International School of Particle & Nuclear Physics, Erice, Sicily, Italy, September 17, 2010

Evolution of Massive Stars

Alexander Heger
Stan Woosley
Rob Hoffman
Candace Joggerst
Weiqun Zhang

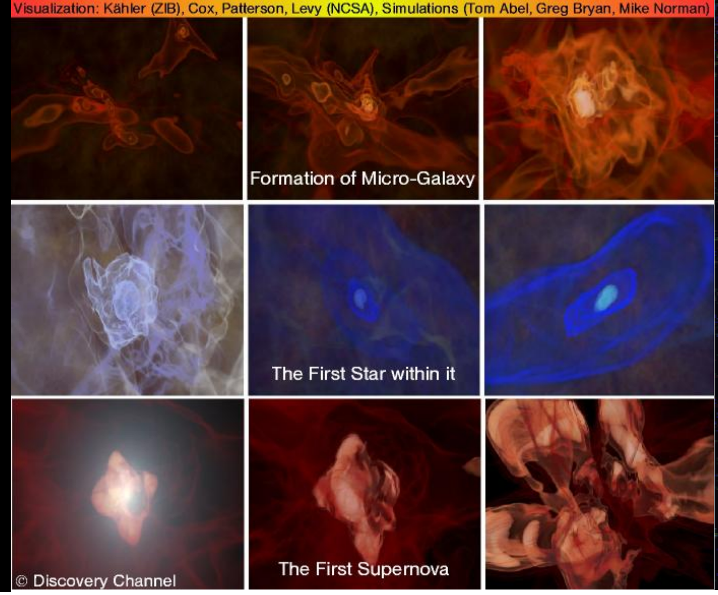
Overview

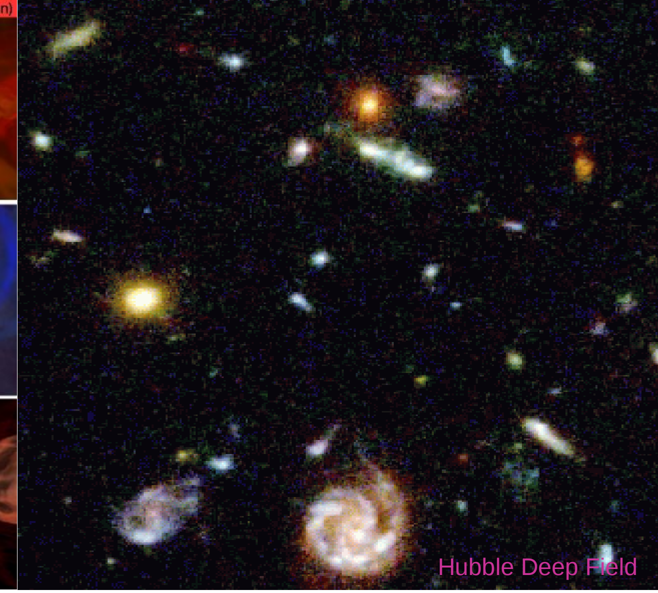
- Presupernova Evolution
- Varieties of Stellar Deaths
- Uncertianties
- Nucleosynthesis

Cosmic Dark Age

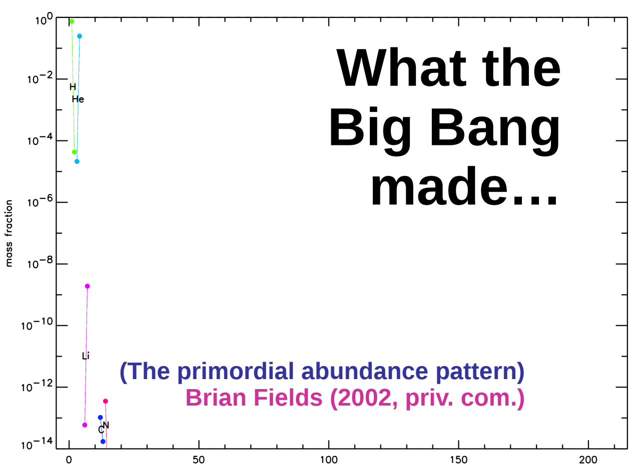
(after recombination)

