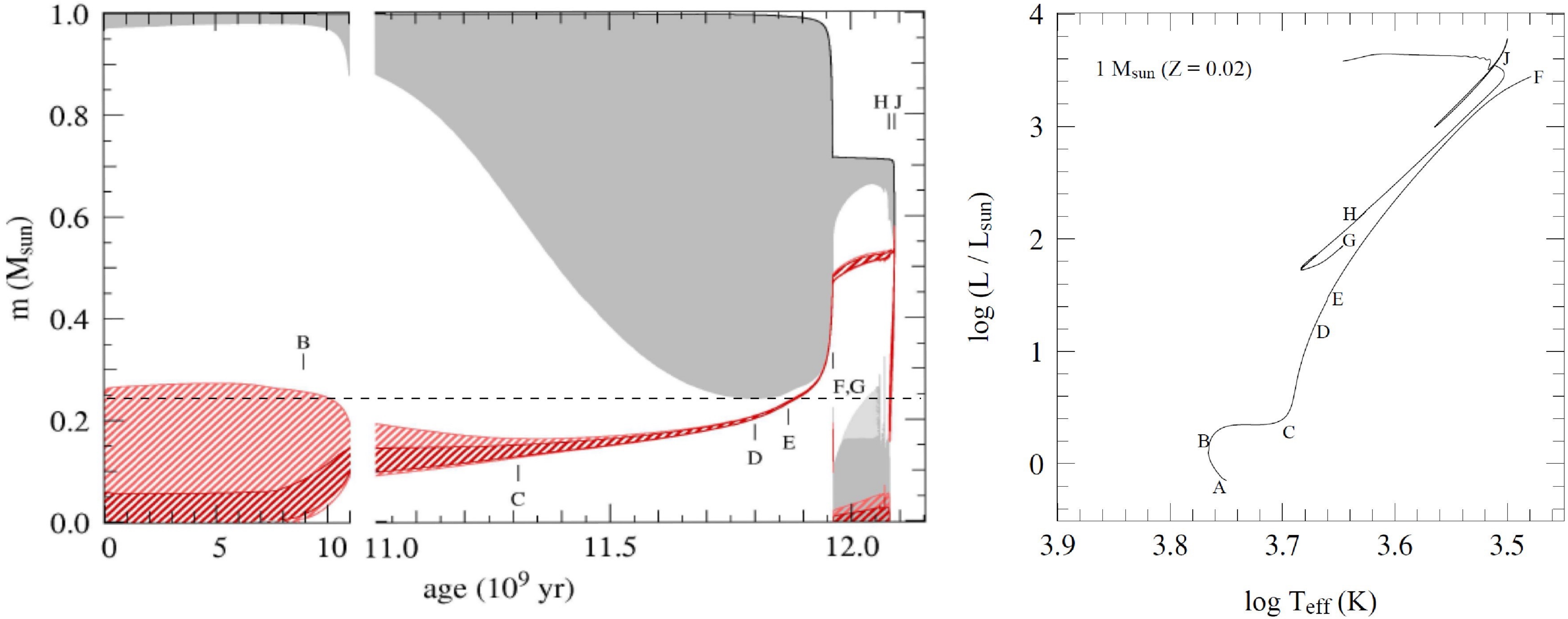
Lecture 13: After the Main Sequence

Lamers & Levesque Ch. 14, 16–19



Midterm: in class Tuesday March 8

will cover course material through March 1st Lecture 13

things to review (roughly in order of importance):
- problem sets 1–3 (& solutions)
- lecture slides
- Phillips Ch. 1–5 (esp. end of chapter summaries)
- Lamers & Levesque Ch. 1–11, 13, 14, 16–19

exam will be 80 minutes; 441/541 have same exam

mix of conceptual questions (short answer), derivation, and some short calculations (bring a calculator)

you are allowed to bring a formula sheet:
- ***one side only*** of a 8.5” x 11” (letter size) sheet of paper

Principles of Post-MS Evolution

Evolution of the core

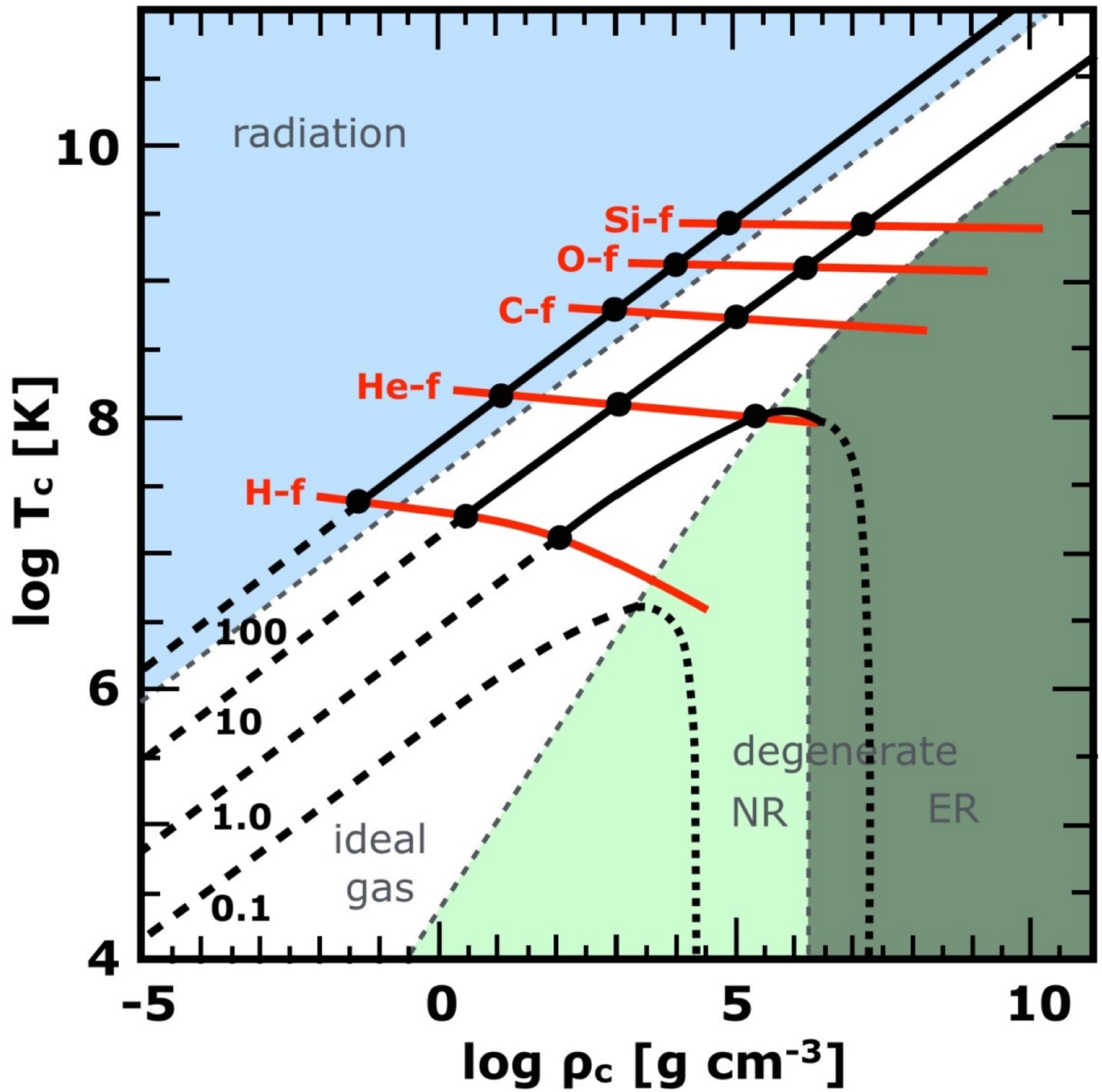
M ≲ 0.08M$_\odot$: stars do not reach H fusion

0.08M$_\odot$ ≲ M ≲ 0.8M$_\odot$: stars reach H but not He fusion

0.8M$_\odot$ ≲ M ≲ 2M$_\odot$: stars reach He fusion

2M$_\odot$ ≲ M ≲ 8M$_\odot$: stars hit C fusion…

8M$_\odot$ ≲ M: stars go through all fusion phases…



Principles of Post-MS Evolution

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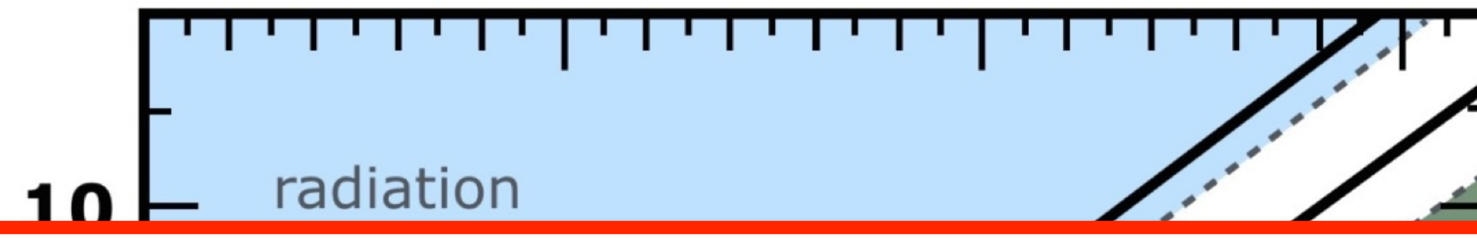
$0.8M_\odot \lesssim M \lesssim 2M_\odot$: stars reach He fusion

$2M_\odot \lesssim M \lesssim 8M_\odot$: stars hit C fusion…

$8M_\odot \lesssim M$: stars go through all fusion phases…

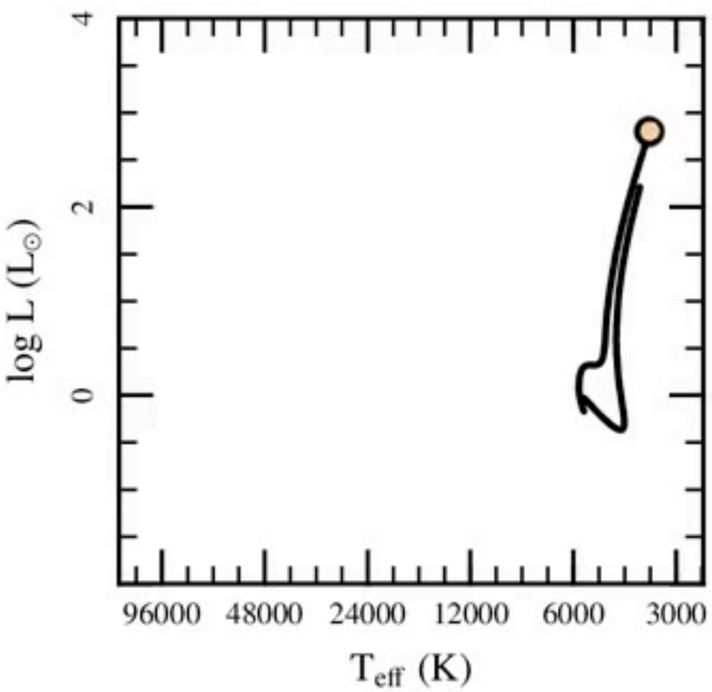


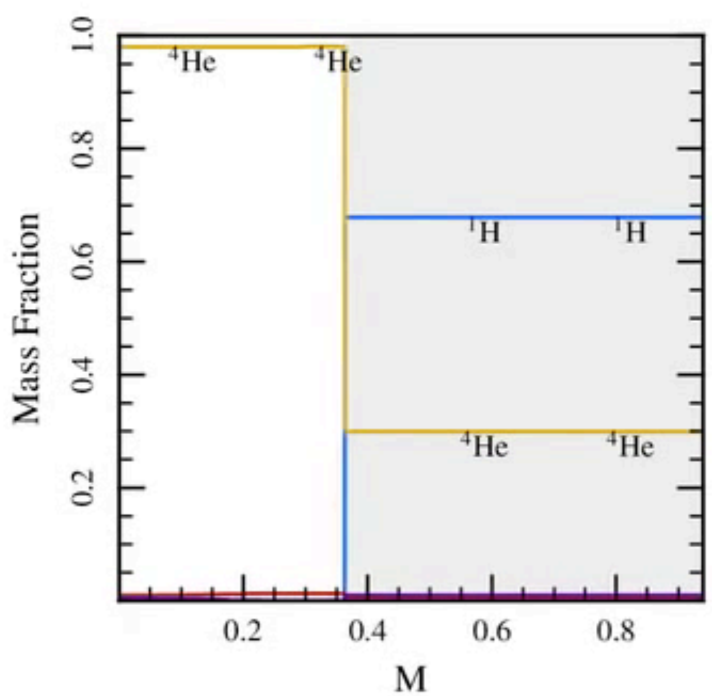
Caveats

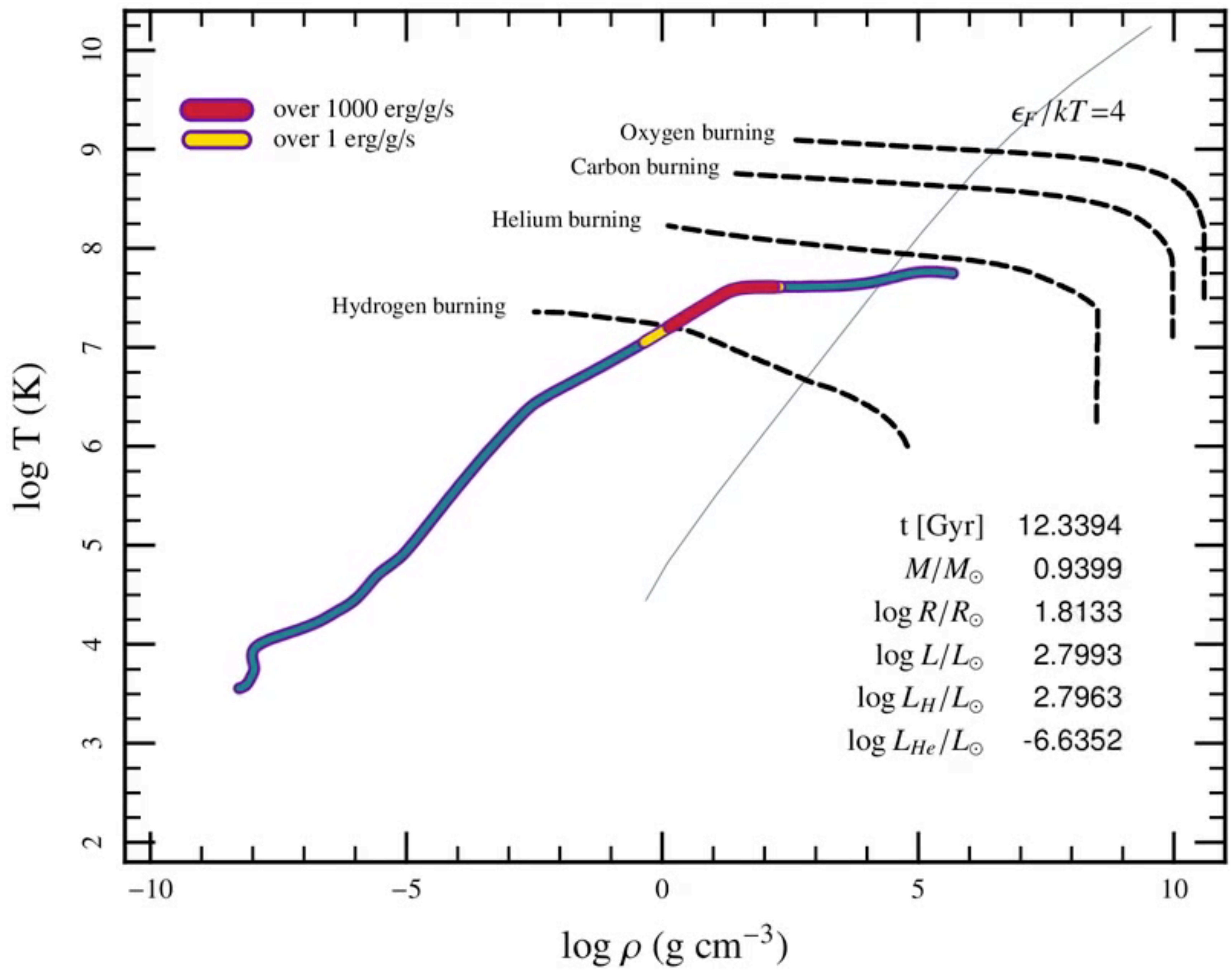
—at the end of a fusion phase, only the region that was taking part in fusion contracts. *That* mass (M_c) is a better predictor of whether or not a star will reach a certain fusion phase.

—mass loss (due to winds or other interactions) also impacts how well we can map *total initial mass* to core mass

MESA: open stellar modeling code

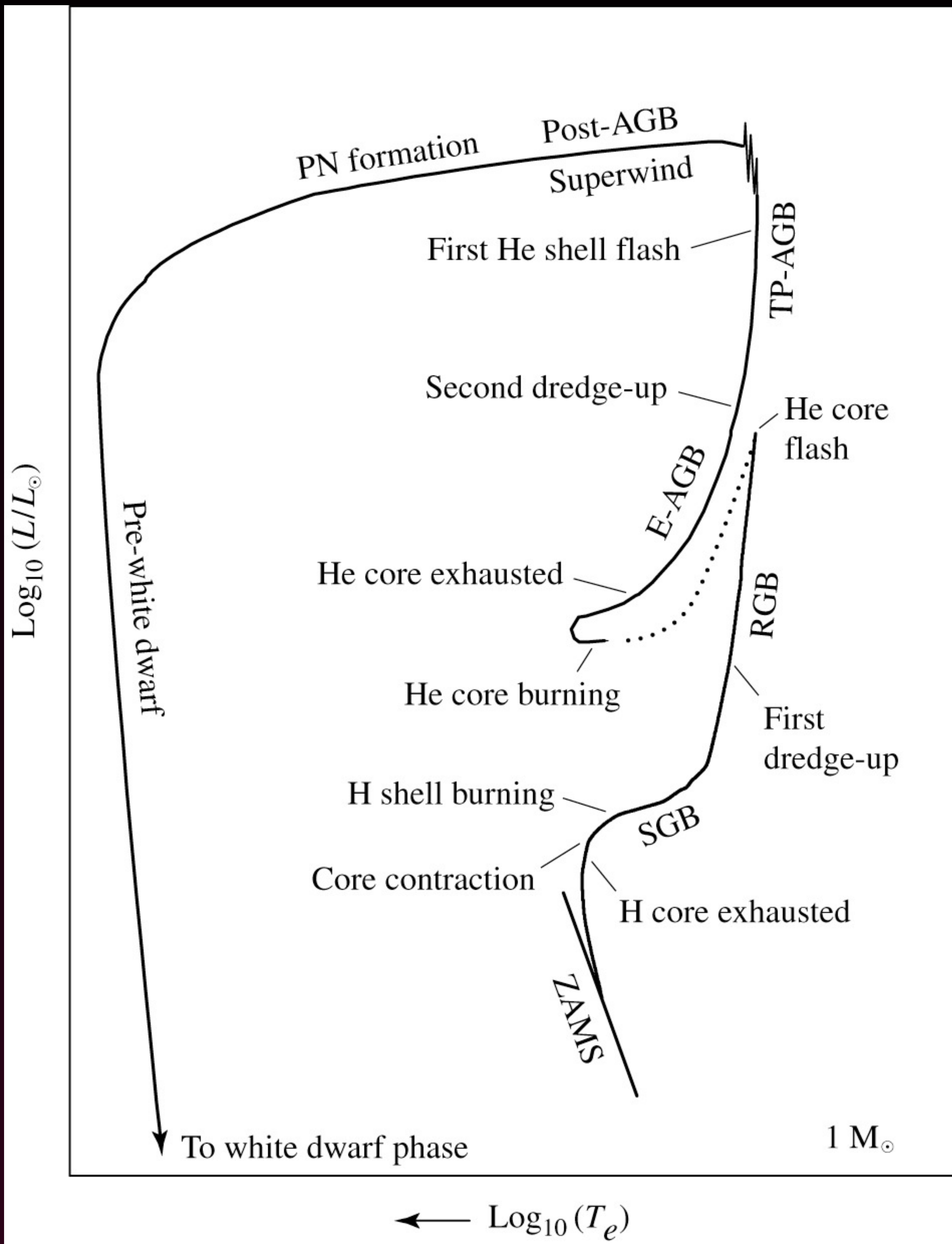






from Josiah Schwab, MESA model of a 1 solar mass star
https://www.youtube.com/watch?v=oZY3TtA63sE

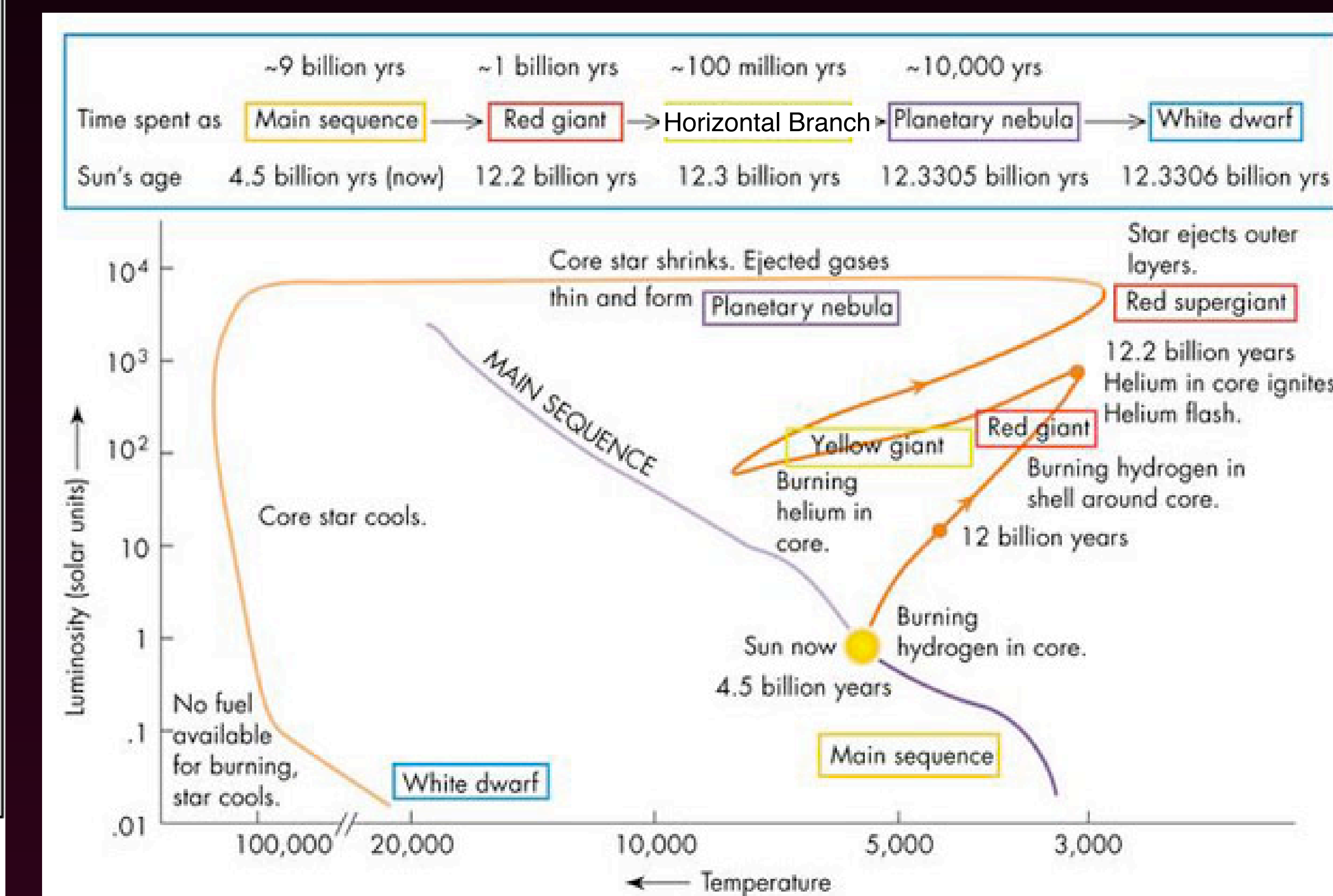
One solar mass stellar evolution



Carroll & Ostlie Figure 13.4

Hydrogen core burning	Main sequence	10^{10} yr
Hydrogen shell burning	Red giant branch	10^{9} yr
Helium core burning	Horizontal branch	10^{8} yr
Helium shell burning	Asymptotic giant branch	10^{7} yr
Mass loss	Planetary nebula	10^{4} yr
Electron degeneracy	White dwarf	

Keeton sec.16.3.1 (p. 340)



from http://cas.sdss.org/dr4/en/astro/stars/stars.asp

Principles of Post-MS Evolution

a) Isothermal cores: the Schönberg-Chandrasekhar limit

see L&L 14.1 for derivation

$$\boxed{\frac{M_c}{M} \lesssim C \cdot \left(\frac{\mu_{\rm env}}{\mu_c}\right)^2}$$

(with C=0.37)

At the end of H-fusion in the core, the remaining isothermal He core with μ_c=4/3 can only be stable if:

$$\frac{M_c}{M} < 0.37 \left(\frac{0.60}{1.33}\right)^2 \approx 0.08$$

In reality the lower part of the envelope also has increased He-abundance so μ_{env} > 0.6 ⟶ **M_c/M < 0.10**

If M_c < 0.10M, H-shell fusion occurs around a stable He core.

If M_c > 0.10M, the He core can't support the shell+envelope, so it will contract during the H-fusion in a shell around it.

