Predicting nucleosynthesis observables in CCSNe with self-consistent simulations

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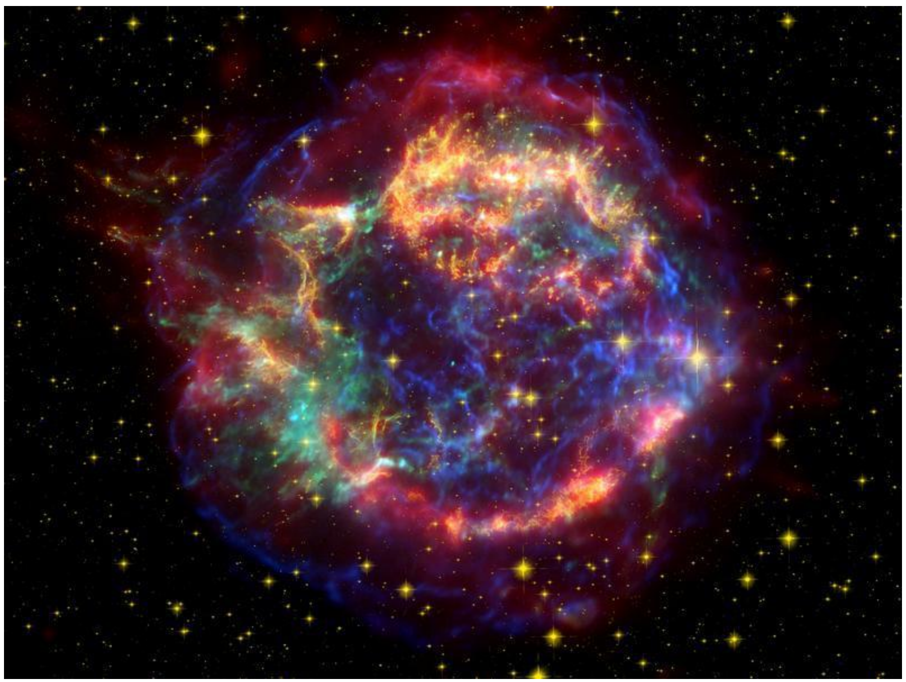

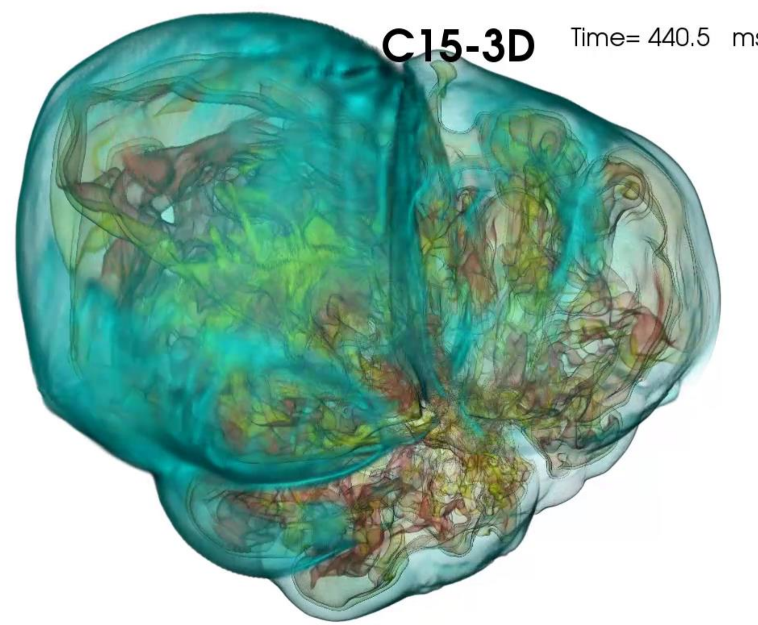

F.O.E., NCSU
June 4, 2015

Collaborators

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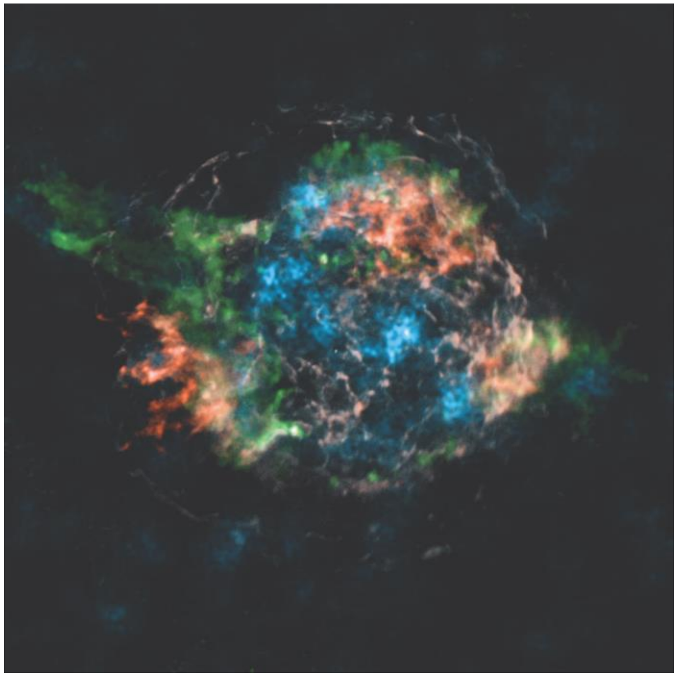
CCSN Paradigm

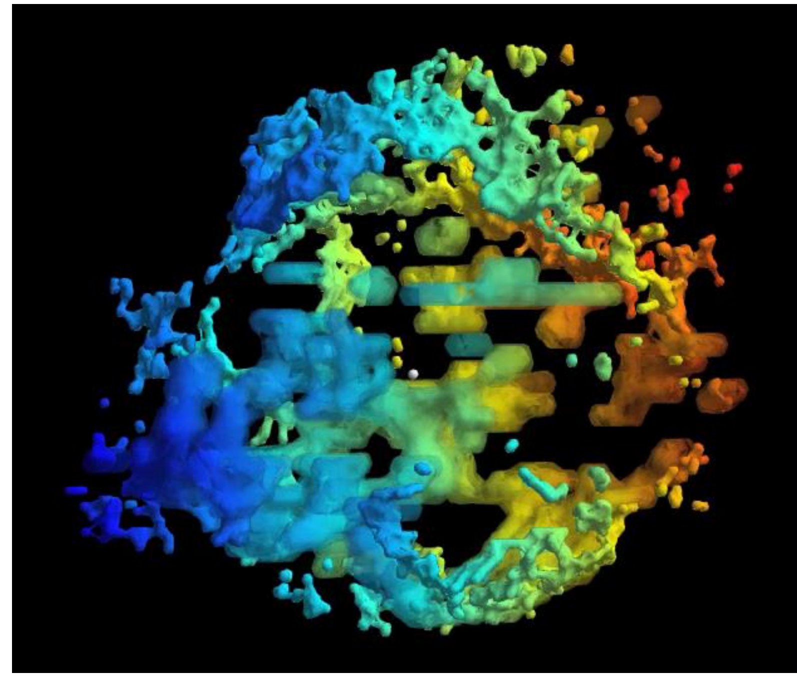
Observational Evidence

(Grefenstette et al., *Nature*, 2014)



