Evolution of Massive Stars

Knowns and Unknowns

Alexander Heger (Monash)
Stan Woosley (UCSC)
Chris West (UMN)
Ken Chen (UCSC)
Tuguldur Sukhbold (UCSC)
Duligur Ibeling (Harvard)

MoCA
Monash Centre for Astrophysics

MONASH University
Science

http://StellarEvolution.org

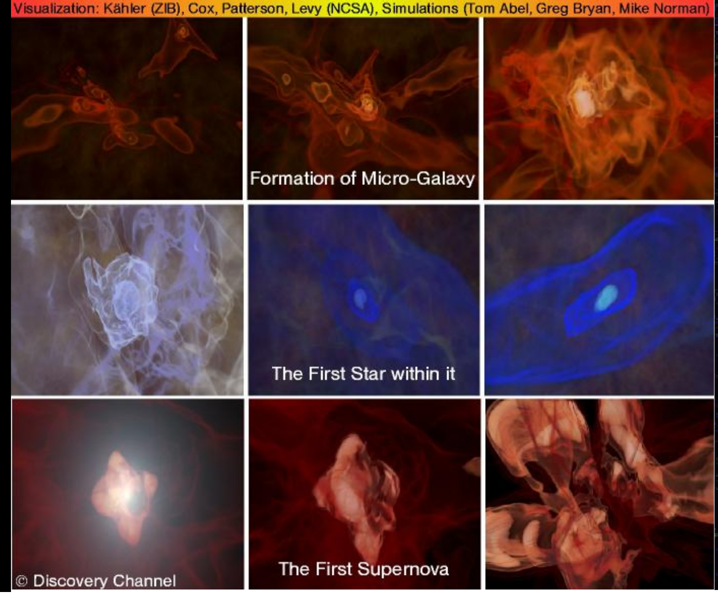
Motivation:

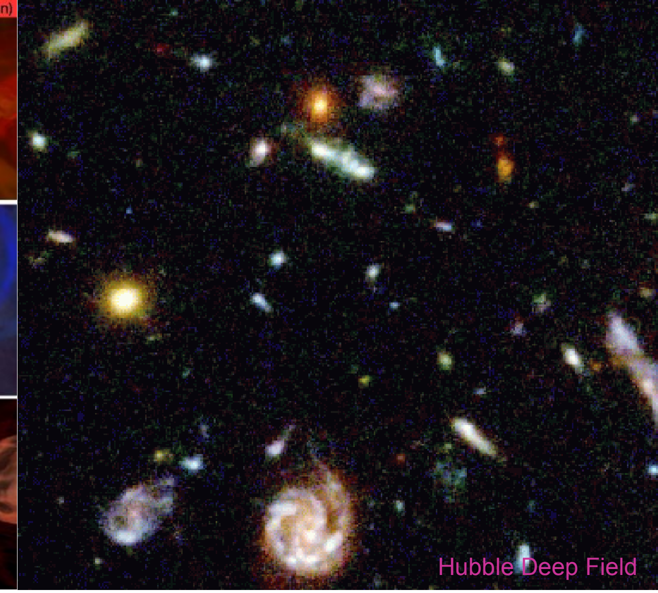
A Brief History of the Universe

Cosmic Dark Age

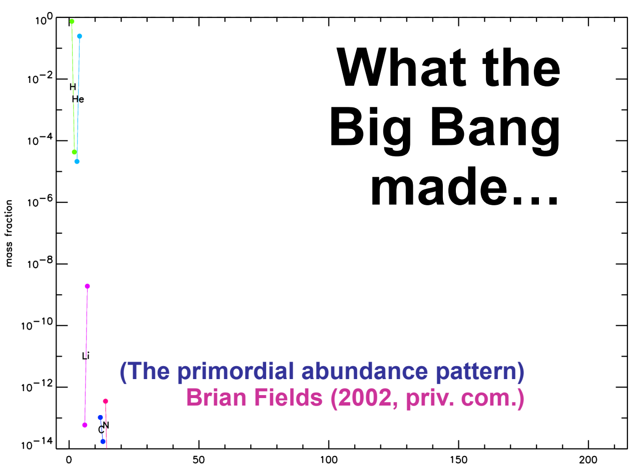
(after recombination)

© Alexander Heger



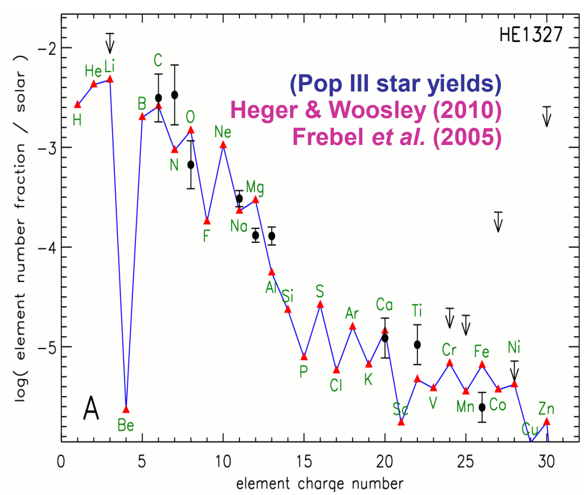


time

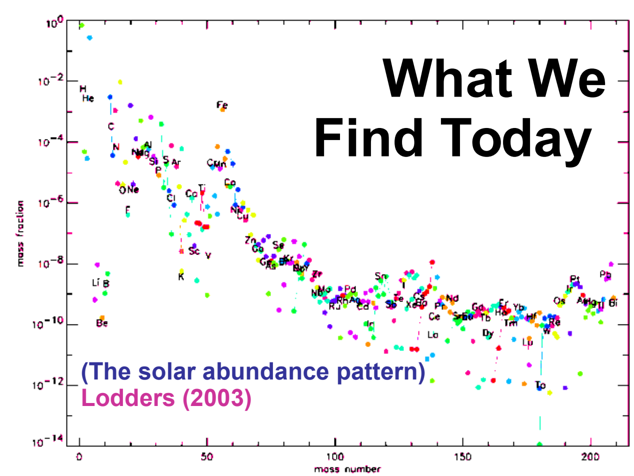


What the Big Bang made…

(The primordial abundance pattern)
Brian Fields (2002, priv. com.)



(Pop III star yields)
Heger & Woosley (2010)
Frebel *et al.* (2005)



What We Find Today

(The solar abundance pattern)
Lodders (2003)

Overview

- Evolution of massive stars
- The Stellar Zoo
- Peculiarities of the different mass regimes

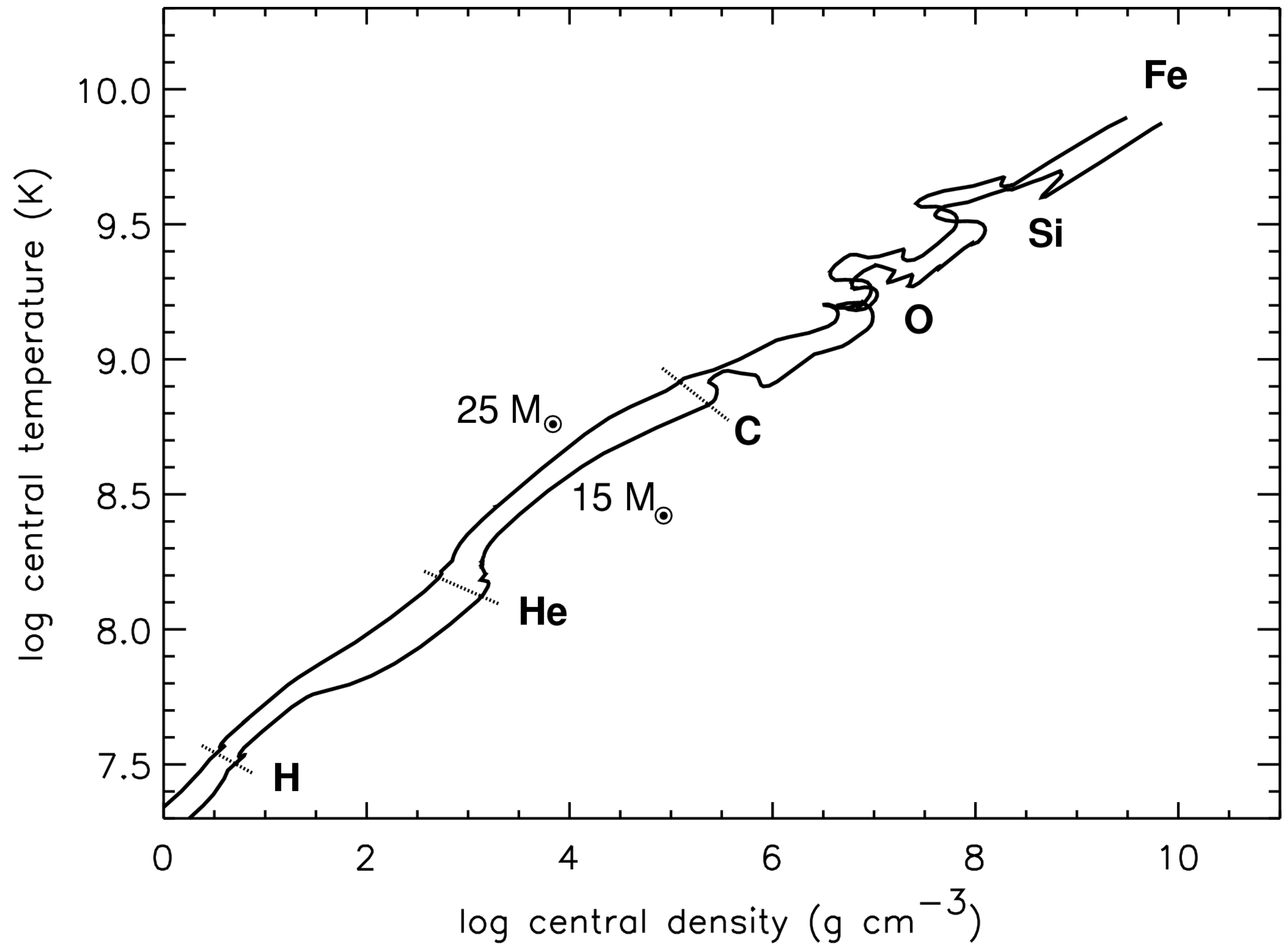
Setting the Stage:

Stellar Evolution

Once formed, the evolution of a star is governed by gravity:

continuing contraction

to higher central densities and temperatures

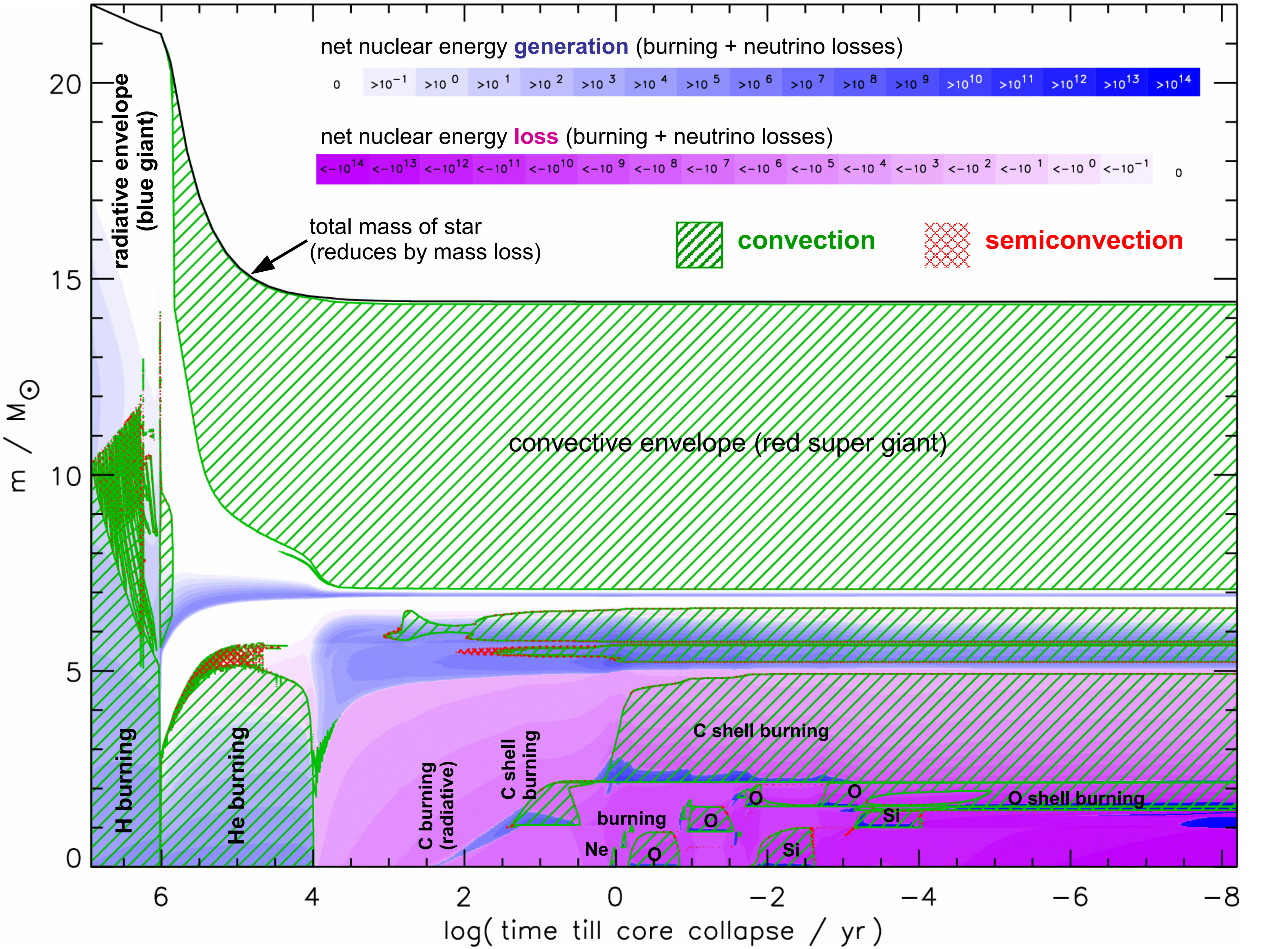


Evolution of central density and temperature of 15 M$_\odot$ and 25 M$_\odot$ stars

