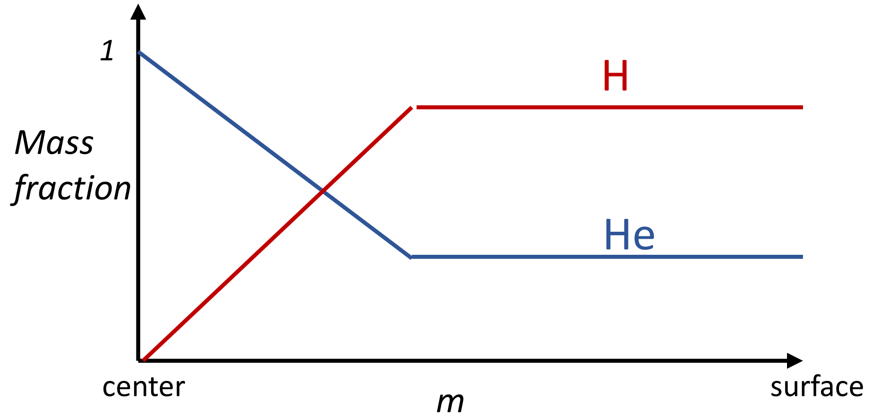
PART B

He burning stars

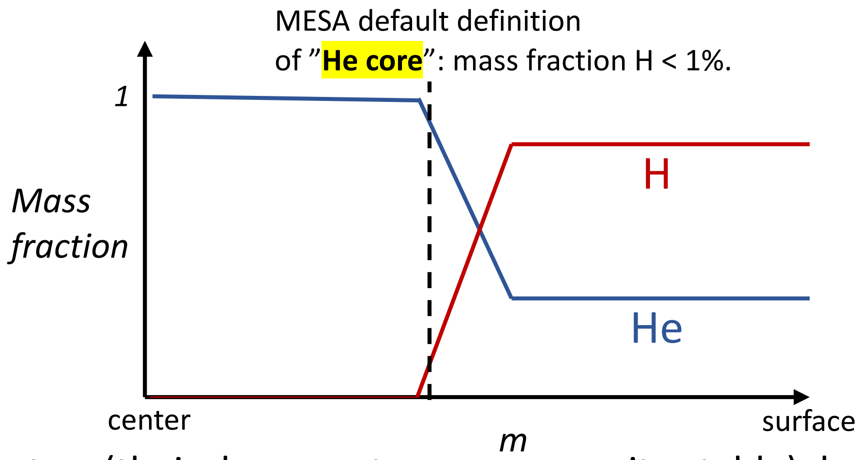
From core H exhaustion to He ignition: **H shell burning**

At core H exhaustion:

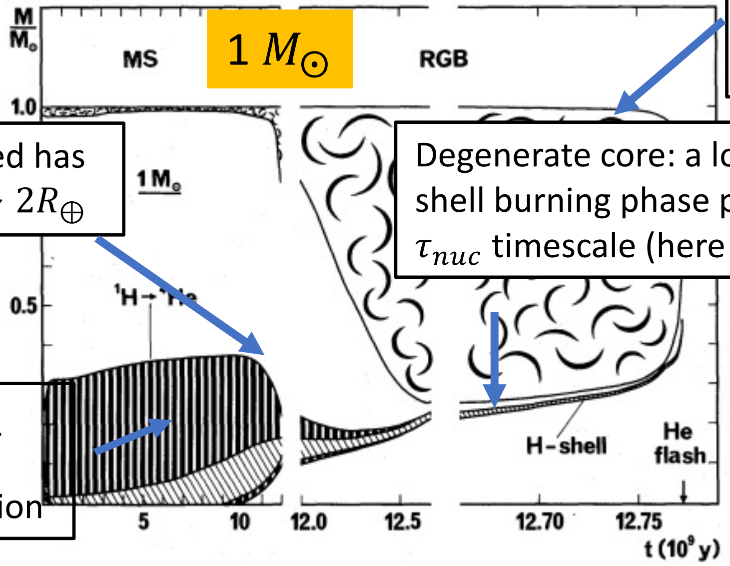
Low-mass stars ($\lesssim 2.5\ M_\odot$) : non-convective core and composition "ramps". "He core" (not well defined here) is stabalized by degeneracy pressure.



Intermediate and massive stars ($\gtrsim 2.5\ M_\odot$): convective center and more well-defined/uniform He core. Non-degenerate.



H burning continues in a shell. The shell phase lasts $\sim\tau_{nuc}$ for low-mass stars (their degenerate cores are quite stable), but a shorter $\sim\tau_{KH}$ for intermediate/massive stars (their non-degenerate cores contract on this time-scale).



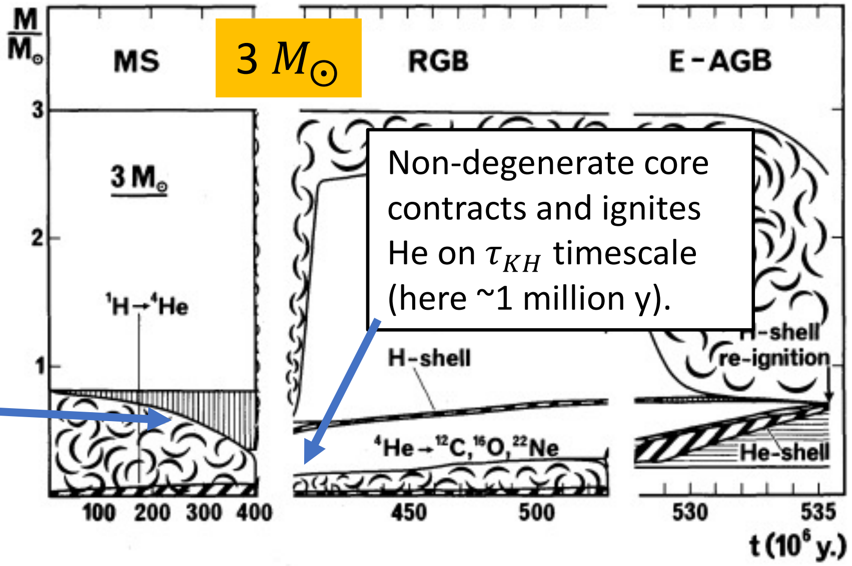
"He core" formed has $M{\sim}0.4\ M_\odot, R\ \sim\ 2R_\oplus$

Dashed/striped regions: high energy generation

Cloudy regions: convective.

Degenerate core: a long isolated H shell burning phase possible on τ_{nuc} timescale (here ~1 billion y).

Convective core shrinks with time



Non-degenerate core contracts and ignites He on τ_{KH} timescale (here ~1 million y).

Maeder & Meynet 1989, ApJ 210,155

White dwarfs and the Chandrasekhar mass

White dwarfs are supported by electron degeneracy pressure (and some thermal pressure until $T \to 0$)[A44].
They represent a possible end state for stellar cores that are not too massive.

Polytropes[A27] with $n = 3/2$ and fixed K (non-relativistic degeneracy) have a solution for any mass M. However, for too large M the assumption of non-relativistic electron velocities breaks down so those solutions are not valid.

In the valid regime ($M \lesssim 1\ M_\odot$) one can derive $R \sim M^{-1/3}$, so more massive white dwarfs have smaller radii.

A polytrope with $n = 3$ and fixed K (strongly relativistic and degenerate gas) turns out to have only a single mass as possible solution, which is called the **Chandrasekhar mass**

$$M_{Ch} = 1.46\ M_\odot \left(\frac{\mu_e}{2}\right)^{-2}$$

In fact, a full solution shows that a star approaching this mass (from below) has a radius going towards zero.

- There are no (cold) white dwarf solutions over M_{Ch}.
- White dwarfs with $M < M_{Ch}$ will collapse if they
  a) Accrete mass so they approach M_{Ch}.
  b) Experience electron removal (so μ_e increases).

Onset of He burning

$T \gtrsim 10^8$ K will be reached in stars with $M_{ZAMS} \gtrsim 0.4\ M_{\odot}$ and then **core He burning** begins.

In general, H shell burning continues while the core burns He: this shell burning generates, in fact, most of the energy (60-90%), whereas the core He burning generates 10-40%.

The duration of this phase is 1-20% of the H burning phase : the fraction increases with M_{ZAMS}.

Low-mass stars ($M_{ZAMS} \lesssim 2.5\ M_{\odot}$) have degenerate He cores when He ignition happens (e.g. $\rho_c \sim 10^6$g cm^{-3} in a 1 $M_{\odot}$ star) → a **He flash** ($L \sim 10^{11} L_{\odot}$ for few seconds, because of extreme T–dependency of He burning, next slide).

Intermediate mass stars ($2.5\ M_{\odot} \lesssim M_{ZAMS} \lesssim 8\ M_{\odot}$): Non-degenerate cores so no flash, an undramatic central ignition.

→ He ignition lowers L as the (dominant) H-burning shell expands and reduces its energy generation.

Massive stars ($M_{ZAMS} \gtrsim 8\ M_{\odot}$) : Even less degenerate cores.

→ L ~ constant.

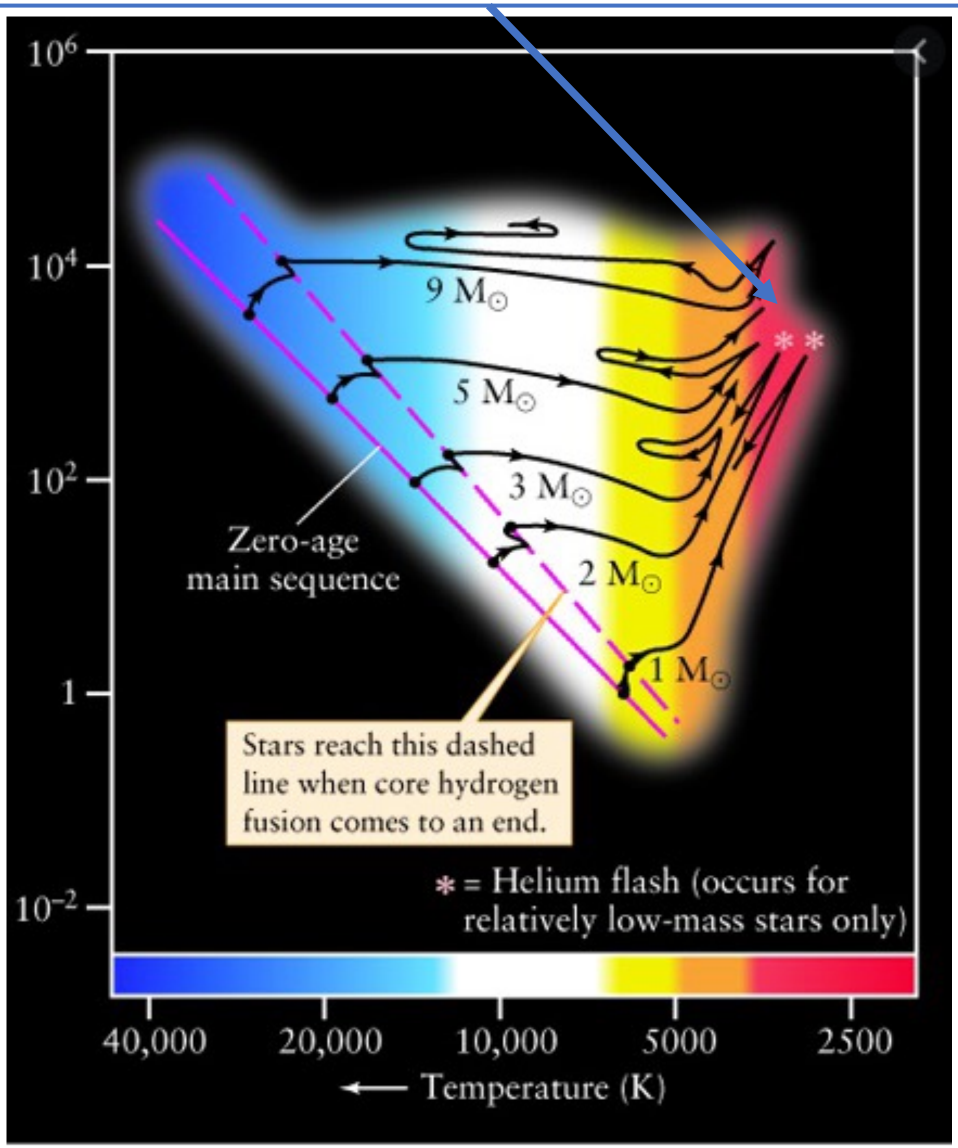
Where are stars in the HR diagram when they ignite He?

