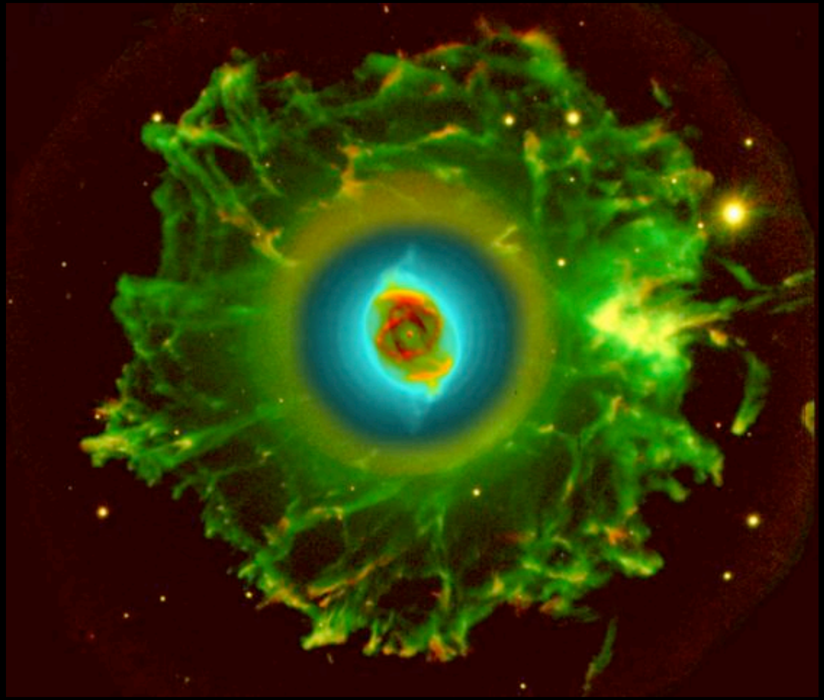
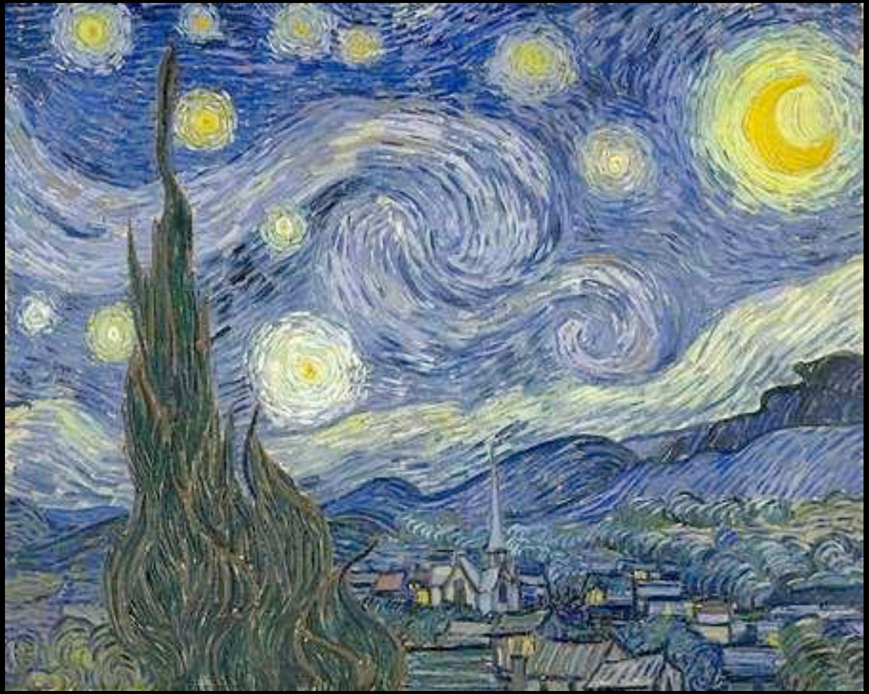
Stellar evolution and nucleosynthesis

- Low- and intermediate mass stars -





Corinne Charbonnel
CNRS & Geneva Observatory

Stellar evolution and nucleosynthesis

- Low and intermediate-mass stars -

- Evolution and nucleosynthesis in stars :

  A global overview of the hydrostatic phases

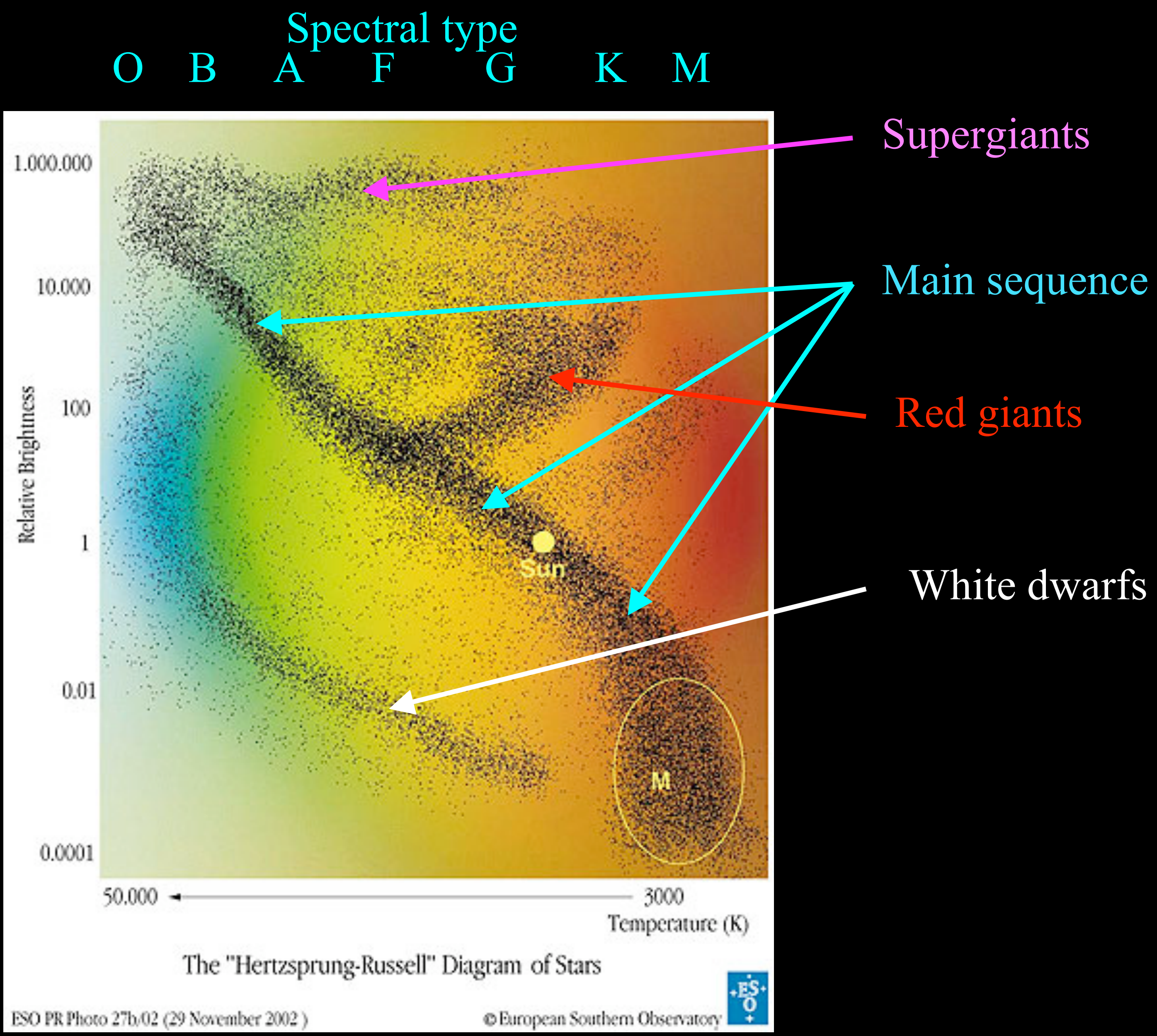
  Diagrams : HRD, log Tc vs log ρc, main evolution and nucleosynthetic phases, mass limits for the various nucleosynthetic paths

- Main sequence nucleosynthesis - Clues from ^{3}He

- Nucleosynthesis in AGB stars

  AGB structure, TP, mass loss, HBB, 3d dredge-up, rotation, processus-s, yields

  Constraints from PNe and post-AGBs



Spectral type

O B A F G K M

Supergiants

Main sequence

Red giants

White dwarfs

The "Hertzsprung-Russell" Diagram of Stars

ESO PR Photo 27b/02 (29 November 2002)

