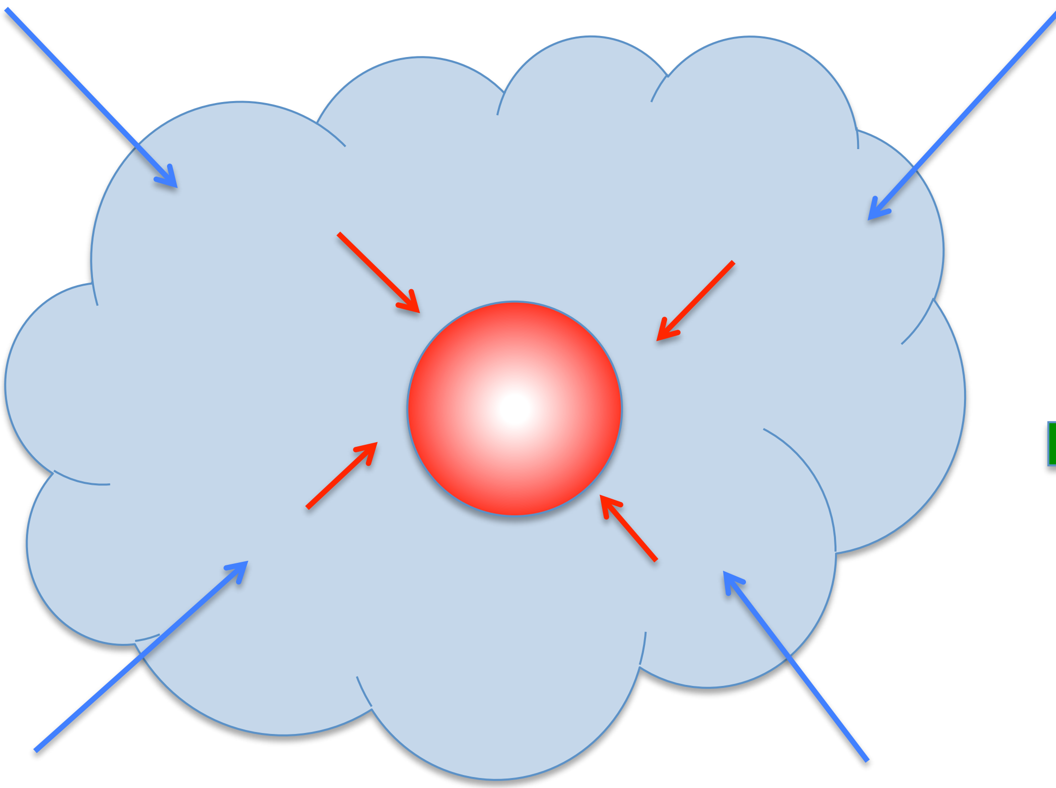
13 - Estágios avançados da evolução estelar (a partir de *The Horizontal Branch*) e Aglomerados estelares

J. Meléndez

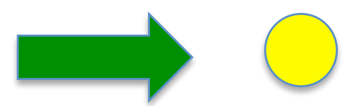
AGA293

Escalas de tempo de evolução estelar

Colapso da nuvem: escala de tempo *free-fall* ~10^5 anos



Escala de tempo da fusão nuclear. Para o Sol ~ 10^{10} anos



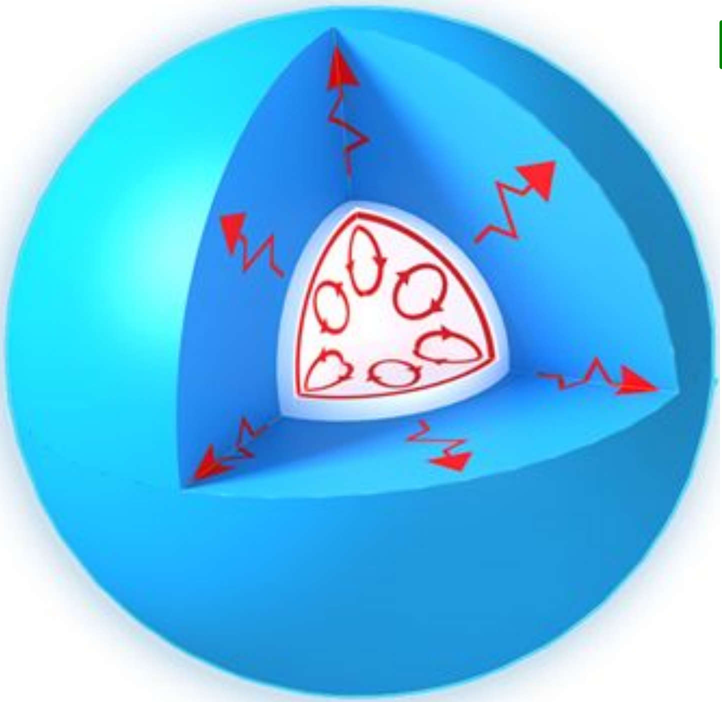
Colapso da proto-estrela: escala de tempo de Kelvin-Helmholtz ~ 10^7 anos

