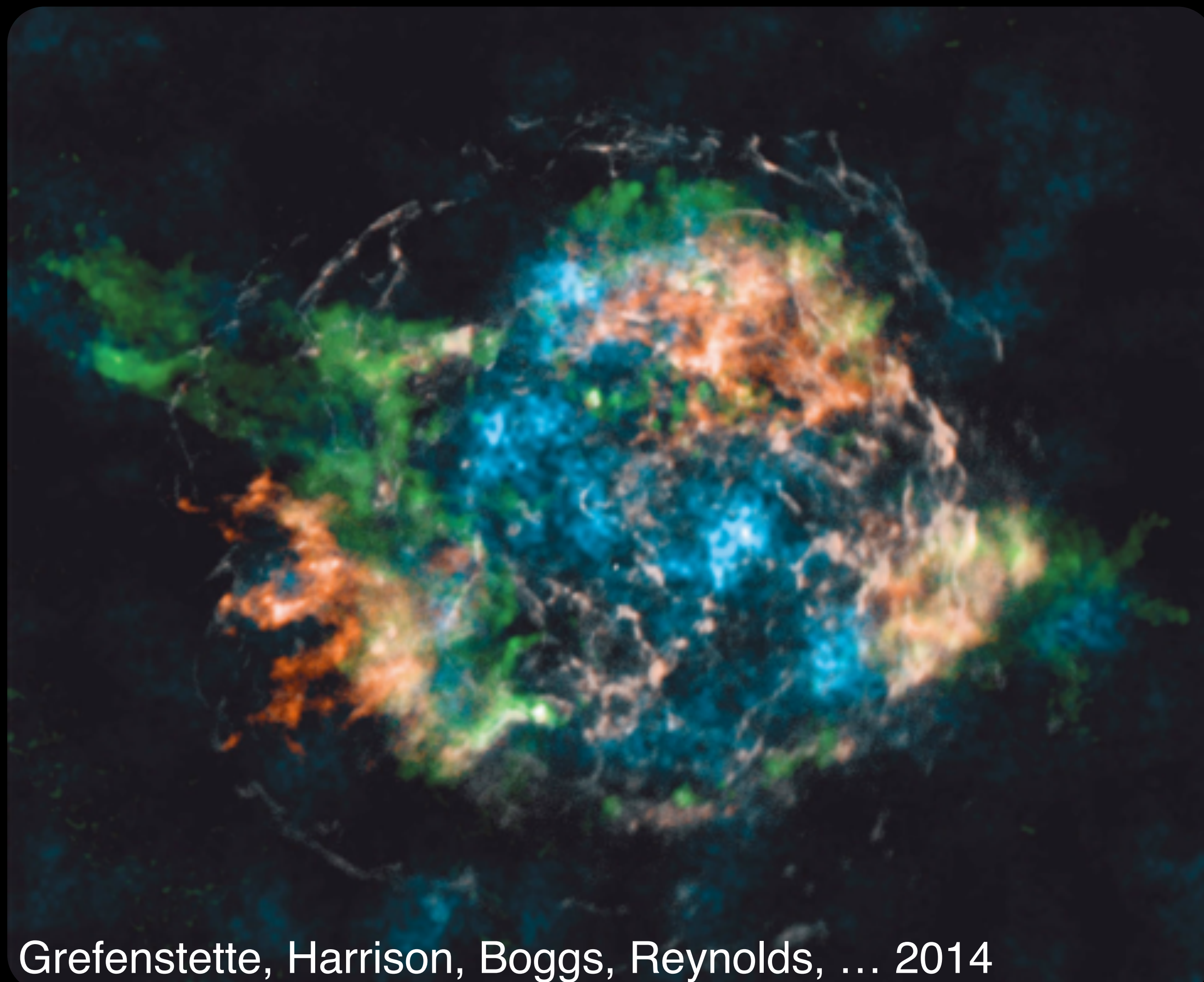
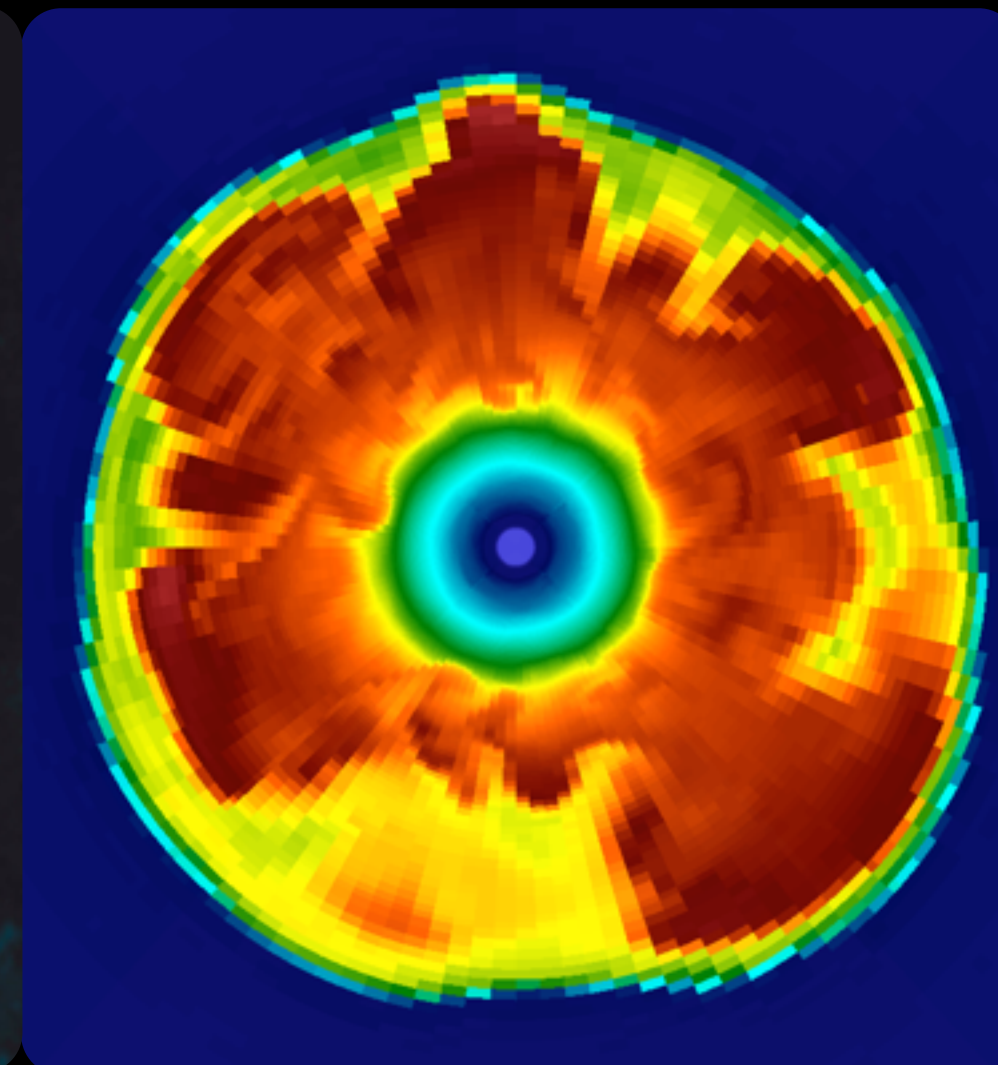
the Nucleosynthesis of



Grefenstette, Harrison, Boggs, Reynolds, … 2014

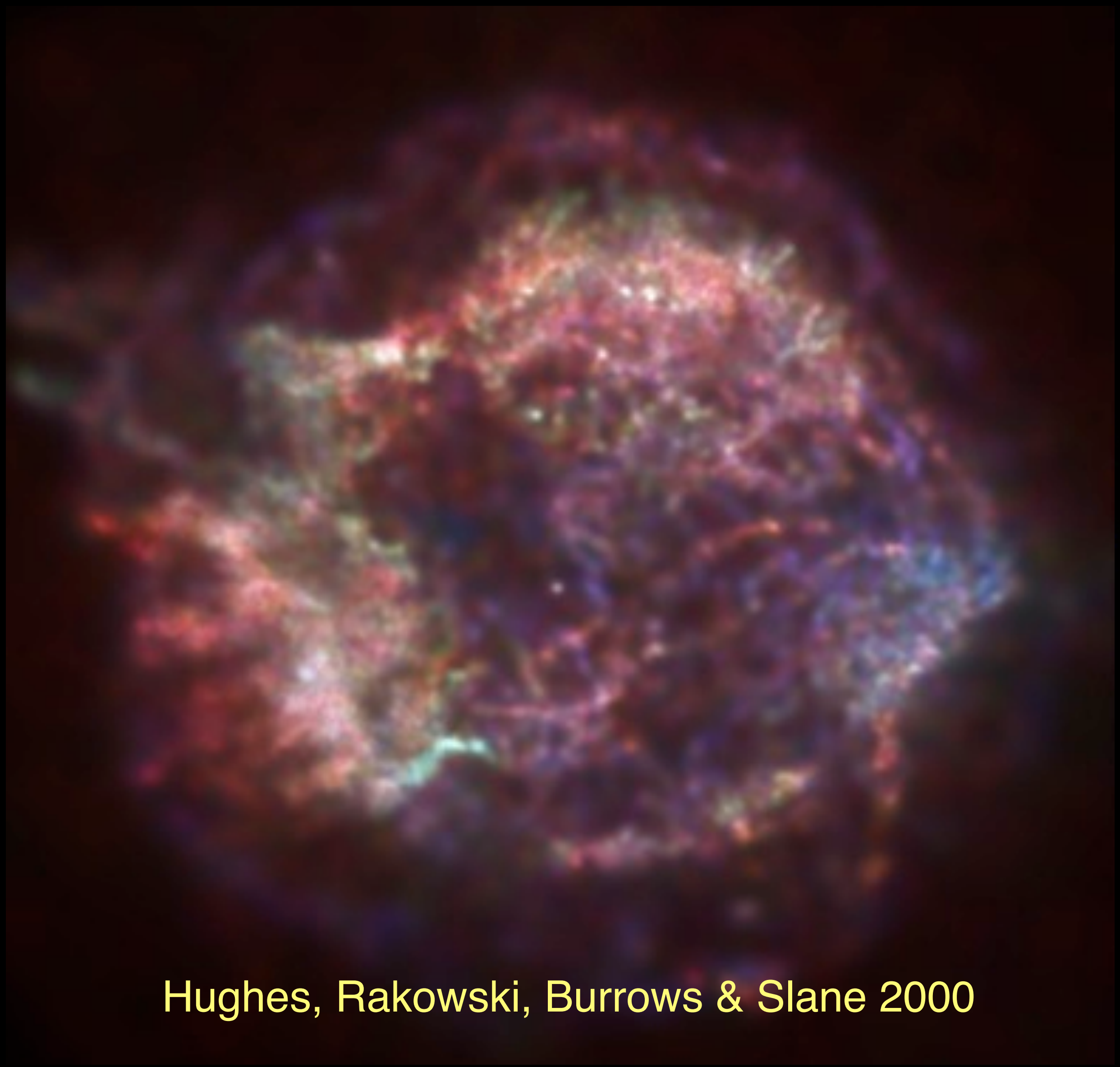


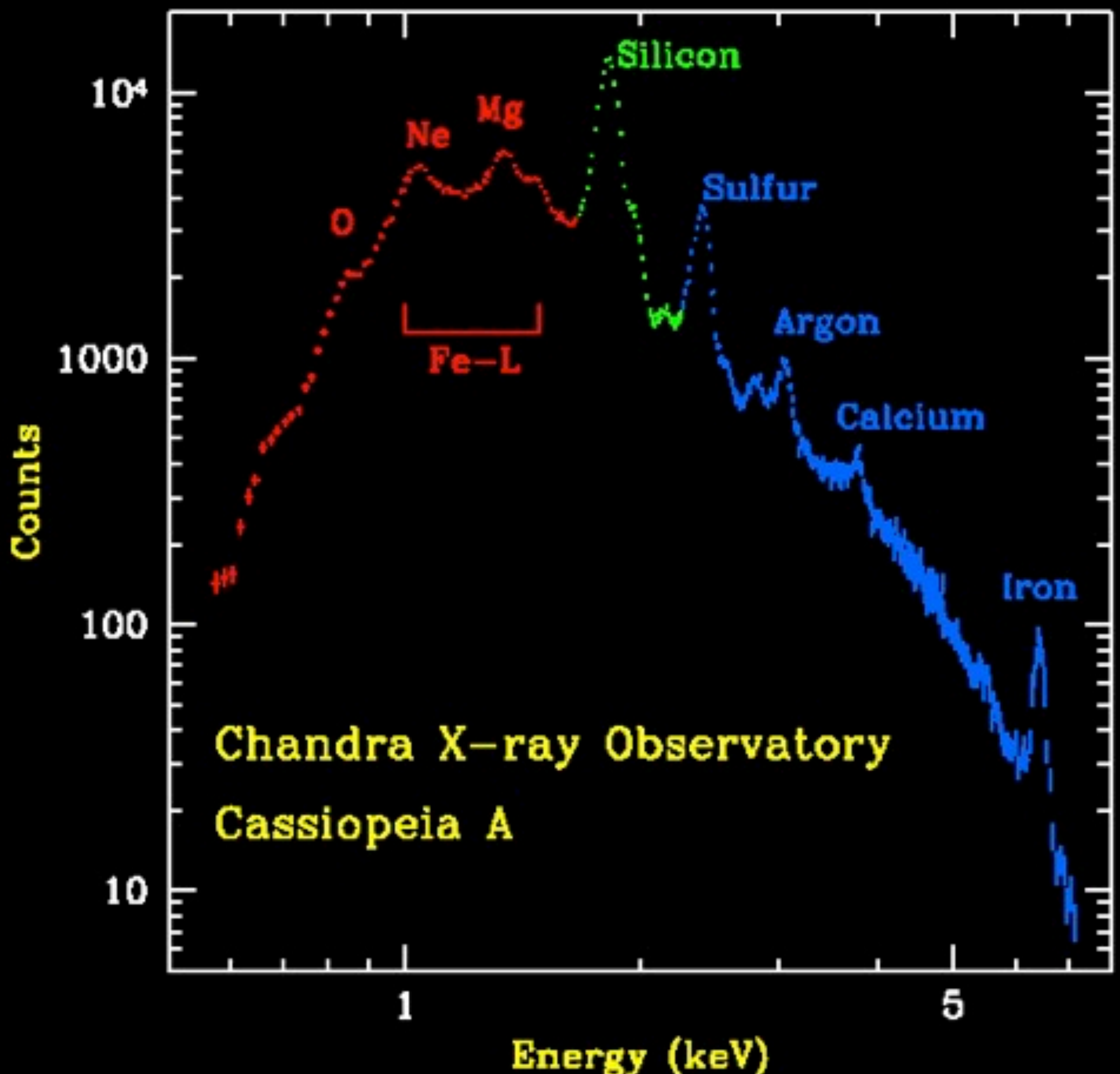
Core-Collapse Supernovae

W. Raphael Hix

ORNL Physics Division and UTK Department of Physics & Astronomy

Ejecta Rich in Heavy Elements



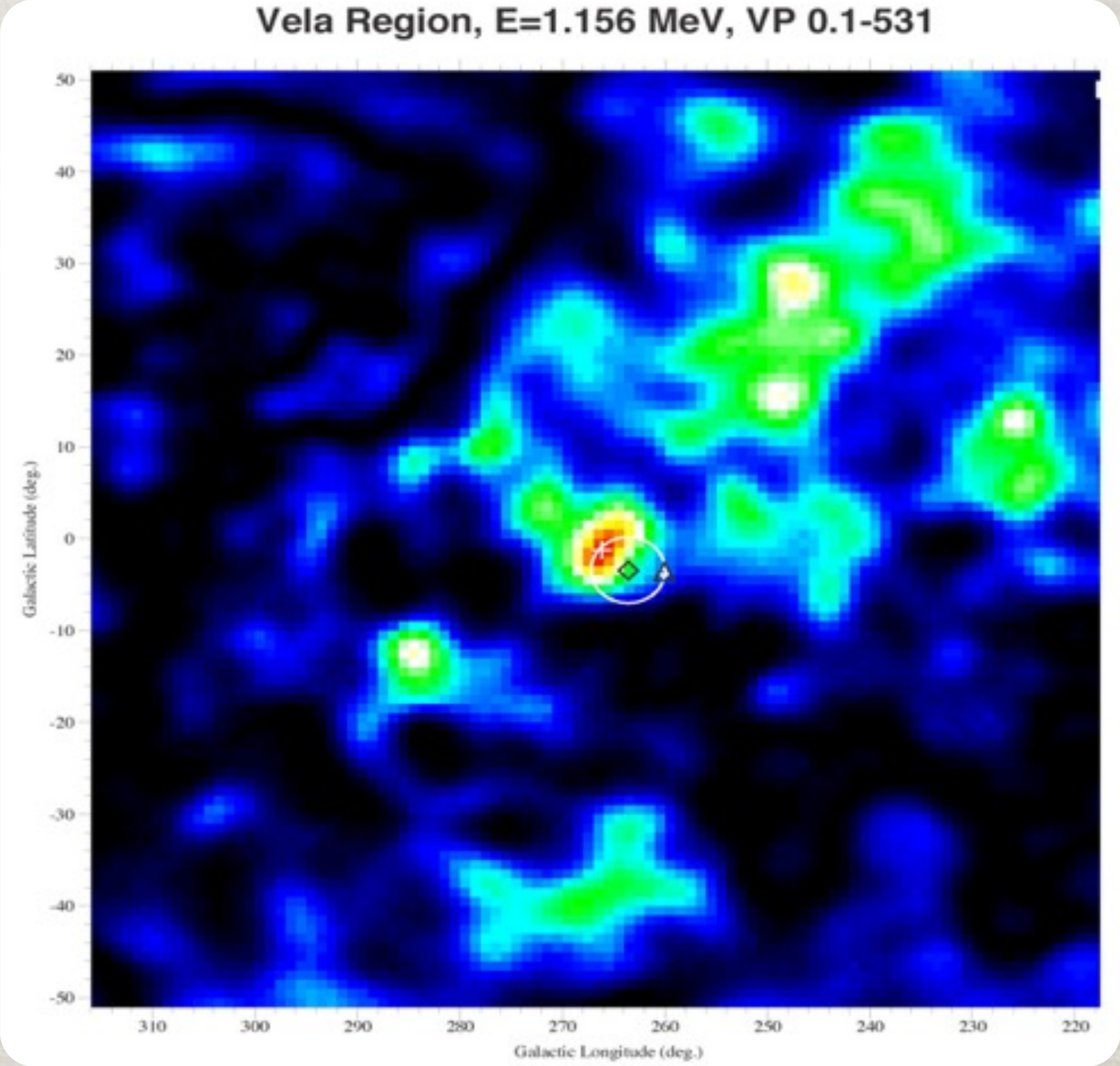


Supernovae from Massive Stars produce most of the elements from Oxygen through Silicon and Calcium and half of the Iron/Cobalt/Nickel.

They may also be responsible for the r-process.

Fresh Nuclei

Observations of core collapse supernovae reveal freshly made nuclear species.

