THE PROGENITORS OF CORE-COLLAPSE SUPERNOVAE

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OVERVIEW

Introduction

- Core-Collapse Supernovae
- The Core-Collapse ‘Problem’
- Possible Solutions

Reaction Rate Uncertainties

- Stellar Evolution Models
- Identifying Key Reactions using STARLIB

3D CCSNe Progenitors

- Previous Efforts
- 3D Hydrodynamic Simulations

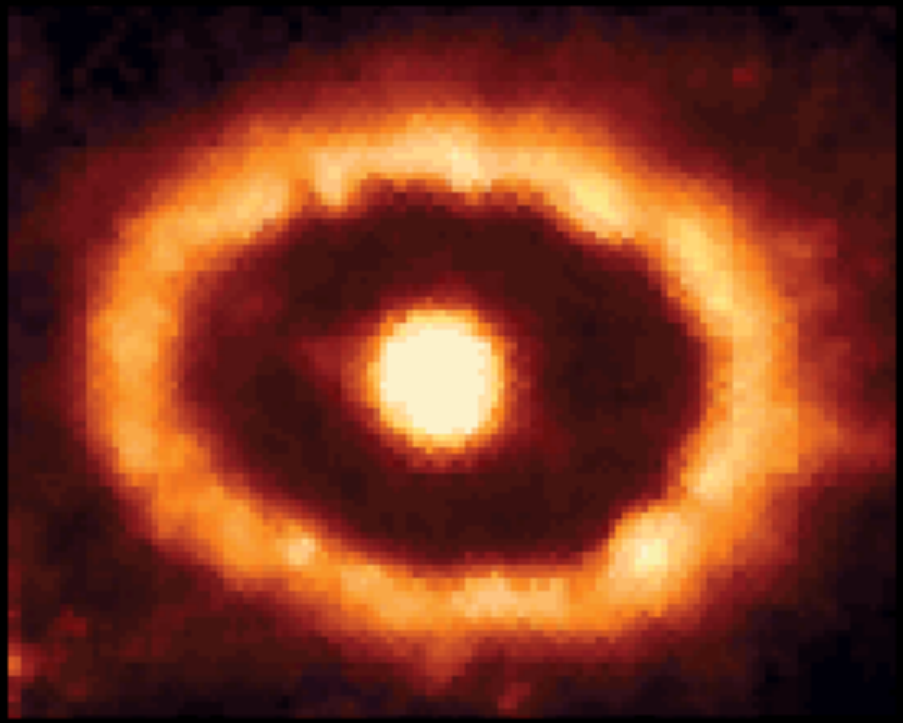
Conclusions

RCW 114, an old supernova remnant with an estimated diameter of 100 lightyears.

CORE COLLAPSE SUPERNOVAE - WHY DO WE CARE?

Understanding core collapse supernova explosions is crucial to many different problems of astronomy.

- Galactic Chemical Evolution
- Massive Star Transients
- Compact object formation



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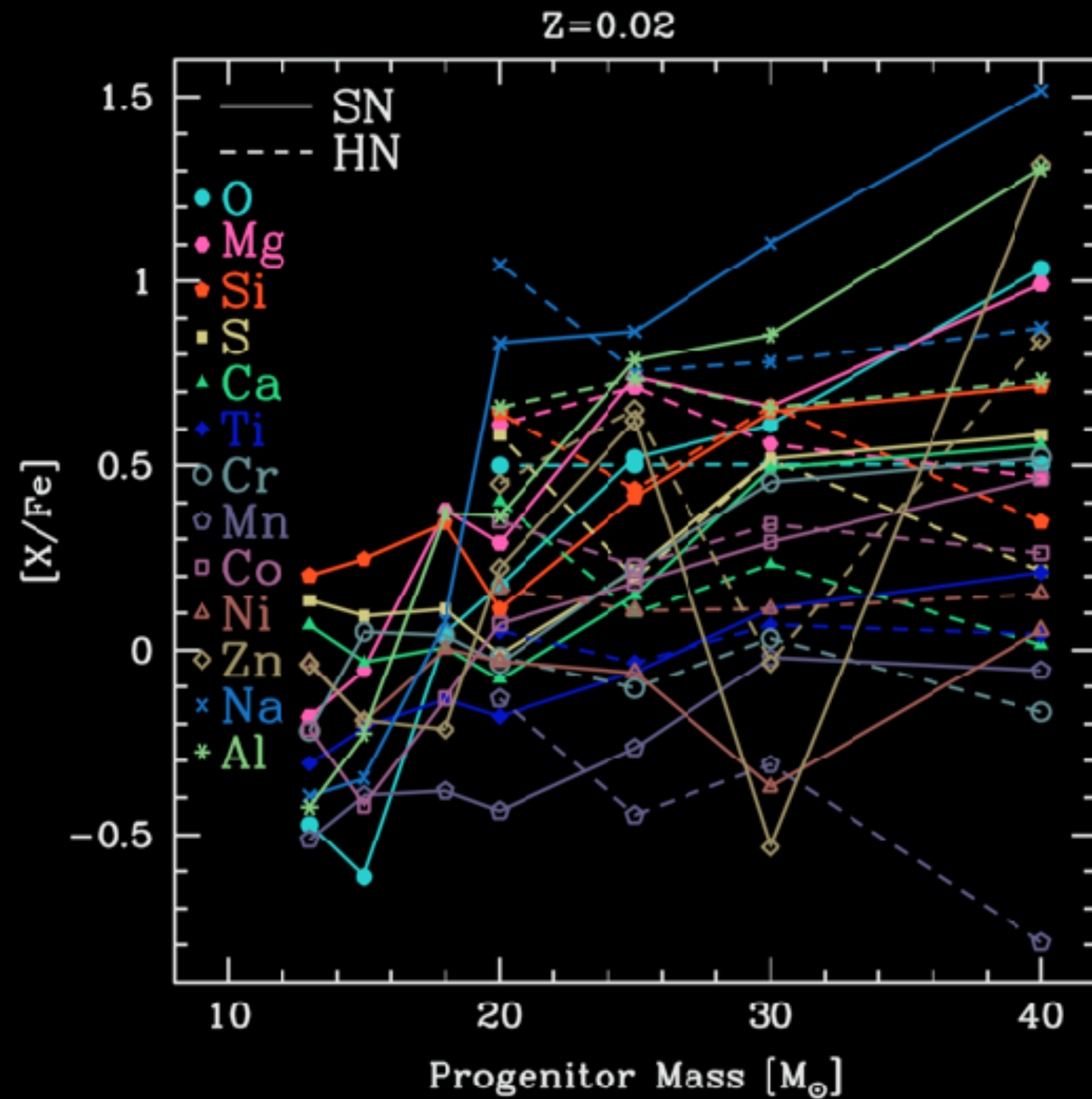
CREDIT: LARSSON, J. ET AL. (2011).

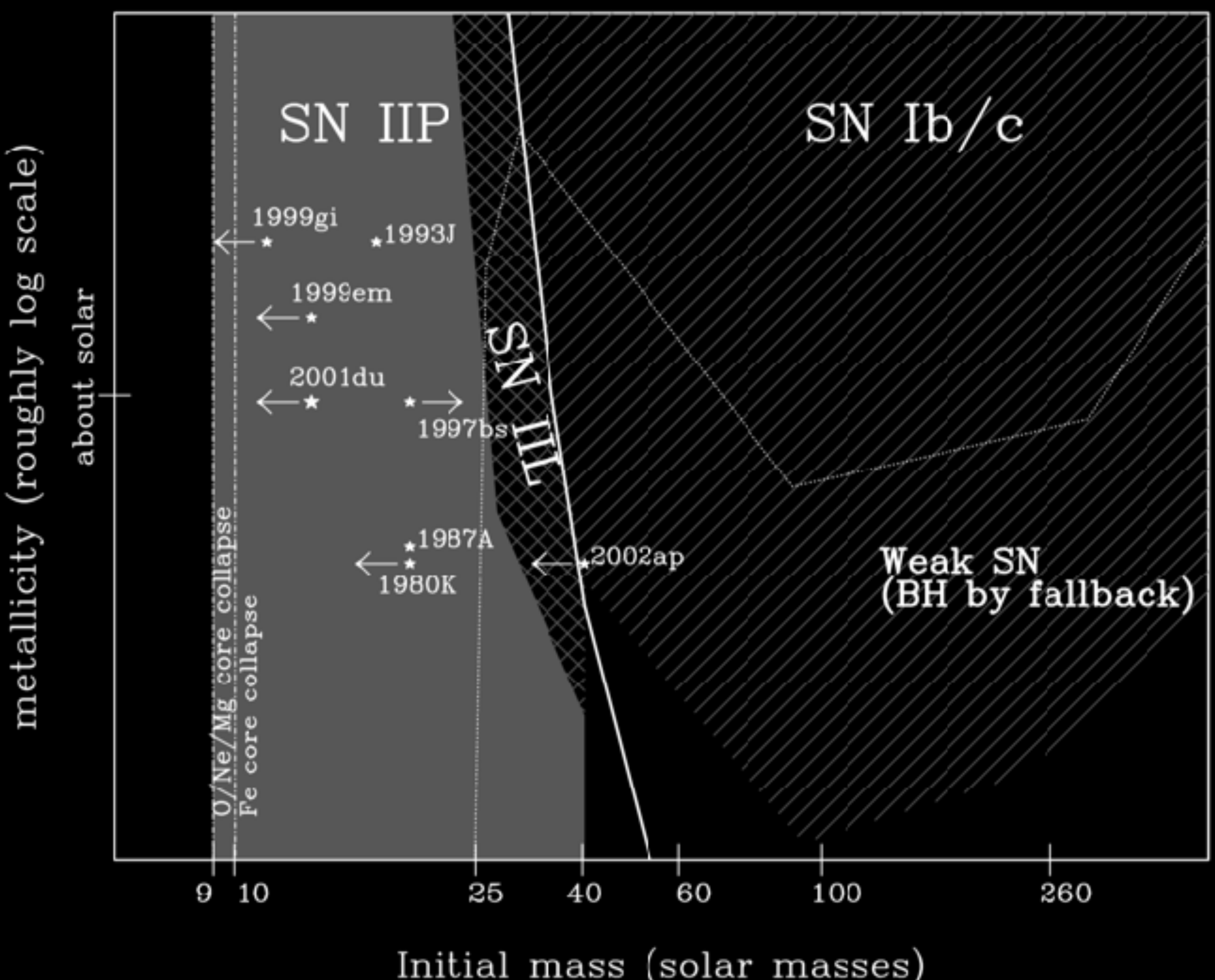
CORE COLLAPSE SUPERNOVAE AND GALACTIC CHEMICAL EVOLUTION

- Core-collapse supernovae are a key component of GCE and solar abundance.
- Help enrich future generation of stars.



