CH 10

POST-MAIN SEQUENCE EVOLUTION THROUGH HELIUM BURNING

Study Chapter 10 Except 10.4

THE SCHOENBERG-CHANDRASEKHAR LIMIT

The inert He core must be isothermal to be in thermal equilibrium:

$$l(m) = \int_m \epsilon_{\rm nuc}\, dm = 0 \text{ and hence } dT/dr \propto l = 0.$$

CORE with **ideal gas and isothermal** can be in hydrostatic equilibrium if

$$\frac{M_c}{M} < q_{SC} = 0.37 \left(\frac{\mu_{env}}{\mu_c}\right)^2 \approx 0.10$$

μ_{env}: 0.55

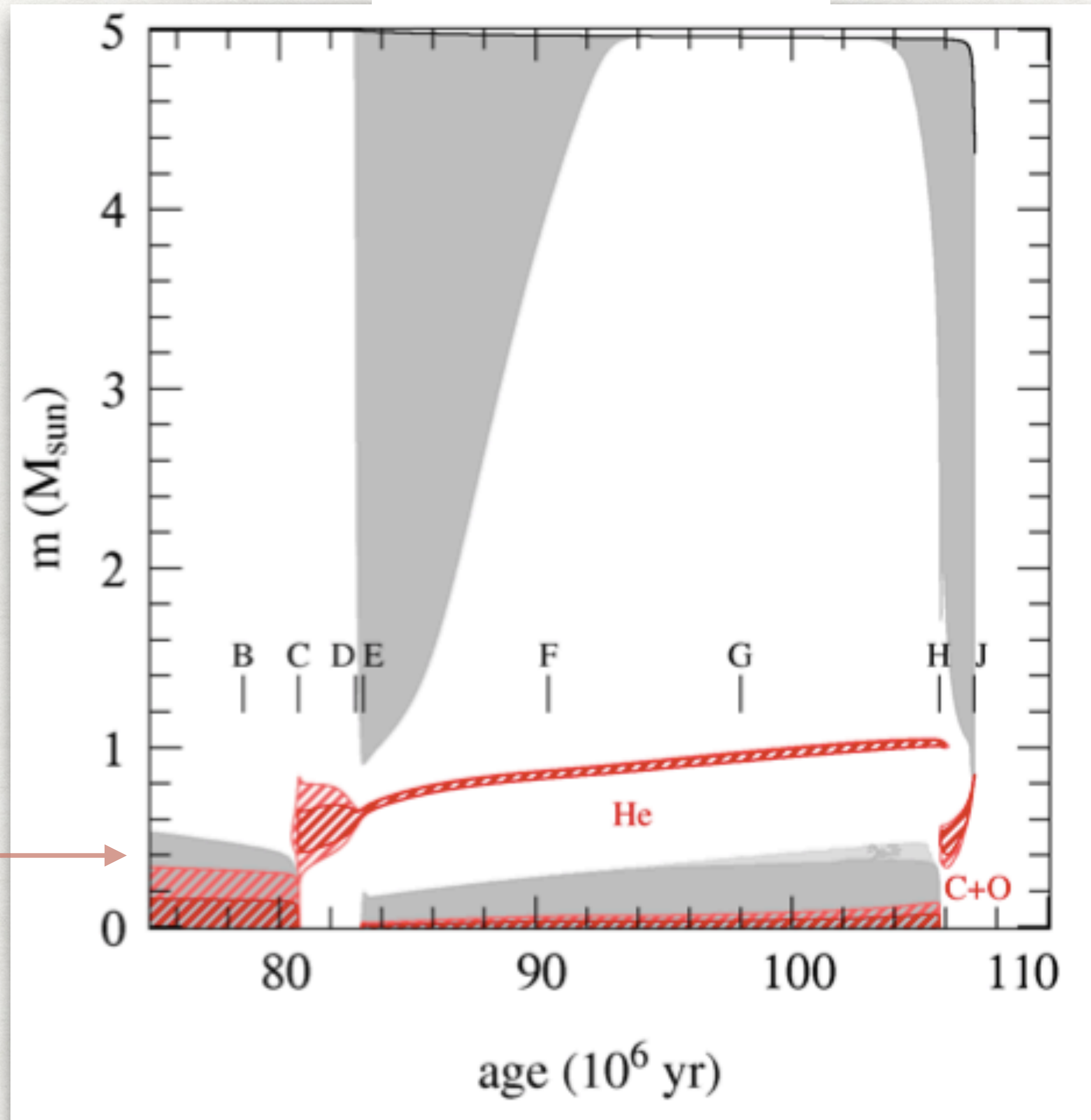
μ_c: 1.3

SUMMARY OF CLASS CONTENT

After the main sequence stars are left with a inert He core and an H-rich envelope

Kippenhahn diagram

- exemple evolution of $M = 5\ M_{sun}$:



- main sequence: H burning in <u>convective</u> core

- point C: beginning of shell burning phase : H is burnt above an inert (<u>radiative</u>) core
- point E: beginning He burning phase

THE MIRROR PRINCIPLE

Whenever a star has an *active shell-burning source*, the burning shell acts as a *mirror* between the core and the envelope:

core contraction	$\Rightarrow$	envelope expansion
core expansion	$\Rightarrow$	envelope contraction

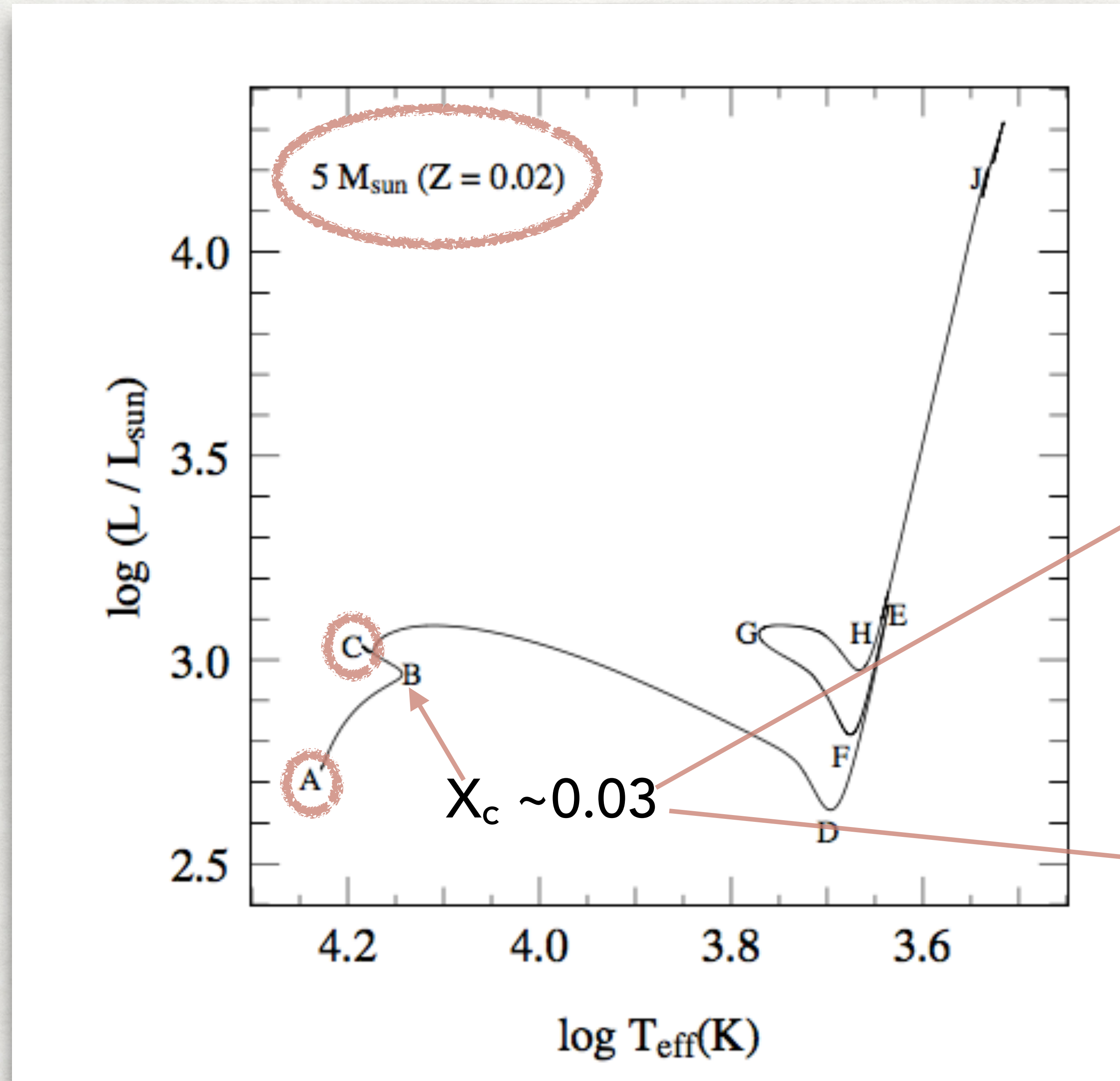
POST MAIN SEQUENCE EVOLUTION

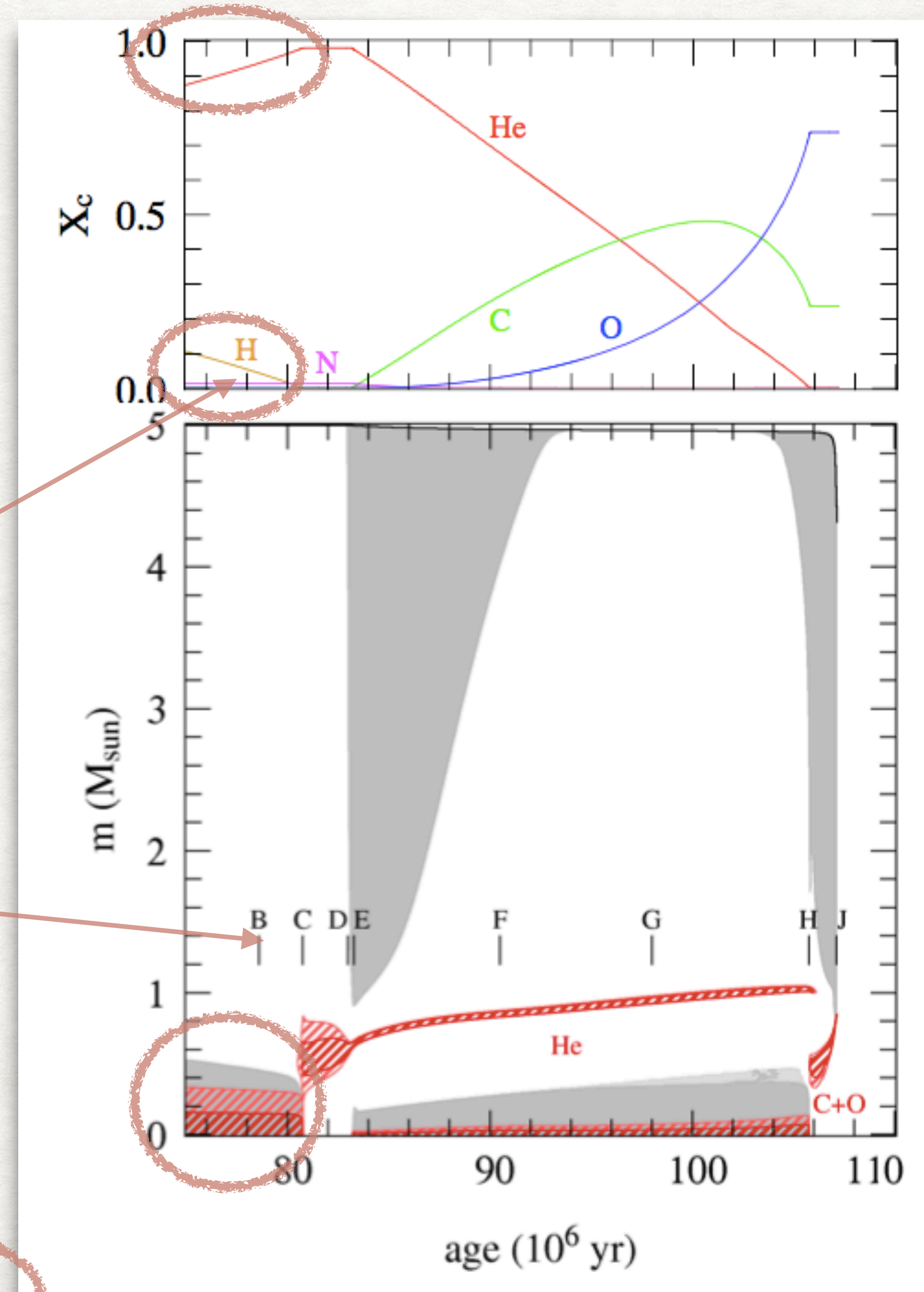
The evolution is significantly different for low mass $M < 2\ M_{sun}$
and intermediate and high mass $M > 2\ M_{sun}$