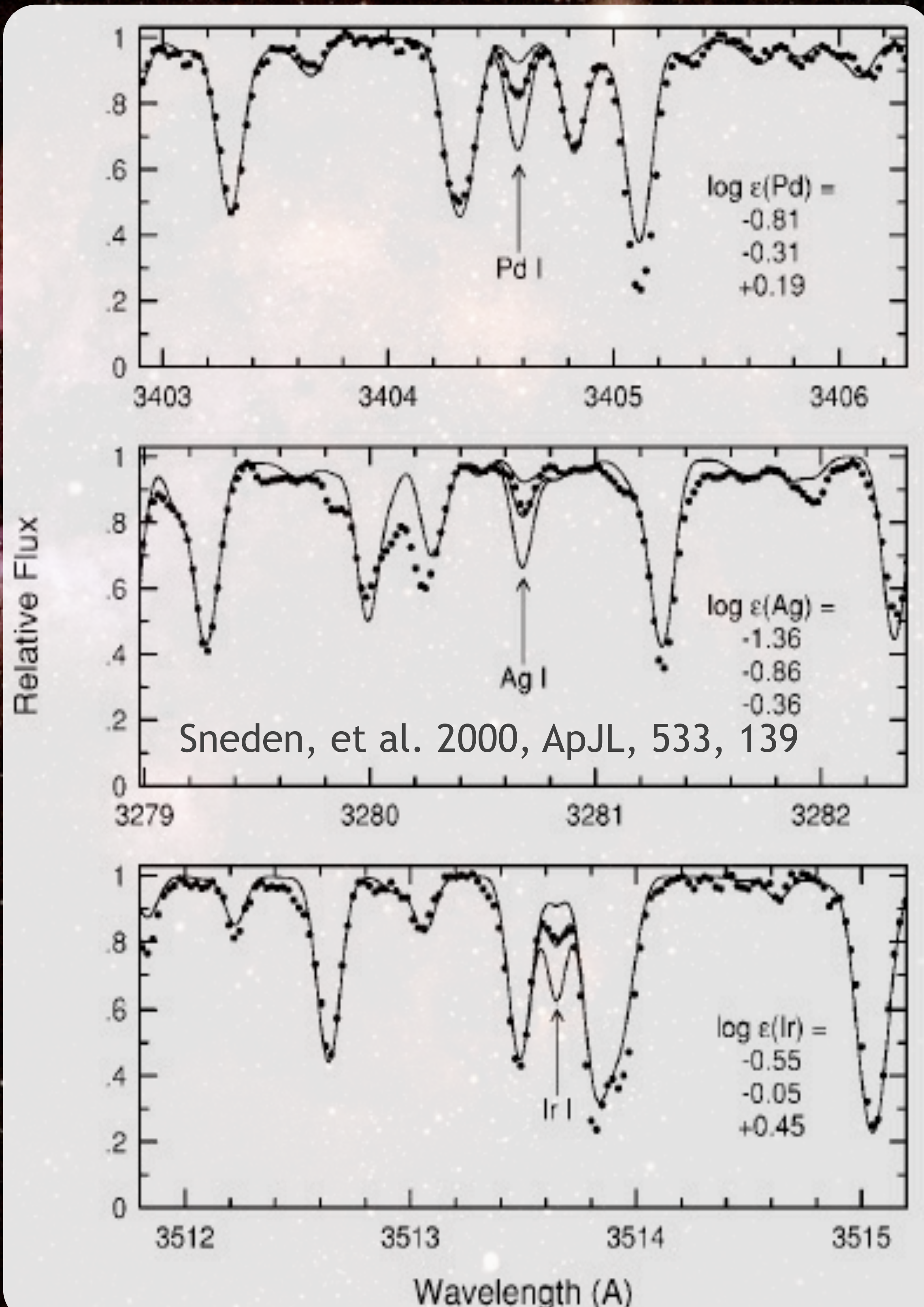


γ-ray telescopes reveal the characteristic γ-ray lines of ^{56}Ni ($t_{½}$ = 6 days), ^{57}Ni ($t_{½}$ = 36 hrs), ^{56}Co ($t_{½}$ = 77 days), ^{57}Co ($t_{½}$ = 272 days) and ^{44}Ti ($t_{½}$ = 60 yrs).

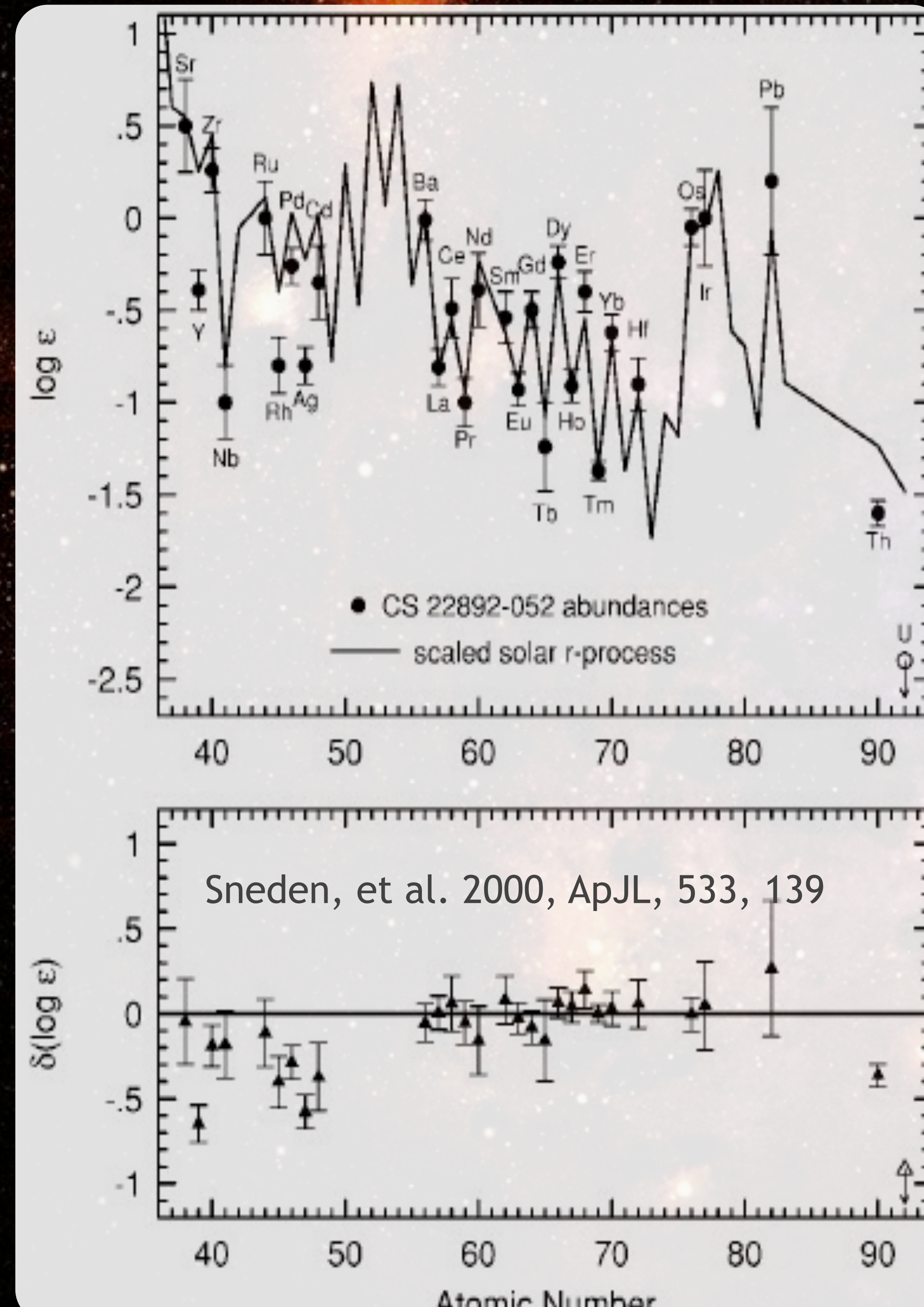
The supernova's light curve in the later, linear phase is powered by the conversion of ~0.1 $M_\odot$ of ^{56}Ni to ^{56}Co and ultimately ^{56}Fe.

Almost half of terrestrial iron was made in this way.

Elements in old stars



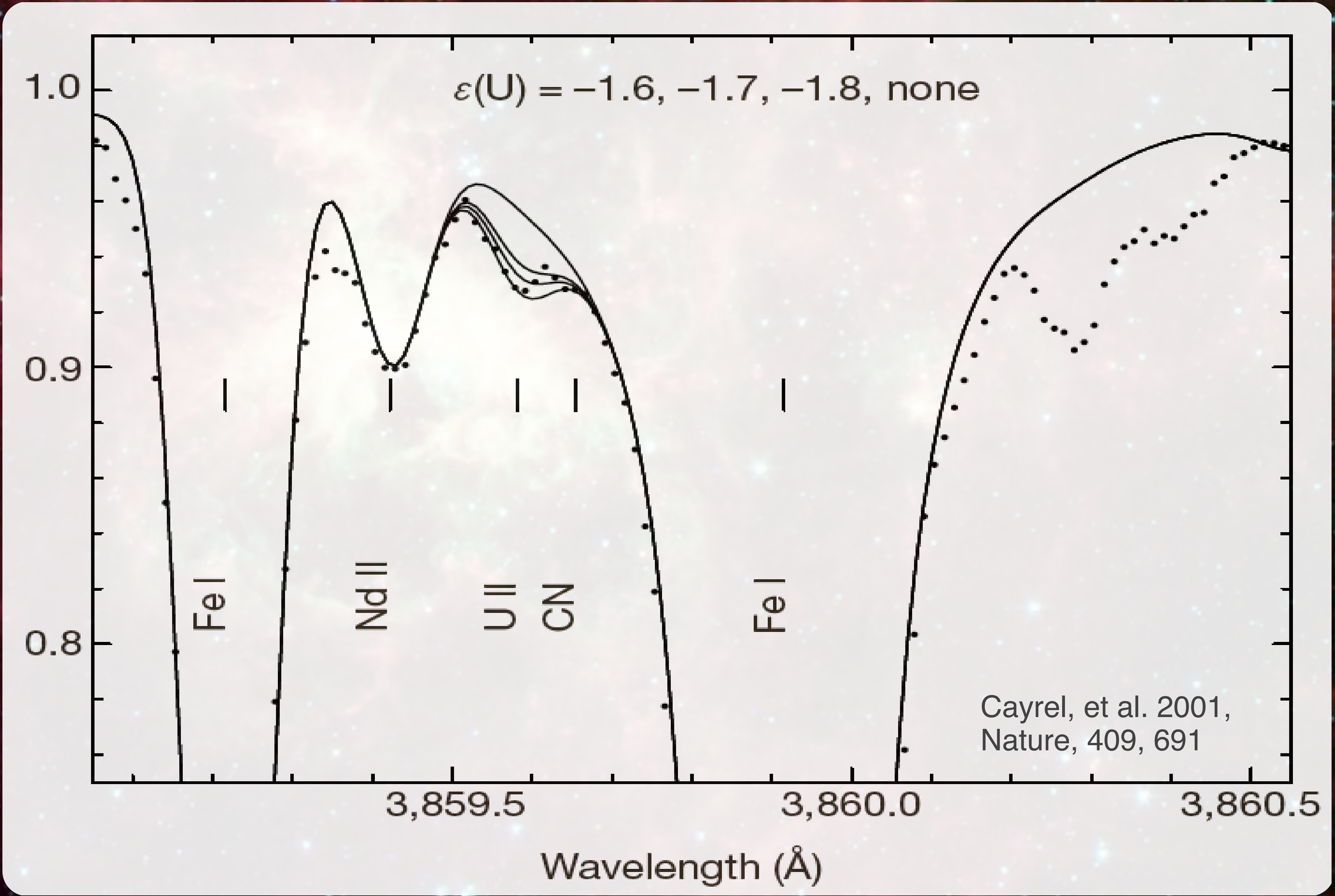
Sneden, et al. 2000, ApJL, 533, 139



Sneden, et al. 2000, ApJL, 533, 139

Uranium?

CS31082-001 has 1/800 Solar Fe but 1/9 Solar Os/Ir



Decay of ^{238}U ($t_{1/2}$ = 4.5 Gyr) implies 12.5±3 Gyr

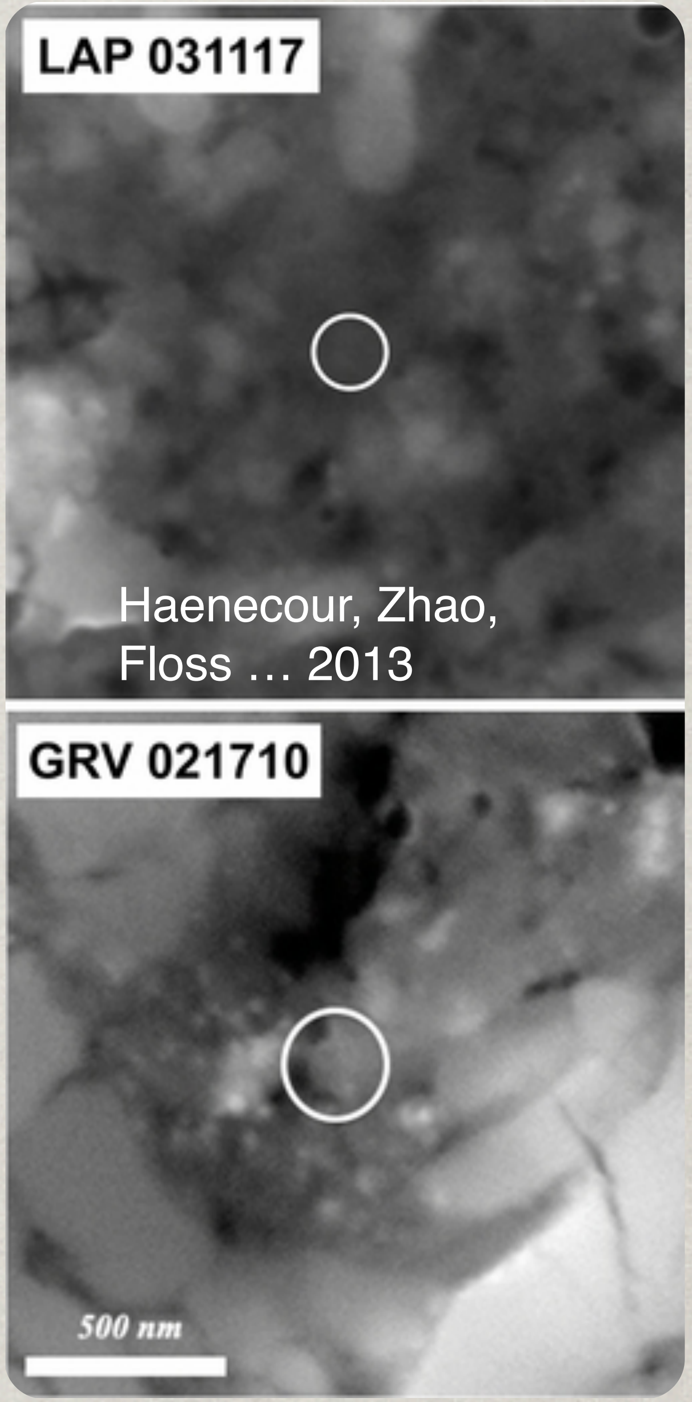
Grains

Aside from γ-ray observations, isotopic composition is challenging to uncover.

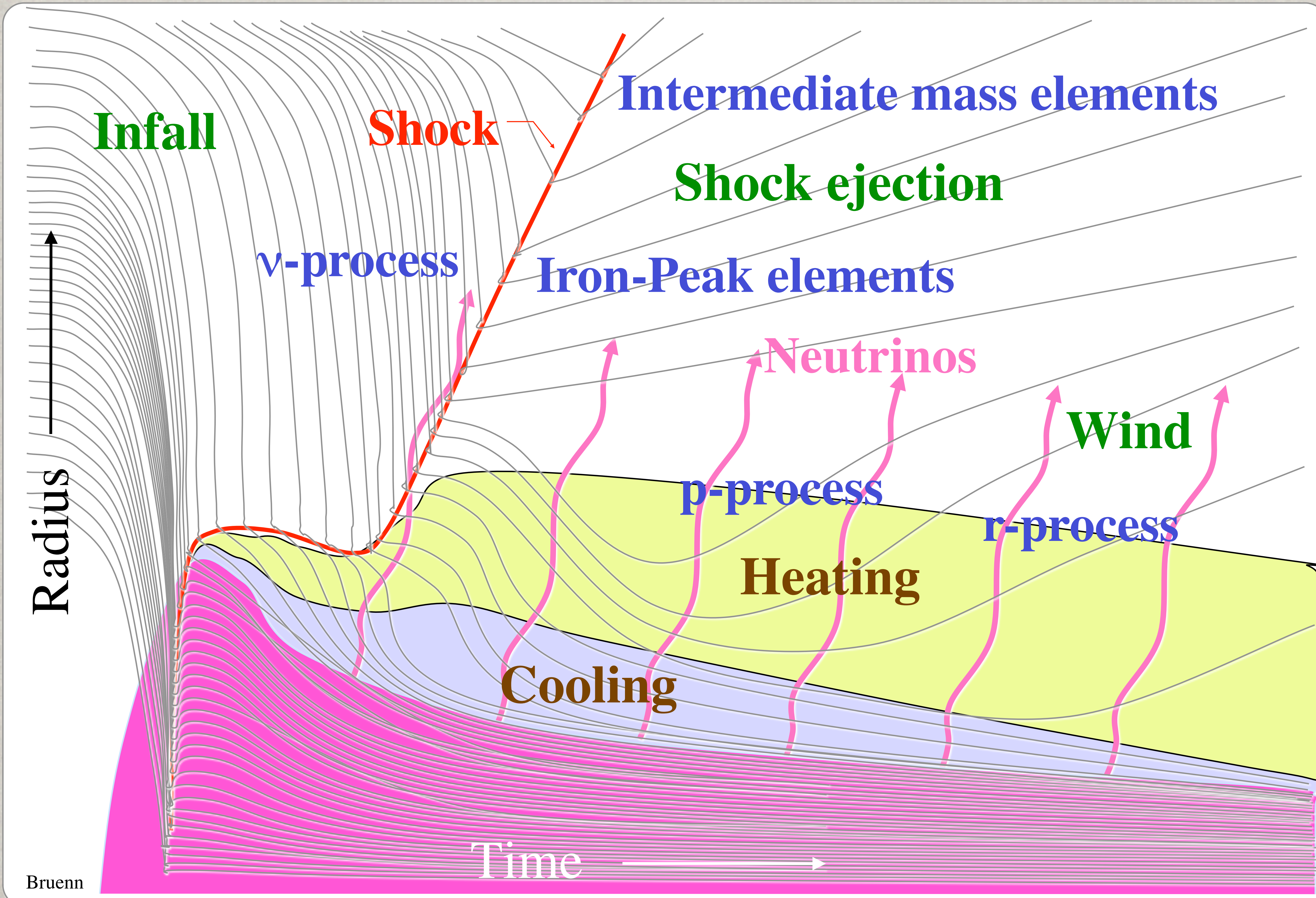
A unique source is presolar grains of SiC, graphite, aluminum oxide, and silicon nitride, up to several μm in size, incorporated into primitive meteorites.

Supernova grains, identified by an excess of ^{18}O, are the second most common type.

