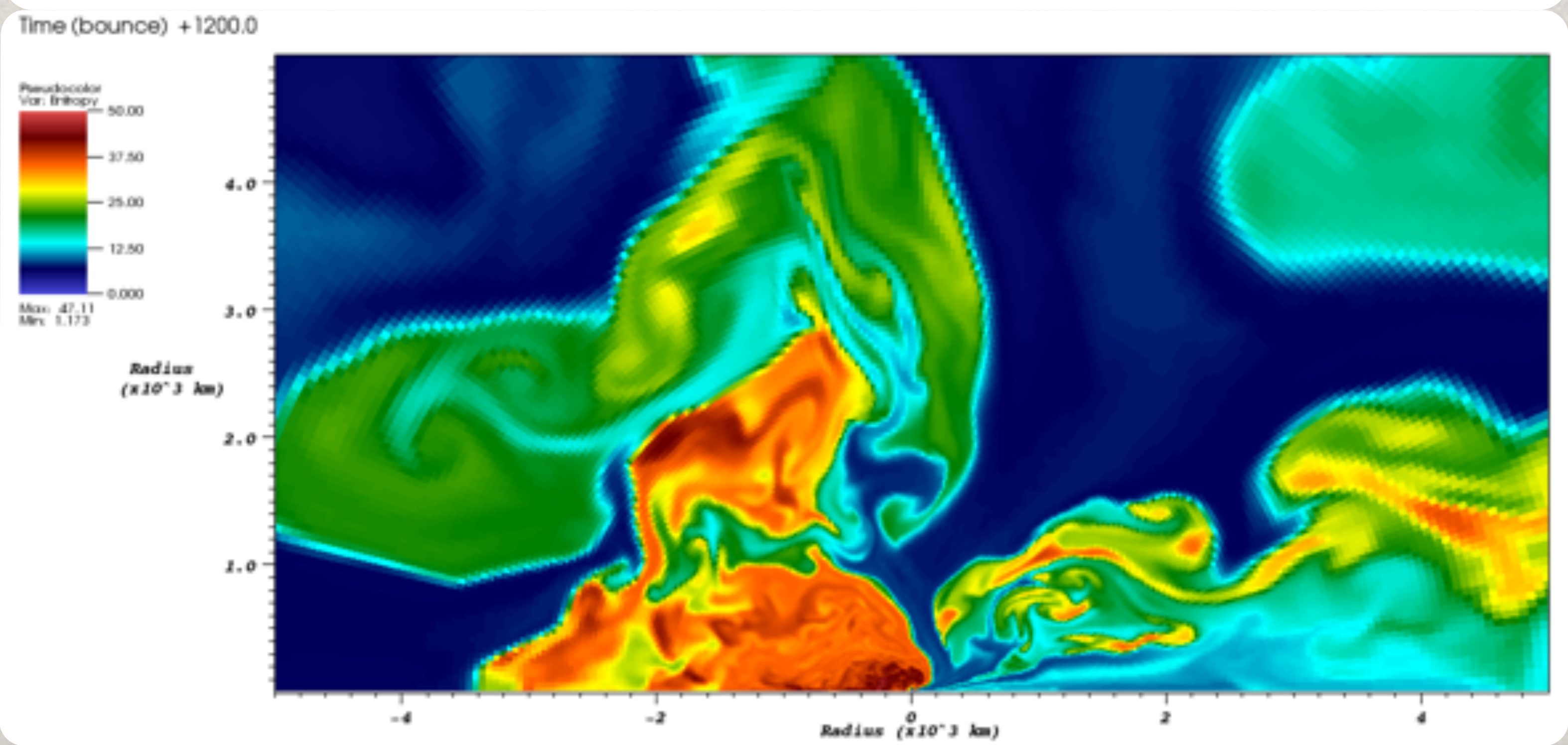

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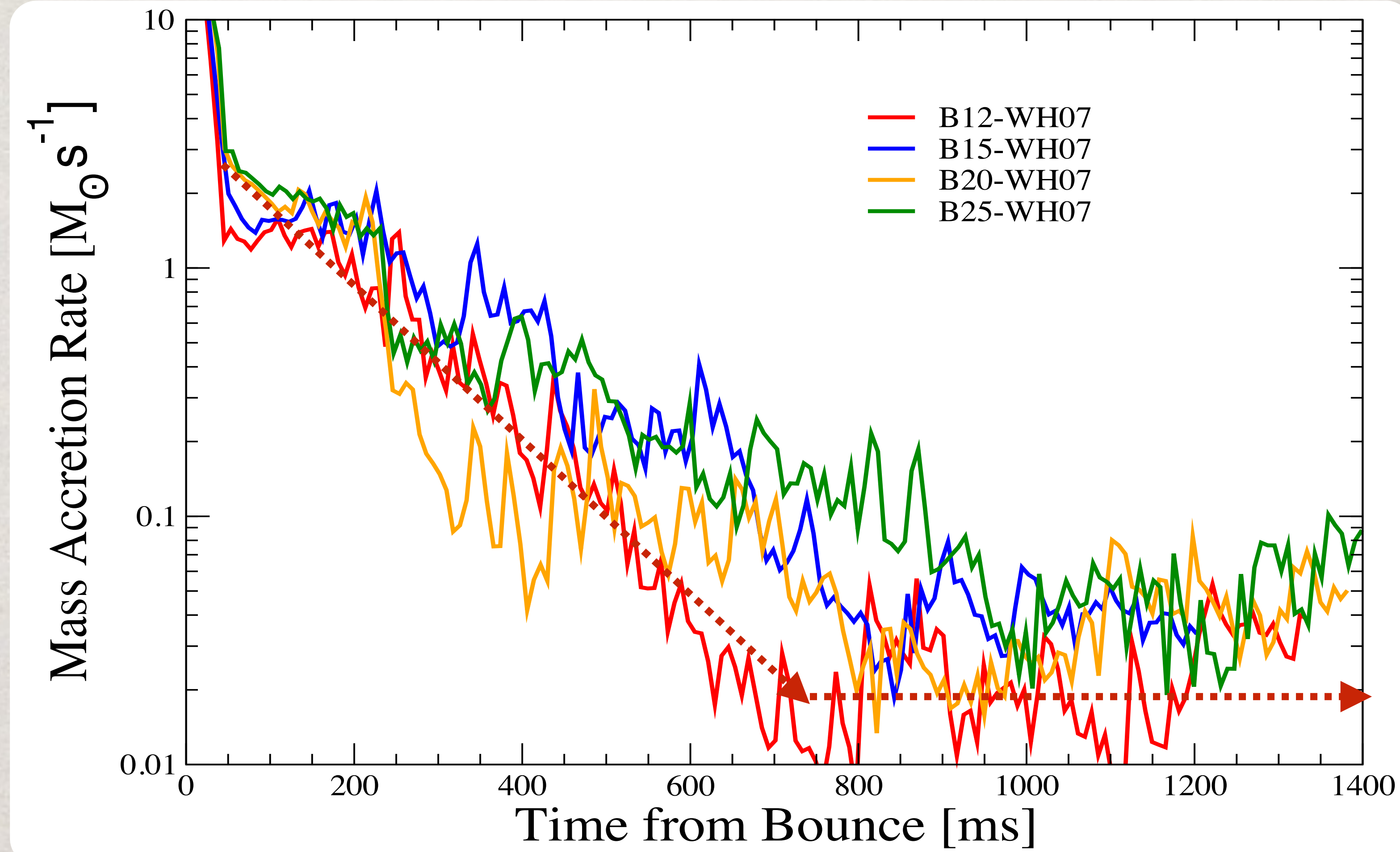
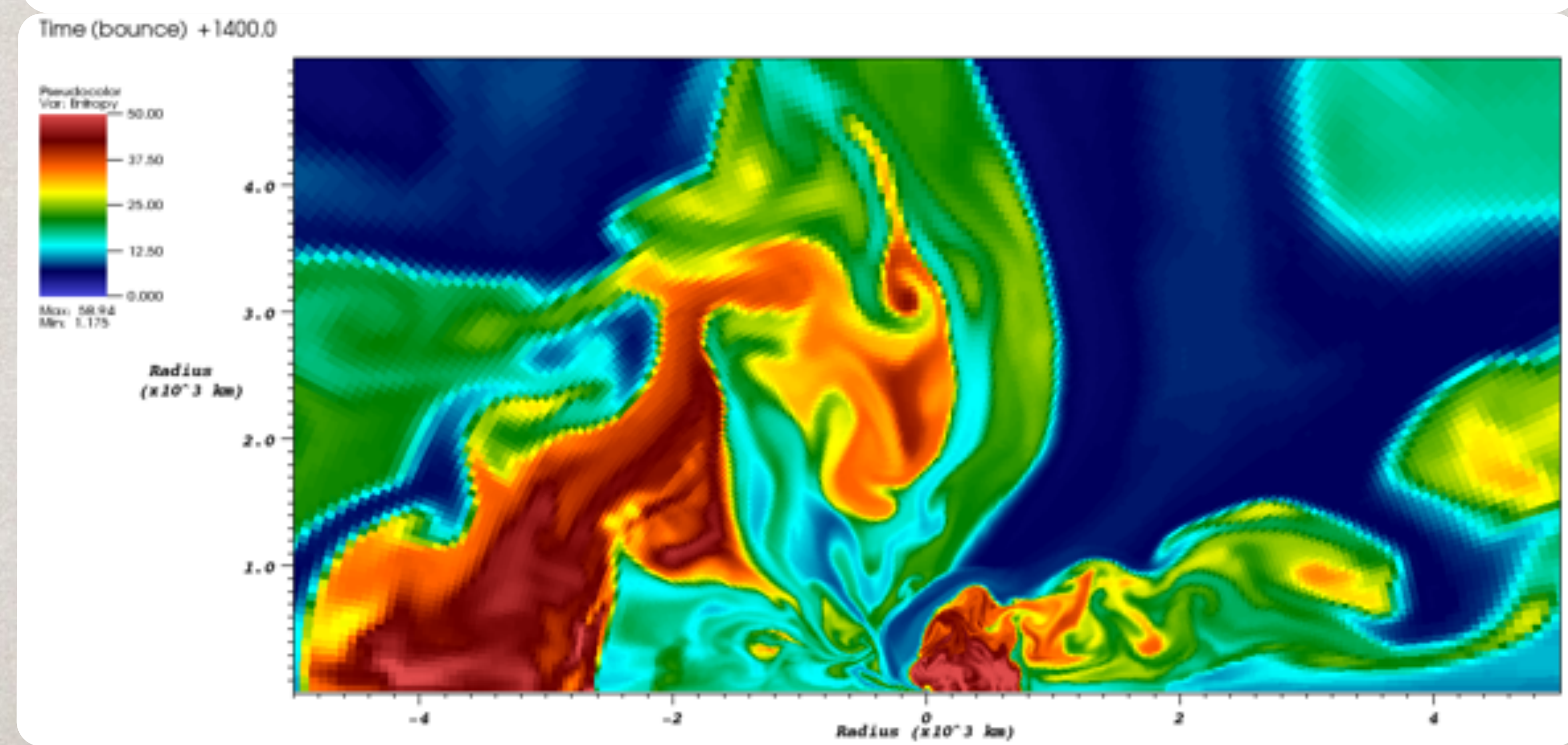
This extends the "hot bubble" phase and suppresses the development of the PNS wind.