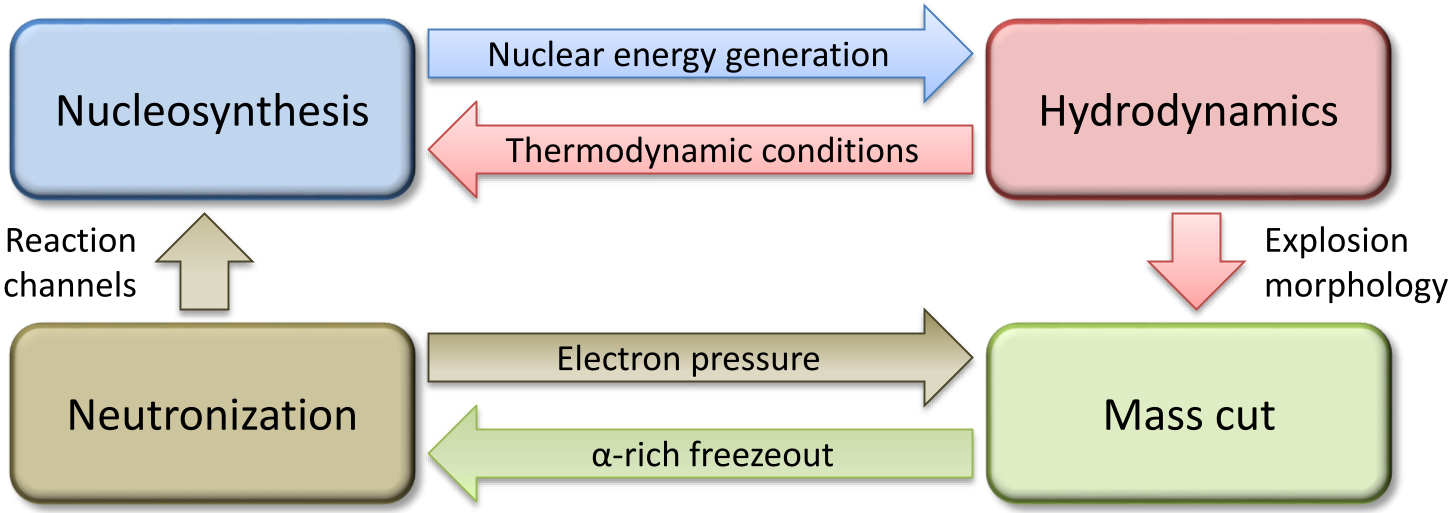
- X-ray: Si/Mg, ^{44}Ti, Fe
  "Sloshing" behavior
  Possible ^{44}Ti w/o Fe-group?

Milisavljevic & Fesen, *Science*, 2015



- Infrared: Sulfur
  Bubble-like interior

Nucleosynthesis in CCSN

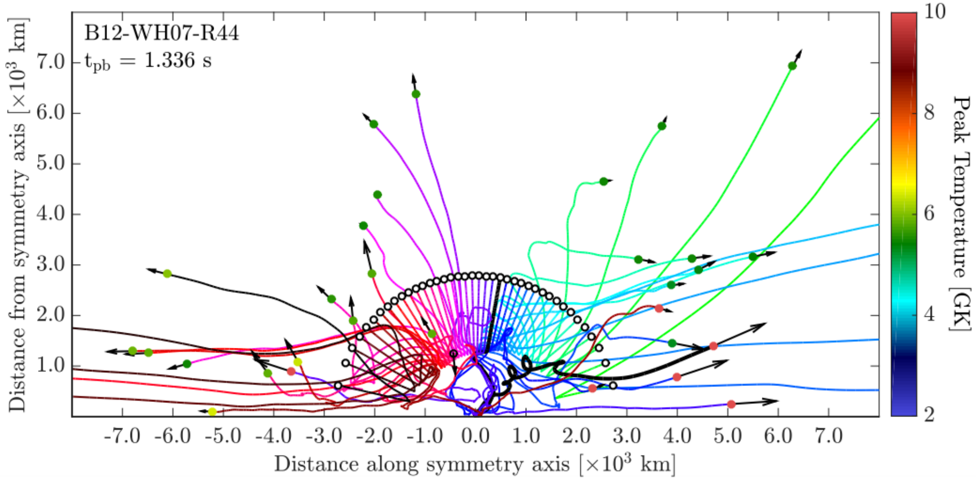


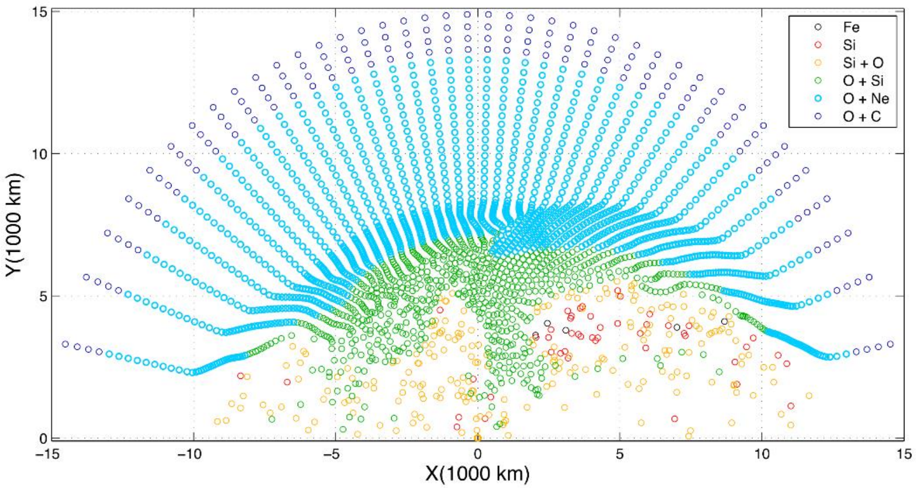
- Hydrodynamics strongly coupled to nucleosynthesis
- Detailed networks are computationally expensive
  - Reduced networks exclude weak reactions and misestimate nuclear energy generation

Nucleosynthesis in CCSN

Tracer Particle Method

- Lagrangian tracer particles track thermodynamic history throughout star
- Temperature and density profile used to “post-process” nucleosynthesis with detailed network