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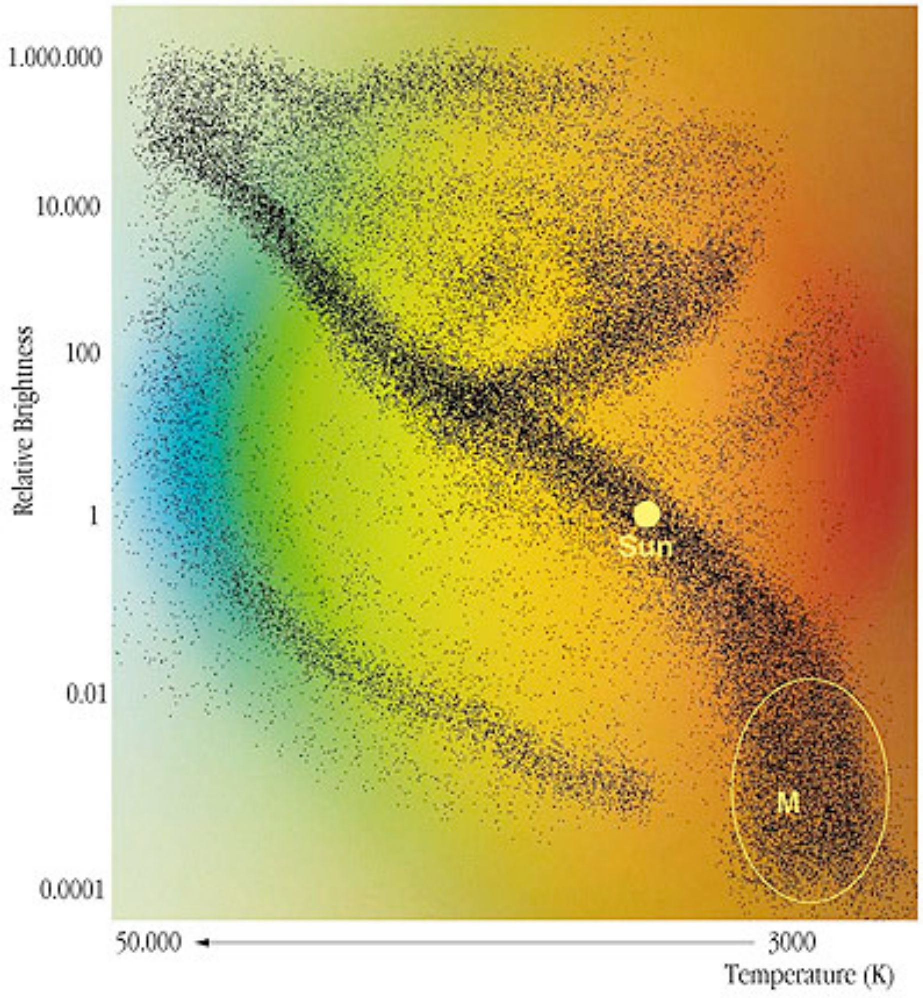
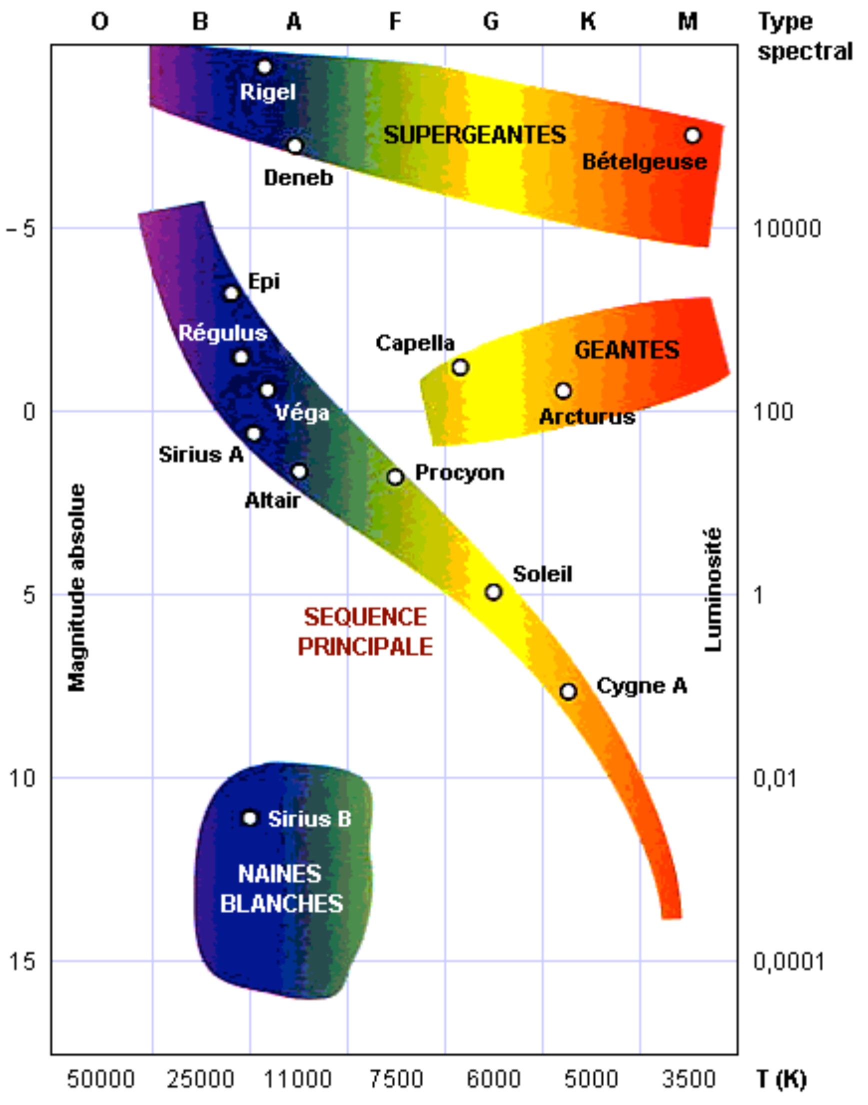
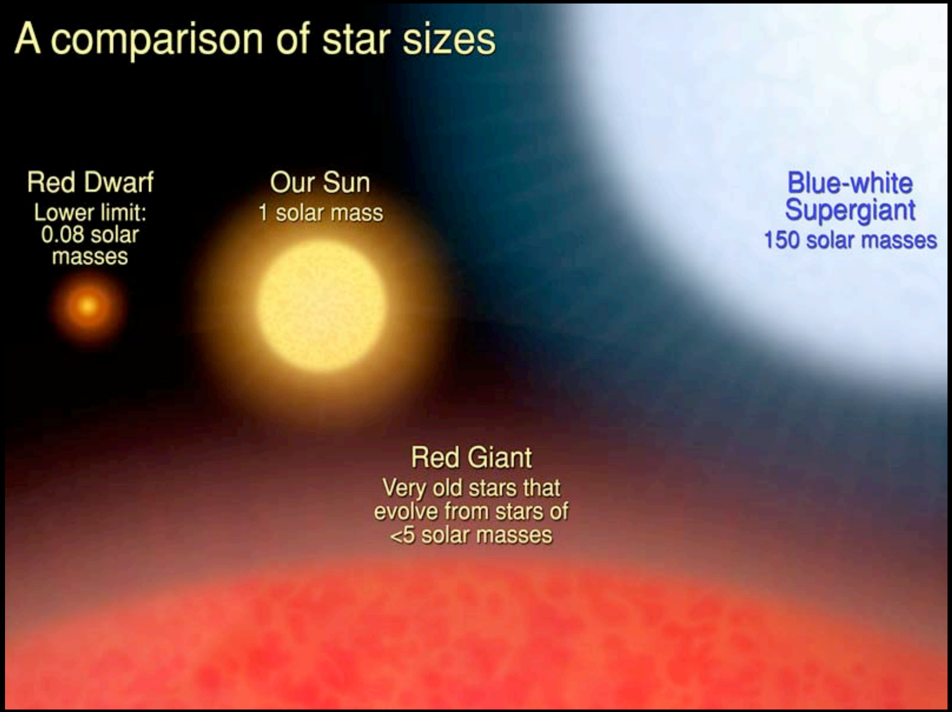
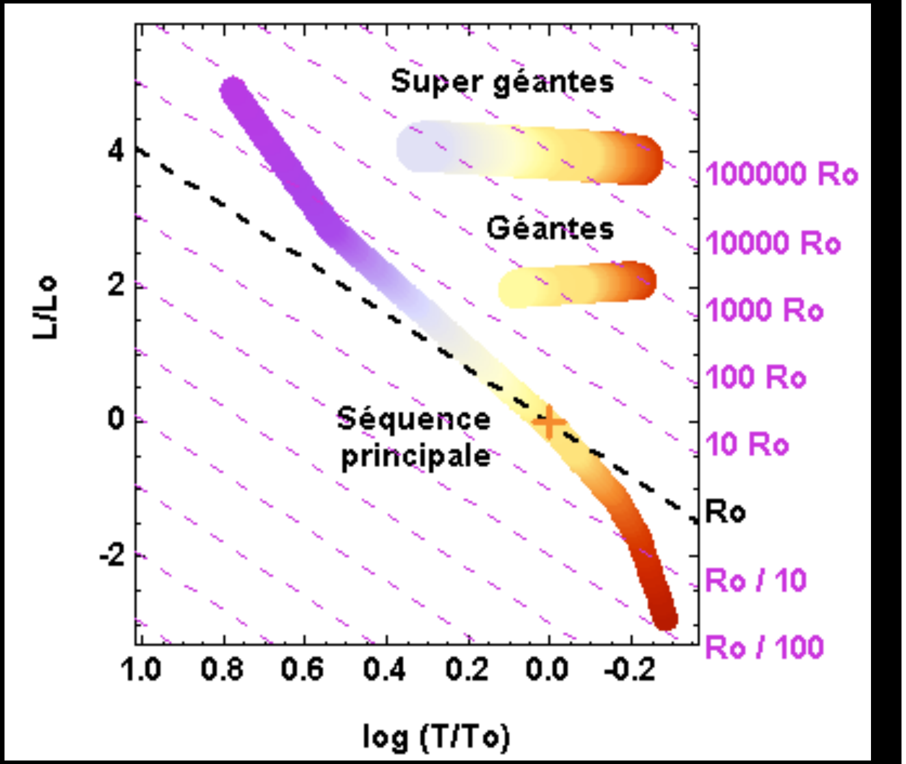


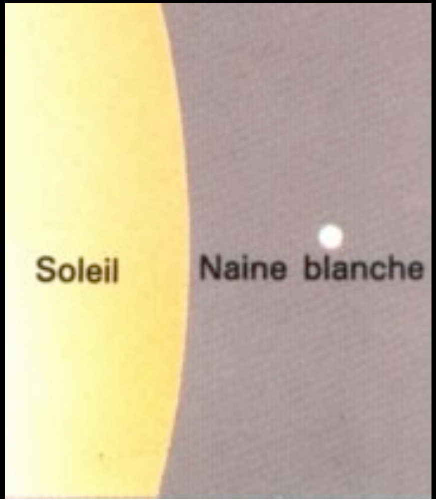
The "Hertzsprung-Russell" Diagram of Stars

ESO PR Photo 27b/02 (29 November 2002)




A comparison of star sizes
Red Dwarf
Lower limit: 0.08 solar masses
Our Sun
1 solar mass
Blue-white Supergiant
150 solar masses
Red Giant
Very old stars that evolve from stars of <5 solar masses


Super géantes
Géantes
Séquence principale
L/Lo
4
2
0
-2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
log (T/To)
100000 Ro
10000 Ro
1000 Ro
100 Ro
10 Ro
Ro
Ro / 10
Ro / 100


Soleil
Naine blanche

Initial stellar mass determines the life stages

- Initial stellar mass determines stages stars go through and how long they last in each stage
  - with just little bit of dependence on composition

- Massive stars evolve faster than small stars
  - Relationship between the luminosity and mass determined by how compressed gases behave
  - Small increase in mass produces a large increase in the luminosity of a star

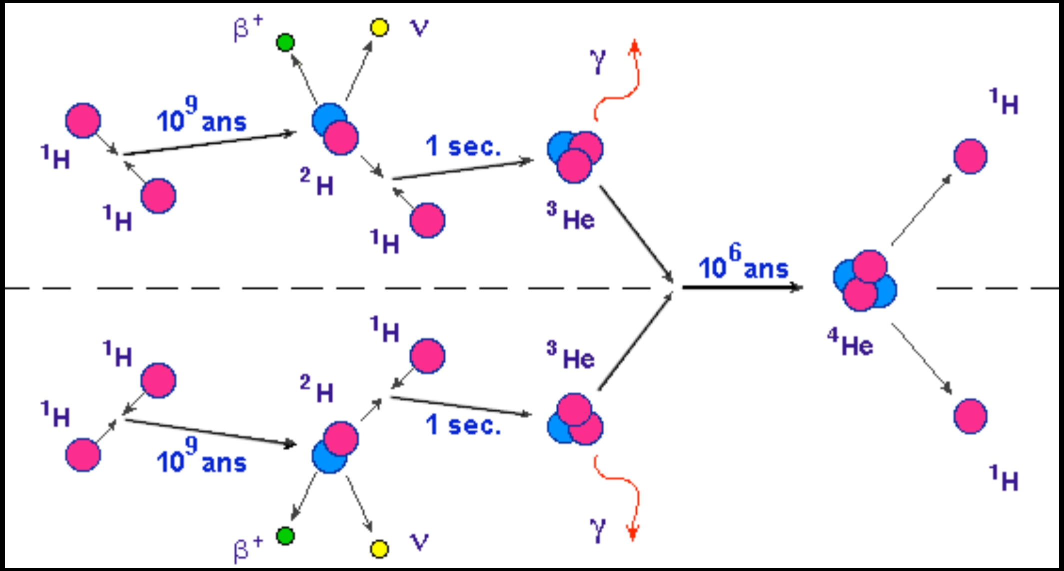
Lifetime vs initial mass

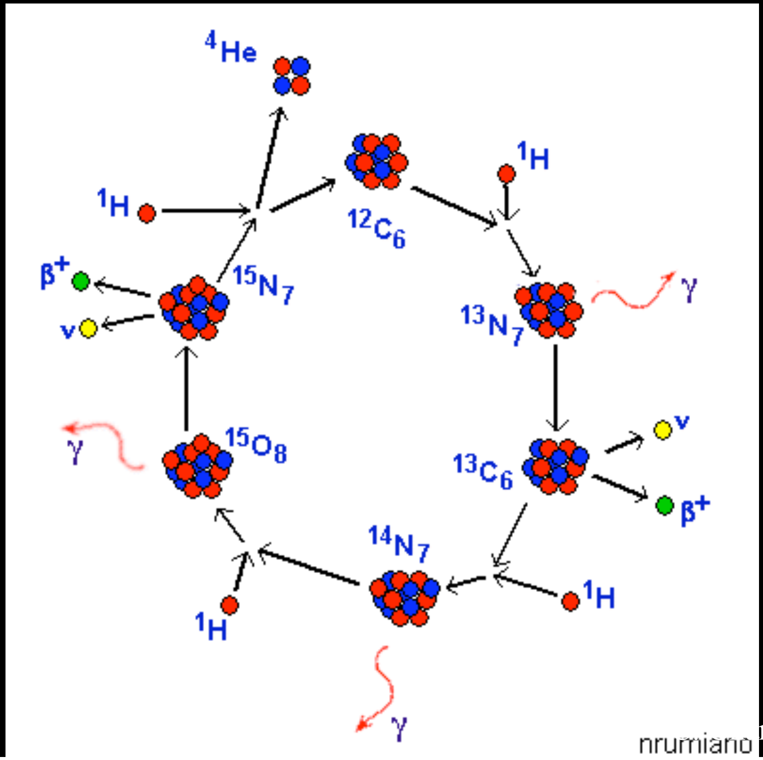
Higher initial mass ⇒ hotter on the main sequence and more short lived

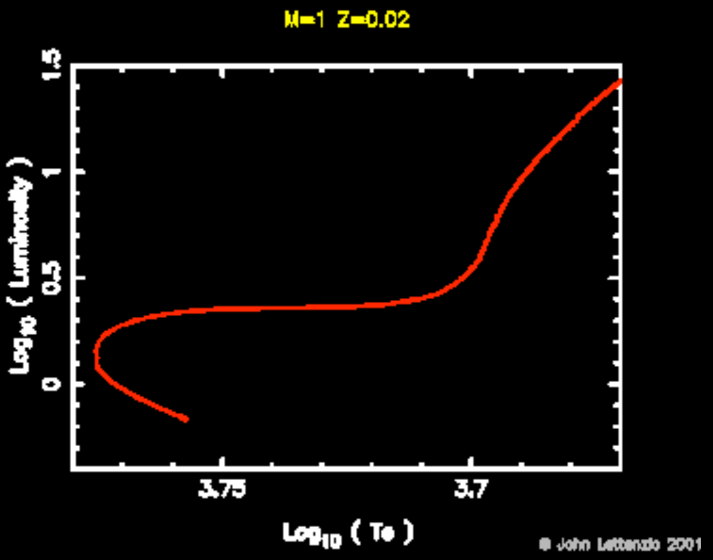
Main sequence lifetime (at solar metallicity) :