A estrutura e tamanho das estrelas muda durante a sua evolução

Estrelas com M < $1.2\,M_\odot$ queimam hidrogênio pelo ciclo próton-próton

$M > 1.2\,M_\odot$

Queima de hidrogênio pelo ciclo CNO → núcleo convectivo



$0.3\,M_\odot < M < 1.2\,M_\odot$

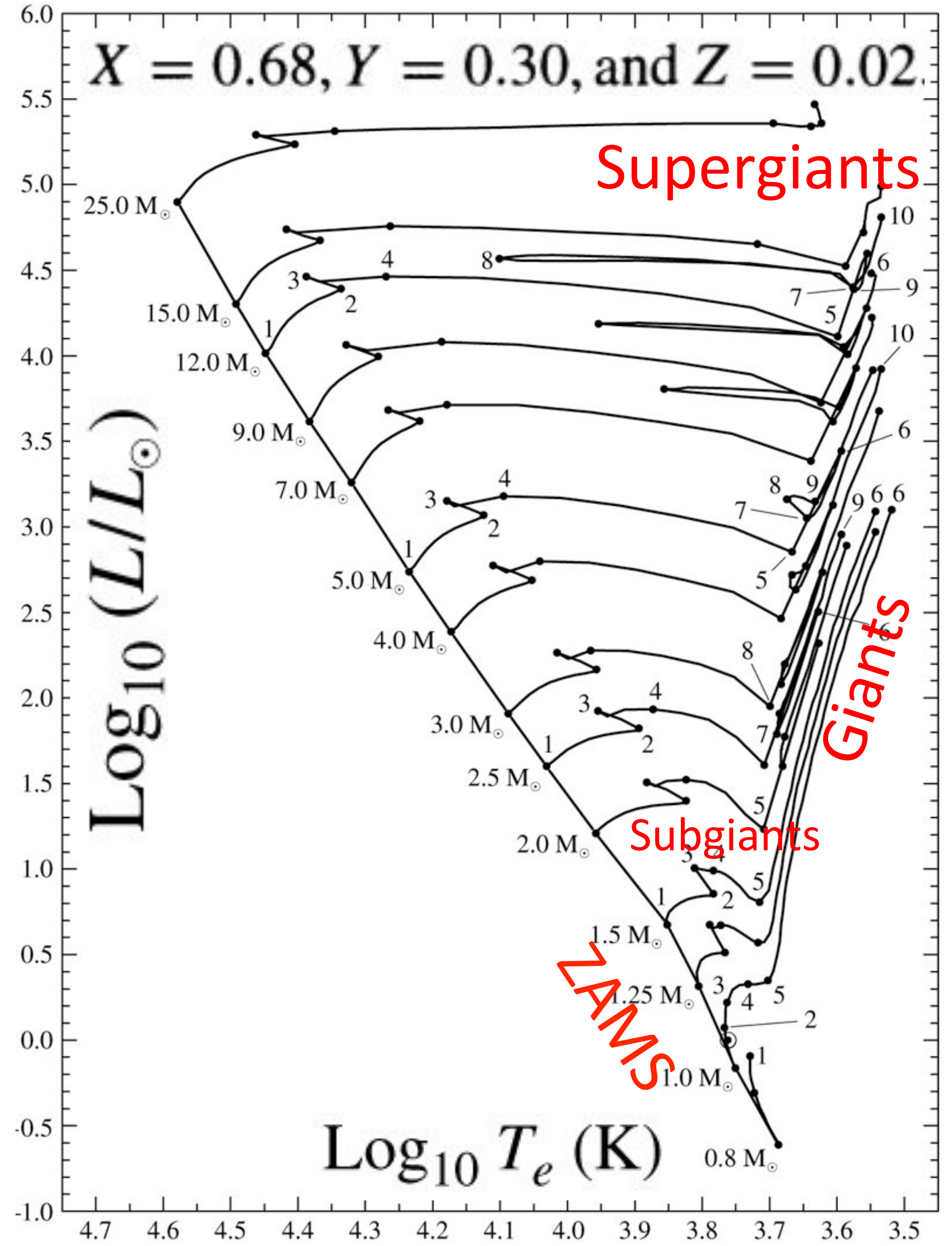
Envelope convectivo

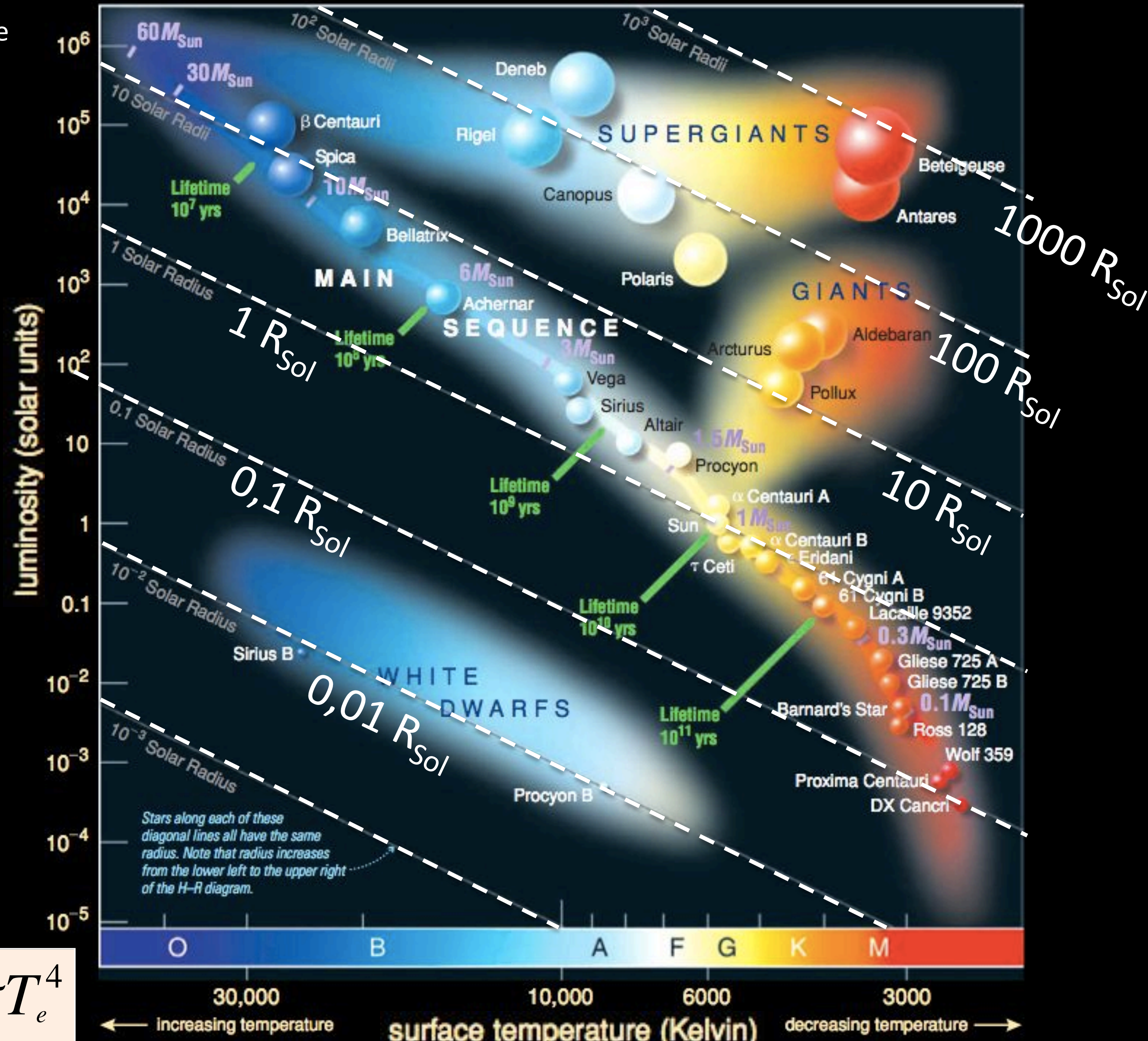
$M < 0.3\,M_\odot$

Totalmente convectivas devido à alta opacidade

Tempo (Myr) a partir da ZAMS

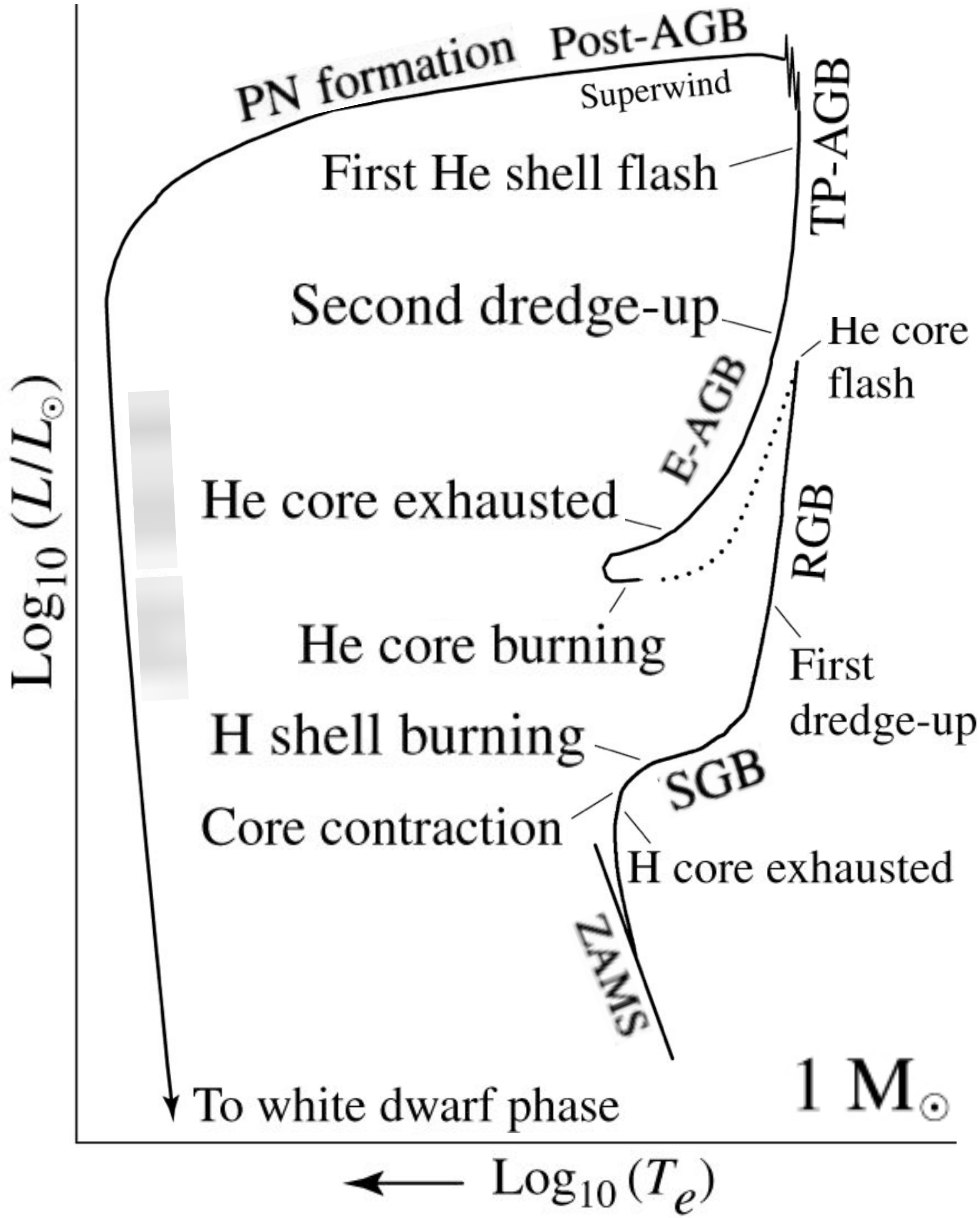
Initial Mass ($M_\odot$)	1 6	2 7	3 8	4 9	5 10
25	0	6.33044	6.40774	6.41337	6.43767
