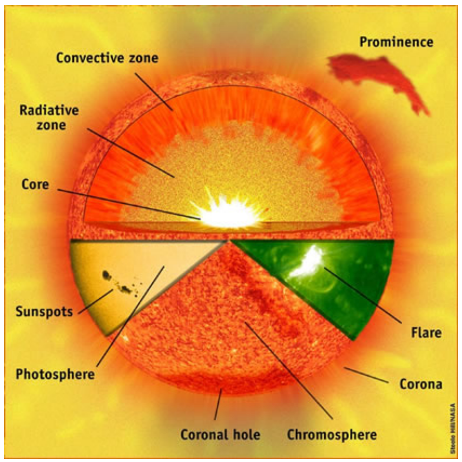
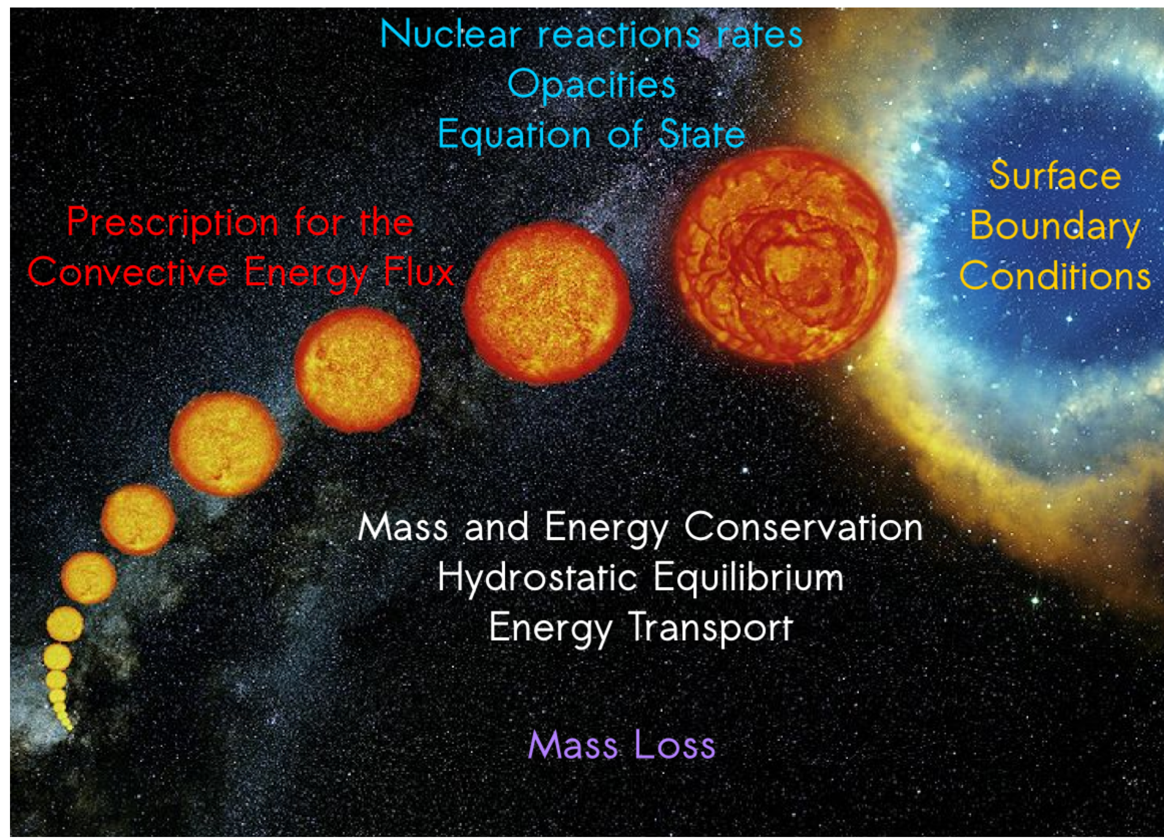
Basic Assumptions for Stellar Evolution Models

From the complex to the “simple” picture : spherical symmetry applied



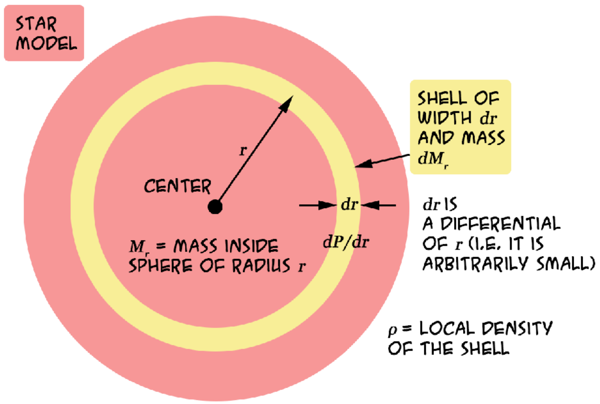
center — photosphere

$r = 0$ → $r = R_*$



Initial mass
and
chemical composition

Stellar structure and evolution equations



space coordinate

$$\frac{\partial}{\partial m} = \frac{\partial r}{\partial m}\frac{\partial}{\partial r}$$

time coordinate

$$\left.\frac{\partial}{\partial t}\right|_m = \left.\frac{\partial}{\partial t}\right|_r + \underbrace{\left.\frac{\partial r}{\partial t}\right|_m}_{v(r)} \frac{\partial}{\partial r} = \frac{D}{Dt}$$

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho}$$

$$\frac{\partial P}{\partial m} = -\frac{1}{4\pi r^2}\left(\frac{Dv}{Dt} + \frac{\partial \Phi}{\partial m}\right) = -\frac{1}{4\pi r^2}\left(\frac{Dv}{Dt} + \frac{Gm}{r^2}\right)$$

$$\frac{\partial L}{\partial m} = \epsilon_n - \epsilon_\nu - C_p \frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t} = \epsilon_n - \epsilon_\nu + \epsilon_g$$

$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P} \left.\frac{d\ln T}{d\ln P}\right|_{medium} = -\frac{GmT}{4\pi r^4 P}\nabla$$

$$\frac{\partial X_i}{\partial t} = \frac{m_i}{\rho}\left(\sum_j r_{ji} - \sum_k r_{ik}\right) \quad \forall i$$

Associated boundary conditions

$$@ \quad m = 0 \quad r(m=0,t) = 0 \quad L(m=0,t) = 0$$

$$@ \quad m = M_* \quad T(m=M_*,t) = T_{phot} \quad \rho(m=M_*,t) = \rho_{phot}$$

if the surface is in radiative equilibrium

$$m = M_* \quad T(m=M_*,t) \approx 0 \quad \rho(m=M_*,t) \approx 0$$

Characteristic timescales of stellar evolution

$$t_{dyn} \ll t_{therm} \ll t_{nuc}$$

→ rates of nuclear processes determine stellar evolution

→ can decouple equation for chemical composition from the others

1. Solve stellar structure equations for given composition

2. Apply time step and determine new composition

Solving stellar structure equations

- Four differential equations with boundary conditions at
  - * center of star ($m = 0$): $r = 0$, $L = 0$
  - * surface of star ($m = M$): fit interior solution to a stellar atmosphere model

- Three "material functions" (for $\boldsymbol{\rho}$, $\boldsymbol{\kappa}$, q)

- Input parameters:

mass M, chemical composition X(t), Y(t), Z(t)

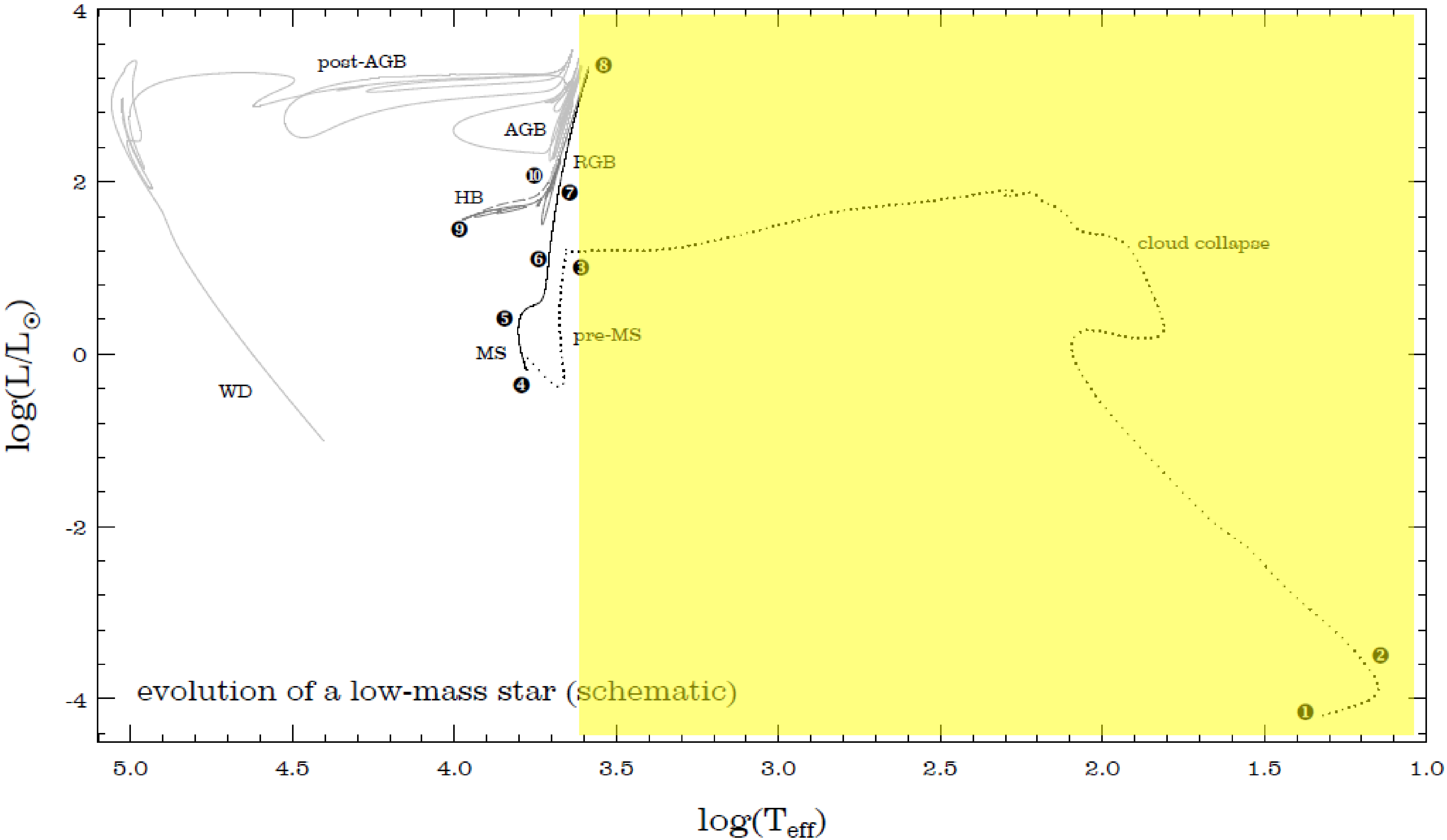
- Output: r(m), P(m), L(m),T(m), $\boldsymbol{\rho}$(m), $\boldsymbol{\kappa}$(m), q(m), for each time t,