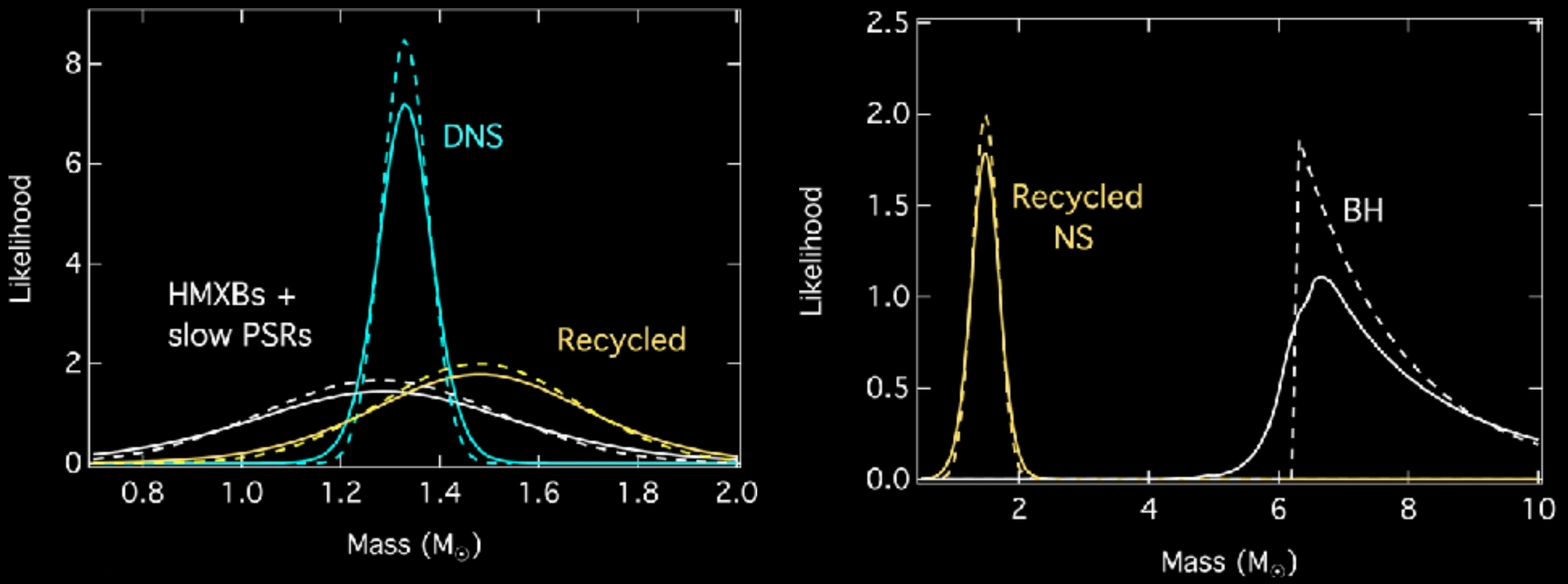
Relative abundance ratios as a function of initial mass. (KOBAYASHI + 2016)

CORE COLLAPSE SUPERNOVAE - MASSIVE STAR TRANSIENTS



SN Populations from Heger+ 2003 models (Smartt + 2013)

CORE COLLAPSE SUPERNOVAE - COMPACT OBJECT FORMATION



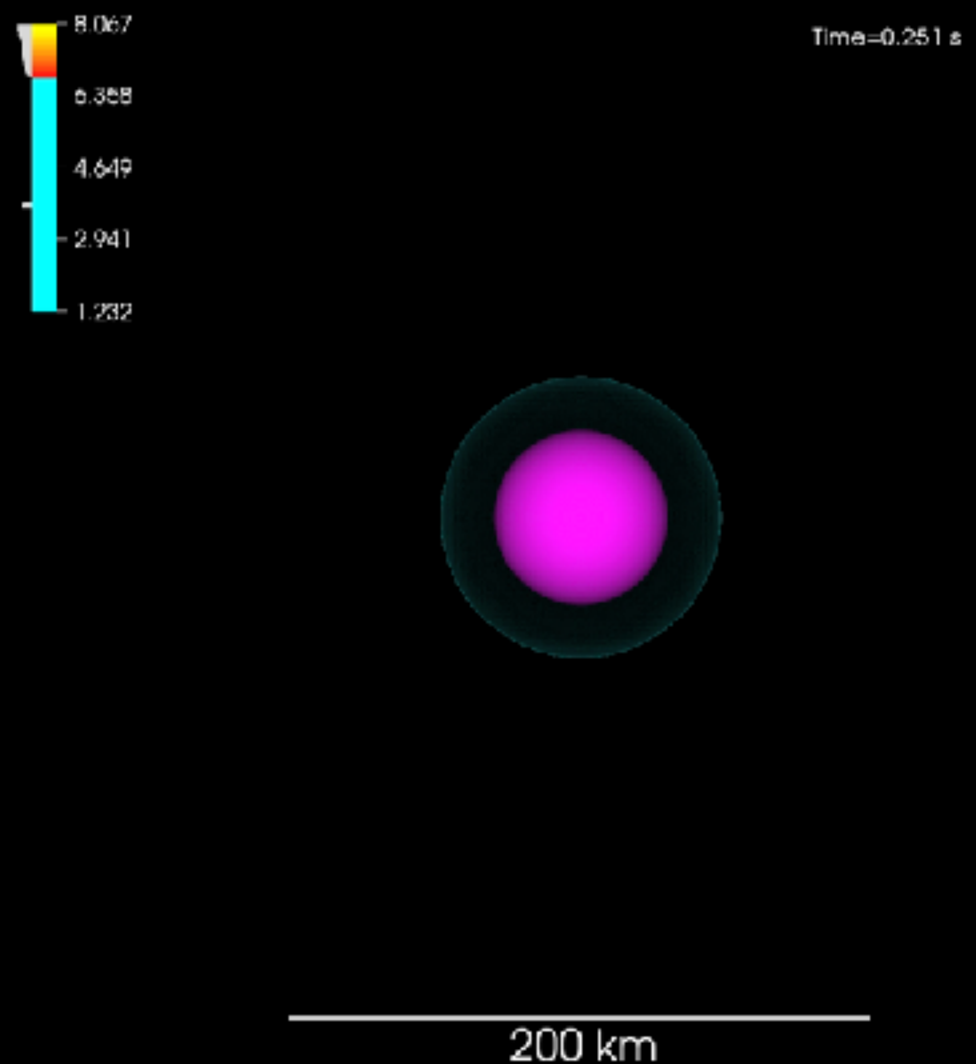
NS and stellar BH mass distributions computed from fits to Bayesian simulations. (Ozel + 2012)

CORE-COLLAPSE SUPERNOVAE ARE IMPORTANT

THE CORE-COLLAPSE 'PROBLEM'

How do we (try) to model stellar explosions?

- 1D Stellar Evolution Codes for pre-supernova evolution.
- Evolve explosion in 2/3D using multi-D hydro codes.
- Explosions fail…?

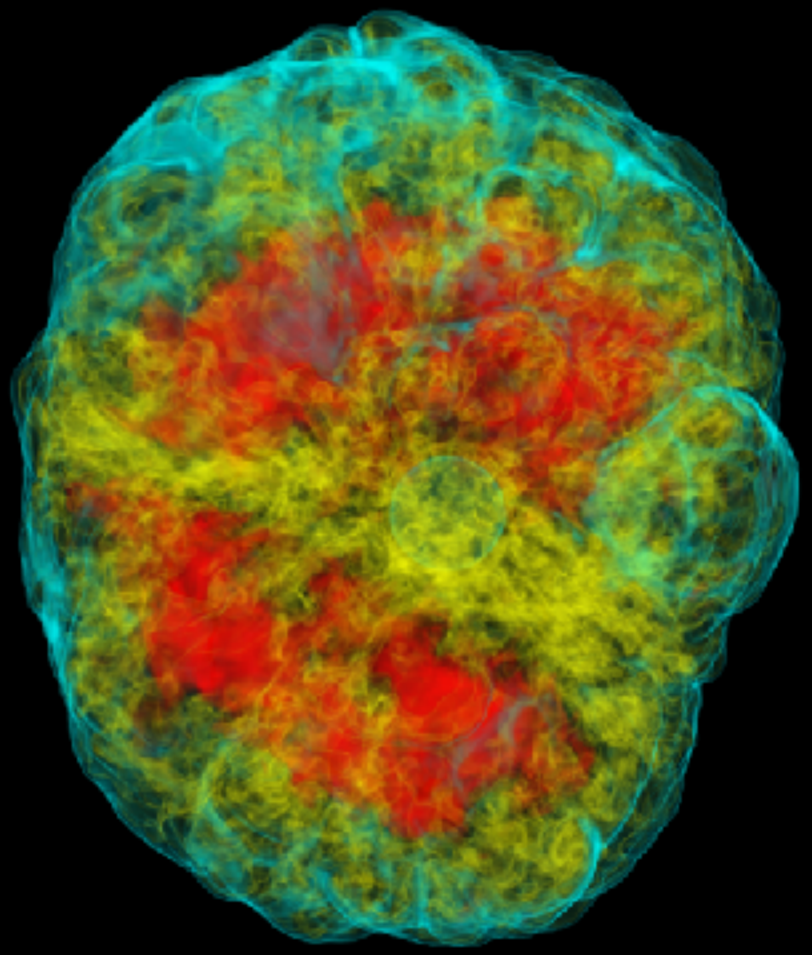


Failed explosion using spherically symmetric 1D model from *Couch + 2013a*.

SOLUTION(S) TO THE CORE-COLLAPSE 'PROBLEM'?

So, whats the deal? What are we missing?

- General Relativity - Maybe, though only small effect. *(Couch + 2013)*
- Complete Neutrino Transport - High resolution + Full Transport + GR can result in explosion. But is this the answer? *(Roberts + 2016)*
- Initial models - Pre-SN models are **not** spherical and can vary due to input physics. *(Couch + 2015)*