We start first with the description of the evolution for $M > 2\ M_{sun}$

LATE MAIN SEQUENCE

for mass star $M > 2\ M_{sun}$

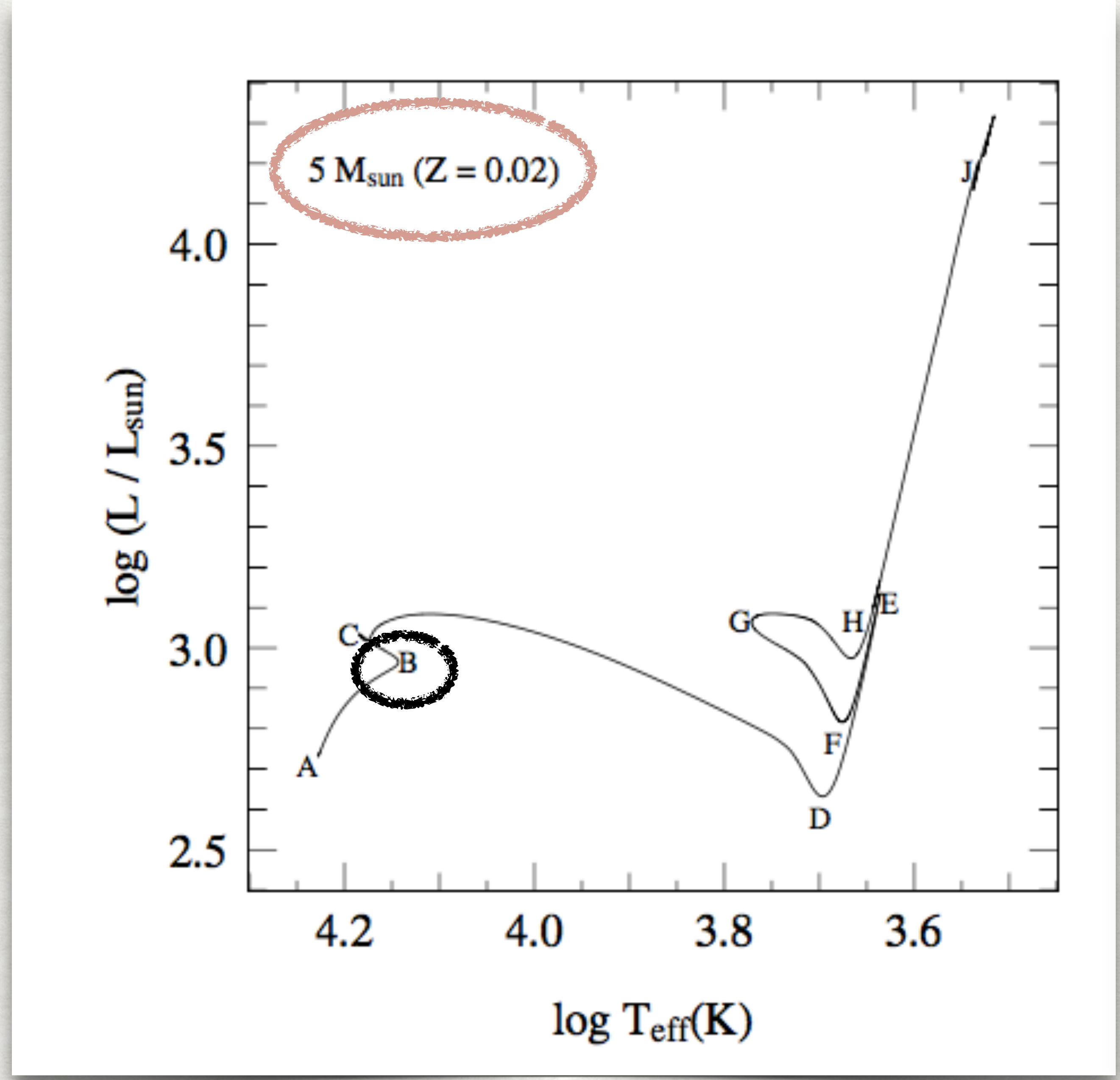


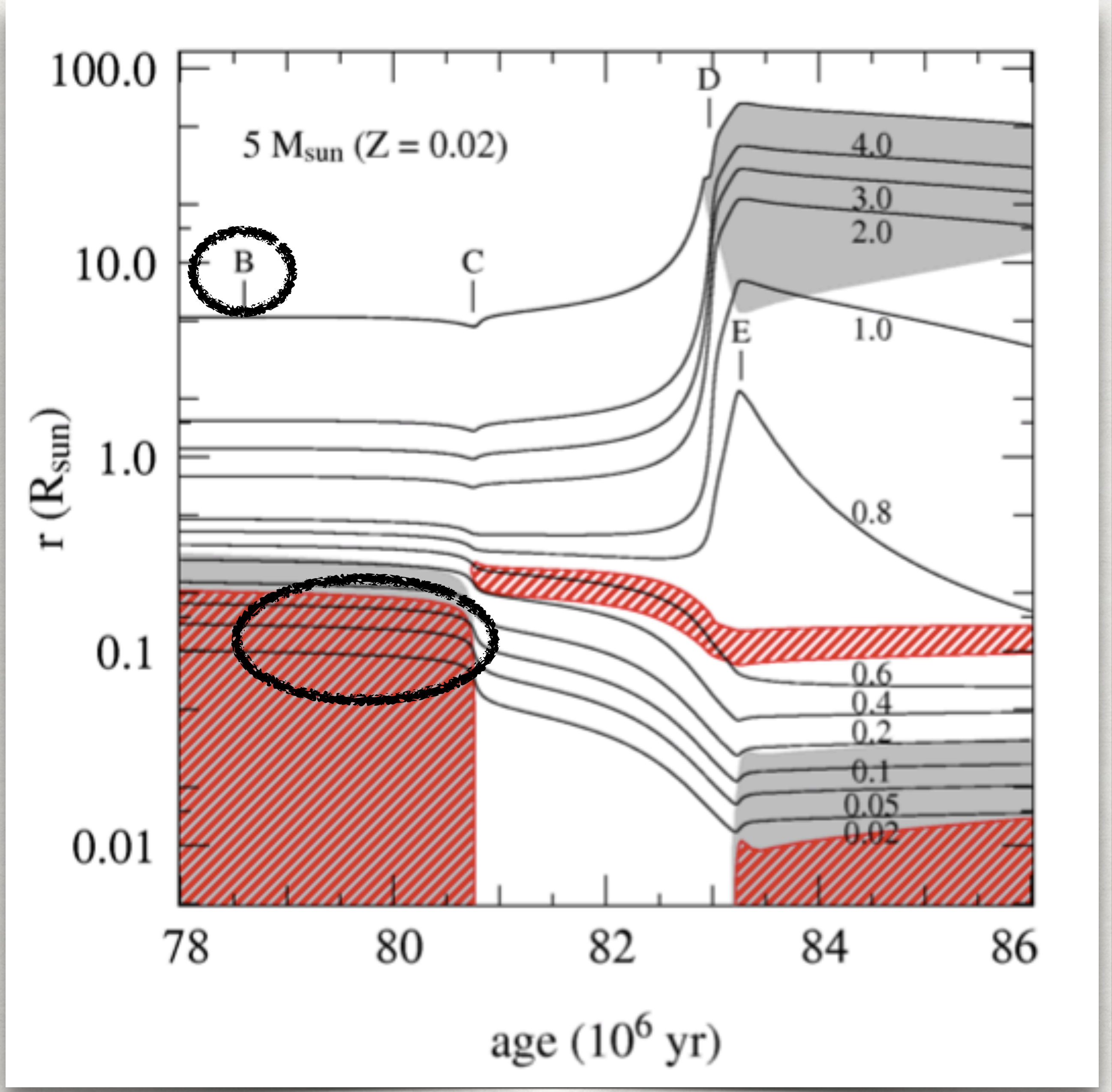


A-C: main sequence, with H fusion in convective core

LATE MAIN SEQUENCE

for mass star M > 2 M_{sun}

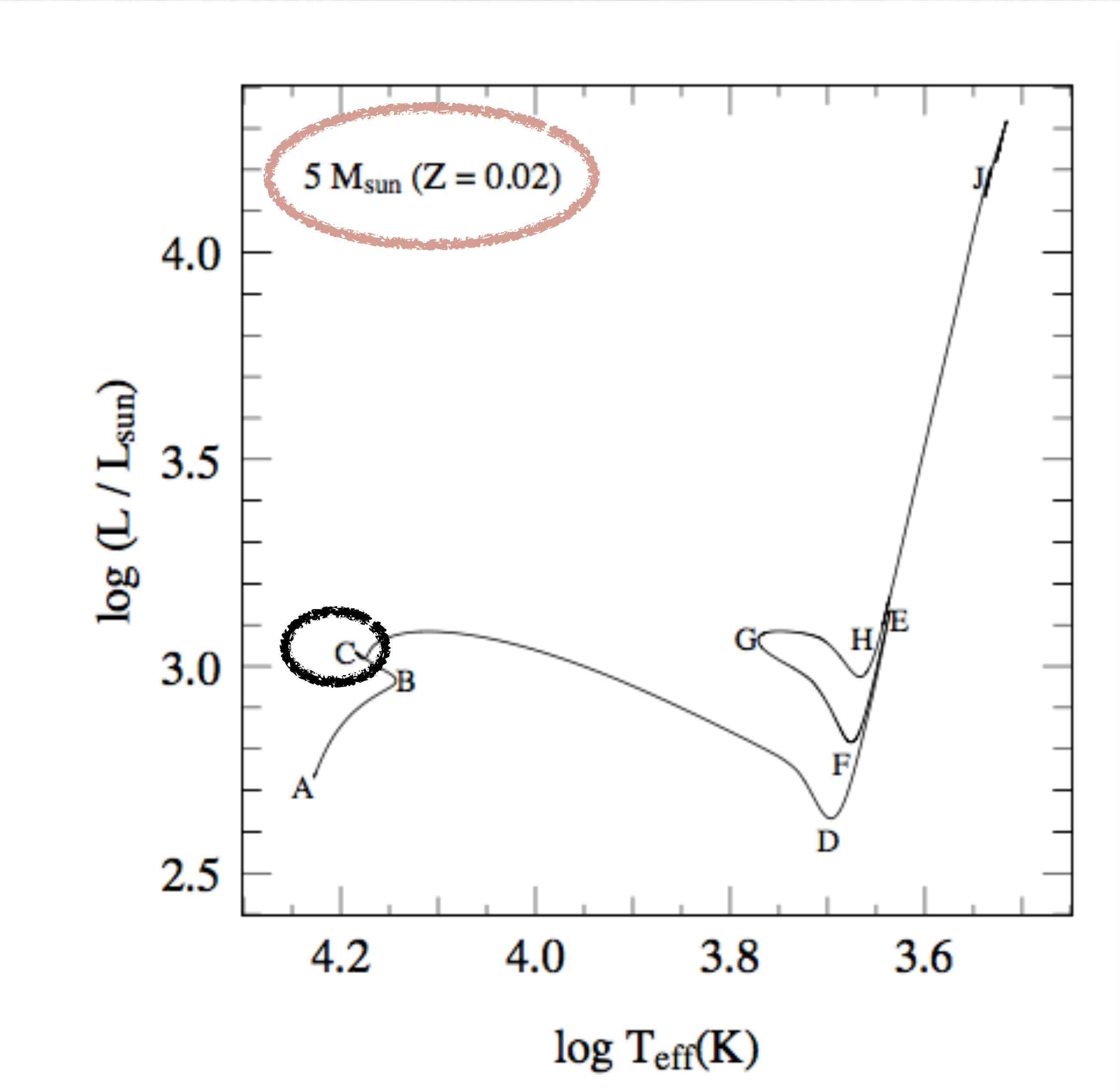


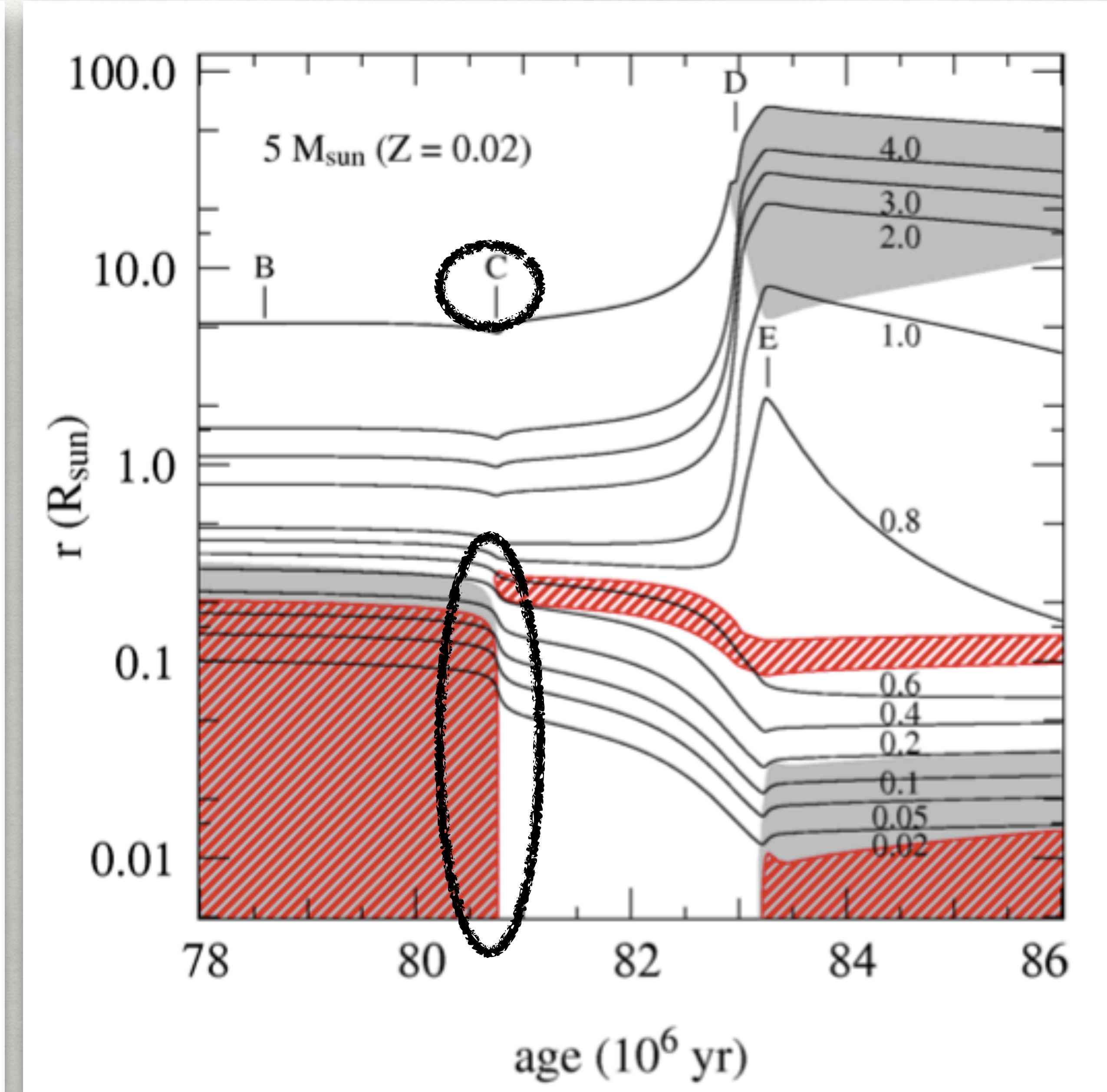


point B: Xc~0.03 and start of contraction phase for core

END OF MAIN SEQUENCE

for mass star M > 2 M_{sun}



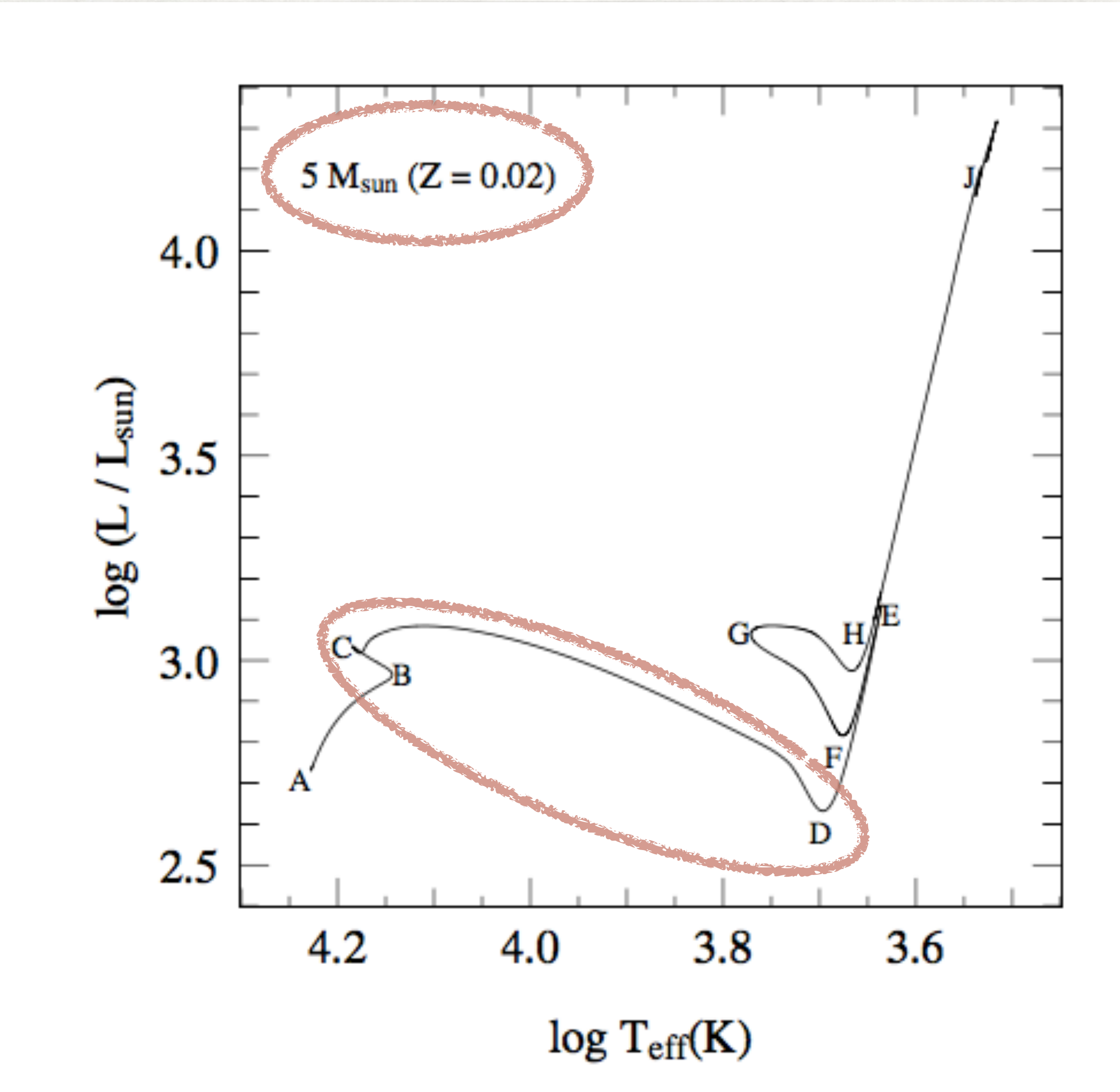


point B: Xc~0.03 and start of contraction phase for core

point C: i) exhaustion of H in core, ii) disappearance convective core, iii) start of H-burning shell==> end of main sequence

THICK H-SHELL BURNING PHASE (C-D)

$M > 2\ M_{sun}$



Relative long duration of ~2 Myr

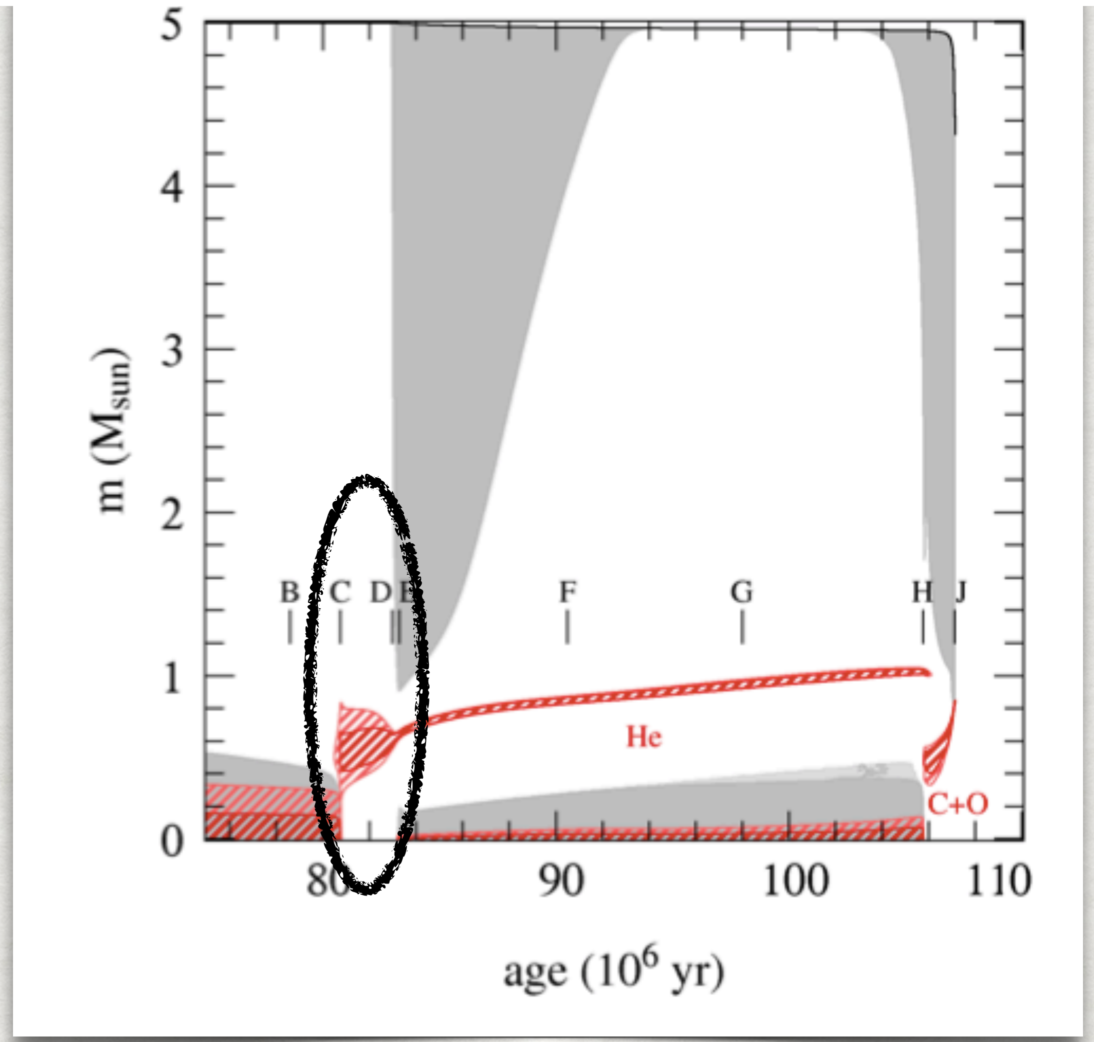
THICK H-SHELL BURNING PHASE

$M > 2\ M_{sun}$

point C: i) energy generation subsides

ii) core becomes isothermal

iii) small temperature gradient between core and envelope : thick region where $T \sim 10^7 K$ and H-burning can occur



THICK H-SHELL BURNING PHASE

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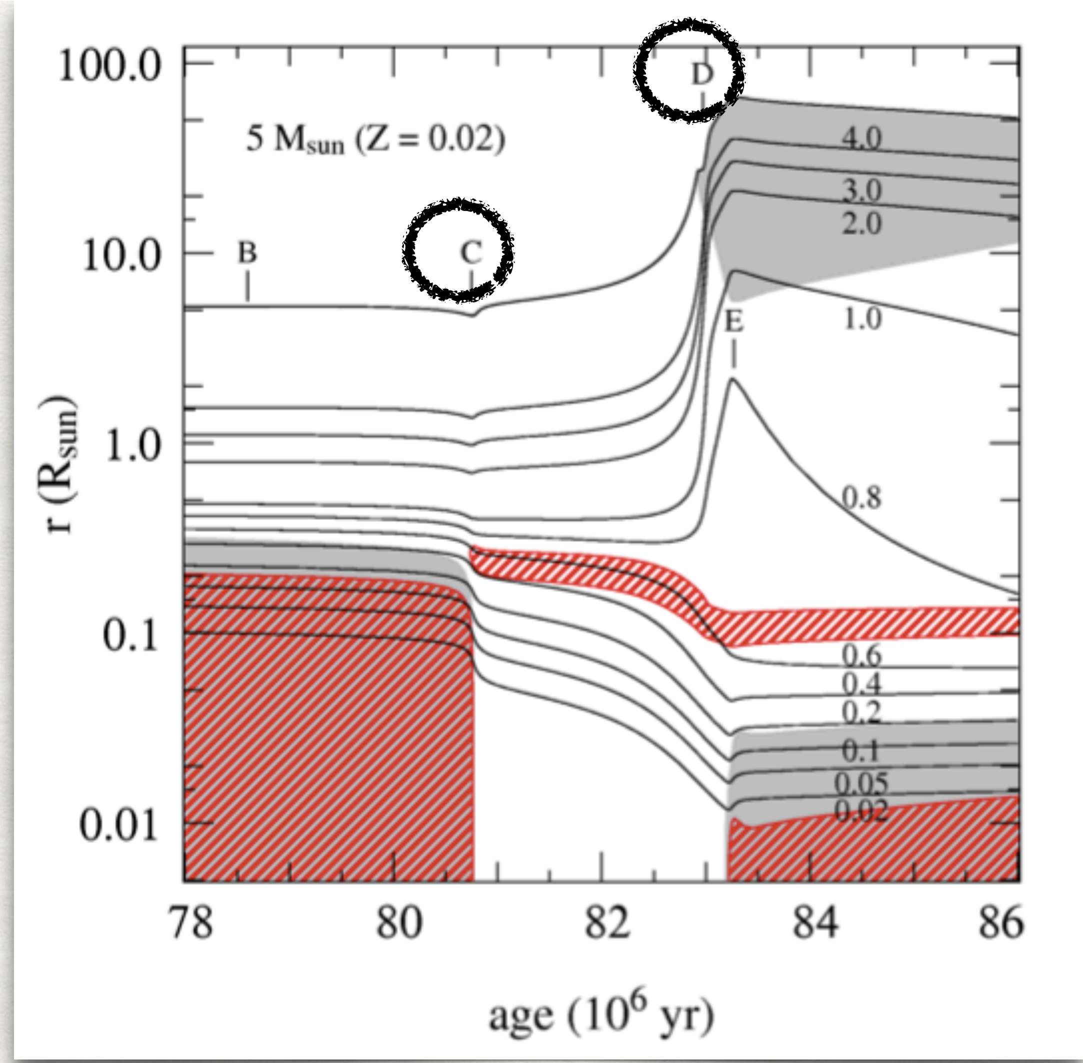
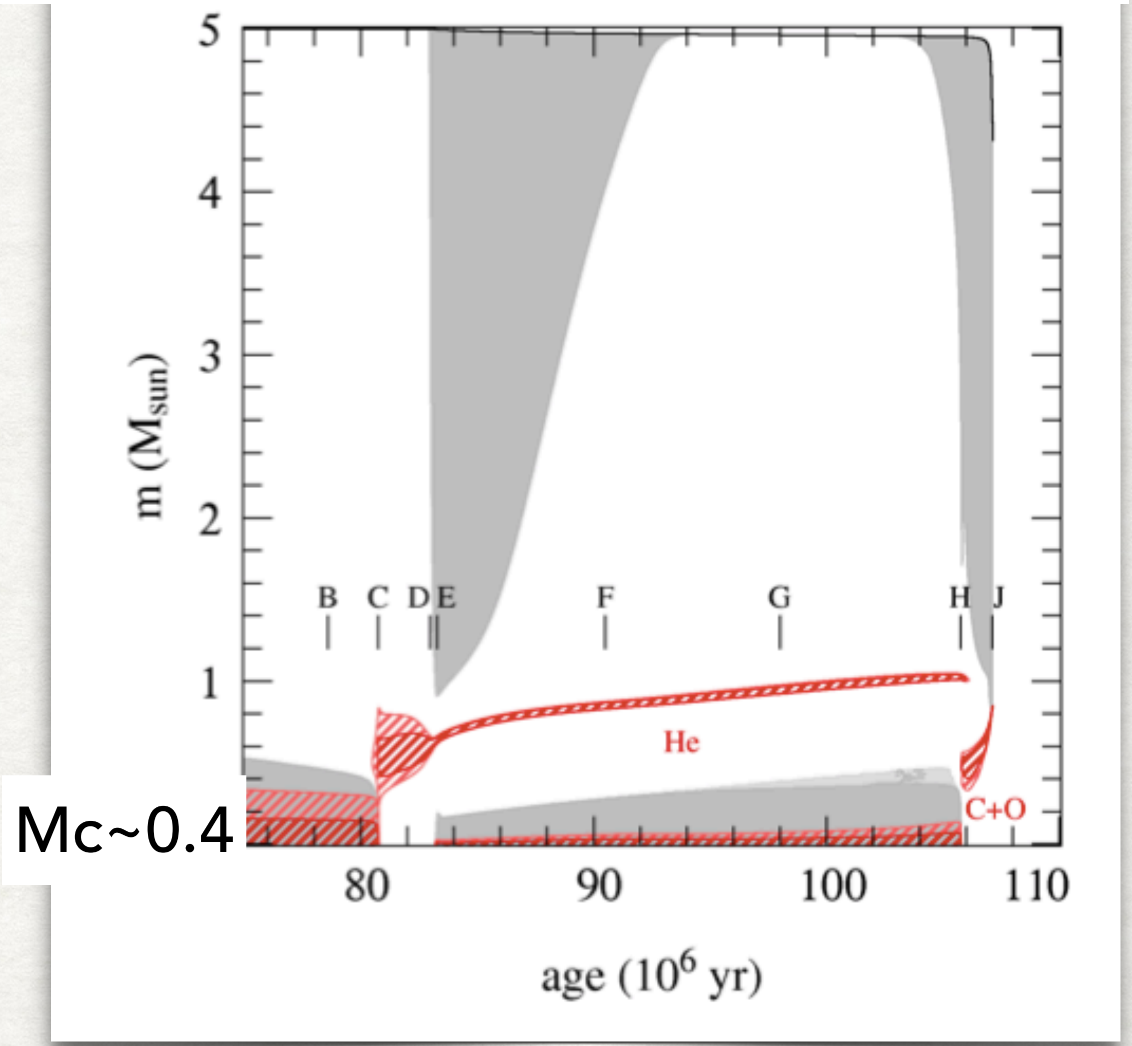
vi) Mc ~0.4 >S-C limit —> collapse of core —-> expansion of envelope