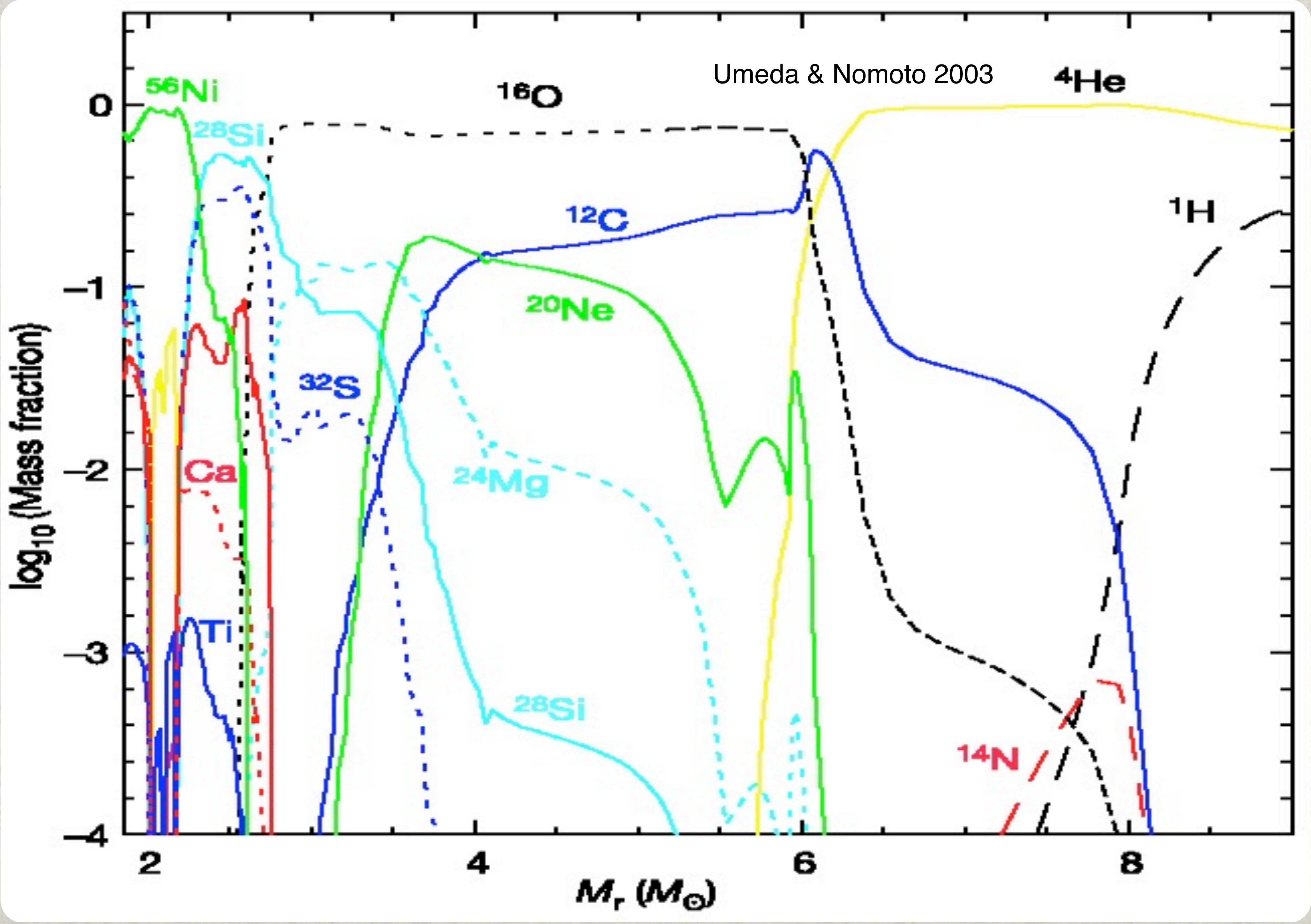
SiO_2 grains recently discovered in separate meteorites reveal very similar isotopic composition and suggest significant mixing of the supernova composition from the O layer, He/C layer and H envelope is needed to produce these grains.



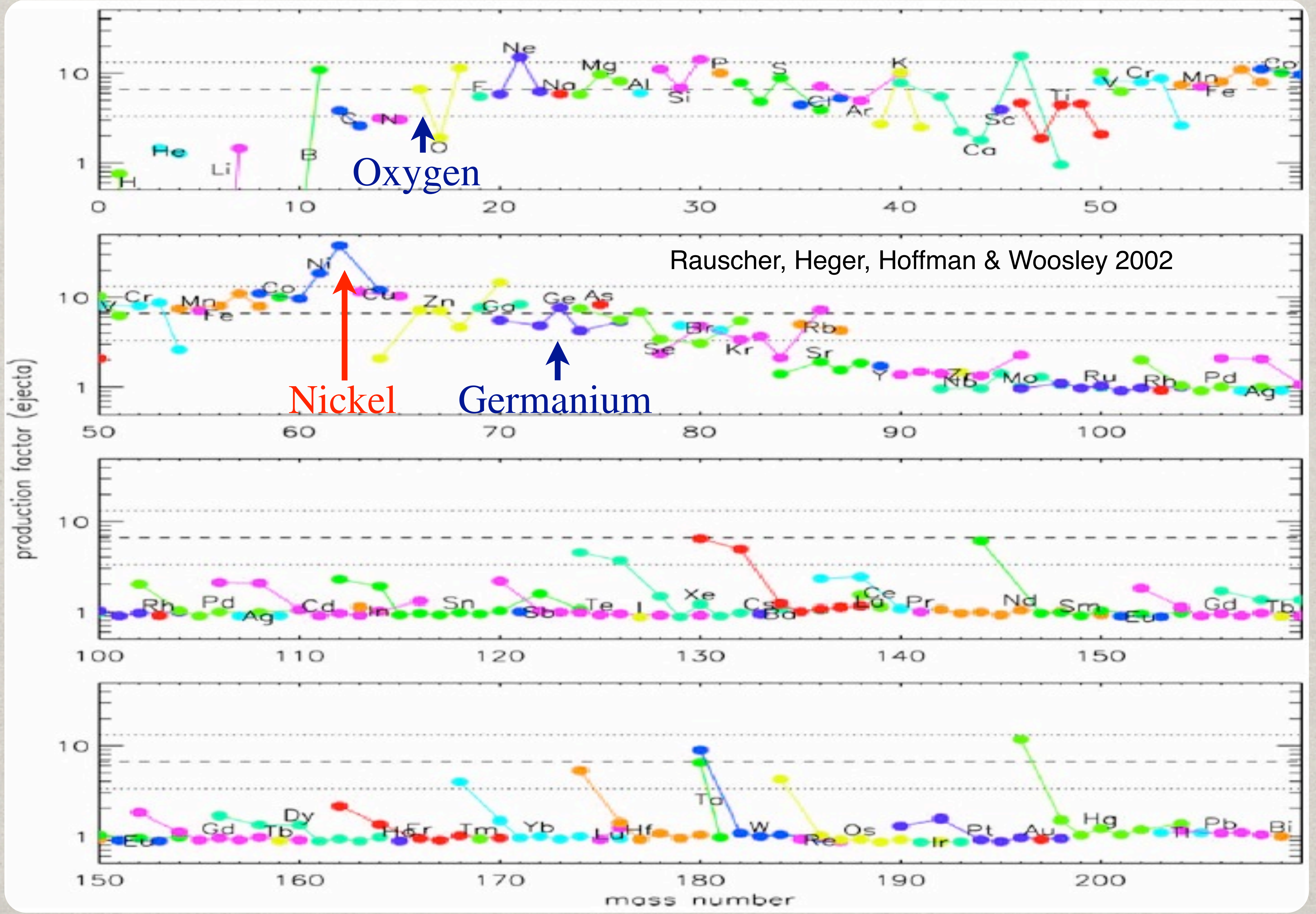
Supernovae Nucleosynthesis



Models rich in heavy elements

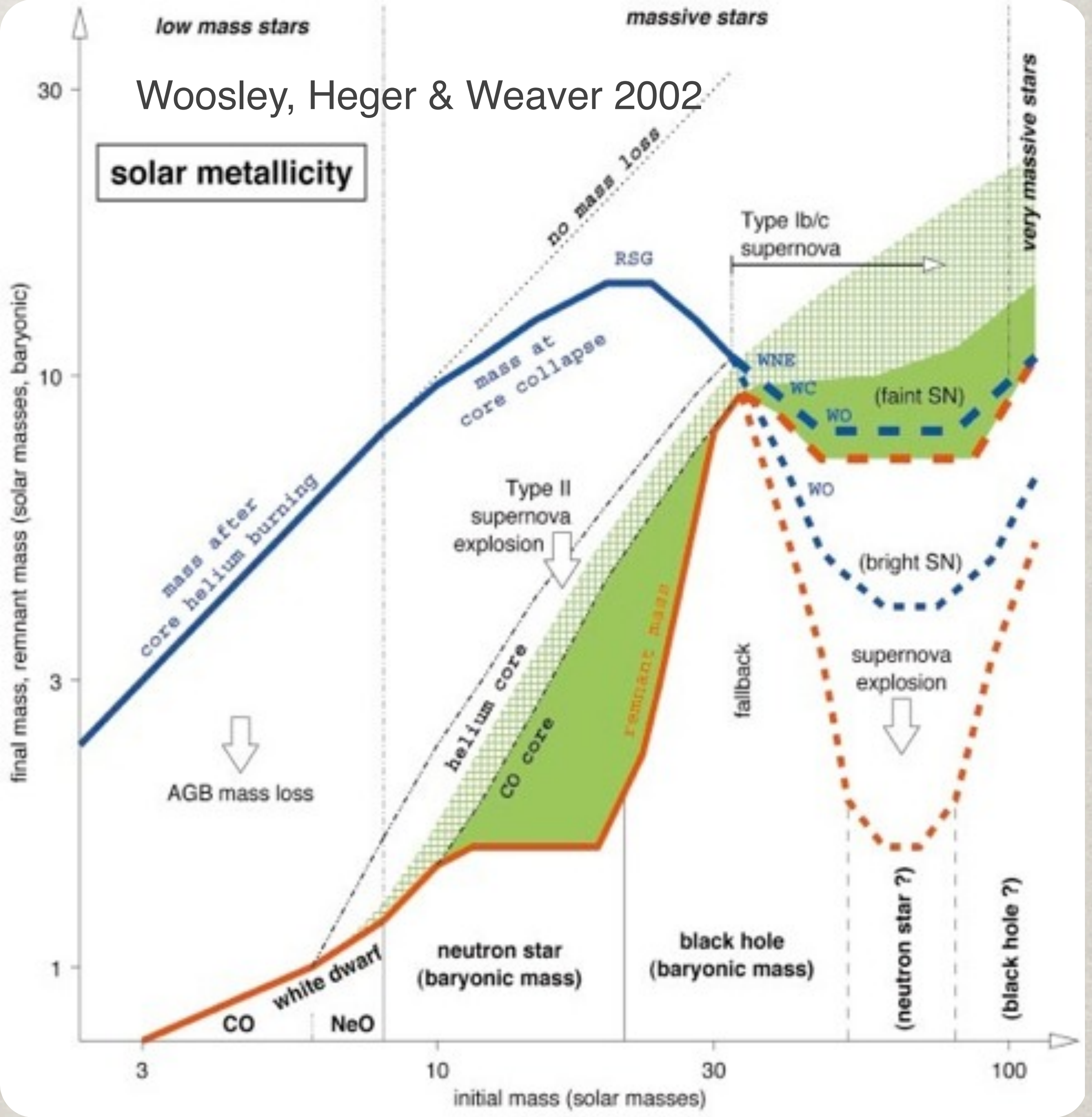


Models rich in heavy elements



Parameterized Supernovae

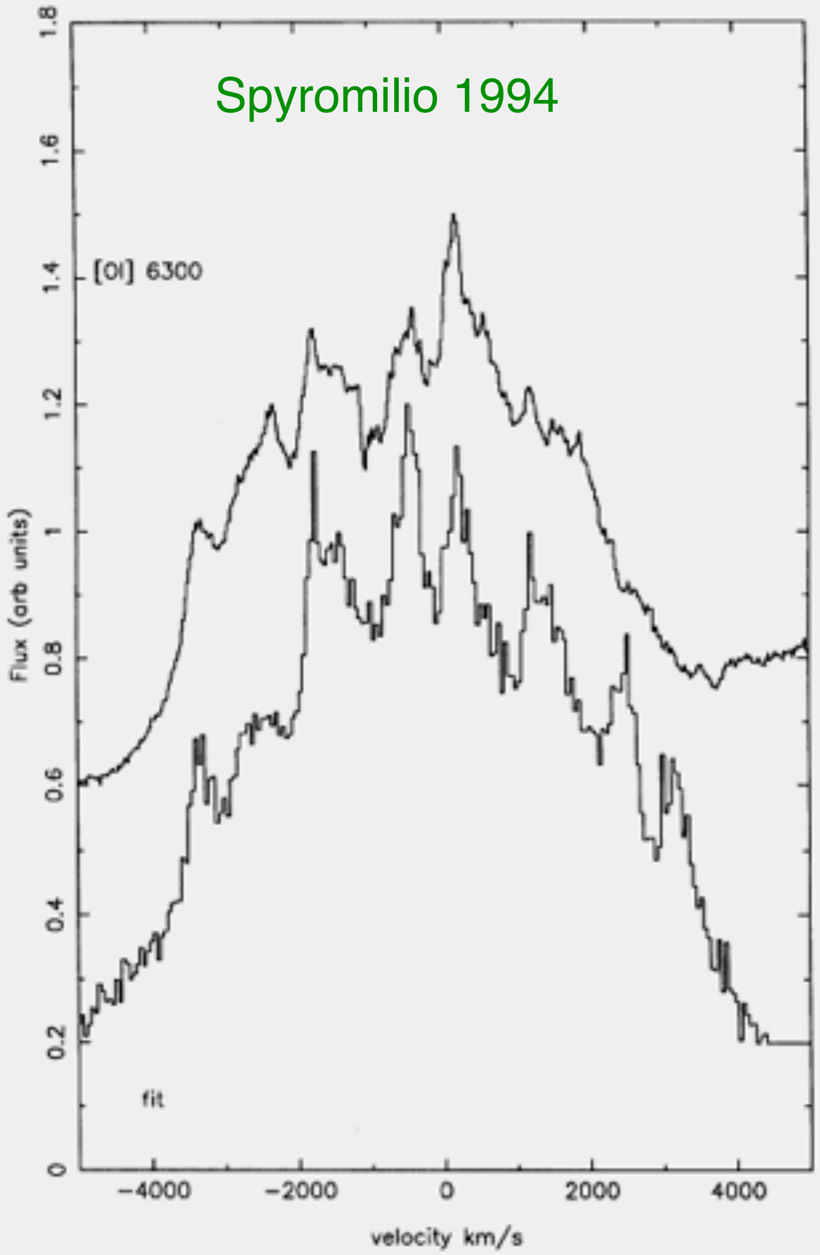
Since the mid-1990s, we have had this appreciation that the supernova mechanism is intrinsically multi-dimensional and driven by neutrino-matter interactions.

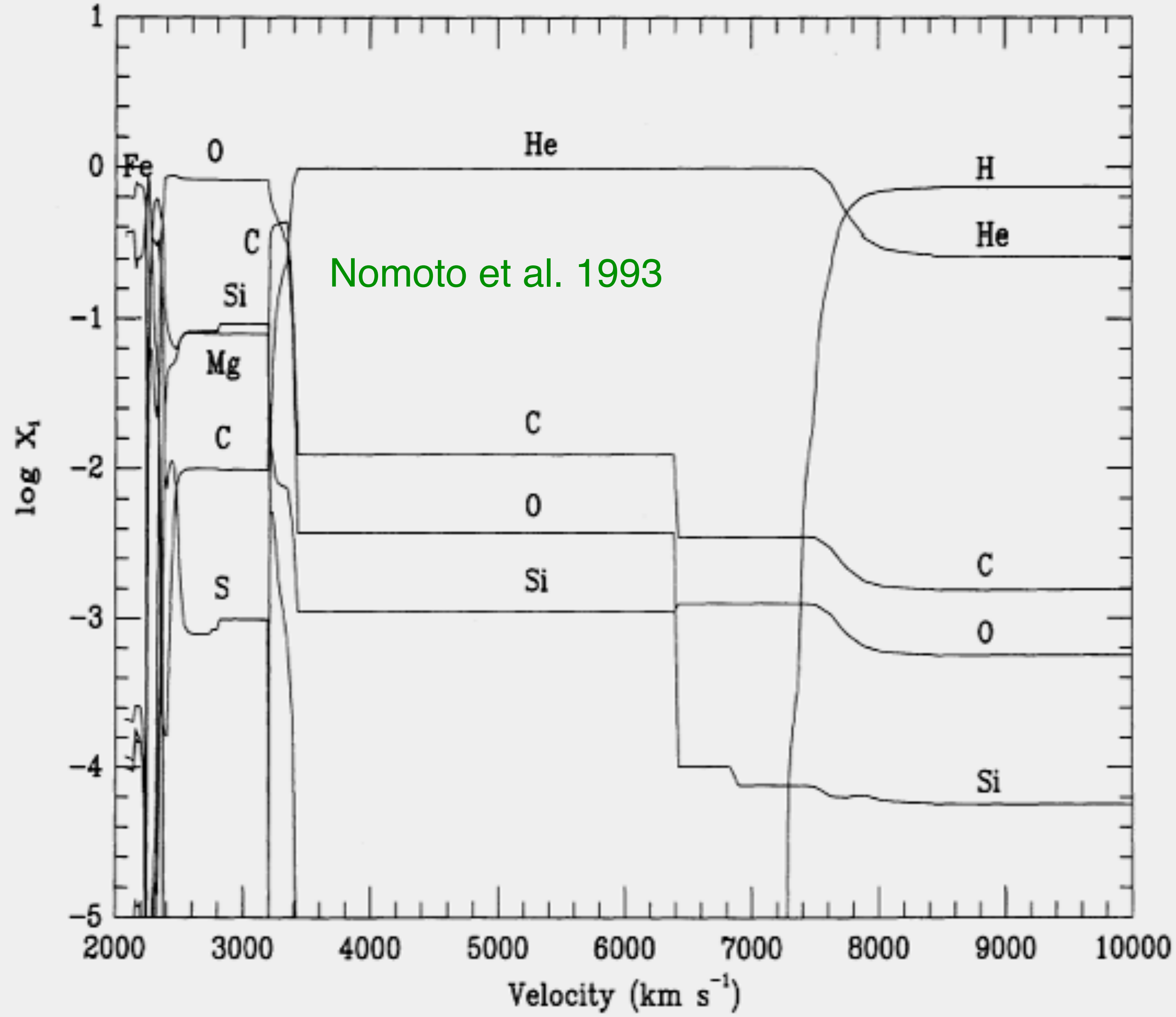


However, much of our understanding of the impact of the central CCSN engine neglects these facts.

For example, discussions of supernova nucleosynthesis or maximum stellar mass that can successfully produce a supernova, are based on spherically-symmetric (1D) models and a parameterized explosion.

Tuning the Explosion





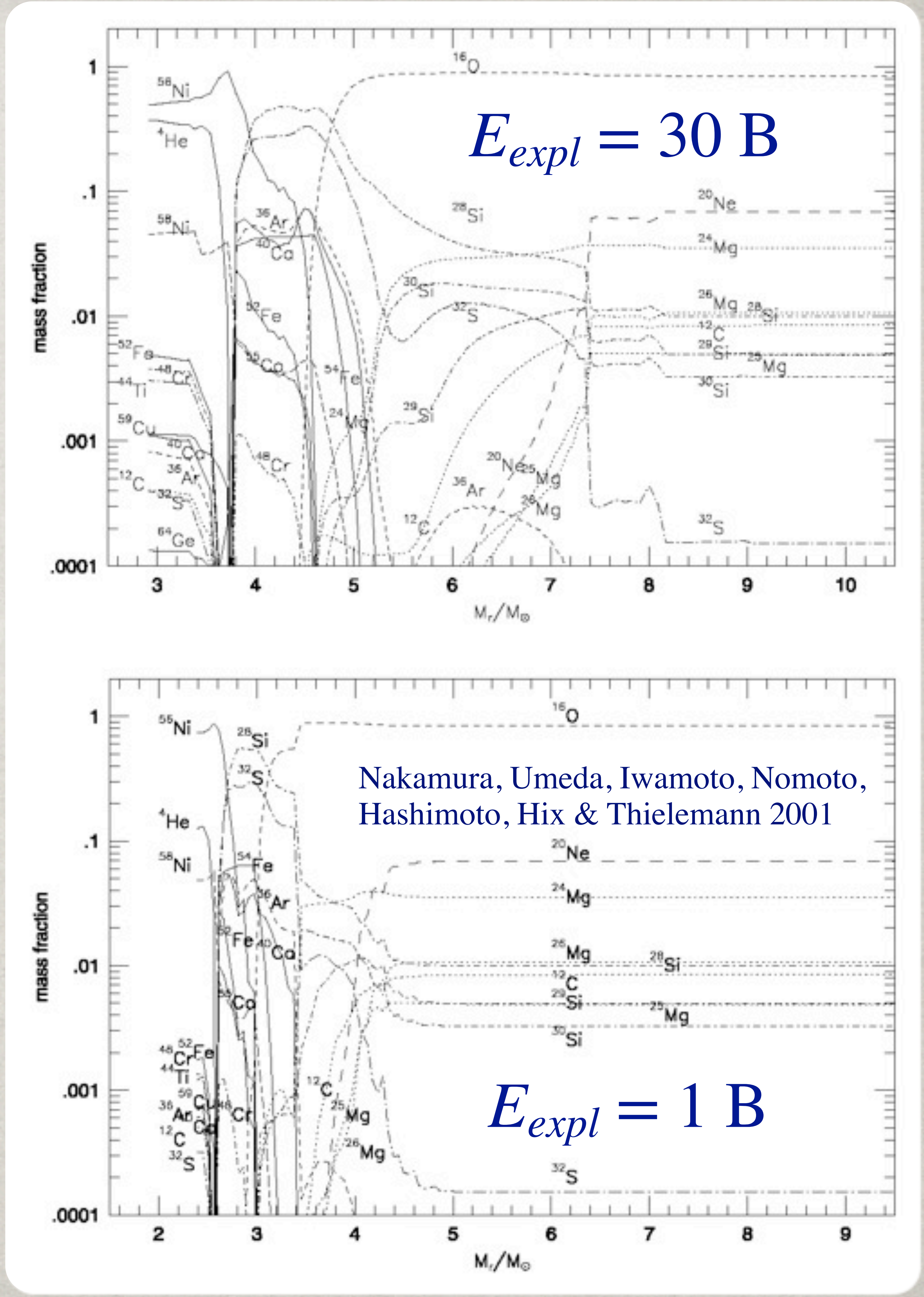
In current nucleosynthesis models, 2 parameters, the Bomb/ Piston energy and the mass cut, are constrained by observations of explosion energy and mass of ^{56}Ni ejected.

