Presupernova Evolution of Massive Stars

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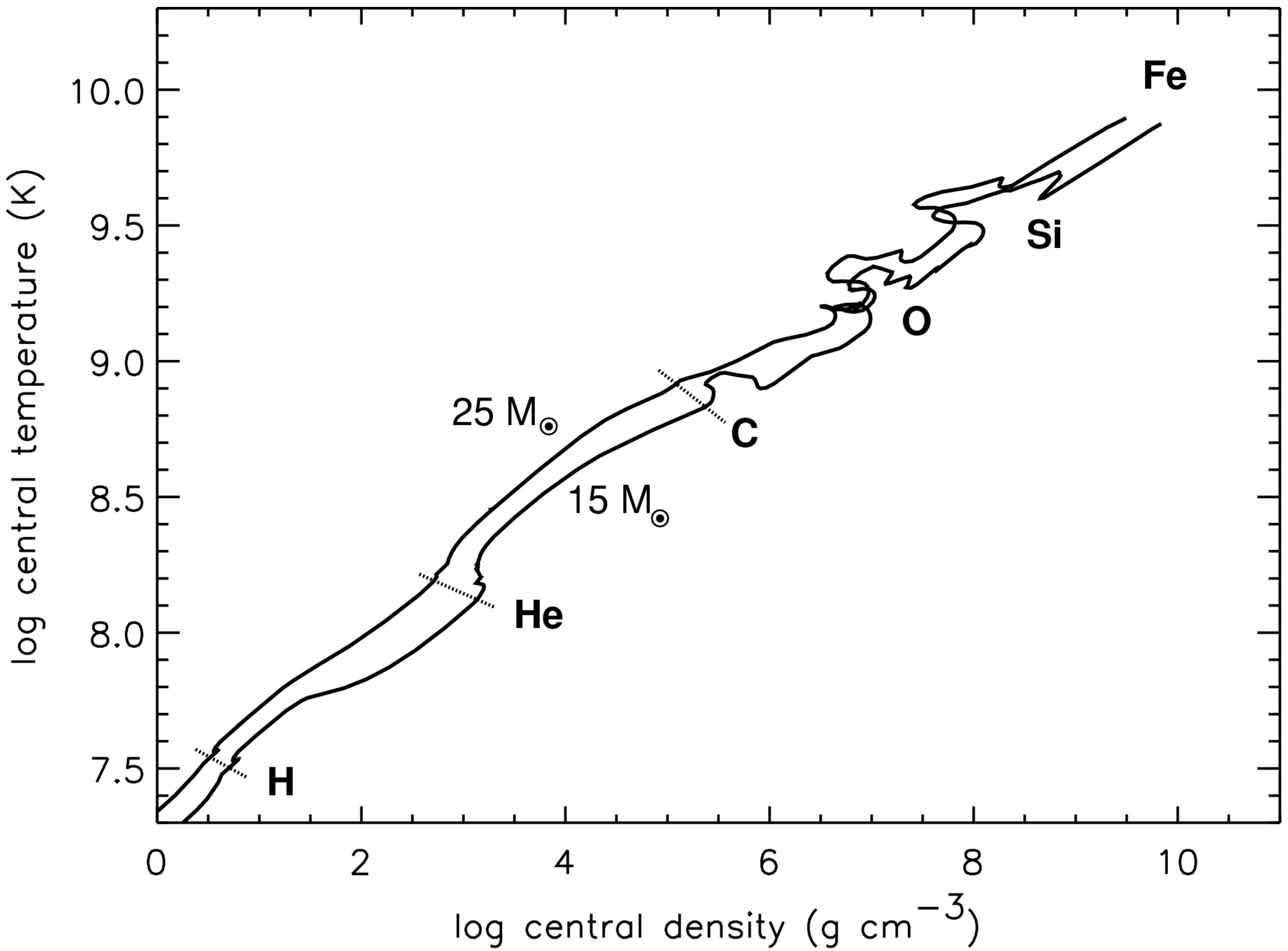
Overview

- Presupernova Evolution
- Varieties of Stellar Deaths
- Uncertianties
- Nucleosynthesis

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

continuing contraction

to higher central densities and temperatures

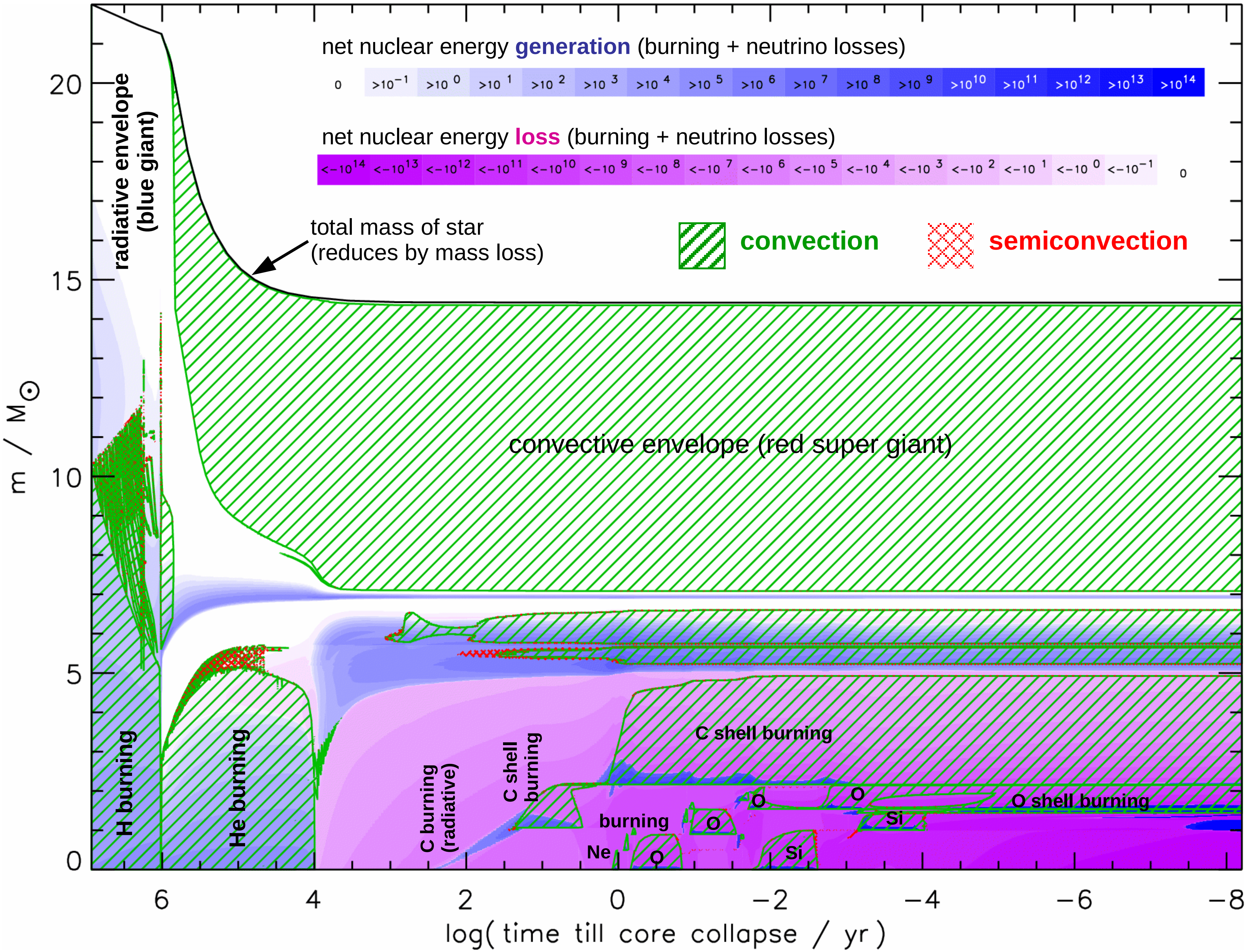


Evolution of central density and temperature of 15 $M_\odot$ and 25 $M_\odot$ stars

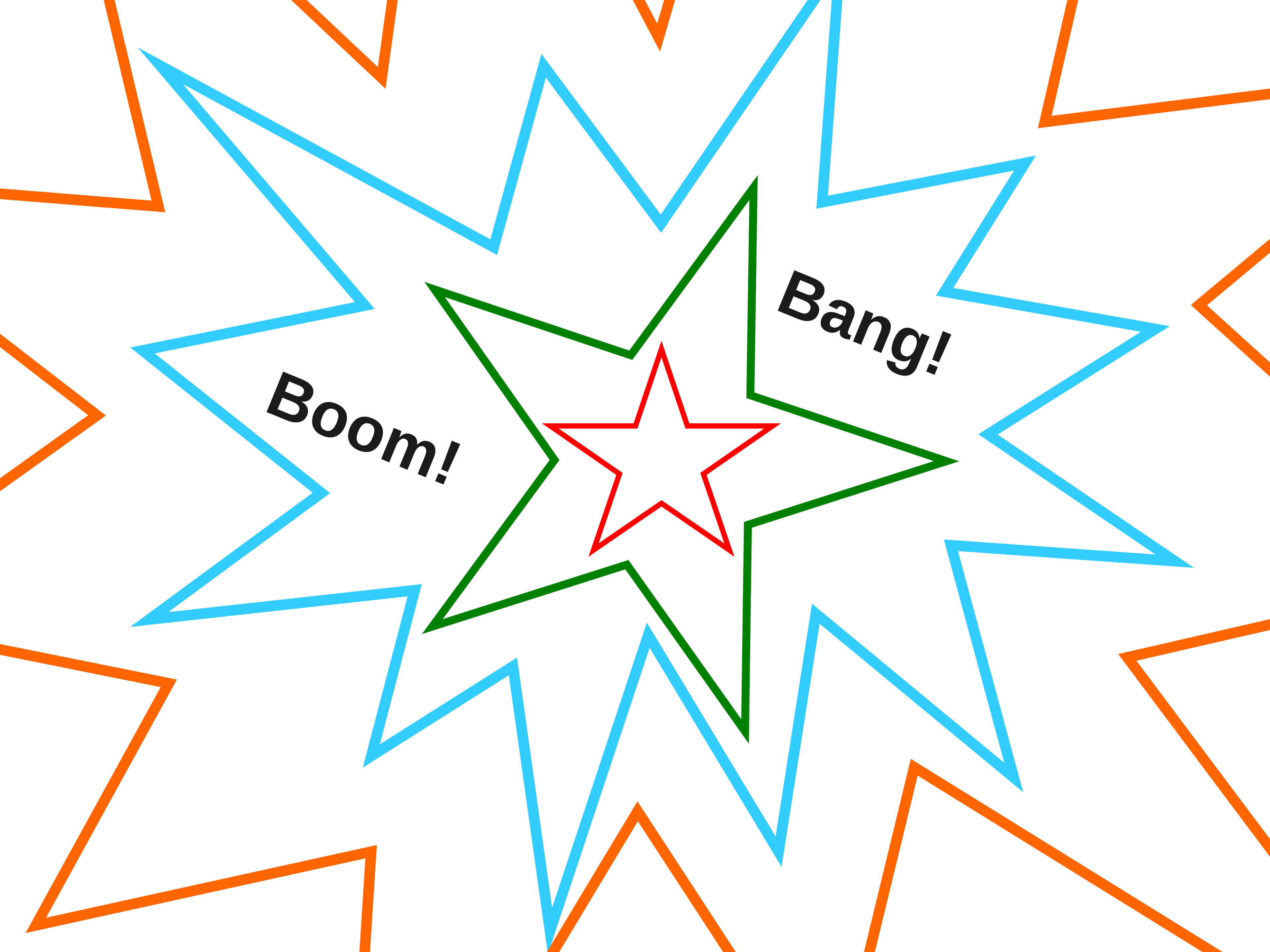
Nuclear burning stages

(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	$4\,H \xrightarrow{CNO} {}^{4}He$
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)
0 >10^−1 >10^0 >10^1 >10^2 >10^3 >10^4 >10^5 >10^6 >10^7 >10^8 >10^9 >10^10 >10^11 >10^12 >10^13 >10^14
net nuclear energy loss (burning + neutrino losses)
<−10^14 <−10^13 <−10^12 <−10^11 <−10^10 <−10^9 <−10^8 <−10^7 <−10^6 <−10^5 <−10^4 <−10^3 <−10^2 <−10^1 <−10^0 <−10^−1 0
convection
semiconvection
radiative envelope (blue giant)
total mass of star (reduces by mass loss)
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)


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	-	>10 low Y_e	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), (α,γ)
		p-process ^{11}B, ^{19}F, ^{138}La, ^{180}Ta	2 - 3	5	(γ,n)
		ν-process		5	(ν, ν'), (ν, e^-)