Study in lab

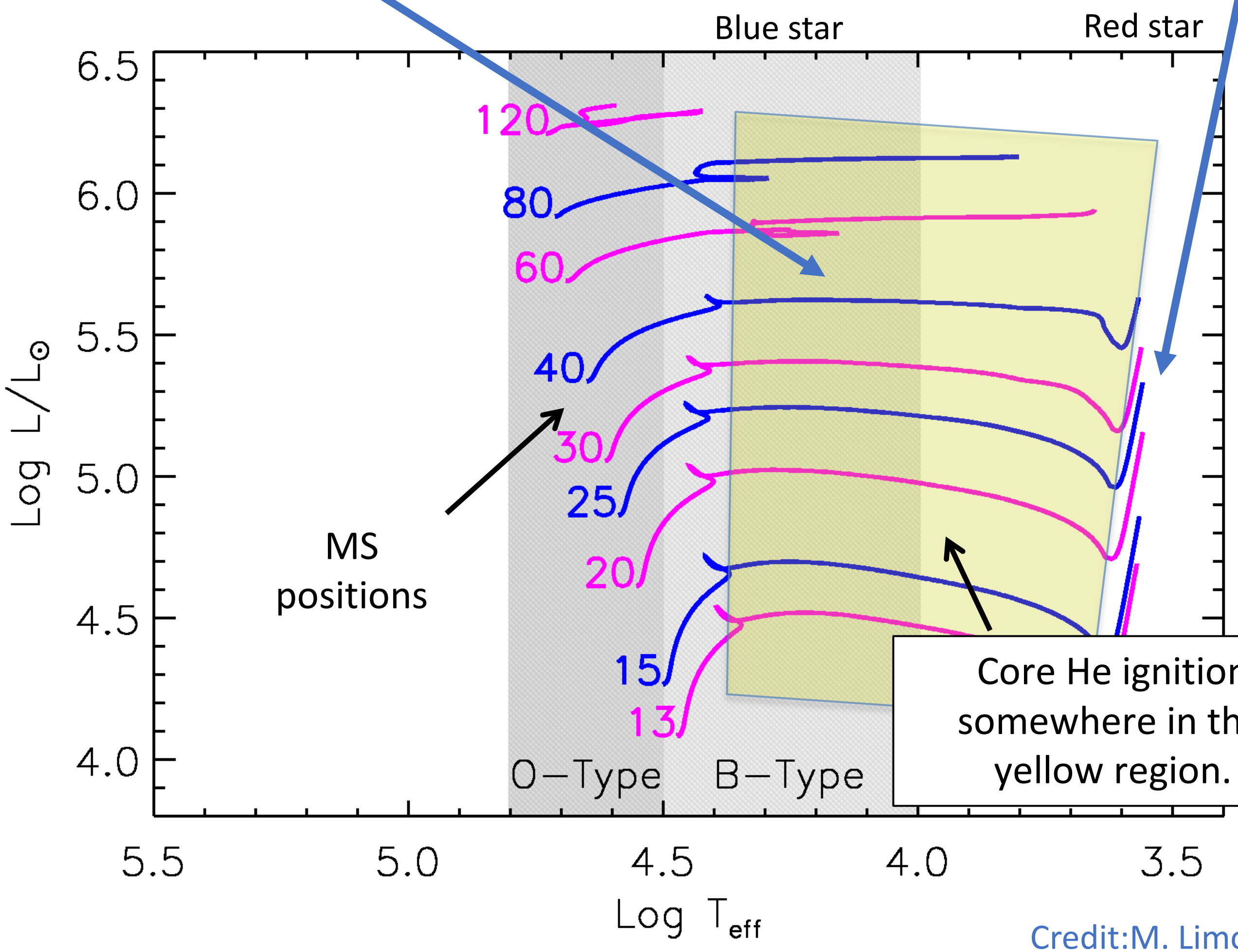
Low and intermediate-mass stars ignite helium at the "red giant tip". L decreases and T_{eff} increases → move down and left.

Typically **massive stars** ignite helium while still blue, having moved partially through this yellow-marked zone. No significant L change at He ignition bacause ~90% of luminosity generated by shell H burning.

How long after He ignition the star reaches the RSG stage ($\log T_{eff} \sim 3.6$) depends on many factors, e.g. the semi-convection efficiency.



Freedman, Geller, Kaufmann

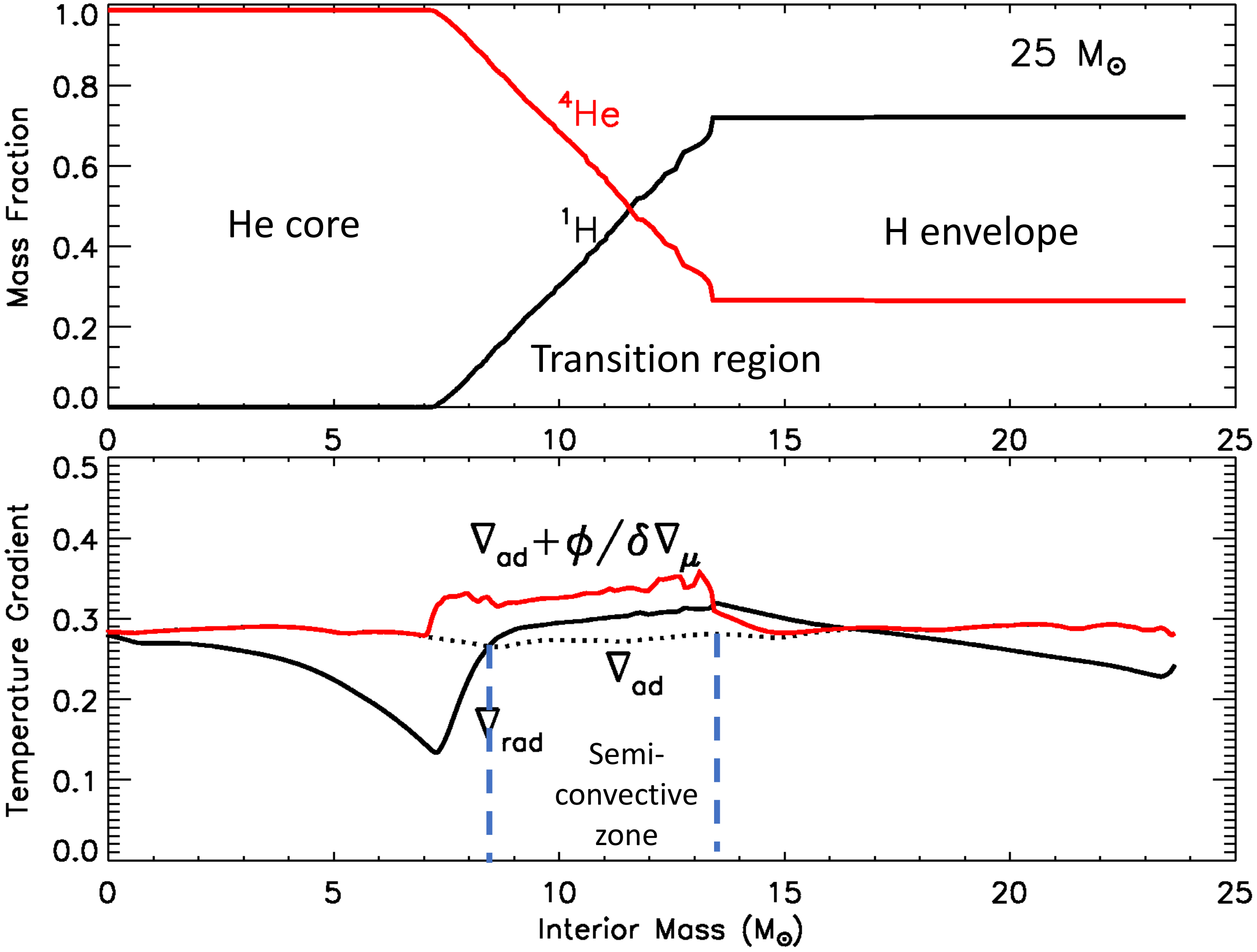


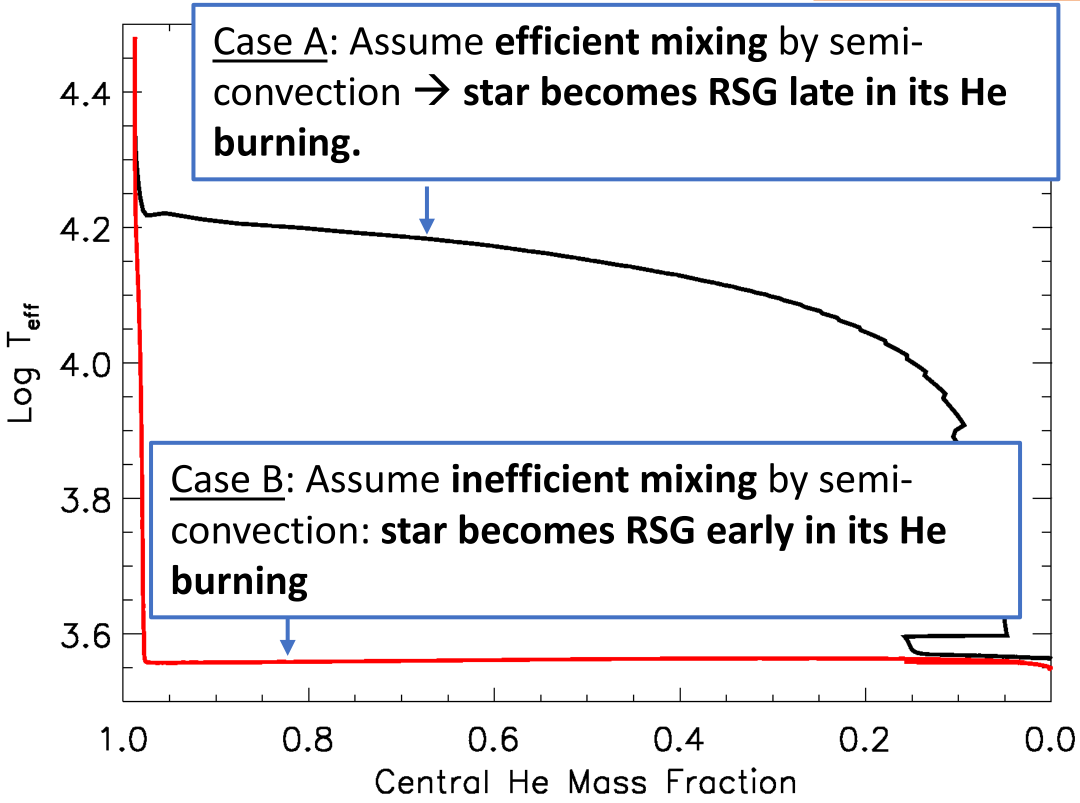
Core He ignition somewhere in this yellow region.

Credit:M. Limongi

In massive stars, the transition layer between the He core and the H envelope (which has a strong composition gradient) is **semi-convective**[A42] and the state of the envelope is uncertain

Study in lab





Case A: Assume **efficient mixing** by semi-convection → **star becomes RSG late in its He burning.**

Case B: Assume **inefficient mixing** by semi-convection: **star becomes RSG early in its He burning**

The RSG settling time in turn affects how much mass is lost by winds in the supergiant phase, as RSGs have higher mass-loss rates than BSGs (Part G).

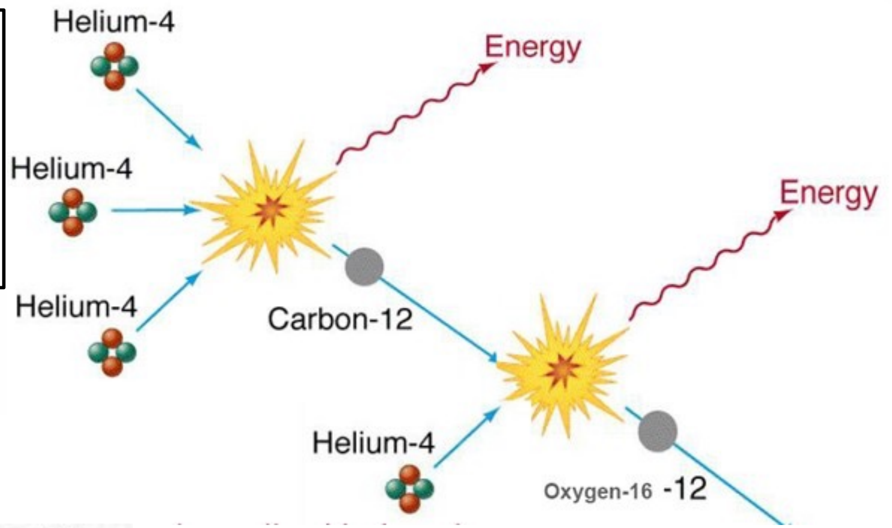
Credit: Marco Limongi

NUCLEAR PHYSICS
OF HE BURNING

He burning: the triple-α reaction

$$^4\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^8\mathrm{Be}$$
$$^8\mathrm{Be} + {}^4\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

^{8}Be decays in $3*10^{-16}$ s: another He must hit within this time to make ^{12}C. Could not be bridged in Big Bang but stars can do it.

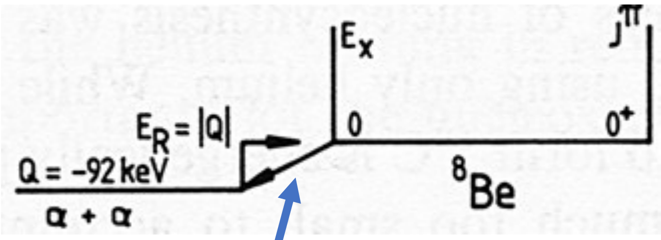


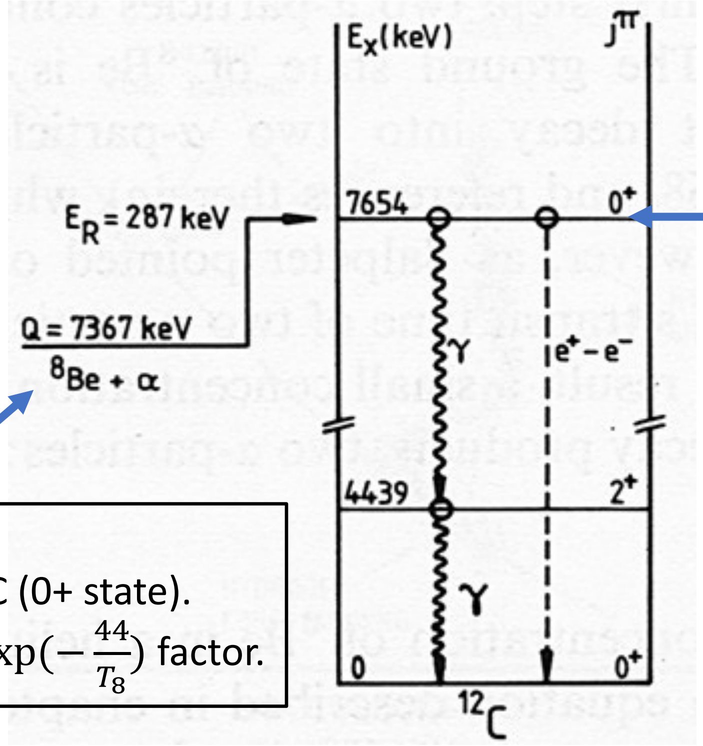
Requires $T \gtrsim 10^8$ K. Denote $T_8 \equiv T/(10^8$ K)

Energy generation rate (erg g^{-1} s^{-1}):

$\varepsilon \propto \rho^2 T^{-3} e^{-44/T_8} \sim T^{41}$ at $T_8 \sim 1$

One can show that $e^{-A/x} \sim x^A$ around $x = 1$





Fred Hoyle predicted this resonance level in 1954. Without it no stars could bridge the ^{8}Be gap.