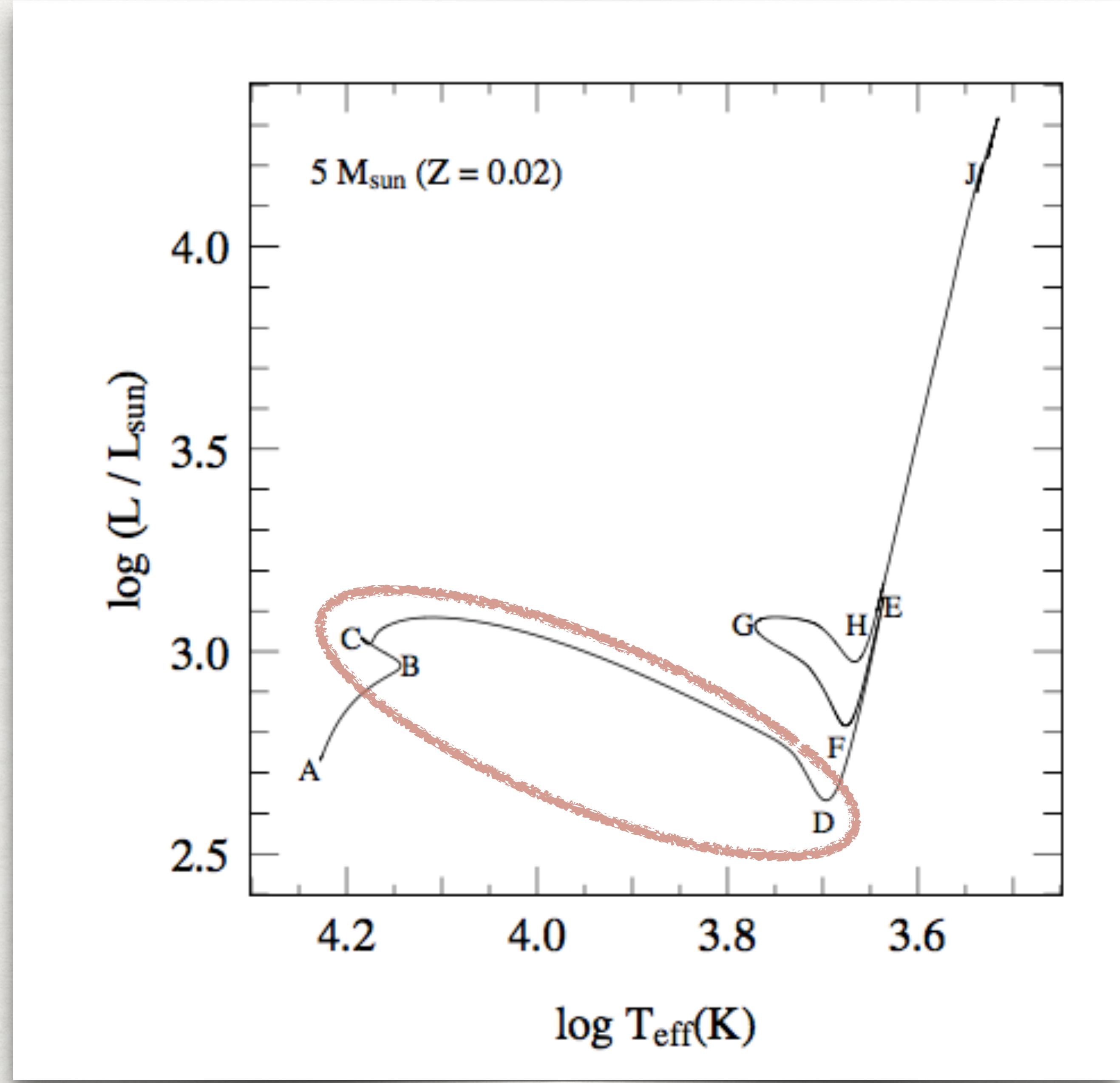




THICK H-SHELL BURNING PHASE

$M > 2\ M_{sun}$

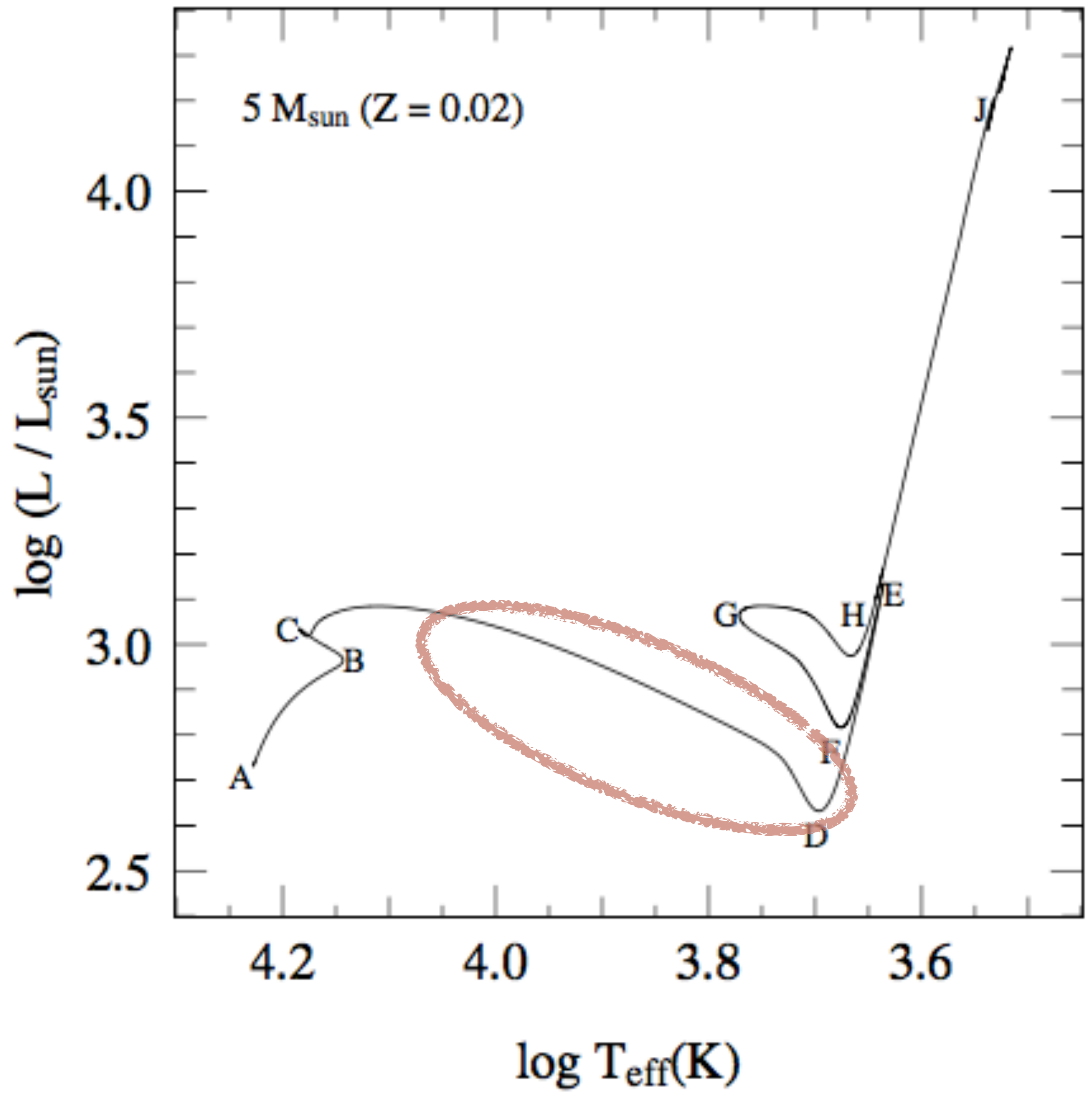
C-D: i) most energy generated is absorbed by the expanding envelope—>
L decreases during this phase; ii) T_{eff} decreases as well



THICK H-SHELL BURNING PHASE

$M > 2\ M_{sun}$

C-D: iii) between $4.05 > \log T_{eff} > 3.7$ most of the expansion takes place and lasts just 10^5 yr (K-H timescale): the probability of detecting a star there is very small: *Hertzsprung gap*

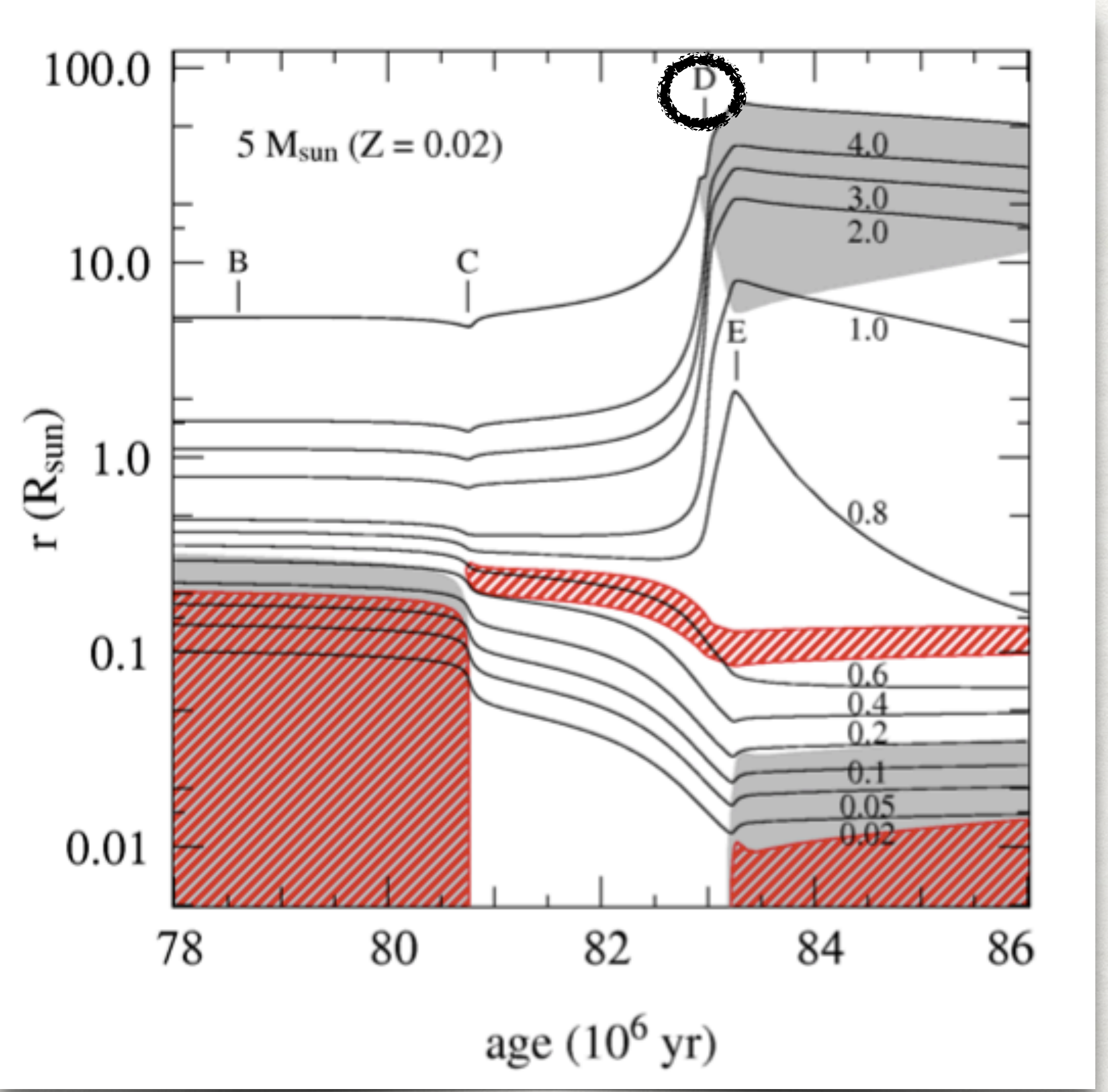


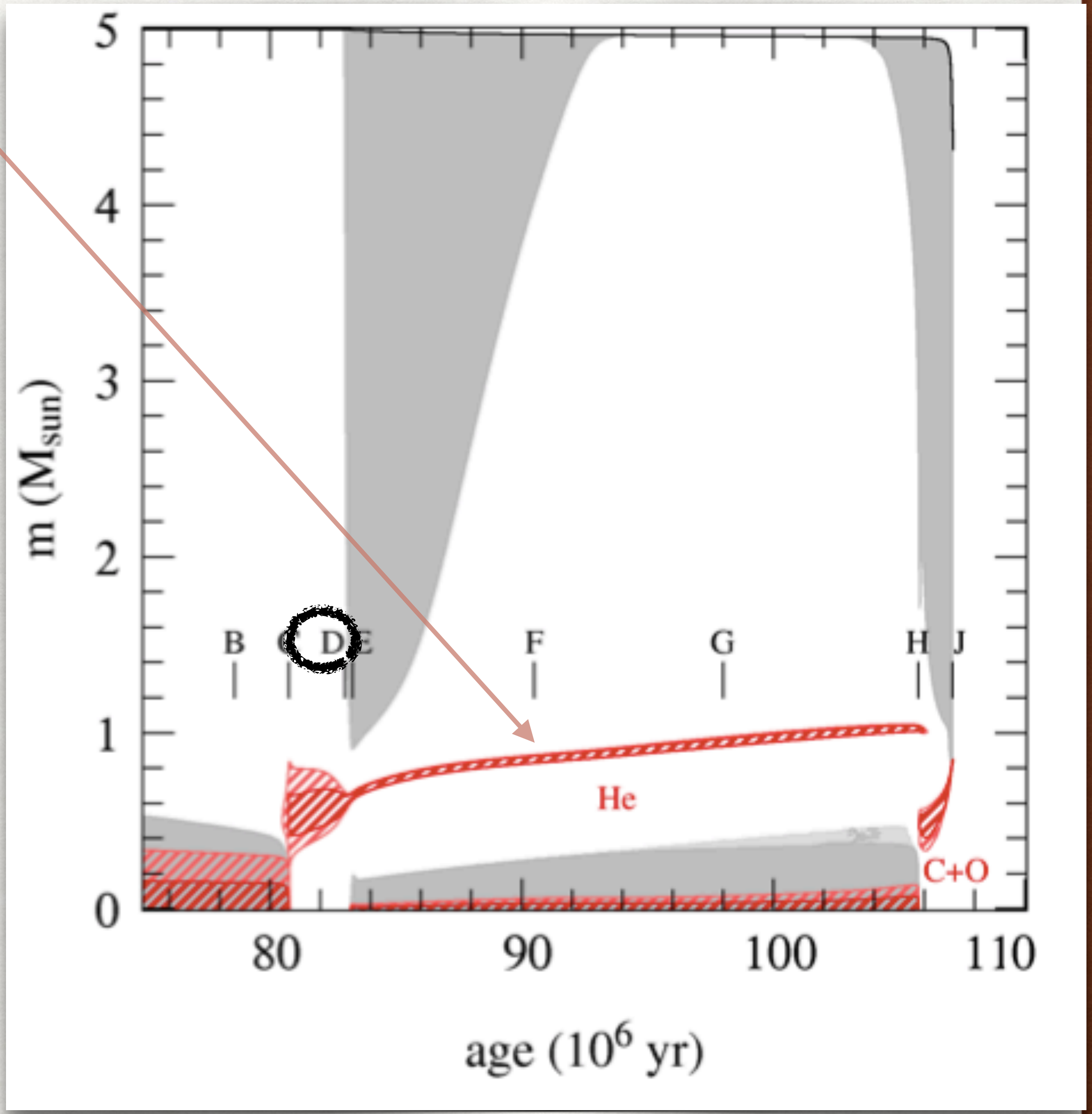
$$L_{\rm core} \approx \dot{E}_{\rm in,core} \approx -\frac{1}{2}\dot{E}_{\rm gr,core} \approx \frac{E_{\rm gr,core}}{\tau_{\rm KH,core}}$$

THIN H-SHELL BURNING PHASE

$M > 2\,M_{sun}$

point D: i) expansion and contraction makes large T gradient and the burning shell becomes and stays thin from this point on

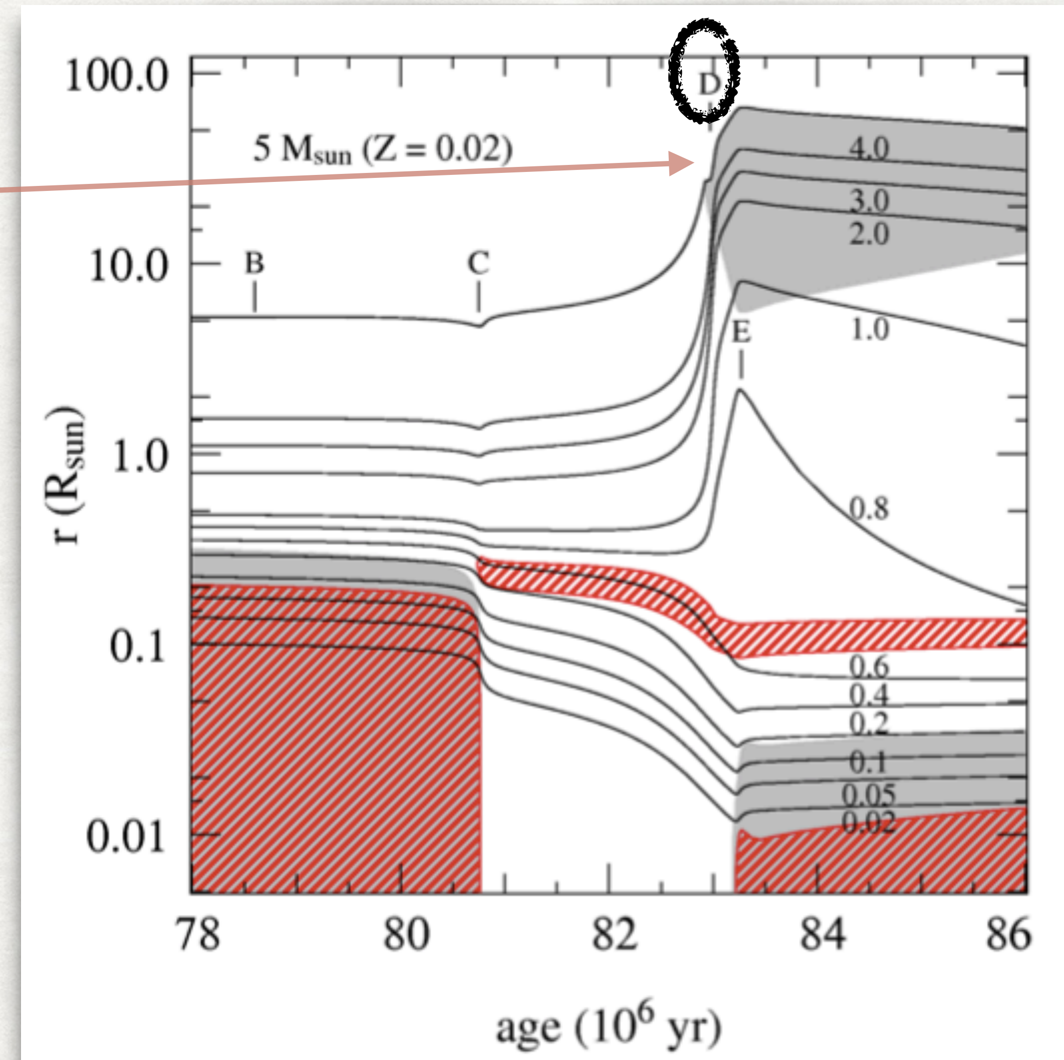




START OF *THIN* H-SHELL BURNING PHASE

M > 2 M_{sun}

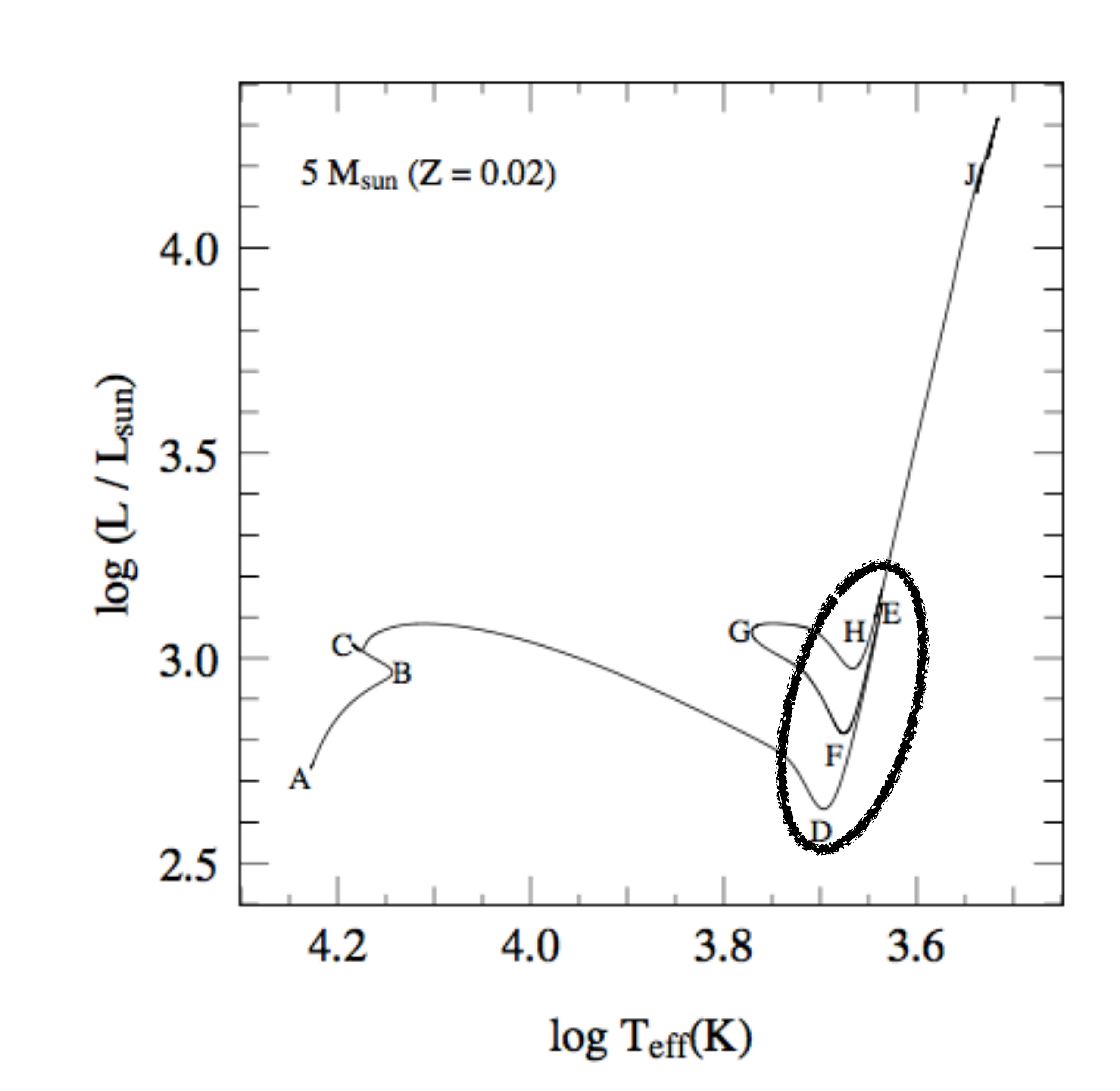
point D: i) expansion and contraction makes large T gradient and the burning shell becomes and stays thin from this point on
ii) T_{eff} lower => opacity higher => convective envelope