Things that blow up

supernovae

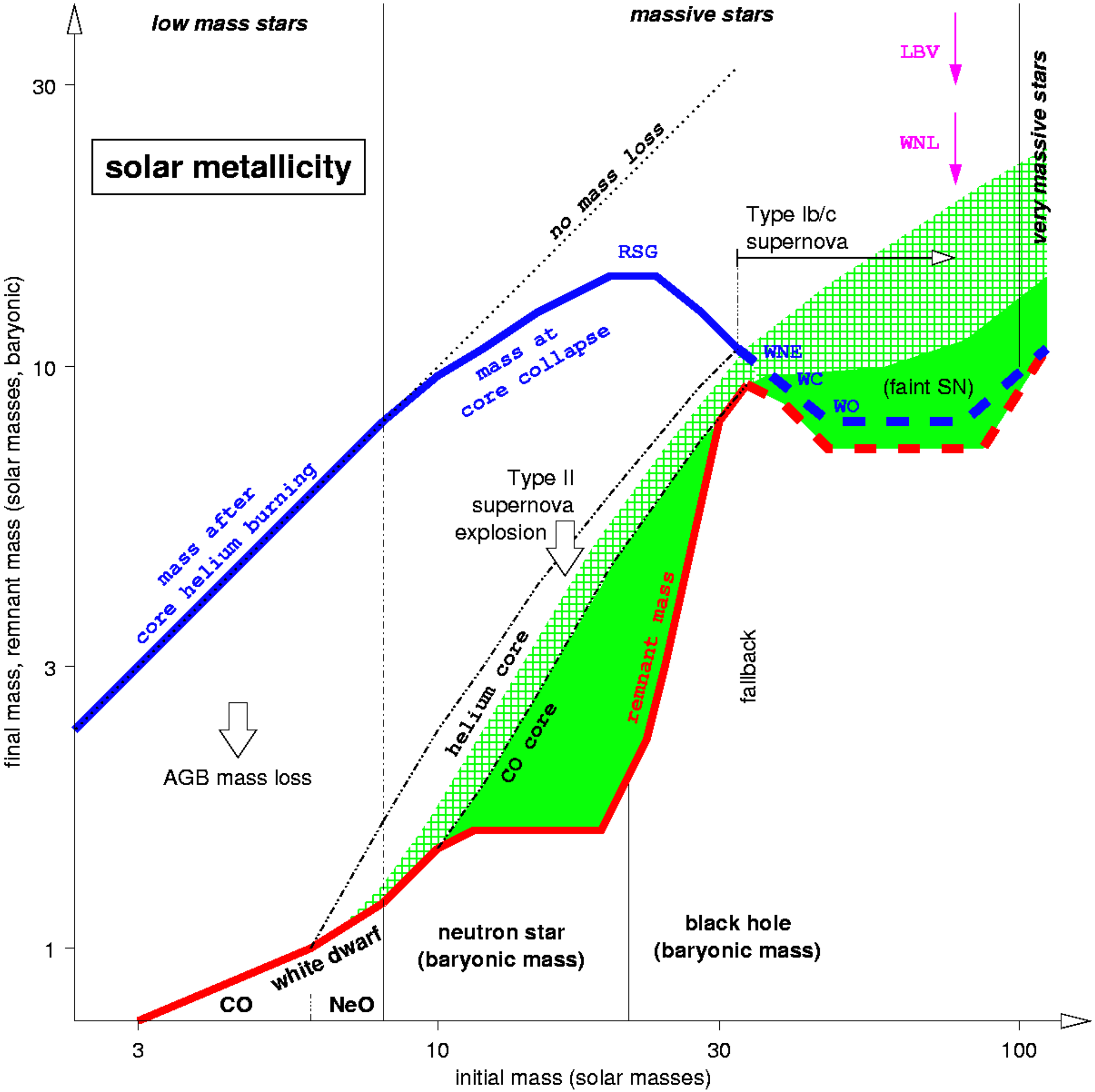
$1B=10^{51}$ erg

MASS

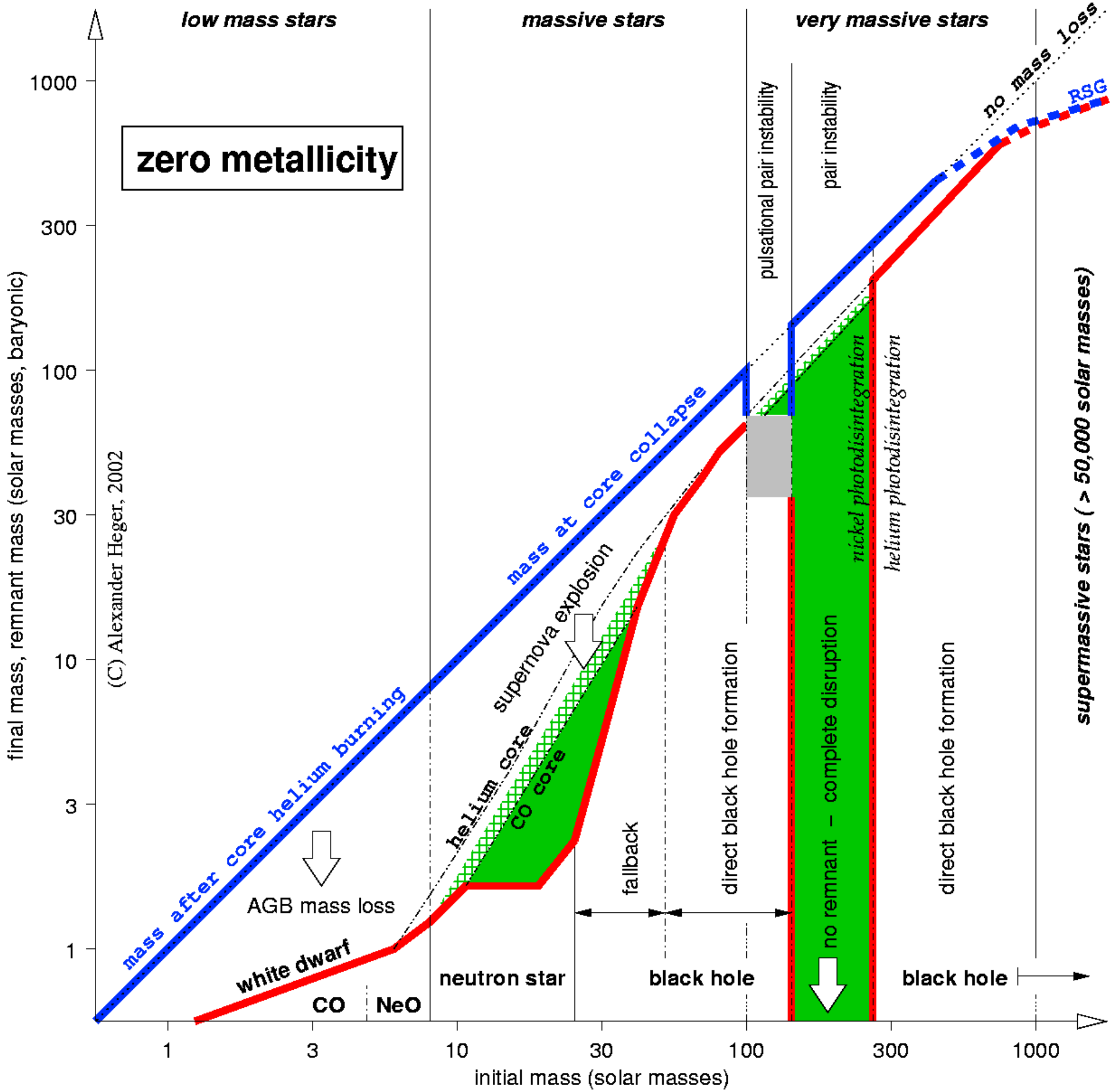
- CO white dwarf ➔ Type Ia SN, $E \approx$ 1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- “SAGB” star (AGB, then SN) ➔ EC SN
- “normal” SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- “Collapsar”, GRB ➔ broad line Ib/a SN, “hypernova”
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN, $\lesssim$100B ($1B=10^{51}$ erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- GR He instability ➔ >100 B SN+SMBH, or 10,000 B
- Supermassive stars ➔ $\gtrsim$100000 B SN or SMBH

Energy Scales

Log E	Explosion	Thermonuclear
39	X-ray Bursts	√
40	Long-Duration He Bursts	√
41		
42	X-ray Superbursts	√
43		
44		
45		
46	Classical Novae	√
48	Faint SN (visible LC?)	
49	SN (visible LC)	
50	Bright SN (LC?)	
51	SN (kinetic)	SN Type Ia total
52	Hypernova? GRB?	Pair-SN total (low-mass end)
53	SN (neutrinos – several 10^{53}erg)	Pair-SN total (upper limit)
54	*(a lot of energy - 0.5 $M_{\odot}$ c^2)*	
55	GR He SN	GR He SN (upper limit)
56	GR H SN, Z > 0 (Fuller *et al.* 1986)	√

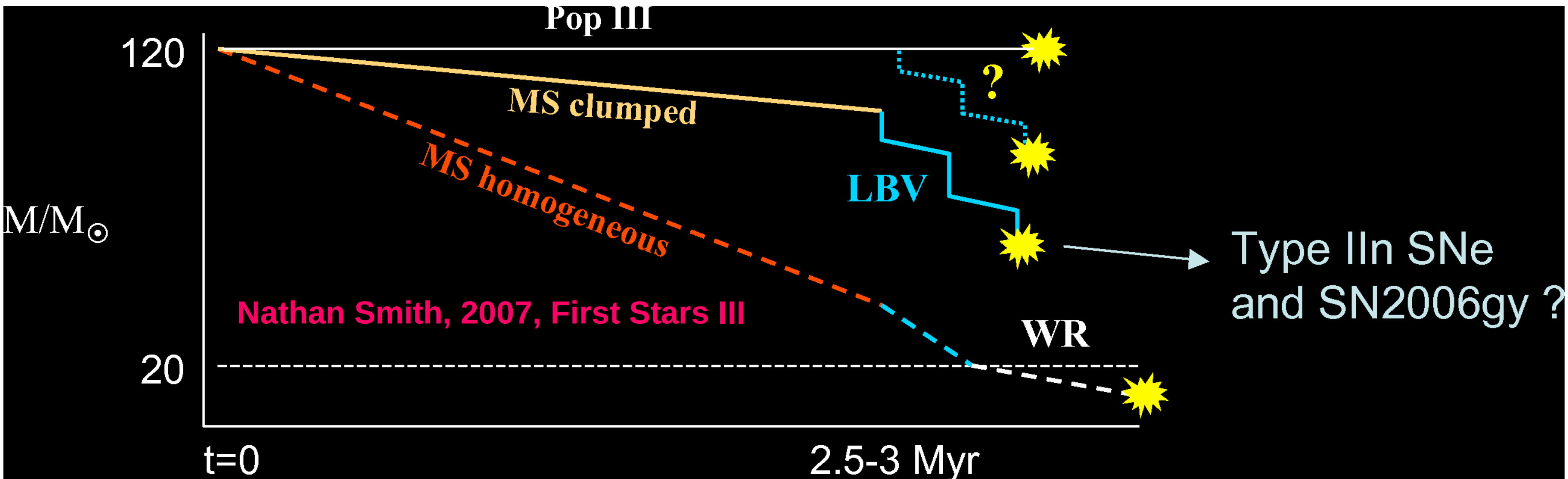


Ejected “metals”



Ejected “metals”

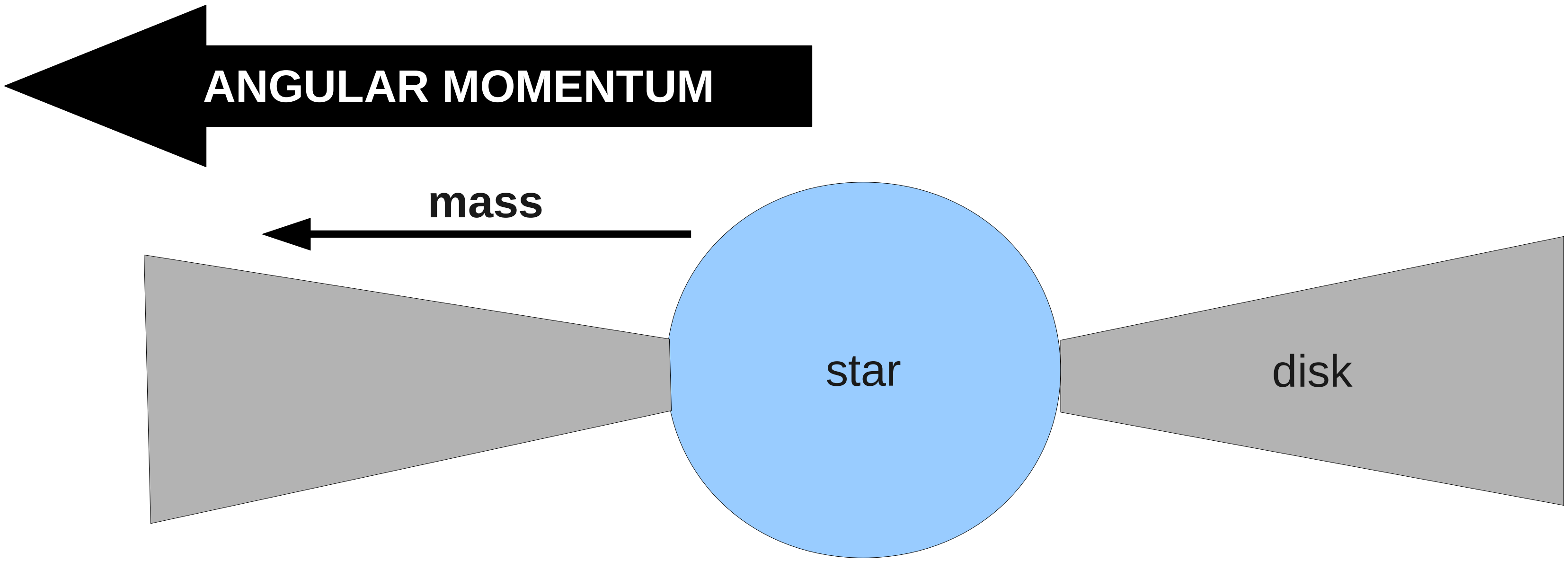
Mass Loss due to Giant Eruptions?