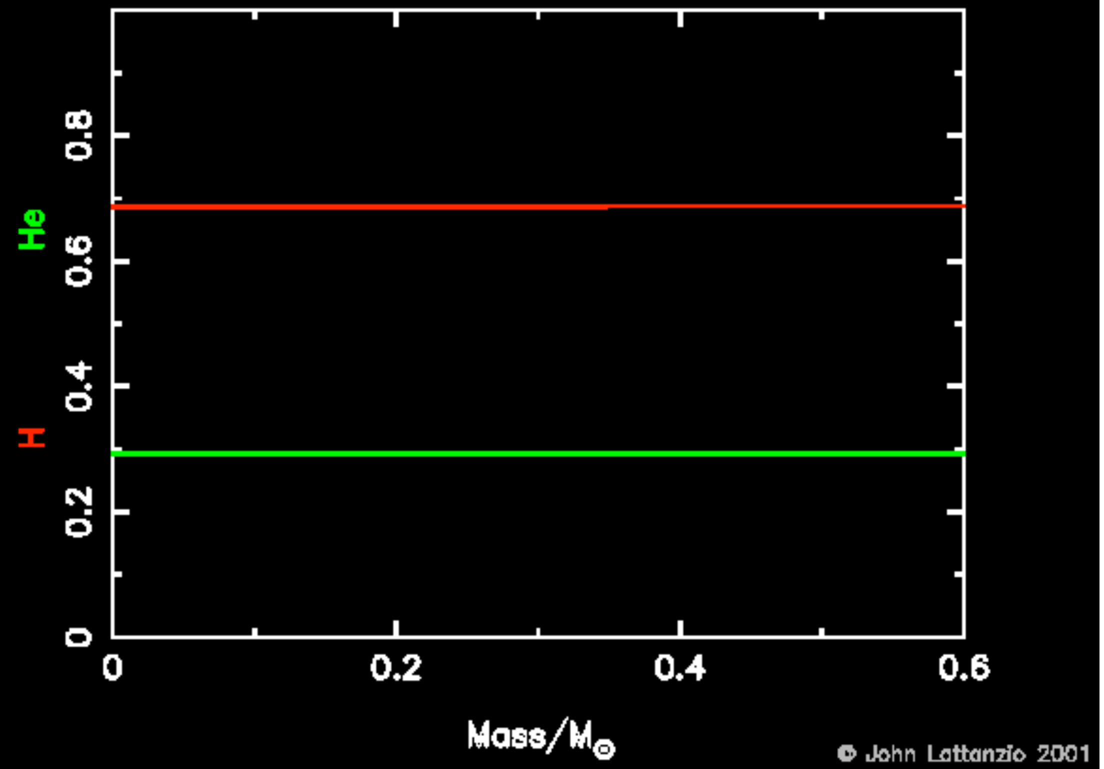
star mass (solar masses)	**time (years)**	**Spectral type**
60	3 million	O3
30	11 million	O7
10	32 million	B4
3	370 million	A5
1.5	3 billion	F5
1	10 billion	G2 (Sun)
0.1	1000's billions	M7

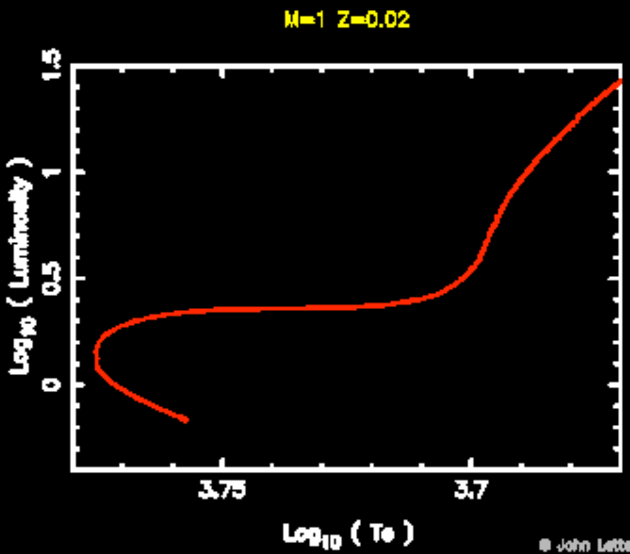
Nucleosynthesis on the main sequence


β+
ν
β+
ν
1H
1H
10^9 ans
2H
1H
1 sec.
γ
3He
10^6 ans
4He
1H
1H
1H
1H
1H
1H
2H
10^9 ans
1 sec.
3He
γ


4He
1H
12C6
1H
β+
15N7
ν
13N7
γ
γ
15O8
13C6
ν
β+
14N7
1H
1H
γ
nrumiano


M=1 Z=0.02
Log$_{10}$ (Luminosity)
1.5
1
0.5
0
3.75
3.7
Log$_{10}$ (Te)
© John Lattanzio 2001


H
He
0
0.2
0.4
0.6
0.8
0
0.2
0.4
0.6
Mass/M$_{\odot}$
© John Lattanzio 2001



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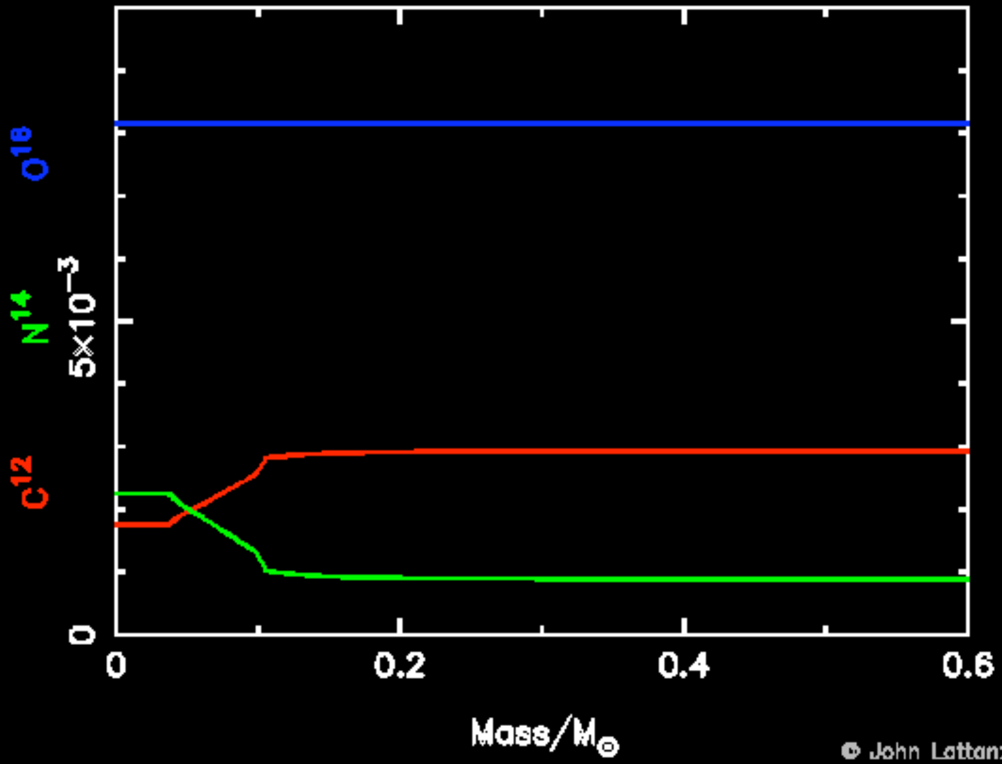

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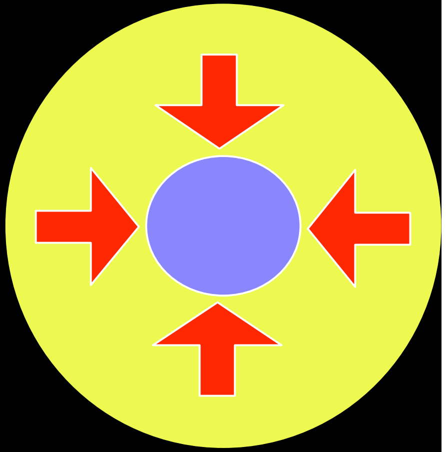
From the main sequence to the red giant branch

- Main sequence: inward gravity balanced by the outward pressure
- Pressure due to fusion in core

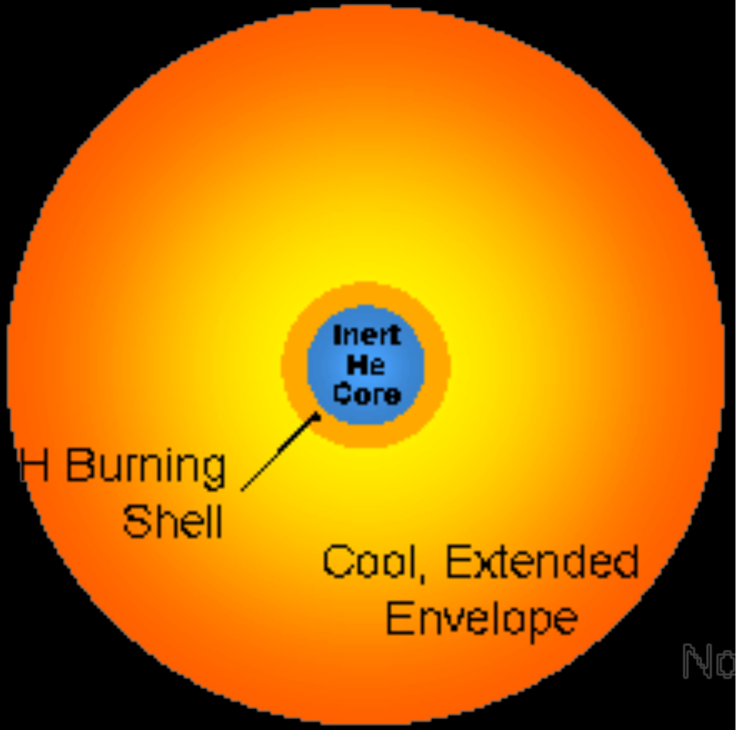
- Hydrogen in the core eventually converted to helium

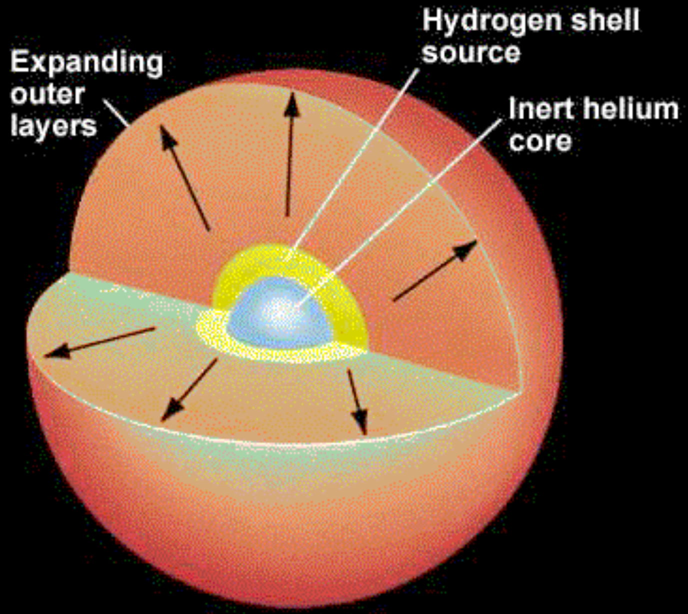
  ⇒ nuclear reactions stop!
- Gravity takes over and the core shrinks
- Outside layers also collapse
- Layers closer to the center collapse faster than those near the surface.
- As the layers collapses, the gas compresses and heats up

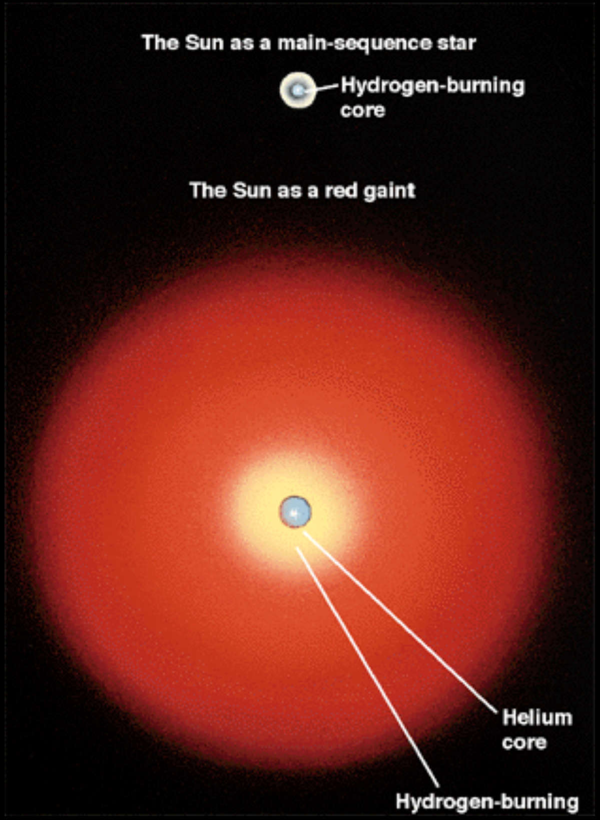


From the main sequence to the red giant branch

- Shell layer outside the core becomes hot and dense enough for fusion to start → ***H-burning shell***
- shell fusion is very rapid because the shell layer is still compressing and increasing in temperature
- luminosity of the star increases from its main sequence value
- Gas surrounding the core puffs outward under the action of the extra outward pressure
- The star expands and becomes a ***subgiant*** and then a ***red giant***