Hypernovae

Observations of GRBs with SN raises question of nucleosynthesis from a "Hyper"-energetic blast wave.

- Si/O, Fe/O increase because more O is destroyed.
- Ti/Fe, Zn/Fe increase because of more α-rich freezeout.
- Cr/Fe, Mn/Fe decrease while Co/Fe increases due to more complete Si burning

Match to puzzles in metal-poor stars and BH companions



Multi-D Explosions

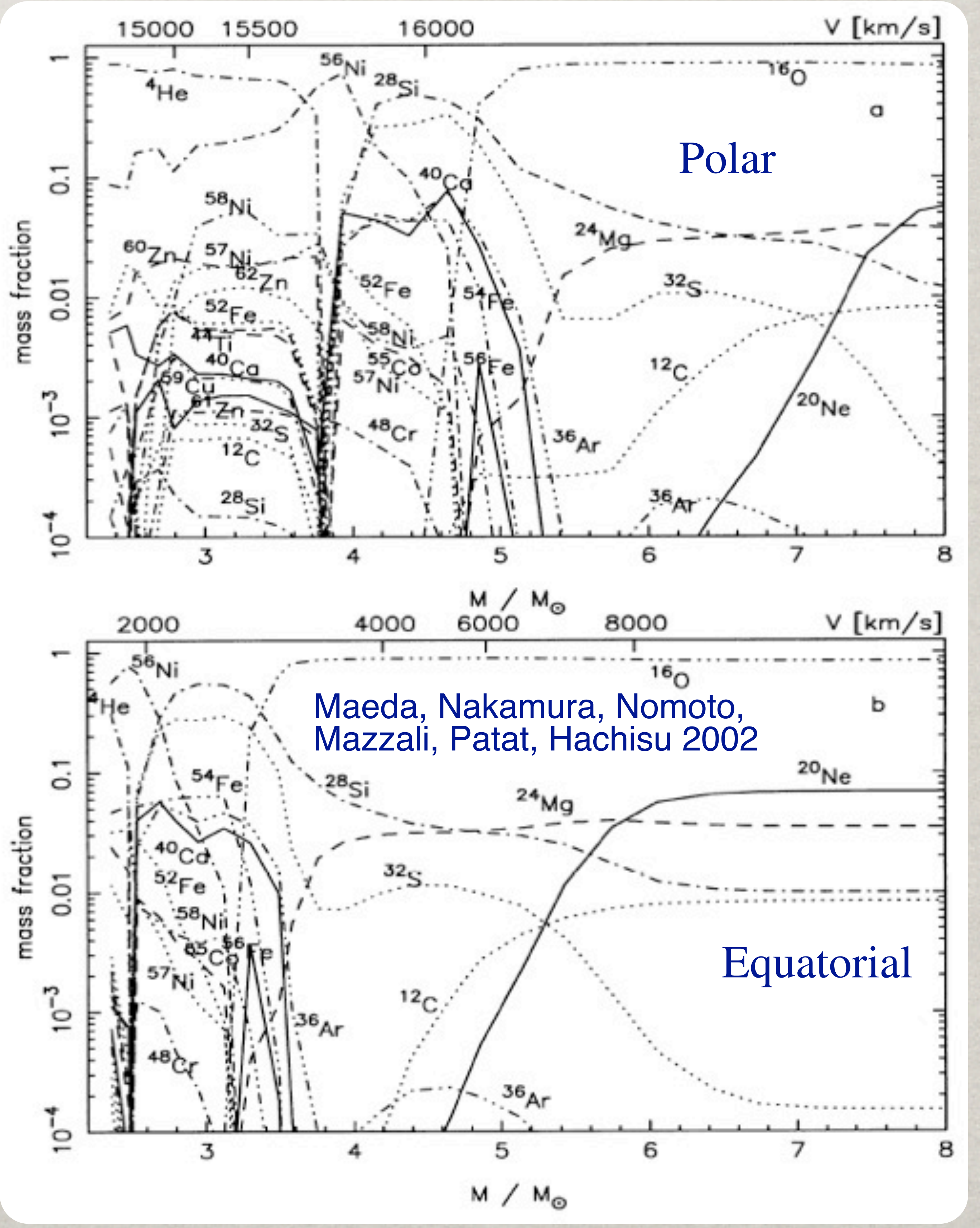
SN associated with GRB can not be spherical. Jet-like models require Multi-D simulations.

In such simulations, Ni production, α-rich freezeout and velocity are enhanced along jet.

Observationally, even ordinary SN evidence non-spherical features.

(Nagataki, Hashimoto, Sato & Yamada 1997, 1998)

But these models omit neutrino-driven SN mechanism.

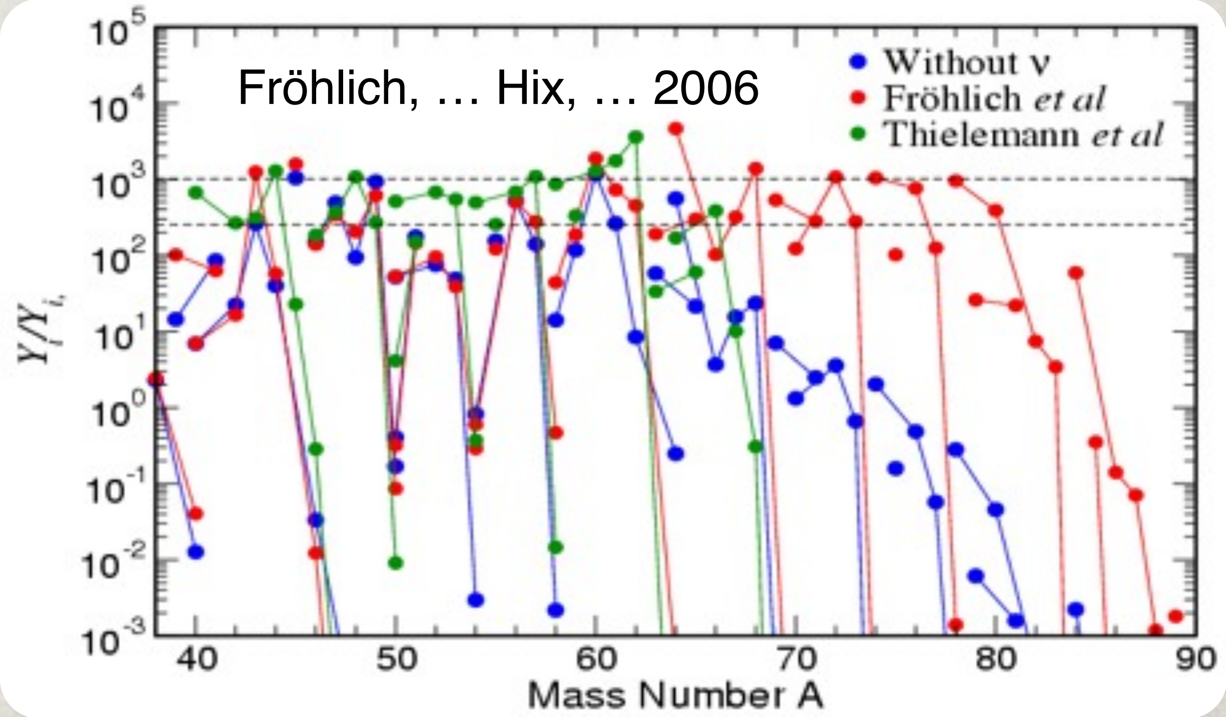


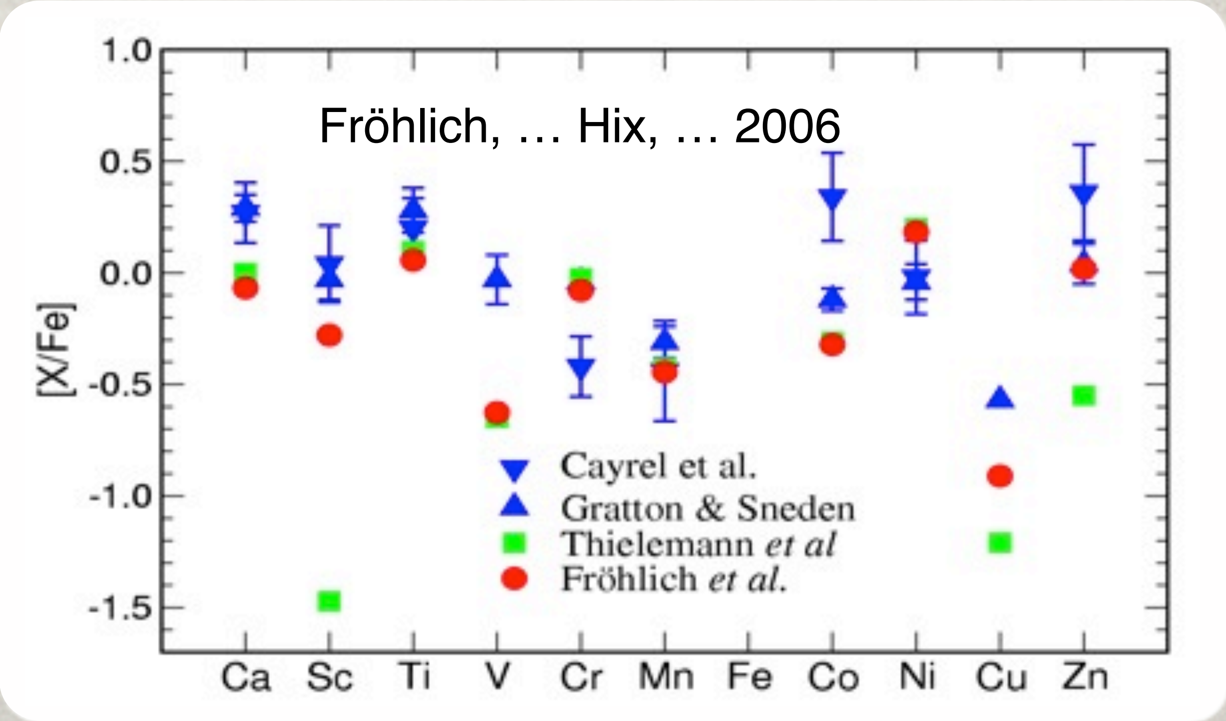
Neutrinos & Nucleosynthesis

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).

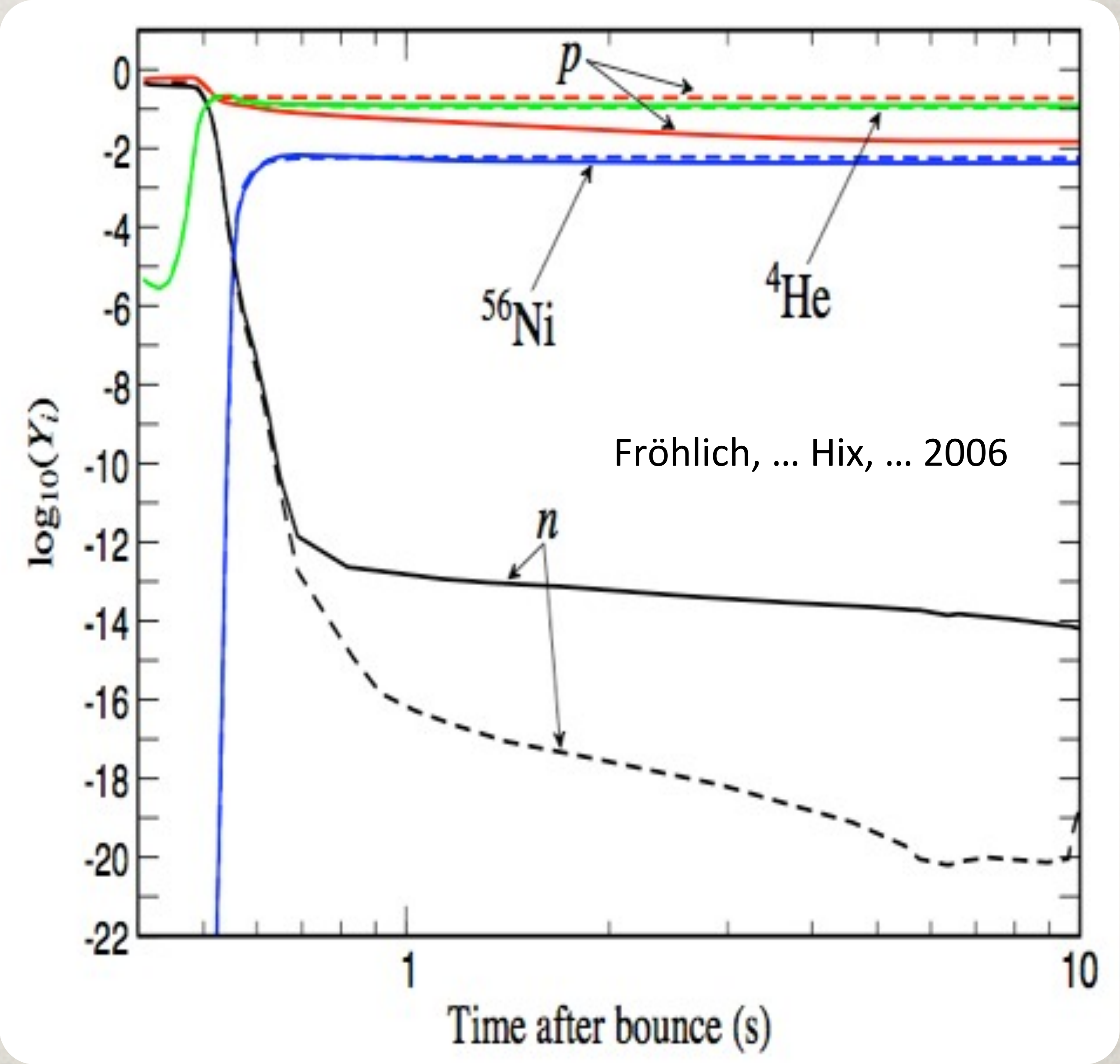




Putting the ν in νp

The νp-process occurs because the supernova ejects proton-rich ($Y_e > 0.5$) gas at high temperature (~10 GK), composed of free neutrons and protons.

Cooling produces a p-rich and α-rich freeze-out. Once temperature drops below 3 GK, free protons can capture on iron-peak species.



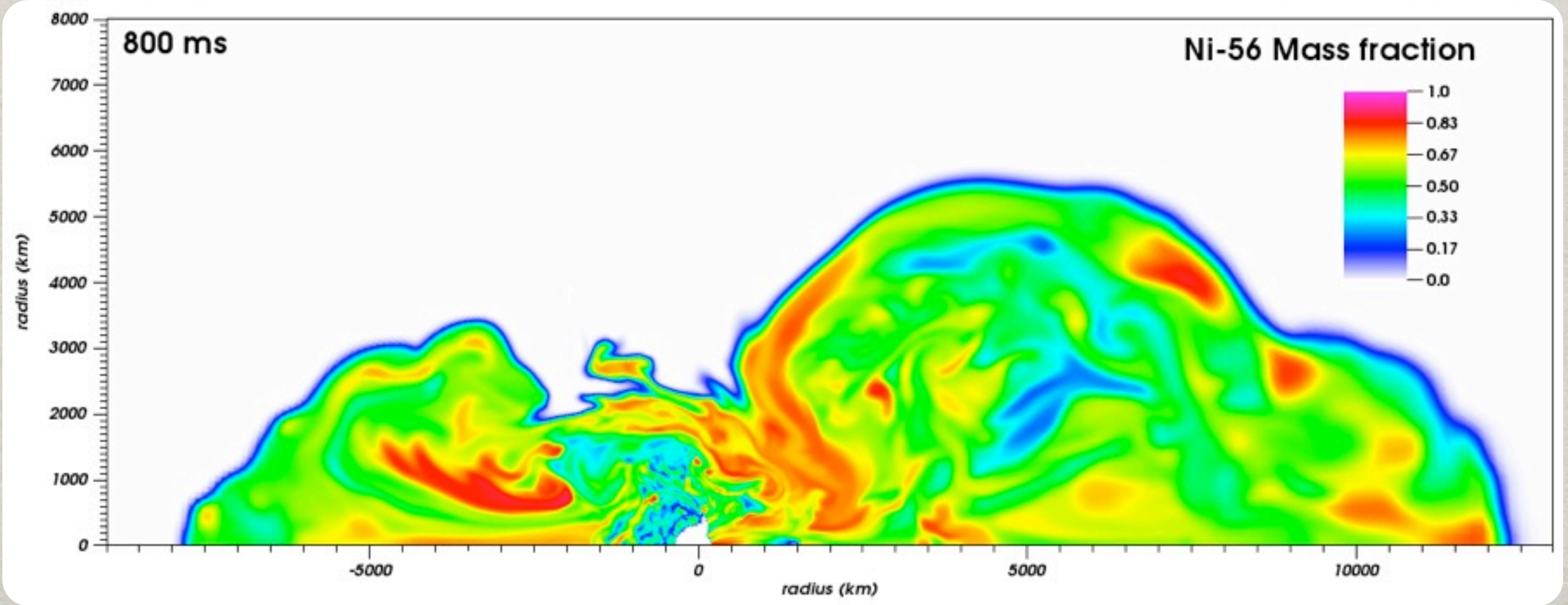
Slow β decays (e.g. ^{64}Ge, $\tau_\beta = 64$ s) would stop this process but (n,p) and (n,γ) reactions effectively “accelerate” β decays.

The needed neutrons are generated from protons converted via anti-neutrino capture.

Improving Nucleosynthesis

If we want to improve our modeling of the nucleosynthesis in CCSN, we need to stop separating models of the mechanism from models of the nucleosynthesis.