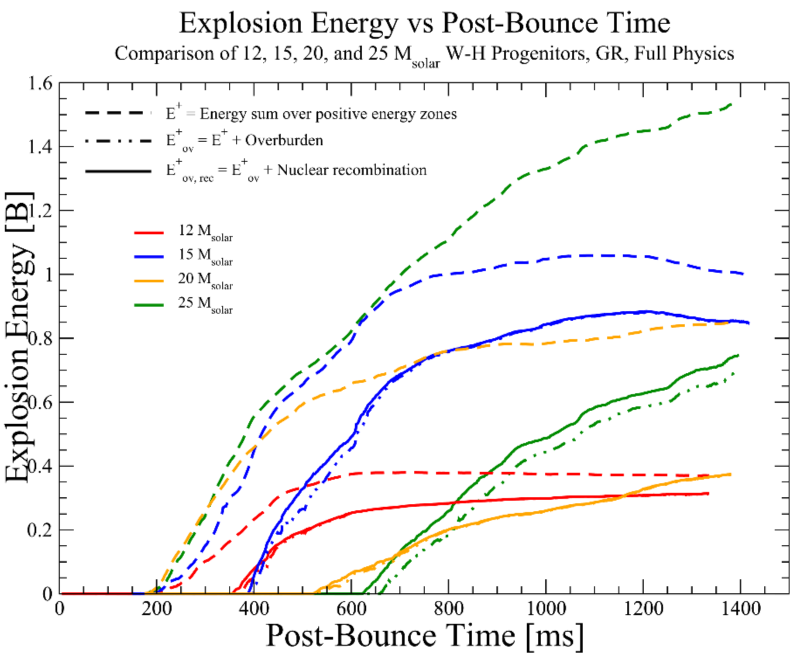


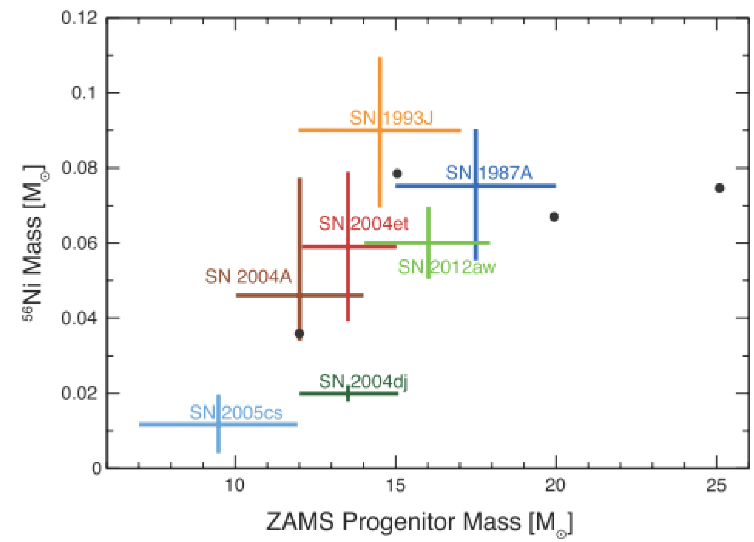
- Does not capture hydrodynamic feedback or microscopic elemental mixing
- Despite deficiencies, still a major improvement to composition distribution

CHIMERA "B-Series"

Current Status

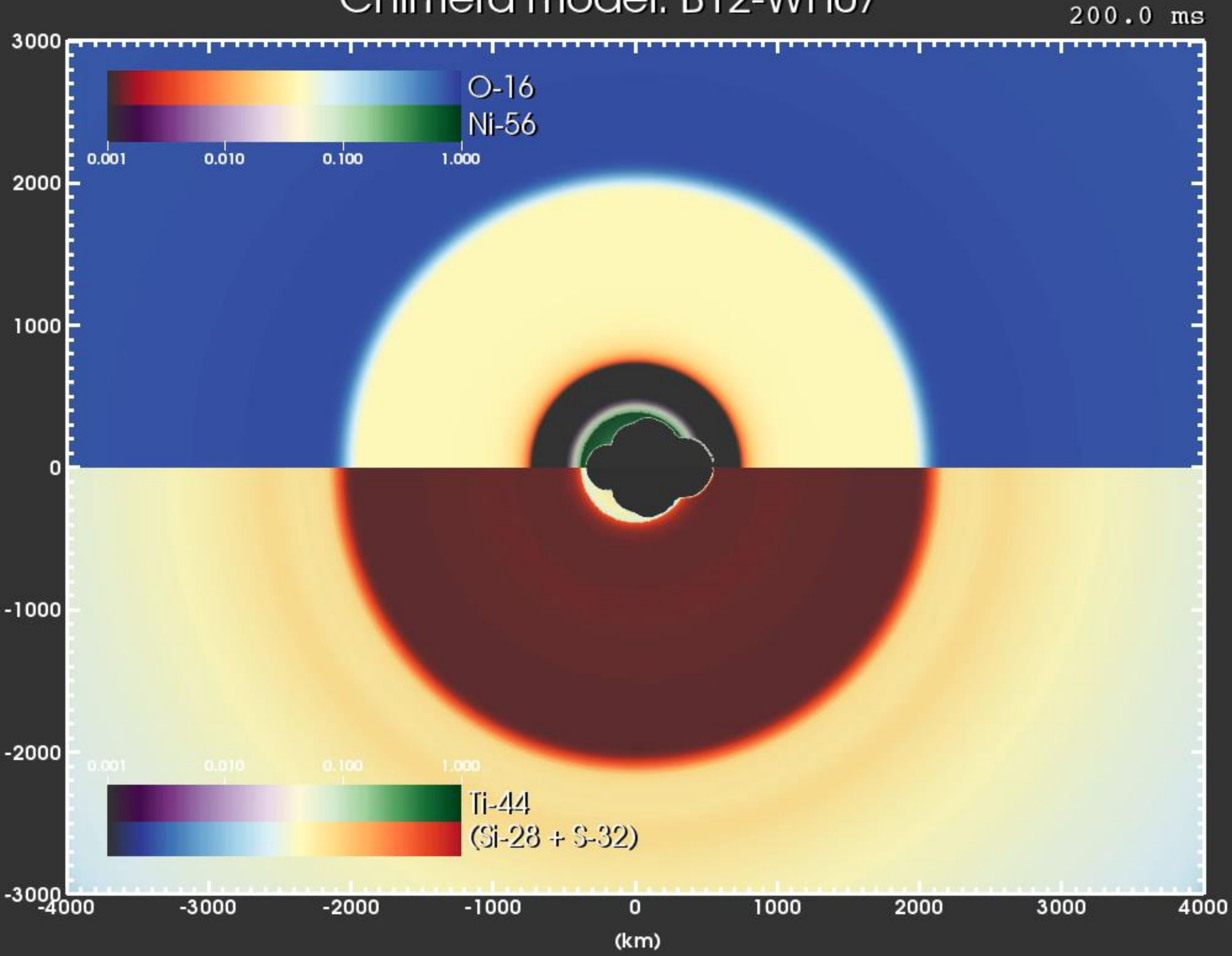
- Four axisymmetric models initiated from stellar metallicity, non-rotating progenitors from Woosley & Heger 2007
- Computational constraints limit *in situ* burning to 14-species α-network
- Lagrangian tracer particles for post-processing with detailed nucleosynthesis
- Letter published on early explosion development; Full paper submitted to *ApJ*