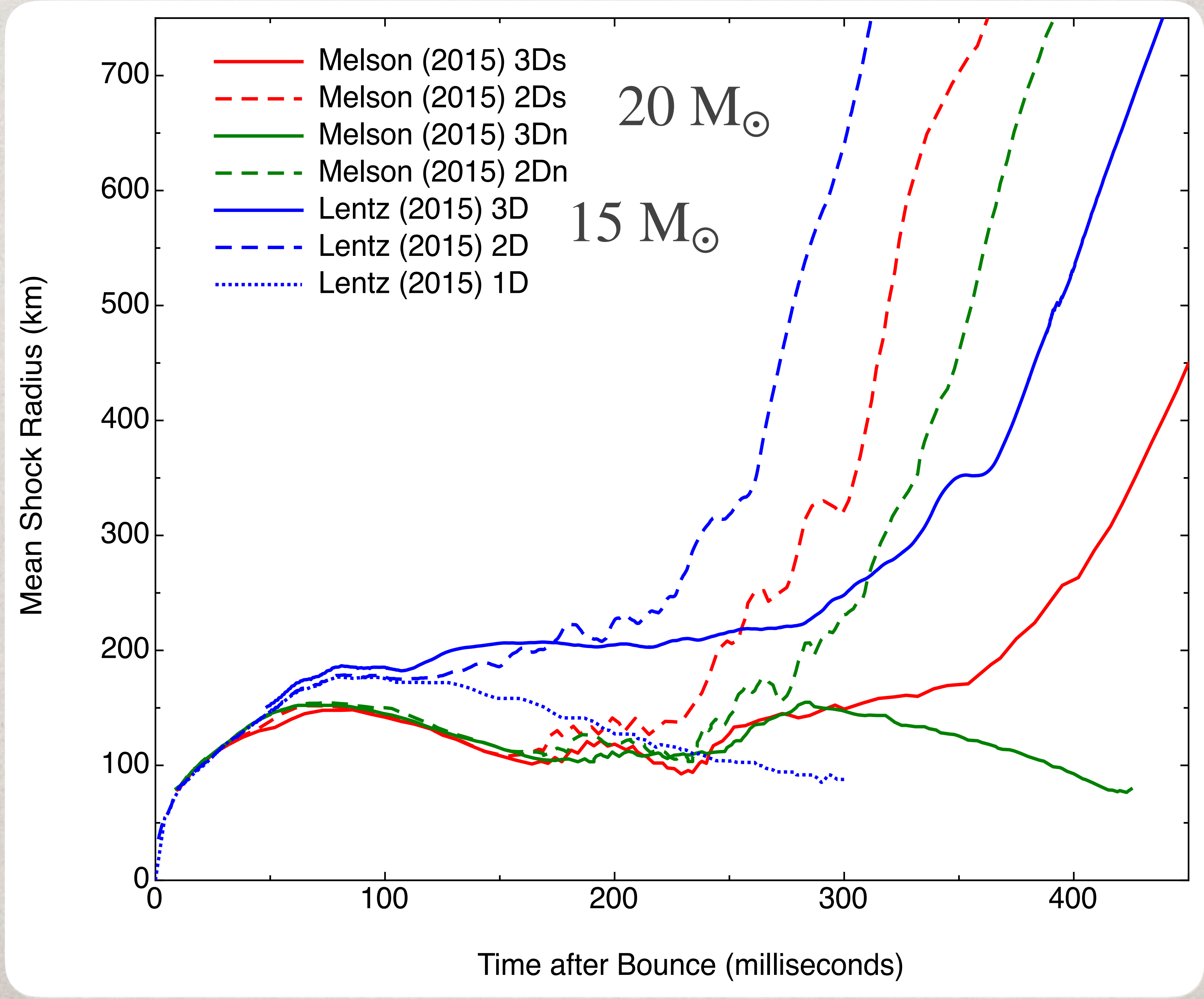


What is 2D good for?

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?

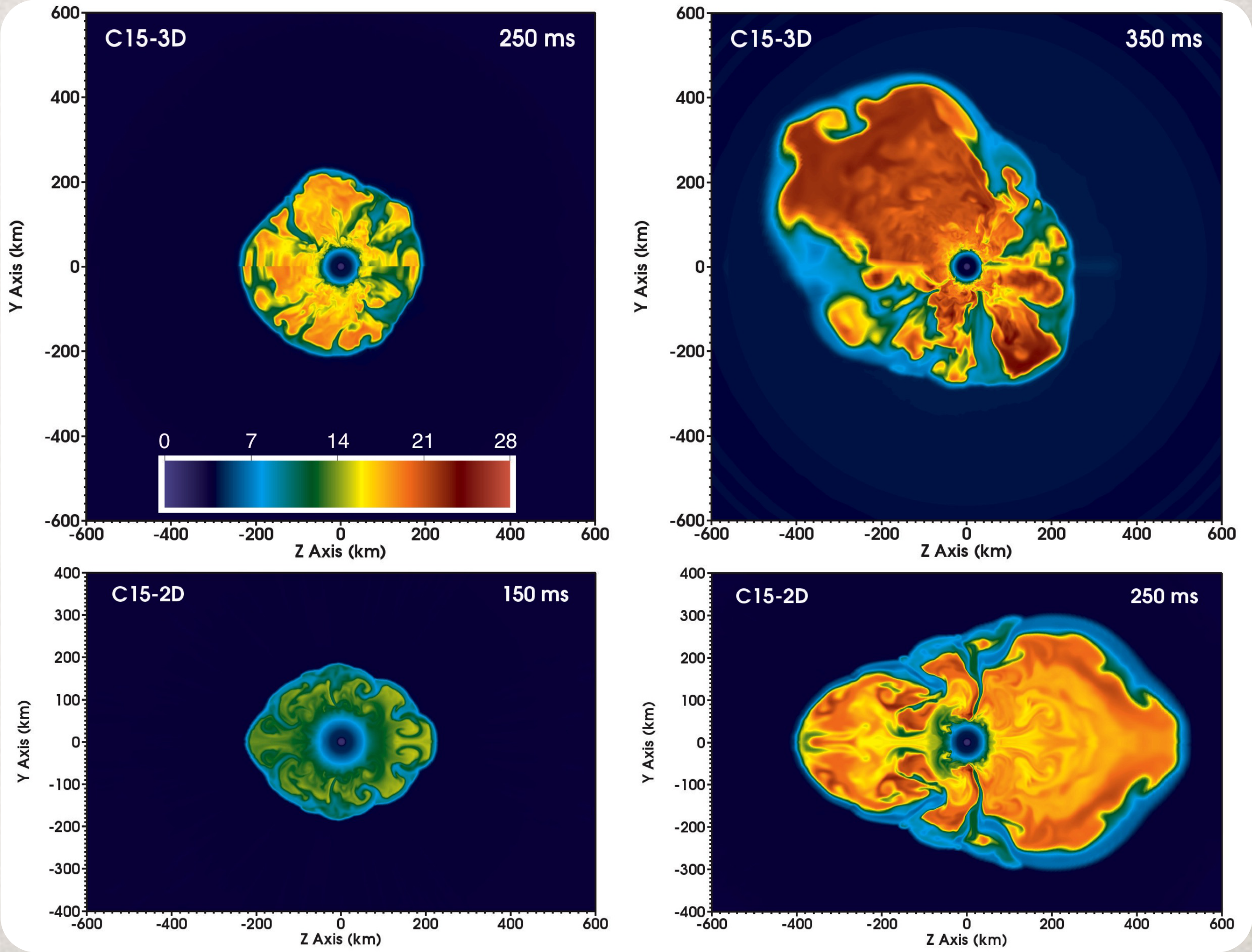


Is 2D Turning down the heat?