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)?

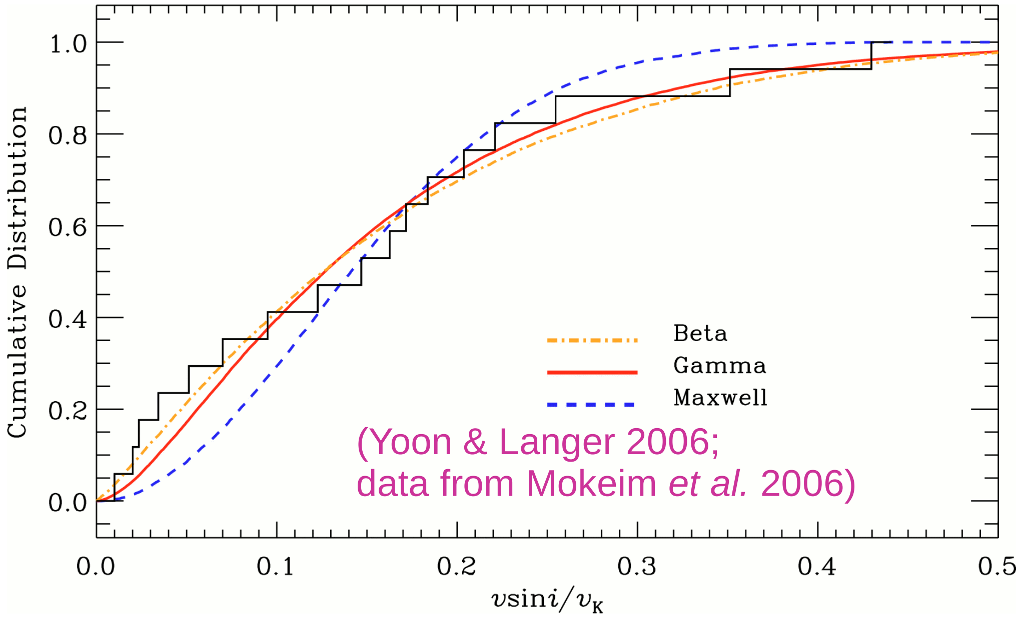
Mass Loss due to Critical Rotation

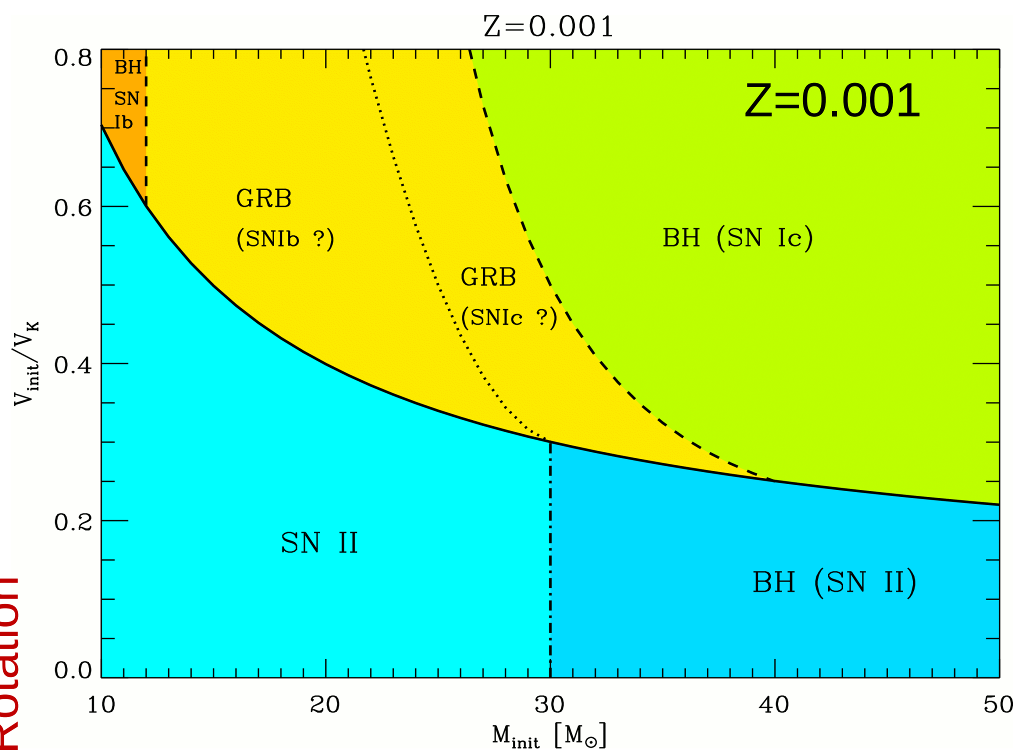


- **How important is mass loss due to critical (or fast) rotation?**
- **How do we quantify mass loss and angular momentum loss?**
- **How does it effect our stellar models?**

(Langer, Meynet, Maeder, Hirschi,...)

Black Holes and GRBs from Rotating Stars





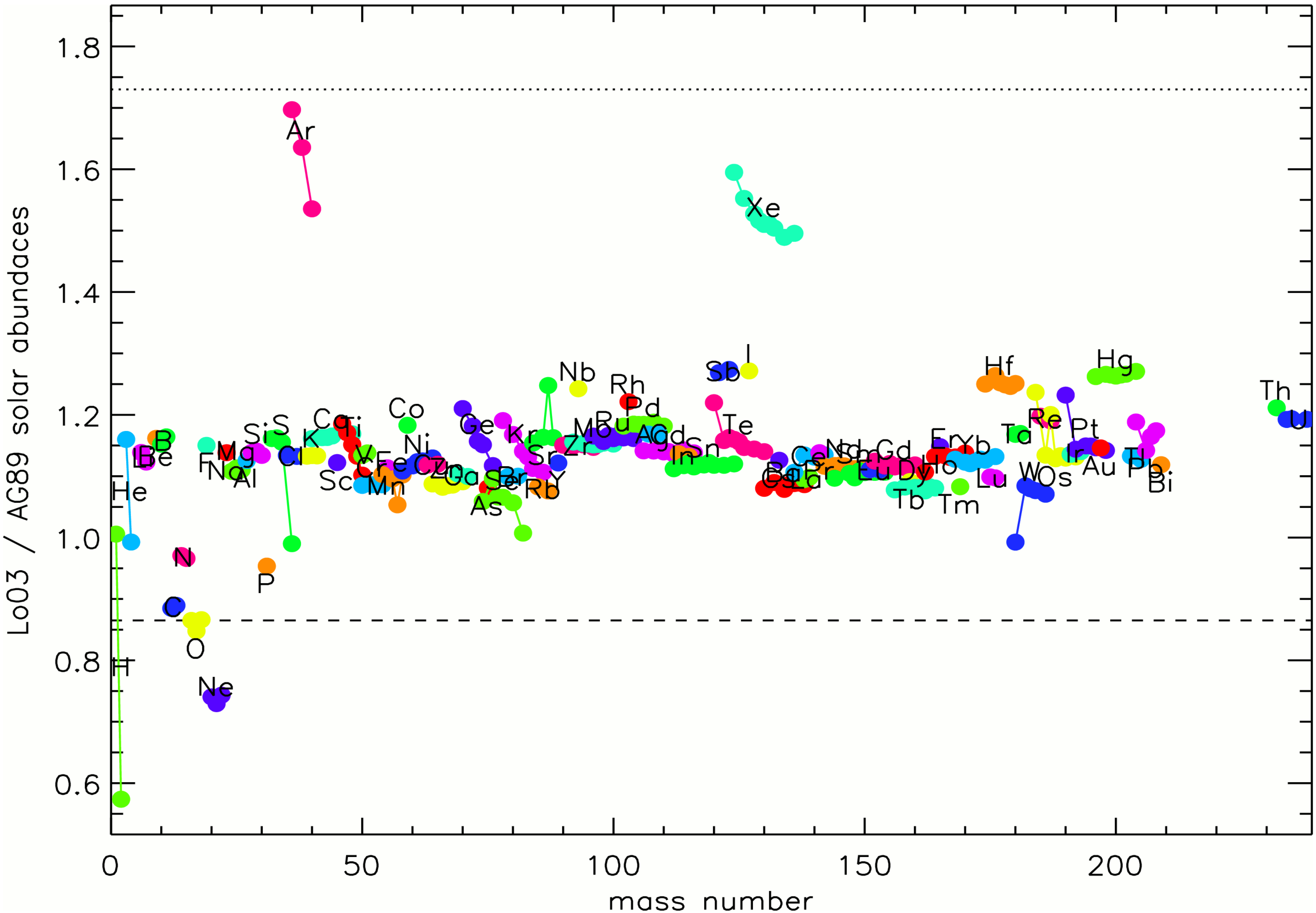
Rotation

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.

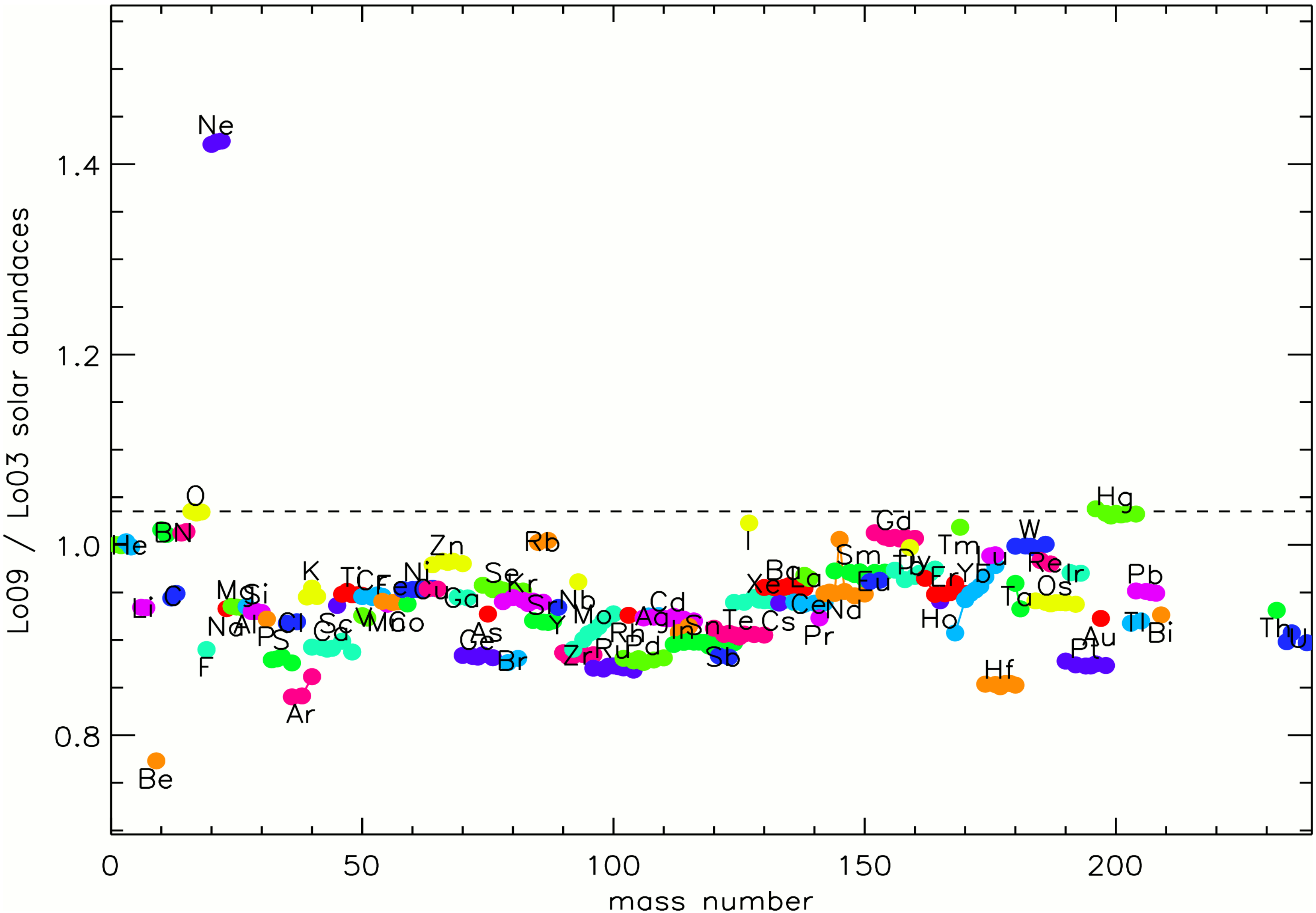
(Yoon & Langer 2006)

