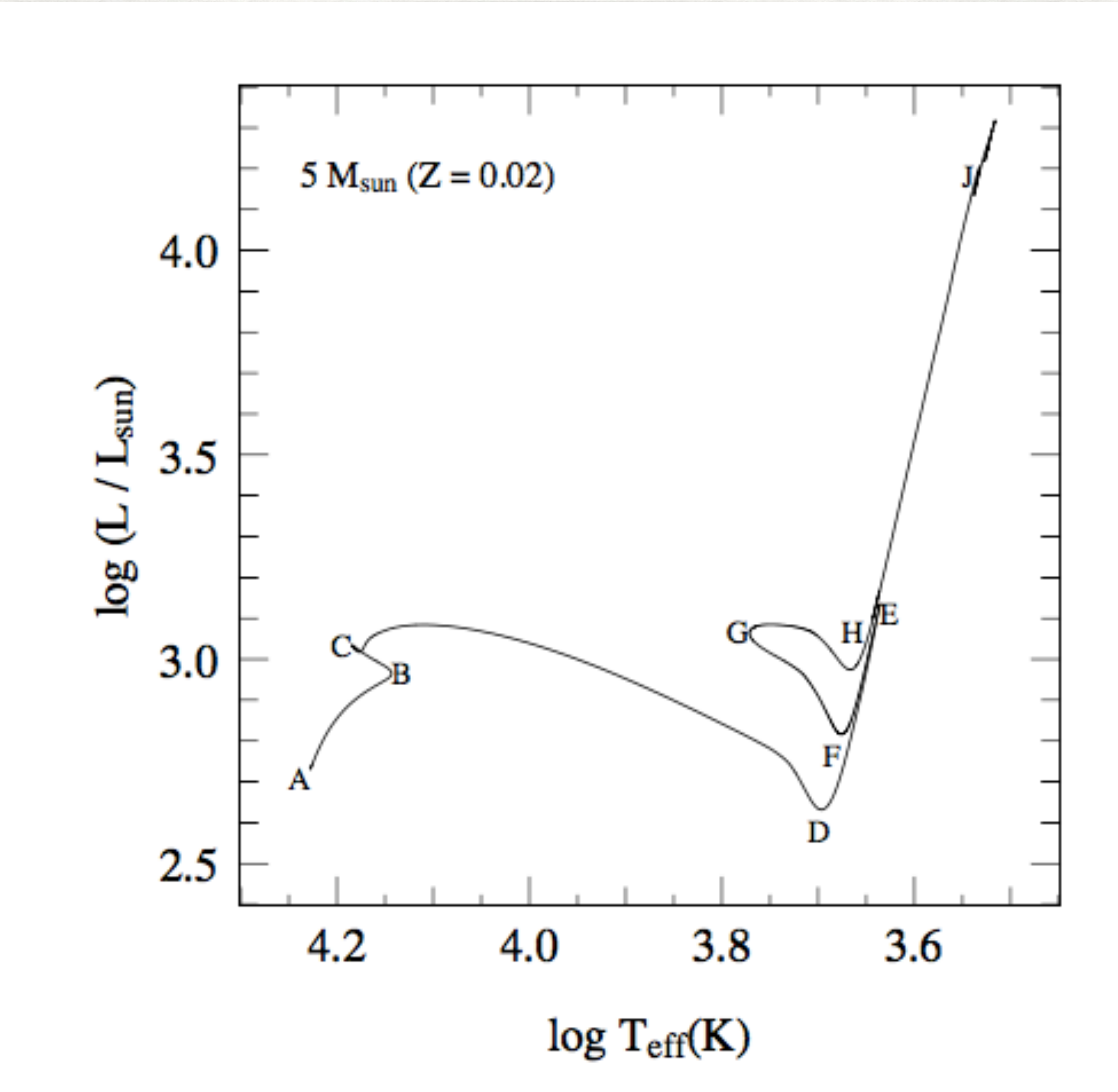
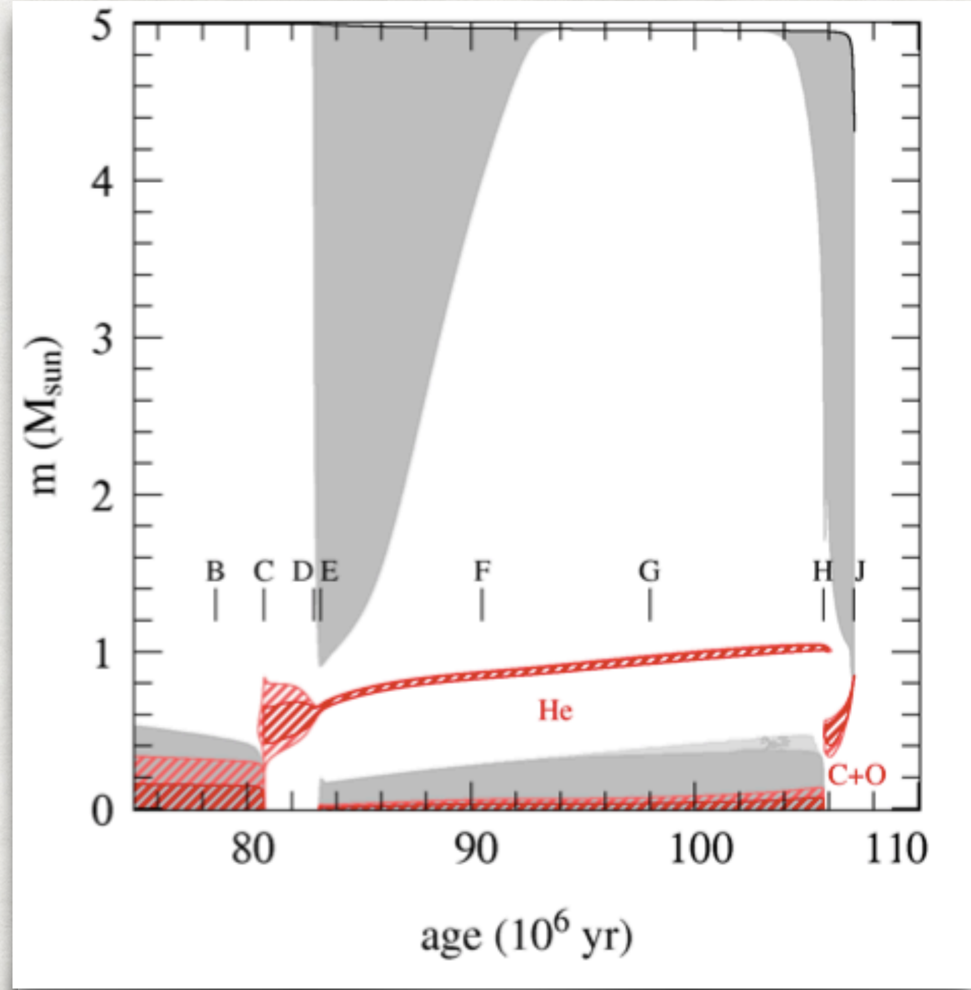
CHAPTER 11

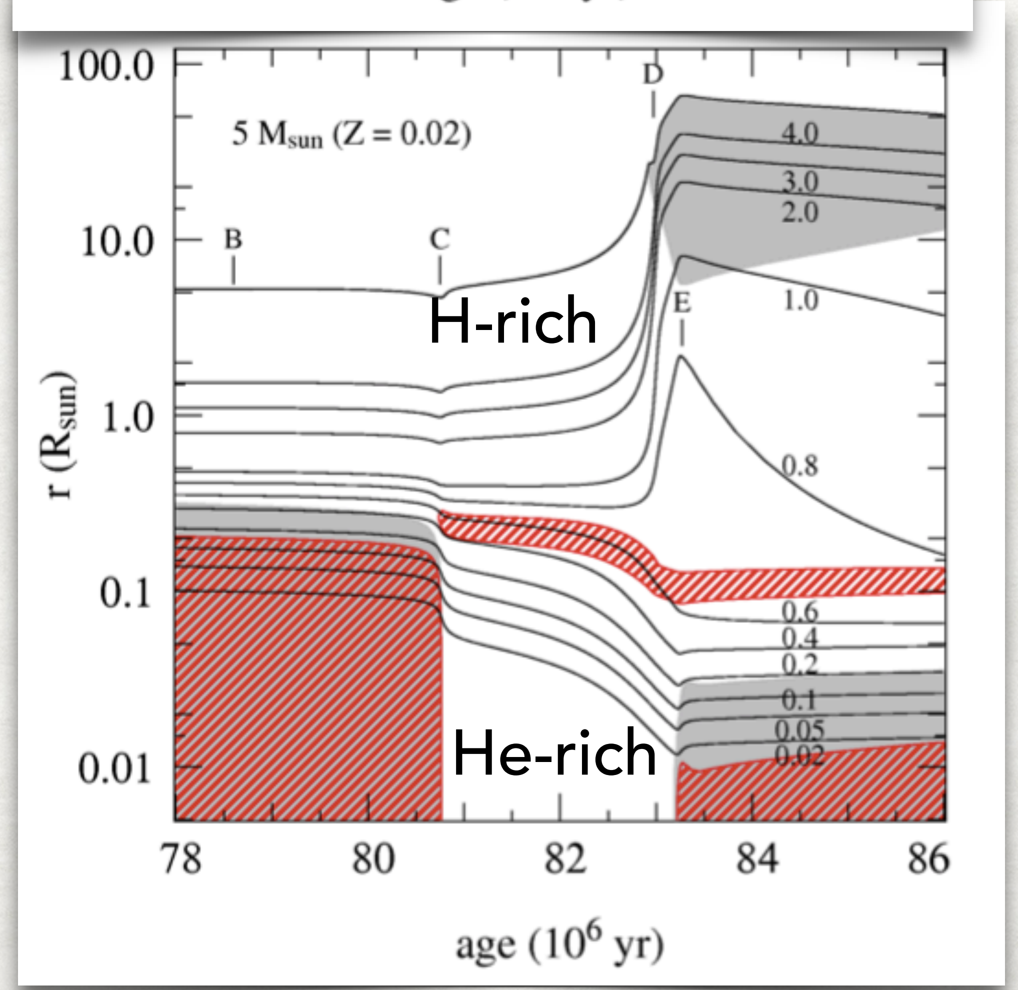
LATE EVOLUTION OF $M < 8\ M_{SUN}$

SUMMARY

M> 2 SOLAR MASSES







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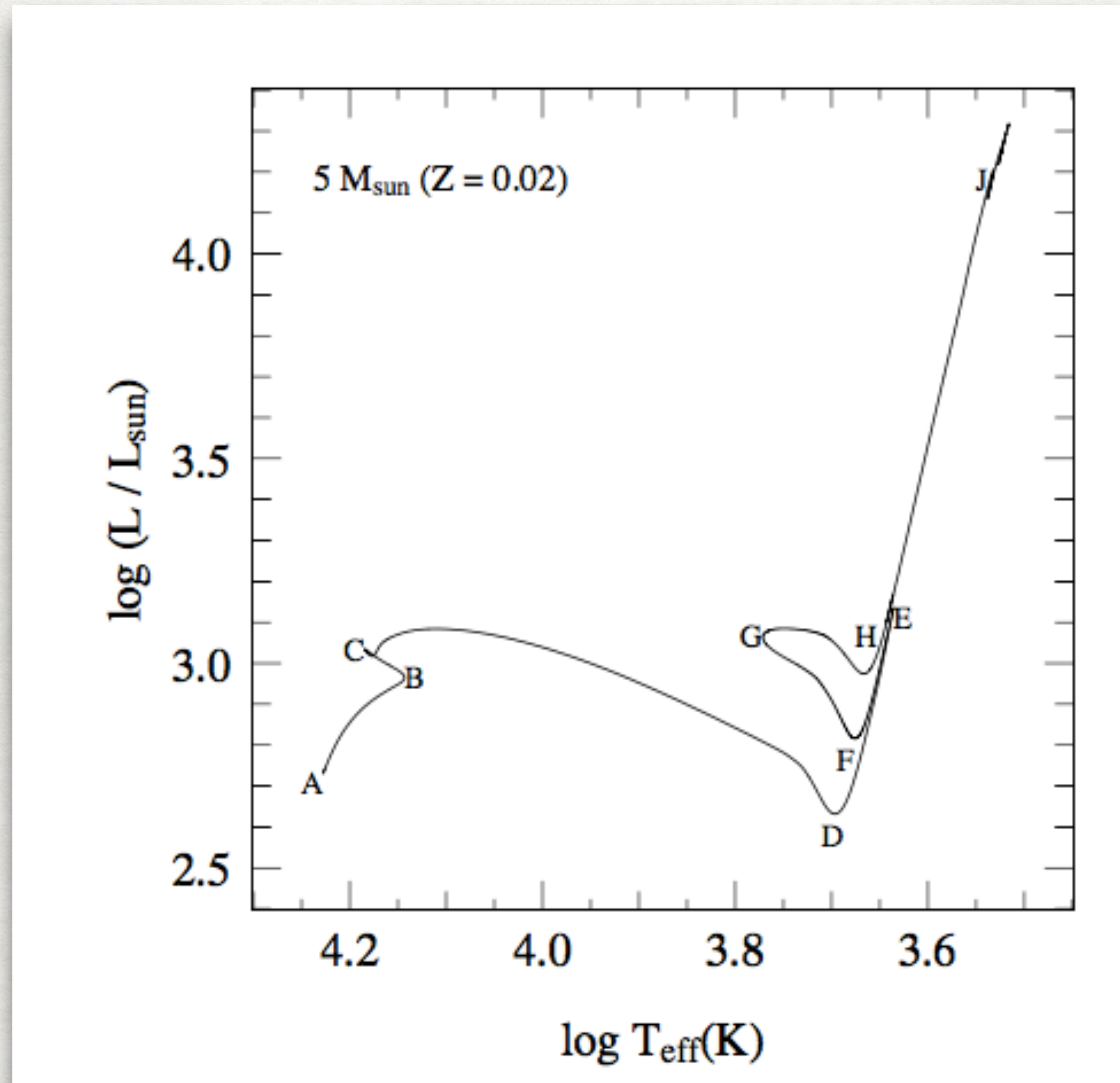