in particular Teff, L, R, $\boldsymbol{\rho}_c$, P_c

- Equations are highly non-linear and coupled → have to be solved

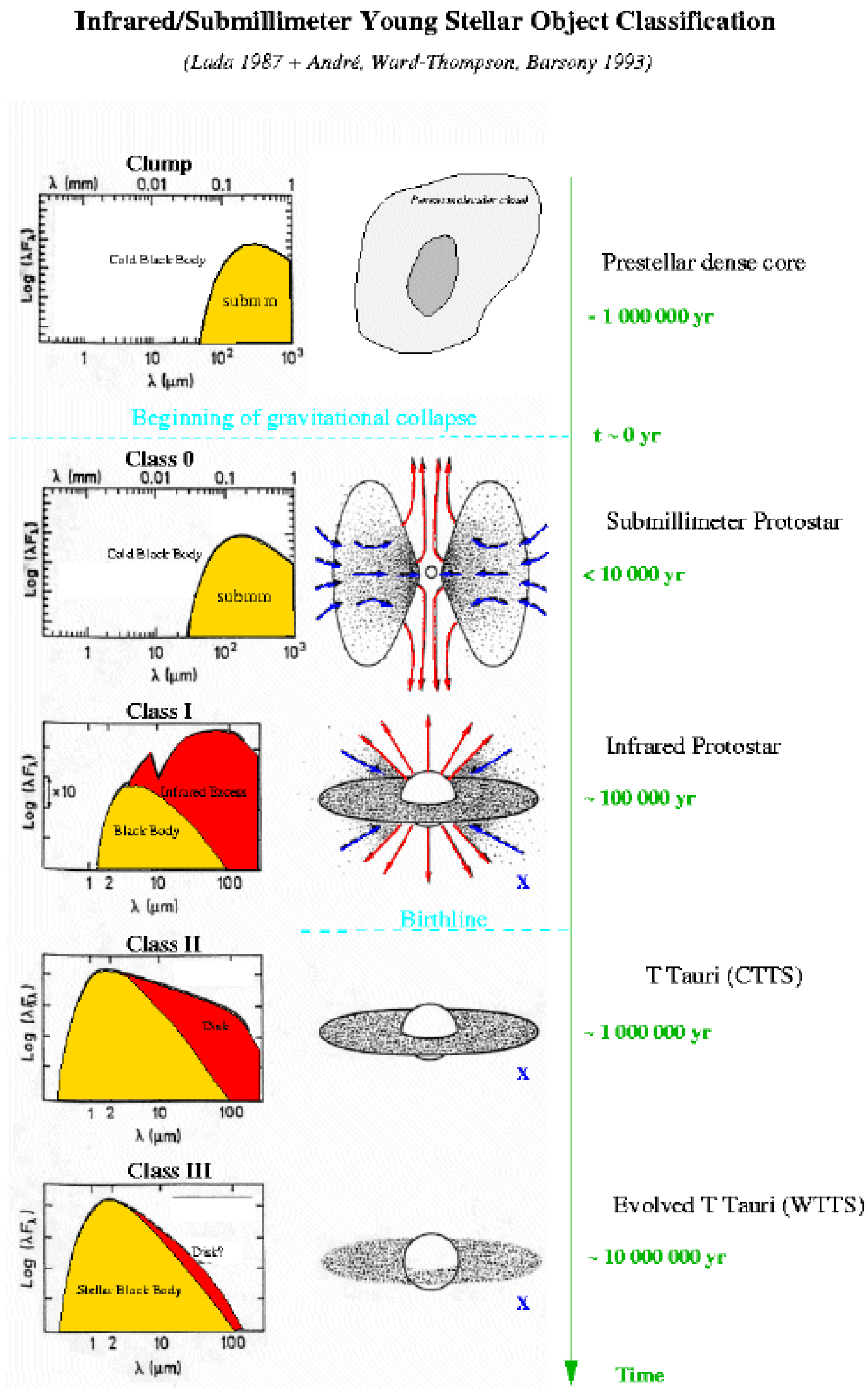
with numerical methods

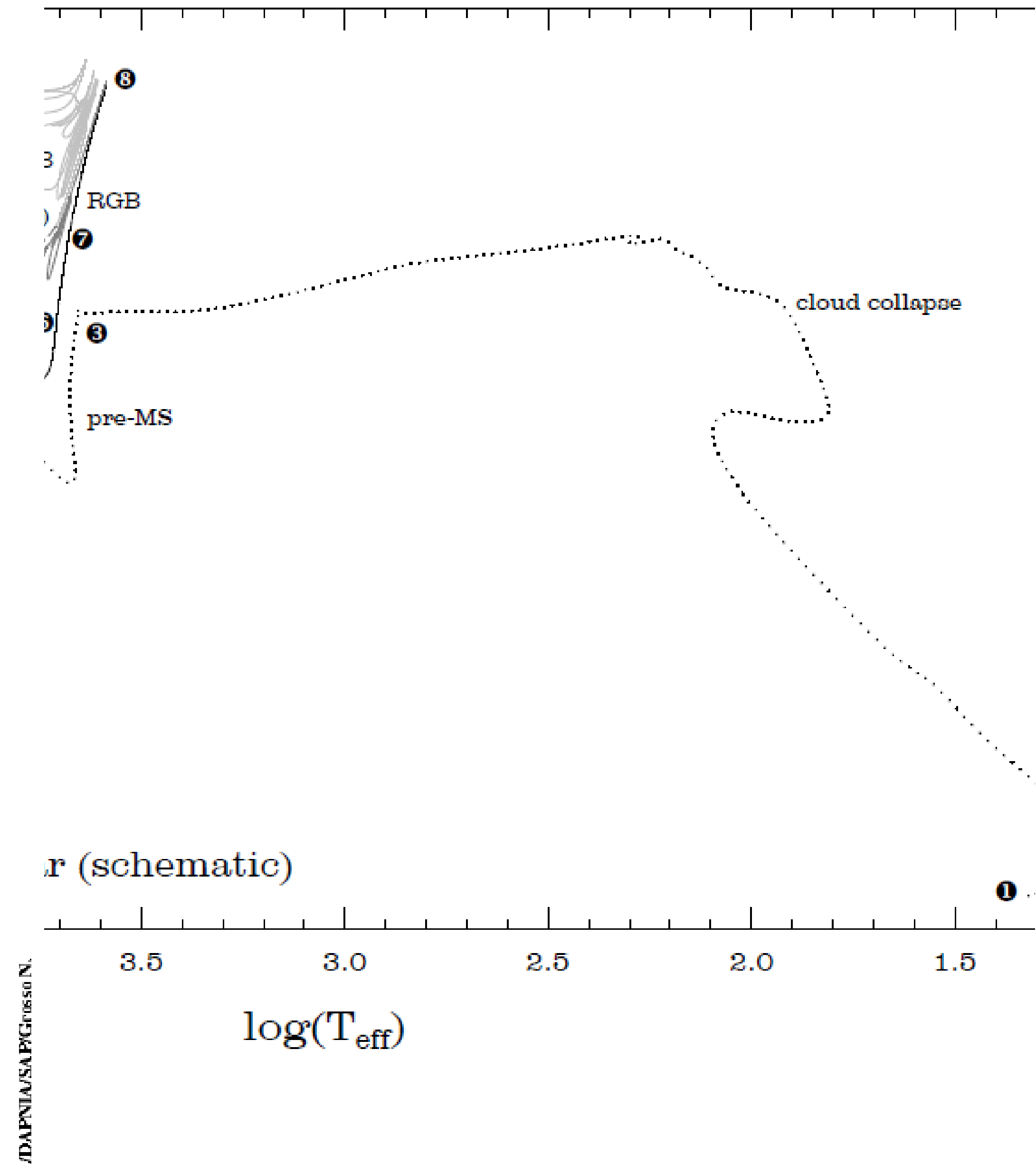
Pre-stellar evolution



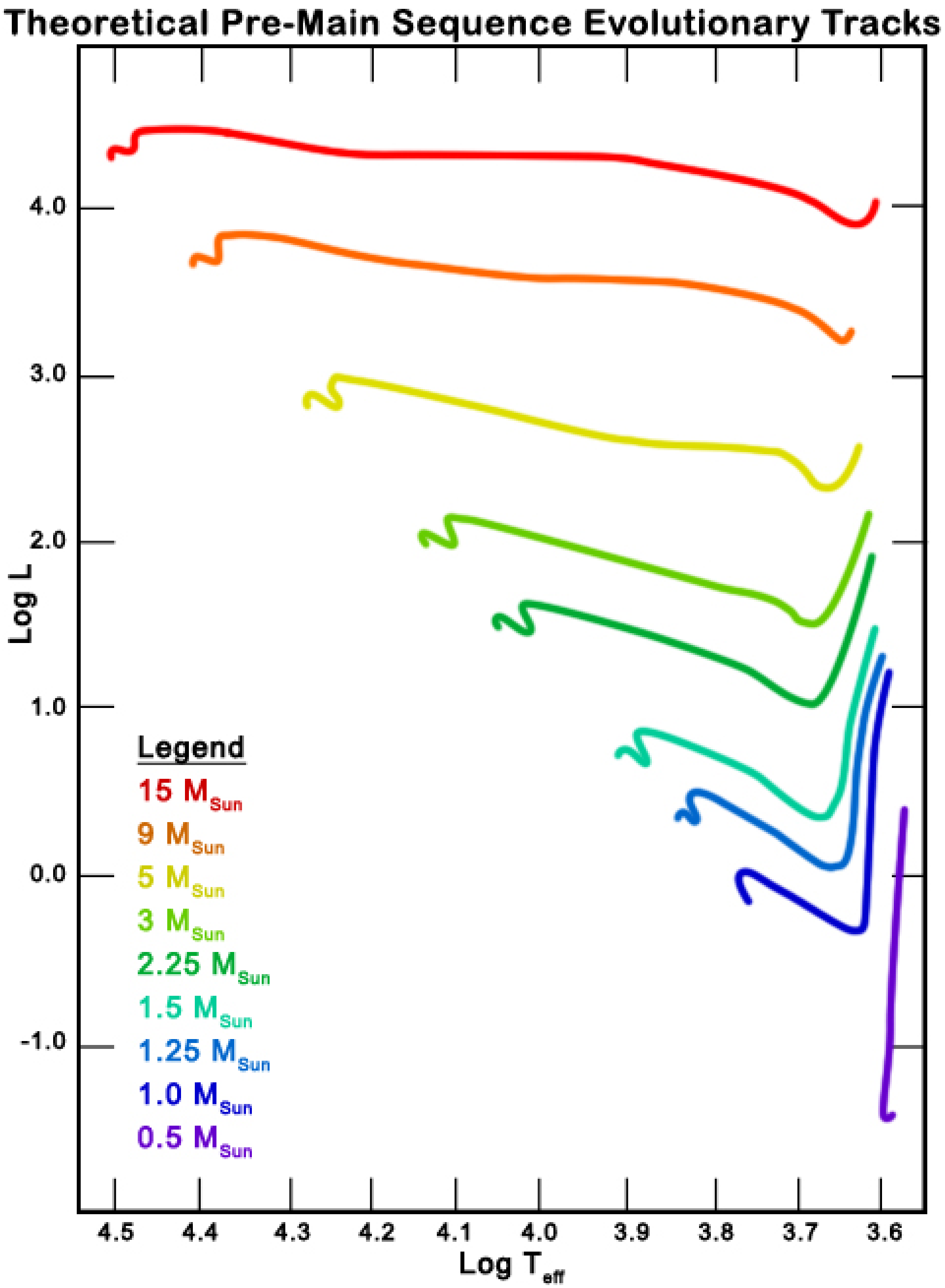
Catelan et al. 2007

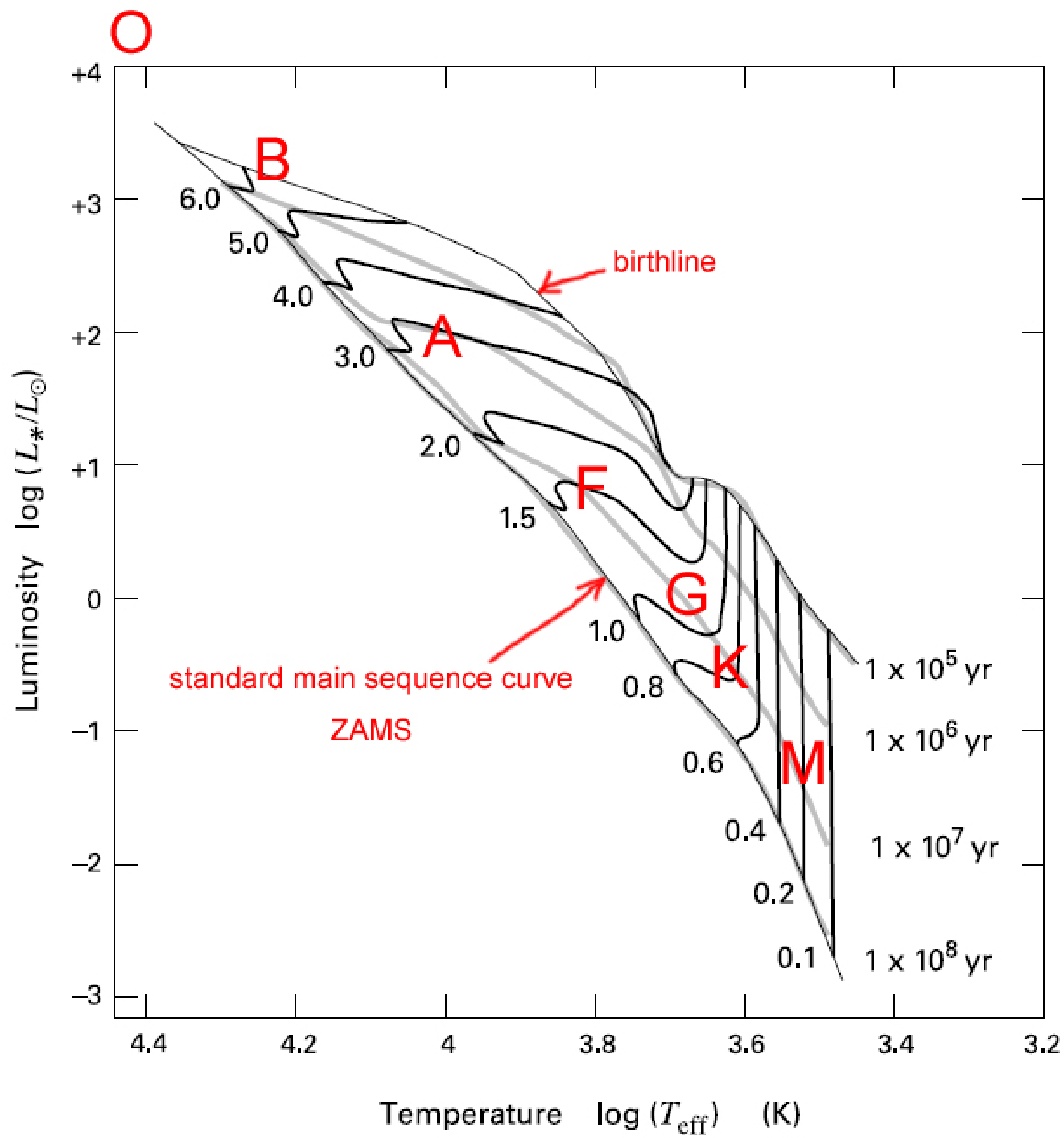
Early evolution



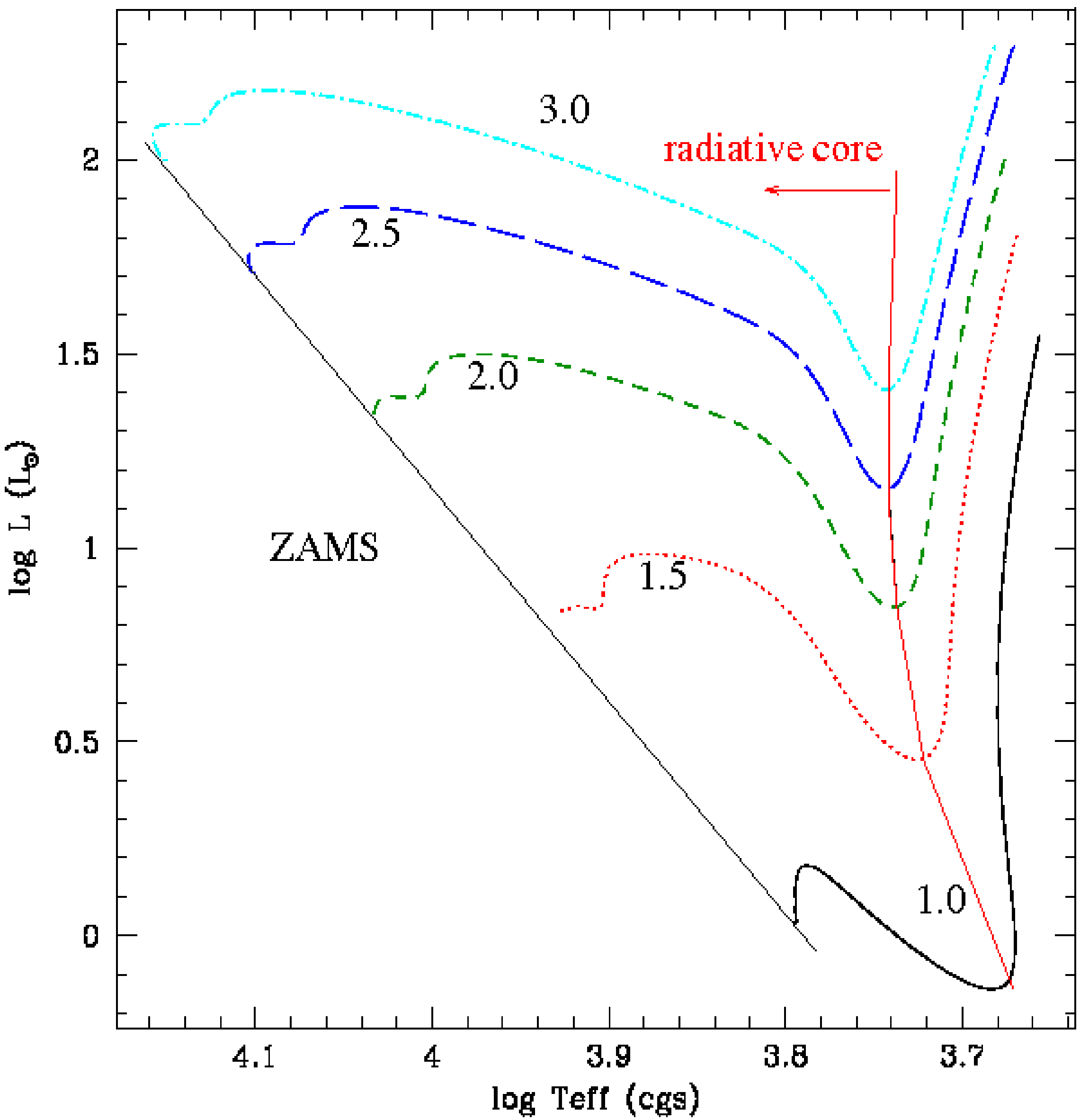


Pre-main sequence evolution





Pre-main sequence evolution



Stars contract and for the low-mass ones, they do it along the *Hayashi track* → Kelvin-Helmoltz timescale

D burning

P and density increase in core → increased T in core → increased ionisation → decreased opacity → radiative core appears

Li burning

→ now move to Henyey track

→ increased core temperature : partial CNO burning → small convective core in solar-type stars until 12C exhaustion

→ ppl chains take over

Zero Age Main Sequence (ZAMS)

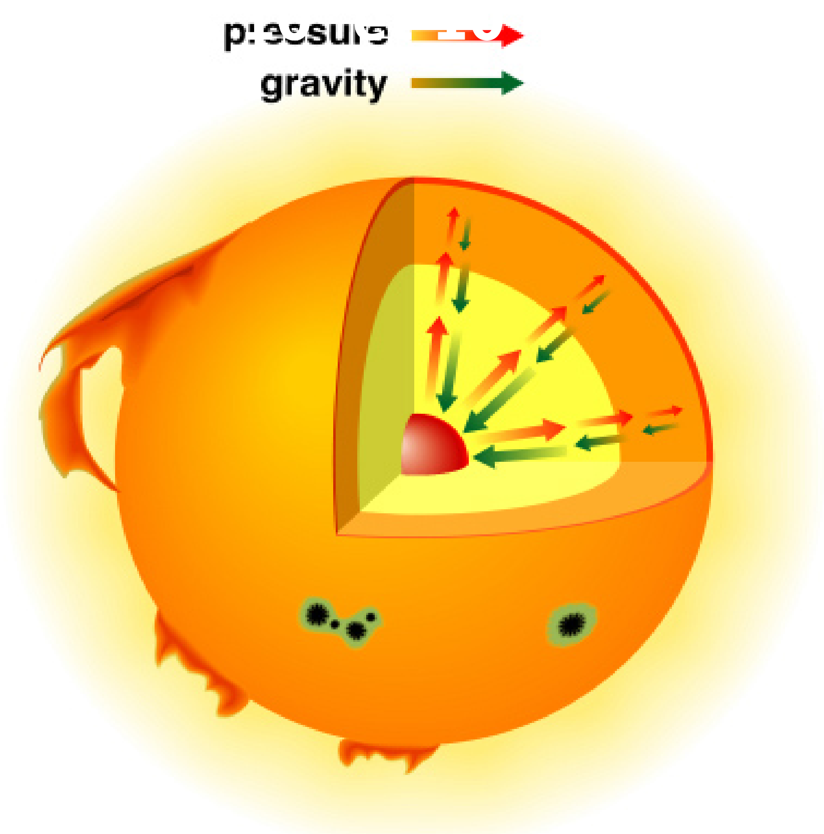
Main sequence evolution

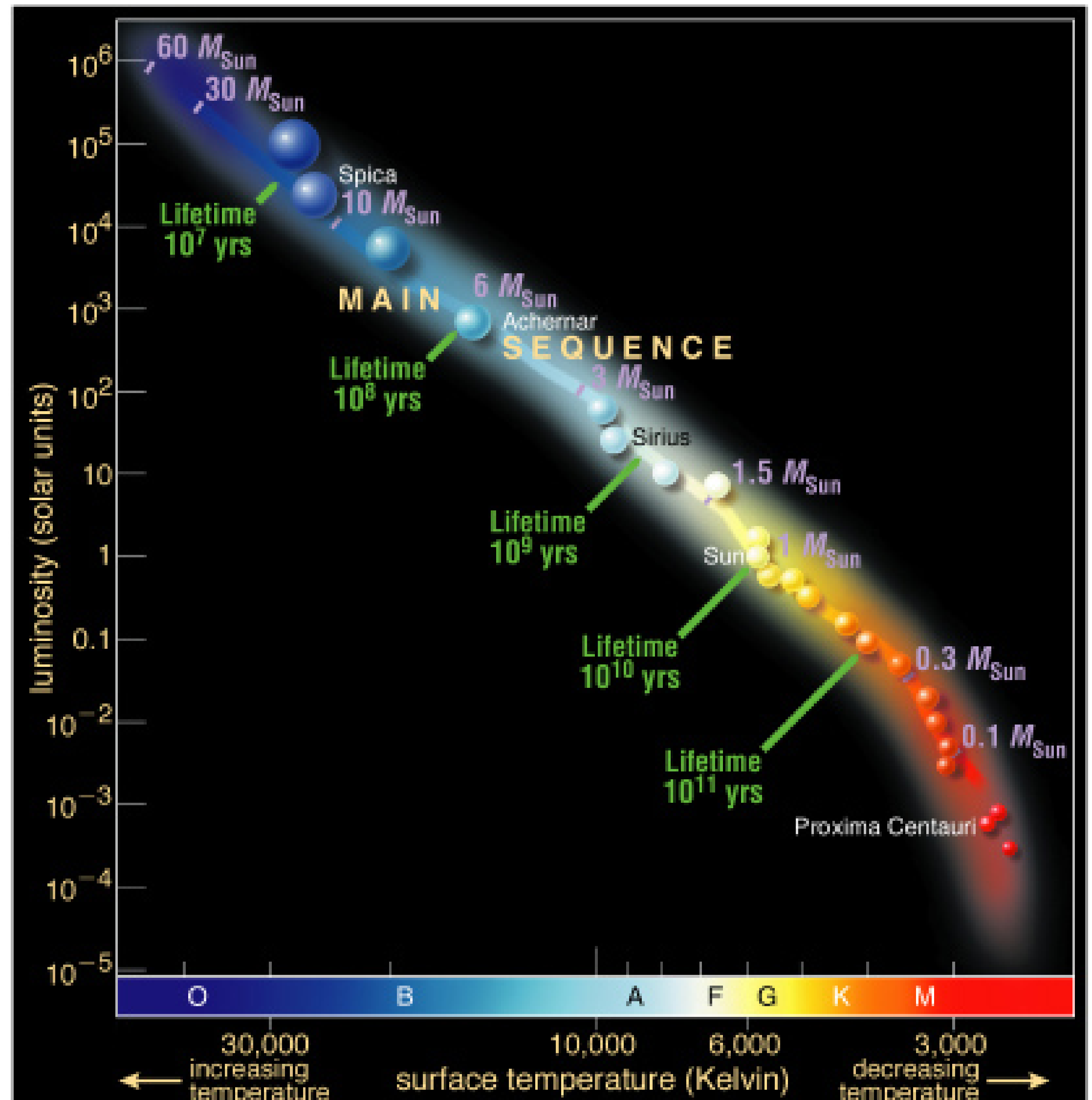
Core H fusion

hydrostatic equilibrium

Duration of main sequence

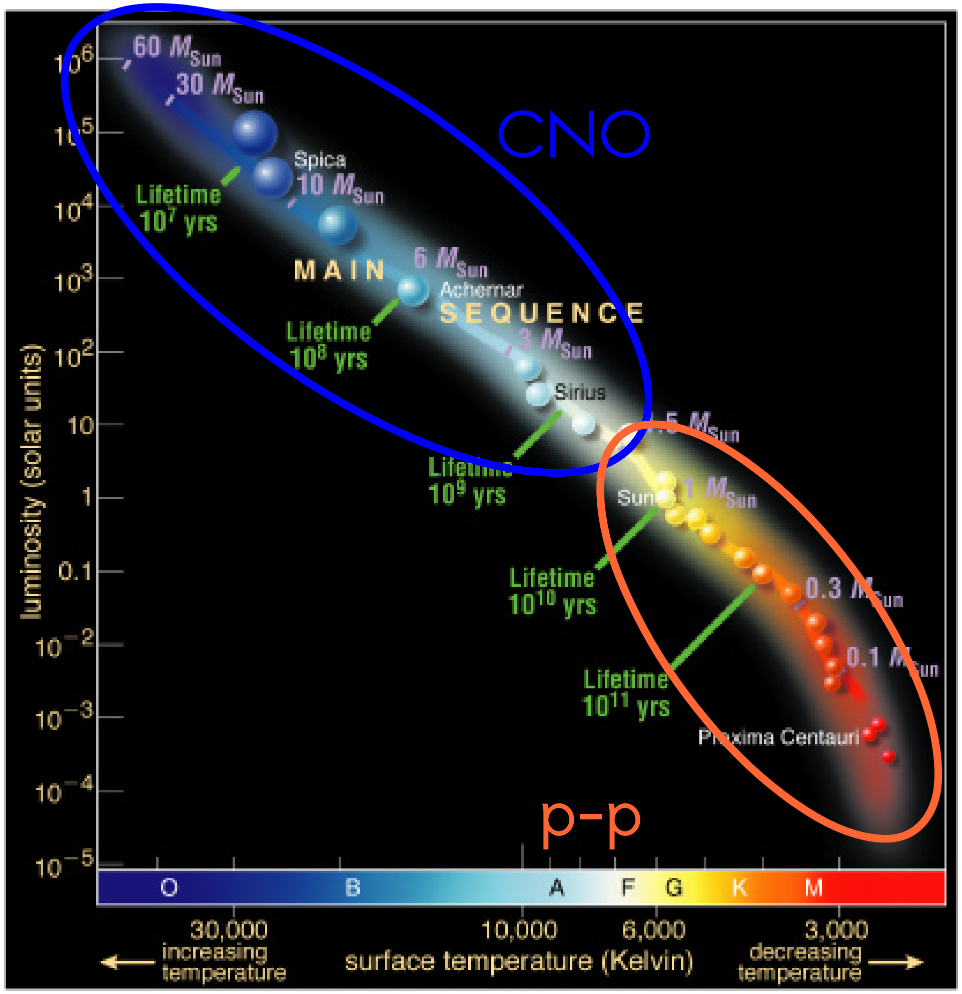
depends on T_c and ρ_c



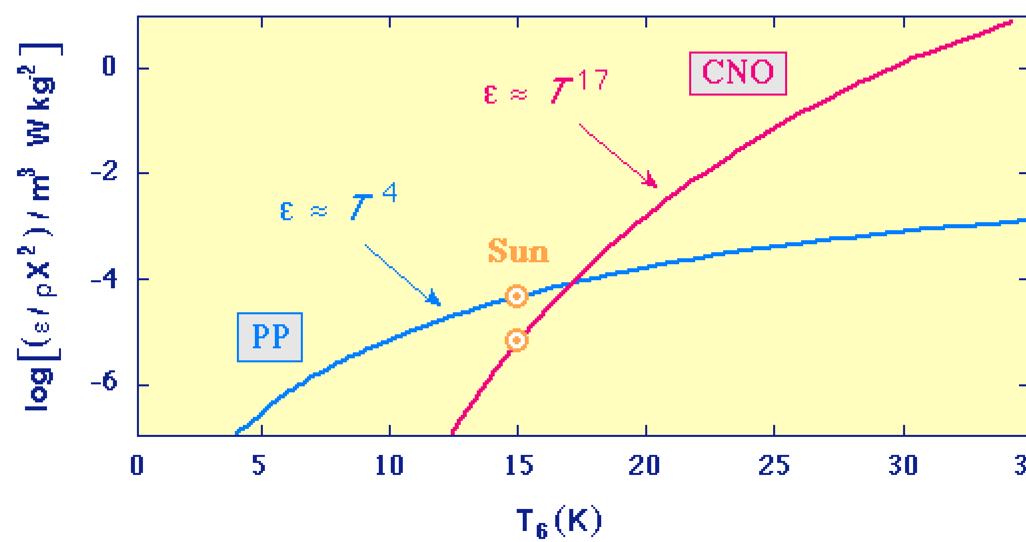


Hydrogen burning

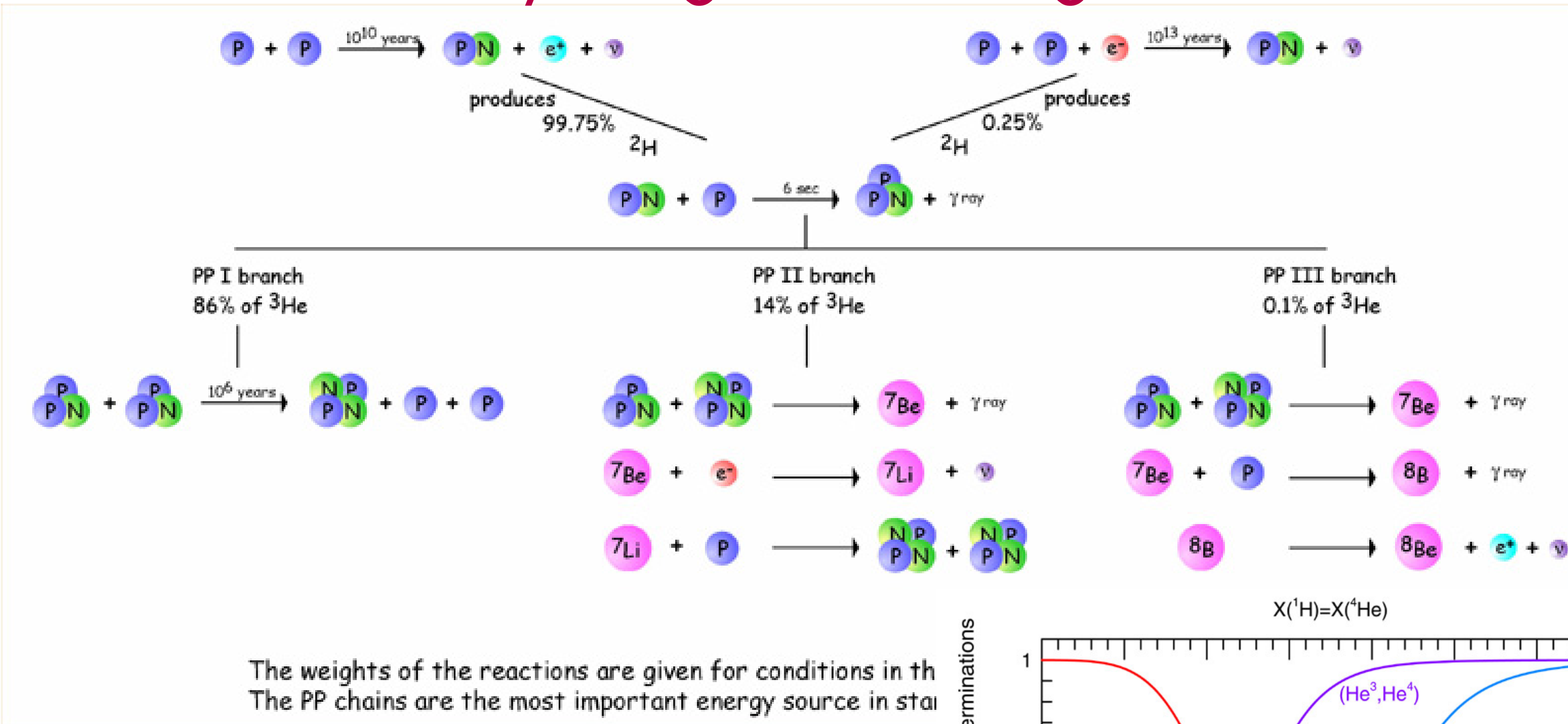
Core hydrogen burning occurs in main sequence stars via different reaction chains depending on the core temperature