Sun 2.0



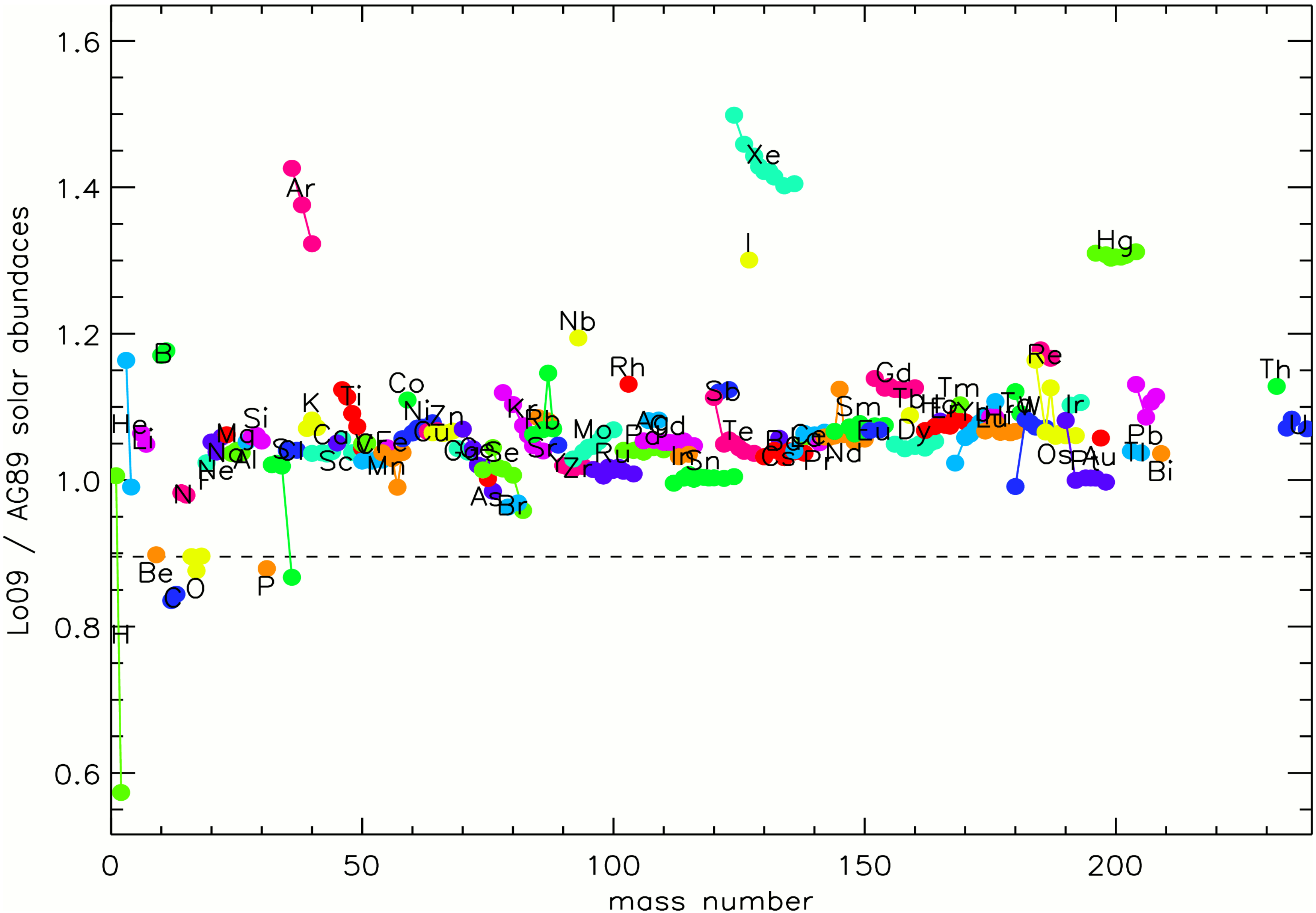
Lo03 / AG89 solar abundaces
mass number
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0
50
100
150
200
Ar
Xe
Nb
Rh
Pd
Sb
I
Te
Hf
Hg
Th
U
Co
Ni
Ge
Kr
Sr
Mo
Ru
Ag
Cd
In
Sn
Ce
Nd
Sm
Gd
Er
Yb
Ta
Re
Pt
Ir
Au
Tl
Pb
Bi
W
Os
Lu
Tm
Tb
Ho
Dy
Eu
Pr
La
Cs
Ba
Rb
Y
Zr
As
Se
Br
Ga
Zn
Cu
Fe
Mn
Cr
V
Ti
Ca
K
Sc
Cl
S
Si
P
Al
Mg
Na
F
N
O
C
Ne
He
H
B
Be

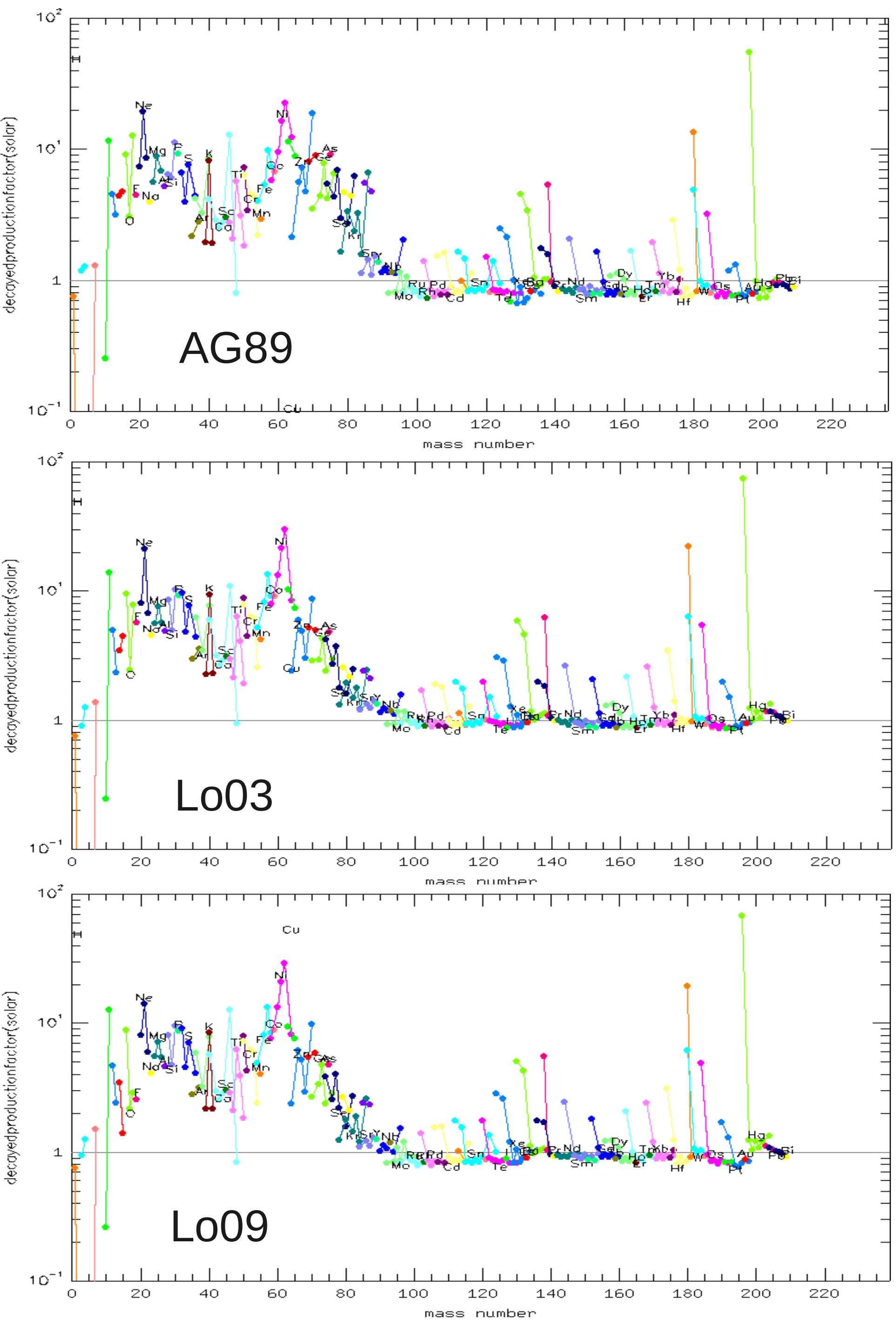
Sun 3.0



Lo09 / Lo03 solar abundaces
mass number
0.8
1.0
1.2
1.4
0
50
100
150
200
Ne
O
Hg
Gd
Be
Ar
Hf