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.



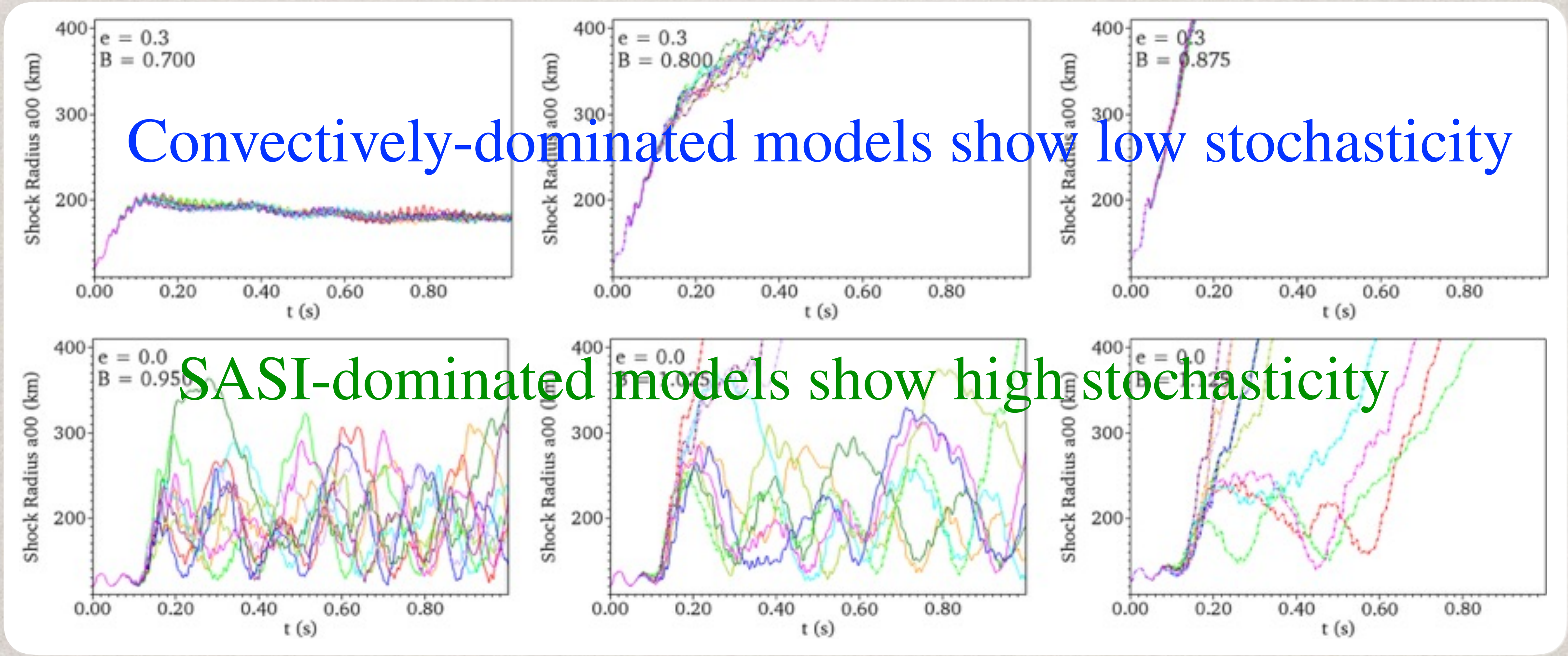
This implies that successful 2D models will tend to have lower entropy in the heating regions.

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

How predictive are the Models?

Multi-D introduces stochastic flow, raising uncertainty in the range of variations if the same model is run multiple times.

Cardall & Budiardja (2015) ran 160 3D hydrodynamic simulations mimicking SASI-dominated and convectively-dominated CCSN.



Convectively-dominated models show low stochasticity

SASI-dominated models show high stochasticity

This gives some hope that convective models, at least, are predictive.

Still Exploding an 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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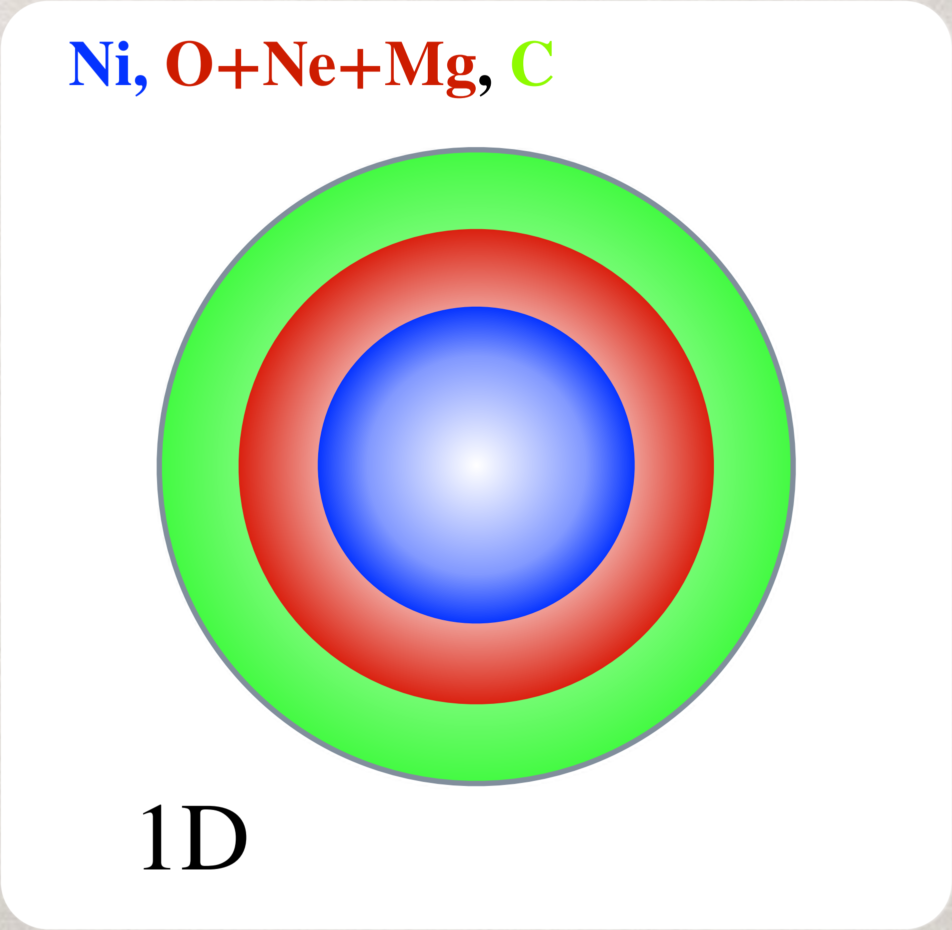

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This colors our discussion, for example the notion that the matter created closest to the neutron star is most sensitive to the "mass cut".