Nuclear burning stages

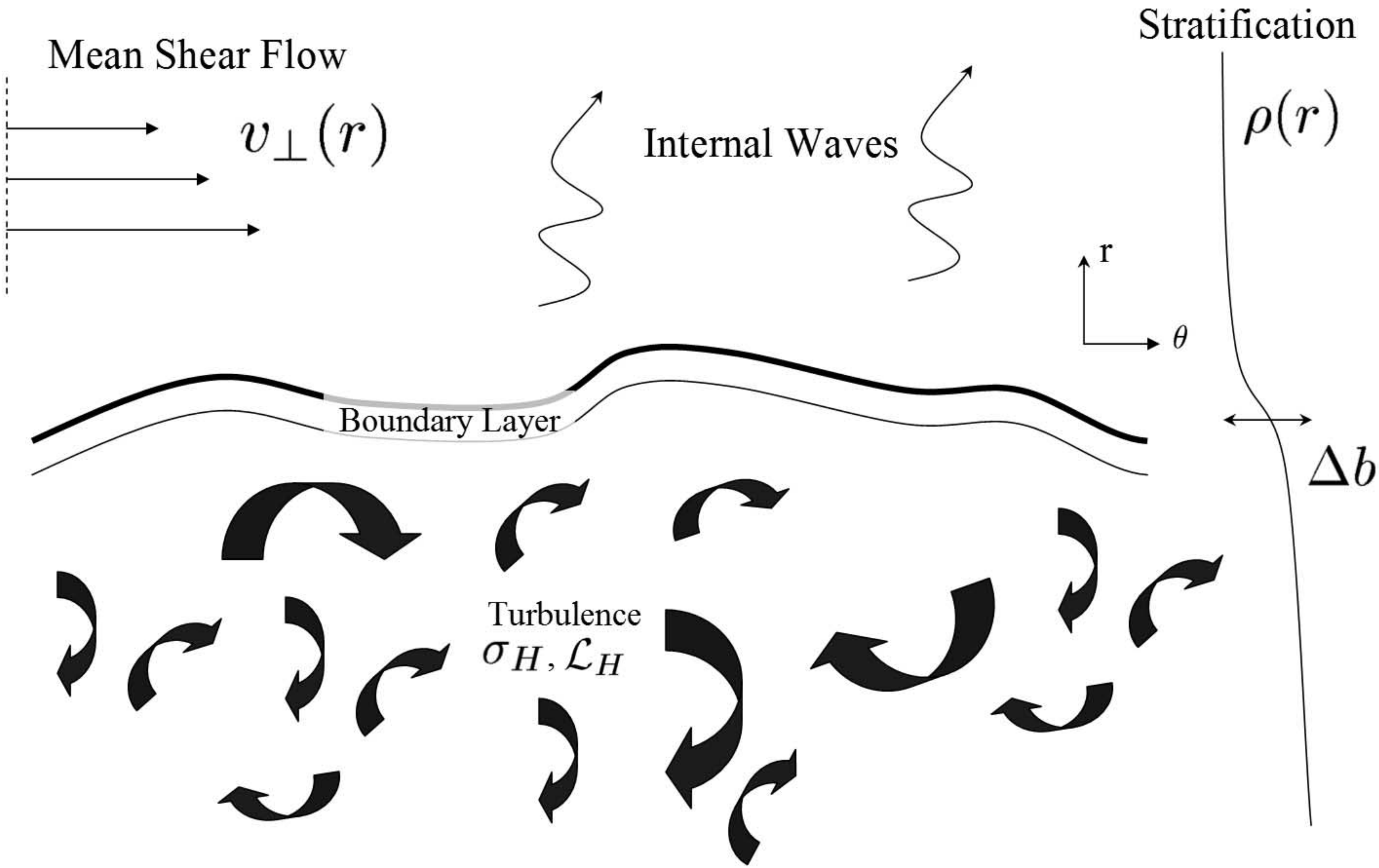
(20 $M_\odot$ stars)

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si,S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)$…



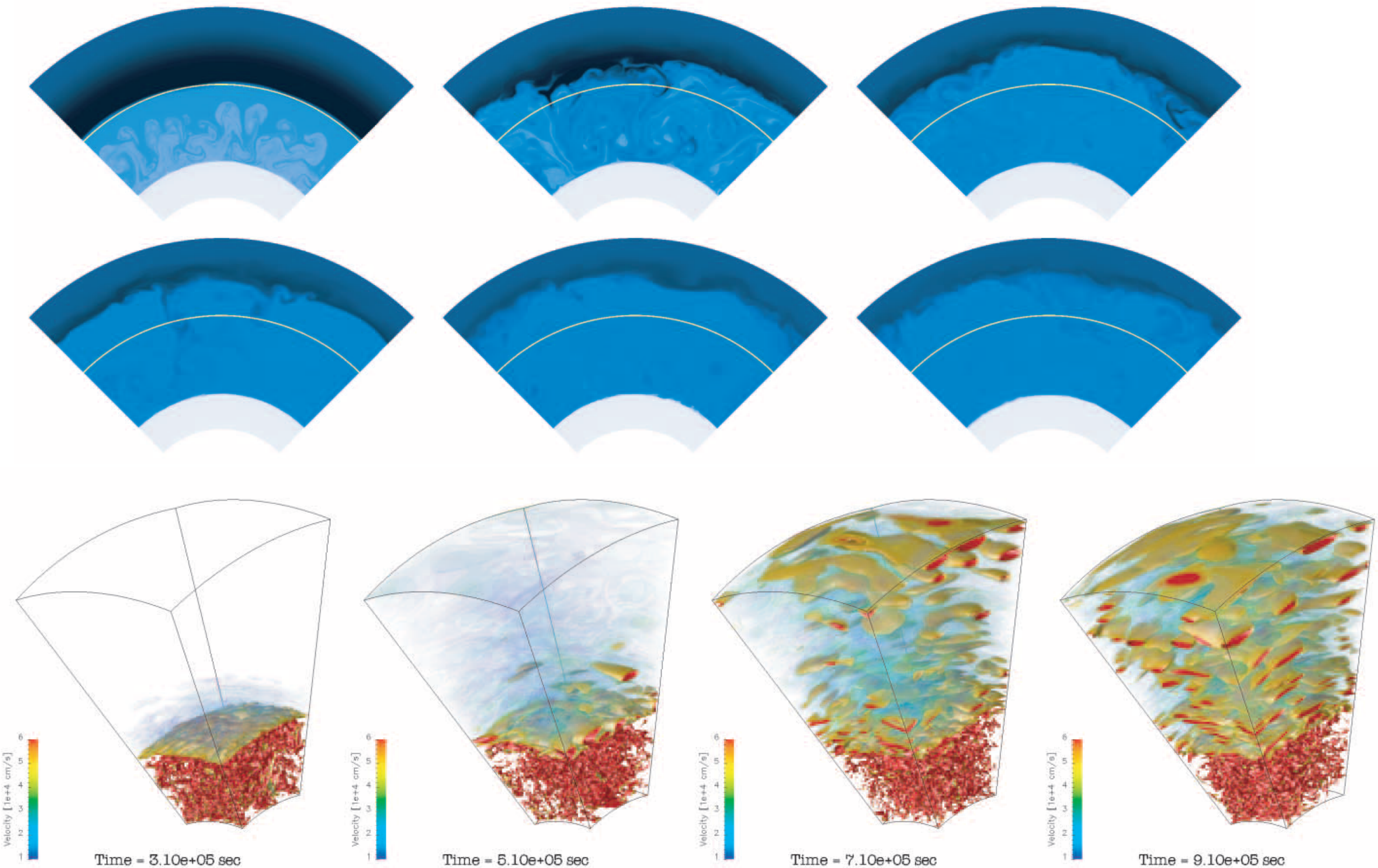
net nuclear energy generation (burning + neutrino losses)
net nuclear energy loss (burning + neutrino losses)
total mass of star (reduces by mass loss)
convection
semiconvection
radiative envelope (blue giant)
convective envelope (red super giant)
H burning
He burning
C burning (radiative)
C shell burning
C shell burning
Ne burning
O
O
O
O
O shell burning
Si
Si
m / M⊙
log(time till core collapse / yr)

Mufti-Dimensional Convection

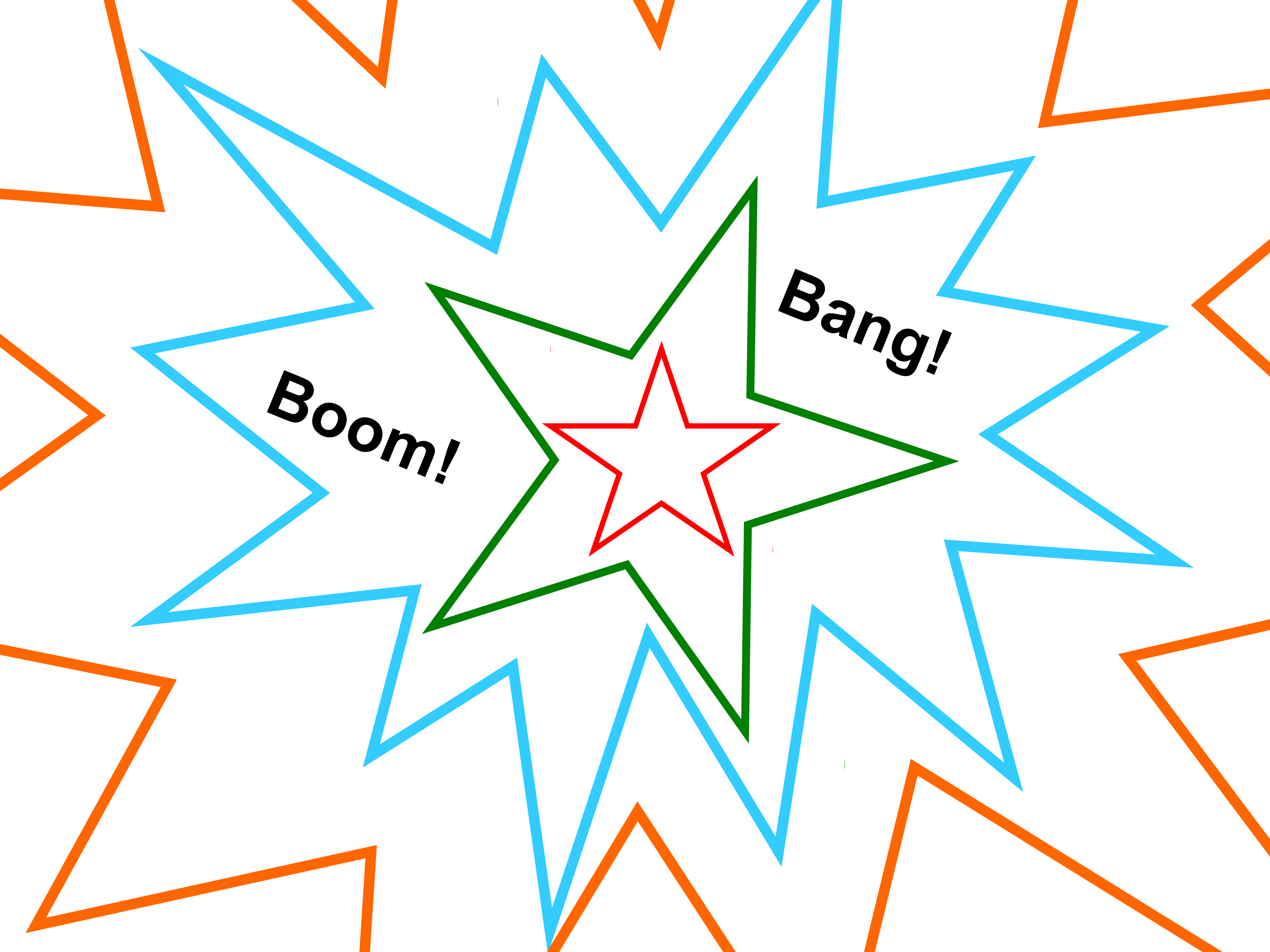


(Meaken & Arnett 2007)

Multi-Dimensional Convection



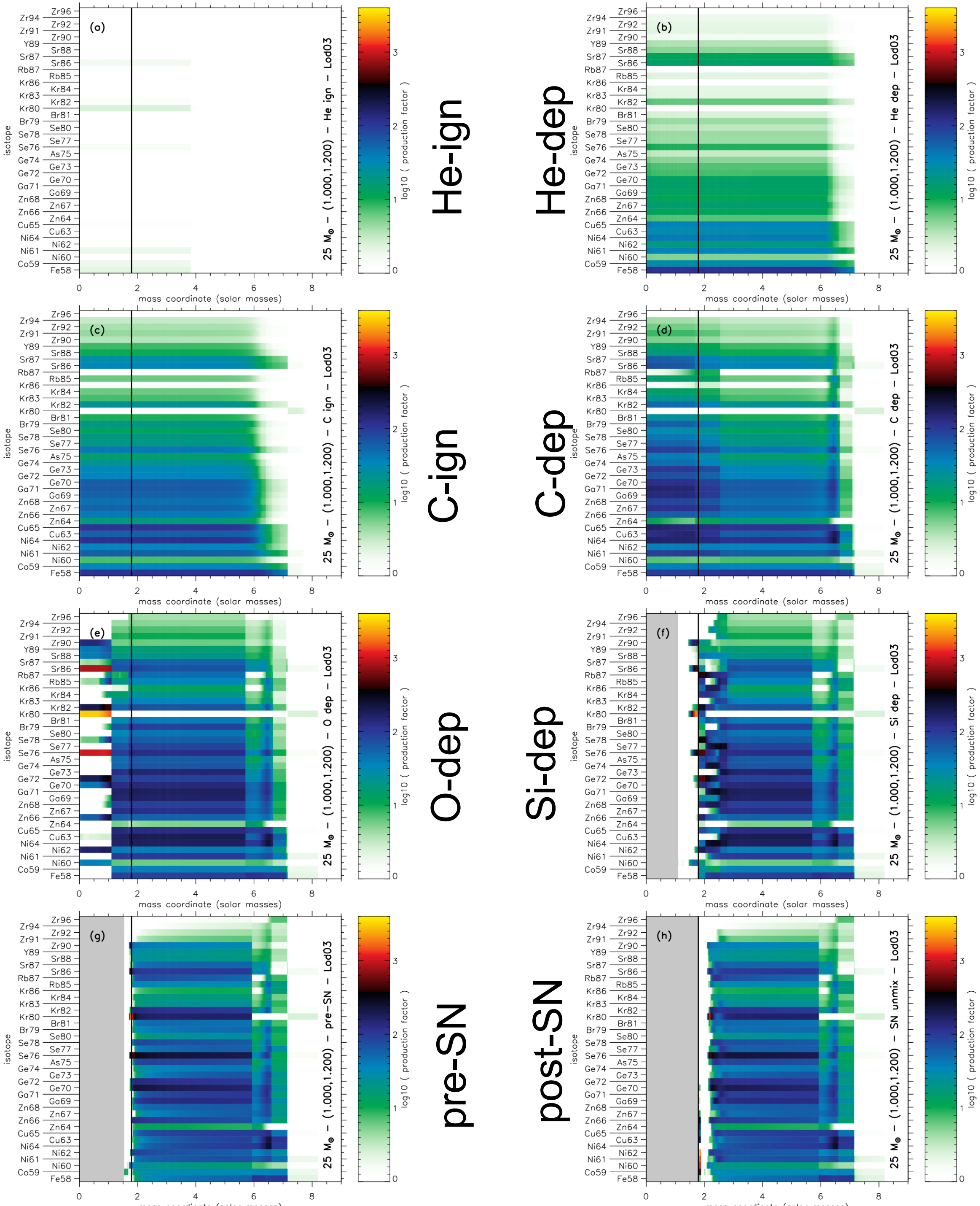
(Meaken & Arnett 2007)


Boom!
Bang!