The contraction creates a dT/dr & energy flux in the core, ∴ must continue until He-fusion starts.

$$\tau_{\kappa \rm H} \simeq \frac{GM_c^2}{R_c} / (L - L_{\rm shell})$$

→ **degenerate He core**

Principles of Post-MS Evolution

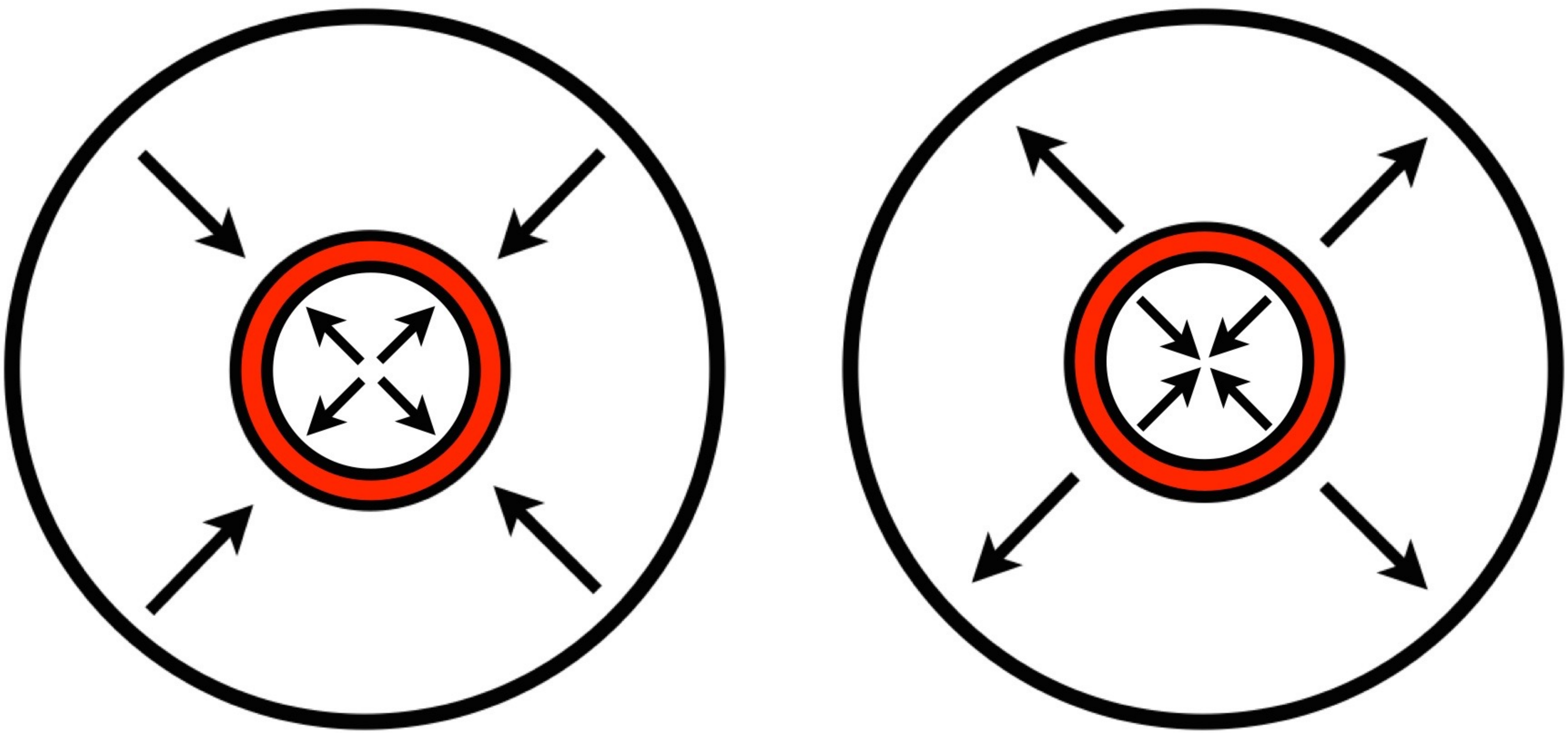
b) the "mirror effect" in stars with shell burning

Whenever a star has a shell burning source, it appears to act like a mirror:

see L&L 14.2 for reasoning, e.g. "virial argument"

expanding core = contracting envelope

contracting core = expanding envelope

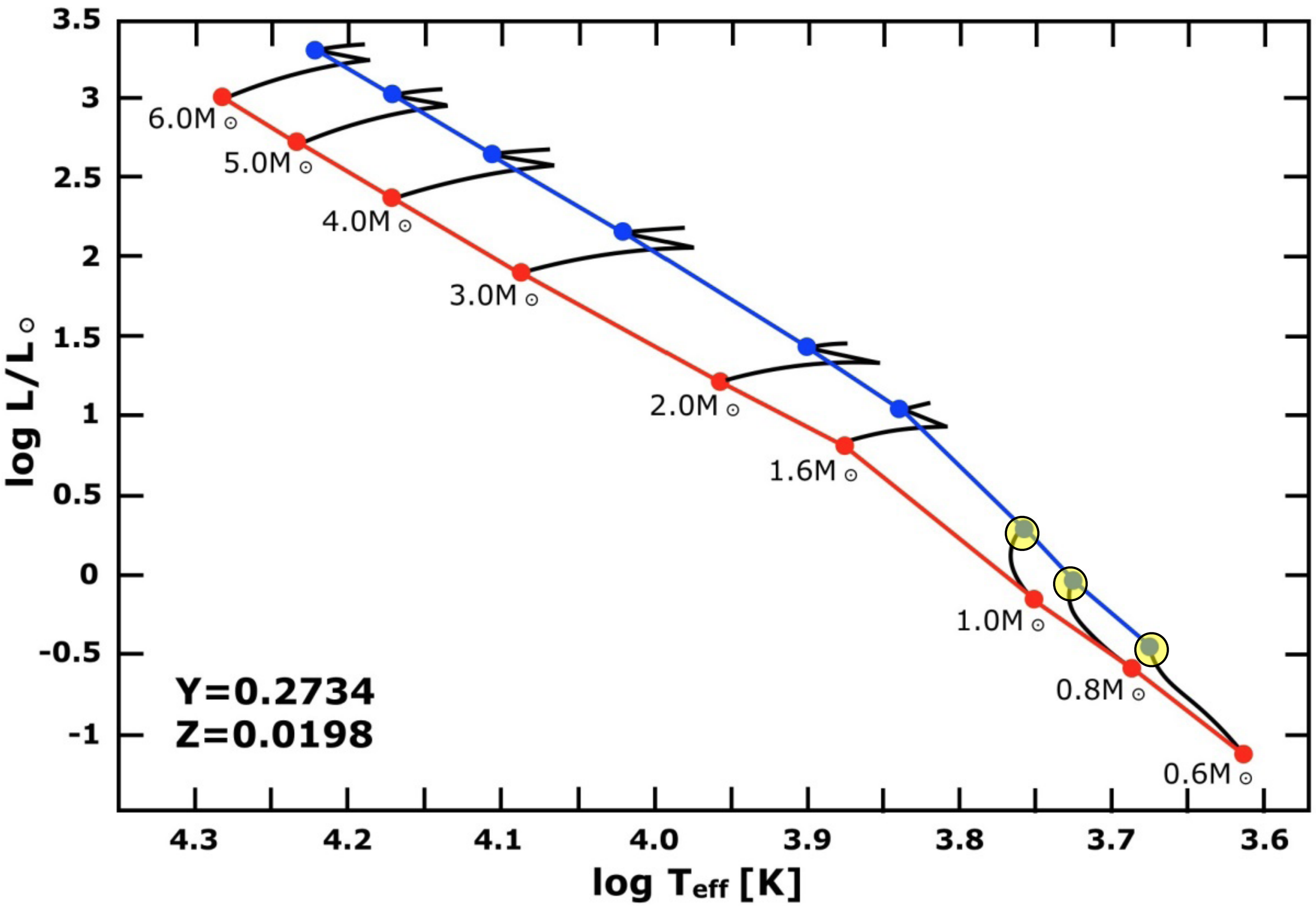


Hydrogen shell fusion

Once hydrogen is exhausted in a star's core, the core begins to contract along with the layers around it. The T of these layers increases, igniting shell fusion at $T > 10^7$ K.

—For $M_i \gtrsim 1.2M_\odot$, which have a convective core on the MS, the whole star contracts before H-shell fusion begins, creating a small left loop in the evolutionary tracks on the HRD.

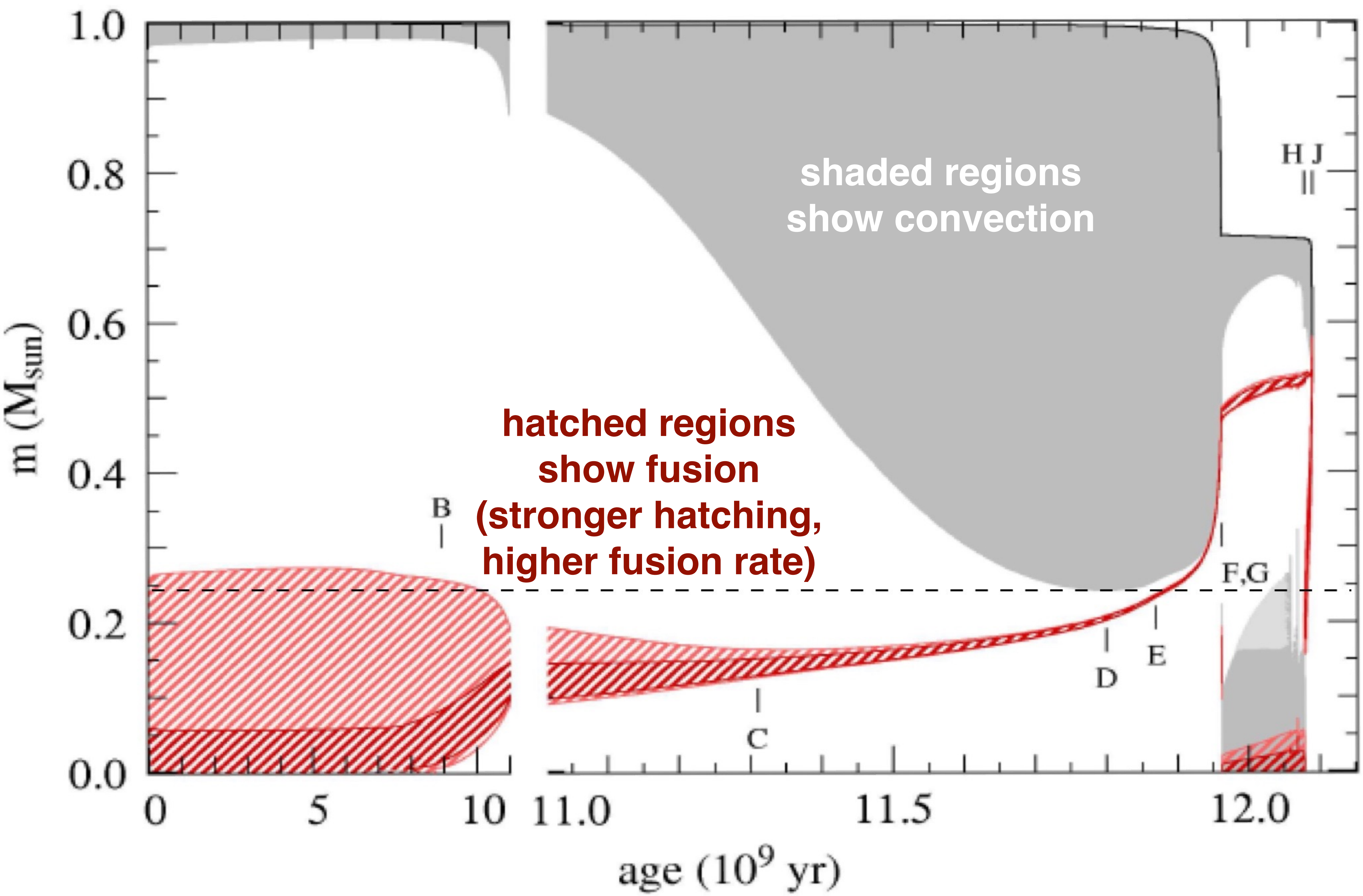
—For $M_i \lesssim 1.2M_\odot$, H-shell fusion starts gradually, reflecting the star's chemical profile. As a result, the star does not contract and there is no corresponding HRD loop.



Kippenhahn diagrams

aim to show star's whole evolution on one plot

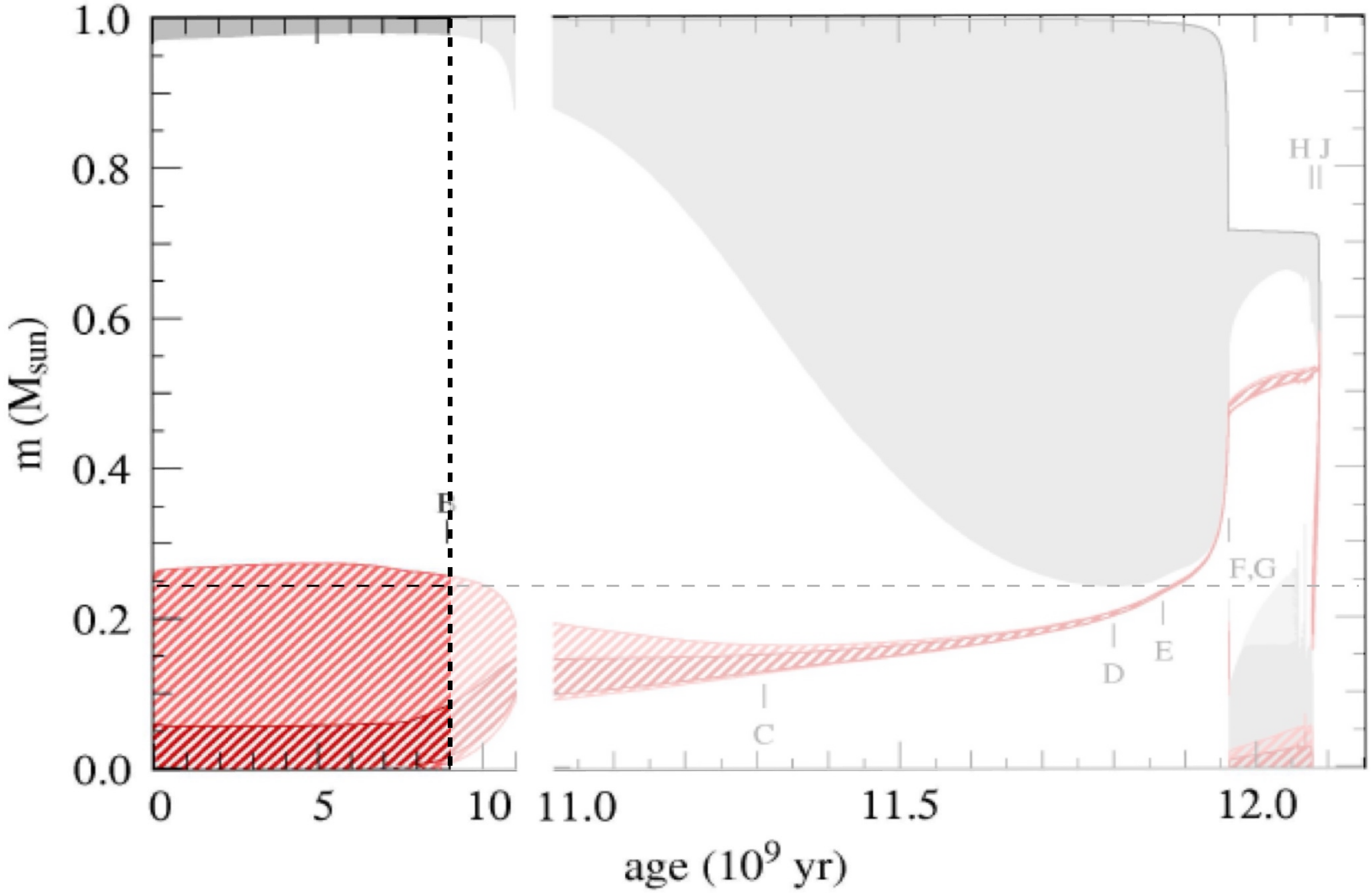
y-axis is enclosed mass (radius can vary)

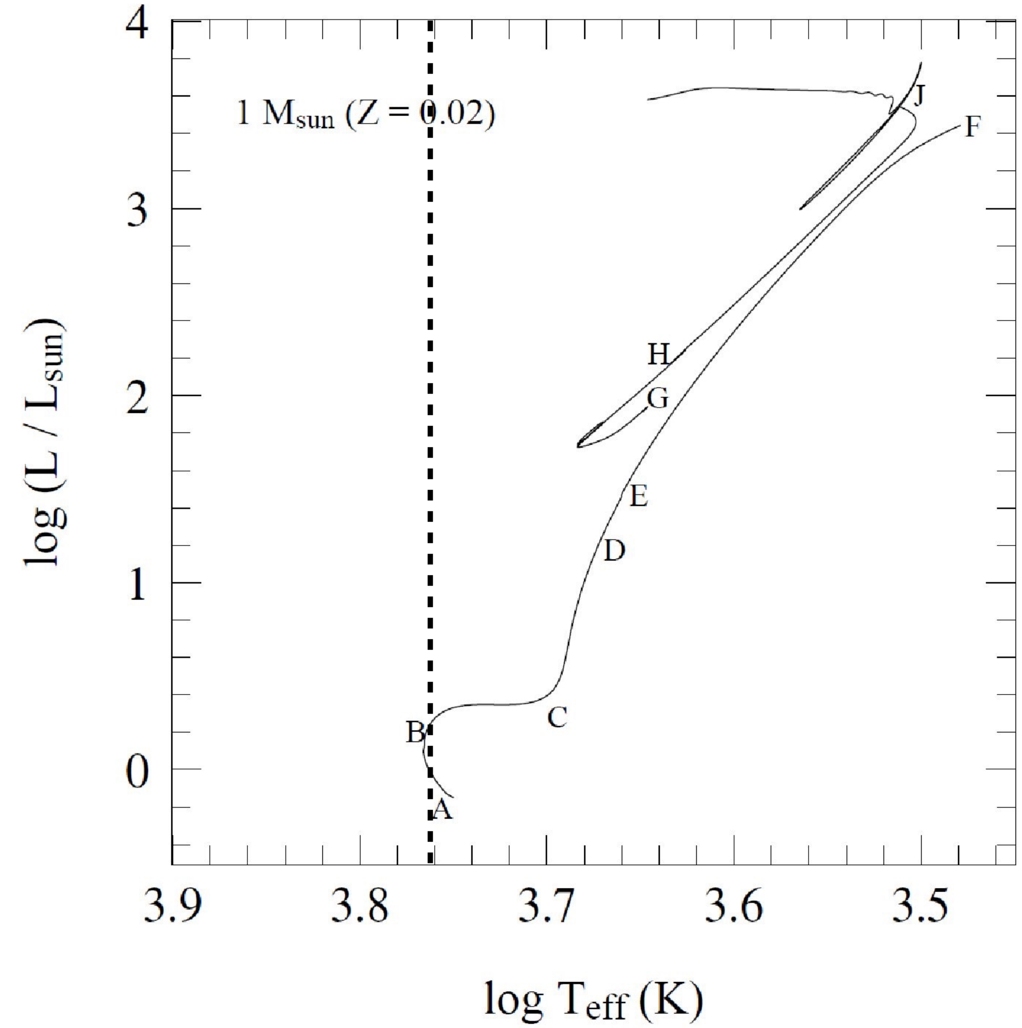


x-axis is time (non-linear! compressed/stretched/broken!)

Hydrogen shell fusion

Kippenhahn diagram & HR diagram for an evolving 1M☉ star:

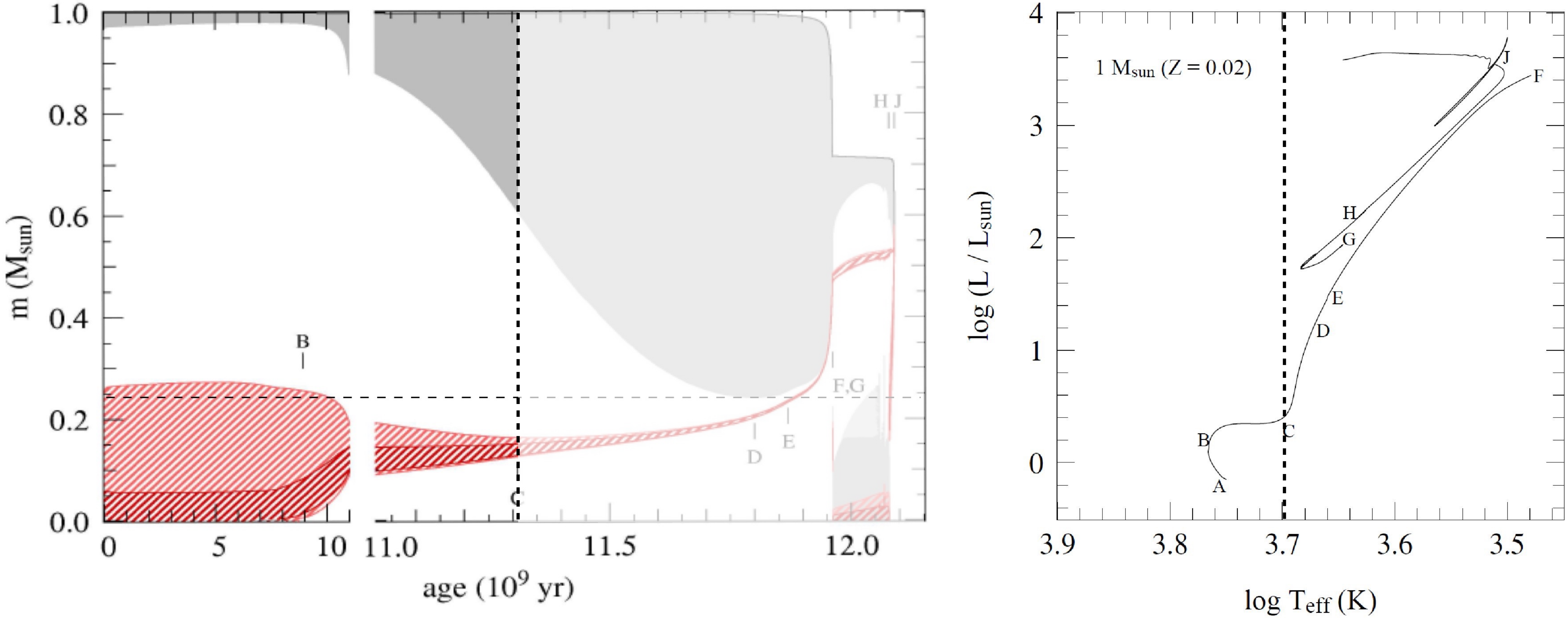




A-B: **main sequence** phase of H fusion in the core

Hydrogen shell fusion

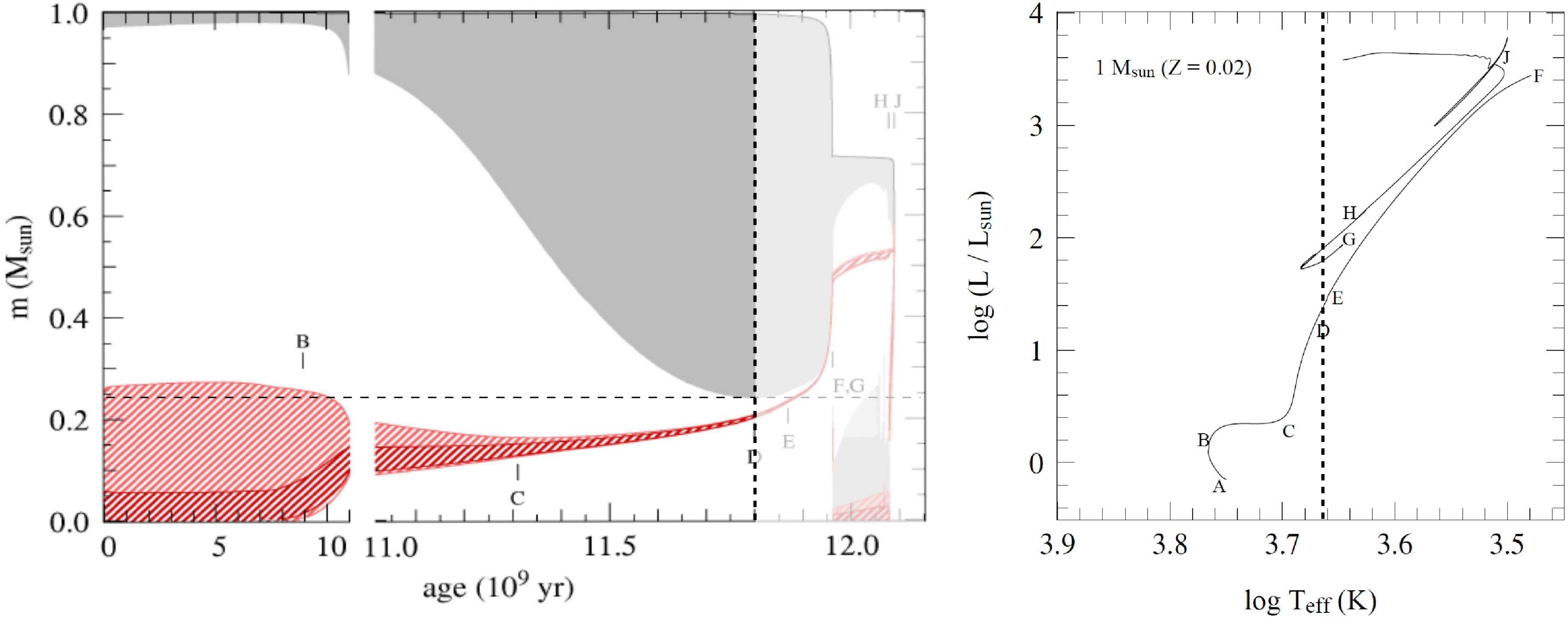
Kippenhahn diagram & HR diagram for an evolving 1M$_\odot$ star:



B-C: H is exhausted in center; core contracts and T increases; H fusion ignites in a shell around the core; He core exceeds SC limit and continues to contract, so envelope expands & larger fraction of star becomes convective; **sub-giant branch**
C: half the star is convective; He core is degenerate; star is a **red giant**

Hydrogen shell fusion

Kippenhahn diagram & HR diagram for an evolving 1M$_\odot$ star:

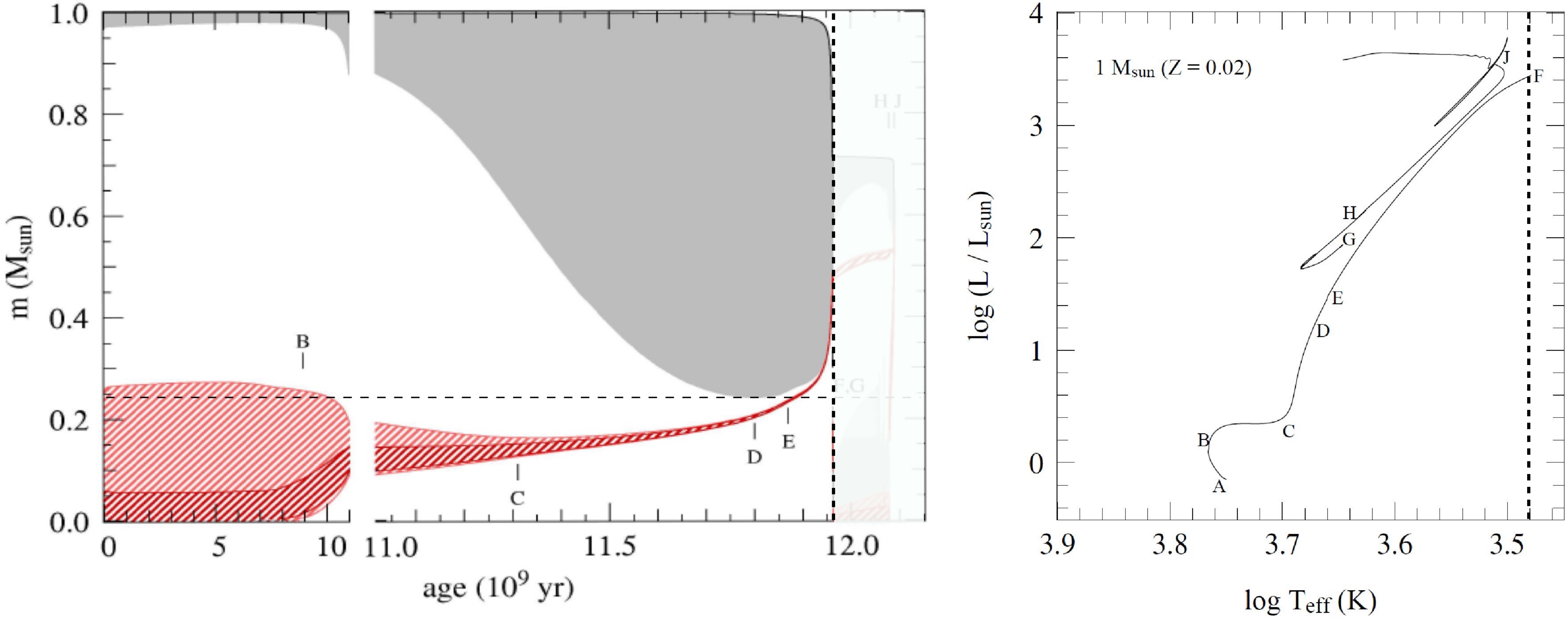


C-D: mirror effect continues as H shell fusion adds mass to degenerate He core; as core contracts, shell moves with it to higher ρ and T, so L increases: **climbing RGB**

D: convection reaches so deep that products of H fusion are mixed to surface, enriching He and N and decreasing C and O; **first dredge-up**

Hydrogen shell fusion

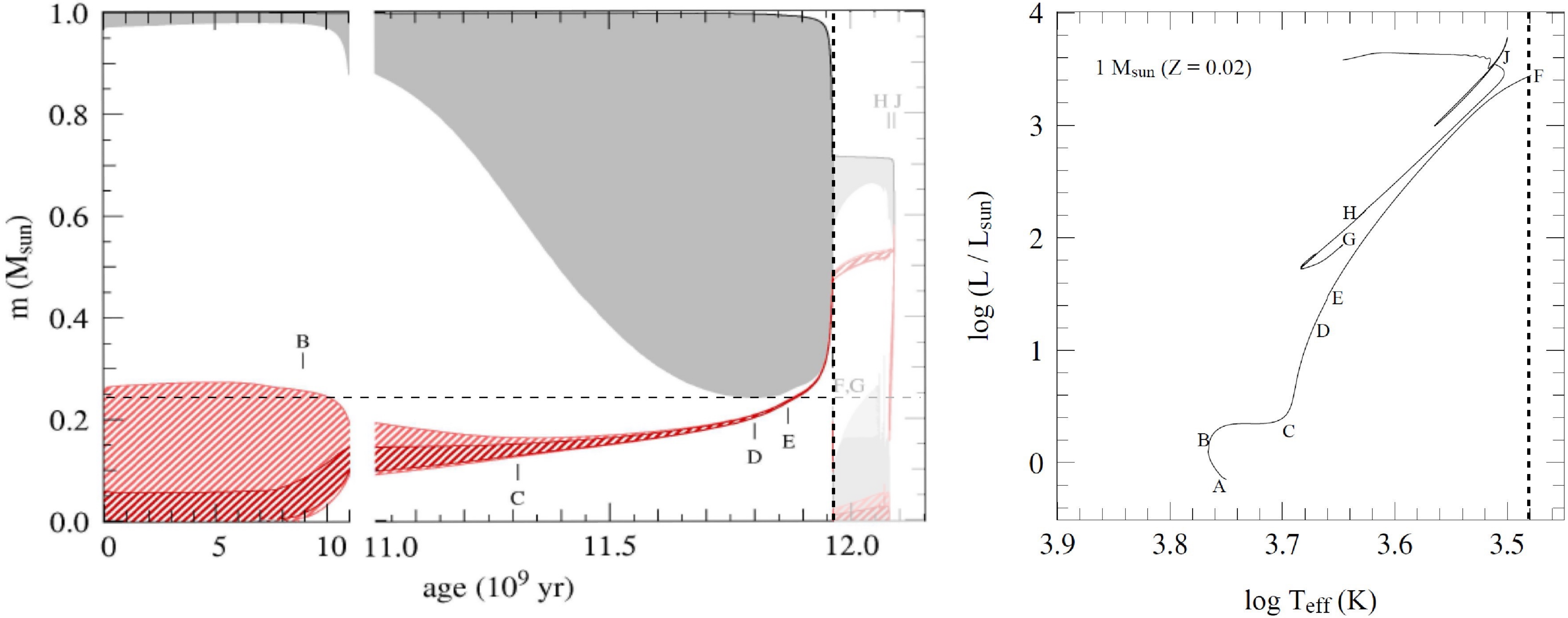
Kippenhahn diagram & HR diagram for an evolving 1M$_\odot$ star:



D-E-F: degenerate core increases in mass and shrinks, continuing envelope expansion and rapid luminosity increase
E: shell reaches mass zone previous hit by deepest extent of convective envelope, now H-depleted. H fusion rate decreases, μ decreases, and L drops, creating a small loop in the evolutionary track.