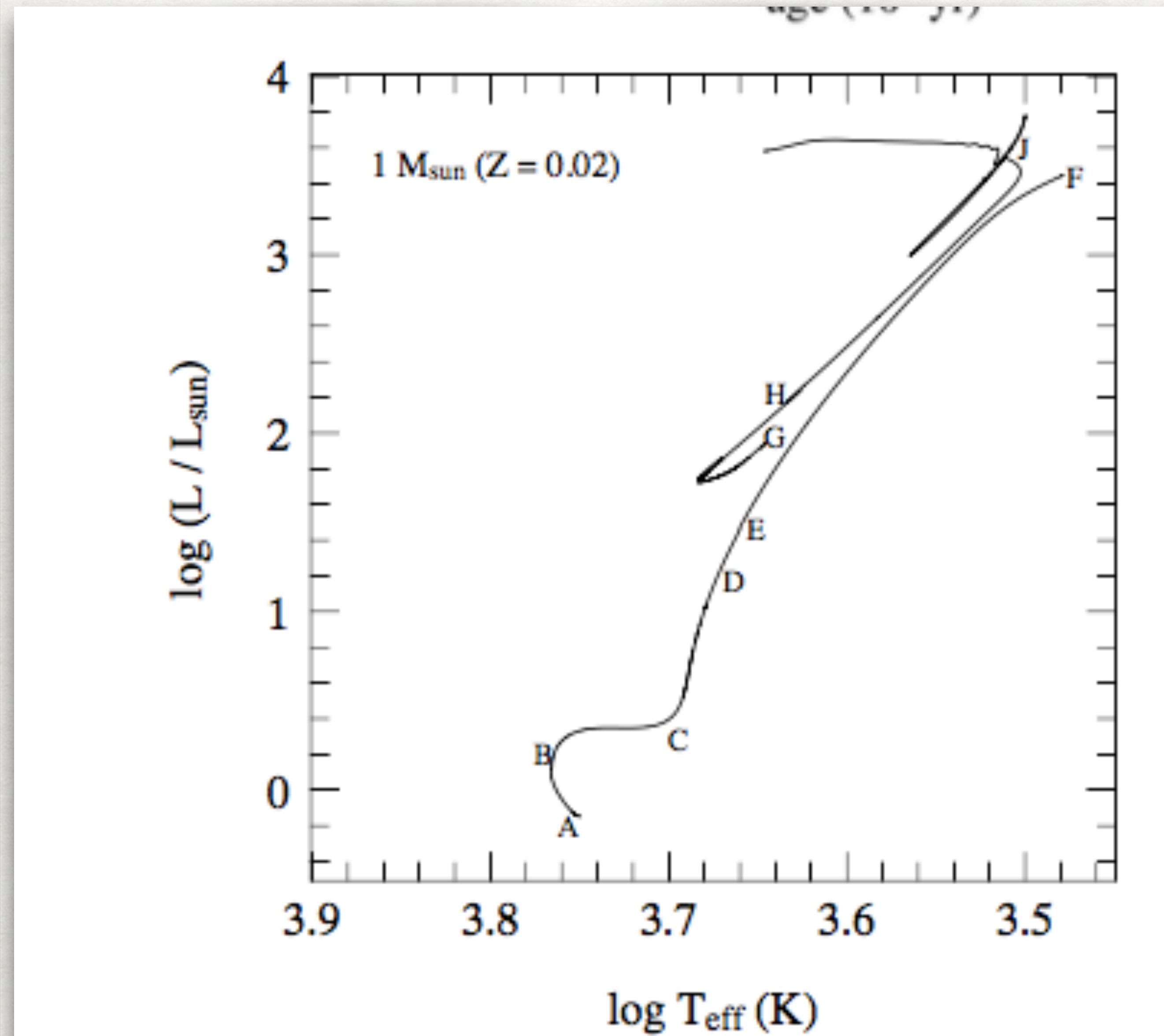
1) evolution on thermal timescale from ~C to E: very fast : ~$10^{5\text{-}6}$ yr ``Hertzspung gap" in H-R diagram

2) stable He burning in a ``blue loop", evolution on nuclear timescale ~ ~10^{7} yr

3) No mass core - luminosity relation for RGB

SUMMARY

M< 2 SOLAR MASSES



Differences:

1) M <1.5 Msun transition from main sequence to H-shell burning gradual (~ a few Gyr) no ``Hertzspung gap" in H-R diagram

2) core-mass luminosity relation for RGB stars (C-F), because core is degenerate

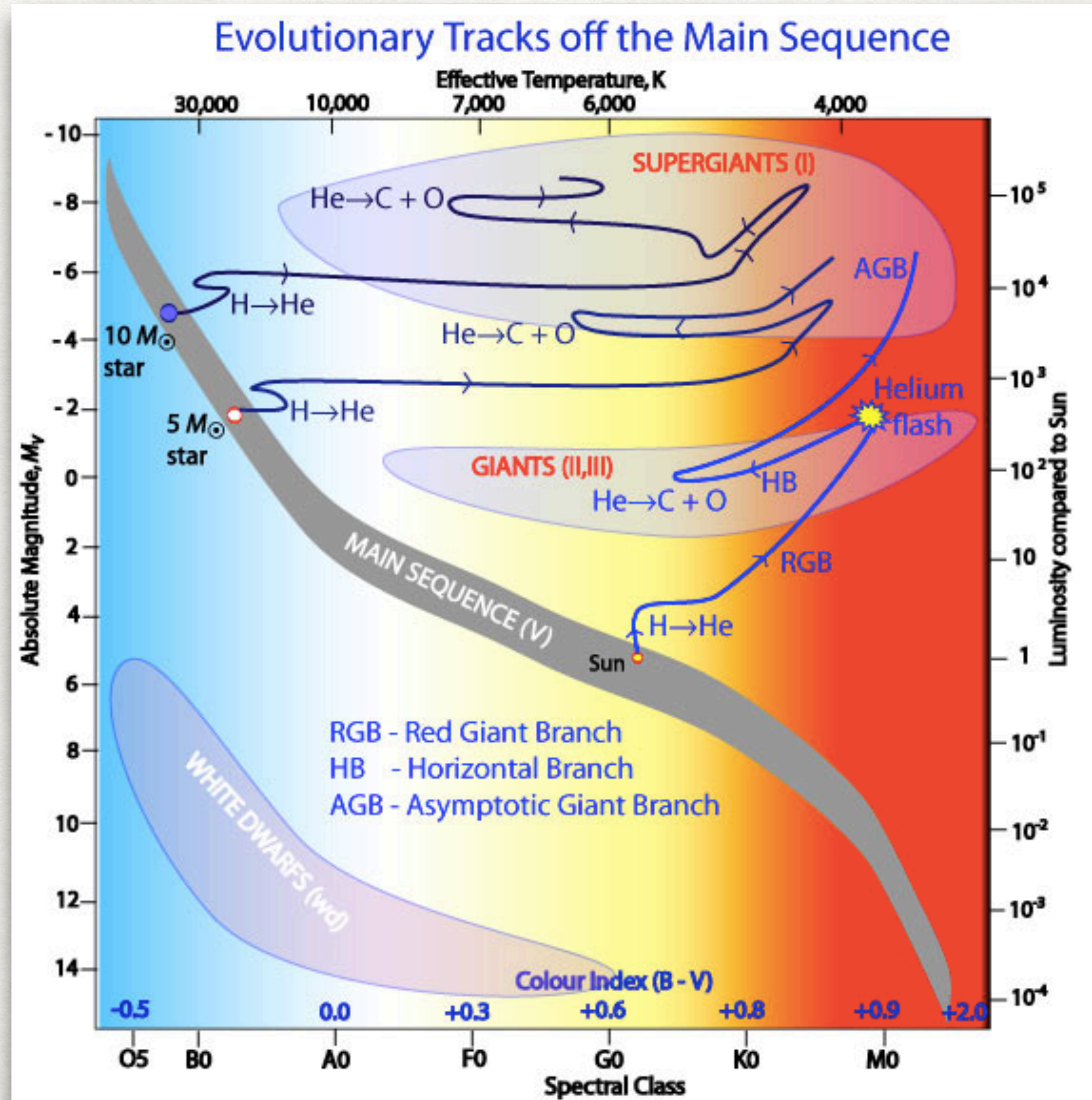
3) in C He core degenerate : UNstable He burning flash at tip of RGB (in F), when core mass ~0.45 M_{sun}

$$L \approx 2.3 \times 10^5 L_{\rm sun} \left(\frac{M_{\rm c}}{M_{\rm sun}}\right)^6 \text{ for } 0.1 < M_{\rm c}/M_{\rm sun} < 0.5$$

the luminosity increases as the mass in

THE ASYMPTOTIC GIANT BRANCH

For $M < 8\ M_{sun}$ the C-O core becomes degenerate



AGB branch: extension of RGB towards higher luminosities at the boundary with the Hayashi track

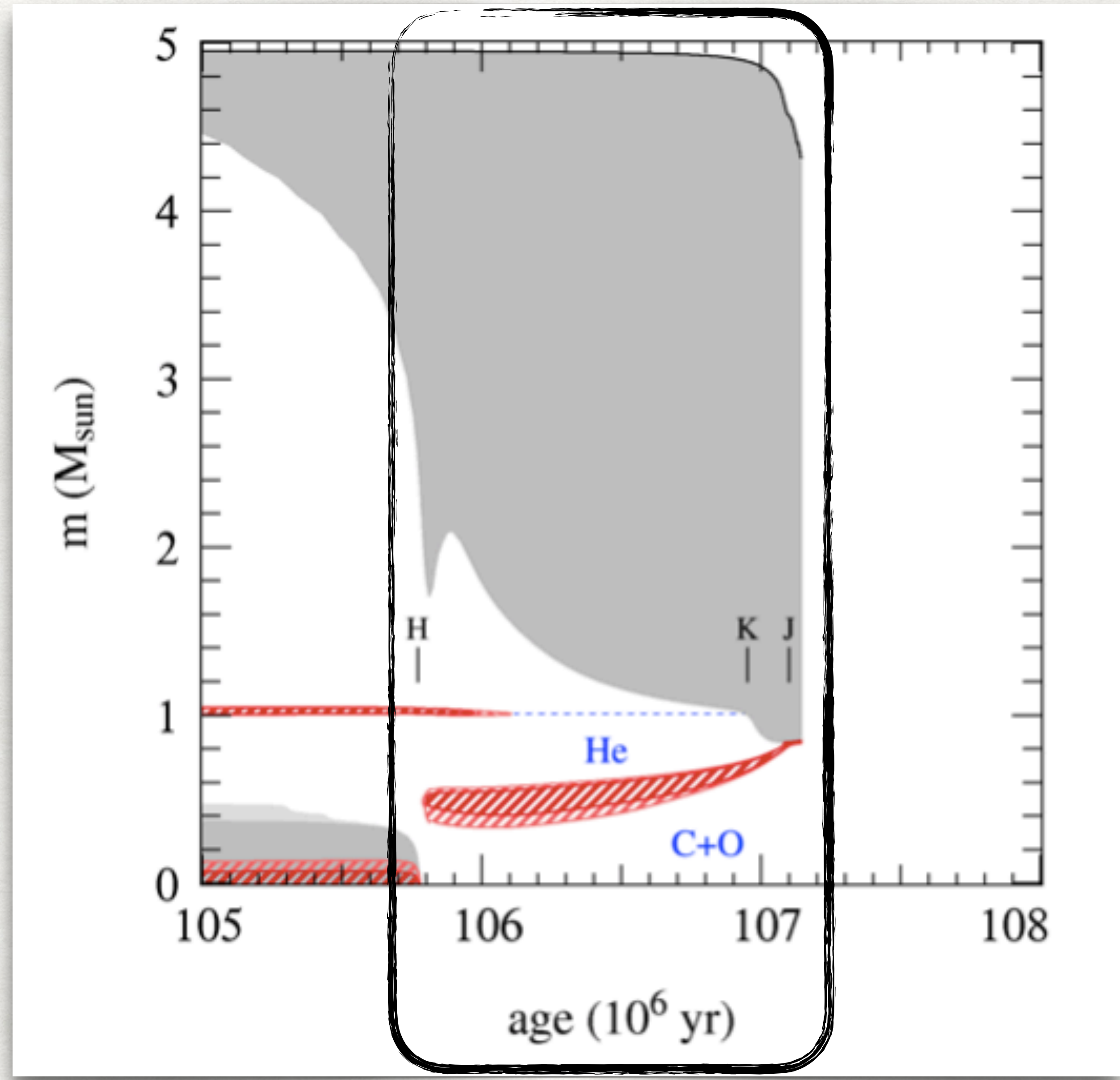
AGB stars are even bigger than the former red giants and are called Supergiants

We now study the evolution from point H on, after central He exhaustion (G-H)

e.g. 5 solar mass

Point H:

- devoid of energy sources, the C+O core contracts and heats up
- consequently the envelope expands, cools and convection sets in again throughout it
- the core contraction causes ignition of He burning to a shell around inert C+O core
- the envelope expansion temporarily extinguishes the H burning shell (back at J)

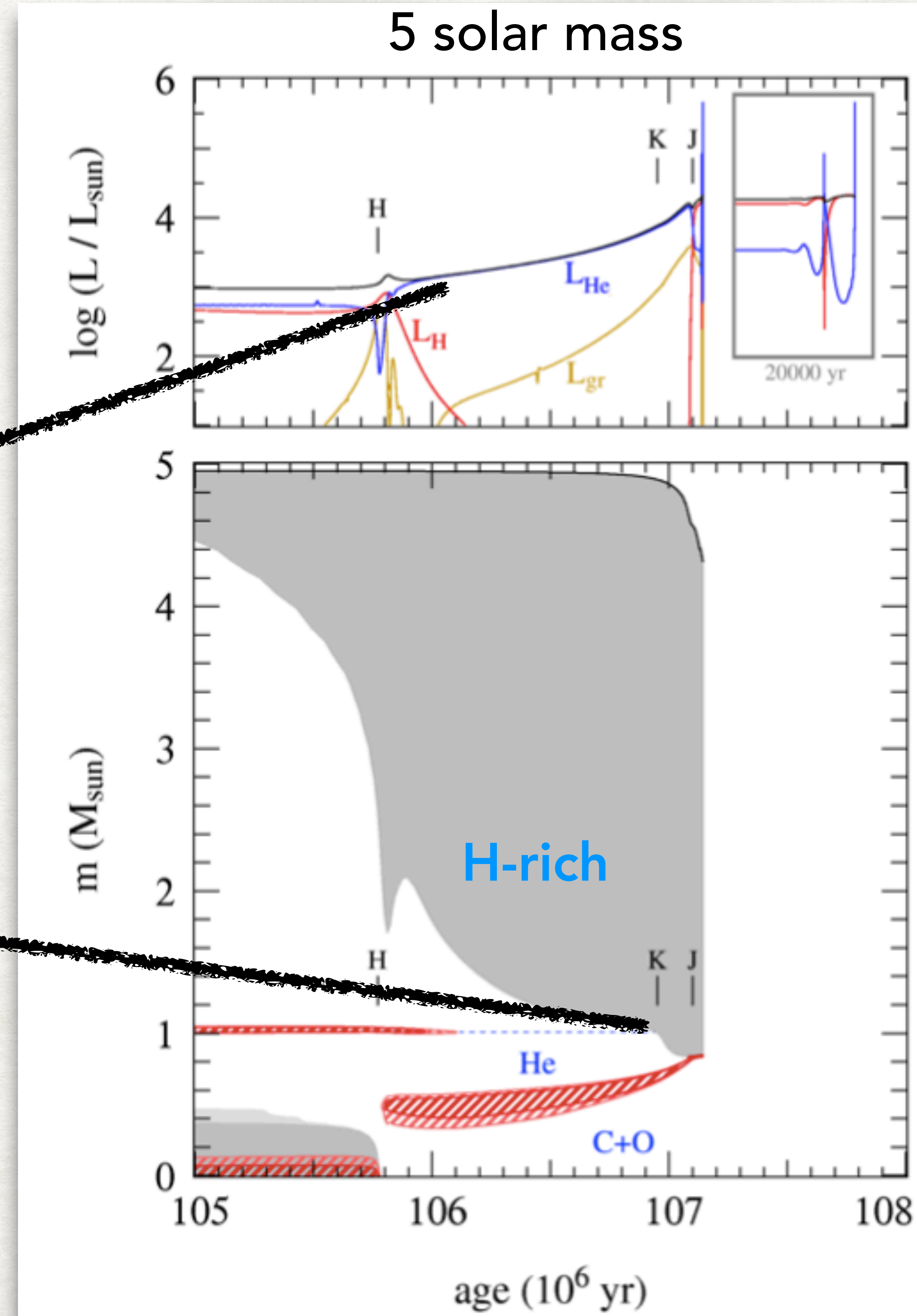


THE EARLY ASYMPTOTIC GIANT BRANCH

Phase: H-K

H-K:

- chemical structure:
  - the inert C+O
  - He burning shell
  - He rich layer
  - H rich envelope
- Luminosity only due to He burning shell only
- He burning shell adds mass to C+O core, density increases==> degenerate C+O core
- The inner boundary of convective envelope overlaps the earlier outer boundaries of now extinguished H-burning shell: second dredge-up: He and N-rich material

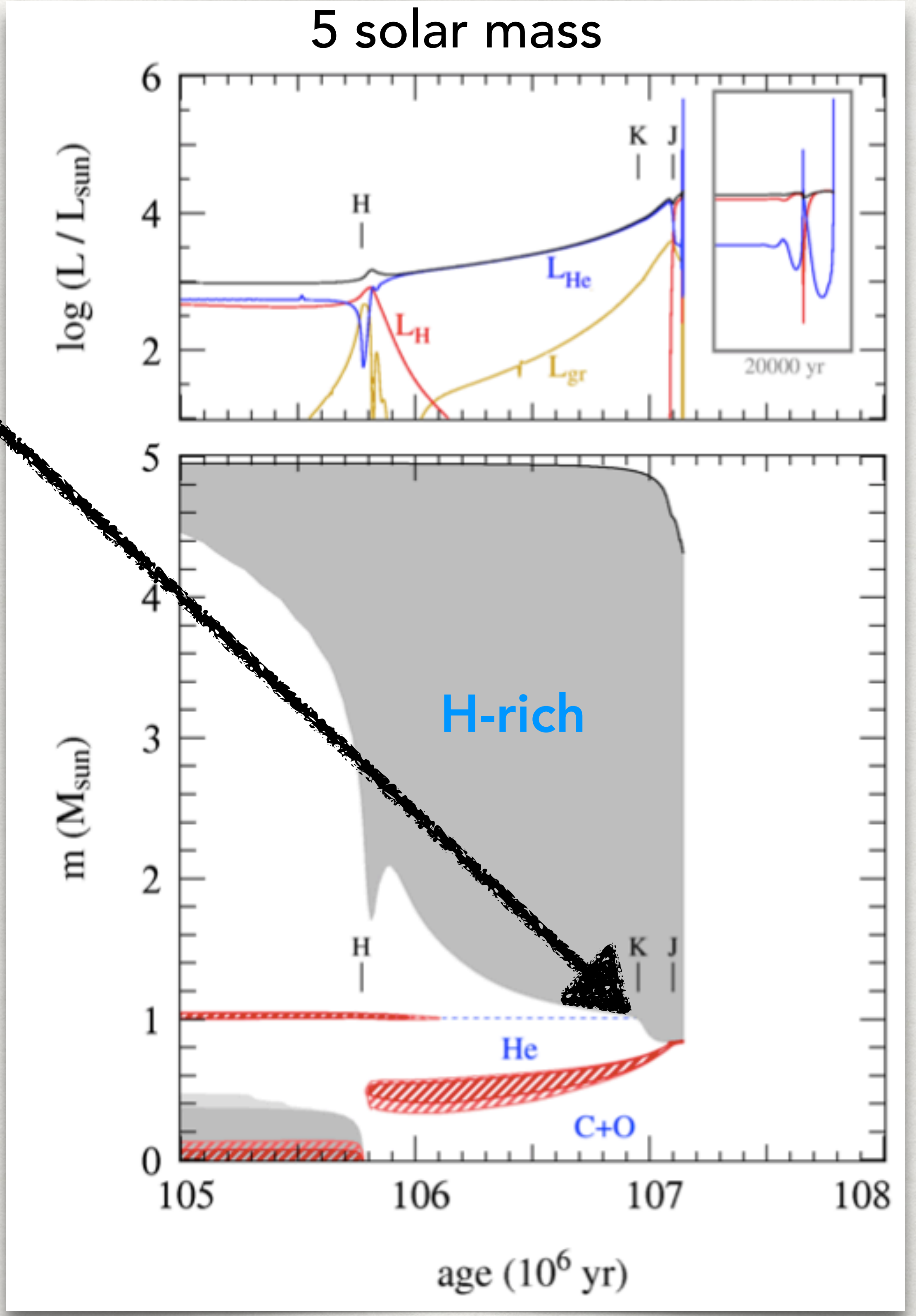


THE EARLY ASYMPTOTIC GIANT BRANCH

Phase: K-J

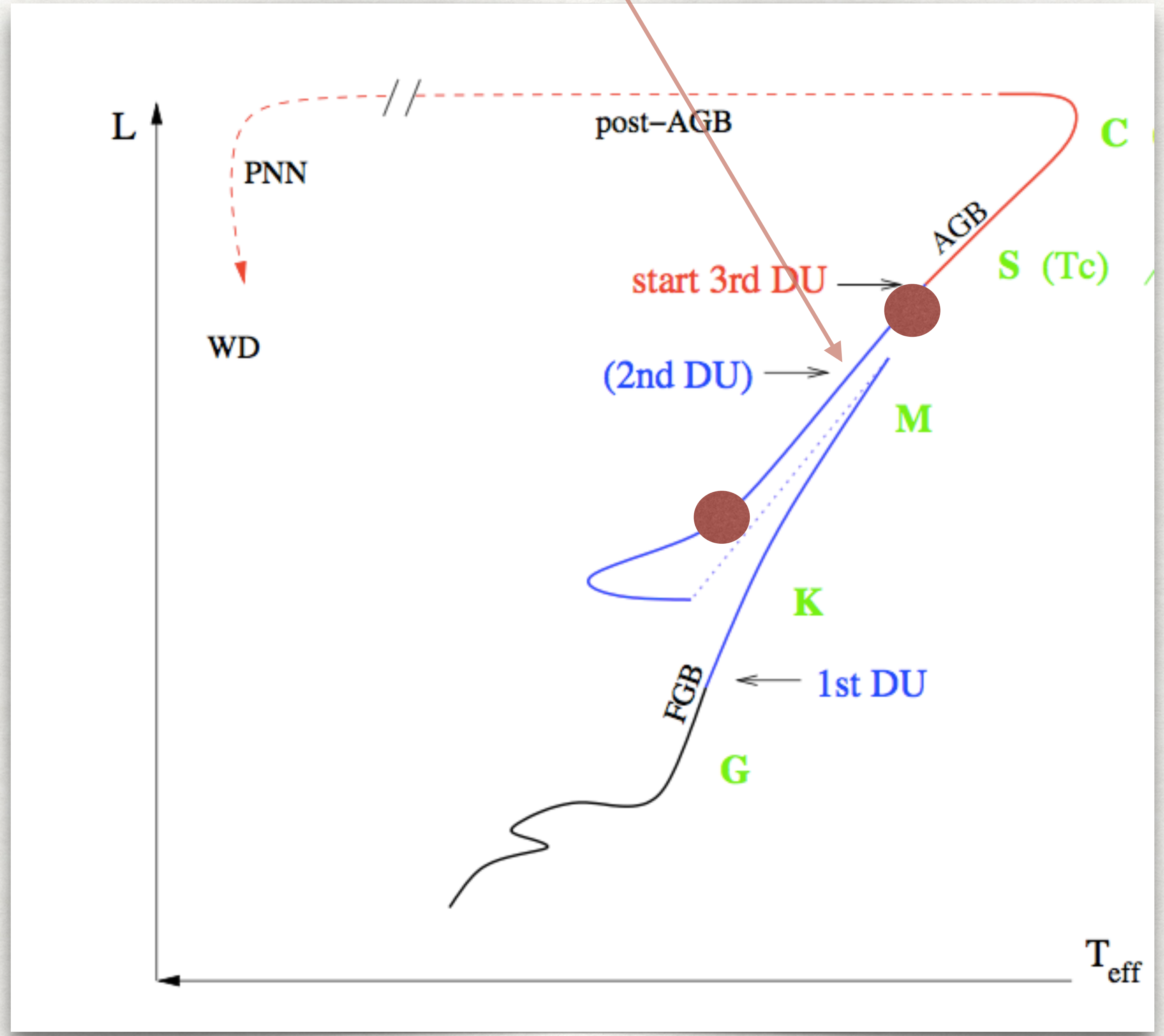
Second dredge-up

- He and N-rich material
- Substancial: 0.2 M_{sun} in this example, up to ~1 M_{sun} in more massive stars
- It decreases the mass of the H-depleted core, limiting the white dwarf mass
- a low level of activity in H-burning shell prevent substantial dredge-up for stars with < 4 M_{sun}



THE EARLY ASYMPTOTIC GIANT BRANCH

On the H-R diagram



schematic diagram for solar type star

THERMALLY PULSING AGB (TP-AGB)

FROM POINT J ON

main features on TP-AGB stars

1. Nuclear burning takes place in two shells, leading to a long series of thermal pulses
2. The luminosity is uniquely determined by the mass of the core, independently of the star mass

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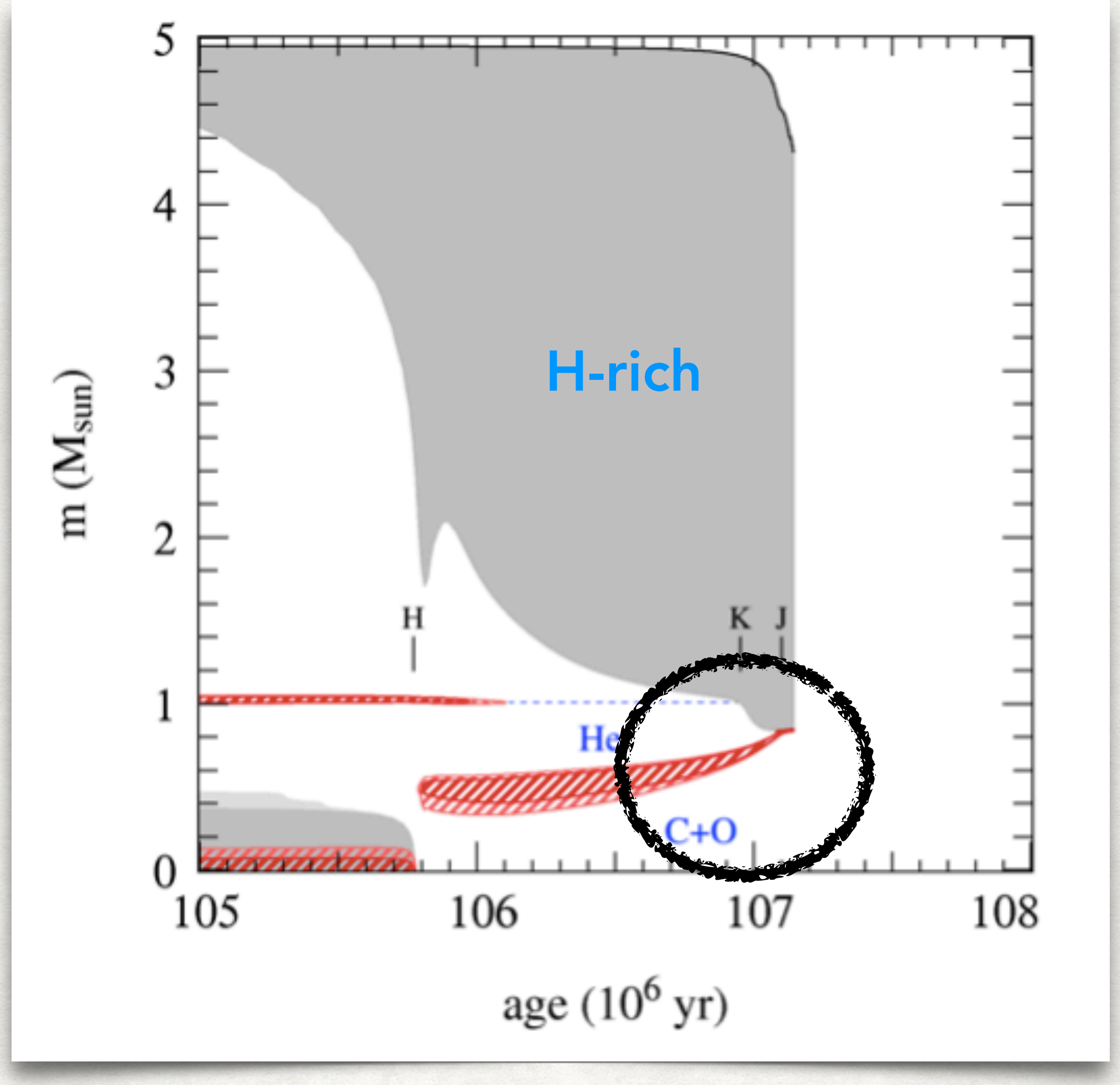
DOUBLE SHELL BURNING

This is how it starts:

- The He—>C+O shell burns fuel, advancing towards the He-H discontinuity
- The He—>C+O shell is running out of fuel
- Luminosity decreases
- In response the envelope contracts a bit, temperature rises and H-burning shell is re-ignited at the base of the envelope