	6.51783	7.04971	7.0591		
15	0	11.4099	11.5842	11.5986	11.6118
	11.6135	11.6991	12.7554		
12	0	15.7149	16.0176	16.0337	16.0555
	16.1150	16.4230	16.7120	17.5847	17.6749
9	0	25.9376	26.3886	26.4198	26.4580
	26.5019	27.6446	28.1330	28.9618	29.2294
7	0	42.4607	43.1880	43.2291	43.3388
	43.4304	45.3175	46.1810	47.9727	48.3916
5	0	92.9357	94.4591	94.5735	94.9218
	95.2108	99.3835	100.888	107.208	108.454
4	0	162.043	164.734	164.916	165.701
	166.362	172.38	185.435	192.198	194.284
3	0	346.240	352.503	352.792	355.018
	357.310	366.880	420.502	440.536	
2.5	0	574.337	584.916	586.165	589.786
	595.476	607.356	710.235	757.056	
2	0	1094.08	1115.94	1117.74	1129.12
	1148.10	1160.96	1379.94	1411.25	
1.5	0	2632.52	2690.39	2699.52	2756.73
	2910.76				
1.25	0	4703.20	4910.11	4933.83	5114.83
	5588.92				
1	0	7048.40	9844.57	11386.0	11635.8
	12269.8				
0.8	0	18828.9	25027.9		





$$L = 4\pi R^2 \sigma T_e^4$$

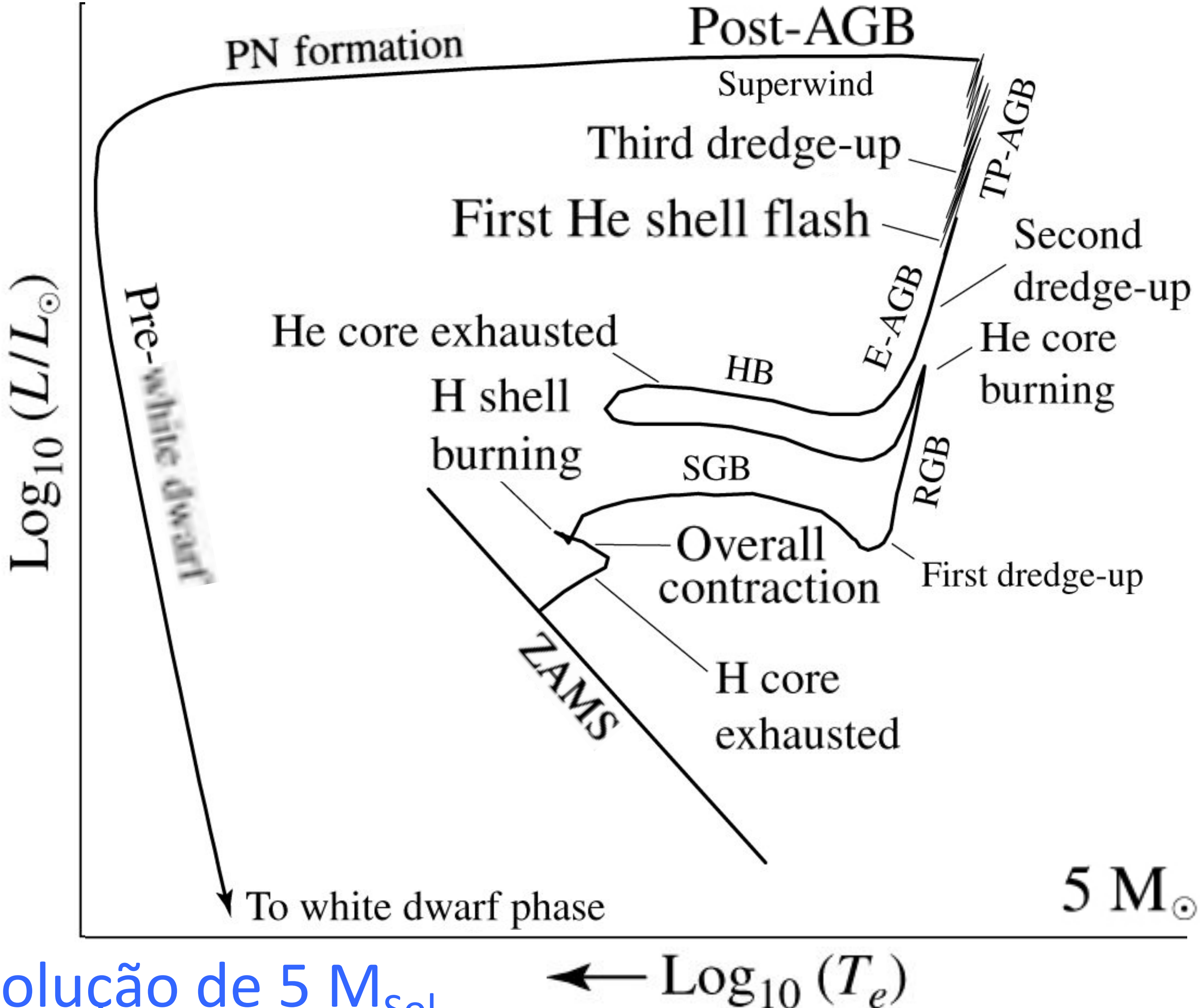
Figure 13.4. A schematic diagram of the evolution of a low-mass star of $1\ M_{\odot}$ from the zero-age main sequence to the formation of the white dwarf star (Section 16.1). The dotted phase represents rapid evolution following the He core flash.



