PRECISION SPECTROSCOPY 2016

Stellar Evolution and Nucleosynthesis

Stellar Evolution of low and intermediate mass stars

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Universidade Federal do Rio Grande do Sul

Porto Alegre, Setember 19

M45, The Pleiades open cluster
2007-01-13
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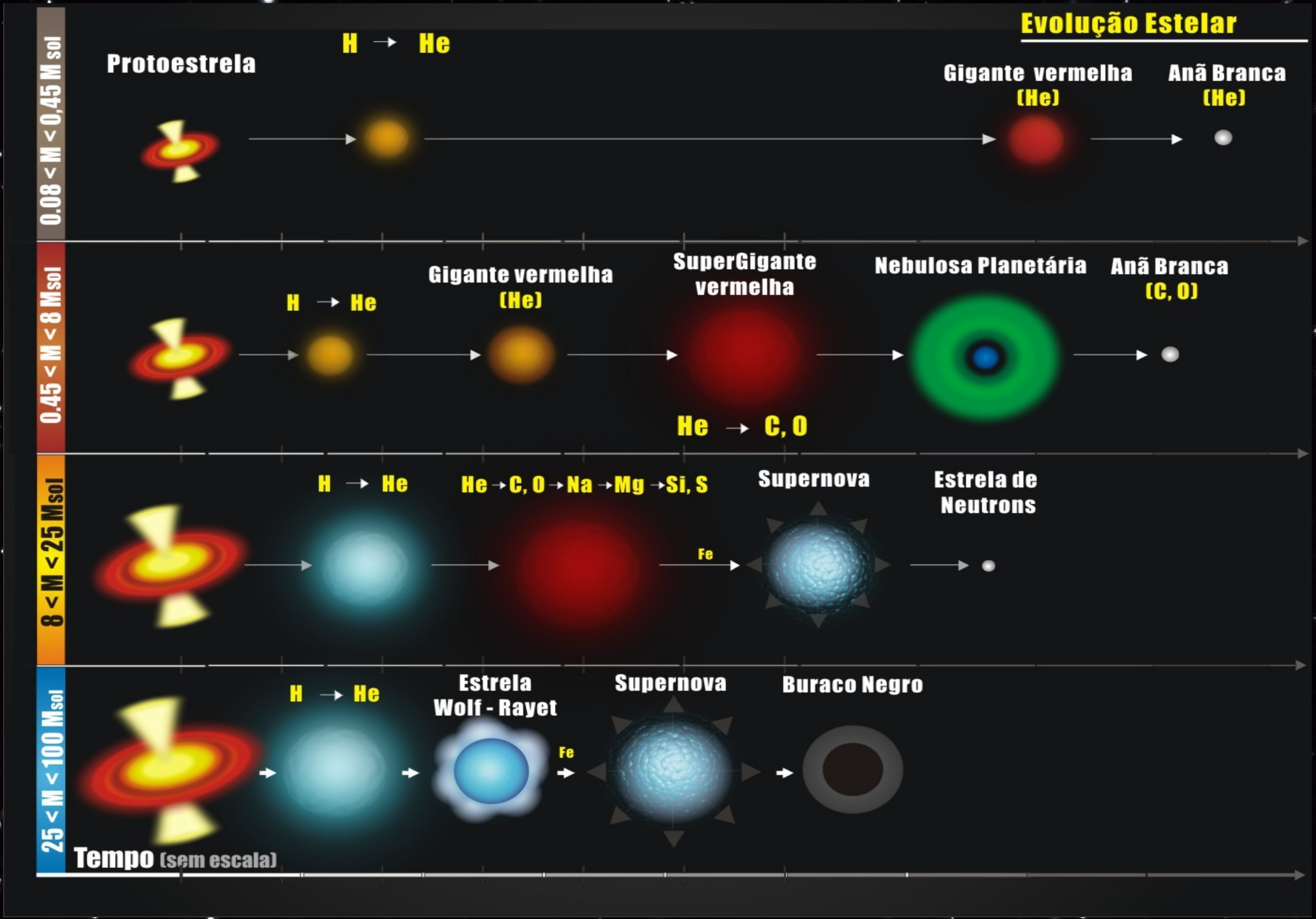
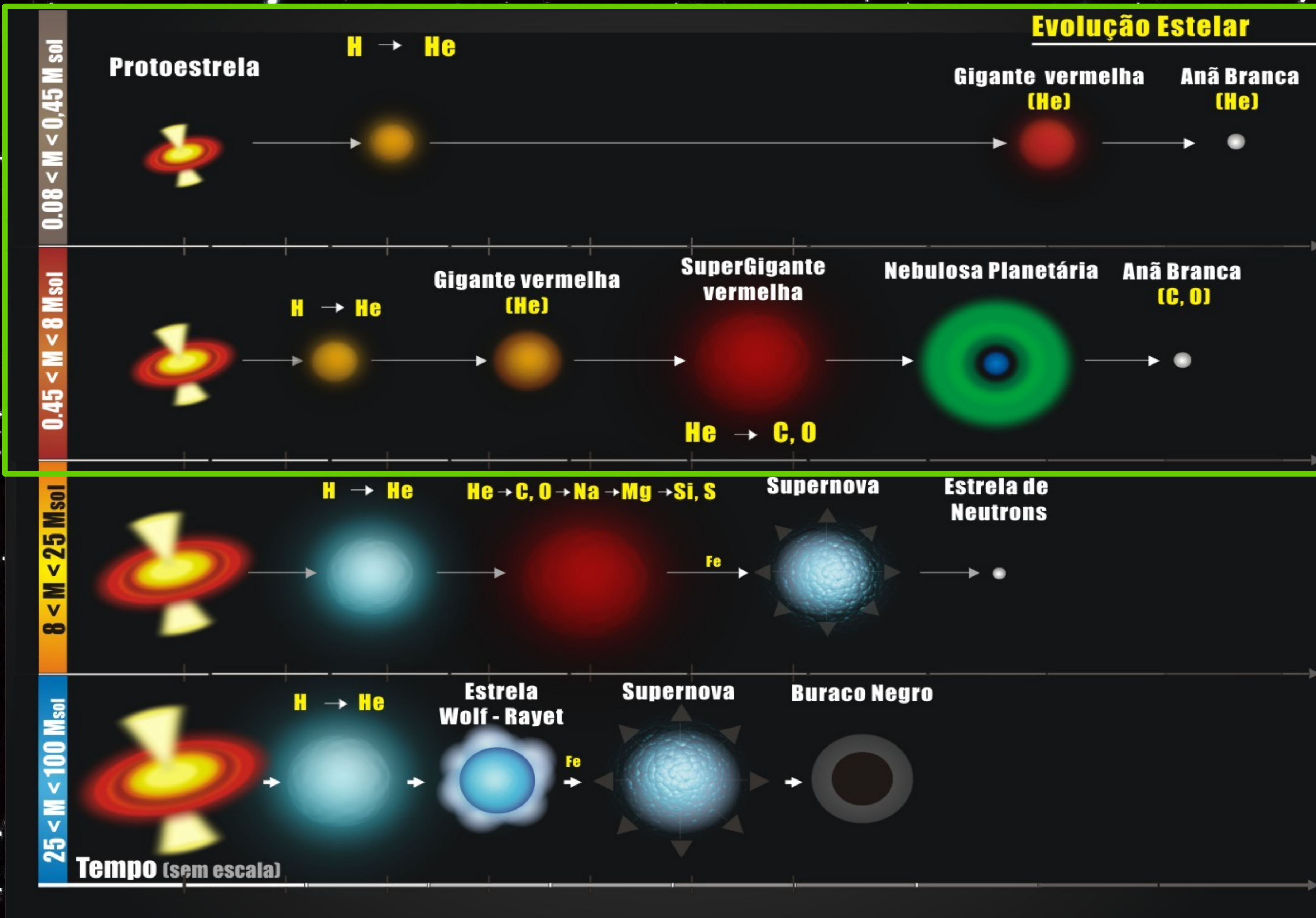
Stellar evolution

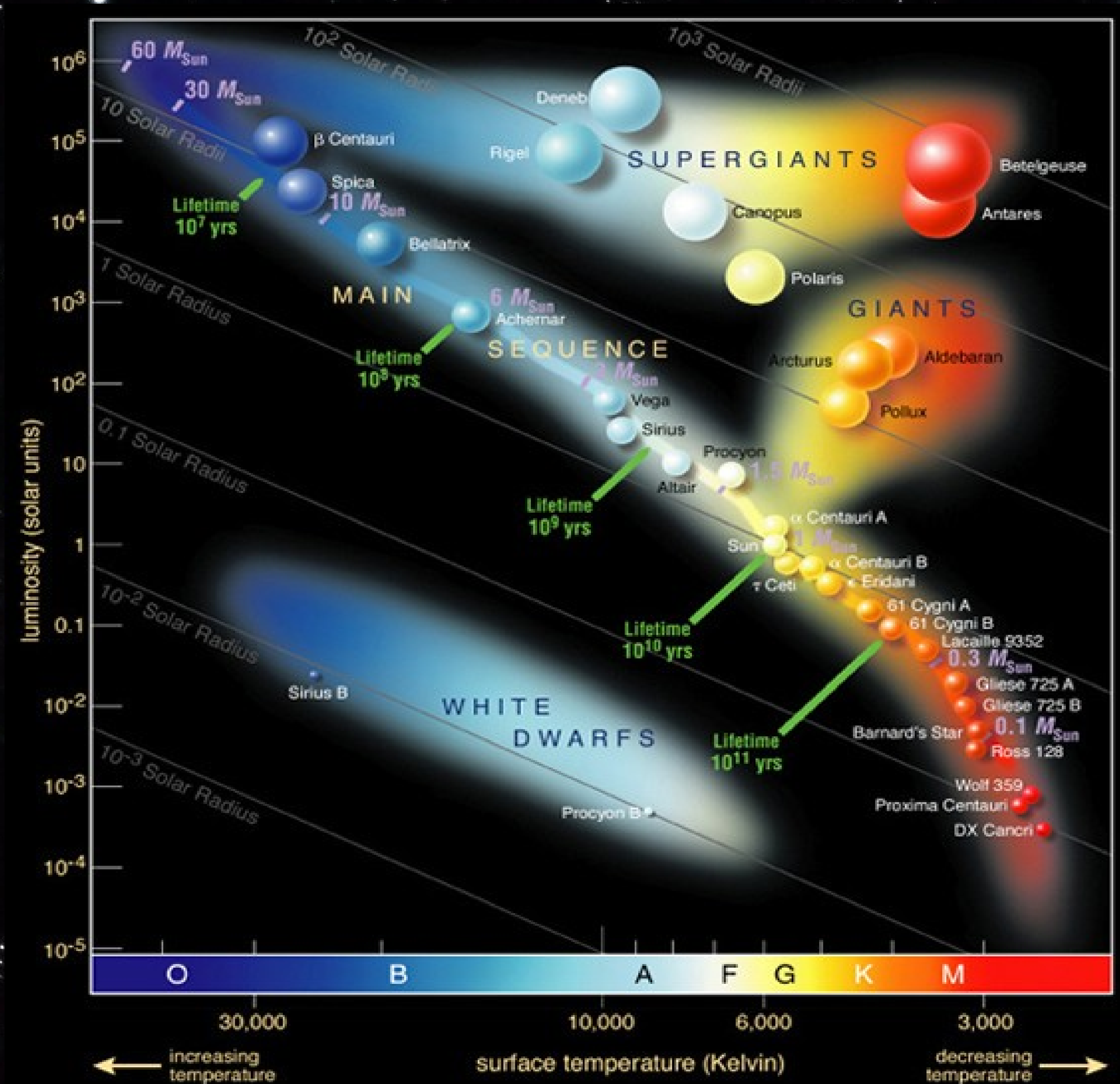


Stellar evolution



cluster

The Hertzprung-Russell diagram



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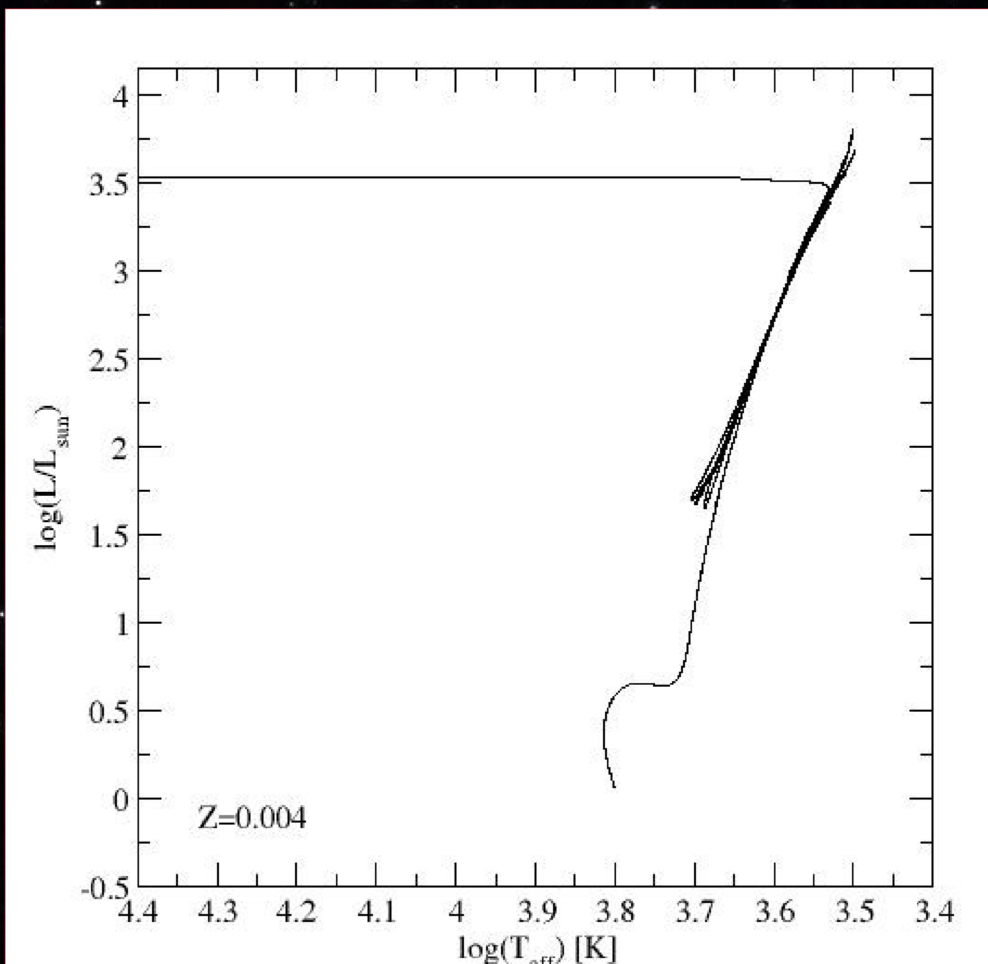
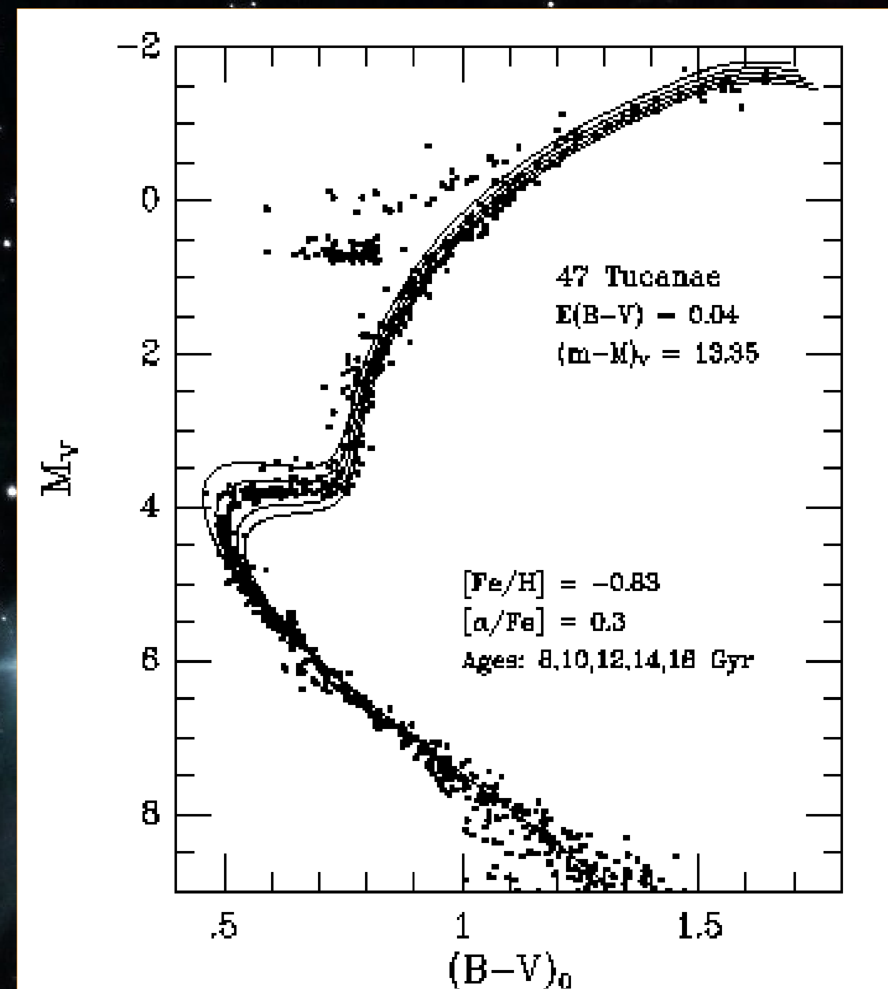
Teff-L/Color-Magnitude diagram

"Single mass" Evolution



H-R diagram Z=0.004 / 1 M_{sun}

"Single age" different masses



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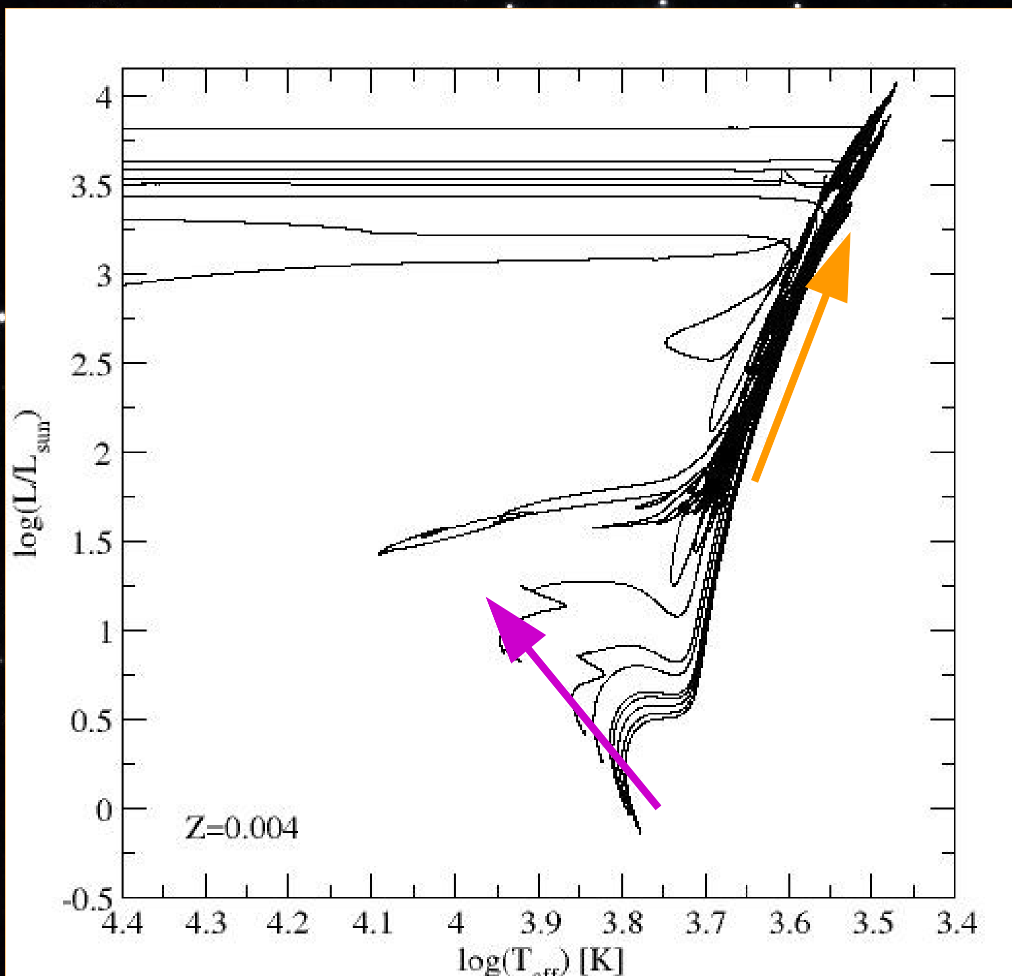
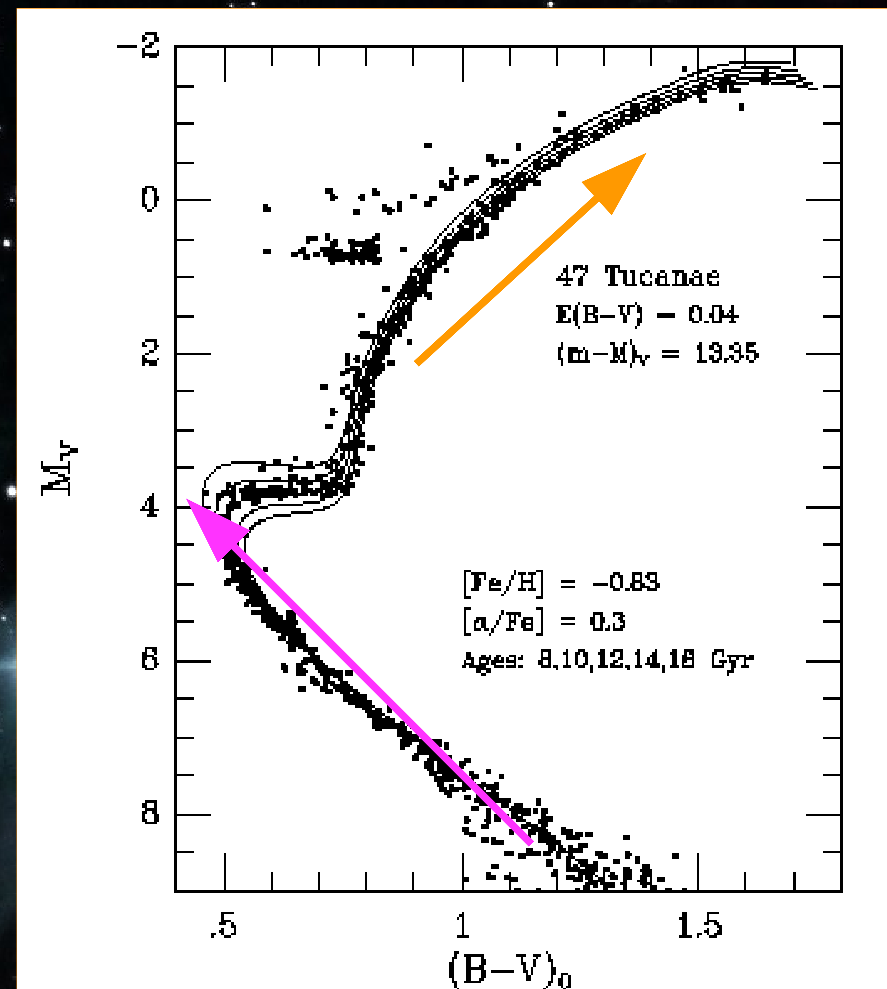
Teff-L/Color-Magnitude diagram