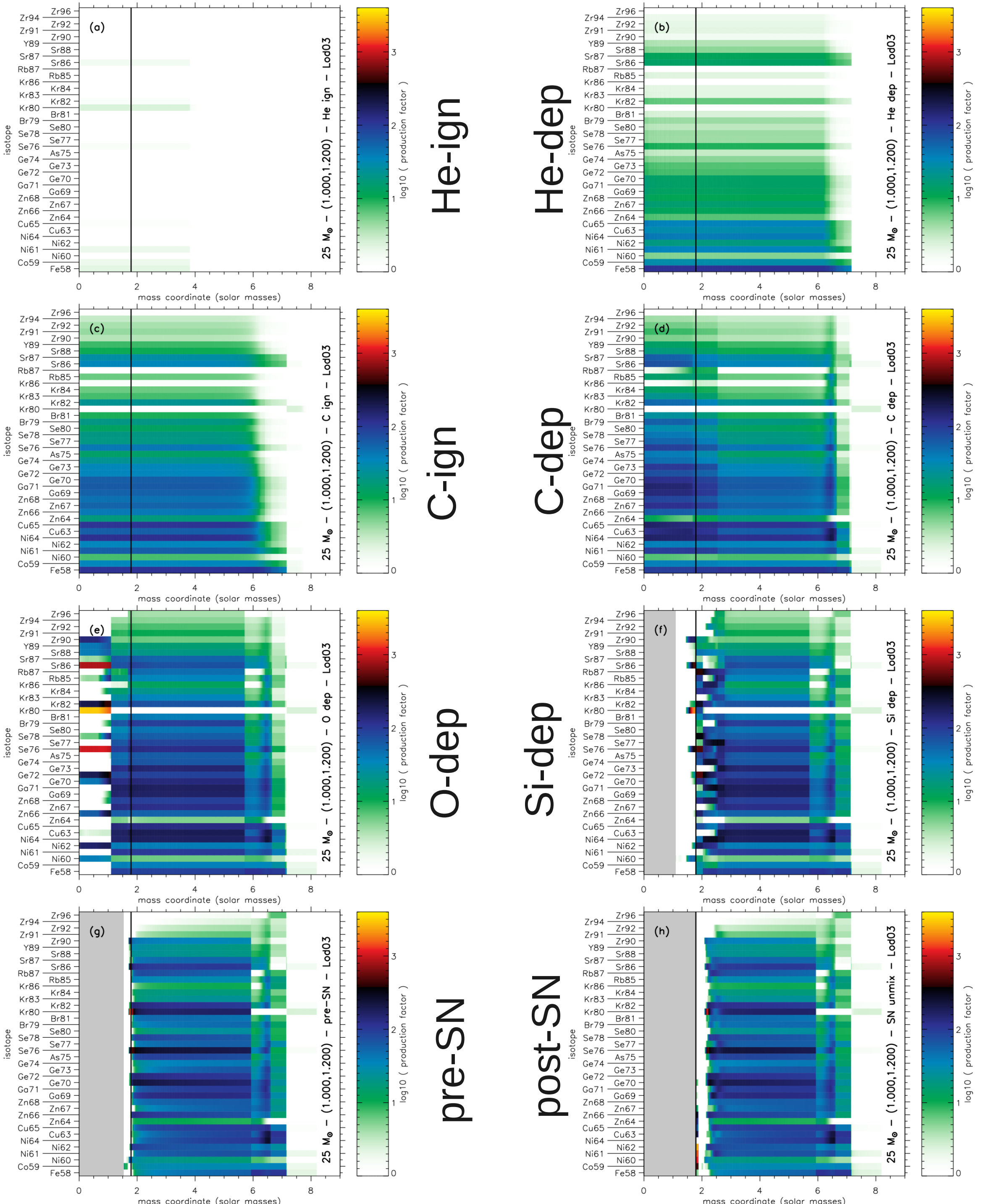
Sun 3.0





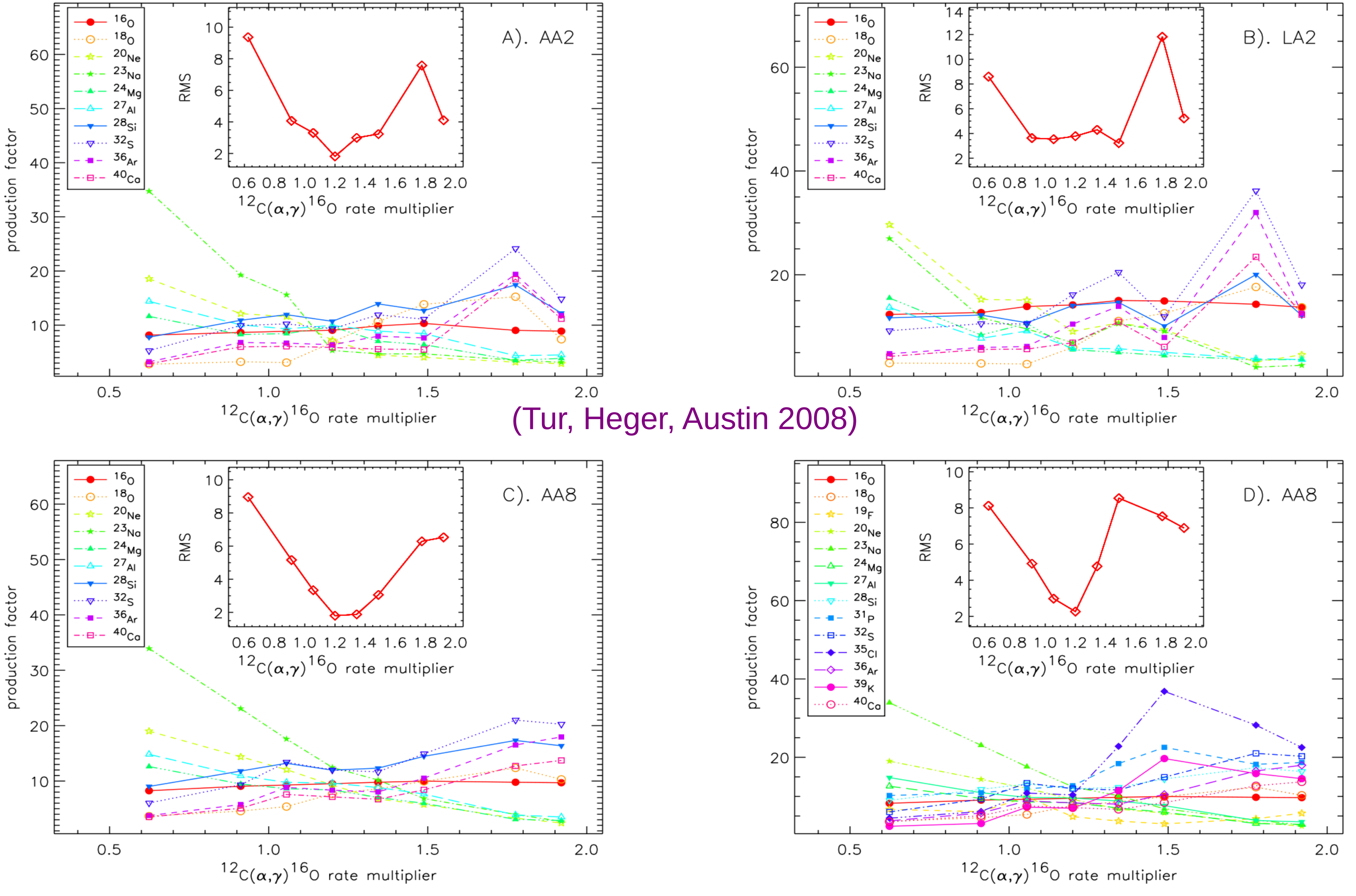
15 solar mass star yields for different initial abundances

- **over-all pattern remains remarkably consistent**
- **but details details in weak s-process pattern do exists**
- sensitivity to nuclear reaction rates and model physics can be well established for ***specific*** stellar models



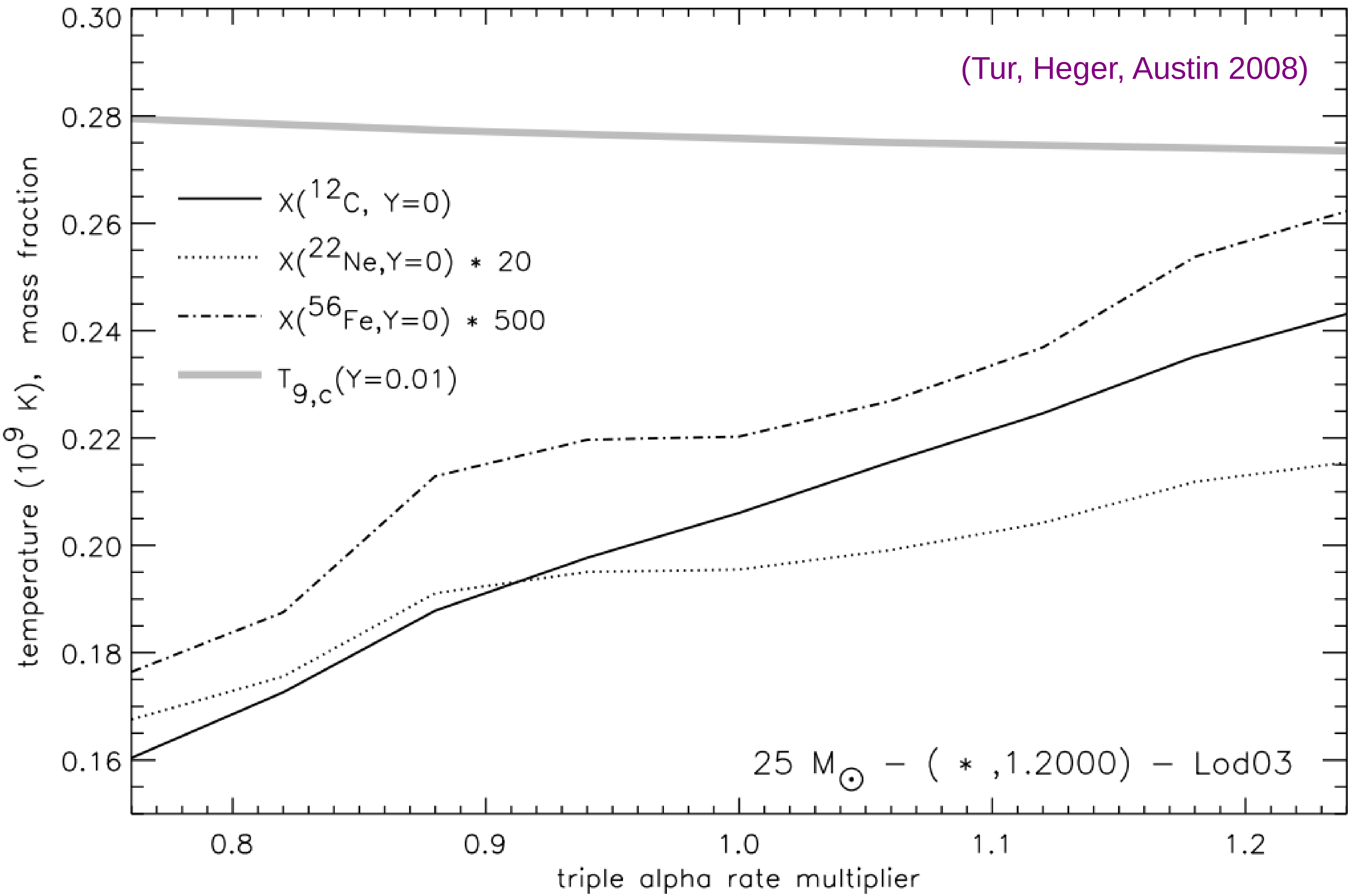
25 solar mass star s-process yields for different evolution stages

Light Isotope Yields - $^{12}C(\alpha,\gamma)^{16}O$

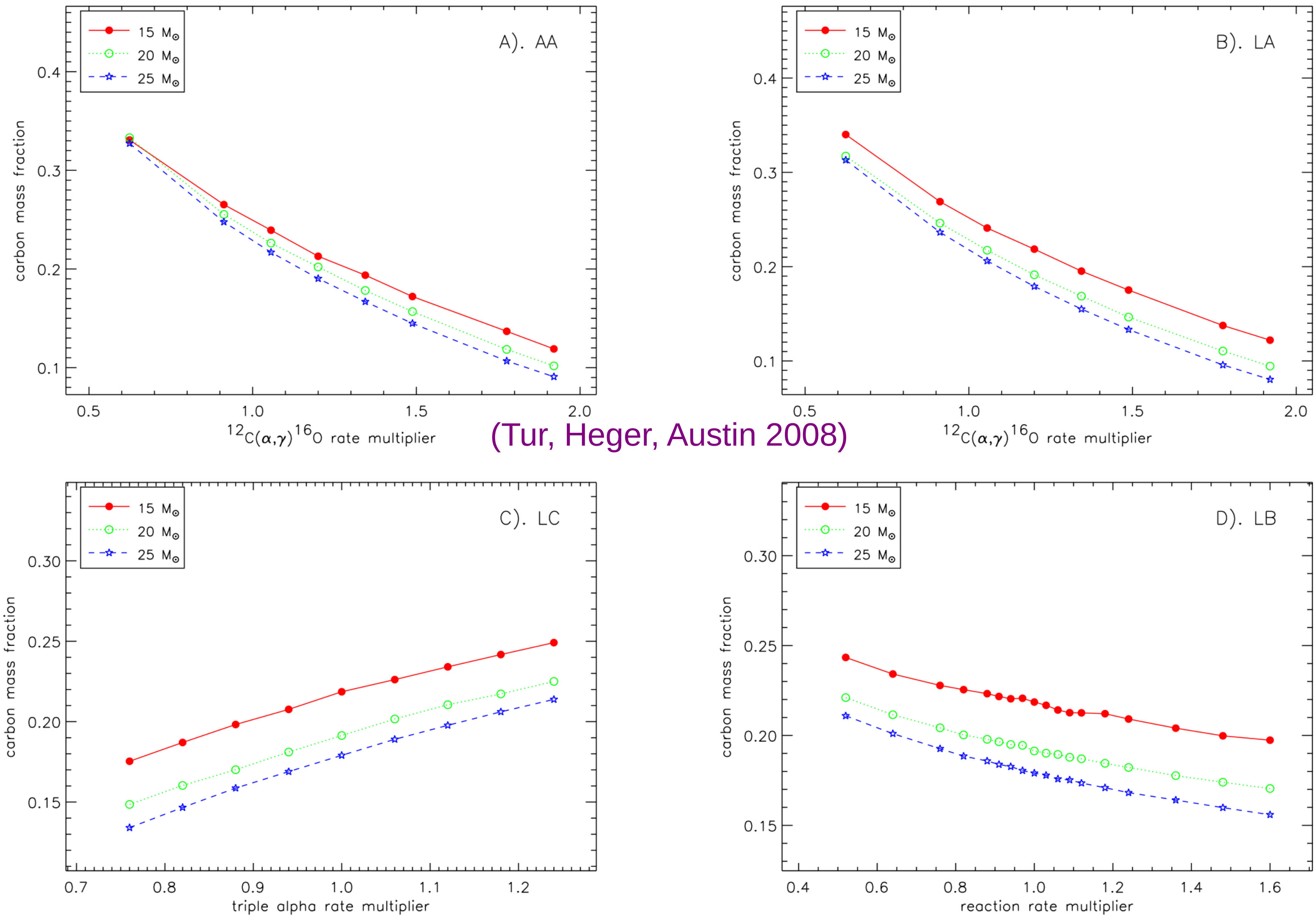


(Tur, Heger, Austin 2008)