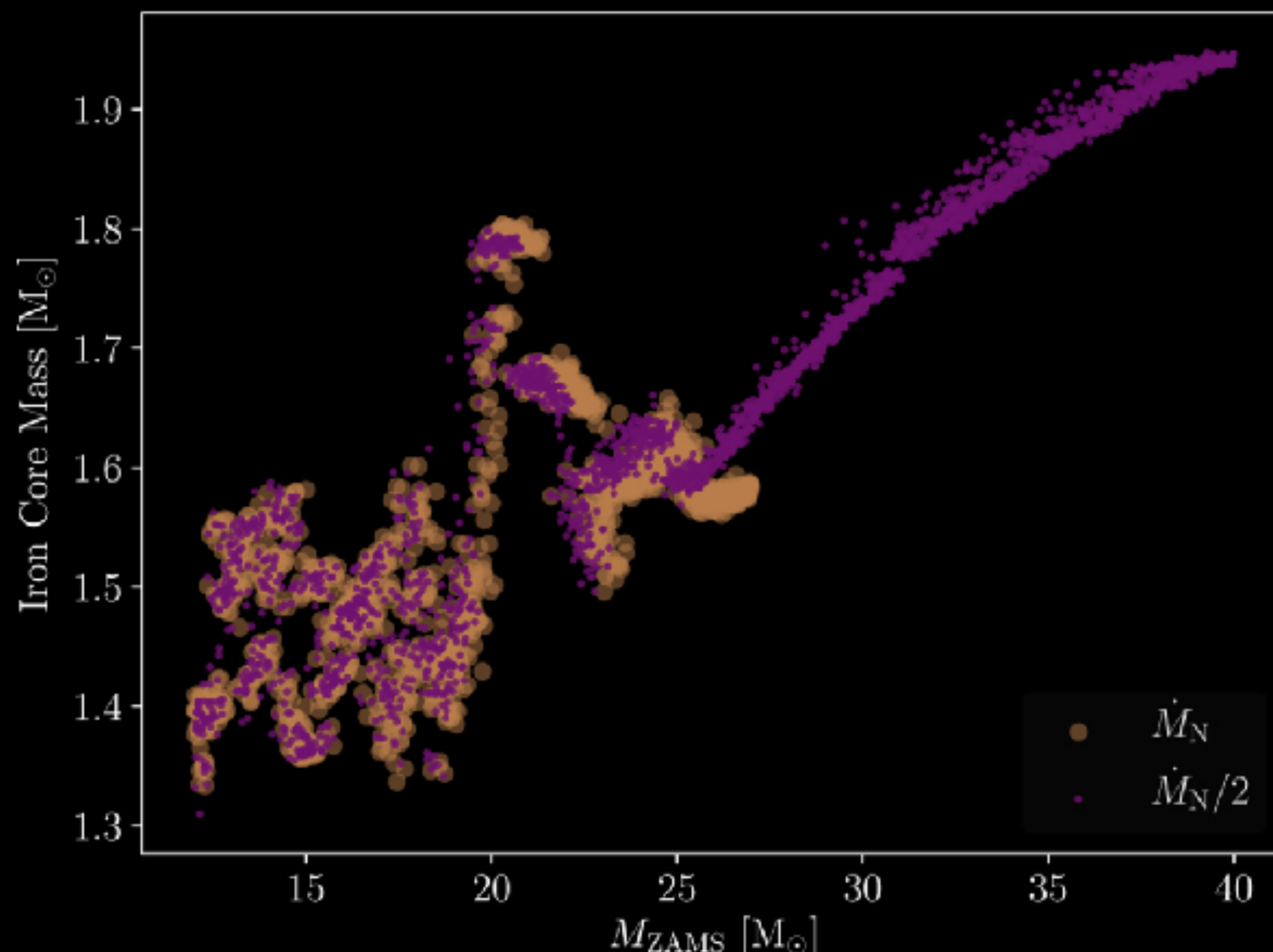


Volume rendering of the entropy distribution from *Roberts + 2016.*

PART 1: NUCLEAR REACTION RATE UNCERTAINTIES AND THEIR ROLE IN MODELS OF CORE-COLLAPSE SUPERNOVA PROGENITORS

PROGENITORS OF CCSNE

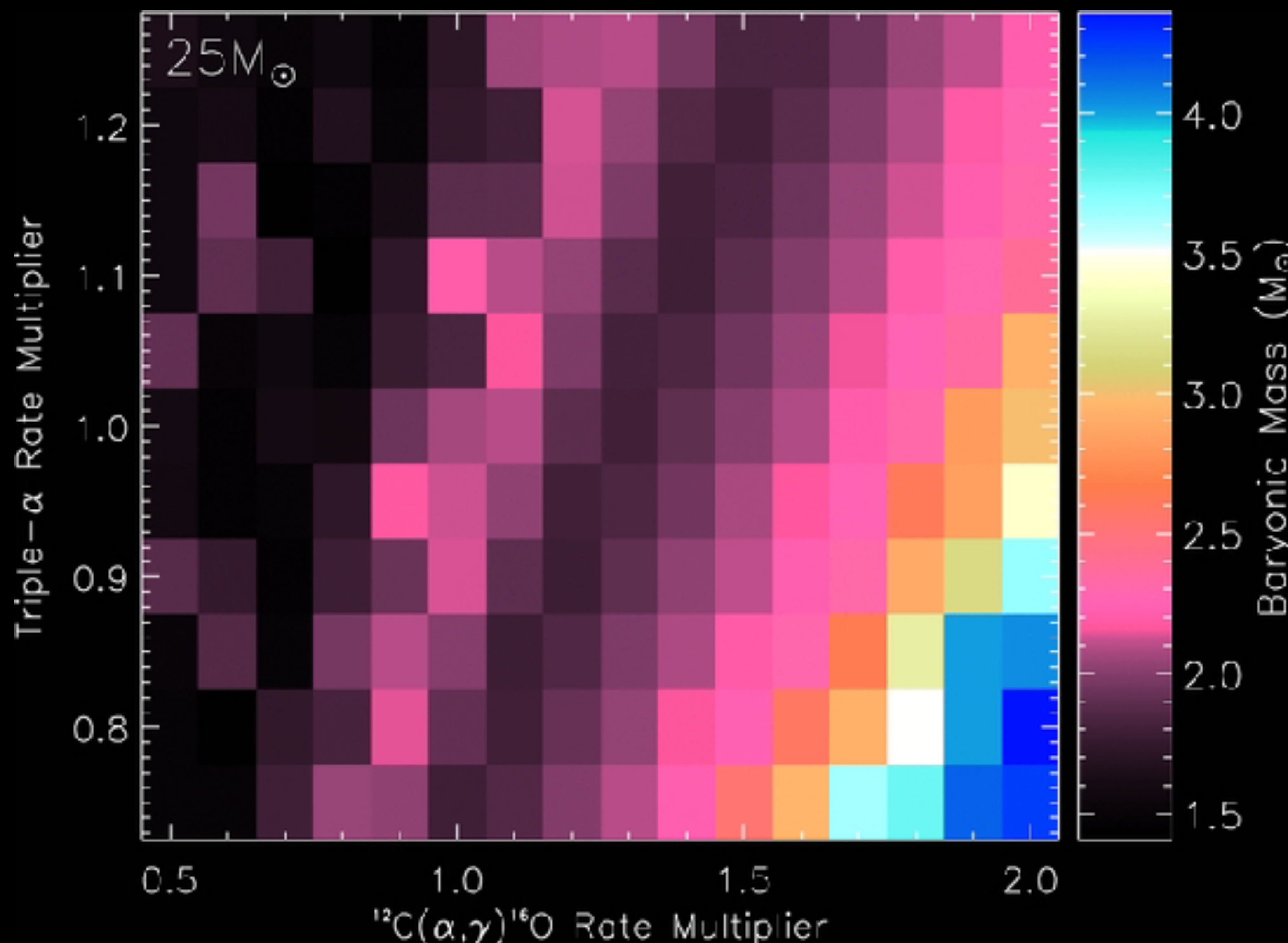
- Models subject to uncertainties in resolution, network size, mass loss, rotation, **reaction rates,** etc.
- These uncertainties lead to variations in the structure at collapse.



Iron Core Mass as a function of initial mass for a large set of models. *(Sukhbold + ApJ, 2018)*

REACTION RATE UNCERTAINTIES AND MASSIVE STARS

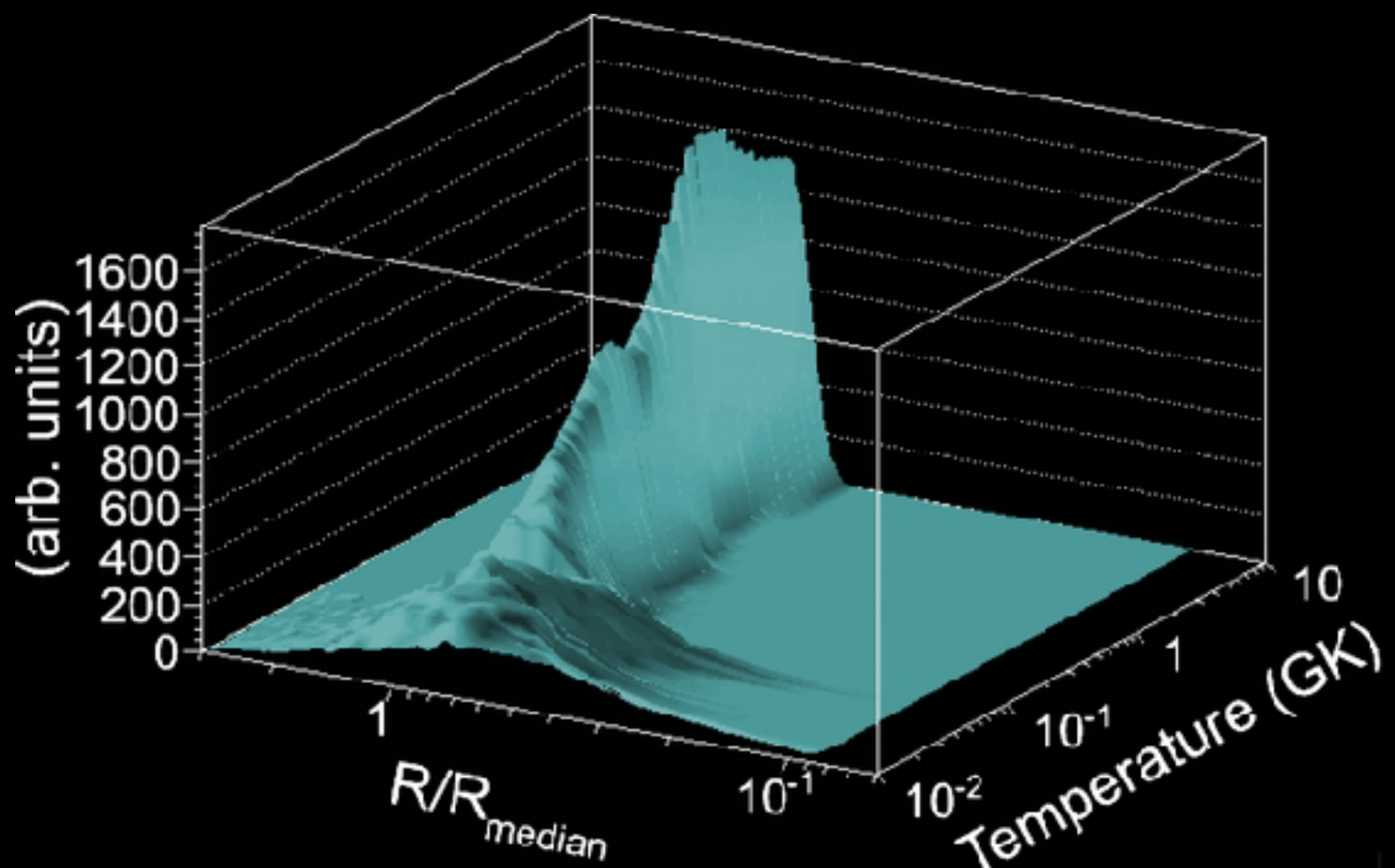
- Previous studies have considered T-independent variations for key He burning reaction rates *(West + 2013)*..
- Studies like these use multiplicative factors on reaction rates.
- Large variation found in baryonic mass of remnant.



Baryonic mass of remnant. (West + ApJ, 2013)

KEY NUCLEAR REACTION RATES

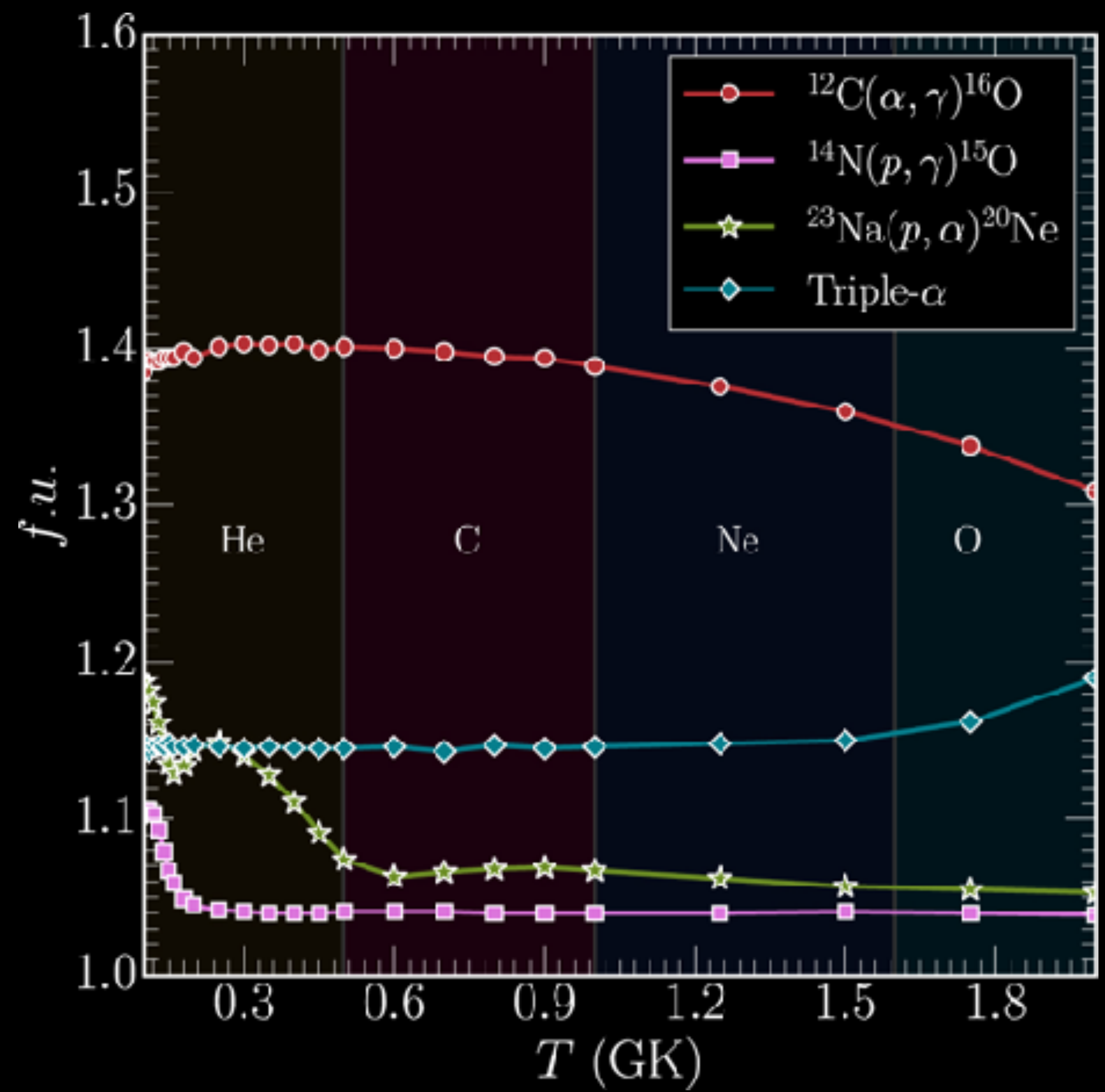
- **STARLIB** provides reaction rates along PDFs as a function of temperature.
- More accurate estimate for variation in models due to rates.
- These distributions provide the basis for our modeling framework.