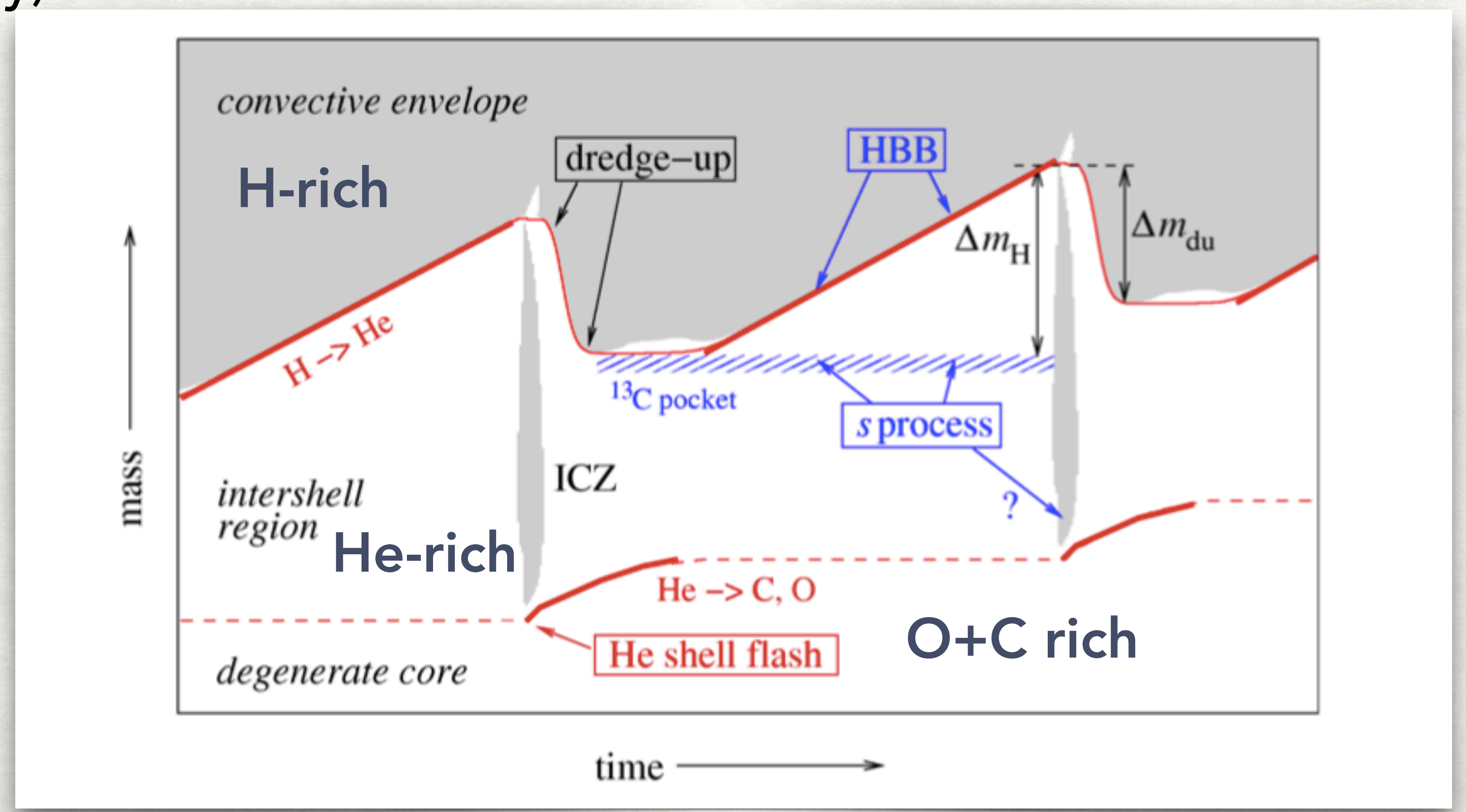


DOUBLE SHELL BURNING

There are two shells burning and providing L during AGB phase

1. The external shell H —>He, adding mass to He-rich layer in between
2. The internal shell He —>C,O adding mass to the inert C+O core and eating into inter shell He-rich region

Steady state with the two burning fronts advancing at the same rate cannot develop because rates a too different: the two shells do not supply energy simultaneously but in turn *in a cycle process* (He-rich region mass changes periodically)



THE CYCLE PROCESS

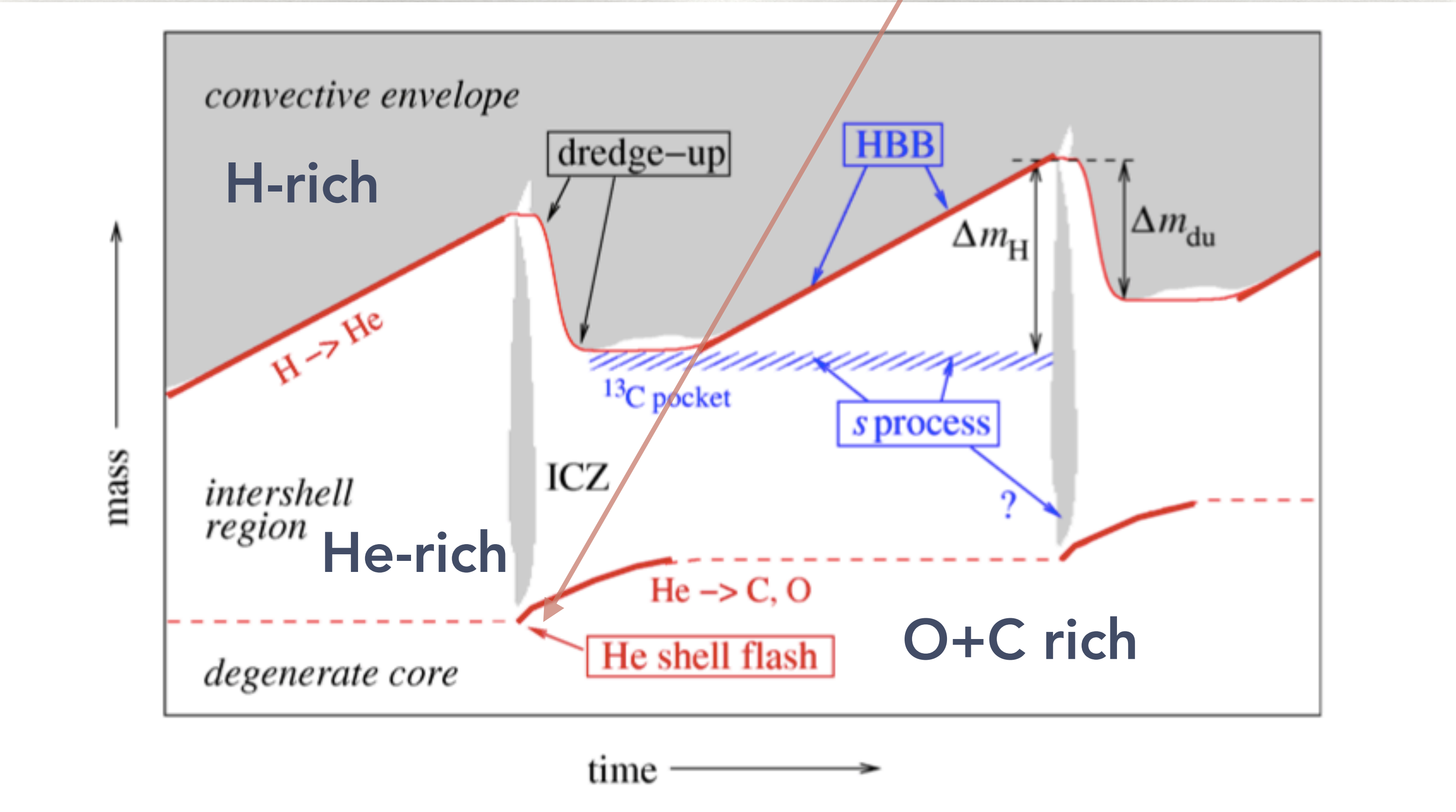
the two shells do not supply energy simultaneously but in turn *in a cycle process*

A: The H—> He shell adds mass to He-rich

B: With no energy supply, He-rich region contracts and heats up

C: Temperature at base of He-rich region becomes high enough for He to ignite

D: He ignition in this thin shell is unstable: short-lived flash with a nuclear generation rate reaching 10^8 L_{sun} for ~1 yr: ***helium shell flash***



THE CYCLE PROCESS

the two shells do not supply energy simultaneously but in turn *in a cycle process*

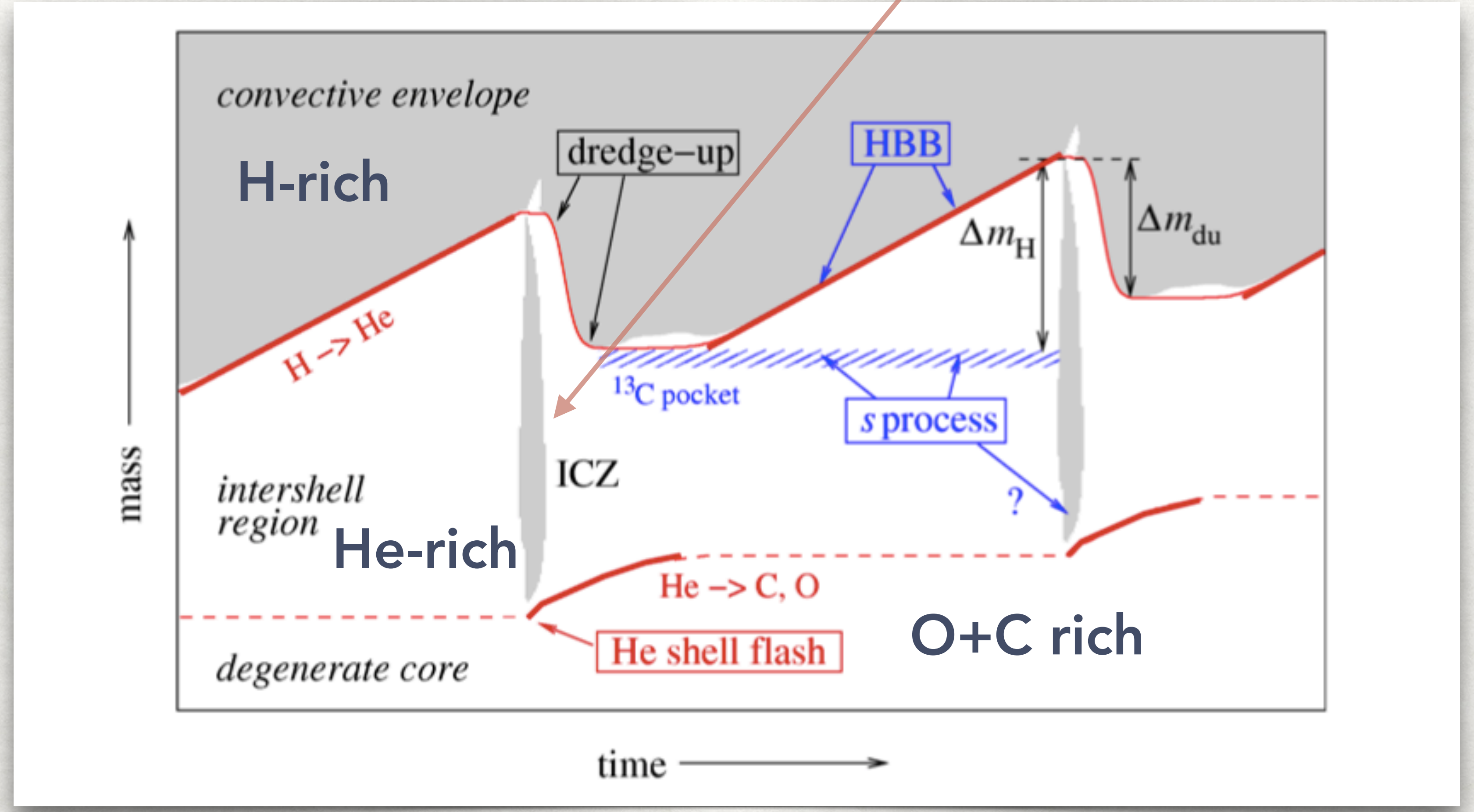
D: *helium shell flash:*

D1: Most energy is absorbed by the intershell that expands and cool

D2: H-burning rate quickly decreases

D3: He-rich region becomes convectively unstable: *intershell convective zone* (ICZ)

D4: He-burning shell expands as well and the unstable burning dies out after several yr



THE HELIUM SHELL FLASH

BURNING UNSTABLE IF SHELL IS TO THIN, EVEN FOR IDEAL GAS

take a thin shell with width $d = r - r_0 << R$ with mass $\Delta m = 4\pi r_0^2 \rho d$

in thermal equilibrium: $\dfrac{\mathrm{d}l}{\mathrm{d}m} = \epsilon_{\mathrm{nuc}}$

A perturbation of energy generation that exceeds the heat flow leads to expansion of shell:

$$\frac{\delta P}{P} = -4\frac{\delta r}{r}.$$

<0

+

$$\frac{\delta\rho}{\rho} = -\frac{\delta d}{d} = -\frac{\delta r}{r}\frac{r}{d}$$

<0

+

Equation of state for ideal gas

>0 <0

$$\frac{\delta T}{T} = \frac{1}{\chi_T}\left(4\frac{d}{r} - \chi_\rho\right)\frac{\delta\rho}{\rho}.$$

There is enough drop in pressure to cool the shell only if

$$4\frac{d}{r} > \chi_\rho$$

RECALL CH 3.4

$$\chi_T = \left(\frac{\partial \log P}{\partial \log T}\right)_{\rho, X_i} = \frac{T}{P}\left(\frac{\partial P}{\partial T}\right)_{\rho, X_i},$$