Hydrogen shell fusion

Kippenhahn diagram & HR diagram for an evolving 1M⊙ star:



E-F: in this phase fusion is slower (H shell is burning in a region of high H abundance), so E-F lasts longer than D-E despite being at a higher L

F: core contracts enough to ignite He core fusion; star leaves the red giant branch

(F-J will be covered a bit later…)

Hydrogen shell fusion

Intermediate Masses (2-8$M_\odot$)

This evolution is very similar to that of lower-mass stars but includes a few key differences:

a) At this higher mass, the He core mass is initially below the SC limit so the core does not immediately contract. This begins later when He is added to the core by H shell fusion.

b) The He core does *not* become degenerate during H shell fusion due to the higher T and lower ρ at the start of H shell fusion.

c) H shell fusion ends when the He core mass is only slightly higher than the value of $M_c \approx 0.5 M_\odot$ for the lower mass stars.

d) Evolution timescales are shorter:

Phase	**1$M_\odot$**	**5$M_\odot$**
MS	9.0 Gyr	82 Myr
TAMS-Hayashi	2.3 Gyr	2.4 Myr
Hayashi climb	160 Myr	0.3 Myr

He fusion - the horizontal branch

He fusion ignition in low mass stars

Once the He core mass reaches ~$0.5M_\odot$, at the tip of the RGB, it reaches $T_c \sim 10^8$K and core He fusion begins, further increasing T.

$M_i \gtrsim 2M_\odot$ (non-degenerate core): T increase leads to P increase so the core expands. This then decreases T and ρ, decreasing fusion efficiency; the star remains in hydrostatic and thermal equilibrium.

$M_i \lesssim 2M_\odot$ (degenerate core): T increase does NOT lead to P increase so core does not expand, thus increasing energy production. This increases fusion efficiency, raising T and energy production further; this is the **helium flash.**

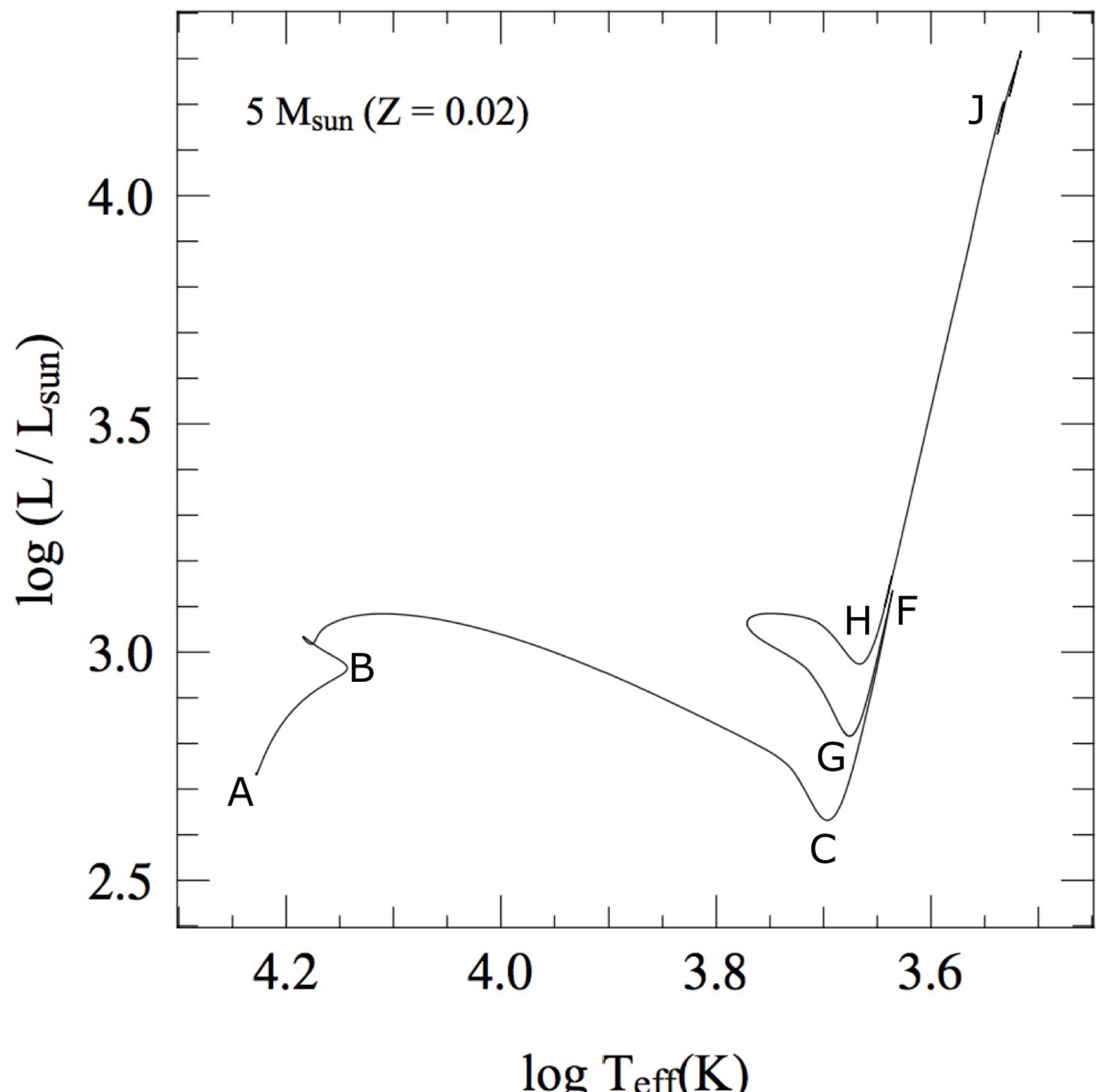
Once T is high enough the core is no longer degenerate, and the star then settles into normal non-degenerate core He fusion.

He fusion - the horizontal branch

He fusion ignition in low mass stars

F: He core fusion ignites

When core He fusion starts the core expands, causing the envelope to contract and decreasing R and L (mirror effect).



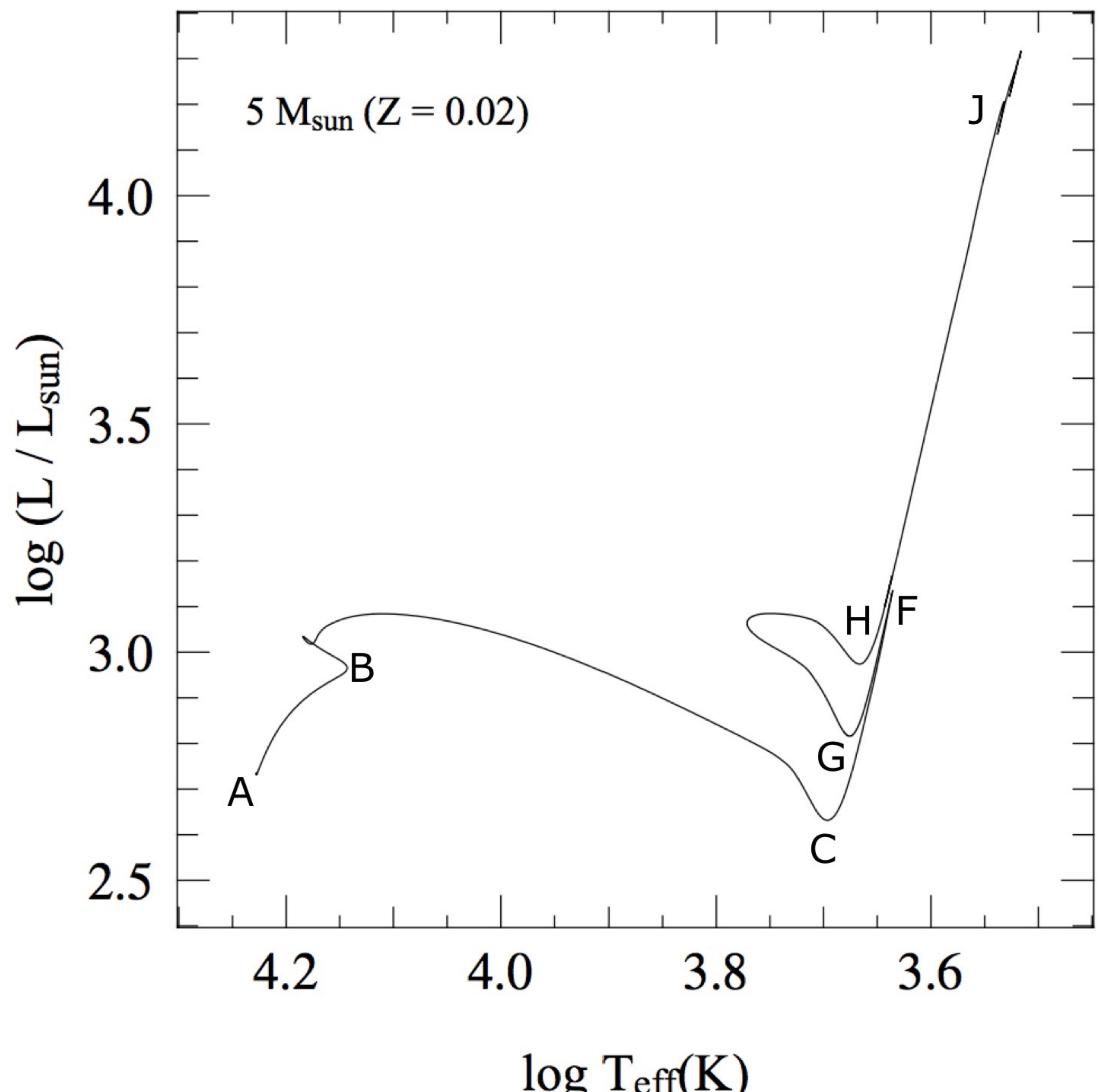
He fusion - the horizontal branch

He fusion ignition in low mass stars

F: He core fusion ignites

When core He fusion starts the core expands, causing the envelope to contract and decreasing R and L (mirror effect).

G: core He fusion in equilibrium begins (F-G cannot be plotted for lower-mass stars that undergo a He flash)



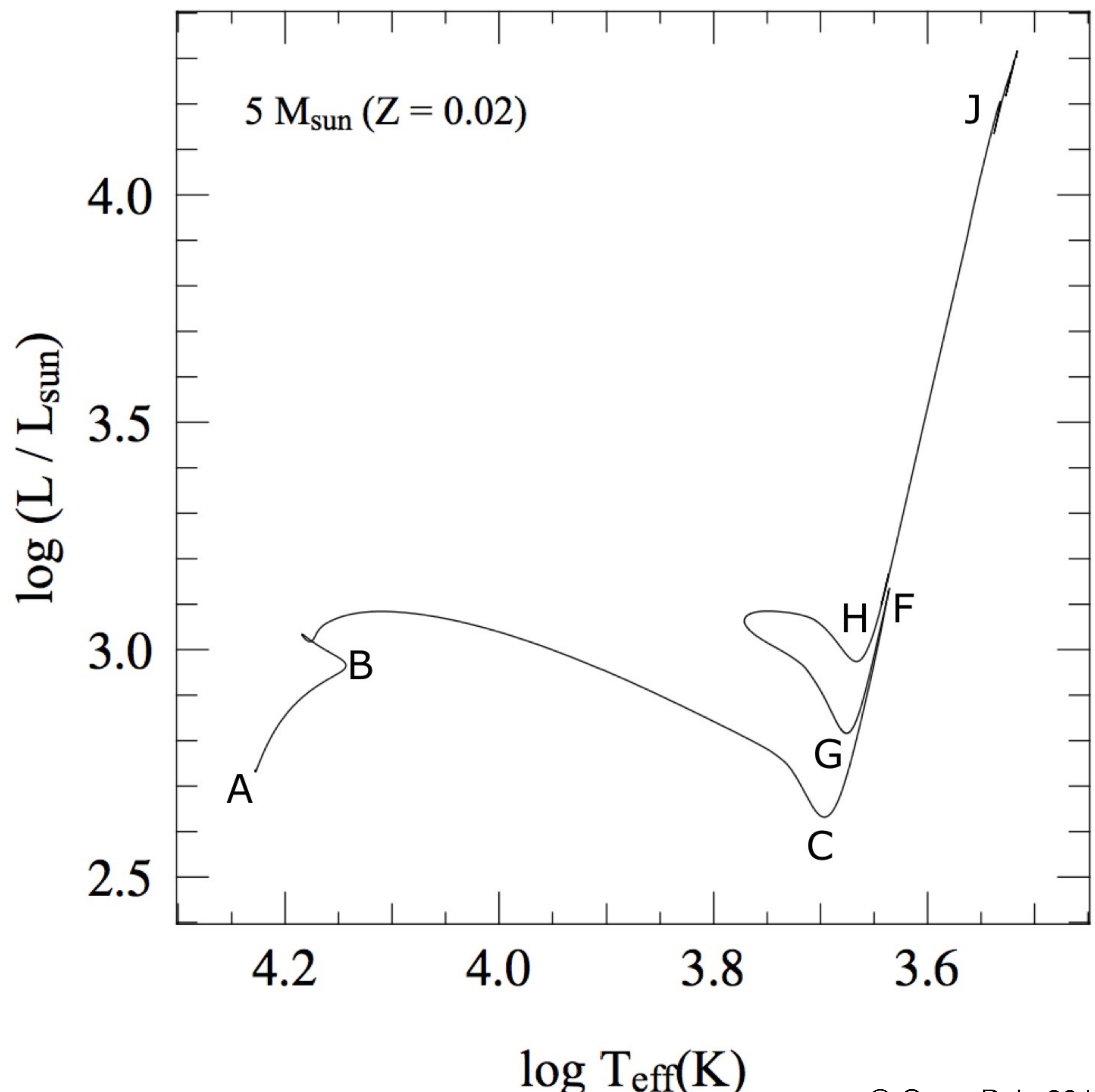
He fusion - the horizontal branch

He fusion ignition in low mass stars

The star traces a **blue loop** in the HRD during core He fusion, due to the increase and decrease of the radius due to the mirror effect.

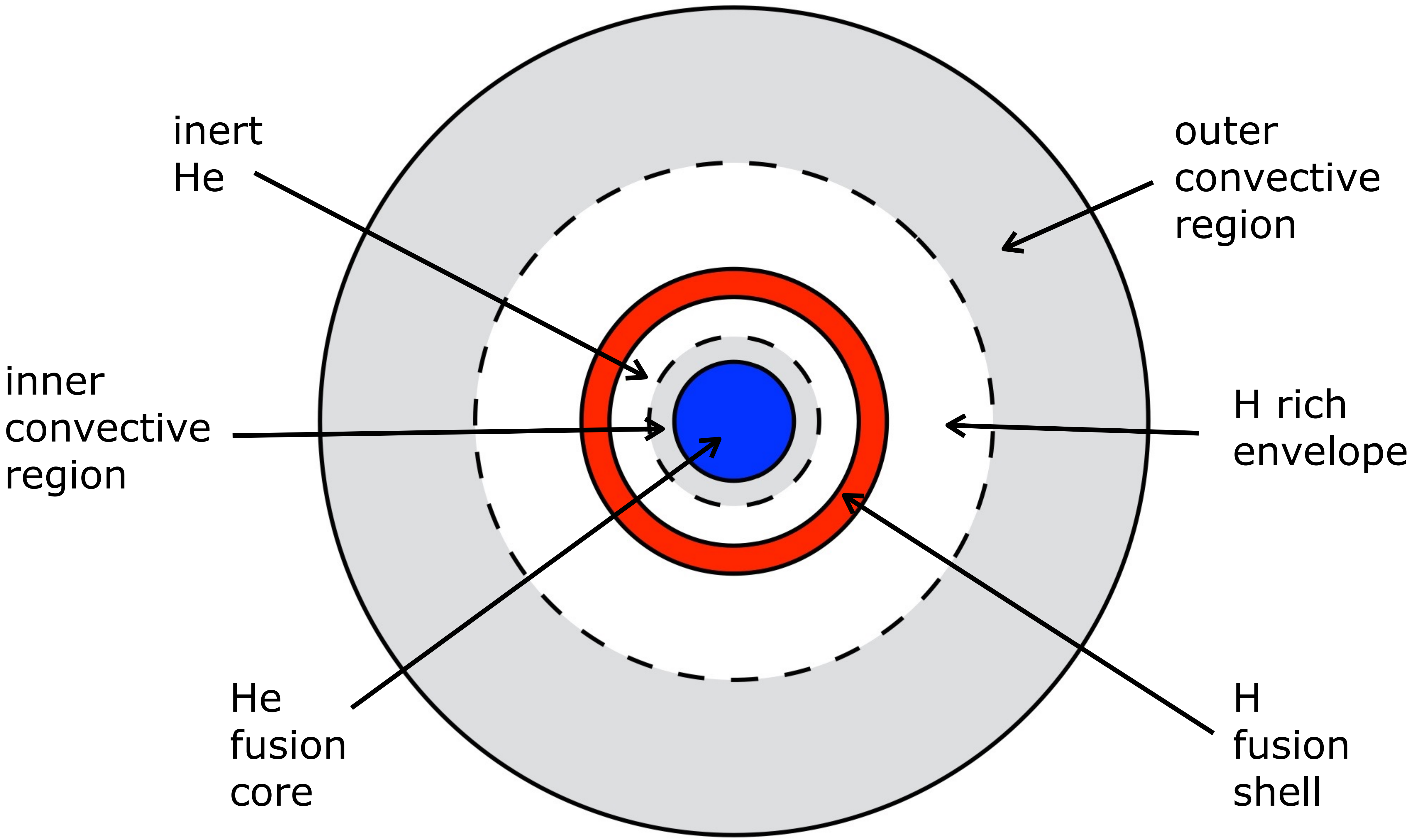
The **G-H** increase in L is once again due to the μ effect that caused brightening during the MS phase.

G-H: the **horizontal branch (HB)**; 120Myr for 1M⊙ star, 22Myr for 5M⊙ star



He fusion - the horizontal branch

Horizontal branch stars



The AGB phase

<u>AGB phase processes</u>

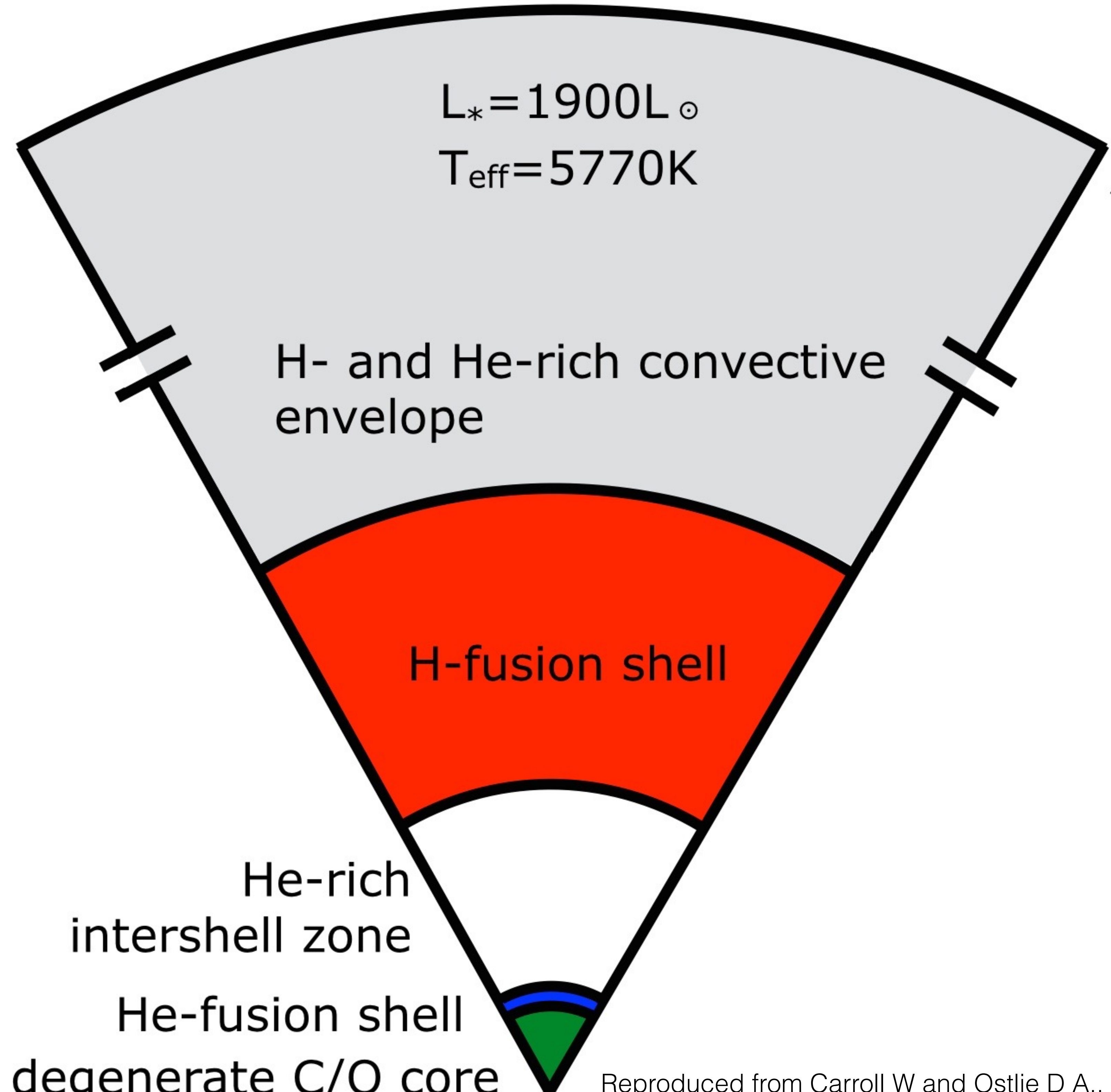
A: degenerate C/O core (M_{core} sets L)

B: periodic swaps between the H-shell and He-shell providing most of the L (thermal pulses)

C: dredge-ups from convective envelope

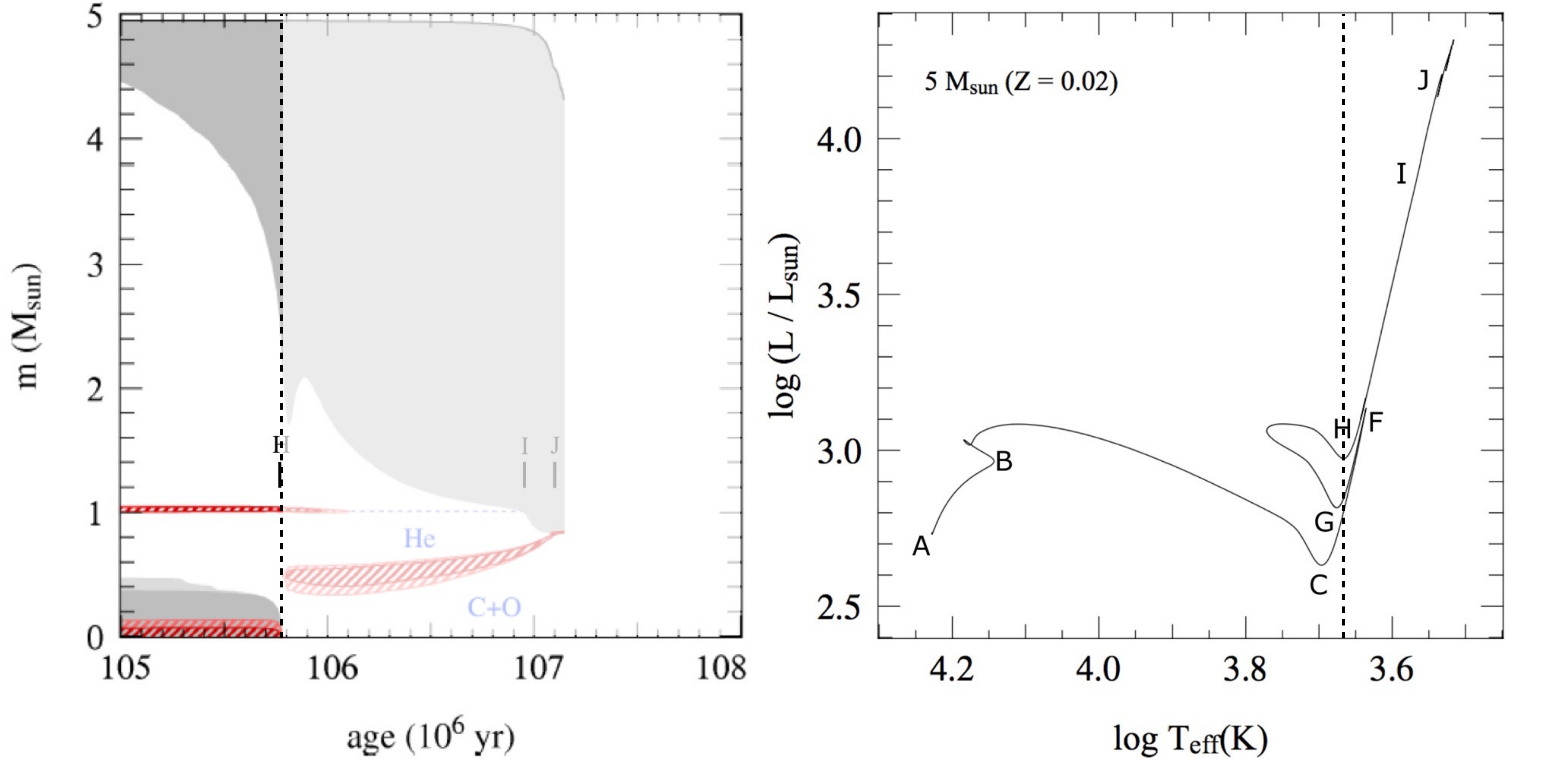
D: very high $\dot{M}$ (pulsation P_{rad} on dust)