Two endothermic steps must be overcome:
92 keV to ^{8}Be (ground state) and then 287 keV to ^{12}C (0+ state).
Activation barrier (92+287) keV/k = $4.4 * 10^9$ K → $\exp(-\frac{44}{T_8})$ factor.

He burning: yields

Alphas capture also on ^{12}C to make ^{16}O. Some also capture on ^{16}O to make ^{20}Ne, but that cross section is low so not much ^{20}Ne made.

$$\frac{dn_{\mathrm{He}}}{dt} = -3\lambda_{3\alpha} n_{\mathrm{He}}^3 - \lambda_{\alpha \mathrm{C}} n_{\mathrm{C}} n_{\mathrm{He}} - \lambda_{\alpha \mathrm{O}} n_{\mathrm{O}} n_{\mathrm{He}}$$

$$\frac{dn_{\mathrm{C}}}{dt} = \lambda_{3\alpha} n_{\mathrm{He}}^3 - \lambda_{\alpha \mathrm{C}} n_{\mathrm{C}} n_{\mathrm{He}}$$

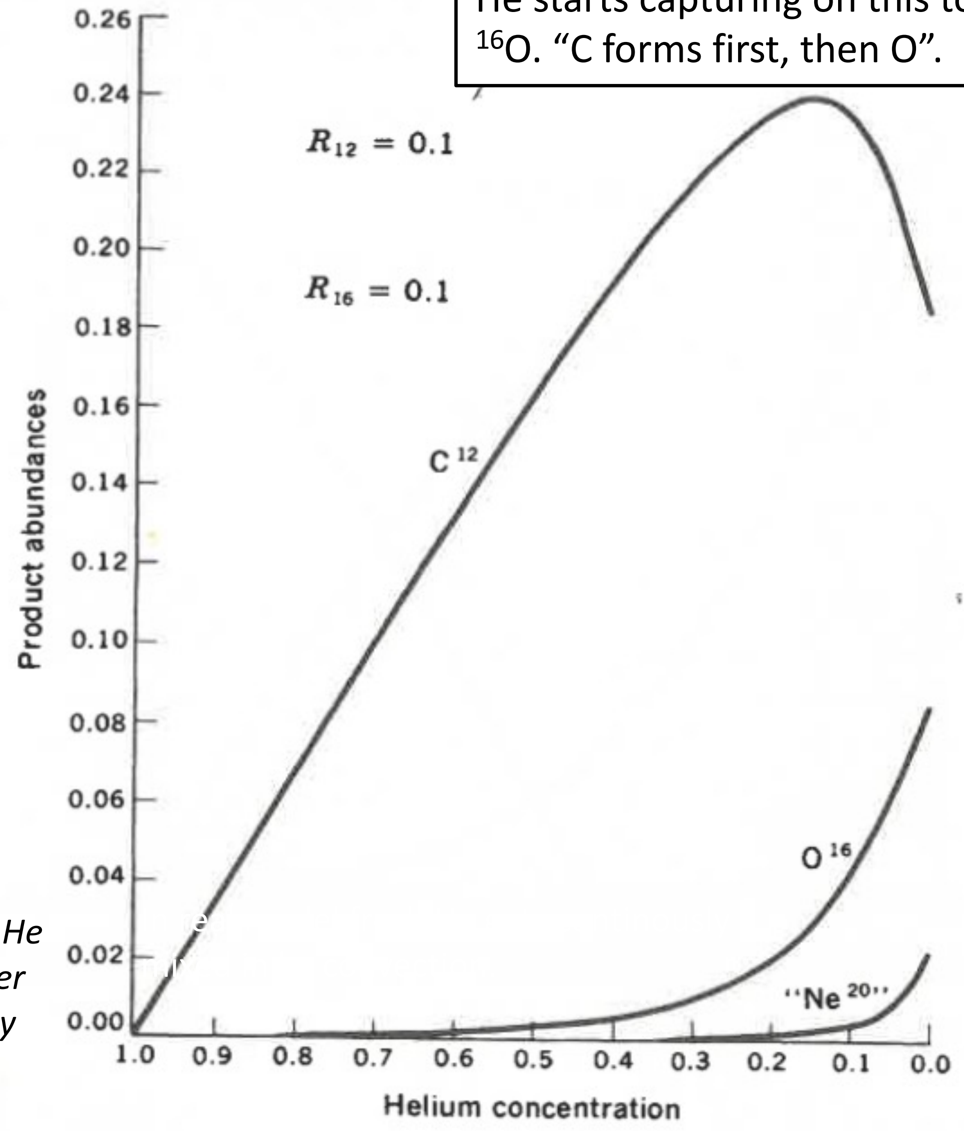
$$\frac{dn_{\mathrm{O}}}{dt} = \lambda_{\alpha \mathrm{C}} n_{\mathrm{C}} n_{\mathrm{He}} - \lambda_{\alpha \mathrm{O}} n_{\mathrm{O}} n_{\mathrm{He}}$$

$$\frac{dn_{\mathrm{Ne}}}{dt} = \lambda_{\alpha \mathrm{O}} n_{\mathrm{O}} n_{\mathrm{He}}$$

Reaction rates ($cm^3\ s^{-1}$)

n are number densities

When C gets abundant enough, He starts capturing on this to form ^{16}O. "C forms first, then O".



Clayton book

Can get insights by investigating constant *T* case. Then reduces to dependency on two constants $R_{12} = \frac{\lambda_{\alpha \mathrm{C}}}{\lambda_{3\alpha} n_{\mathrm{He}}^0}$ and $R_{16} = \frac{\lambda_{\alpha \mathrm{O}}}{\lambda_{3\alpha} n_{\mathrm{He}}^0}$.

Initial He number density

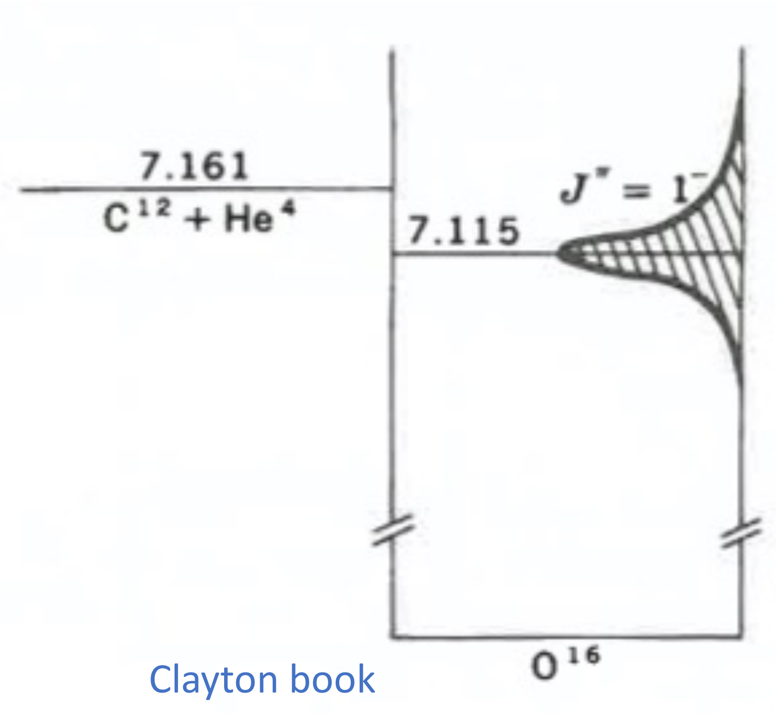
This process should be the main source of C and O in the universe.
One can show that ^{20}Ne is not predominantly made in this burn step.

Q-values: 7.27 MeV (3α), 7.16 MeV (C→O), 4.73 MeV (O → Ne), 9.31 MeV (Ne → Mg). Compare H fusion Q = 26 MeV.

He burning: rates

Determining $\lambda_{\alpha C}(T)$ is one of the longest-standing problems and most important challenges in nuclear astrophysics. The uncertainty is still $\pm$ 30%.

MESA uses the rate formula from Kunz et al. 2002. Caughlan & Fowler 1988 rate (used in most stellar evolution models 1988-2002) is a factor ~2 too low.



Clayton book

The rate is difficult to both calculate and measure because the reaction lies "in the tail of a resonance".

Constraints from gravitational wave detections of binary black hole mergers on the $^{12}C(\alpha,\gamma)^{16}O$ rate

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(Dated: June 15, 2020)

ABSTRACT

Gravitational wave detections are starting to allow us to probe the physical processes in the evolution of very massive stars through the imprints they leave on their final remnants. Stellar evolution theory predicts the existence of a gap in the black hole mass distribution at high mass due to the effects of pair-instability. Previously, we showed that the location of the gap is robust against model uncertainties, but it does depend sensitively on the uncertain $^{12}C(\alpha,\gamma)^{16}O$ rate. This rate is of great astrophysical significance and governs the production of oxygen at the expense of carbon. We use the open source `MESA` stellar evolution code to evolve massive helium stars to probe the location of the mass gap. We find that the maximum black hole mass below the gap varies between $40\,M_\odot$ to $90\,M_\odot$, depending on the strength of the uncertain $^{12}C(\alpha,\gamma)^{16}O$ reaction rate. With the first ten gravitational-wave detections of black holes, we constrain the astrophysical S-factor for $^{12}C(\alpha,\gamma)^{16}O$, at 300keV, to $S_{300} > 175$ keV barns at 68% confidence. With $\mathcal{O}(50)$ detected binary black hole mergers, we expect to constrain the S-factor to within ±10–30 keV barns. We also highlight a role for independent constraints from electromagnetic transient surveys. The unambiguous detection of pulsational pair instability supernovae would imply that $S_{300} > 79$ keV barns. Degeneracies with other model uncertainties need to be investigated further, but probing nuclear stellar astrophysics poses a promising science case for the future gravitational wave detectors.

POSSIBLE PROJECT

He burning : creating neutron-rich nuclei by radioactive decays

^{4}He, ^{12}C, ^{16}O, and ^{20}Ne have the same number of neutrons as protons (due to successive α-captures). Certain weak interaction processes can convert protons to neutrons and increase the **neutron excess η** of the material.

$$\eta = \frac{N_n - N_p}{N_n + N_p}$$

From left-over ^{14}N from CNO burning (**during CNO burning most C and O is locked up in N and this stays so when burning stops**):

A nucleus with more neutrons than protons is created (^{18}O) as p → n + e+ in the ^{18}F nucleus.

^{14}N + α → ^{18}F → ^{18}O + ν + e^{+} ^{18}F half-life = 2h.

^{18}O will burn further to ^{22}Ne by another α capture.

^{22}Ne serves later as a key nucleus for the s-process to begin, by ^{22}Ne + α → ^{25}Mg + n.

Note the production depends on metallicity Z because the amount of ^{14}N is proportional to Z.

The neutron-richness of nuclear burning ashes will become important when diagnosing supernova yields later on.

He burning is convective in all $M_{ZAMS} \gtrsim 2\ M_\odot$ stars. Radiation pressure becomes important for the more massive He cores.

The extreme *T*-sensitivity of He burning ($\sim T^{41}$) concentrates the energy production to a small core region. A large luminosity generated in a small volume cannot be efficiently transported by radiation → convection sets in for $M_{ZAMS} \gtrsim 2\ M_\odot$.

Further**, radiation pressure** becomes important for massive stars.