Evolutionary Phases:

ZAMS: Zero-Age Main Sequence
SGB: Sub-Giant Branch
RGB: Red Giant Branch
E-AGB: Early Asymptotic Giant Branch
TP-AGB: Thermal Pulse AGB
Post-AGB: Post-AGB
PN-formation: Planetary Nebula formation

Evolução de 1 M_{Sol}



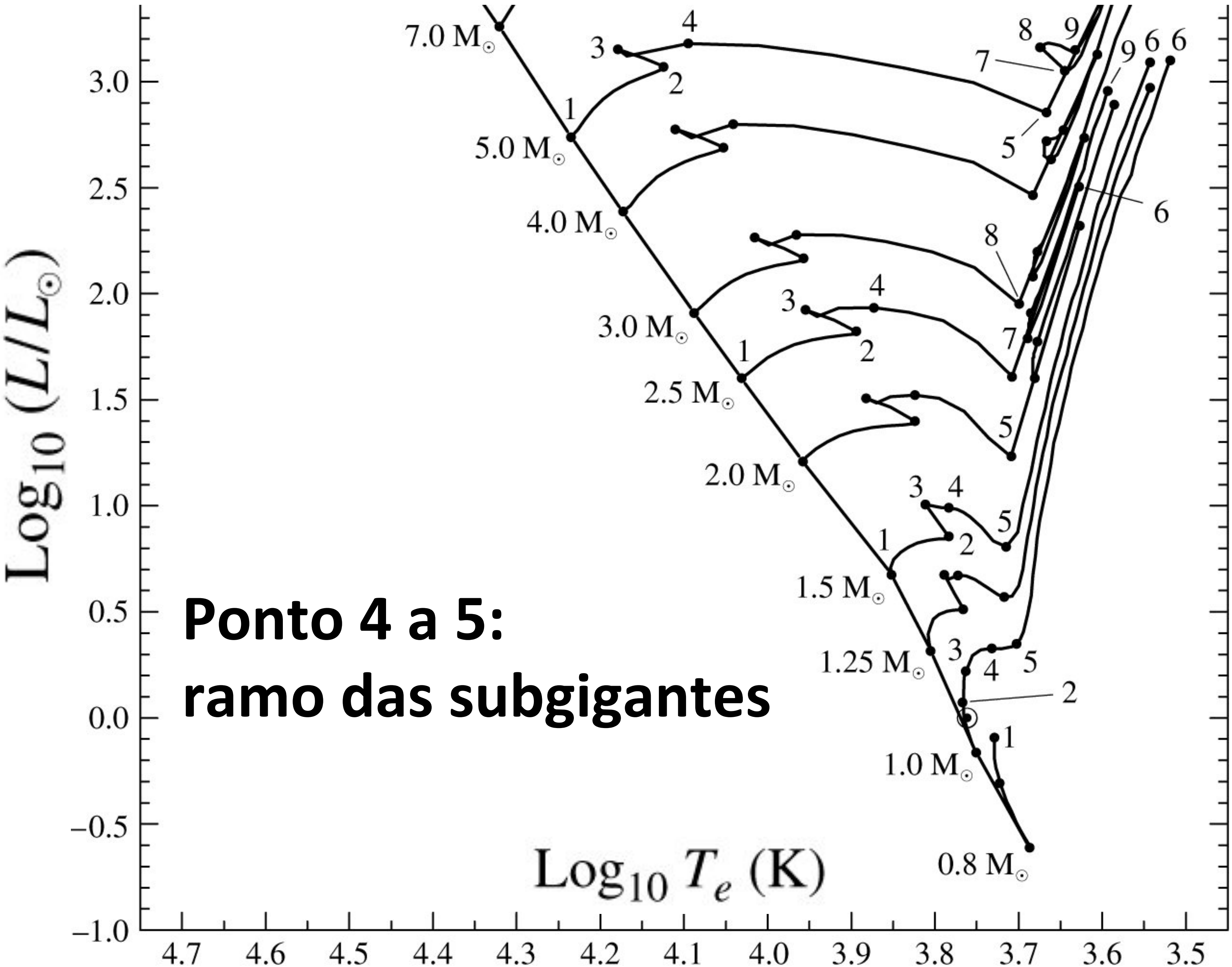