E: end phase (WD) dictated by AGB $\dot{M}$



The AGB phase

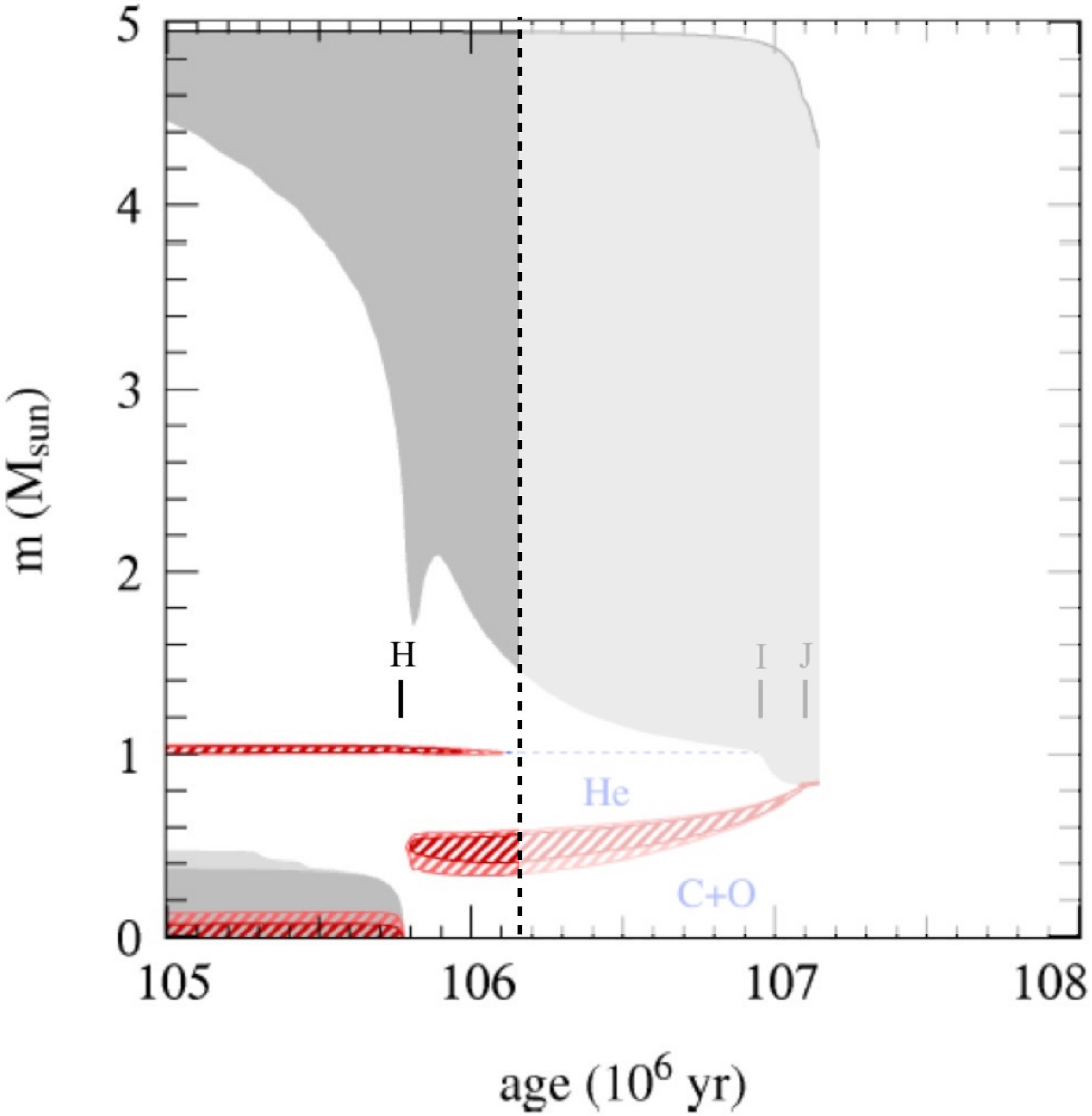
The second dredge-up (start of AGB) (first was during RGB)

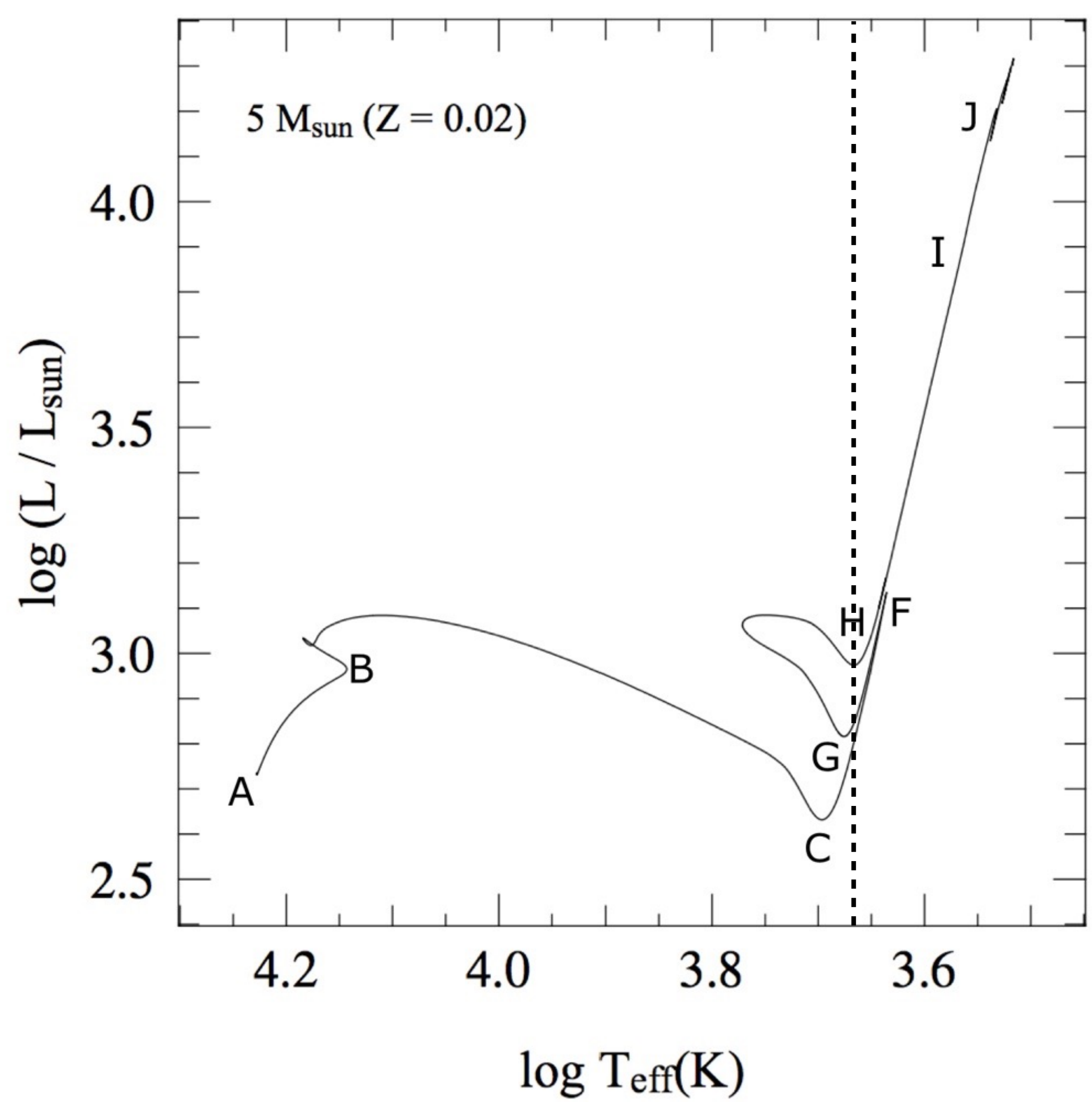


H: start of He shell fusion

The AGB phase

The second dredge-up (start of AGB) (first was during RGB)



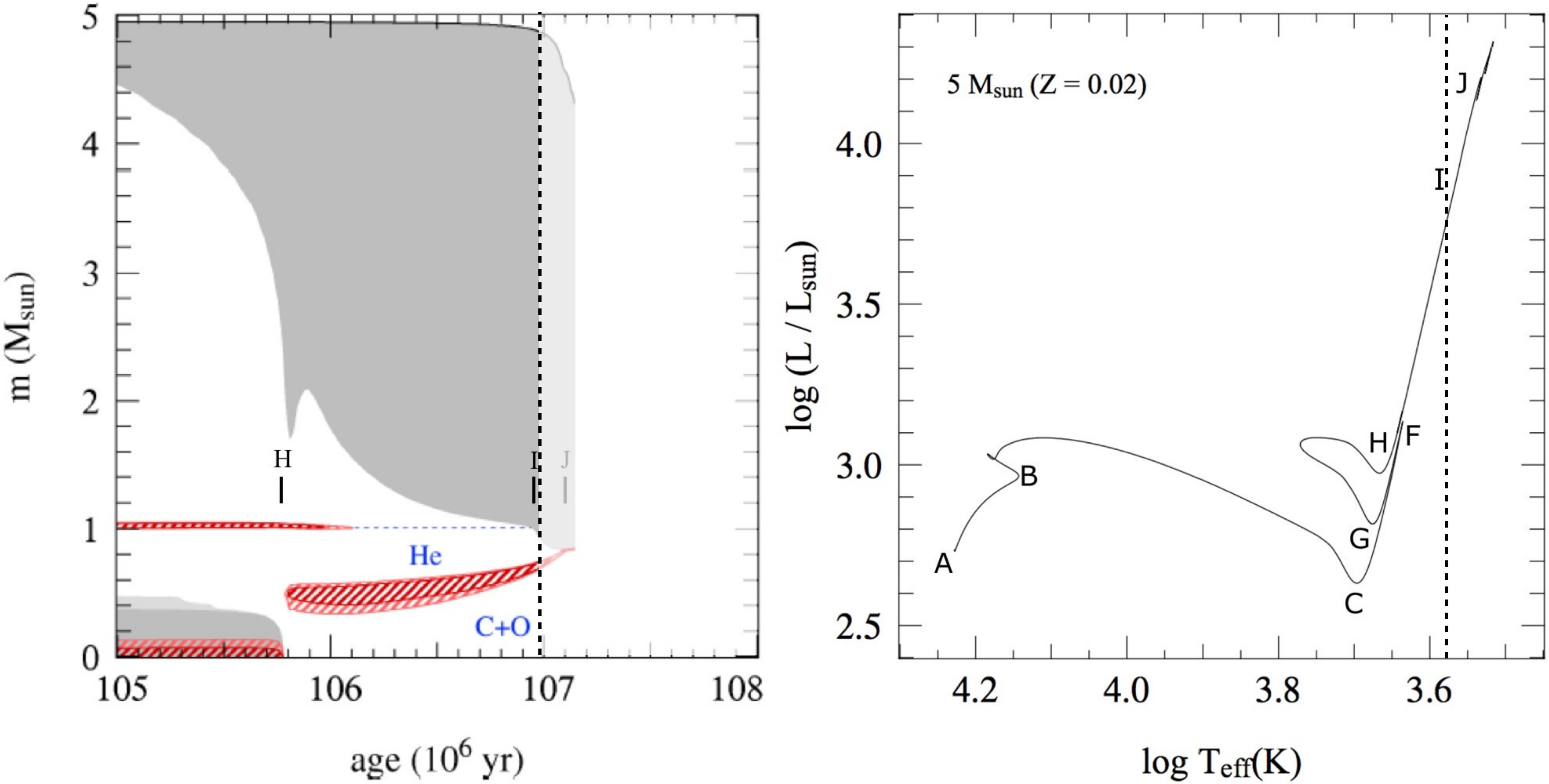


H: start of He shell fusion

shortly after H: H shell fusion switches off, expanding the layers above it and deepening the convective region

The AGB phase

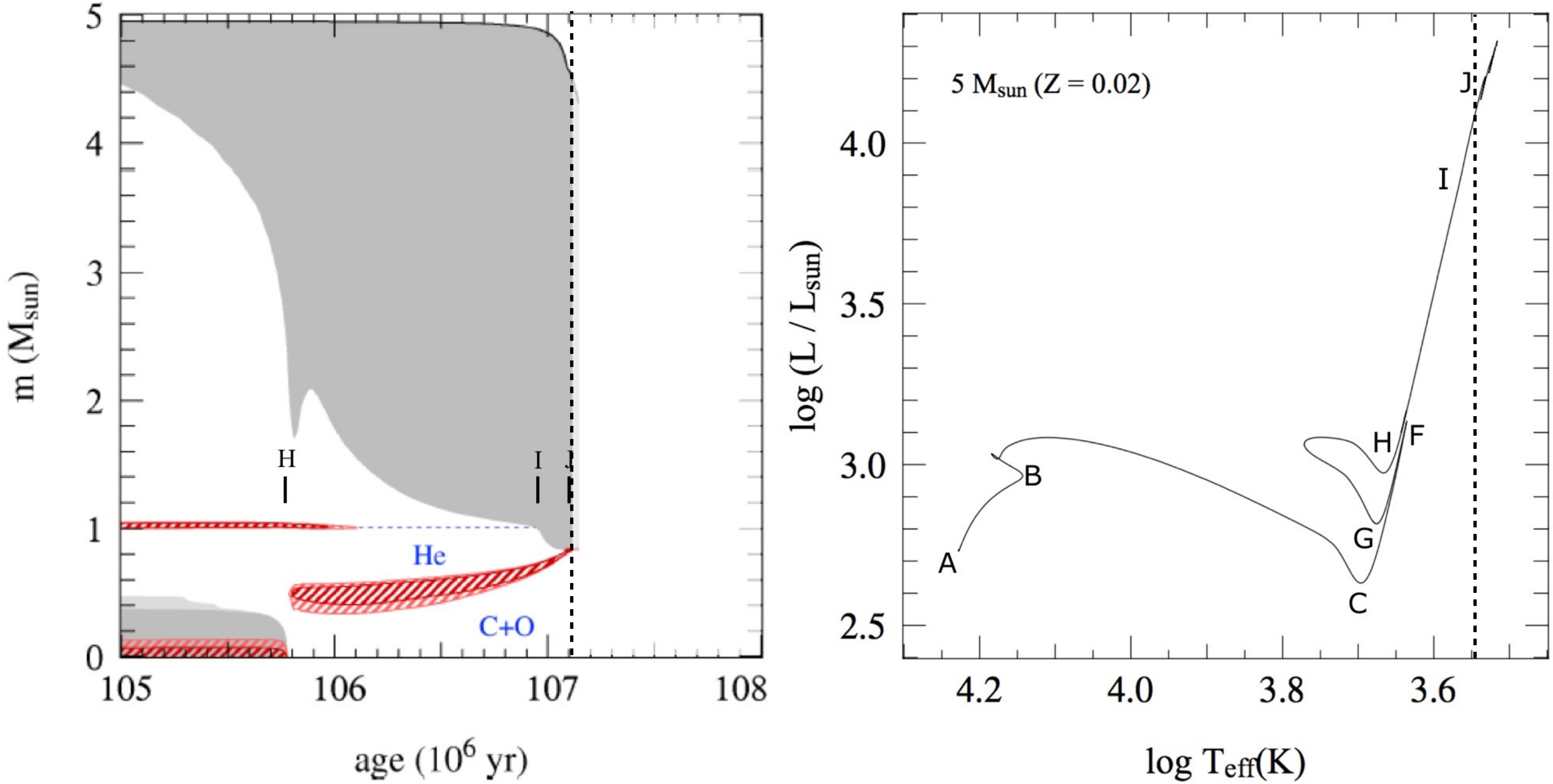
The second dredge-up (start of AGB) (first was during RGB)



I: convection zone reaches He-rich intershell zone, mixing CNO cycle products into envelope; **second dredge-up**

The AGB phase

The second dredge-up (start of AGB) (first was during RGB)



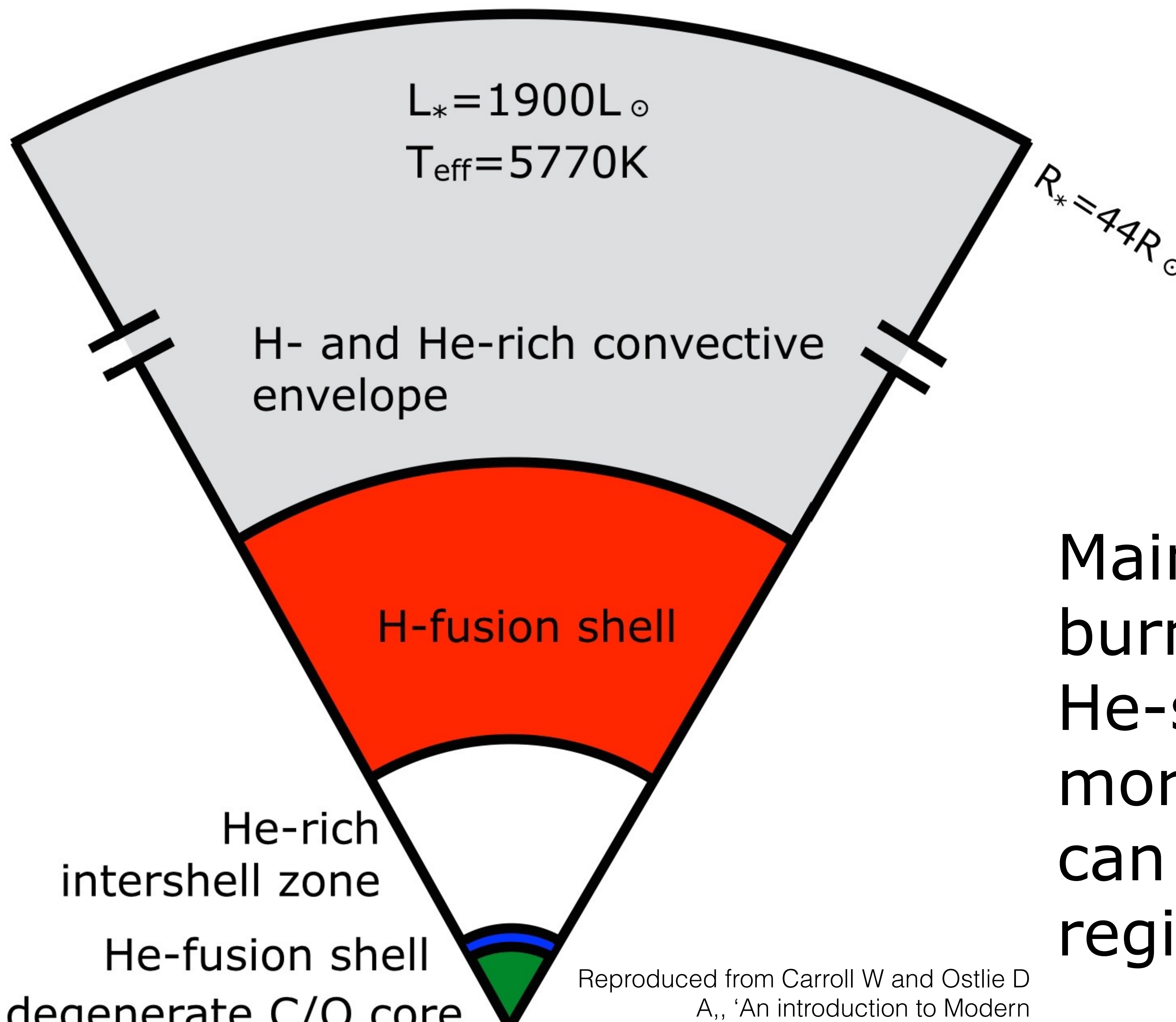
I: convection zone reaches He-rich intershell zone, mixing CNO cycle products into envelope; **second dredge-up**

J: to here AGB star increases in L due to increase of core mass

The AGB phase

Thermal pulses and the third dredge-up

As a star climbs the AGB it goes through a series of He-flashes called “thermal pulses” on 1,000-10,000 yr timescales.



Mainly driven by unequal burning rate of the H- and He-shells; H-shell supplies more He than the He-shell can fuse, so the intershell region grows in mass…

The AGB phase

Thermal pulses and the third dredge-up

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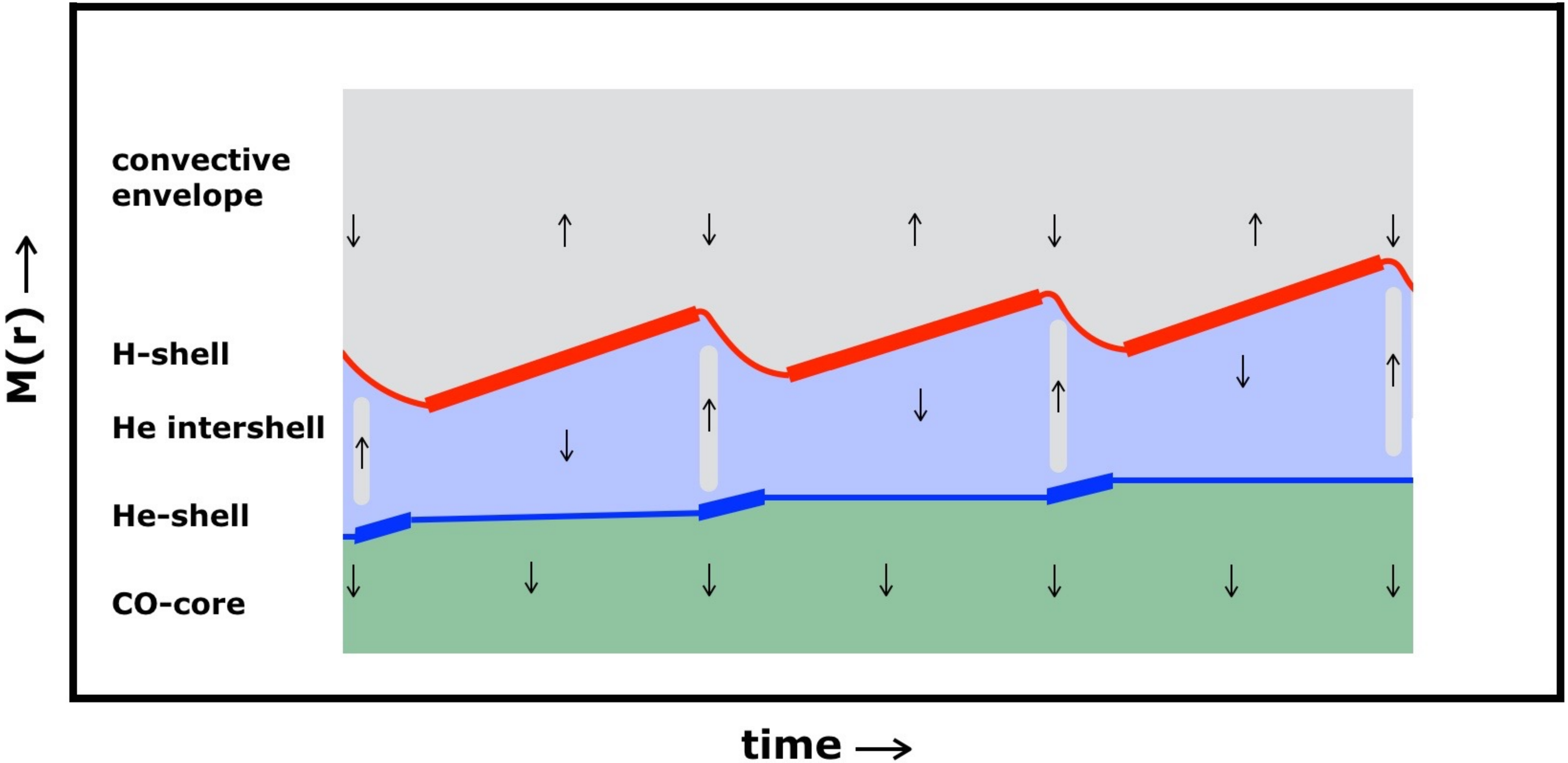
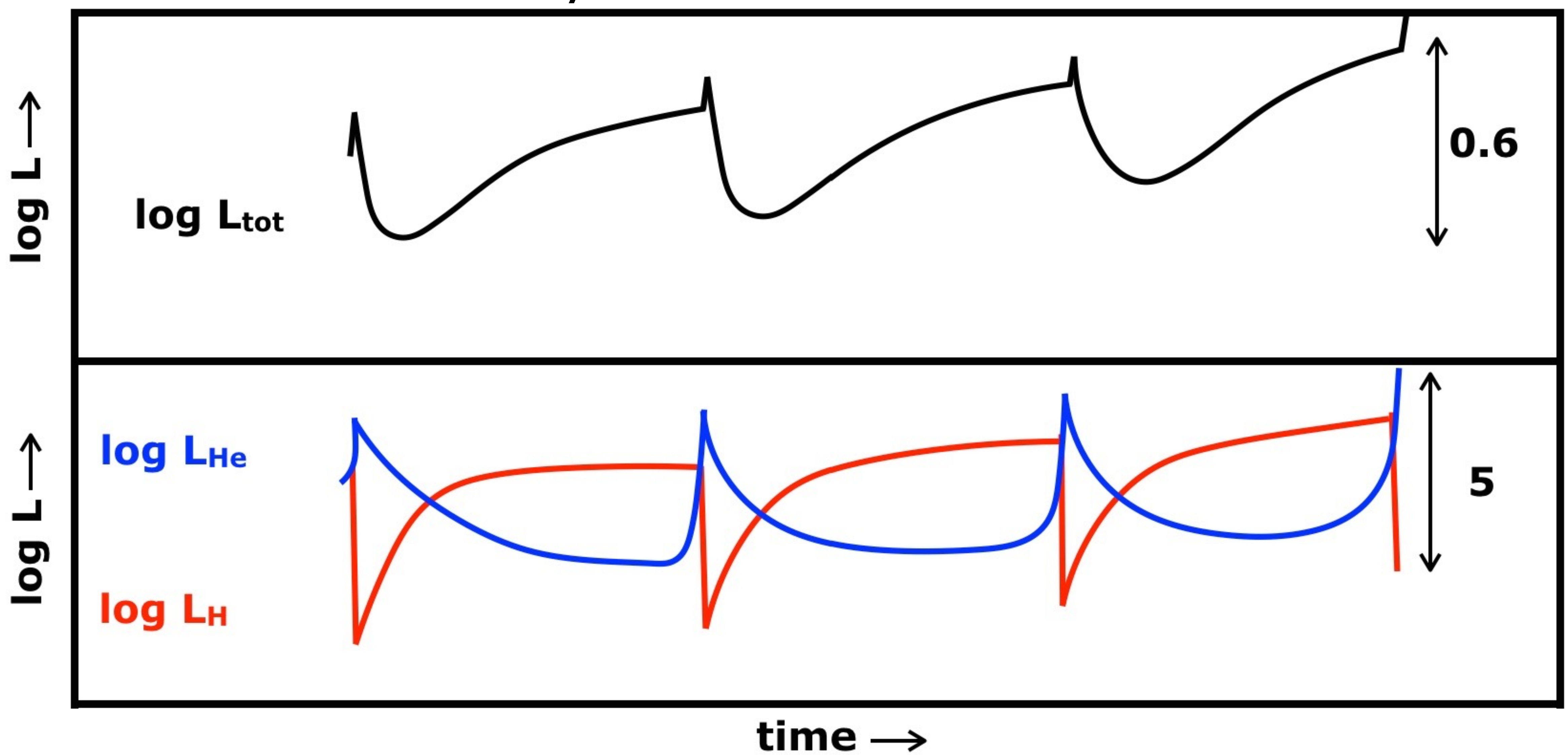


The AGB phase

Thermal pulses and the third dredge-up

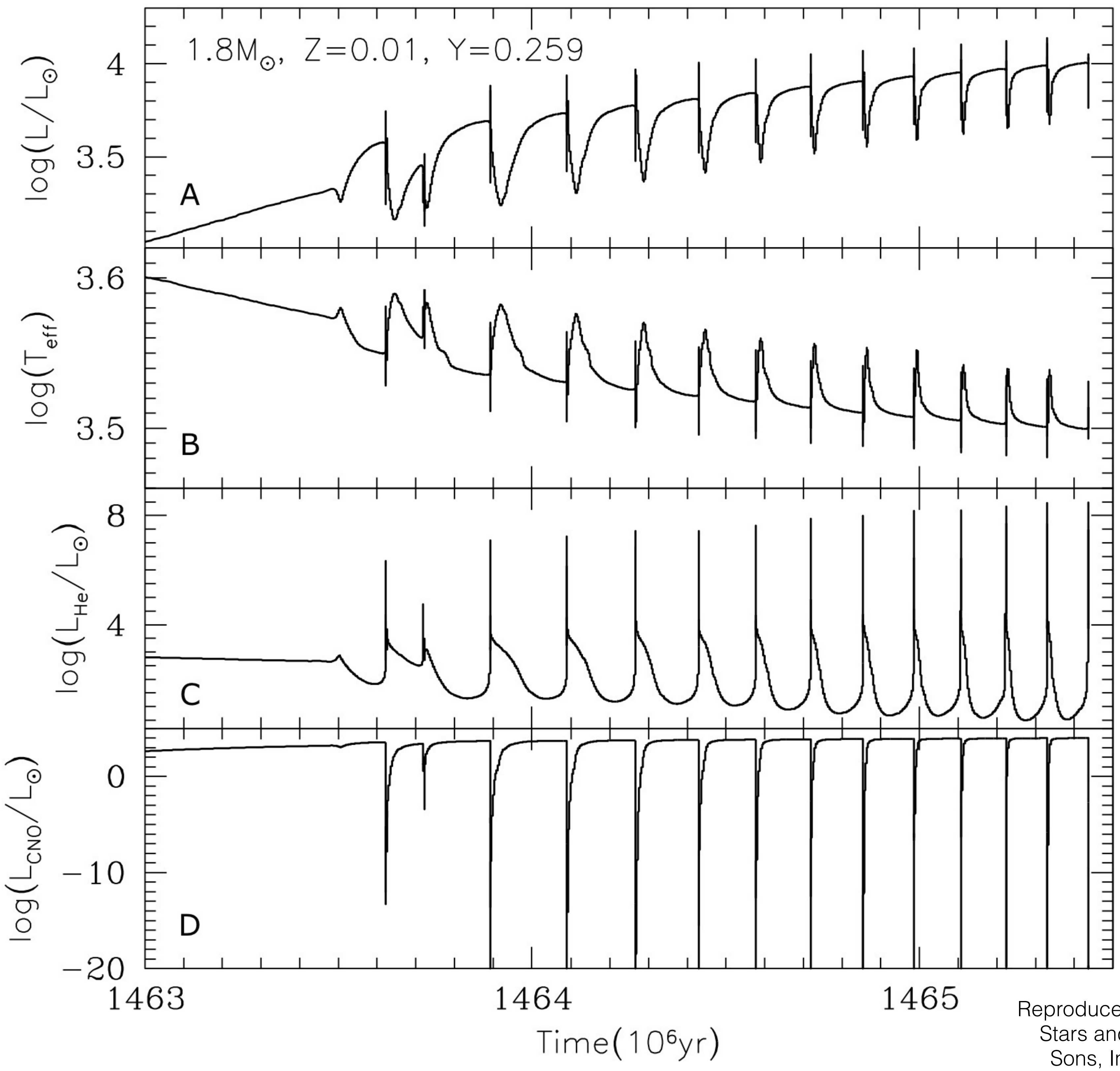
As a star climbs the AGB it goes through a series of He-flashes called "thermal pulses" on 1,000-10,000 yr timescales.