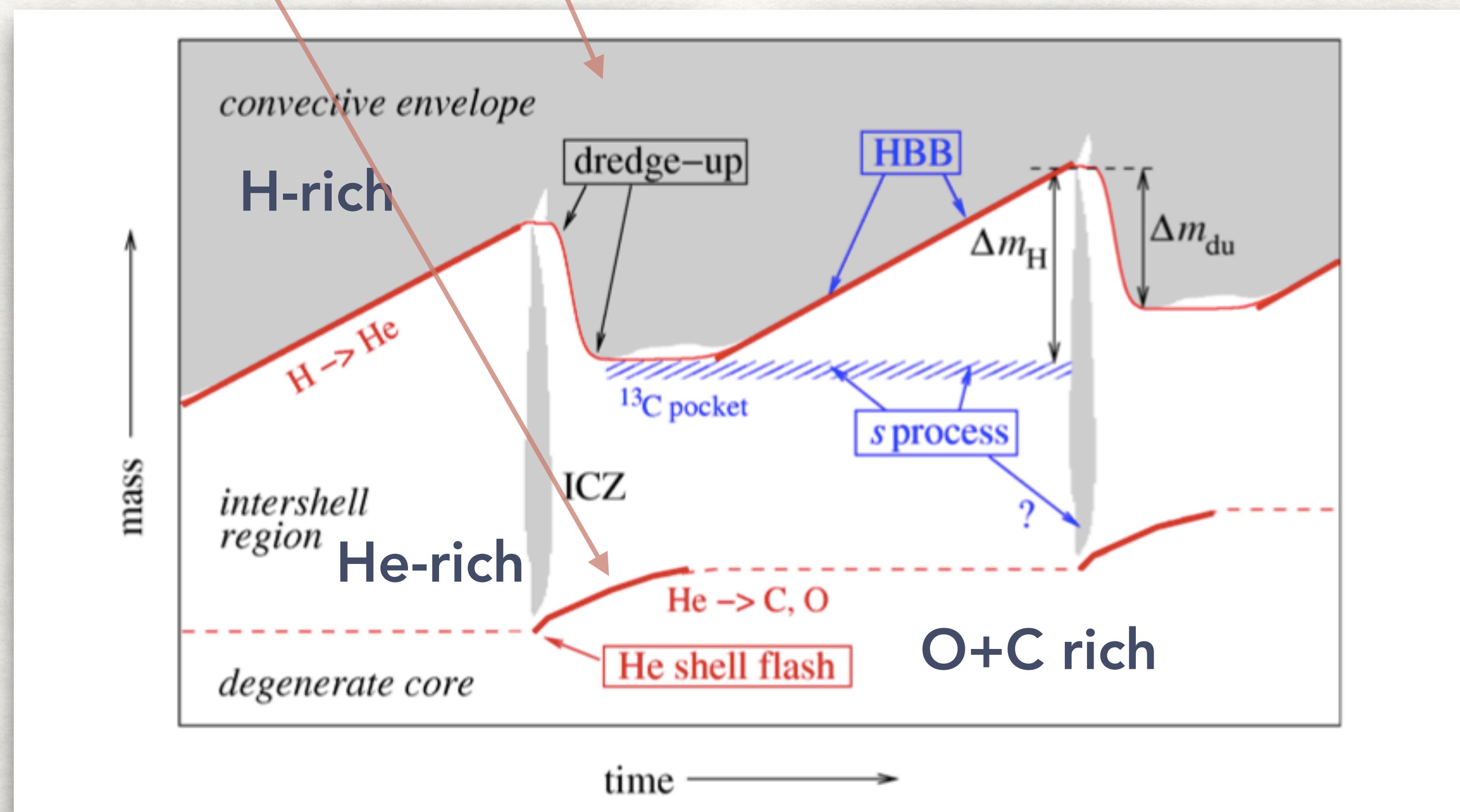
$$\chi_\rho = \left(\frac{\partial \log P}{\partial \log \rho}\right)_{T, X_i} = \frac{\rho}{P}\left(\frac{\partial P}{\partial \rho}\right)_{T, X_i}.$$

THE CYCLE PROCESS

the two shells do not supply energy simultaneously but in turn *in a cycle process*

E: phase of stable He-burning, with no H-burning shell : a few 100 yr duration

E1: third dredge-up : He and He burning products (^{12}C) appears at the surface



THE CYCLE PROCESS

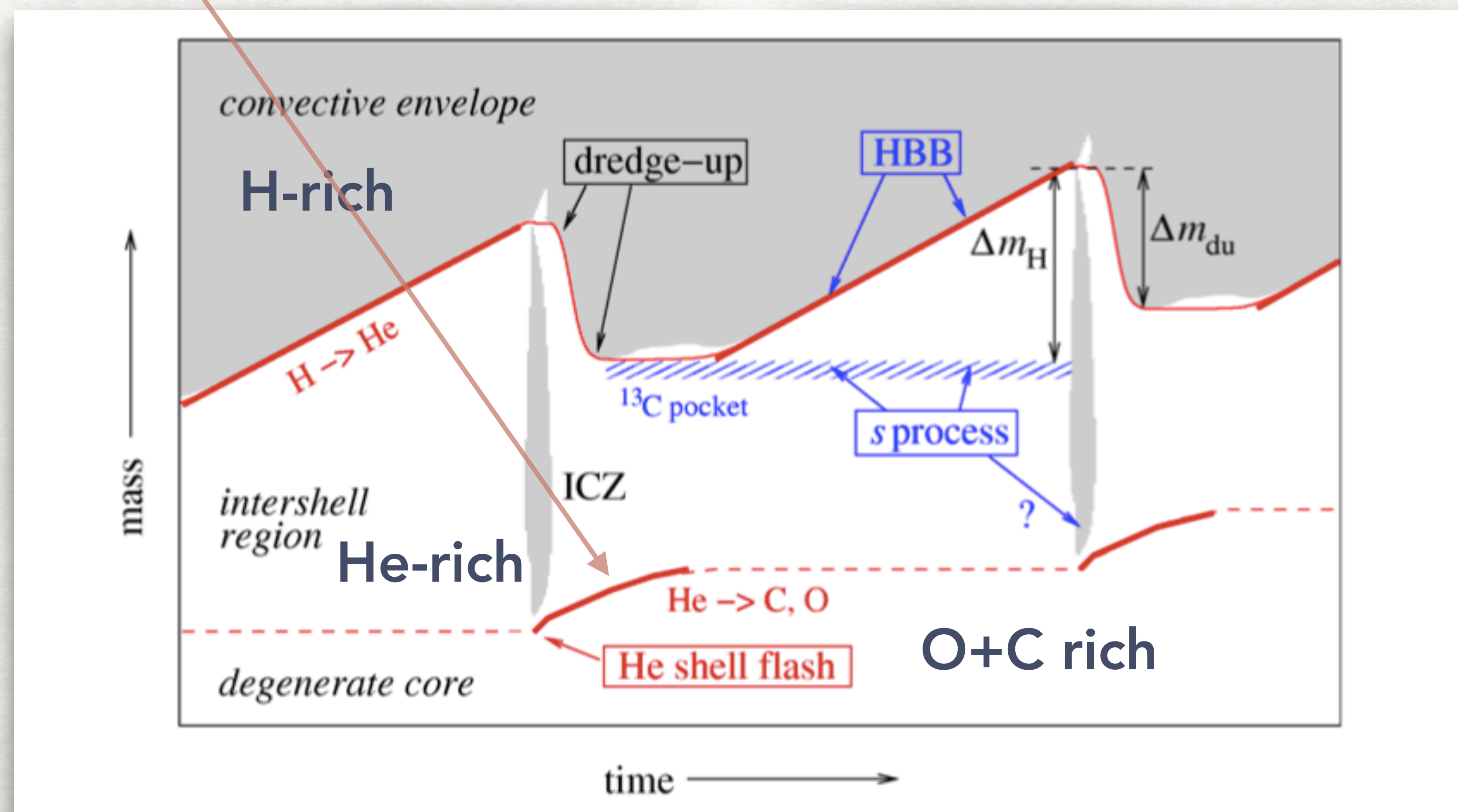
the two shells do not supply energy simultaneously but in turn *in a cycle process*

E: **phase of stable He-burning**, with no H-burning shell : a few 100 yr duration

E1: **third dredge-up :** He and He burning products (^{12}C) appears at the surface

E2: the He-burning front advances through the He shell getting closer to H-shell

E3: the base of convective H-rich envelope gets lower



THE CYCLE PROCESS

the two shells do not supply energy simultaneously but in turn *in a cycle process*

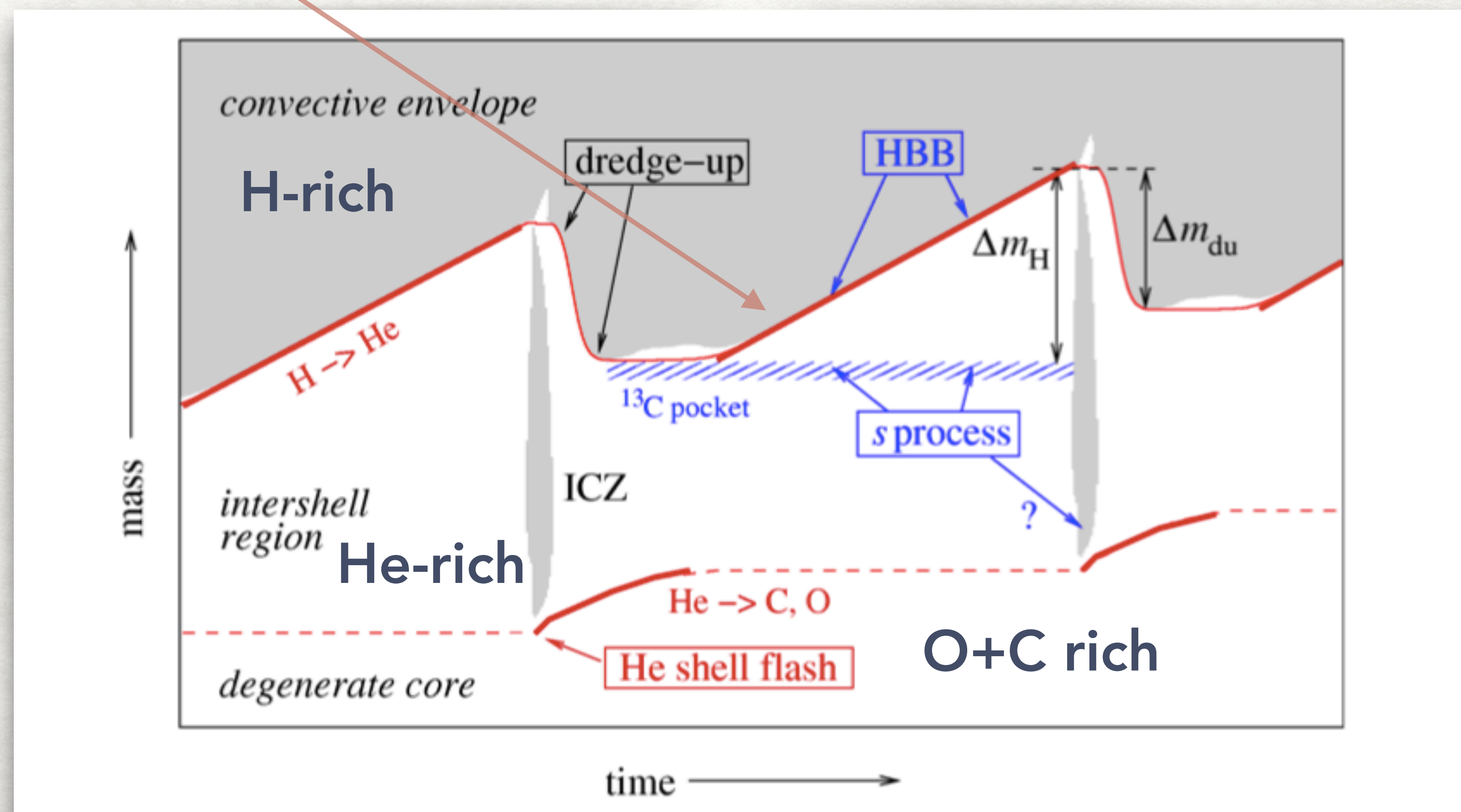
E4: the proximity of the high temperature in He-burning shell reignites H-burning shell

E5: the density and temperature around H-burning shell adjust to equilibrium and burning is stable (because H-fusion is less sensitive to T)

E6: Now temperature are too low for He-burning shell

G: phase of stable H-burning, with no He-burning shell: 1000 yr and 50000 yr duration

We are back to ``A"



S-PROCESS NUCLEOSYNTHESIS

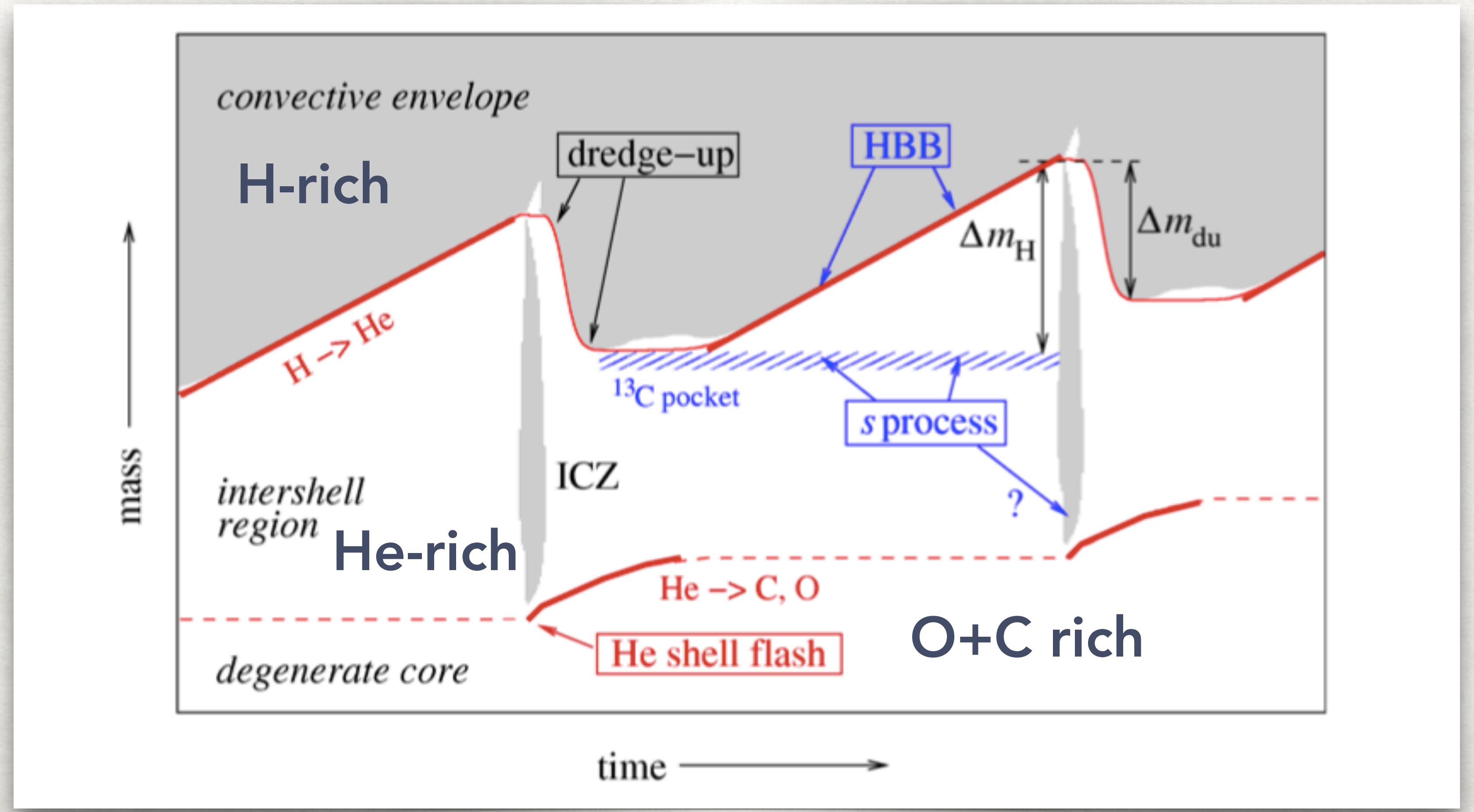
the He fusion leads to a chain of reaction that produces neutrons