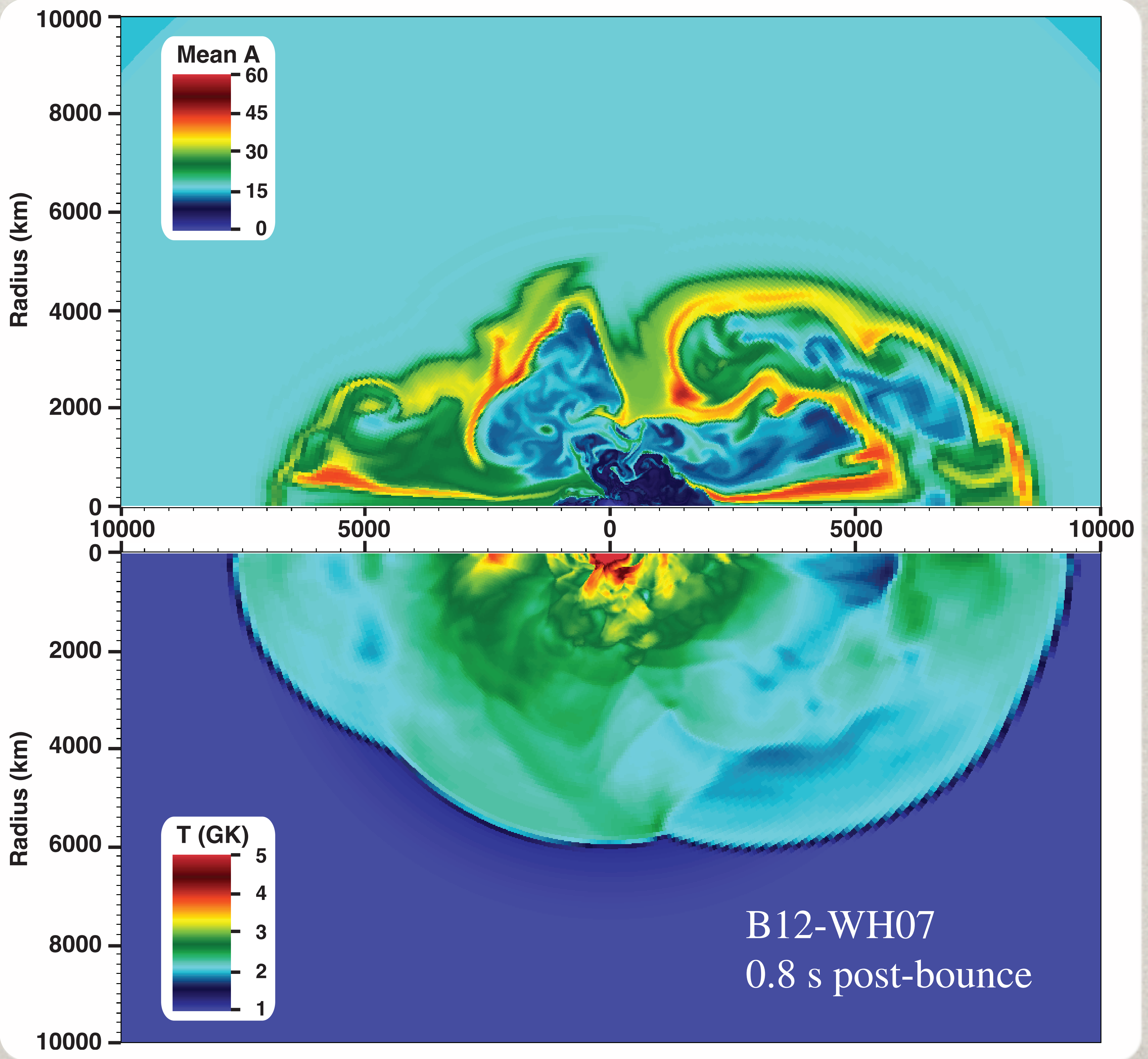
We can start by investigating the nucleosynthesis using the α-network included in CHIMERA and many other supernova models.



CHIMERA Shock Burning

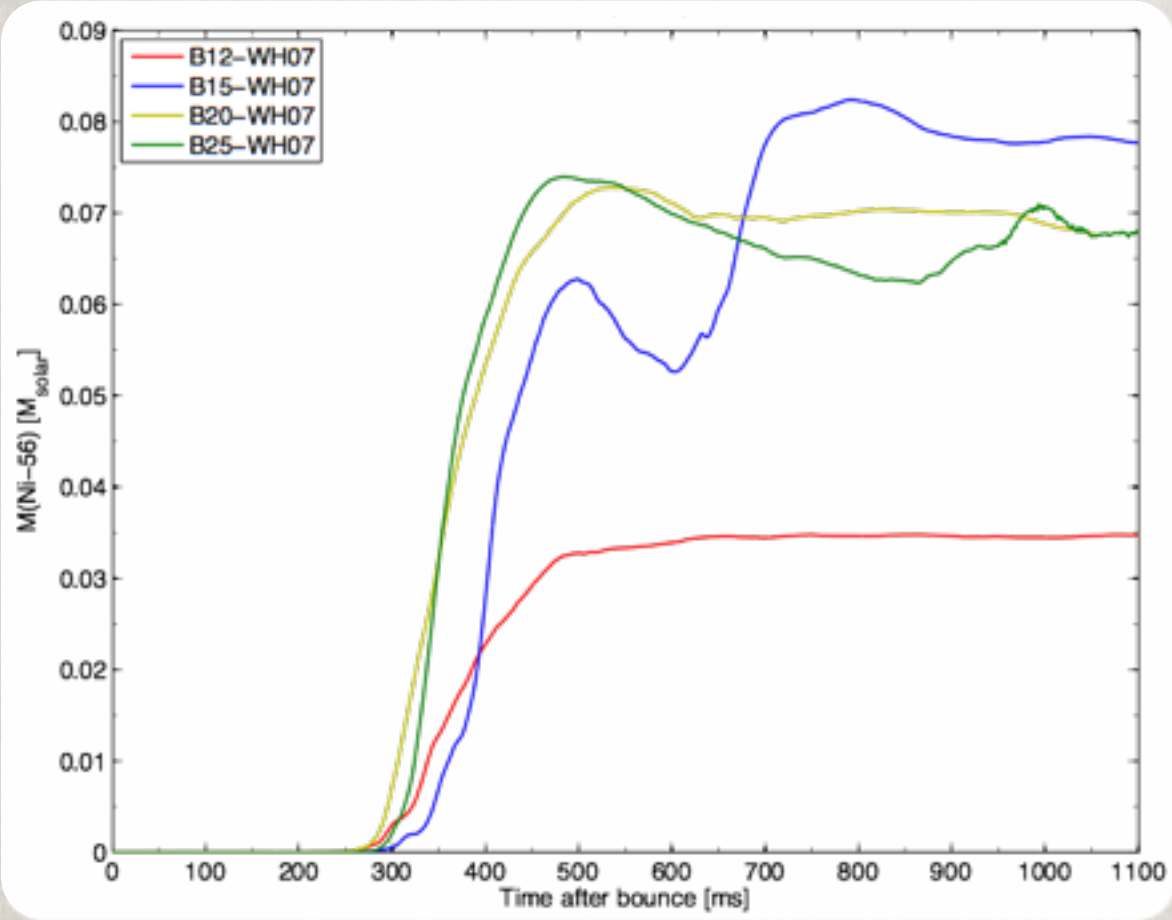
By 800 ms after bounce, shock burning in the 12 $M_{\odot}$ model is nearly complete with a shock temperature of ~2 GK.

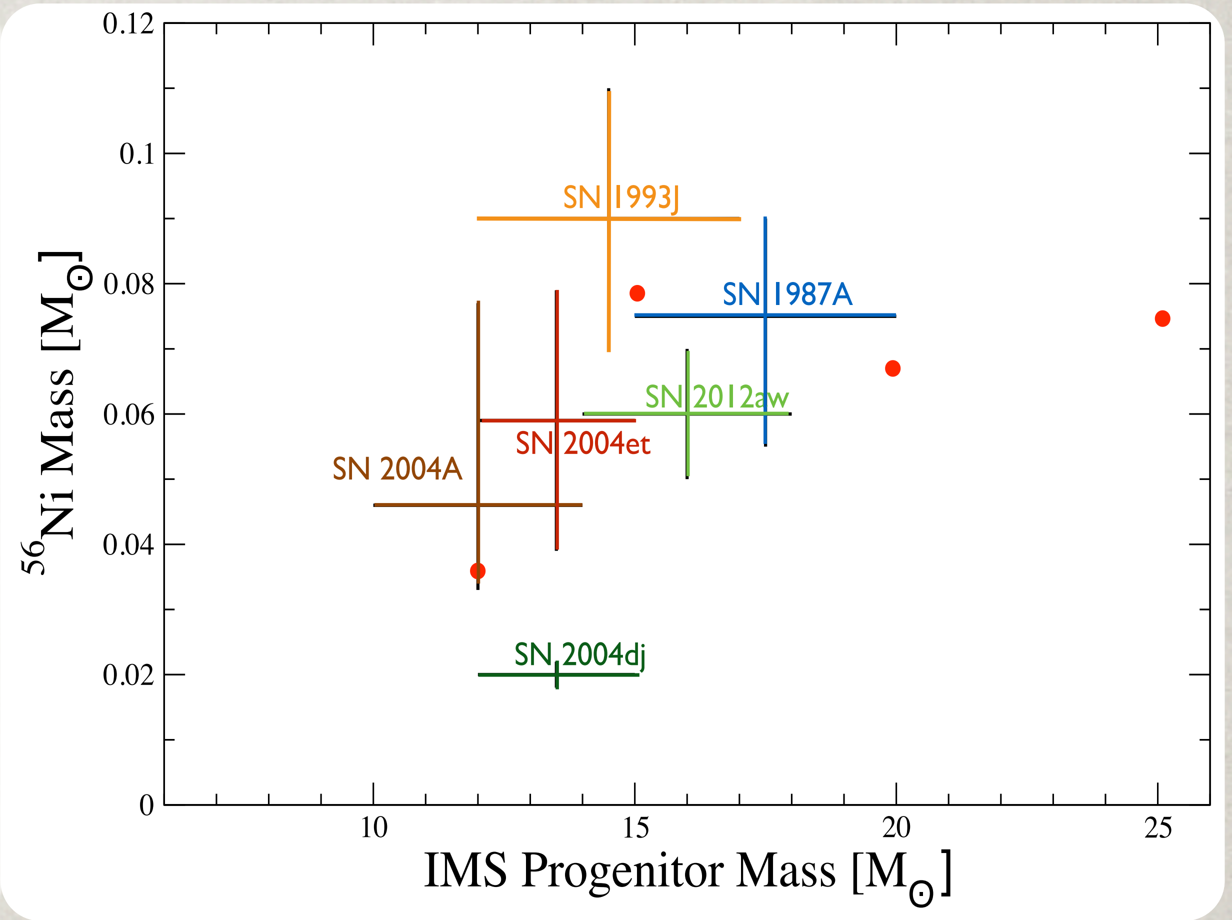
However, placement of the mass cut continues to evolve as cut-off downflows accrete.



Nickel Mass

Another important observable, related to the explosion energy and very relevant to the nucleosynthesis is the mass of ^{56}Ni.





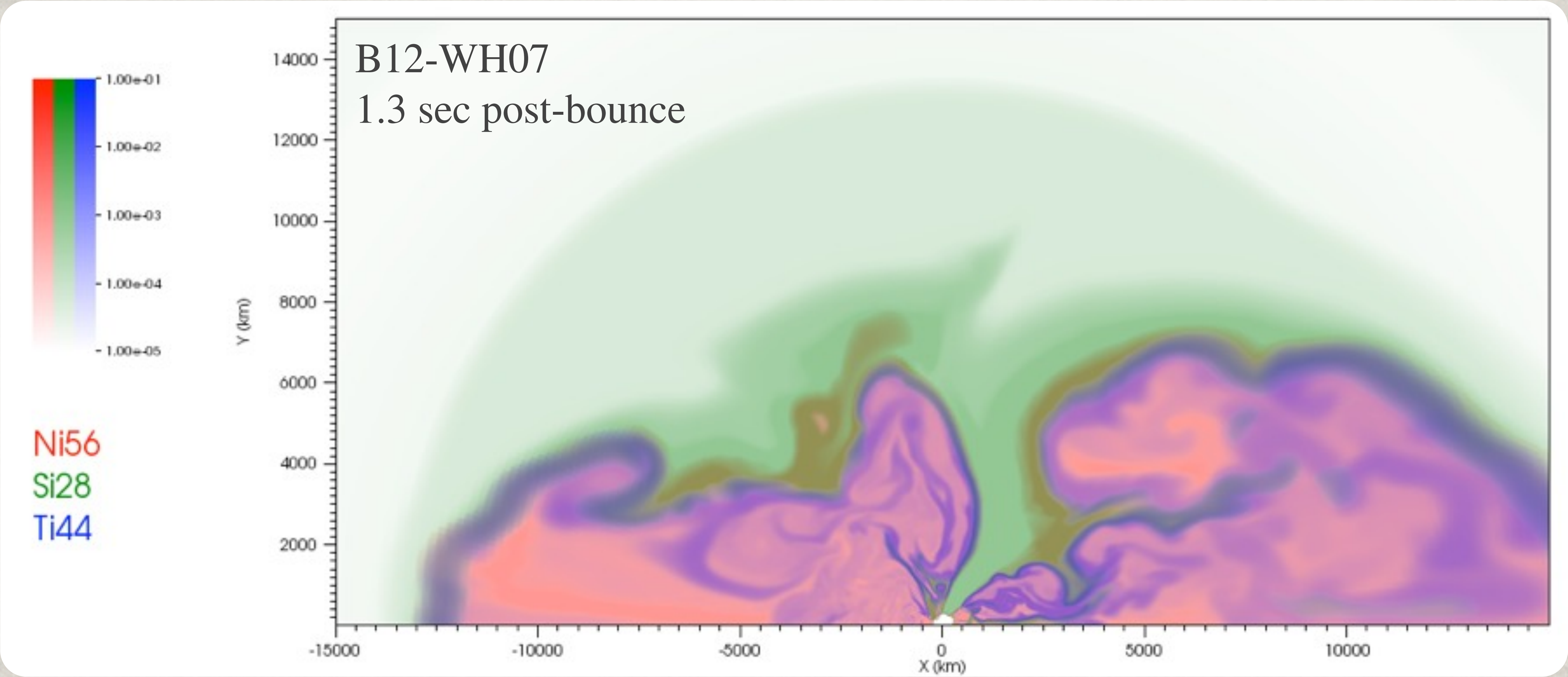
The ejected ^{56}Ni mass saturates in time with the explosion energy.

Mass of other iron-peak species is comparable to ^{56}Ni.

Results are reasonable, though fallback over longer timescales is uncertain. Recent studies are finding differing results on fallback.

Nucleosynthesis Limits

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



Nucleosynthesis Limits

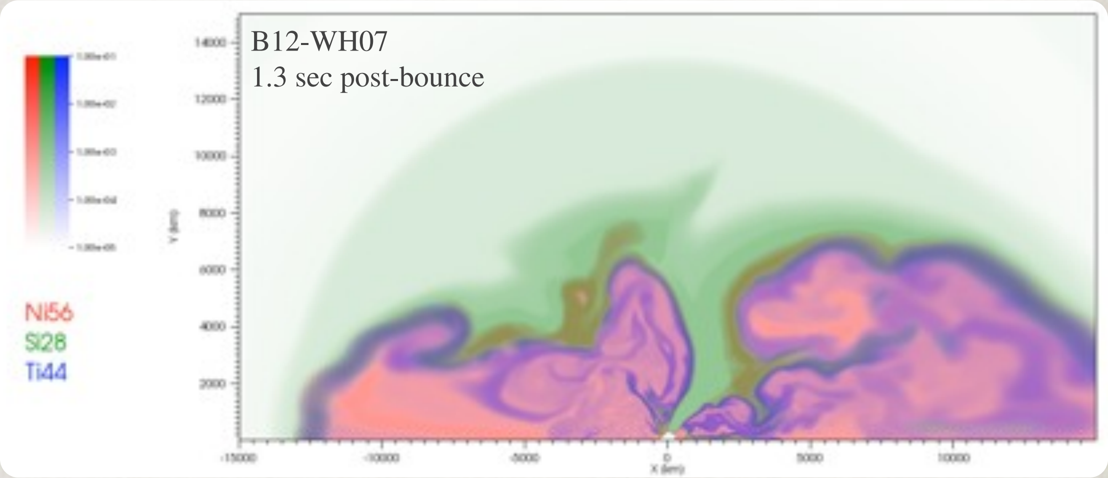
We can calculate nucleosynthesis directly with the α-network (plus neutrons, protons and auxiliary heavy) in CHIMERA.

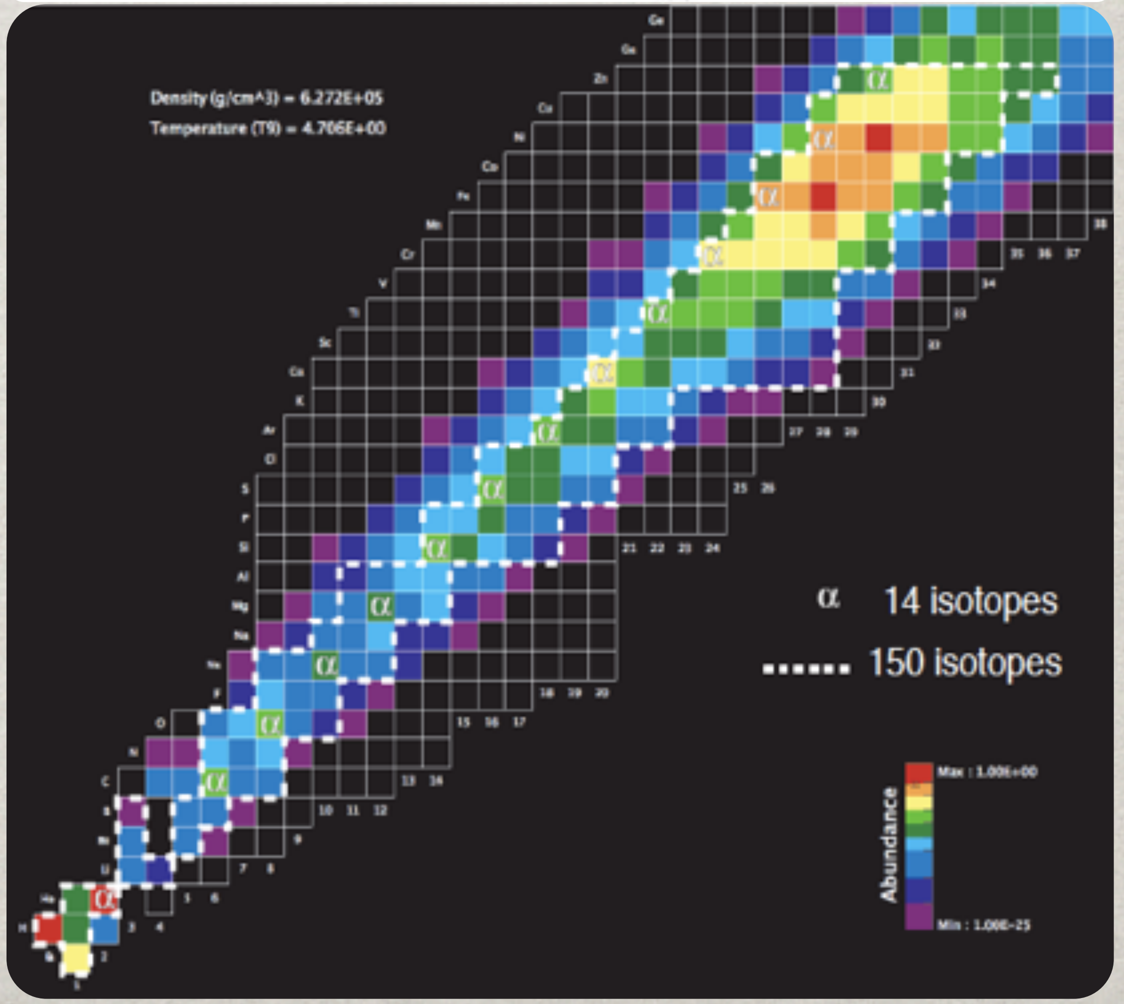
As the mass cut is resolved, we will be able to examine the nucleosynthesis of these models with increased accuracy.

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

Doing the same in CHIMERA requires post-processing of tracer particles, or a larger network.

This is important even for species included in the α-network.