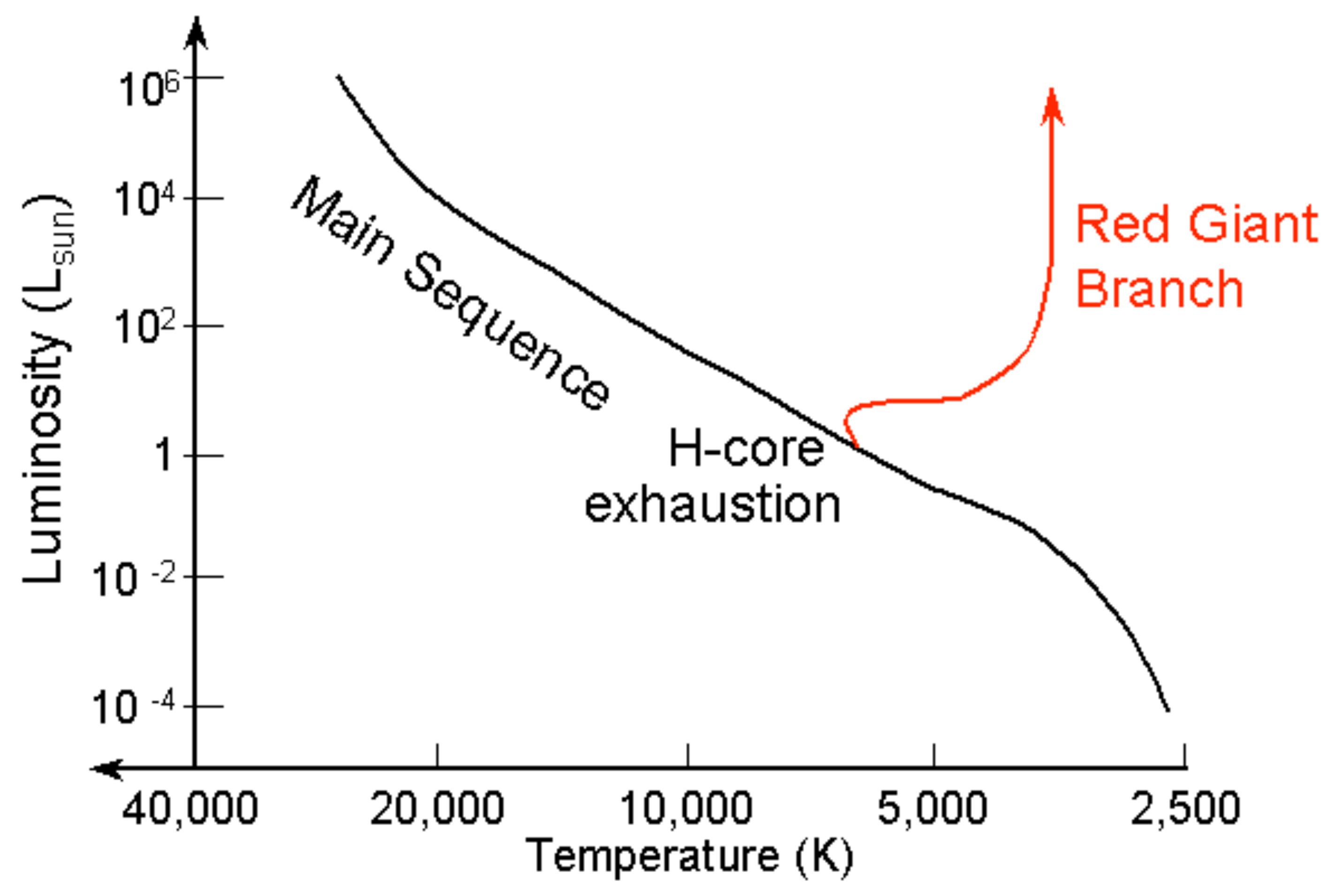






Figures from Lattanzio

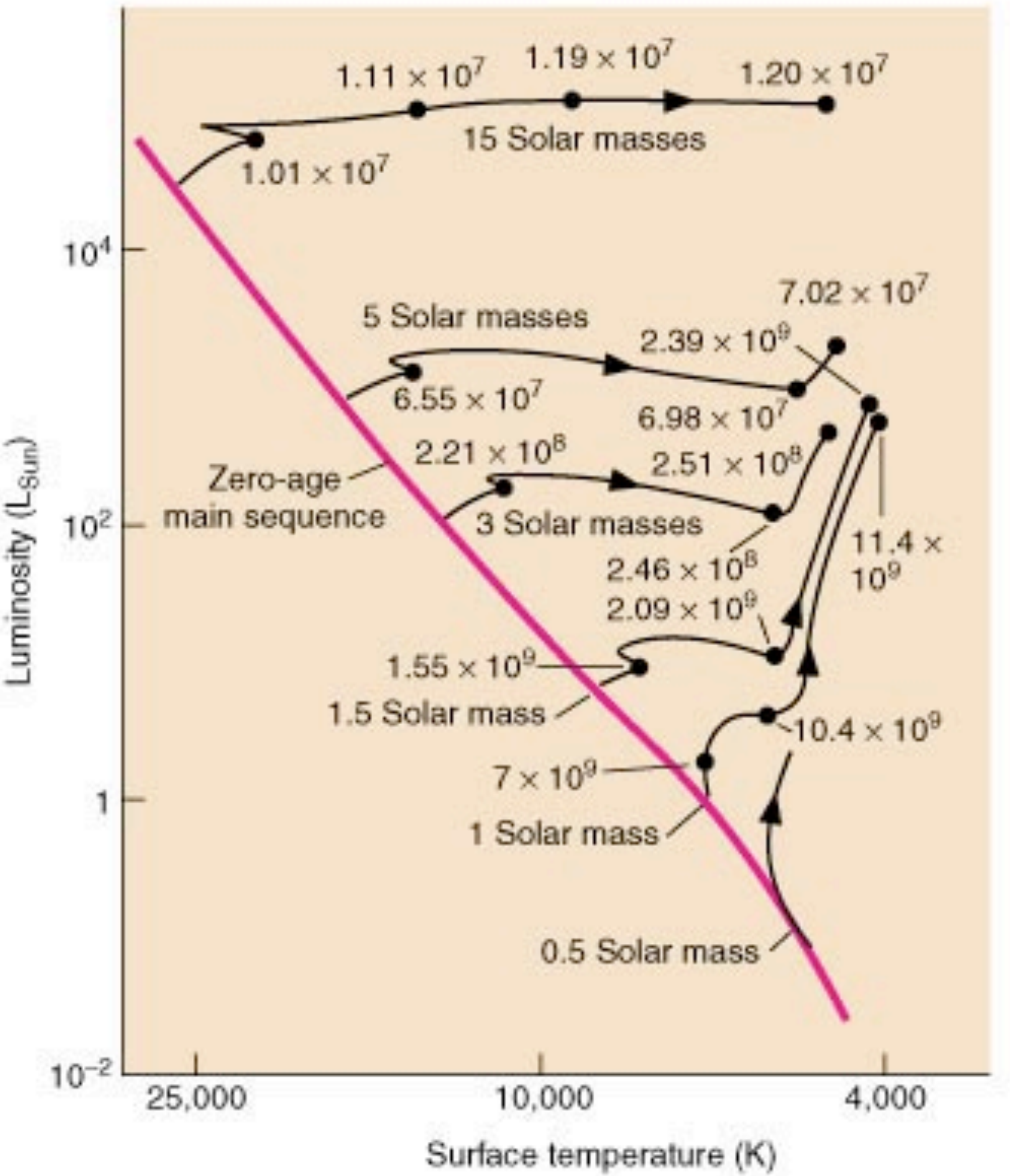
From the main sequence to the red giant branch



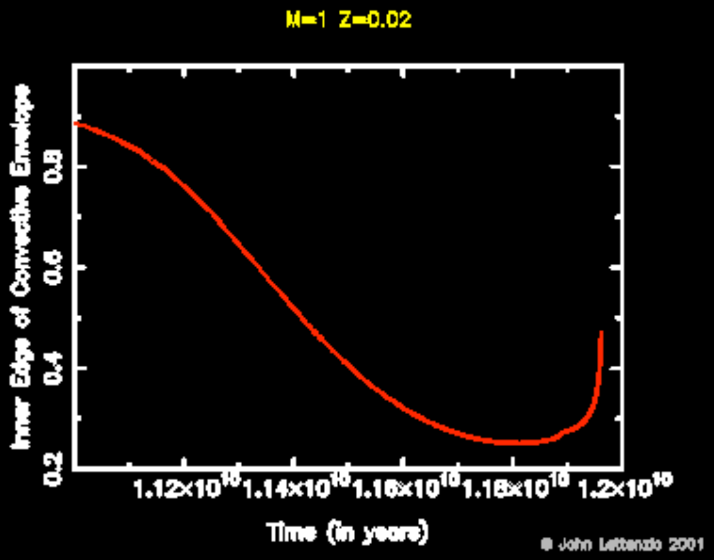
Time to reach the red giant stage

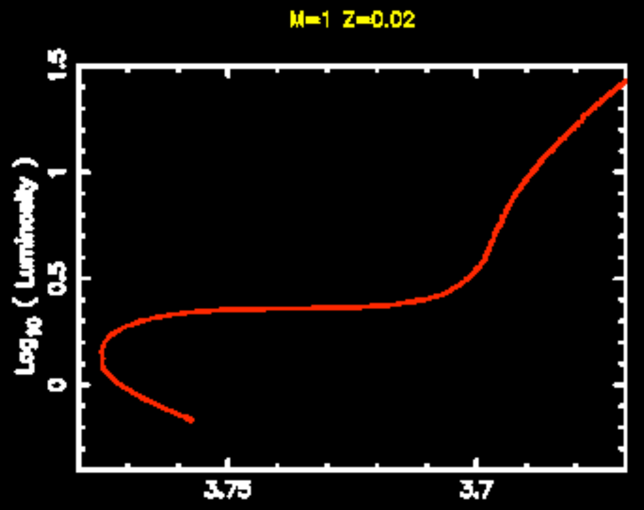
short for big stars
→ as low as 10 million (10^7) years

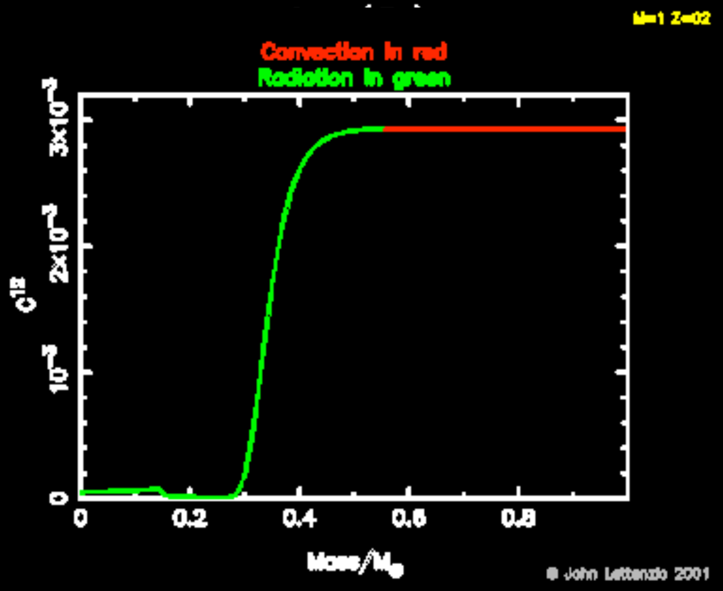
long for little stars
→ up to 10 billion (10^{10}) years for low mass