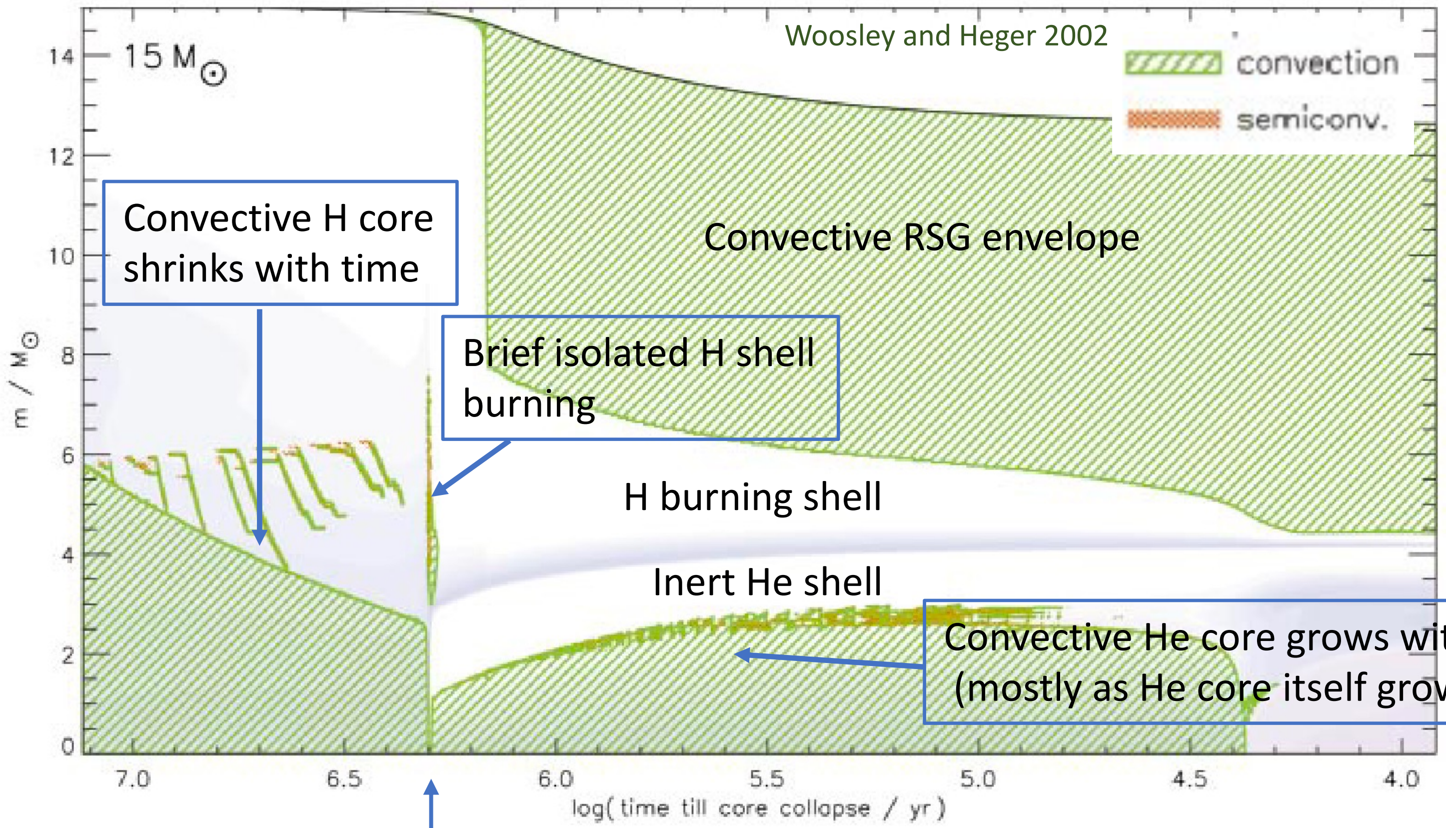
$$\nabla_{rad} \equiv \frac{3}{16\pi acG}\frac{\kappa l_{tot}(m)P}{mT^4}$$

When ∇_{rad} is too high, e.g. by a high $l_{tot}(m)/m$ ratio, energy cannot be transported by radiative diffusion only.

$M_{He-core}$	P_{rad}/P_{tot}
$1\ M_\odot$	0.02
$5\ M_\odot$	0.18
$10\ M_\odot$	0.32

$$\frac{P_{rad}}{P_{gas}} \sim \frac{\frac{1}{3}aT^4}{\frac{R}{\mu}\rho T} \propto \frac{T^3}{\rho}.$$

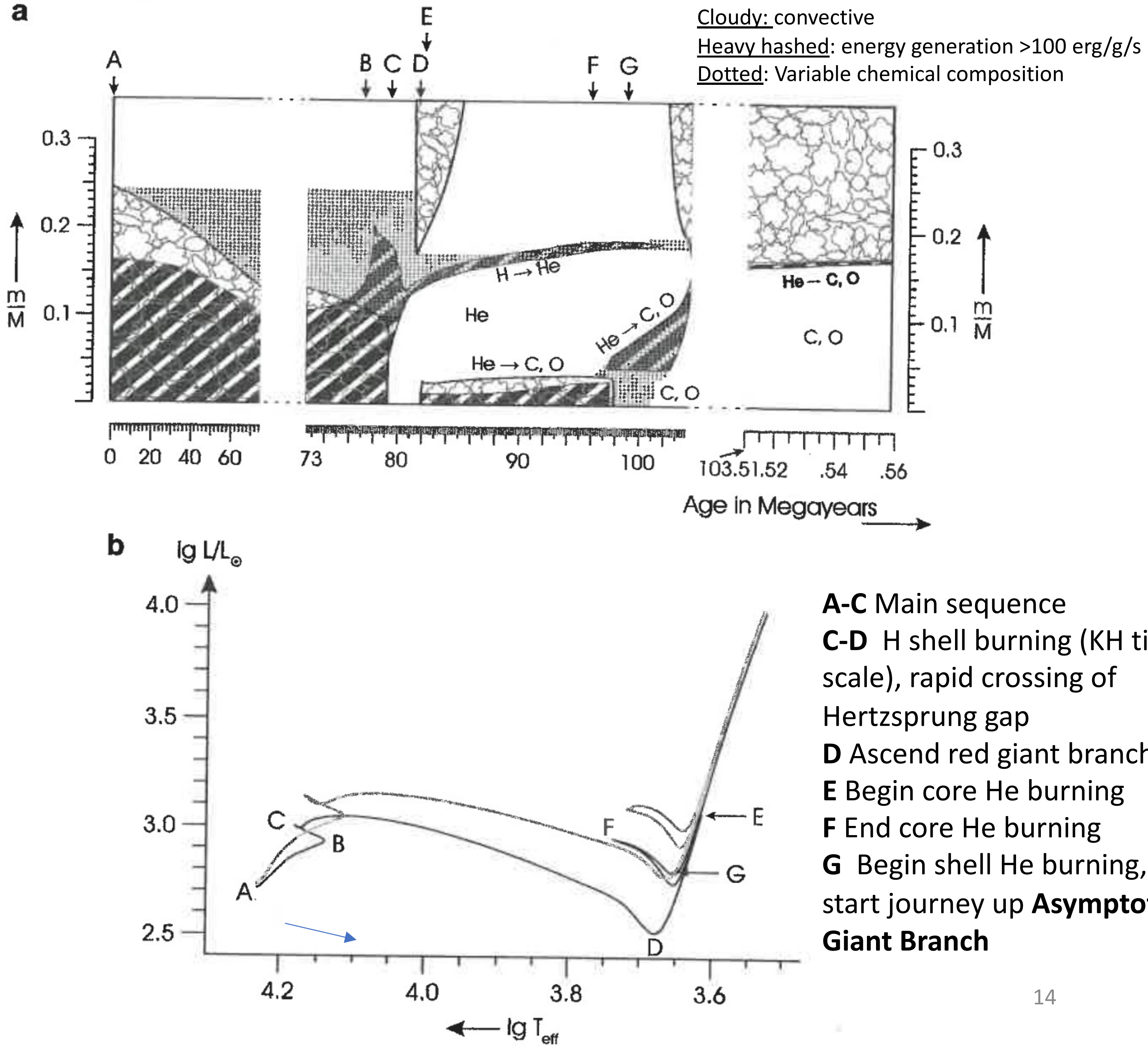
More massive stars have higher T for same ρ.



He ignition on time scale $< \tau_{KH}$ (core *T* is already close to He ignition temperature)

Evolution of a 5 $M_\odot$ star through H and He burning phases

- Luminosity decreases when He ignites.
- Only a small inner part of He core burns (~5%) and convects (~10%).
- Core He burning is followed by shell He burning: most of the final CO core is in fact made by this process.



Kippenhahn Fig 31.2

A-C Main sequence
C-D H shell burning (KH time-scale), rapid crossing of Hertzsprung gap
D Ascend red giant branch
E Begin core He burning
F End core He burning
G Begin shell He burning, start journey up **Asymptotic Giant Branch**

Shell He burning at
at low and intermediate mass:
Asymptotic Giant Branch (AGB) stars

Shell He burning: AGB stars

Core He burning is followed by **shell He burning.** For low and intermediate mass stars the CO core formed has significant degeneracy support and its stability allows a long next phase of He shell burning (and outside that still ongoing H shell burning): **Asymptotic Giant Branch (AGB)** phase. Important stage for all low and intermediate-mass stars (~0.4 - 10 $M_\odot$).

More massive stars move instead quickly to ignite the next fuel (carbon) in the centre (compare to how $\gtrsim 2.5\ M_\odot$ stars quickly ignite He after core H exhaustion).

Both burning shells are located within $\sim 2 R_\oplus$ and have **low mass:**

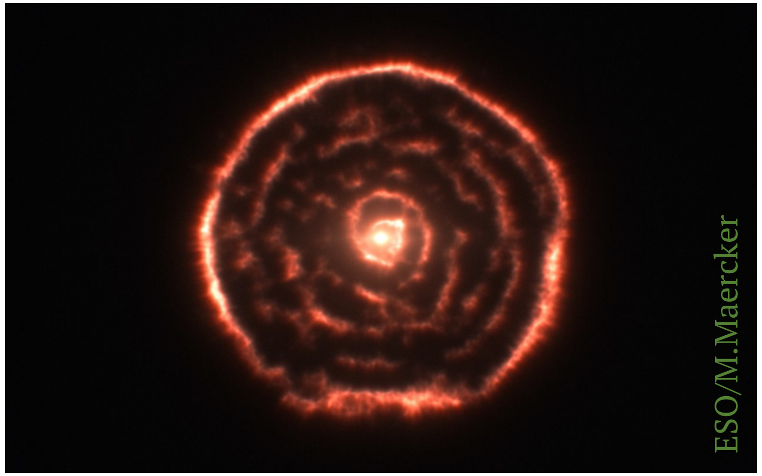
- $\sim 0.01\ M_\odot$ (He-burning shell)
- $\sim 0.001\ M_\odot$ (H-burning shell).

$L \sim 10^4 L_\odot$ for $M_{ZAMS} \sim 1\ M_\odot$. Low $T_{eff}(\sim 3000\ K)$ → **molecules and dust** form. Dust is believed to be the main driver of mass loss, but difficult to model.

A series of **thermal pulses (**order ~10, intervals $\sim 10^3 - 10^4$y**),** driven by chaotic on-off behaviour of the double shell burning, help to shed the mantle. **This mass loss by AGB stars constitutes 10-20% off all material returned to the ISM by stars.**

A degenerate CO core is formed at the centre (new-formed white dwarf with $T \sim 10^5$ K). It illuminates the shedded mantle with UV light → **planetary nebula**.

AGB star **R Sculptoris**



AGB stars : the ”third dredge-up” allows ejection of He-burning products

C (and some O) made in the shell He burning is, along with s-process products, dragged to the surface. This occurs following each thermal pulse.

These form CO molecules which becomes an important component of the atmosphere.

If C/O number ratio > 1 (as in early He burning), left-over C can also form other carbon-based molecules → ”**C stars**” (one variant of AGB stars).

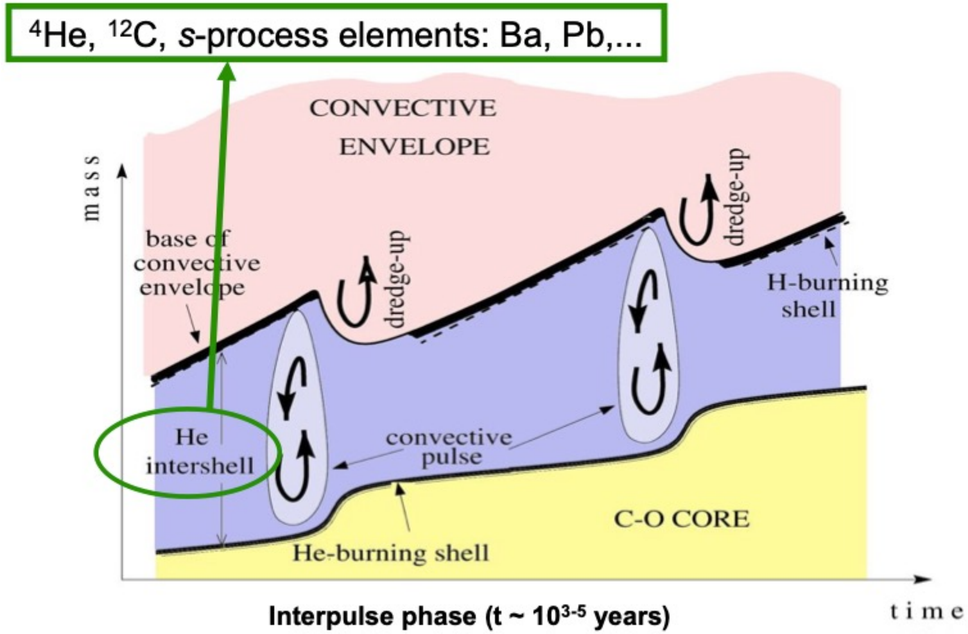
This “third dredge-up” is inferred observationally but has turned out to be challenging for models to reproduce satisfactorily. May be related to unsuitability of standard MLT formalism where α_{MLT} is tuned to the Sun.

But also physical effects like rotation may be important, as well as overshooting that behaves differently at different boundaries.

Believed to be main source of C in the Universe.

Previous dredge-ups (1st and 2nd) have allowed ejection of the primary H burning product (apart from He) : N. **Believed to be main source of N in the Universe.**

Merrill 1952: Radioactive heavy s-process elements (^{99}Tc,Z=43) discovered in atmospheres of AGB stars.