"Single mass" Evolution



H-R diagram Z=0.004 / 0.9-3 M_{sun}

"Single age" different masses



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"Single mass" Evolution

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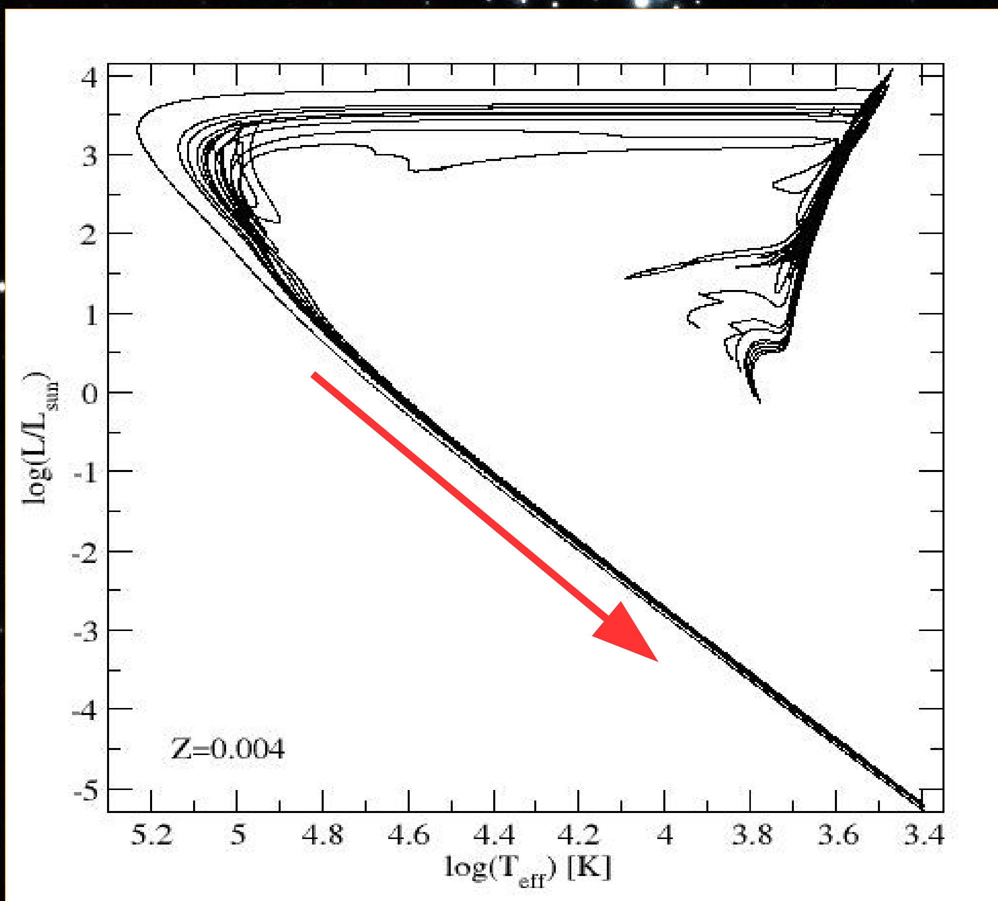

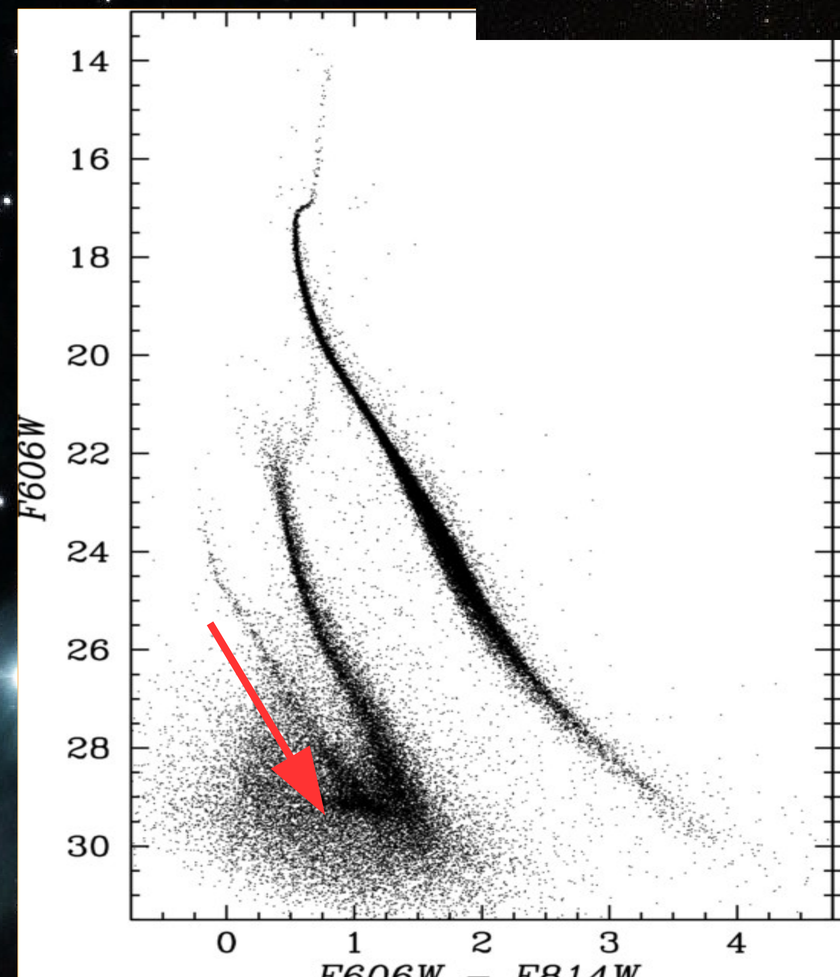

H-R diagram Z=0.004 / 0.9-3 M_{sun}

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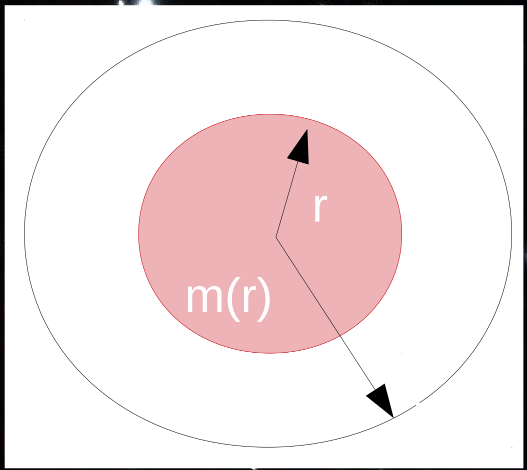
Stellar evolution computations

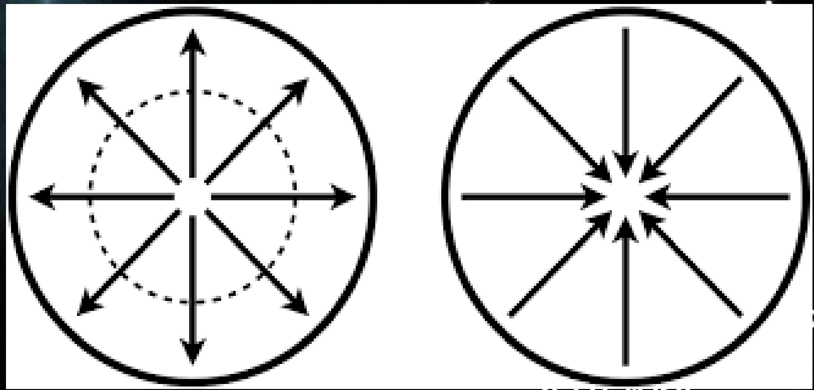
Spherical symmetry

Mechanical structure

$$\frac{dM}{dr} = 4\pi r^2 \rho$$

$$\frac{dP}{dr} = -\frac{GM\rho}{r^2}$$





Stellar evolution computations

Mechanical structure

$$\frac{dM}{dr} = 4\pi r^2 \rho$$

$$\frac{dP}{dr} = -\frac{GM\rho}{r^2}$$

$$\frac{dL}{dr} = 4\pi r^2 \rho \left(\epsilon - T\frac{dS}{dt} \right)$$

Conservation of energy

Energy transport

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{L_r}{4\pi r^2}$$

$$\frac{dT}{dr} = -\frac{\Gamma_2 - 1}{\Gamma_2}\frac{T}{P}\frac{dP}{dr}$$

Boundary conditions

$$M(r=0) = 0$$

$$L(r=0) = 0$$

$$P(r=R) = 0$$

$$T(r=R) = 0$$

Stellar evolution computations

Mechanical structure

$$\frac{dM}{dr} = 4\pi r^2 \rho$$

$$\frac{dP}{dr} = -\frac{GM\rho}{r^2}$$

Equation of state

$$P = \frac{\rho}{m} kT + \frac{1}{3} a T^4$$

$$P = K\rho^n$$

$$\frac{dL}{dr} = 4\pi r^2 \rho \left(\epsilon - T \frac{dS}{dt} \right)$$

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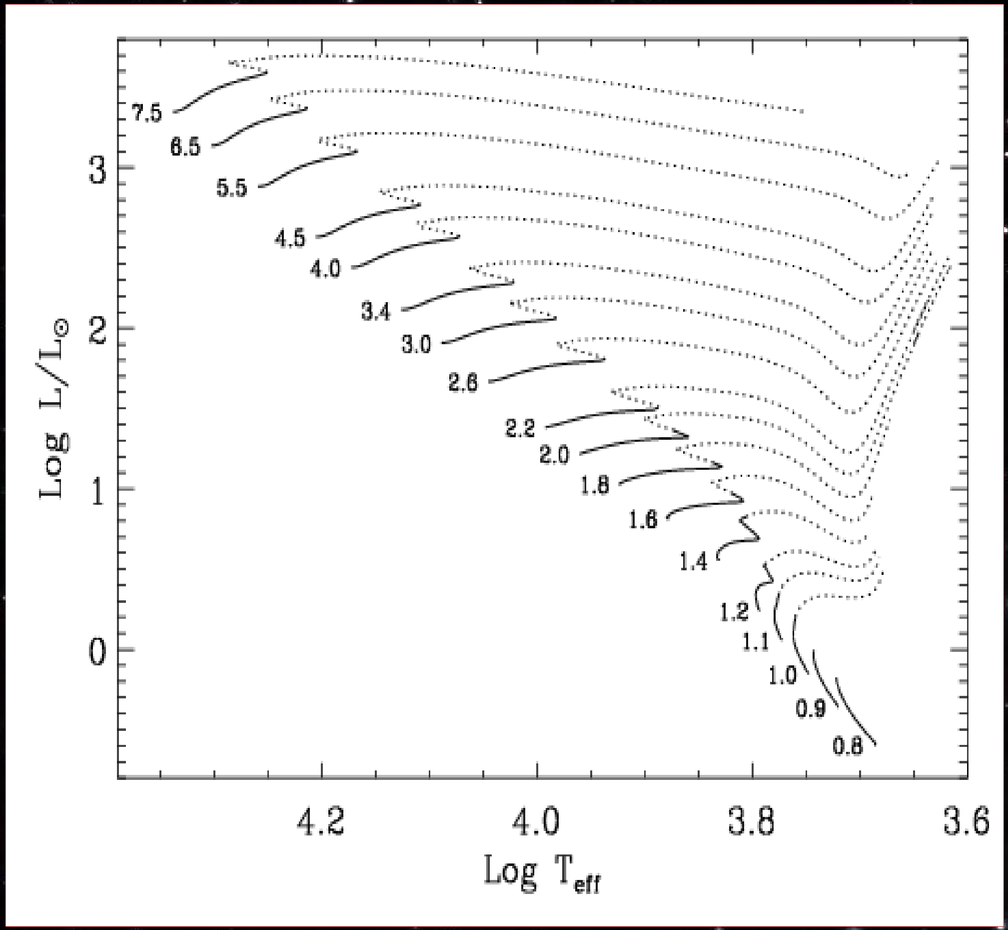
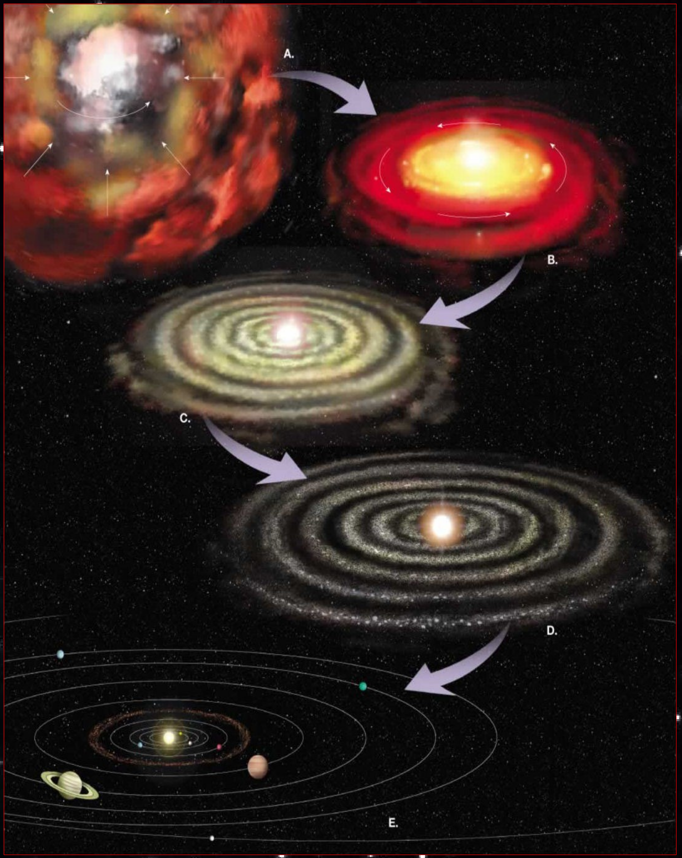
Chemical evolution

$$\frac{\partial n_i}{\partial t} = \left(\frac{\partial n_i}{\partial t}\right)_{nuc} + \left(\frac{\partial n_i}{\partial t}\right)_{mix} \qquad i = 1, \ldots\ldots, I$$

Main Sequence



Marques, J.P. et al. Astrophys.Space Sci. 316 (2008)



- Energy source: Hydrogen burning
- Longest stage in the life of stars
- Sequence in stellar mass

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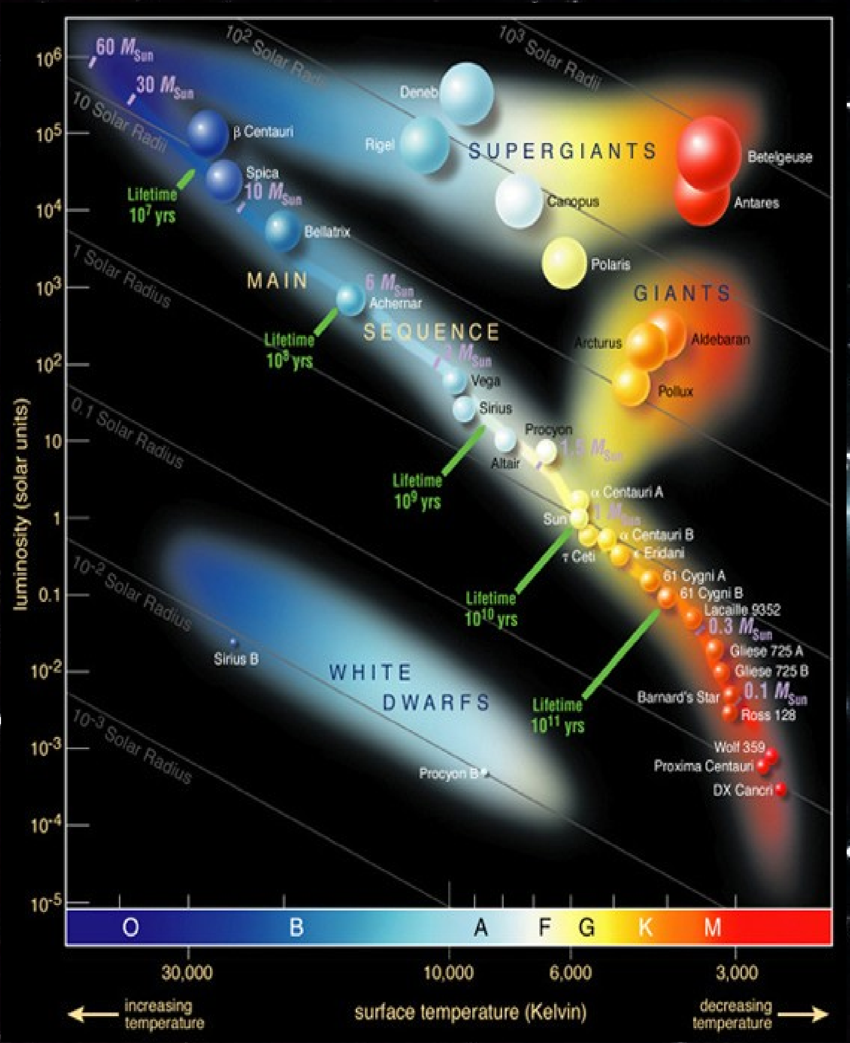
Main Sequence

$$\tau_{SP} \propto \frac{X_H M c^2}{L} \sim 10^{10} \left(\frac{M}{M_\odot} \right)^{-2} \text{ anos}$$



10^{10} yr for a 1 M_{sun}

6×10^{6} yr for a 20 M_{sun}

Mass -Luminosity relation for Main Sequence stars

$$L \simeq M^3 \mu^4$$

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Main Sequence

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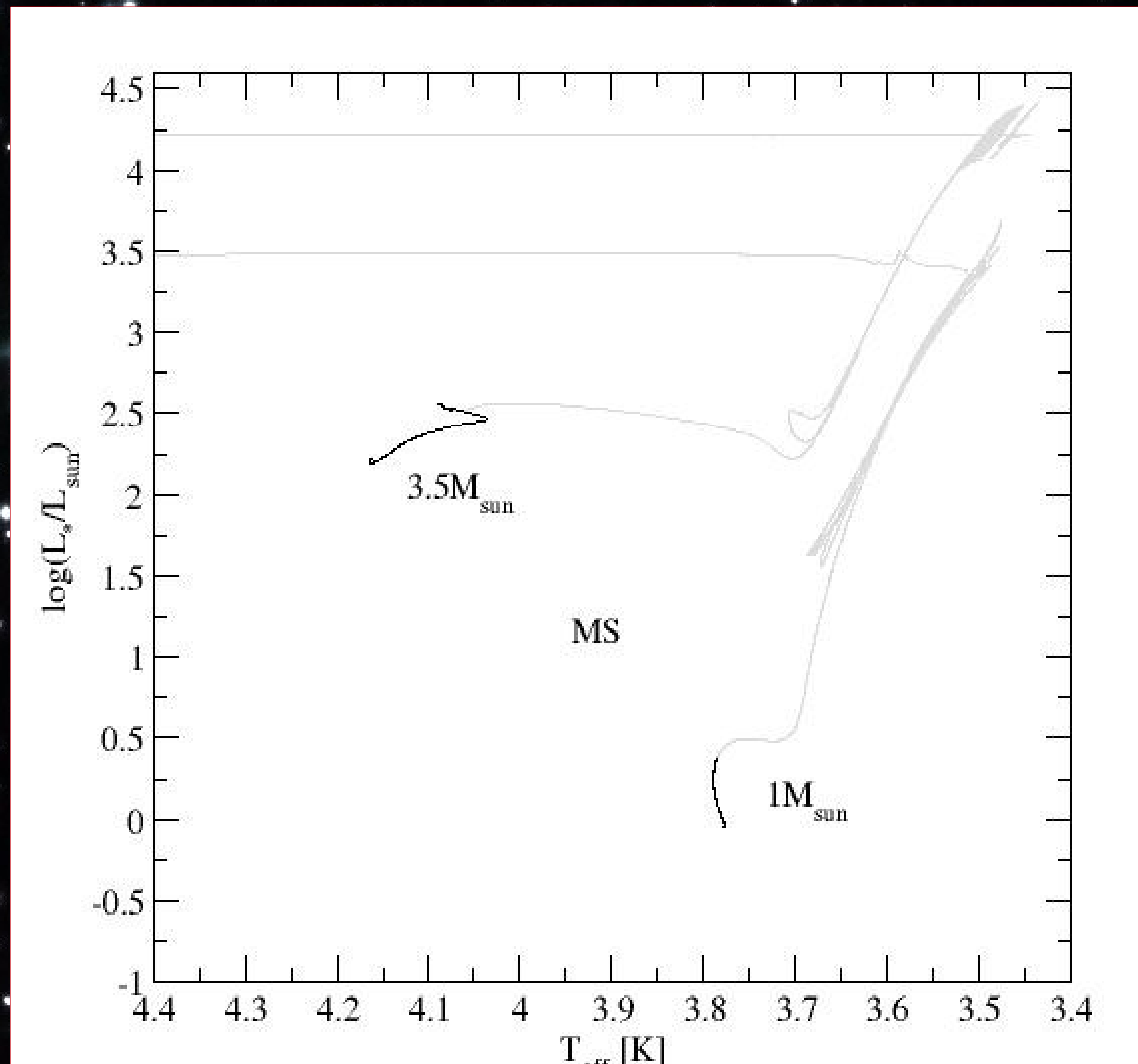