Explosive Nucleosynthesis

in supernovae from massive stars

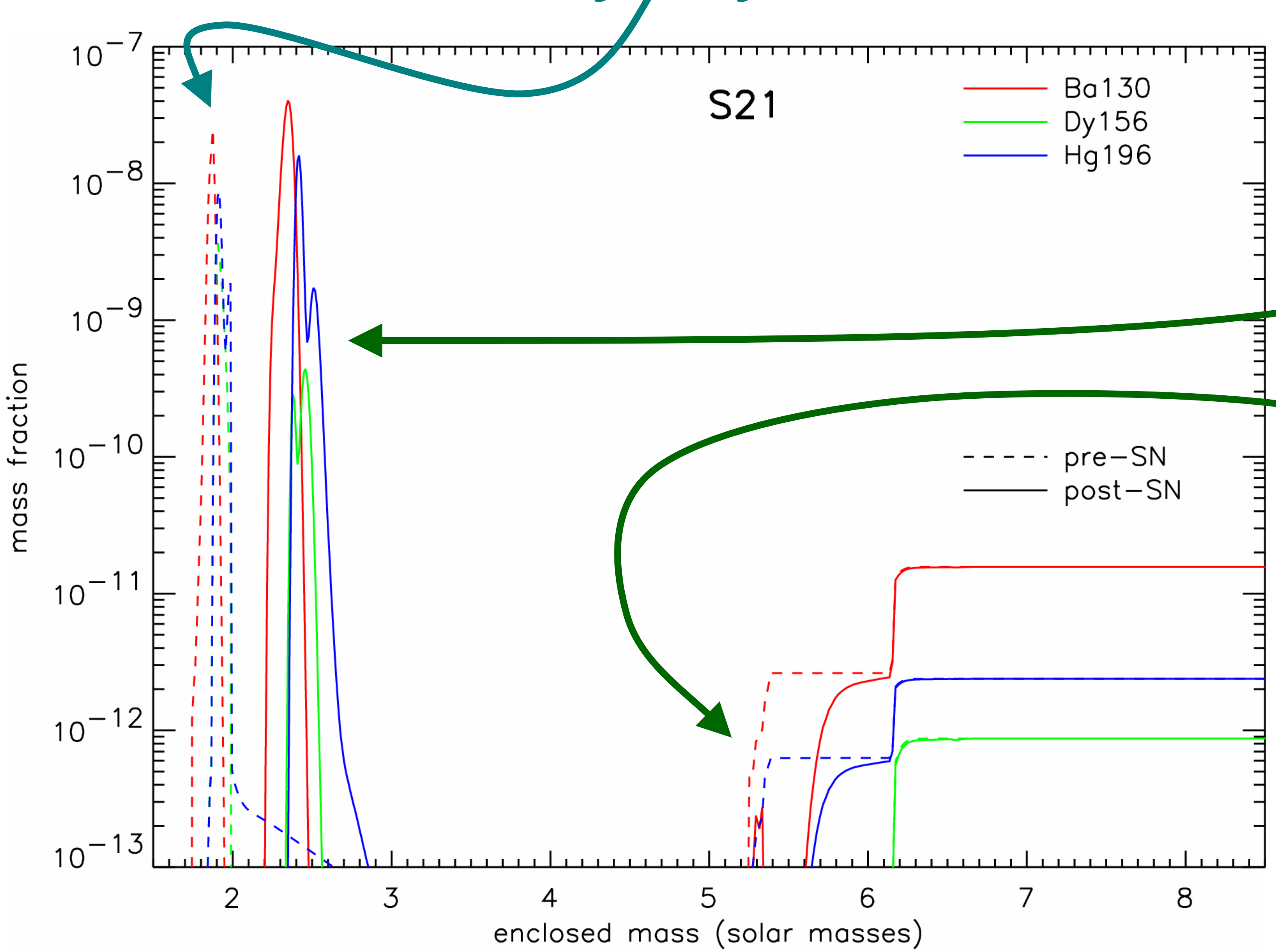
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (s)	Main Reaction
Innermost ejecta	***r*-process** ***νp*-process**	-	**>10?**	**1**	**(n,γ), β^-**
Si, O	**^{56}Ni**	**iron group**	**>4**	**0.1**	**(α,γ)**
O	**Si, S**	**Cl, Ar, K, Ca**	**3 - 4**	**1**	**$^{16}O + ^{16}O$**
O, Ne	**O, Mg, Ne**	**Na, Al, P**	**2 - 3**	**5**	**(γ,α)**
		***p*-process** **^{11}B, ^{19}F, ^{138}La, ^{180}Ta**	**2 - 3**	**5**	**(γ,n)**
		***ν*-process**		**5**	**(ν, ν'), (ν, e^-)**



25 $M_{\odot}$ star *s*-process yields for different evolution stages

"Relocation" of the γ-process

γ-process can be made in implosive O shell burning, but peak abundance is **destroyed by SN** and **recreated further out**