Credit: A. Karakas

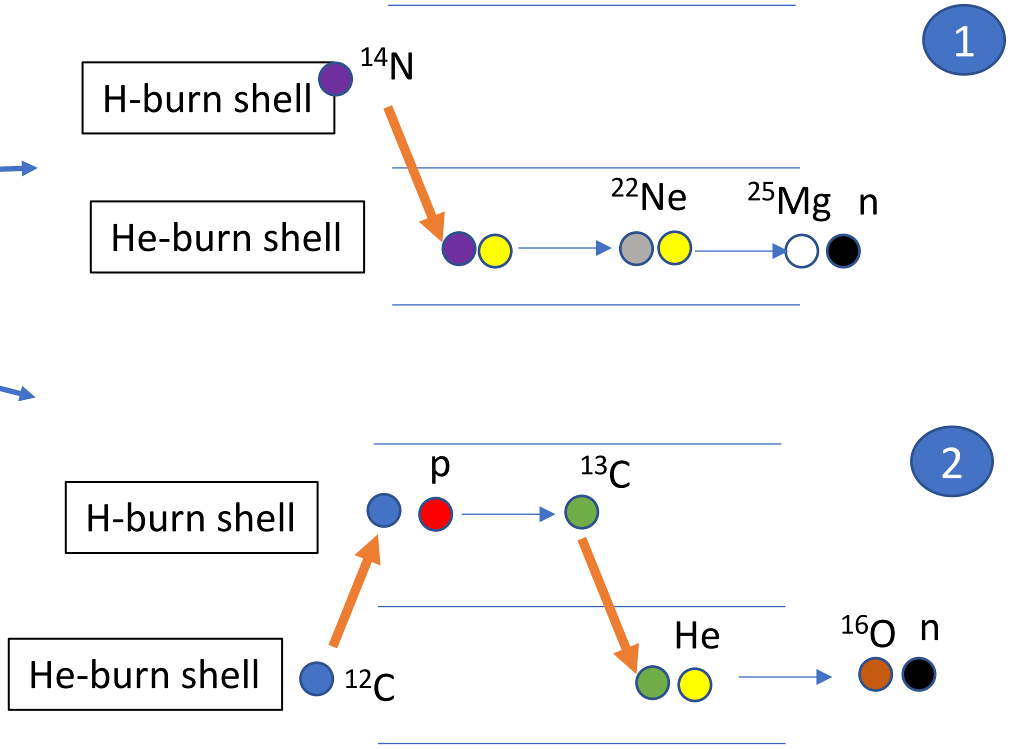
AGB star nucleosynthesis: the s-process

AGB stars provide a unique environment where **nuclei can be exposed to both H and He burning in a complex fashion**, and this material can also be efficiently ejected by the thermal pulses/third dredge-up.

Two main reactions produce a free neutron:

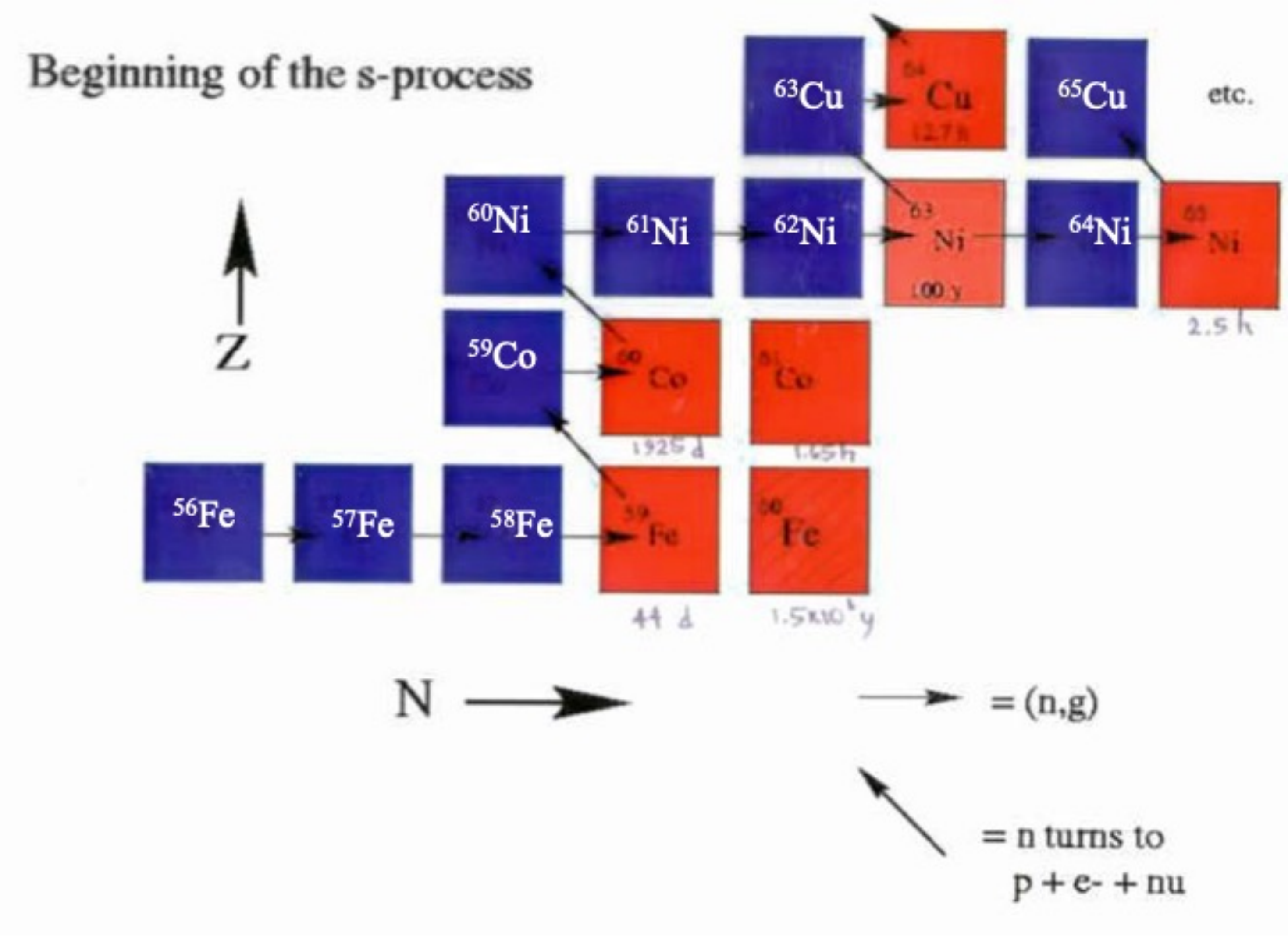
1) $^{22}Ne + ^{4}He \rightarrow ^{25}Mg + n$. Needs one shell mixing step.

2) $^{13}C + ^{4}He \rightarrow ^{16}O + n$ Needs two shell mixing steps.



The mechanisms for these shell mixing processes are however not well understood (overshooting, rotation-induced mixing, and gravity waves all seem to play a possible role).

Released neutrons start an s-process from (primordial) ^{56}Fe seeds



Credit: S. Woosley

Further up the chain…

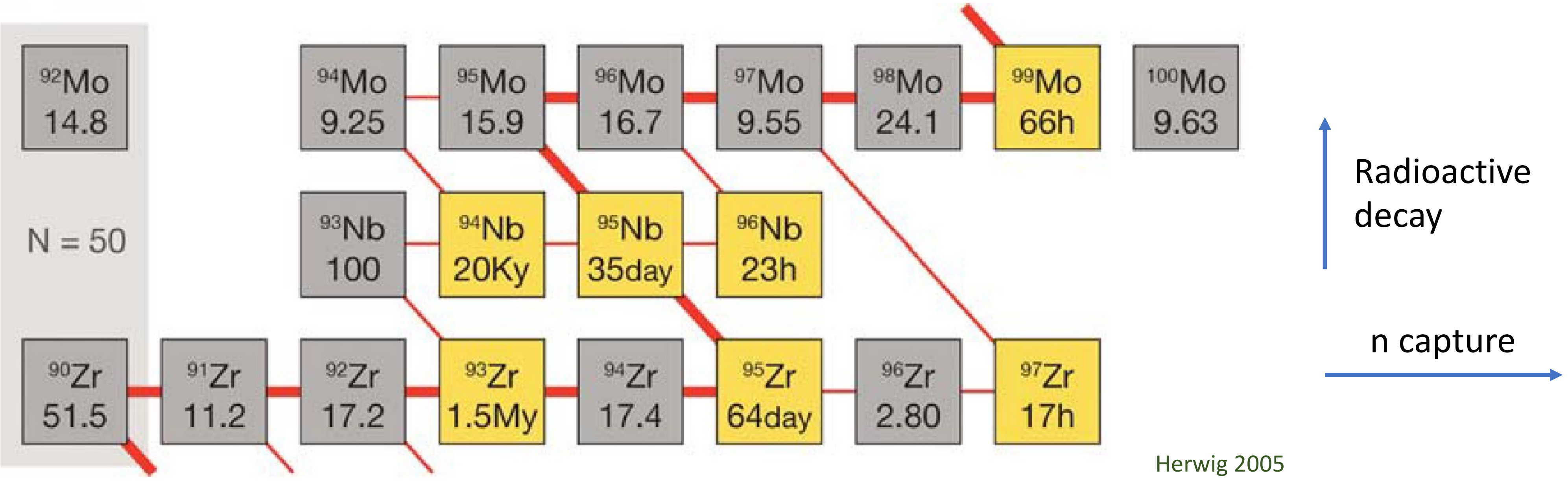


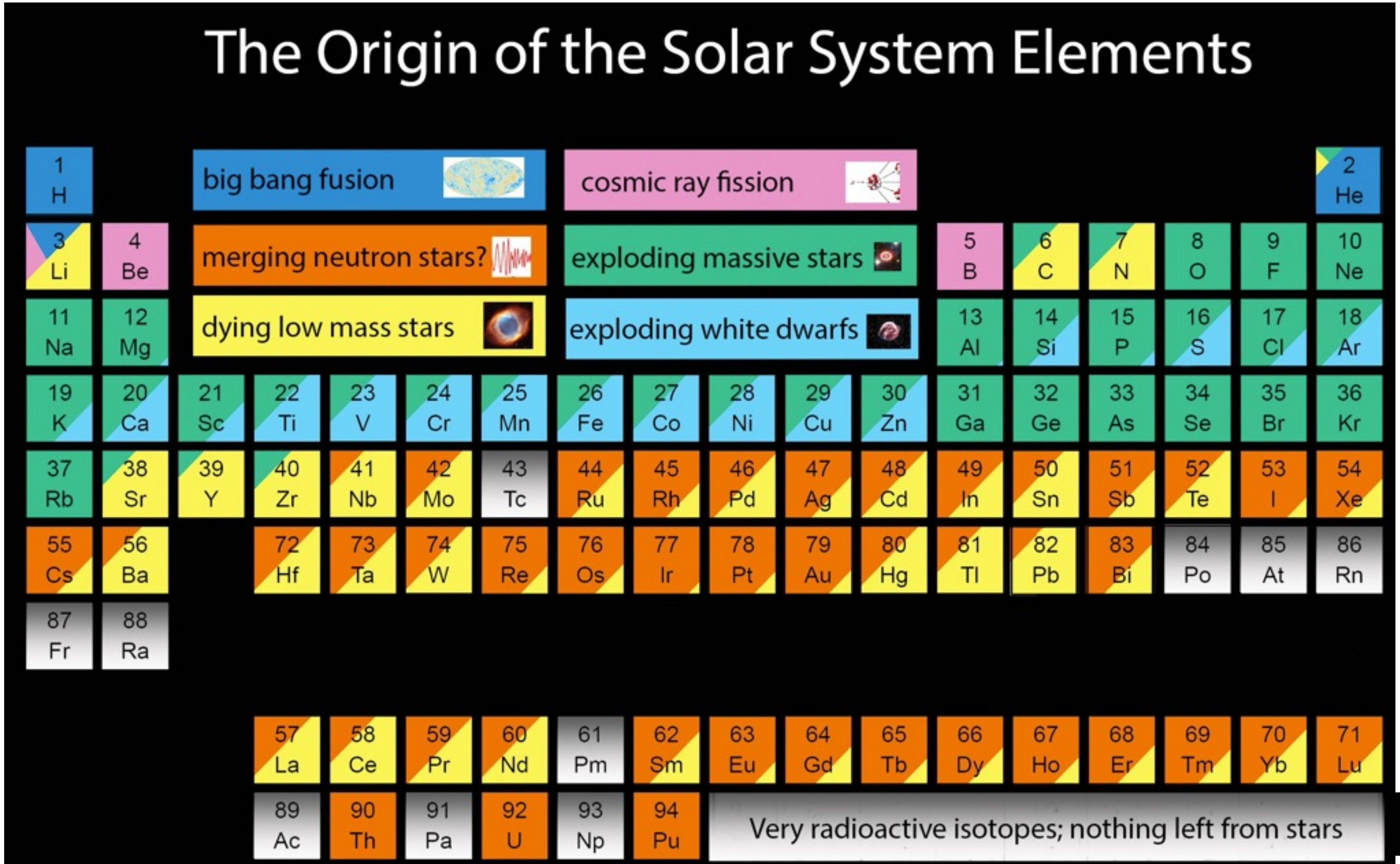
Figure 7 Detail of the chart of isotopes from zirconium to molybdenum. Unstable isotopes are represented in yellow. The *thicker red line* shows the main path of the *s* process; the *thinner red line* shows generally less important side branches. The additional numbers in the boxes give the half-life of unstable isotopes and the isotopic abundance fraction for the stable isotopes.

Cross sections on unstable nuclei typically not measured and theory can give factor ~10 uncertainty.

AGB star nucleosynthesis contributions: C, N, and strong s-process elements (> ^{38}Sr)

The s-process turns out to be most effective in low-mass AGB stars ($M_{ZAMS}{\sim}1-4\ M_{\odot}$). About half the elements heavier than iron made here (”**strong s-process**”, A > 88, ^{38}Sr and up).