Evolução de 5 M_{Sol}

O ramo das subgigantes

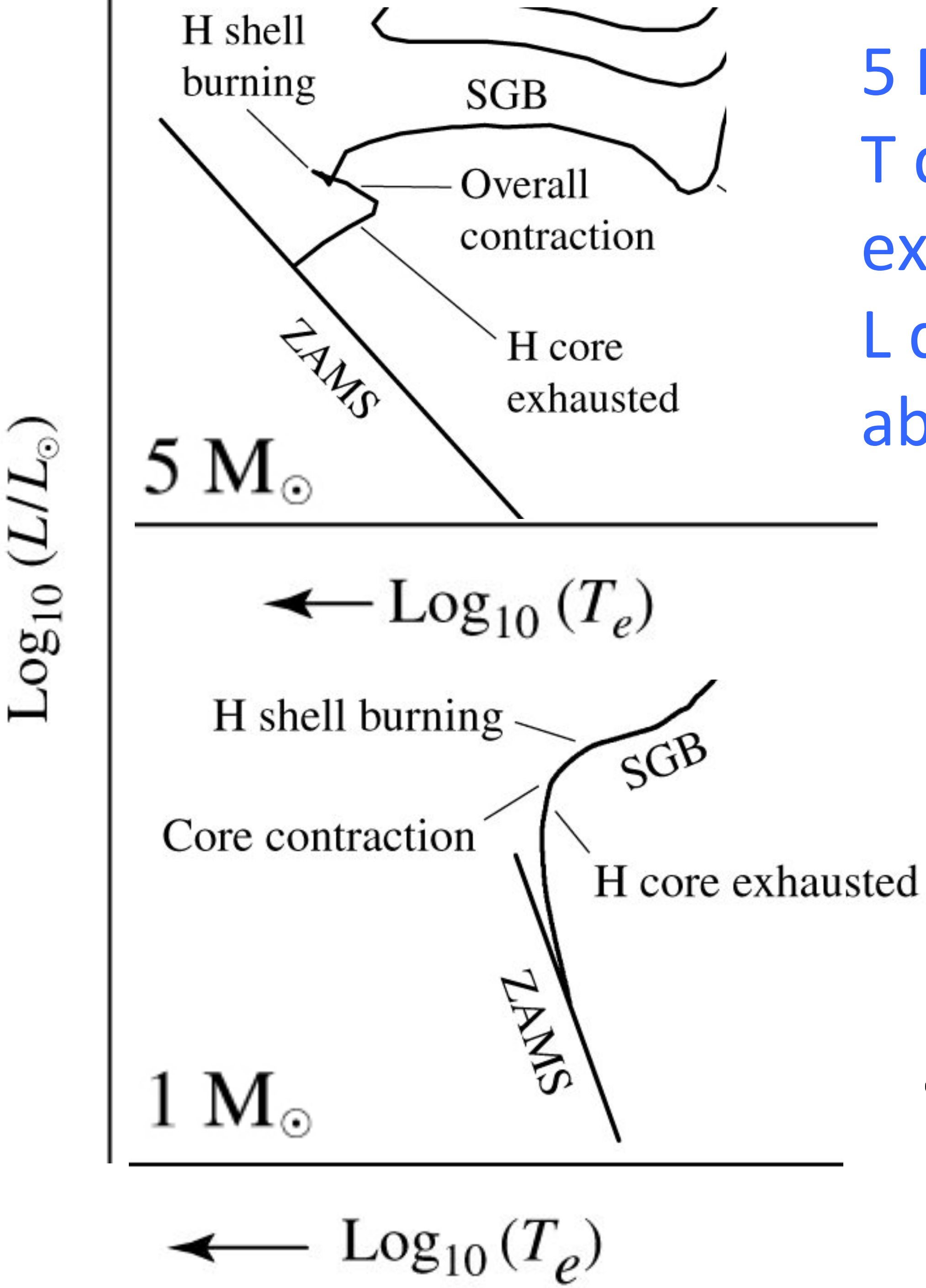
Quando o limite de **Schönberg–Chandrasekhar** é atingido, a estrela entra em **rápida contração**, evoluindo muito mais rapidamente, na escala de tempo de Kelvin-Helmholtz.