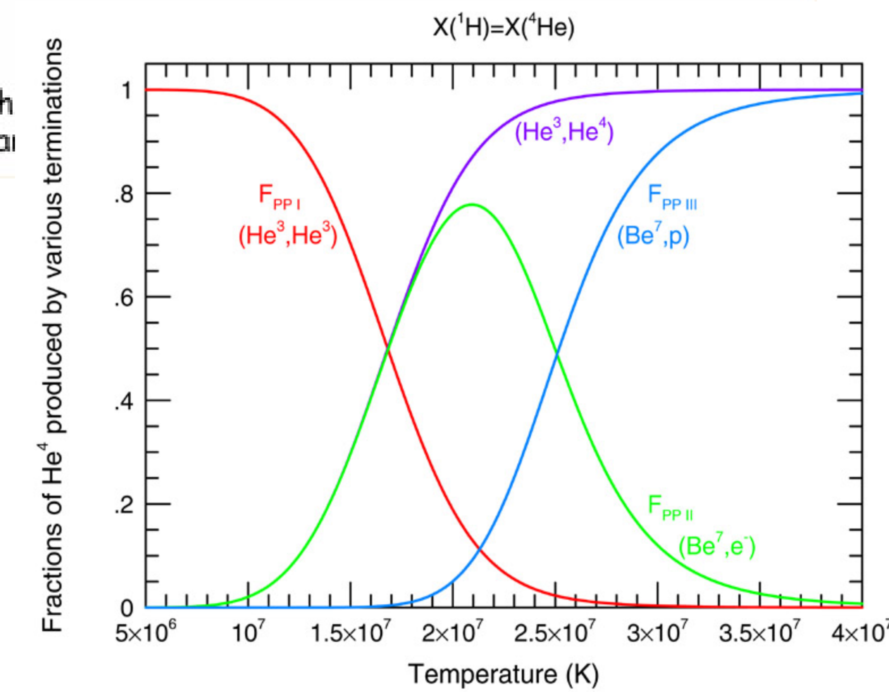


For a typical ratio $X_{CN}/X_H = 0.02$



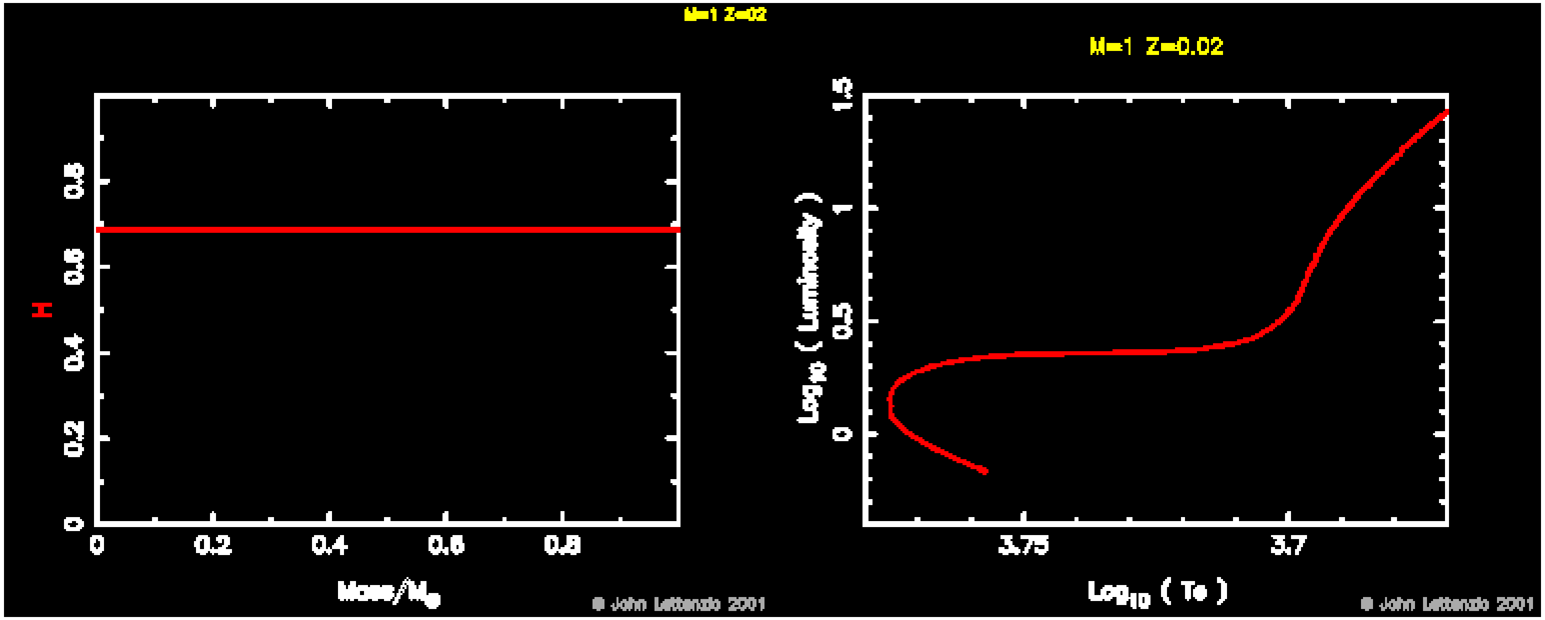
Hydrogen burning

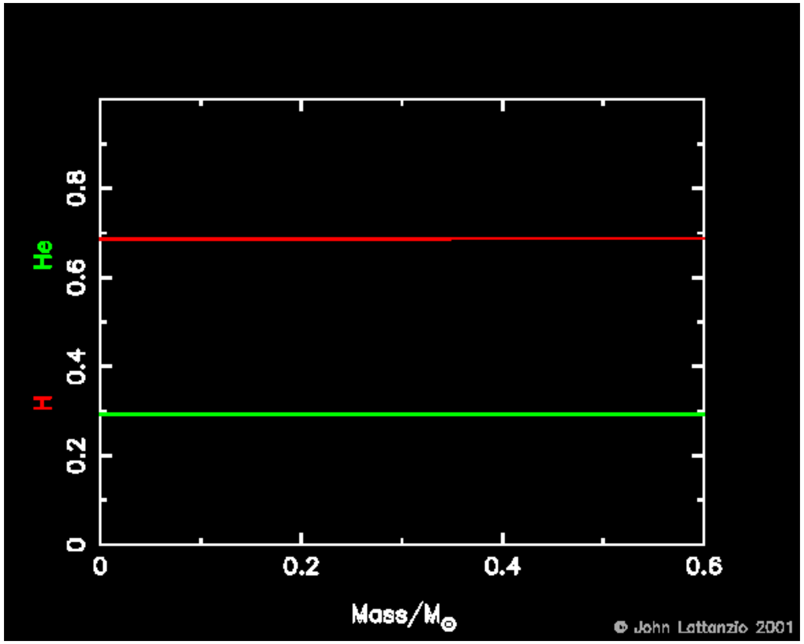




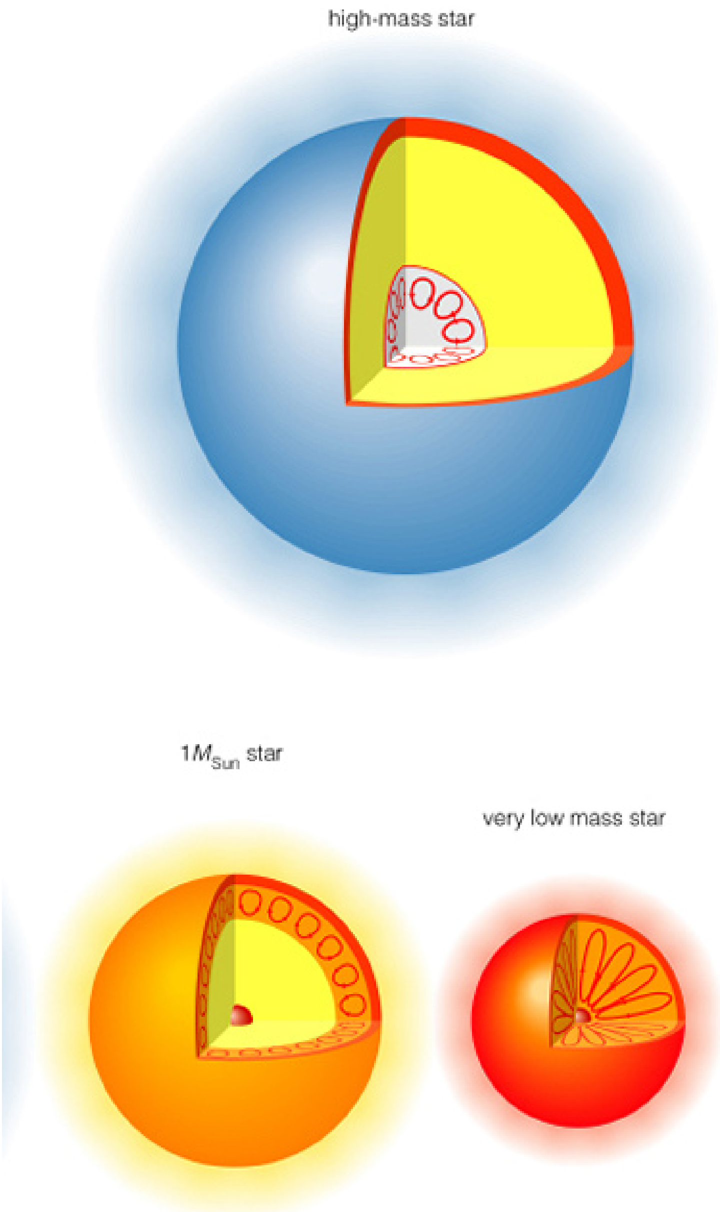
Low mass stars ($T_c \leq 17\ 10^6$ K)

Main sequence evolution of a 1Msun star





Main Sequence



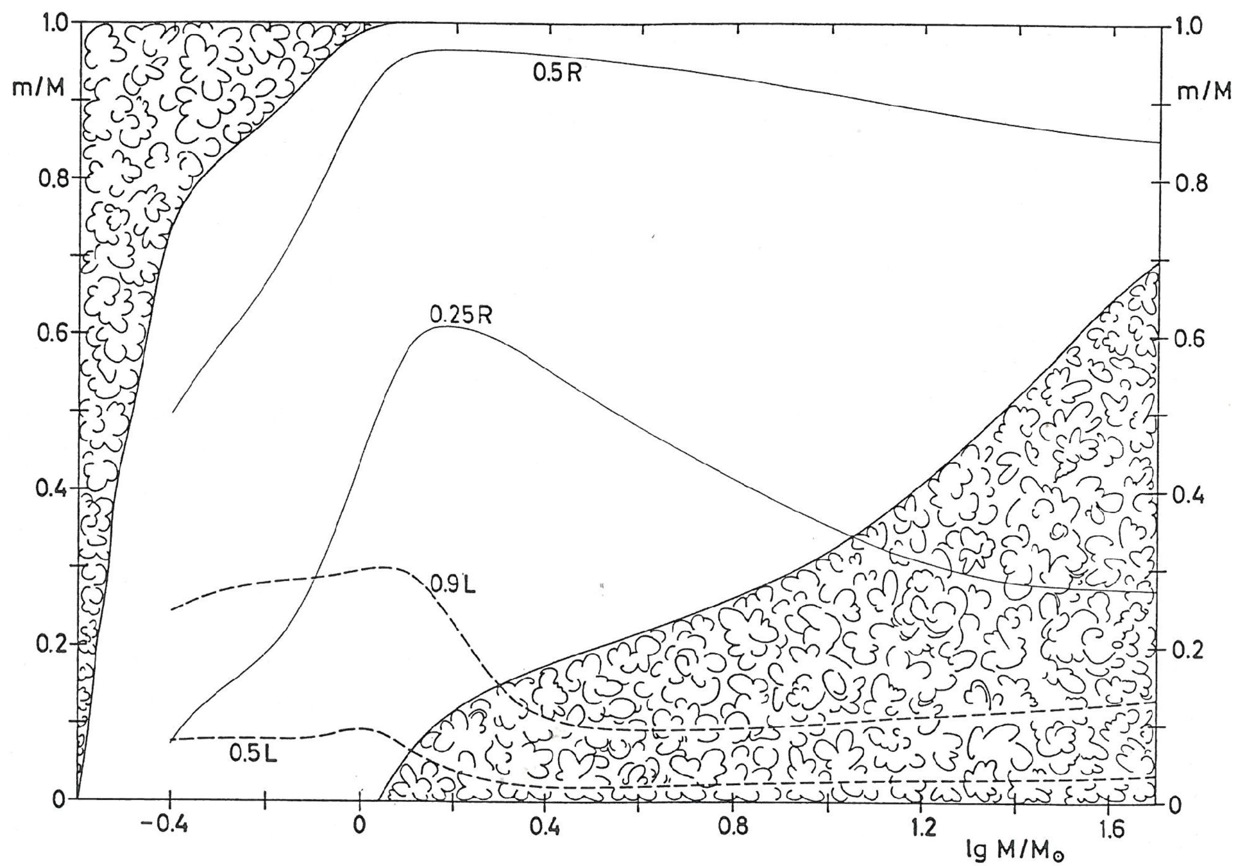


Fig. 22.7. The mass values m from centre to surface are plotted against the stellar mass M for the same zero-age main-sequence models as in Fig. 22.1. "Cloudy" areas indicate the extension of convective zones inside the models. Two solid lines give the m values at which r is 1/4 and 1/2 of the total radius R. The dashed lines show the mass elements inside which 50% and 90% of the total luminosity L are produced

Kippenhahn & Weigert, Stellar Structure and Evolution, Spri

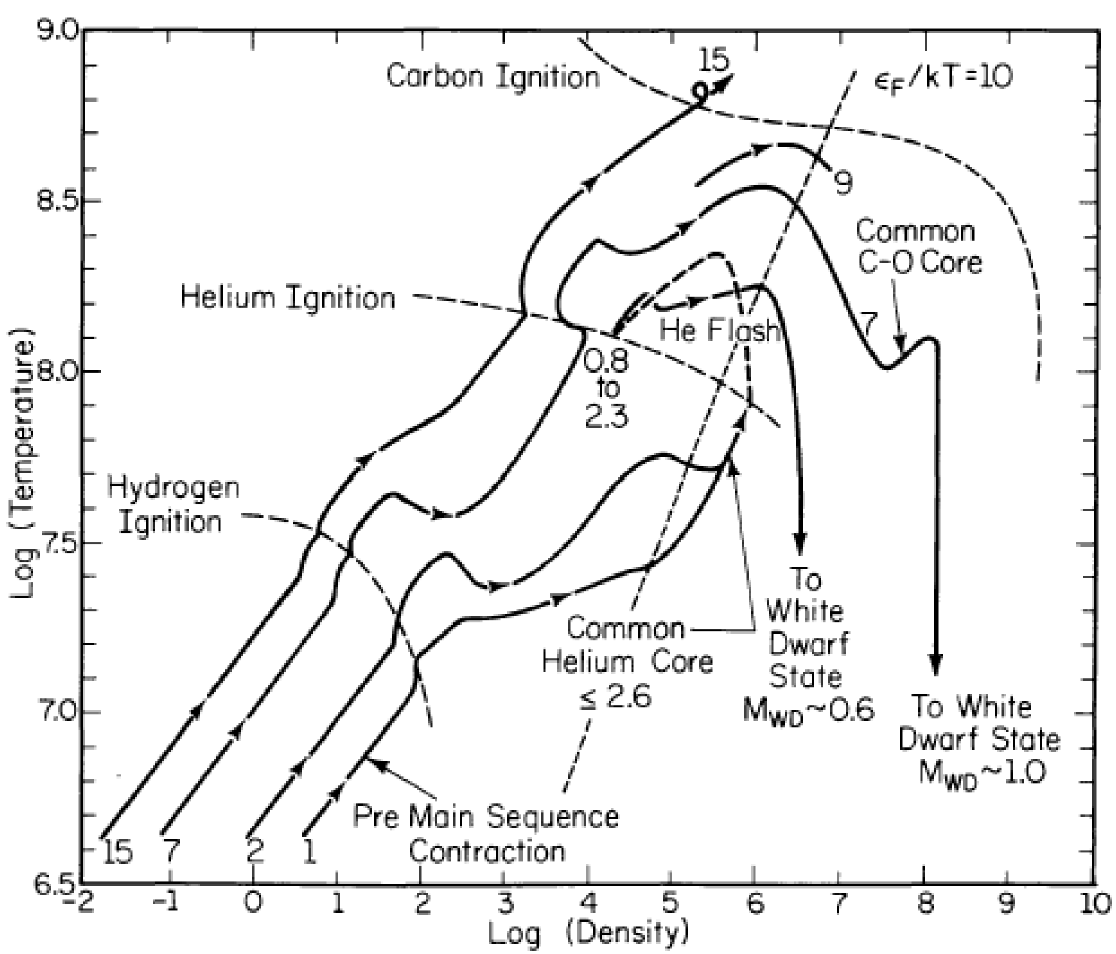
Main Sequence

Main sequence stars are supposed reflect the chemical composition of the ISM they were born out of.

Light elements (Li, Be, B) can be partially destroyed during the PMS and appear depleted on the main sequence

No abundance variation of heavy elements is expected at the stellar surface during this phase compared with the initial content

Post Main Sequence evolution



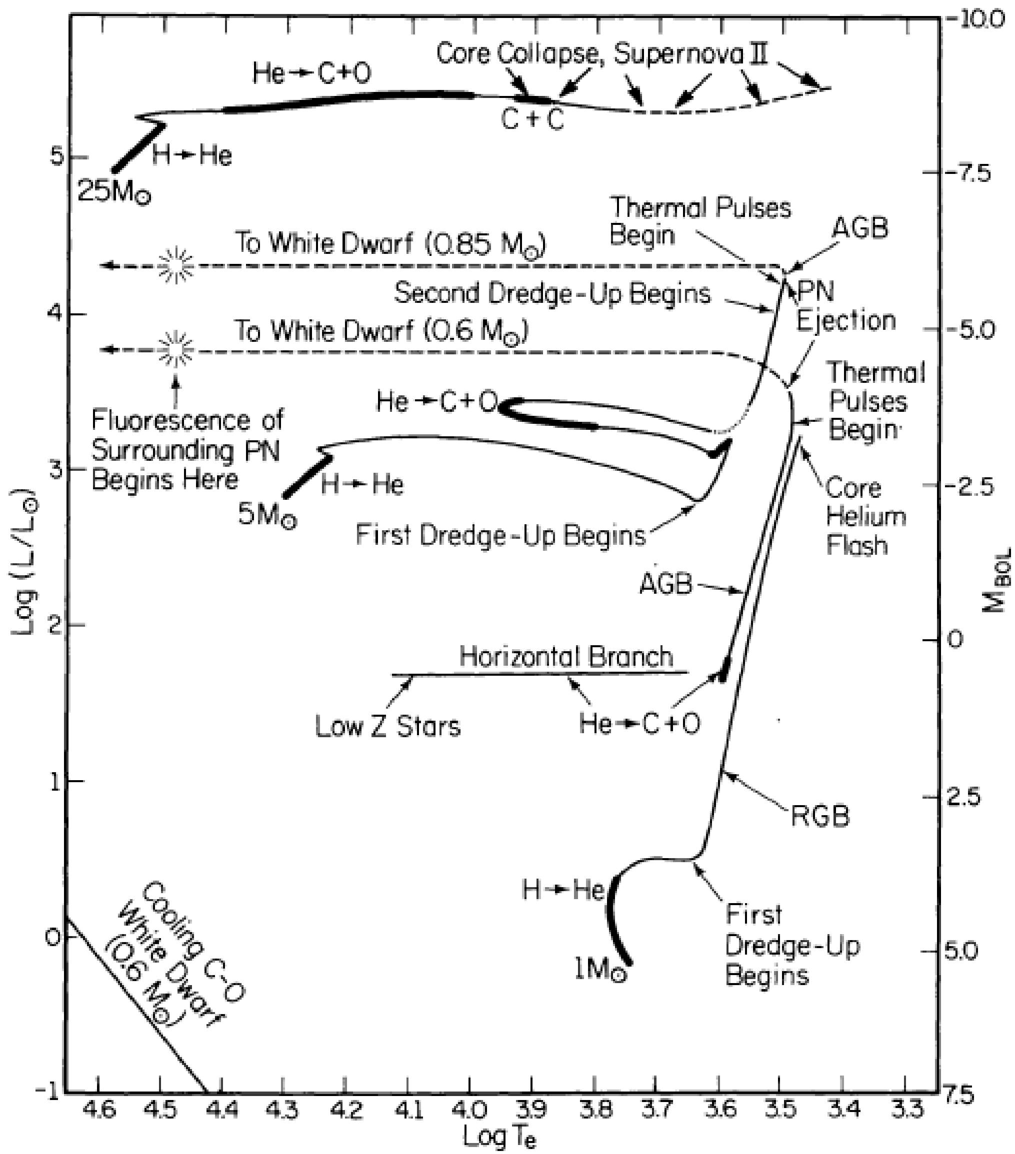
Iben, 1991, ApJSS 76, 55

Evolution (beyond the MS) is mainly dictated by the evolution of T and density in the core, which determine the nuclear energy production.

The path in the HR diagram will also be influenced by modifications of the opacity in the external layers.

Stars of different masses will have different evolutions.

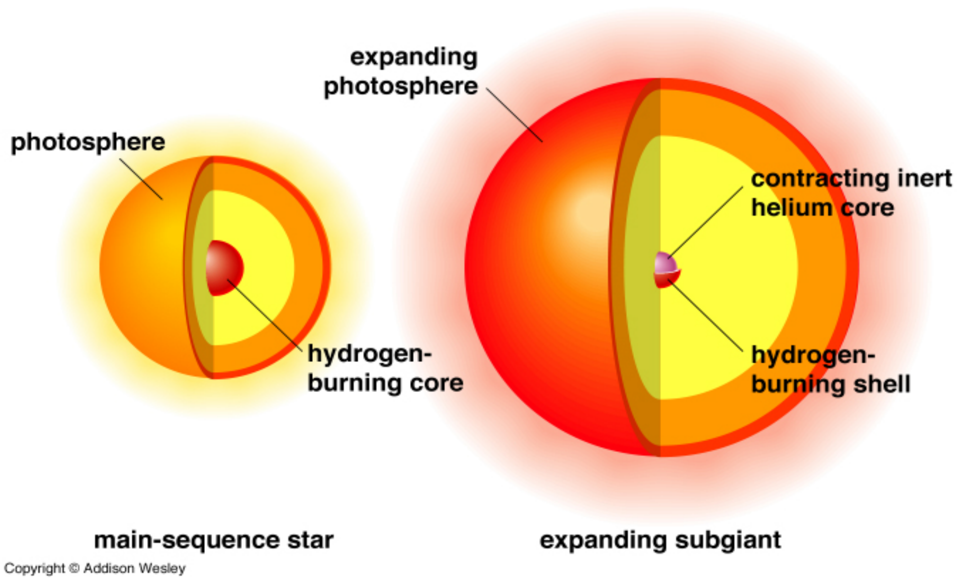
Post Main Sequence evolution



Iben, 1991, ApJSS 76, 55

Succession of phases of hydrostatic equilibrium and non-equilibrium phases (contraction/expansion) during which the star temperature decreases (for low and intermediate mass stars).

Post-Main sequence evolution of low-mass stars



Increase of potential gravitational energy in the stellar centre at central H exhaustion → core contraction

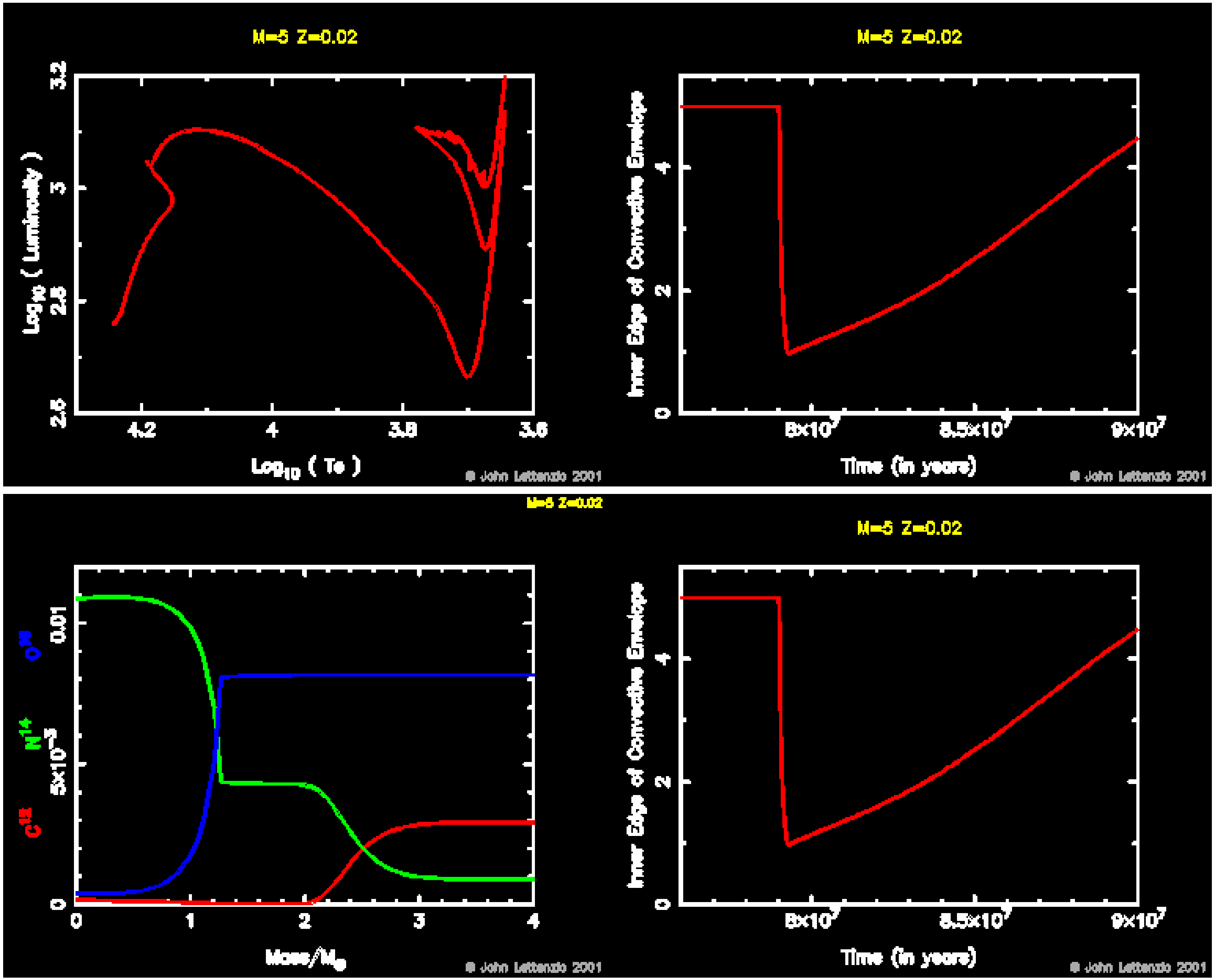
Temperature continuity → T increases in regions surrounding the core → HBS

T increases in central regions → expansion of envelope to maintain the temperature gradient →

the star moves to the right in the HR diagram

Cooling associated with radius increase → increased opacity in external layers → deepening of the convective envelope → first dredge-up