The Pleiades open cluster
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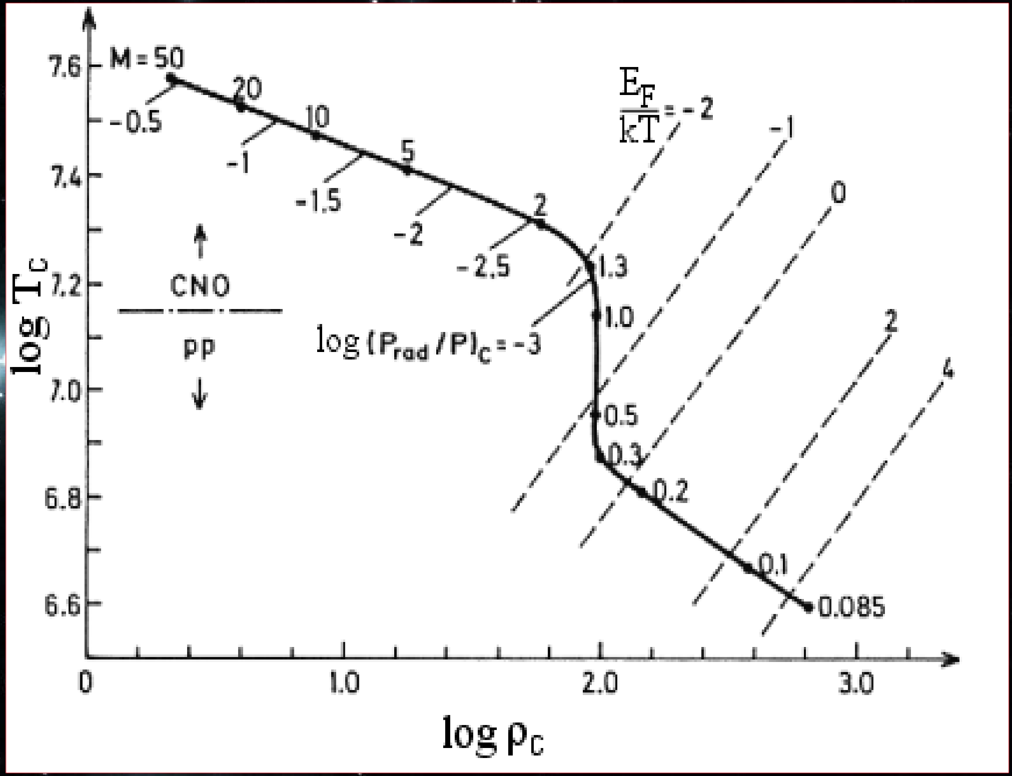
Main Sequence: Inner structure

- M >1.3Msun: High Main Sequence

  convective core + raditive envelope

- M < 1.3 Msun: Low Main Sequence

  raditive core + convective envelope



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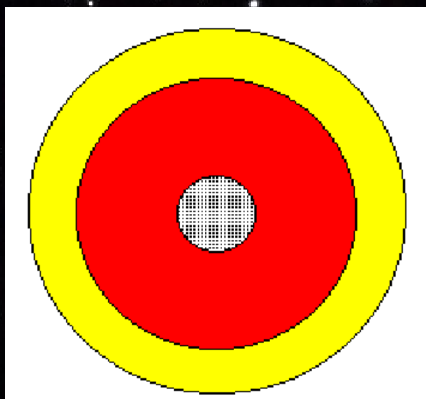
Low Main Sequence



Proton-proton cycle

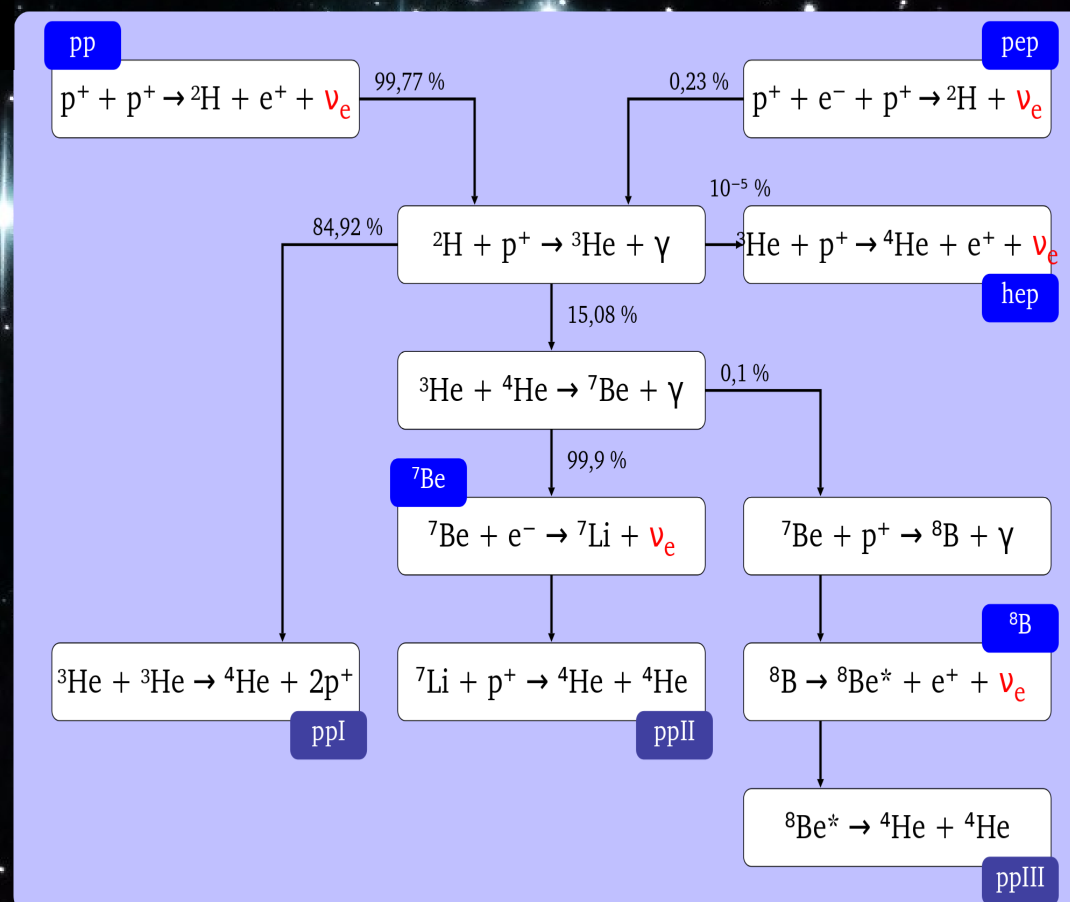
$$4H \longrightarrow He^4 + 2e^+ + 2\nu_e + \gamma$$

Radiative core +

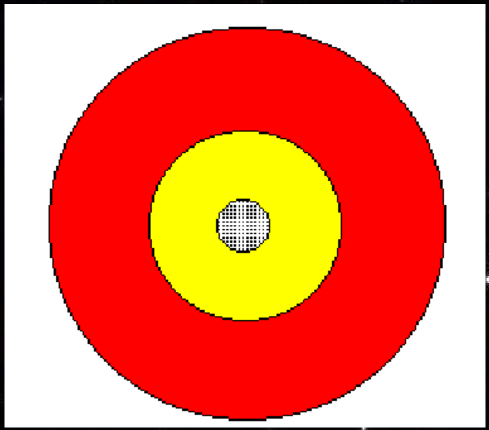
Convective envelope

$$\nu_{pp} : T^{5-3.5} \qquad T : 5 - 20\times10^6 \text{ K}$$

$$-\left(1-\frac{1}{\gamma}\right)\frac{T}{P}\frac{dP}{dr} > -\frac{dT}{dr}$$



High Main Sequence



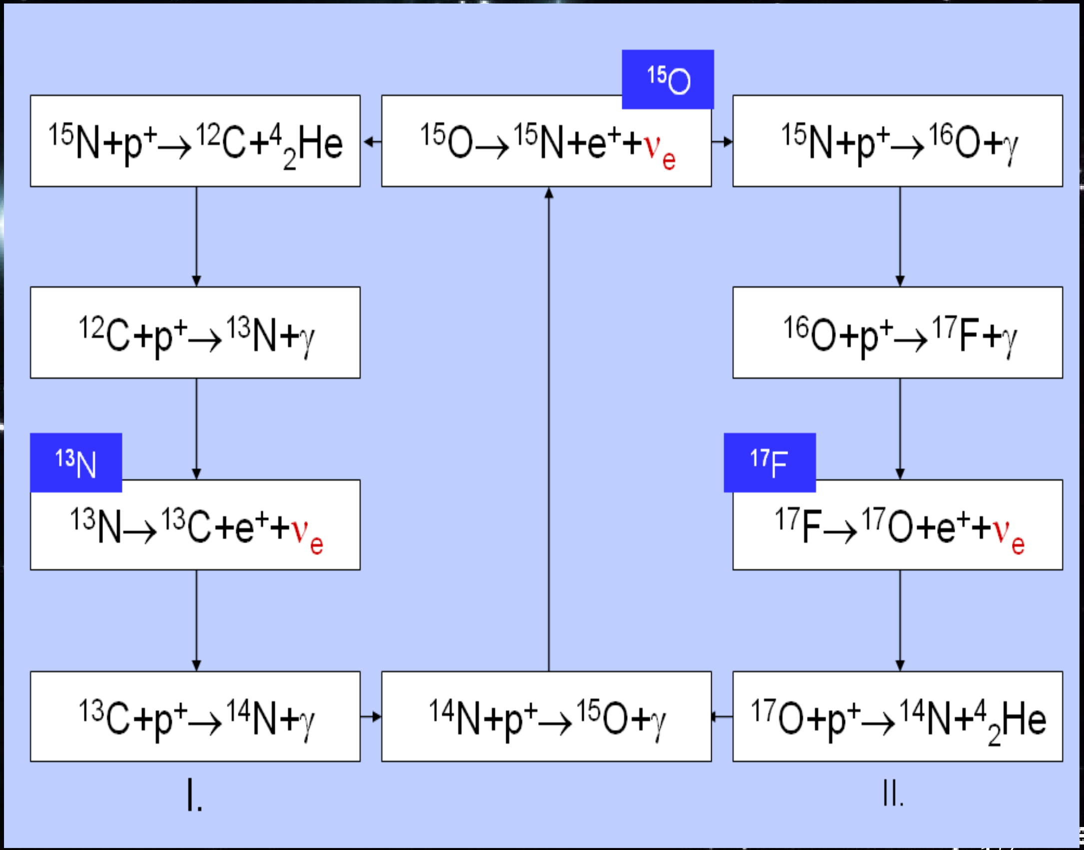
CNO cycle

$$C^{12}+4H \rightarrow C^{12}+He^{4}+2e^{+}+2\nu_e+\gamma$$

Convective core + radiative envelope

$$\nu_{CNO} : T^{8-20} \qquad T : 10-50\times 10^{6}\ \mathrm{K}$$

$$-\left(1-\frac{1}{\gamma}\right)\frac{T}{P}\frac{dP}{dr} > -\frac{dT}{dr}$$



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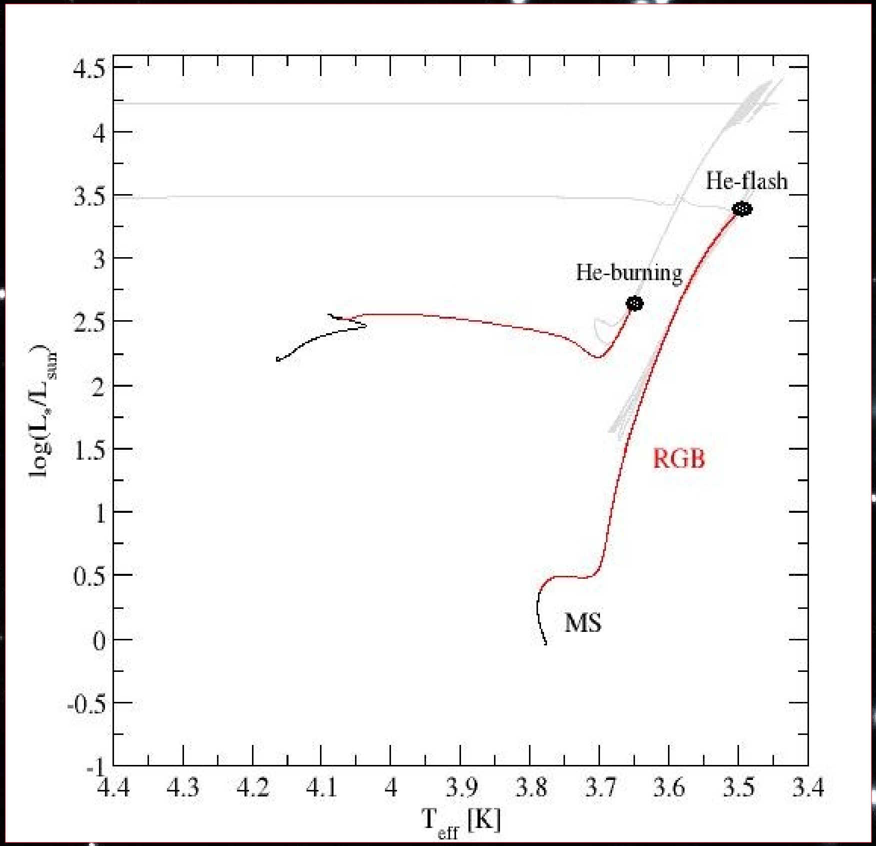
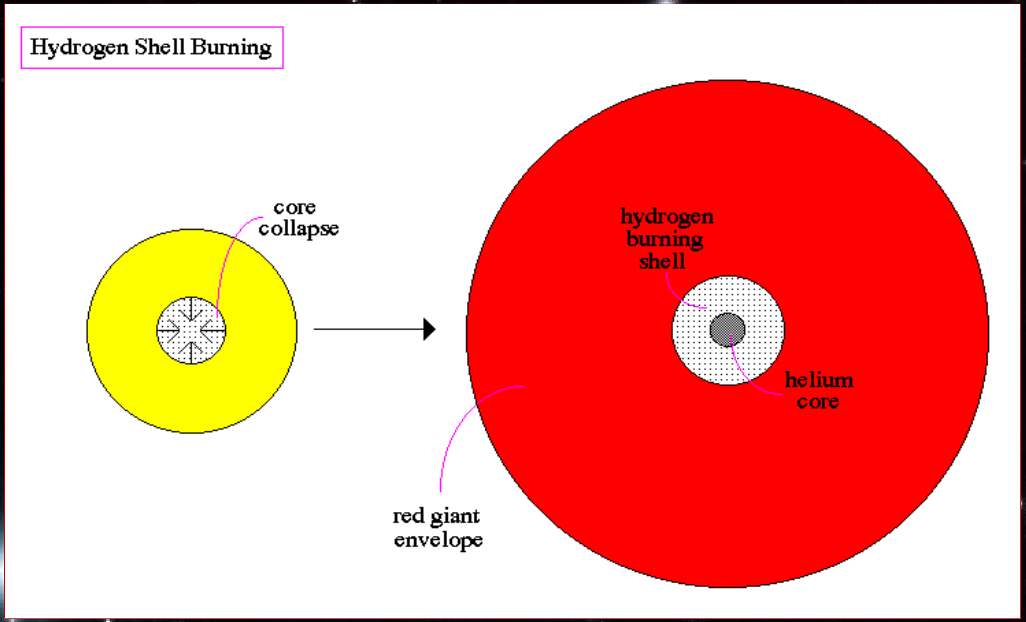
Post-Main Sequence: Red Giant Branch





- Energy source: H-burning in a shell
- Contraction of the core

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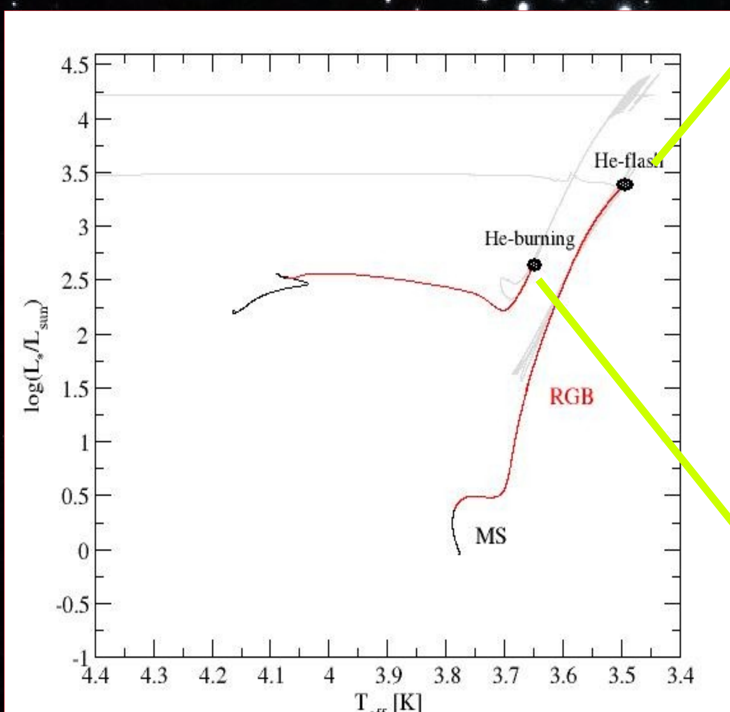
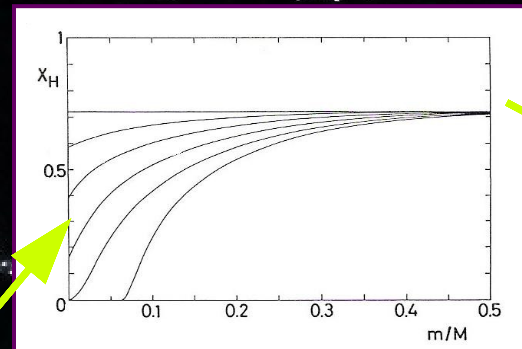
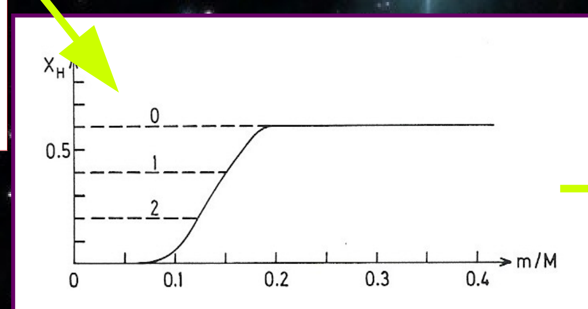
Post-Main Sequence: Red Giant Branch





He core degenerates and grows in mass due to the H-shell

$M_{core} \sim 0.45\ M_{sun}$ He flash



$M_{core} \sim 0.1\ M_{*}$

$T \sim 10^8$ K He-burning

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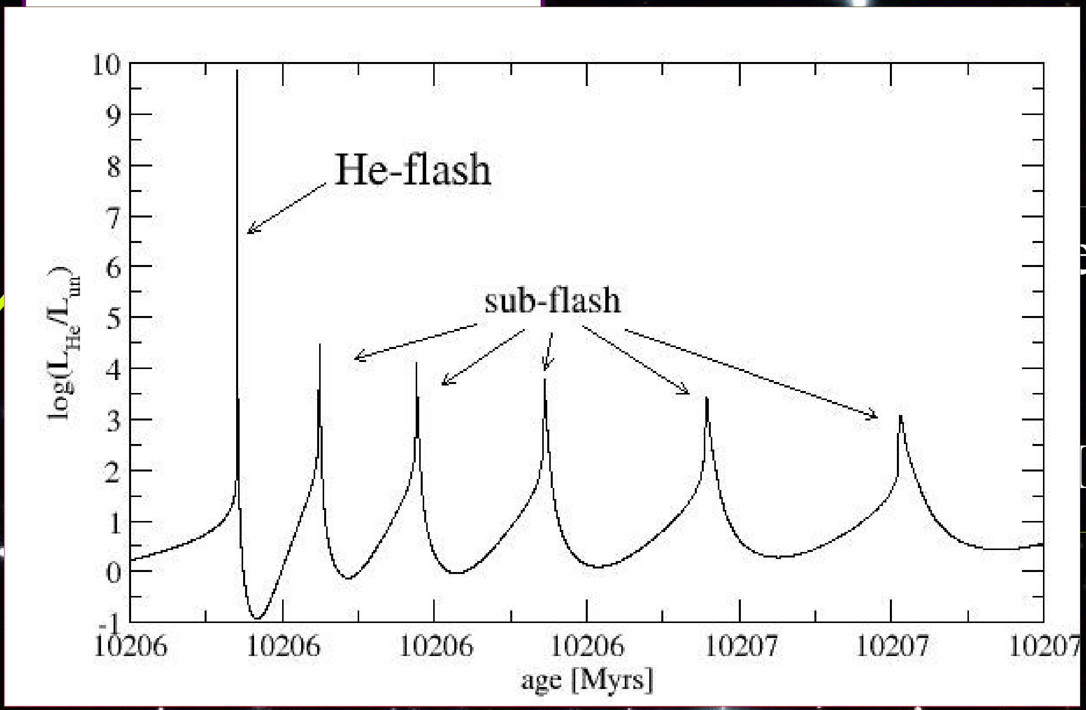
Post-Main Sequence: Red Giant Branch