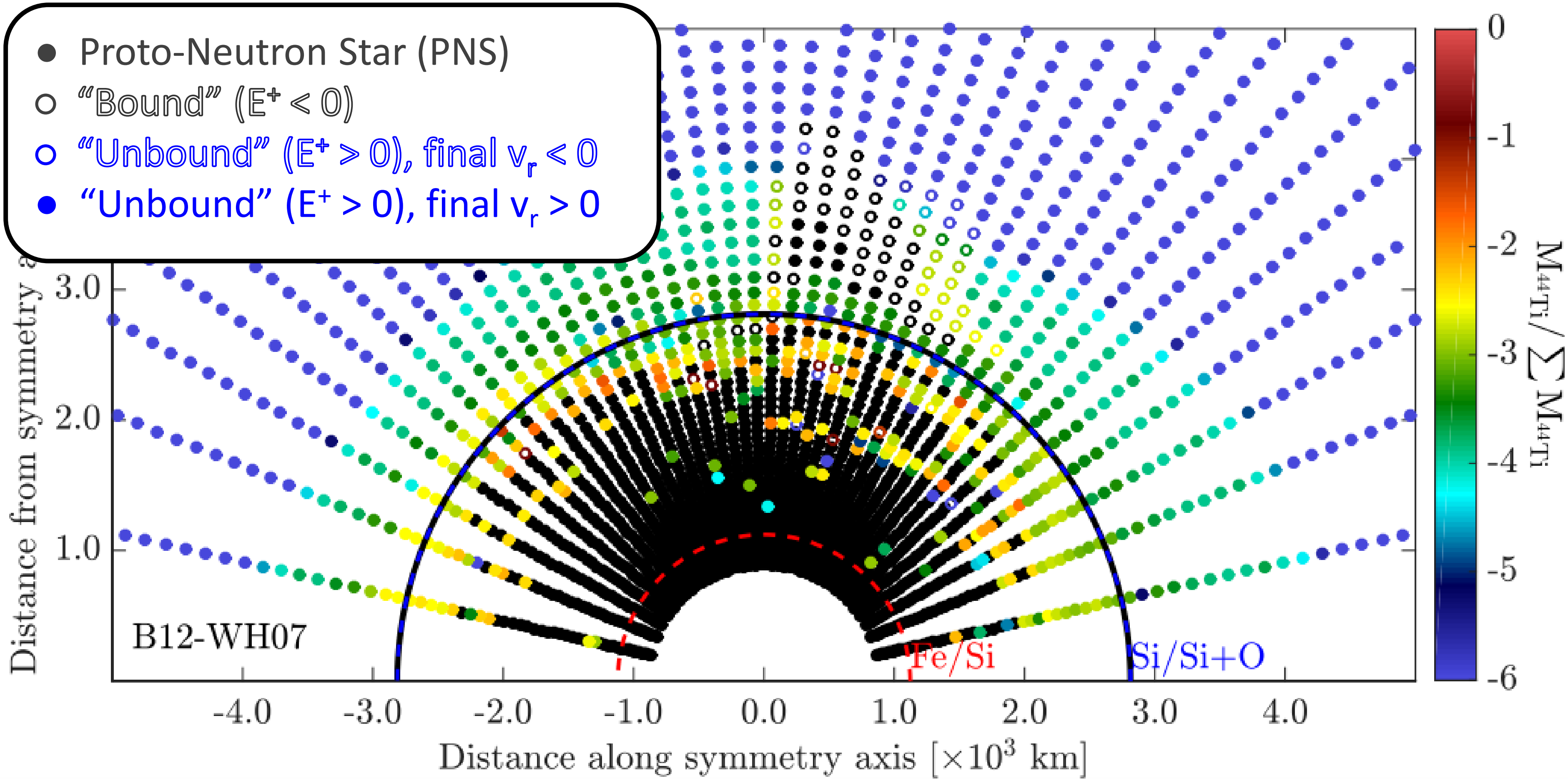
Bruenn et al. 2013, ApJ, 767, L6
Bruenn et al. 2015; arXiv:1409.5779