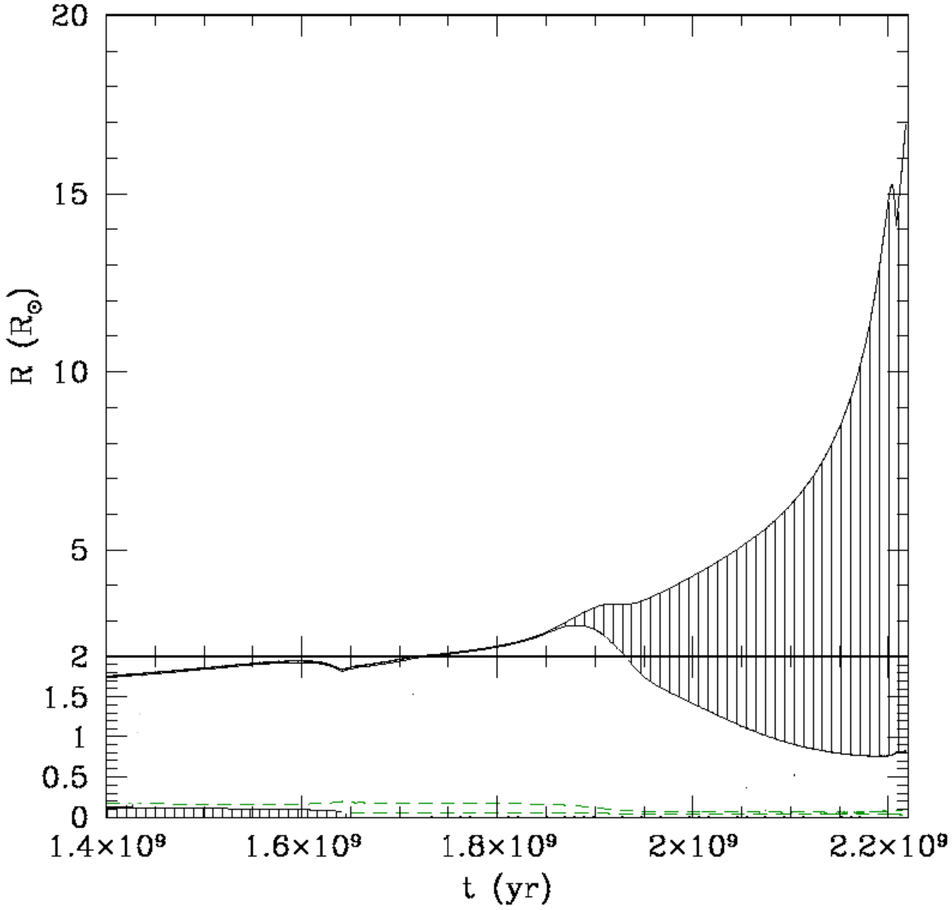
First dredge-up

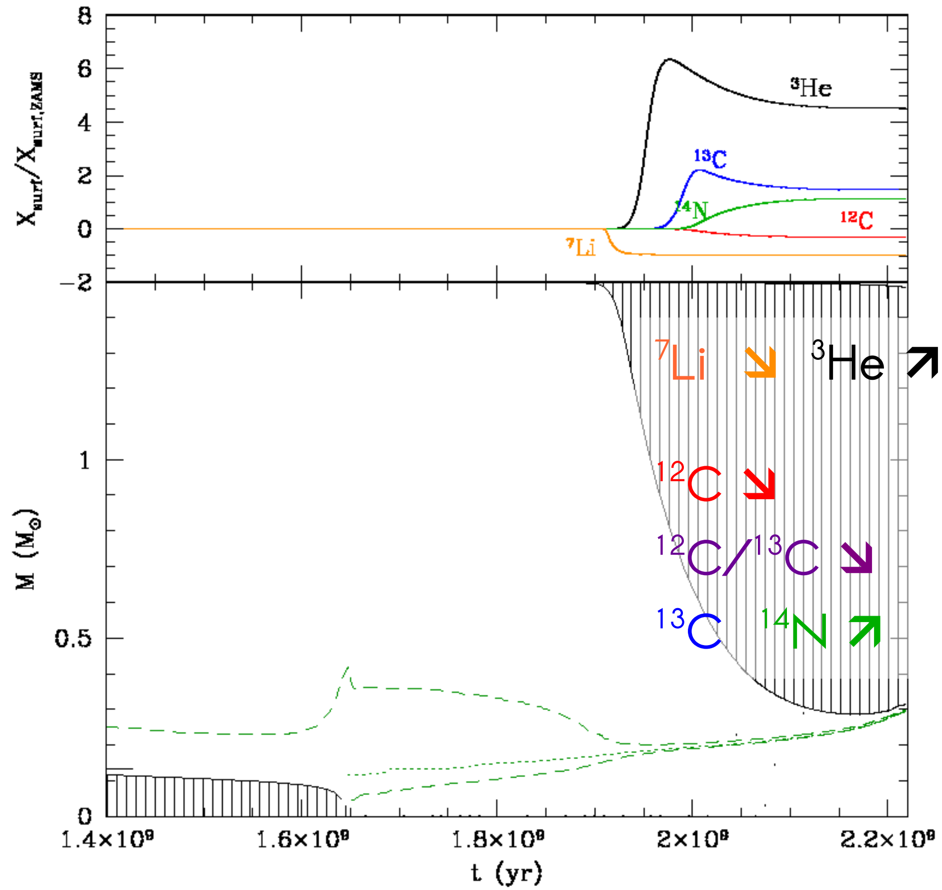


First dredge-up

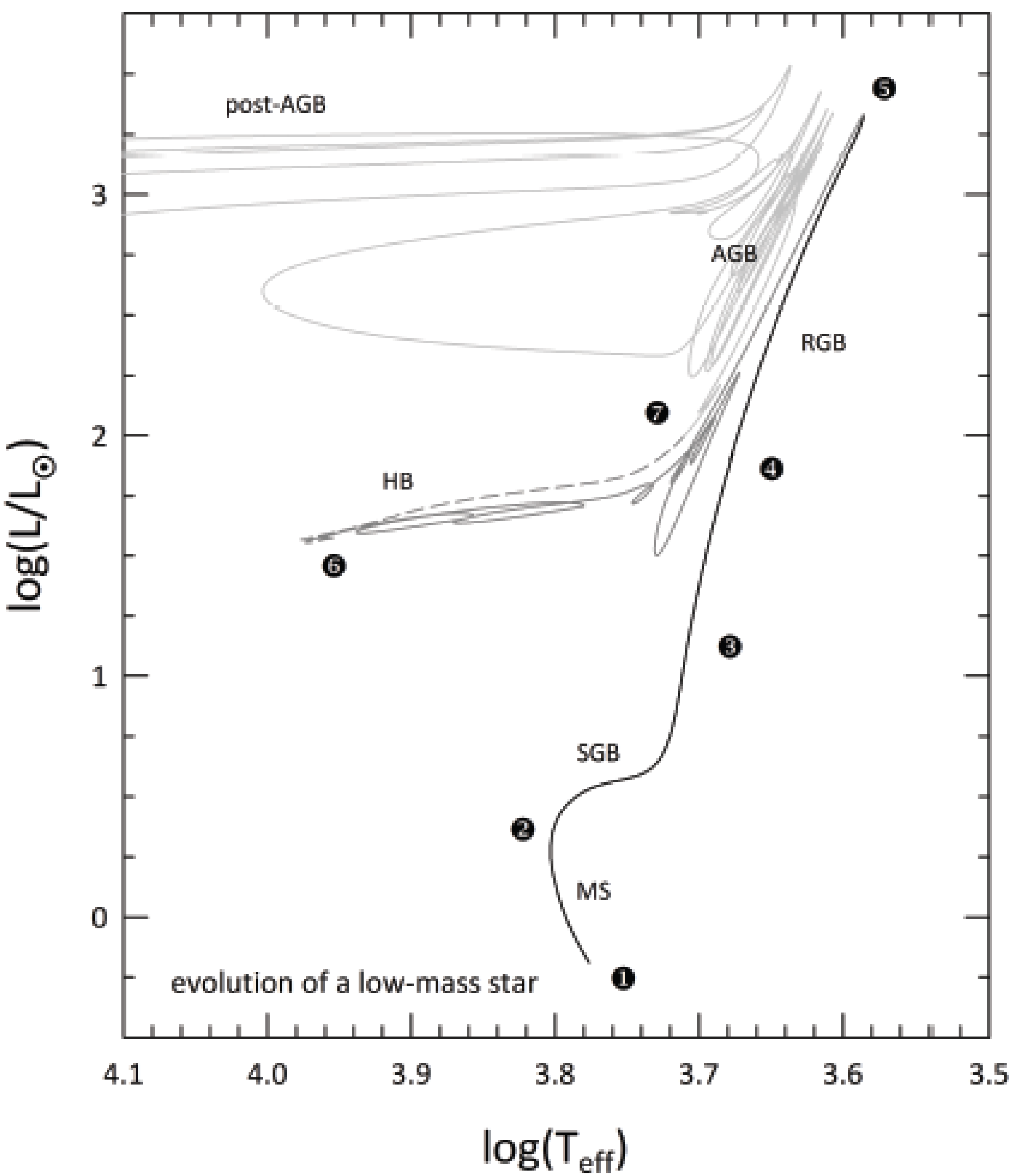
Deepening of the convective envelope in mass reaching regions that have been processed through nuclear reactions →

Stellar surface abundances modification





Post-Main sequence evolution of low-mass stars



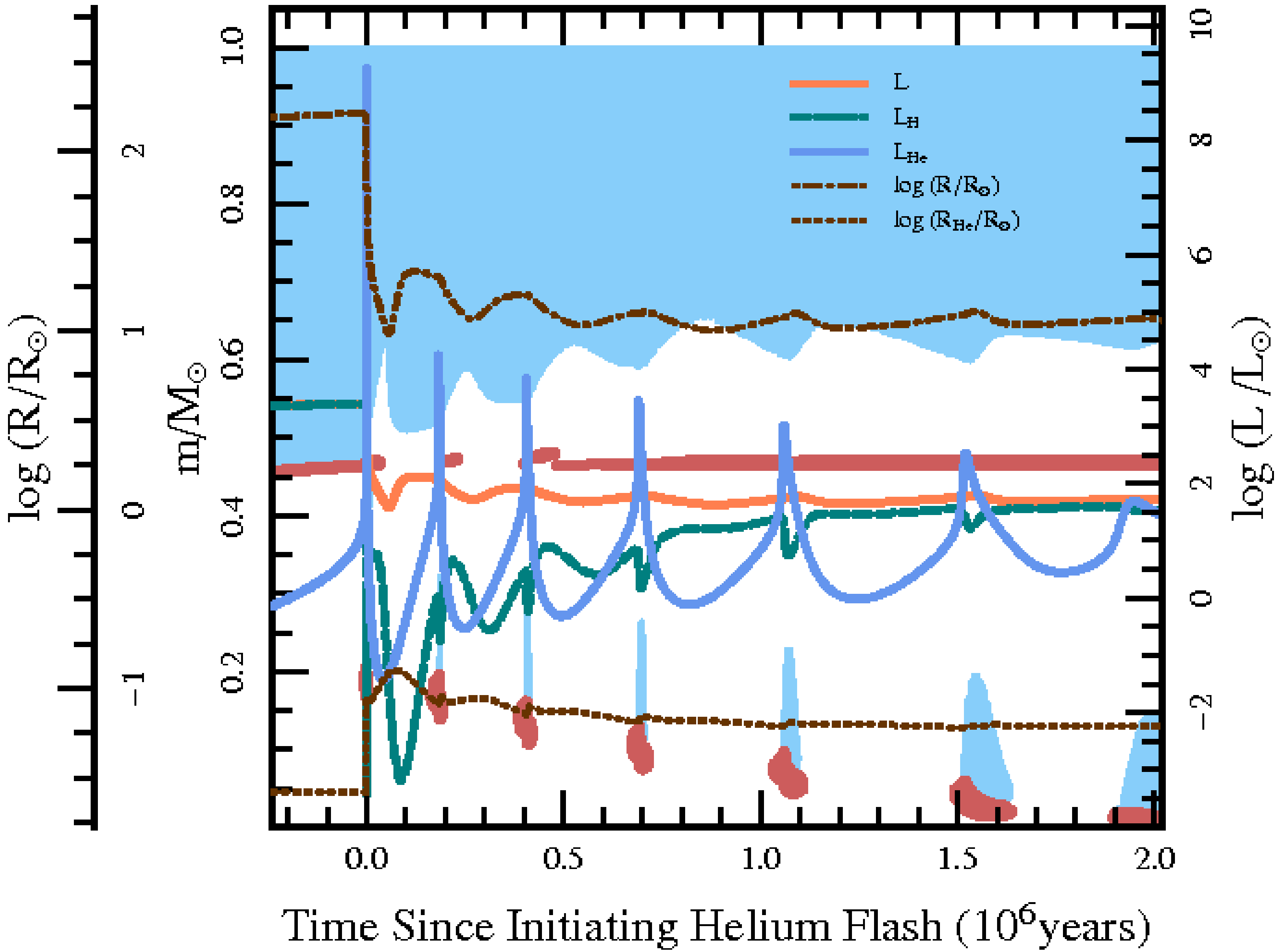
RGB stars ahve a partially degenerated core → evolves independantly of temperature variations.

Core mass increases in core regions as the stars ascends the RGB

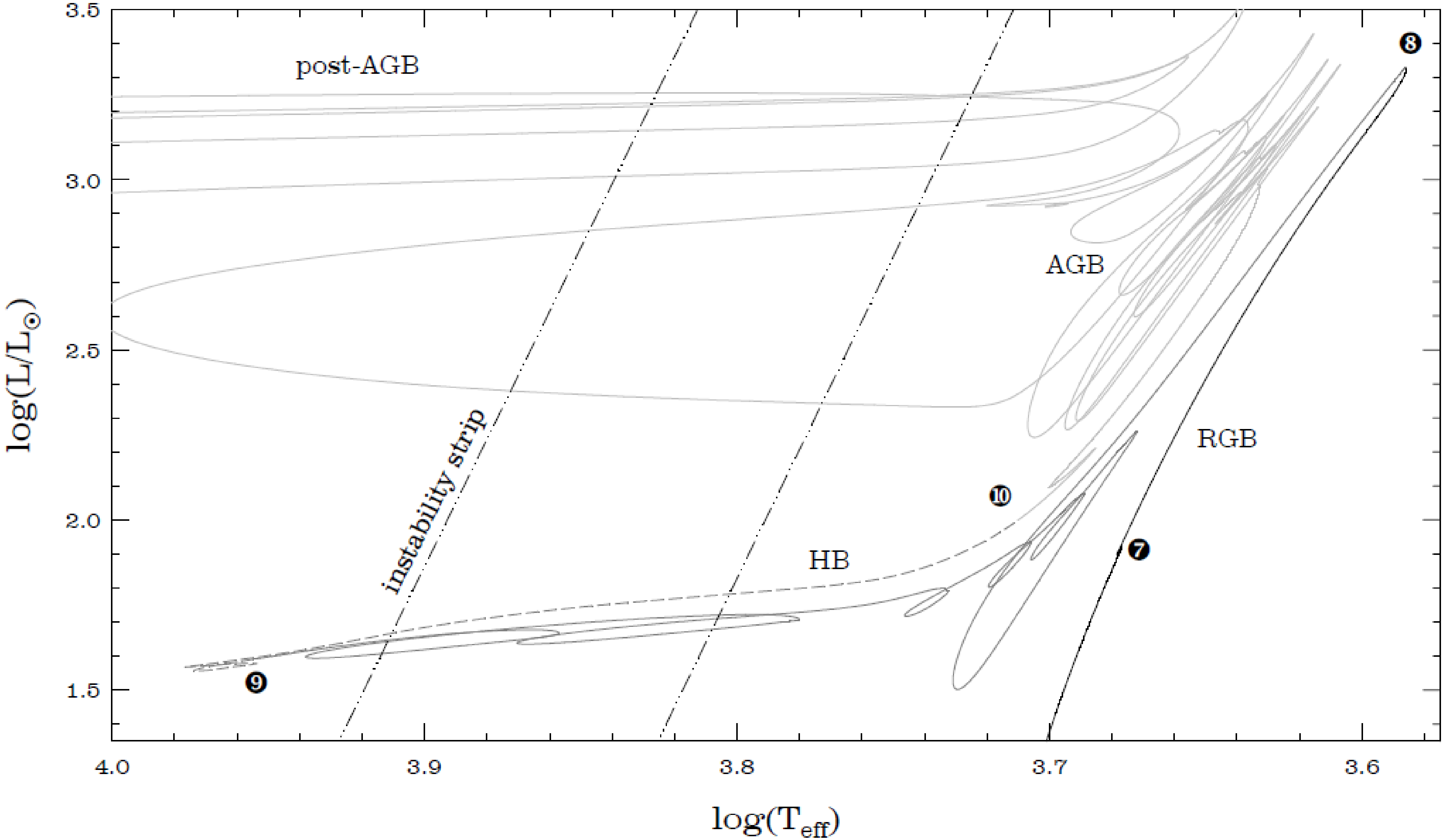
When the core mass reaches 0.45 $M_{\odot}$, and Tc and ρ_c, get large enough → He fusion reactions ignite in degenerate medium

Helium flash

He flash



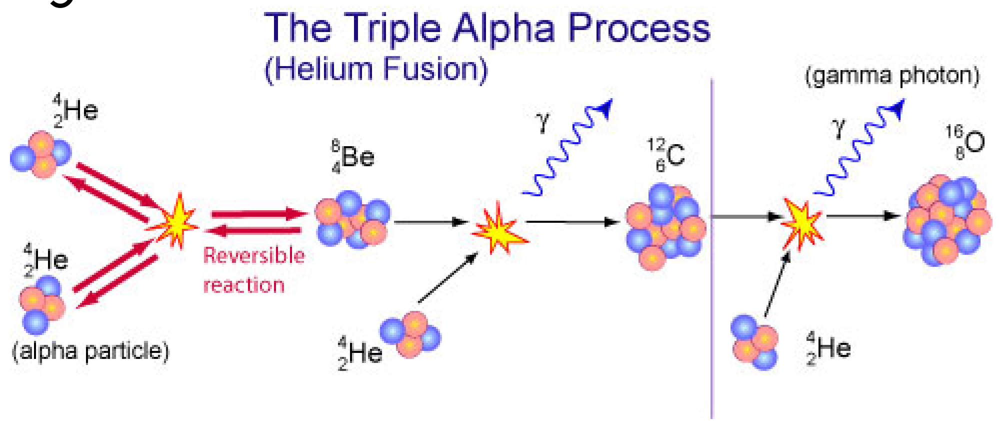
L
L_H
L_{He}
log (R/R☉)
log (R_{He}/R☉)
log (R/R☉)
m/M☉
log (L/L☉)
Time Since Initiating Helium Flash (10^6years)
0.0
0.5
1.0
1.5
2.0
0.2
0.4
0.6
0.8
1.0
−1
0
1
2
−2
4
6
8
10



post-AGB
AGB
RGB
HB
instability strip
log(L/L⊙)
log(Teff)
3.5
3.0
2.5
2.0
1.5
4.0
3.9
3.8
3.7
3.6

He burning / red clump

3α reactions dominate the energy production in He rich regions with $T_c >$ 10^8 K and $\rho_c > 10^5$ g/cm^3



These reactions will start in partially degenerated plasma in low-mass stars

Helium Flash

He fusion products

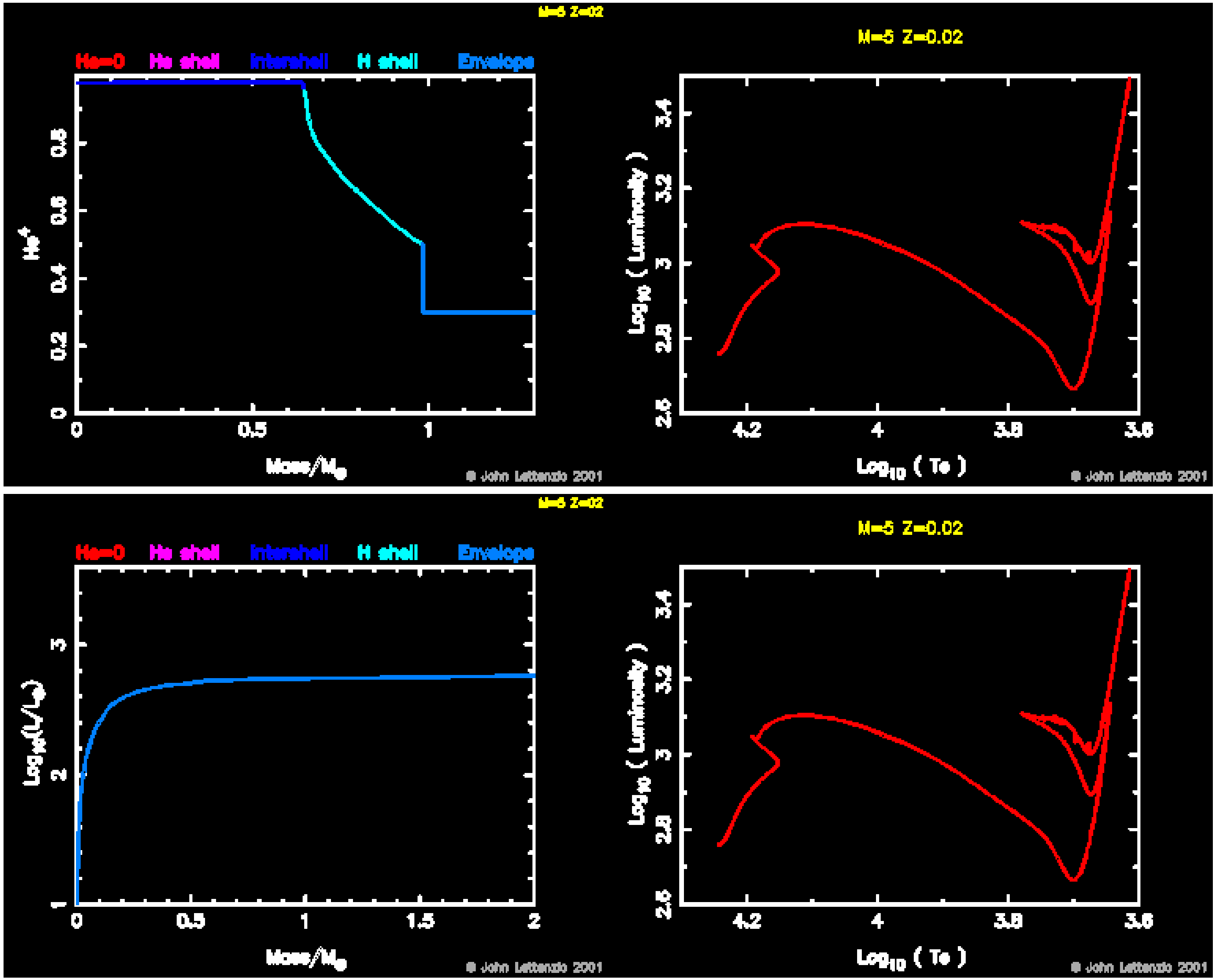
Carbon ^{12}C $\quad$ $^4He(\alpha,\gamma)^8Be(\alpha,\gamma)^{12}C$

Oxygen ^{16} O, ^{18} O $\quad$ $^{12}C(\alpha,\gamma)^{16}O(\alpha,\gamma)^{20}Ne$

Neon ^{20}Ne, ^{22}Ne

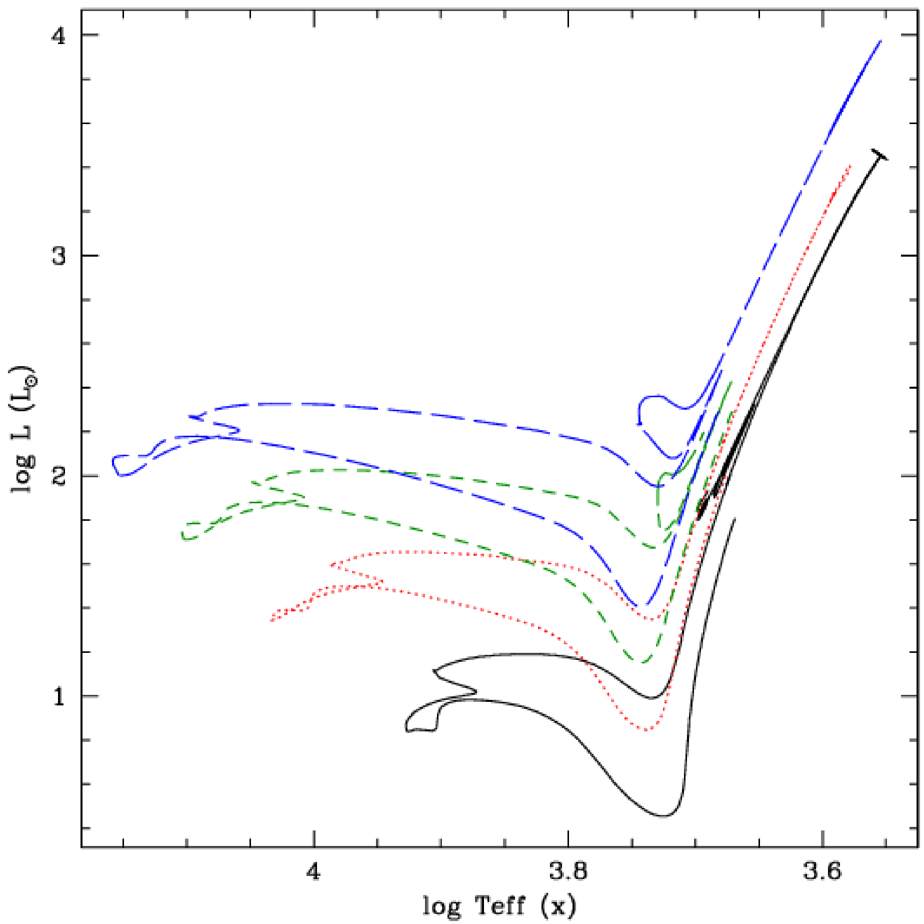
neutrons via $\quad$ $^{13}C(\alpha,n)^{16}O$ et $^{22}Ne(\alpha,n)^{25}Mg$