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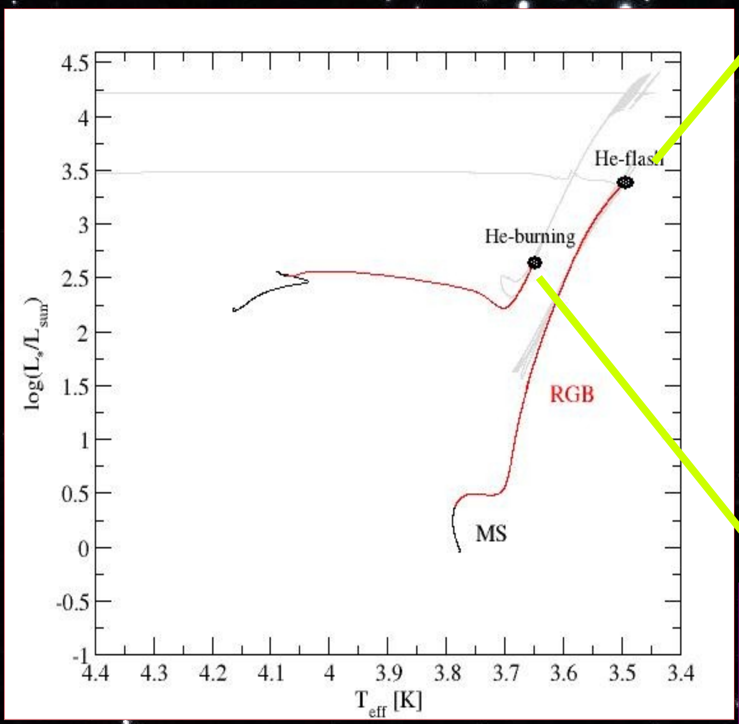
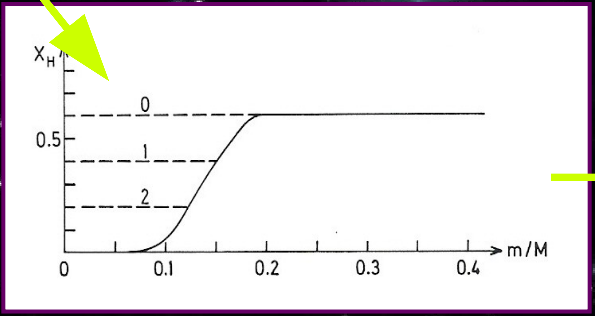
le flash





$M_{core} \sim 0.1\ M_*$

$T \sim 10^8$ K He-burning

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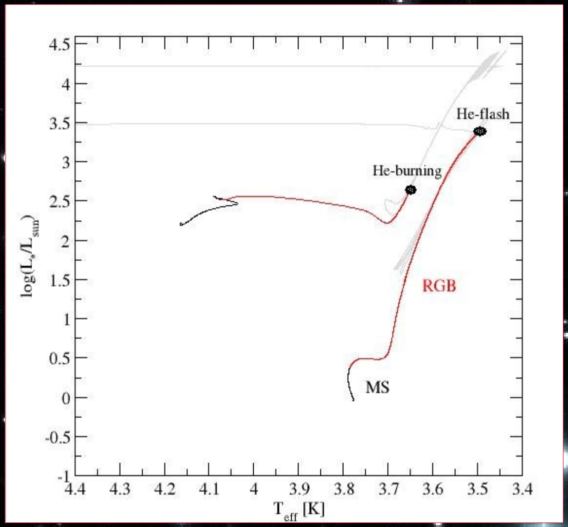
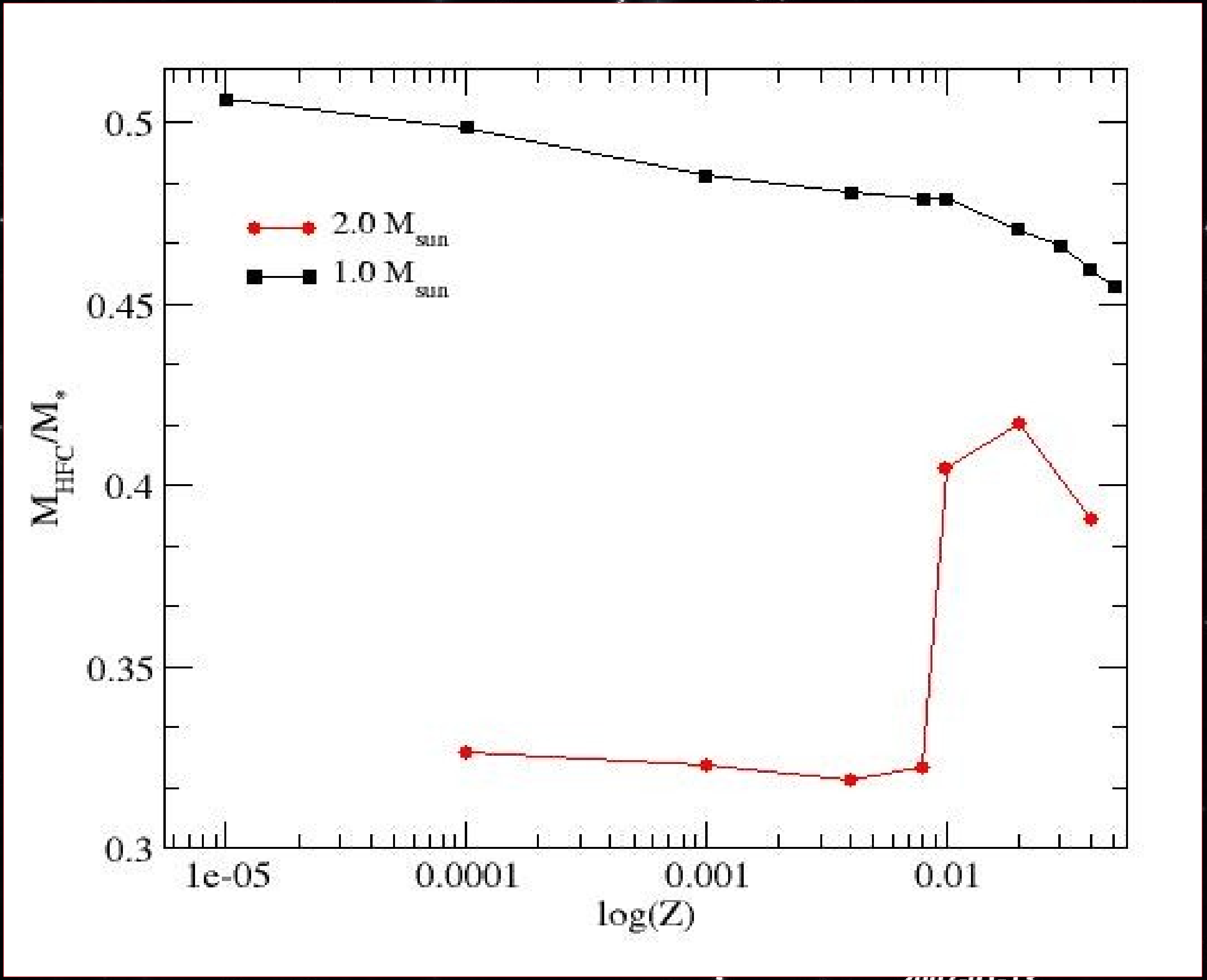
Beginning of the He-burning stage



He core mass for He-flash depends on initial metallicity



$$[Fe/H] = \log(Z/Z_{\odot})$$

$$Z_{sun} = 0.0169$$

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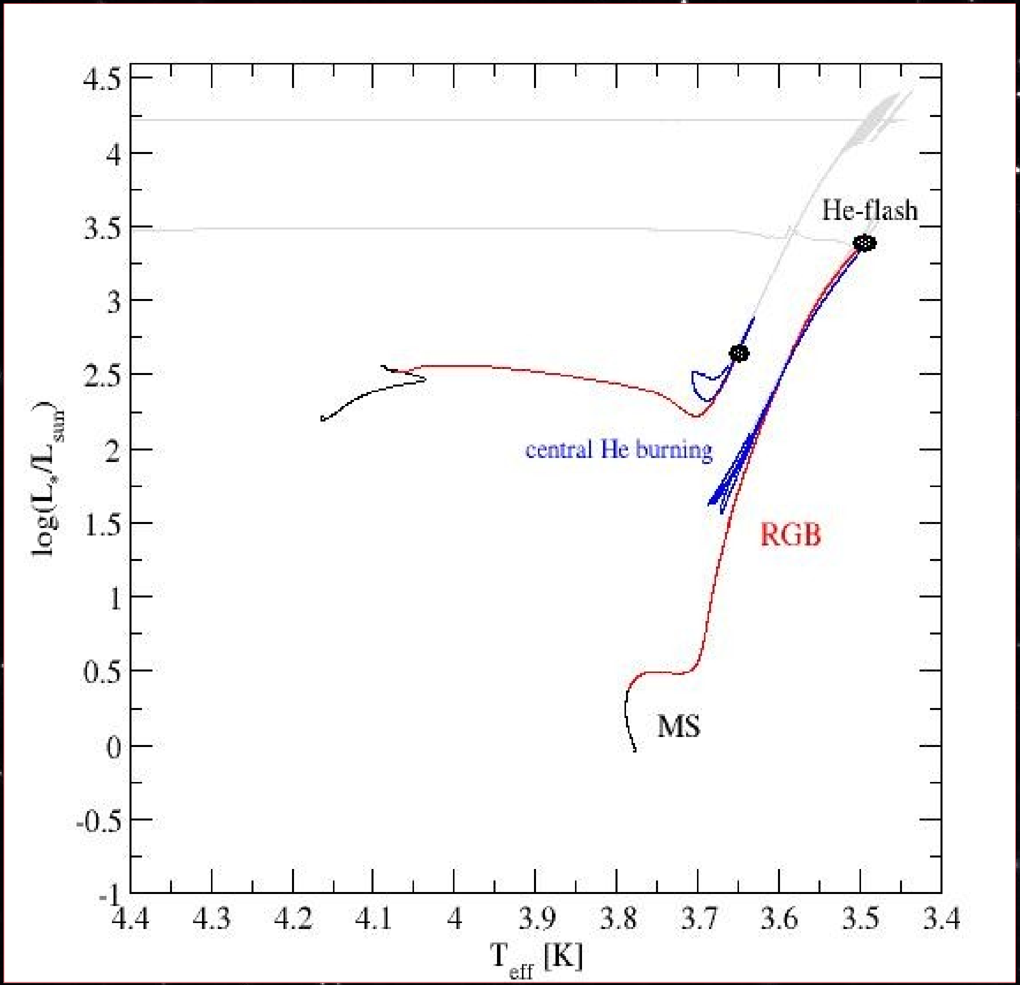
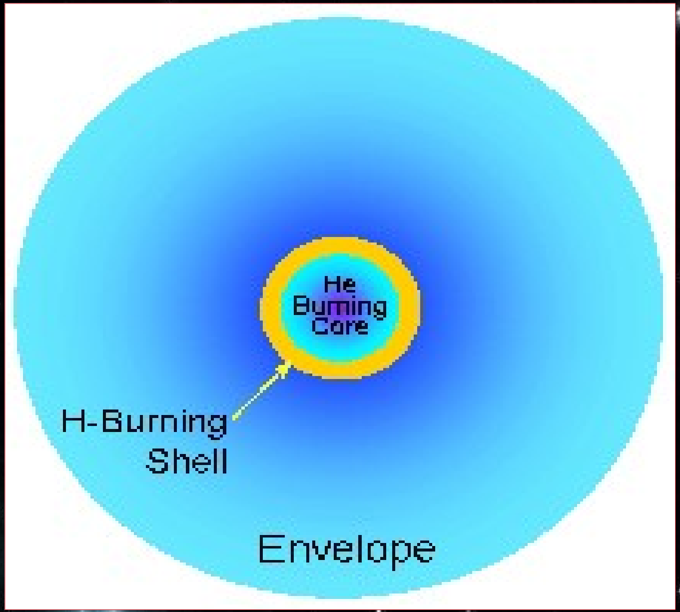
Central He burning





Energy source:

- 3α cycle

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

$$\nu_{3\alpha} \sim T^{20\text{-}40}$$

H-shell: CNO cycle

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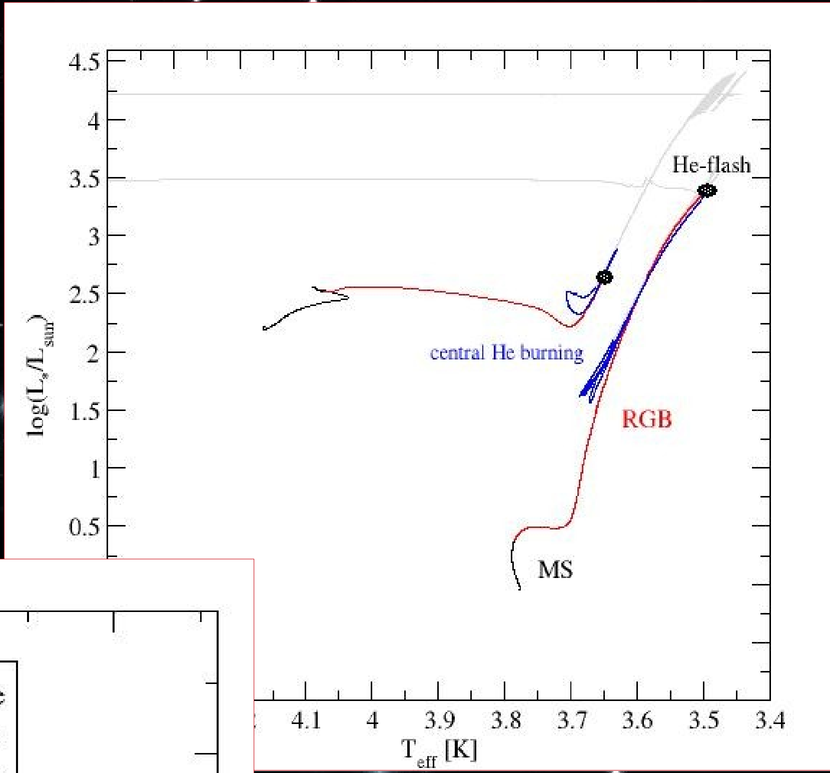
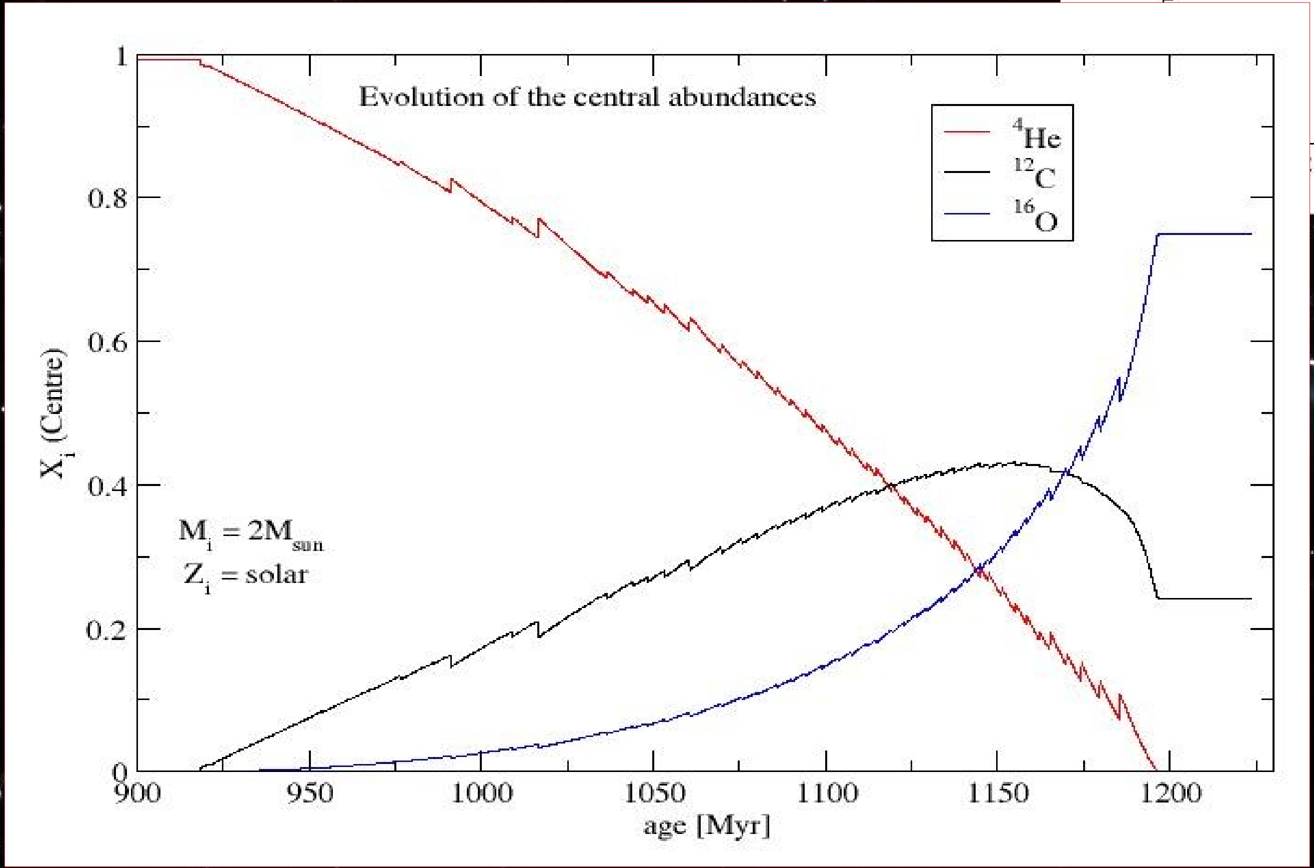
Central He burning