Chimera model: B12-WH07

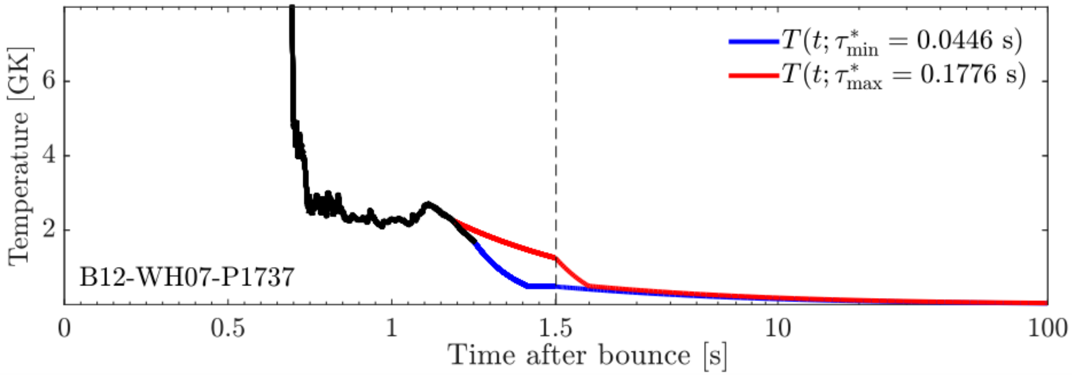


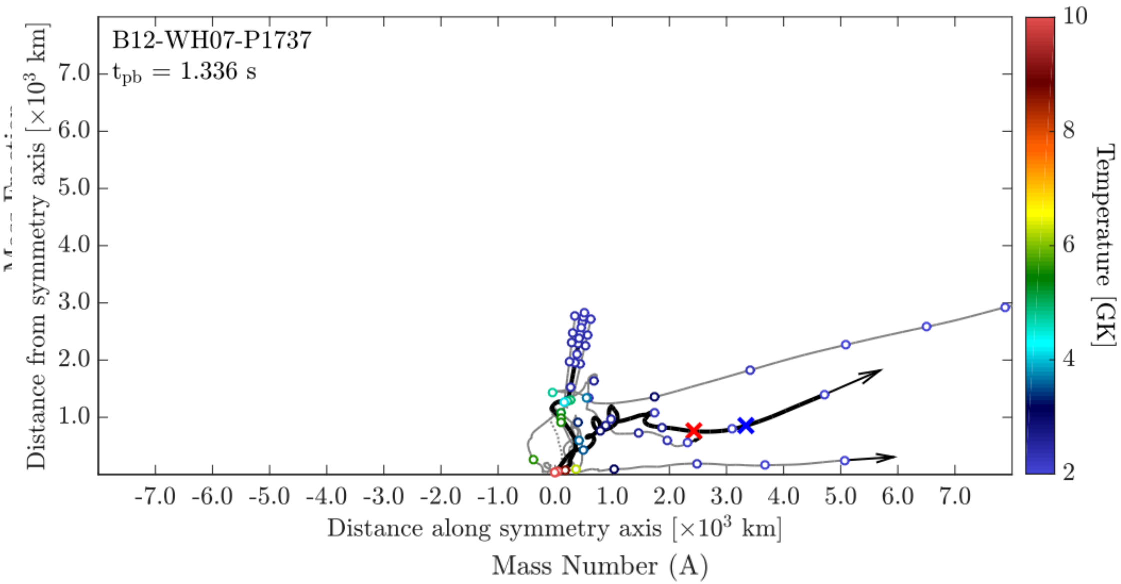
Post-processing Challenges

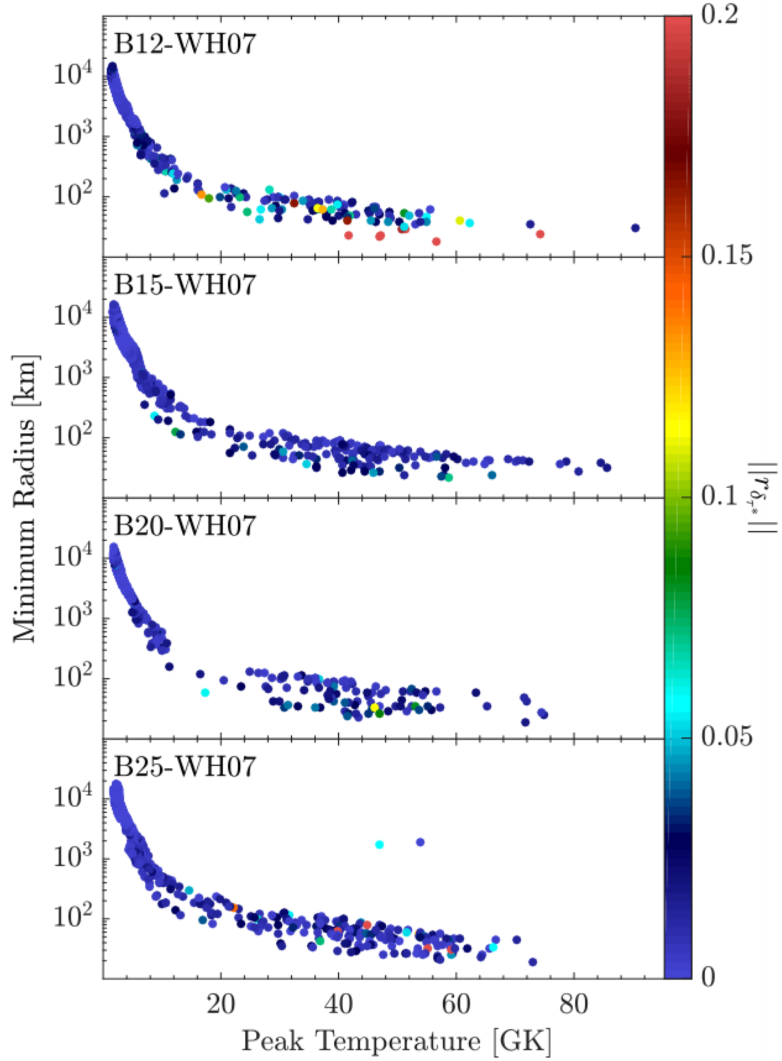
Multi-D Mass-cut



Post-processing Challenges Thermodynamic Extrapolation







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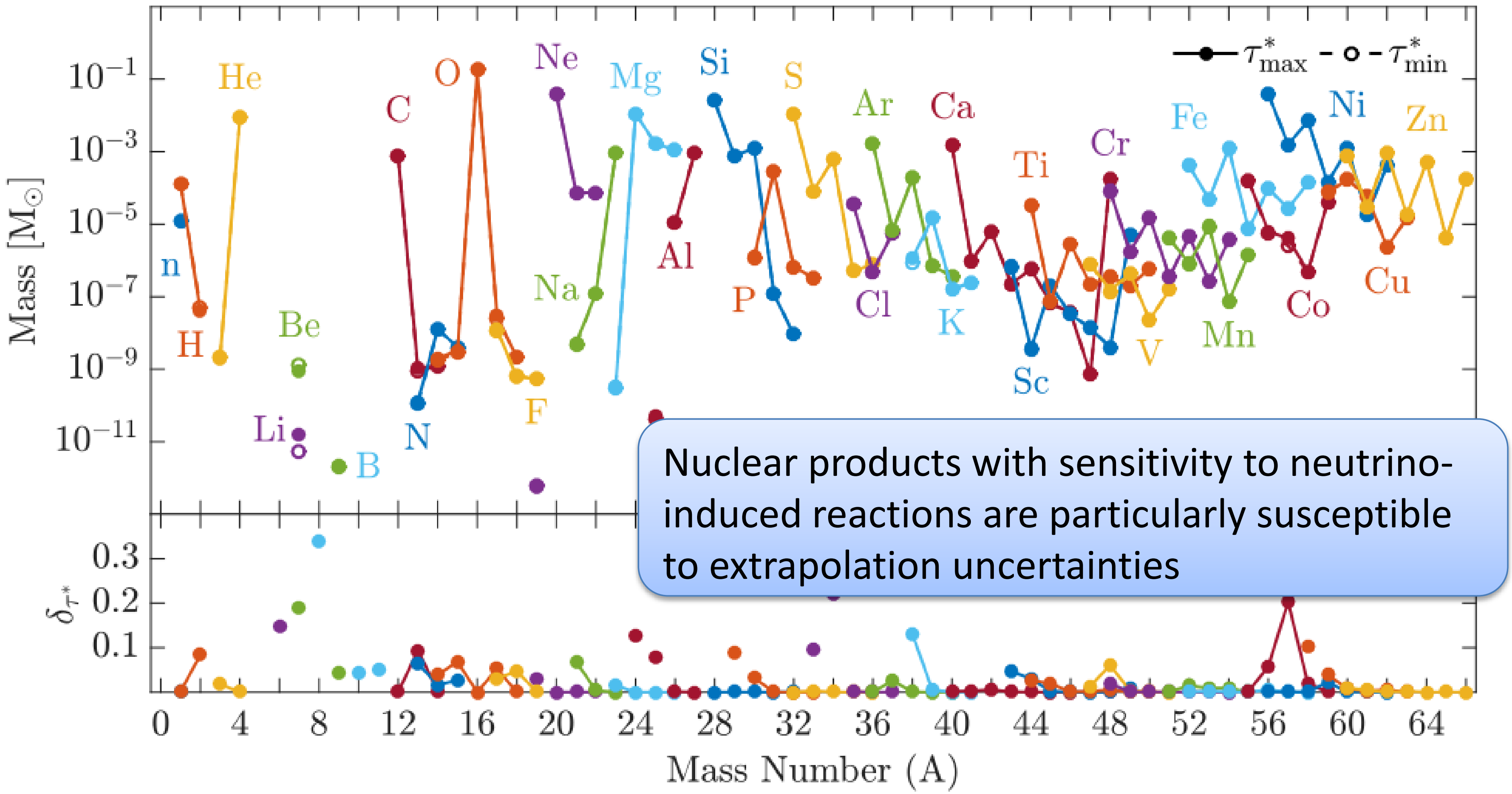
Post-processing Challenges

Extrapolation Uncertainties



Nuclear products with sensitivity to neutrino-induced reactions are particularly susceptible to extrapolation uncertainties