He burning / red clump - 5 Msun star

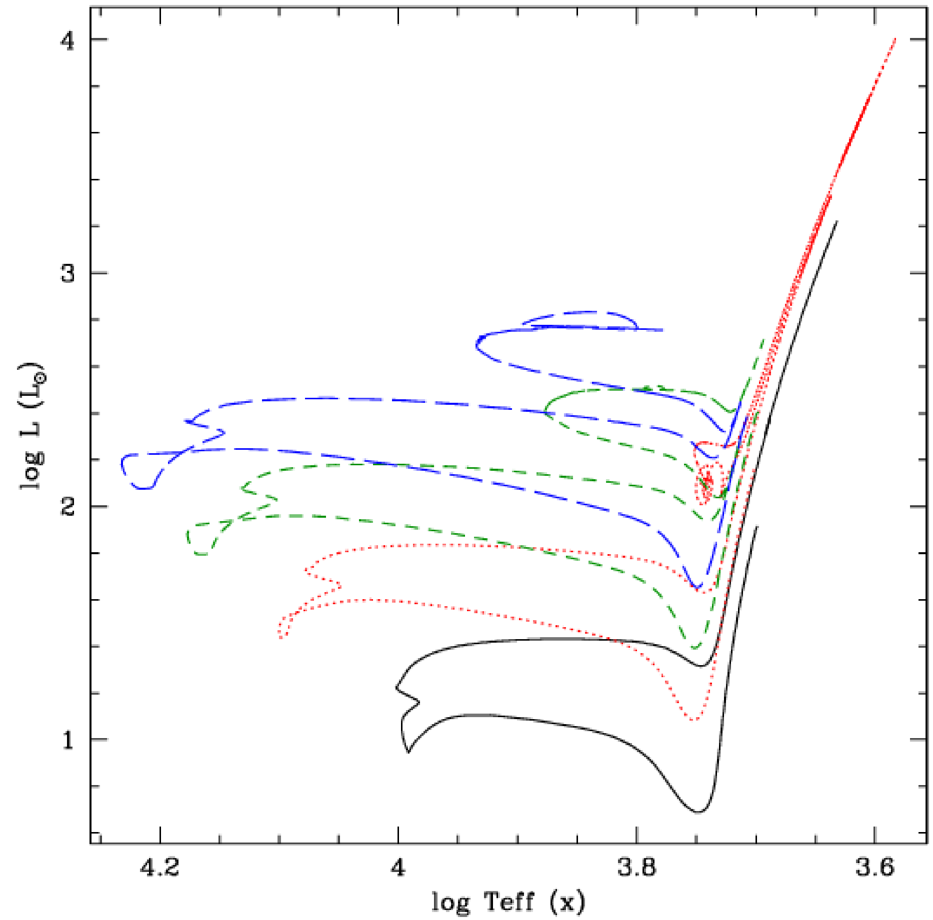


Impact of metallicity on evolution

[Fe/H] = -0.5



[Fe/H] = -1.5



Models between 1.5 $M_\odot$ and 3 $M_\odot$

Intermediate mass stars evolution and 2nd DUP

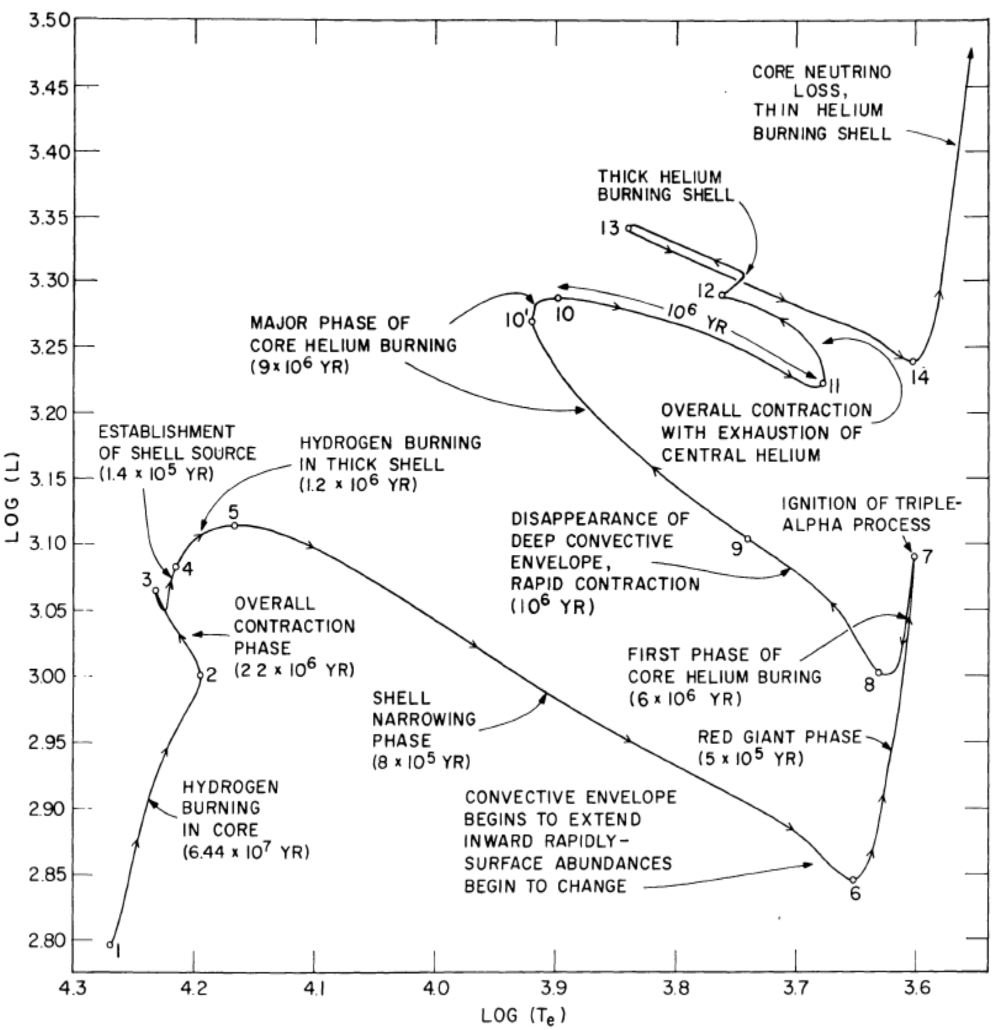
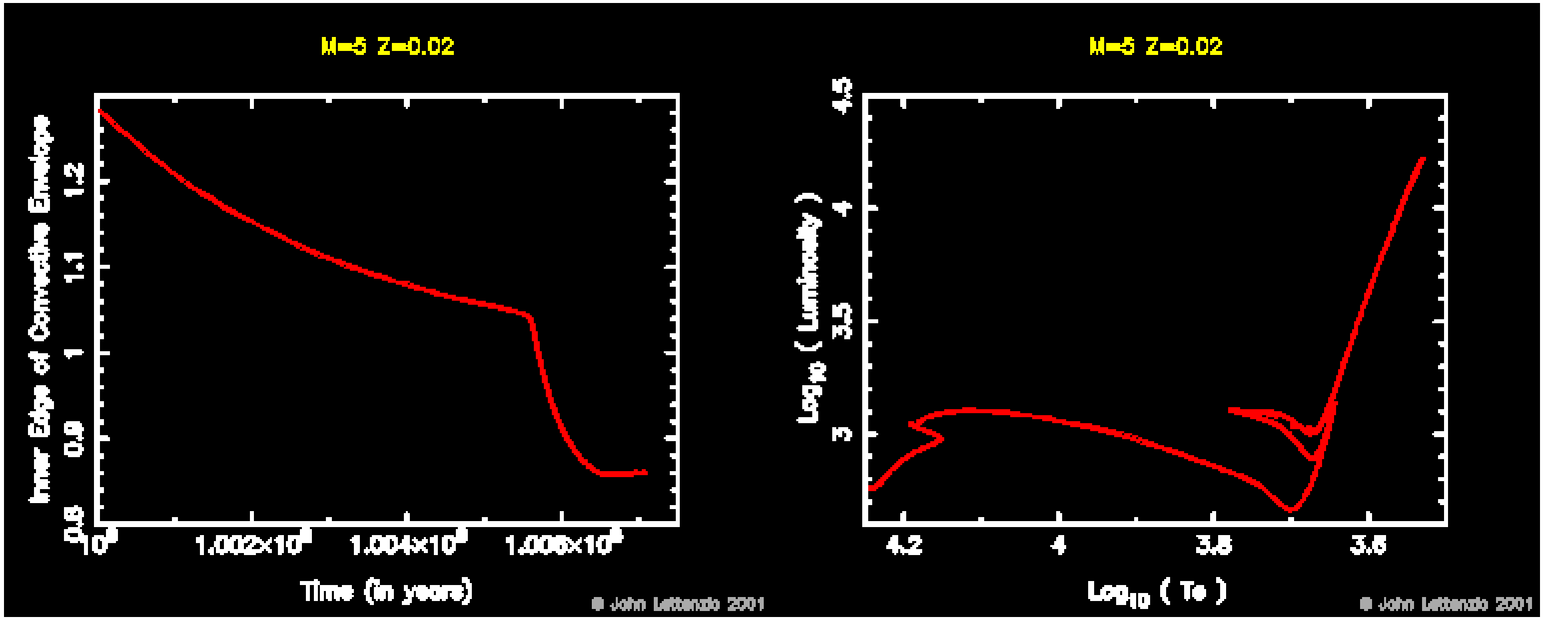
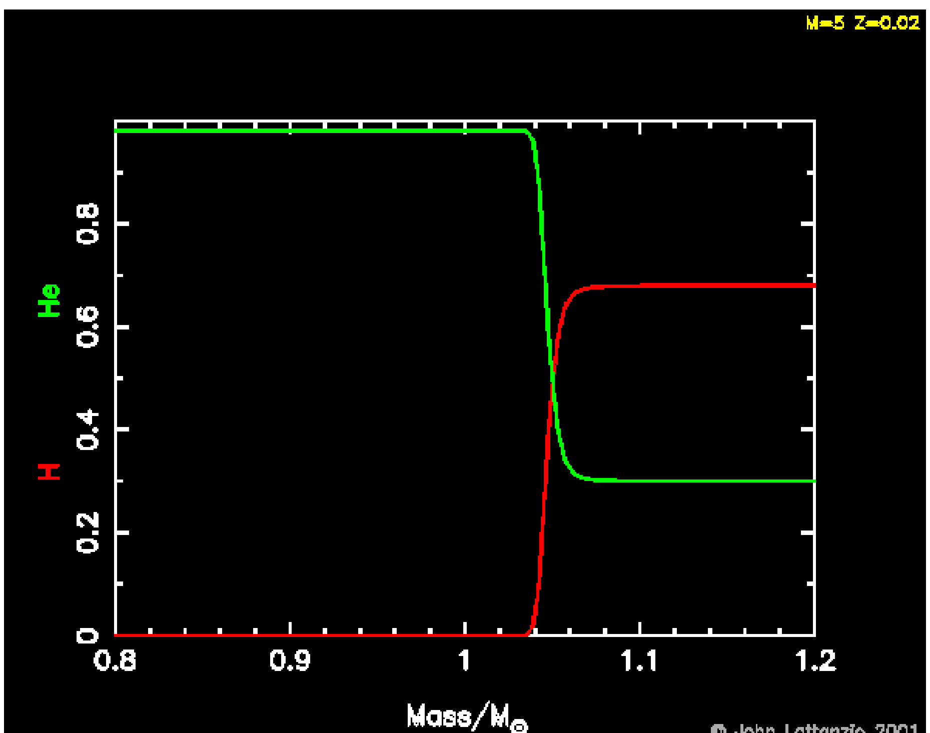


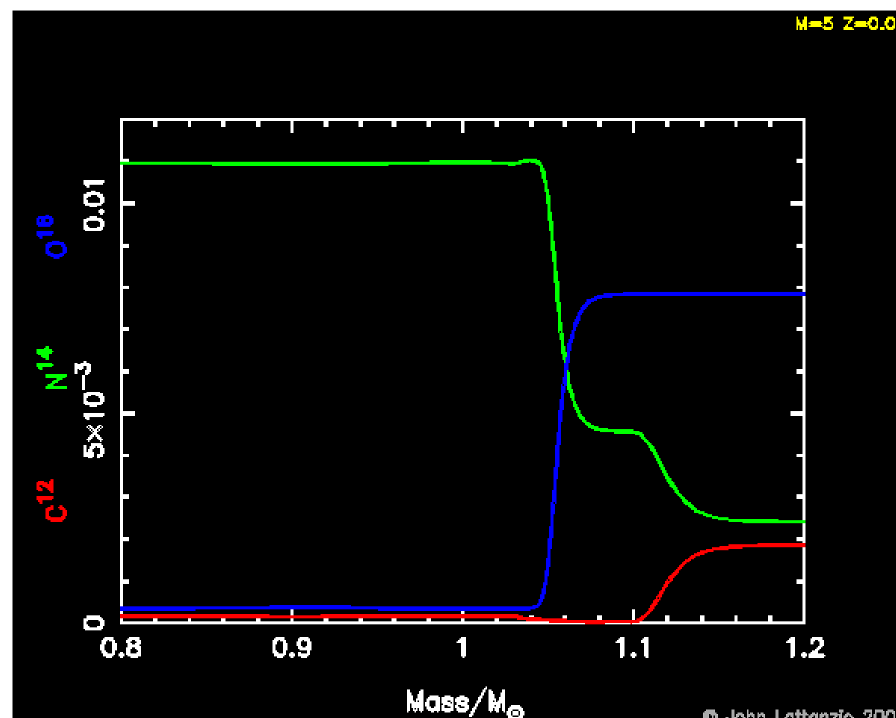
FIG. 2.—The track in the H-R diagram of a theoretical model star of mass 5 $M_\odot$ and of Population I composition. Text beside various portions of the track describe an important physical process occurring within the star at the indicated position. From Iben (1967c).

Core He fusion in non-degenerate plasma → second dredge-up occuring at the end of the core He burning → similar to 1st DUP.

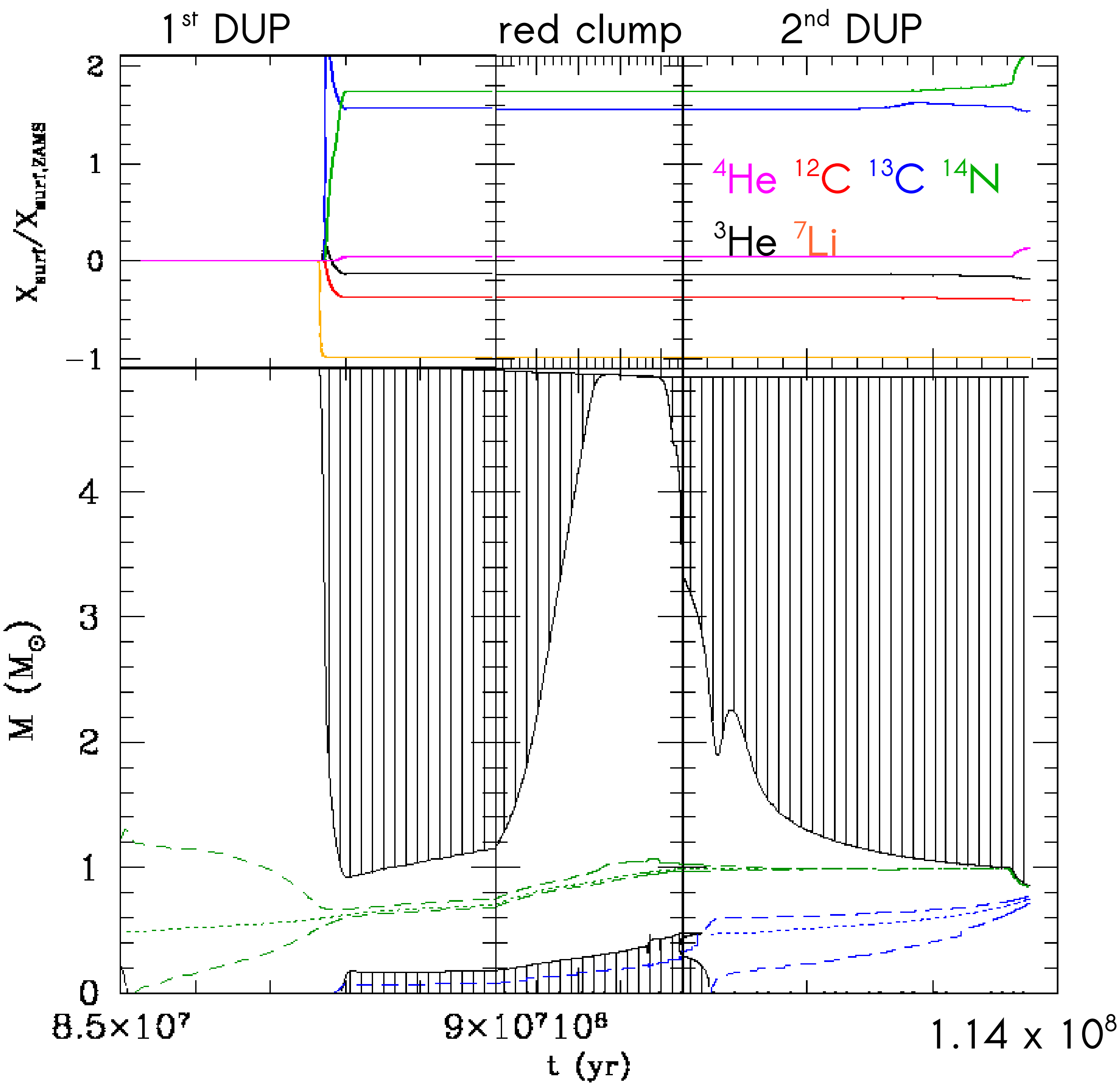
Intermediate mass stars evolution and 2nd DUP







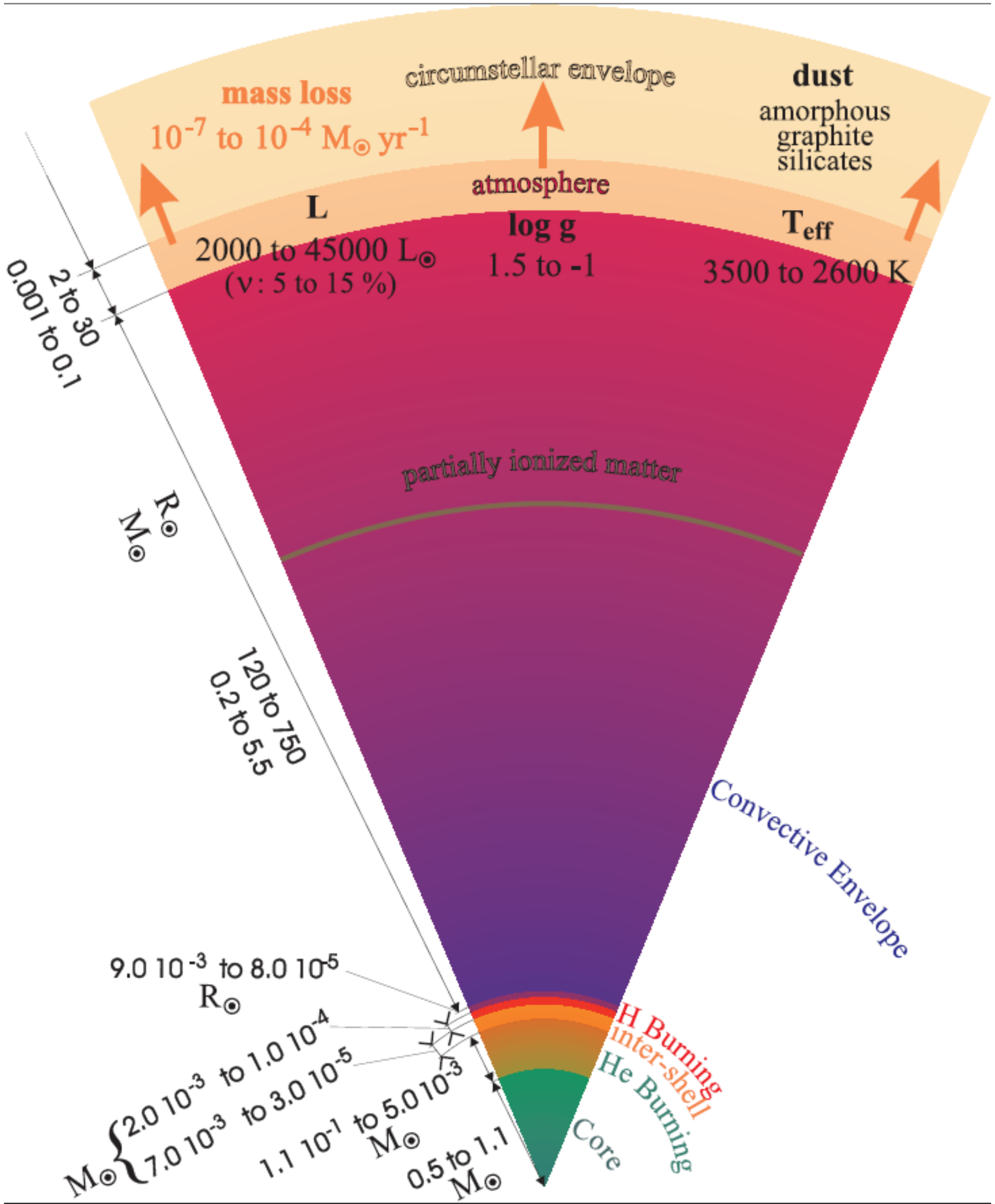
Intermediate mass stars evolution and 2nd DUP



5 $M_\odot$ @ solar metallicity

After the 2nd DUP, ^{4}He and ^{14}N increase at the stellar surface

AGB phase



Stars with masses <= 10 Msun ascend the red giant branch for the second time after core He burning → AGB stars

Very luminous → undergo important mass loss and peculiar nucleosynthesis due to double shell nuclear fusion

Essential contributors to the chemical evolution of interstellar medium

TP-AGB phase

HBS et HeBS advance at different paces : intershell mass ↗ , T(HeBS) ↗

→ thermal pulse

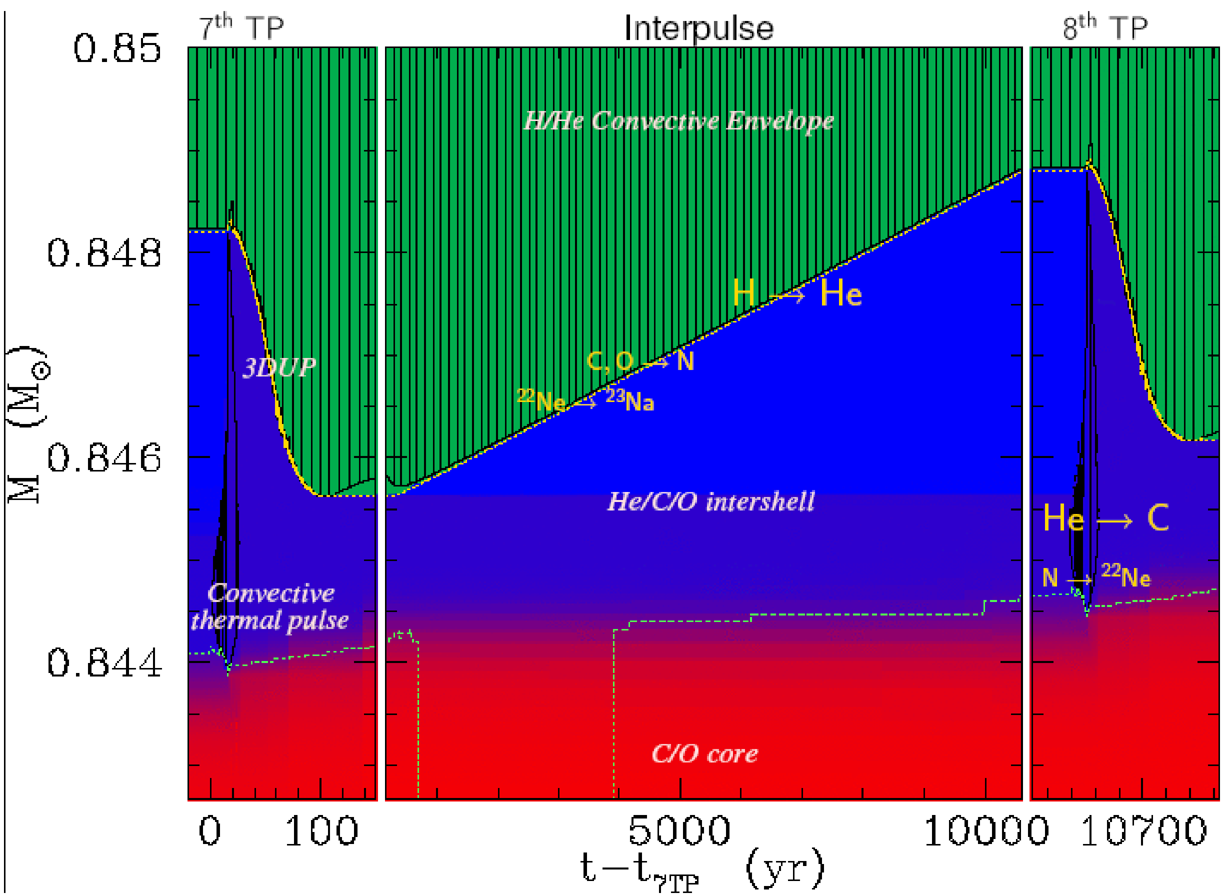
The pulse swallows the products of H nuclear fusion

peculiar nucleosynthesis

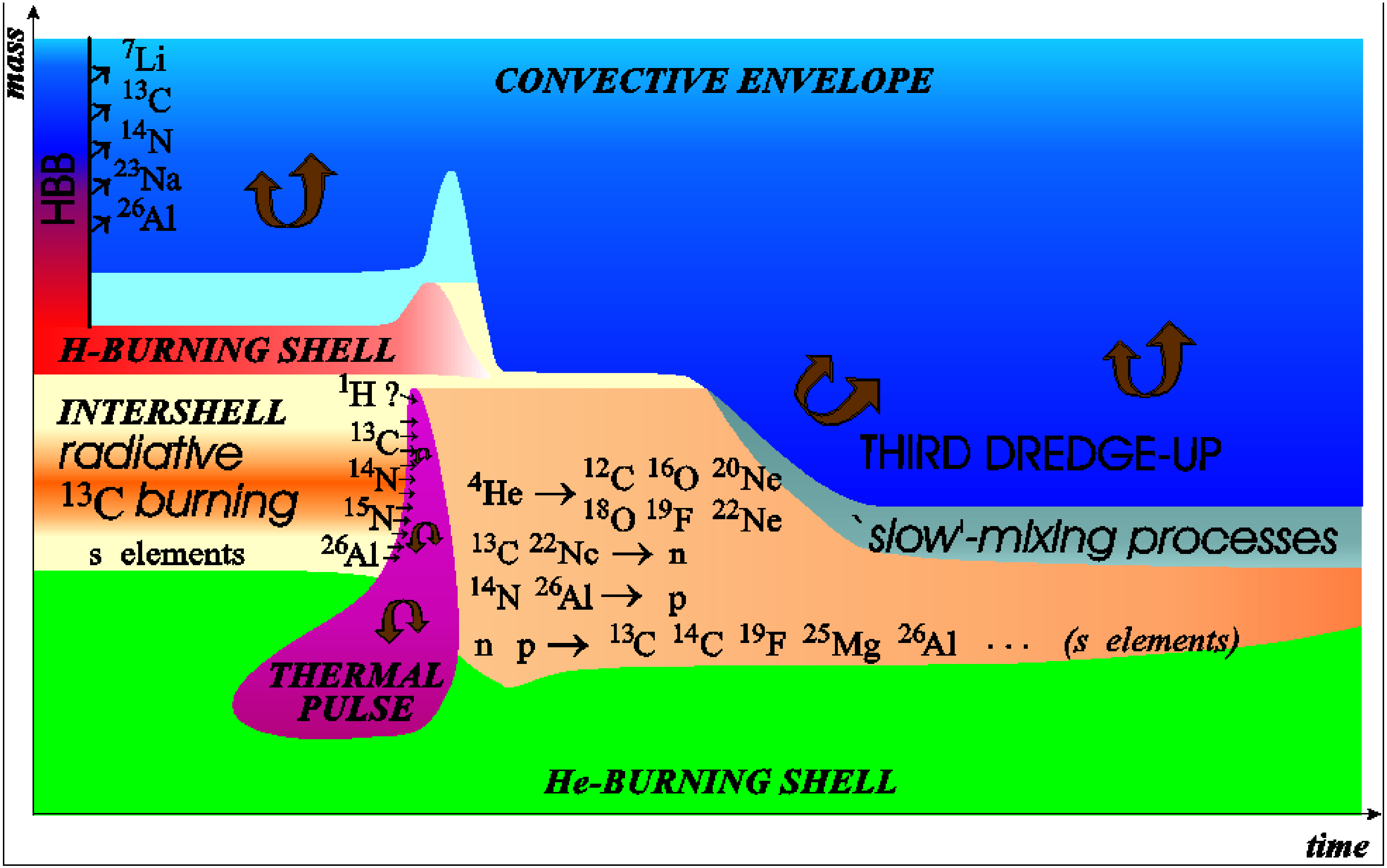
Pulse acts like a piston

- lifts up the envelope
- shuts down the HBS
- possibly further deepening of falling back envelope into regions processed in the pulse