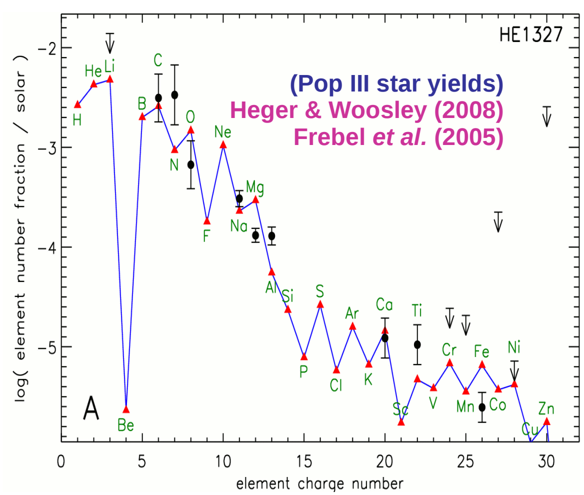
© Alexander Heger

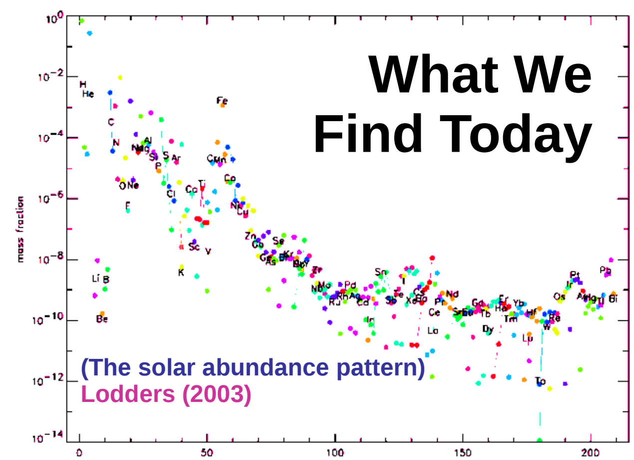




time

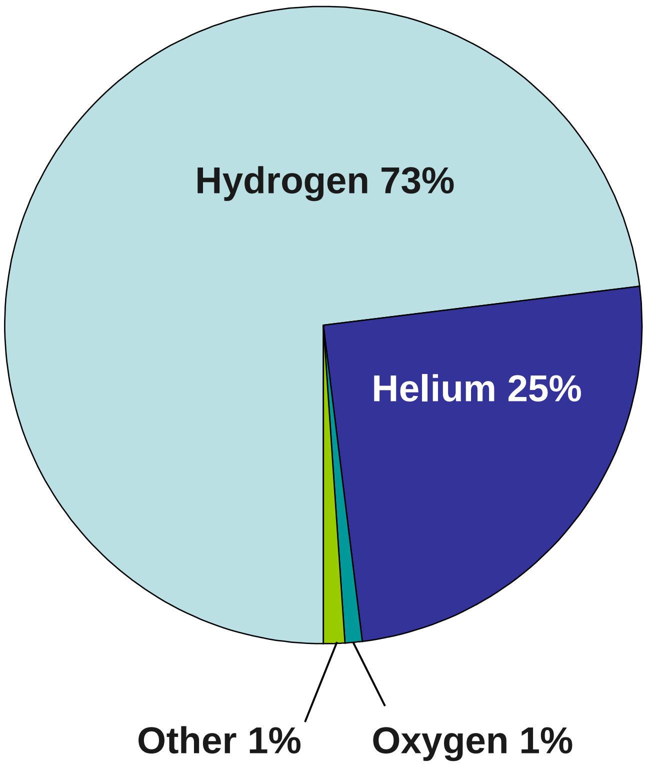




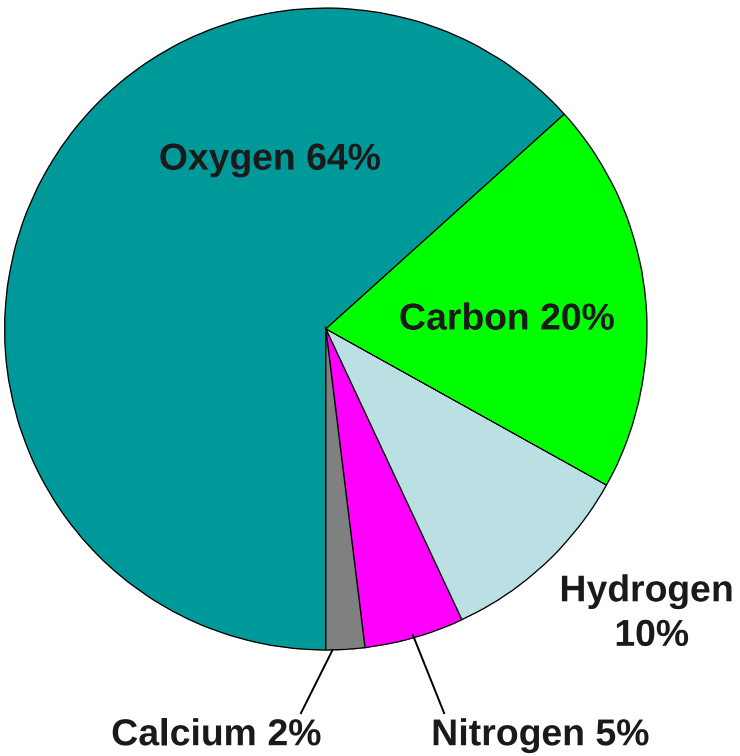


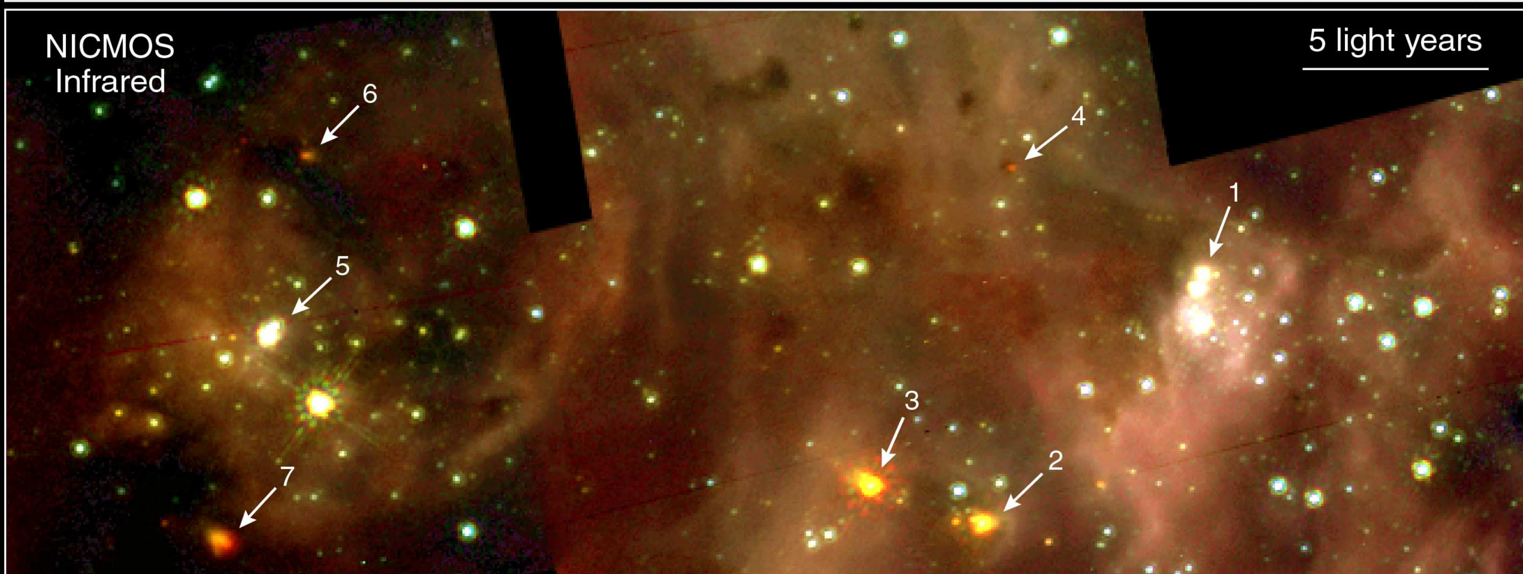
Abundance by Weight

Universe



Humans



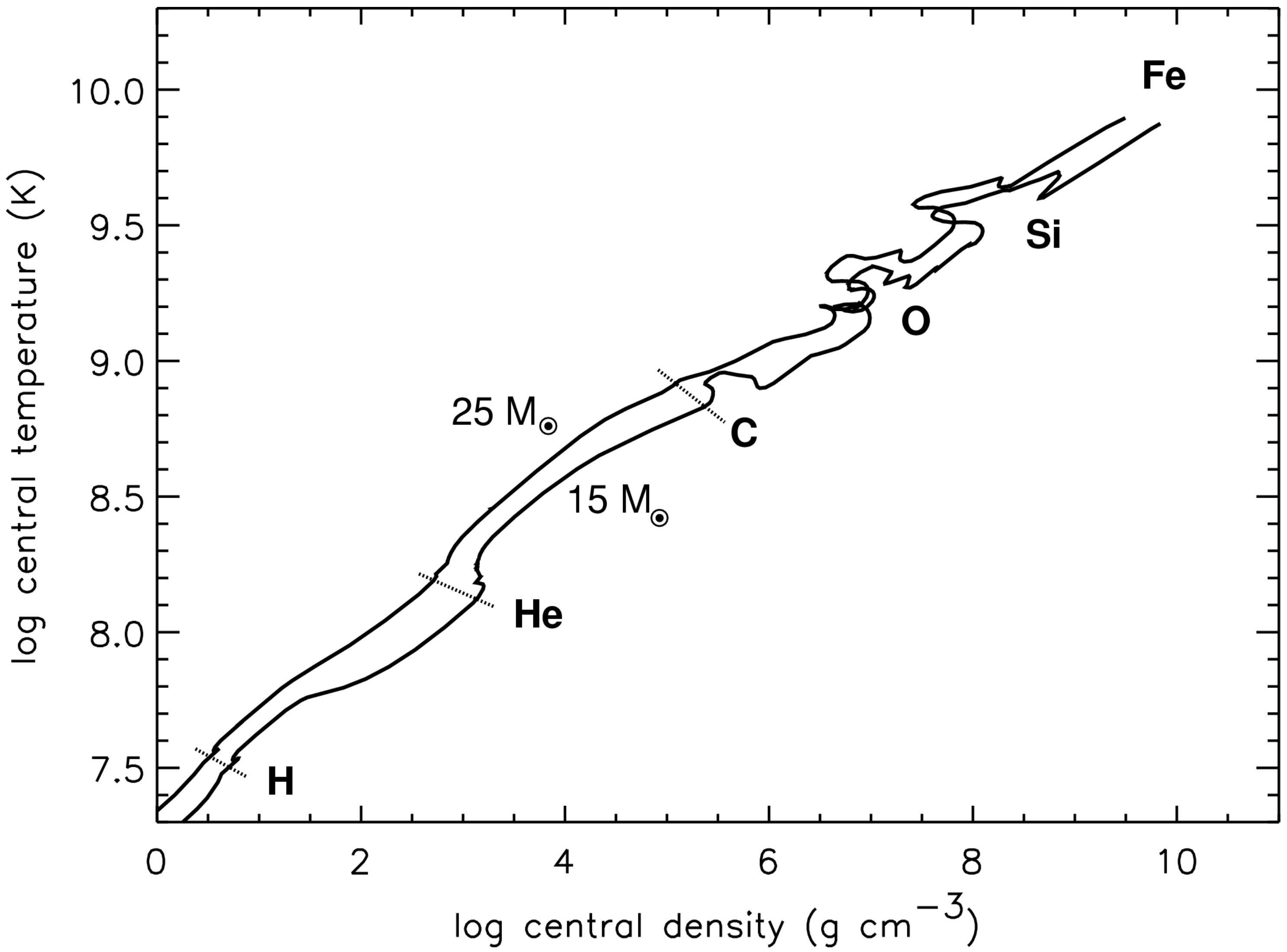


30 Doradus Details

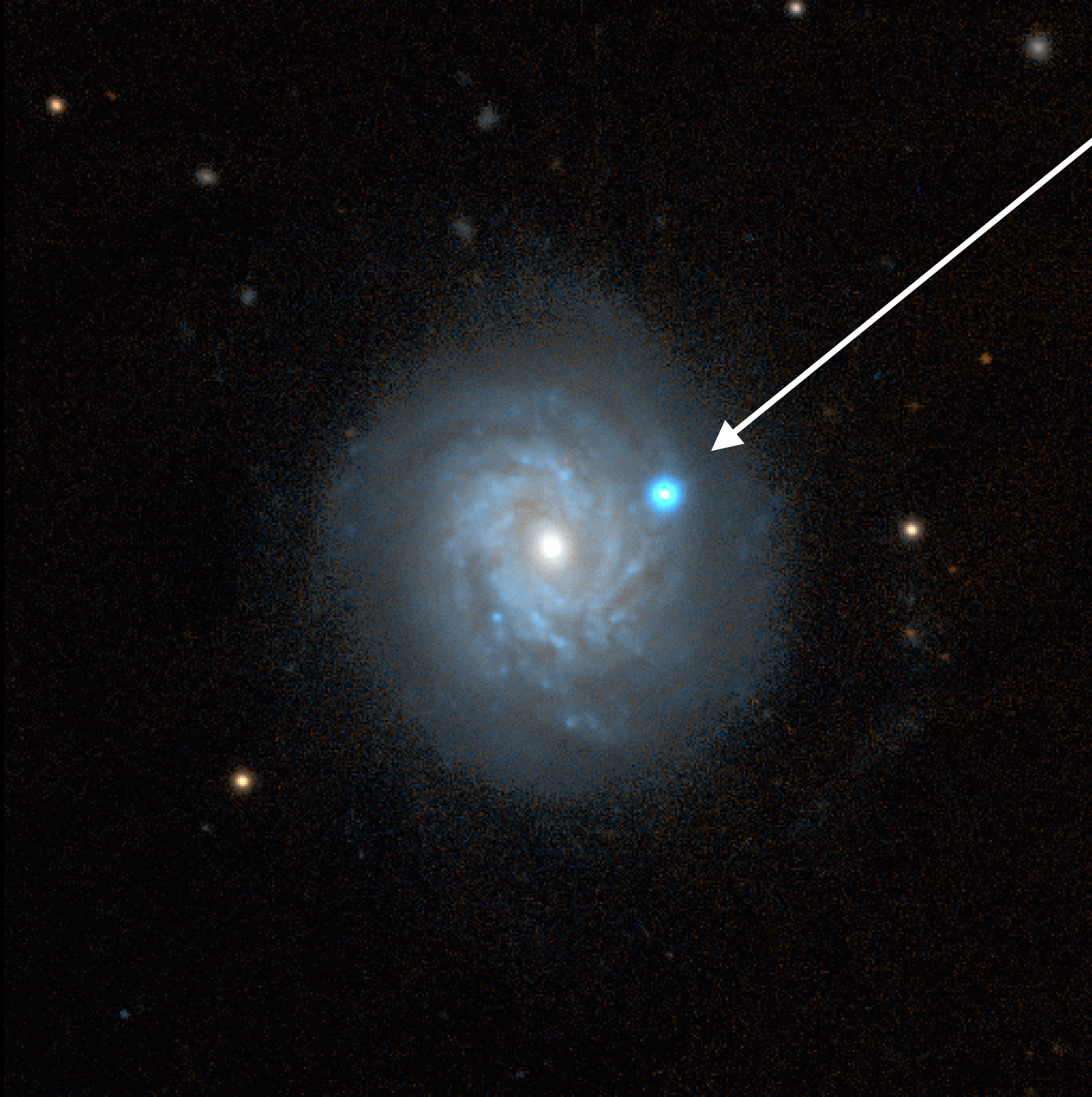
Hubble Space Telescope • WFPC2 • NICMOS

PRC99-33b • STScI OPO • N. Walborn (STScI), R. Barbá (La Plata Observatory) and NASA

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