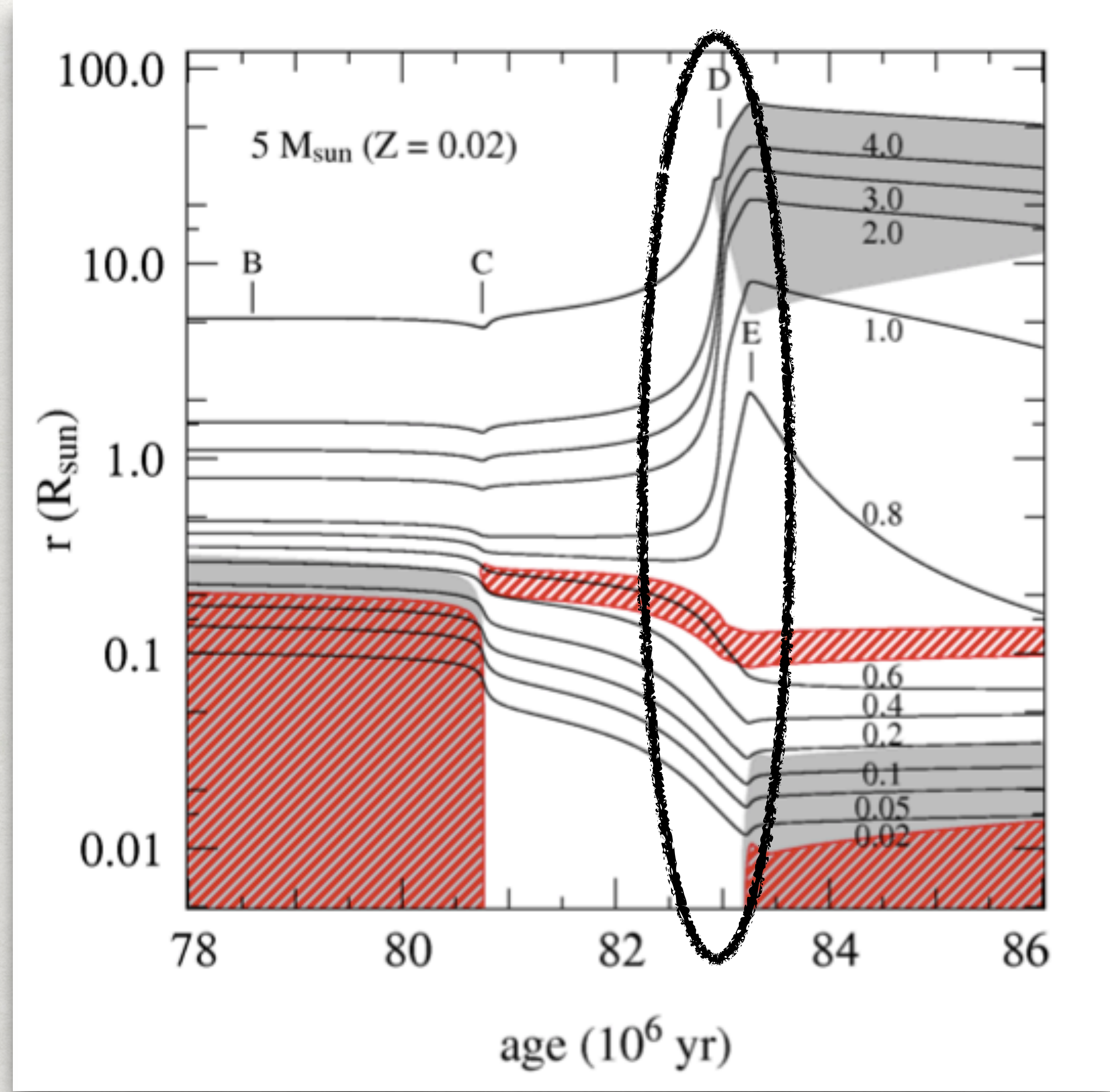


RED GIANT PHASE (D-E)

M > 2 M_{sun}

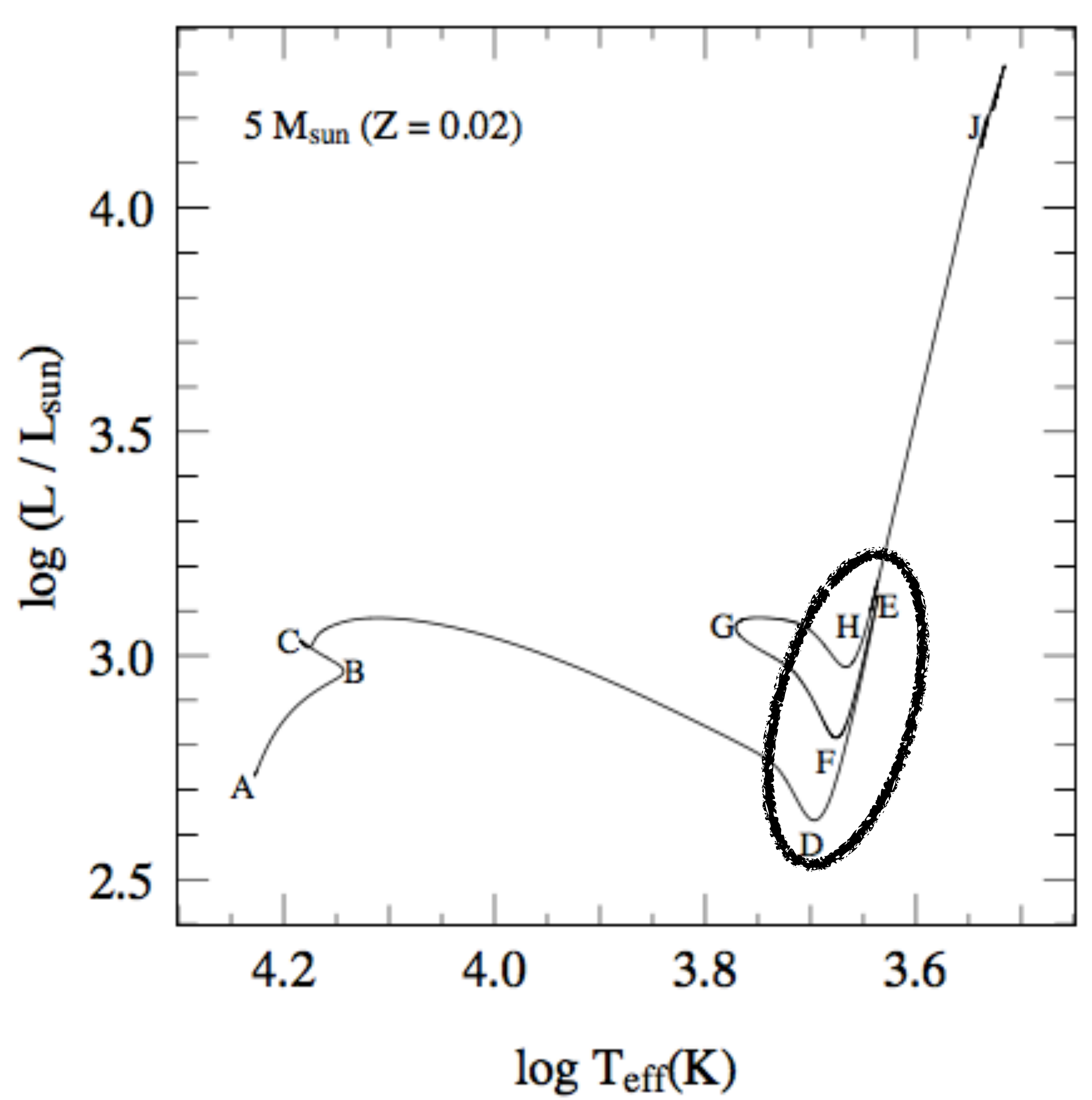
D-E: i) convective envelope (star close to Hayashi track)
ii) H-burning shell
iii) envelope keeps expanding in K-H timescale: short lived phase
iv) expansion=> L increases

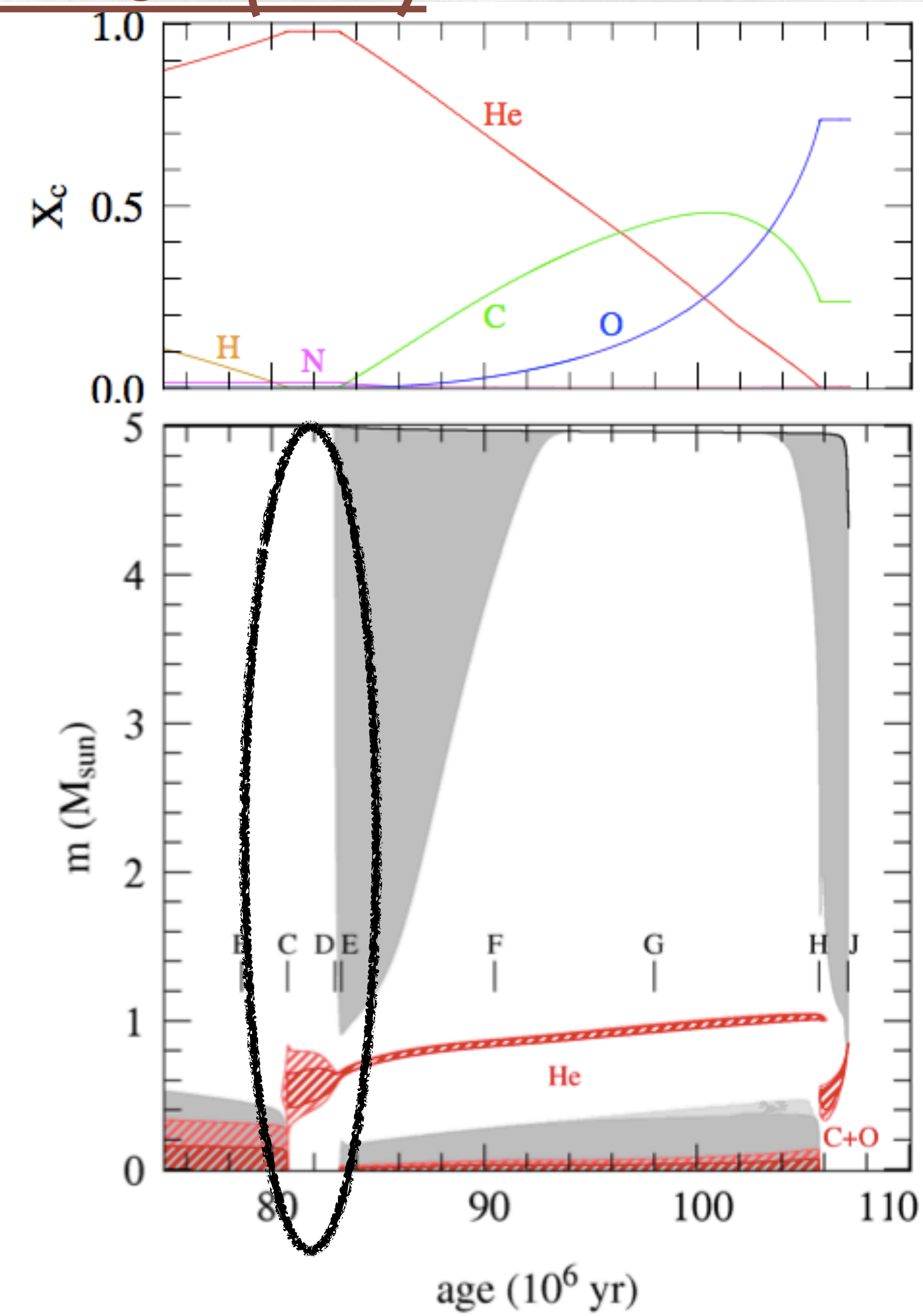




RED GIANT PHASE (D-E) M > 2 M_{sun}

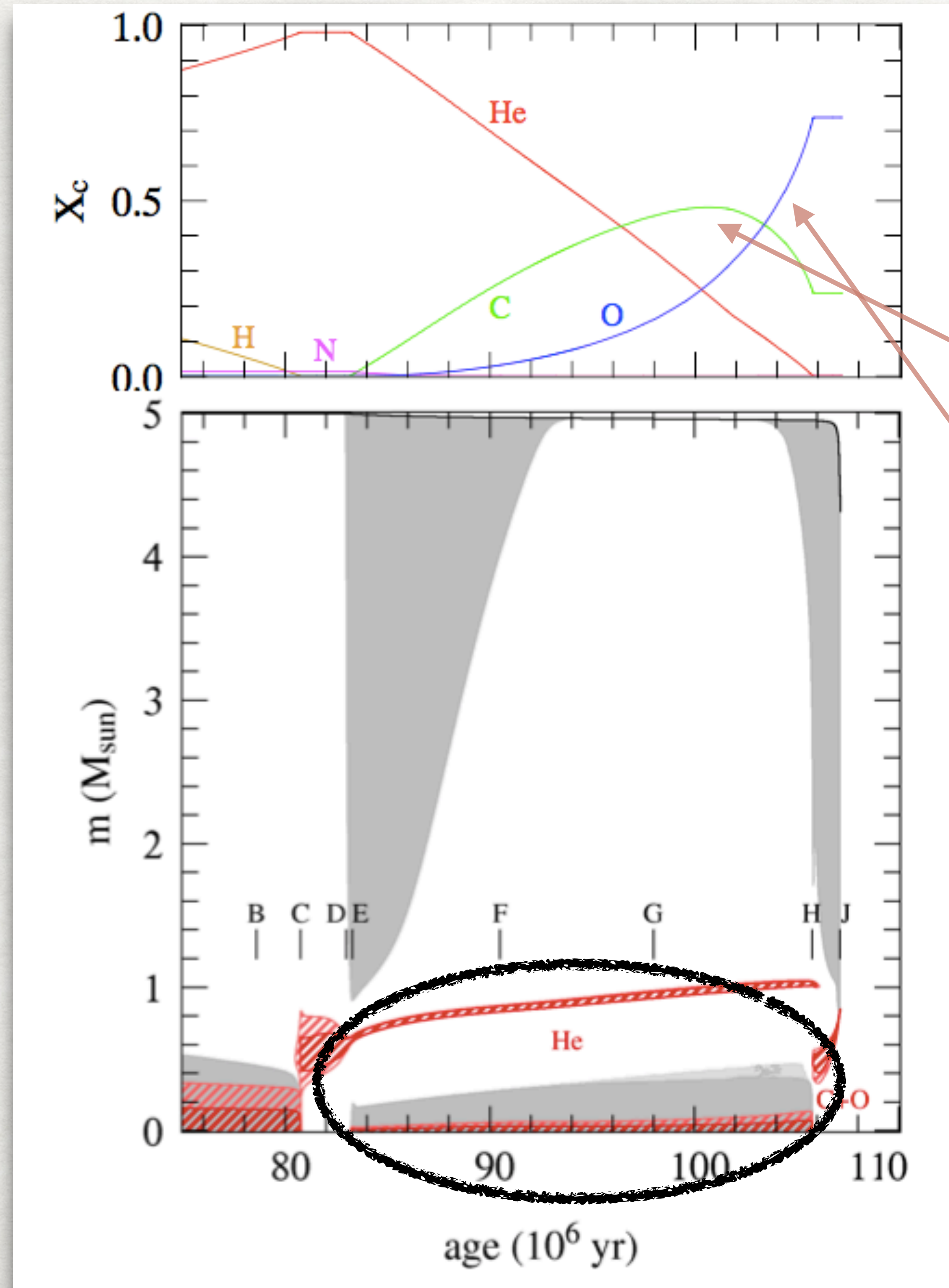
D-E: v) convective envelope at E extends to m~0.9, formerly inside the burning core: dredge-up of heavy elements to surface!





HE FUSION (E-H)

when H is exhausted in core, He core re-starts contracting



when T_c ~10^8 K He burning sets in,
at lasts for ~22 Myr : 0.27 main sequence lifetime

Helium burning: ``triple alpha reaction"

$$3\,^4\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma,$$

$$\epsilon_{3\alpha} \propto Y^3 T^{40}$$

when X_{He} <0.2 mass fraction of ^{12}C decreases
because lower production rate and consumed to form ^{16}O

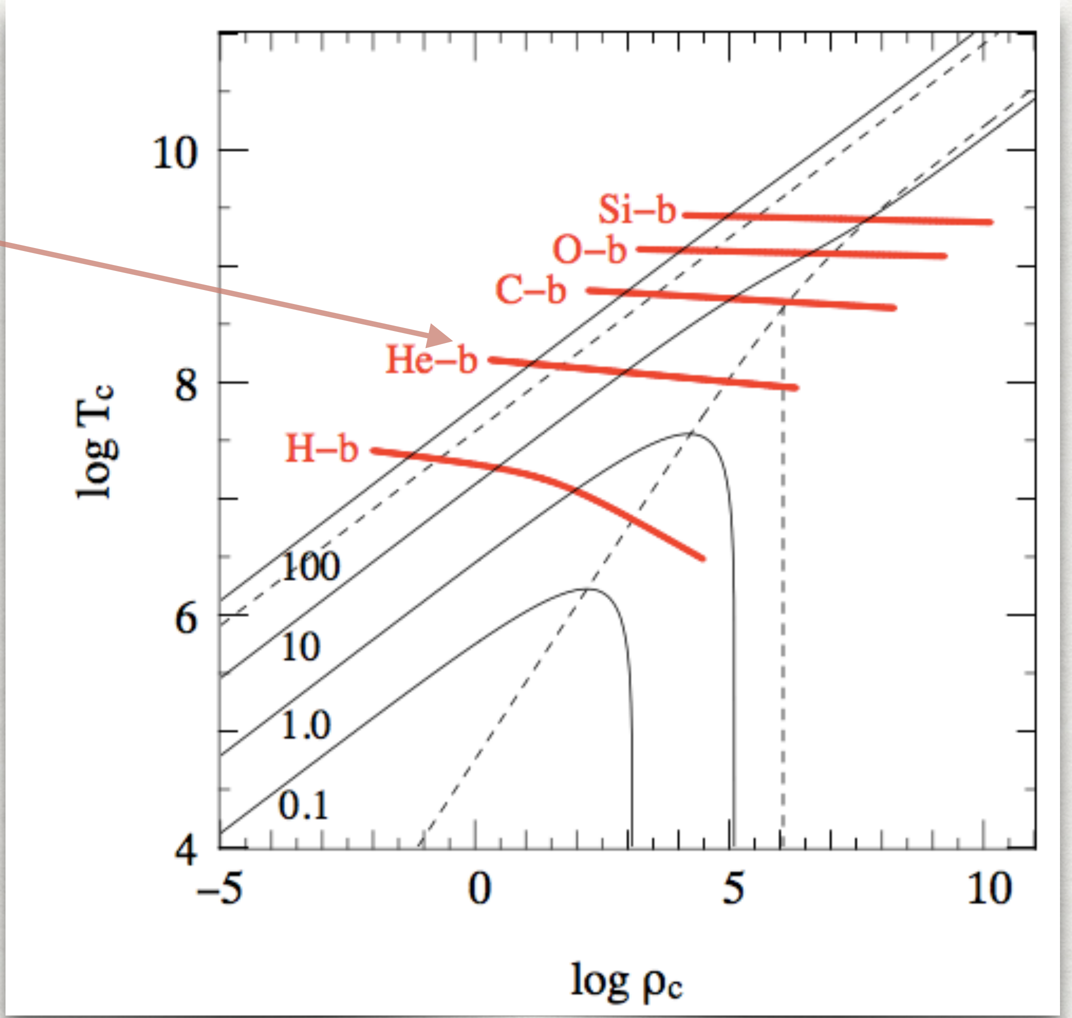
$$^{12}\mathrm{C} + {}^4\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \gamma,$$