25 solar mass star: central values

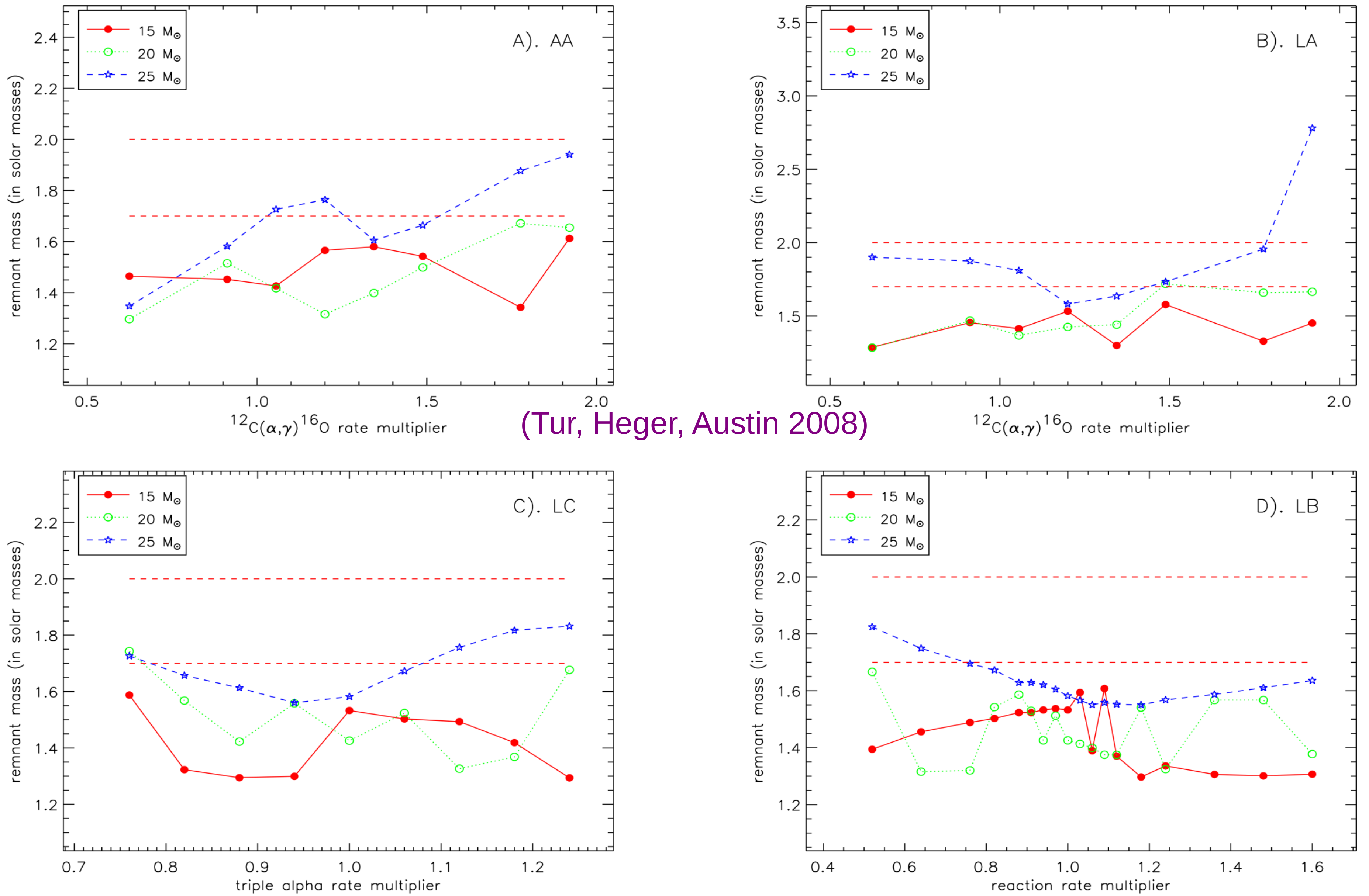


Central Carbon Mass Fraction



(Tur, Heger, Austin 2008)

Remnant Masses – NS or BH?



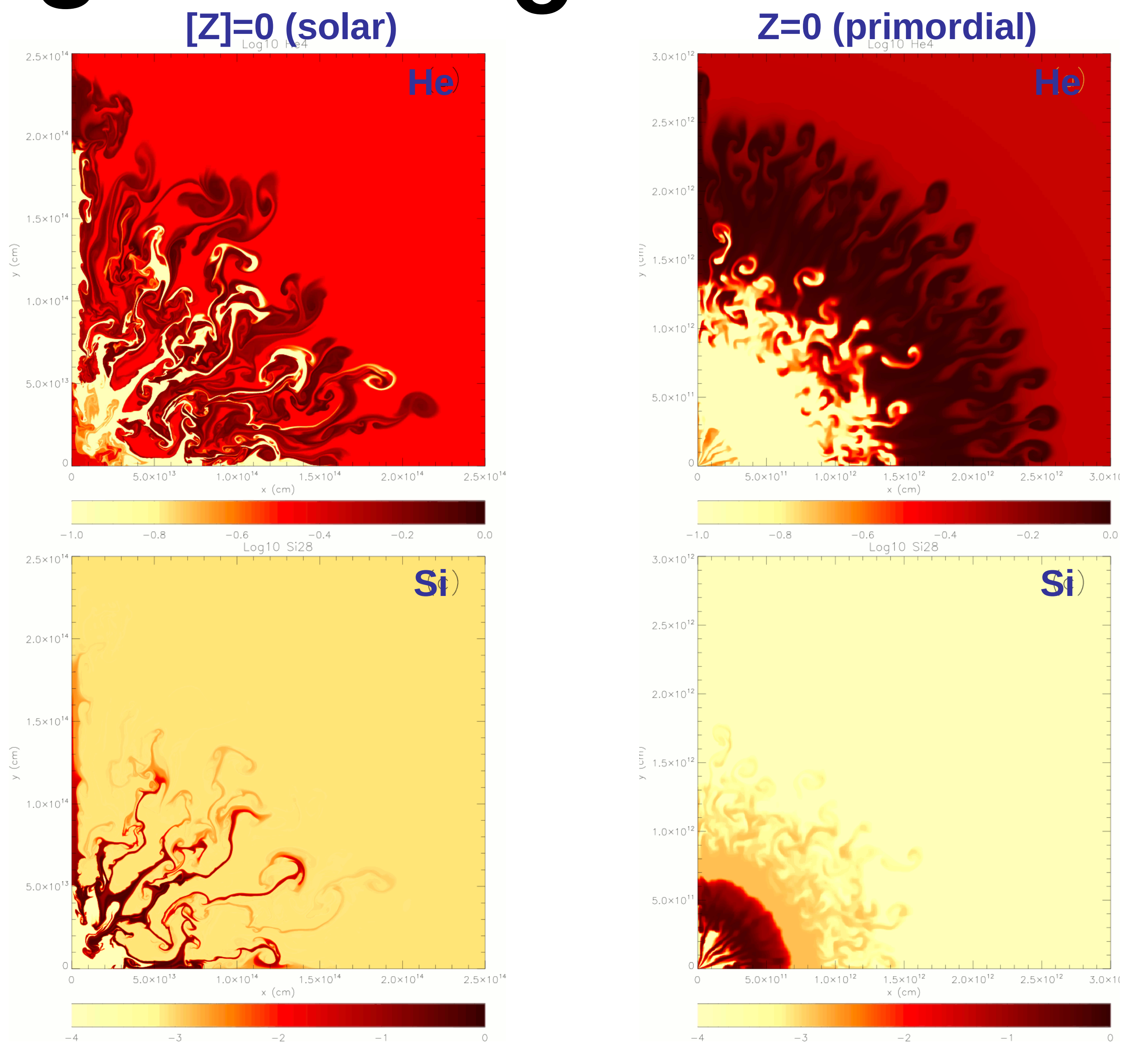
(Tur, Heger, Austin 2008)

Mixing in 25 $M_\odot$ Stars

Growth of Rayleigh-Taylor instabilities

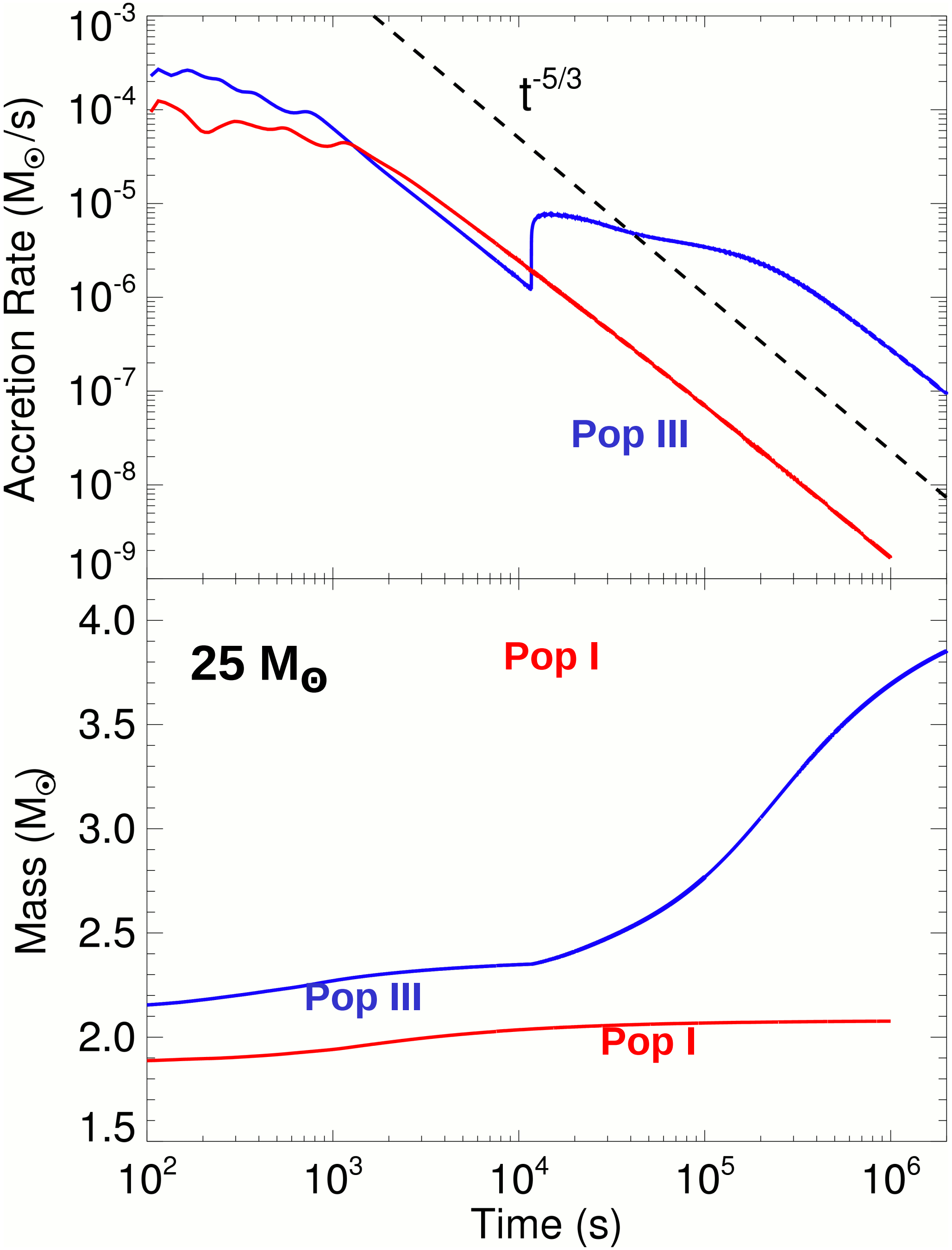
Interaction of instabilities (mixing) and fallback determines nucleosynthesis yields

➔ Pop III stars show much less mixing than modern Pop I stars due to their compact hydrogen envelope



Simulations: Candace Joggerst (UCSC/LANL T-2)

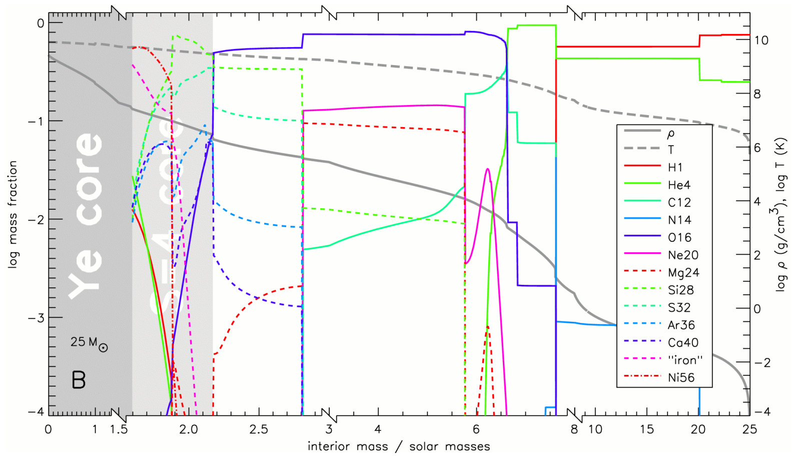
Fallback and Remnants



➔ **Pop III stars show much more fallback than modern Pop I stars due to their compact hydrogen envelope**