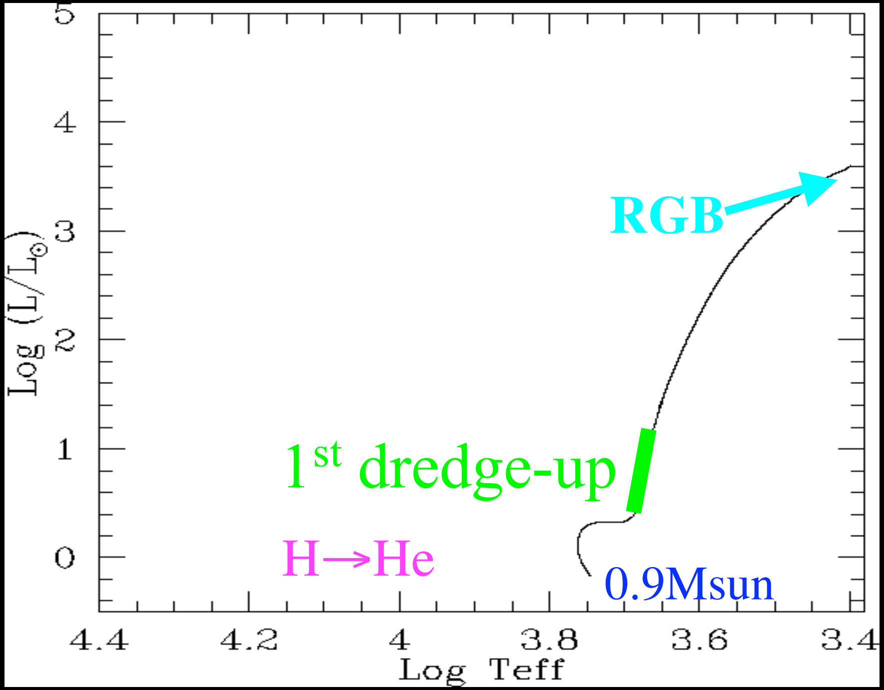
1st dredge-up

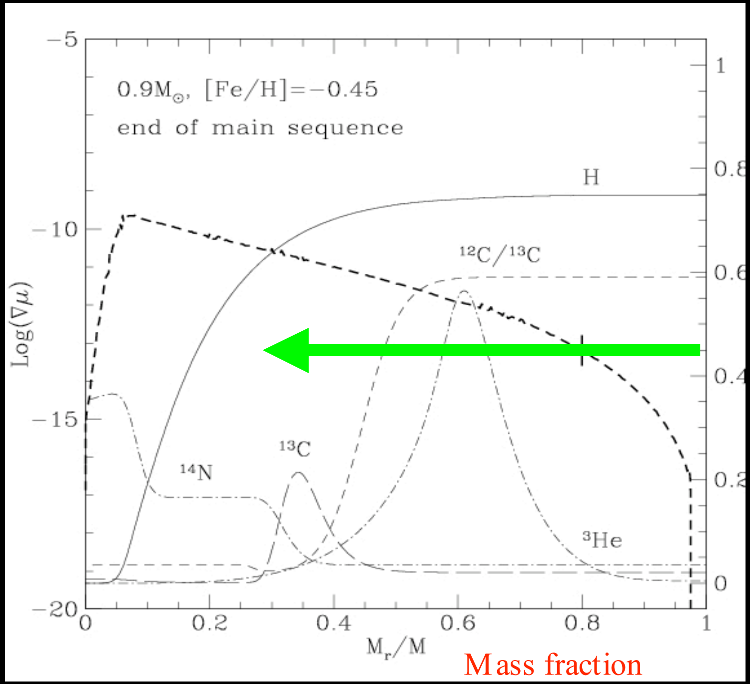






Changes of surface abundances during the 1st dredge-up





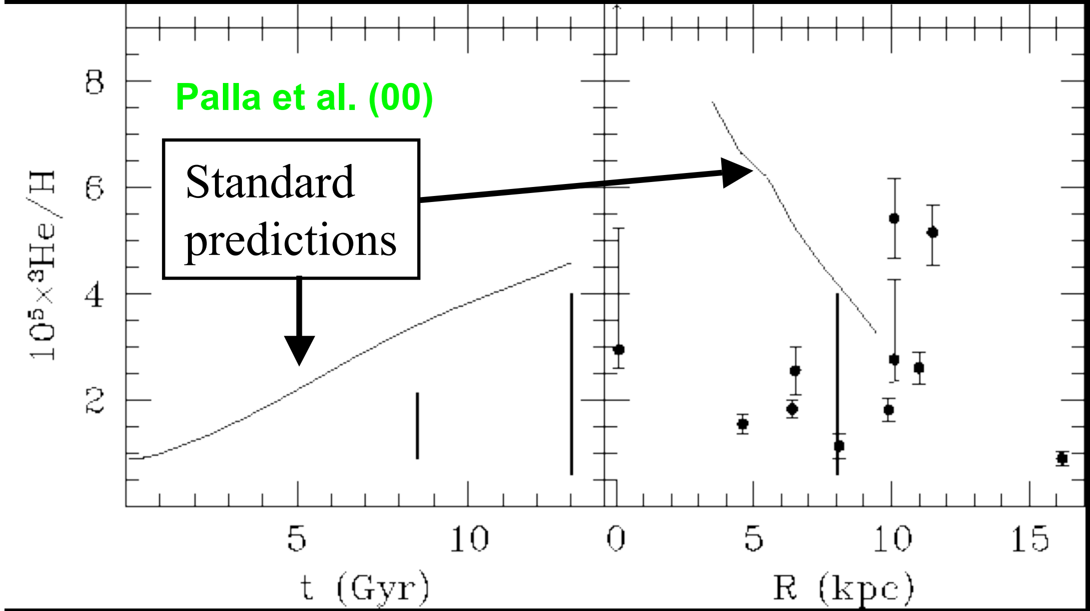
Mass fraction
100 x X(^{3}He, ^{14}N)
1000 x X(^{13}C)
^{12}C/^{13}C/100

^{3}He ↑, ^{12}C/^{13}C ↓ (90→ 30, 20), ^{12}C ↓ (~30 %) , ^{14}N ↑ (x 2)

O, heavier elements ~ (No NaNe nor MgAl on the main sequence)

No additional variations after the end of the 1st dredge-up

Consequences for the evolution of ^{3}He in the Galaxy ?



Palla et al. (00)

Standard predictions

Solar neighborhood
(PSC & LIC)
Geiss (93)
Gloeckler & Geiss (96)

HII regions

Rood et al. (95)

A nuclear solution?

Low energy resonance in the cross section of

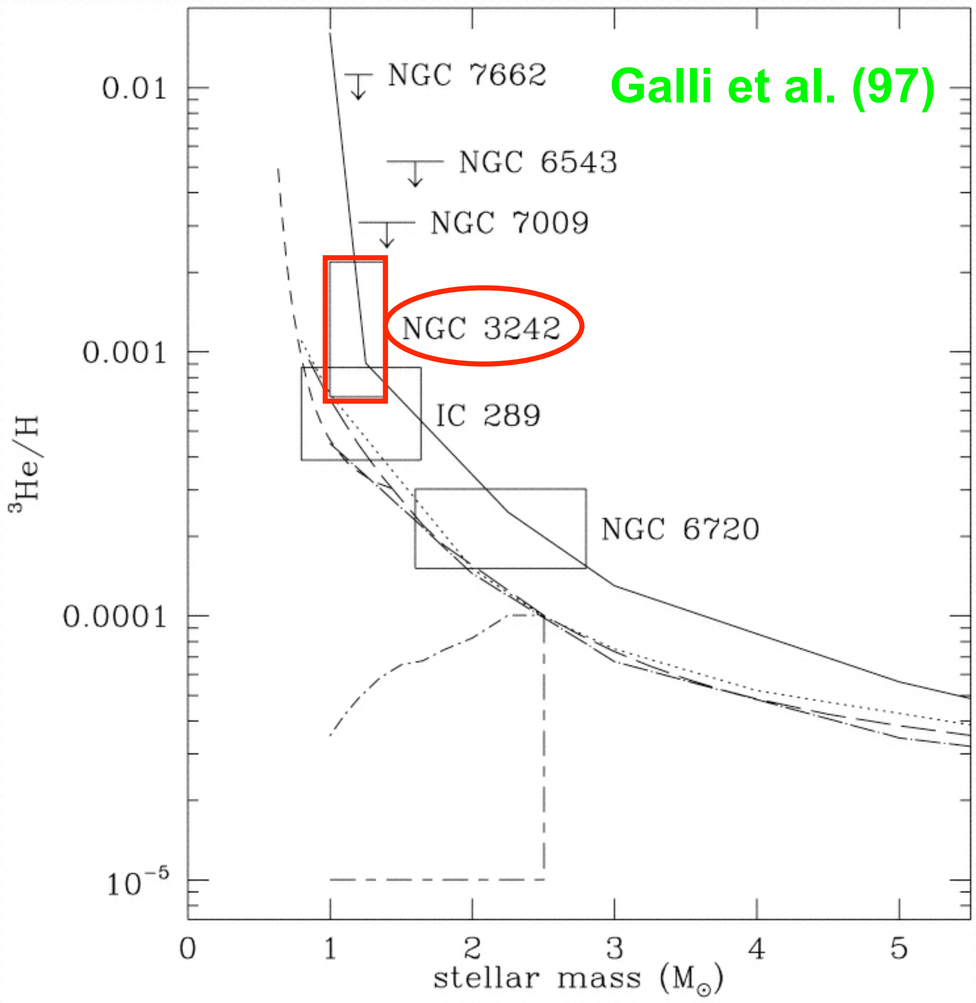
$^3He(^3He,2p)^4He$?

Excluded by the LUNA experiment (Gran Sasso)

Junker et al. (98)

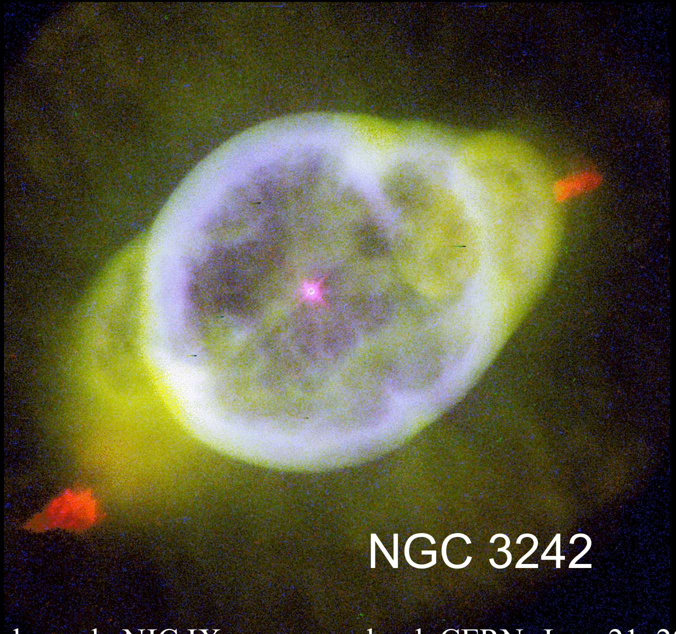
« The galactic ^{3}He problem »

Consequences for the evolution of ^{3}He in the Galaxy ?



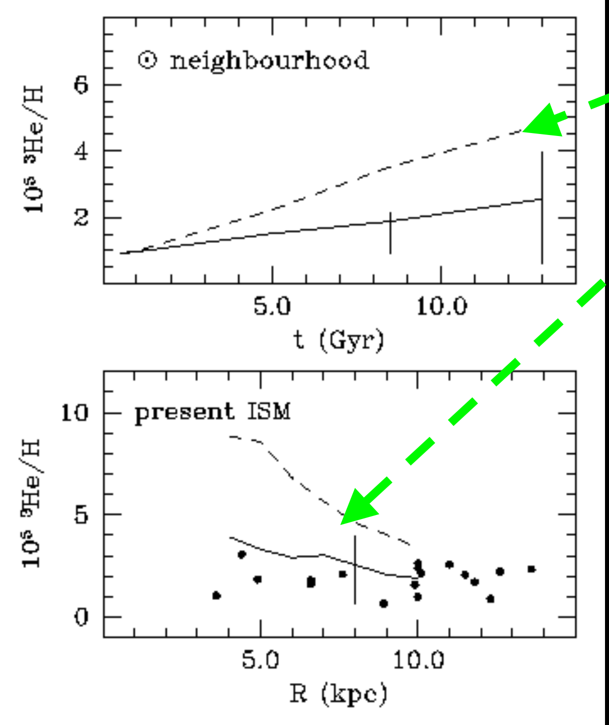
A nuclear solution?