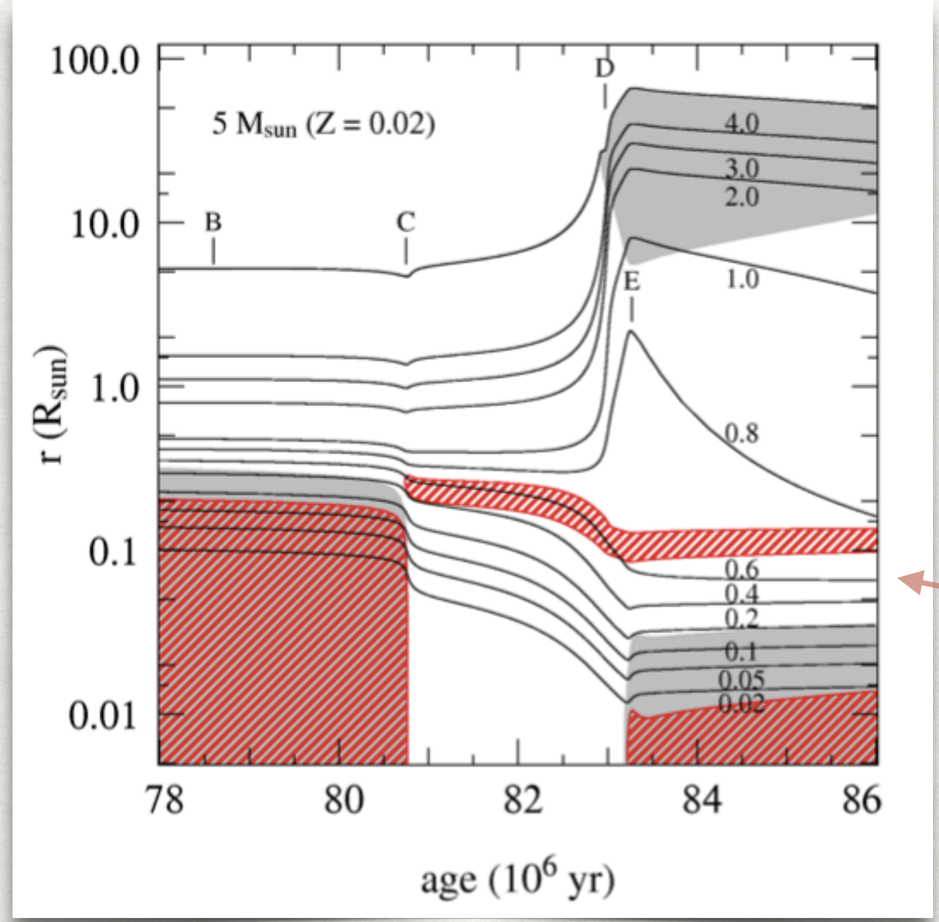
Unlike H-burning, He-burning happen through
triple alpha reaction
for any stellar mass

HE FUSION: MINIMUM CORE MASS

- there is a minimum core mass for He

detailed calculations with varying composition give core > 0.3 M_{sun}





In our example core mass 0.6

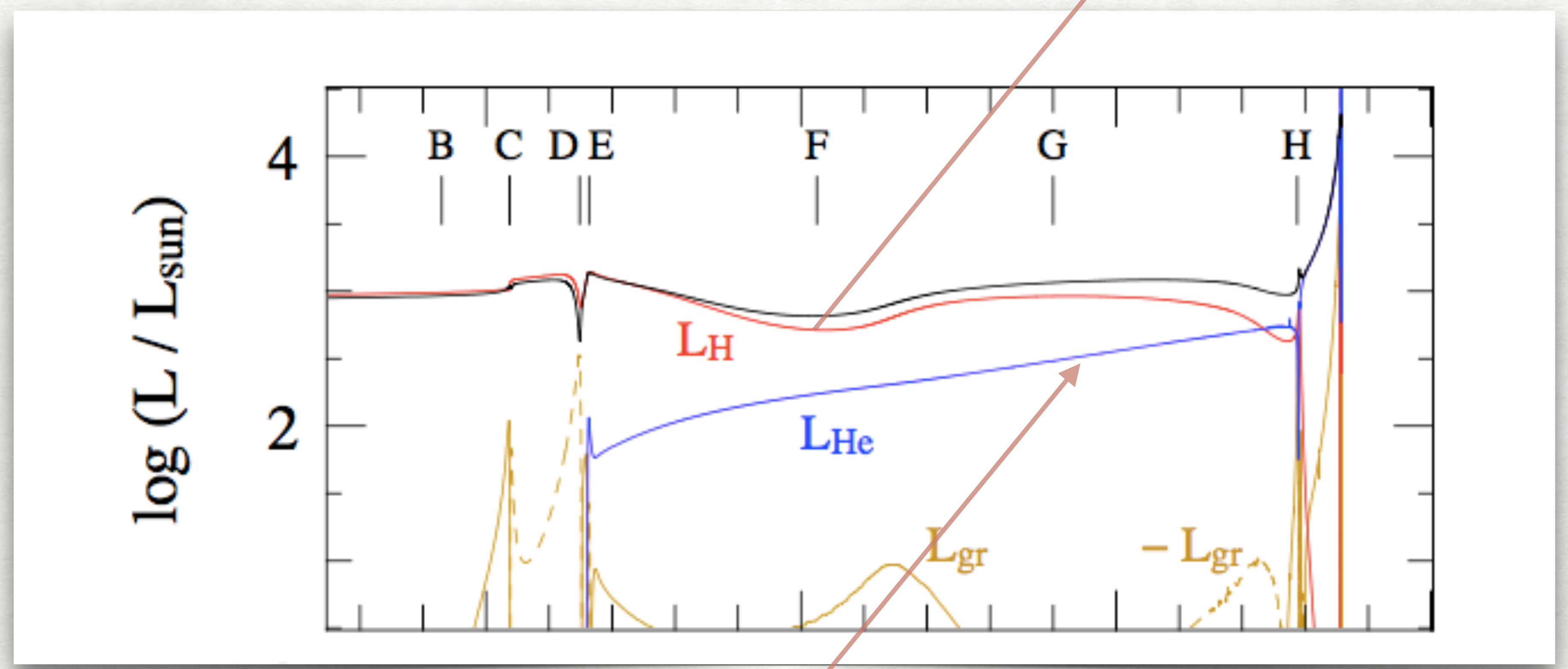
He burning i) happens and ii) it is stable: it does not happen in a degenerate core as for M < M_{Ch}

LUMINOSITY AND DURATION

The duration 22 Myr is rather long even if

i) energy per gram is 10% of that of H
ii) L radiated is higher than in the main sequence

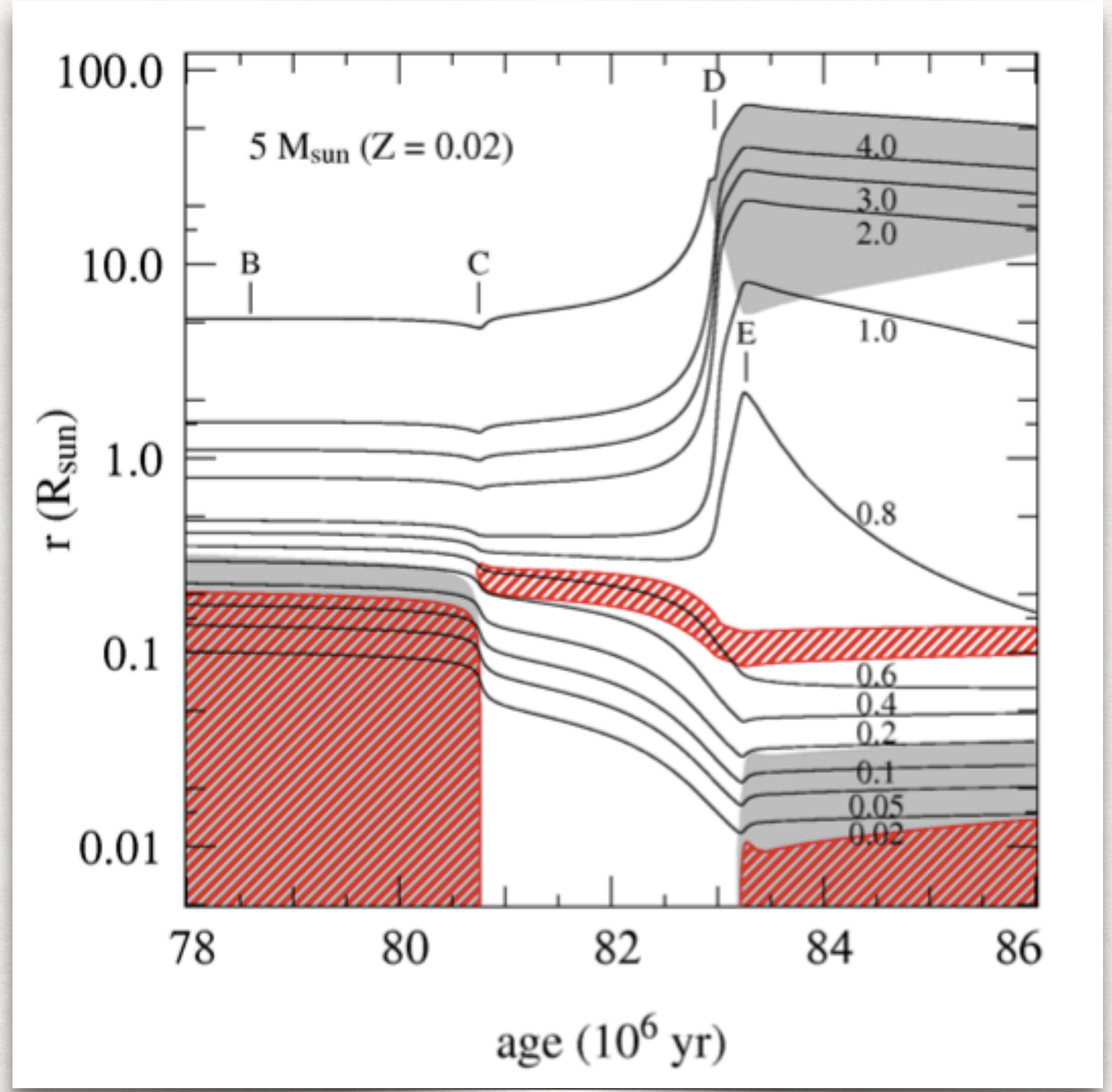
Answer: Luminosity still supplied by H-burning in shell



Luminosity produced by He burning remains subdominant

CORE CONVECTION

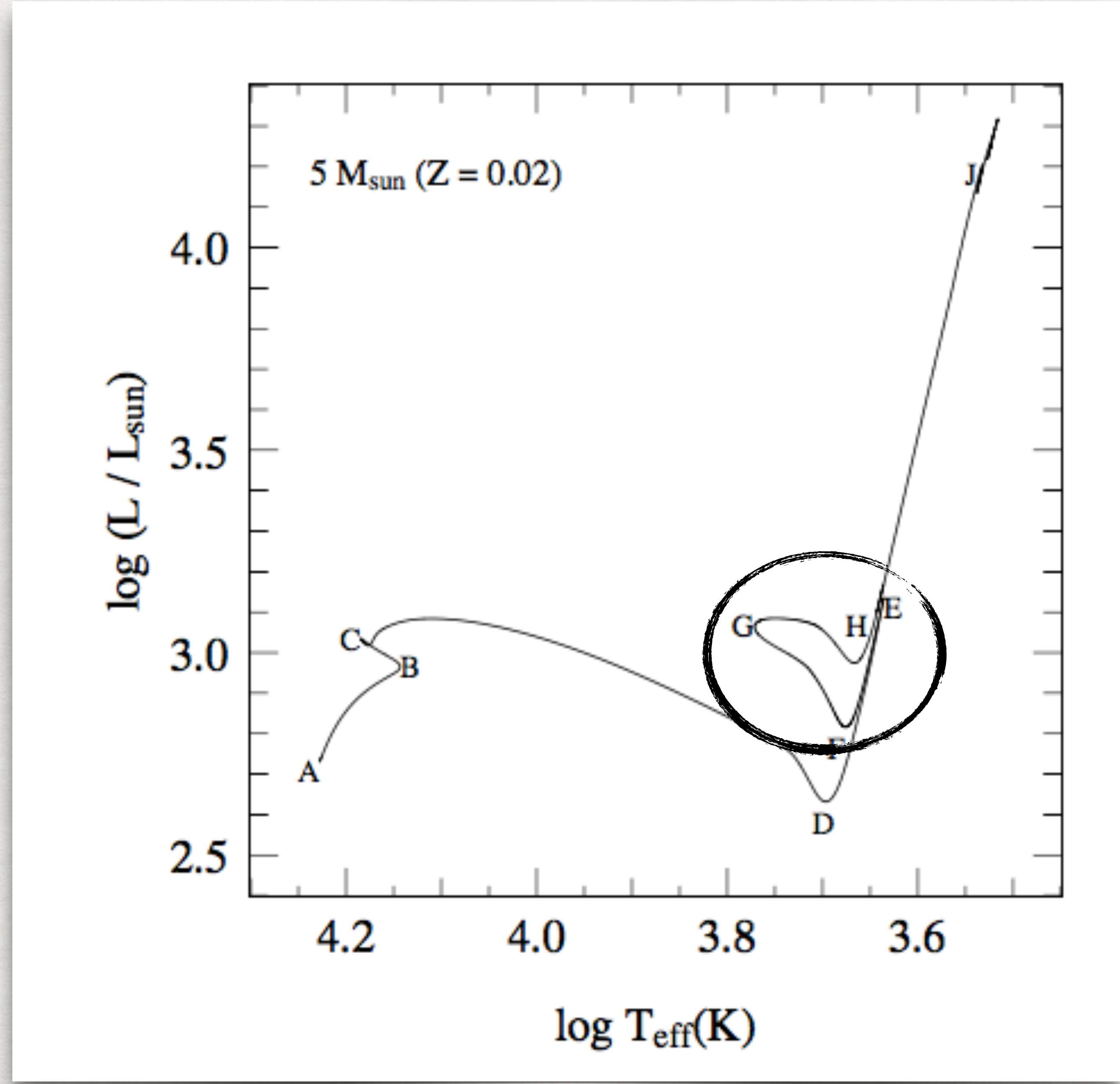
He burning is even more concentrated than H-burning: the core becomes convectively unstable



gray area: convection

BLUE LOOPS IN H-R DIAGRAM

only for intermediate mass stars



- Results of simulations, difficult to understand analytically
- The extension depends on composition, mass of He core versus mass envelope, extent of convective core in main sequence

BLUE LOOPS IN H-R DIAGRAM

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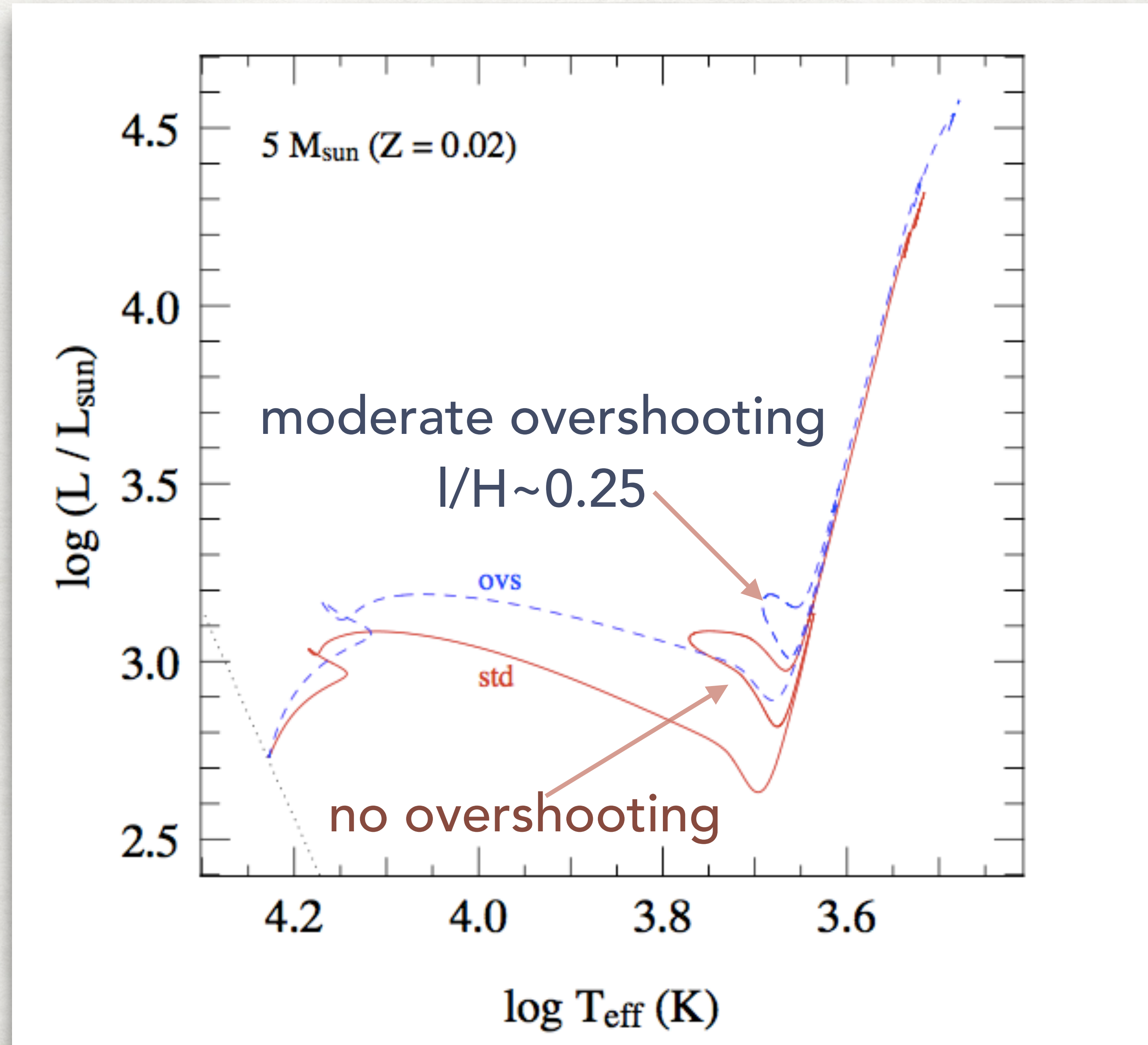


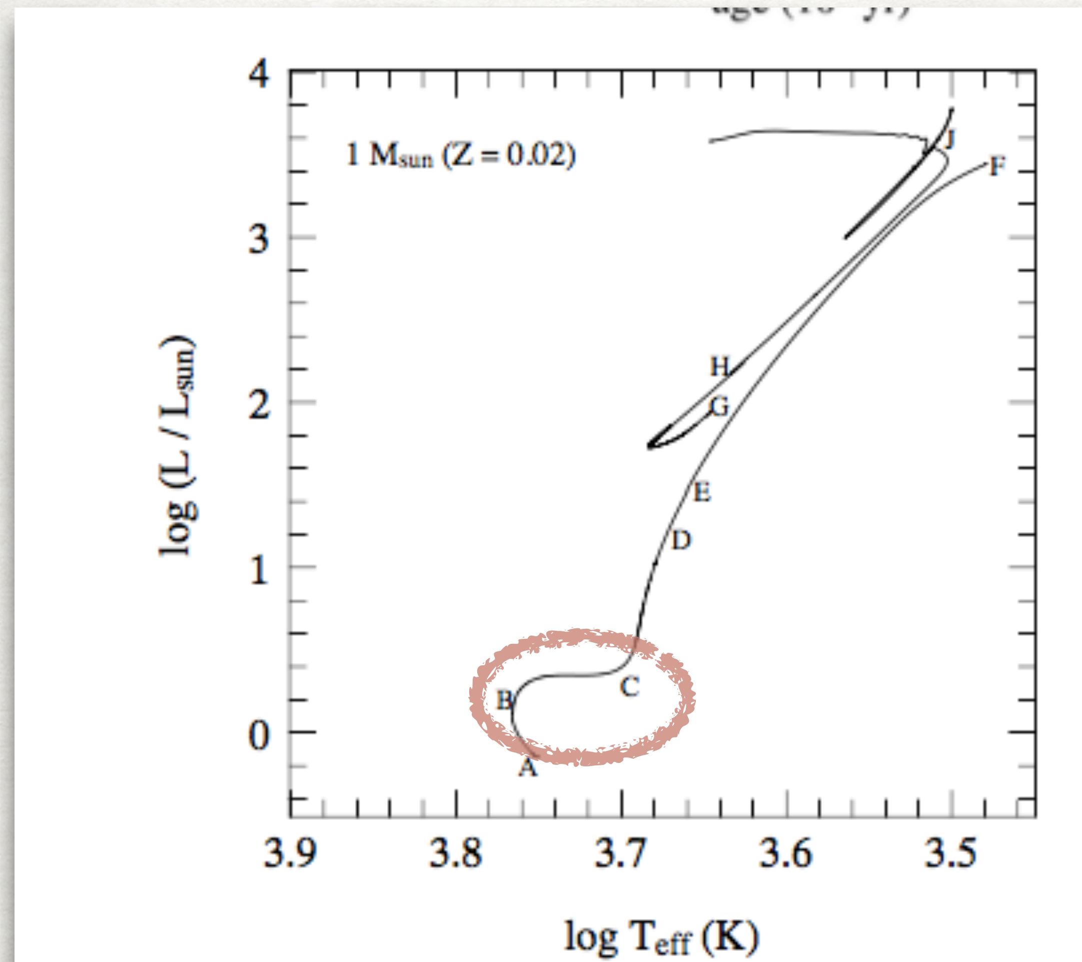
- Results of simulations, difficult to understand analytically
- The extension depends on composition, mass of He core versus mass envelope, extent of convective core in main sequence
- dependence on model for overshooting that determines extension of He core
- This is a slow evolution phase: many observations expected used to calibrate M.L.T.