3rd DUP events



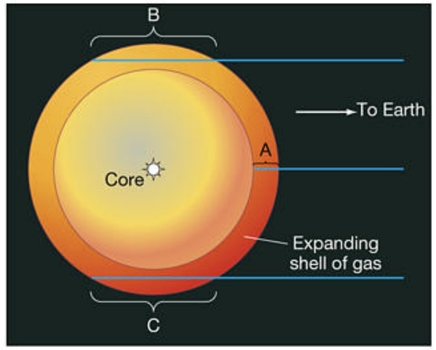
TP-AGB nucleosynthesis



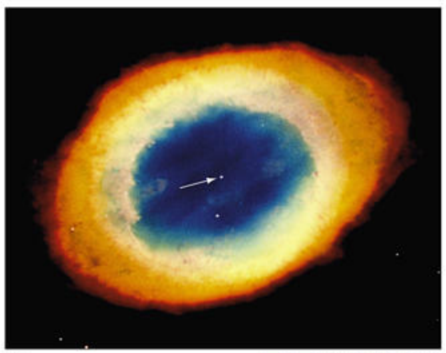
This is a way to increase C/O stellar atmospheres and to produce heavy neutron-rich elements

Post-AGB evolution and PNae

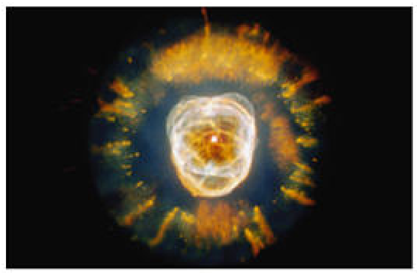
(a)



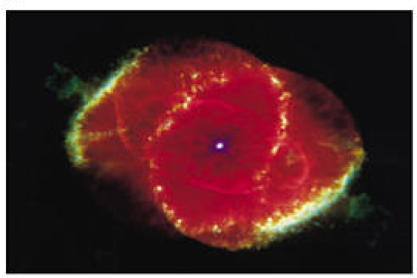
(b)



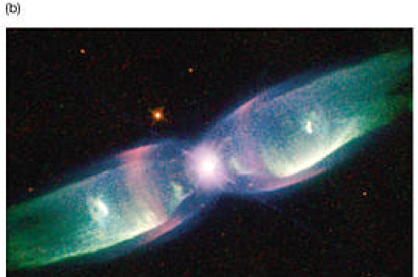
(c)



(a)

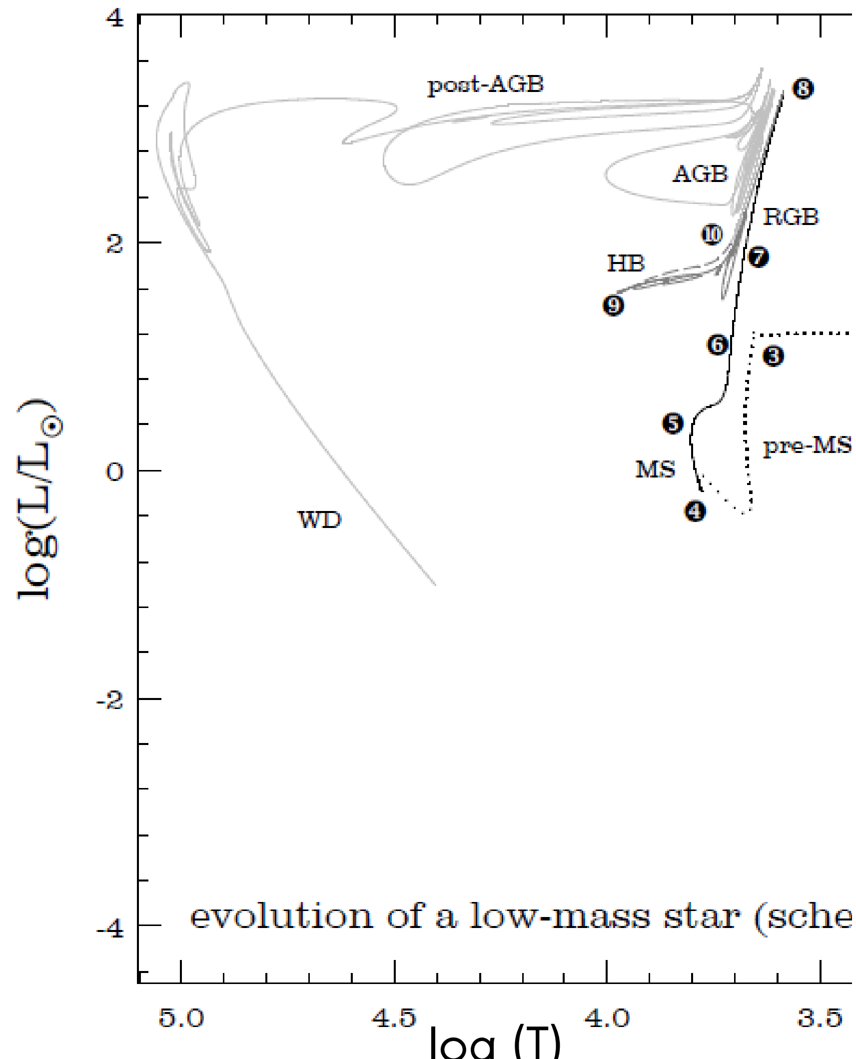


(b)

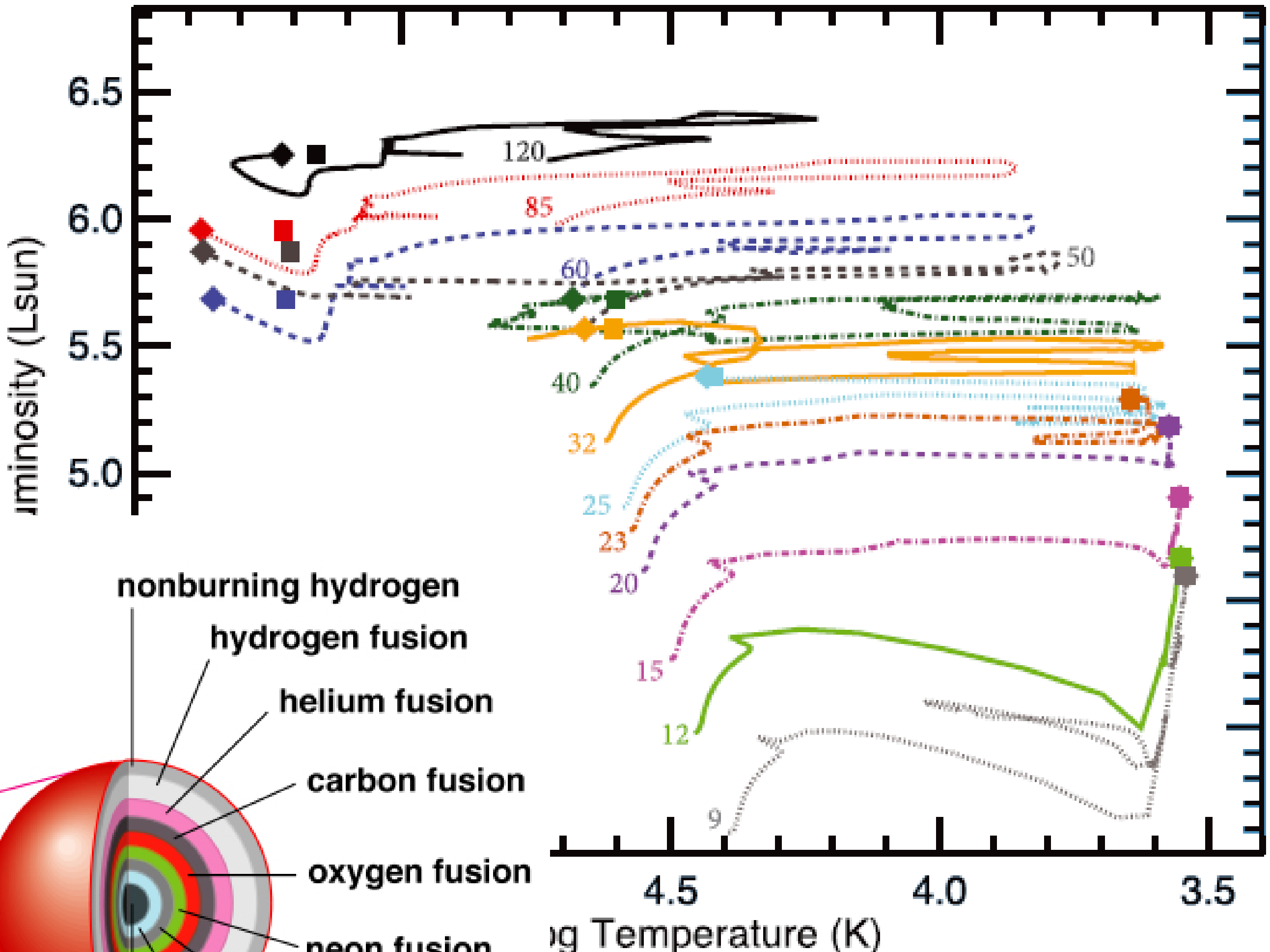


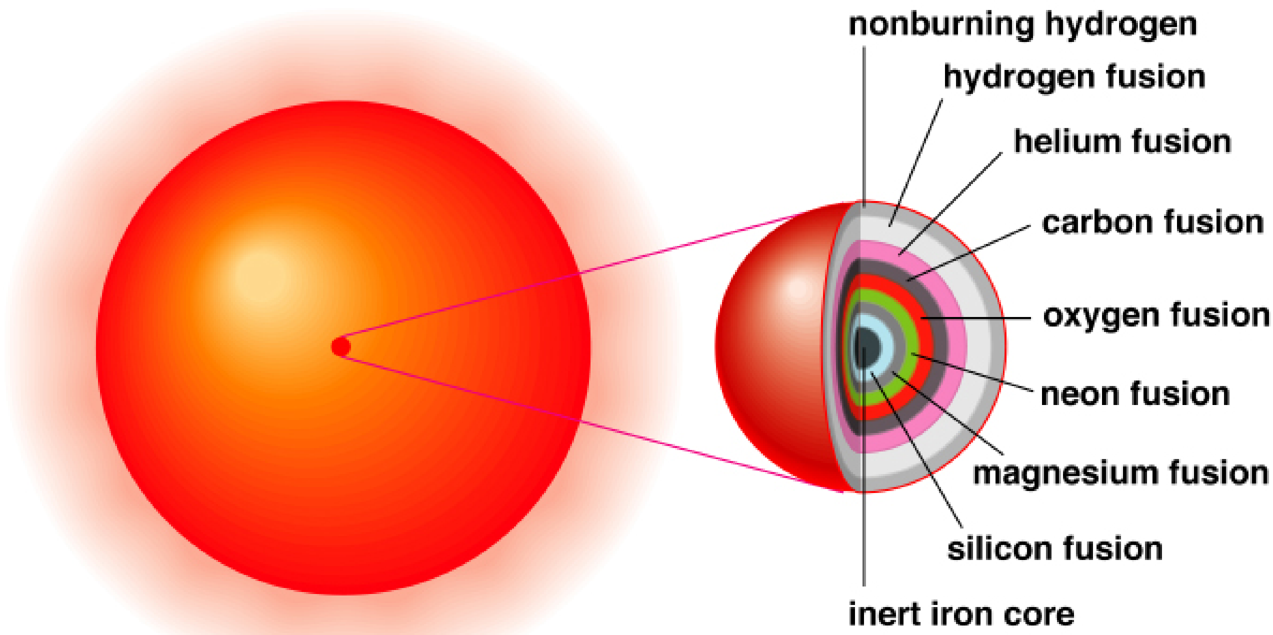
(c)

Thermal pulses + global radial pulsations (Mira type)
→ ejection of envelope
→ potentially a PNae



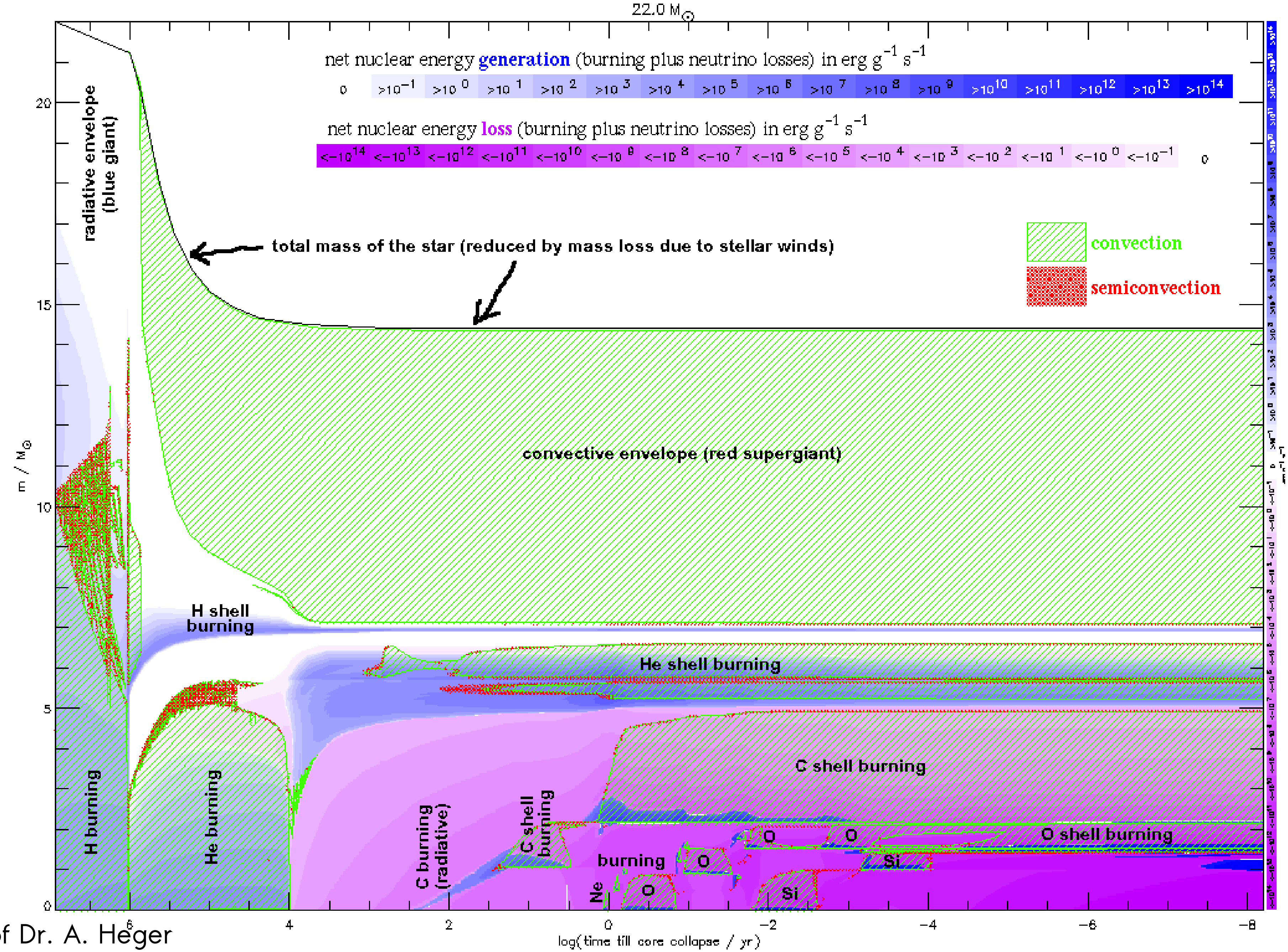
Post Main Sequence evolution of massive stars





onion shell structure

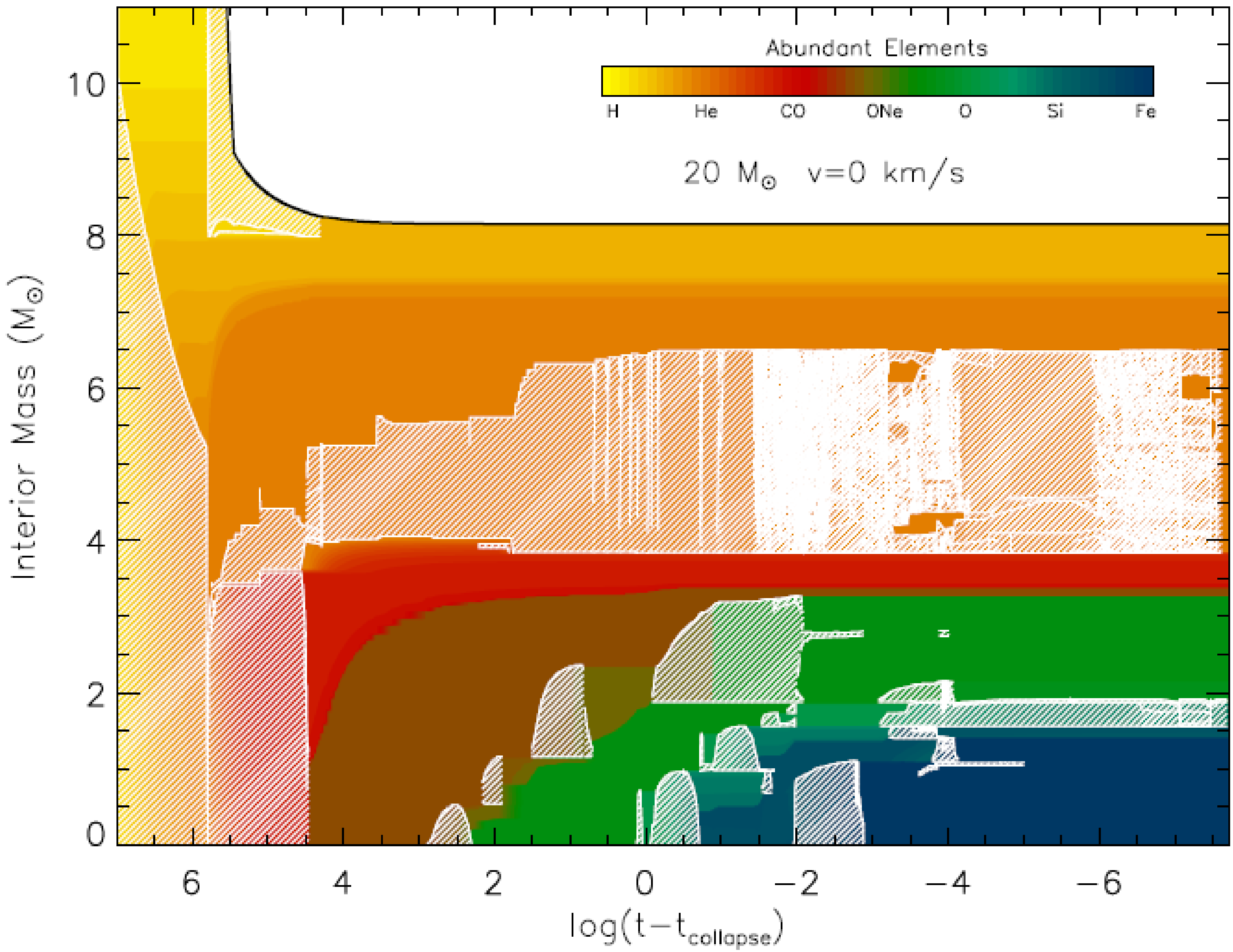
Post Main Sequence evolution of massive stars



Courtesy of Dr. A. Heger

http://www.ucolick.org/~alex/stellarevolution/

Post Main Sequence evolution of massive stars



Post Main Sequence evolution of massive stars

TENTATIVE FILIATIONS:

Always blue

$M > 90\ M_\odot$: O – Of – WNL – (WNE) – WCL – WCE – SN (Hypernova ?)

$M > 60\text{-}90\ M_\odot$: O – Of/WNL ←→ LBV – WNL(H poor) – WCL-E – SN (SNIIn?)

$M > 40\text{-}60\ M_\odot$: O – BSG – LBV ←→ WNL – (WNE) – WCL-E – SN (SNIb)
— WCL-E — WO — SN (SNIc)

Blue – red - blue

$M > 30\text{-}40\ M_\odot$: O – BSG – RSG – WNE – WCE – SN (SNIb)
OH/IR ←→ LBV ?

Blue – red

$M > 25\text{-}30\ M_\odot$: O – (BSG) – RSG – BSG ←→ RSG SNIIL
BLUE LOOP

$M > 10\text{-}25\ M_\odot$: O – RSG – (Cepheid loop for $M < 15\ M_\odot$) – RSG – SN SNIIp

Mass loss driven evolution

Normal evolution

This is far from being clear yet!