Reaction rate PDF for Na proton capture. (Sallaska + ApJ, 2013)

REACTION RATE SAMPLING IN MASSIVE STARS

- We considered a 15 solar mass model at solar and subsolar metallicity using MESA.
- Each model sampled 665 nuclear reaction rates simultaneously and independently.
- Each rate has a different factor uncertainty (f.u.) that varies with temperature.

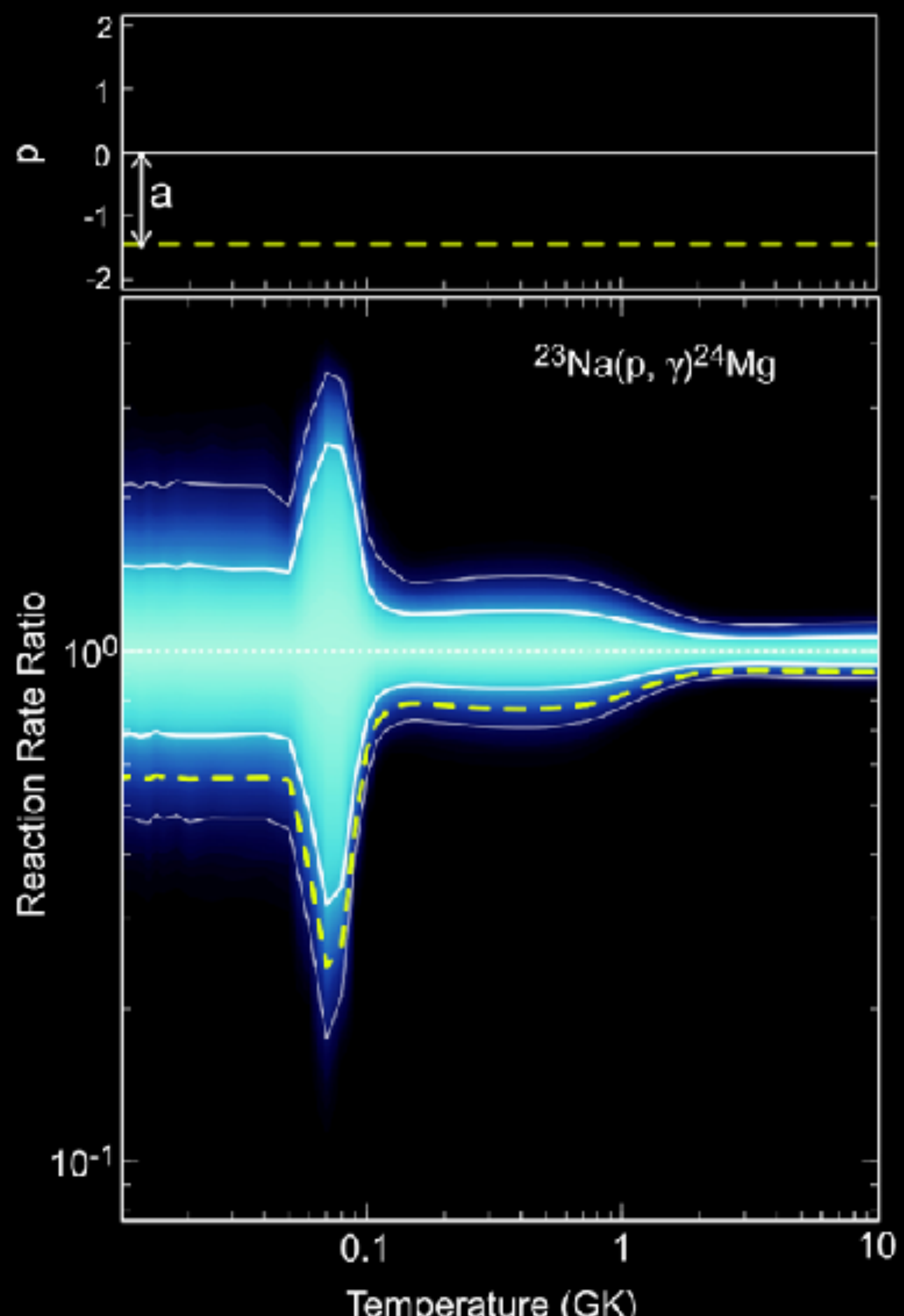


Factor uncertainty for key reaction rates. (Fields + ApJ, 2018)

REACTION RATE SAMPLING IN MASSIVE STARS

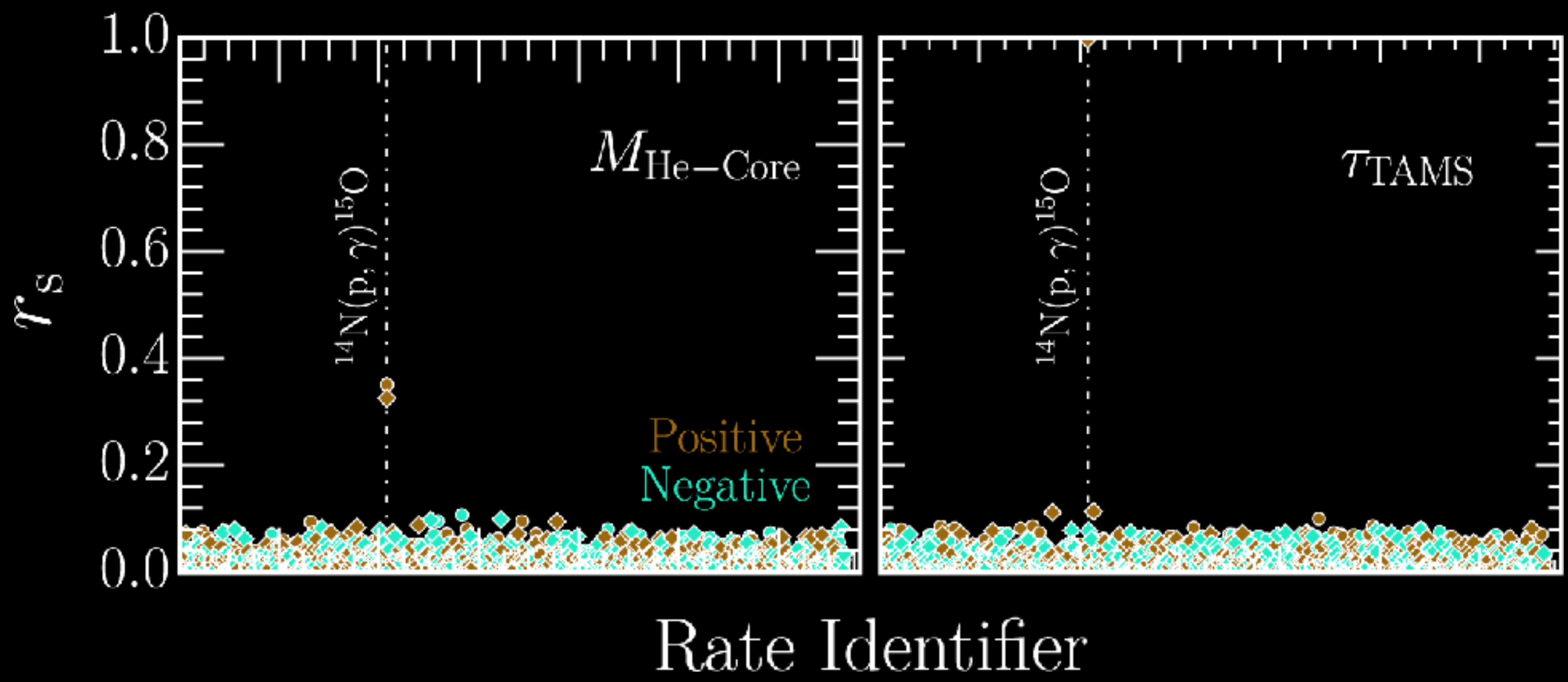
$$\langle \sigma v \rangle_{\rm samp} = \langle \sigma v \rangle_{\rm med} \, (f.u.)^{p_{i,j}}$$

- Each model gets 665 random Gaussian deviates used to generate a sample rate.
- The sample uses the factor uncertainty to construct a new rate within the limits.
- Each model is then evolved to O-dep. using the sampled rates.



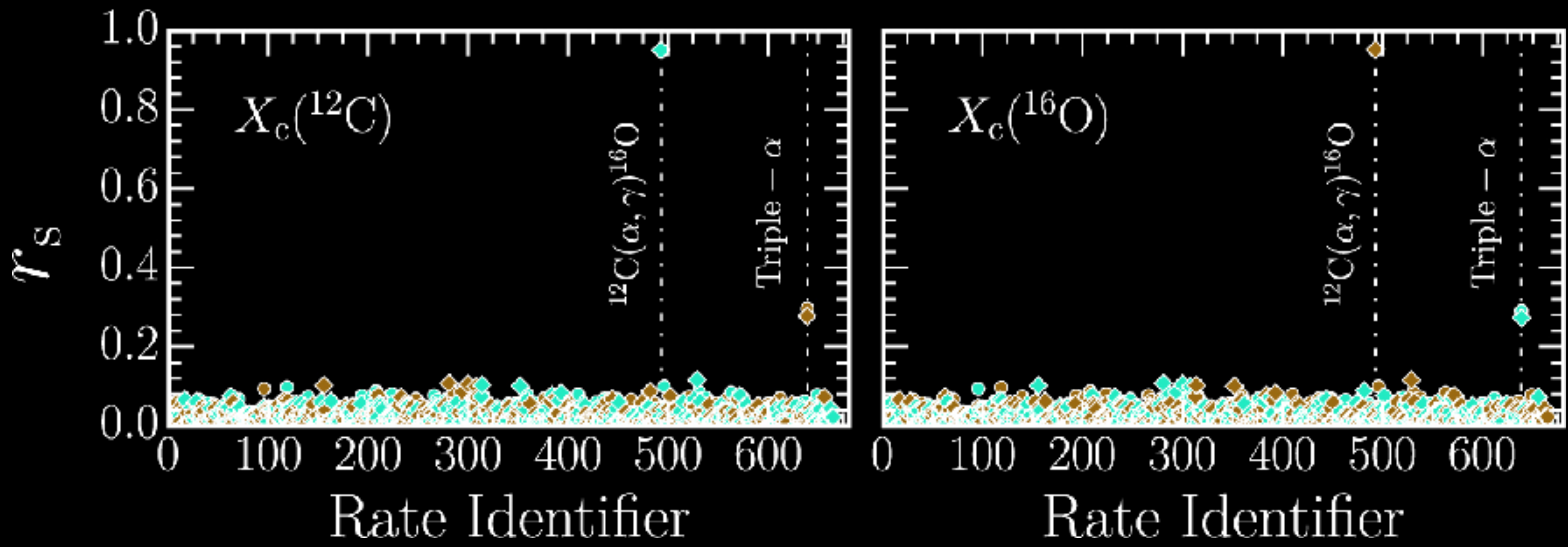
Sampled nuclear reaction rate. (Iliadis + JPhG, 2015)

EVOLUTION TO TERMINAL AGE MAIN SEQUENCE



- We performed analysis on our models at five epochs, each fuel depletion stage and computed ***Spearman Rank Order Correlation Coefficient*** to identify key reaction rates.