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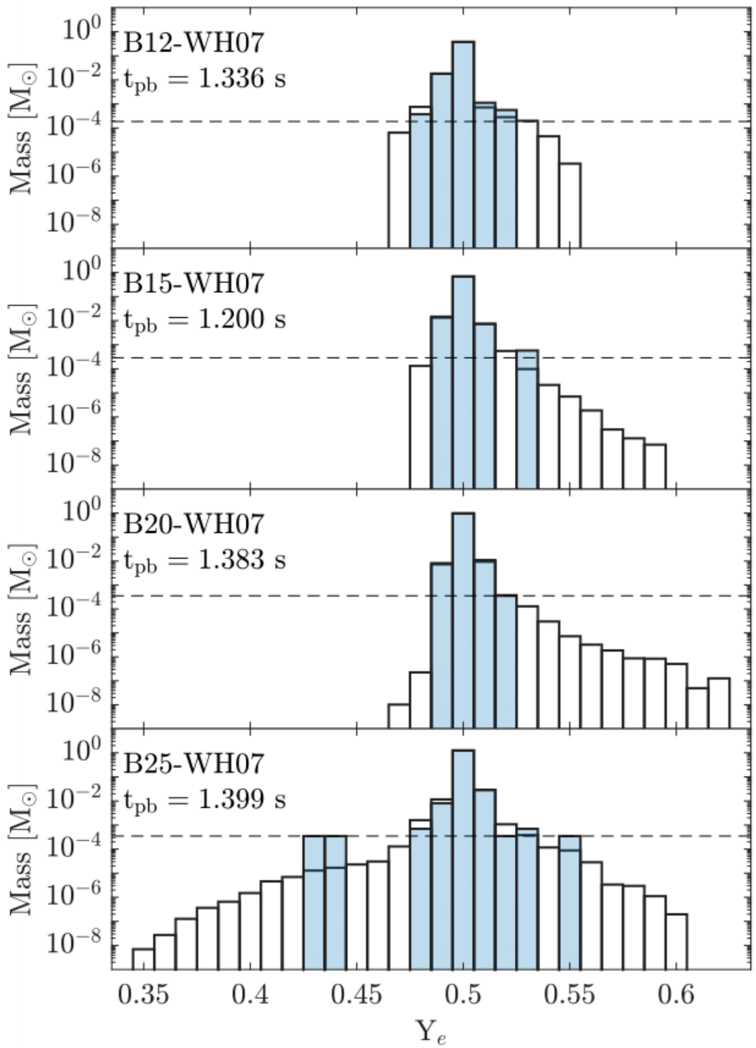
Post-processing Challenges

Resolution Uncertainties



- Extrapolation and mass-cut uncertainties could be reduced by extending simulations
- Tracer particle resolution is a more fundamental concern

Label	Particles	M_{tracer} [$\times 10^{-4}$ $M_\odot$]
B12-WH07	4000	1.868E-4
B15-WH07	5000	2.864E-4
B20-WH07	6000	3.545E-4
B25-WH07	8000	3.486E-4

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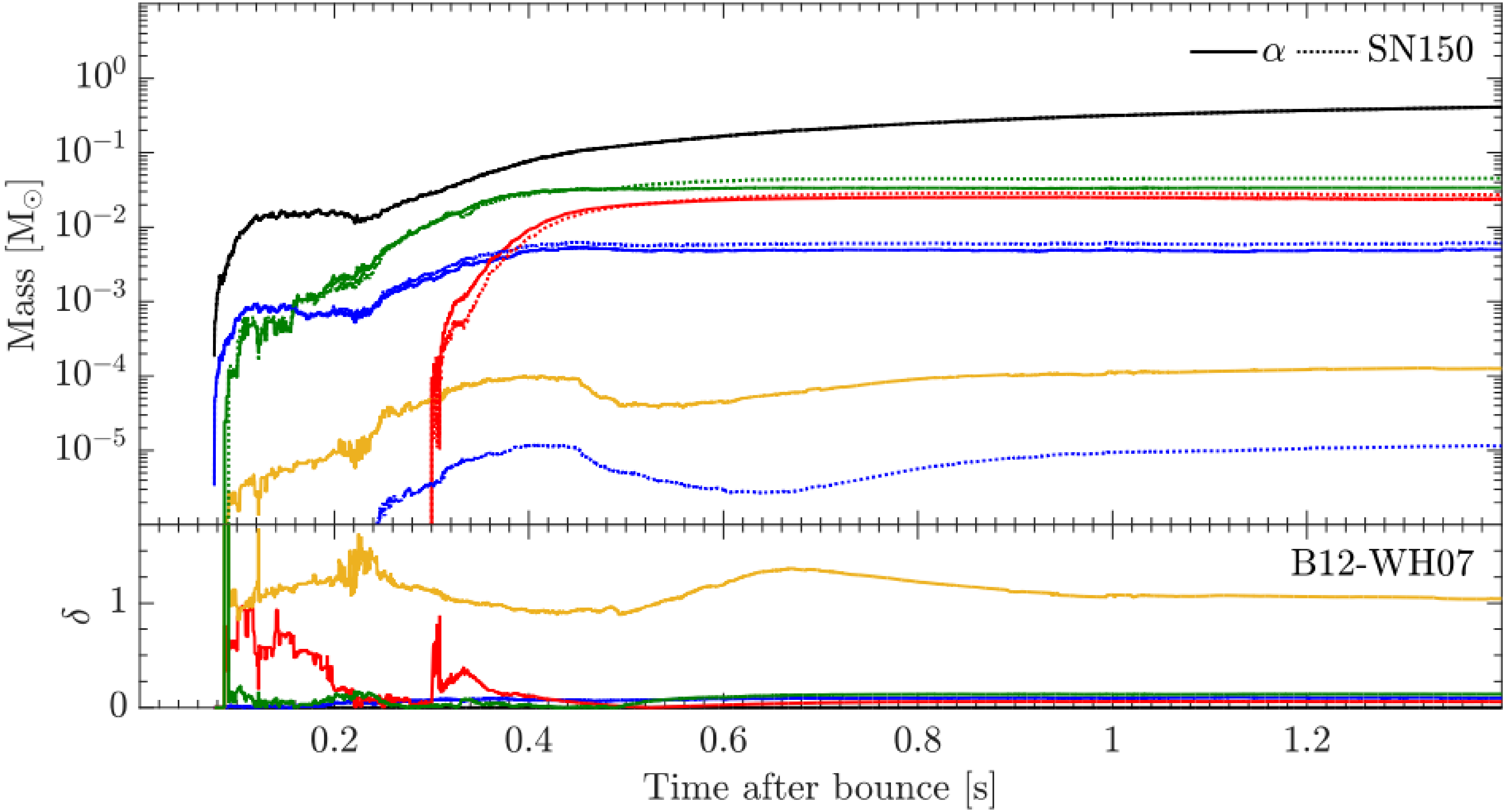
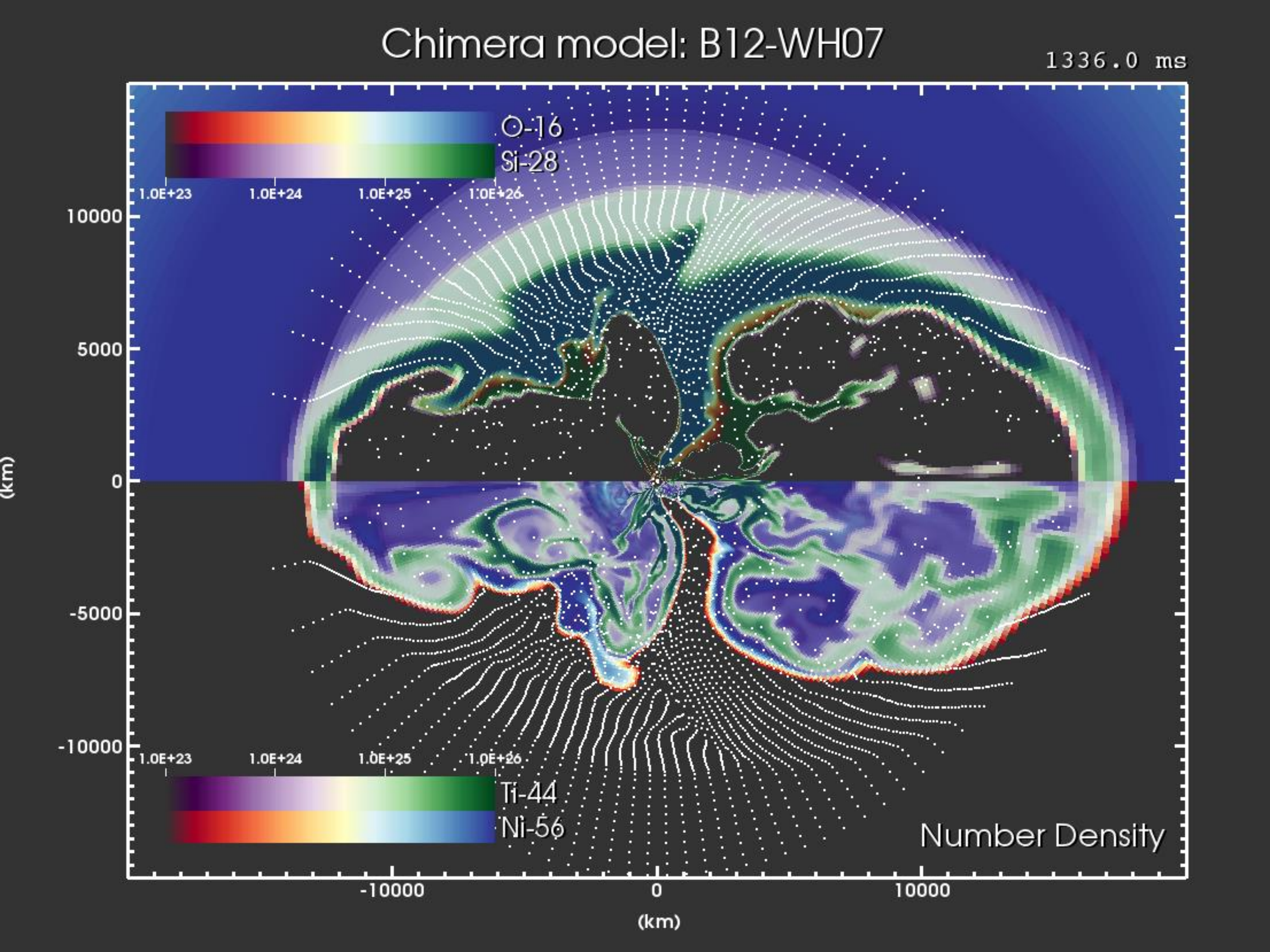
Post-processing Challenges