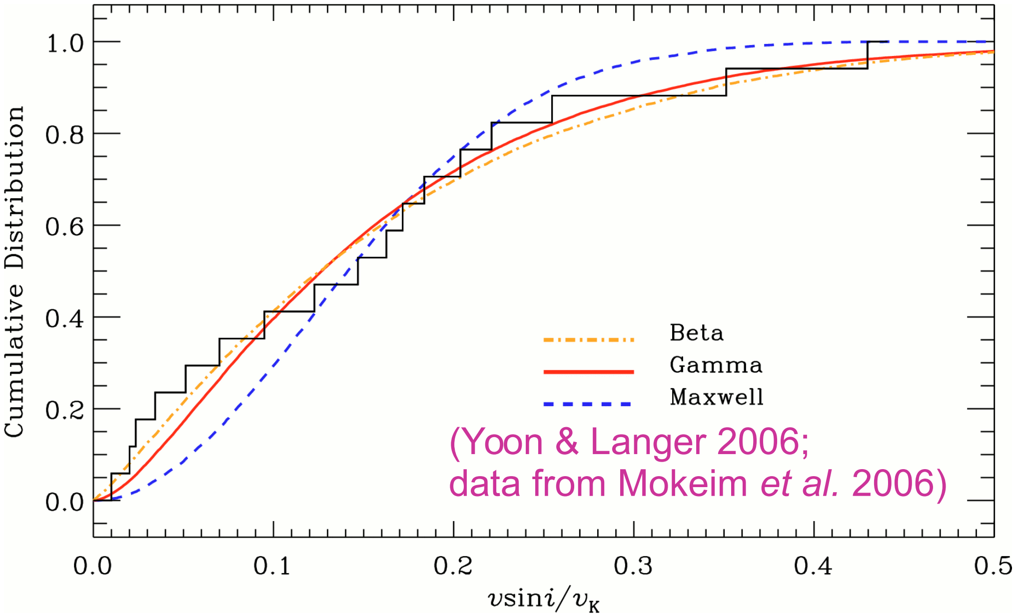


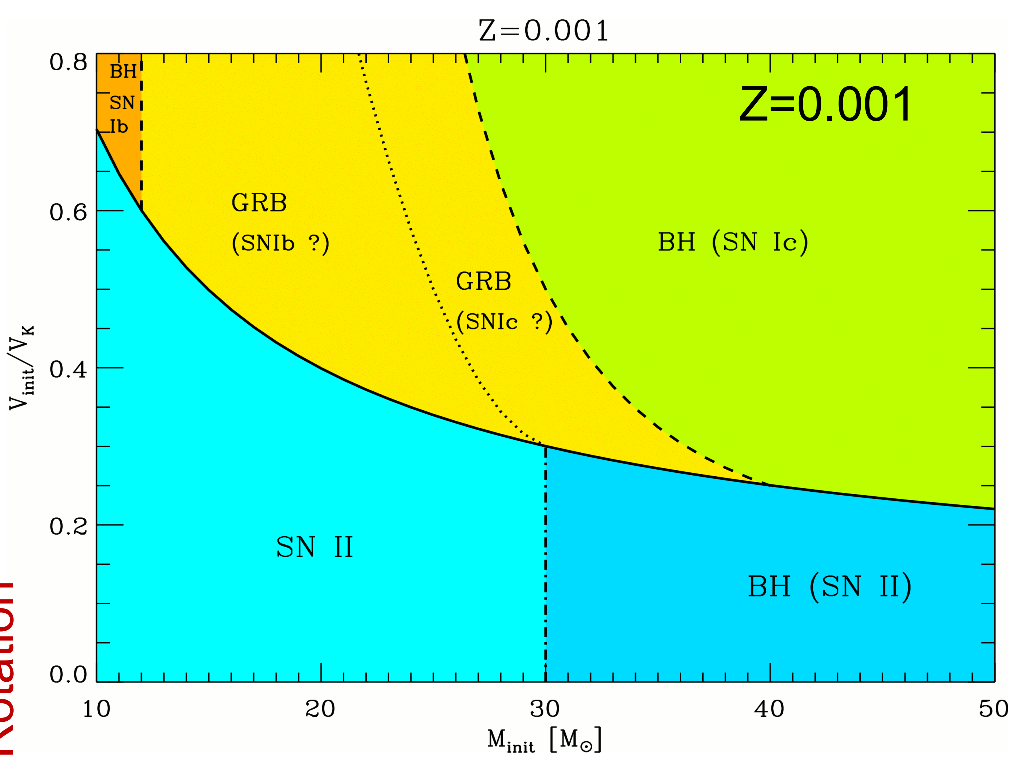
destruction by n-exposure in He shell

21 $M_{\odot}$ star

The Stellar Zoo

Black Holes and GRBs from Rotating Stars





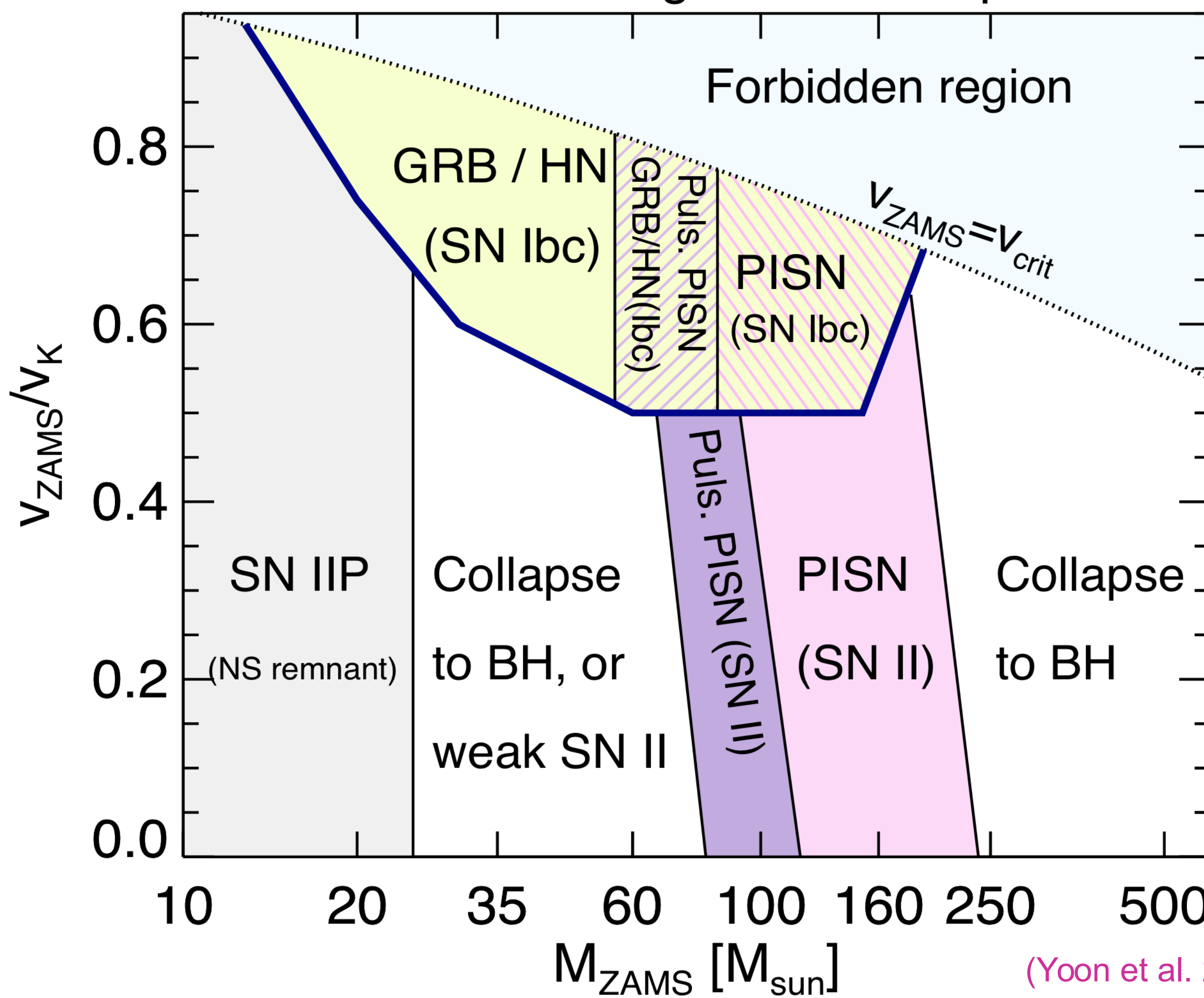
Rotation

A small fraction of single stars is born rotating rapidly

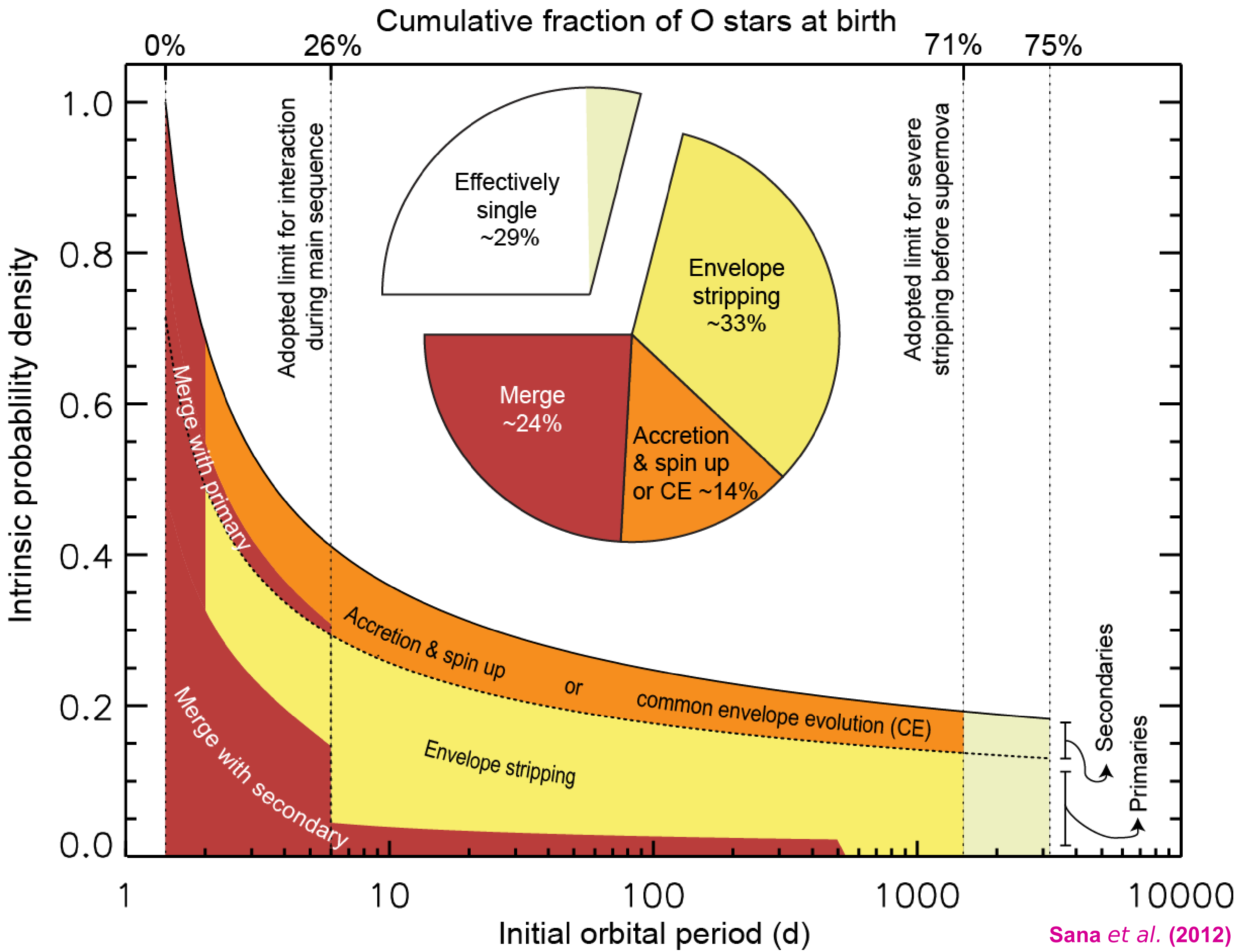
The fastest rotators evolve chemically homogeneously, become WR stars on the MS, and may lose less angular momentum.

(Yoon & Langer 2006)

Final fates of rotating massive Pop III stars



(Yoon et al. 2012)



Cumulative fraction of O stars at birth
0%
26%
71%
75%
1.0
0.8
0.6
0.4
0.2
0.0
Intrinsic probability density
Adopted limit for interaction during main sequence
Adopted limit for severe stripping before supernova
Effectively single ~29%
Envelope stripping ~33%
Merge ~24%
Accretion & spin up or CE ~14%
Merge with primary
Merge with secondary
Accretion & spin up or common envelope evolution (CE)
Envelope stripping
Secondaries
Primaries
1
10
100
1000
10000
Initial orbital period (d)
Sana et al. (2012)

Evolution of Non-Rotating Singe Stars

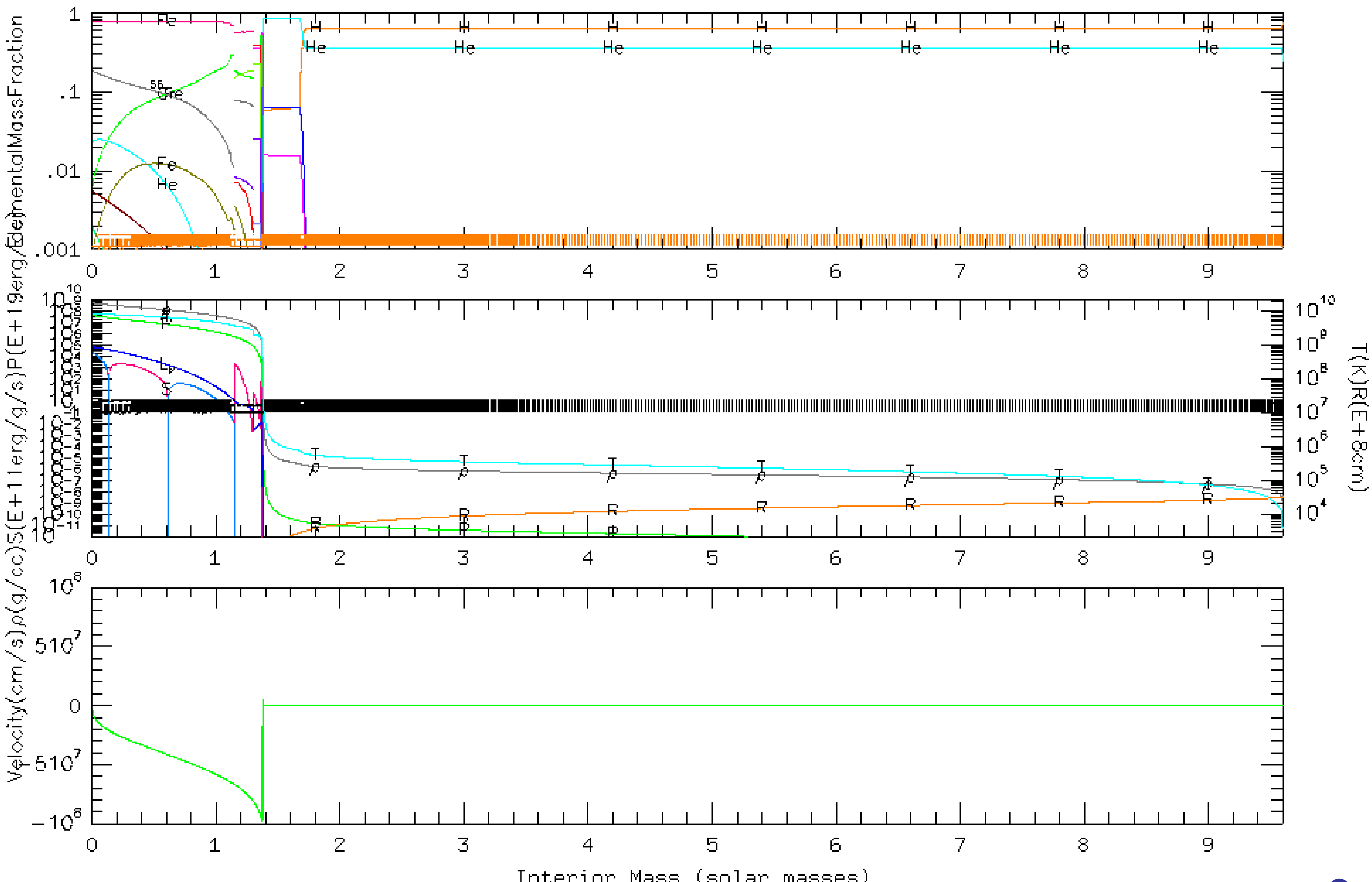
Current Questions

Evolution of ...

- Lowest-mass supernova progenitors (Jones)
- “Normal” massive stars
- High-mass supernova progenitors (Yoshida)