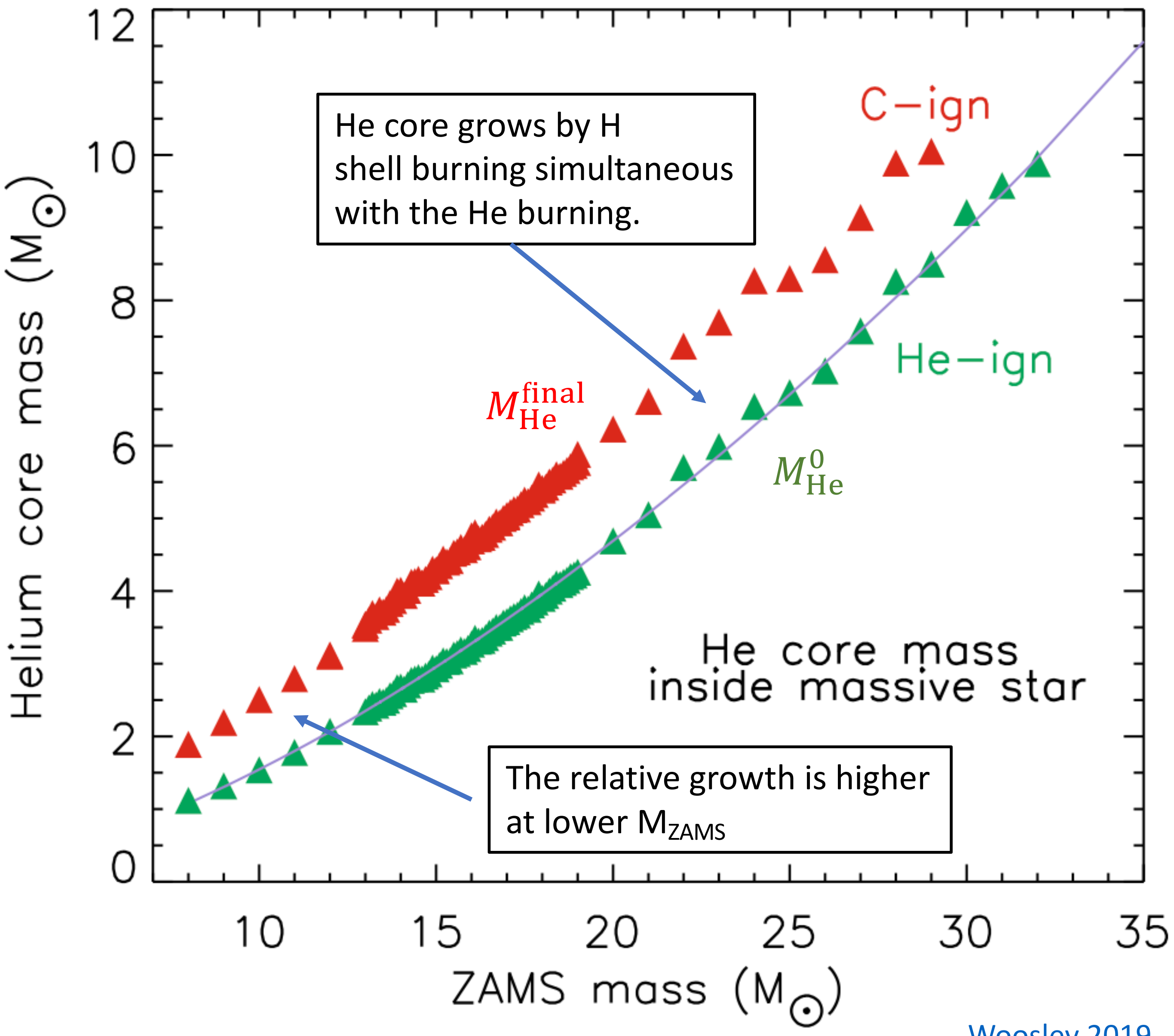
However the ”**weak s-process**” (60 < A < 90) is by massive stars.



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

He burning
at high mass:
supergiants

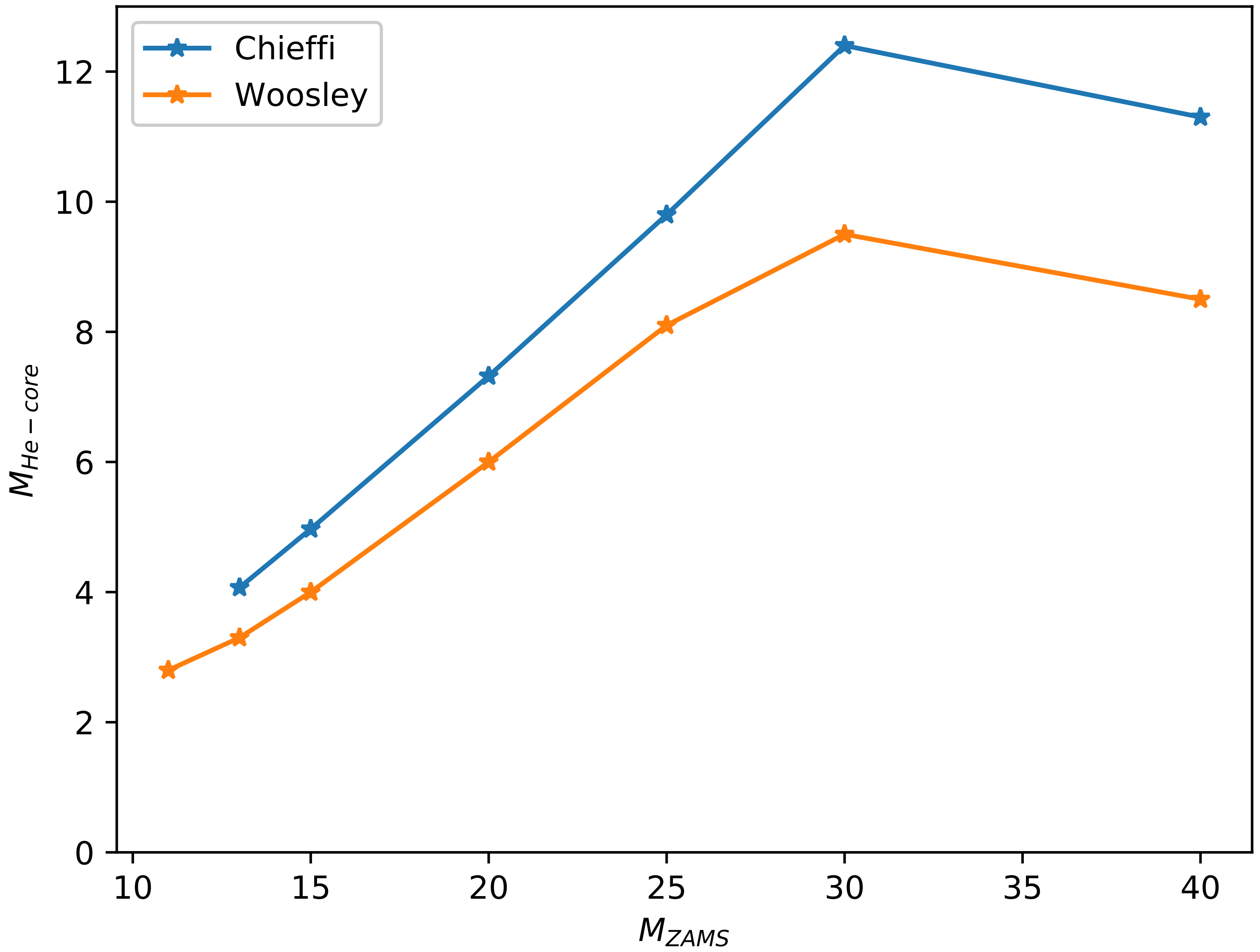
He core masses vs M_{ZAMS}



Woosley 2019

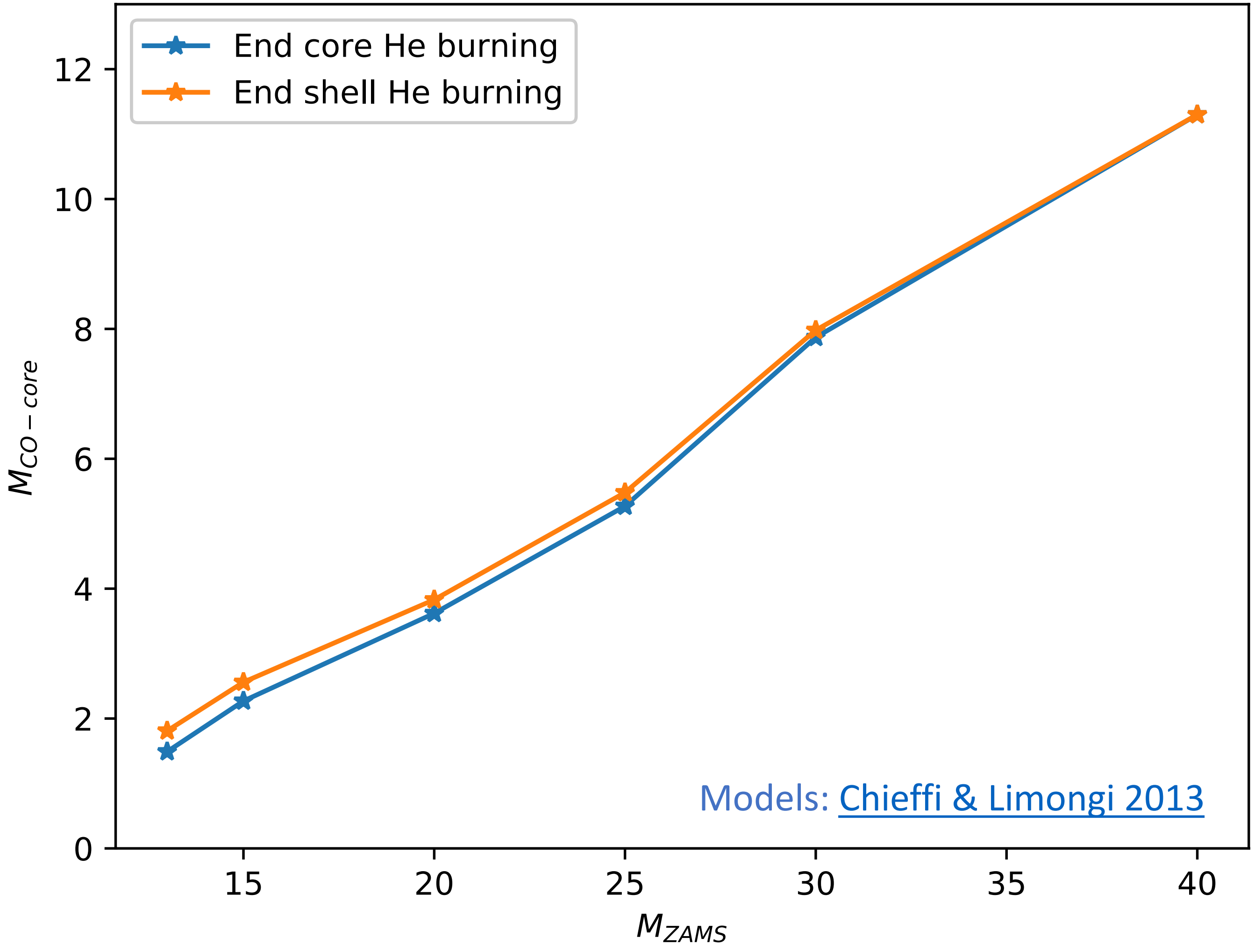
Continued growth of the He core beyond C ignition is neglegible.

Variation of final He core masses with different modelling assumption



Study in lab

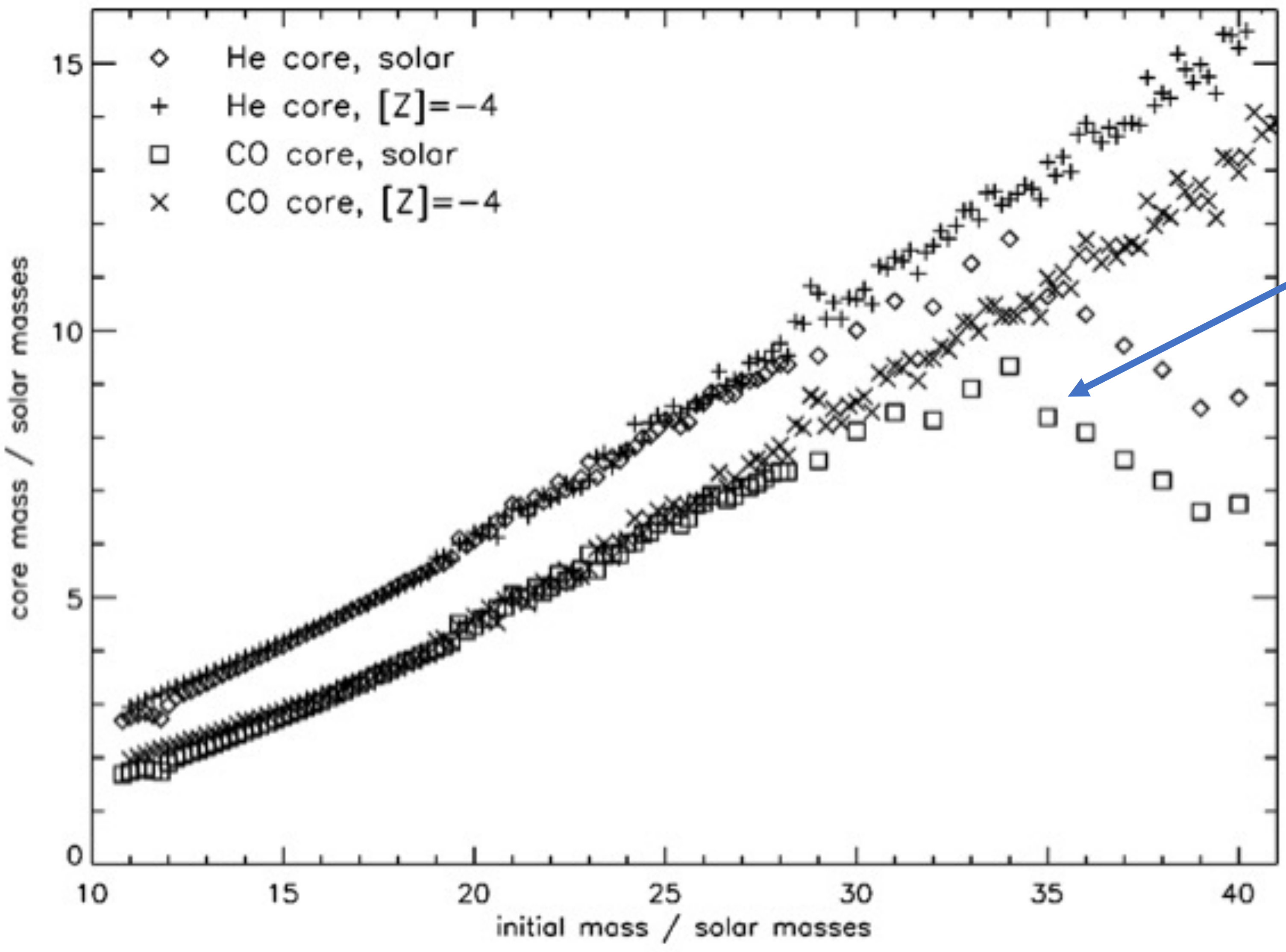
CO core masses: Shell He burning makes only modest growth (so the CO core is well defined at core He exhaustion)



Final CO core masses vs M_{ZAMS}

A "standard" stellar evolution grid predicts CO core masses of ~1.5 - 10 M_{sun} for solar metallicity stars.