Hughes, Rakowski, Burrows & Slane 2000

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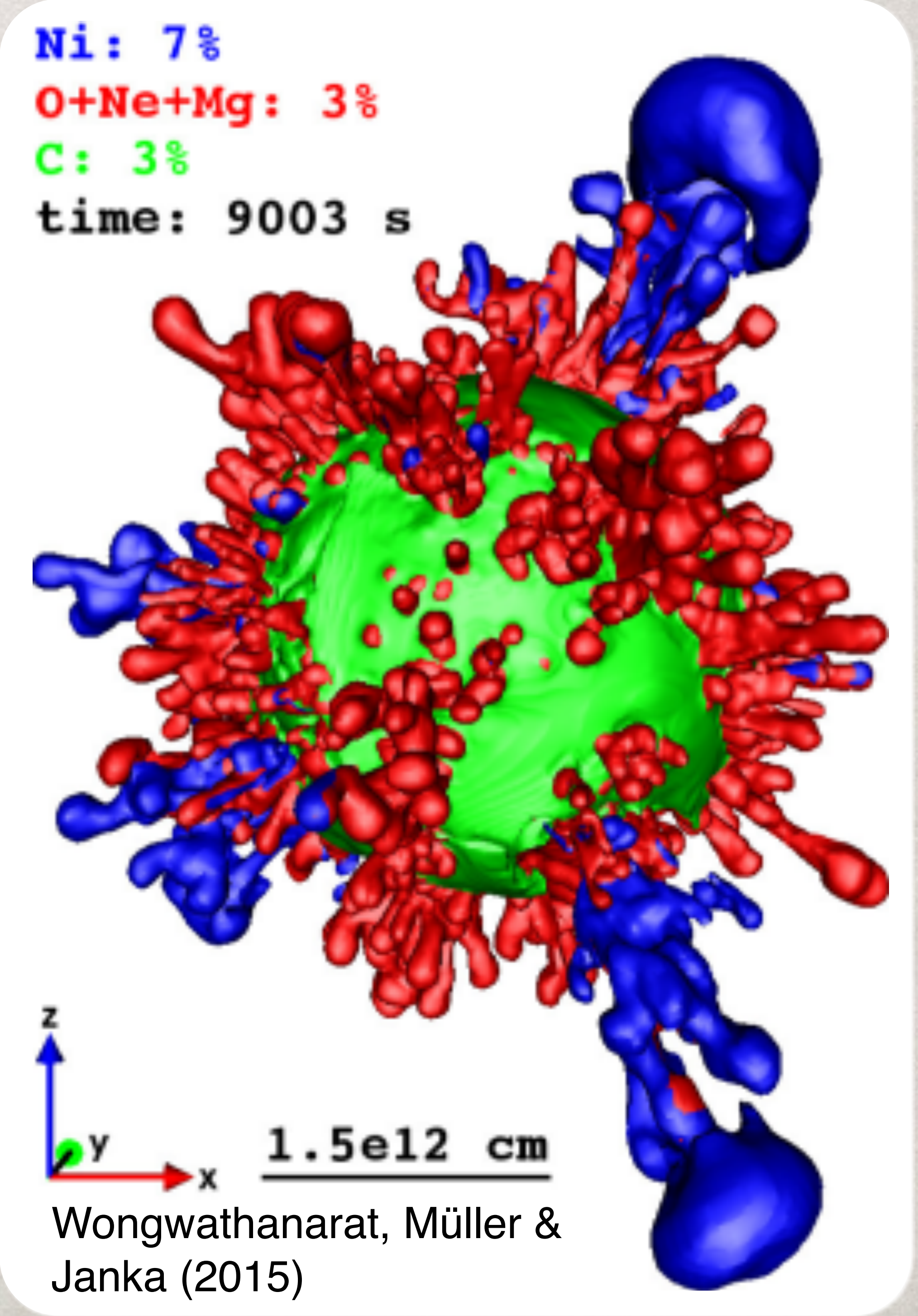
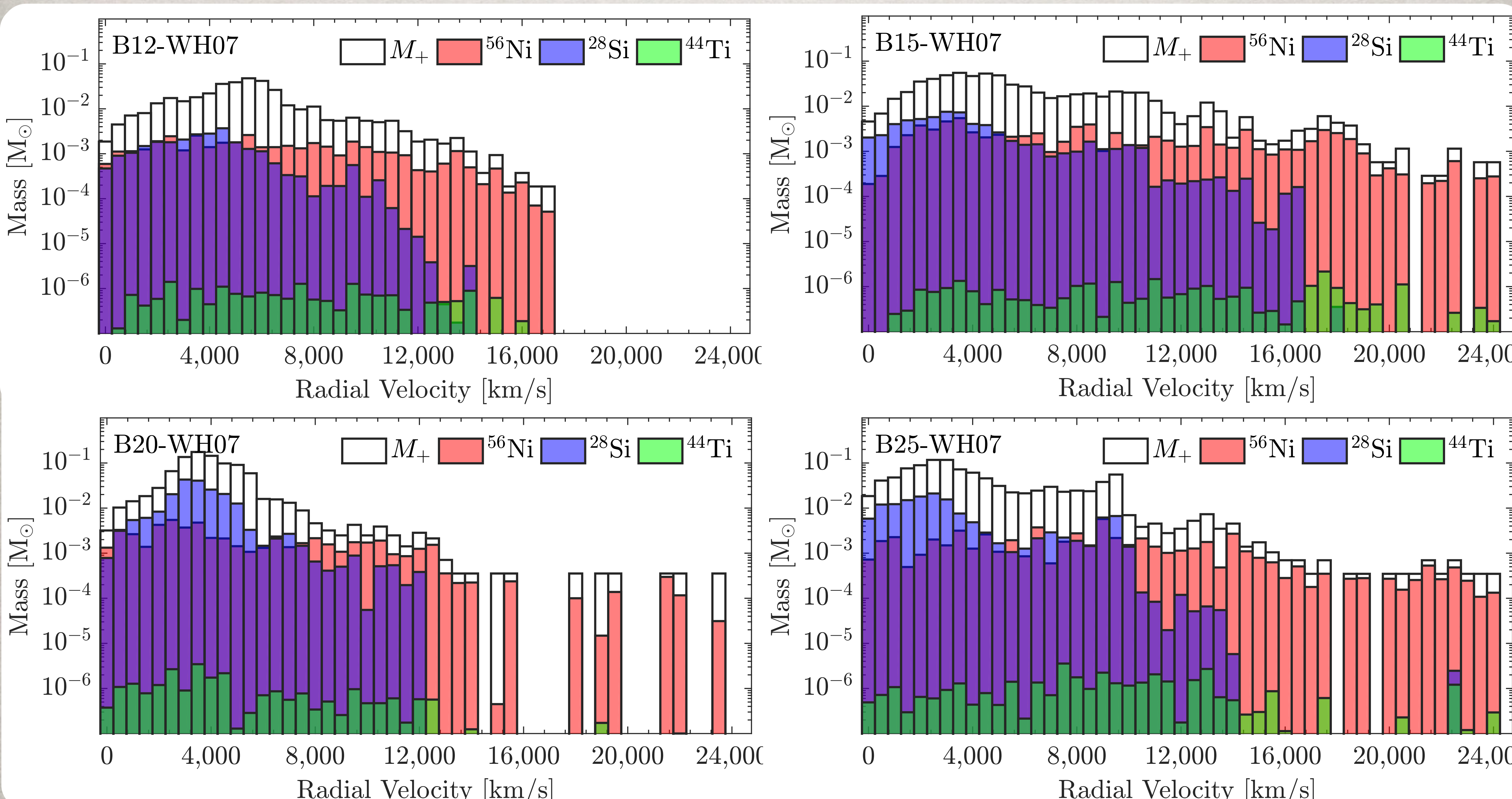


Wongwathanarat, Müller & Janka (2015)

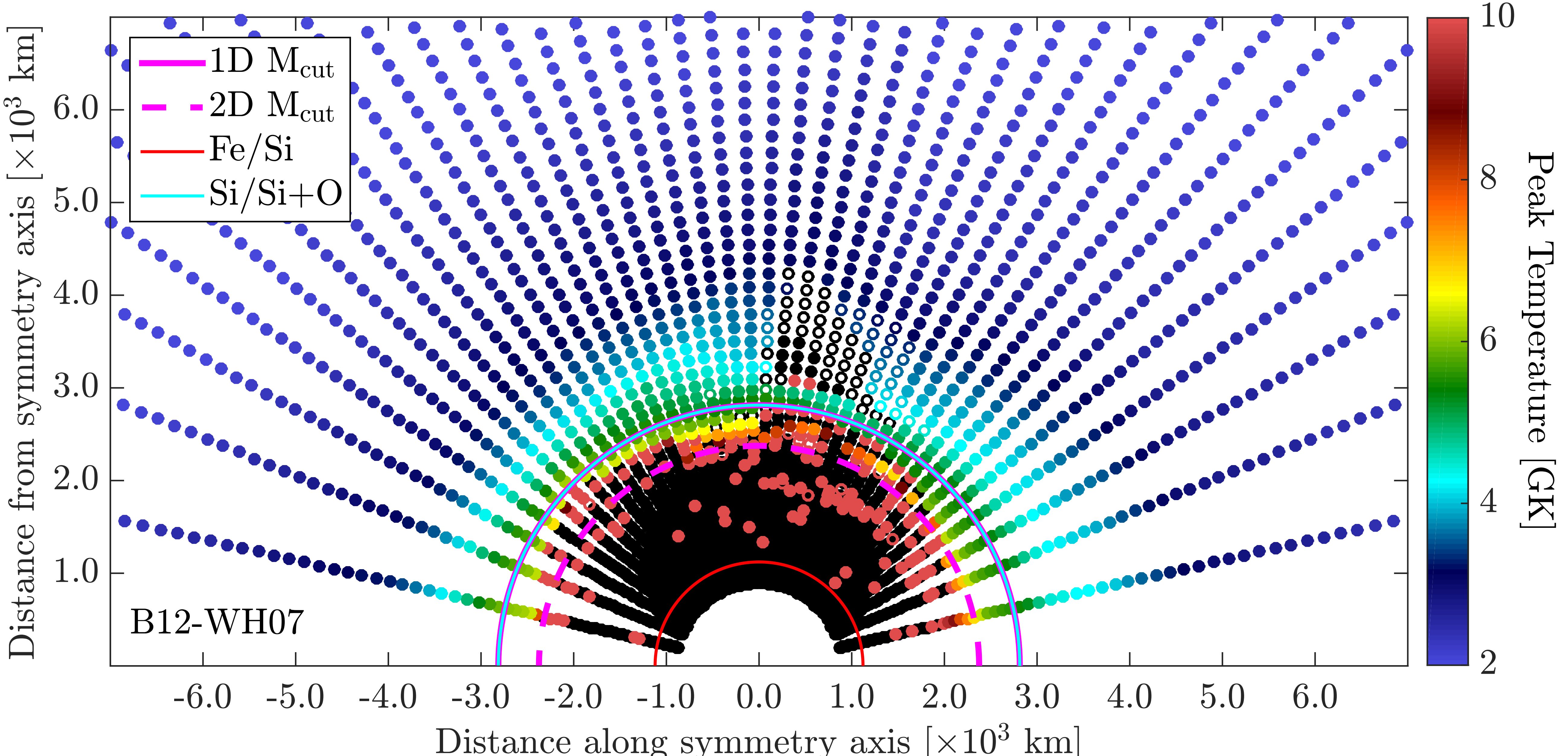
Slow Ni?