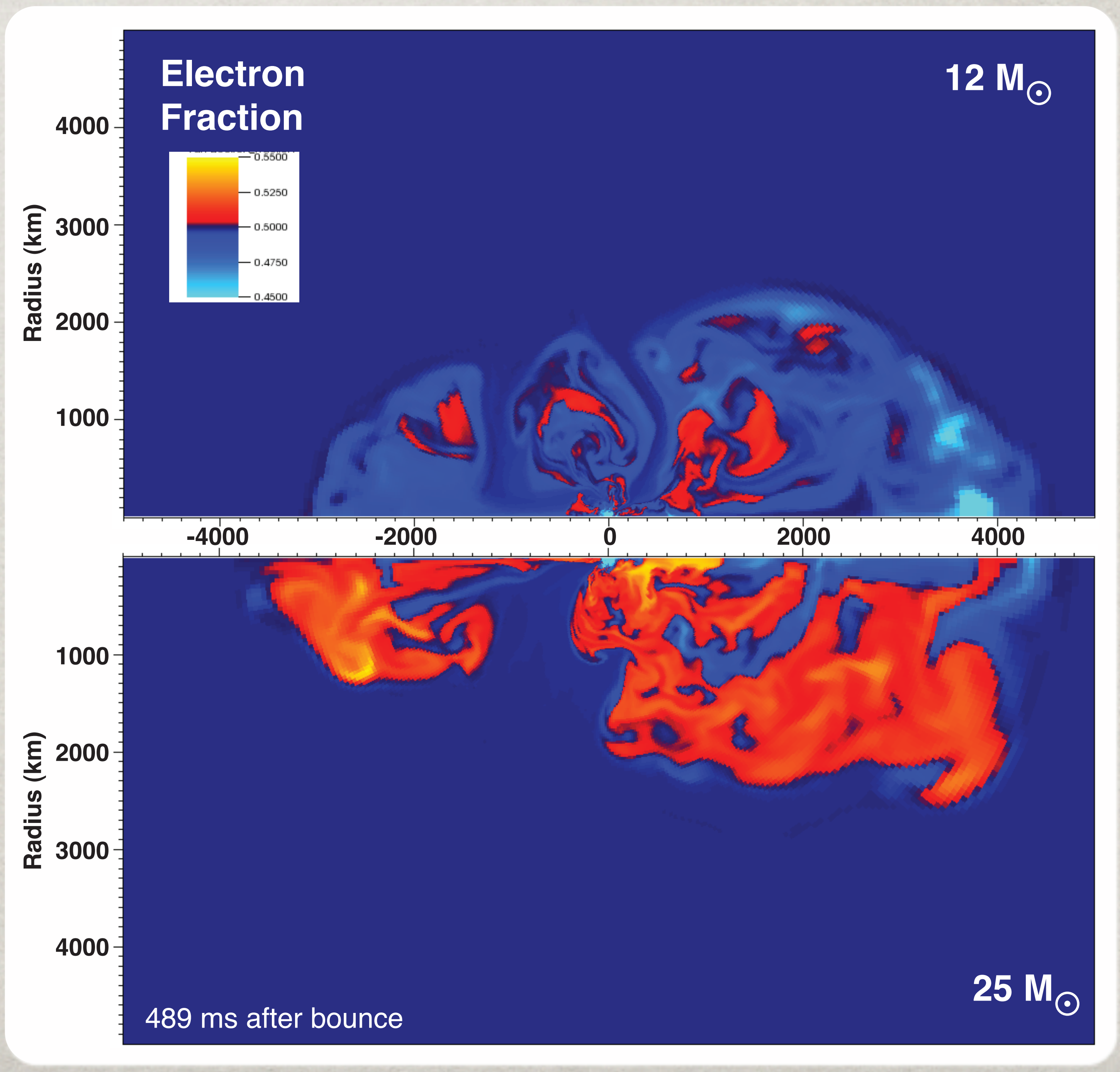
Multi-D νp-process?

The open question is will the results of self-consistent multi-dimensional simulations match those of the parameterized neutrino-driven models that discovered the νp-process?

Unfortunately, the νp-process occurs deep in the star, near the mass cut.

We can get an early indication by examining the neutronization.

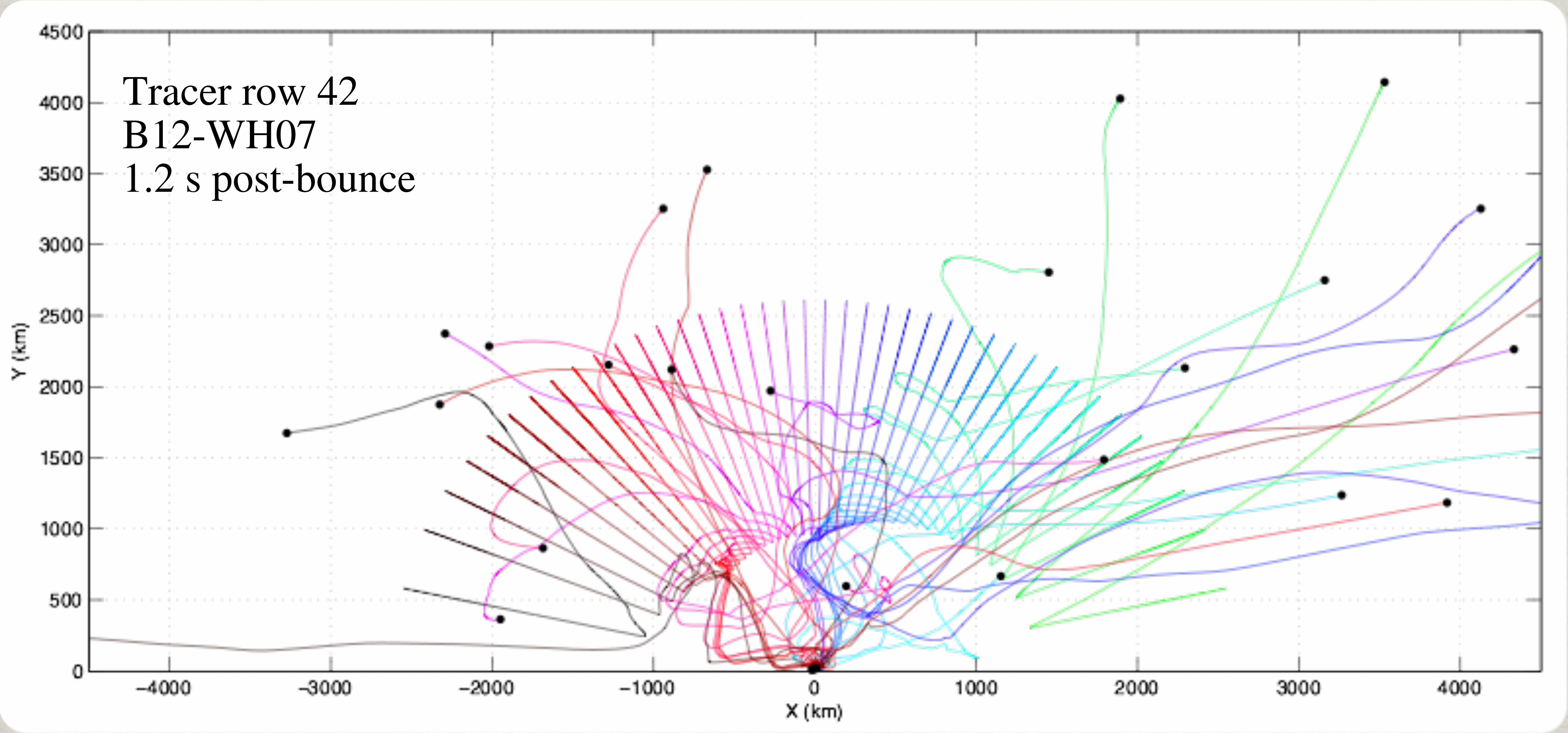
There is a clear trend in the Y_e distribution, with more massive models having more proton-rich material.



Tracing the Mass Cut

Post-processing of tracer particles will allow nucleosynthesis predictions that capture the multi-D effects beyond the α-network.

They reveal the complexity of defining the mass cut.



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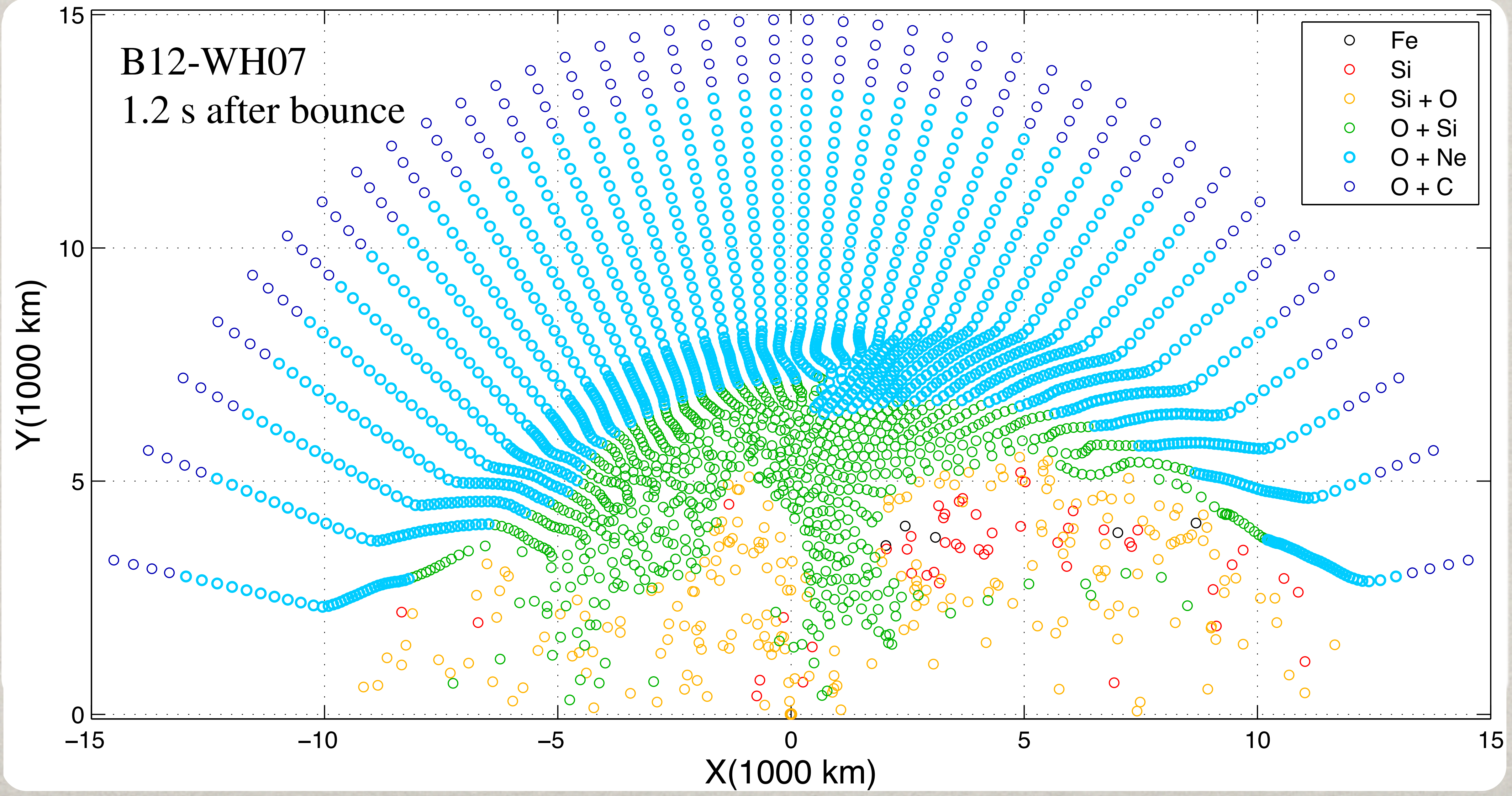
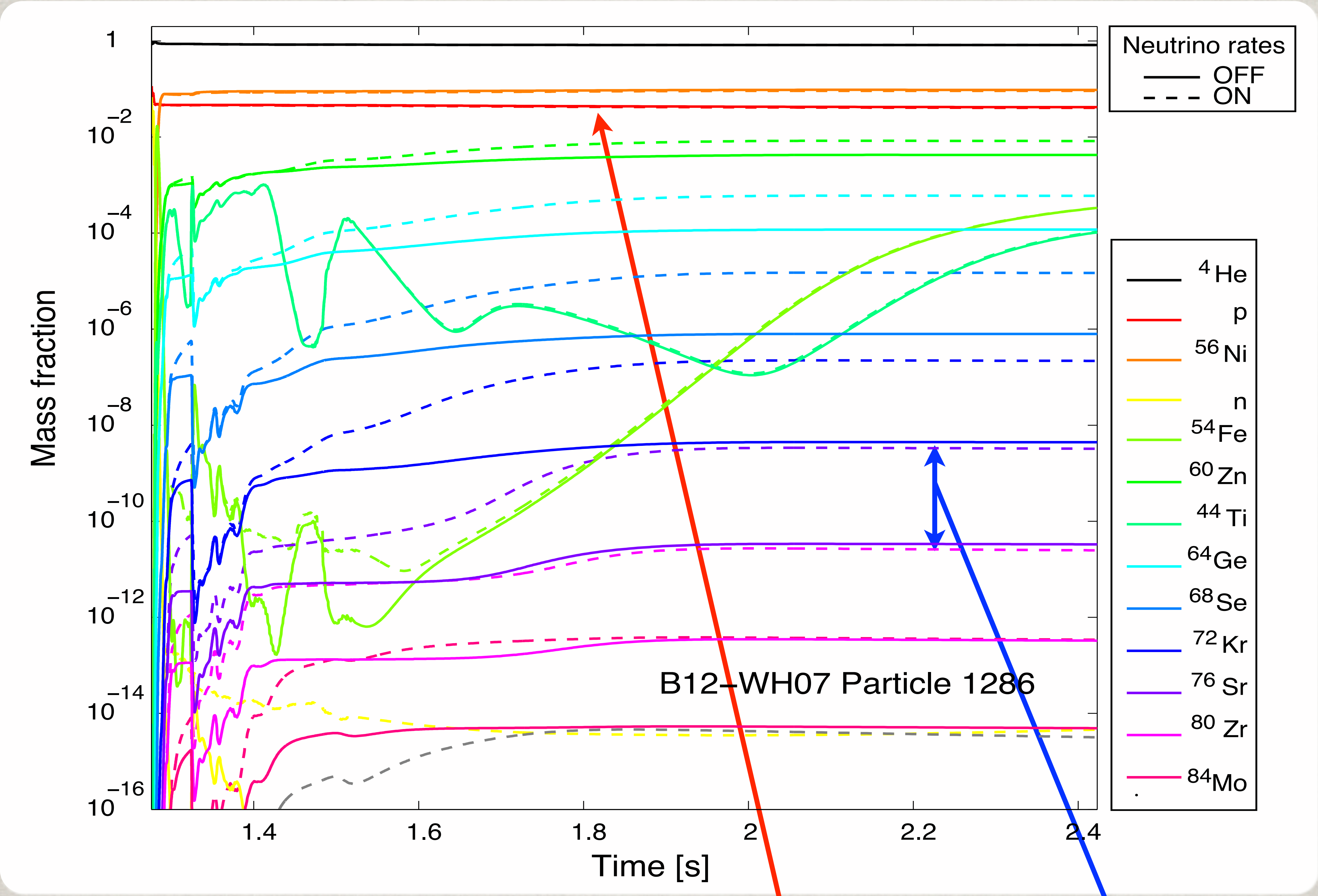


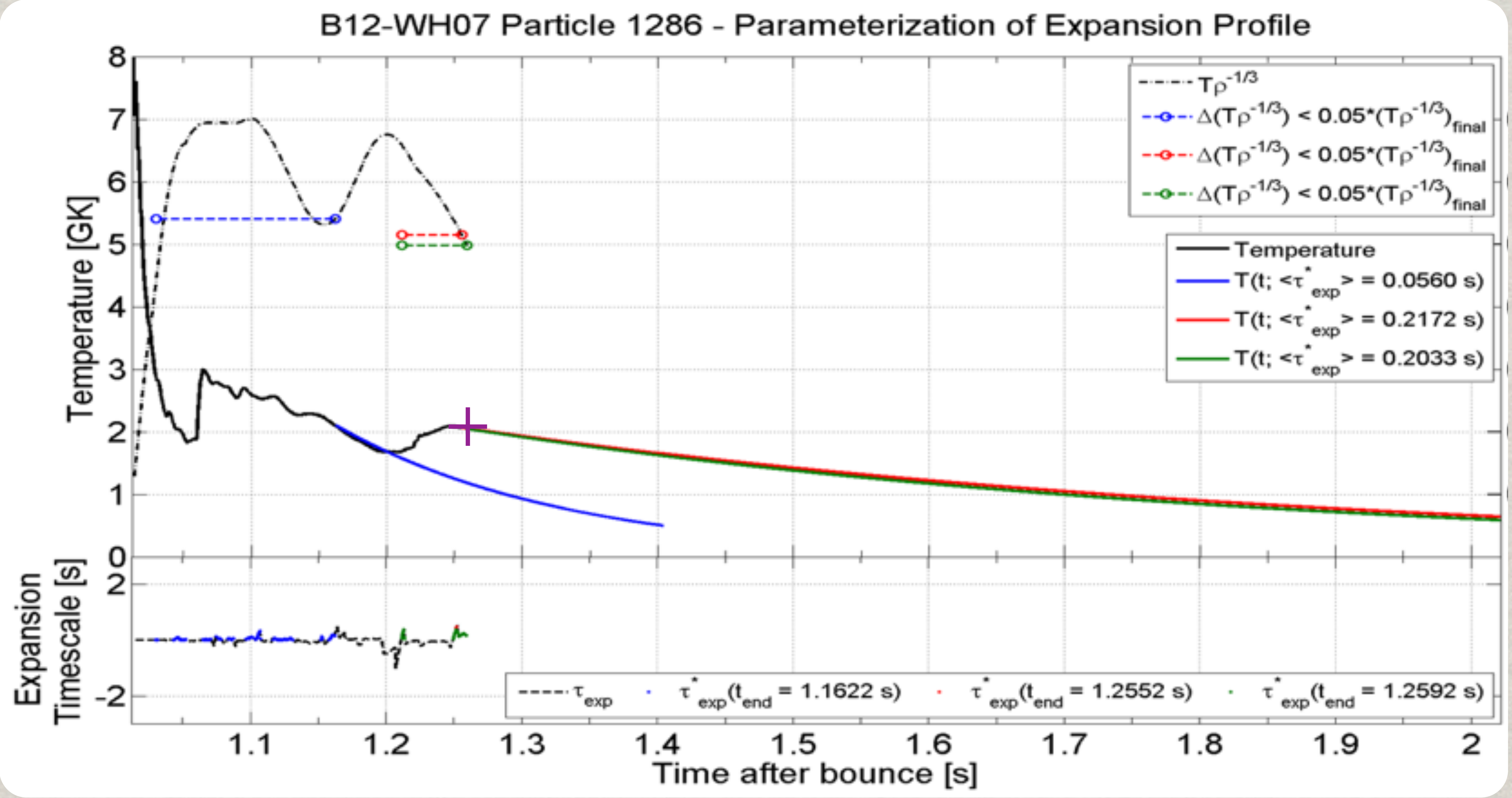
νP-PROCESS



Our preliminary results show proton-rich ejecta and νp-process (dotted lines), but more weakly than previous results.

Are We There Yet?