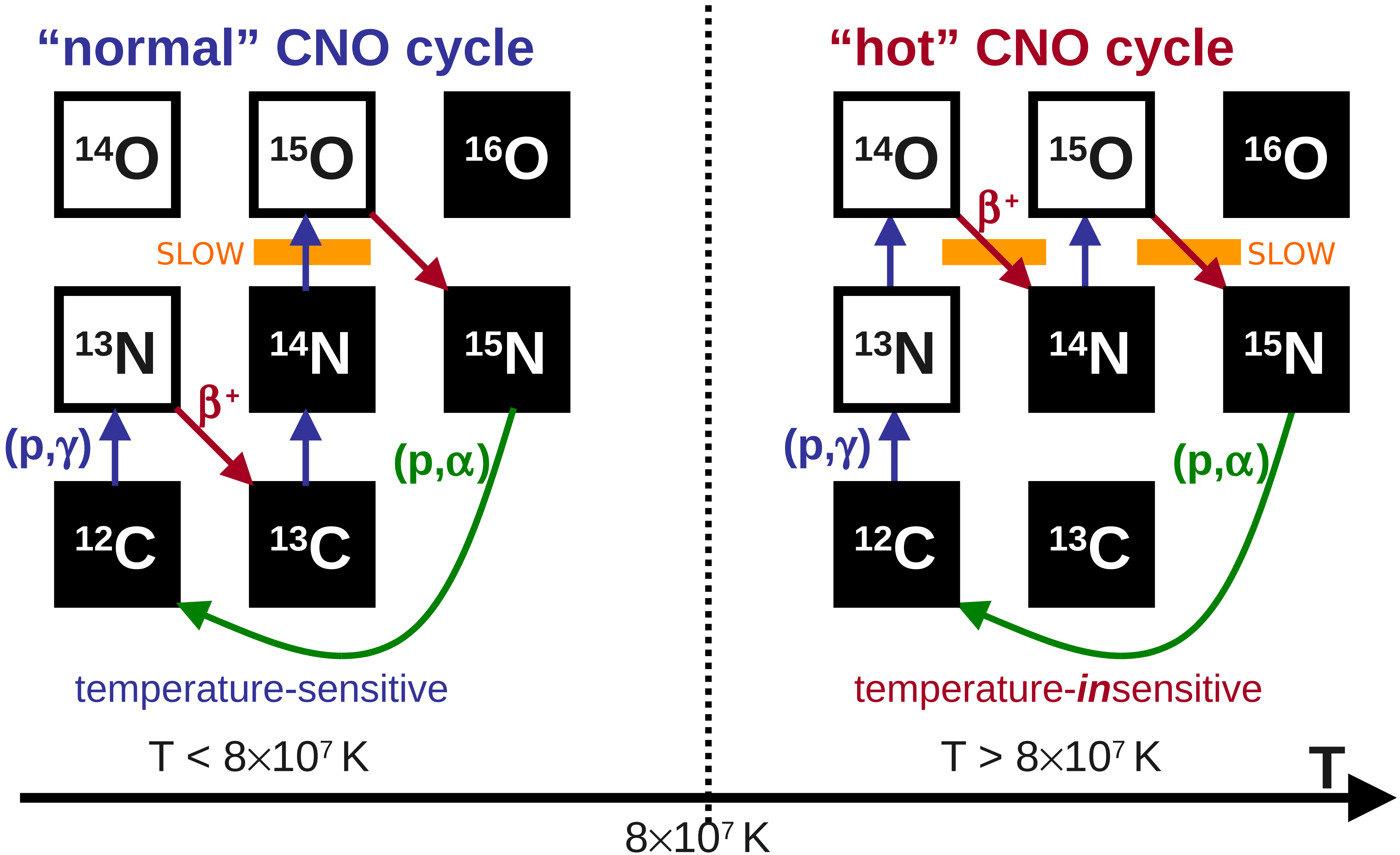
NGC3982

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	$^{28}Si(\gamma,\alpha)$…

Hydrogen Burning by CNO Cycle



Neutrino losses from electron/positron pair annihilation

- Important for carbon burning and beyond

- For T>10^9 K (about 100 keV), occasionally:

  $\gamma \rightarrow e^+ + e^-$

  and usually

  $e^+ + e^- \rightarrow 2\gamma$

  but sometimes

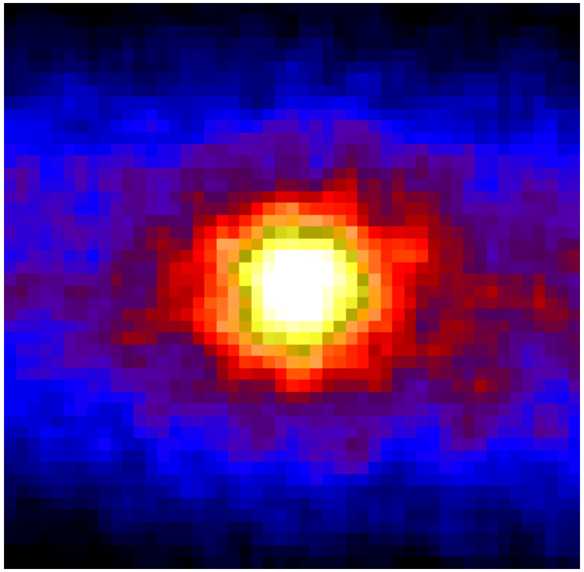
  $e^+ + e^- \rightarrow \overline{\nu}_e + \nu_e$

- The neutrinos exit the stars at the speed of light while the e^+, e^-, and the γ's all stay trapped.