This results in alternating phases where the H-shell or He-shell dominate the luminosity.



The AGB phase

Thermal pulses and the third dredge-up



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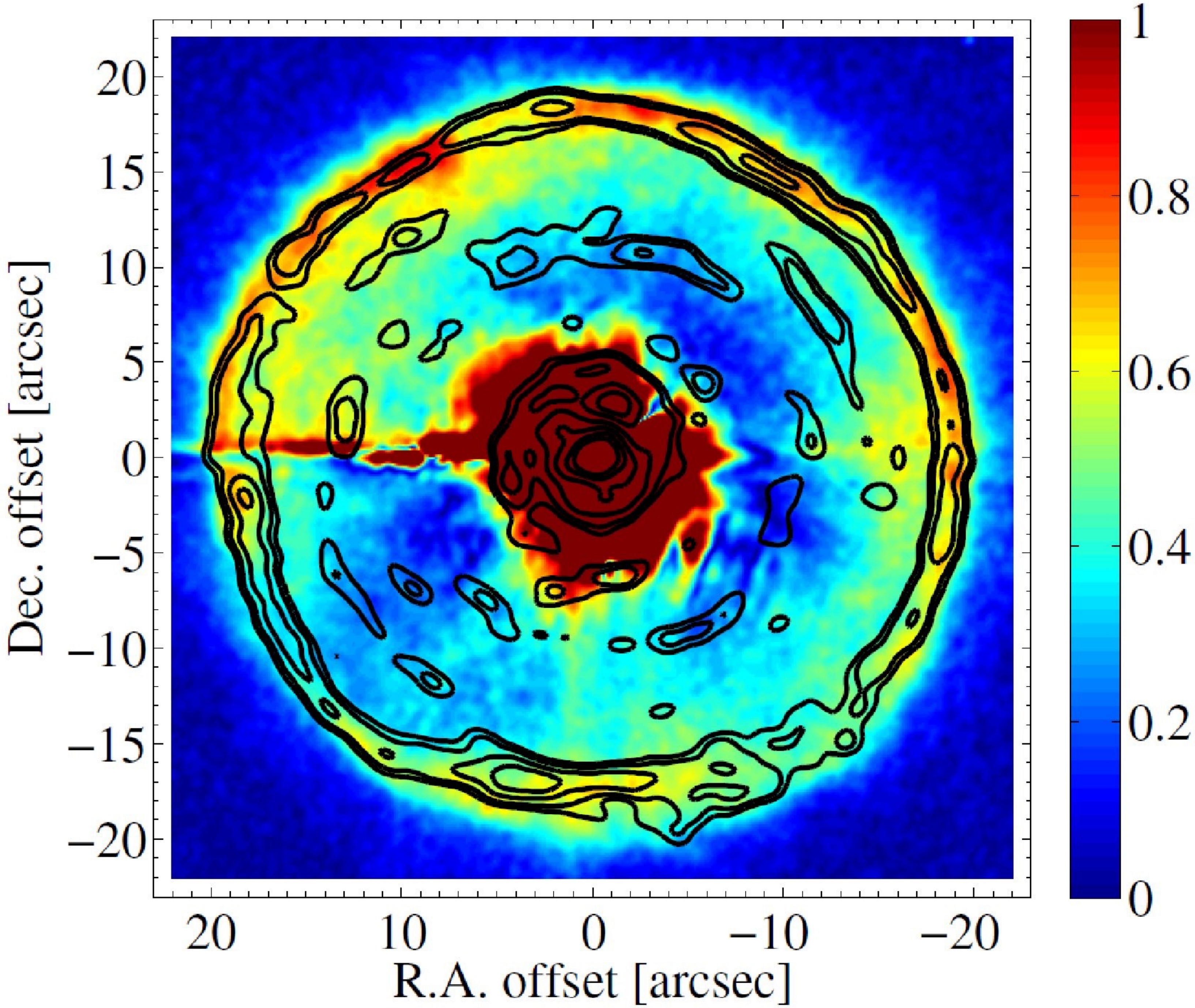
The AGB phase

Thermal pulses and the third dredge-up

During a thermal pulse the mass loss rate increases, producing a circumstellar shell as in the case of R Scl:



The AGB phase

Thermal pulses and the third dredge-up

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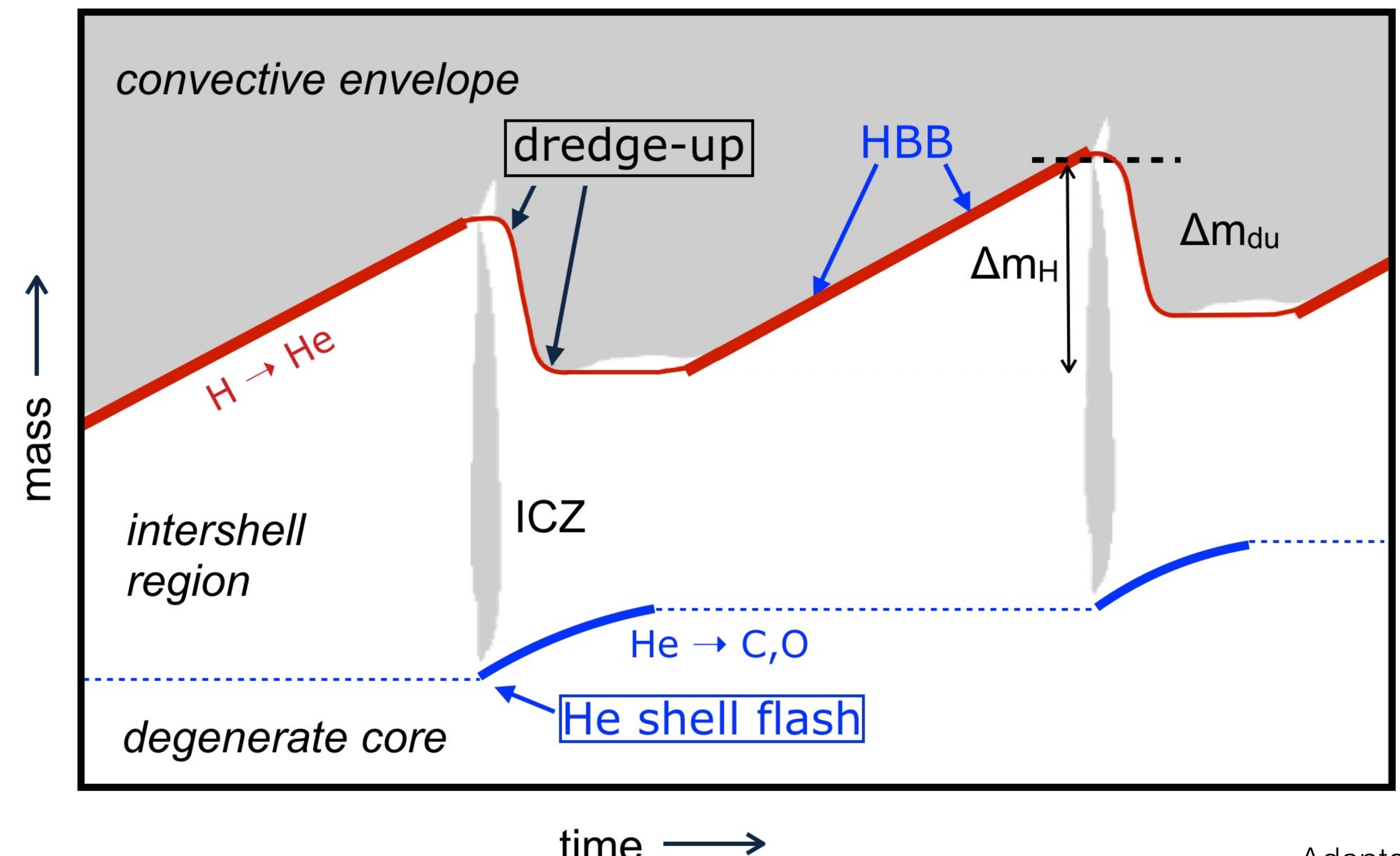
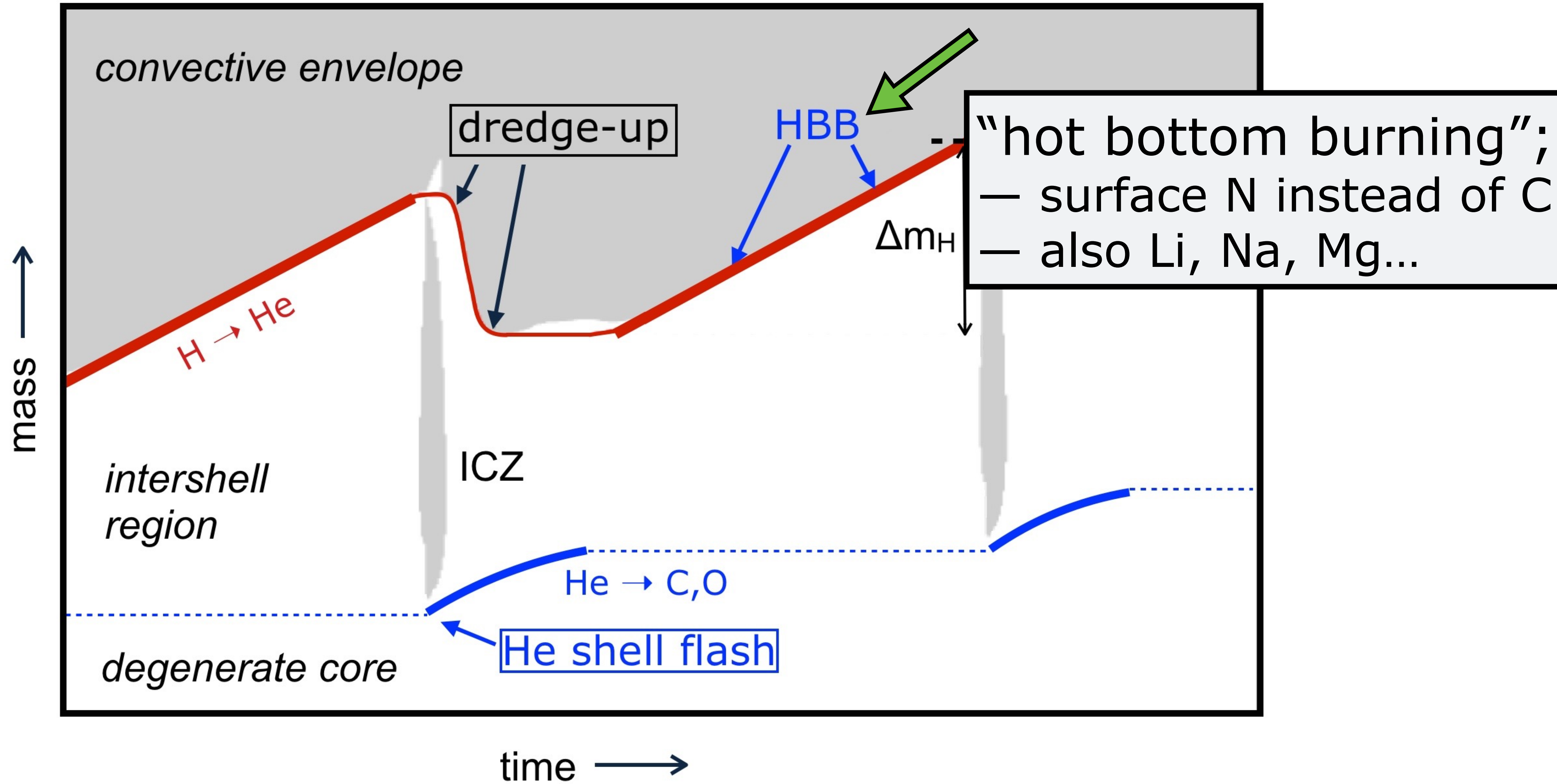


Adapted from Onno Pols, 2011.

The AGB phase

Thermal pulses and the third dredge-up



— duration of the He-shell is ~10^2 yr; H-shell is ~10^3-10^4 years

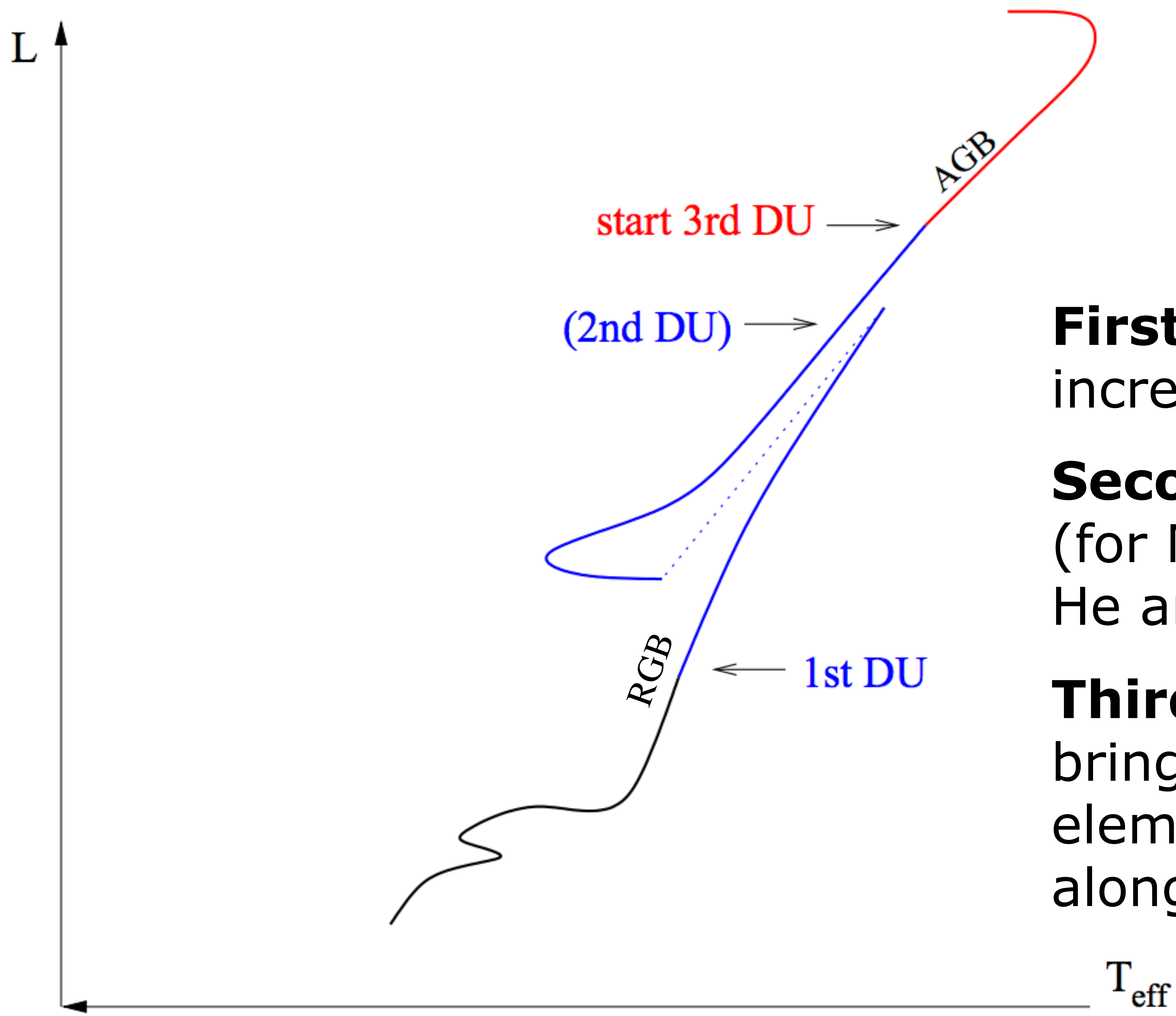
— this phase of evolution is the "TP-AGB" phase; successive cycles increase surface C, eventually yielding surface C/O > 1

— in most massive cases H fusion happens via CNO cycle…

Adapted from Onno Pols, 2011.

The AGB phase

Summary of dredge-up phases



First: during RGB; small increase in surface He

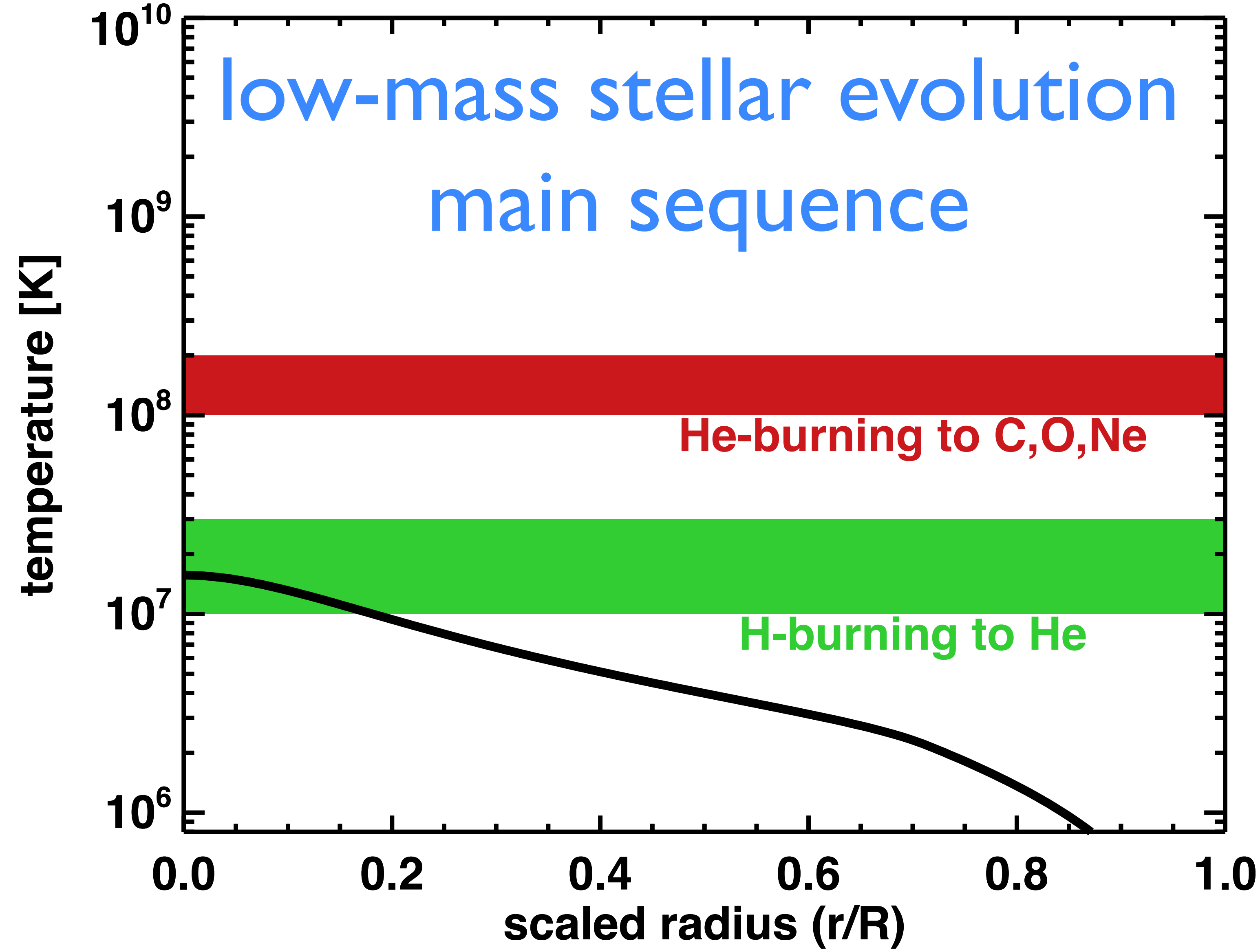
Second: early in AGB (for M_{init} > 4); increases He and N at surface

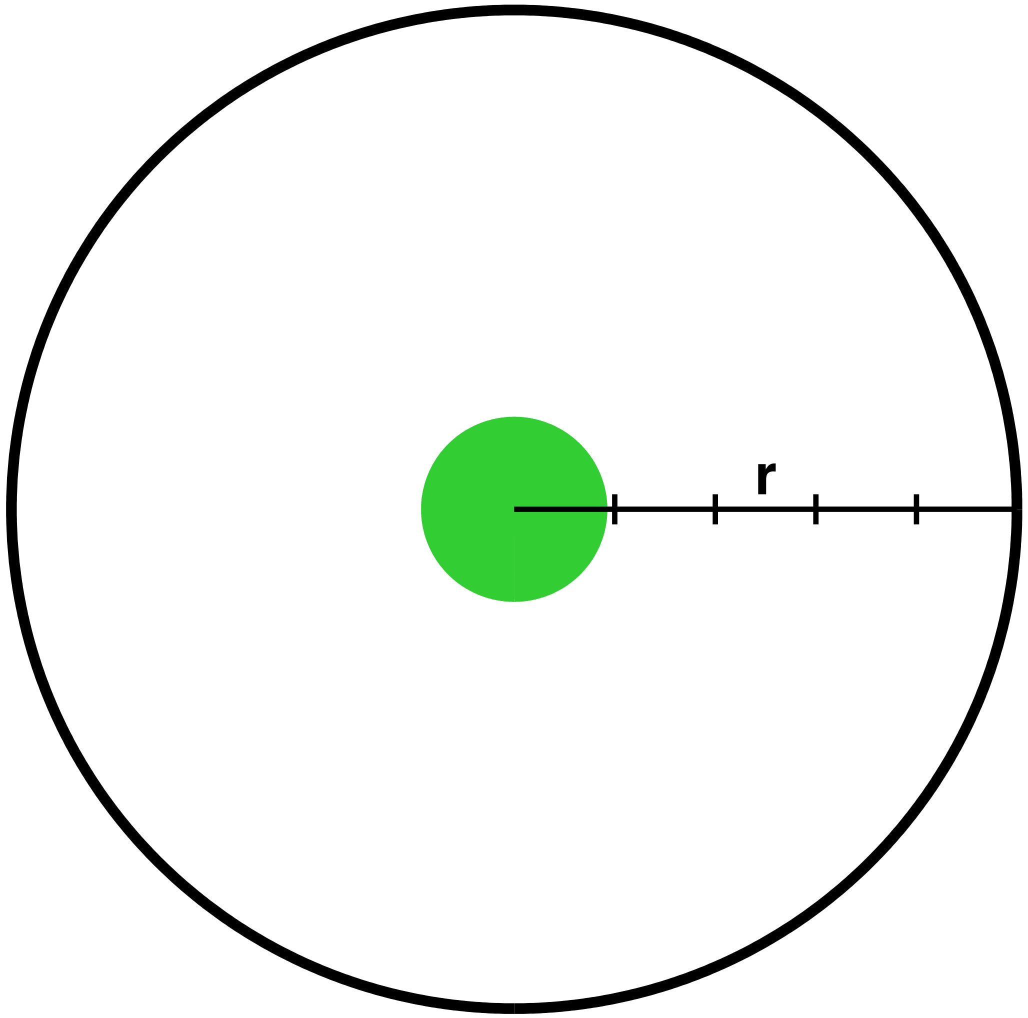
Third: during TP-AGB; brings s-process elements to surface along with C