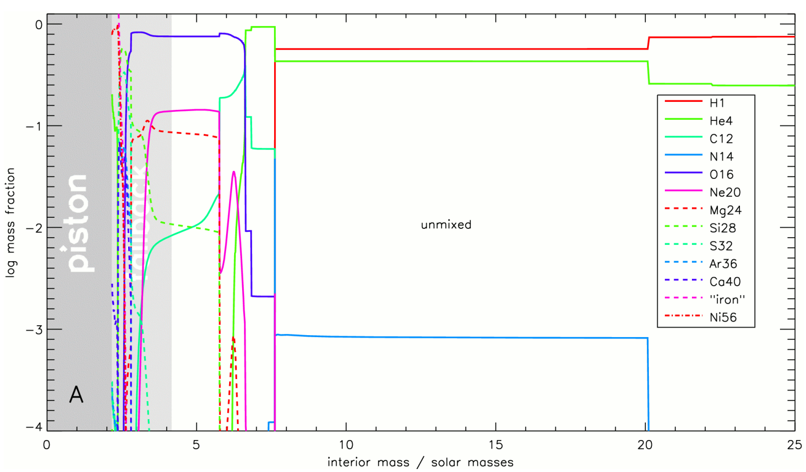
(Zhang, Woosley, Heger 2007)

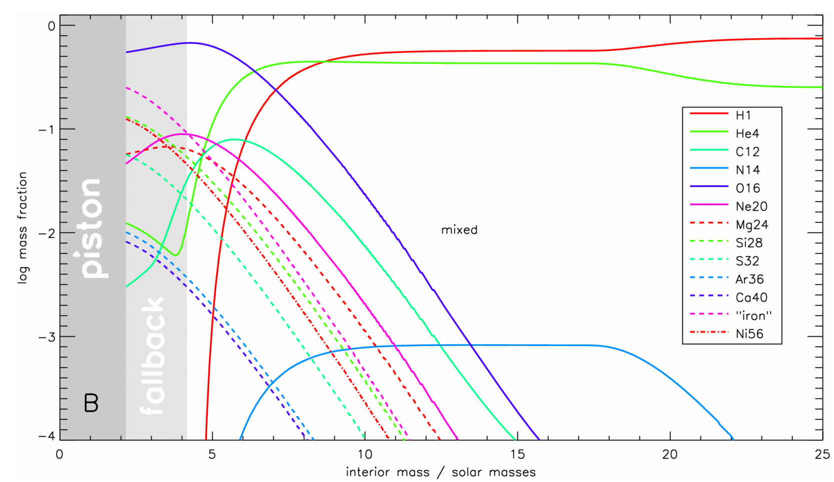
Supernovae, Nucleosynthesis, & Mixing



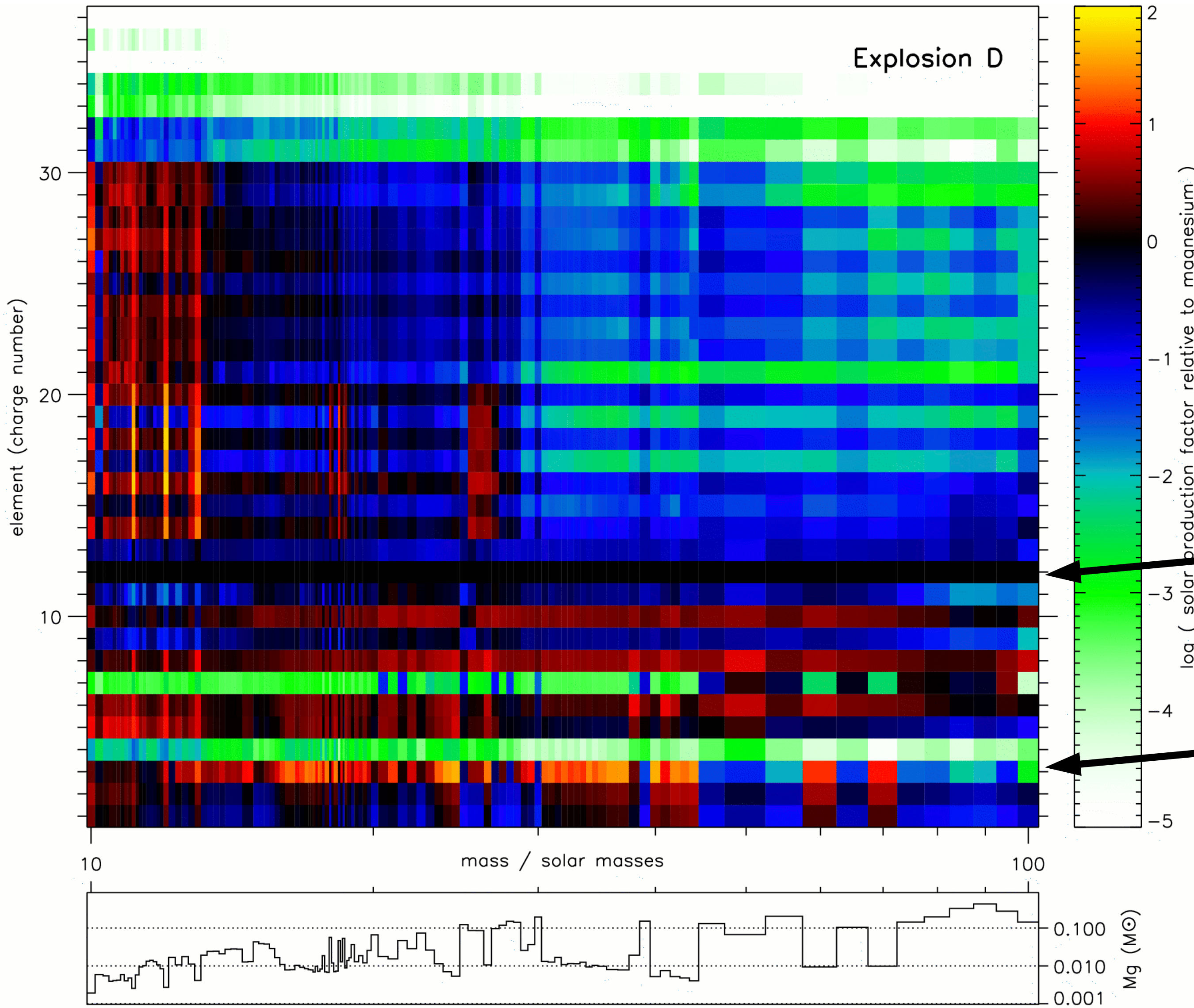
SN, no mixing

SN + mixing





Pop III Nucleosynthesis



Mg yield (ejecta mass fraction)

Elemental Yields as a function of initial mass

non-rotating stars

120 stellar masses

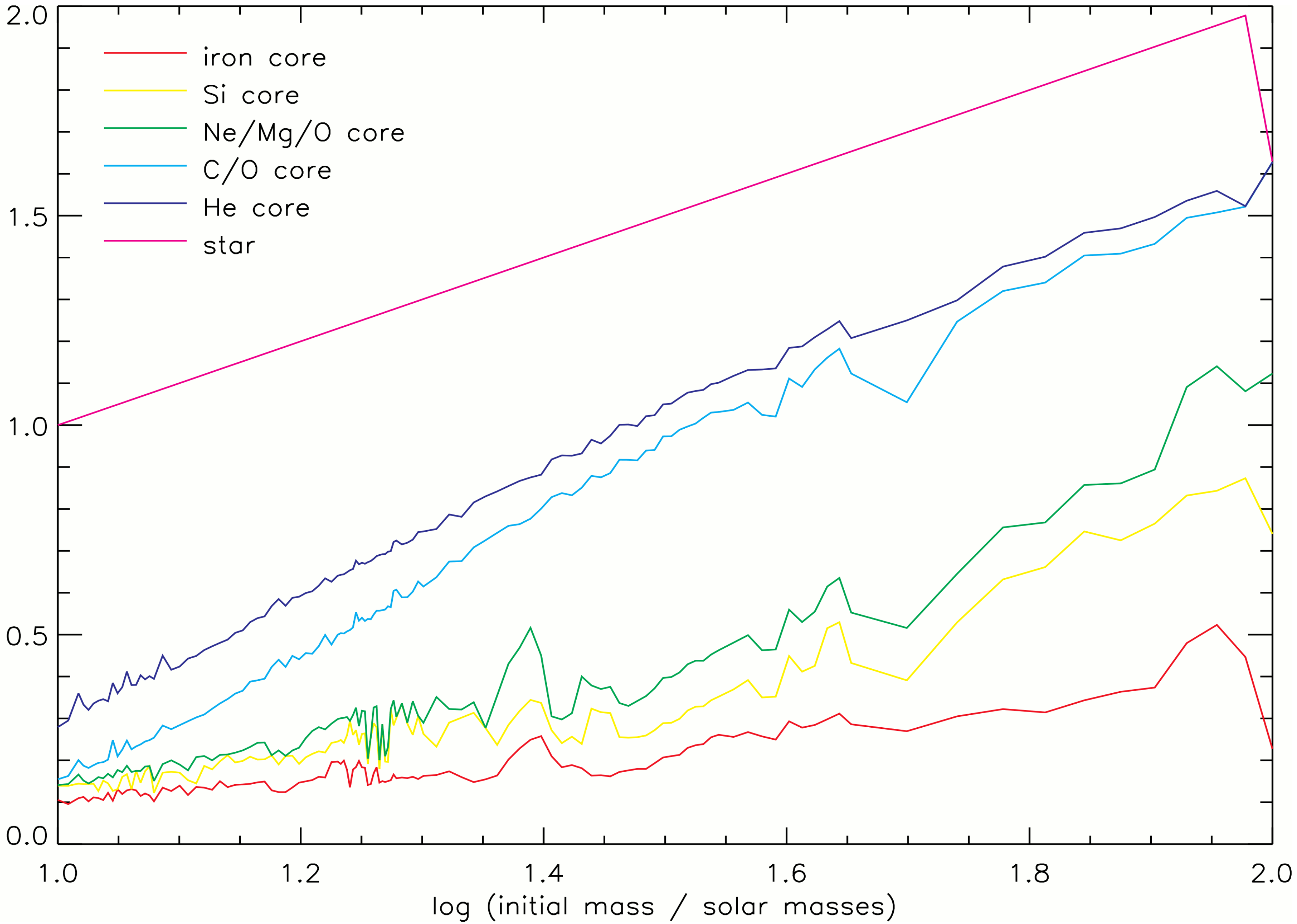
"complete" reaction network

normalized to Mg

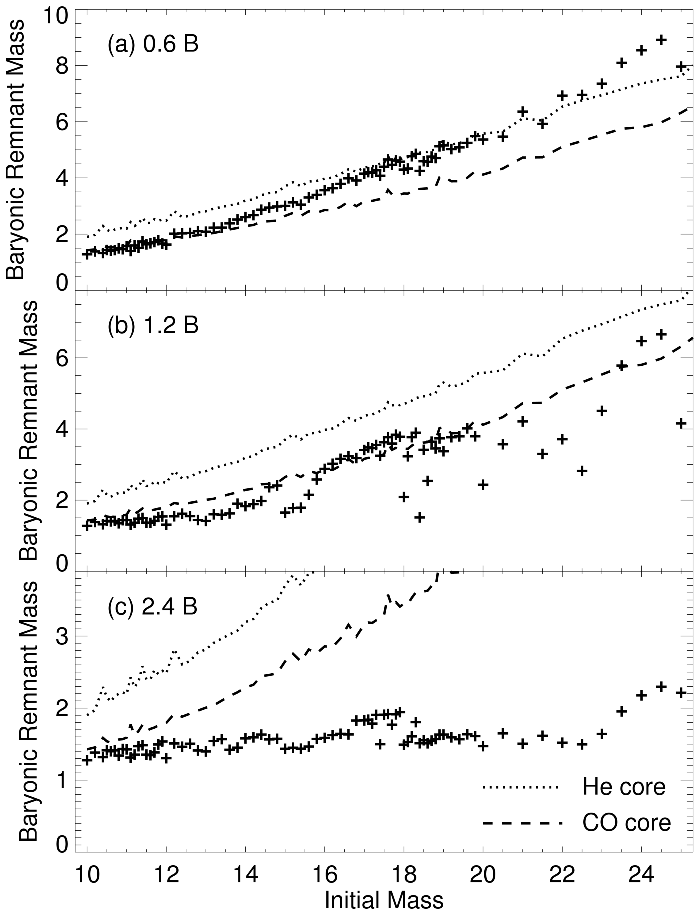
RESULTS:
e.g.,
Production of ^{7}Li by neutrino interaction in very compact stellar envelope!