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



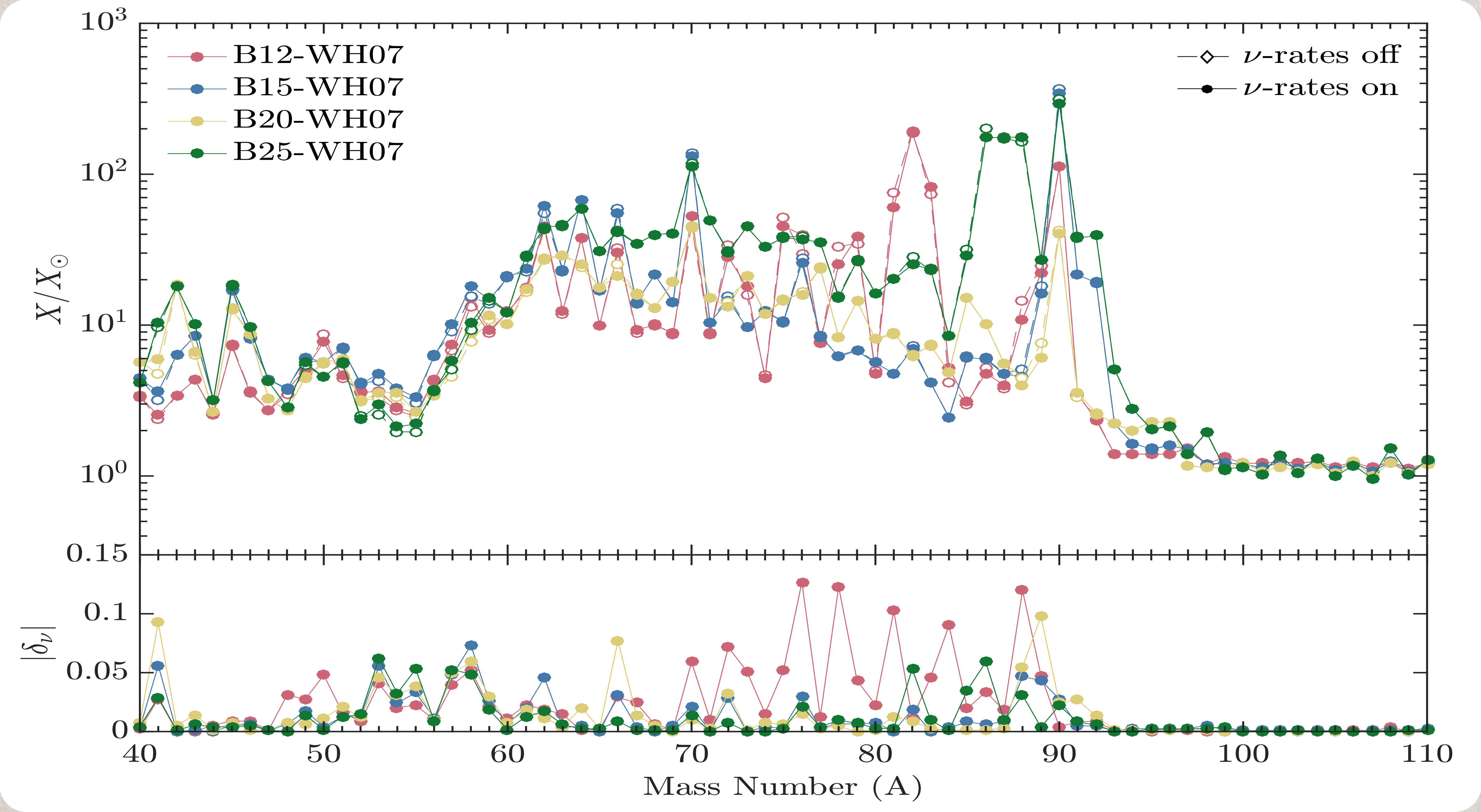
How distorted is the Mass Cut?

The Lagrangian view provided by tracer particles reveals the complexity of the mass cut, with discontiguous patches of ejecta (color dots) and bound matter (black dots).



Where is the νp-process?

The νp-process is very weak in our models, even at 1.2-1.4 seconds.



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

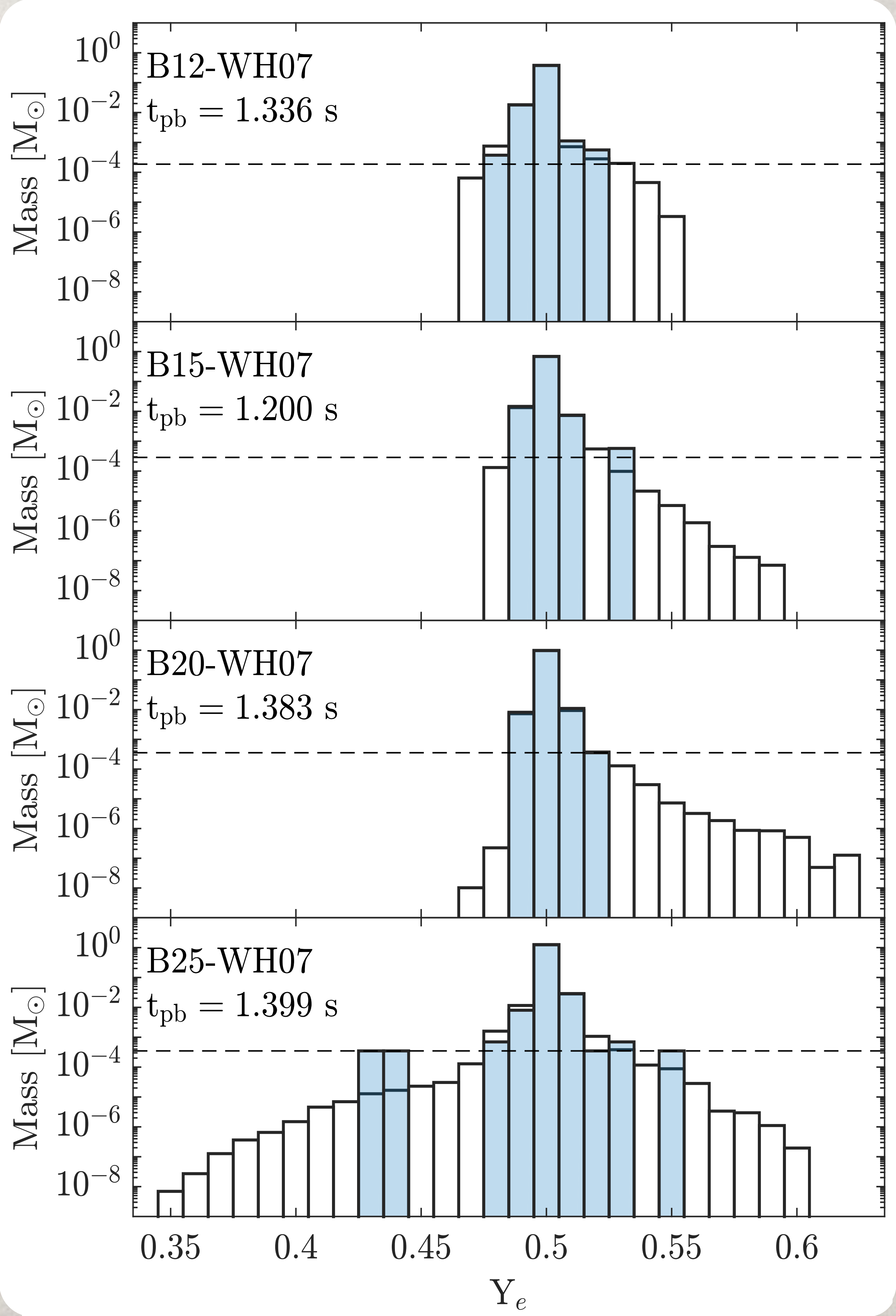
How many Tracers is Enough?

One way to view 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.