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

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





Central He burning stage lasts ~ 10 % of the MS

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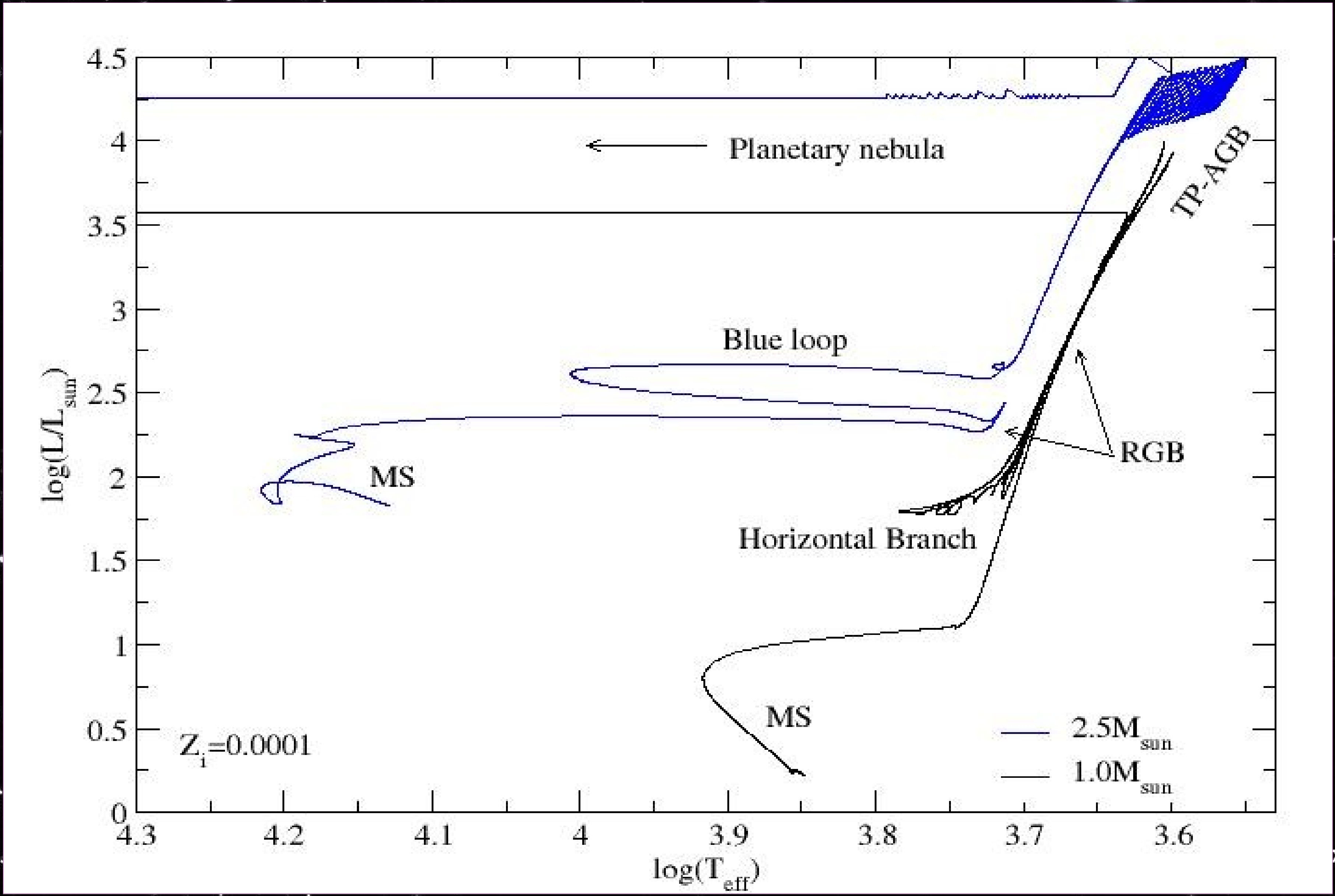
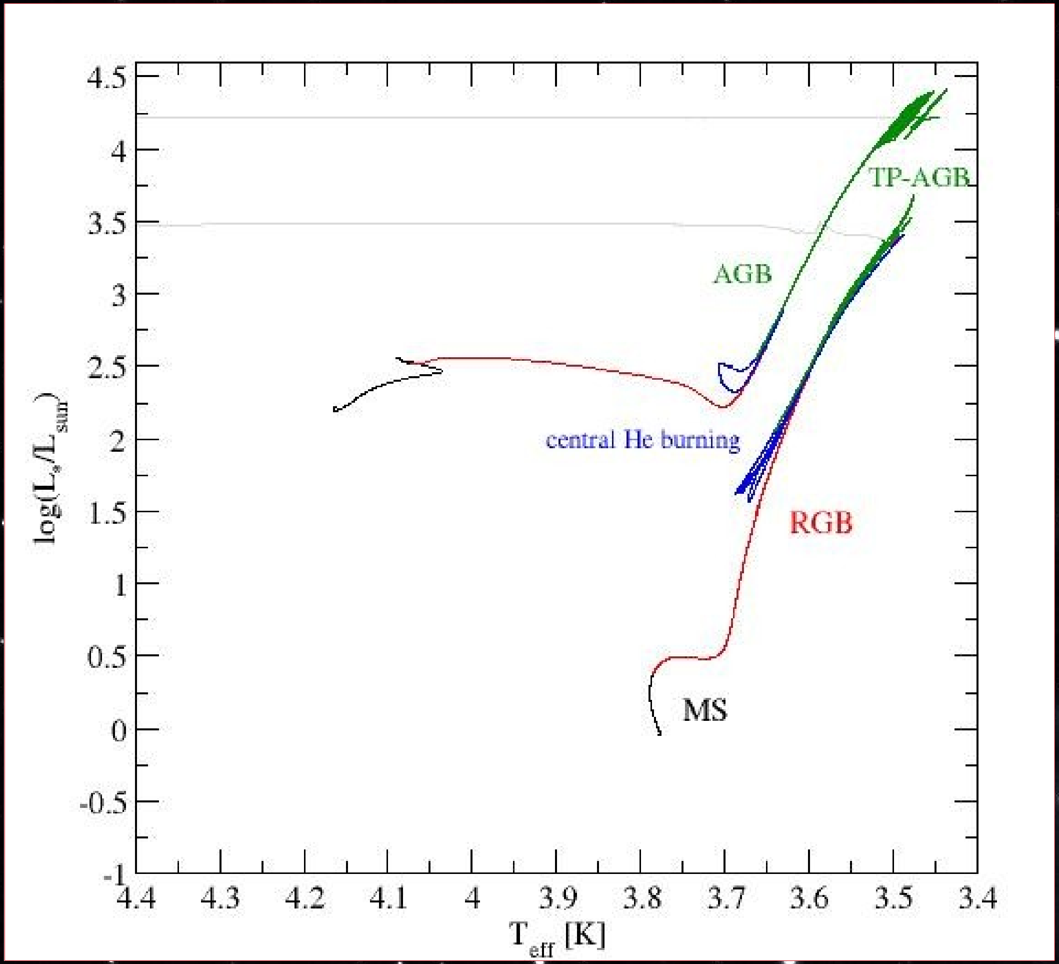
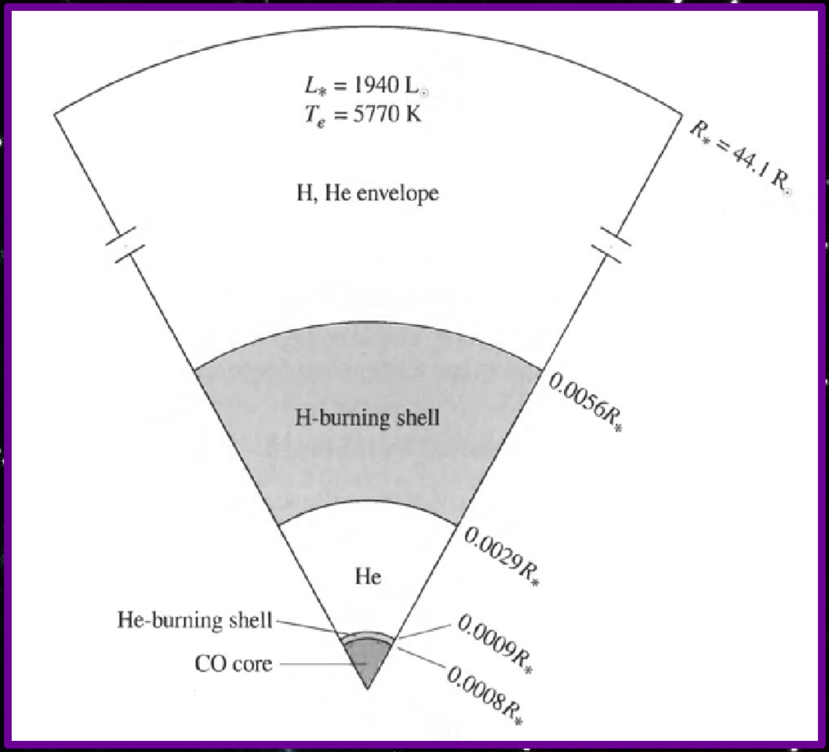
Central He burning



Asymptotic giant branch





Double shell burning:

- He to C: 3α
- H to He CNO cycle

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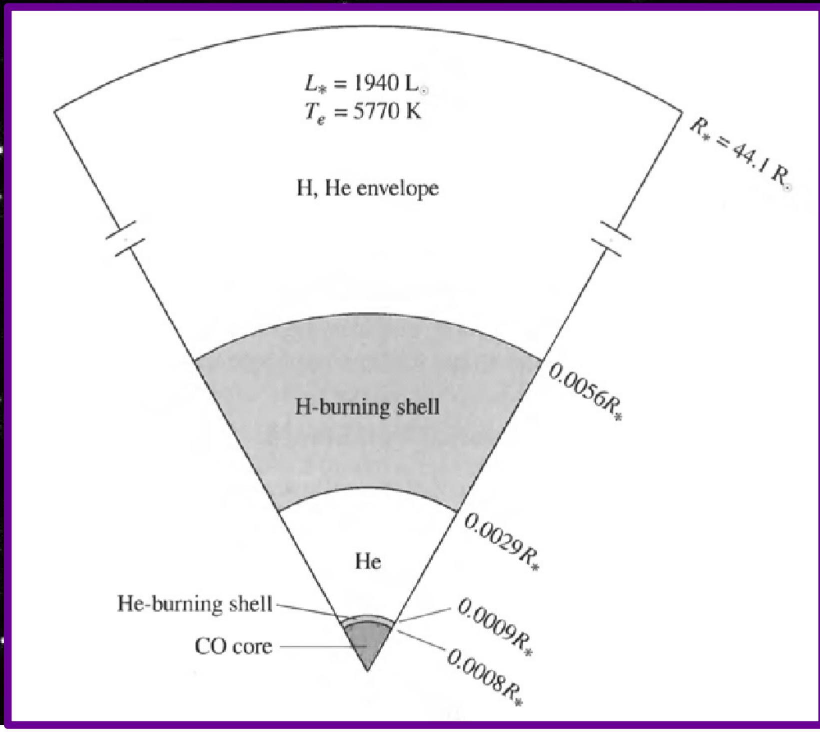
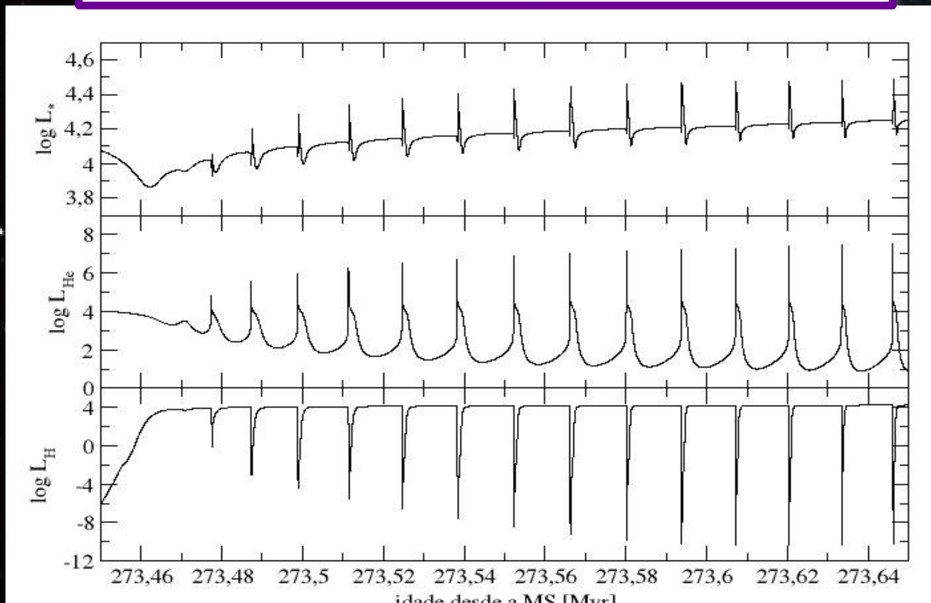
Thermal Pulsing AGB





1. Two stable burning shells
2. He shell gets too thin and triggers unstable He burning: L_{He} grows
3. Energy expands the shells above the He-burning shell
4. The H-burning shell gets cooler and H burning turns down
5. The star contracts again and the H burning starts: L_H grows
6. Two stable burning shells

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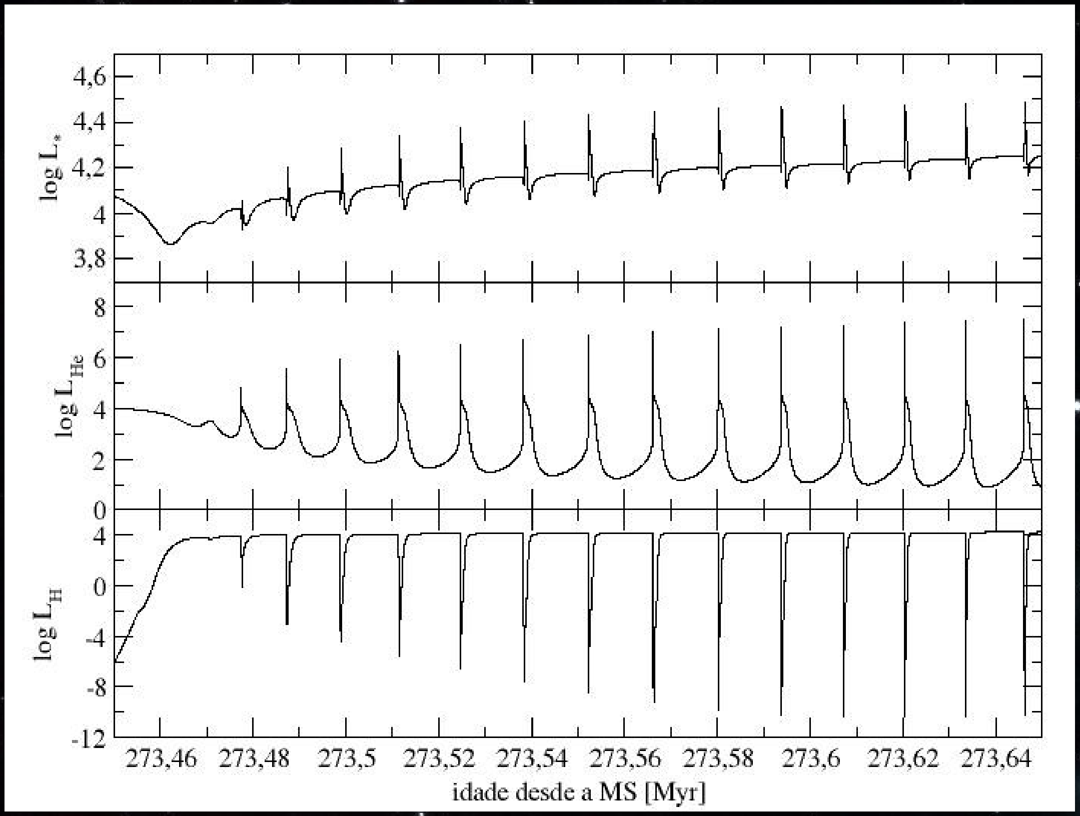
Thermal Pulsing AGB



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3. Energy expands the shells above the He-burning shell
4. The H-burning shell gets cooler and H burning turns down
5. The star contracts again and the H burning starts: L_H grows
6. Two stable burning shells

$M_{core} \sim 0.5\ M_{sun}$ $\tau \sim 10^5$ yr

$M_{core} \sim 1.4\ M_{sun}$ $\tau \sim 10$ yr

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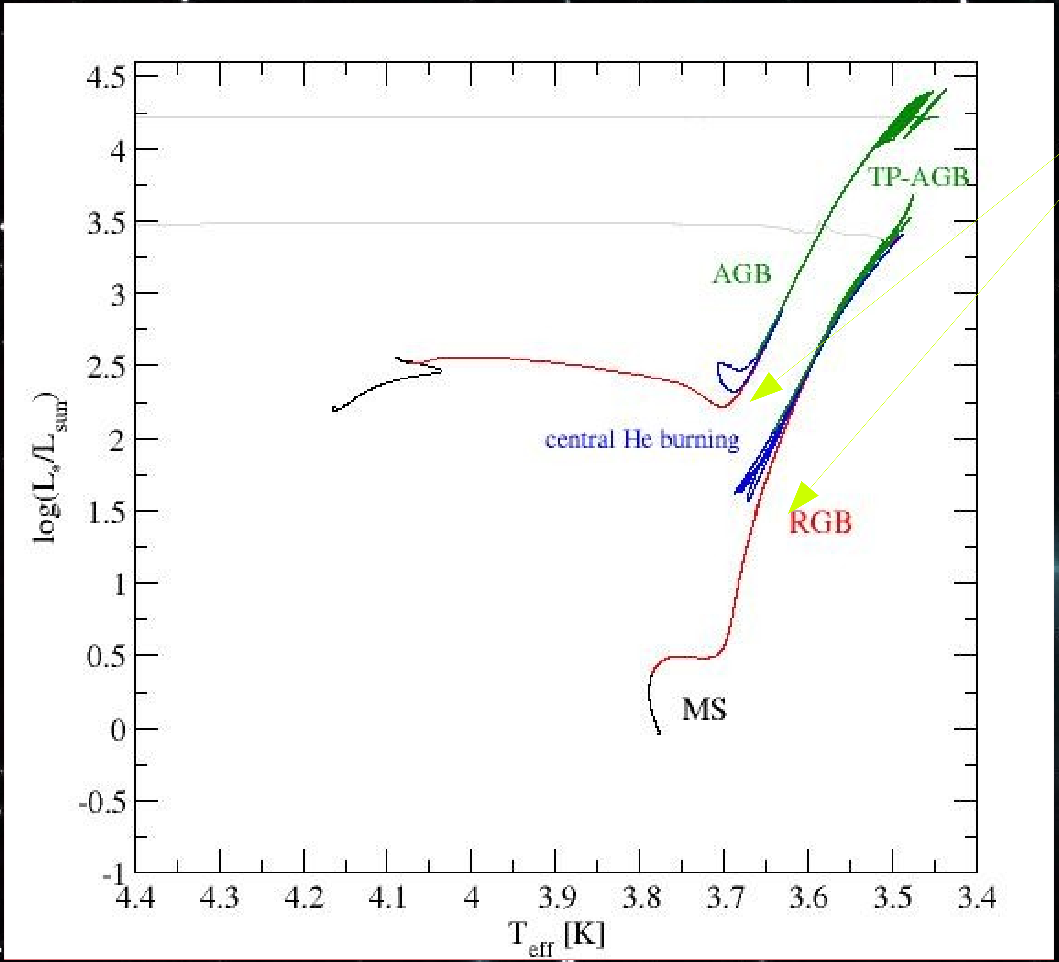
Thermal pulsing AGB: third dredge-up

Dredge-up: Convection brings processed material to the envelope of the star



First Dredge-up: RGB (post H central burning)

Second Dredge-up: E-AGB (post He central burning)

Third dredge-up: Thermal pulses

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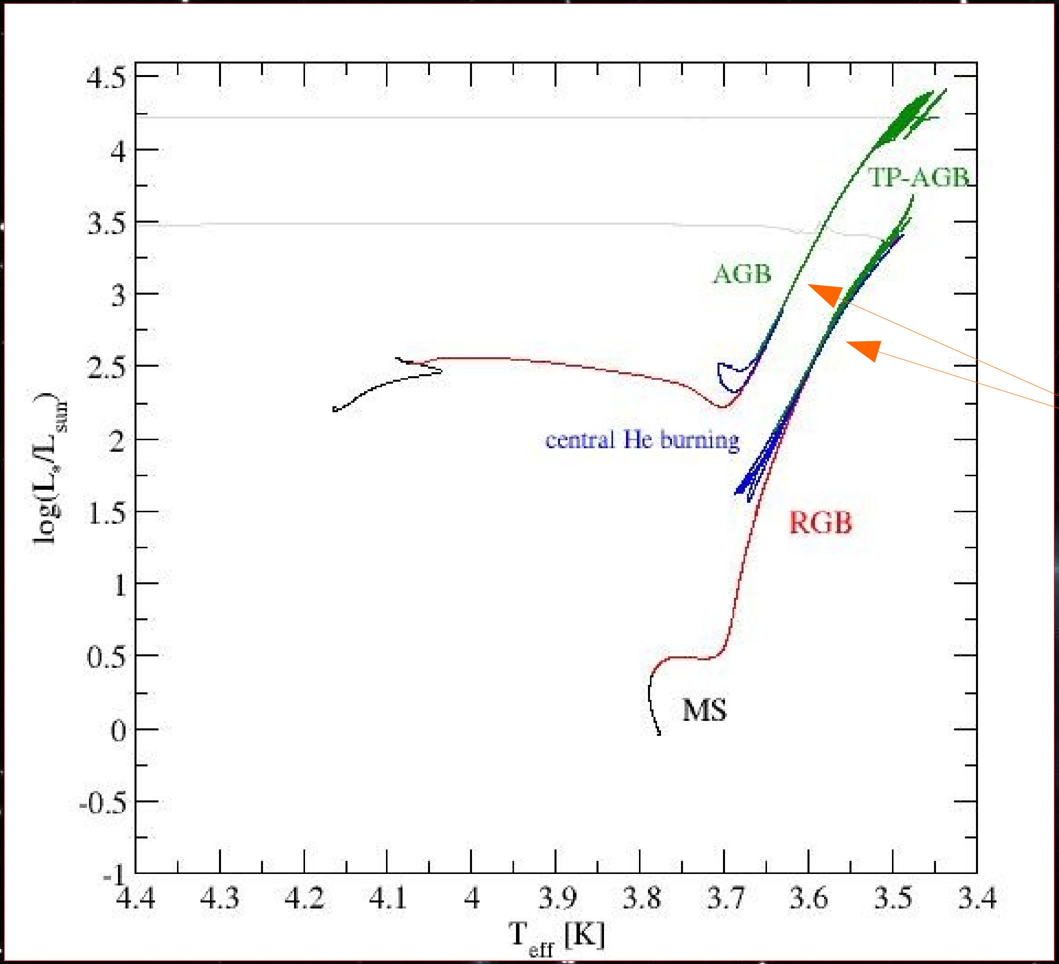
Thermal pulsing AGB: third dredge-up

Dredge-up: Convection brings processed material to the envelope of the star



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Third dredge-up: Thermal pulses

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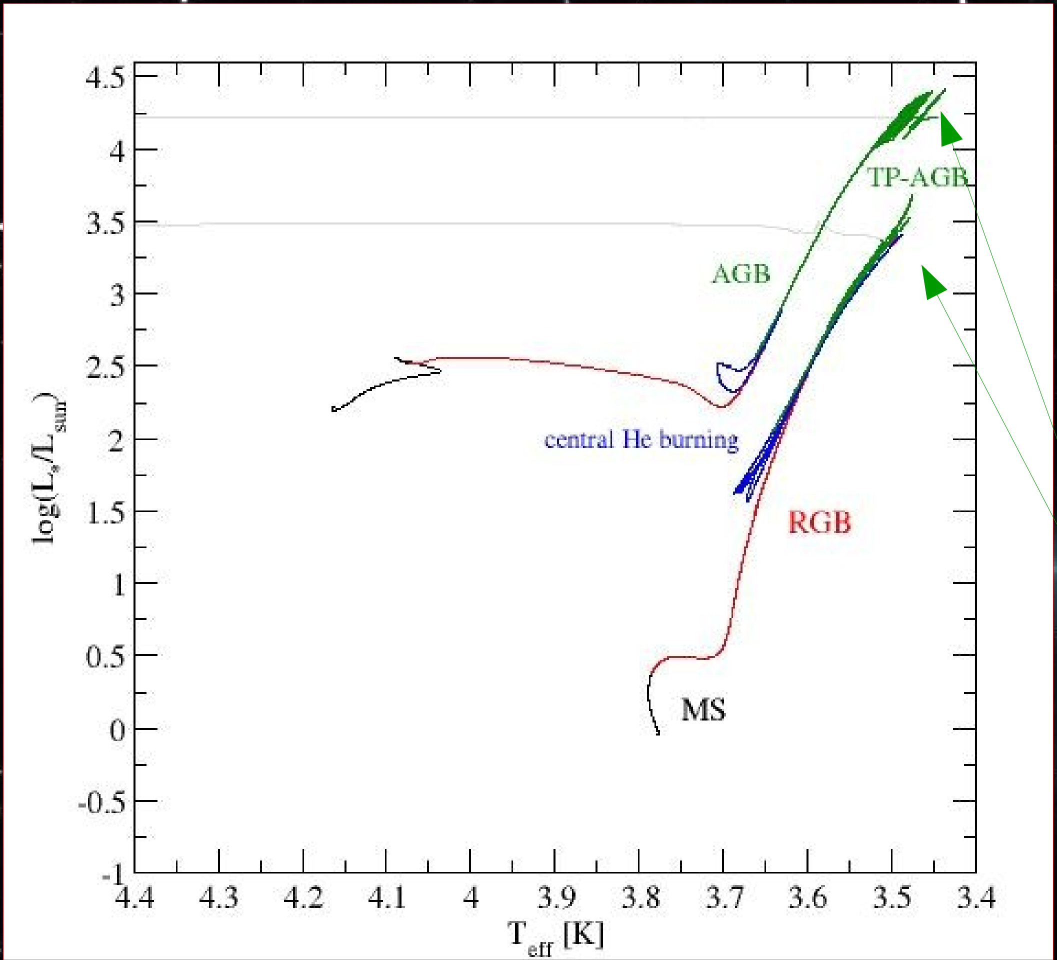
Thermal pulsing AGB: third dredge-up