The AGB phase

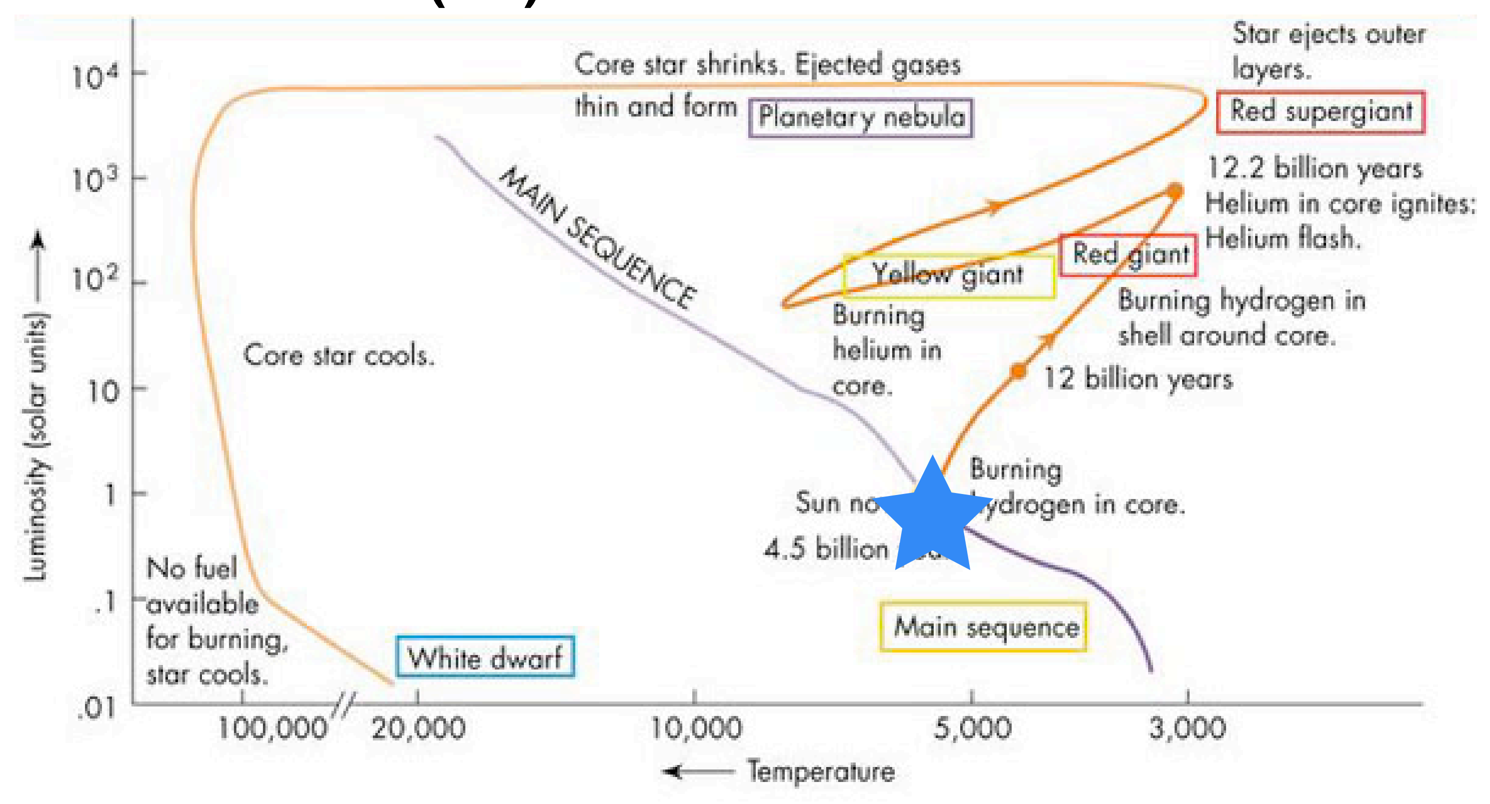
Mass loss and the end of the AGB phase

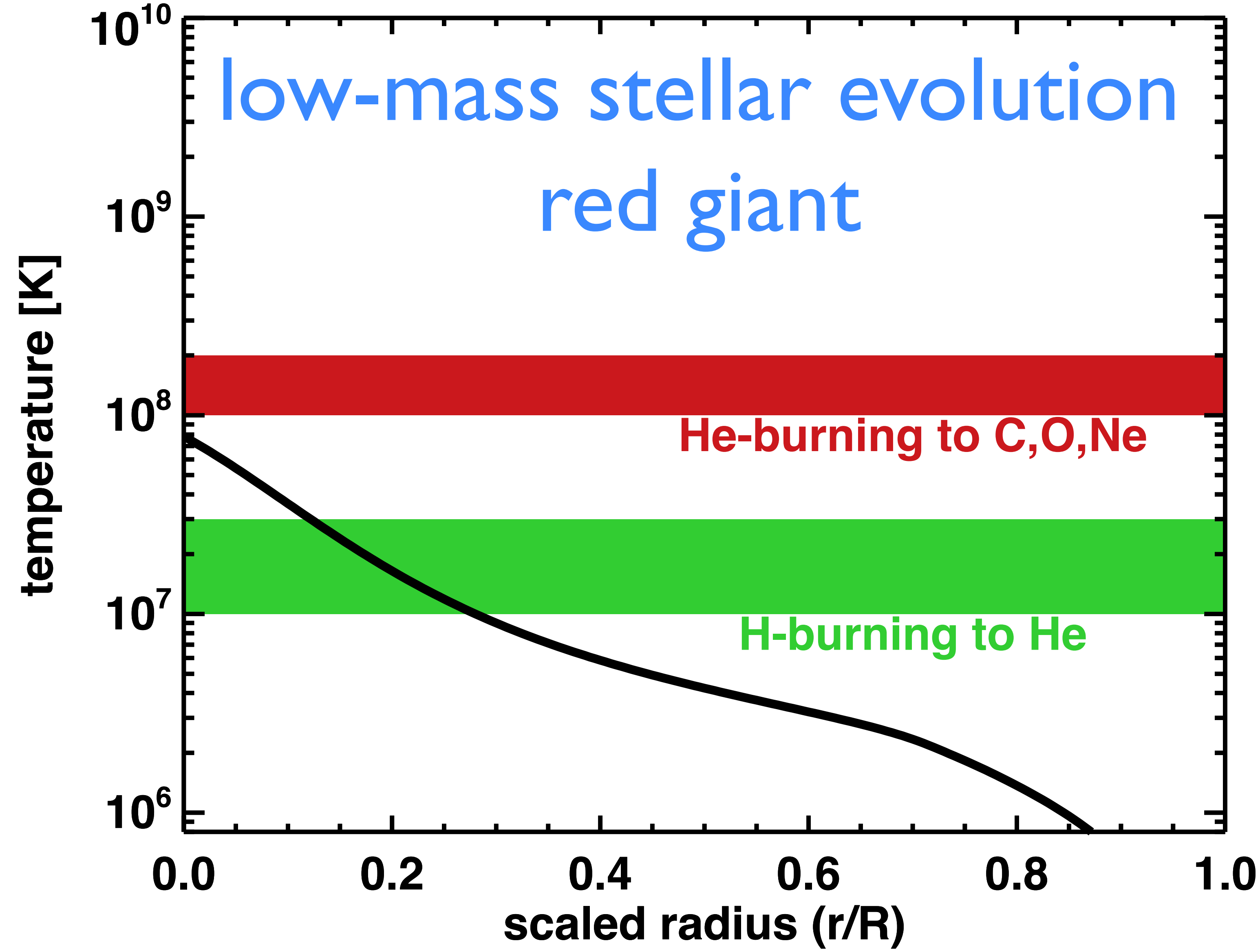
1. AGB terminates because mass loss has stripped away most of the envelope.
2. The final mass of the WD remnant is determined by $\dot{M}_{AGB}$
3. The max L of the AGB star is determined by $\dot{M}_{AGB}$
4. $\dot{M}_{AGB}$ is what prevents 2-8$M_\odot$ stars from becoming SNe
5. From our simple estimate, $t_{AGB} \sim$ 3Myr and it ends at $L \sim 10^4 L_\odot$ with a mass of $\sim 0.6 M_\odot$ and a degenerate core

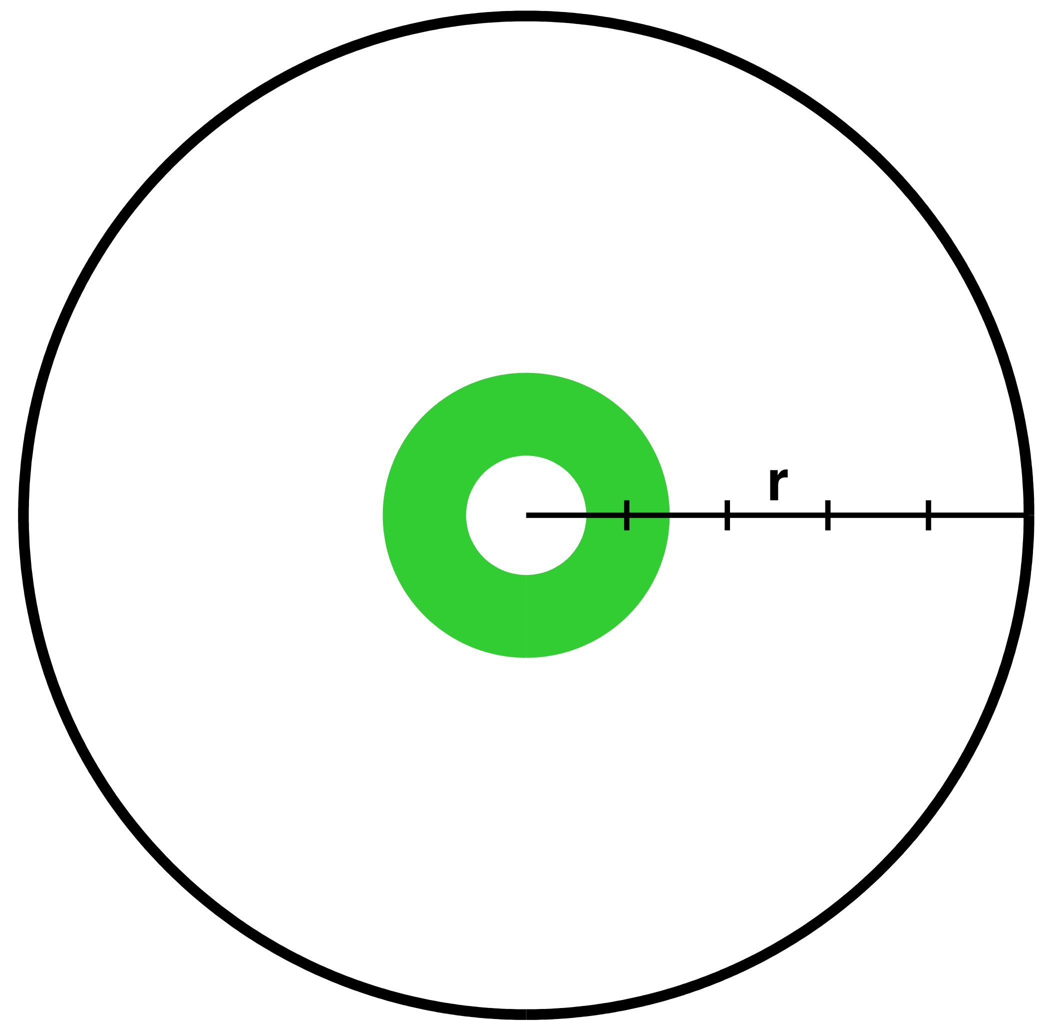




schematic, not to scale!







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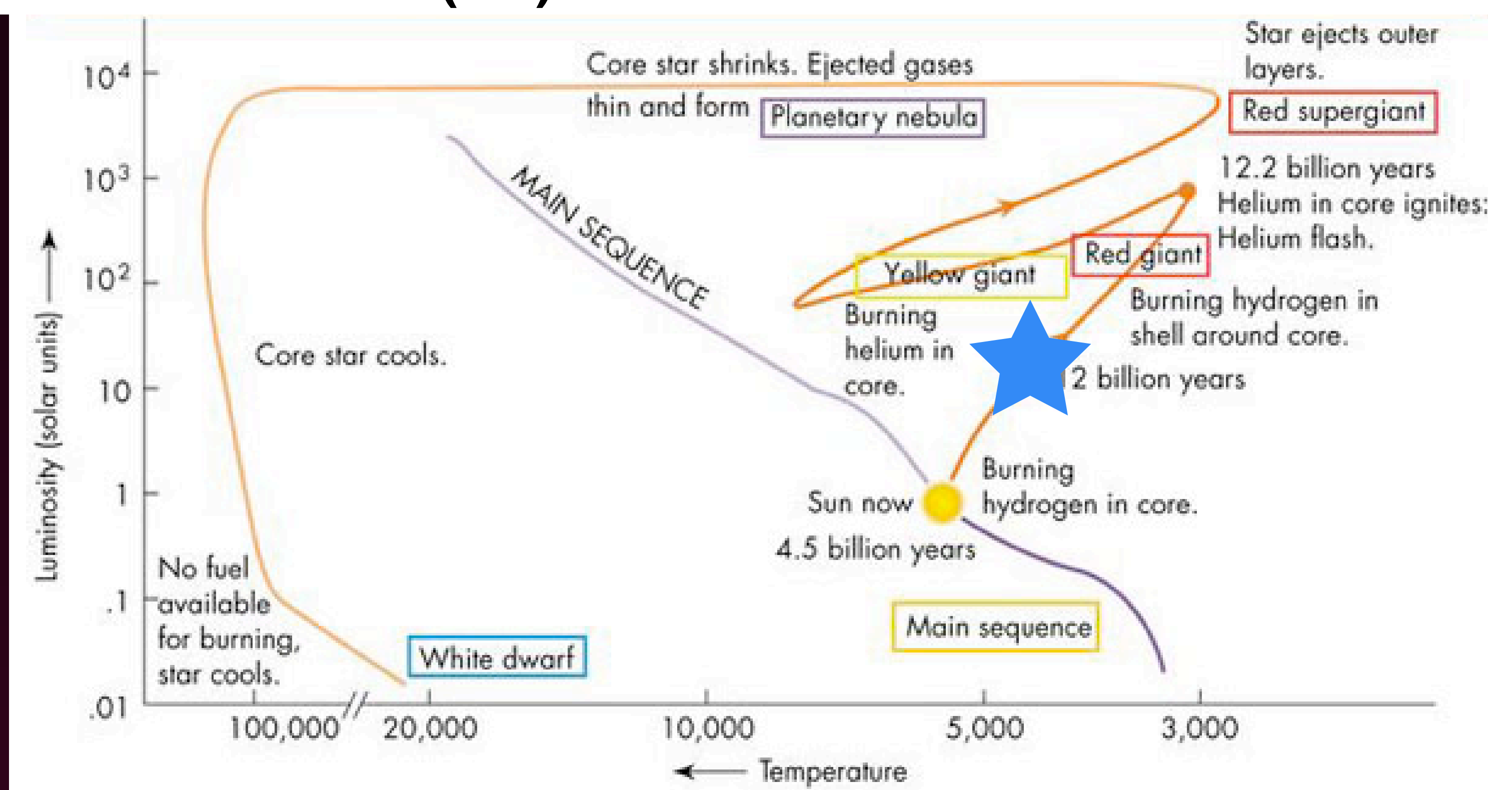
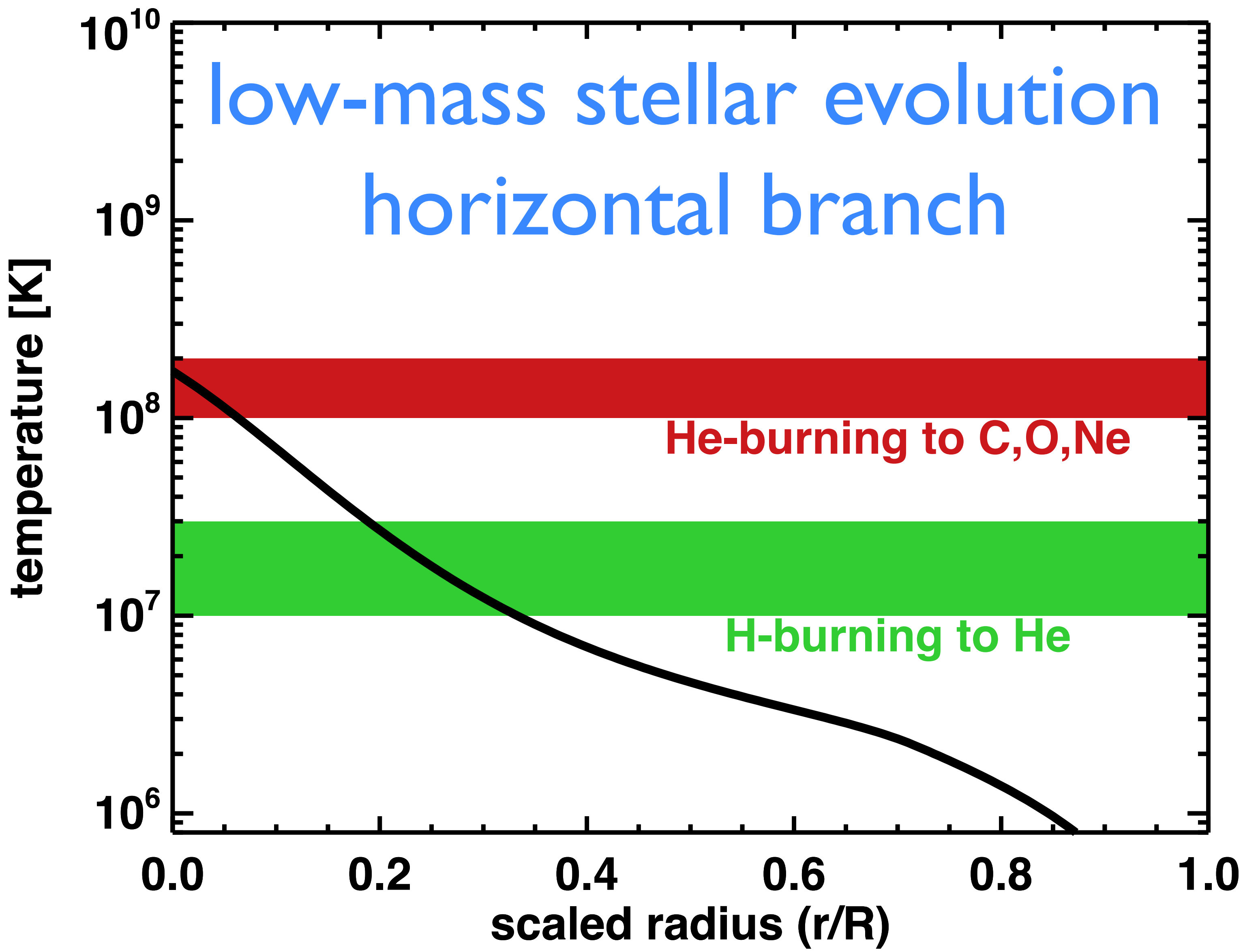
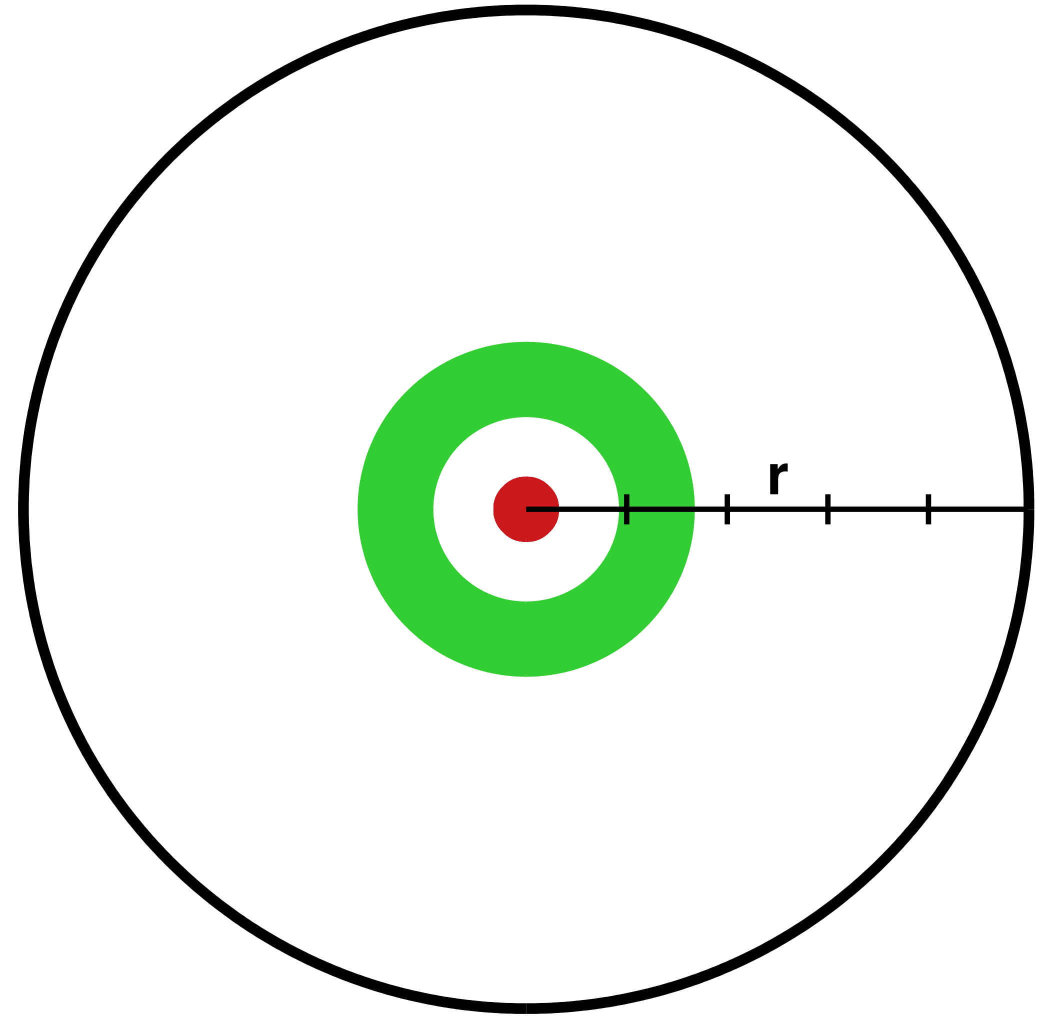
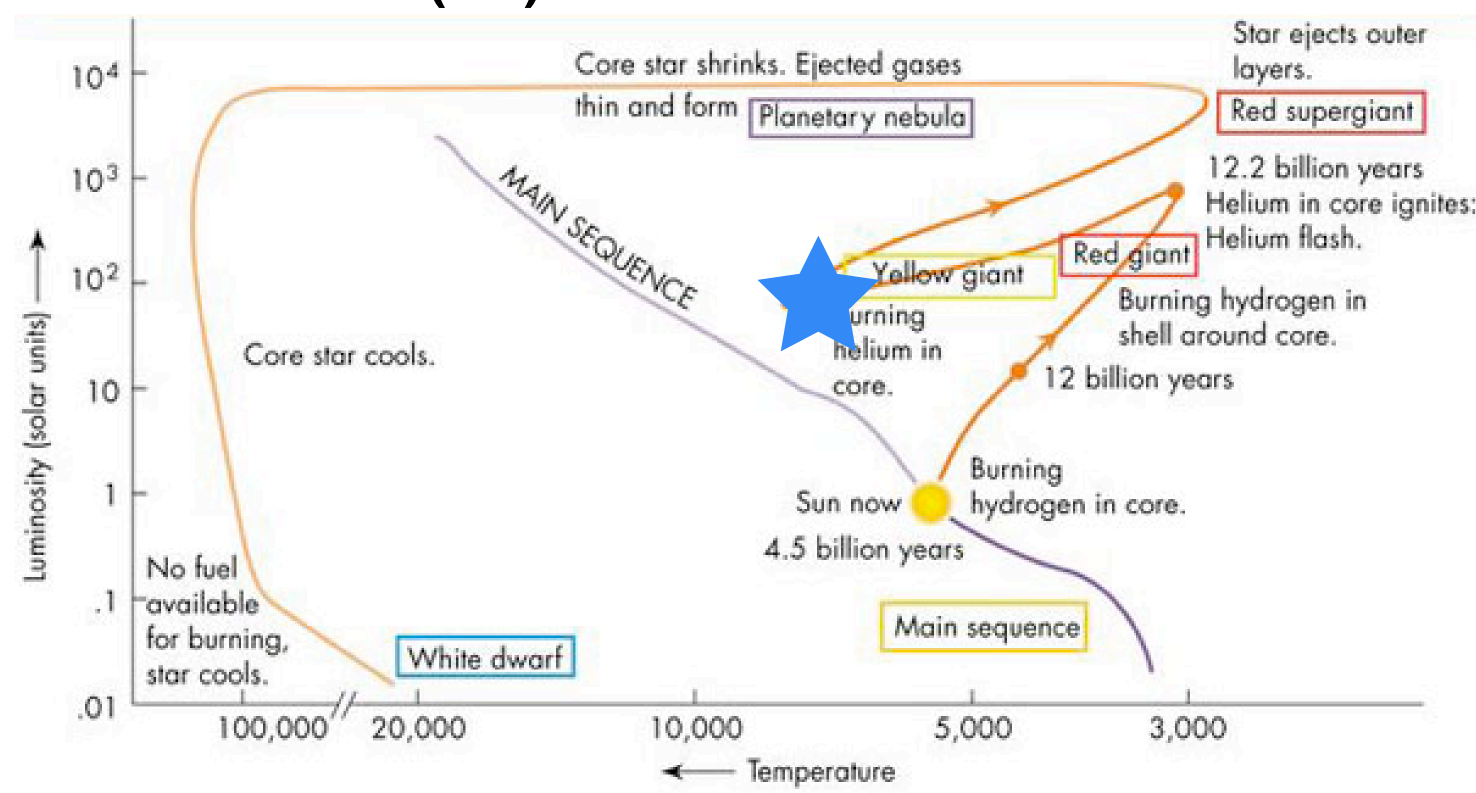
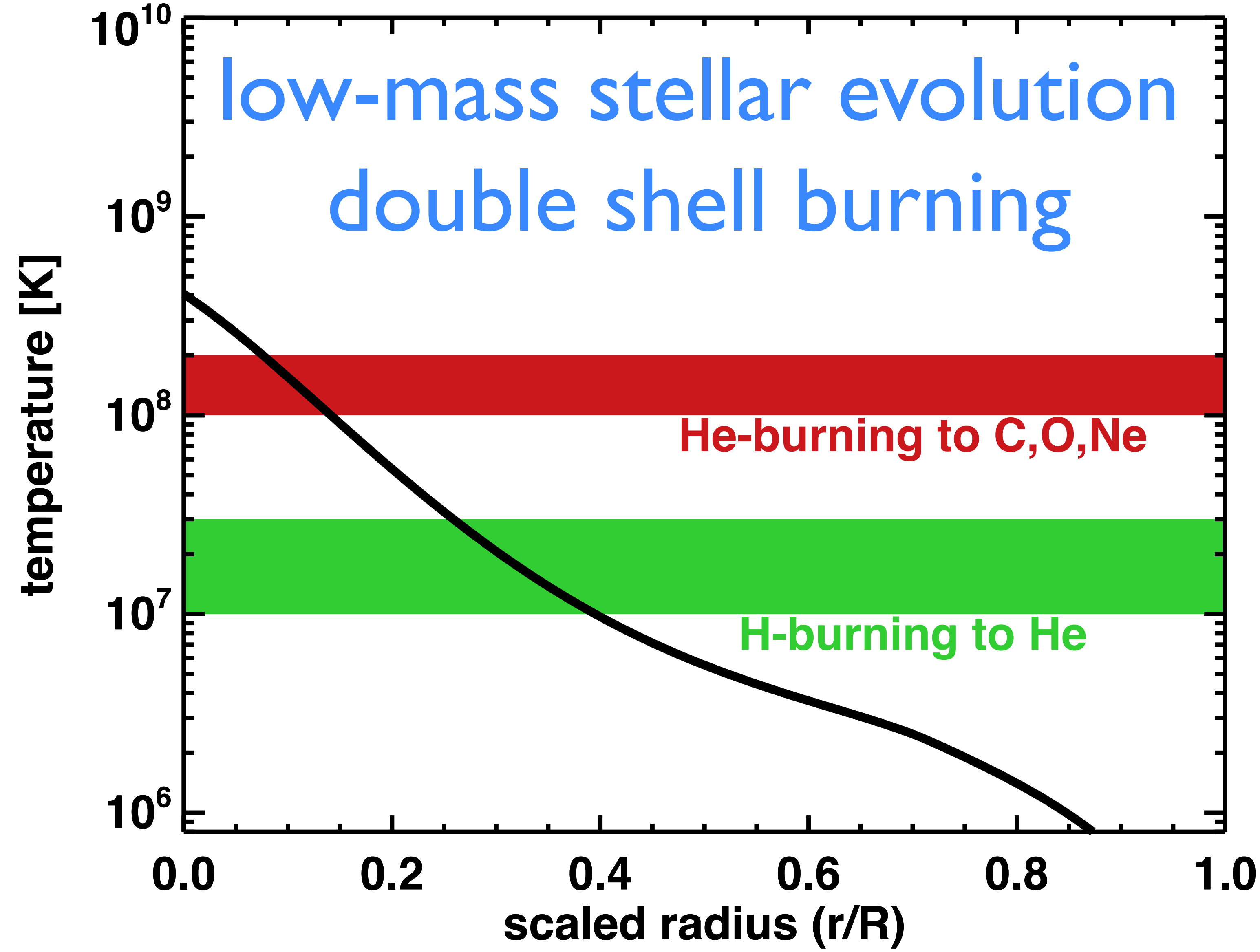