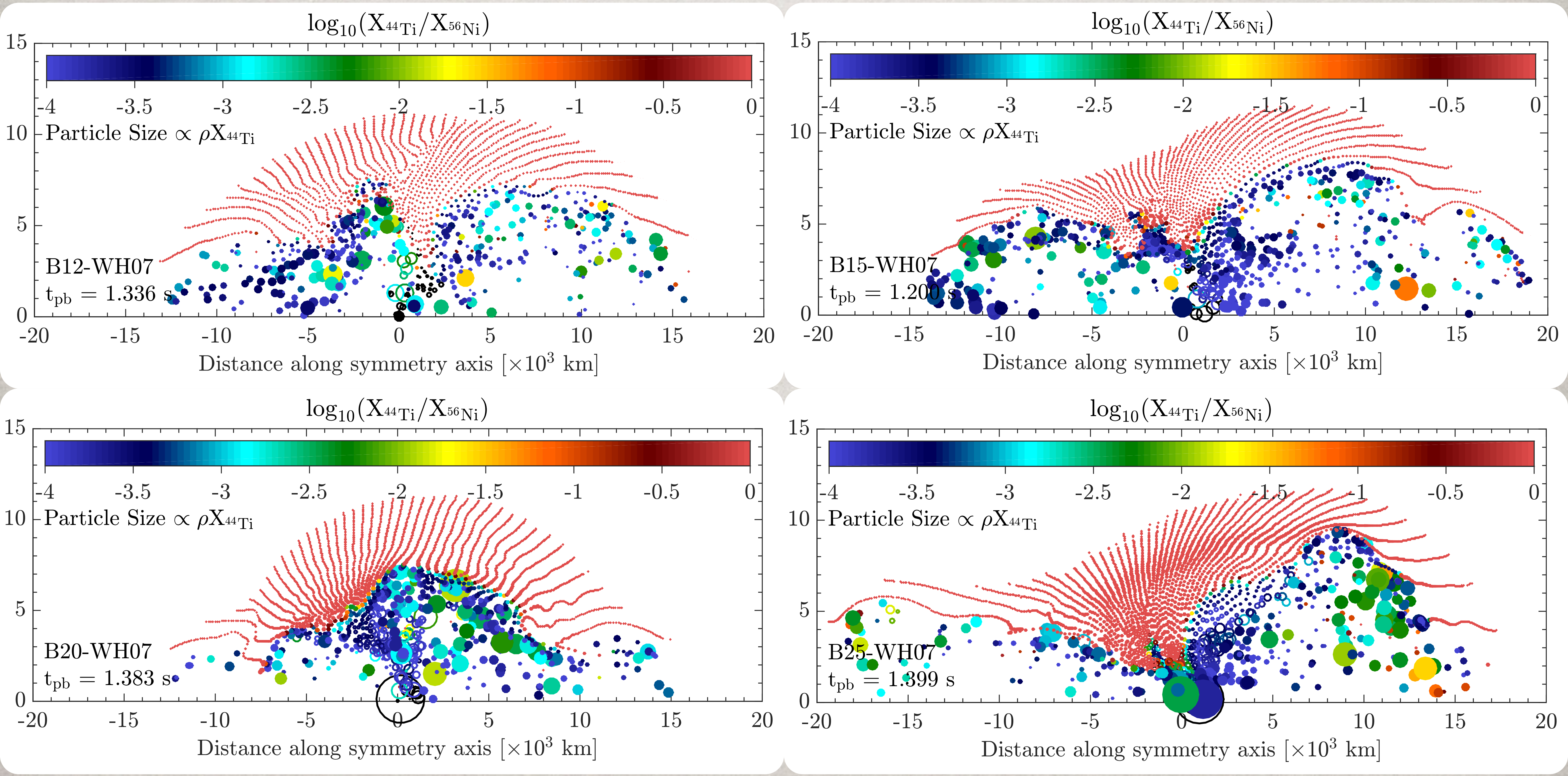
For the CHIMERA B-series, run to 1.2-1.4 s after bounce, this is the largest uncertainty, though it only affects α-rich freezeout.

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}**



Can we make Ti without Ni?

The observations of Cas A by Grefenstette, … (2014), and follow-ups at other wavelengths, put significant limits on the amount of Fe (Ni) that is co-resident with ^{44}Ti, which 1D models can't replicate.



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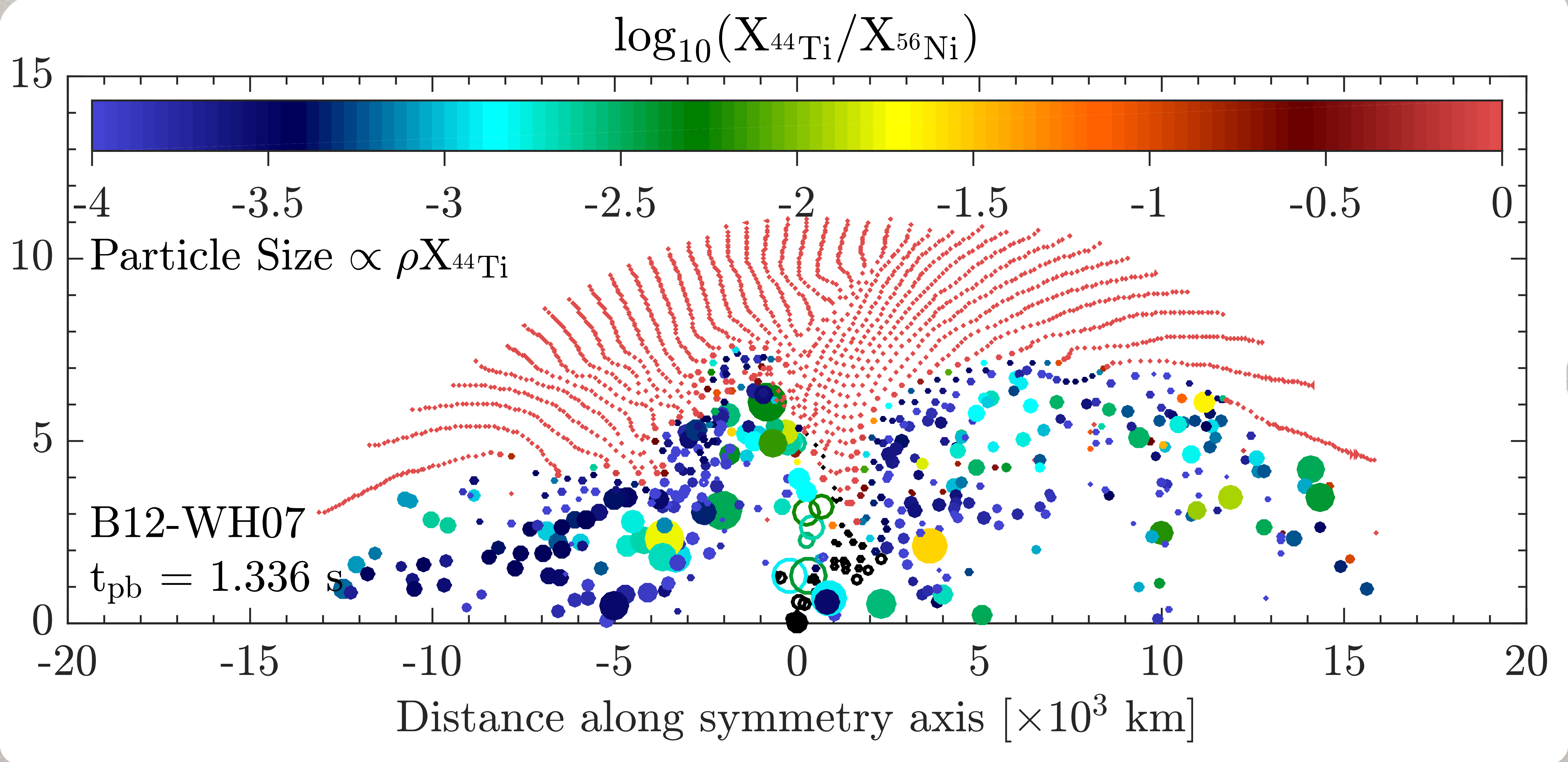
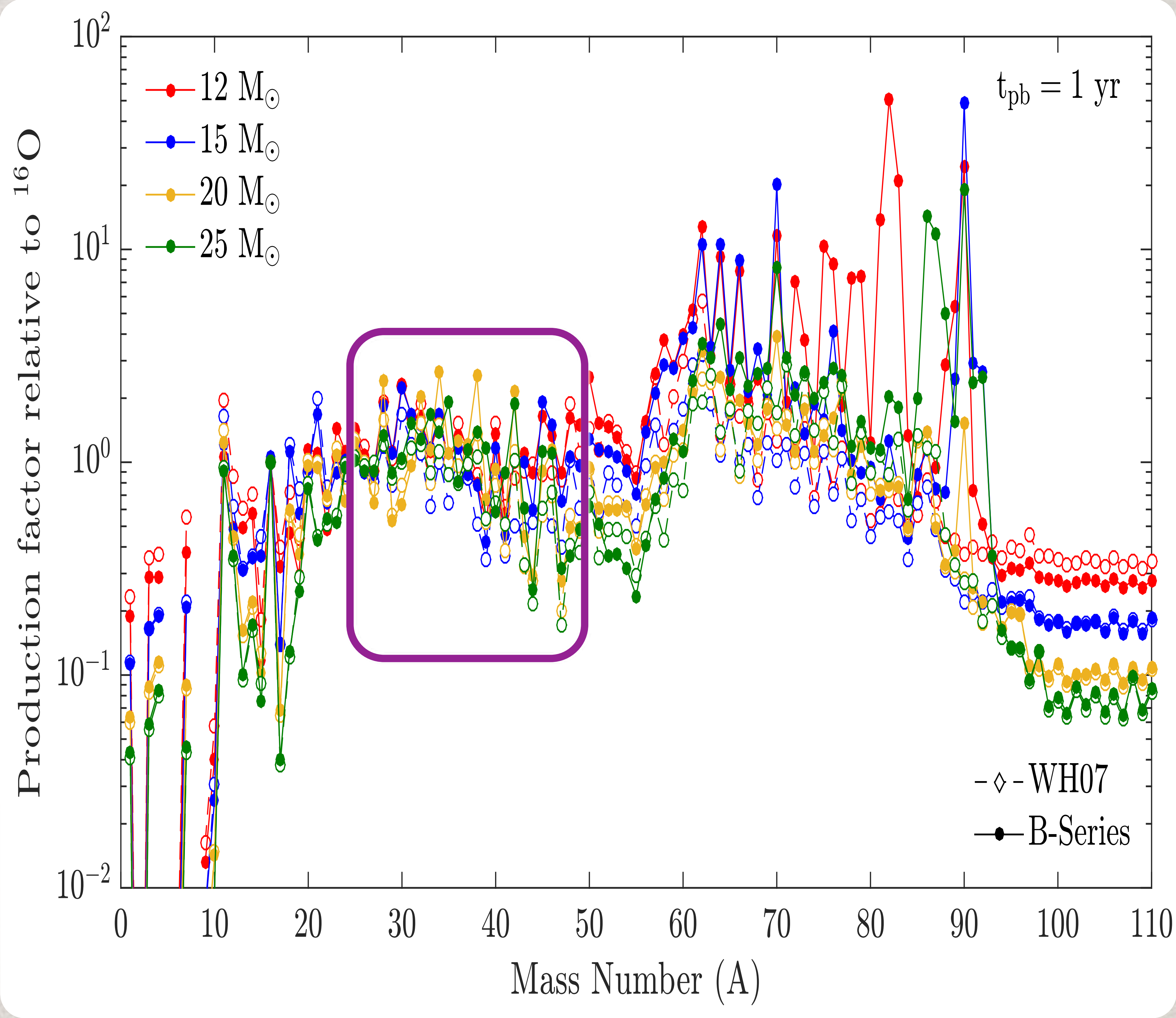