Excluded by the ^{3}He measurement in PNe



C. Charbonnel. NIC IX summer school. CERN. June 21, 2006

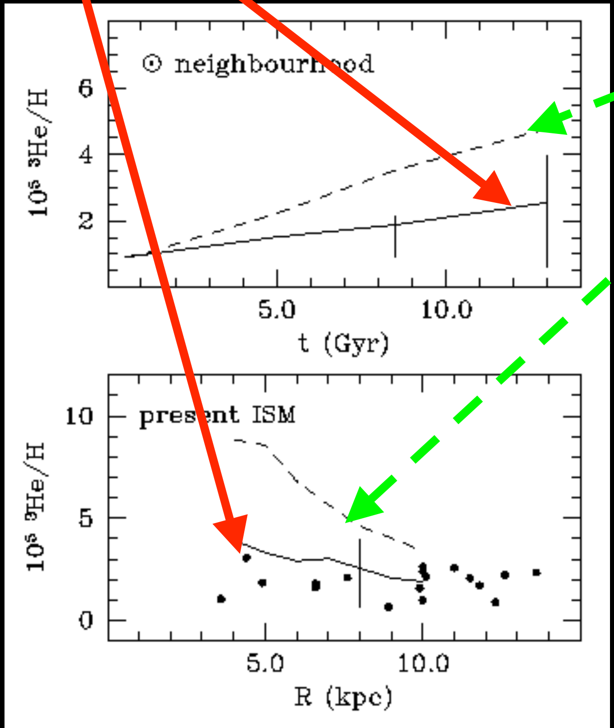
Standard predictions



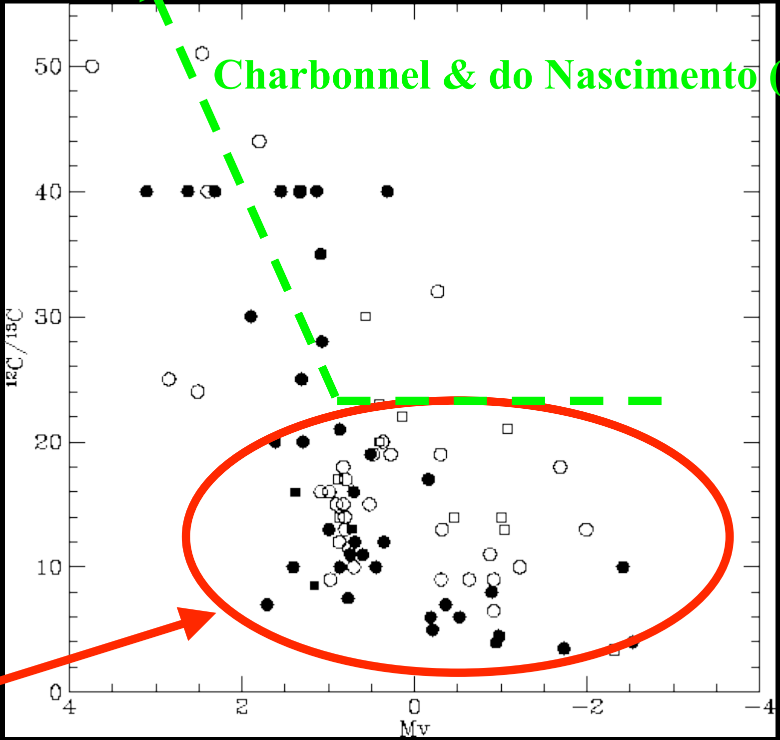
Palla et al. (02)
See also Tosi (98)

> 90% of the low-mass stars must destroy ^{3}He

Standard predictions



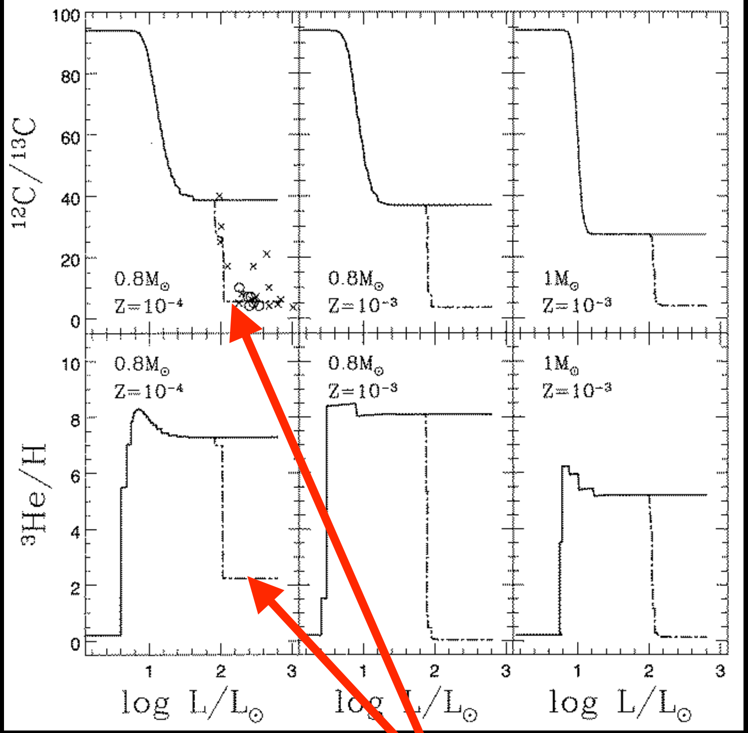
Palla et al. (02)
See also Tosi (98)



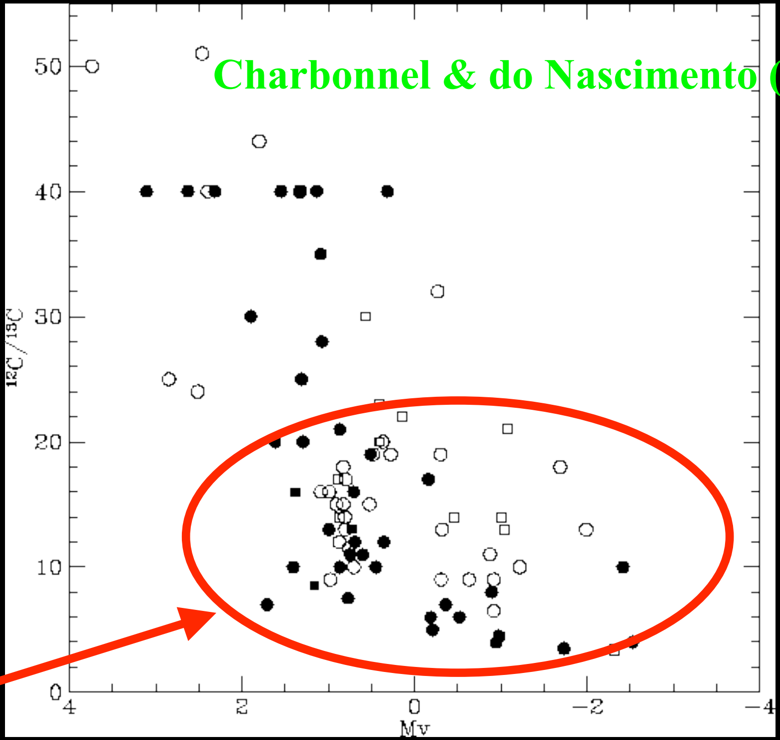
Charbonnel & do Nascimento (98)

> 96% of the low-mass stars further decrease ^{12}C/^{13}C (mixing process beyond standard theory)

> 90% of the low-mass stars must destroy ^{3}He



Charbonnel (95)



Charbonnel & do Nascimento (98)

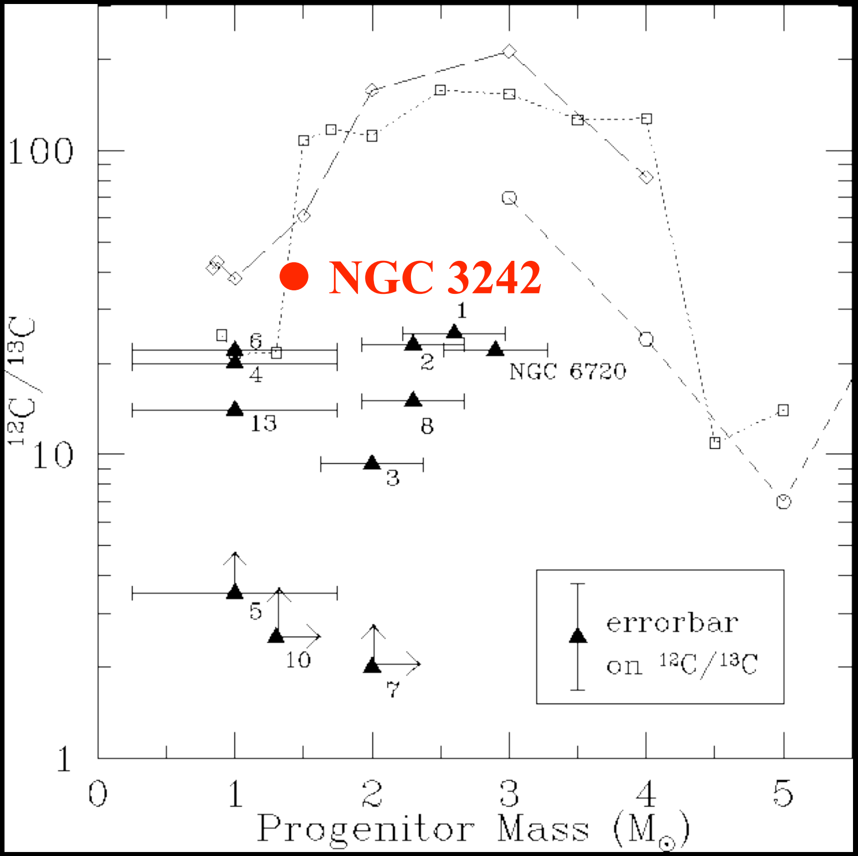
—— Standard

- - - - - - Rotation

> 96% of the low-mass stars further decrease $^{12}C/^{13}C$

(mixing process beyond standard theory)

$^{12}C/^{13}C$ in PNe



Palla et al. (00)

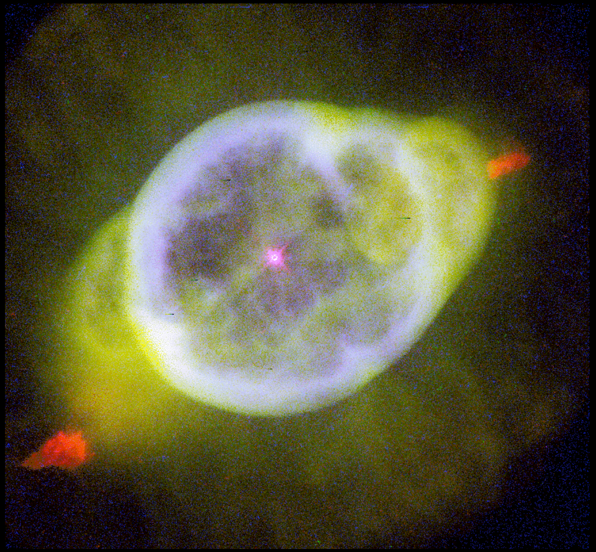
Palla et al. (02)

Ejecta at the tip of the AGB (ZM) :

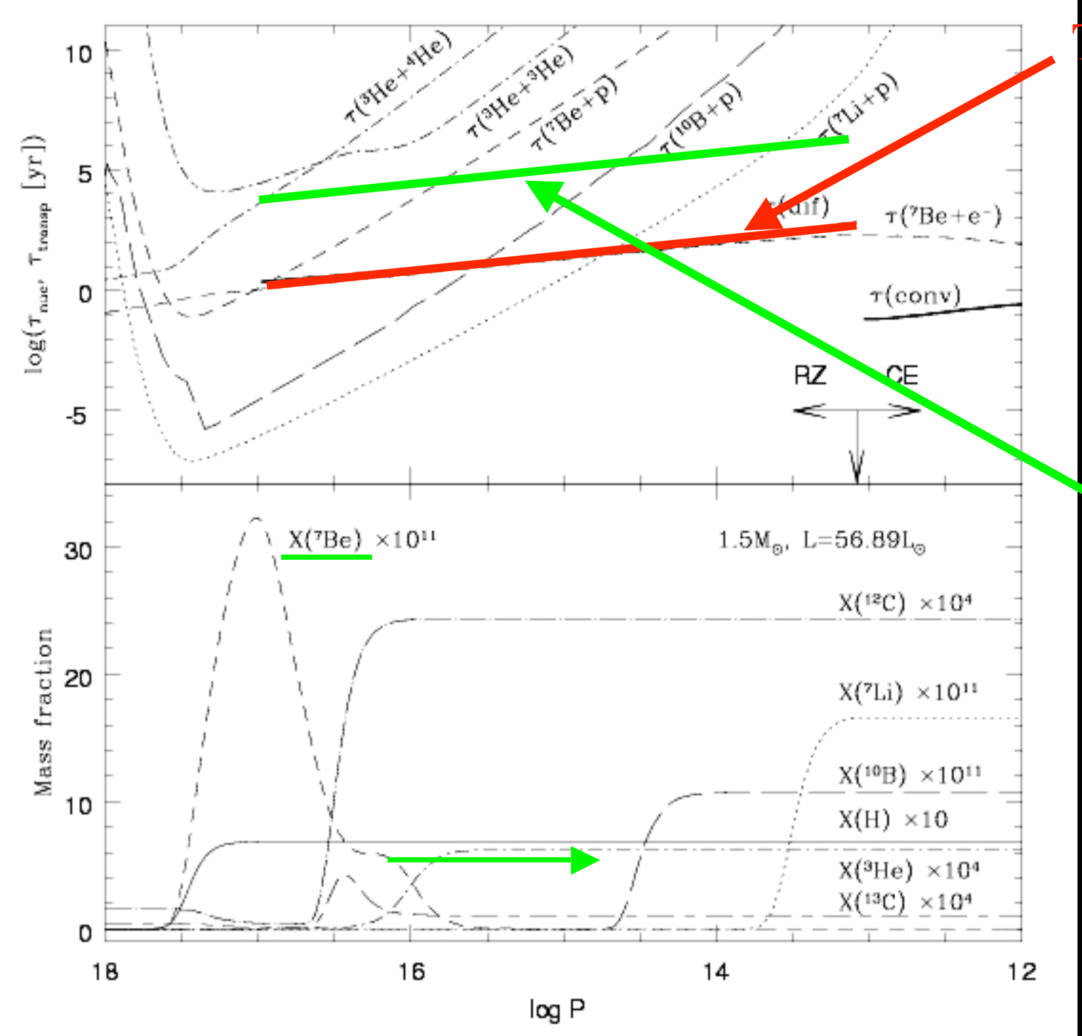
Van den Hoek & Groenewegen (97) ·········