Dredge-up: Convection brings processed material to the envelope of the star



First Dredge-up:
RGB (post H central burning)

Second Dredge-up:
E-AGB (post He central burning)

Third dredge-up:
Thermal pulses

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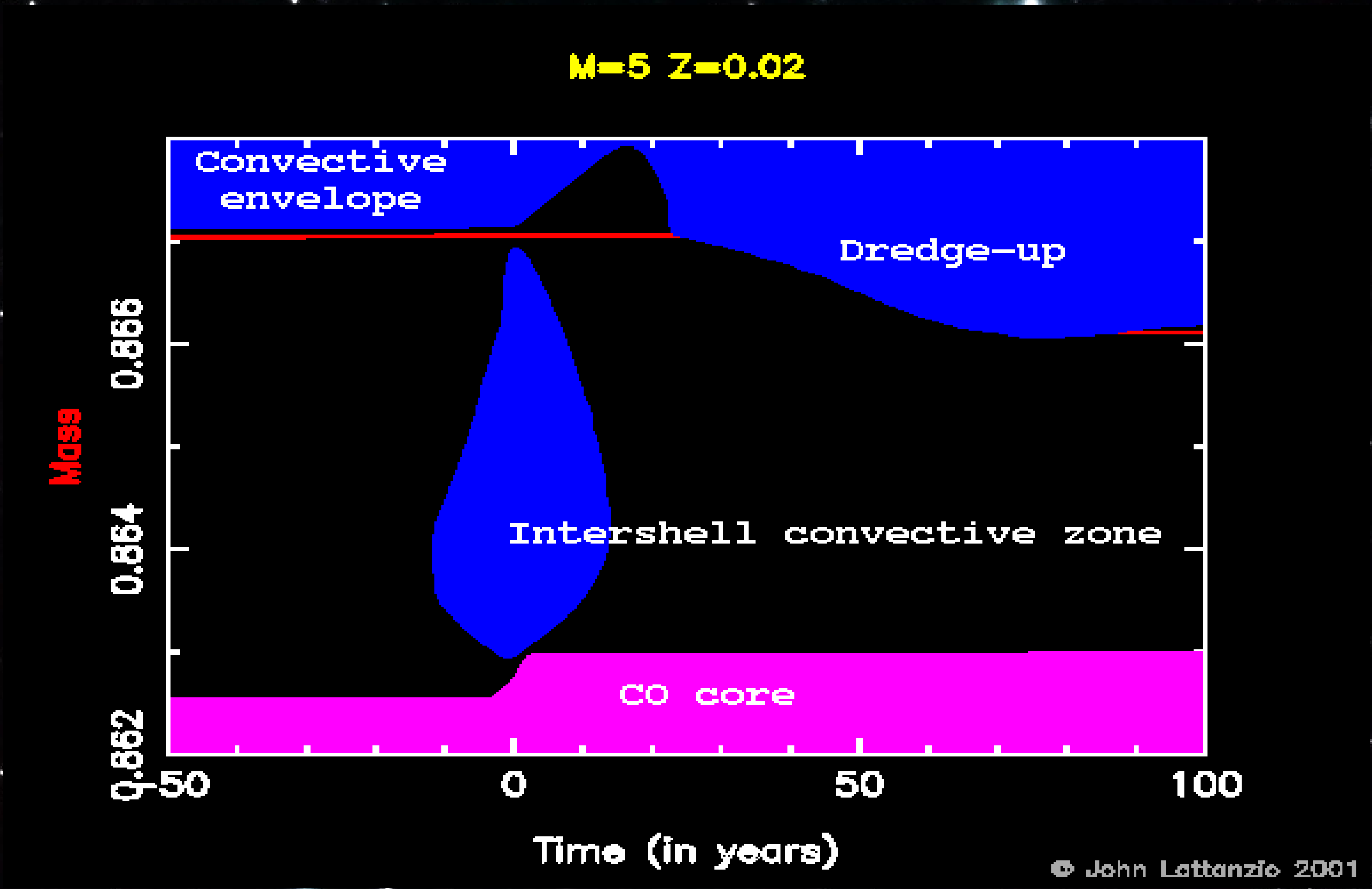
Thermal pulsing AGB: third dredge-up

A convection zone appears and dredges up processes material to the envelope -- C and O rich stars – reduces the mass of the core



Pleiades open cluster
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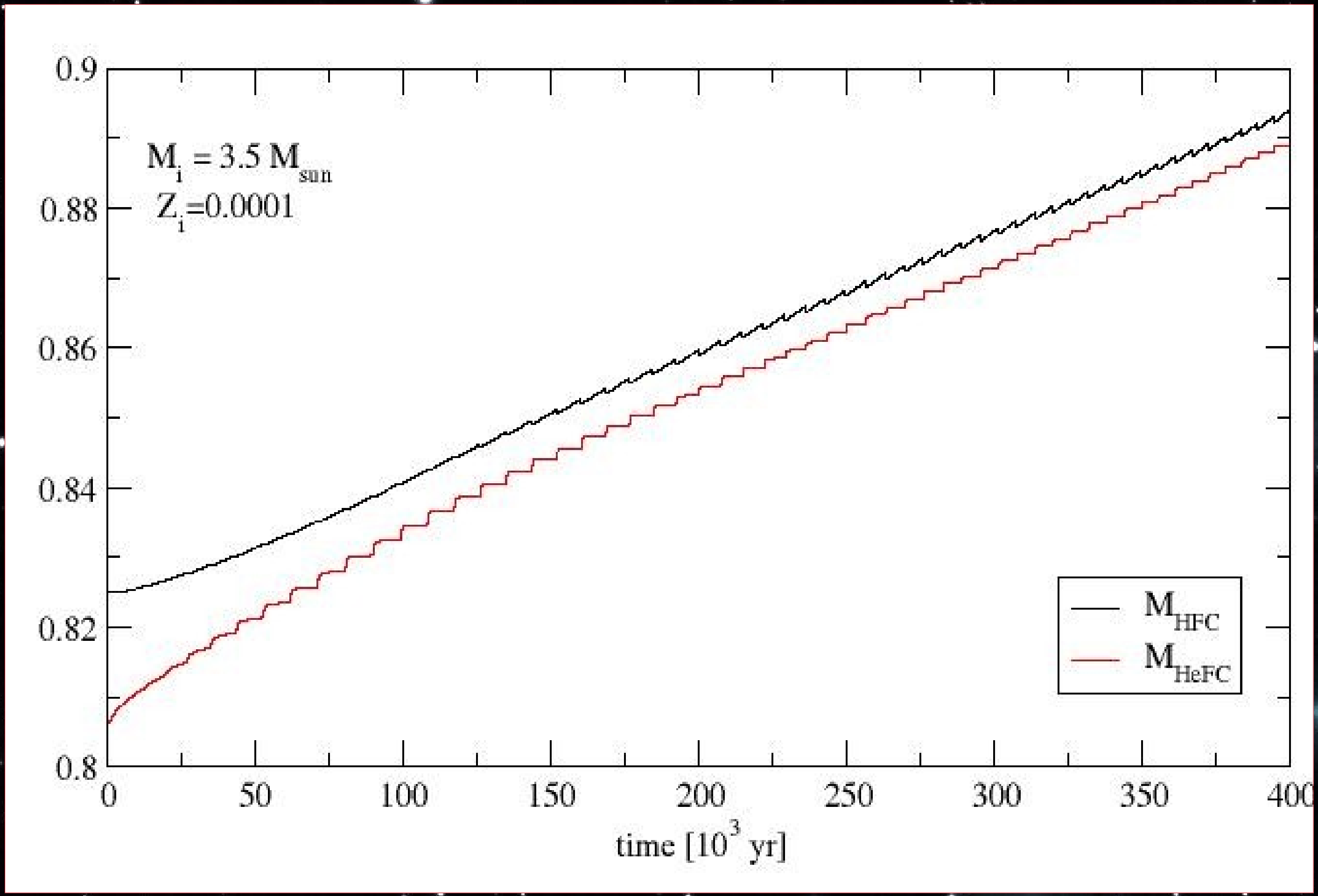
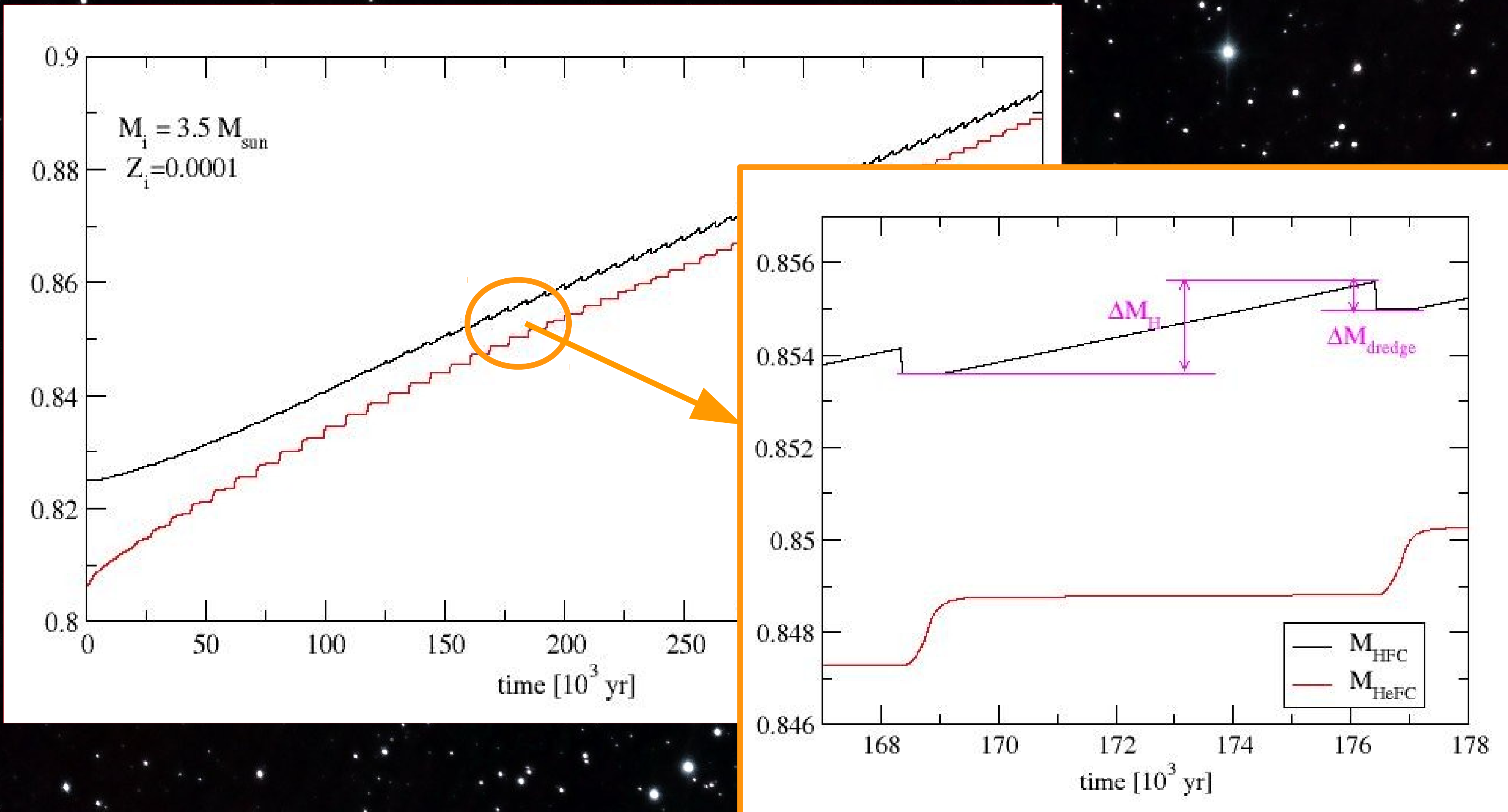
Thermal pulsing AGB: third dredge-up



$$\lambda = \frac{\Delta M_H}{M_{dredge}}$$

Dredge up parameter λ increases with Num. Of Tps
Evolution codes: overshooting parameter f (0.016 for solar envelope)

Thermal pulsing AGB: third dredge-up



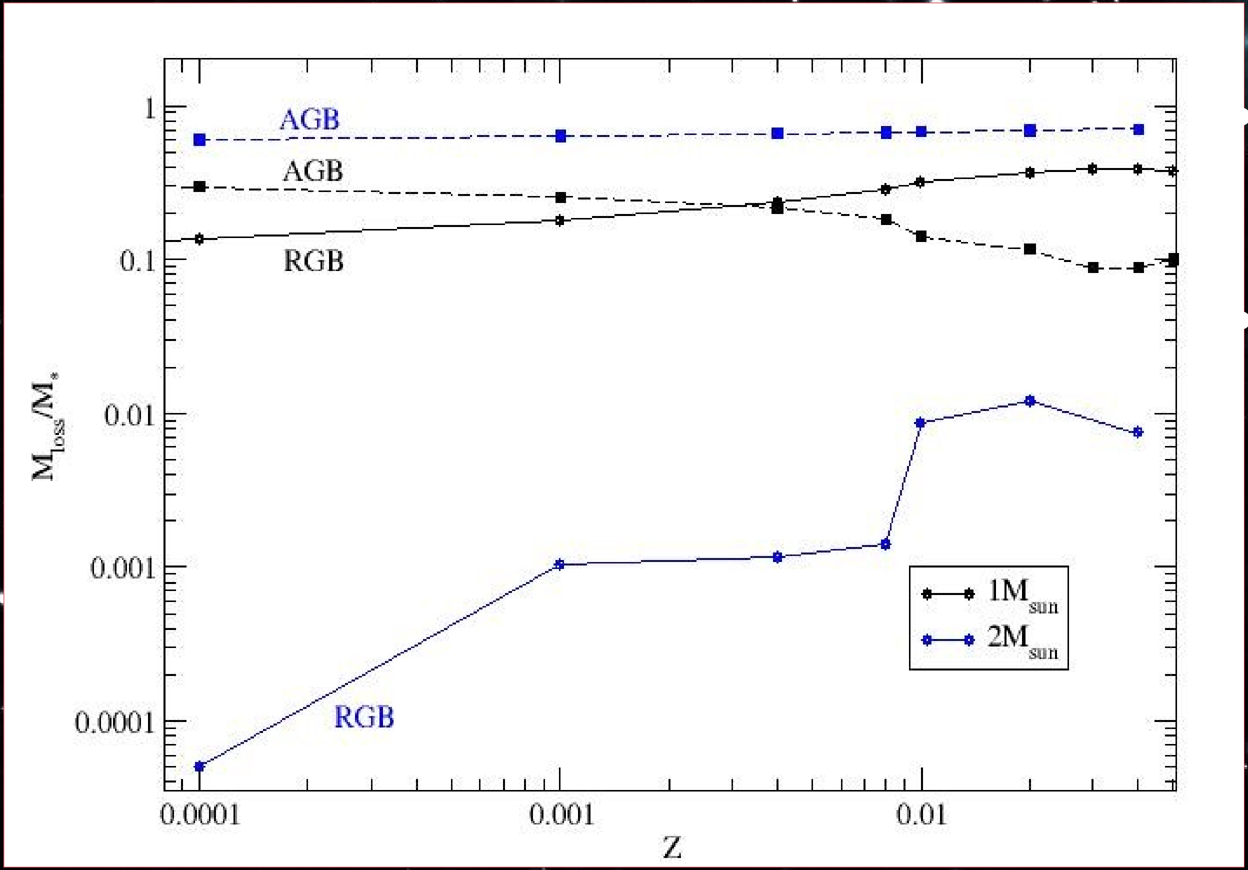
Third dredge up efficiency increases with metallicity

$$\lambda = \frac{\Delta M_H}{M_{dredge}}$$

Mass loss during giant phases

RGB: Schröeder & Cuntz (2005) η=0.5

AGB: Vassiliadis & wood (1993, modified), Groenewegen et al. (2009)



- $1M_{sun}$: $M_{RGB} \sim M_{AGB}$ (22 %) for Z=0.004
- $2M_{sun}$: $M_{AGB} >> M_{RGB}$

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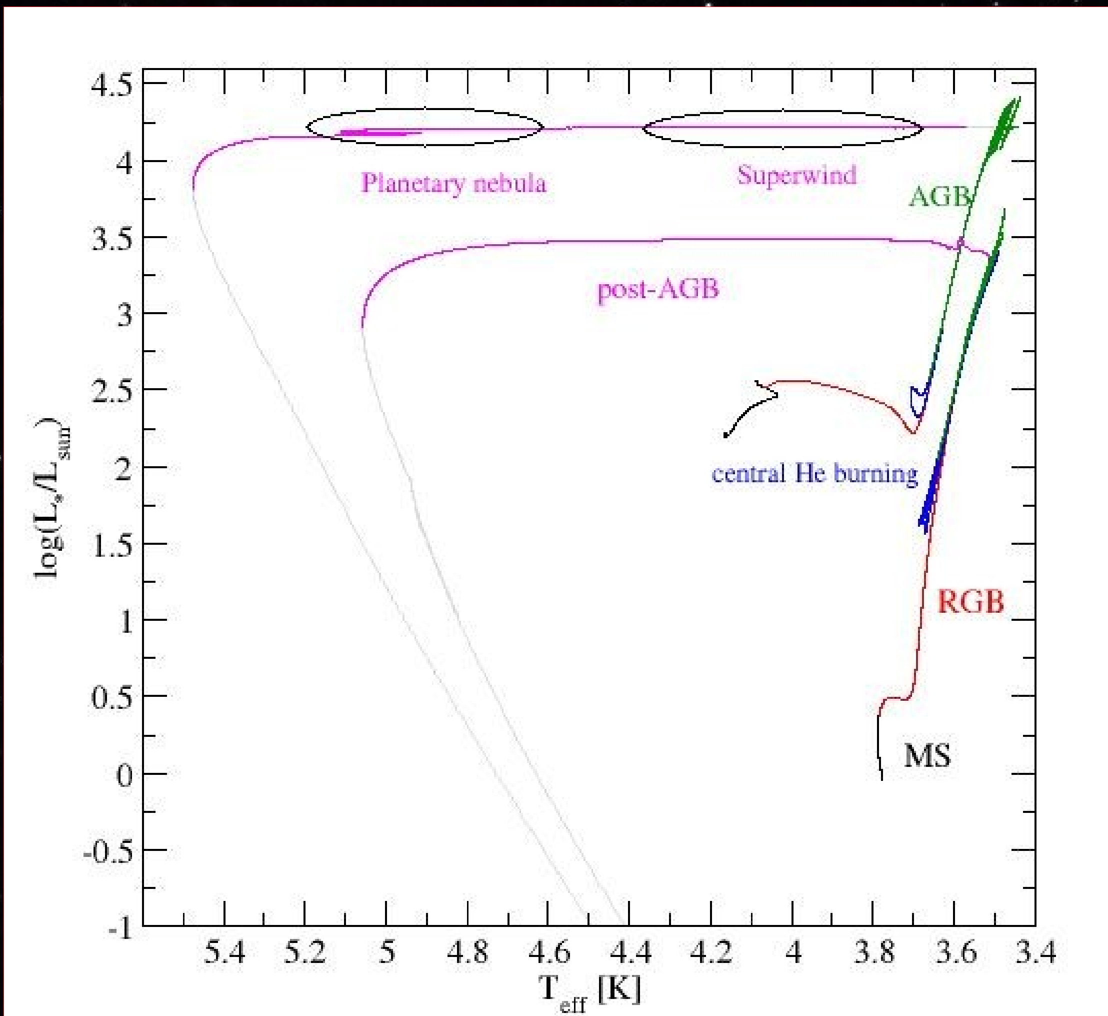
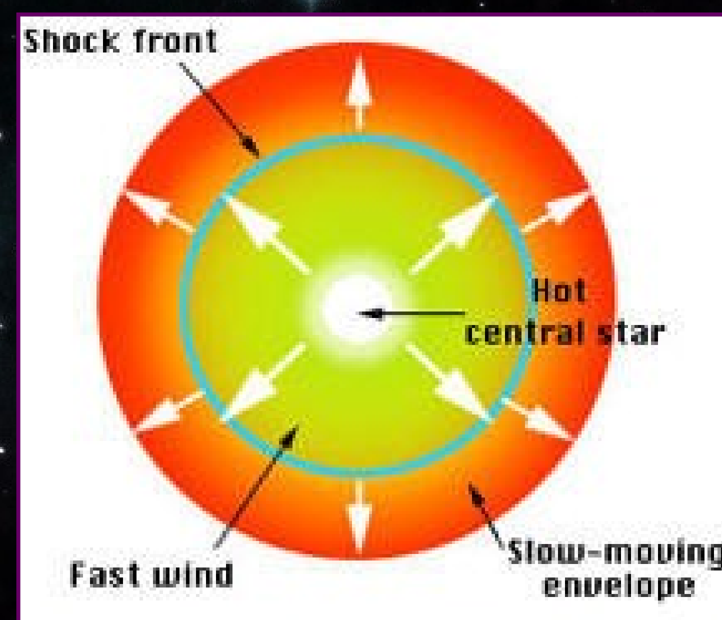
Post-AGB evolution