Lowest-Mass Massive Stars

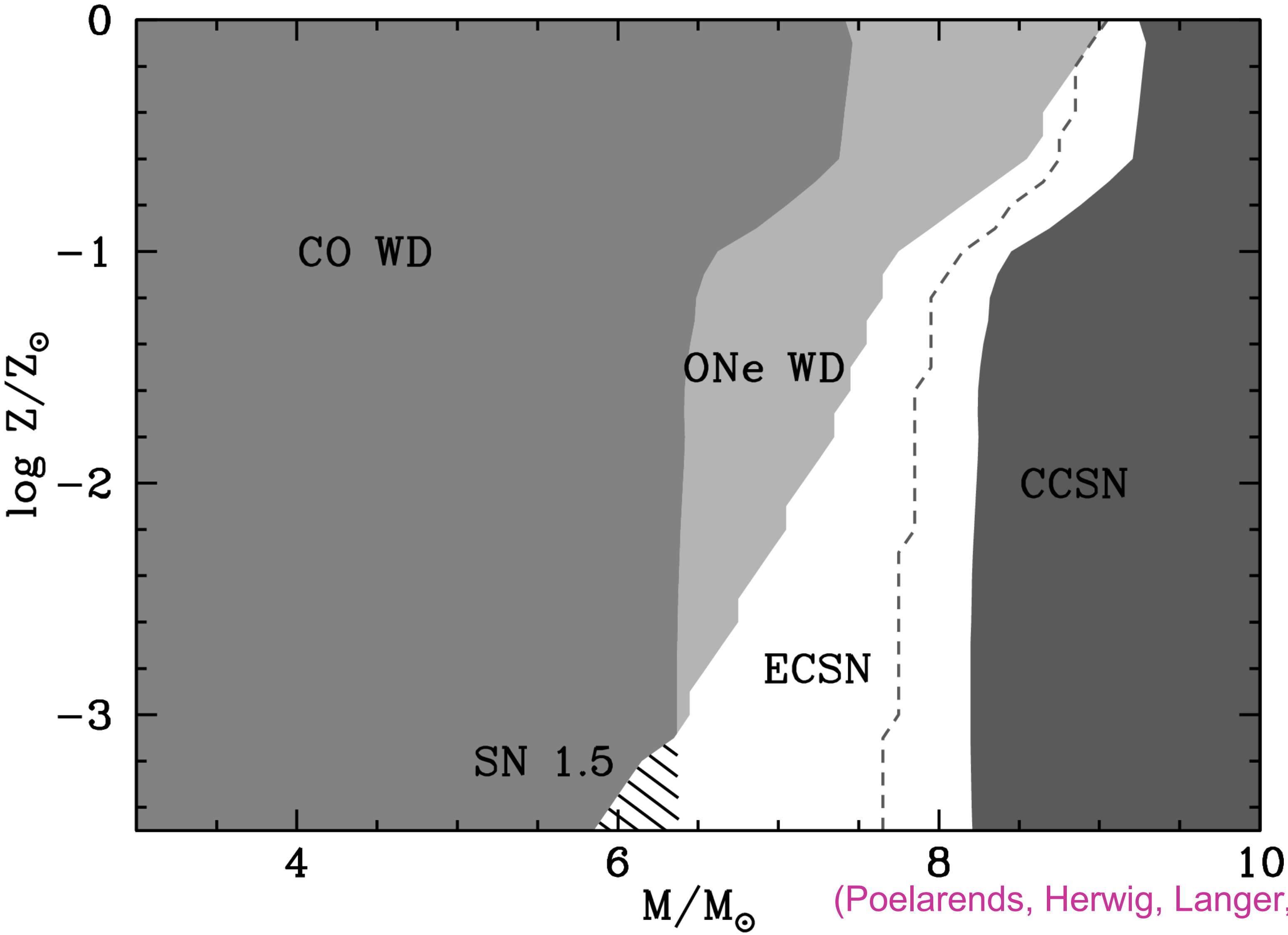
Low-Mass Pre-SN Structure



Heger et al., in prep

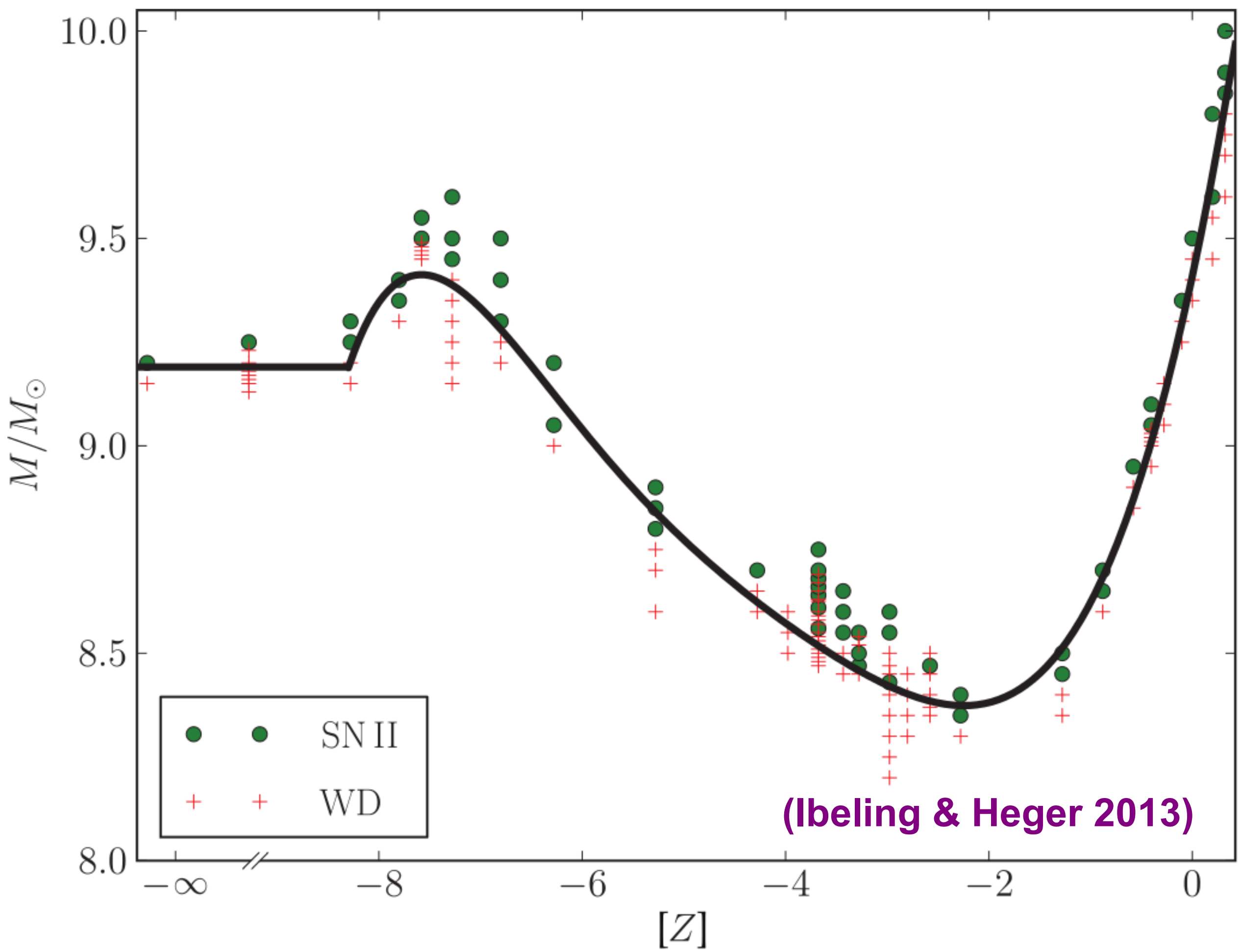
z9.6

The Lowest Mass Core Collapse SNe



(Poelarends, Herwig, Langer, Heger 2007)

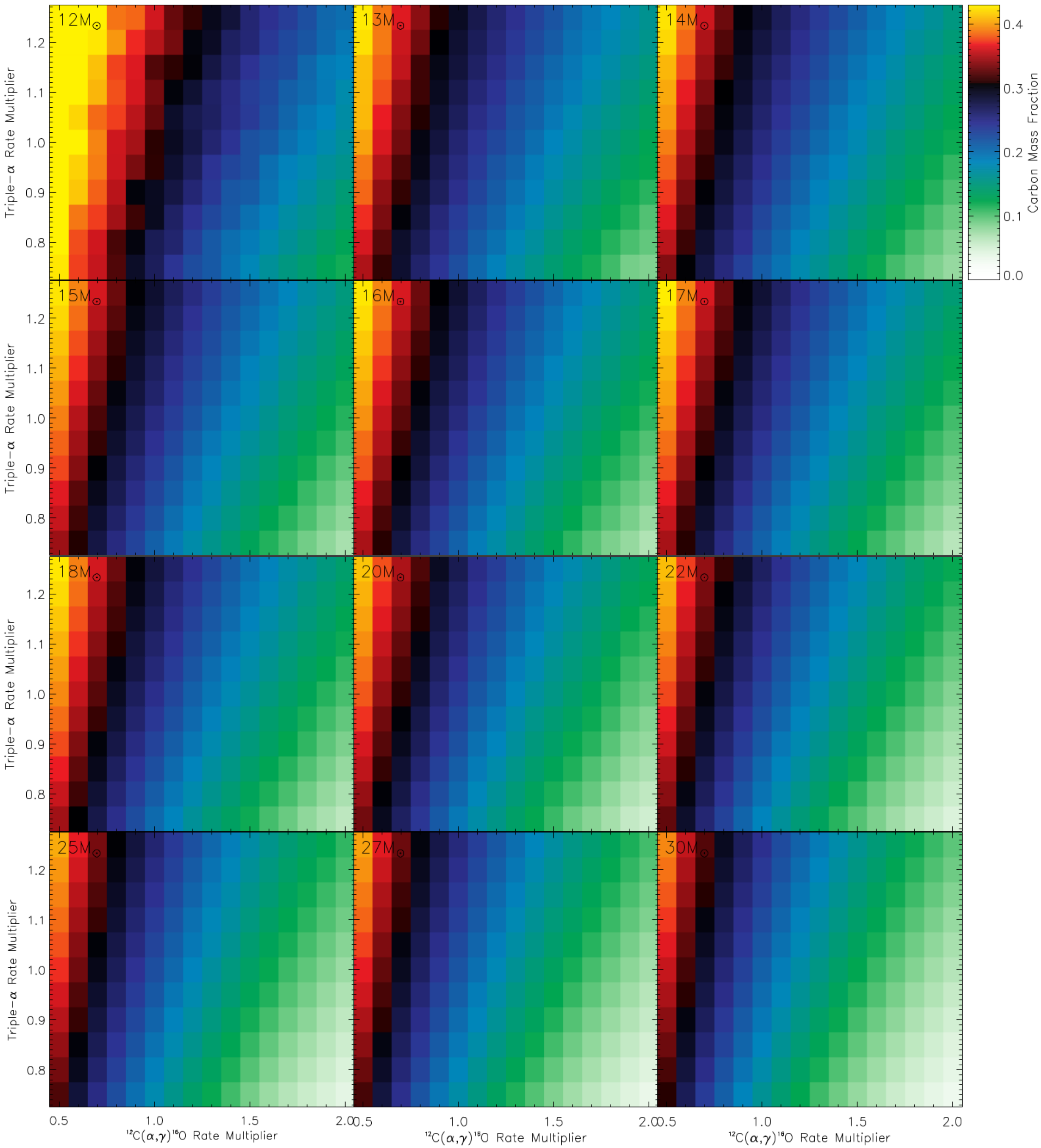
Metallicity-Dependence of Lower SN Mass Limit



Core masses for bigger stars are not affected by this

→ At [Z] = -2 the SN rate increases by >25% relative to solar, but will drop for higher metallicities.

“normal” massive Stars



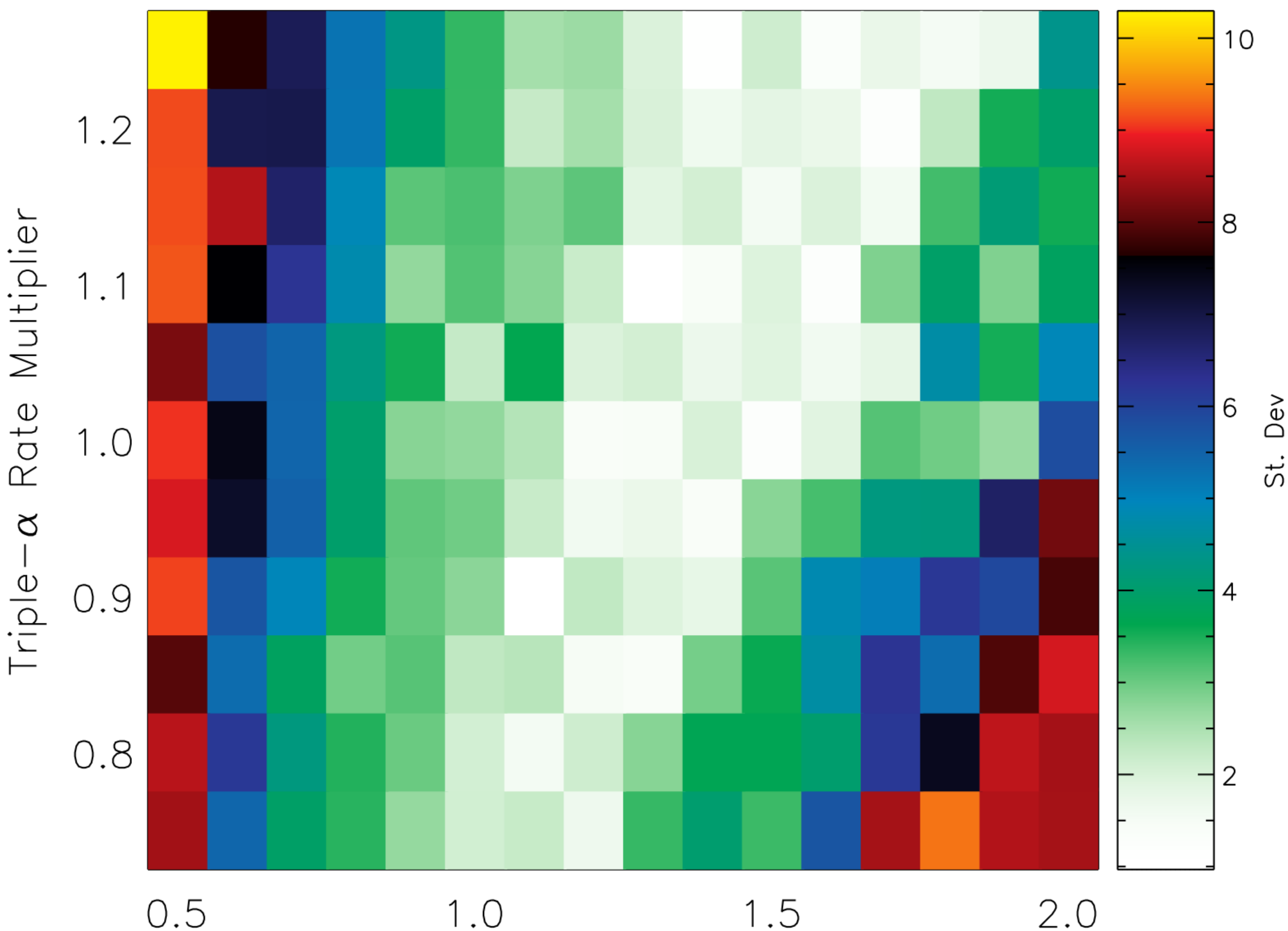
^{12}C Production as a function of $^{12}C(\alpha,\gamma)$ and 3α reaction rates

Carbon mass fraction at the end of helium burning depends the reaction rates and the mass of the star

~2000 stellar models

(West+ 2013)

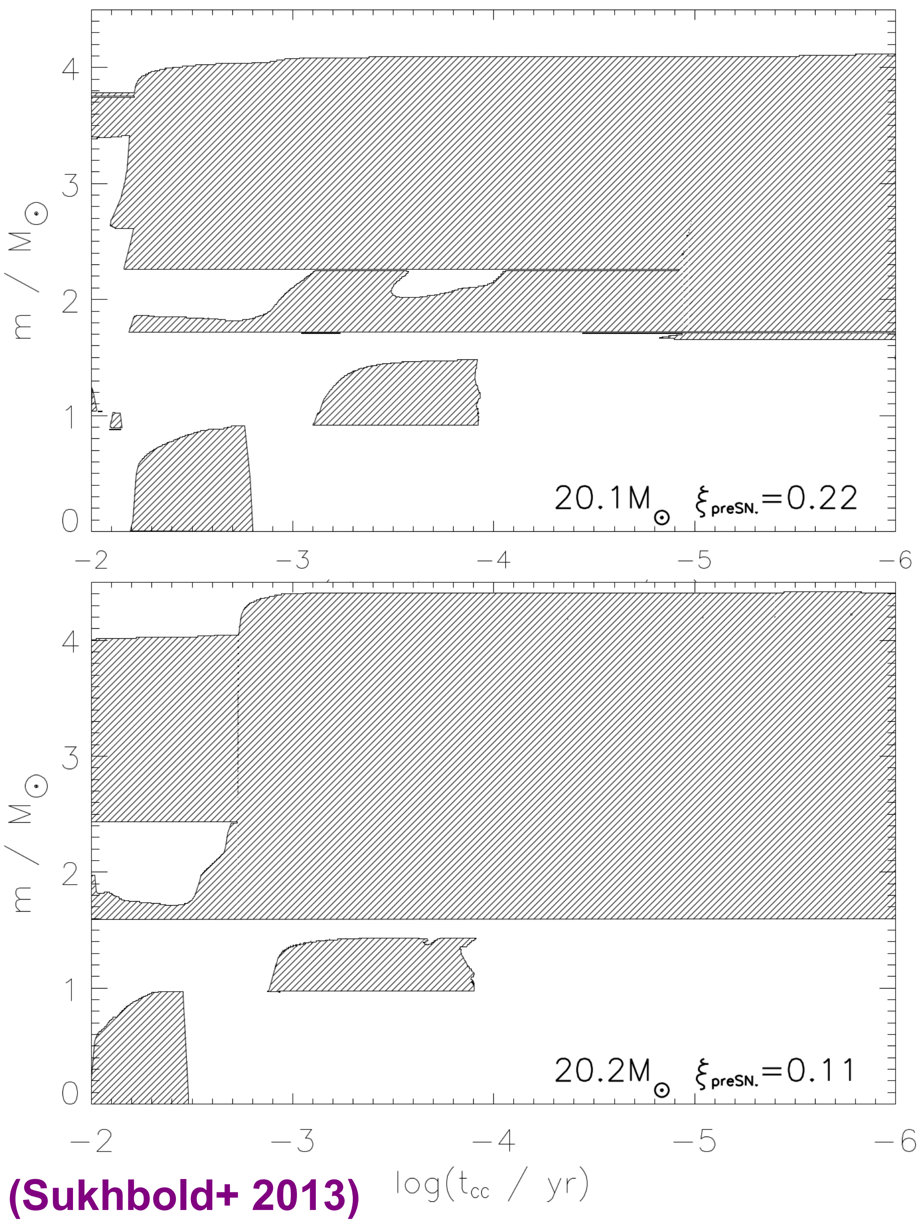
Deviations from solar production as a function of $^{12}C(\alpha,\gamma)$ and 3α reaction rates



(West+ 2013)

A "valley" of good production can be found – some degeneracy in the rates, though a shift in "reference" mass occurs.