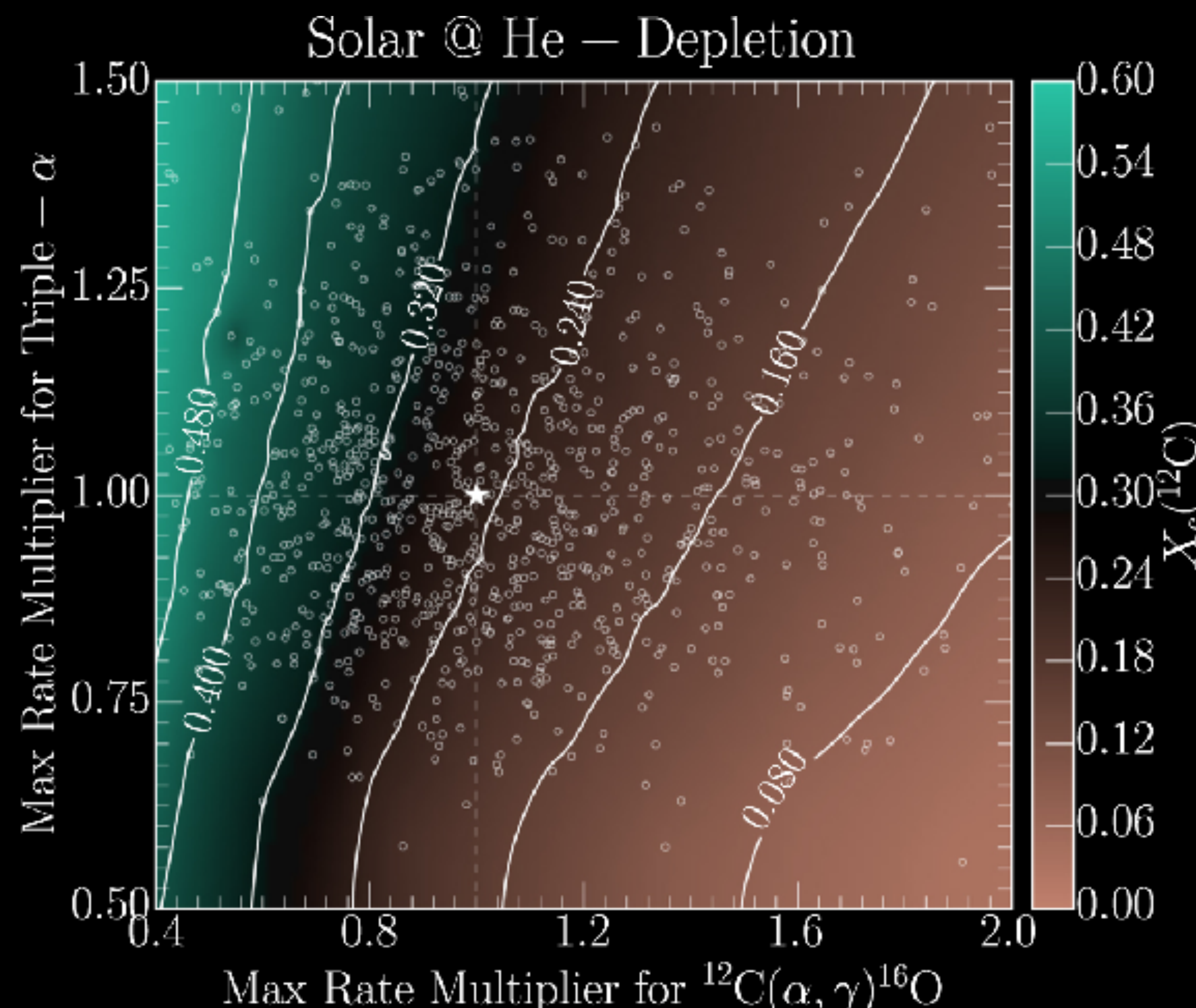
EVOLUTION TO CORE HELIUM DEPLETION



- Carbon production almost single handedly determined by 12C(a,g) reaction rate. Triple-alpha initiates the burning but is then overtaken.

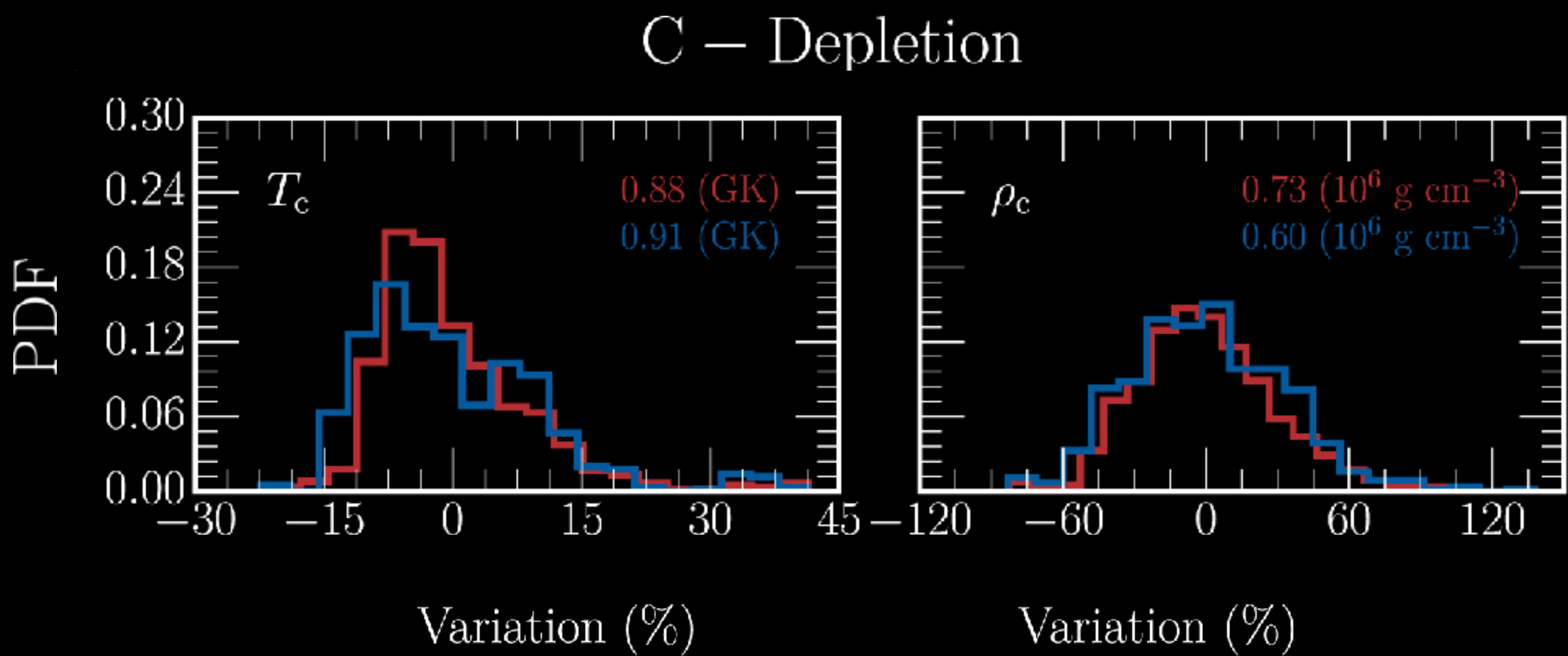
EVOLUTION TO CORE HELIUM DEPLETION

- Carbon production can range from 0-0.6 due to uncertainties from rates.
- West + 2013 find correlation with carbon mass fraction and remnant mass.
- Anti-correlation of carbon and remnant mass due to energetics of carbon shell burning episodes.



Carbon-12 mass fraction as a function of helium burning reactions. (Fields + ApJ, 2018)

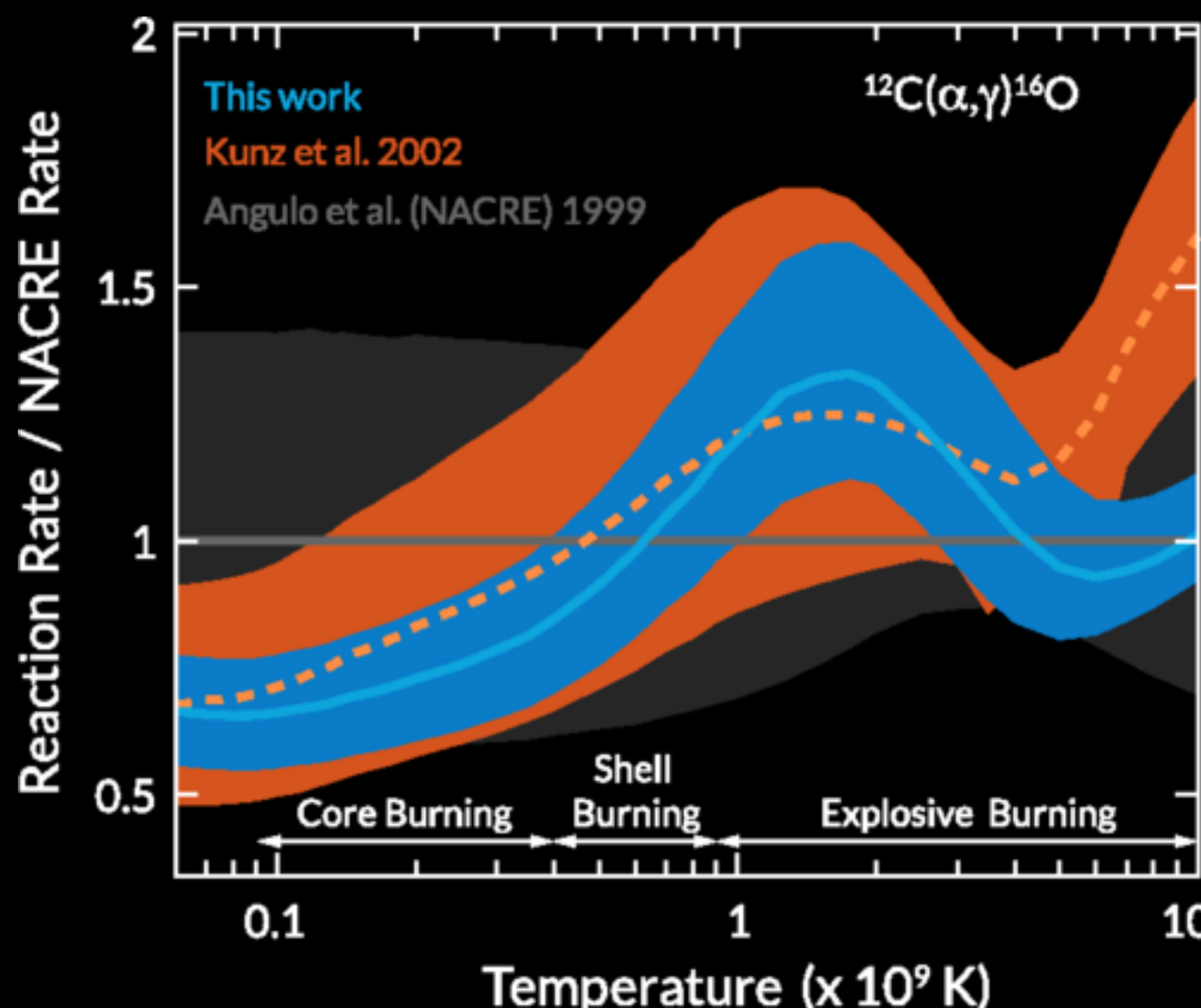
ADVANCED BURNING STAGES



- In general, most properties show variations **comparable** to uncertainties in mass and network resolution.
- Post He-depletion, uncertainties in the rates begin to dominate.