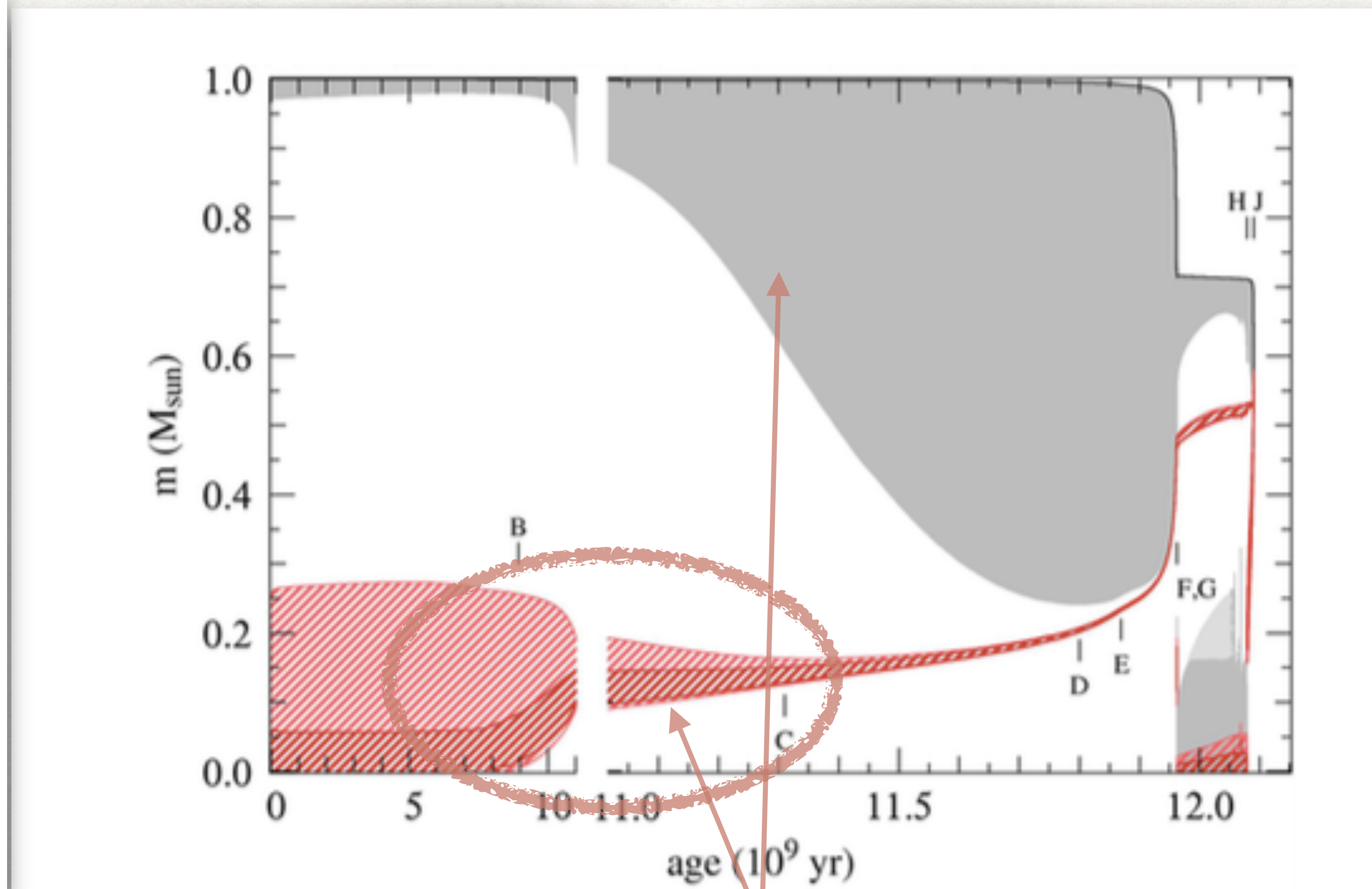
POST MAIN SEQUENCE EVOLUTION

The evolution is significantly different for low mass $M < 2\ M_{sun}$
and intermediate and high mass $M > 2\ M_{sun}$

We know consider the evolution for $M < 2\ M_{sun}$

END MAIN SEQUENCE EVOLUTION (B-C)



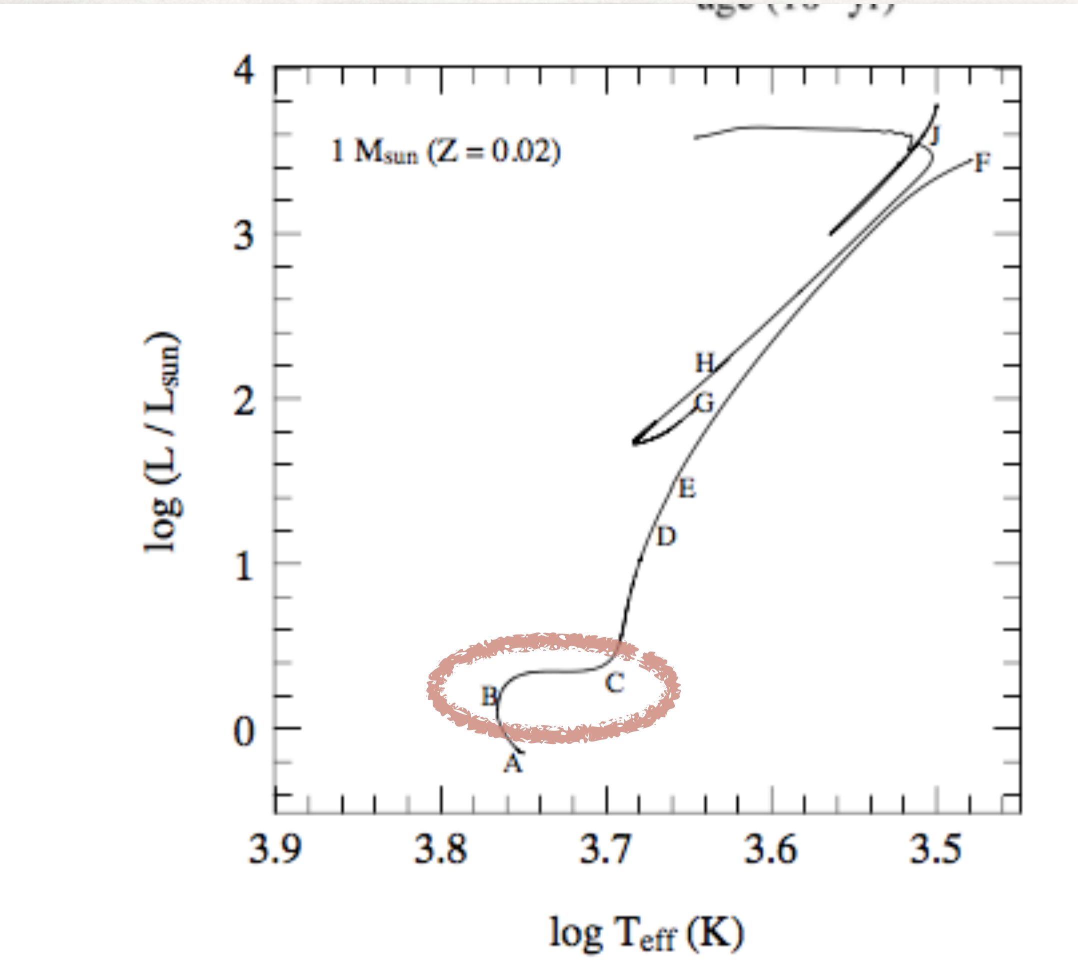


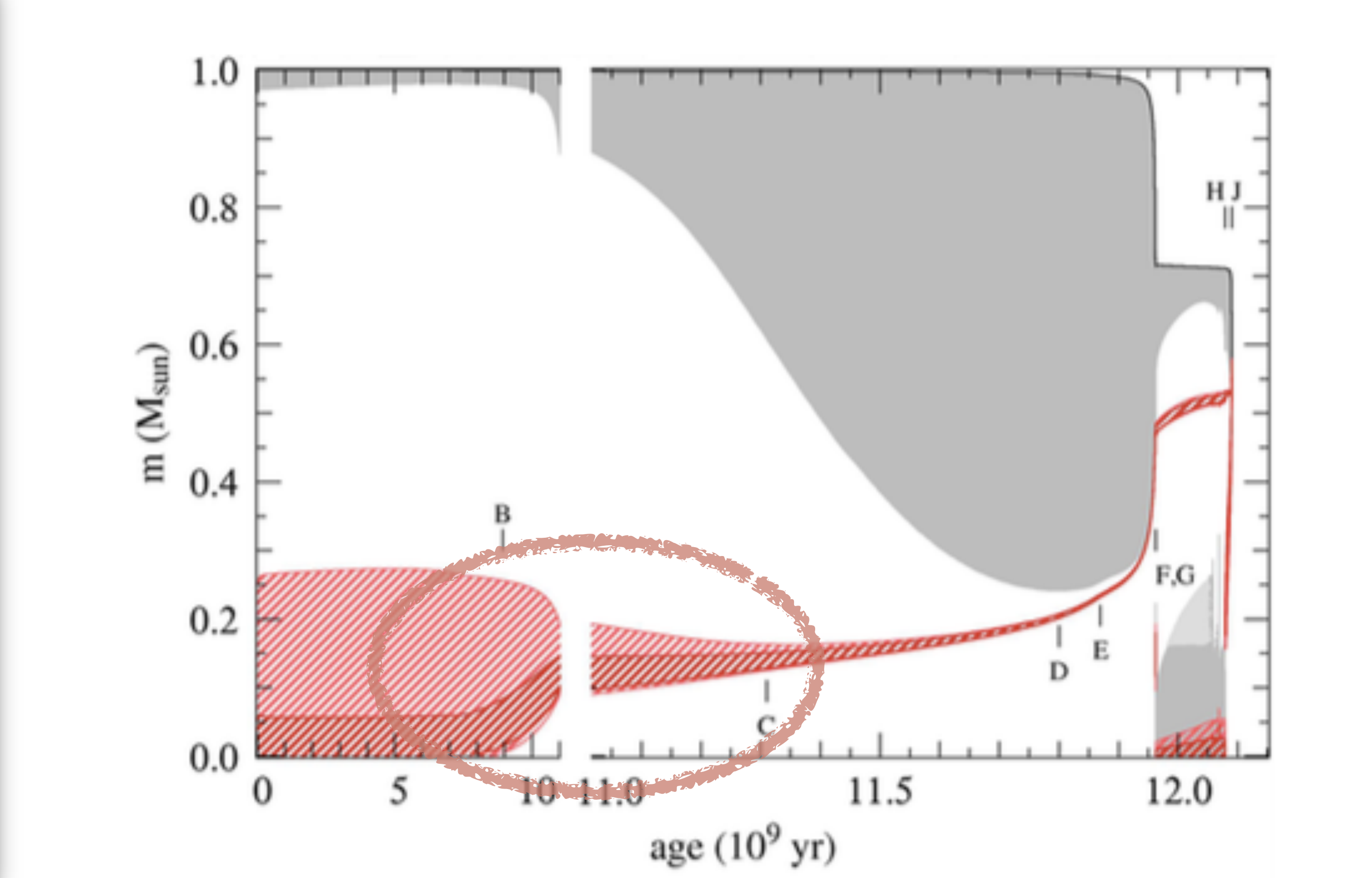
Main sequence: radiative H-burning core

After ~1 Gyr Xc ~10^{-3} :

- Core starts collapsing and H-burning moves outward to a thick shell —> thin shell
- Envelope expands, cools down and becomes increasingly convective

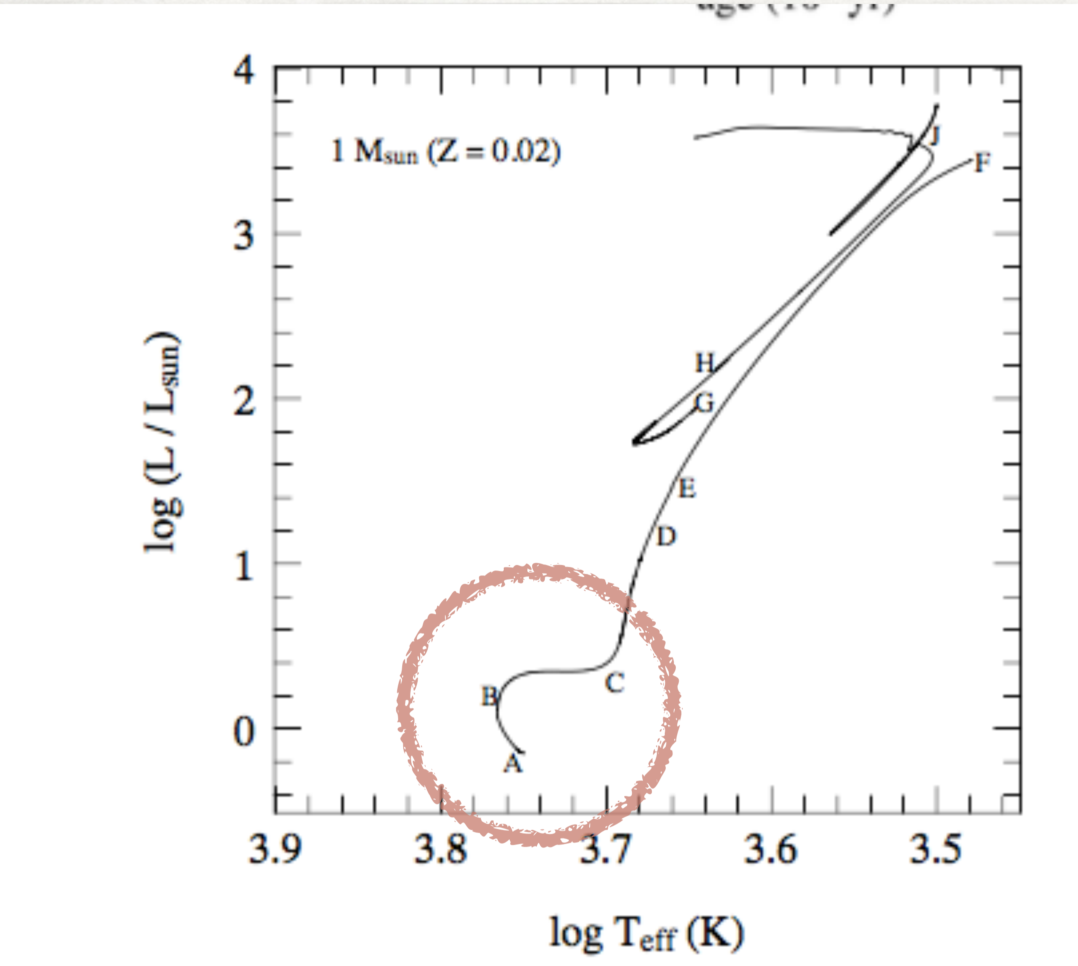
END MAIN SEQUENCE EVOLUTION (B-C)

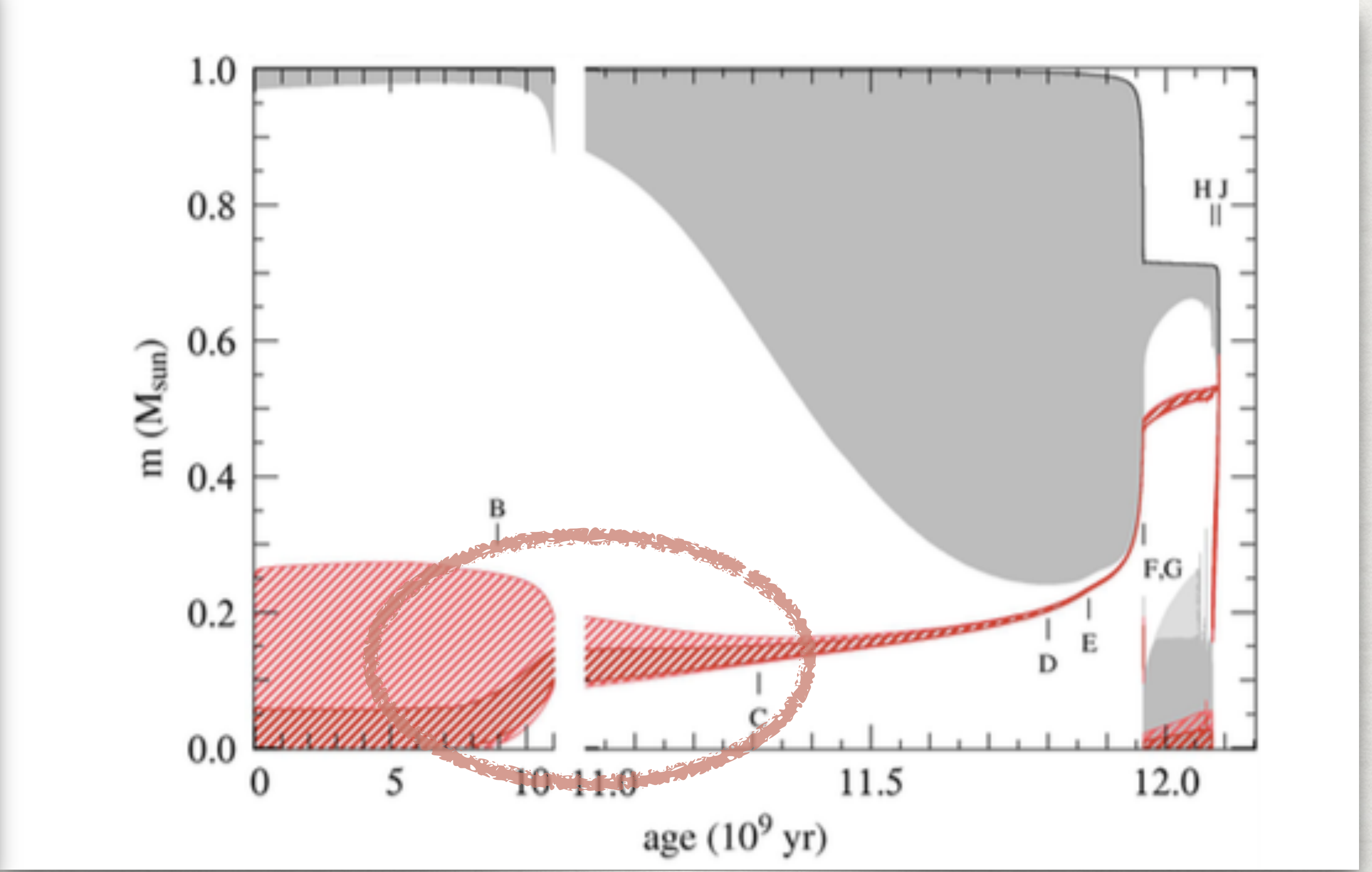




- Unlike more massive stars, **the He core becomes degenerate by point C**
- The degenerate core (if < Chandrasekhar mass) can provide pressure support for envelope
- In the degenerate core **electron conduction** can provide energy transport and keep core isothermal
- **==> low mass stars are in HE and TE during the whole shell burning phase beyon C**

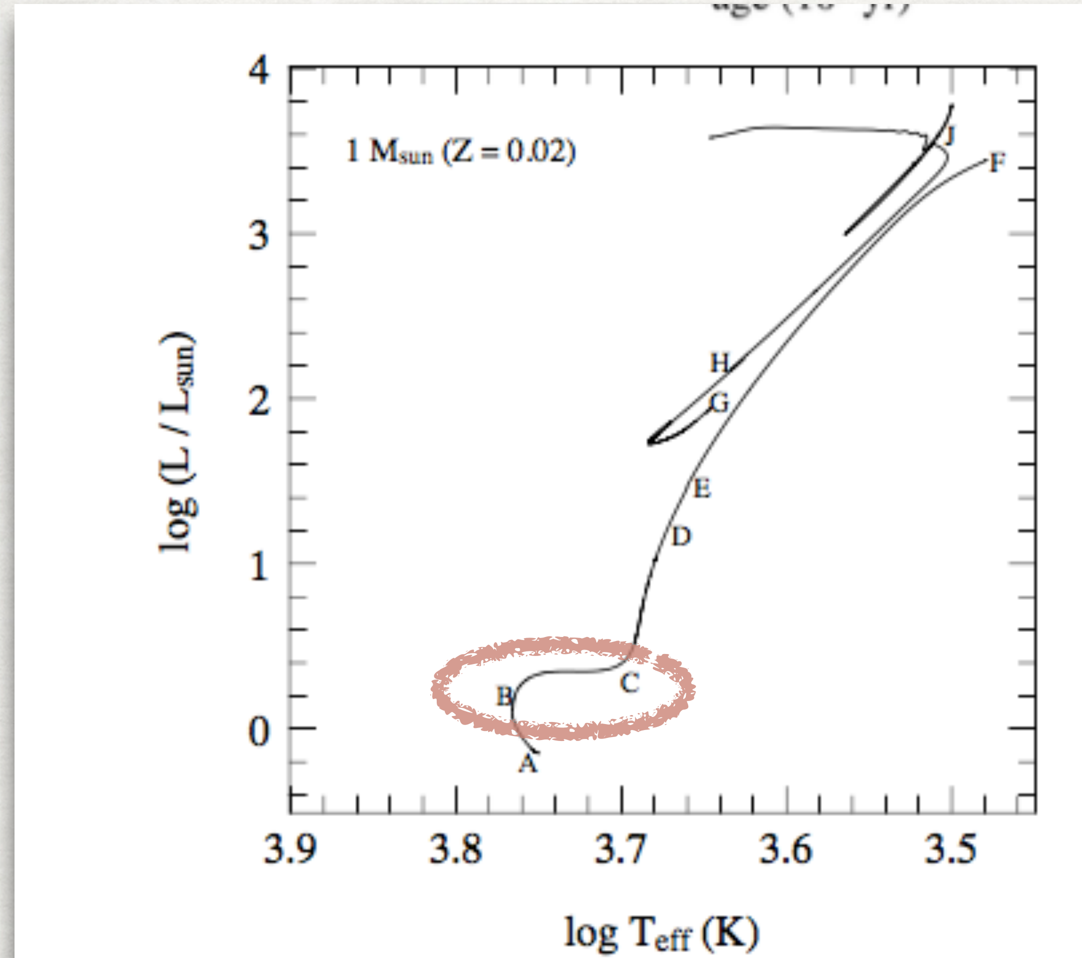
END MAIN SEQUENCE EVOLUTION (B-C)