Forestini & Charbonnel (97) – – –

Marigo (98) — —



Lifetimes of various chemical elements in the radiative zone around the hydrogen burning shell



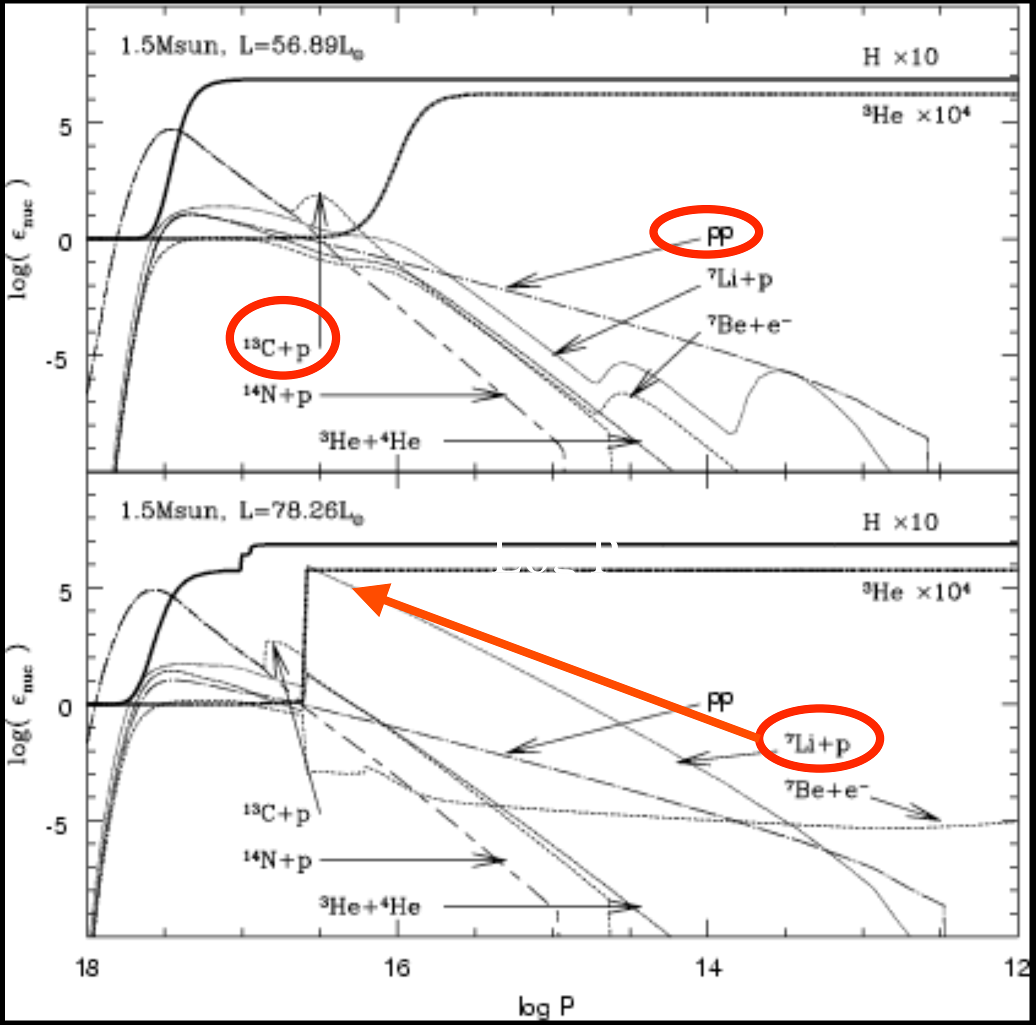
The «Cameron-Fowler» mechanism requires $D_{mix} > 10^{11}$ cm^{2}sec^{-1} →τ(dif)

Mixing timescale for Drot ~ 10^5 to 10^8 cm^2.sec^{-1}
→ ^{7}Be is transported outward, but decays in a region where ^{7}Li burns

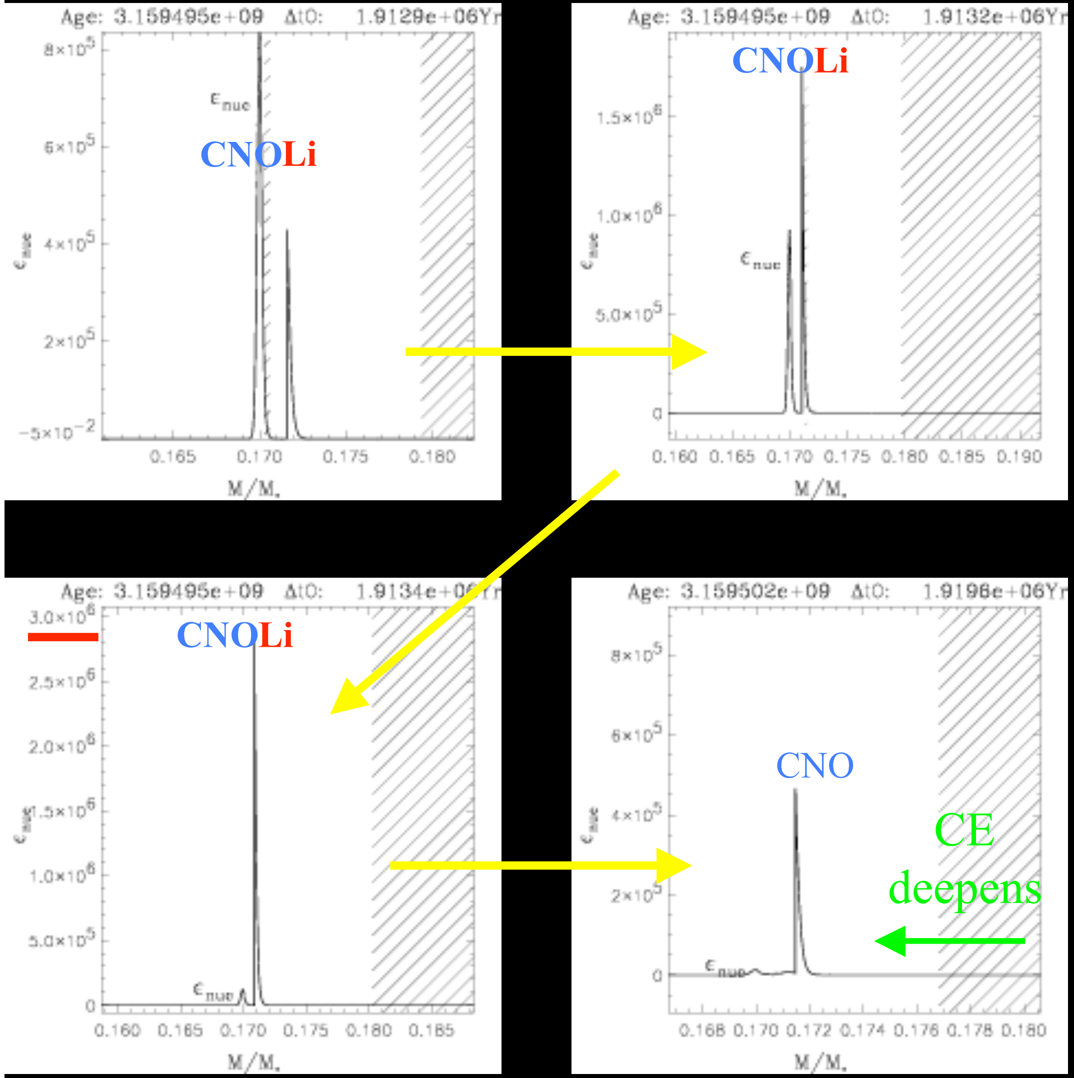
→ « Li-flash »

Palacios, Charbonnel & Forestini (01)

The Lithium flash



The Lithium flash



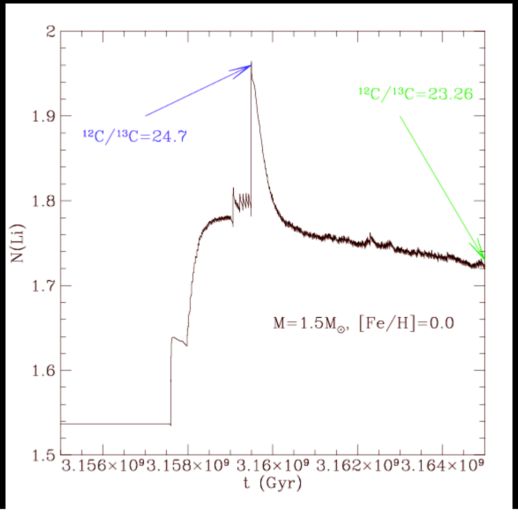
Palacios, Charbonnel & Forestini (01)

ε_{nuc} ↗↗ ⇒ Ur ∝ εnuc ↗

⇒D_{mix} ↗

⇒^{7}Li ↗ in the convective envelope

⇒**Super lithium-rich red giant phase** at the very beginning of the extra-mixing episode



From rotation-induced mixing to the Lithium flash

1) Rotation $\Rightarrow D_{mix} \sim 10^5$ to 10^8 cm^2/s

2) ^{7}Be is transported outward, but decays in a region where ^{7}Li burns

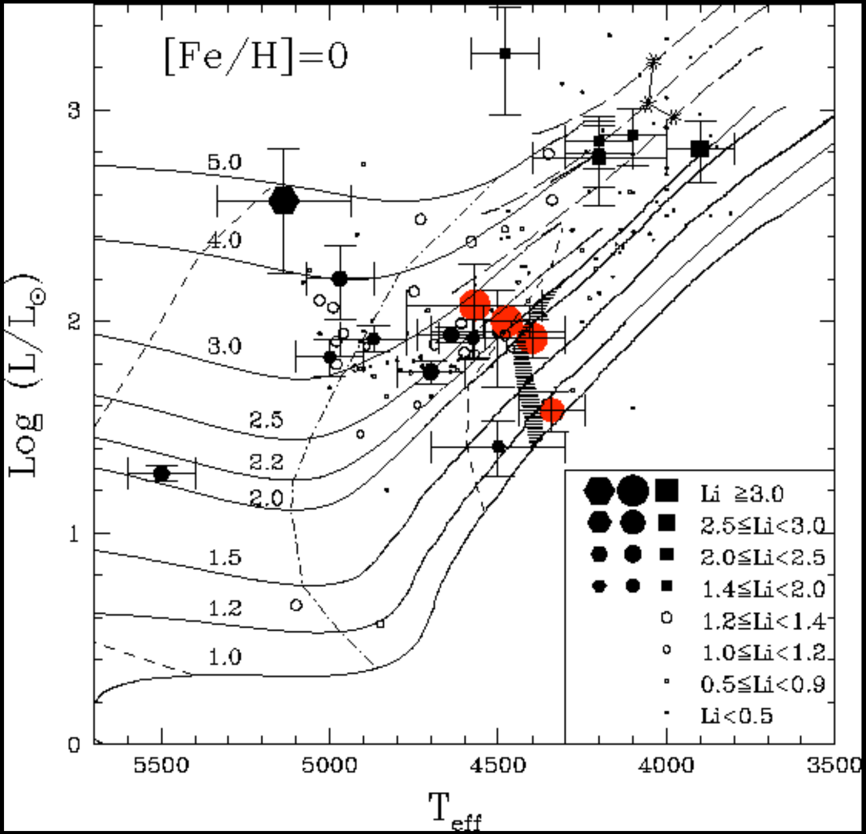
3) $\varepsilon_{nuc} \nearrow\nearrow$ via ^{7}Li(p,α)^{4}He $\Rightarrow$ FLASH = $\nearrow\nearrow$ L☆, dM/dt (IRAS fluxes)
(Bright Li rich stars in GCs and formation of a dust shell)