+

the ICZ mixing the neutrons and O+C throughout the intershell zone

=

Capture of neutrons by traces of heavy elements creates trans-iron isotopes by the s-process (e.g. section 4.8 Dina Prialnik's book)



THERMALLY PULSING AGB (TP-AGB)

FROM POINT J ON

main features on TP-AGB stars

1. Nuclear burning takes place in two shells, leading to a long series of thermal pulses
2. The luminosity is uniquely determined by the mass of the core, independently of the star mass

The net result of 1) is the growth of the C+O core which leads us to 2)

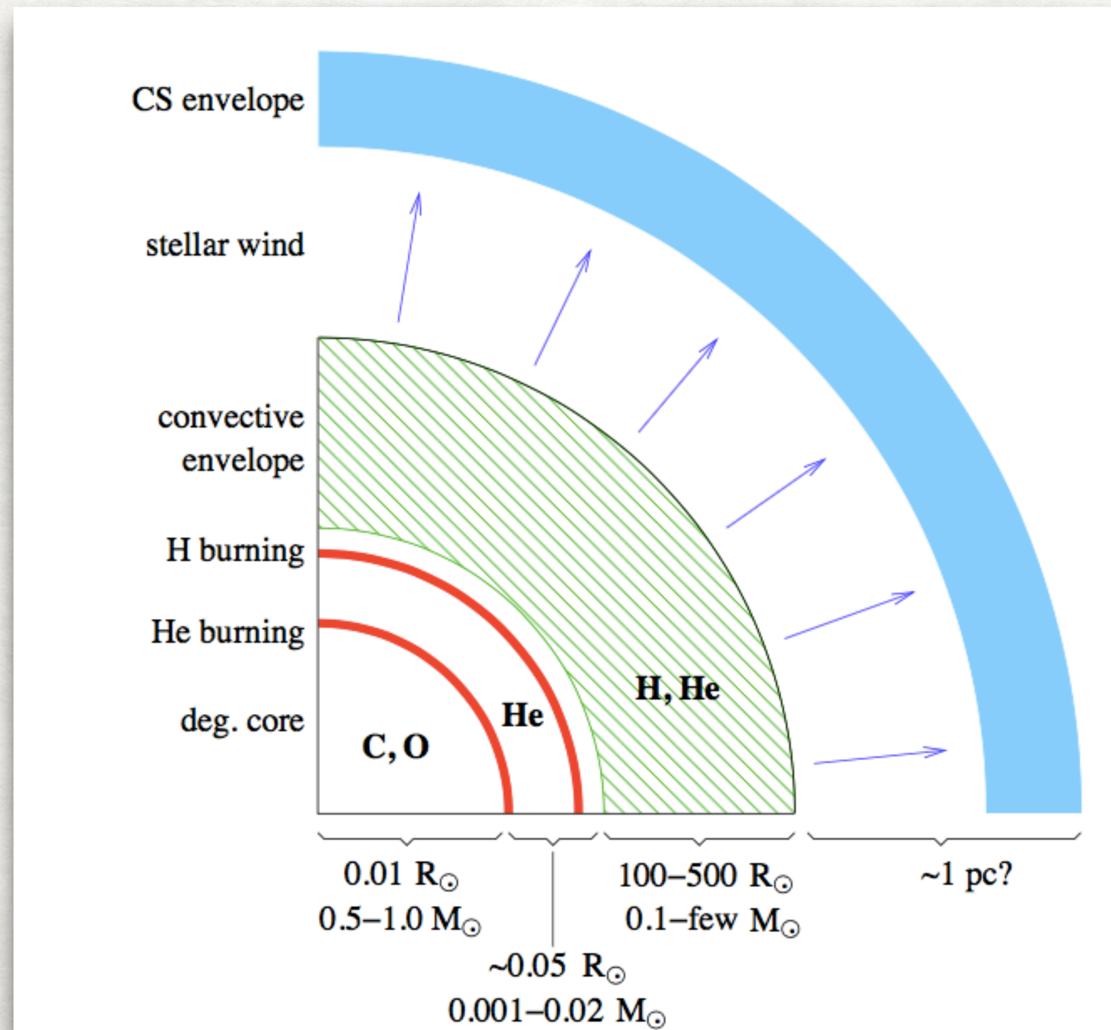
CORE MASS-LUMINOSITY RELATION

Stellar evolution calculations show that for $M_c > 0.5\ M_{sun}$

$$L = 5.9 \times 10^4 L_\odot \left(\frac{M_c}{M_\odot} - 0.52 \right),$$

Paczynski 1971

regardless of the stellar mass; like the RGB but less steep



Envelope versus core:

1) equally massive

2) 10^4-10^5 more extended

→ envelope exerts negligible pressure on the core, so it is mechanically and thermally negligible

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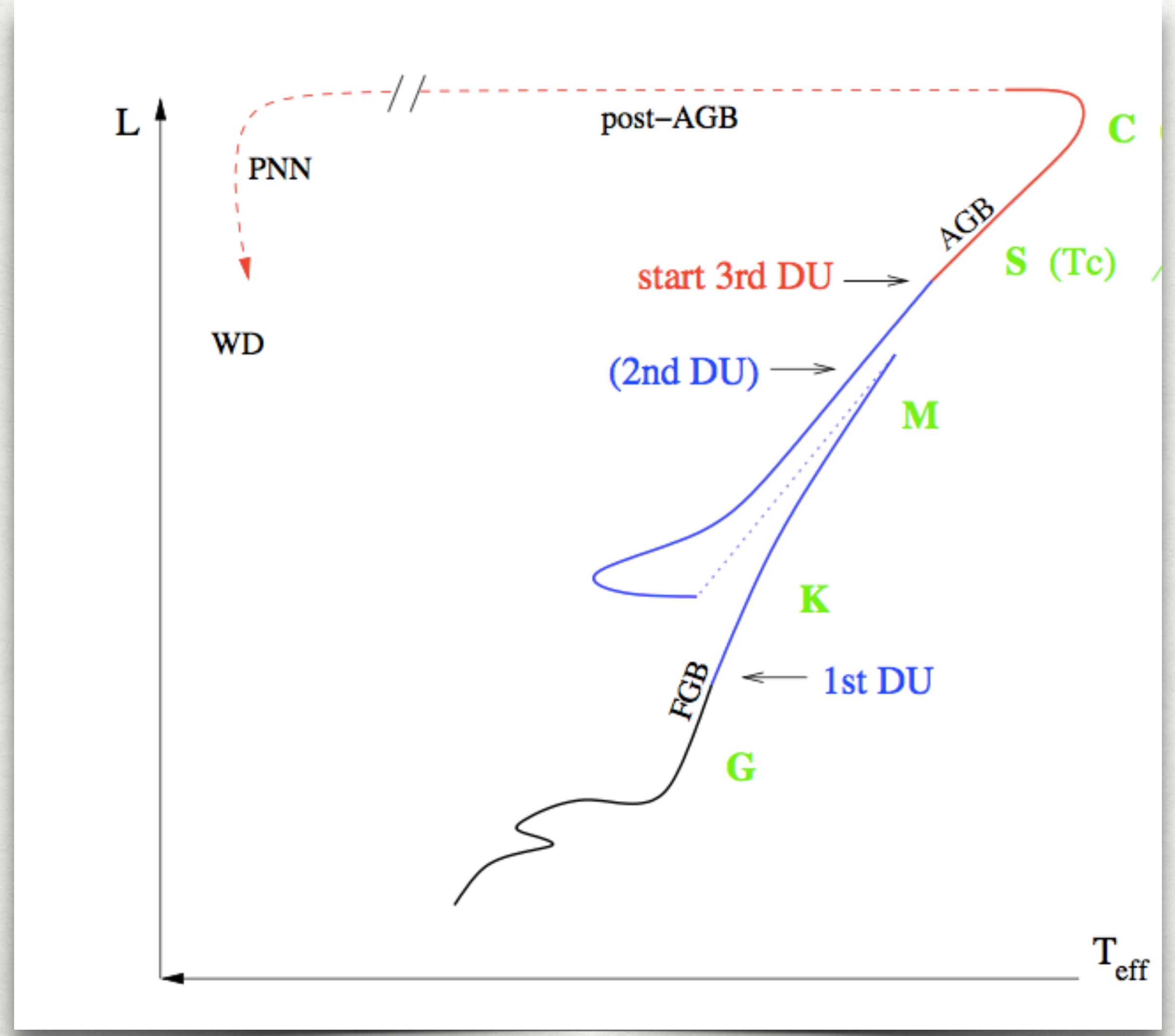


1) stars with <u>same mass core</u>, same hight in H-R diagram

2) Luminosity increases because Mc grows (as for RGB stars)

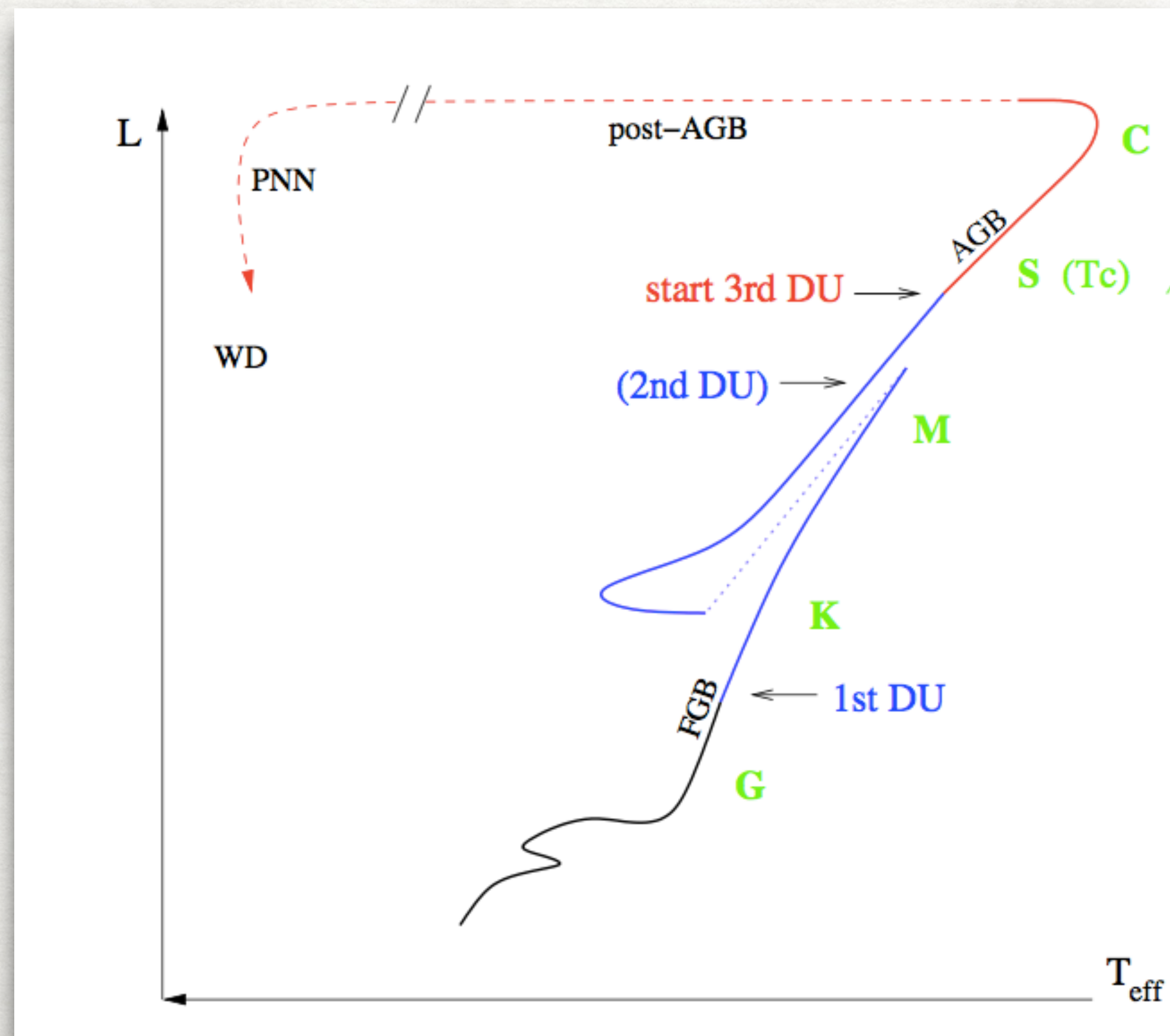
3) stars reach AGB at different points depending on Mc left after He core burning

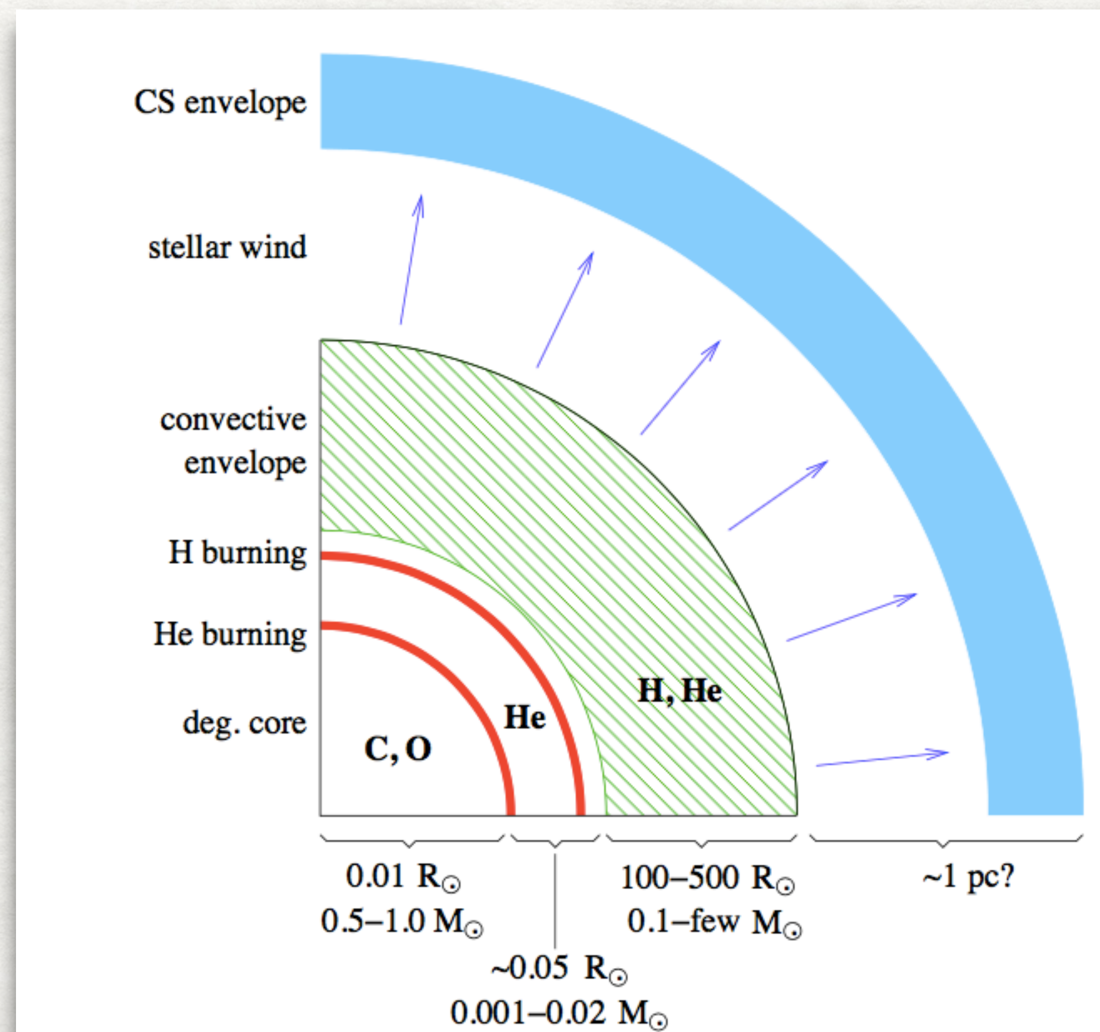
TERMINATION OF AGB PHASE

As stars climb up the AGB the envelope mass decreases because:

1) the core grows
2) mass loss at the surface (main factor)

After a few 10^6 yr all H-rich envelope is removed : end of AGB phase :

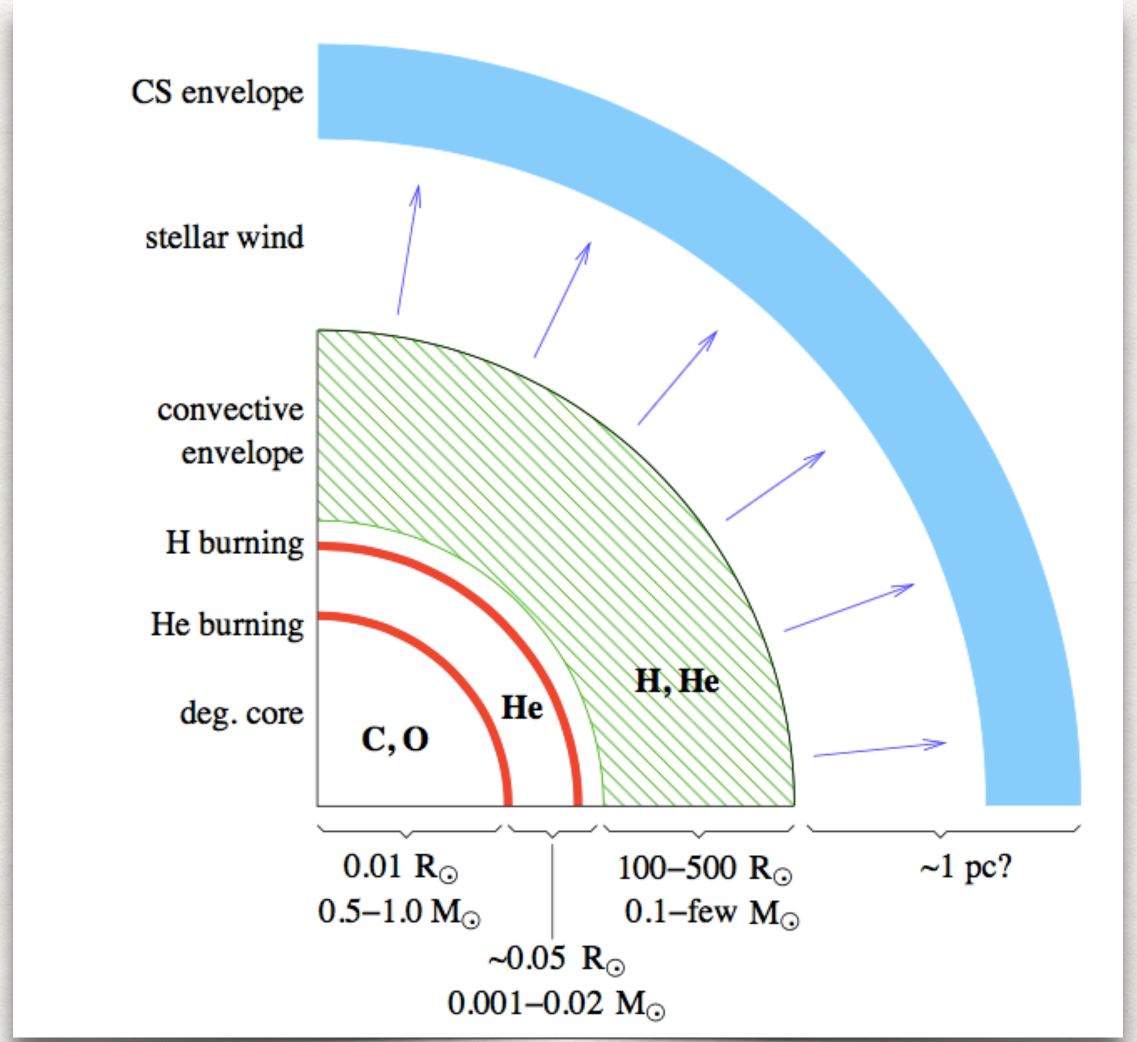




TERMINATION OF AGB PHASE

when a star leaves AGB is therefore determined by

- mass of envelope at the end of He-core burning phase
- strength of mass loss



MASS LOSS IN AGB STARS

Observations of red giants and supergiants reveal mass loss between

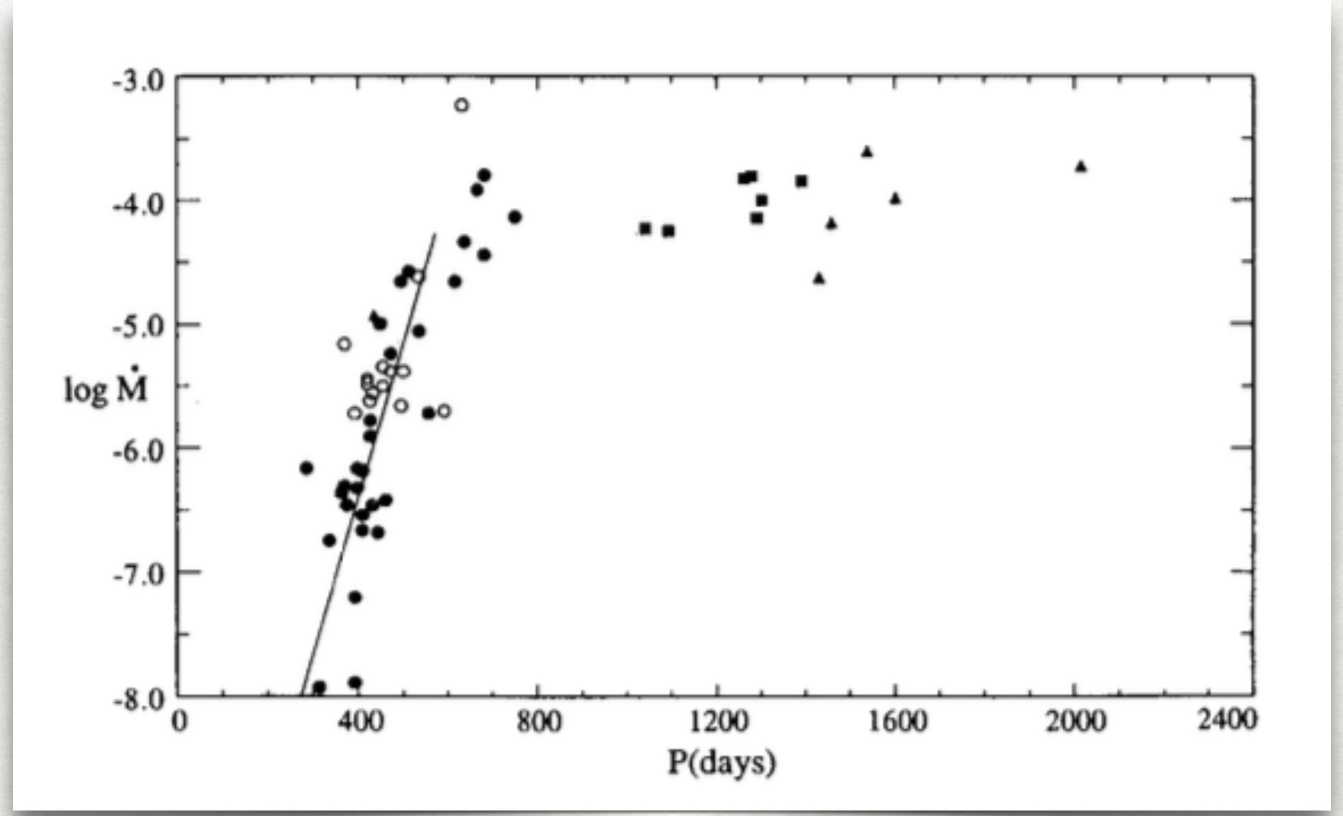
10^{-9} to 10^{-4} M_{sun} yr-1 !

because:

-cold envelopes: have outer layers with molecules and dust: high opacity

-large envelopes: weakly bound

Still calculation from first principle are difficult to perform and stellar evolution codes rely on empirical laws based on observations



Vassiliadis & Wood 93

MASS LOSS IN AGB STARS

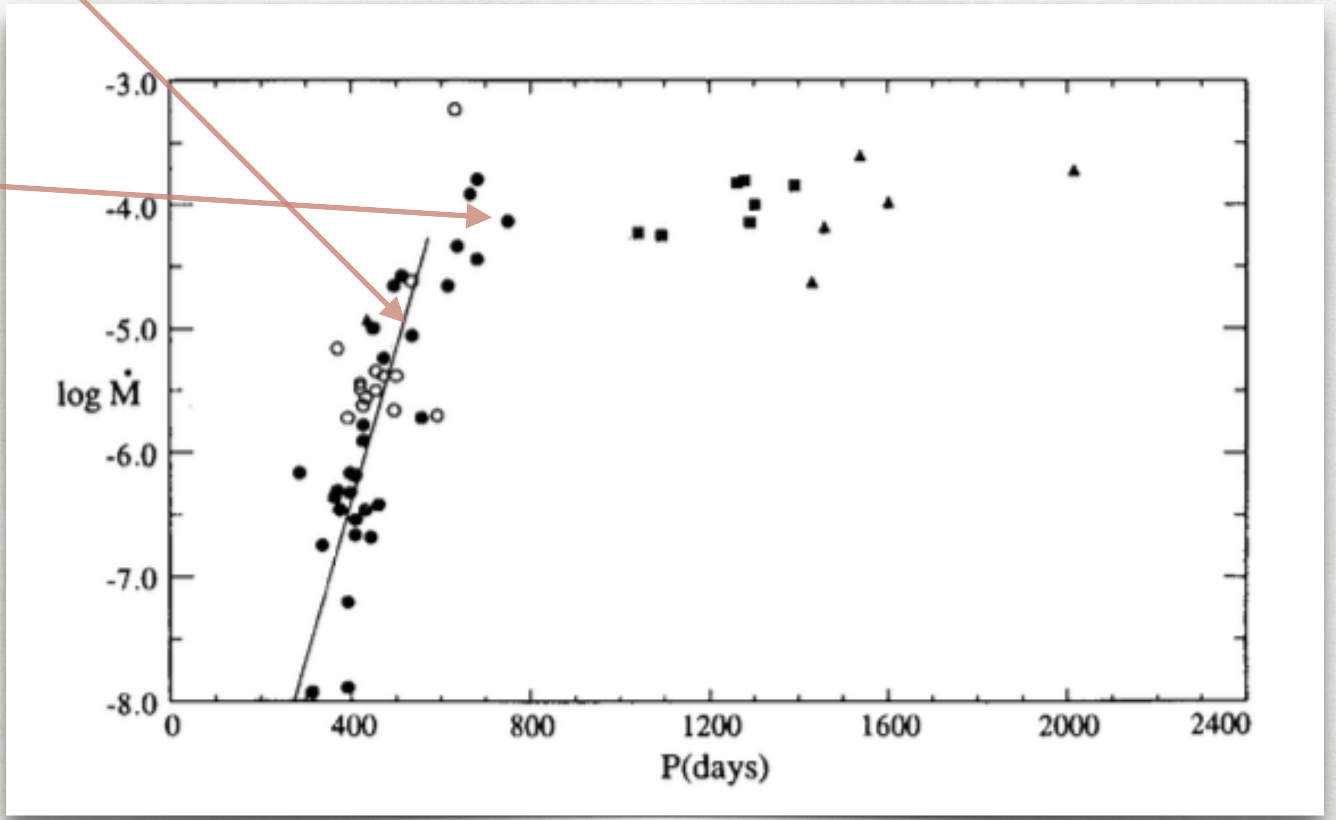
Mass loss is classified in two types of winds:

1) stellar wind, described by the empirical law due to Deiter & Reimers

$$\dot{M} \approx 10^{-13} \frac{L}{L_{\rm sun}} \frac{R}{R_{\rm sun}} \frac{M_{\rm sun}}{M} \quad \frac{M_{\rm sun}}{\rm yr}$$