Resolution Uncertainties

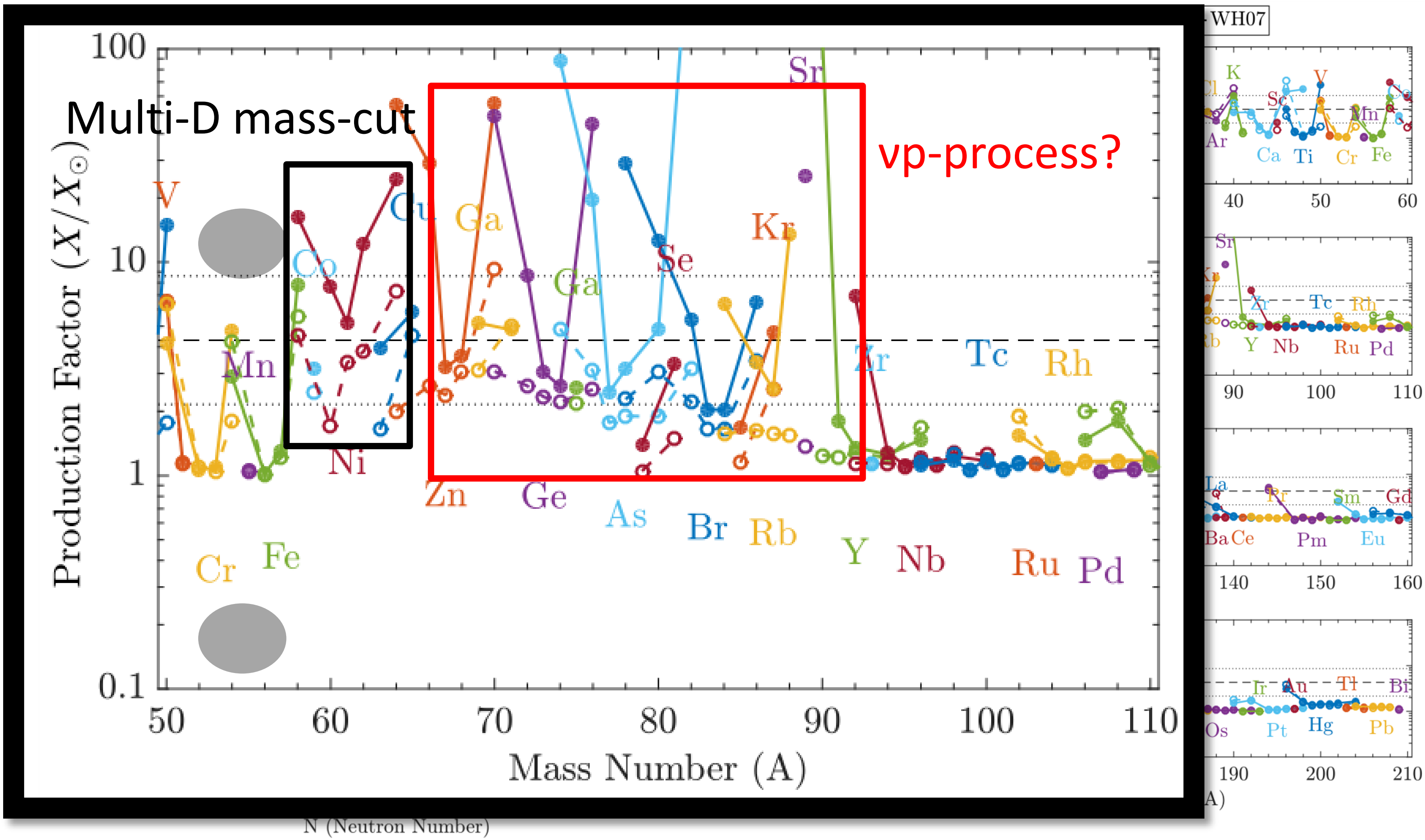




Chimera model: B12-WH07
1336.0 ms
O-16
Si-28
1.0E+23
1.0E+24
1.0E+25
1.0E+26
10000
5000
0
-5000
-10000
(km)
1.0E+23
1.0E+24
1.0E+25
1.0E+26
Ti-44
Ni-56
Number Density
-10000
0
10000
(km)