4) $\varepsilon_{nuc} \nearrow\nearrow \Rightarrow U_r \propto \varepsilon_{nuc} \nearrow \Rightarrow D_{mix} \nearrow + D_{conv} \nearrow$
$\Rightarrow$ ^{7}Li $\nearrow$ in the convective envelope
$\Rightarrow$ Super lithium-rich red giant with ~ standard ^{12}C/^{13}C
(~ 50 - 60 % of τ(bump) ~ few 10^6 years)

5) $\Rightarrow$ Decrease of ^{7}Li , ^{12}C et ^{12}C/^{13}C
Deepening of the convective envelope
$\Rightarrow$ Build up of a new μ-gradient that inhibits further mixing

Lithium rich RGB stars

Field stars with Π (Hipparcos)

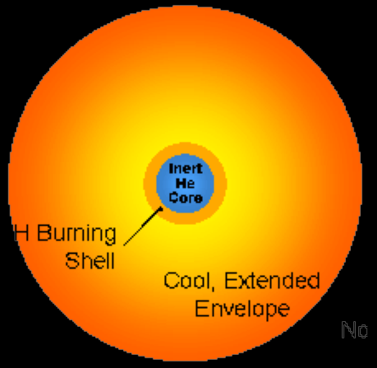


Charbonnel & Balachandran (00)

Central Helium burning

From the red giant branch

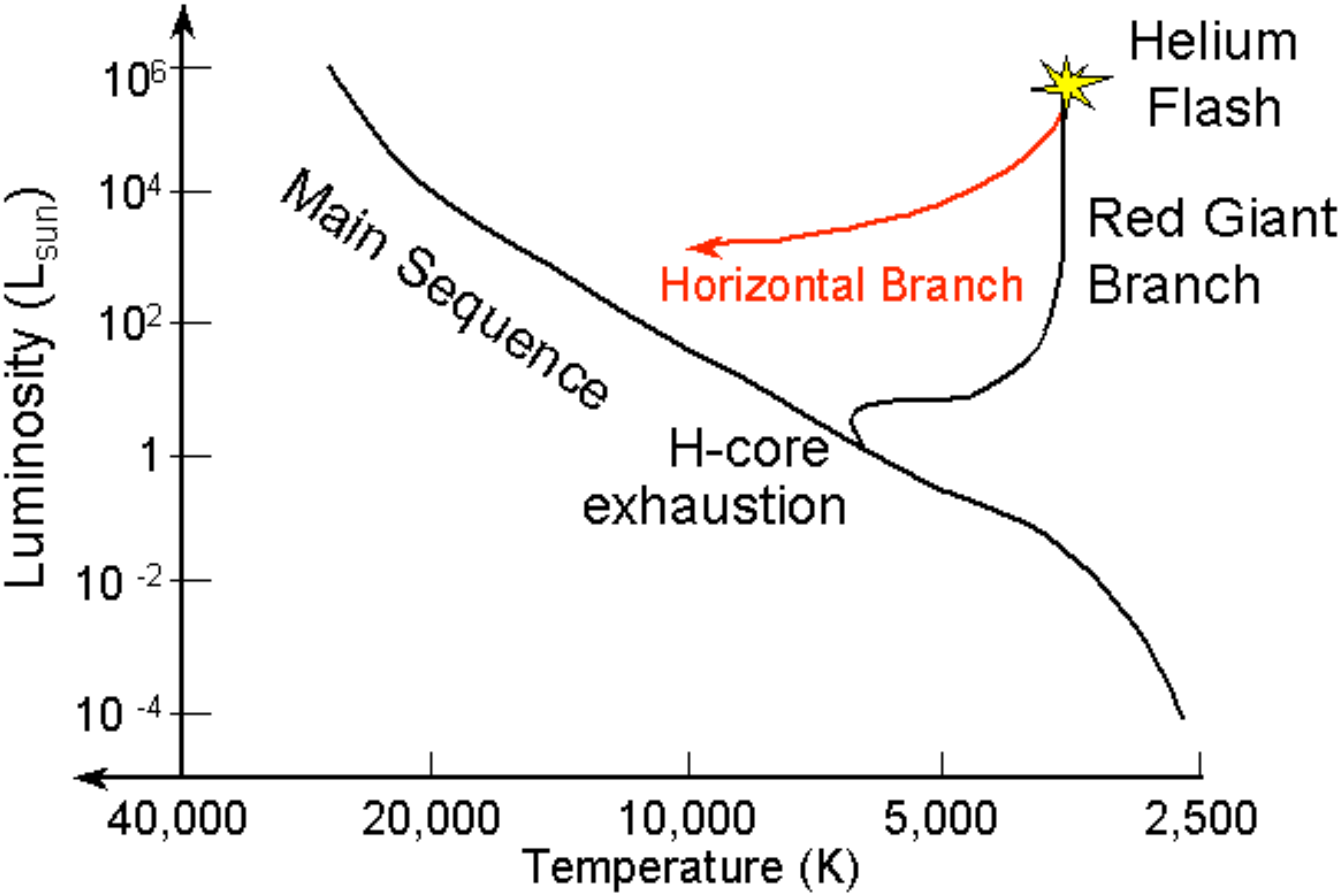
- Red giant branch : degenerate helium core surrounded by hydrogen burning shell
- Mass of the He-core increases
- Helium fusion starts at 100 million K
- Triple alpha process: three ^{4}He → ^{12}C

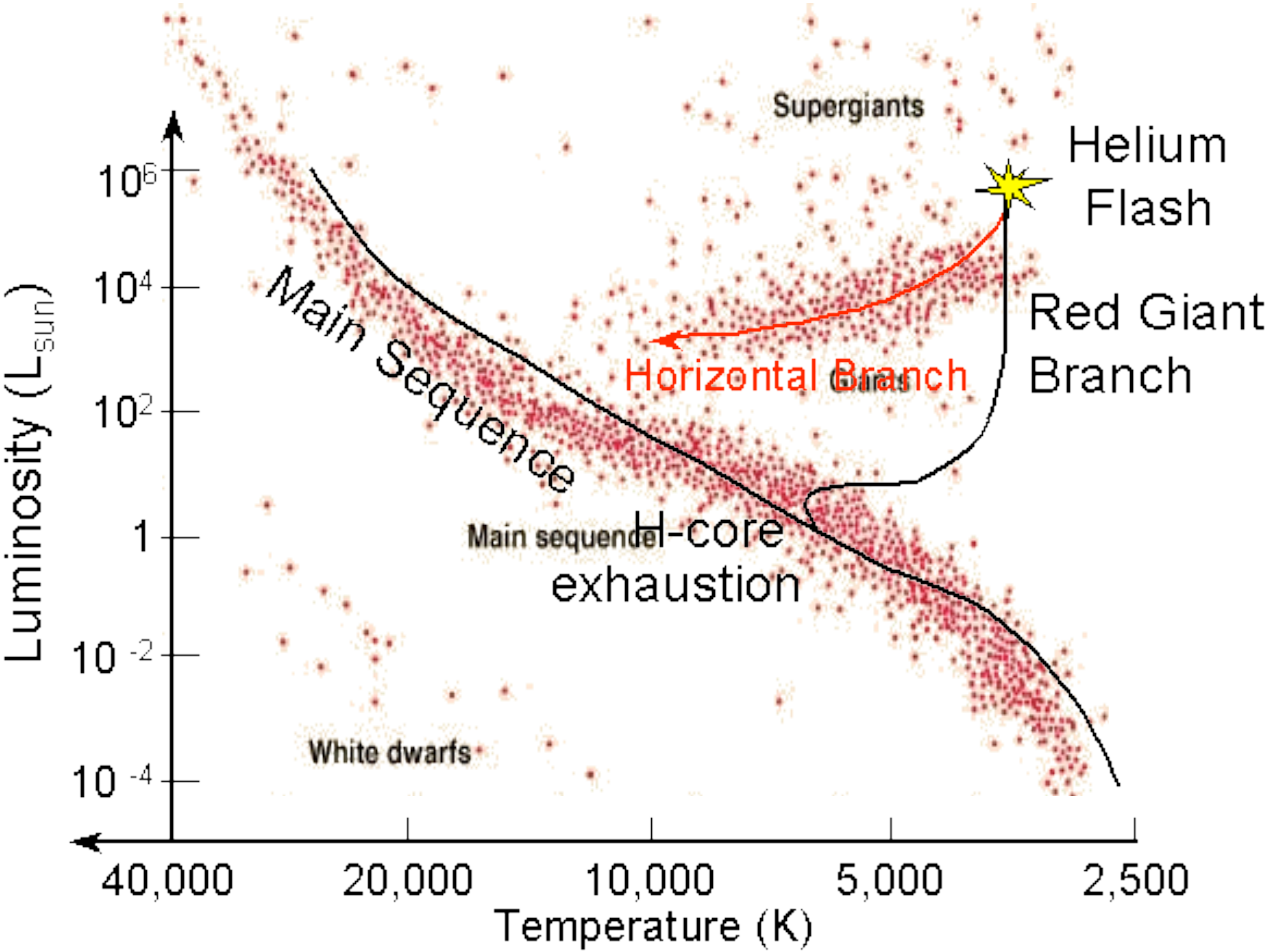


to the horizontal branch

- **Helium flash** : onset of helium fusion produces a burst of energy
- Reaction rate settles down
- Fusion in the core releases more energy/second than core fusion in main sequence
  - star is smaller and hotter, but stable!
  - hydrostatic equilibrium holds until the core fuel runs out.

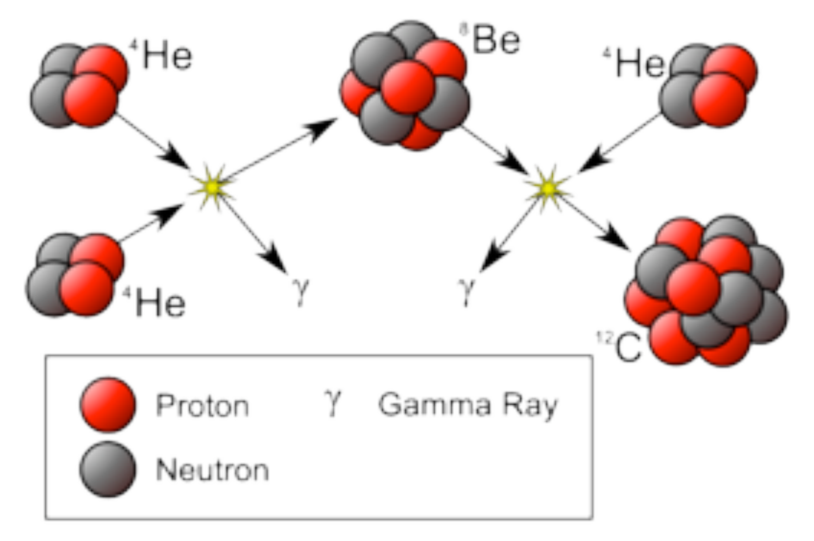
stage 6: helium flash → yellow giant




Supergiants
Helium
Flash
Red Giant
Branch
Horizontal Branch
Giants
Main Sequence
Main sequence
H-core
exhaustion
White dwarfs
Luminosity (L_{sun})
10^6
10^4
10^2
1
10^{-2}
10^{-4}
40,000
20,000
10,000
5,000
2,500
Temperature (K)

Central Helium-Burning

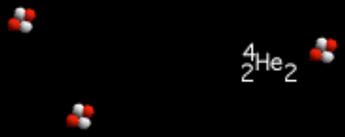
When $T_c \geq 10^8$ K and $\rho \geq 10^5$ g.cm^{-3} :

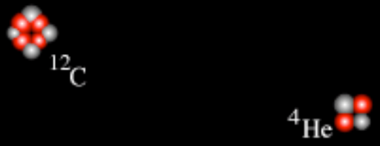


Triple-alpha reaction

^{4}He (α,γ) ^{8}Be (α,γ) ^{12}C

$\varepsilon \propto T^{40}$





^{12}C (α,γ) ^{16}O (α,γ) ^{20}Ne
^{13}C (α,n) ^{16}O

$$
\begin{array}{l}
\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \nearrow\ (\alpha,\gamma)\ ^{25}\mathrm{Mg} \\
^{14}\mathrm{N}\ (\alpha,n)\ ^{18}\mathrm{F}\ (\beta,\nu)\ ^{18}\mathrm{O} \rightarrow (\alpha,\gamma)\ ^{22}\mathrm{Ne} \rightarrow (\alpha,n)\ ^{26}\mathrm{Mg} \\
\qquad\qquad\qquad\qquad\qquad\qquad\qquad \searrow\ (\alpha,n)\ ^{21}\mathrm{Ne}
\end{array}
$$

End of Central Helium-Burning

Meynet (1990) : Central abundances of ^{12}C and ^{16}O in mass fraction

Initial stellar mass ($M_\odot$)	**^{12}C**	**^{16}O**
120	0.01245	0.81178
60	0.04321	0.89021
20	0.11675	0.85075
9	0.13063	0.84164
4	0.089322	0.88376
3	0.05249	0.92081
2	0.09247	0.88122

stage 6: yellow giant → red giant or supergiant