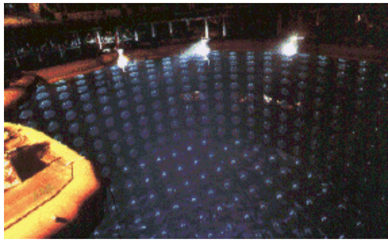
- This is an important energy loss with

  $\varepsilon_\nu \approx -10^{15}\ (T/10^9 K)^9$ erg g^{-1} s^{-1}

- For carbon burning and beyond, each burning stage gives about the same energy per nucleon, thus the lifetime goes down as T^{-9}



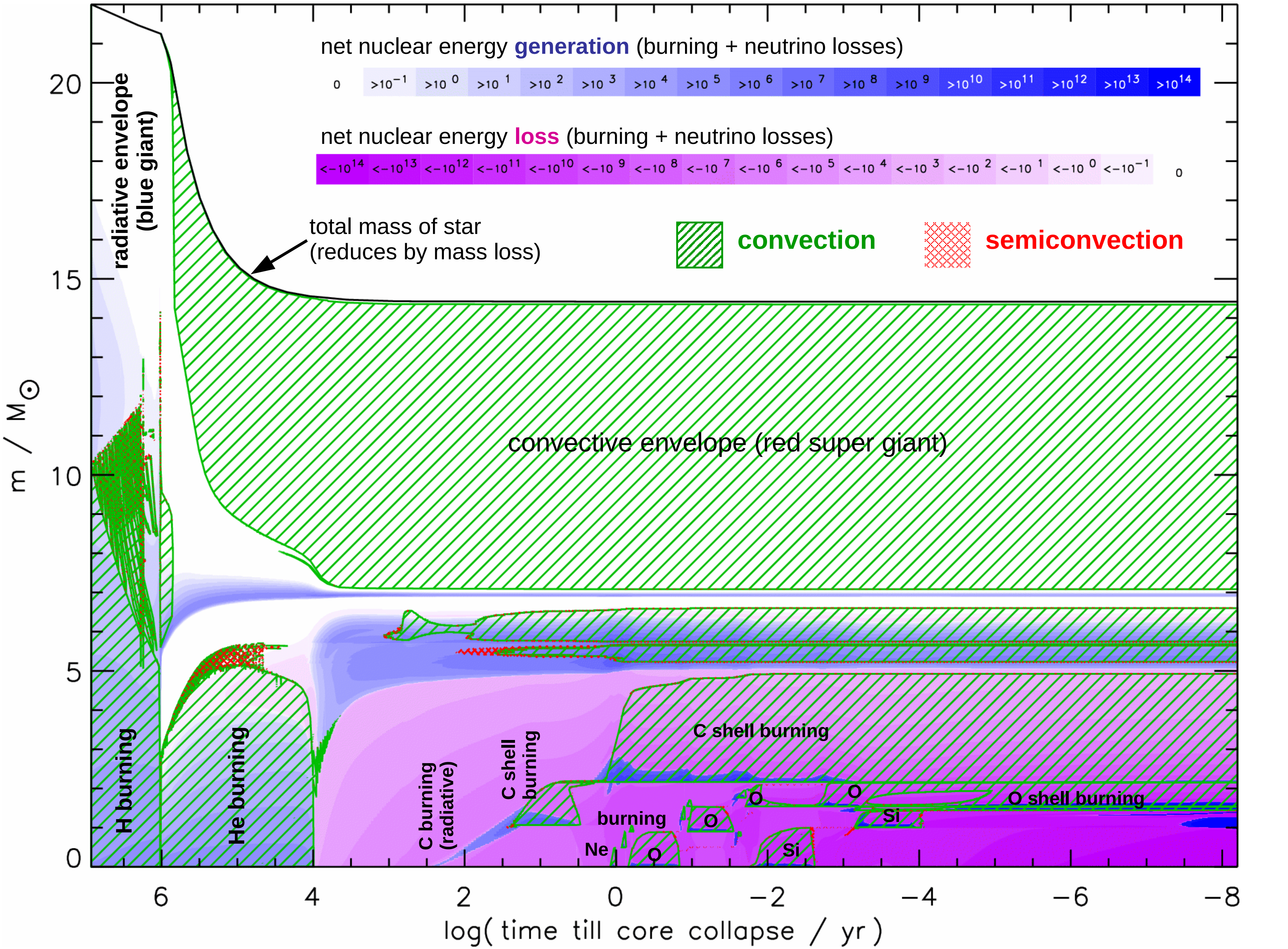
The sun as seen by Kamiokande



Nitrogen Burning

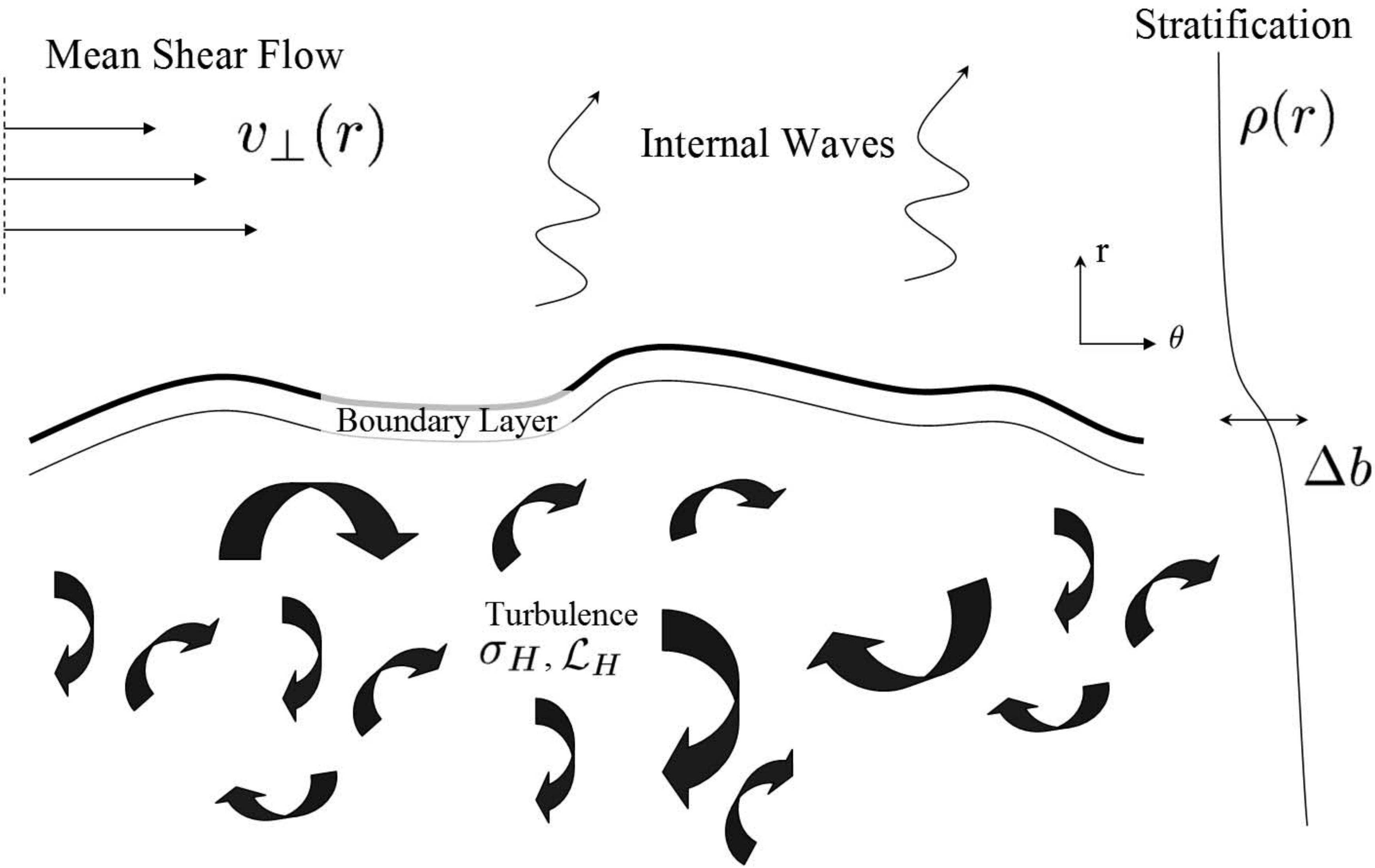
$$^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu_{e})^{18}O(\alpha,\gamma)^{22}Ne$$

- ^{14}N is made as slowest reactant in CNO cycle
- It is made from initial metals, not as a primary product
- Depending on metallicity, the abundance can be come significant; it will be more important for more metal-rich stars.
- ^{14}N burning occurs at the onset – before – central helium burning and can have its own convective burning phase, take a few % of helium burning time.