KEY REACTIONS IN CORE-COLLAPSE SUPERNOVA PROGENITORS

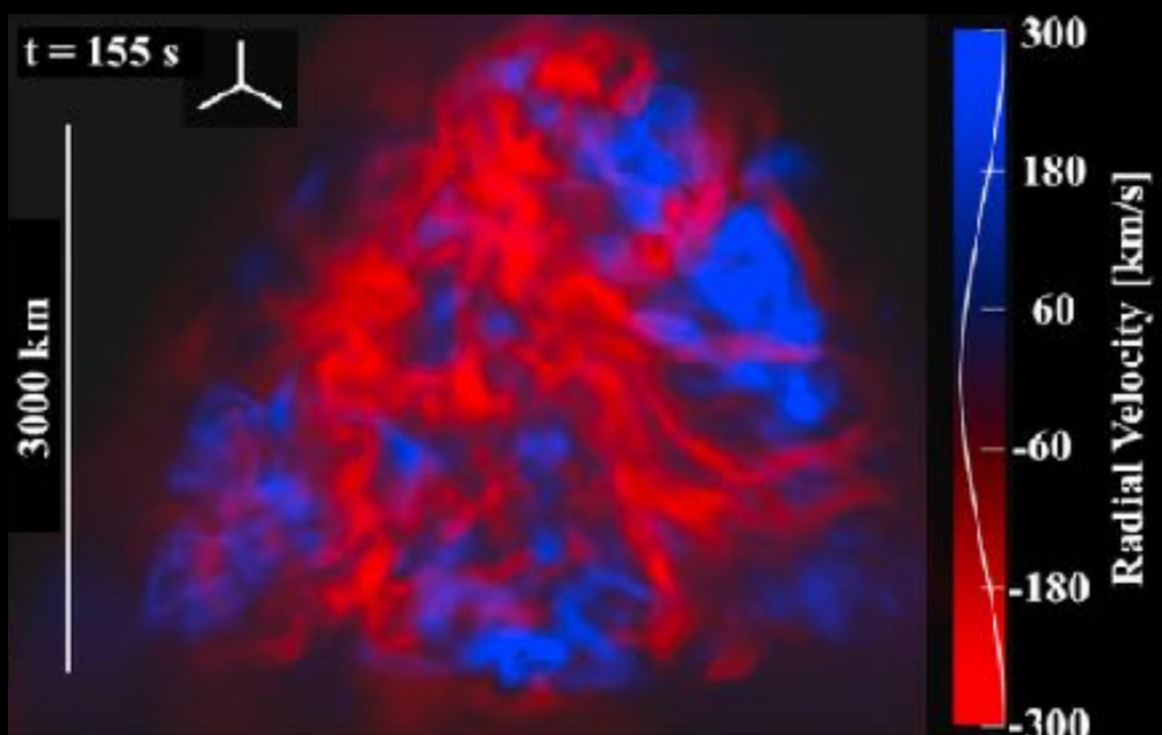
- In general, the He- and C-burning reactions dominated the subsequent evolution of the model.
- The relative efficiency of the 12C(alpha,gamma)16O and triple-alpha reactions can determine the fate of the model.
- Work is ongoing to help constrain these reactions.



12C(alpha,gamma)16O reaction rate relative to the NACRE rate. (deBoer + RMP, 2017)

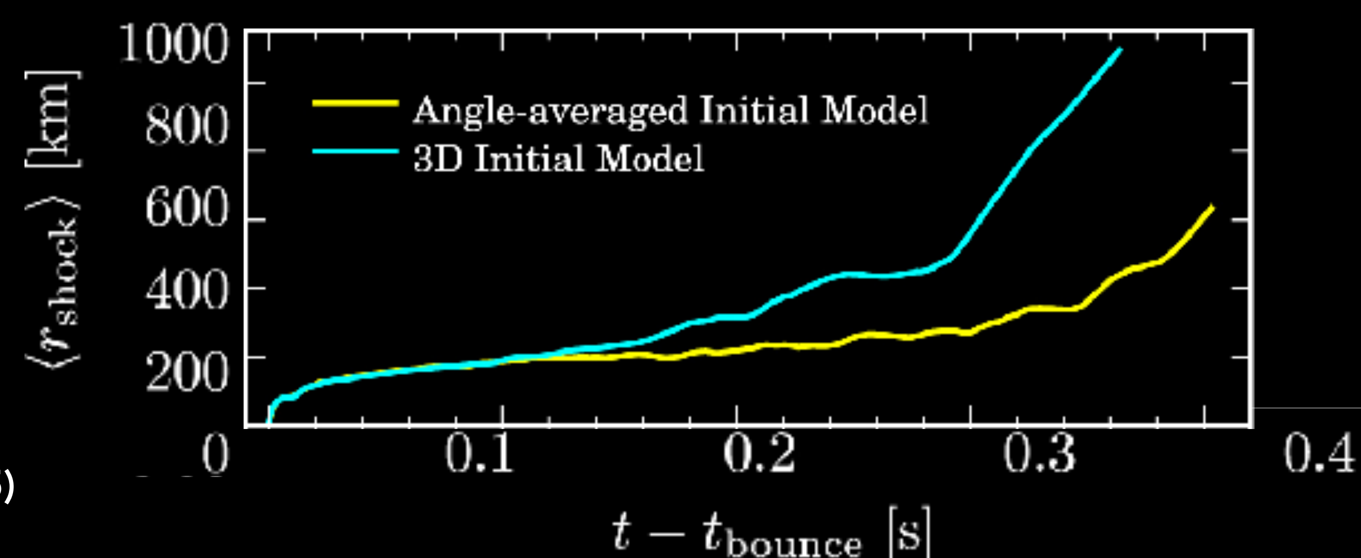
PART 2: MULTI-DIMENSIONAL SIMULATIONS OF CORE-COLLAPSE SUPERNOVA PROGENITORS

PERTURBATIONS IN THE PRE-SUPERNOVA MODEL



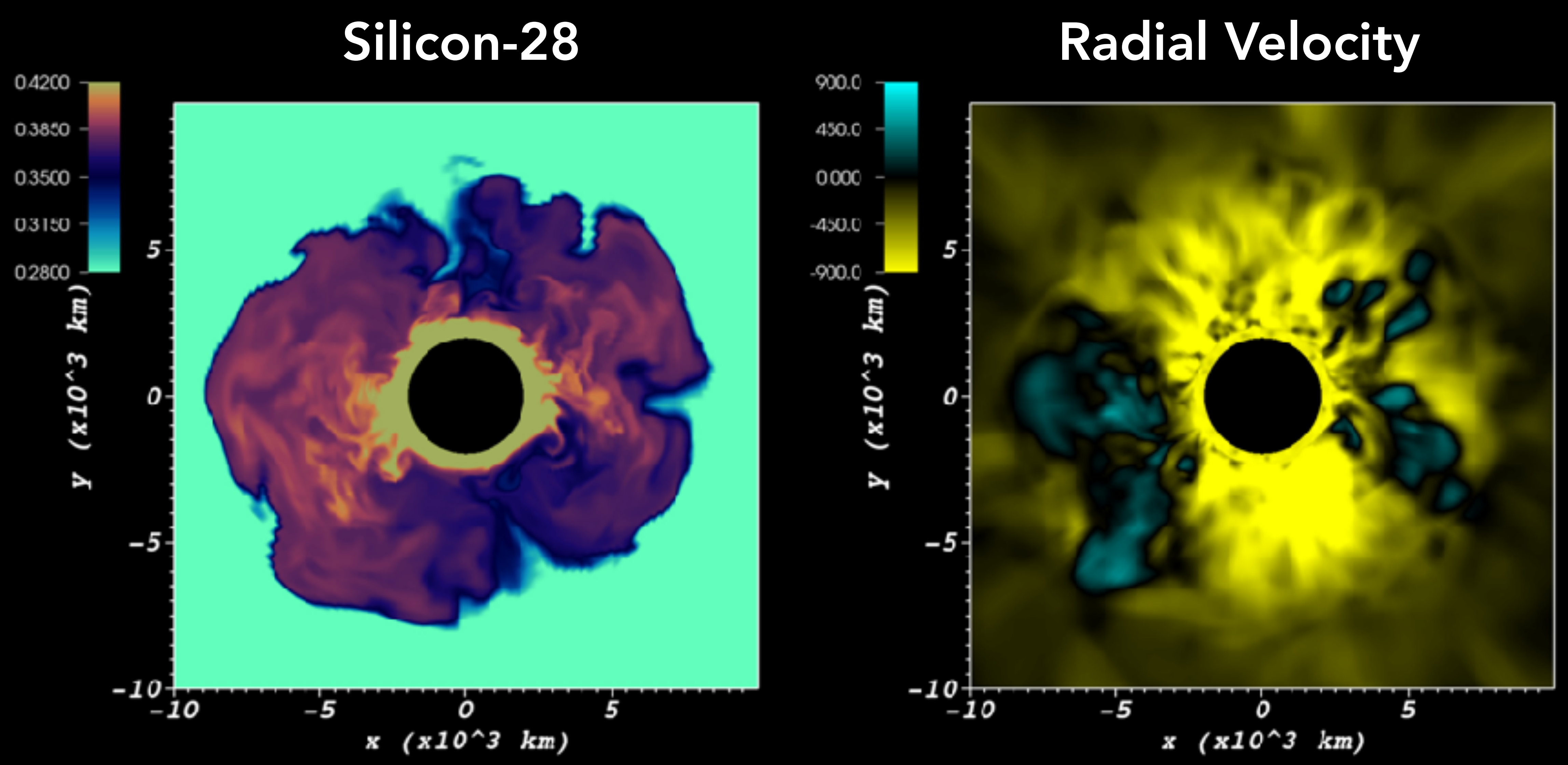
3D Octant Collapse Simulation (Couch + ApJL, 2015)

3D Initial model leads to faster, stronger explosion.



- Multi-D progenitors provide a solution to the core-collapse problem.

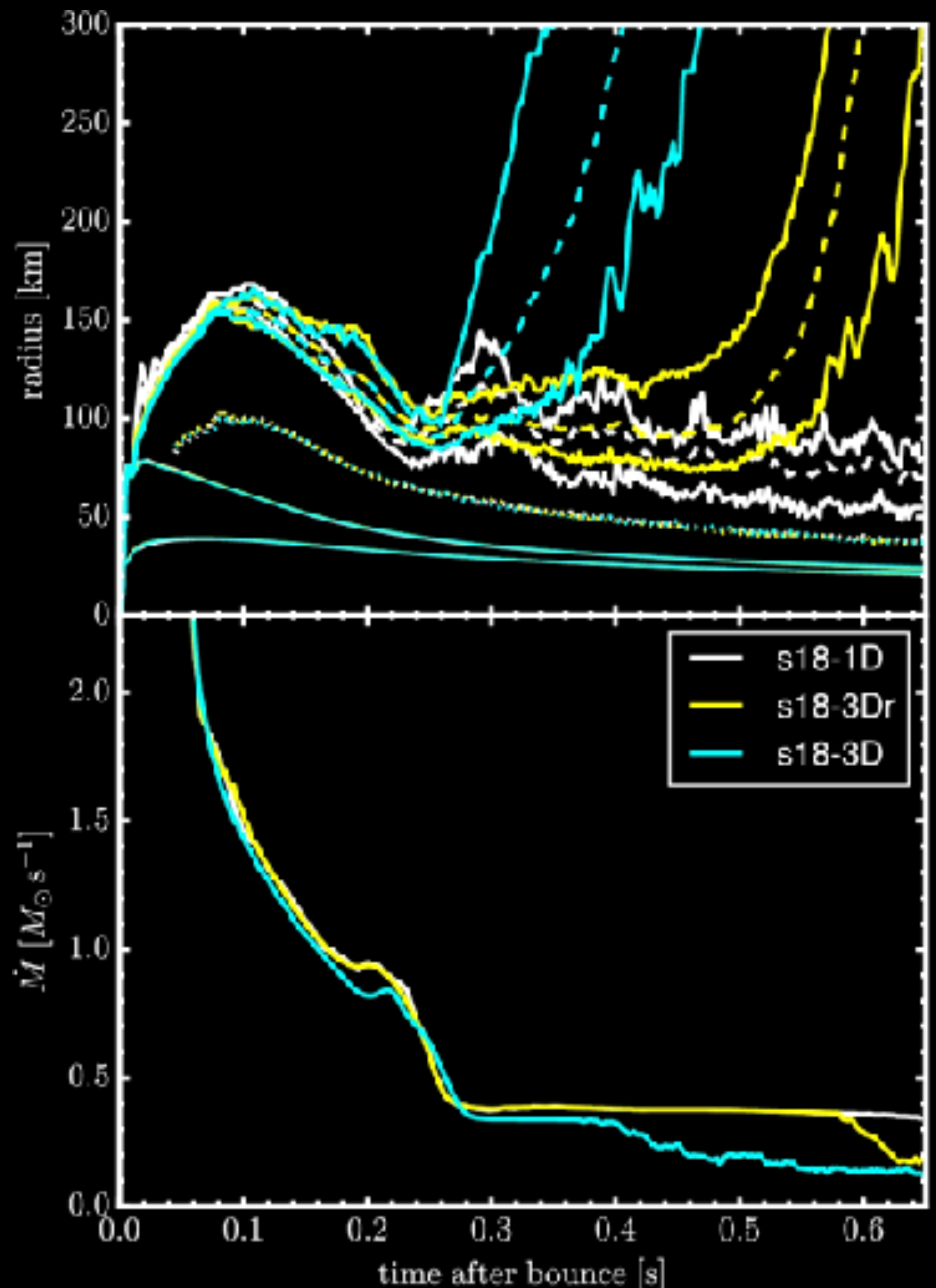
MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS