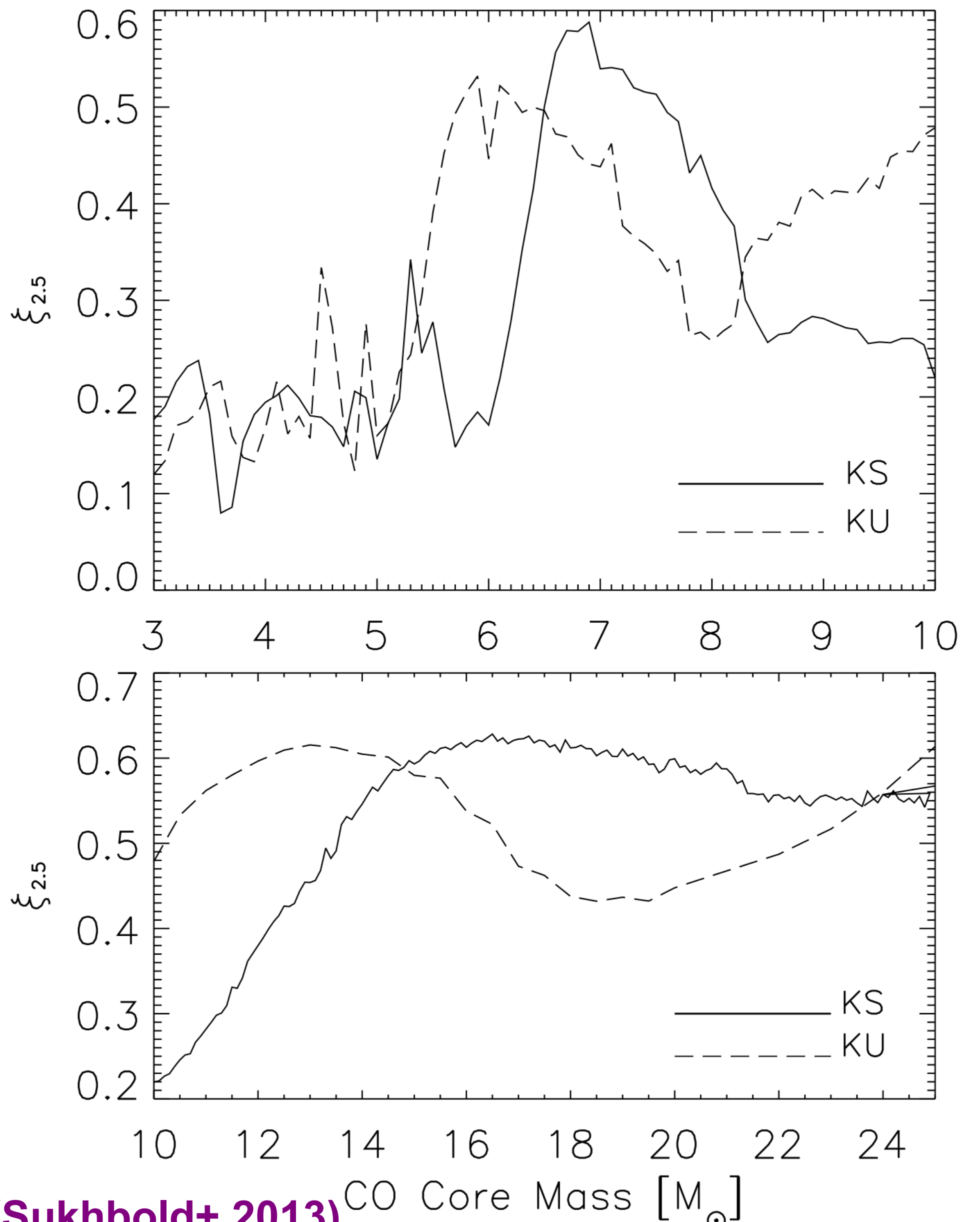
Sensitivity of Structure to Initial Mass



(Sukhbold+ 2013)

Small changes in initial mass can result in large changes in progenitor structure

Sensitivity of "Compactness" to Initial Mass



(Sukhbold+ 2013)

There is a peak in compactness at around 20 $M_\odot$ initial mass

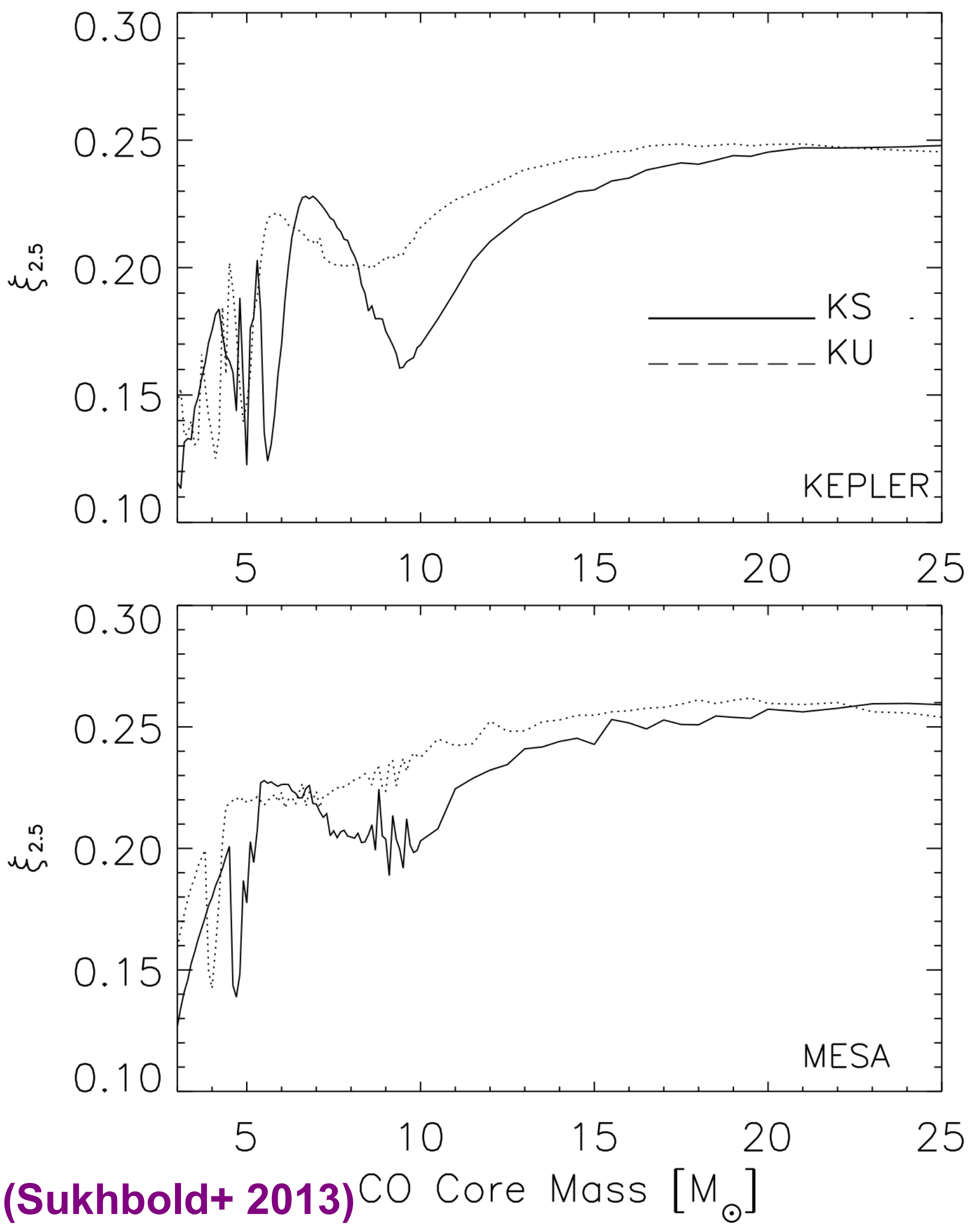
S: [Z] = 0
U: [Z] = -4

Compactness Parameter

$$\xi_M = \frac{M/\mathrm{M}_\odot}{R(M_{bary} = M)/1000\,\mathrm{km}}\Big|_{t_{bounce}},$$

(O'Conner & Ott 2011)

Sensitivity of “Compactness” to Codes



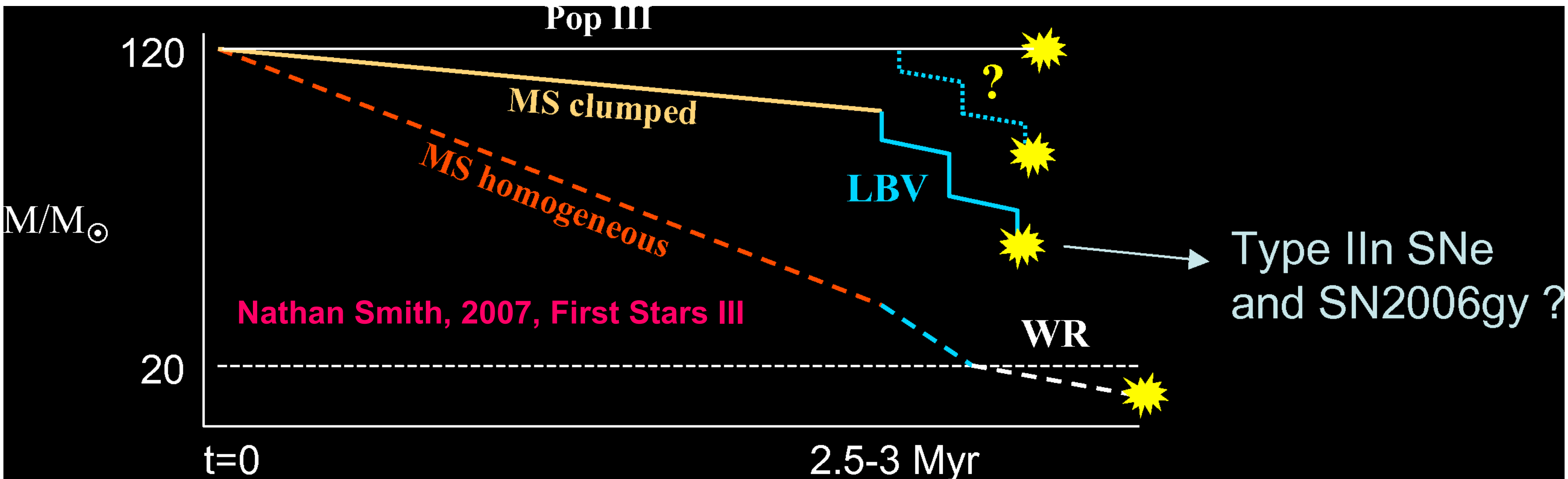
KEPELR and MESA show noticeable differences in detail but general feature can be reproduced if physics parameters are adjusted accordingly.

S: [Z] = 0
U: [Z] = -4

(Sukhbold+ 2013)


Big Stars

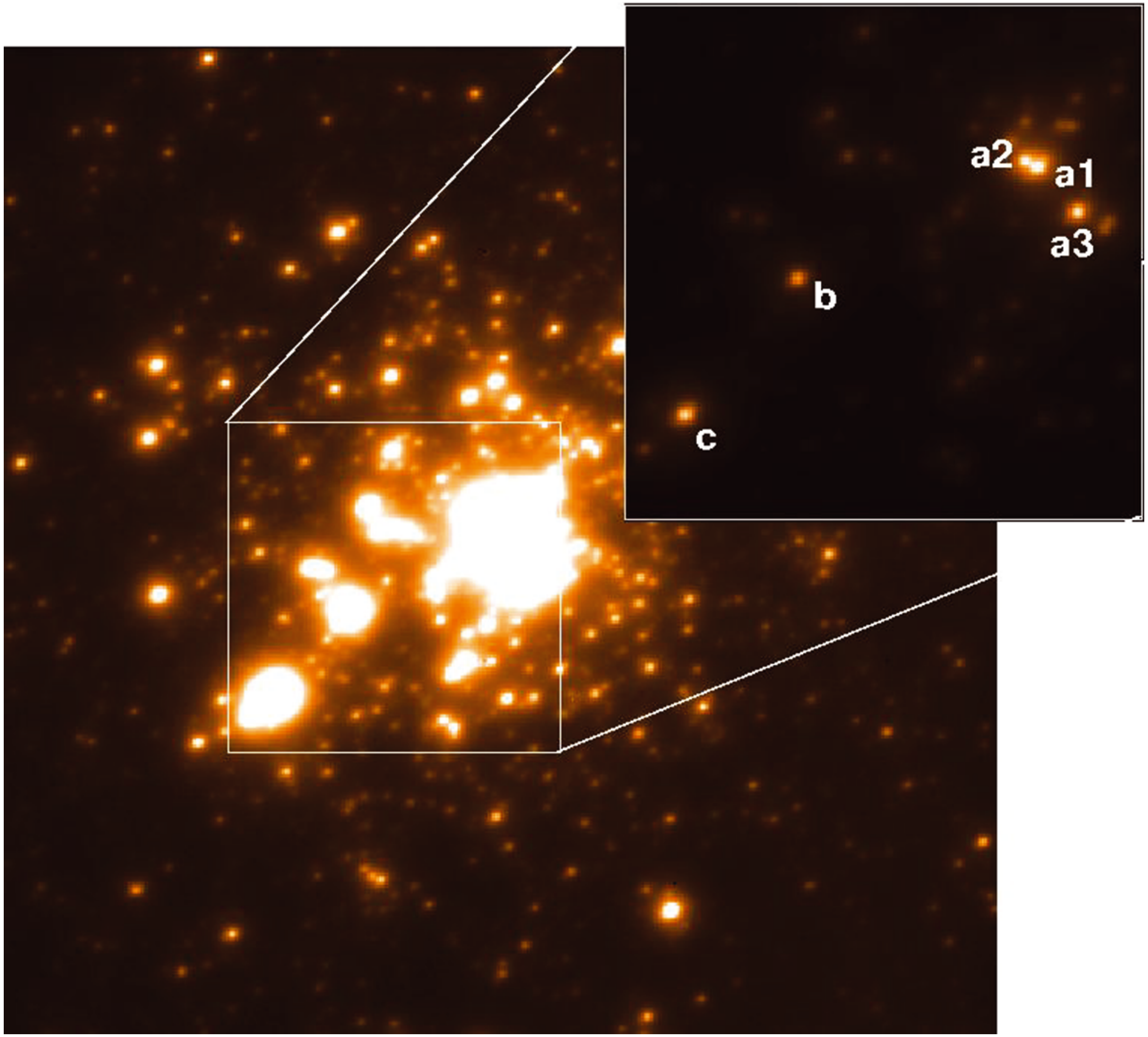
Mass Loss due to Giant Eruptions?