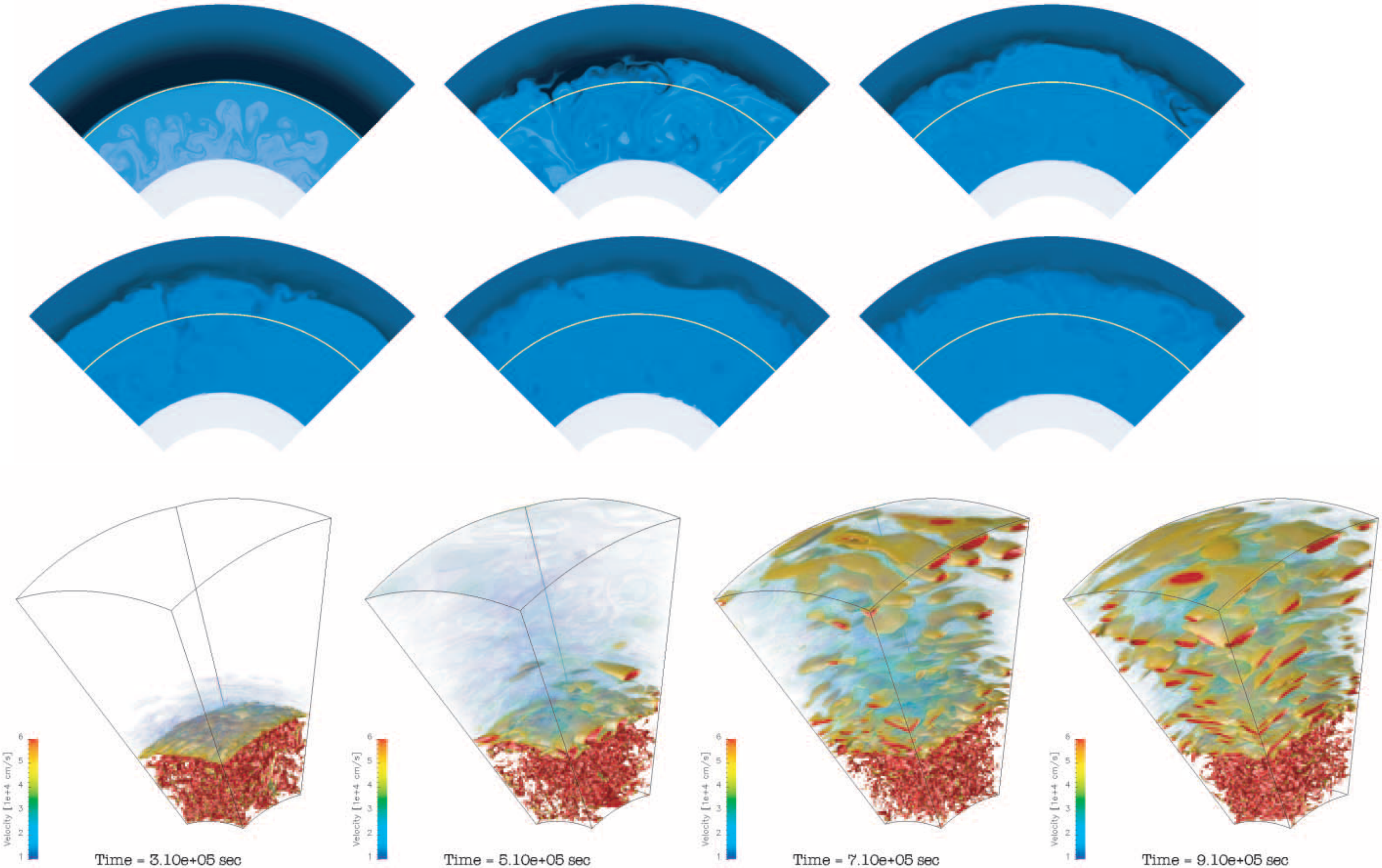
net nuclear energy generation (burning + neutrino losses)
0 >10^−1 >10^0 >10^1 >10^2 >10^3 >10^4 >10^5 >10^6 >10^7 >10^8 >10^9 >10^10 >10^11 >10^12 >10^13 >10^14
net nuclear energy loss (burning + neutrino losses)
<−10^14 <−10^13 <−10^12 <−10^11 <−10^10 <−10^9 <−10^8 <−10^7 <−10^6 <−10^5 <−10^4 <−10^3 <−10^2 <−10^1 <−10^0 <−10^−1 0
convection
semiconvection
total mass of star
(reduces by mass loss)
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)
0
5
10
15
20
6
4
2
0
−2
−4
−6
−8

Mufti-Dimensional Convection



(Meaken & Arnett 2007)

Multi-Dimensional Convection



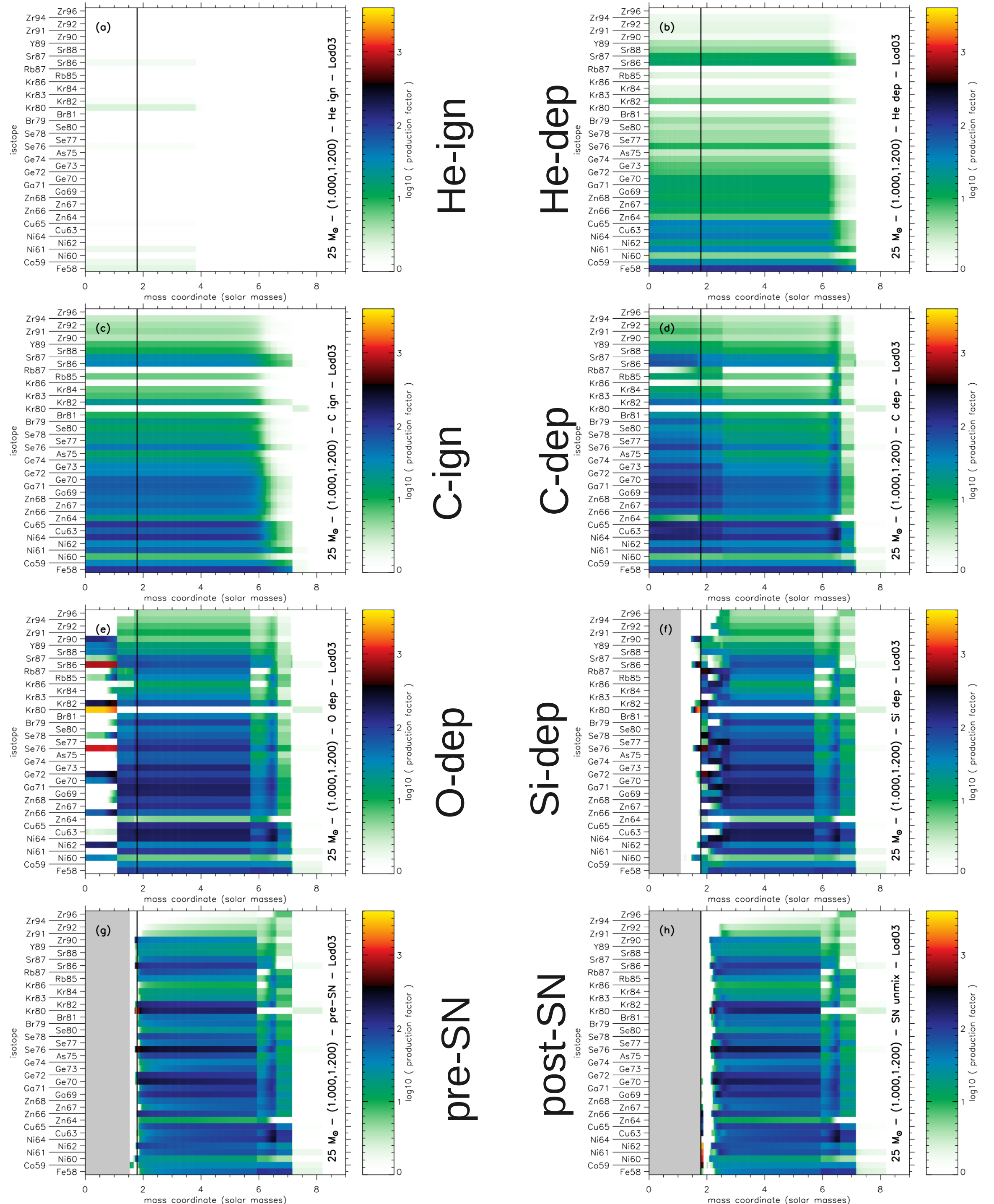
(Meaken & Arnett 2007)


Boom!
Bang!