$M_{env} \sim 10^{-3} M_*$ end of TP-AGB stage

Superwind stage followed by the formation of a planetary nebula



luster

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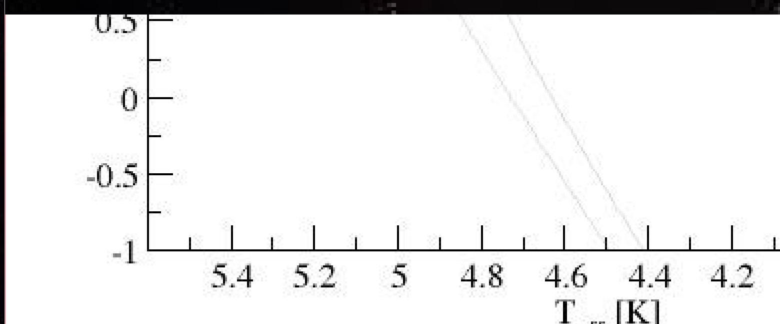
Post-AGB evolution



$M_{env} \sim 10^{-3}$ M_* end of TP-AGB stage

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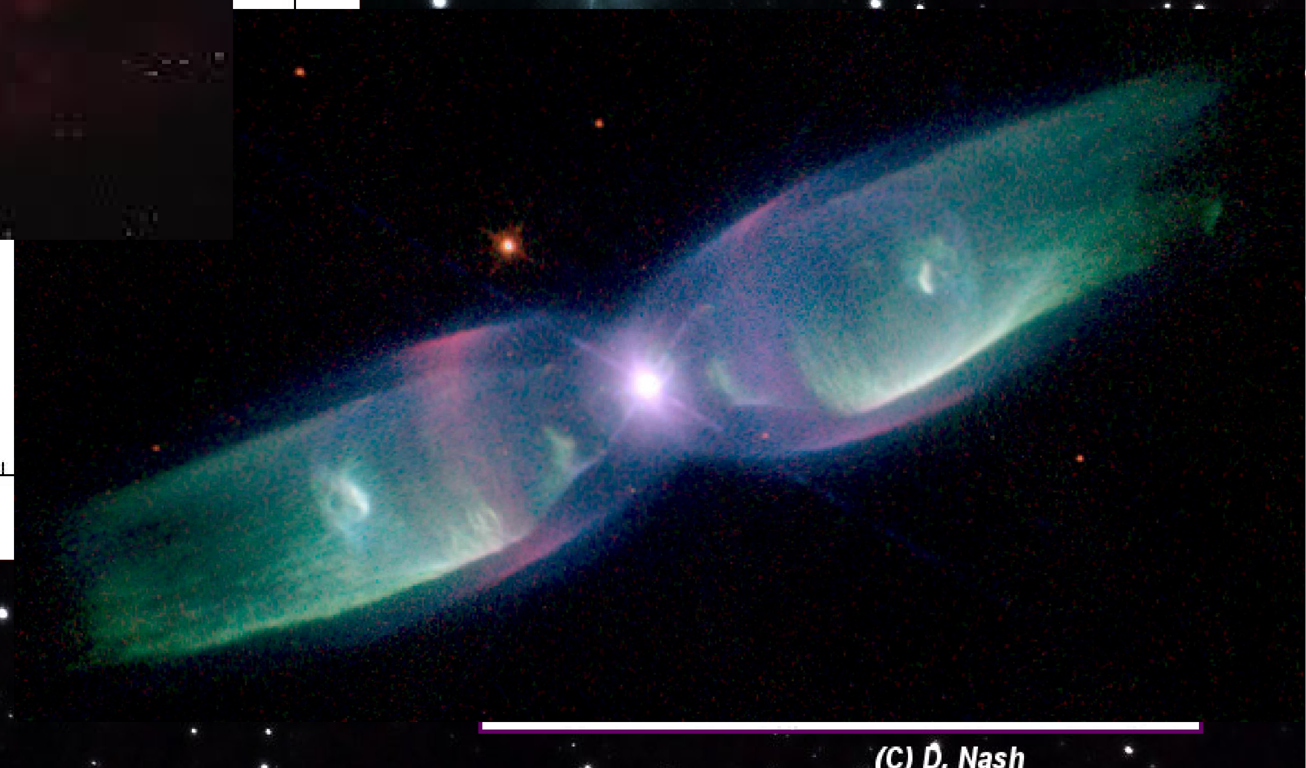

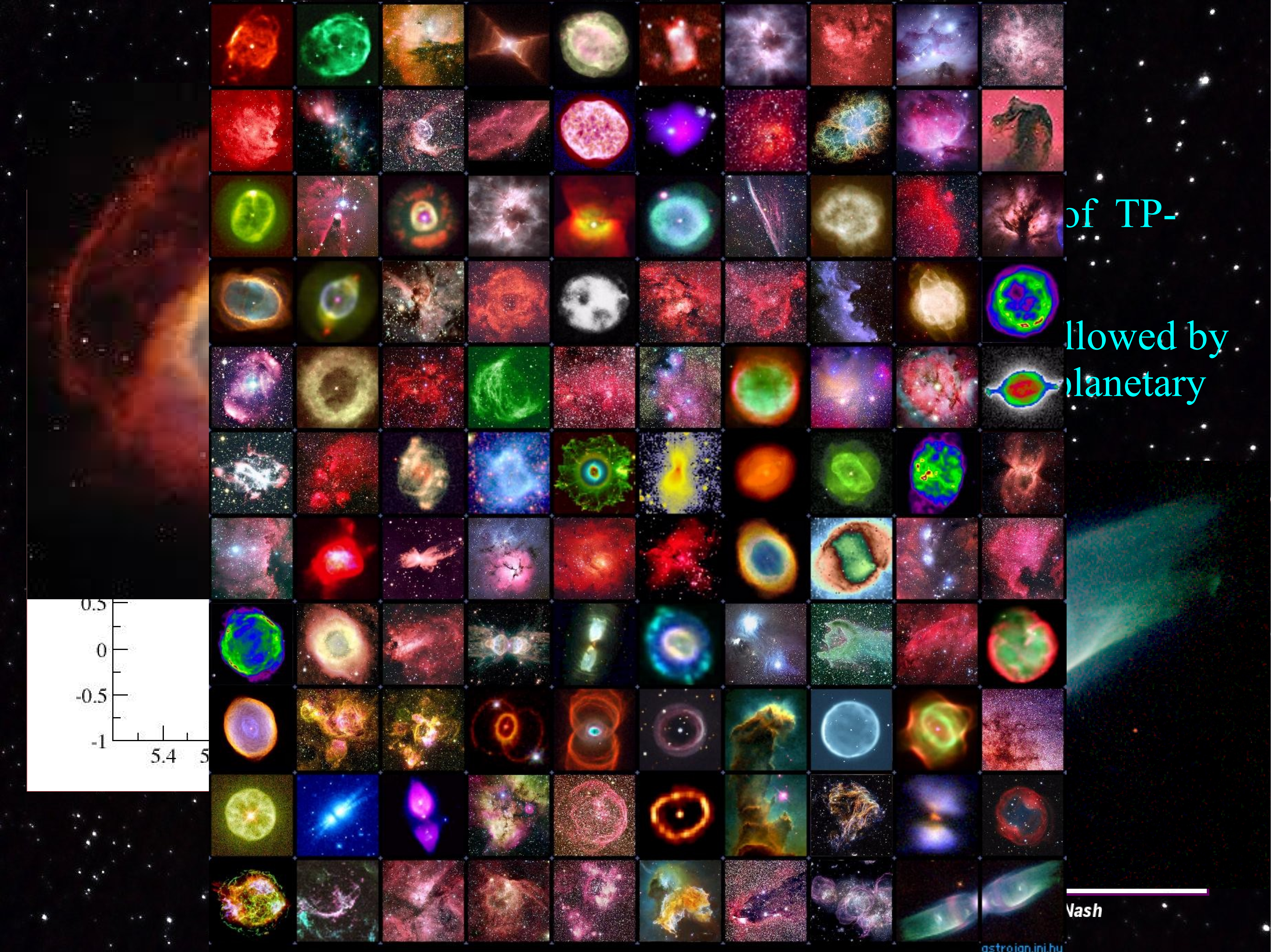

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llowed by
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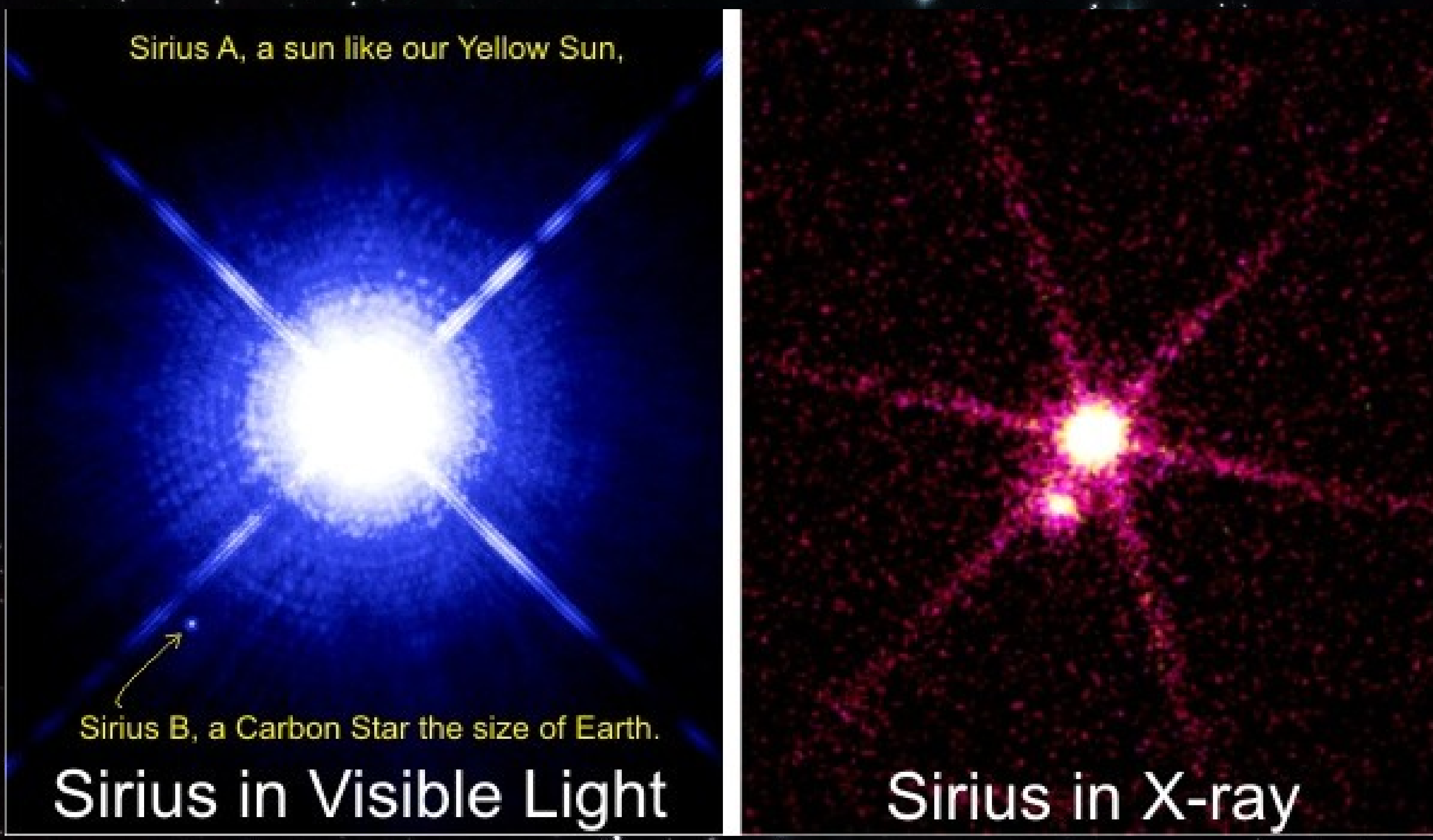
0
-0.5
-1
5.4
Nash
astrojan.ini.hu

White dwarf stage



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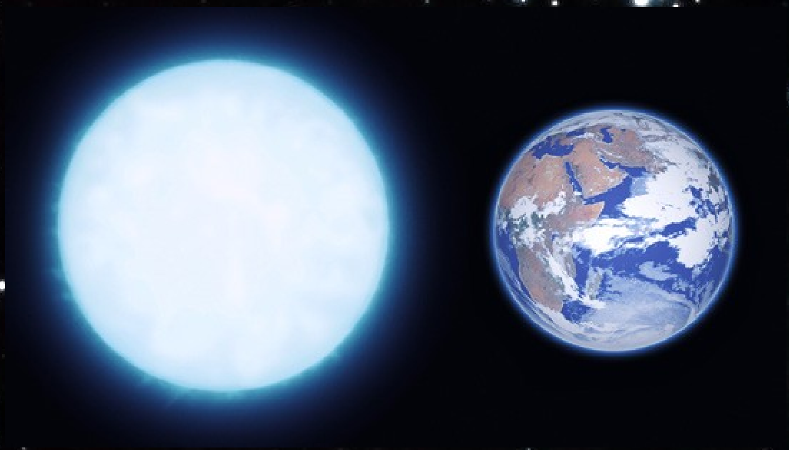
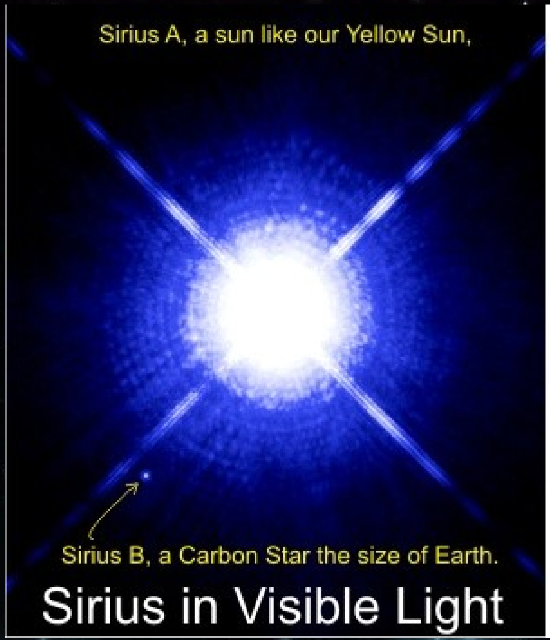
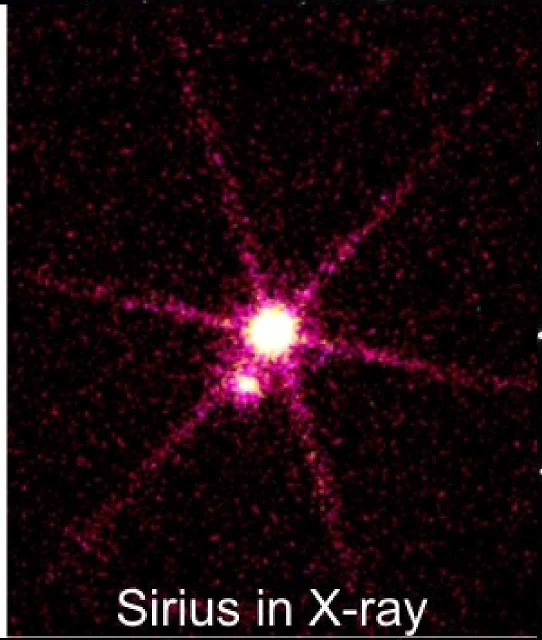
White dwarf stage





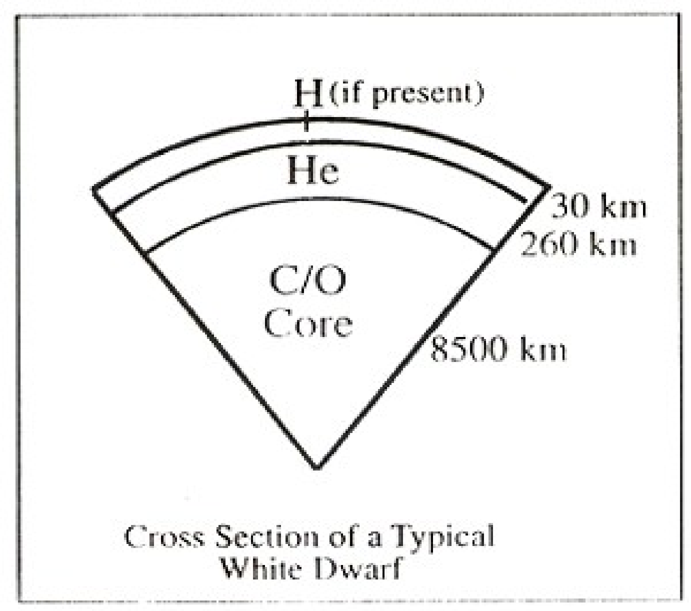


Spectral type O-B-A

$M \sim 0.6\ M_{sun}$, $R \sim 10.000$ km, $\rho \sim 10^6$ g/cm^3

(one tee spoon weights 1000 kg)

Mass-radius relation : $M \sim R^{-3}$



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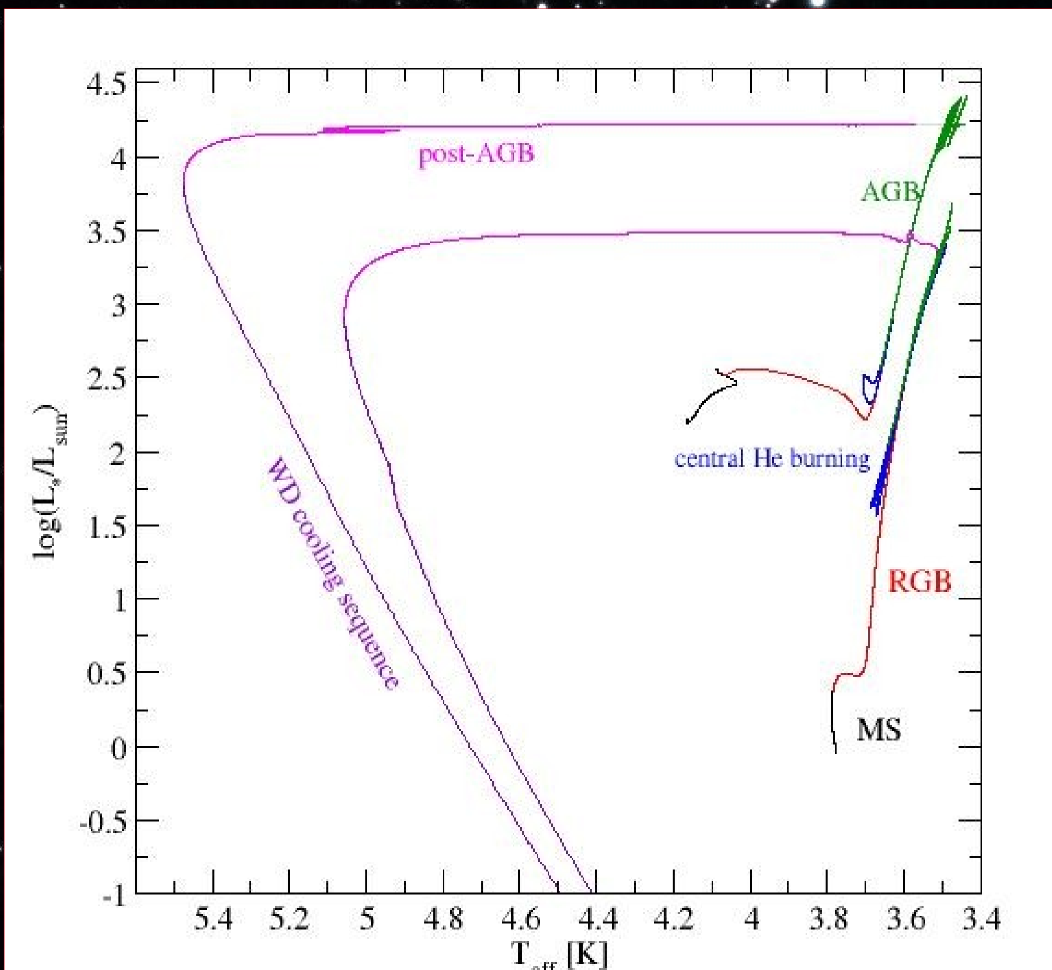
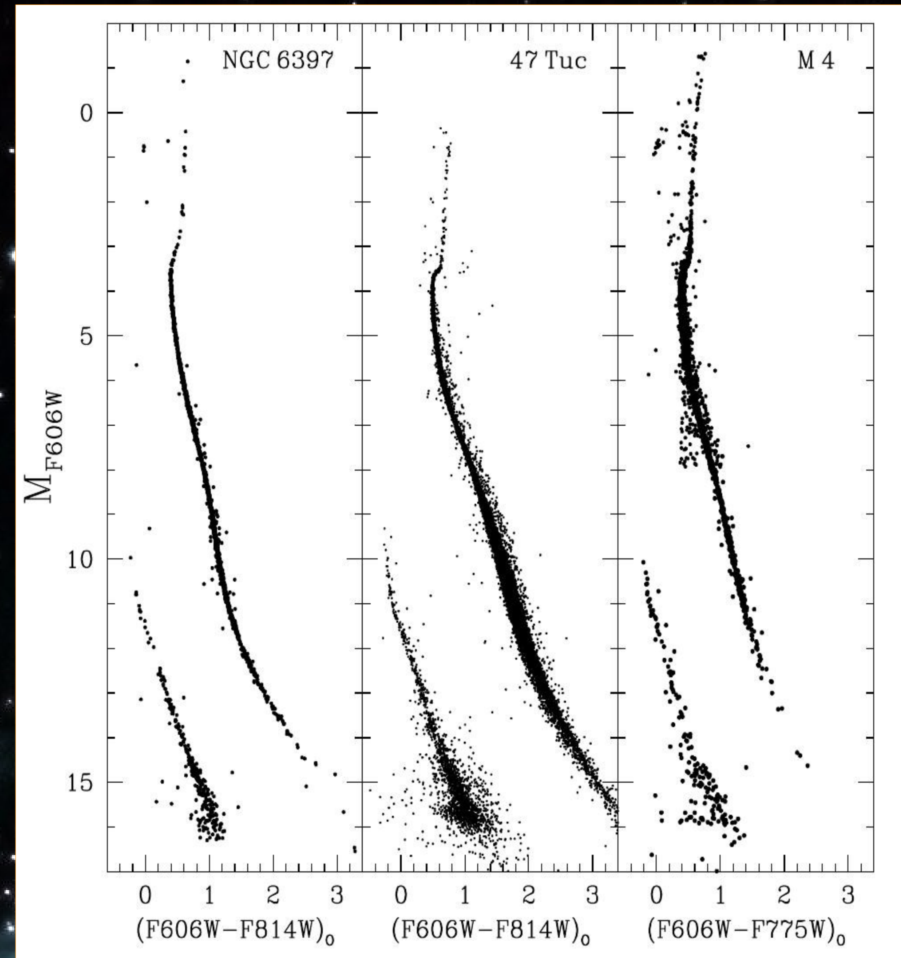
White dwarf stage