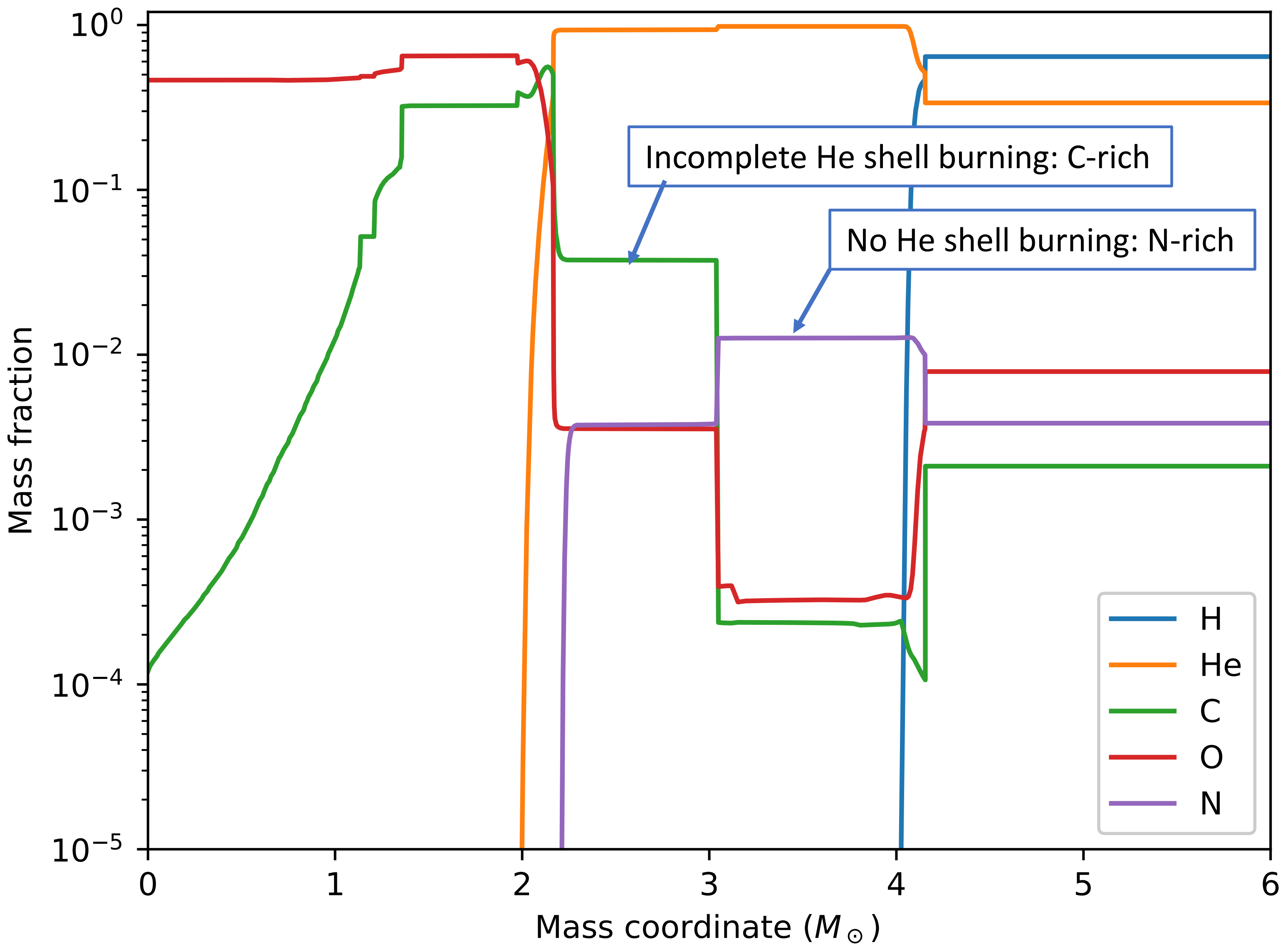
He core masses ~2.5 - 12 $M_{sun.}$



At ~ solar metallicity, mass loss leads to declining final CO masses for $M_{ZAMS} > 35\ M_{\odot}$.

Woosley, Heger, Weaver 2002

Incomplete He shell burning converts part of the He/N layer to a He/C layer that is ejected in the eventual supernova and is an important diagnostic.

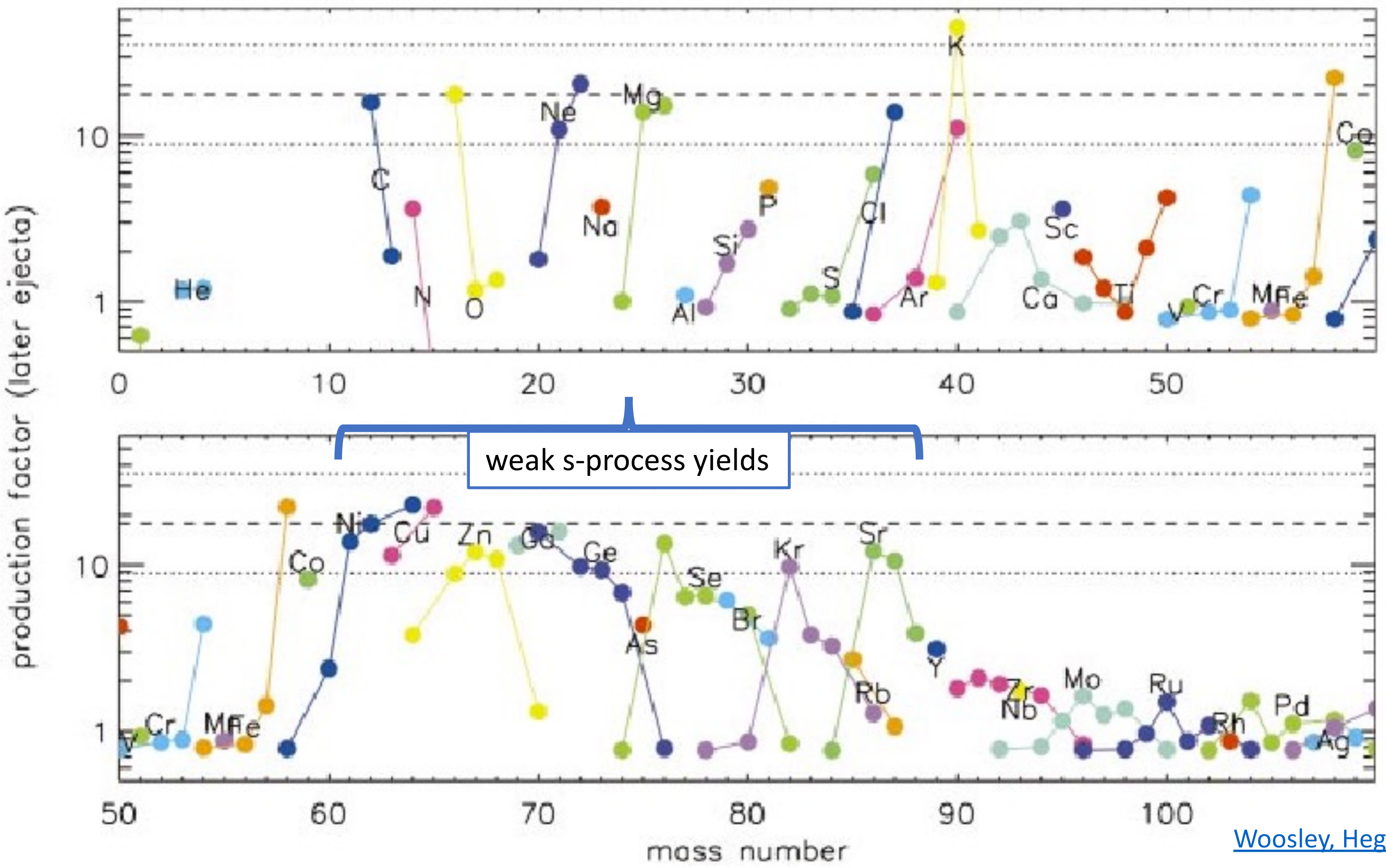


MESA simulation of a 15 M_{sun} star, core C exhaustion stage.

Shell He burning: massive stars

- The **weak s-process** occurs mainly during the He burning stage in massive stars. Lower neutron fluxes than in AGB stars → harder to bridge over fast radioactive steps and the chain is limited to lower A nuclei.

- Starting reaction ^{22}Ne + He requires $T \gtrsim 3 * 10^8\ K$: only at end of He burning is it that hot.

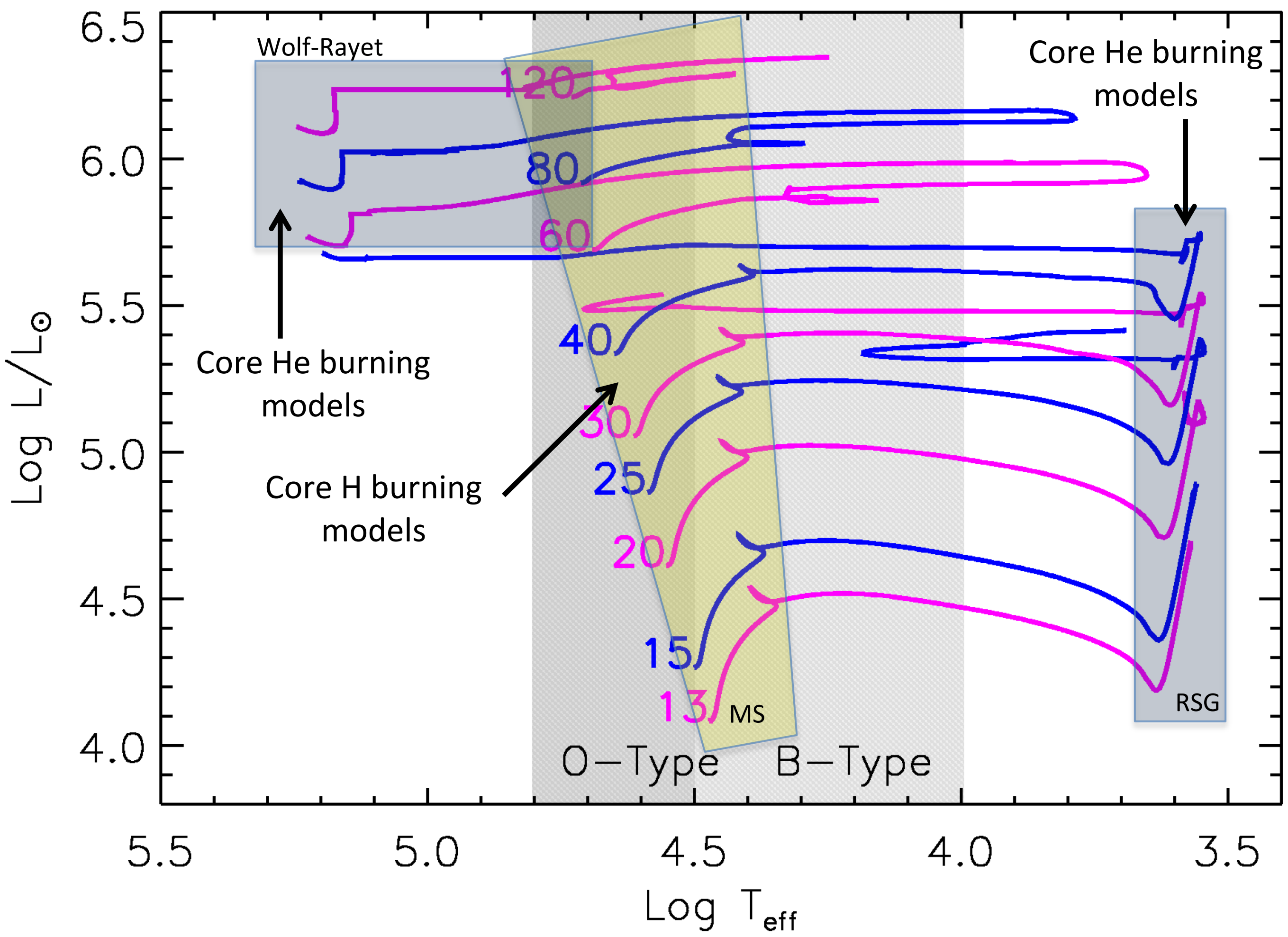


M_{ZAMS} = 25 M_{sun}, end of He burning.