Explosive Nucleosynthesis

in supernovae from massive stars

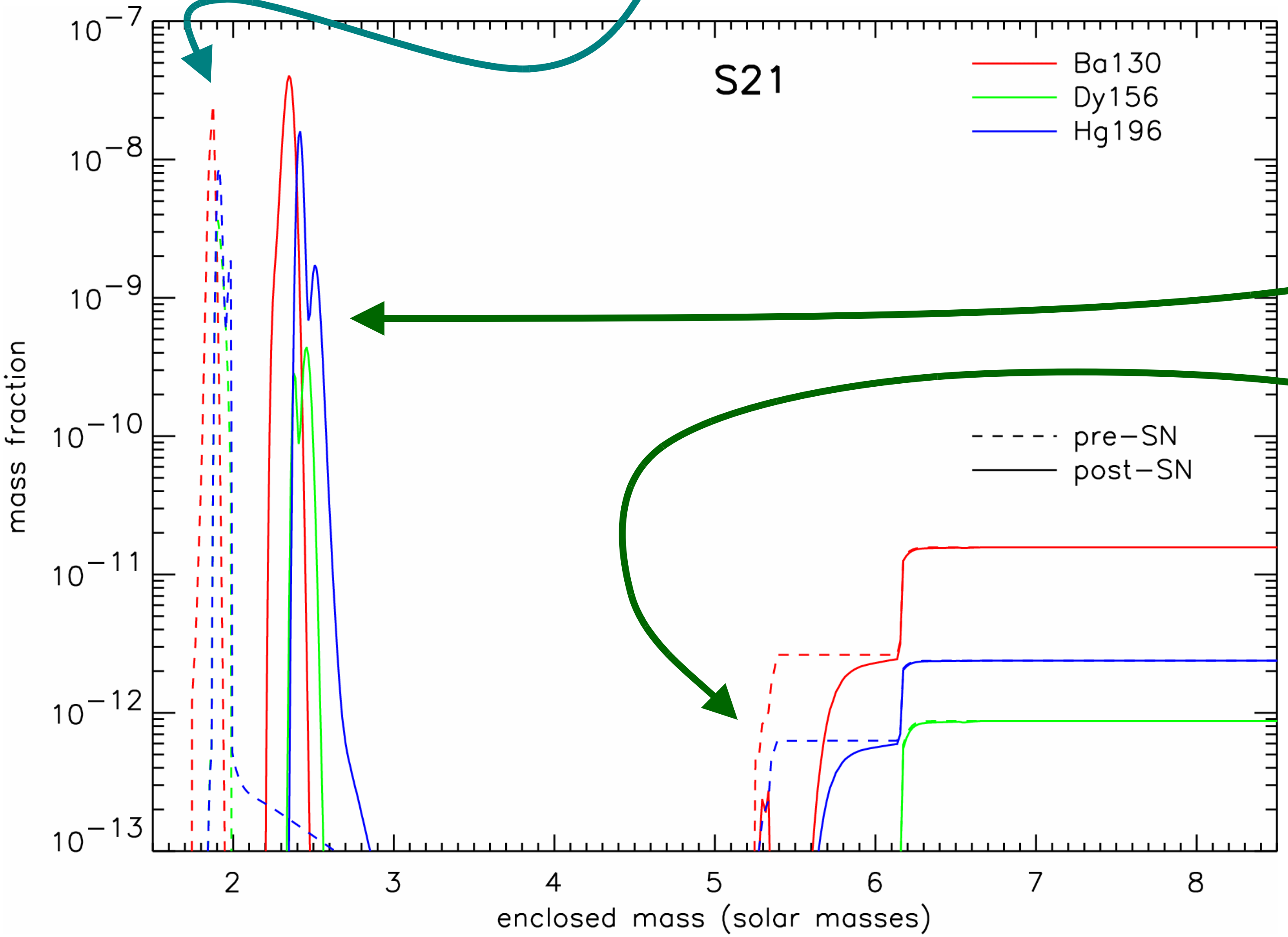
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (s)	Main Reaction
Innermost ejecta	*r*-process *νp*-process	-	>10?	1	(n,γ), β^-
Si, O	^{56}Ni	iron group	>4	0.1	(α,γ)
O	Si, S	Cl, Ar, K, Ca	3 - 4	1	$^{16}O + ^{16}O$
O, Ne	O, Mg, Ne	Na, Al, P	2 - 3	5	(γ,α)
		p-process ^{11}B, ^{19}F, ^{138}La, ^{180}Ta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



25 solar mass 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**

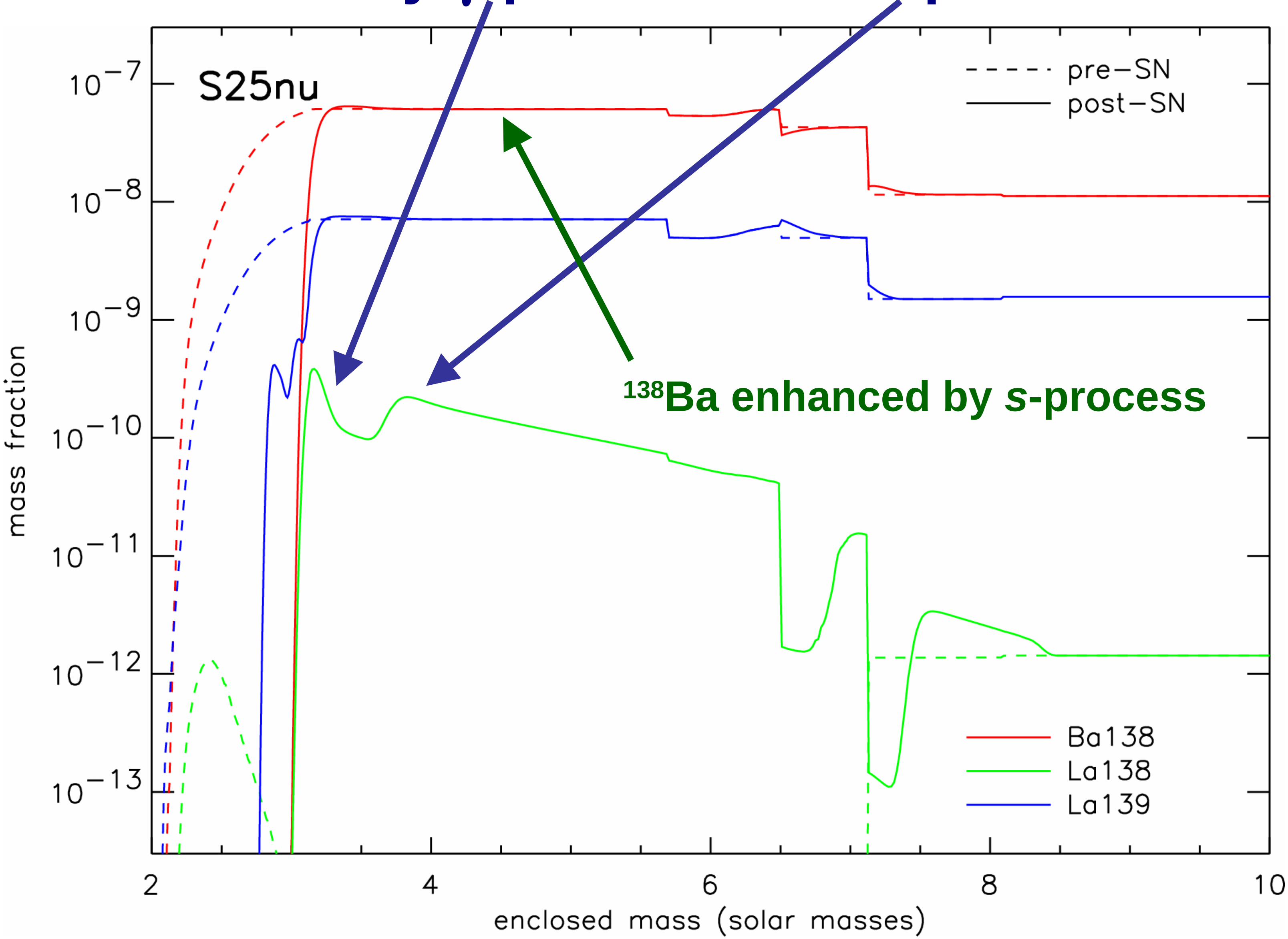


destruction by n-exposure in He shell

21 $M_\odot$ star

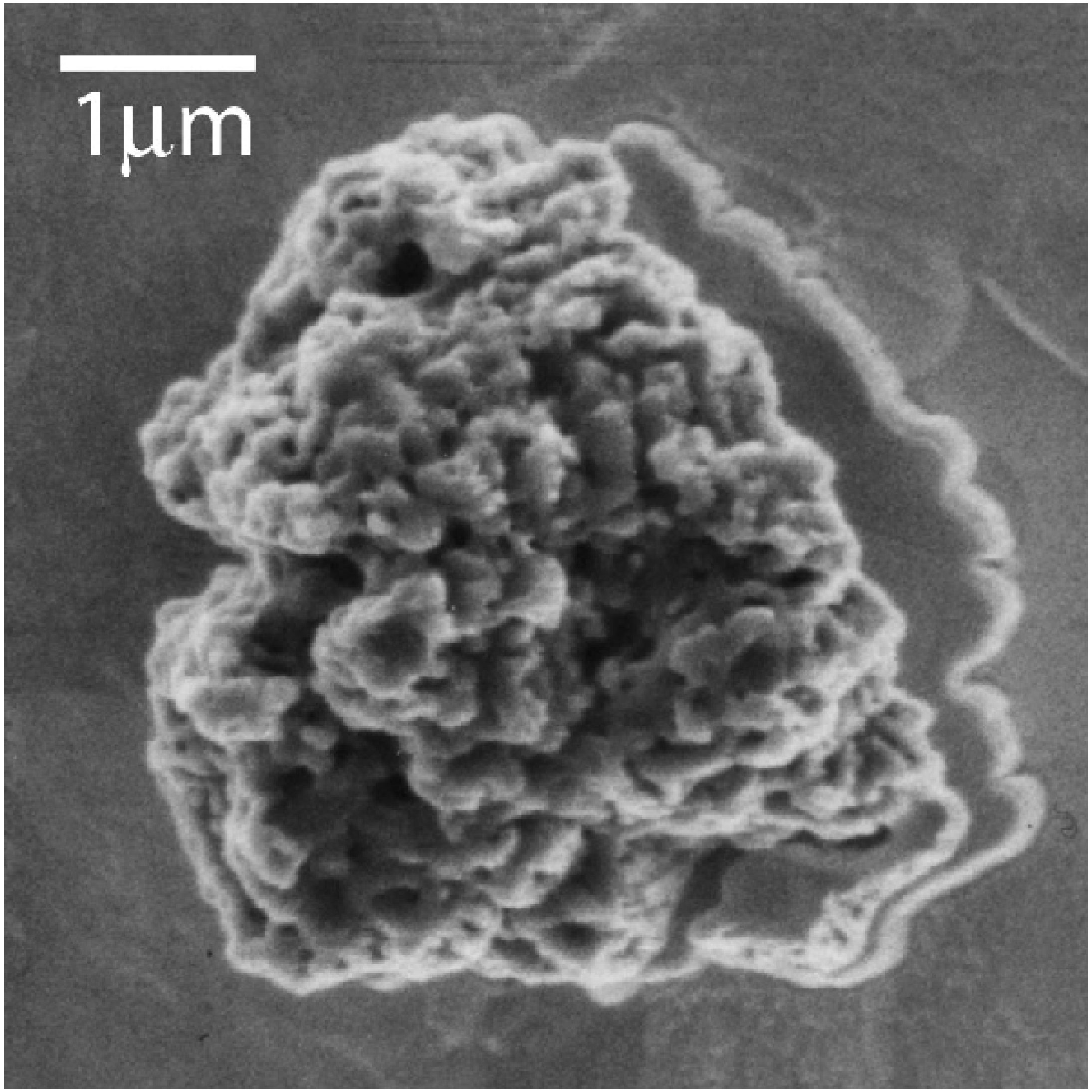
The Production of ^{138}La

by γ-process and ν-process



Presolar grains

Direct access to pristine SN nucleosynthesis?