Surface abundances evolution for massive stars

O :

no expected variation

BSG à RSG :

^{4}He ↗

1H↘

^{14}N ↗

WN :

^{14}N ↗↗

^{12}C and ^{16}O ↘↘

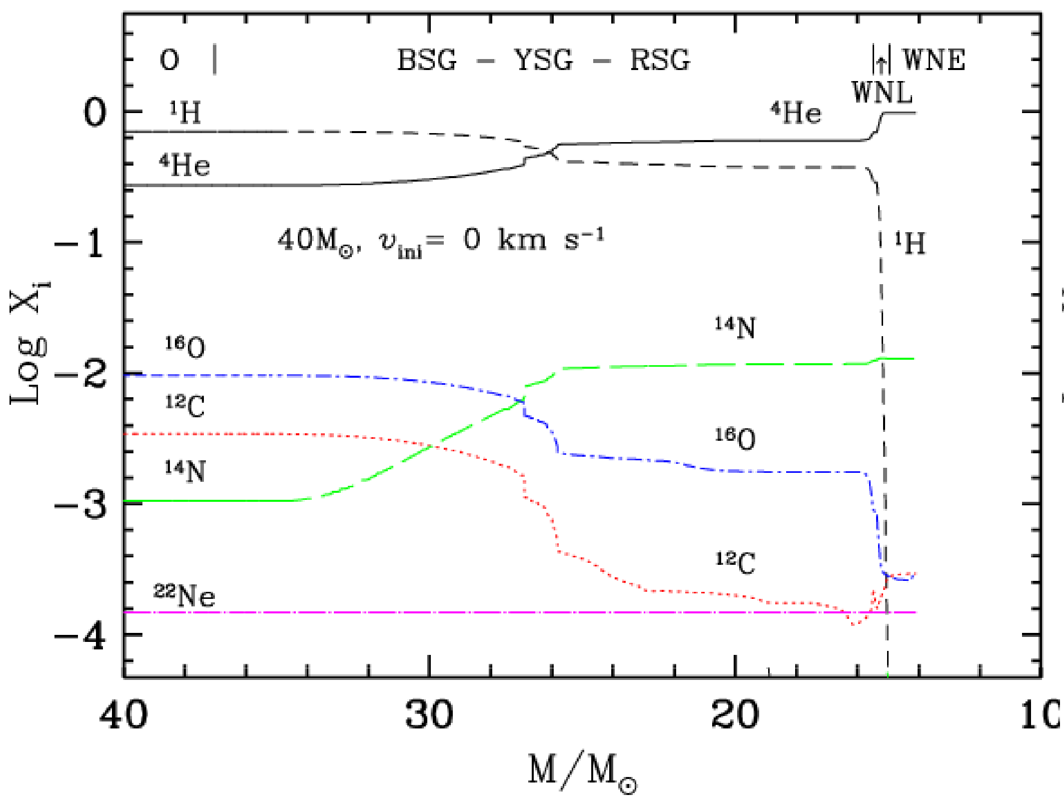
^{22}Ne and ^{25}Mg ↘

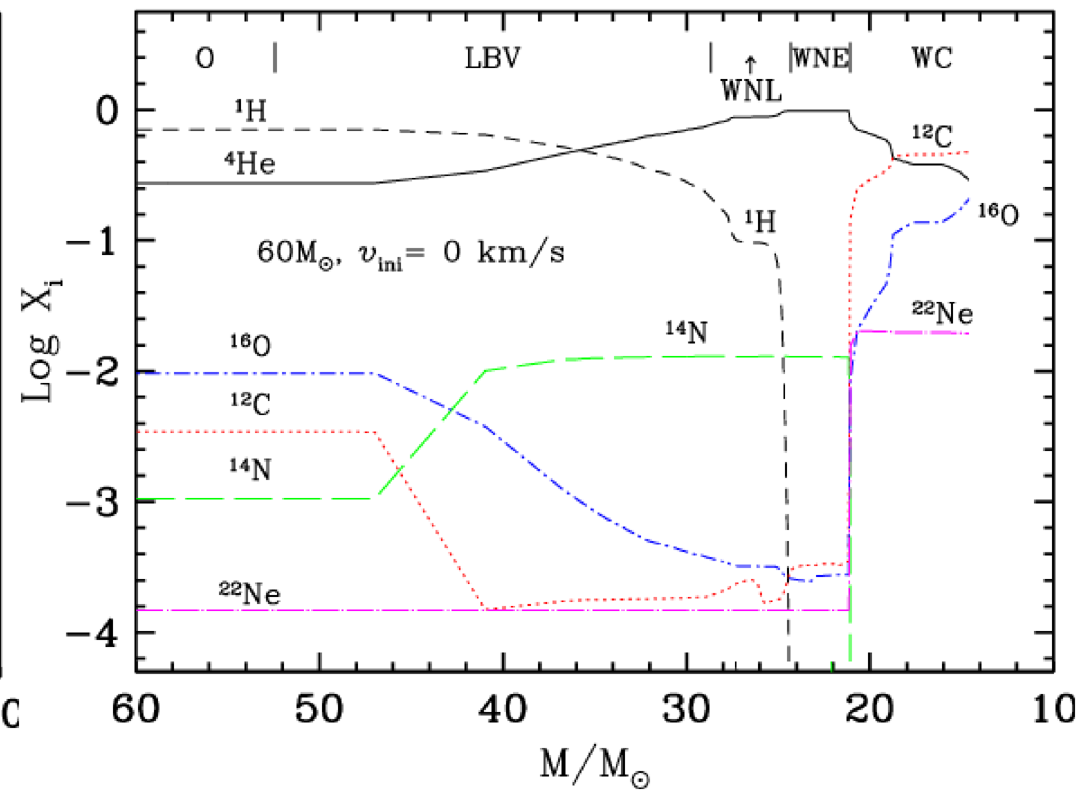
WC:

^{14}N ↘

^{12}C and ^{16}O ↗

^{22}Ne ↗↗

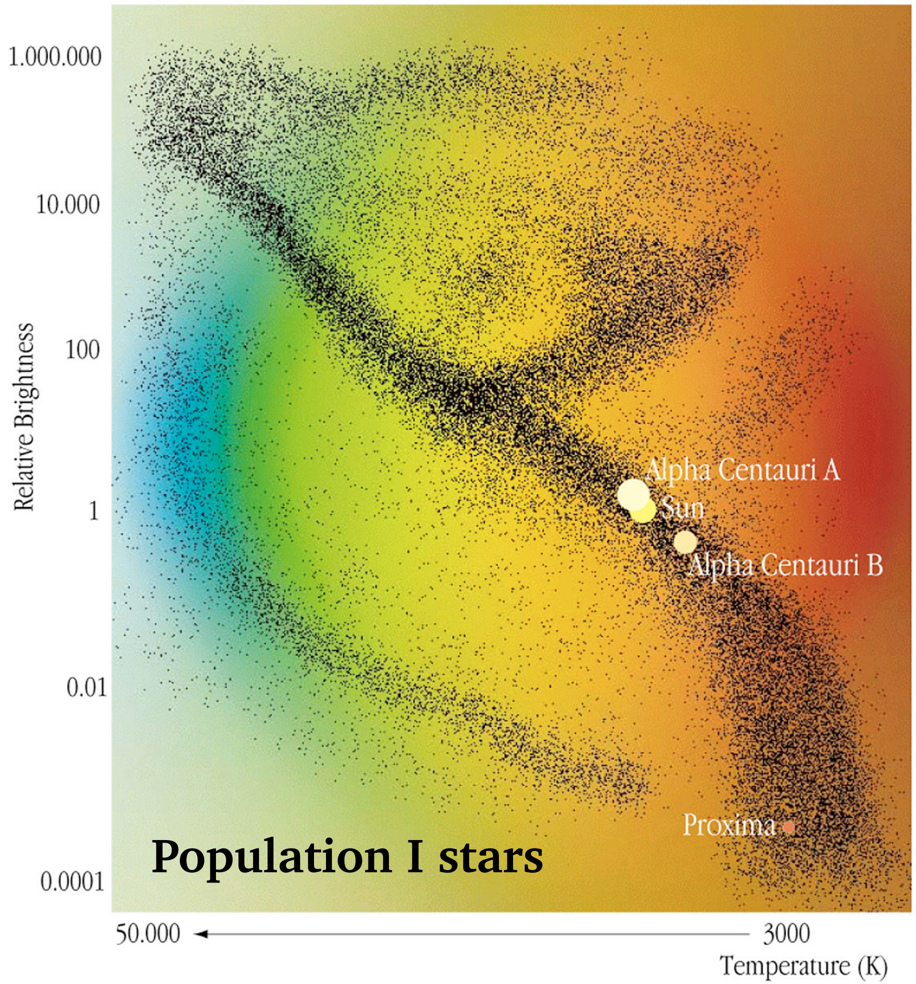




But there is more to it : lots of challenges!

A wealth of "abundance anomalies"

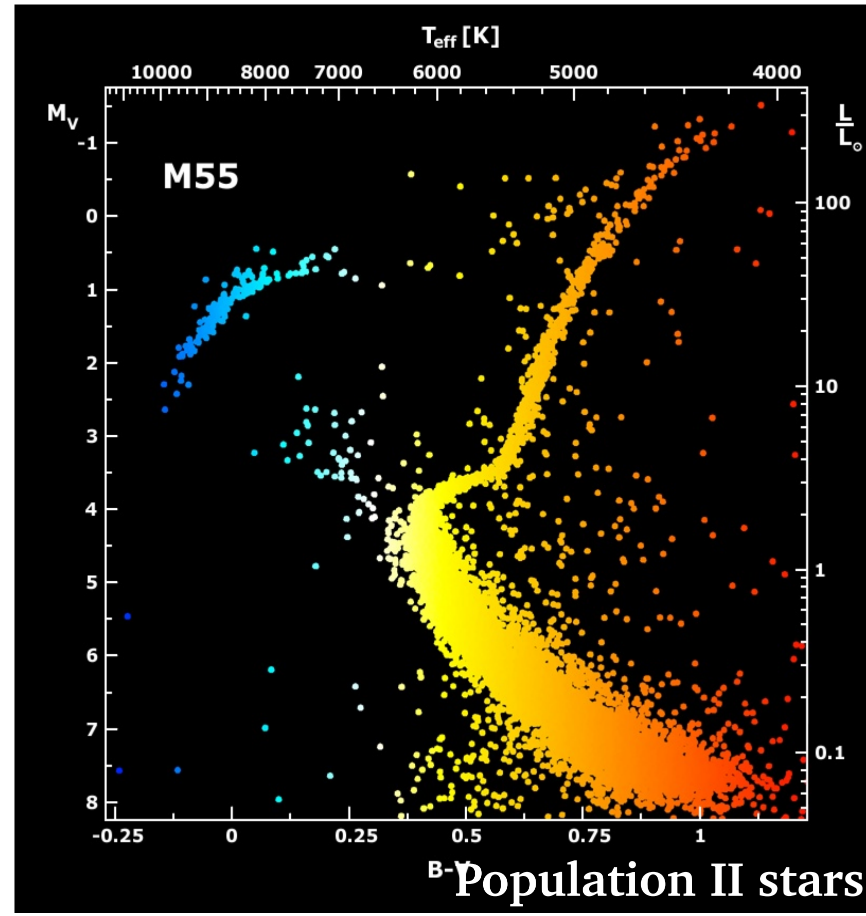
Li anomalies N and He overabundances CP stars



Anomalous Fe and Fe peak elements

Anomalous Li, C, N

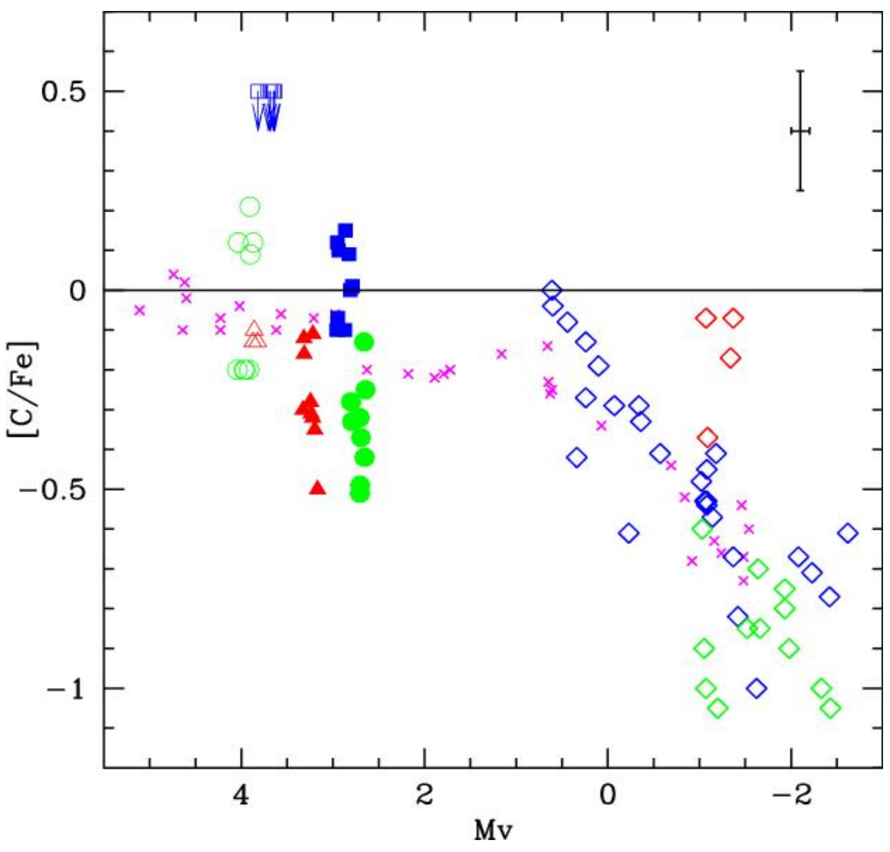
Low Li
Anomalous O, Na, Mg, Al



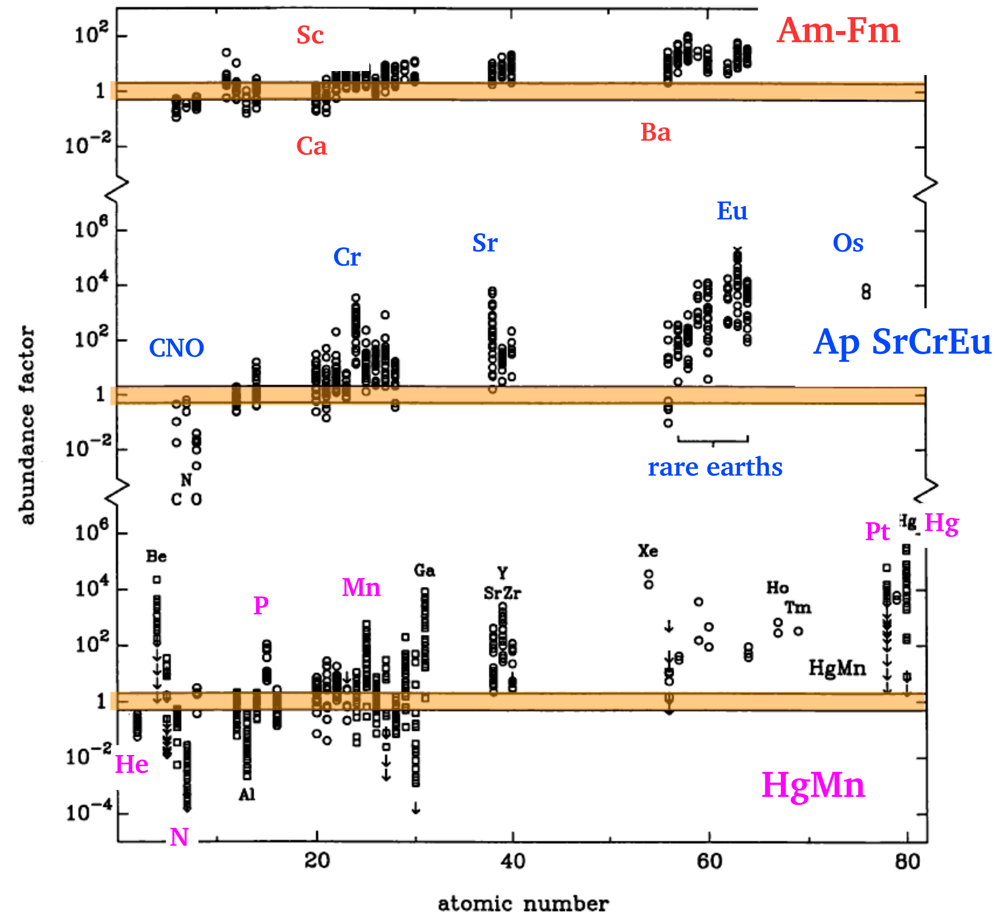
But there is more to it : lots of challenges!

<u>A wealth of "abundance anomalies"</u>

Carbon deficiency in evolved red giants of globular clusters



Strong departures from the solar values for the surface abundances of heavy elements in B, A and F type stars

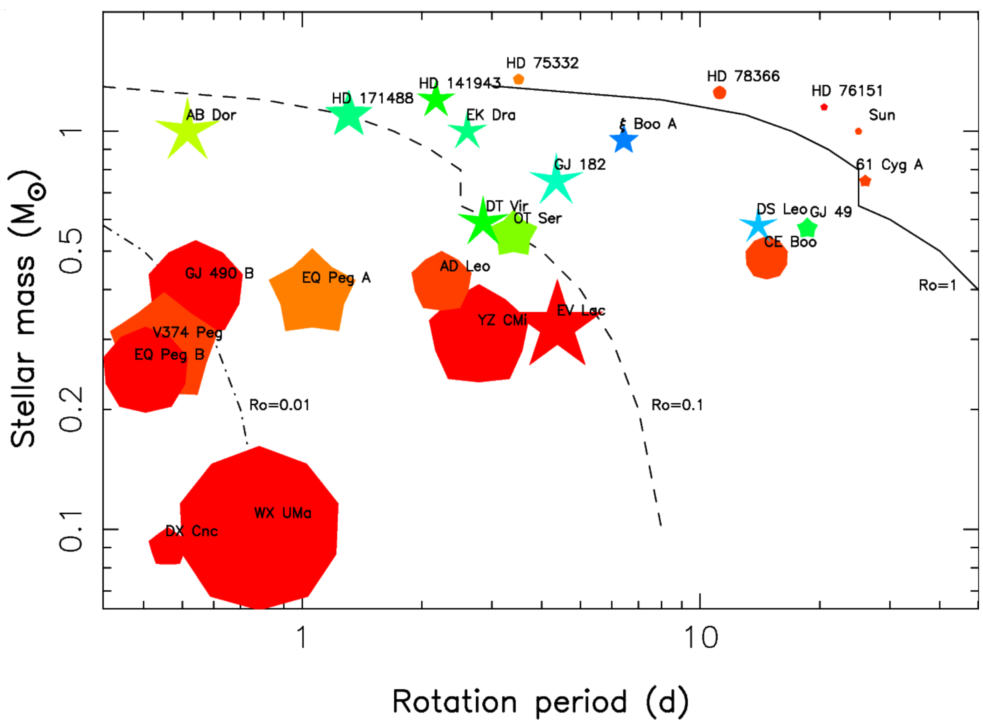


But there is more to it : lots of challenges!

Direct evidence of dynamical processes in stars

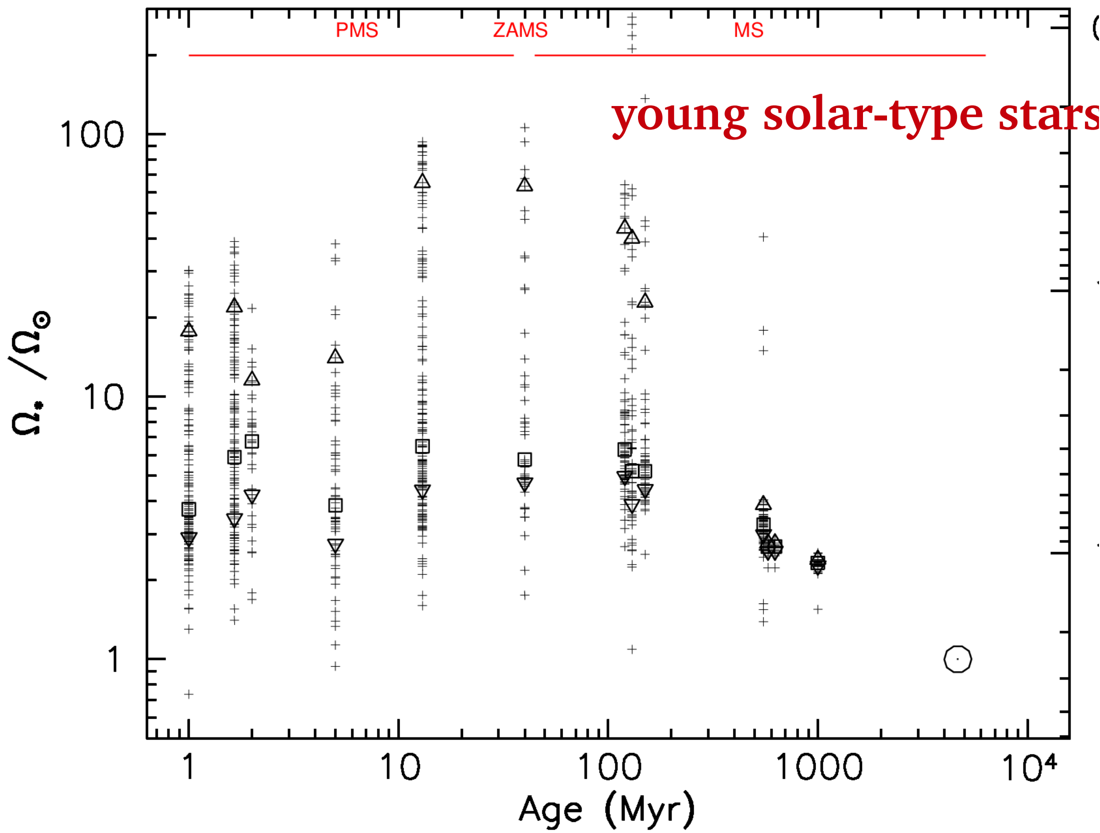
magnetic fields

Donati & Landstreet, 2009



Low-mass dwarfs

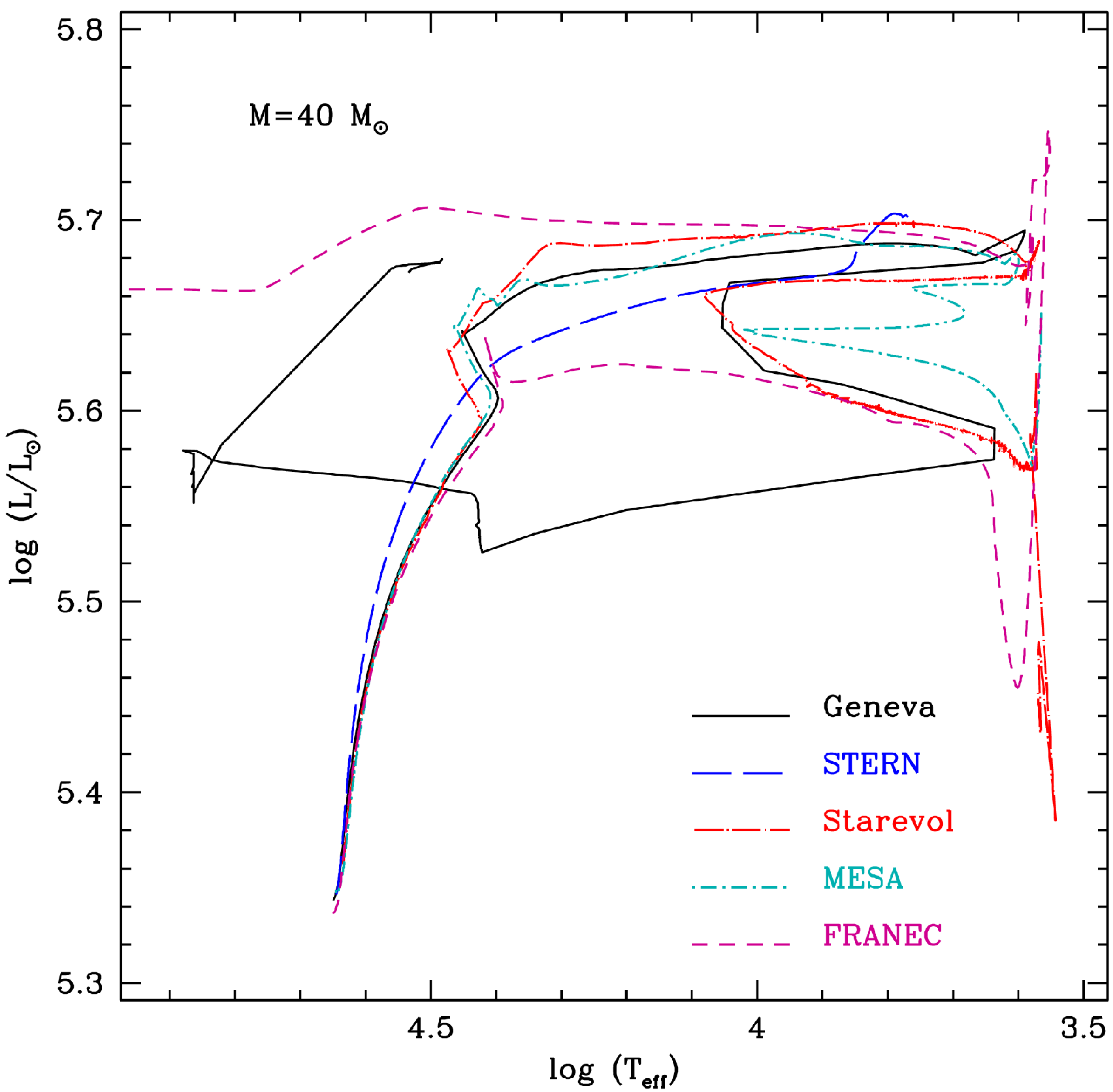
rotation



Gallet & Bouvier 2013

But there is more to it : lots of challenges!

Mass loss driven evolution ???



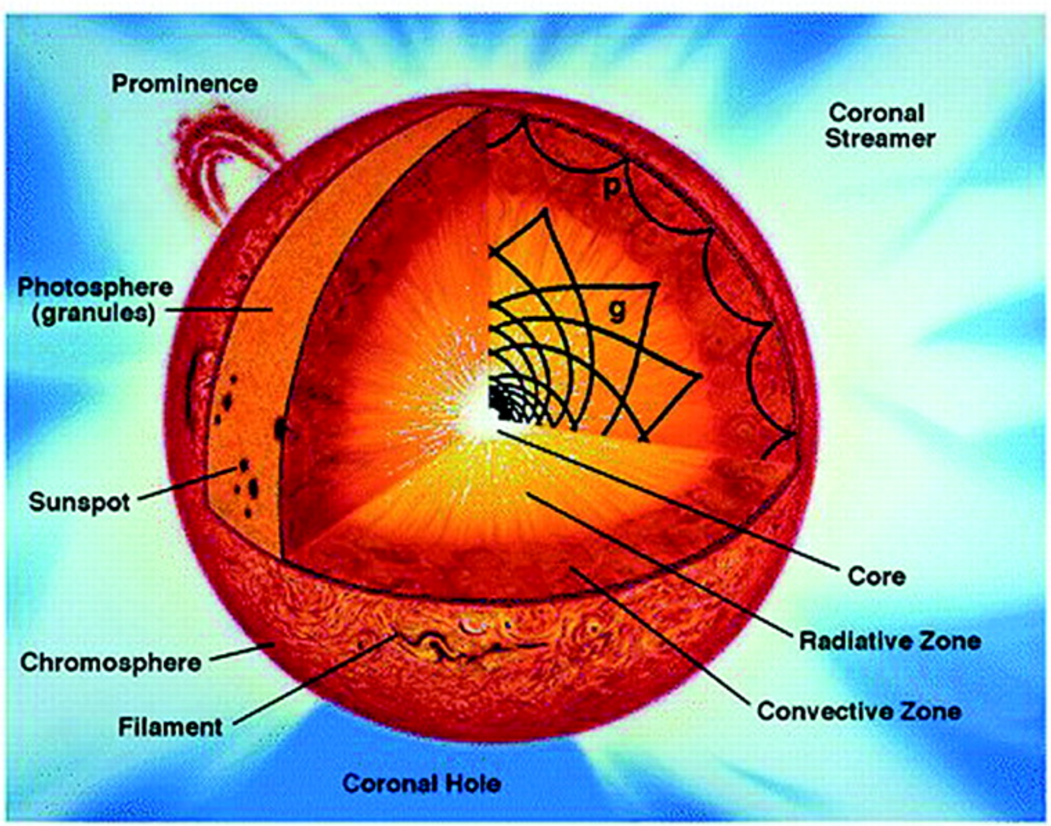
But there is more to it : lots of challenges!