Woosley, Heger, Weaver 2002

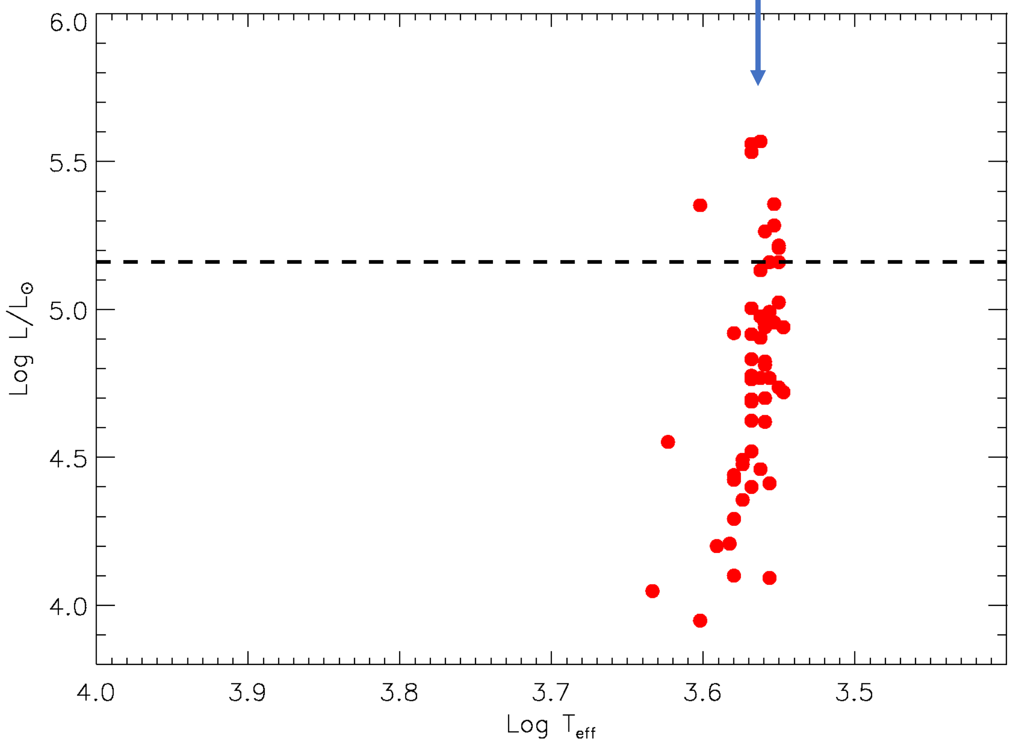
OBSERVATIONAL PROPERTIES OF HE BURNING STARS

The most massive stars ($M_{ZAMS} \gtrsim 40\ M_{\odot}$) blow off much mass (Part G) and spend most of their He burning phase as compact Wolf-Rayet stars rather than as supergiants.



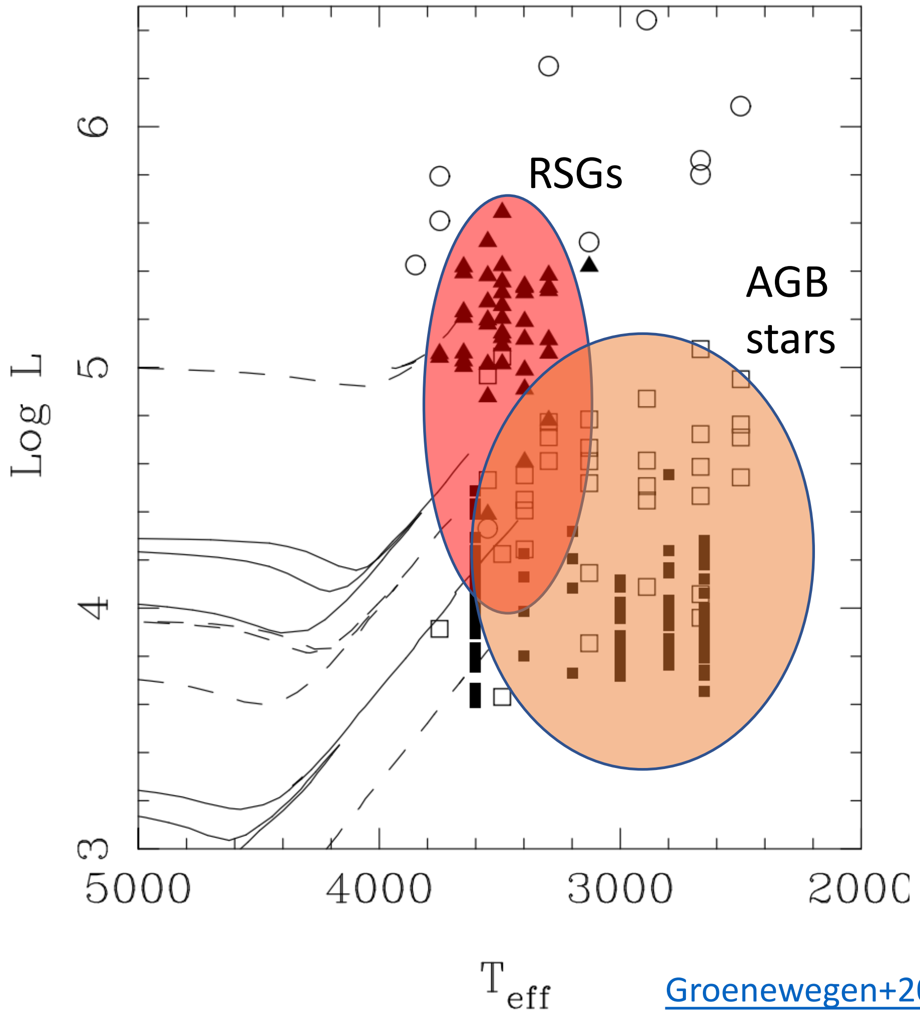
Credit:
Marco Limongi

Most luminous observed RSGs are at log L ~ 5.6



Levesque+2005

What differs red supergiants from AGB stars?



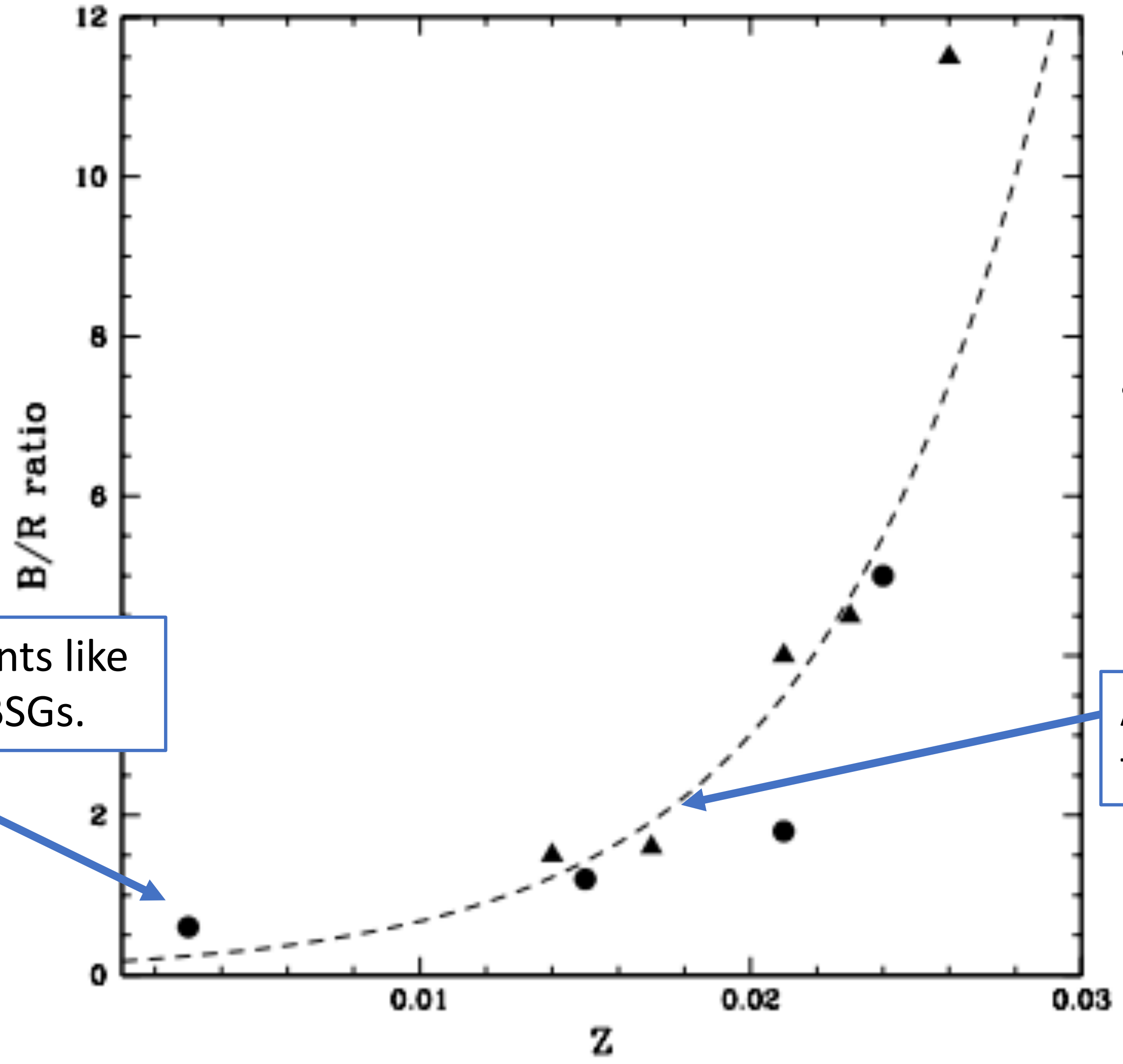
Groenewegen+2009

Fig. 9. The Hertzsprung-Russell diagram. C-stars are plotted as filled squares, M-type AGB stars as open squares, RSGs as filled triangles, and foreground objects as open circles. Lines indicate evolutionary tracks by Bertelli et al. (2008) for 20, 10, 8, 5, and 3 $M_{\odot}$ (*top to bottom*) for $Z = 0.008$.

- Red supergiants are somewhat brighter and somewhat hotter than AGB stars.

	RSG	AGB
Log L	4.8 - 5.5	3.5 - 5.0
T_{eff}	2500 - 3600 K	3300 - 3800 K

Observed supergiants can be red or blue. More often in blue state at higher metallicity.



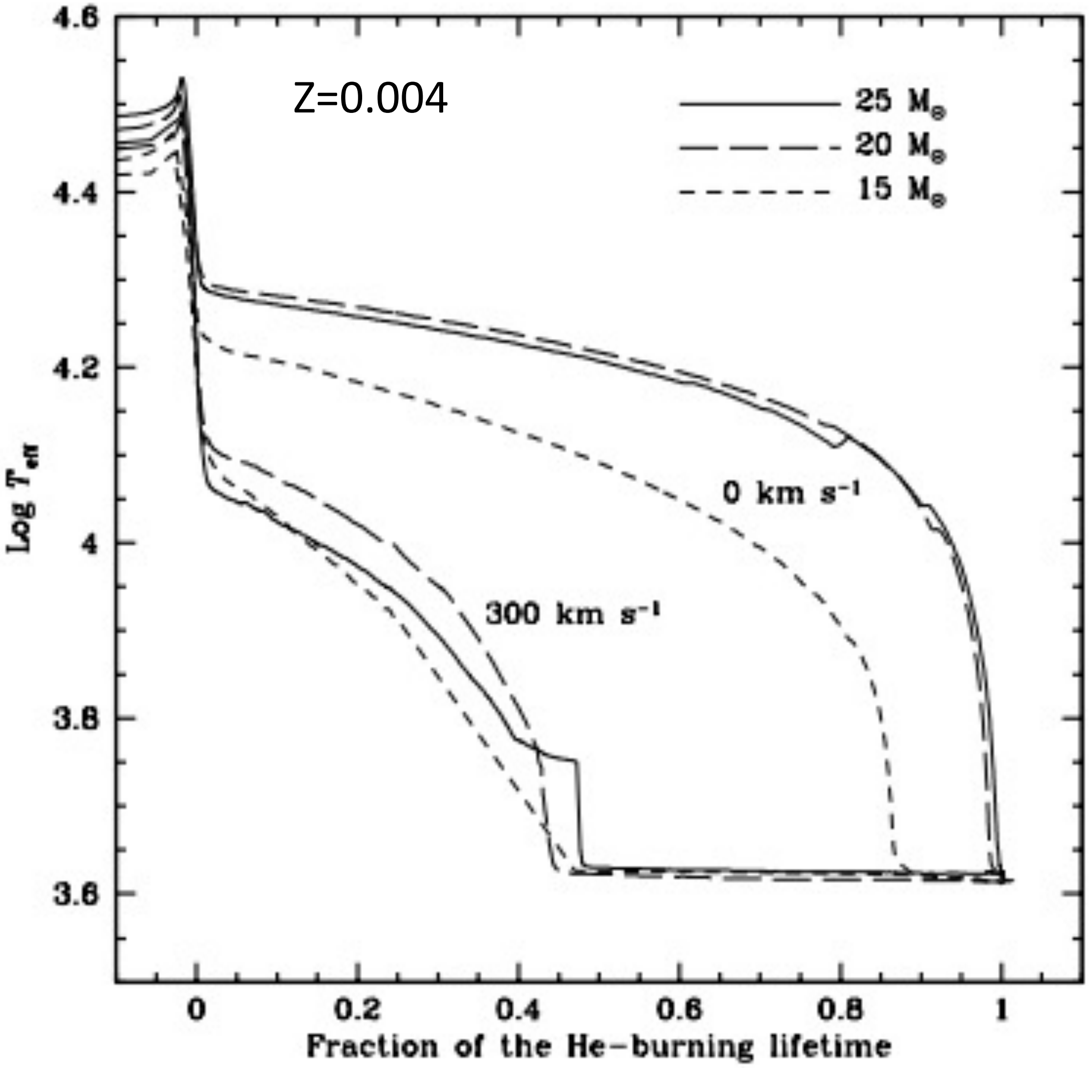
In low-metallicity environments like LMC/SMC, more RSGs than BSGs.

At solar metallicity about 2 BSGs for each RSG.

- Movements between blue and red sensitive to details in envelope. Physics is not fully understood. Higher mass loss at higher *Z* could be one reason BSG favoured at high *Z*.
- Efficiency of semi-convection can be calibrated to best reproduce BSG/RSG ratio vs *Z*.

Eggenberger+2002

Evolution is predicted to be BSG → RSG (mainly).



BSG

RSG

"Blue loops" (RSG → BSG → RSG) can also occur in some models (not shown here).

Maeder+2001

After decades of stellar evolution modelling, in the mid 1980s there was complete consensus that all massive stars will *end* as RSG.

Then, the first naked eye SN seen in 400 years (SN 1987A) was the explosion of a BSG!