are 1D results reasonable?

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.



ARE 1D RESULTS REASONABLE?

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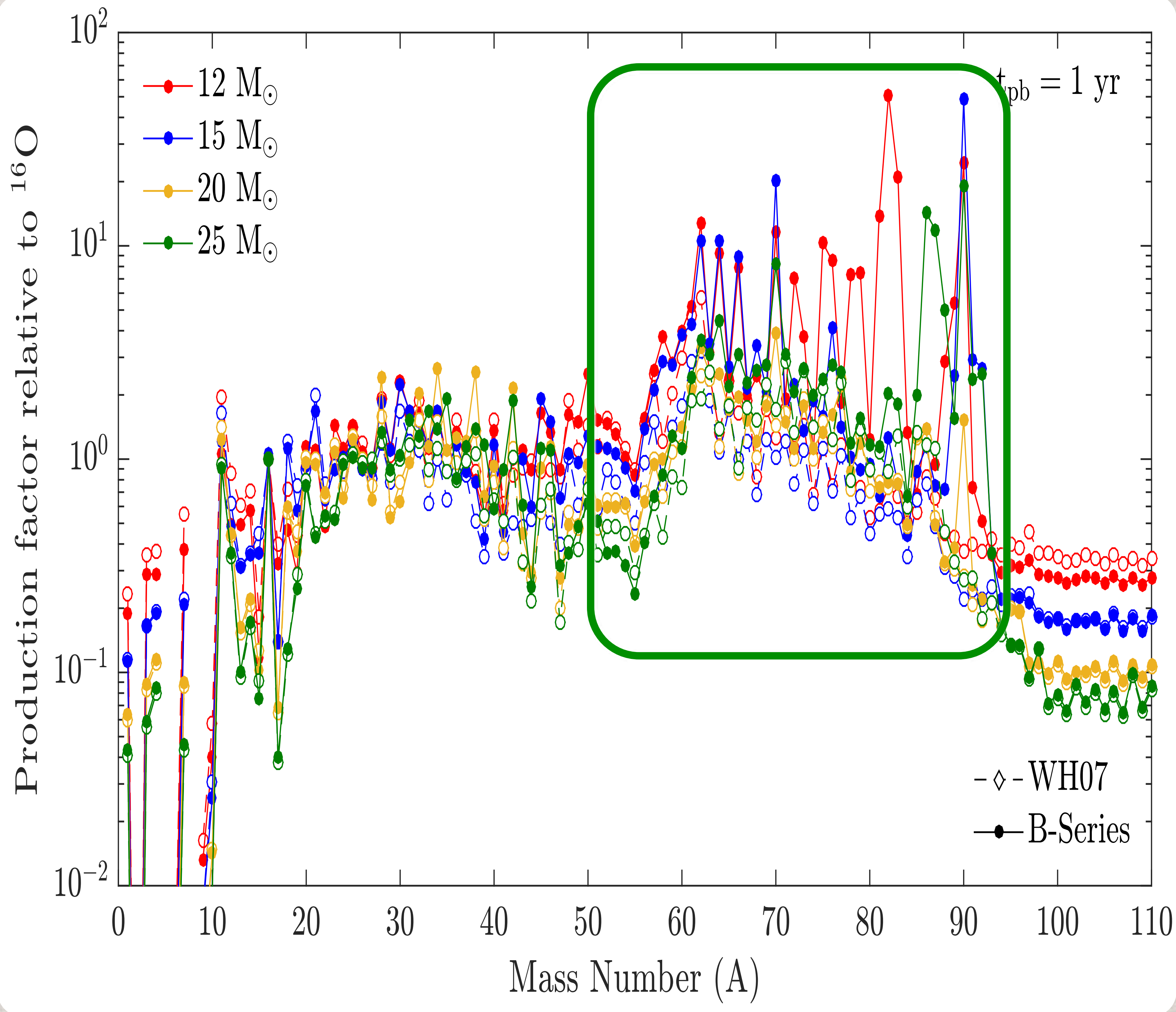
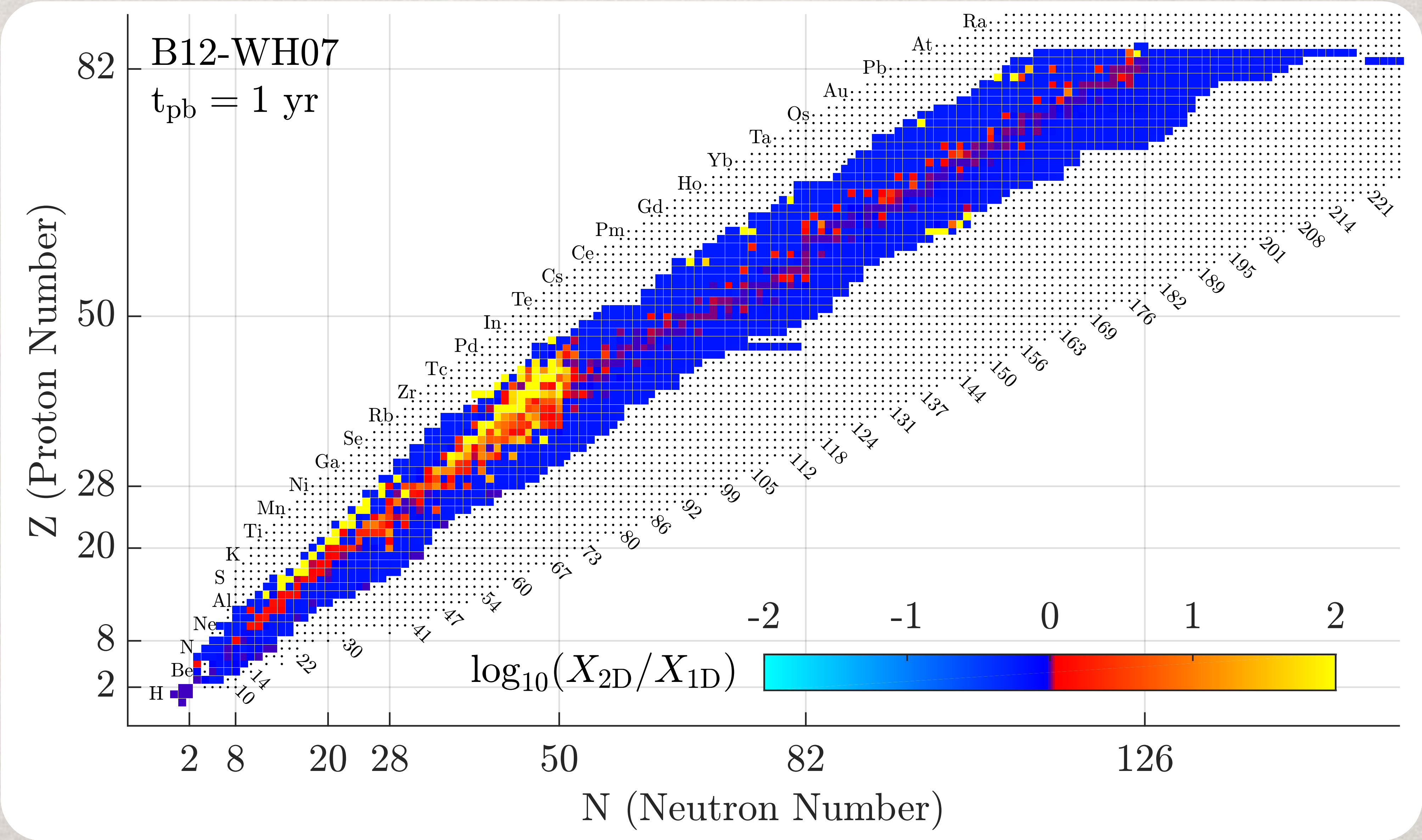


Iron peak and heavier, up to A=90, the differences get larger.