2) Super wind

$$\dot{M} \approx 10^{-4} \quad \frac{M_{\rm sun}}{\rm yr}$$



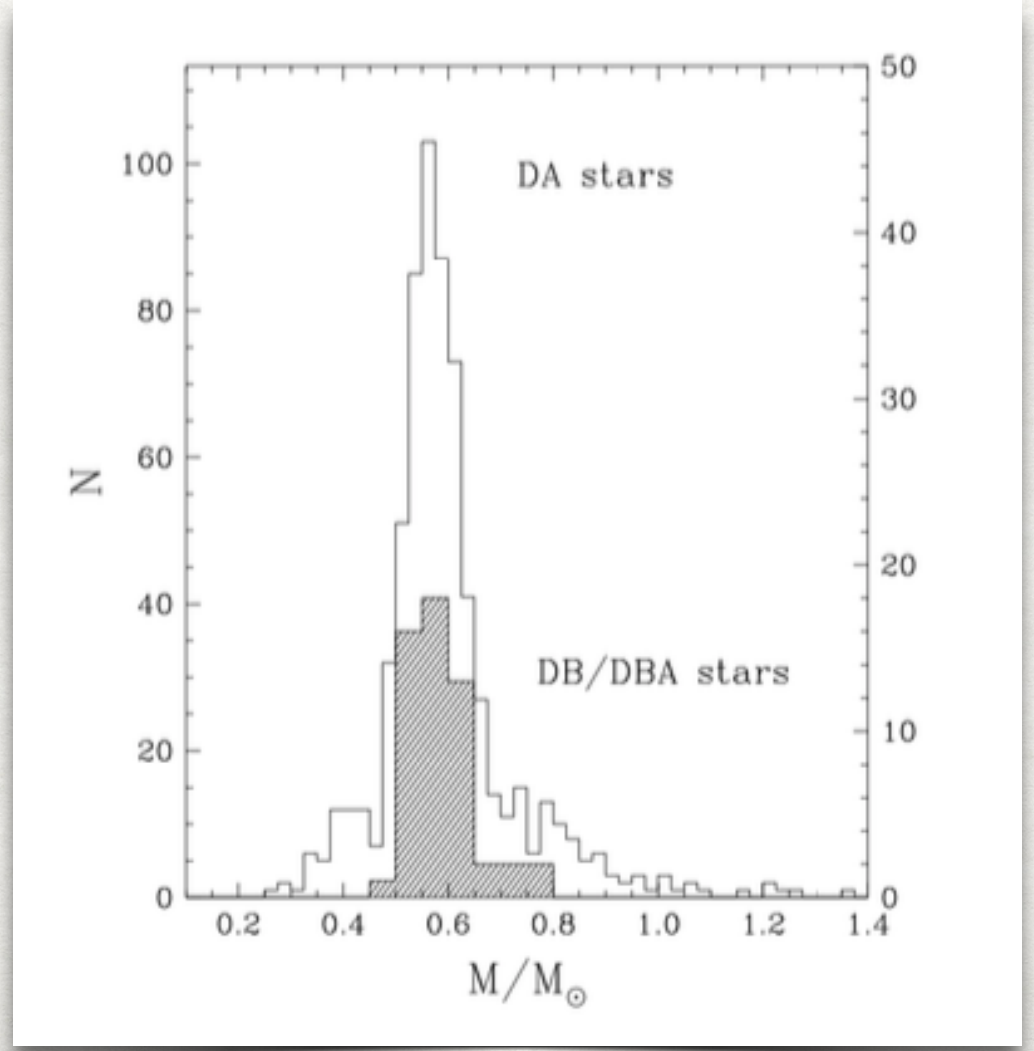
MASS LOSS IN AGB STARS

we think that mass loss increases and most stars enter the super wind phase

Soon after stars enter the super wind phase the entire envelope is lost and stars with $1<M<9\ M_{sun}$ leave a C+O core of mass between 0.6-1.1 solar masses < the Chandrasekhar mass

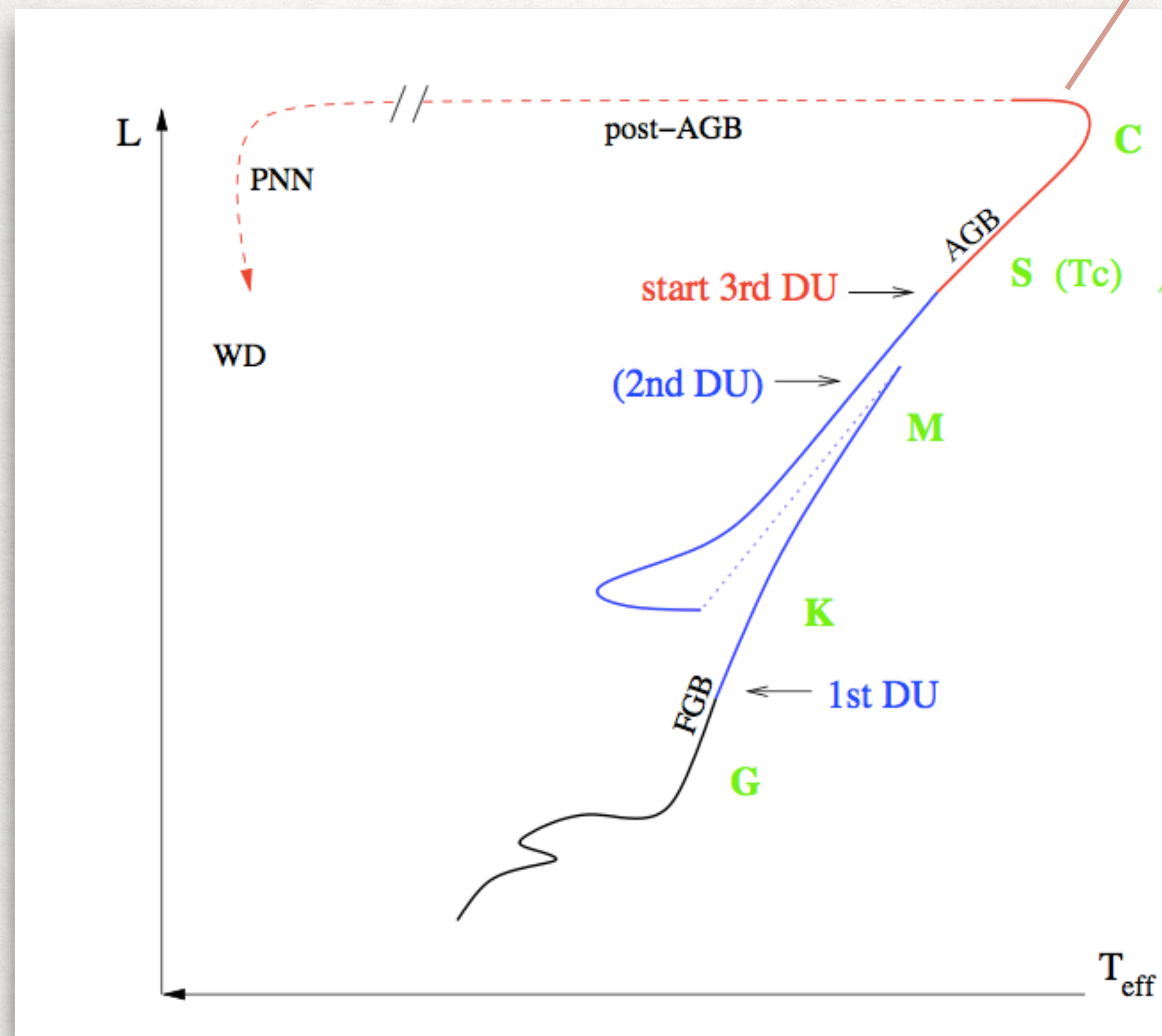
These core will develop into white dwarfs

Average CO WD mass around 0.55-0.6 M_{sun} because most WD comes from progenitors with $M< 2\ M_{sun}$



Bergeron et al. 2007

POST-AGB EVOLUTION



Starts when envelope mass ~0.01-0.001 M_{sun}

-R envelope contracts

-L remains constant as H-burning shell still active

- T_{eff} increases

$$T_{\text{eff}}^4 \propto L/R^2$$

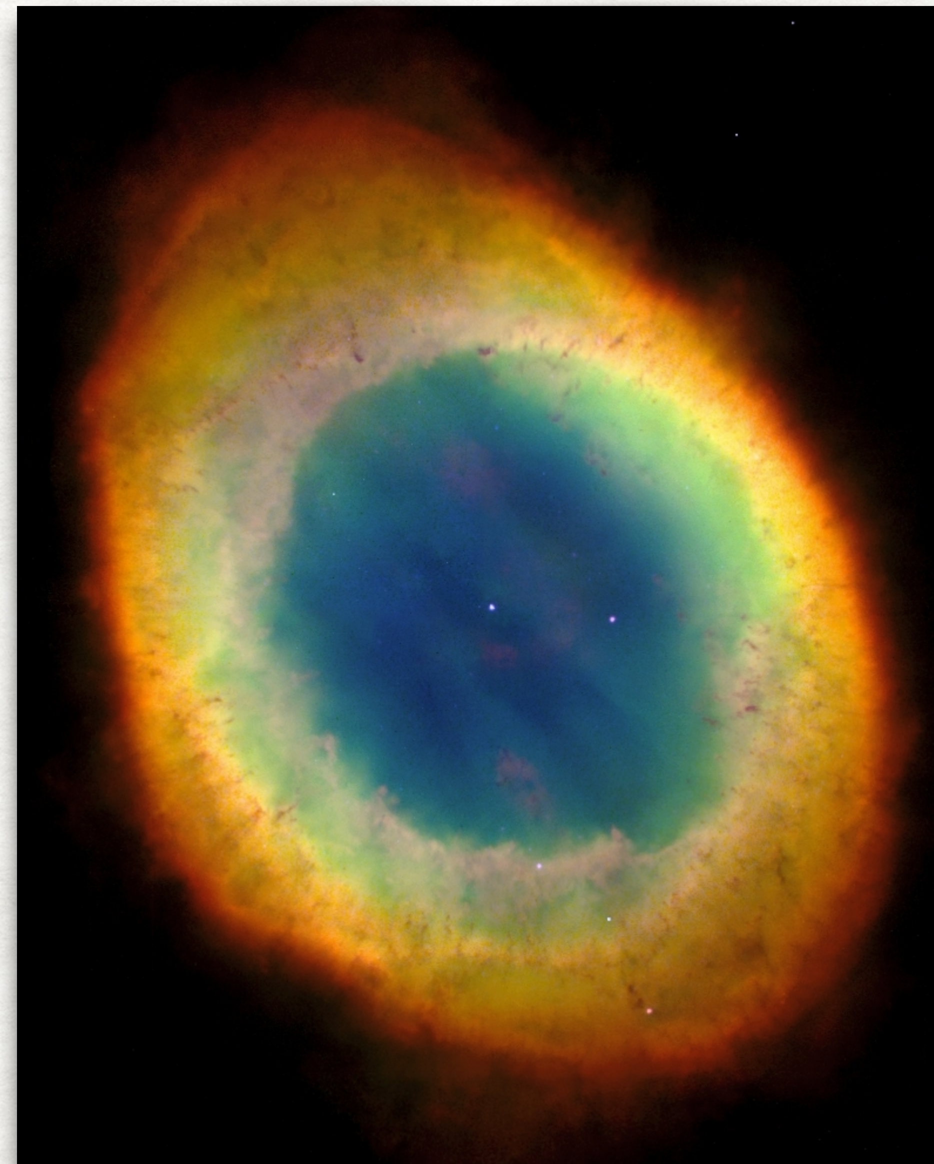
the post AGB star follows an horizontal track towards higher temperature

PLANETARY NEBULA

Herschel 1780 through they look like Uranus…

When T_{eff} reaches 30000 K photons can ionise the atoms in the surrounding nebula (the envelope ejected by the wind) and cause them to shine by fluorescence (to absorb light at a certain wavelength and re-emit it a longer wavelength)

Dumbbell nebula
1st nebula observed 1764 by Messier



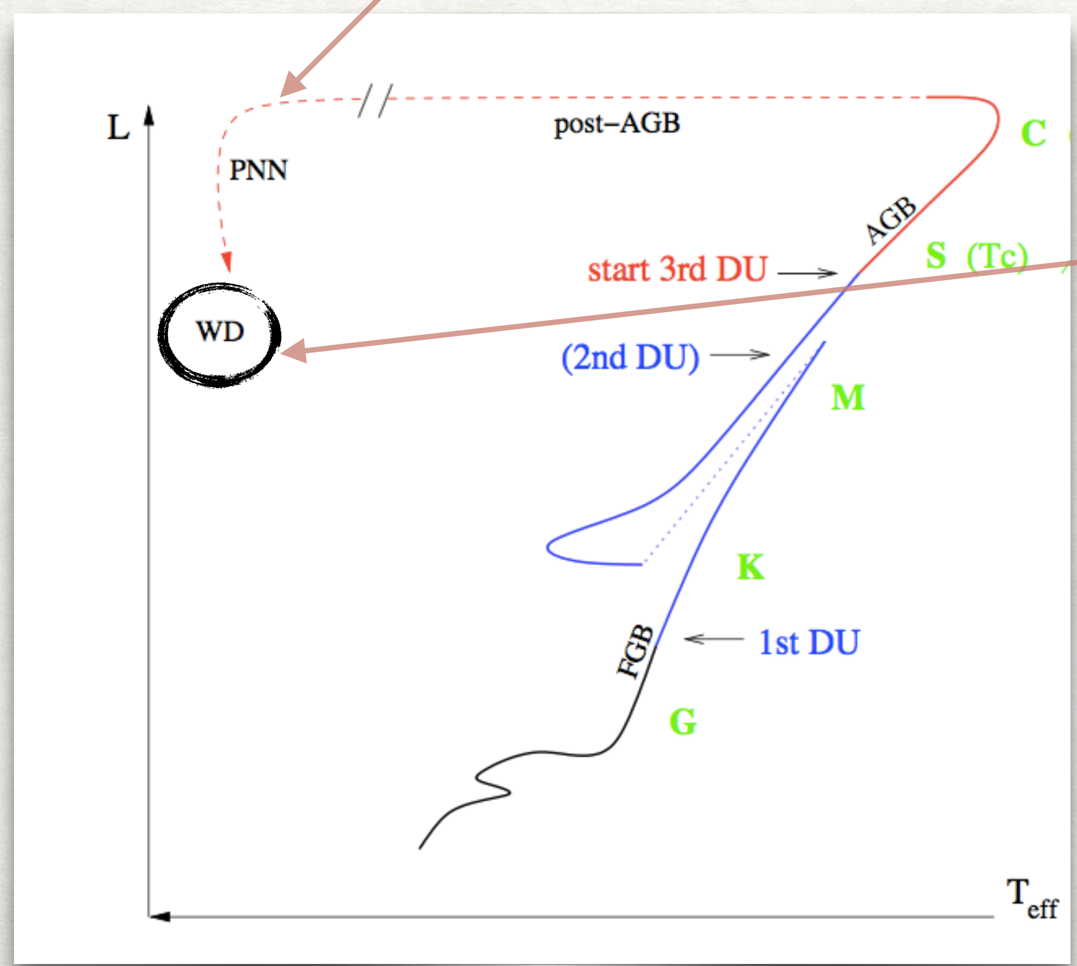
Ring nebula
2nd nebula observed 1779 (by Darquier)

A WHITE DWARF IS BORN

The H-fusion stops when the mass in the H-burning shell ~10^{-3}-10^{-4} M_{sun}

Luminosity decreases, it ionisation power drops and the wind moves outward the nebula (left over envelope) with a 10 km/s speed

The nebula grows in size and disperse: duration 10^4-10^5 yr



We are left with a degenerate C+O core that cools down: a white dwarf