Nucleosynthesis in Ejecta

Preliminary Results



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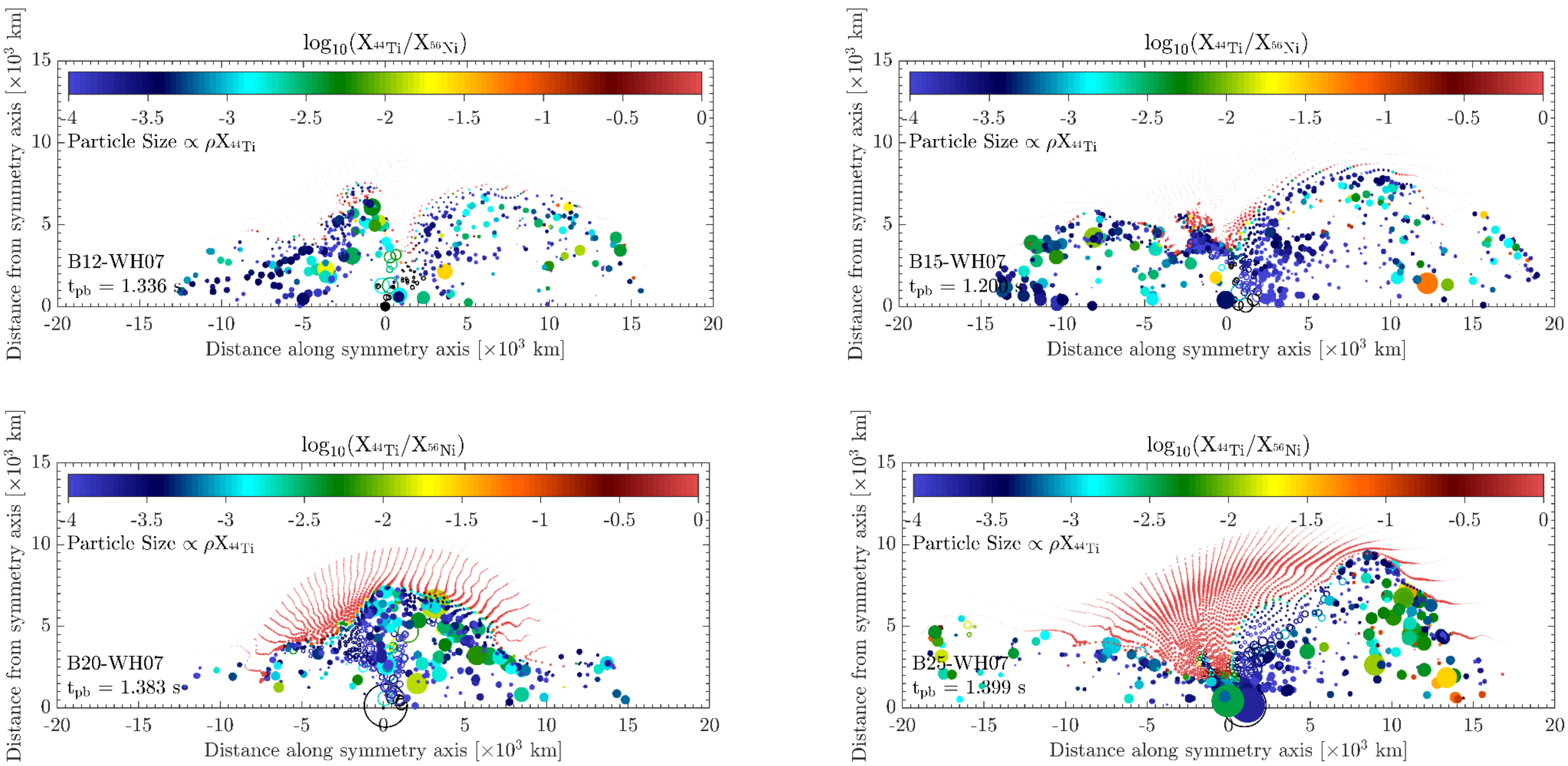
Nucleosynthesis in Ejecta

~~^{44}Ti without ^{56}Ni?~~

Not Exactly



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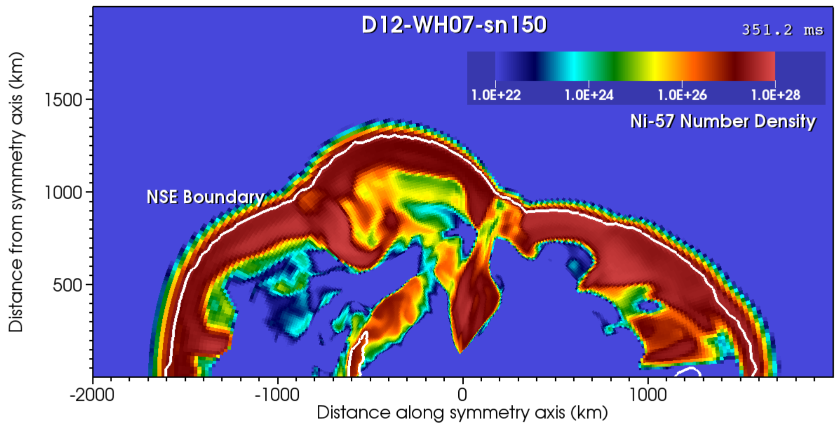
CHIMERA "D-Series"

New Models

Reference	Mass	Particles	SN150
Woosley & Heger 2007 "KEPLER"	$12\ M_\odot$	~50000	Yes
	$13\ M_\odot$	?	Yes
	$14\ M_\odot$	?	Yes
	$15\ M_\odot$	?	Yes
	$20\ M_\odot$	?	Yes
	$25\ M_\odot$	?	Yes
	$30\ M_\odot$	?	
	$35\ M_\odot$	?	
	$40\ M_\odot$	?	
Ellinger et al. 2012 "TYCHO"	$12\ M_\odot$	TBD	
	$15\ M_\odot$	?	Yes
Chieffi & Limongi 2013 "FRANEC"	$15\ M_\odot$	TBD	
Umeda & Nomoto 2005	$15\ M_\odot$	TBD	



- Large *in situ* network will address the deficiencies of the α-network directly
- Currently evolving models with 150-species nuclear network

Summary

- Simulating supernovae takes a **very** long time
  - Code improvements help, but still a long way from the edge of the star

- Post-processing nucleosynthesis must be done with care
  - Uncertainty in the "mass cut" and particle expansion timescales represent significant uncertainties in the final abundances
  - Low tracer particle resolution in low density regions of freezeout makes abundance predictions on species like ^{44}Ti extremely difficult
  - Correcting for this, we see $\approx 1—3 \times 10^{-4}\ M_{\odot}$ of ^{44}Ti in our models

- Preliminary nucleosynthesis results from CHIMERA "B-series" runs suggests qualitative differences from parameterized 1D simulation of same models
  - Enhanced production for many species from multi-dimensional "mass cut" and availability of neutrino-dependent reaction pathways

- Need larger nuclear network with sufficient reaction channels (150 species) evolved *in situ* to capture freezeout
  - Computational improvements are now making this possible (large network models in progress)