- 4pi simulations of oxygen shell burning find bipolar flow near collapse in simulation of 18 solar mass star. *(Muller +2016)*

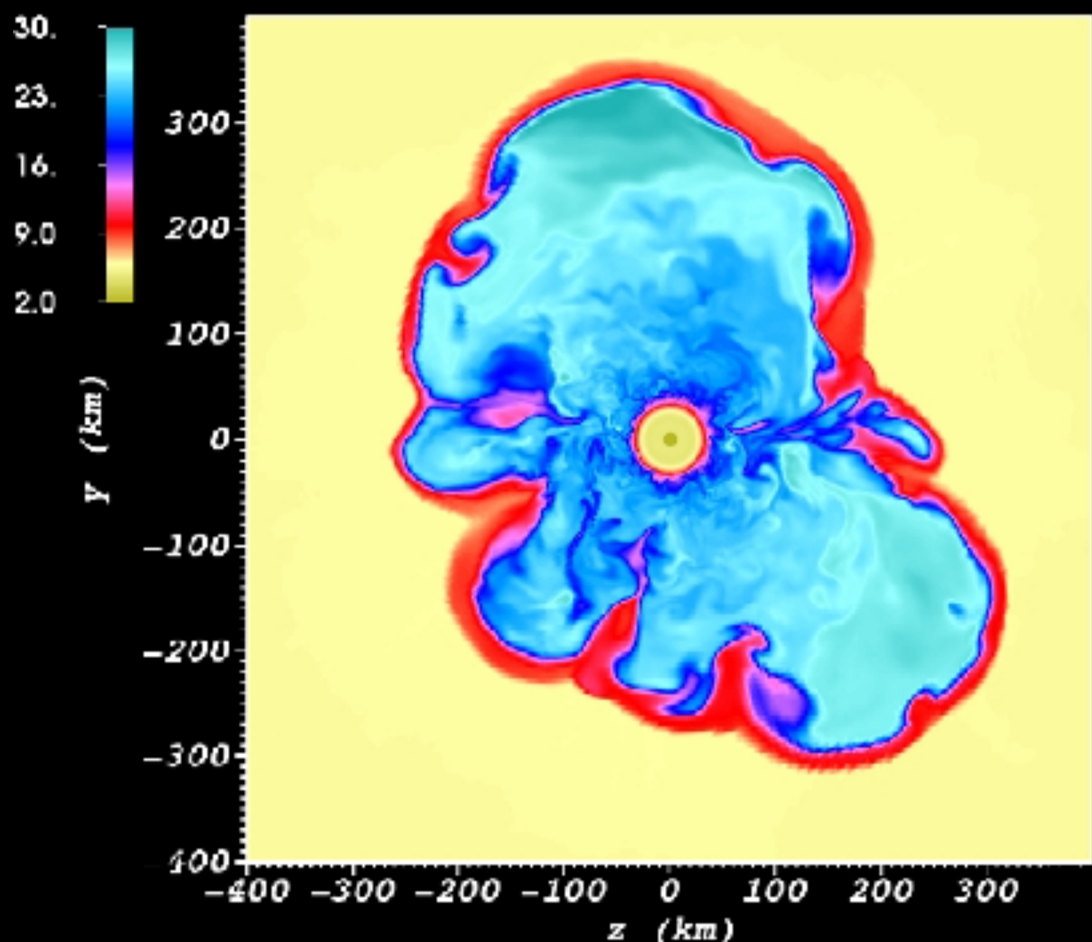
IMPACT OF PROGENITORS ON EXPLOSION MECHANISM

- Favorable impact found on the explosion mechanism.
- Reduced convection velocities results in later explosion.
- Impact partly due to accretion evolution.

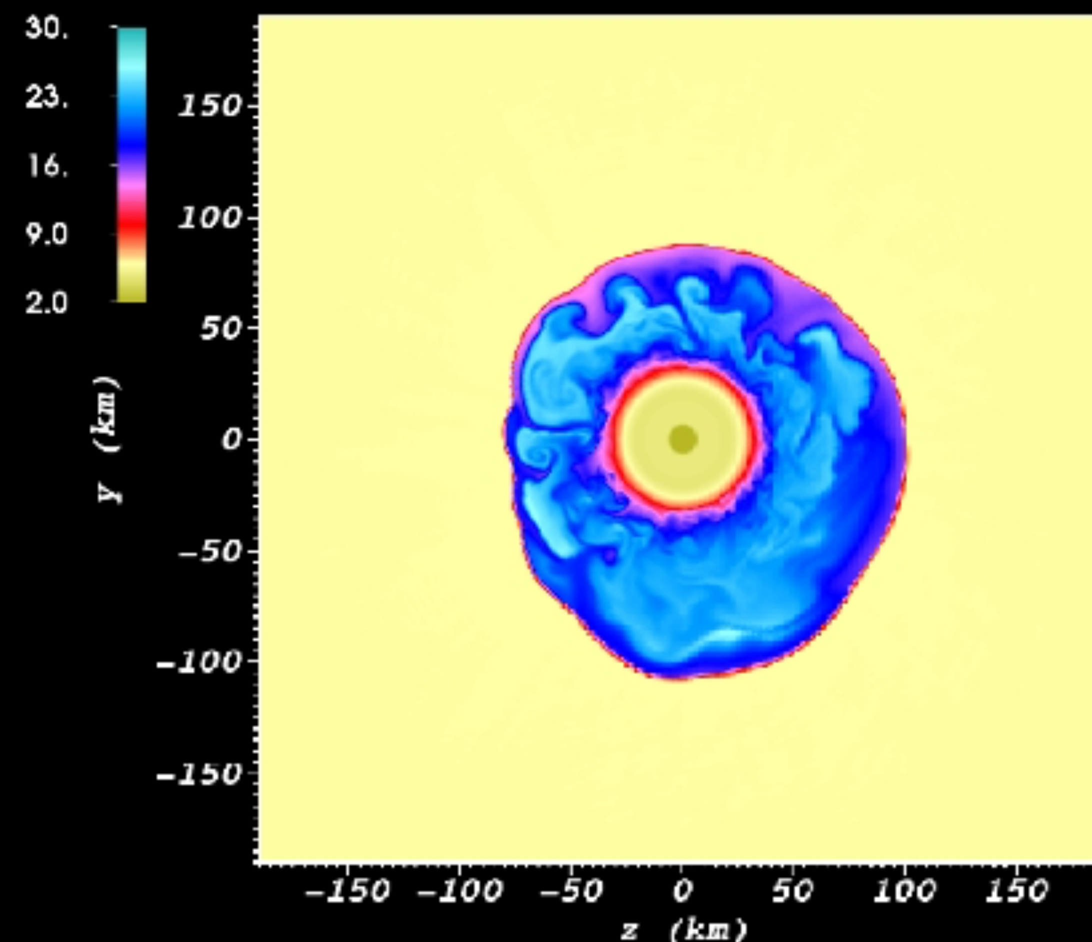


(Muller + 2017)

IMPACT OF PROGENITORS ON EXPLOSION MECHANISM



3D initial progenitor

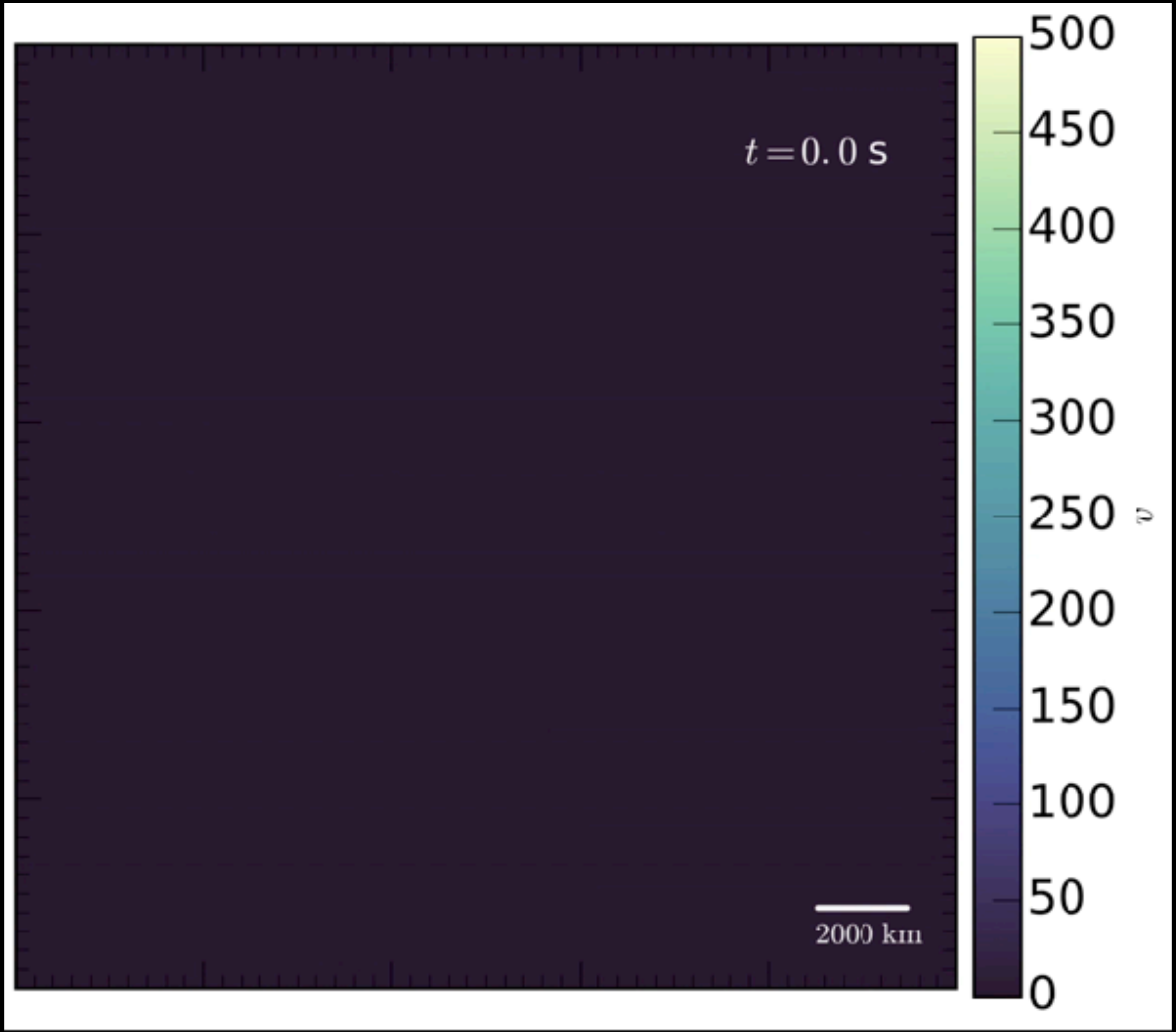


1D initial progenitor

(Muller + 2017)