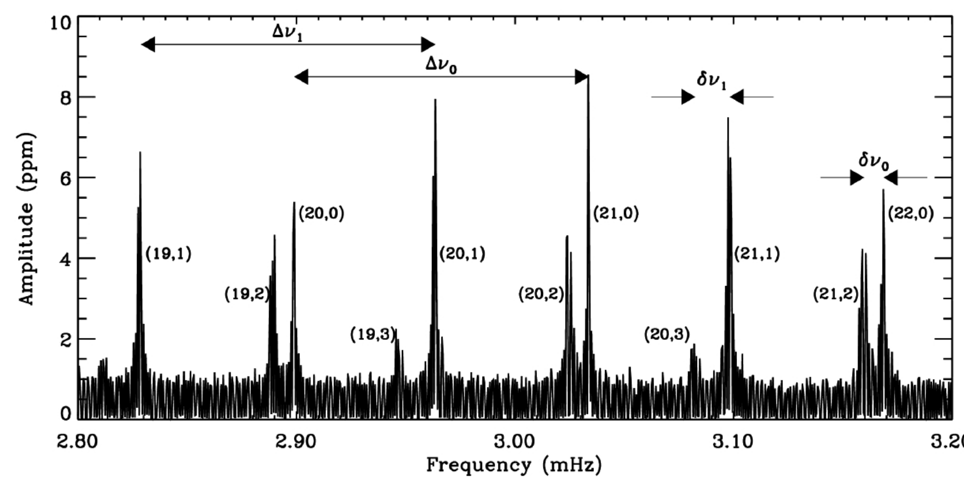
Probe stellar structure equations in detail

Helioseismology probes the outer 80% of the solar radius via p-modes.

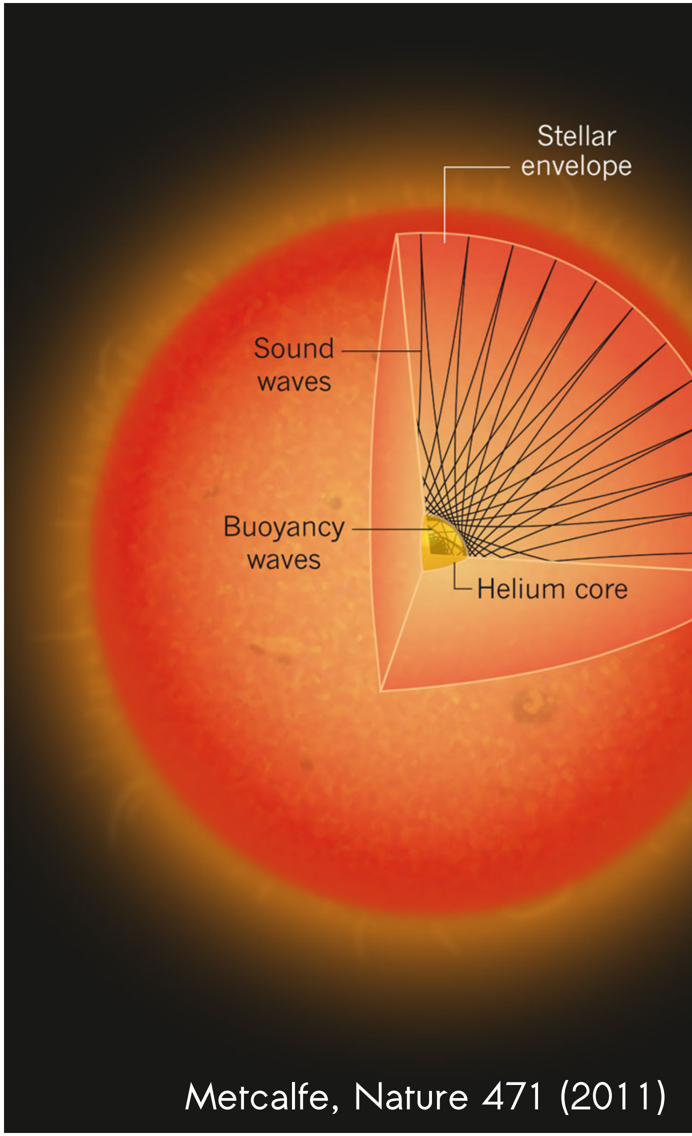
g-modes propagate in the solar core and are not detected in the surface oscillation spectrum.

→ It is extremely difficult to probe the core of the Sun, since only g-mode candidates are found.





But there is more to it : lots of challenges!

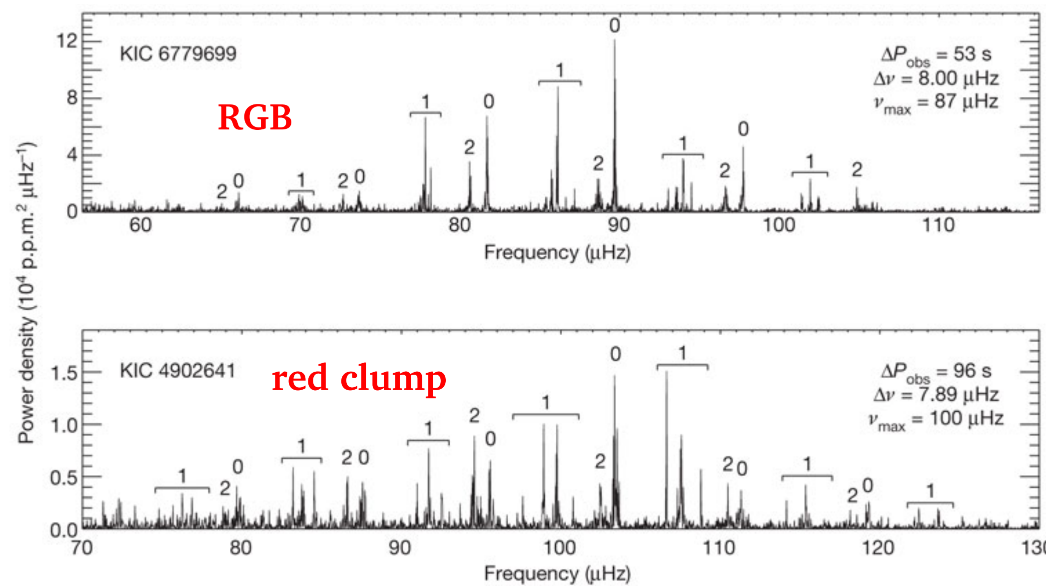


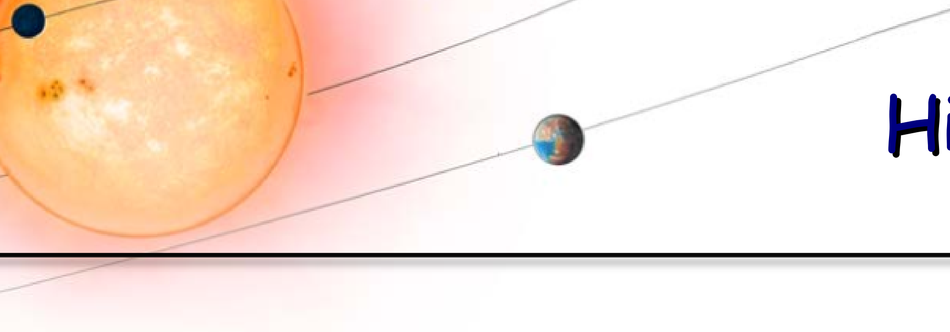
Metcalfe, Nature 471 (2011)

The solar-like oscillations discovered in red giant stars correspond to p-modes and so-called mixed-modes.

g-modes and p-modes propagate in common cavities

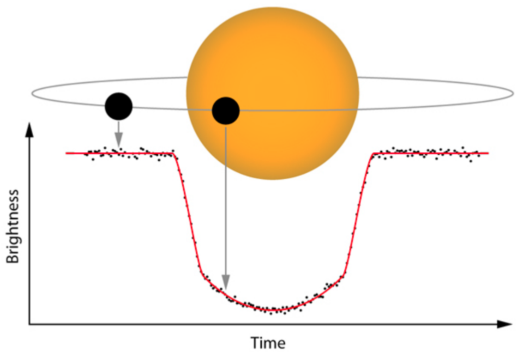
→ they make it possible to probe the core of red giants

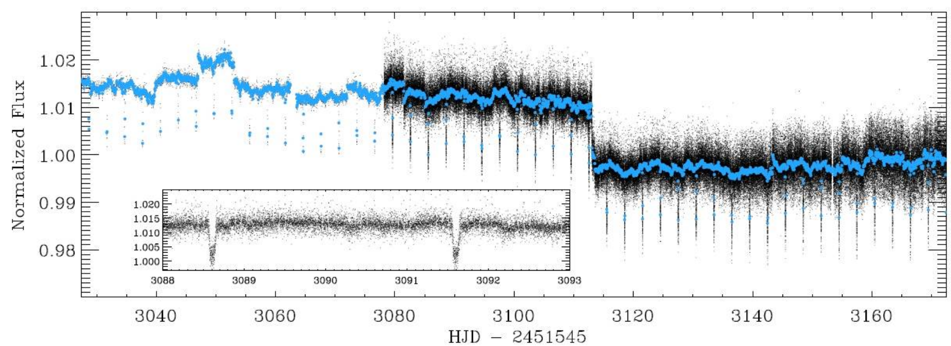


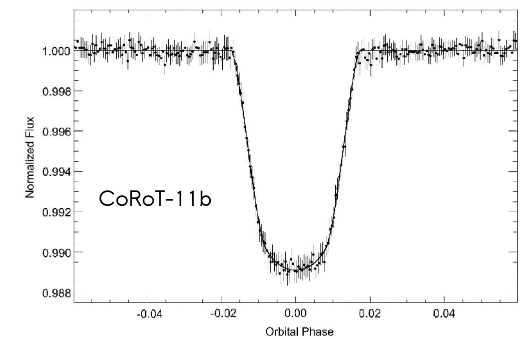


High precision space photometry

High-precision photometry from space + radial velocity follow-up → detection of exoplanetary transits





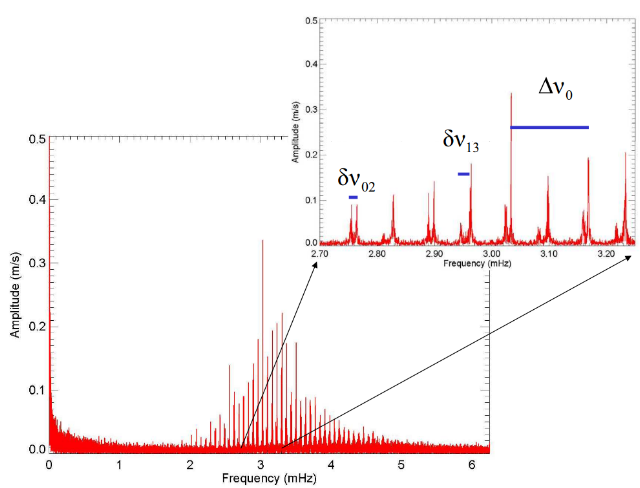


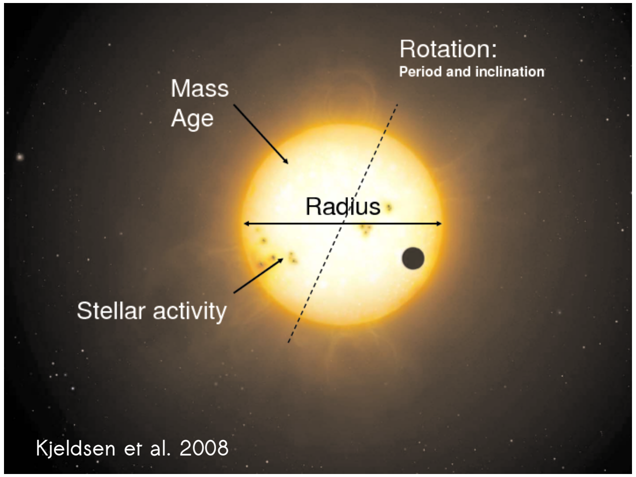
Gandolfi et al., 2010

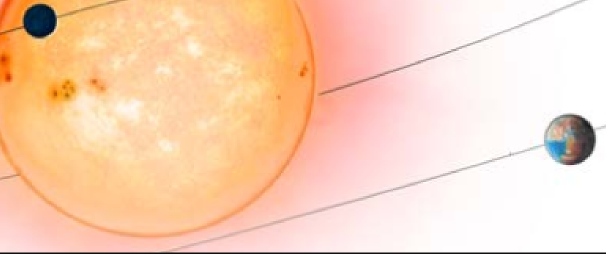
Fourier analysis of the lightcurves → power-spectrum

→ asteroseismology

→ probe the internal structure + measure basic properties of stars

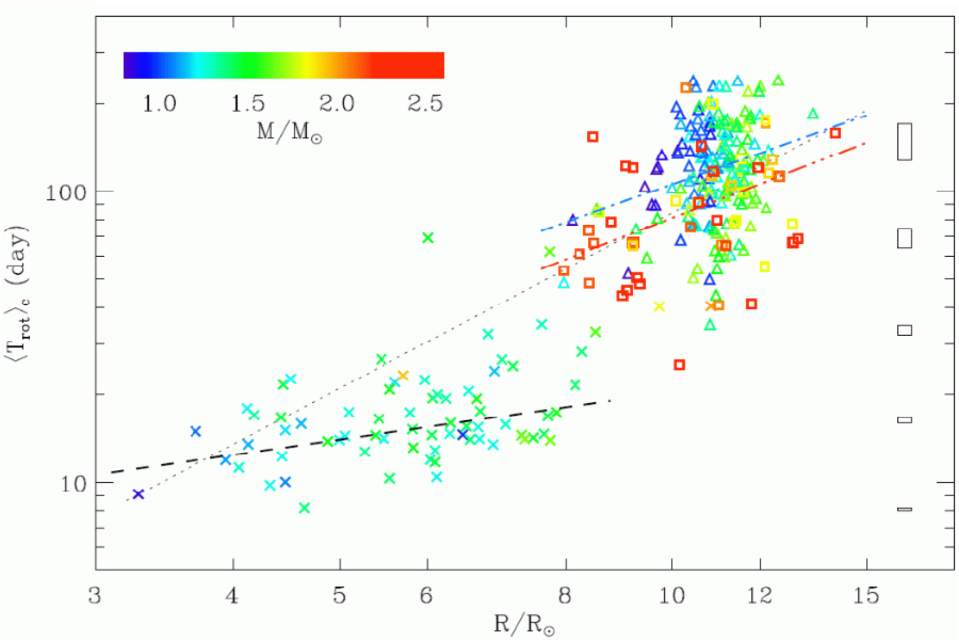






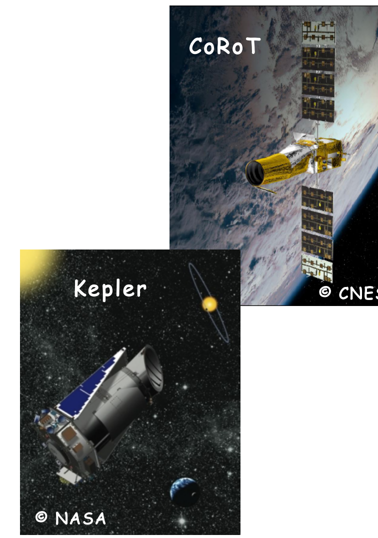
Some results from CoRoT & Kepler

Very successful CoRoT and Kepler missions dedicated to exoplanets detections and asteroseismology



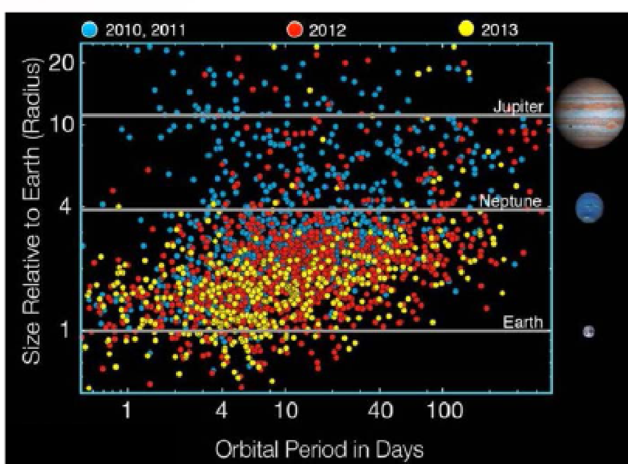
New era for stellar physics

internal rotation of red giants



Large diversity of planetary systems

Kepler planet candidate statistics



CoRoT confirmed exoplanets

Goal of the PLATO 2.0 mission

Main goal of PLATO :

detect terrestrial exoplanets in the habitable zone of solar-type stars and characterise their bulk properties

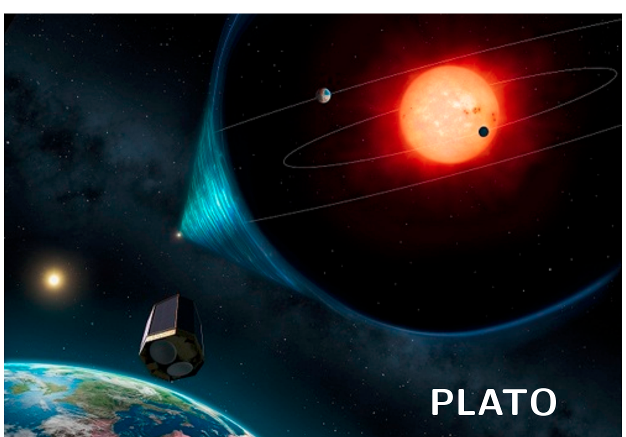
PLATO will be leading this effort by combining:

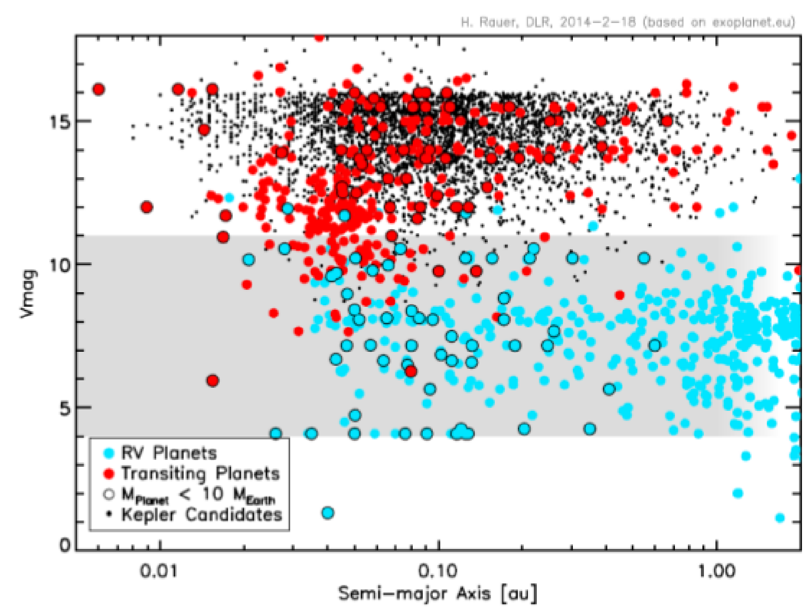
planet detection and radius determination from photometric transits,

determination of planet masses from ground-based radial velocity follow-up,

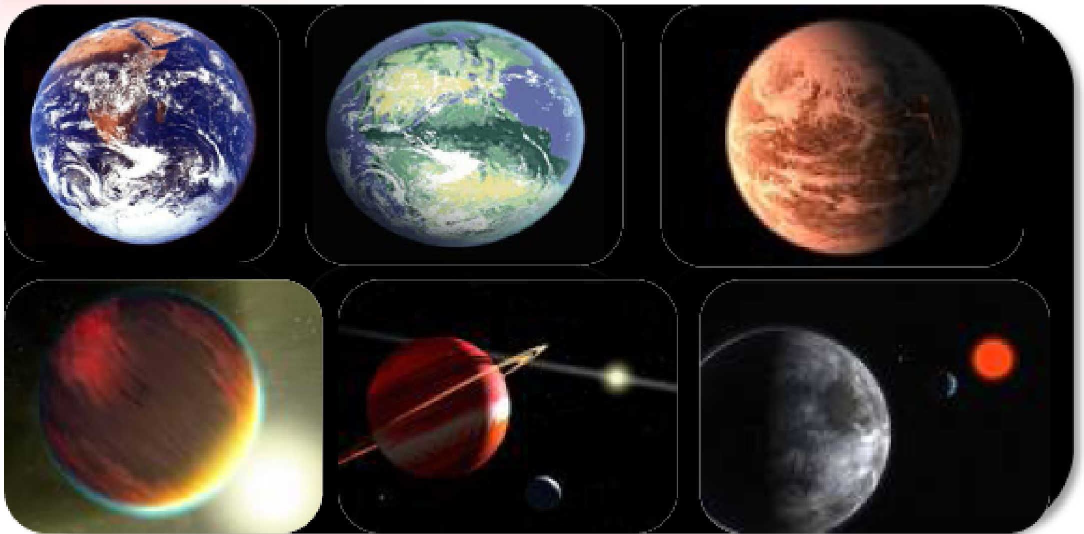
determination of accurate stellar masses, radii, and ages from asteroseismology,

identification of bright targets for atmospheric spectroscopy.





PLATO 2.0: Exoplanets and Stars



Characterization of exoplanets ... **needs characterization of stars**

- Mass + radius → mean density
  (gaseous vs. rocky, composition, structure)
- Orbital distance, atmosphere
  (habitability)
- Age
  (planet and planetary system evolution)

- Stellar mass, radius
  (derive planet mass, radius)
- Stellar type, luminosity, activity
  (planet insolation)
- Stellar age
  (defines planet age)

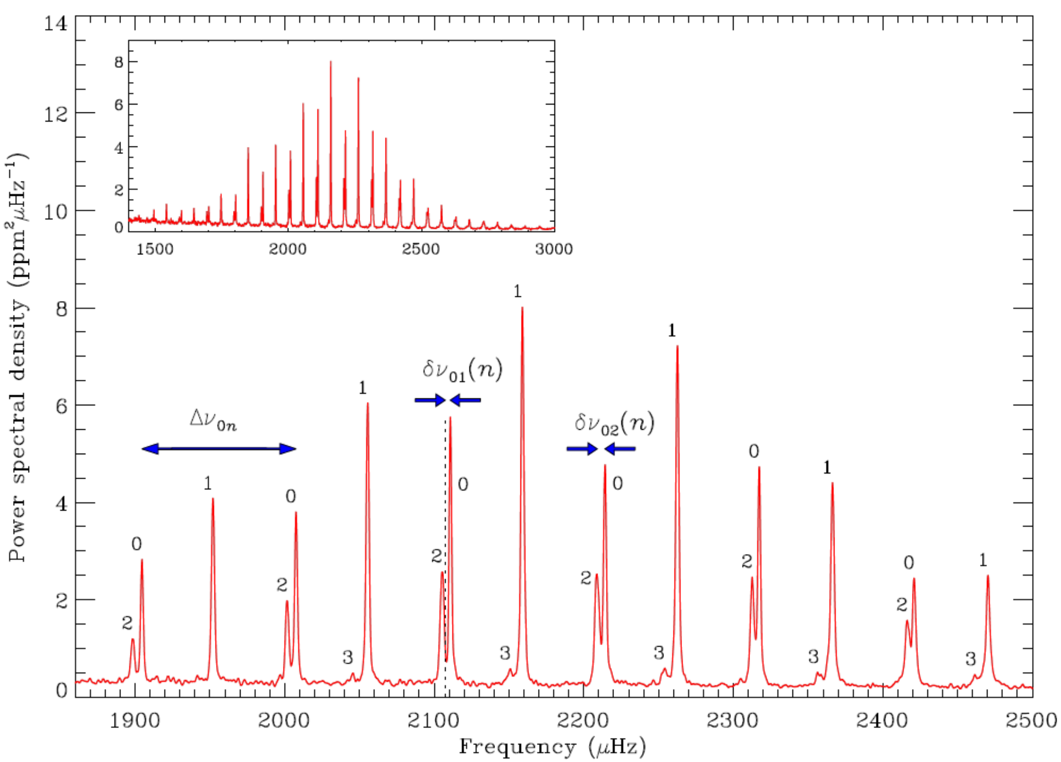
Stellar modelling for asteroseismology

Oscillation spectra computed from stellar models guide the identification of modes.

The separations between modes allow to retrieve M and R provided that T_{eff} is well known

→ need to combine high precision photometry and spectroscopy

→ need a grid of precise stellar models to interpret oscillation spectra



Chaplin & Miglio, 2013

$$\frac{\Delta\nu}{\Delta\nu_\odot} = \left(\frac{M}{M_\odot}\right)^{0.5} \left(\frac{R}{R_\odot}\right)^{-1.5}$$

$$\frac{\nu_{max}}{\nu_{max,\odot}} = \left(\frac{M}{M_\odot}\right) \left(\frac{R}{R_\odot}\right)^{-2} \left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{-0.5}$$

$$\delta\nu \propto \frac{dc_s}{dr} \quad \rightarrow \quad \text{age dependent}$$

PLATO shall give

M within 2%

age within 10 %