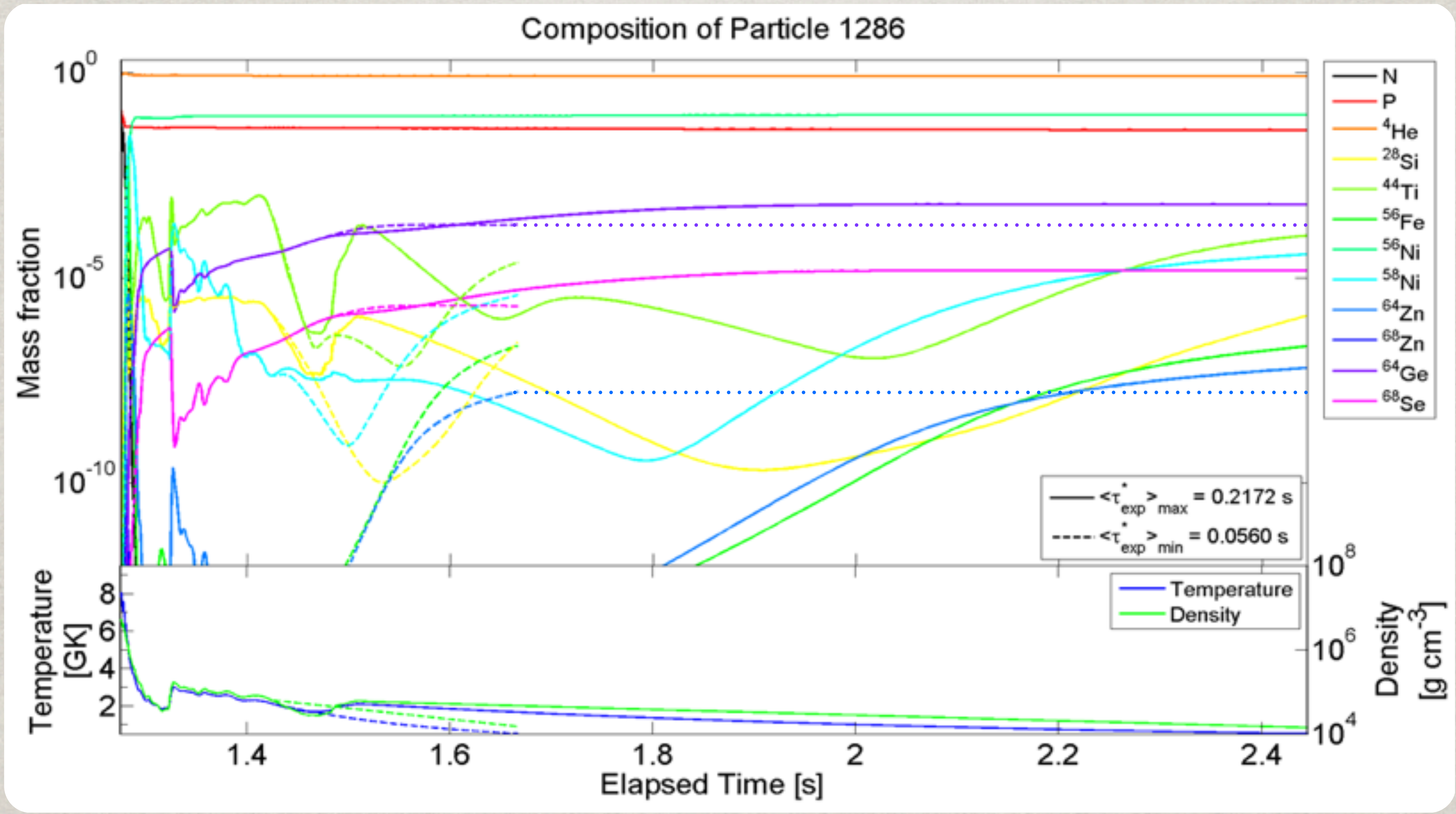
To fully investigate the νp-process, we need for all of the ejecta to cool to ~ 0.5 GK, or at least to be able to extrapolate that far.



Extrapolation for freely expanding (isentropic) matter is straight-forward, but hydrodynamics can interfere.

Expansion Uncertainty

Since this "hydrodynamic event" occurs at temperatures below 2GK, the composition of the dominant abundances are unaffected.

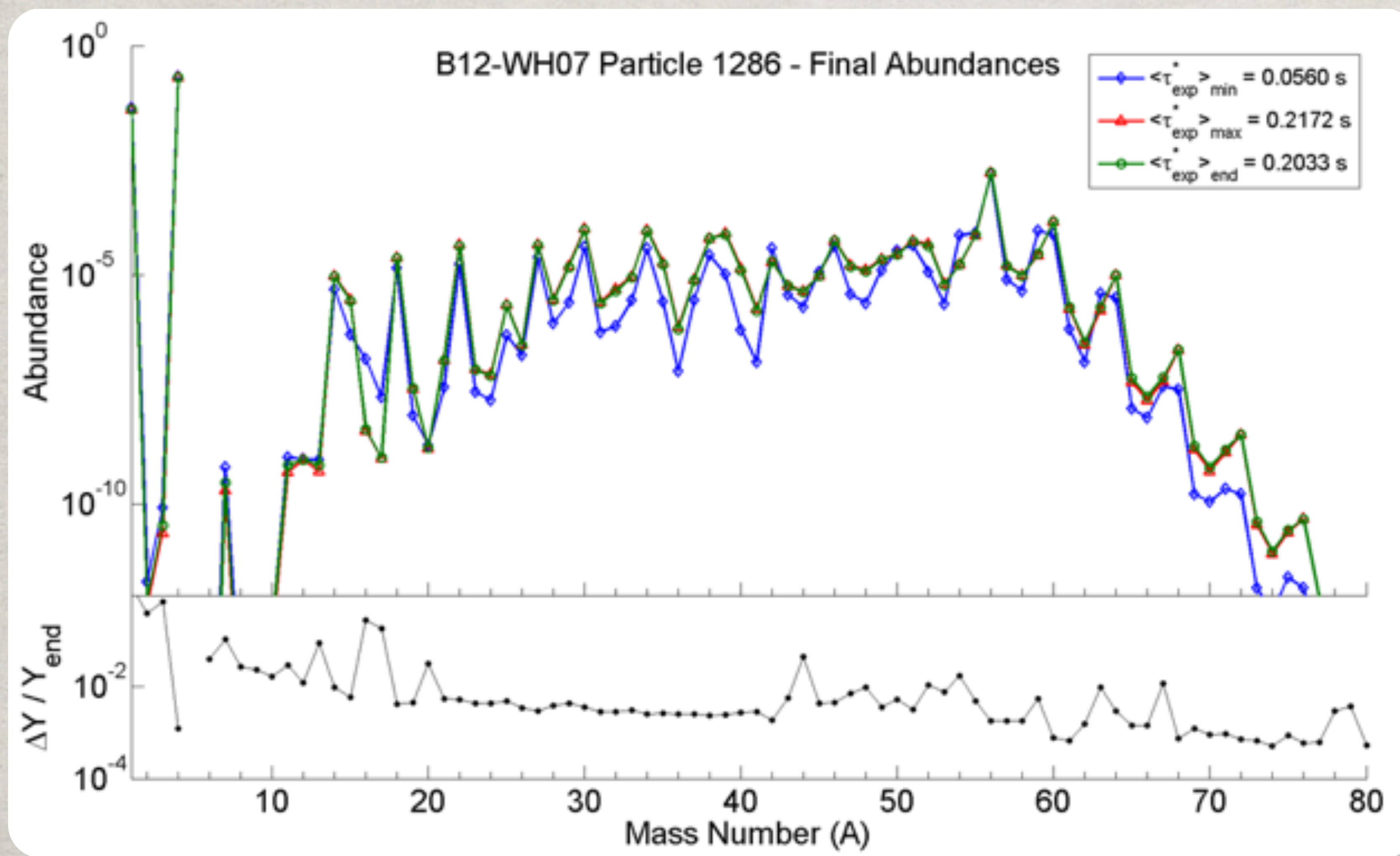


For smaller abundance, there are dramatic temporal differences, but the final abundances show smaller variations.

Localizing Uncertainty

The result for this particle is significant uncertainty in the smaller abundances, including the νp-process.

For most particles, especially in the outer ejecta, the timescales, and hence the nucleosynthesis, show less variation.



our errors are
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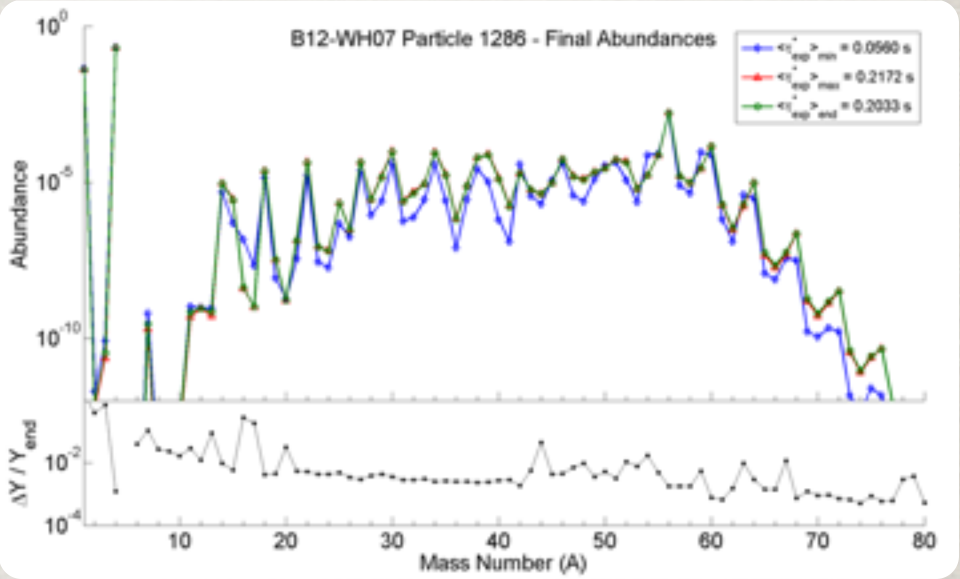

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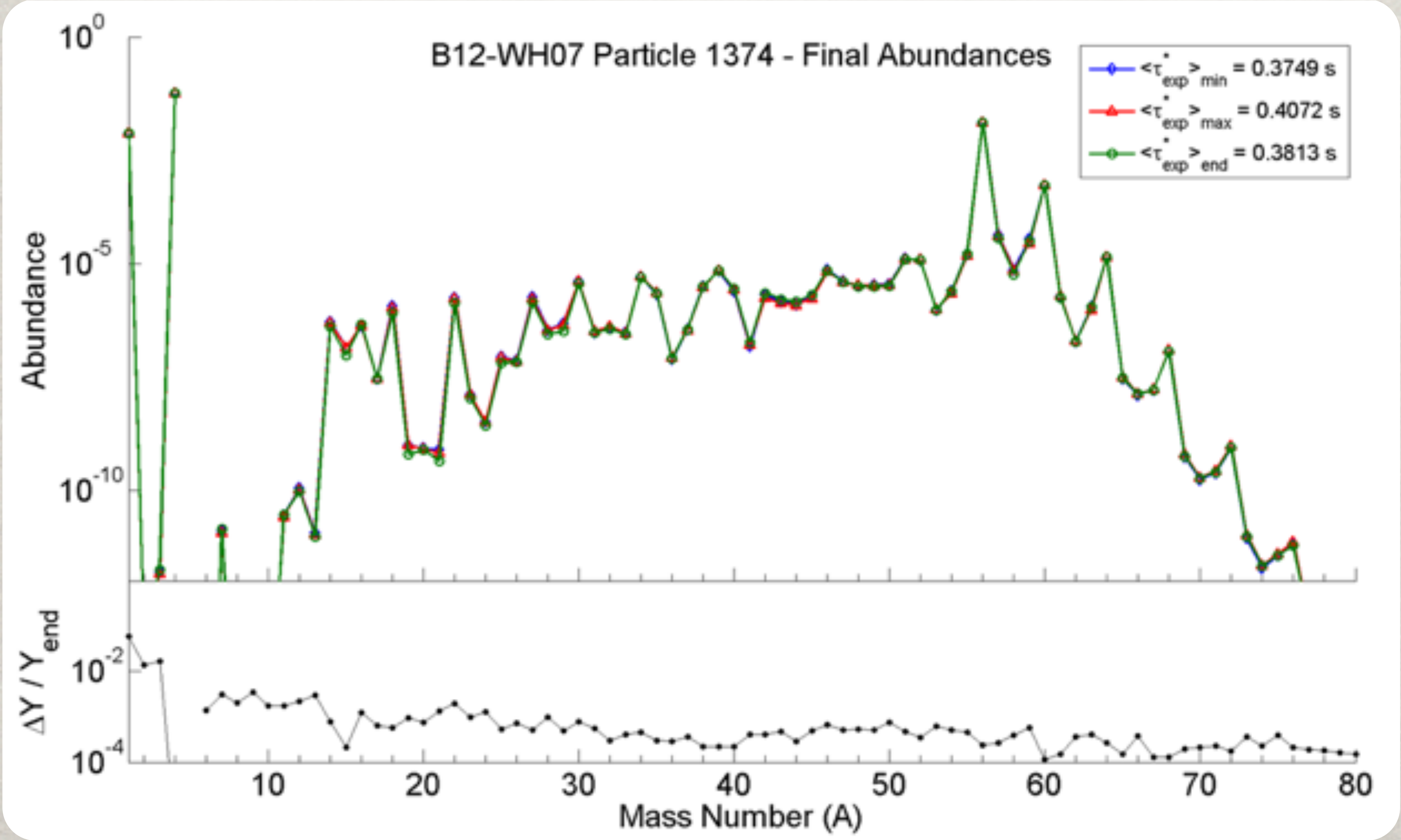

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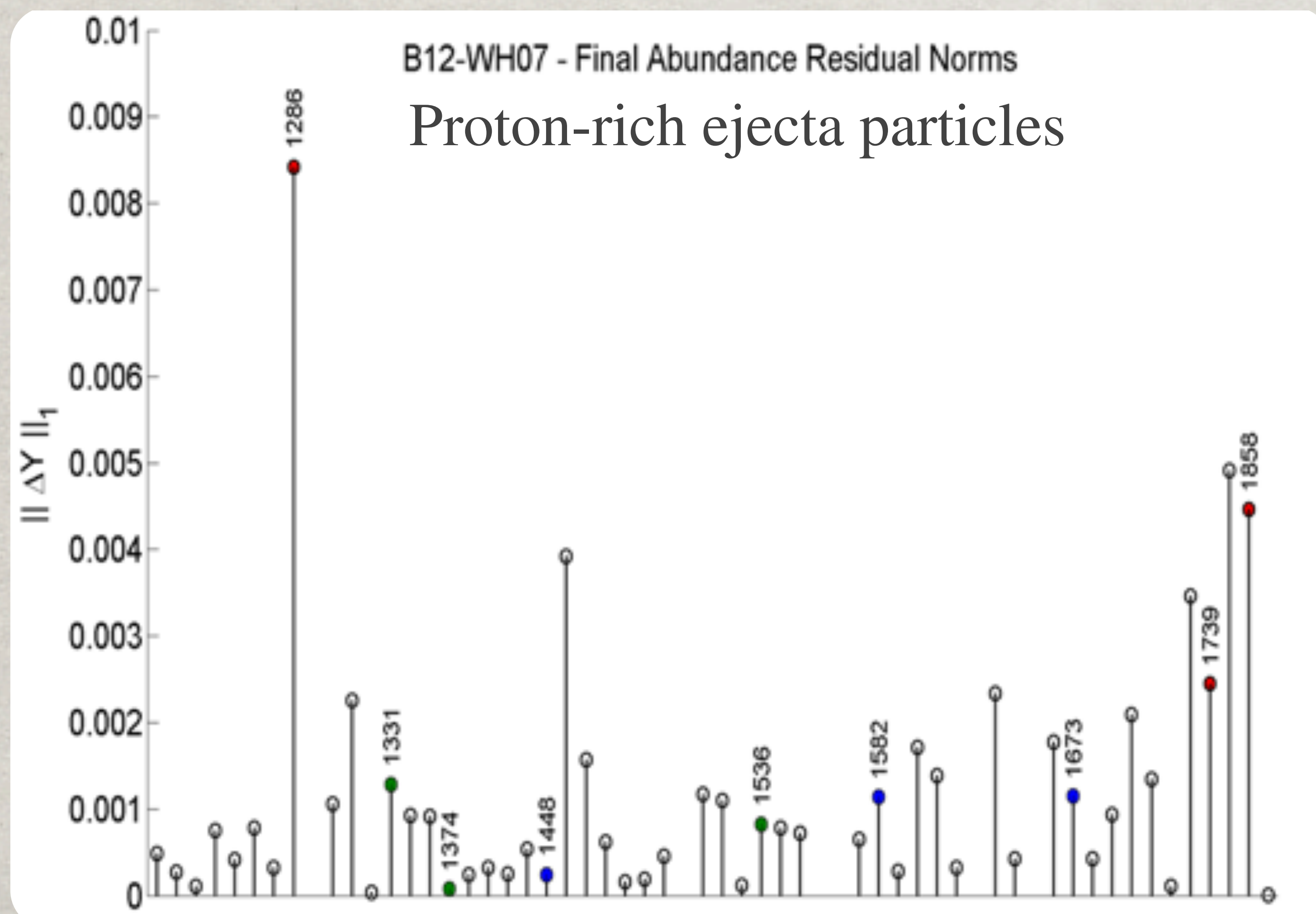
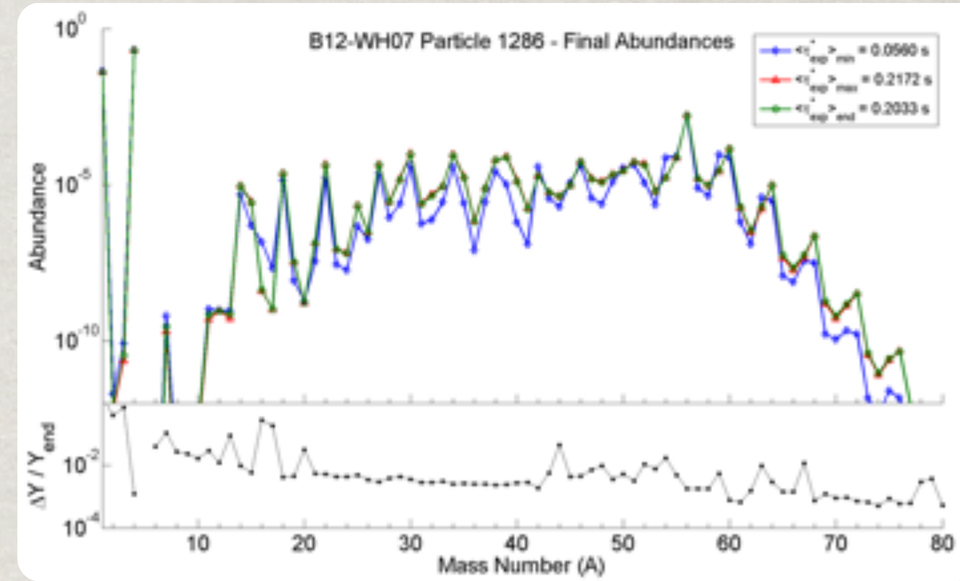
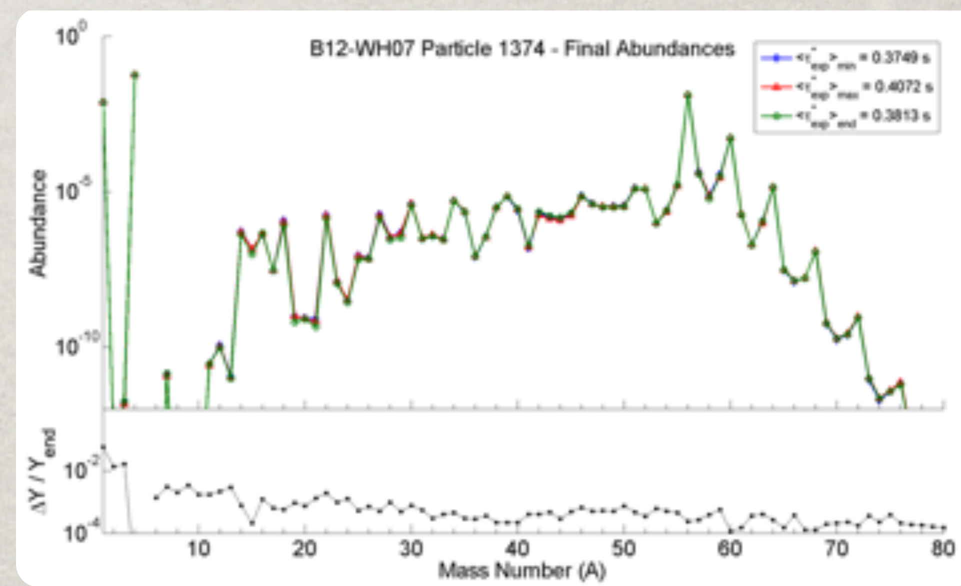


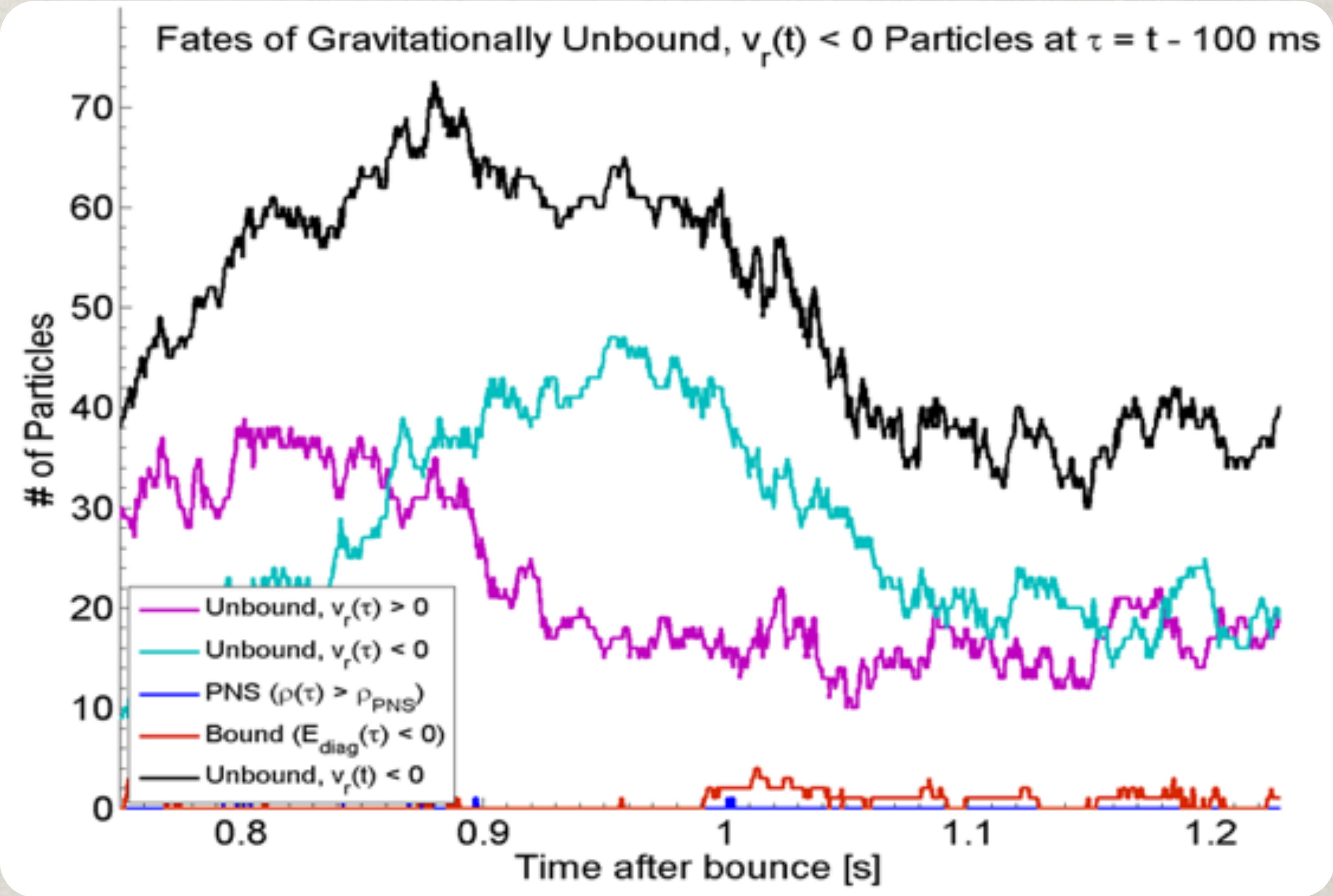




Thus our errors are concentrated in a few particles, in the innermost part of the ejecta.