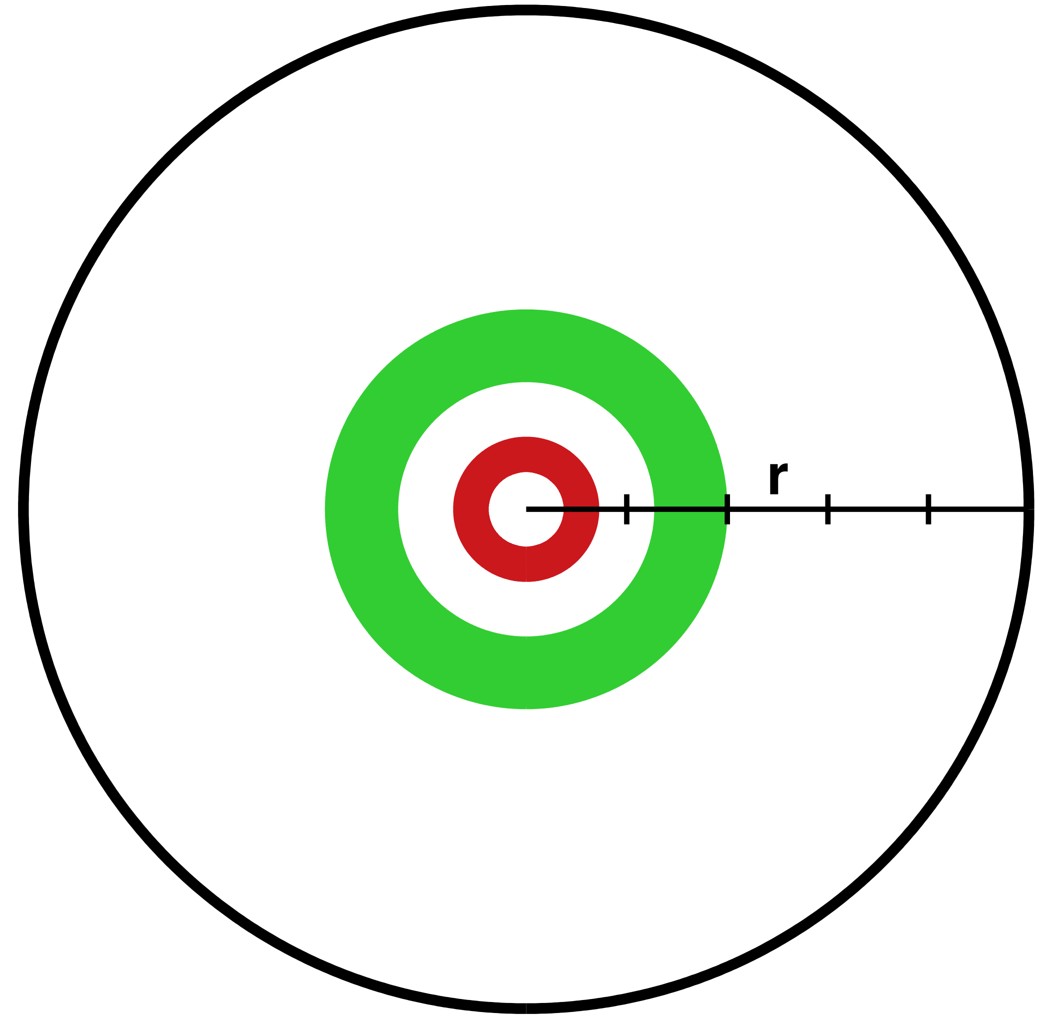




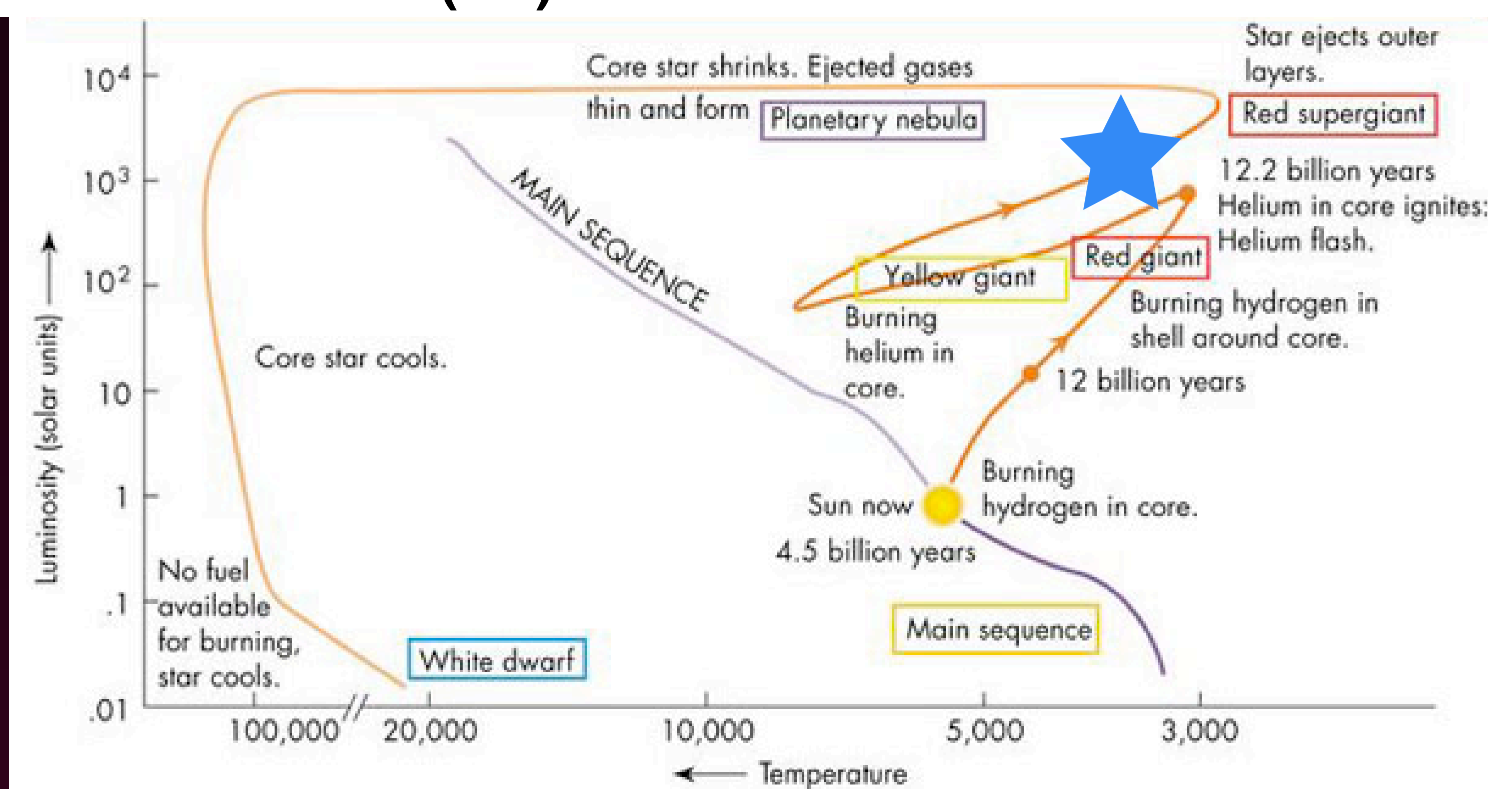
schematic, not to scale!



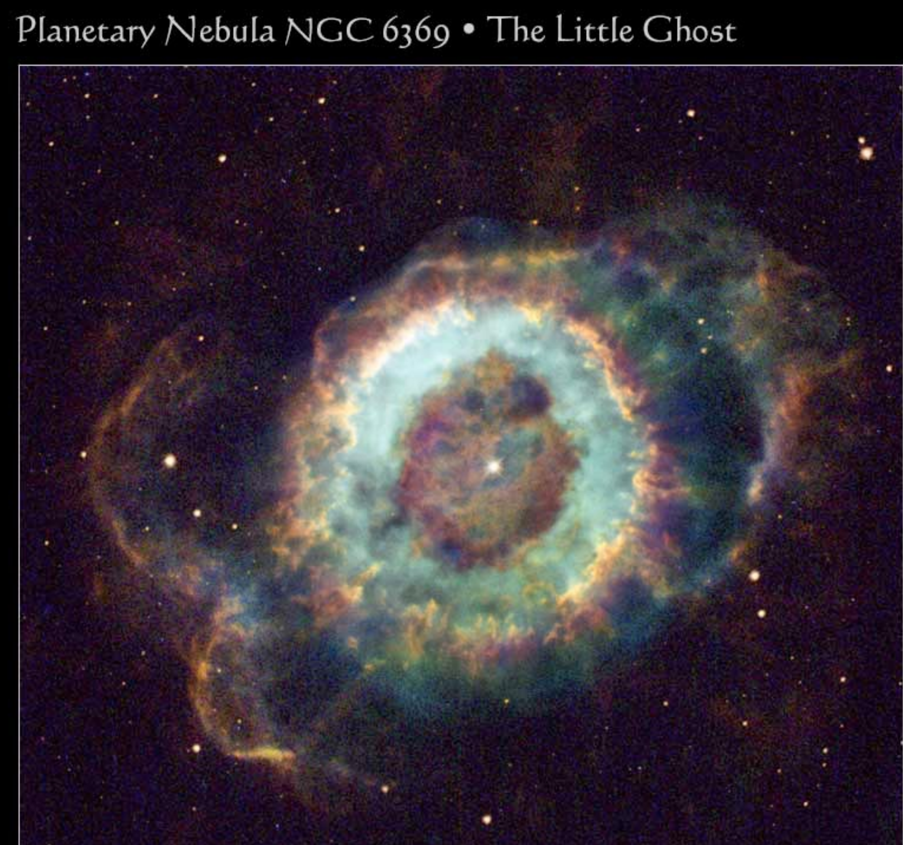


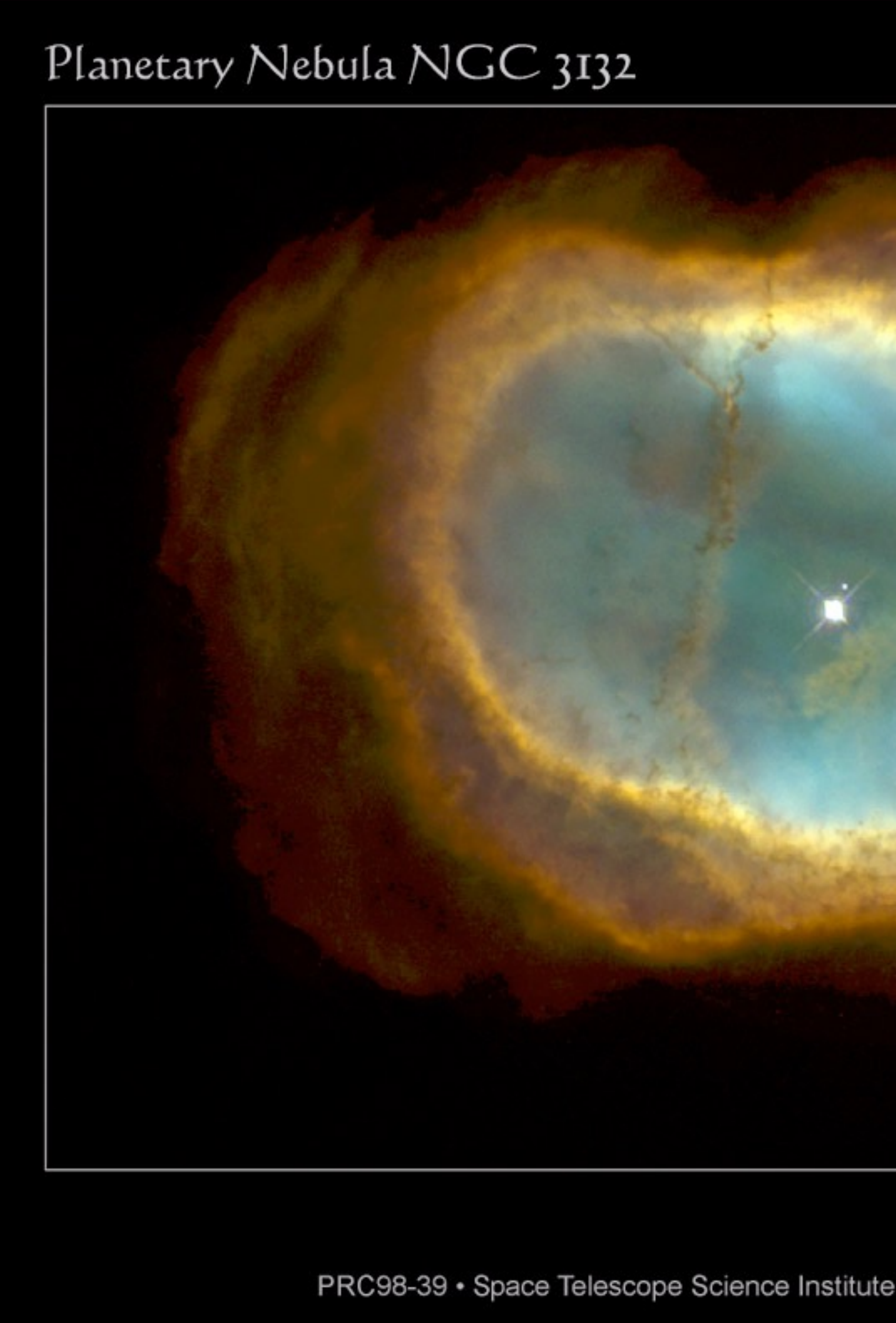


schematic, not to scale!



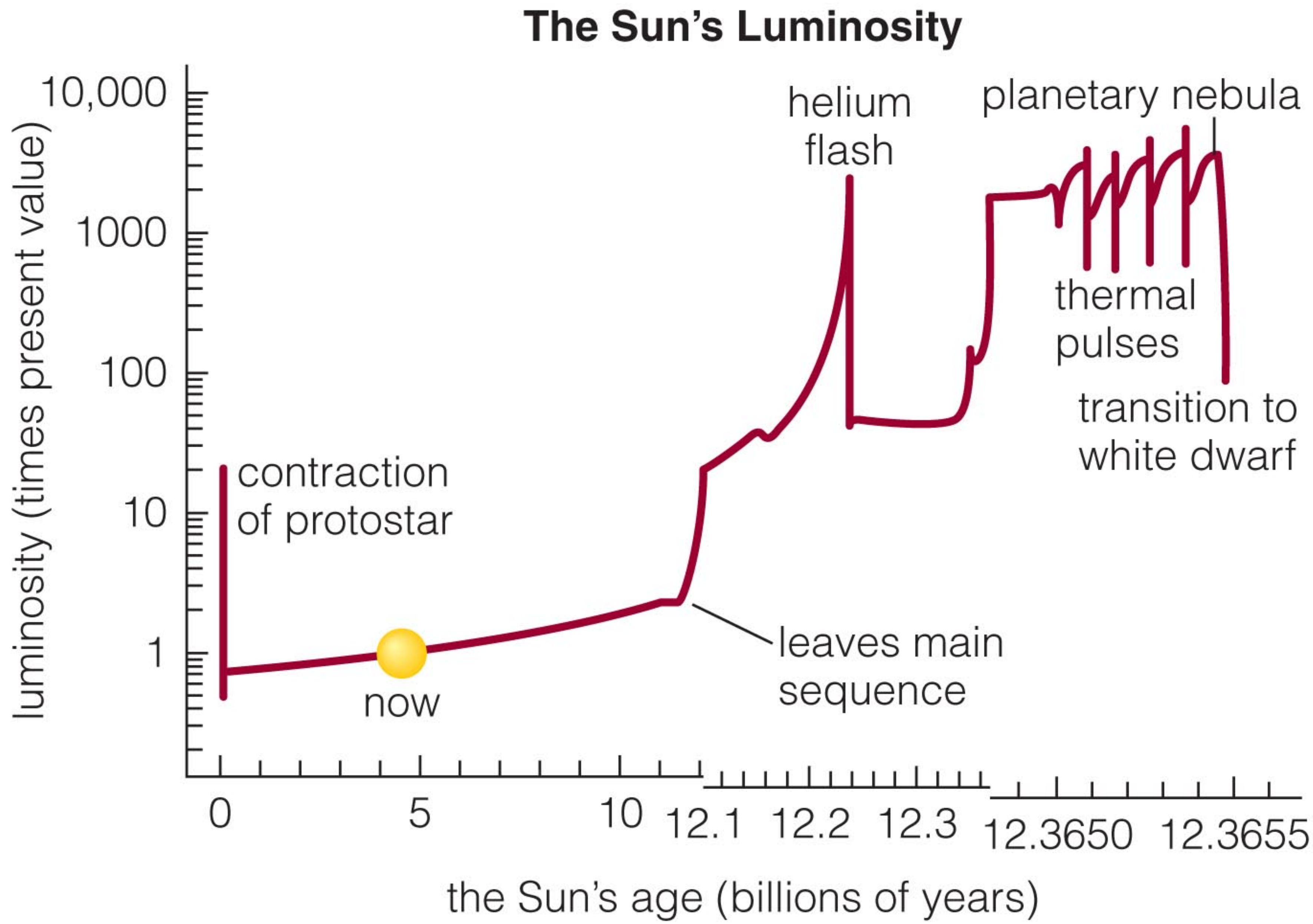
planetary nebulae





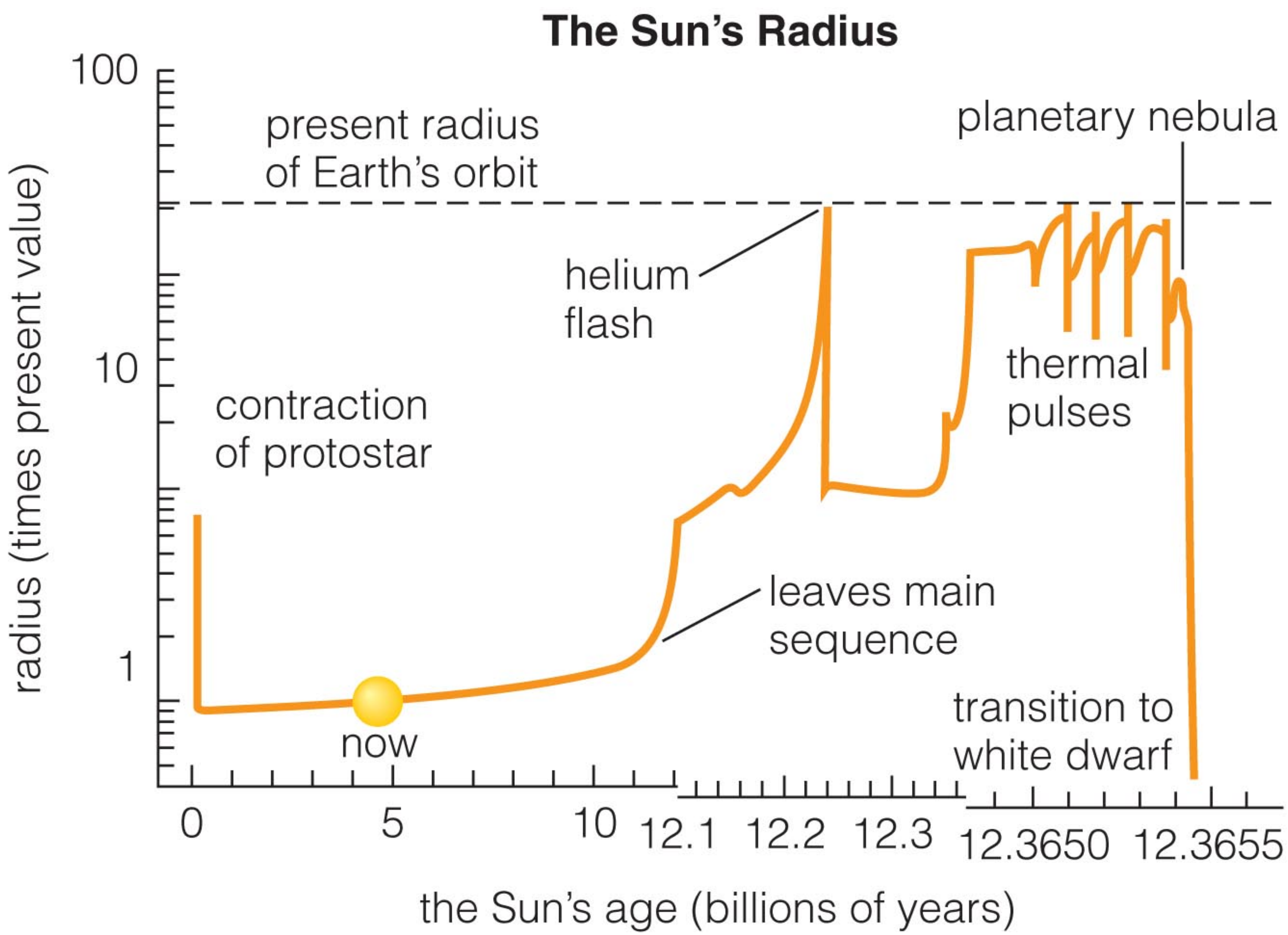
planetary nebulae observed by the Hubble Space Telescope

Earth's Fate



- The Sun's luminosity will rise to 1000 times its current level—too hot for life on Earth.

Earth's Fate



- The Sun's radius will grow to near current radius of Earth's orbit.

Advanced burning: massive stars

$$\begin{aligned} {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} &\rightarrow {}^{16}_{8}\mathrm{O} + \gamma \\ {}^{16}_{8}\mathrm{O} + {}^{4}_{2}\mathrm{He} &\rightarrow {}^{20}_{10}\mathrm{Ne} + \gamma \end{aligned}$$

T > 10^8 K

$$\begin{aligned} {}^{12}_{6}\mathrm{C} + {}^{12}_{6}\mathrm{C} &\rightarrow {}^{16}_{8}\mathrm{O} + 2\ {}^{4}_{2}\mathrm{He} \\ &\rightarrow {}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} \\ &\rightarrow {}^{23}_{11}\mathrm{Na} + p \\ &\rightarrow {}^{23}_{12}\mathrm{Mg} + n \\ &\rightarrow {}^{24}_{12}\mathrm{Mg} + \gamma \end{aligned}$$

carbon burning,
T > 6 × 10^8 K

oxygen burning,
T > 10^9 K

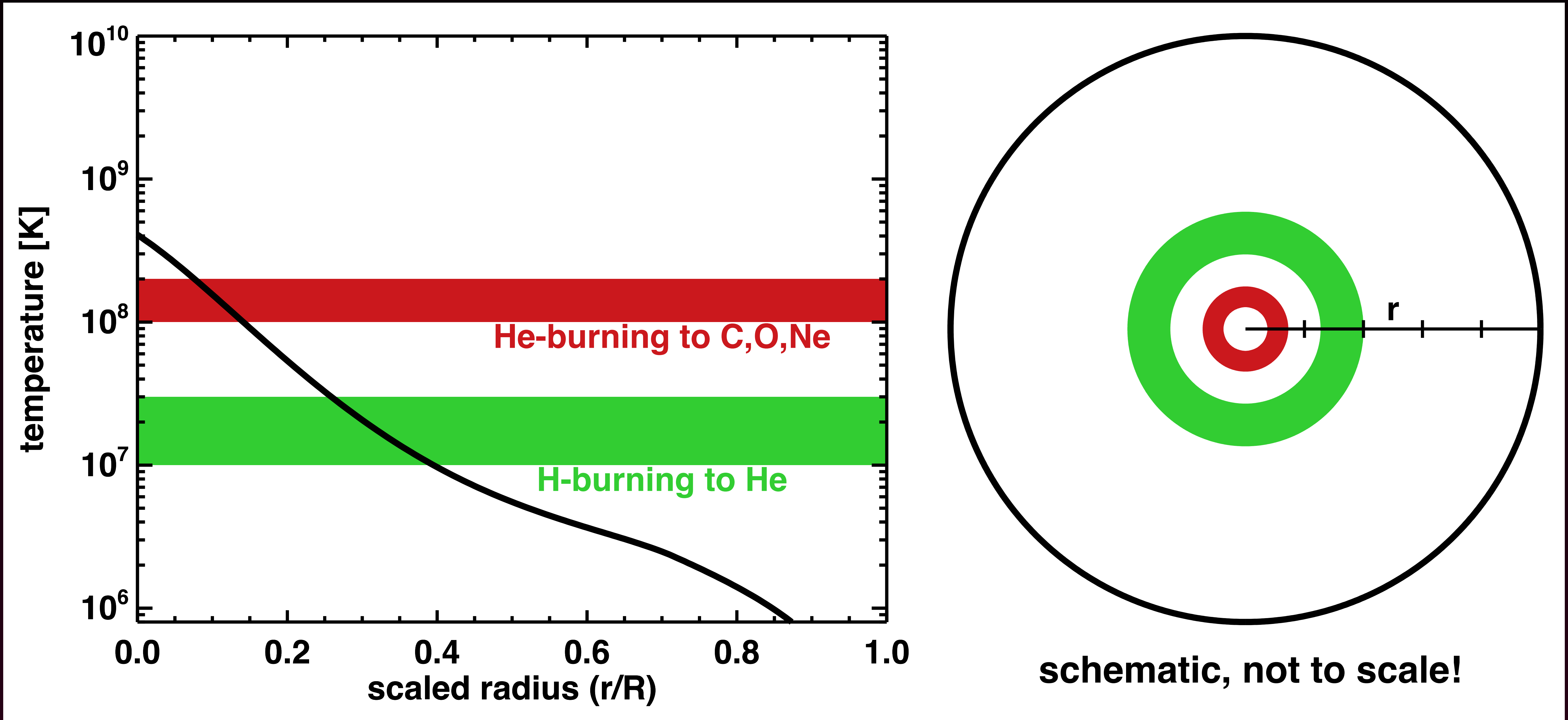
$$\begin{aligned} {}^{16}_{8}\mathrm{O} + {}^{16}_{8}\mathrm{O} &\rightarrow {}^{24}_{12}\mathrm{Mg} + 2\ {}^{4}_{2}\mathrm{He} \\ &\rightarrow {}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} \\ &\rightarrow {}^{31}_{15}\mathrm{P} + p \\ &\rightarrow {}^{31}_{16}\mathrm{S} + n \\ &\rightarrow {}^{32}_{16}\mathrm{S} + \gamma \end{aligned}$$

silicon burning,
T > 3 × 10^9 K

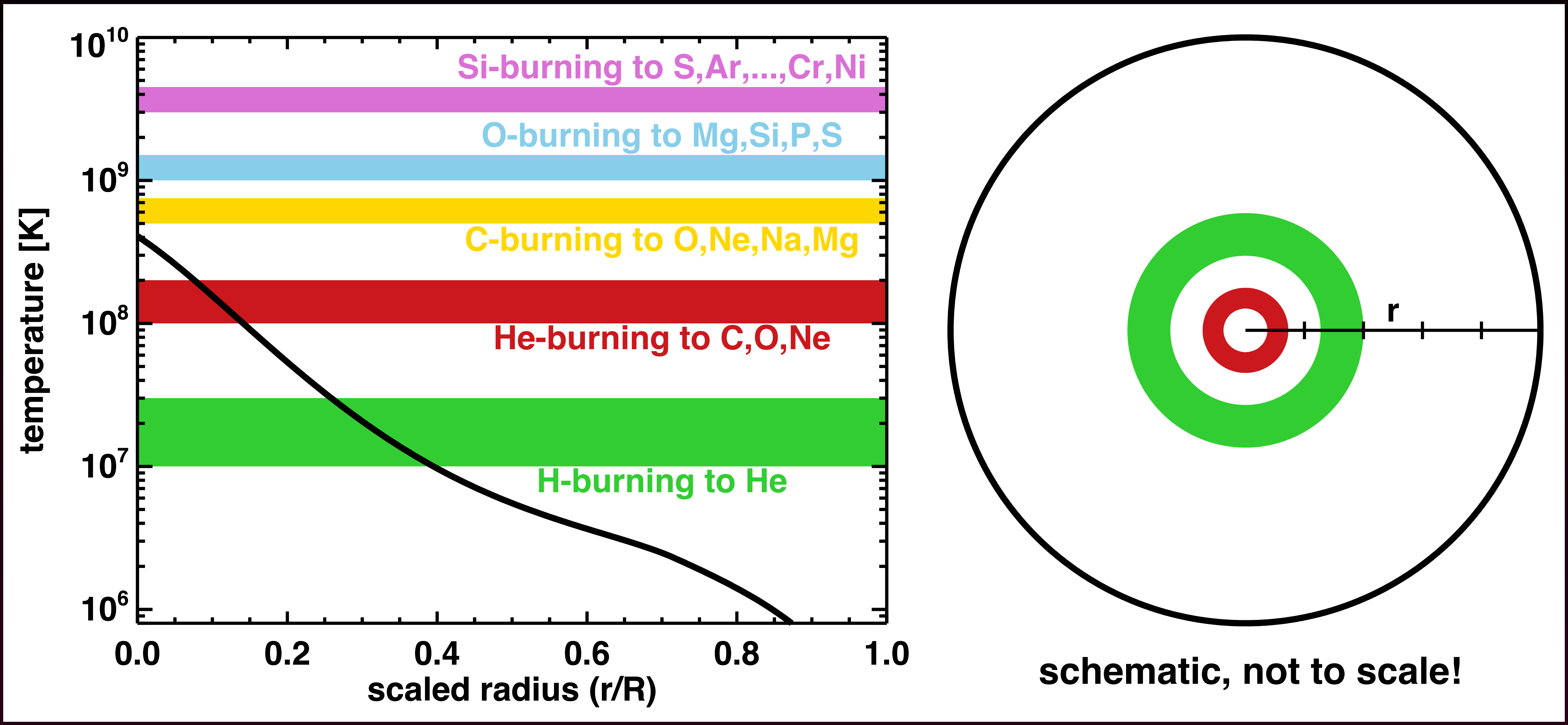
$$\begin{aligned} {}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} &\rightleftharpoons {}^{32}_{16}\mathrm{S} + \gamma \\ {}^{32}_{16}\mathrm{S} + {}^{4}_{2}\mathrm{He} &\rightleftharpoons {}^{36}_{18}\mathrm{Ar} + \gamma \\ &\vdots \\ {}^{52}_{26}\mathrm{Fe} + {}^{4}_{2}\mathrm{He} &\rightleftharpoons {}^{56}_{28}\mathrm{Ni} + \gamma \end{aligned}$$

photodisintegration!