How do the most massive stars evolve?

- Reduced mass loss on the main sequence followed by LBV & giant eruptions?
- What are these eruptions?
  (physics, number, recurrence)
- When do they occur?
  (internal evolution stage?)
- How do we model these eruptions?
- Pulsational Pair-Instability Supernovae (PPSN)?

The Most Massive Stars Today

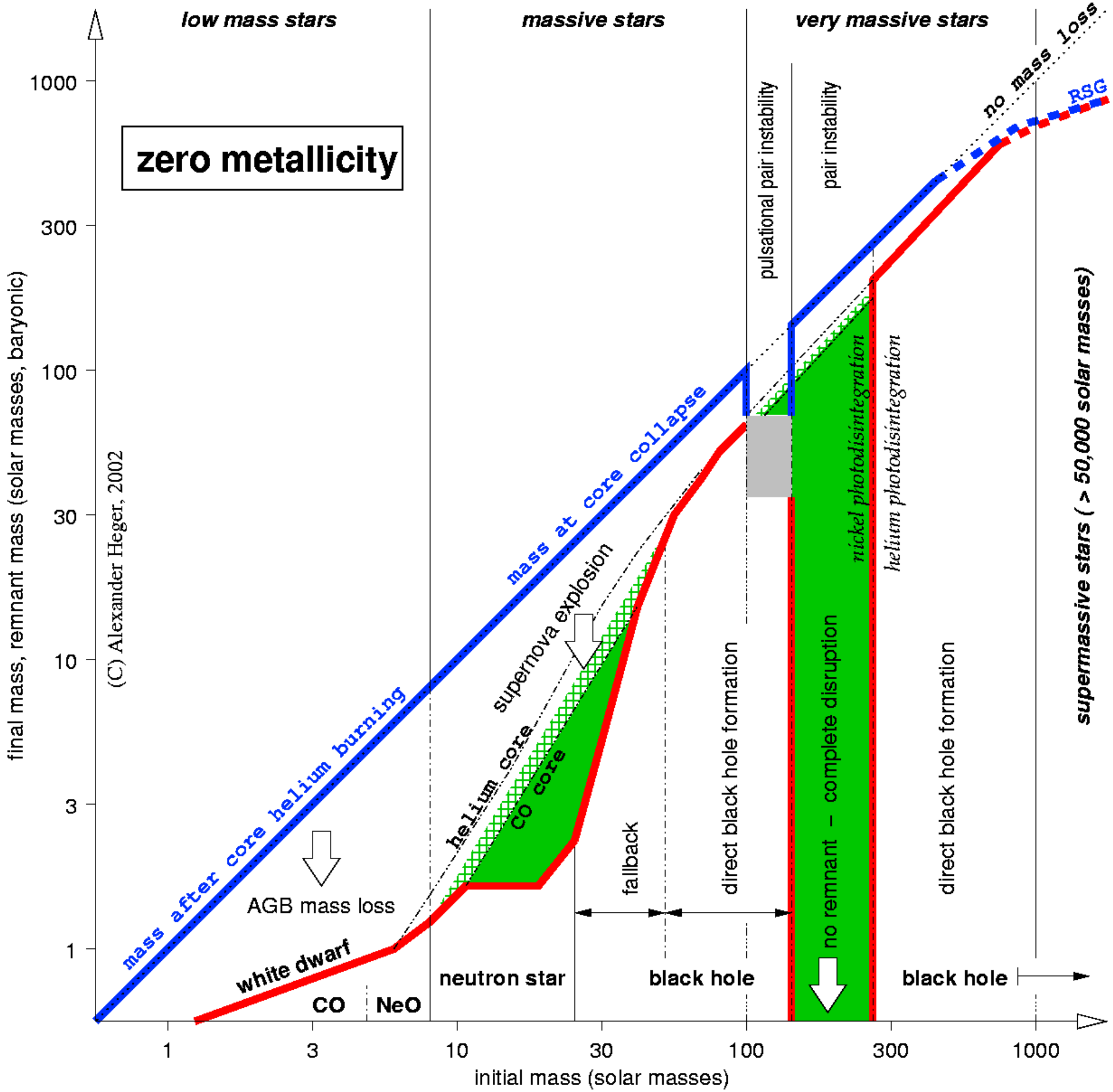


R136

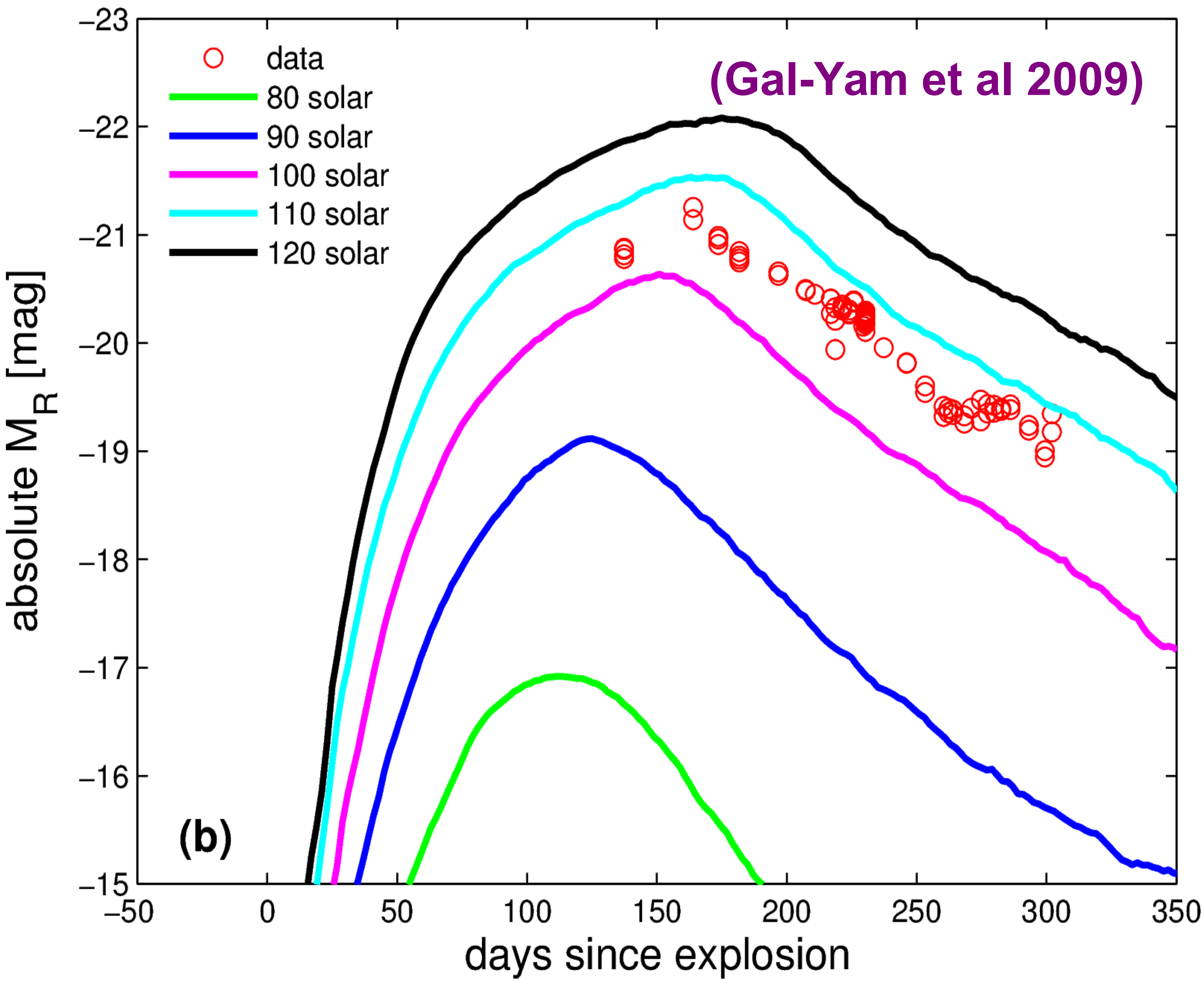
- young massive star cluster
- Age around 1.5 Myr
- Star “a1”: maybe 200 $M_\odot$ initial mass

(Crother et al. 2010)

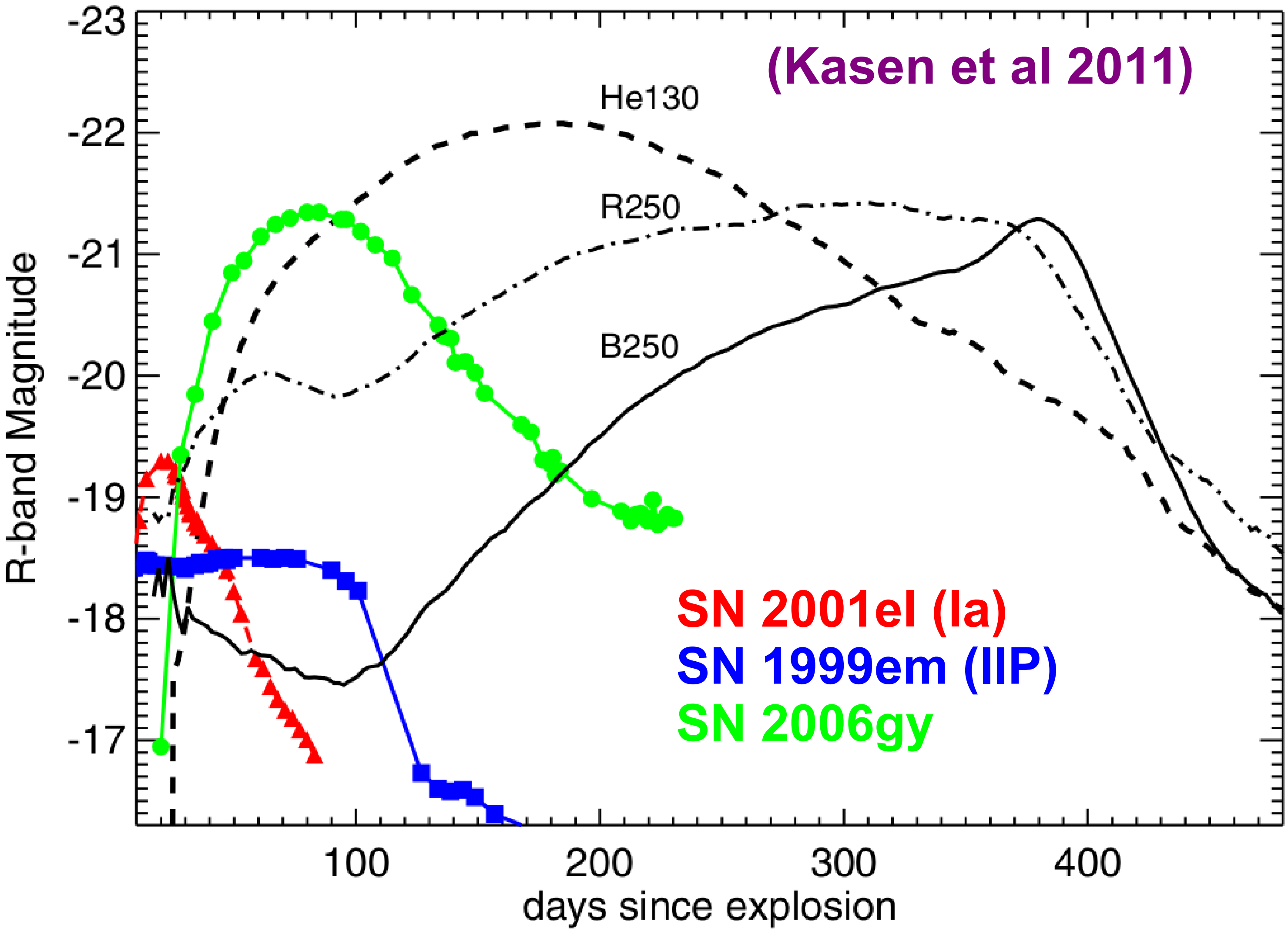
Ejected “metals”