Devido à energia liberada pela contração o envelope se expande → temperatura diminui. Estrelas nesse estágio são chamadas de subgigantes

$$L = 4\pi R^2 \sigma T_e^4$$



Ponto 4 a 5:
ramo das subgigantes



5 M_{Sol}:
T decresce devido à expansão do envelope.
L decresce pois envelope absorve muita energia

1 M_{sol}:
L pequeno aumento.
T decresce devido à expansão do envelope

SGB: ***sub-giant branch***
Ramo das subgigantes

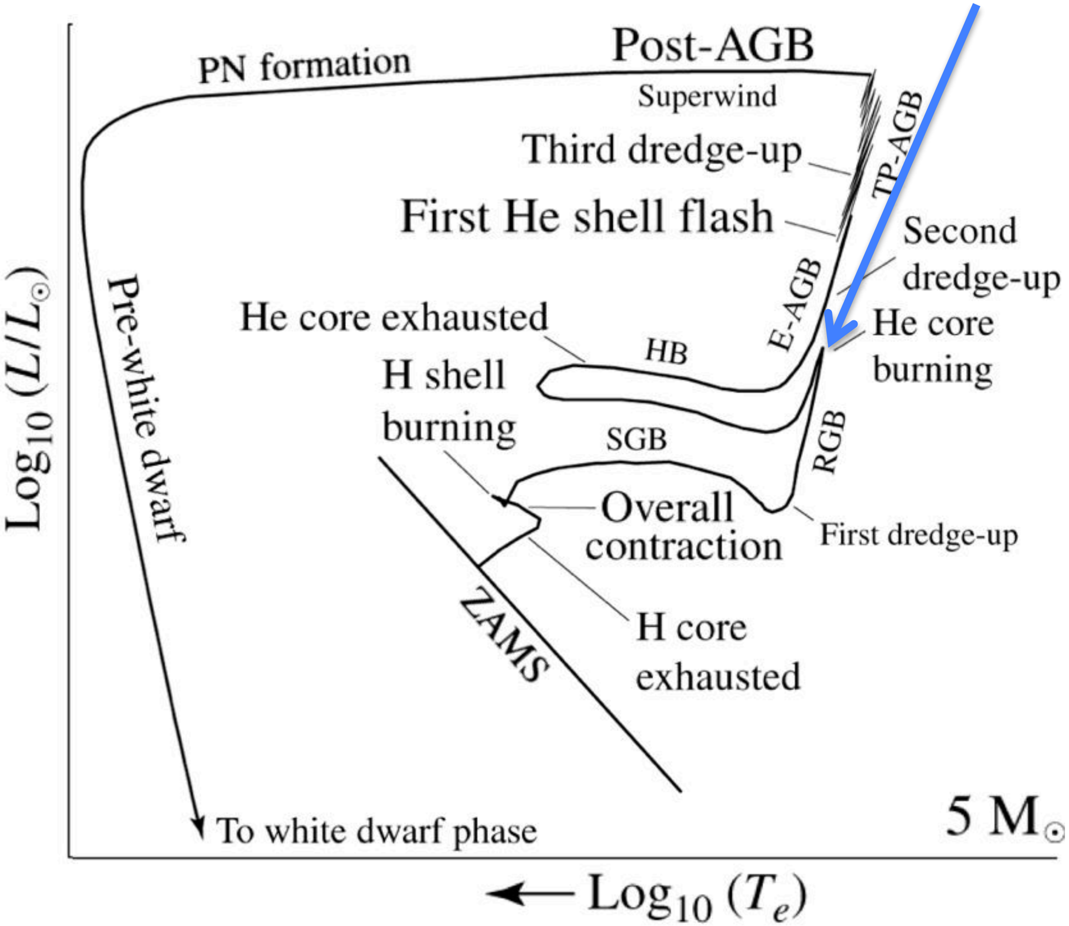
O ramo das **gigantes:** núcleo continua a se contrair e envelope continua expandindo

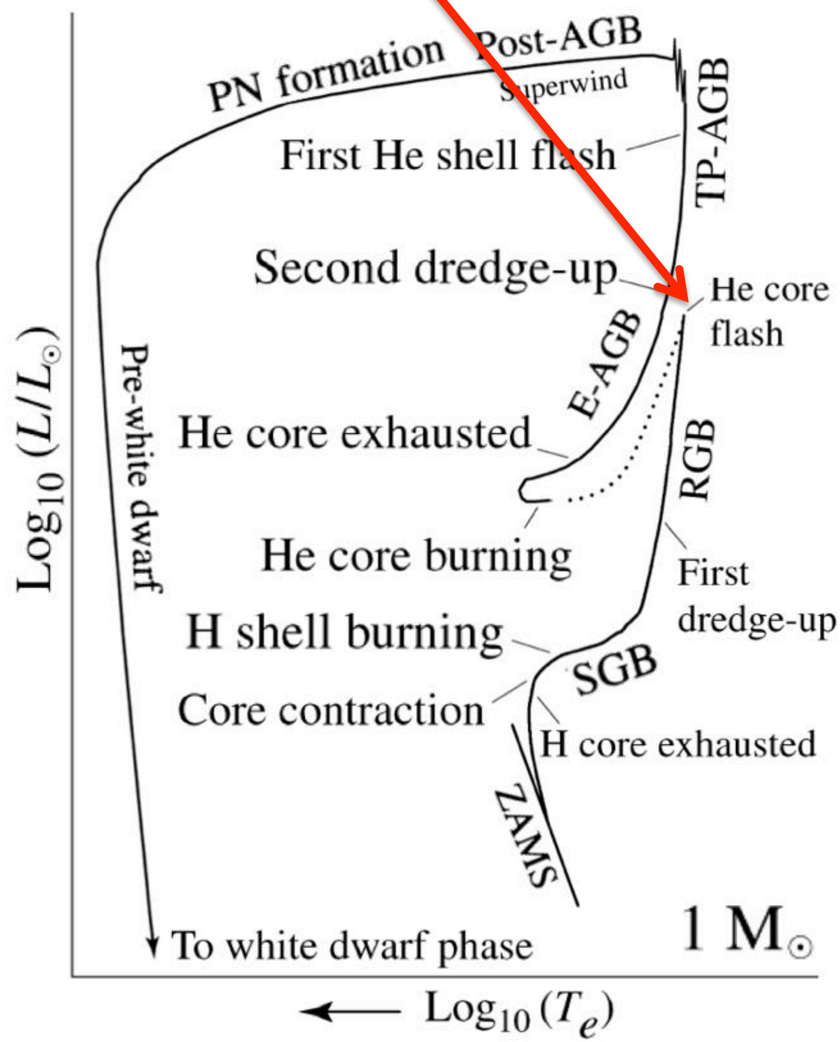
Como T diminui em subgigante → opacidade interior aumenta (H^-) → Convecção