Unpredictable Particles

For particles which are headed inward, compression raises the temperature and density, making it impossible to extrapolate to freezeout.

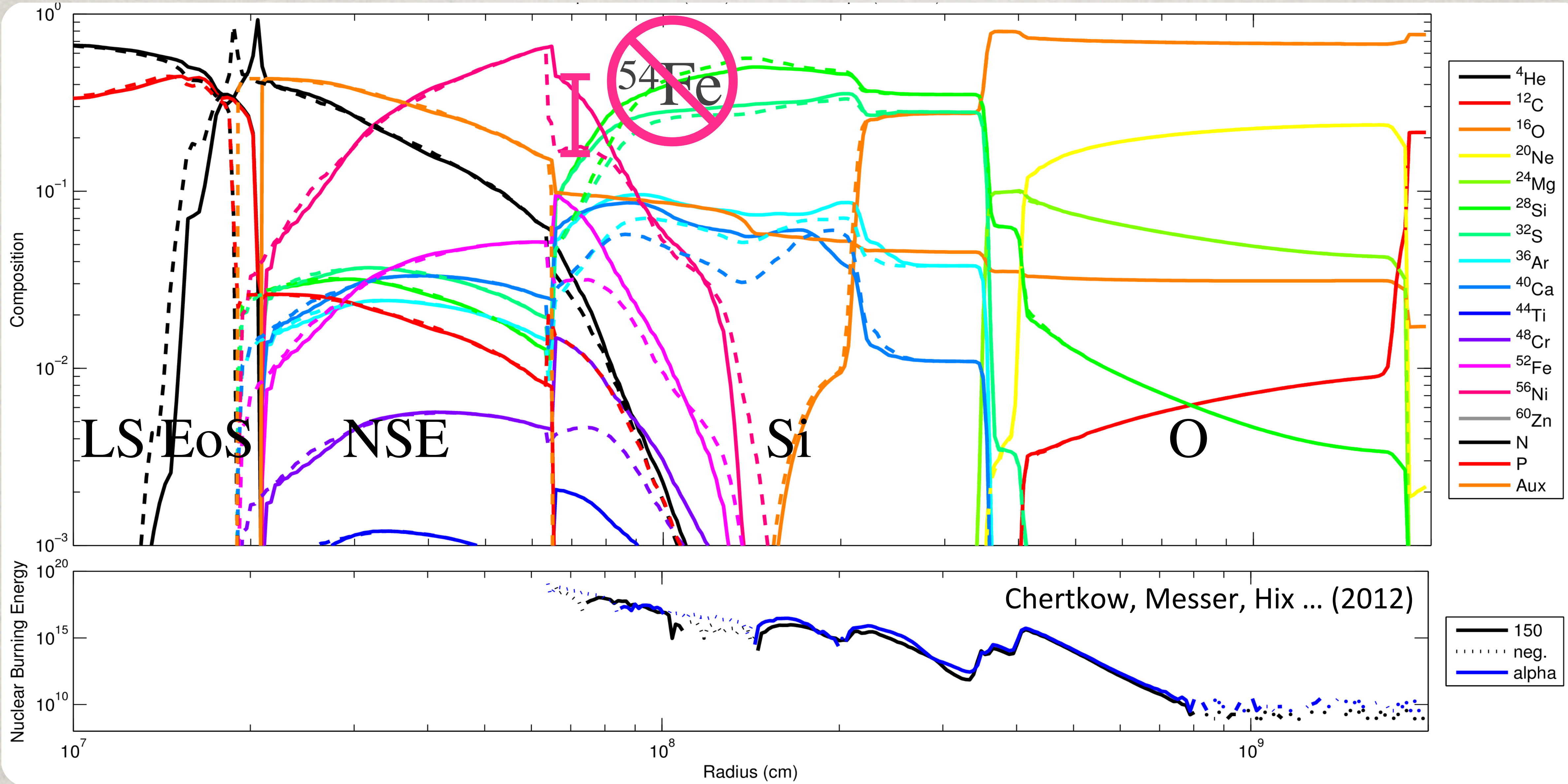


At present, ~40 tracers, carrying 0.0075 $M_\odot$, have $v_r < 0$ but $E_{diag} > 0$.

About half of these were expanding (had outward velocities) 100 ms earlier, indicating they are likely trapped in convective eddies whose fate is uncertain. Another 20 are part of cut-off downflows, which may be accreted or may be ejected.

This gives us an uncertainty of ~0.01 solar mass in the ejecta, even before we consider fallback at much later times.

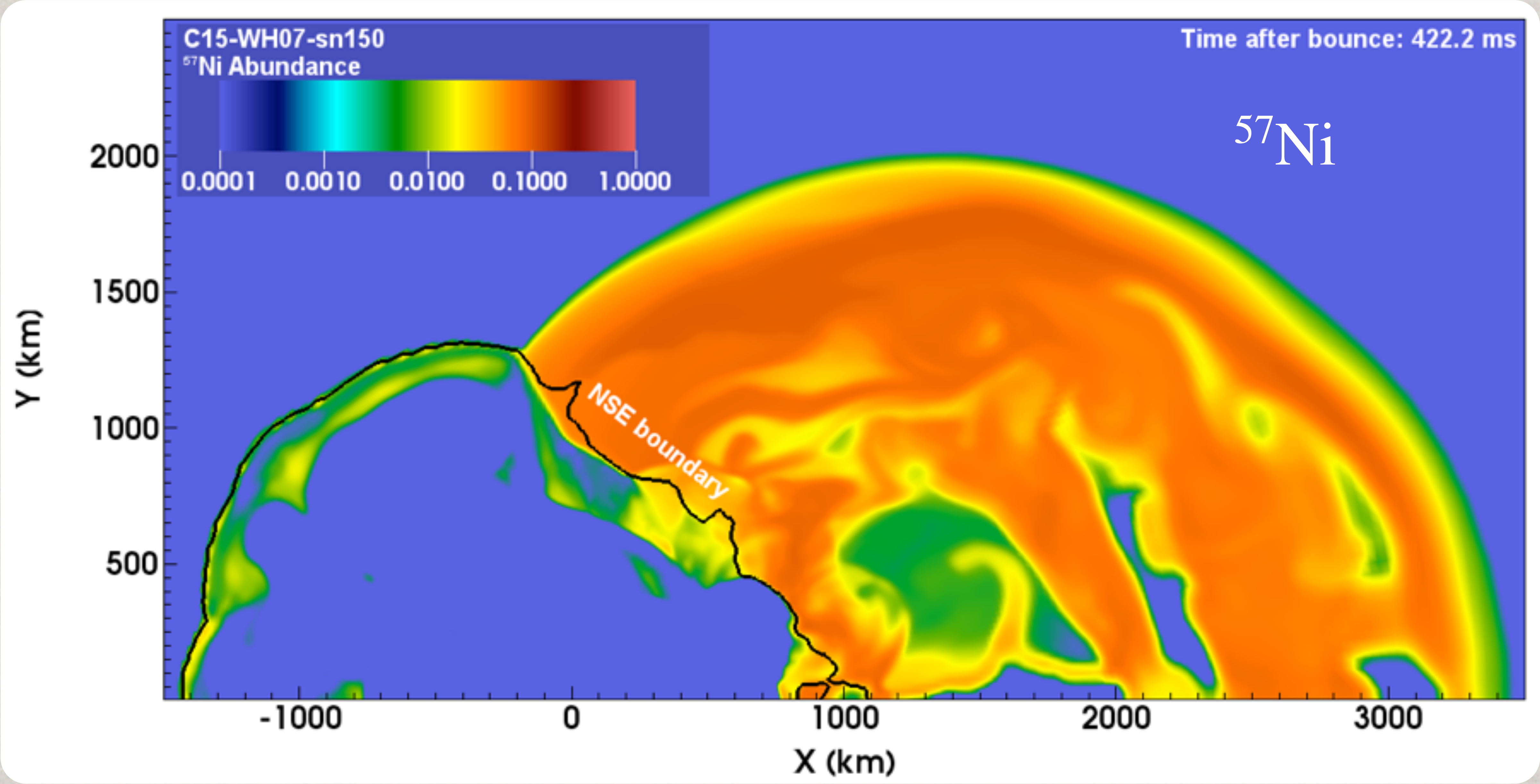
Detailed Composition



To explore the limitations of using a coupled α-network and tracer particles, we've installed 150 species network in CHIMERA.

The network cost grows from 3-5% of the simulation to 200%-400%, making the total simulation 3-5× as expensive.

Large Network Benefits



The use of fully-coupled large reaction network has several benefits:

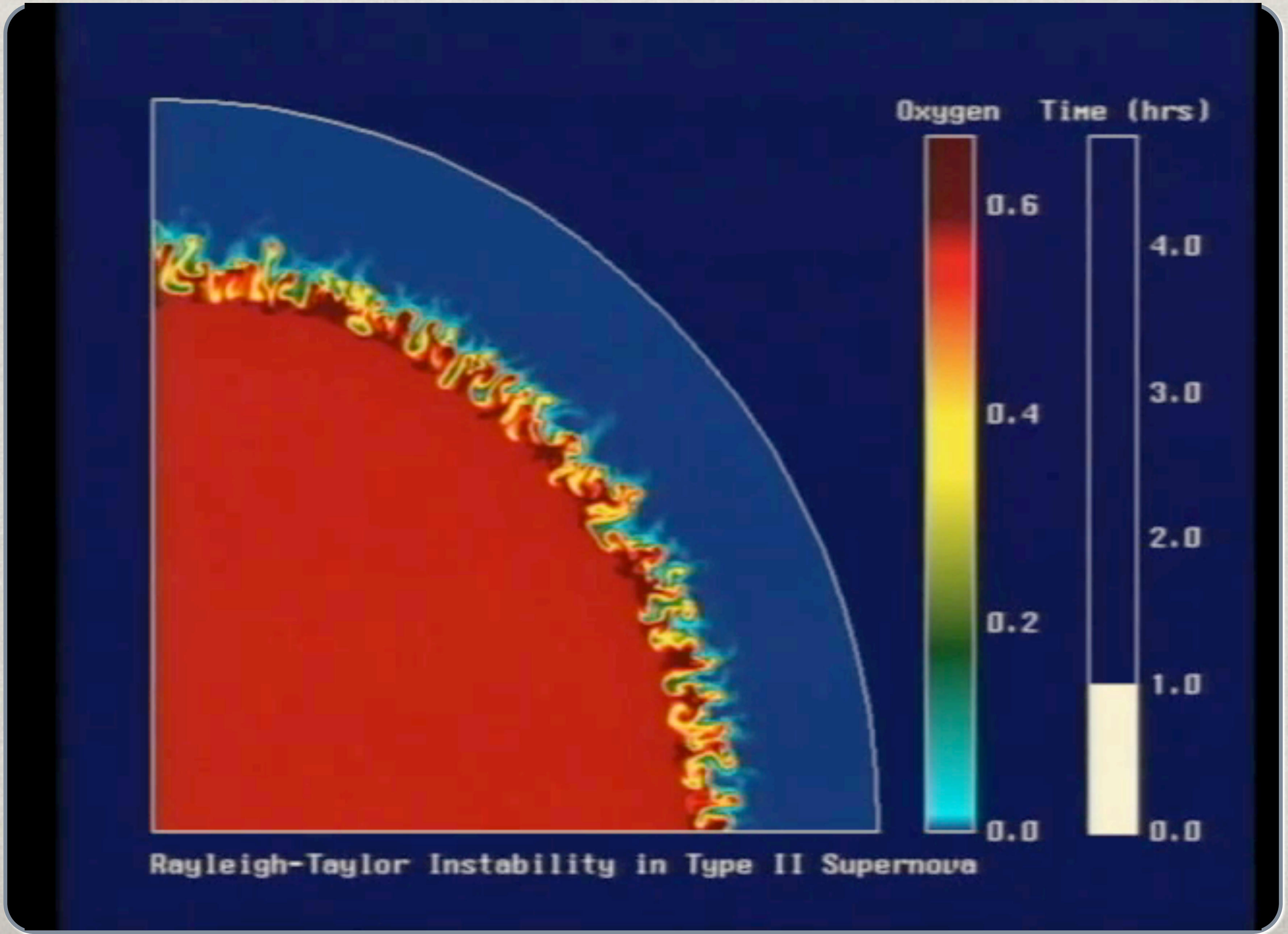
1) More accurate nuclear composition

2) More accurate and self-consistent nuclear energy generation

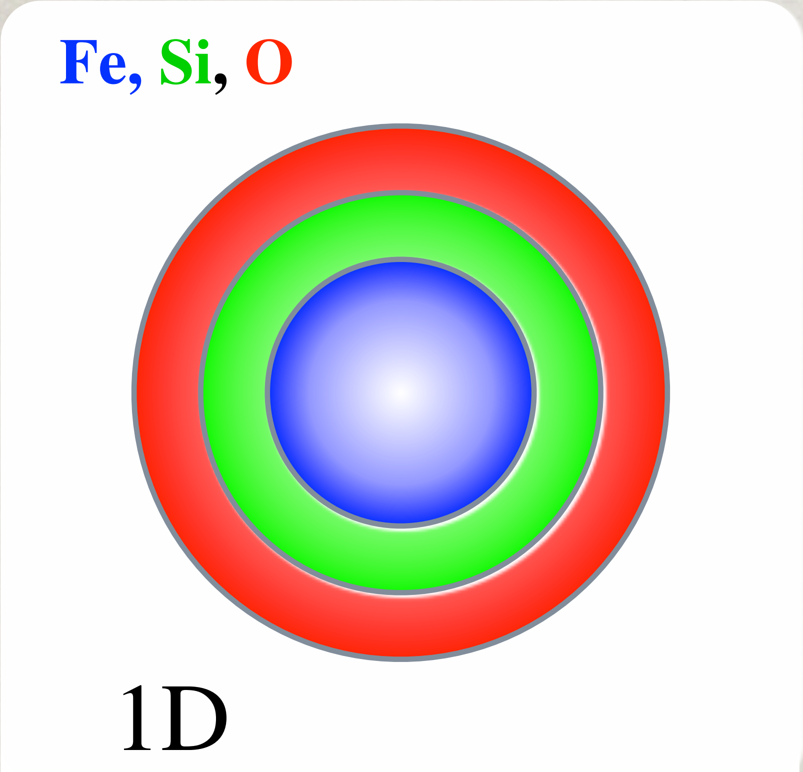
3) Better resolution (>100,000 zones vs. <10,000 tracers)

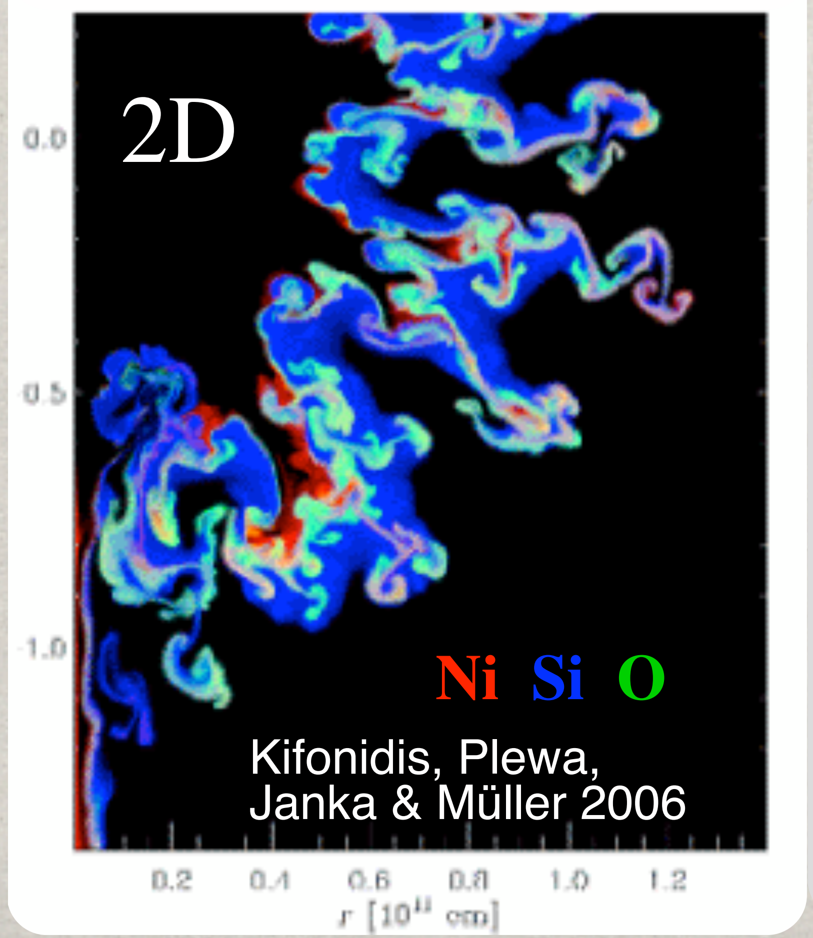
Ejecta Evolution

Completion of nucleosynthesis does not mark the last changes to the ejecta. Interaction of the supernova shock with the star's H/He and He/CO interfaces produces Rayleigh-Taylor instabilities, which alter the velocity distribution of the ejecta.



Meeting Observations





Ultimately, matching observations compels models with detailed nucleosynthesis to run until the explosion is fully developed.

The observations compel us to examine stellar explosions (and stellar evolution) in multi-dimensions throughout their history.

We must extend our 2D & 3D simulations until they reach the surface of the stars.