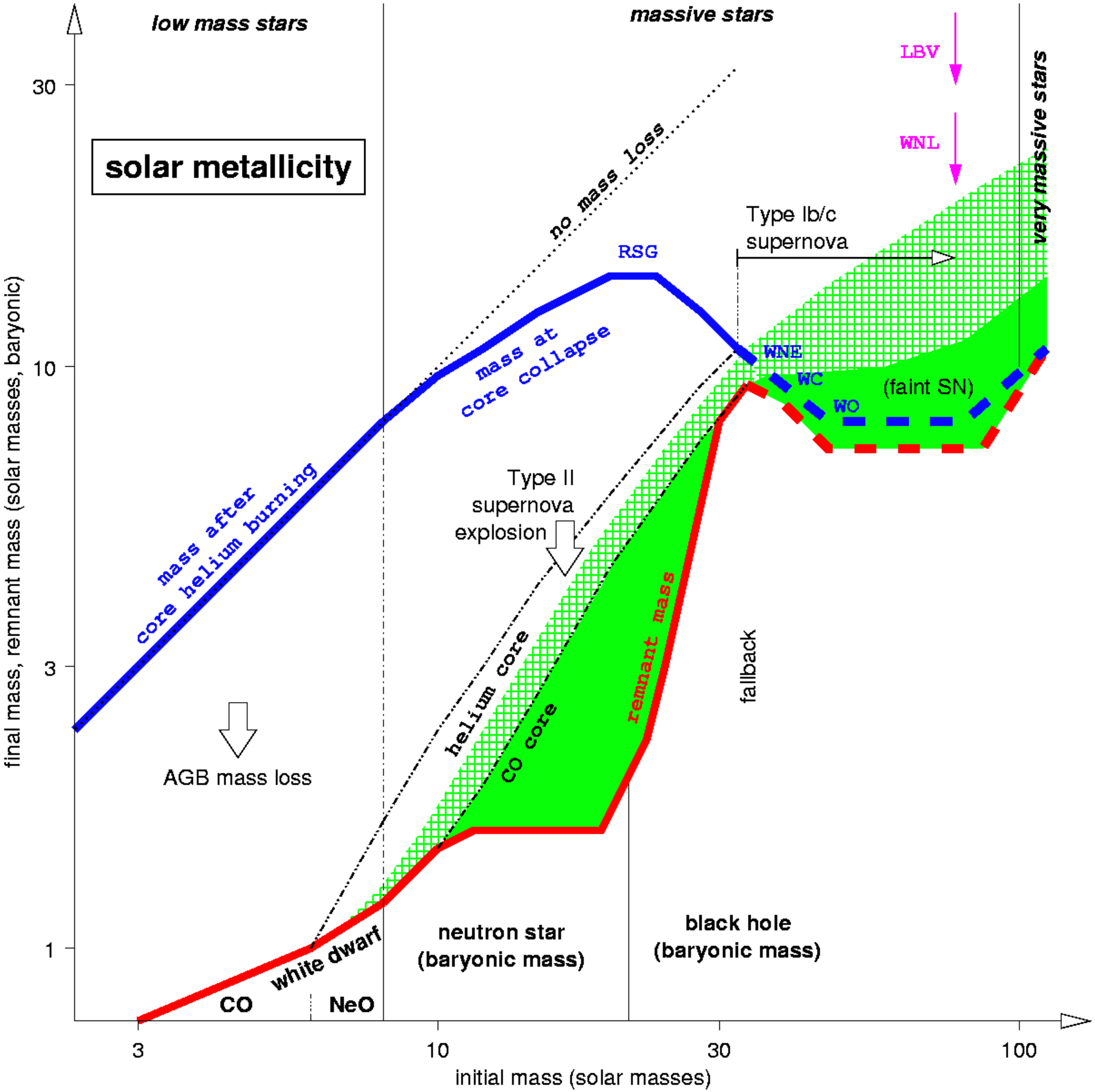
However:
need to understand

- chemistry
- condensation
- SN mixing
- implantation

see Denault, Clayton & Heger (2003)

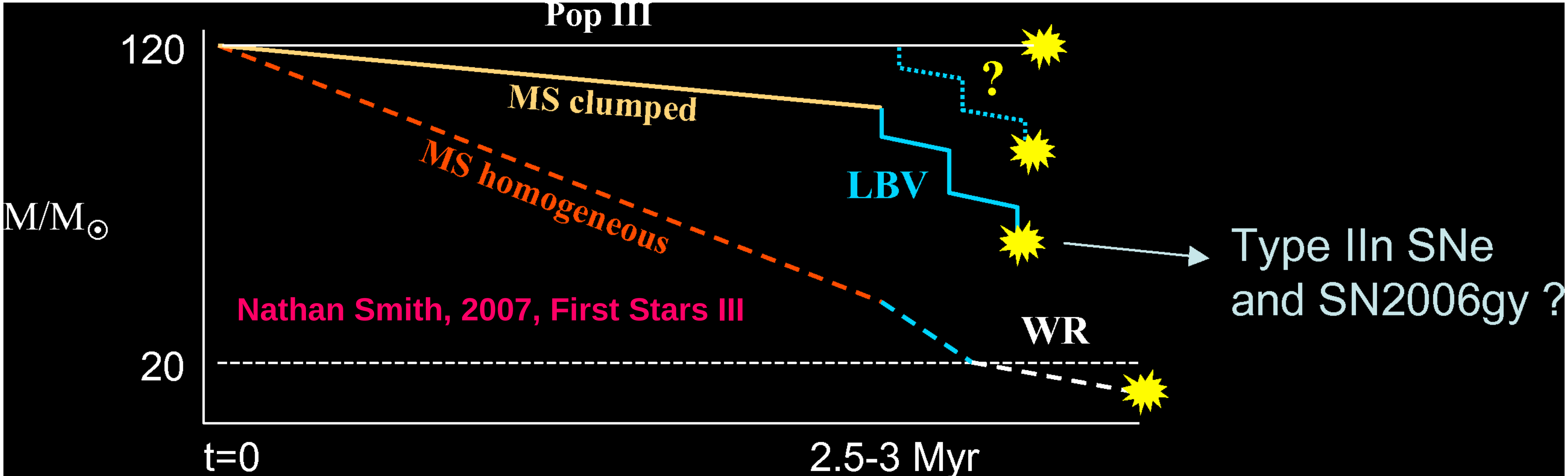
Massive Star Fates as Function of Initial Mass

(solar metallicity)



Ejected “metals”