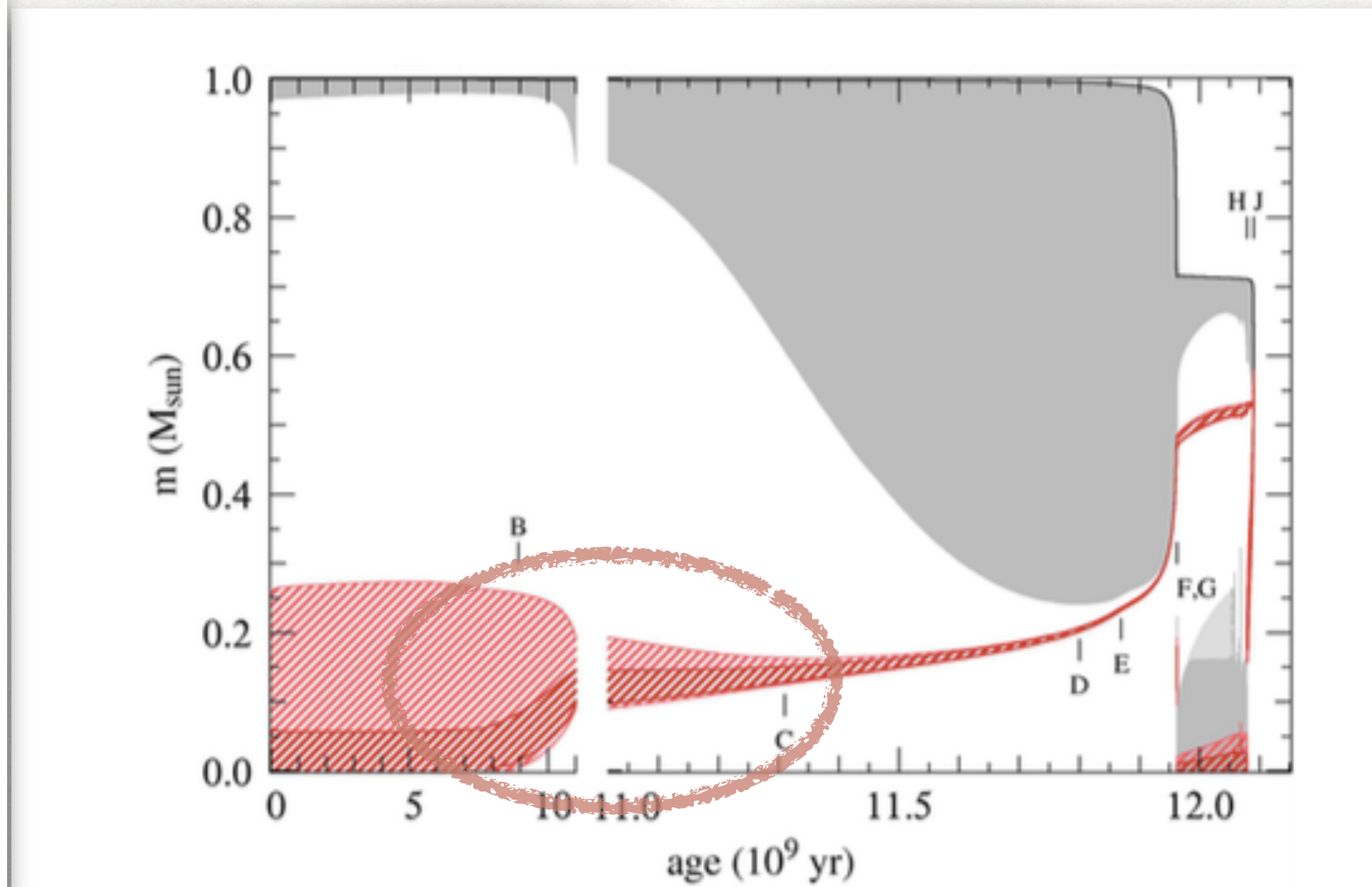




- For **M <1.5 M_{sun}** the the Schonberg-Chandrasekhar limit is never reached as the core becomes first degenerate
- ==> transition from main sequence to shell H-burning phase is gradual and there is no Hertzsprung gap in the H-R diagram,
- phase B-C lasts ~ 2 Gyr

MAIN SEQUENCE EVOLUTION (A-C)

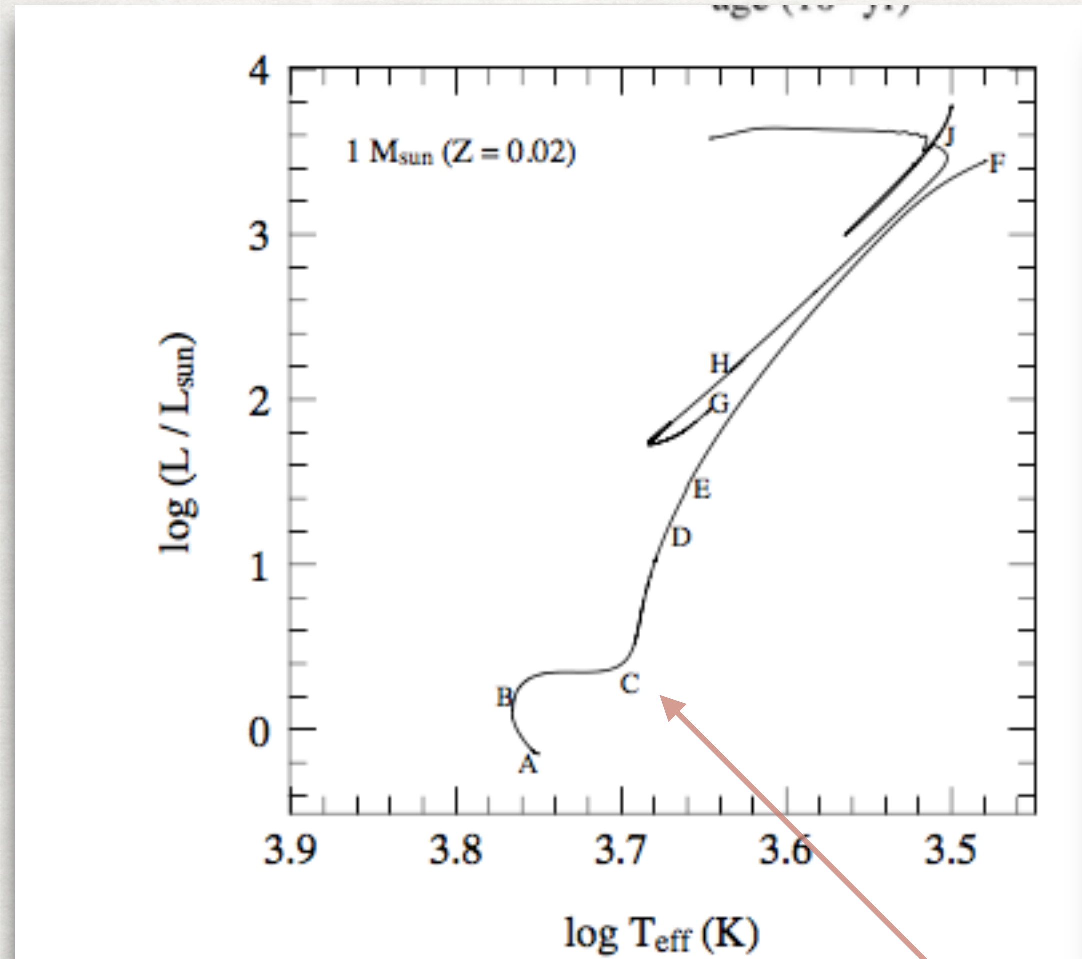


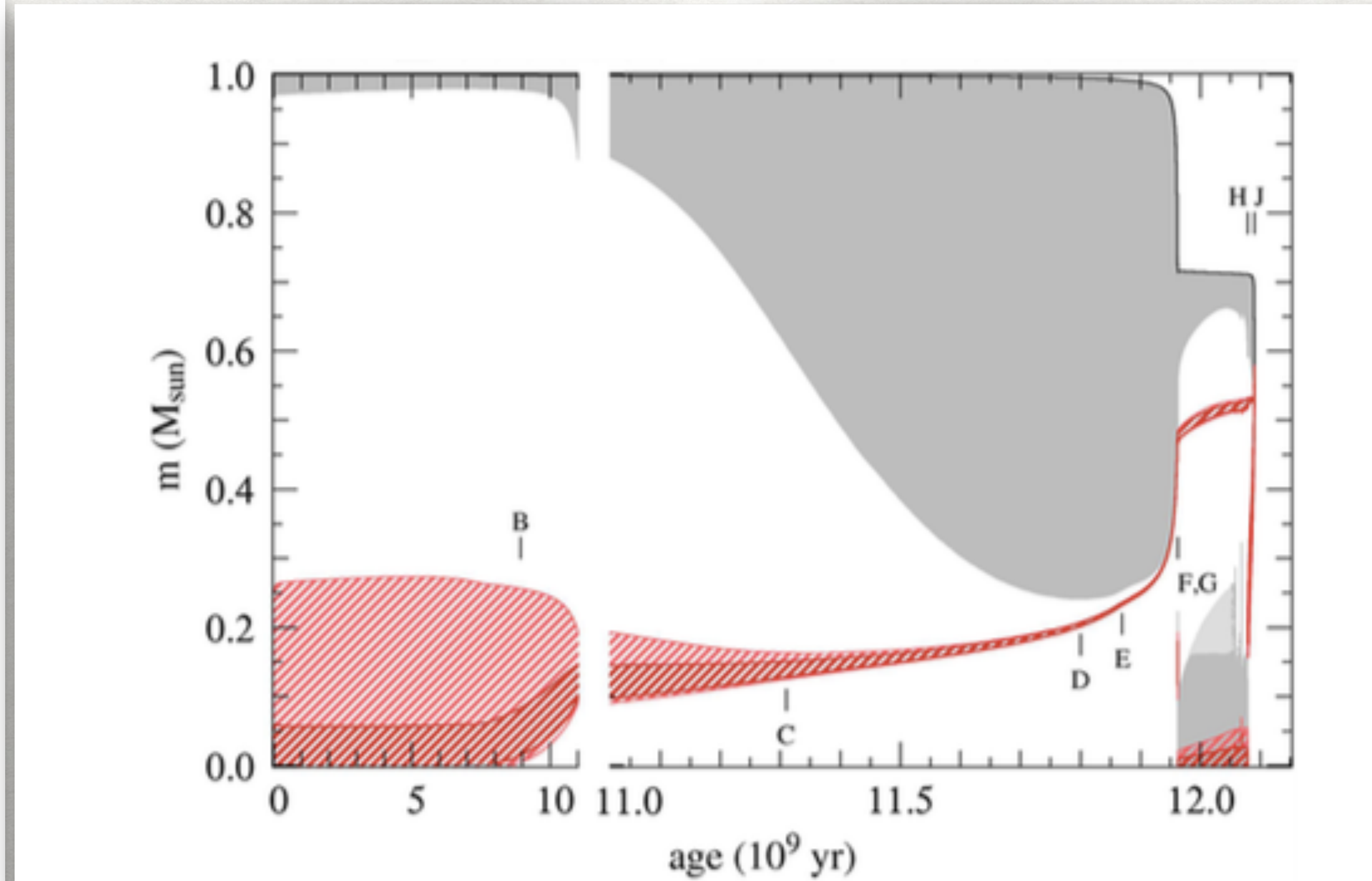


For 1.5 M_{sun} <M< 2 M_{sun} The core reaches the Schonberg-Chandrasekhar limit before becoming degenerate and there is a small Hertzsprung gap due to the fact that evolution happens on the K-H timescale

- still core becomes degenerate before He burning

THE BASE RED GIANT BRANCH BASE

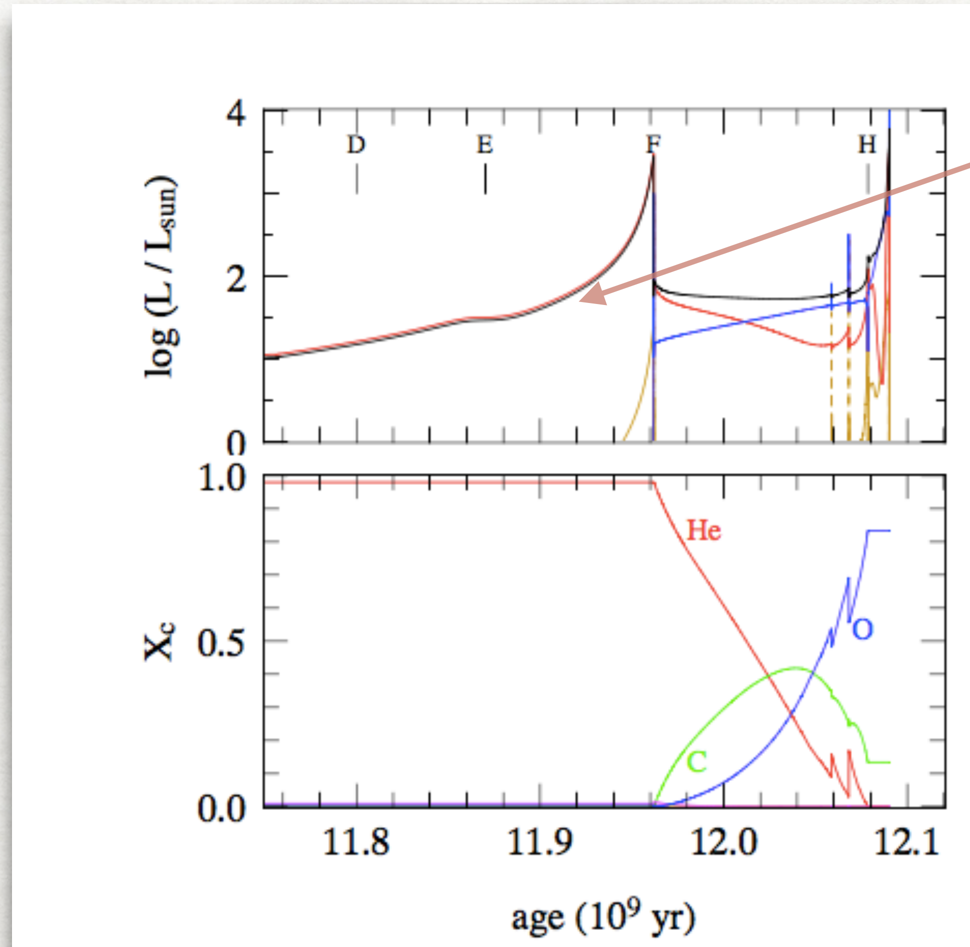




At point C: base of the RED GIANT BRANCH (close to Hyashi line)

- Degenerate core and large convective envelope

RED GIANT BRANCH (C-F)



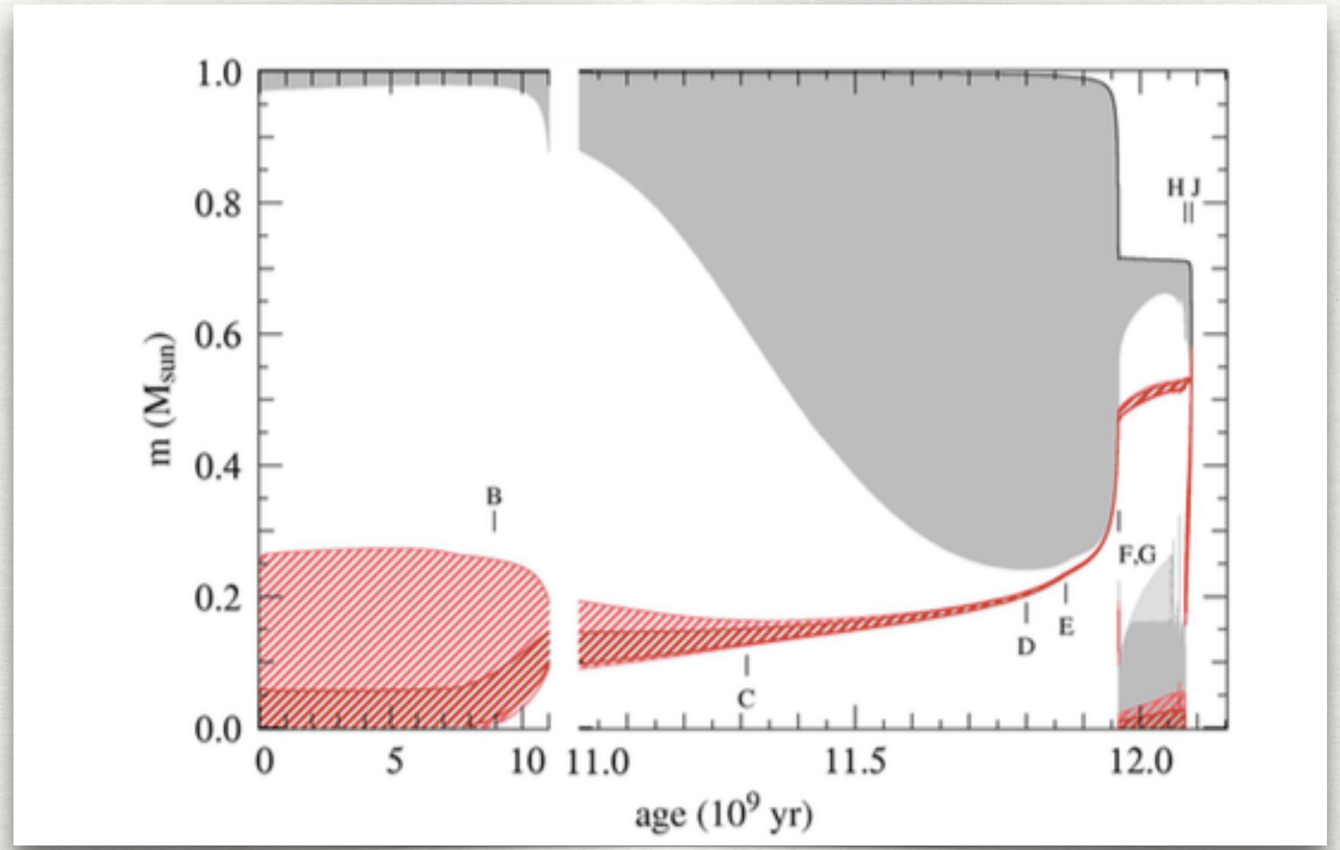
- L given by H-burning shell only
- The evolution is independent of star mass: the stellar structure depends entirely on the core, whose structure depends only on mass (not thermal properties, it is a polytope structure!)

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

the luminosity increases as the mass in He increases

RED GIANT BRANCH (C-F)

- adding mass to core ==> contraction for HE of a polytopic equation of state non-relativistic M ~ R^{-3}
- envelope keeps expanding, cooling and convective
  - At D dredge-up becomes important
  - Vigorous Mass loss:
    0.3 Msun lost by tip of giant branch (point F)



HE BURNING PHASE

Facts:

1. At tip of RGB T ~ 10^8 K
2. He ignition occurs in degenerate core
3. He burning starts when star has core mass ~0.45 solar masses independent of star mass (L~ 2000 L_{sun})

HE BURNING

Facts:

1. At tip of RGB T ~ 10^8 K
2. He ignition occurs in degenerate core
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THERMAL/ SECULAR STABILITY

Recall: in ideal gas + radiation stars the negative heat capacity ensures **stability**:

$\partial T > 0$ —-> $L_{nuc} > L$ —-> $\partial T < 0$ —-> $\partial L_{\mathbf{nun}} < 0$

(expansion decreases internal energy: Virial Theorem)

Recall: $\epsilon_{\rm nuc} \propto \rho^{\mu} T^{\nu}$

THERMAL/ SECULAR STABILITY

In degenerate stars or cores of evolved stars P independent of T. This can cause thermal INstability: **Thermonuclear Runaway!**

$\partial T > 0$ —-> $L_{nuc} > L$ but $\partial\rho \sim 0$ —-> $\partial T > 0$ —-> $\partial L_{\rm nuc} > 0$ and so on…

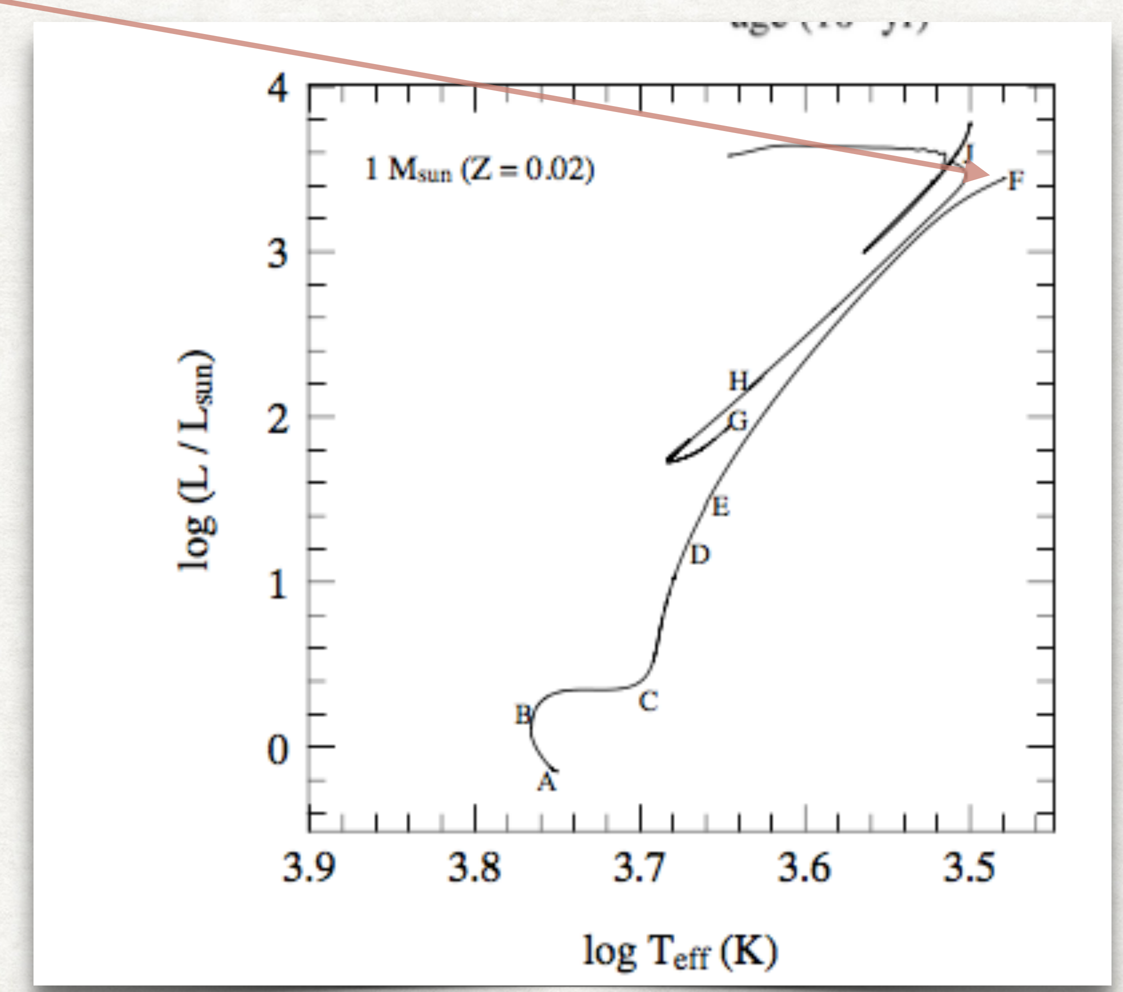
no expansion!