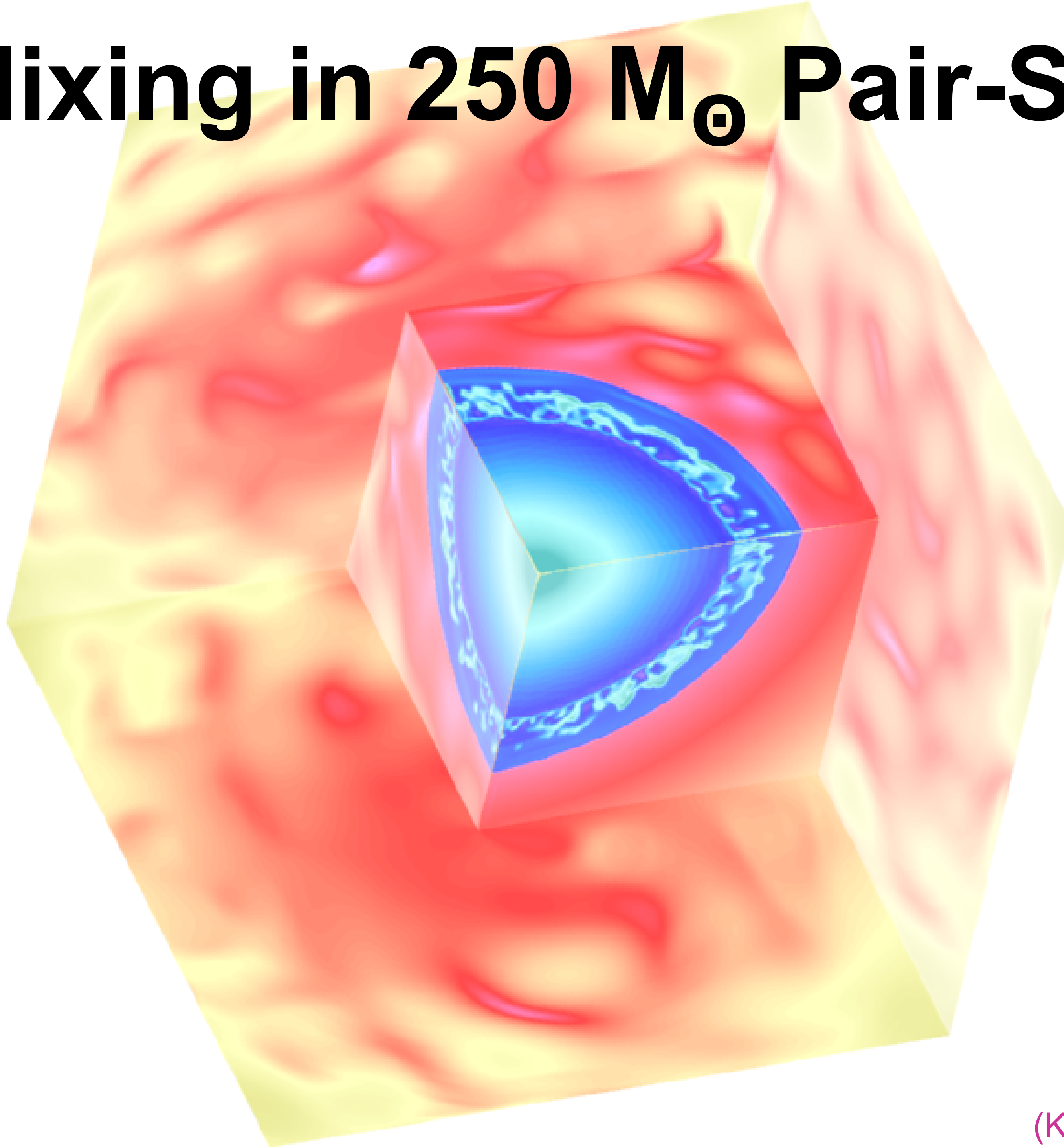
PSN observed?



Pair-SN Models

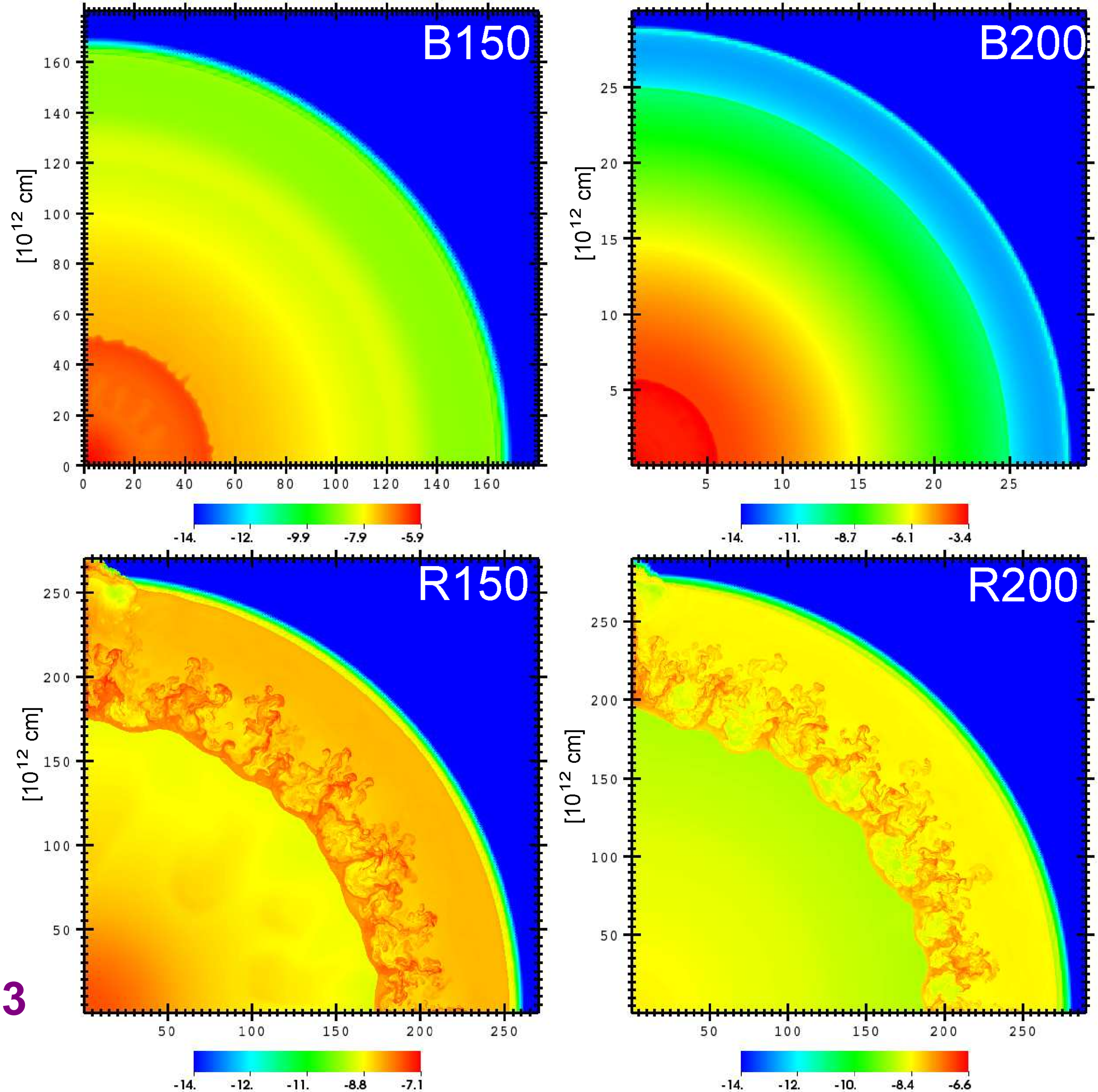


Mixing in 250 $M_{\odot}$ Pair-SN

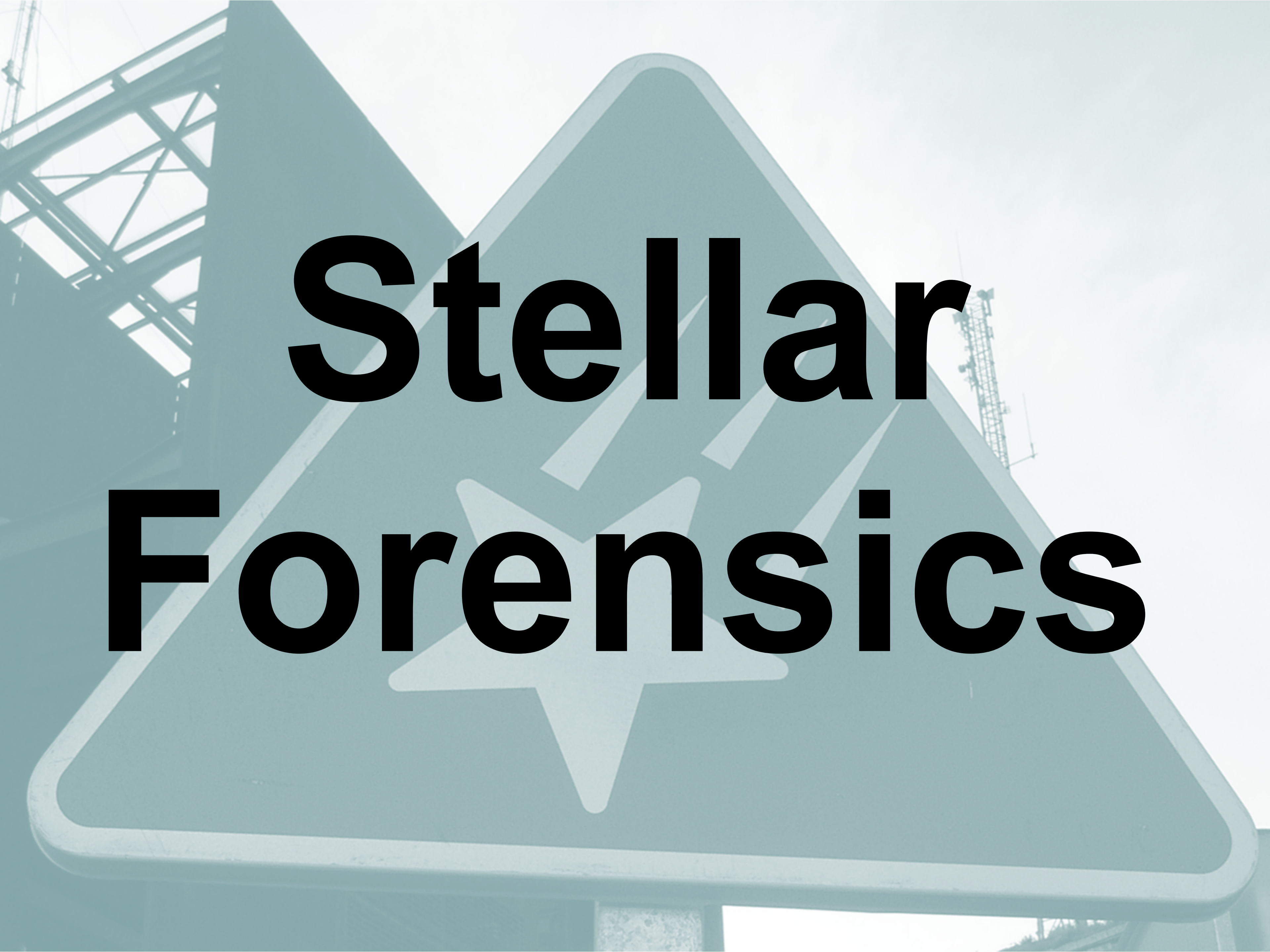


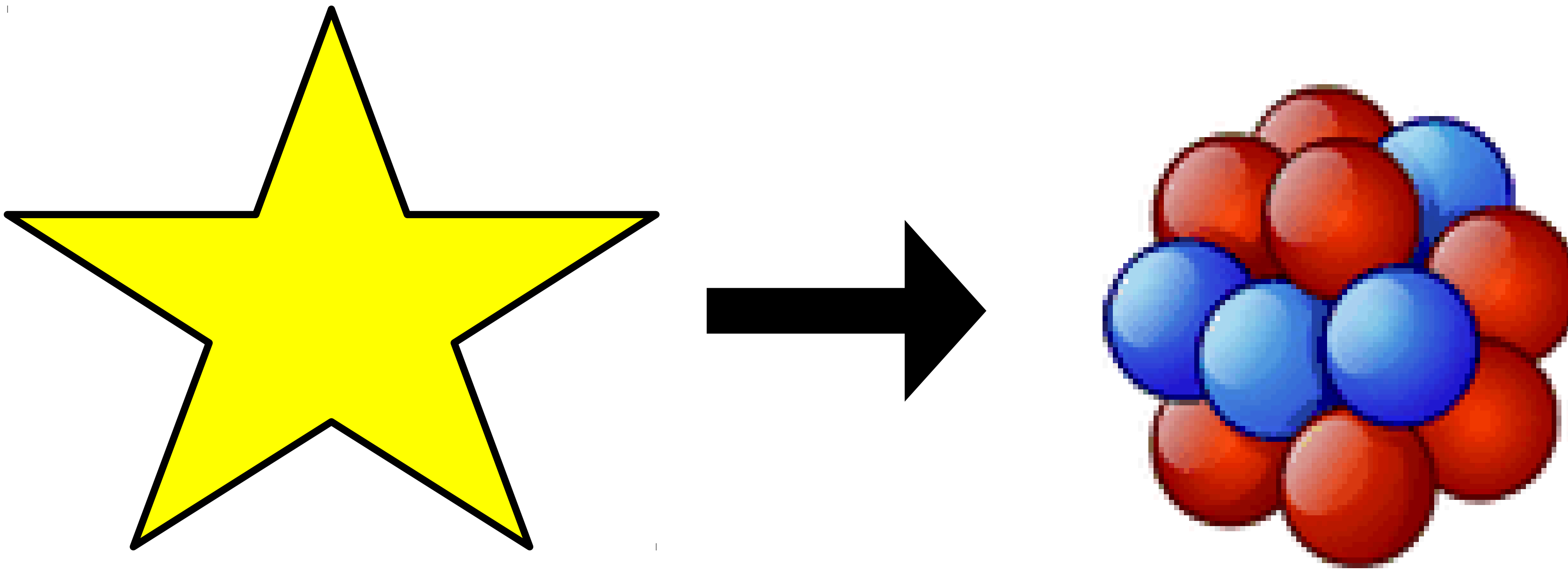
(Ken Chen 2011)

log (ρ) [g/cm³]



Chen 2013 in prep.


Stellar
Forensics



Conclusions

The Evolution of Stars, especially of massive stars that make supernovae, is far from being a closed chapter.

- **Uncertainties in Fates of massive stars also come from uncertainties in their initial properties: mass, rotation, binarity**
- Significant uncertainty still exists in the modeling of the stellar physics, including rotation, mixing processes, binary star evolution, and wind mass loss, but also uncertainties in nuclear physics and key nuclear reaction rates matter.
- Stellar forensics, determining abundance patterns of stellar ashes, may be our best tool in the near future (e.g., constraints on pair-SNe)