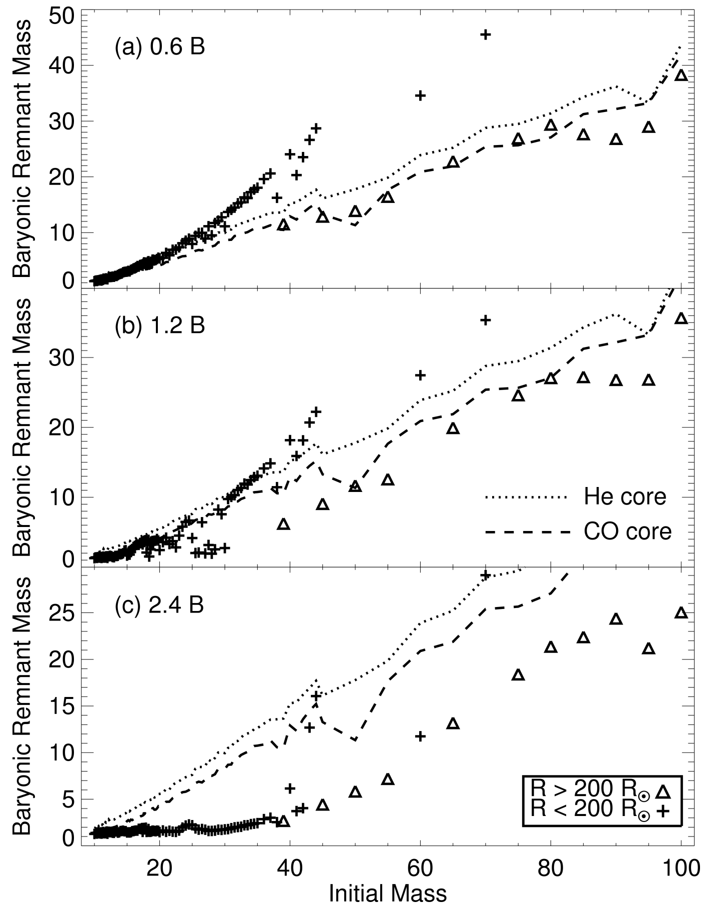
Heger & Woosley, in prep., (2010)

Pop III Star Core Masses



Pop III Stars

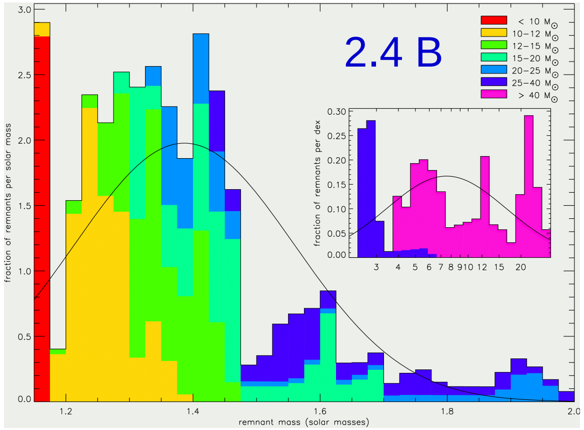


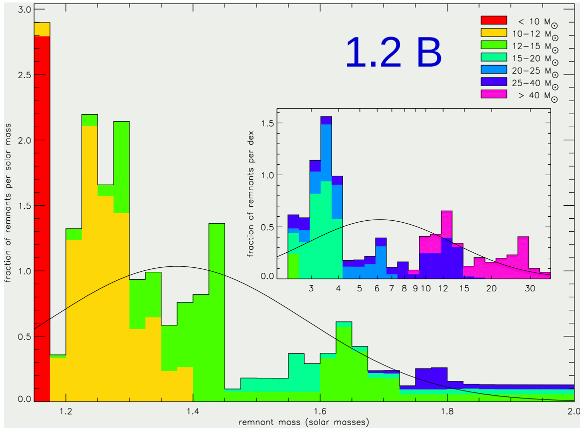


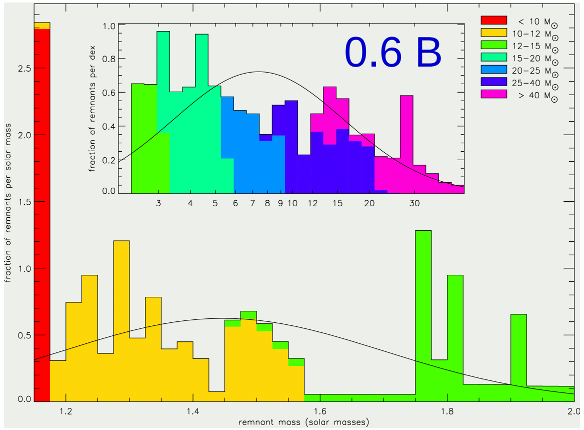
Much fallback for compact stars ("+")

Less fallback for RSG ("Δ")

(Zhang, Woosley, Heger 2007)

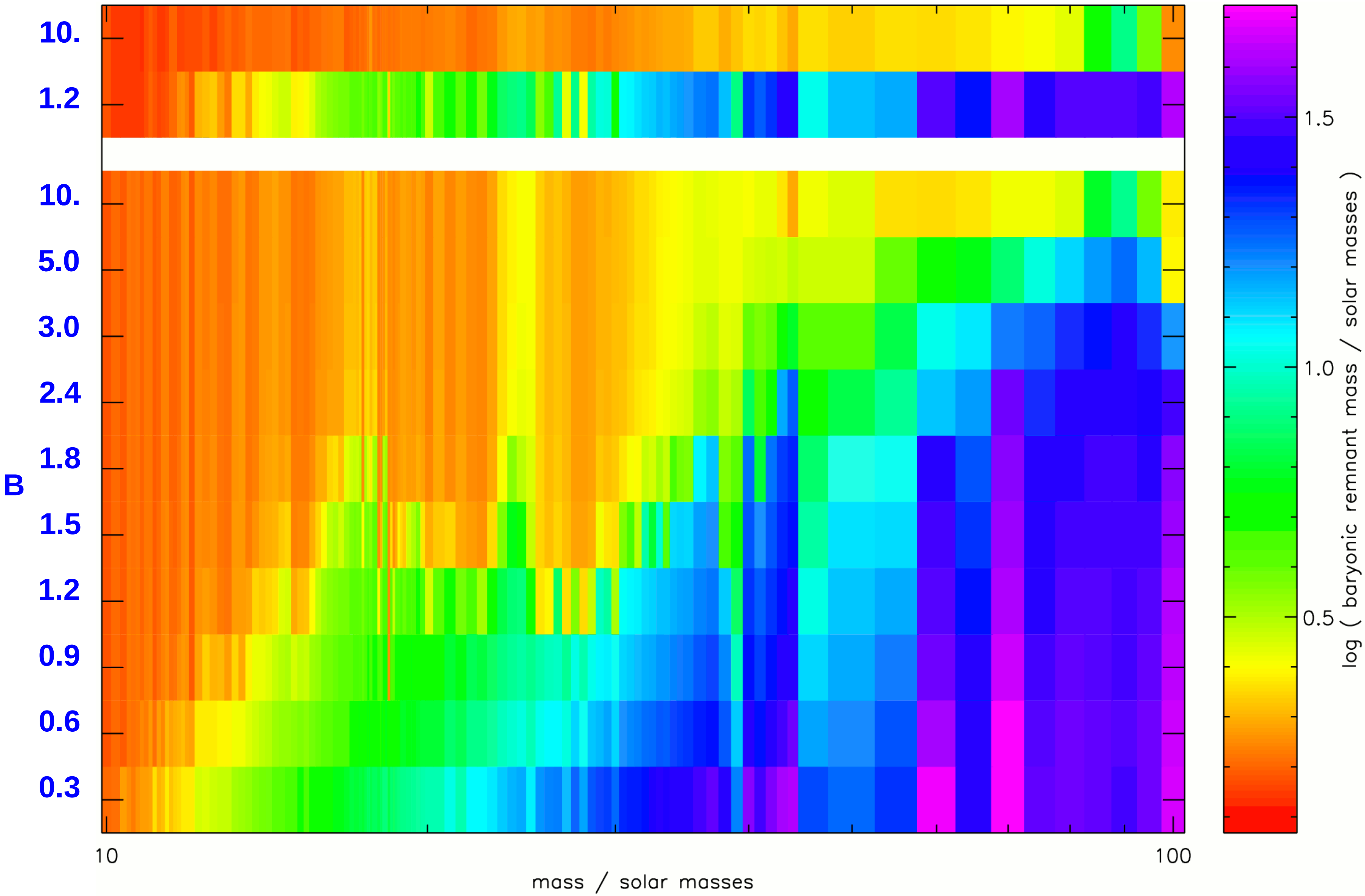


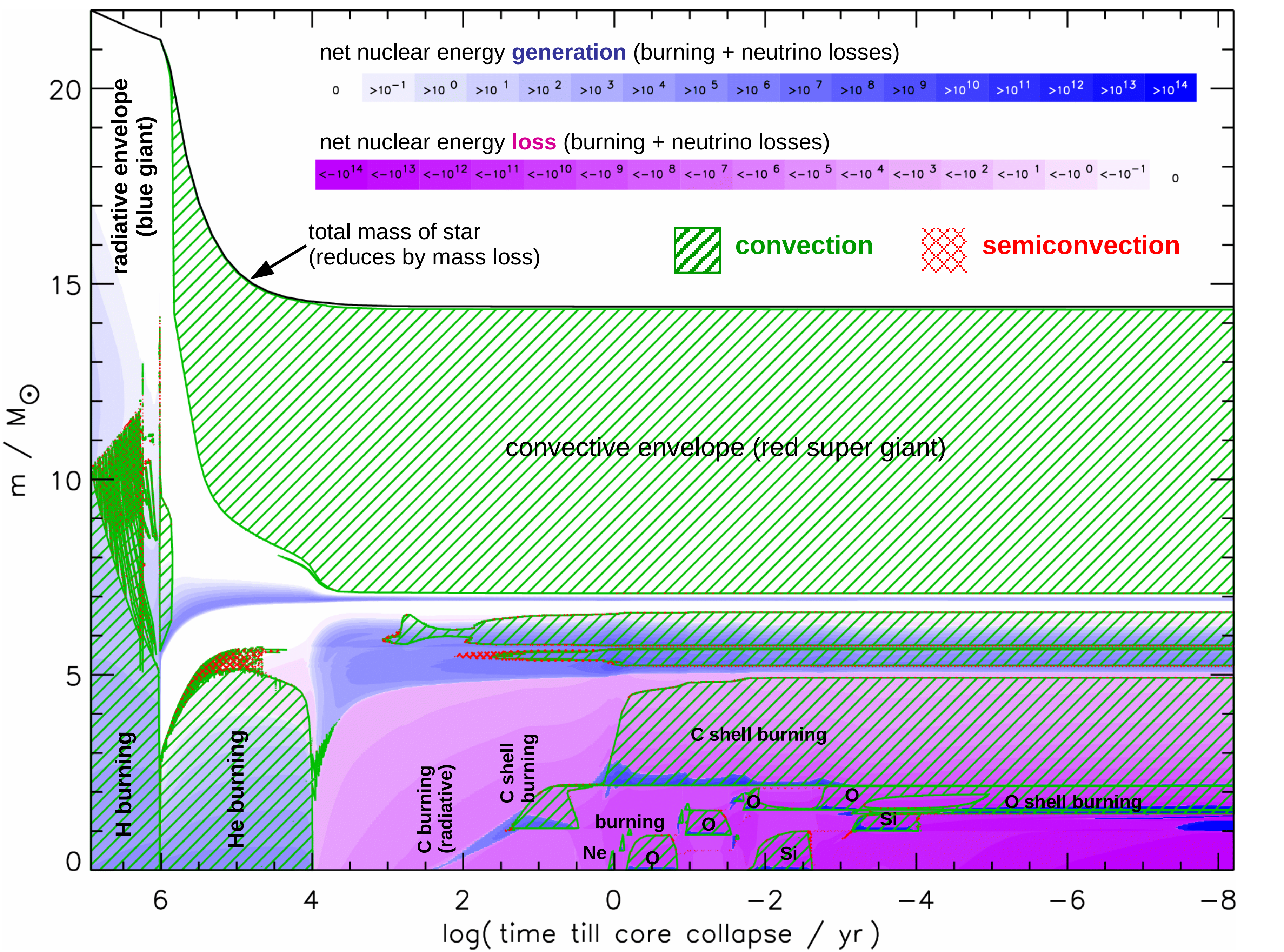




Pop III Star Remnant Masses

(from Zhang, Woosley, Heger 2007)





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net nuclear energy loss (burning + neutrino losses)
<−10^14 <−10^13 <−10^12 <−10^11 <−10^10 <−10^9 <−10^8 <−10^7 <−10^6 <−10^5 <−10^4 <−10^3 <−10^2 <−10^1 <−10^0 <−10^−1 0
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H burning
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C burning
(radiative)
C shell
burning
C shell burning
Ne
burning
O
O
O
O
Si
Si
O shell burning
m / M⊙
log(time till core collapse / yr)

Summary

- **Uncertainties** in stellar and supernova physics (and variations of author's choices) limit association of progenitor mass and supernova and remnant.
- **Outcome** of stellar evolution is not “smooth” – due to physics of shell burning – not even with ideal numerical implementation & physics
- **Degeneracy** of unknown initial parameters – rotation, composition, binarity.
- Stellar and supernova “*weather*”?