Recall: $\epsilon_{\rm nuc} \propto \rho^\mu T^\nu$

HE FLASH

Thermonuclear Runaway!

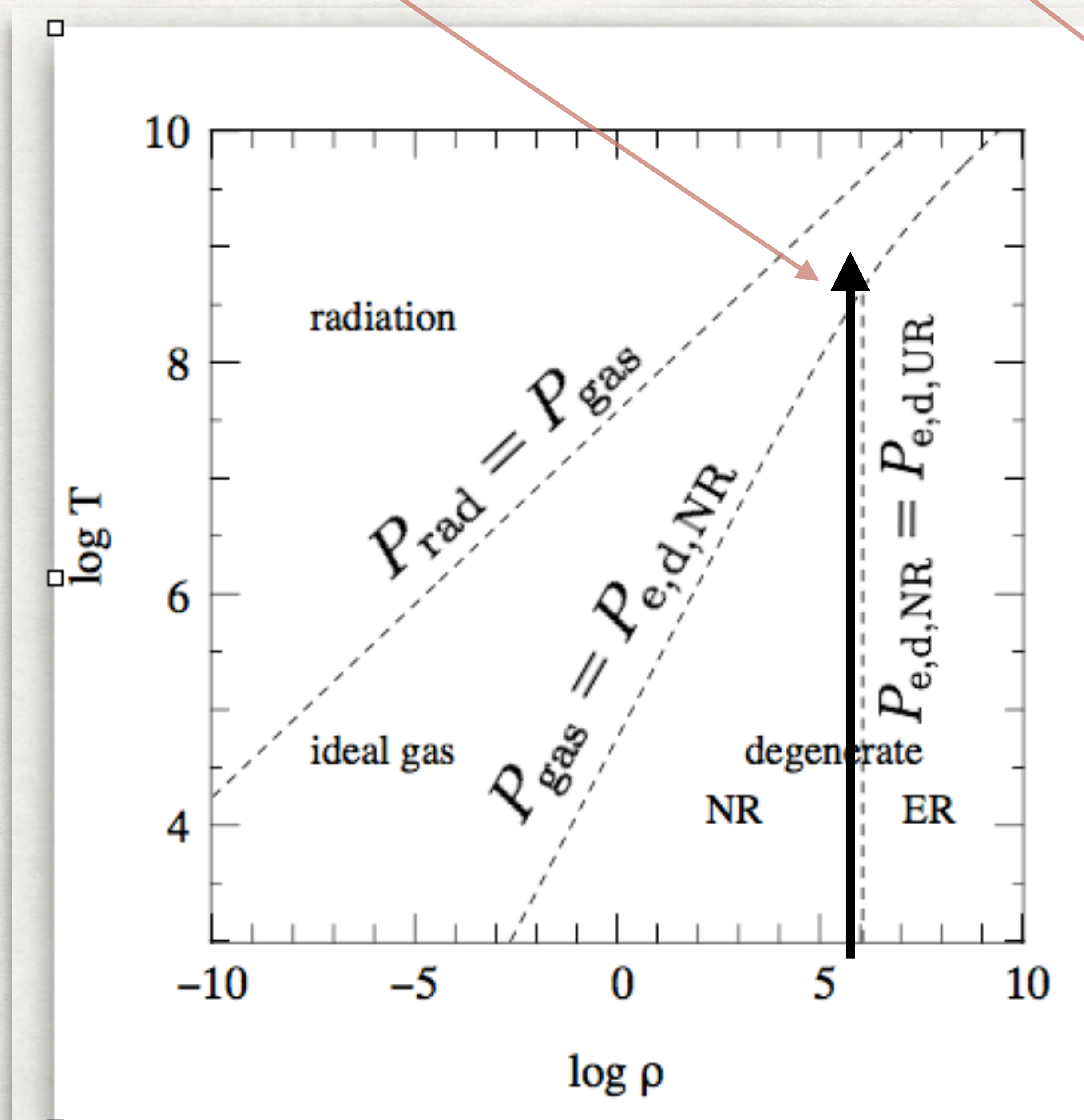
Ignition of He fusion in degenerate core of stars < 2 M_{sun} : sudden increase in luminosity called``Helium flash" during ``red giant" phase ==> locally in core l~ 10^{10} L_{sun} for a few second!

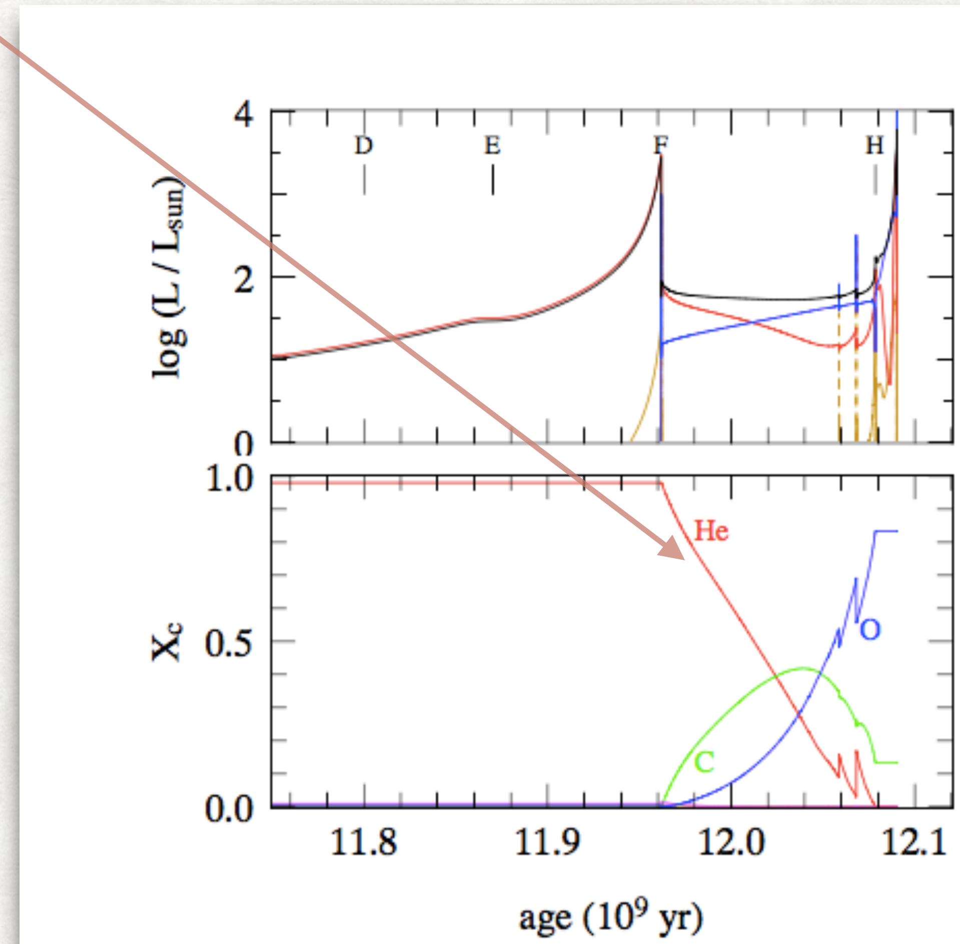


note: evolution through He flash (F to G) not modelled

AFTER HE FLASH

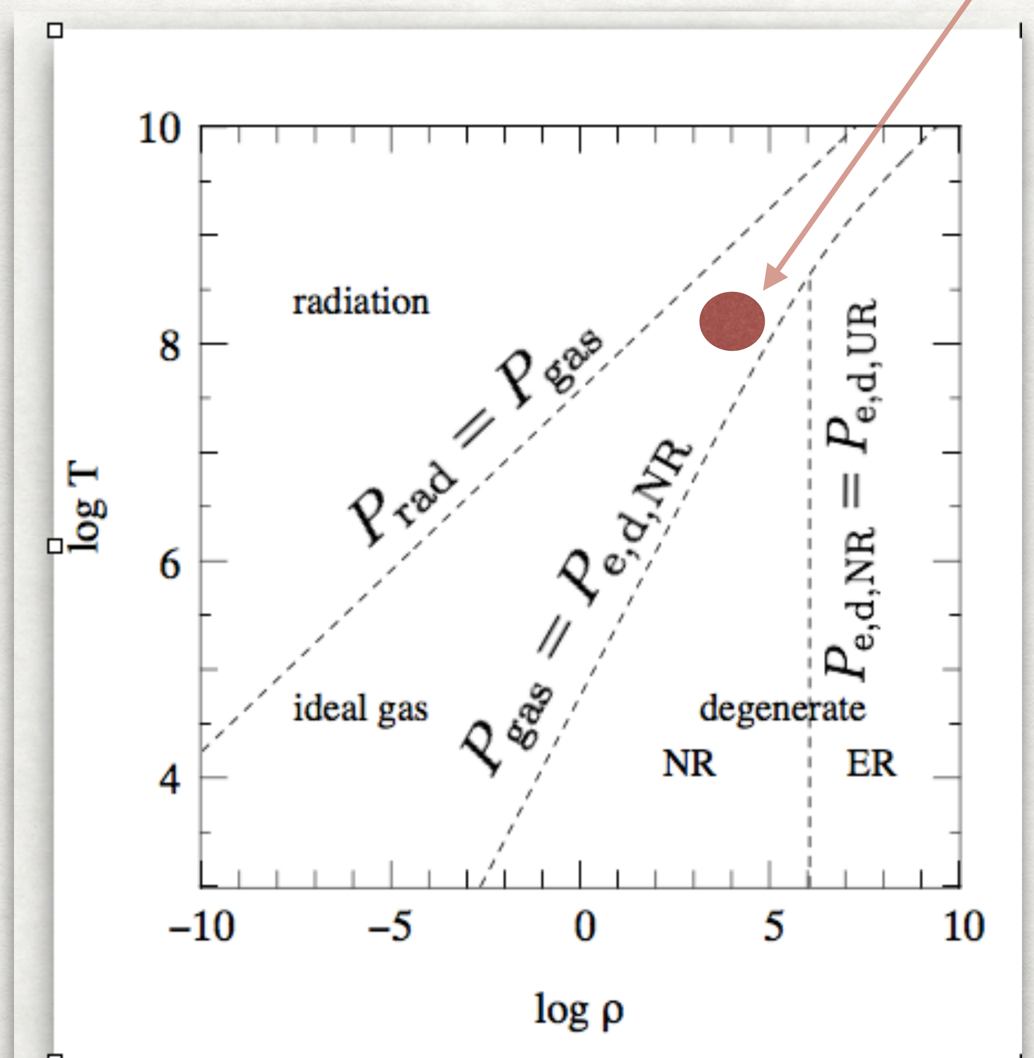
- The sudden increase in temperature at constant density makes the core NON-degenerate and further He burning is stable in a non degenerate core, beyond ``G"

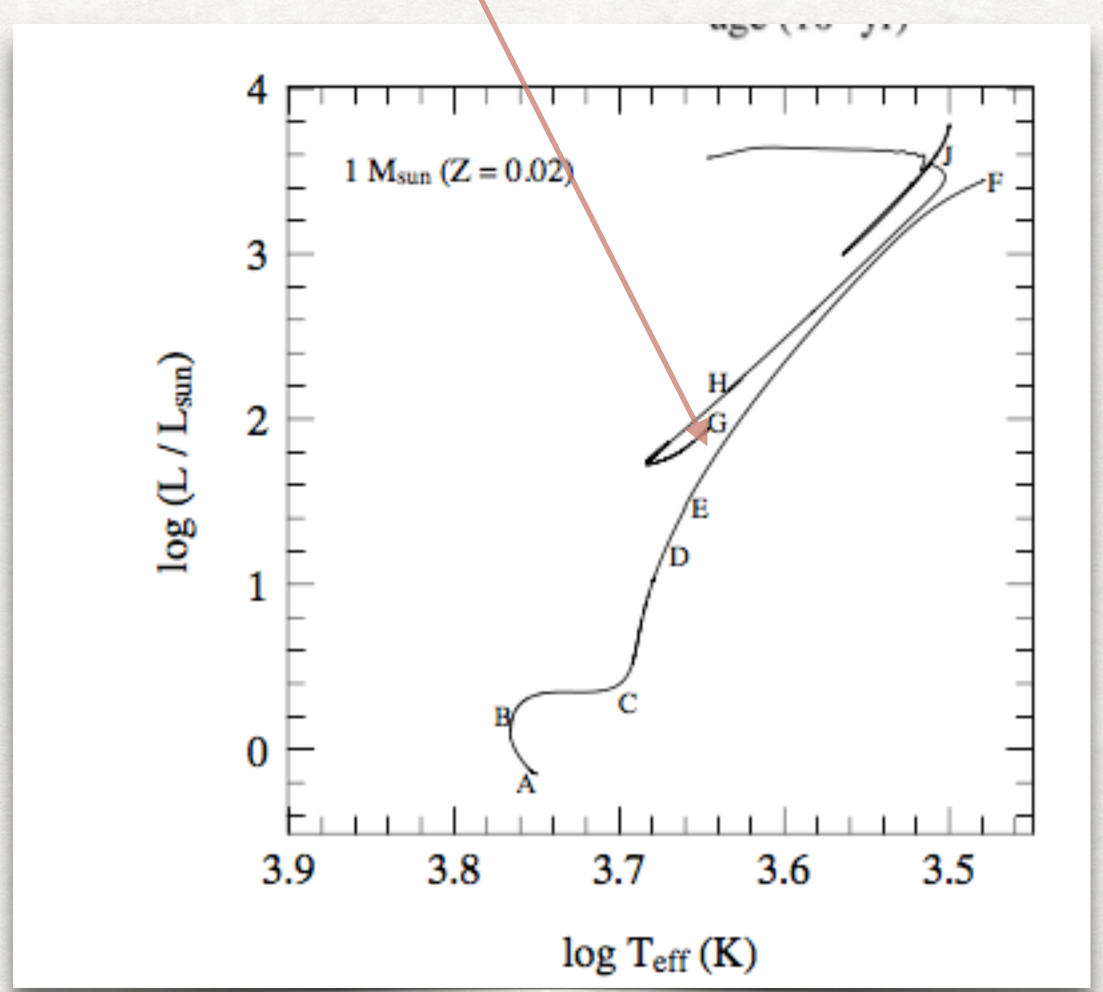




AFTER HE FLASH (F-G)

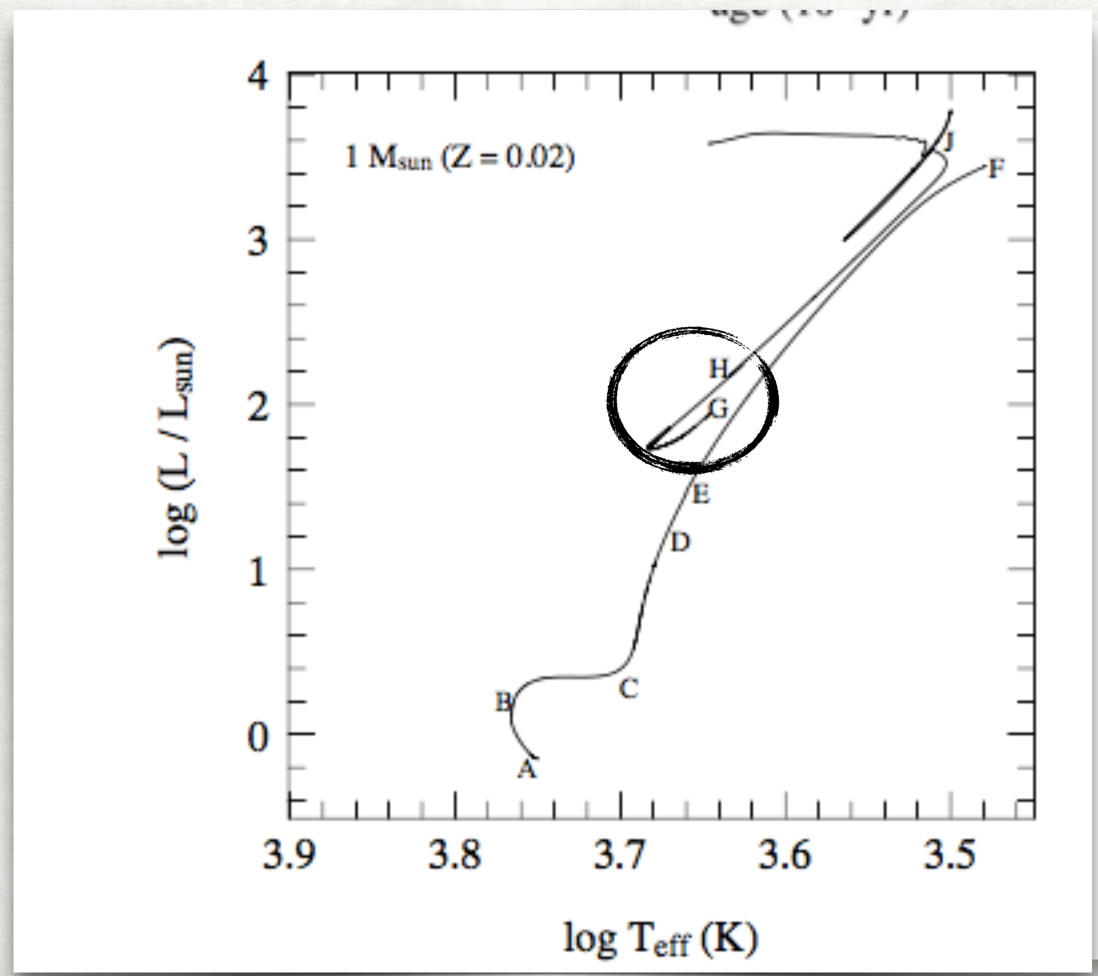
- The energy in flash has been used to expand the (non degenerate) core: $T_c \approx 10^8 K$ and $\rho_c \approx 2 \times 10^4 g/cm^{-3}$
- The core has expanded and envelope contracted=> L decreases

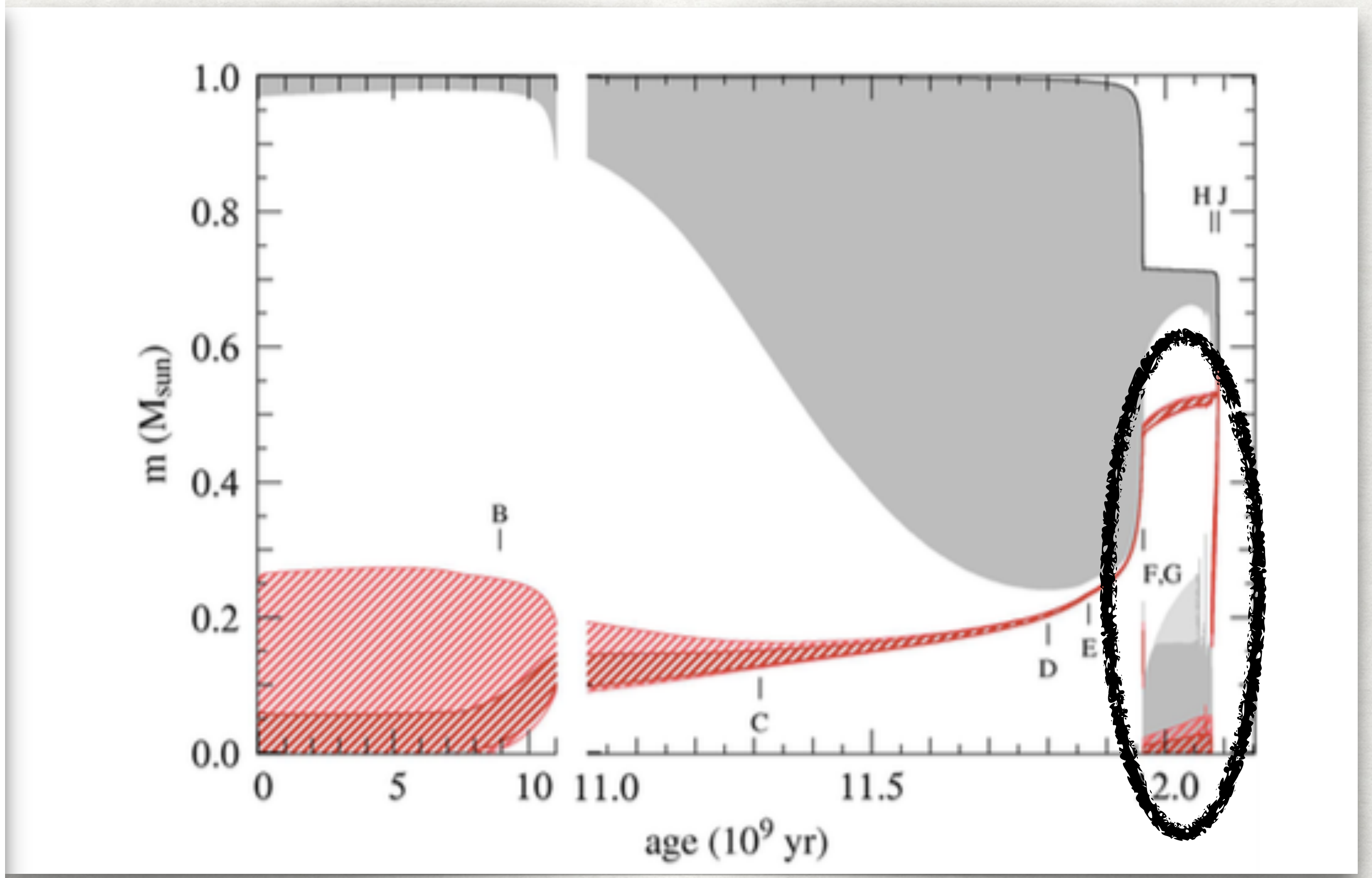




AFTER HE FLASH (G-H)

- H-burning in a shell
- He burns stable
- star does not move much in H-R





THE HORIZONTAL BRANCH (G-H)

- The luminosity in G depends on the core mass and all low mass stars have similar core mass
- The radius and effective temperature instead depends on envelope mass: small masses, hotter
- ==> formation of a sequence called horizontal branch
- it lasts 120 Myr