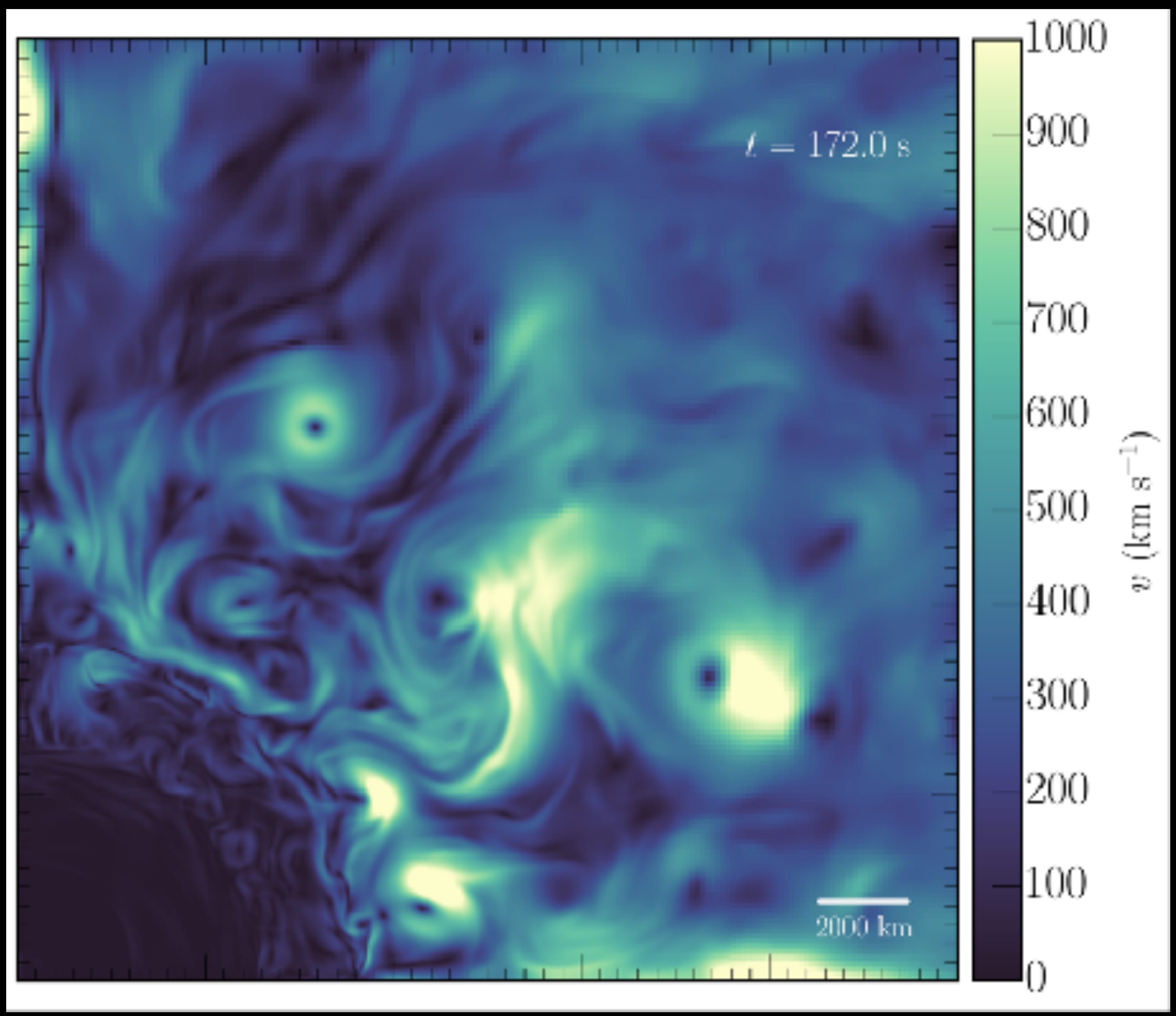
MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

- 3D Hydrodynamic simulations using FLASH.
- Evolved ~90 seconds from collapse using approximate network.
- Large convective plumes, perturbations.
- Enhanced electron capture rate.

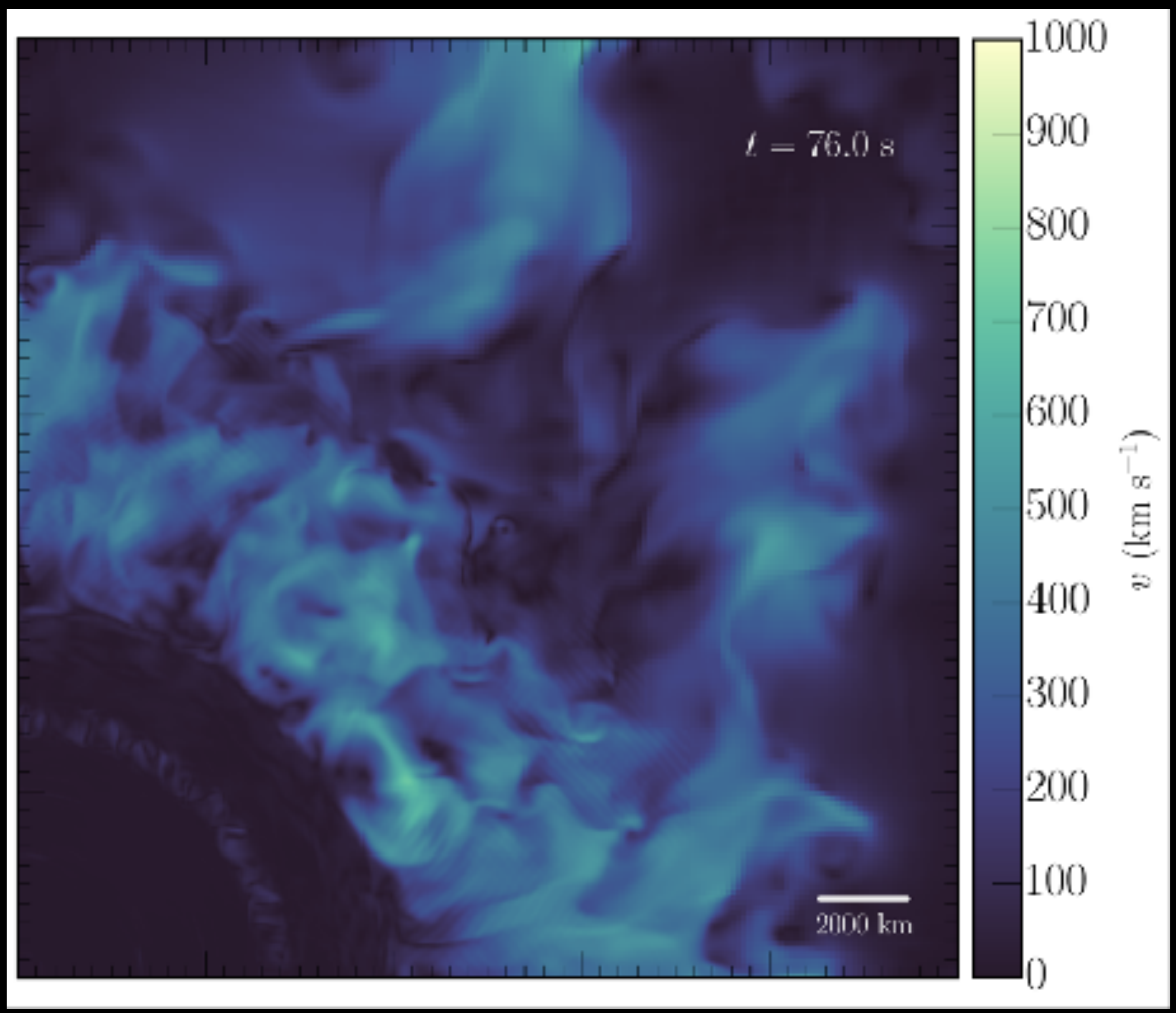


(Fields +, in prep.)

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS



2D



3D

- 2D model dominated by eddies and stronger mixing in SI/O interface.

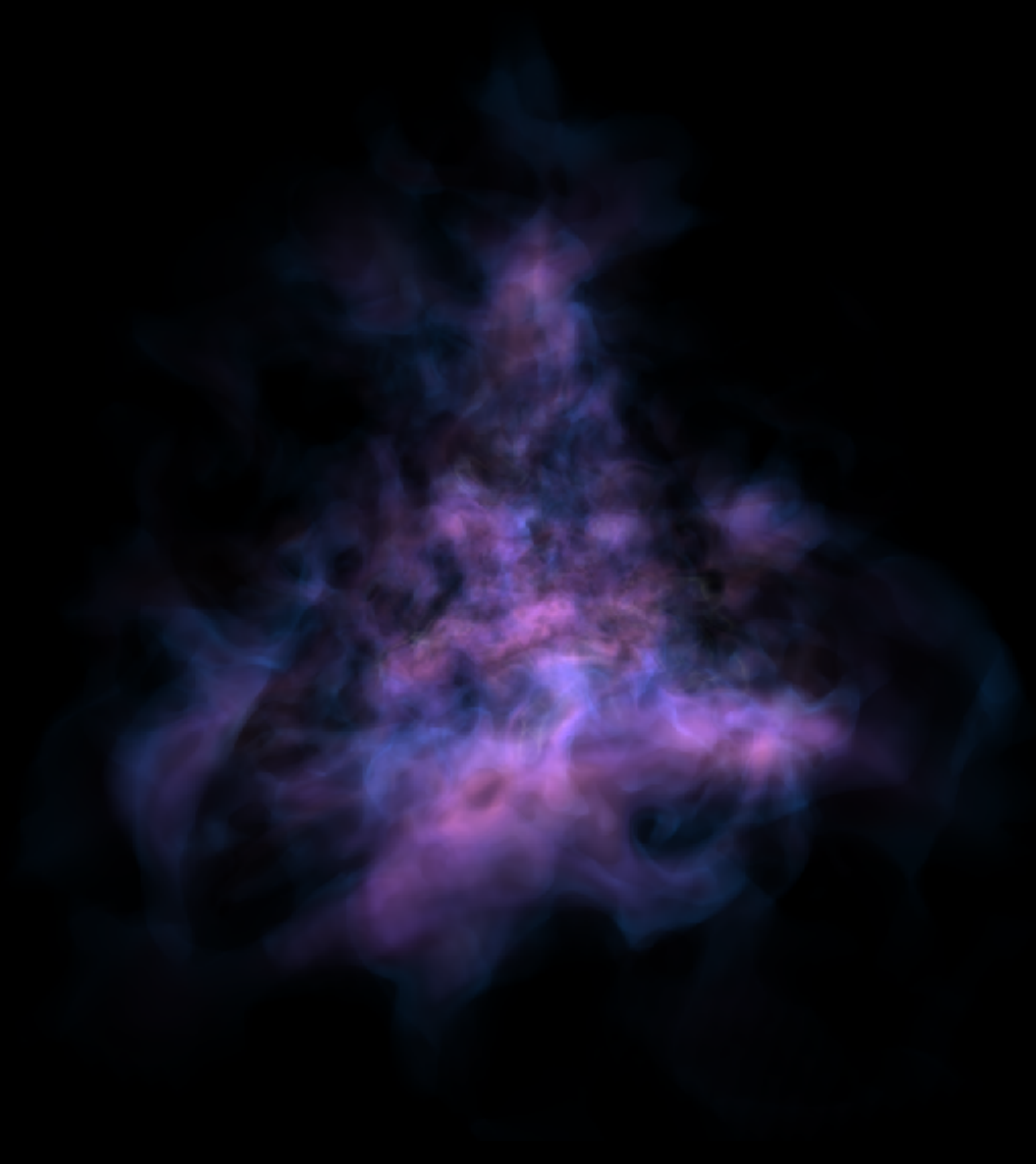
MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

- Evolved ~420 seconds before collapse.
- Core follows MESA structure using table interpolation.
- No enhancements to electron capture rate.

(Fields +, in prep.)

CONCLUSIONS

- Reaction rates are a **key source of uncertainty** in stellar models.
- Pre-collapse perturbations are possible solution to 'problem'.
- We plan to further these models to include MHD and rotation.
- Next generation, multi-D models of progenitors are upon us *(Couch + 2015, Muller + 2016,2017, Jones + 2017).*



Velocity field volume rendering. (Fields + in prep., 2018)

THANK YOU

Questions?

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