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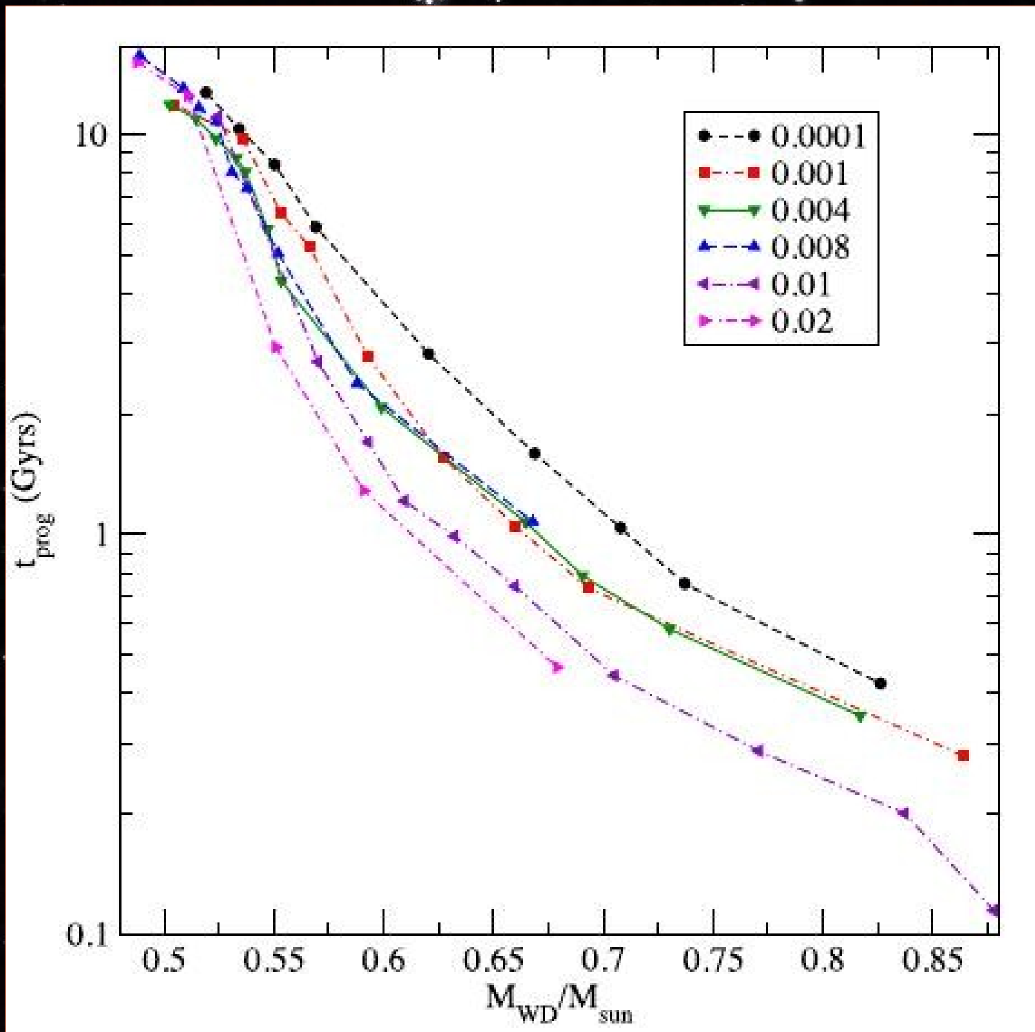
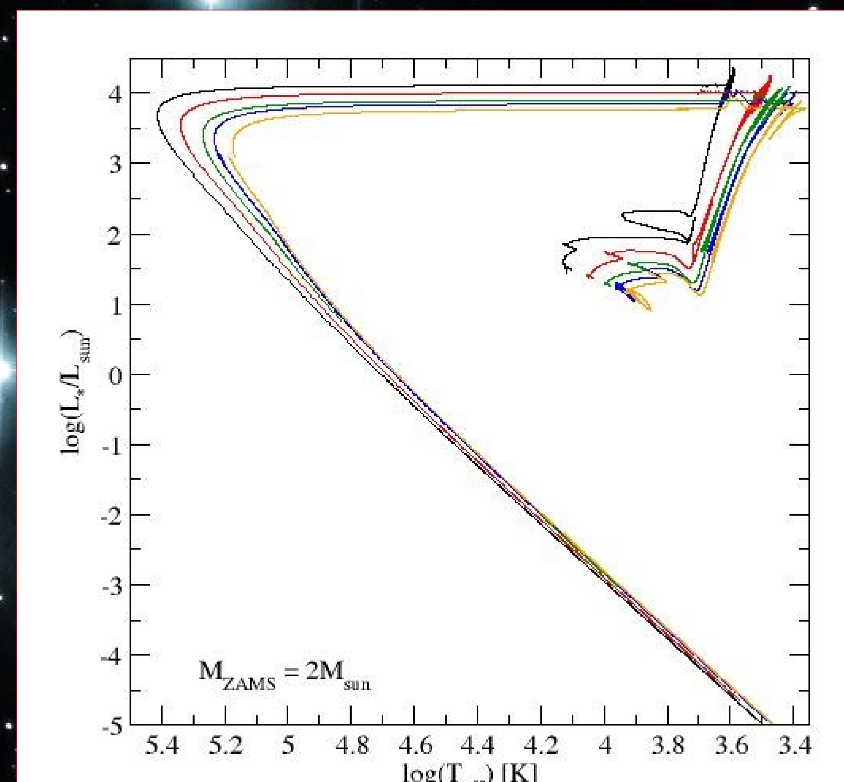


Romero et al. (2015)

Cosmocronology: Pre-WD age depends on initial Mass and metallicity



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White dwarf stage

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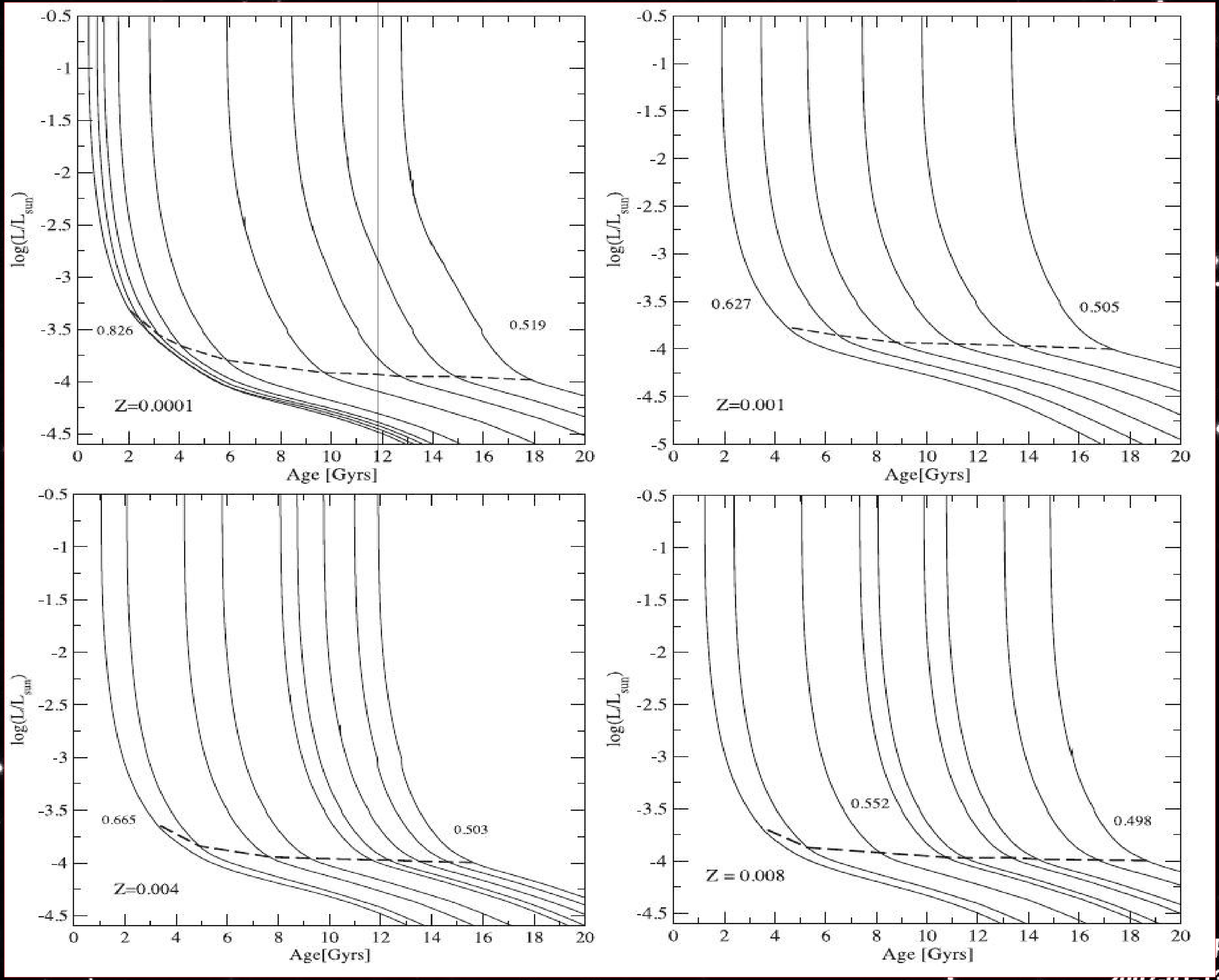

Romero et al. (2015)

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White dwarf stage

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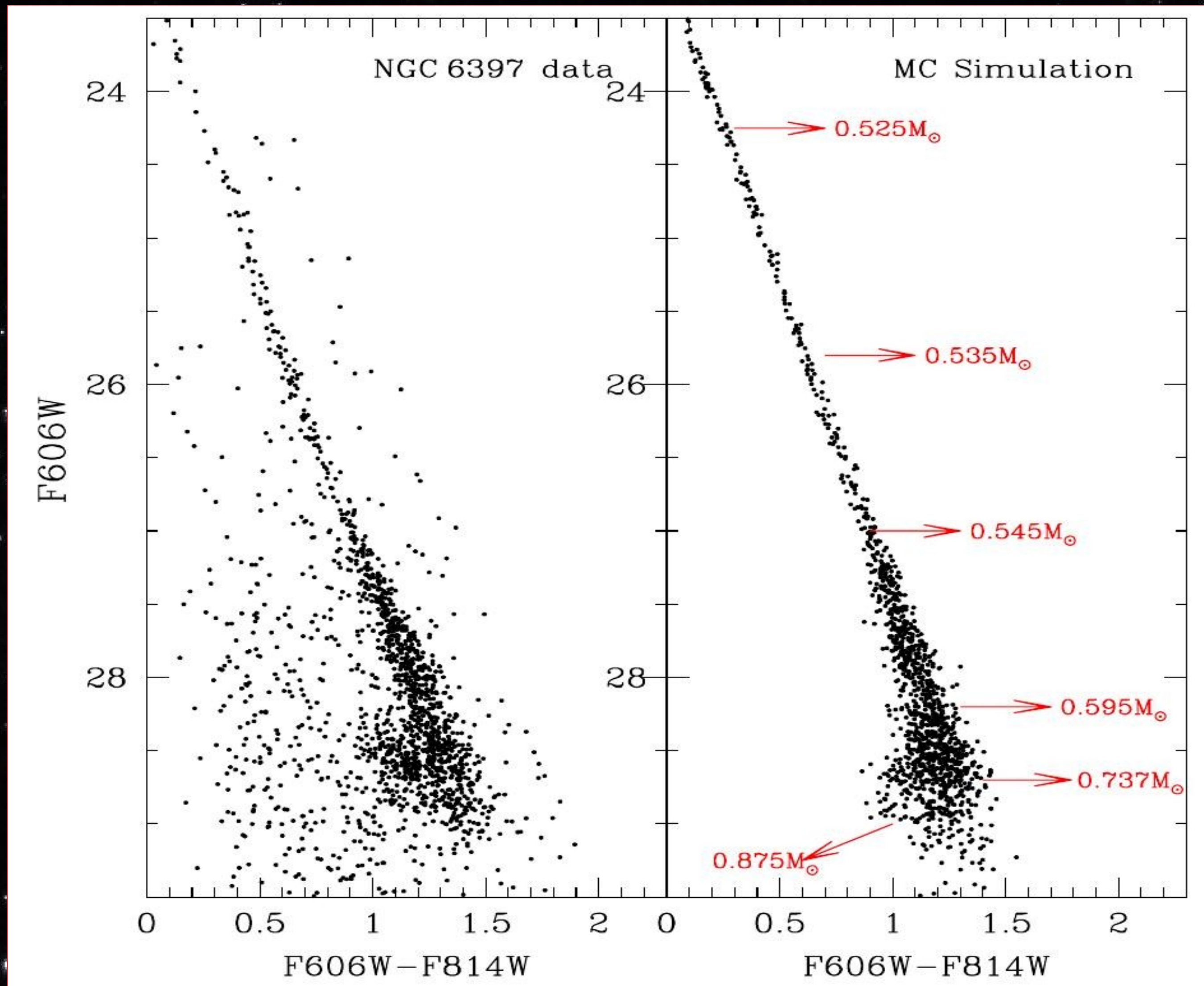

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Campos et al. (2016)

White dwarf stage

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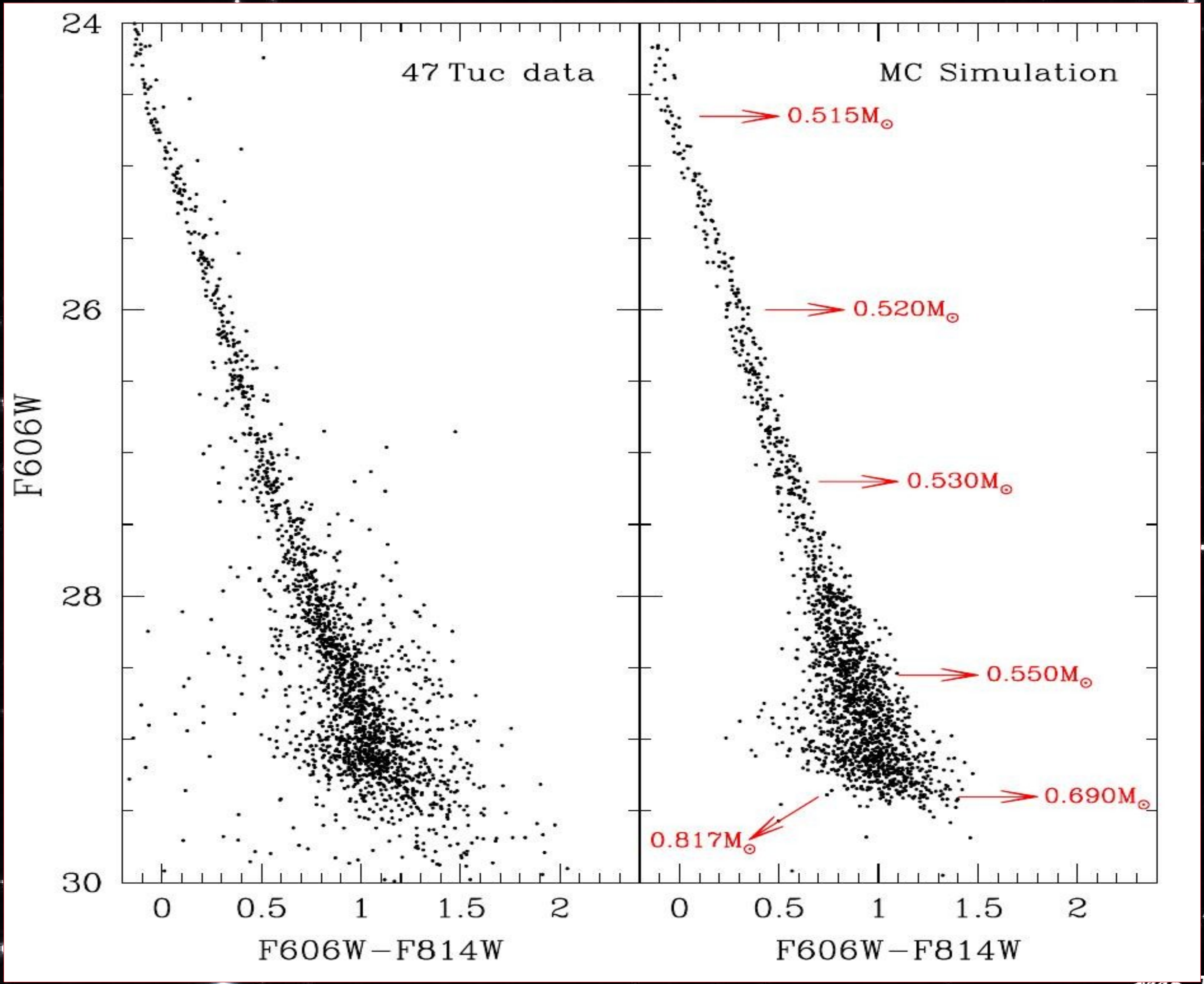

Campos et al. (2016)

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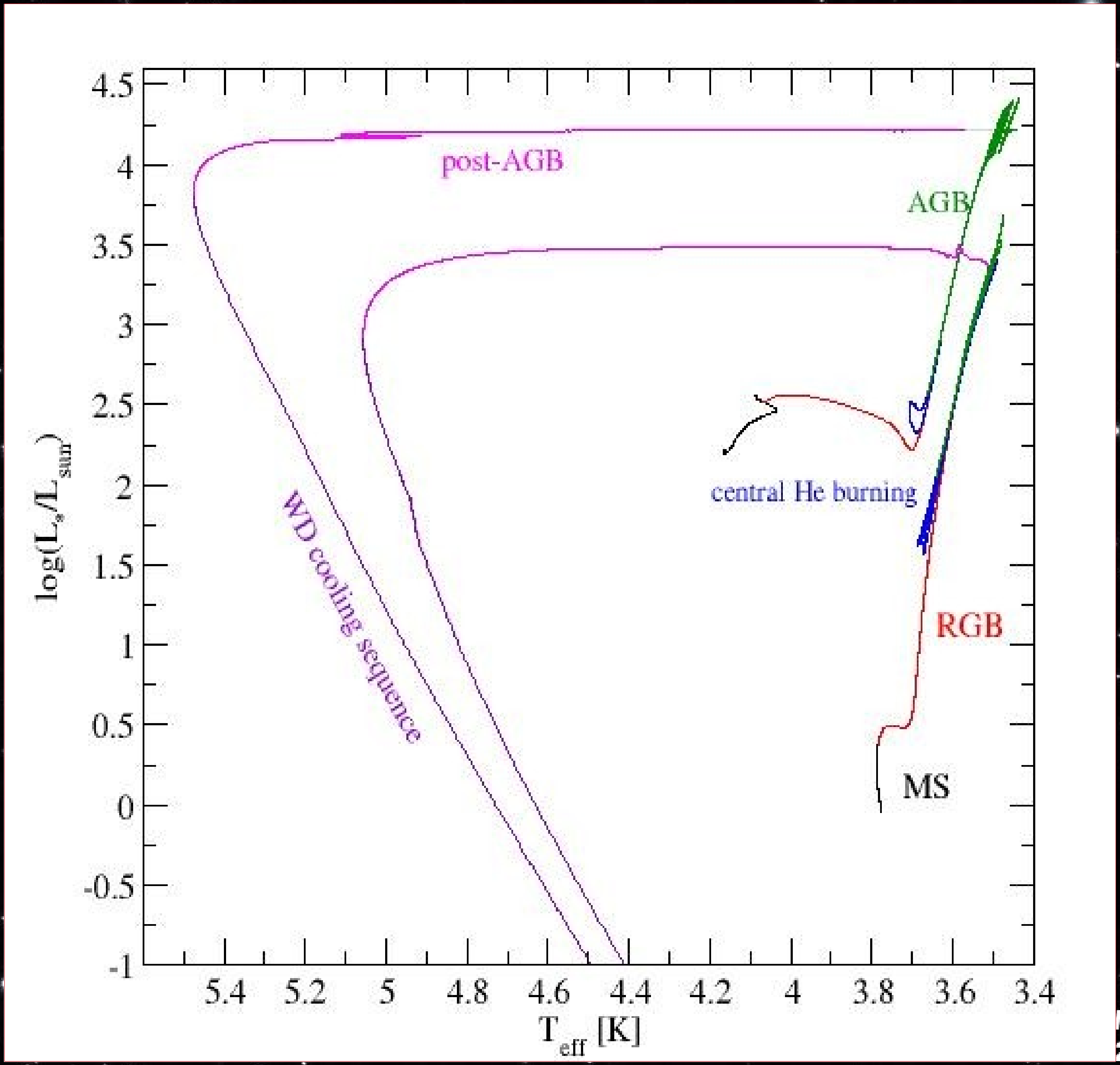
Thank you!



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