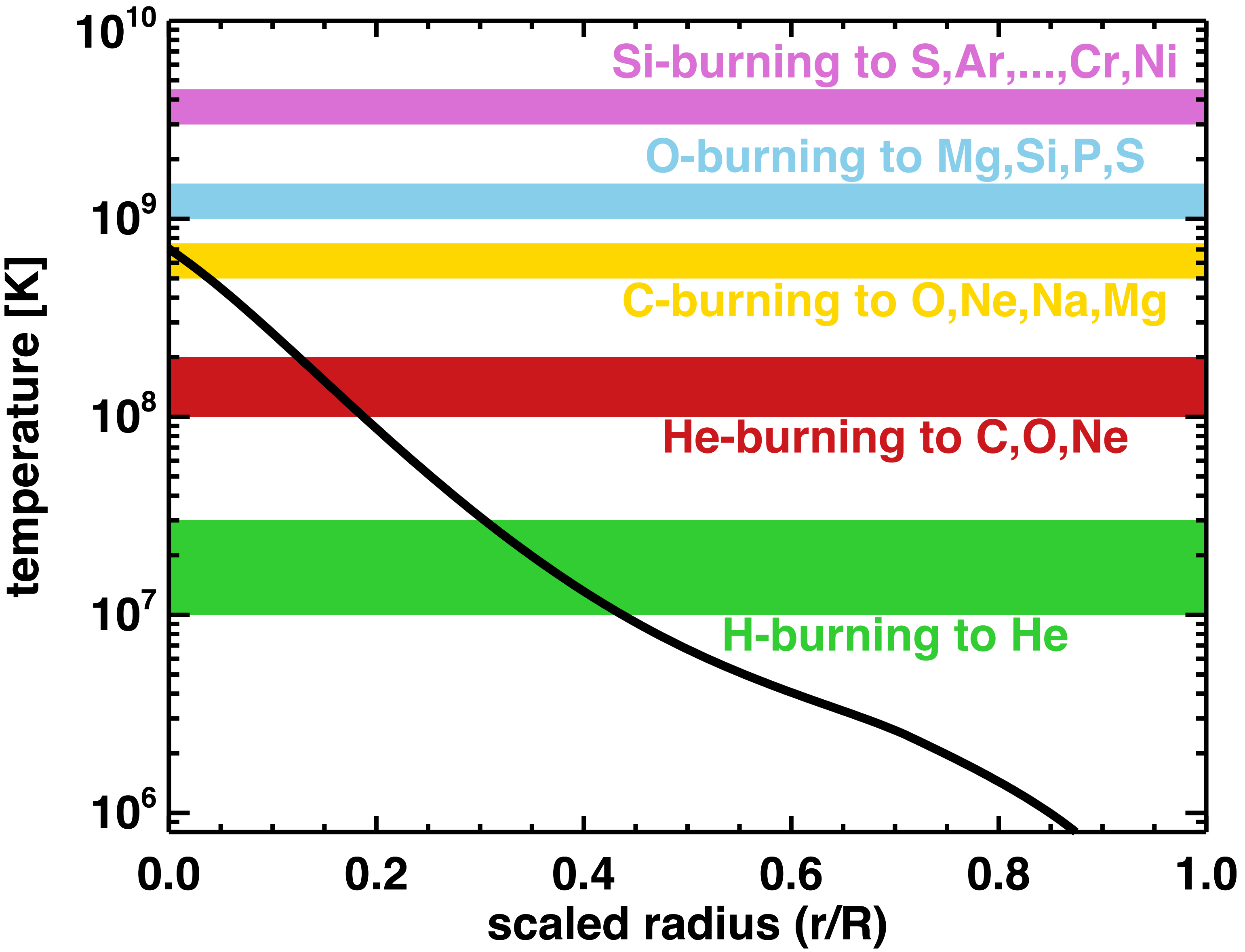
high mass stellar evolution

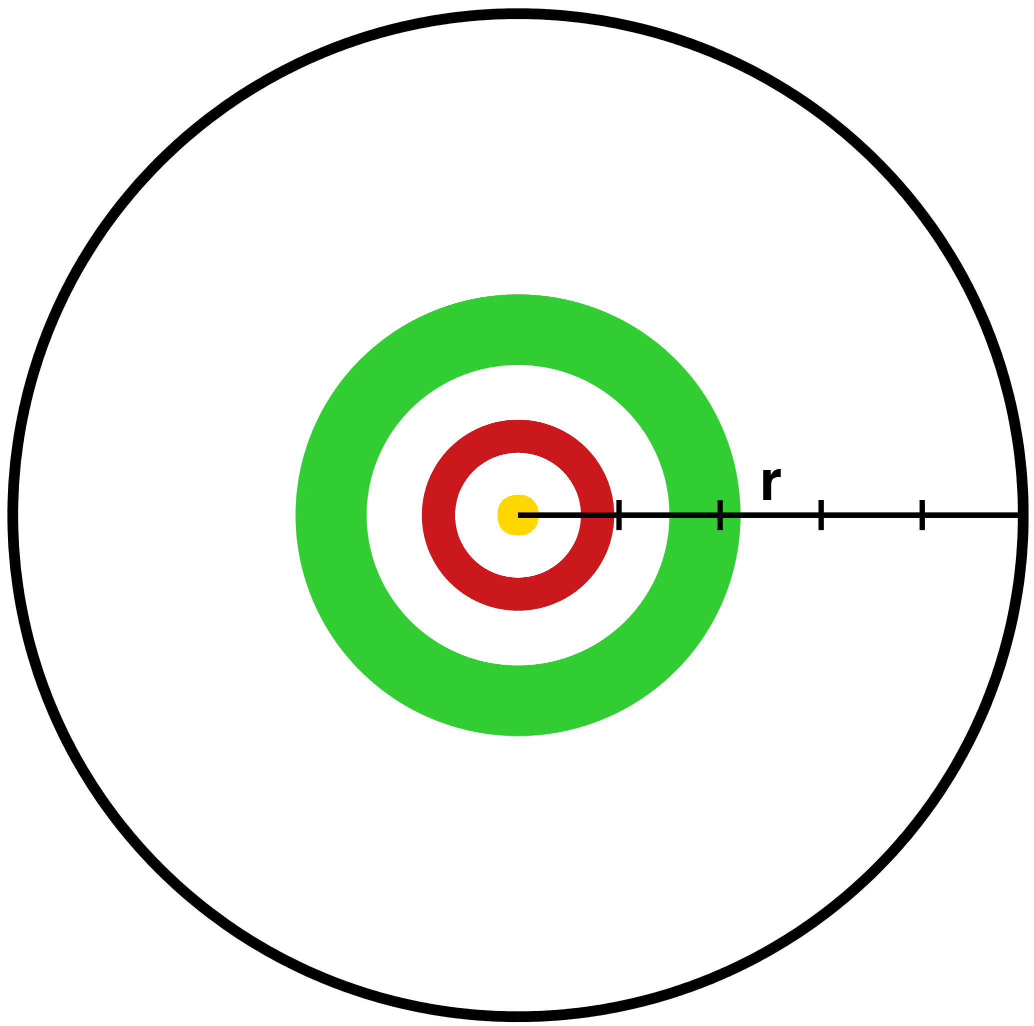


high mass stellar evolution



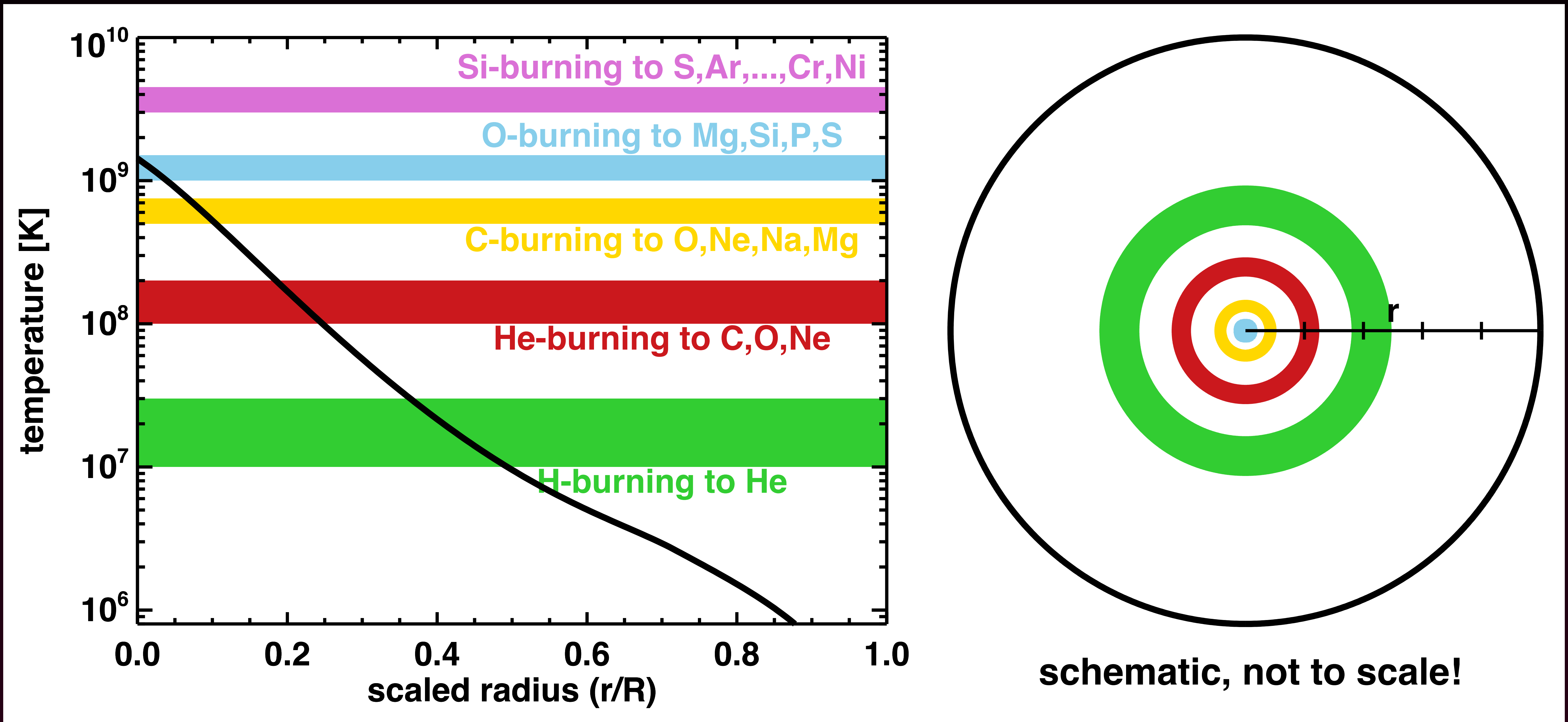
high mass stellar evolution



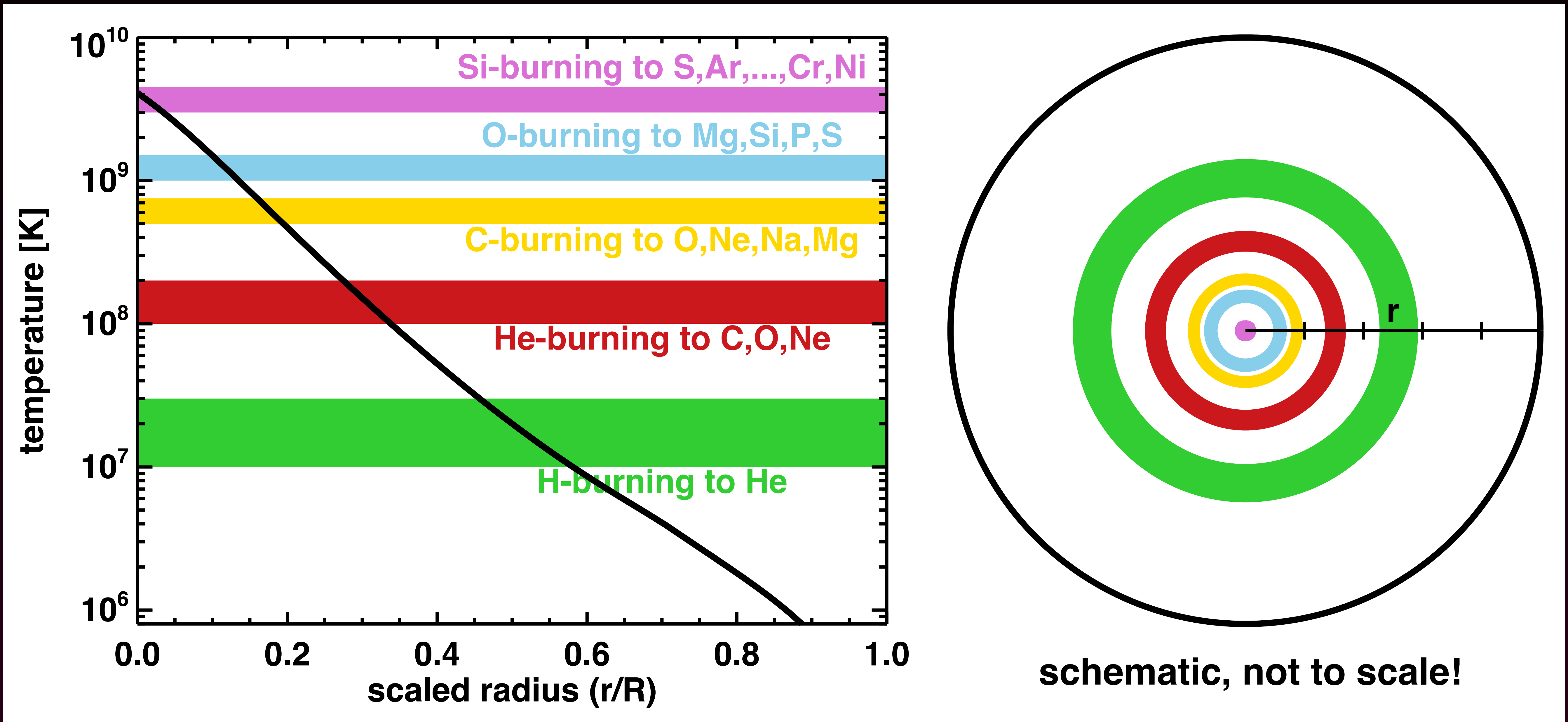


schematic, not to scale!

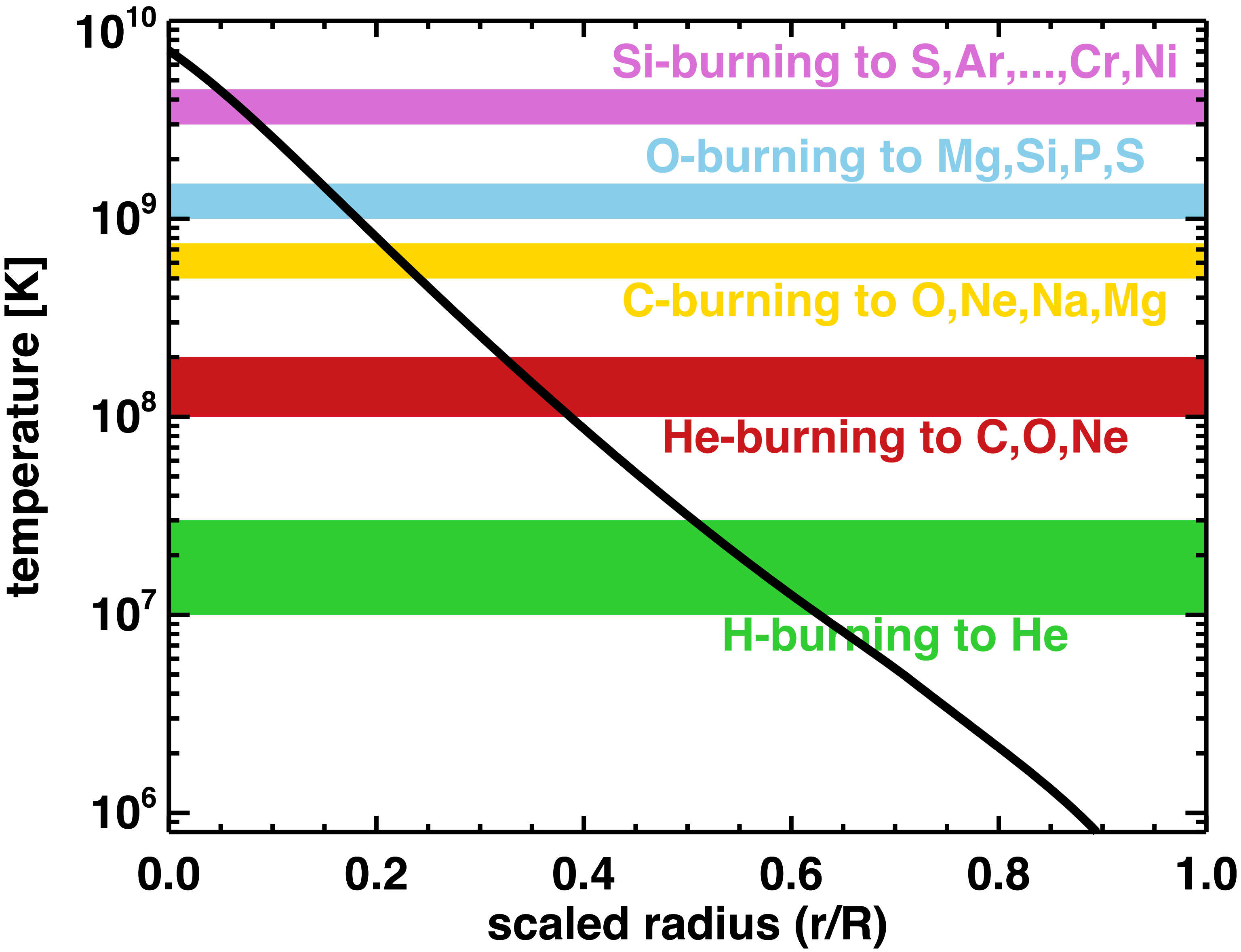
high mass stellar evolution

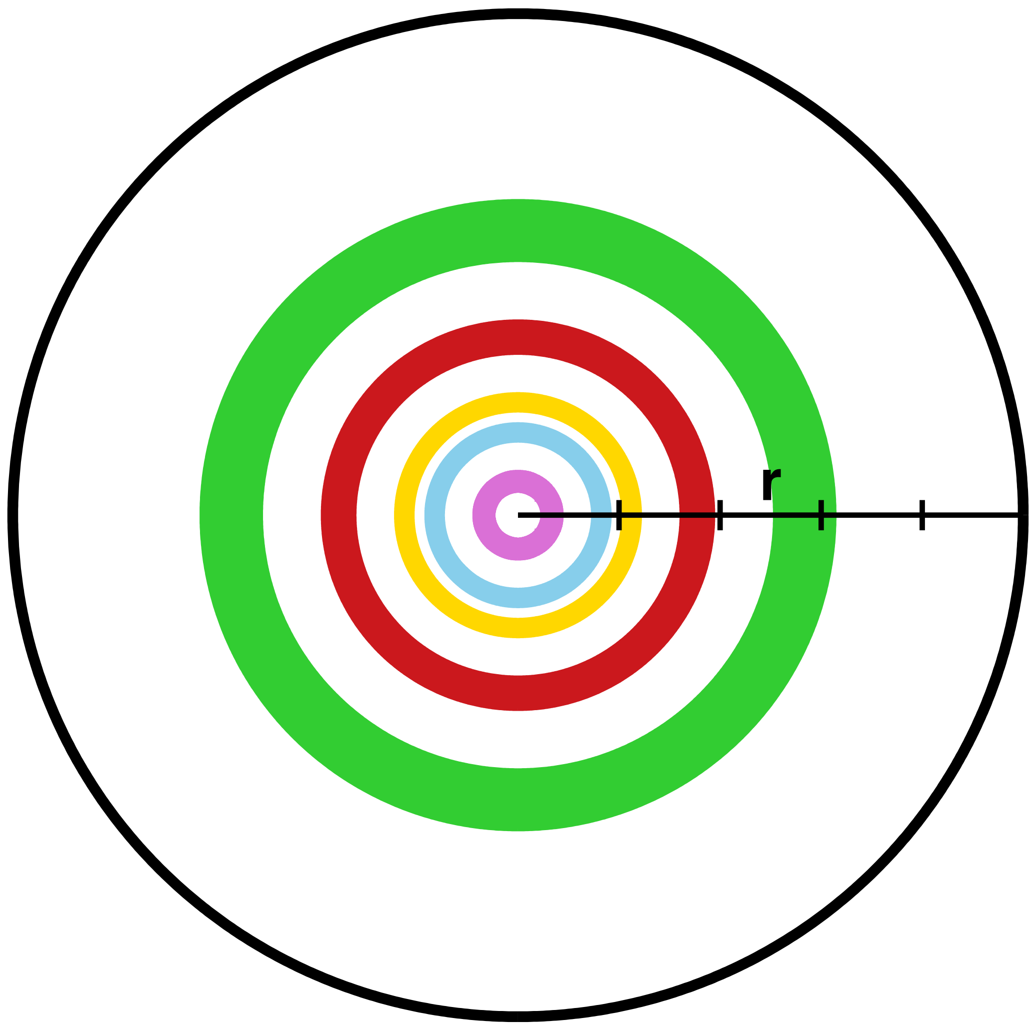


high mass stellar evolution



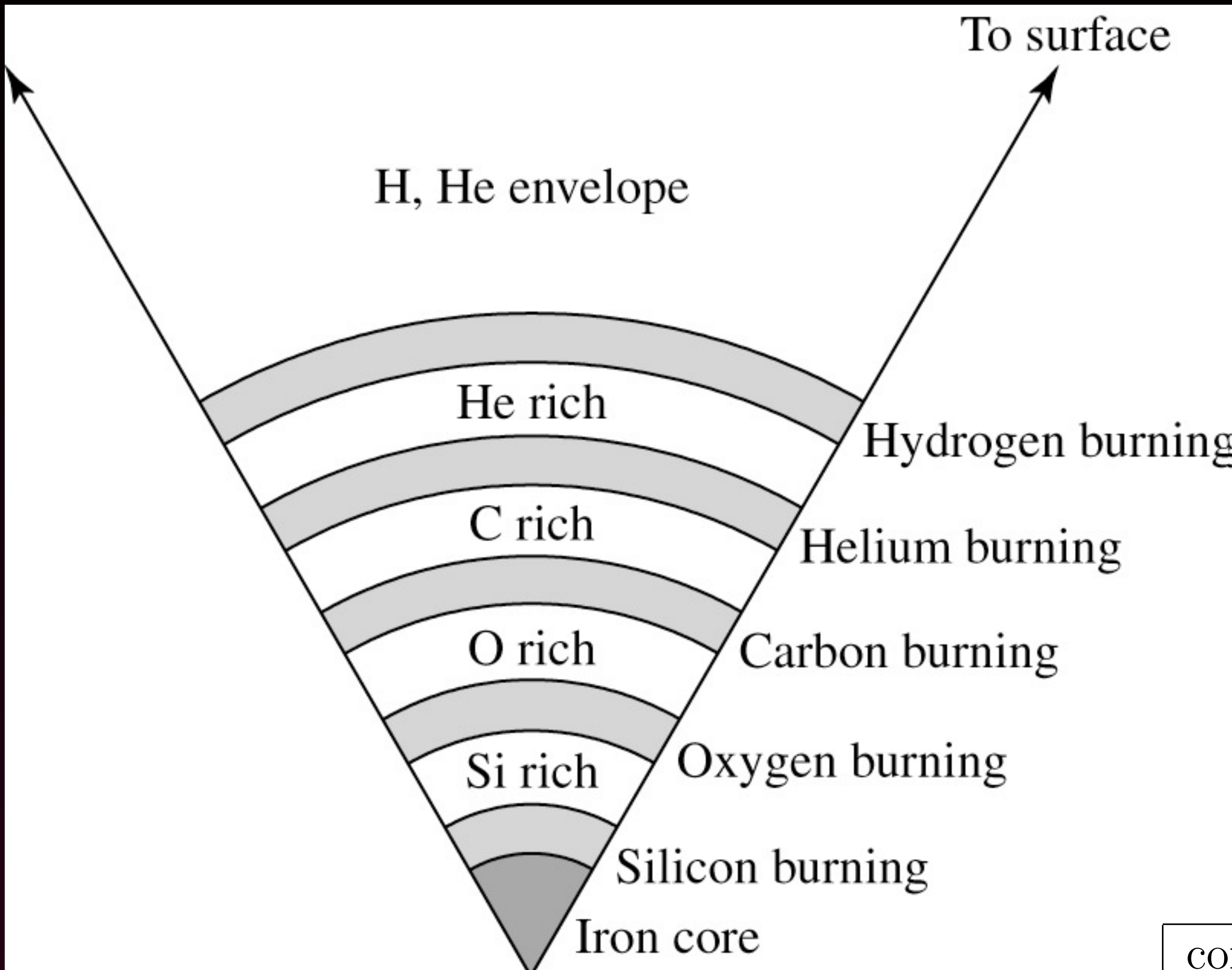
high mass stellar evolution





schematic, not to scale!

“onion” structure



core hydrogen burning	10^7 yr
core helium burning	10^6 yr
core carbon burning	300 yr
core oxygen burning	200 days
core silicon burning	2 days

Carroll & Ostlie Figure 15.10
and core burning lifetimes for a 20 solar mass star