How does Multi-D impact ejecta?

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



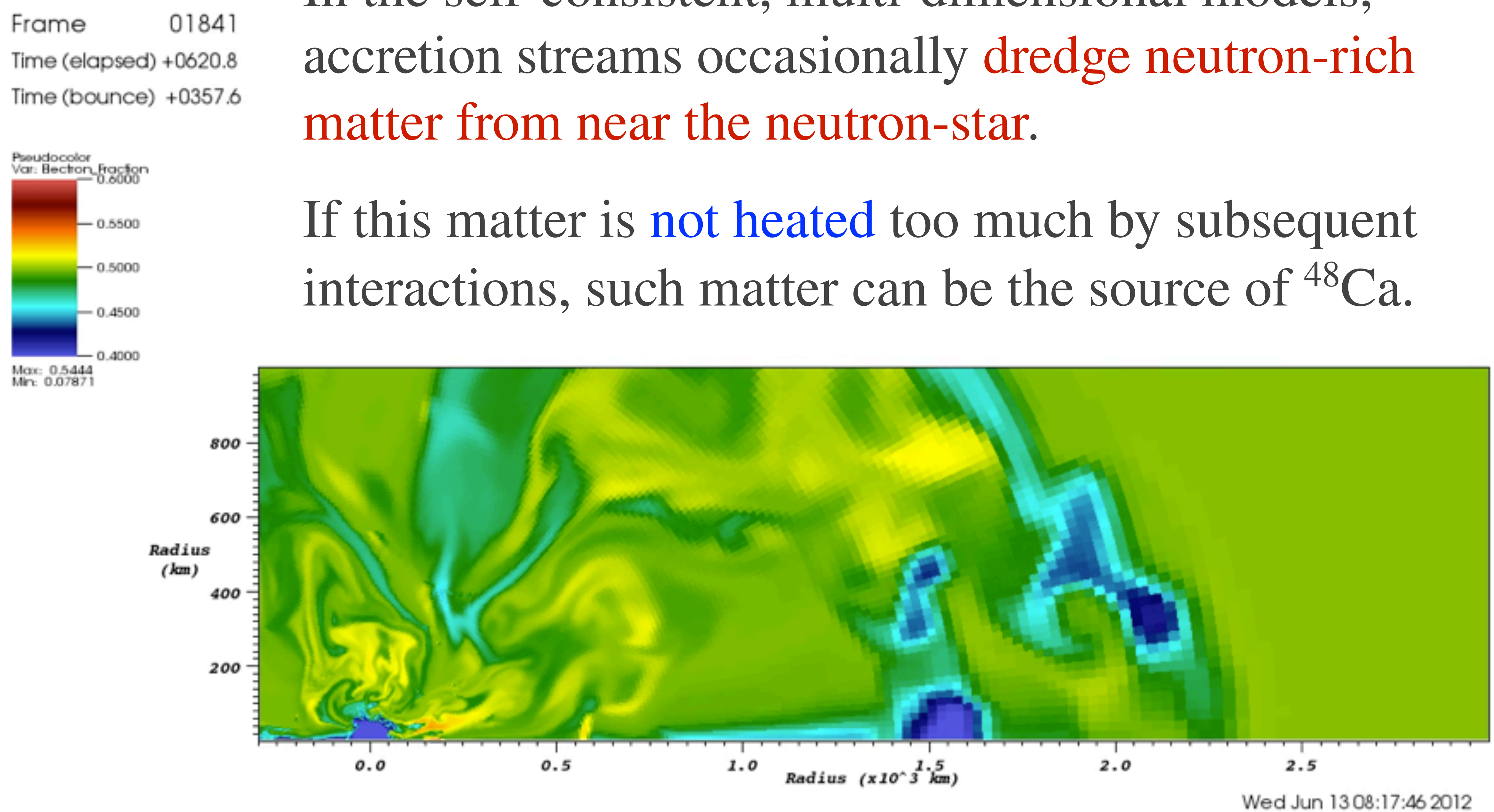
Deeper Mass Cut results in modest increase in intermediate mass and iron-group elements.

Can we make ^{48}Ca in a CCSN?

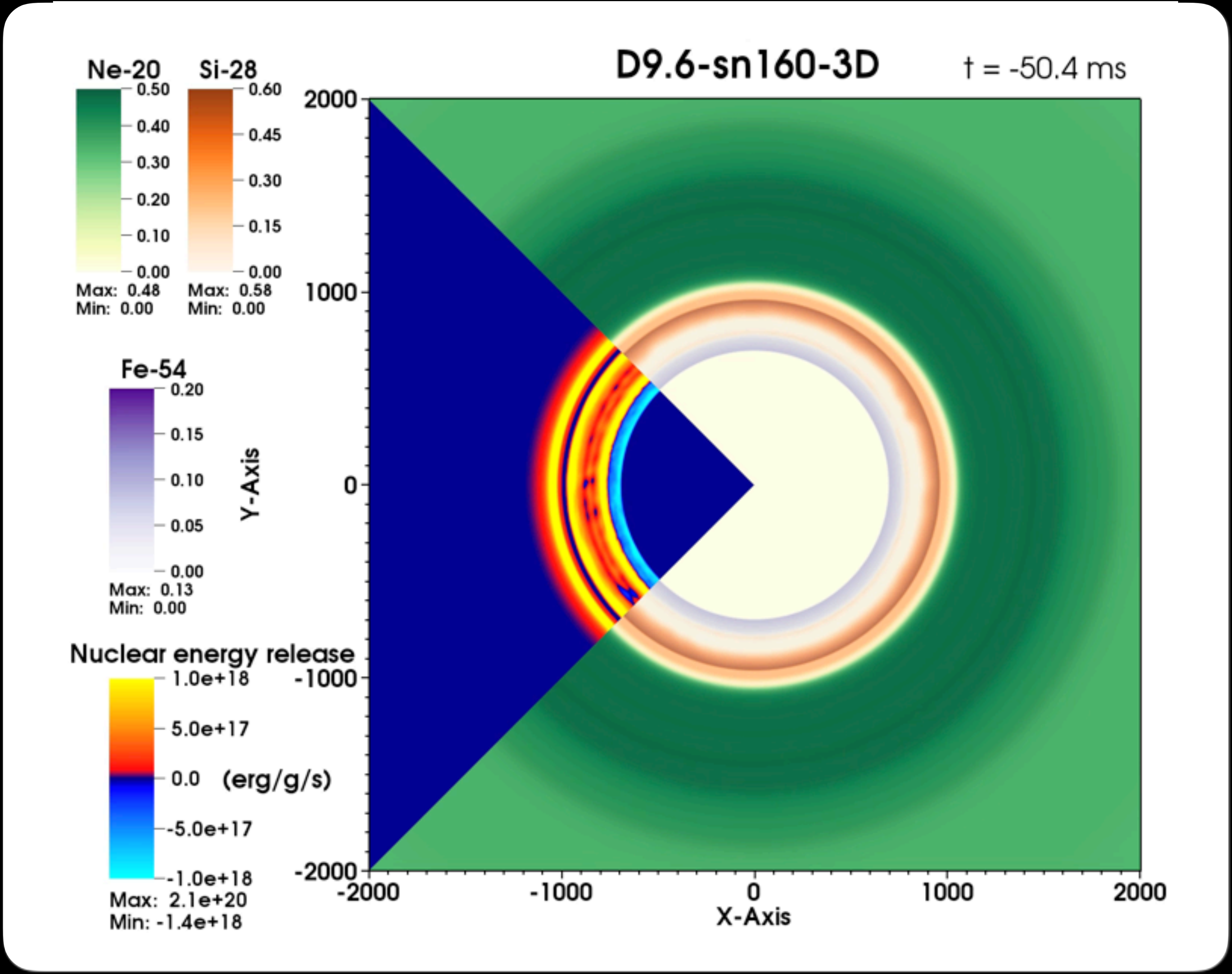
Argument has been that ejecta in parameterized spherically symmetric models is all too high in entropy to make ^{48}Ca.

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

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



What Else Can we Find?



Answers, so far

Examining the nucleosynthesis of CCSN with models that self-consistently treat the explosion mechanism is possible but it requires running models to times > 1 second 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 a lot of work yet to be both on the mechanism (especially in 3D) and on the nucleosynthesis.