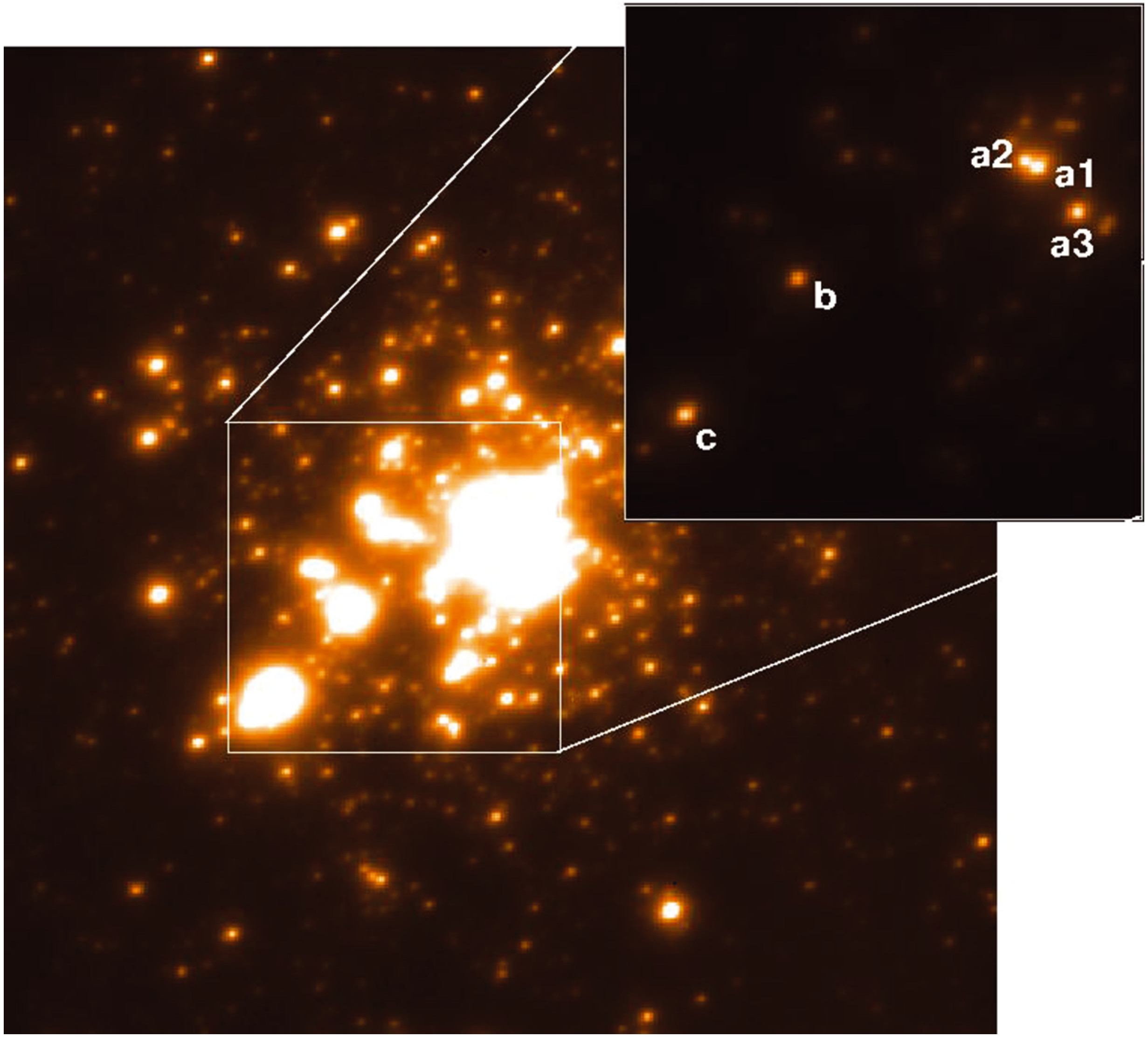
Mass Loss due to Giant Eruptions?



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)?

The Most Massive Stars Today

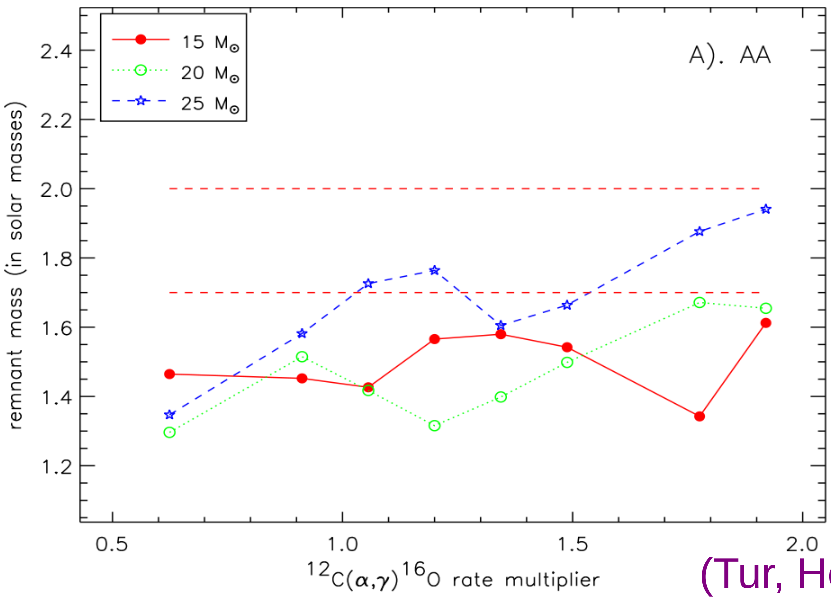


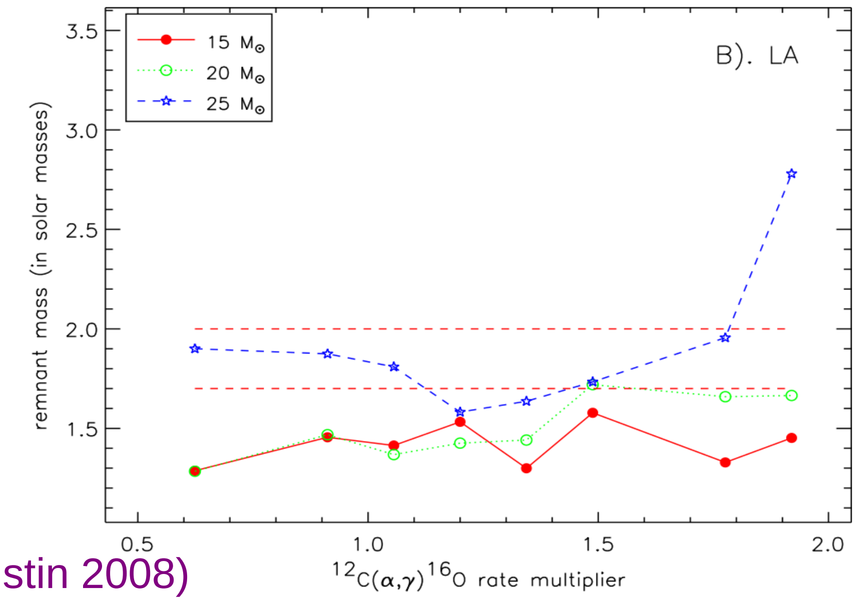
R136

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

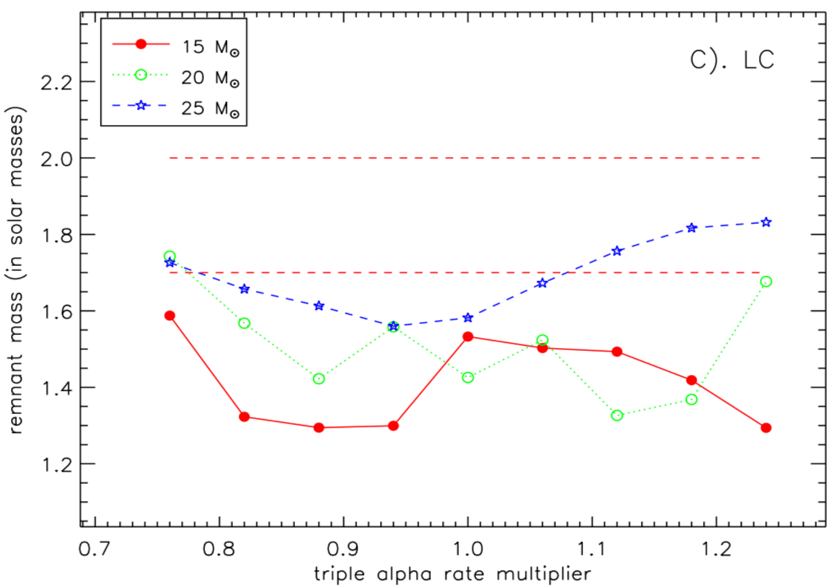
(Crother et al. 2010)

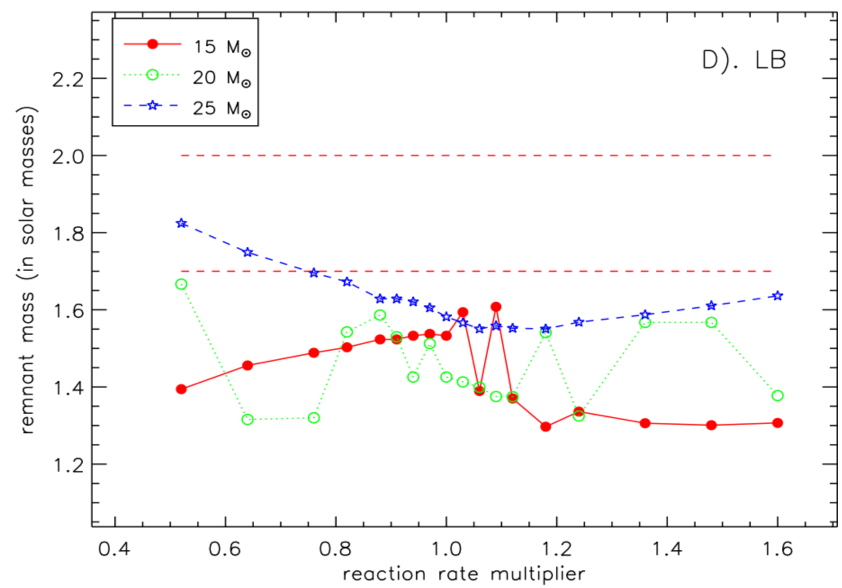
Remnant Masses – NS or BH?





(Tur, Heger, Austin 2008)





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*”?