Fim do ramo das gigantes (RGB): início da queima de He

Para M < 2 M_{Sol} o início da queima de He é explosiva

Para M > 2 M_{Sol} a queima de He no núcleo acontece mais suavemente

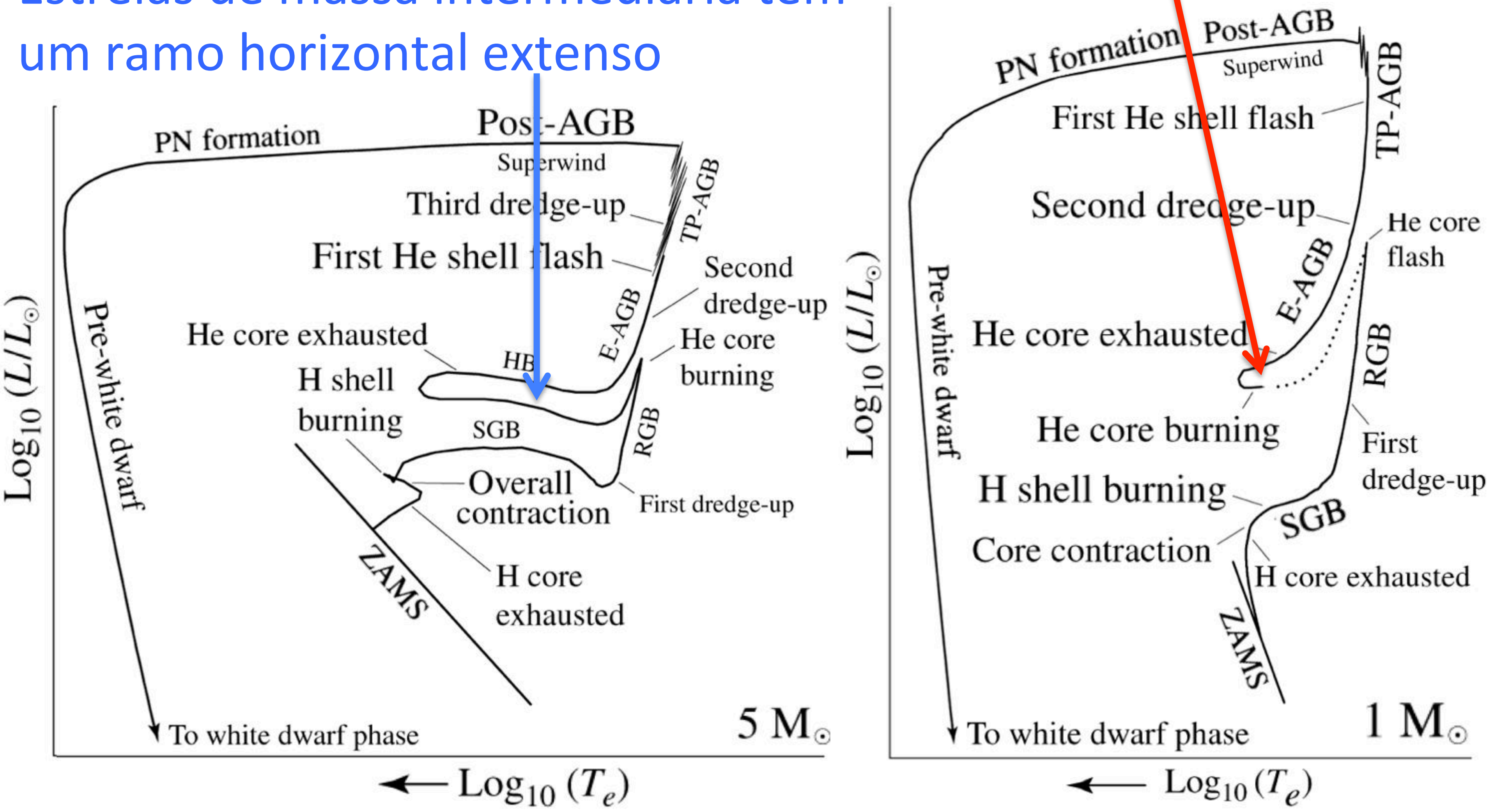




O ramo horizontal

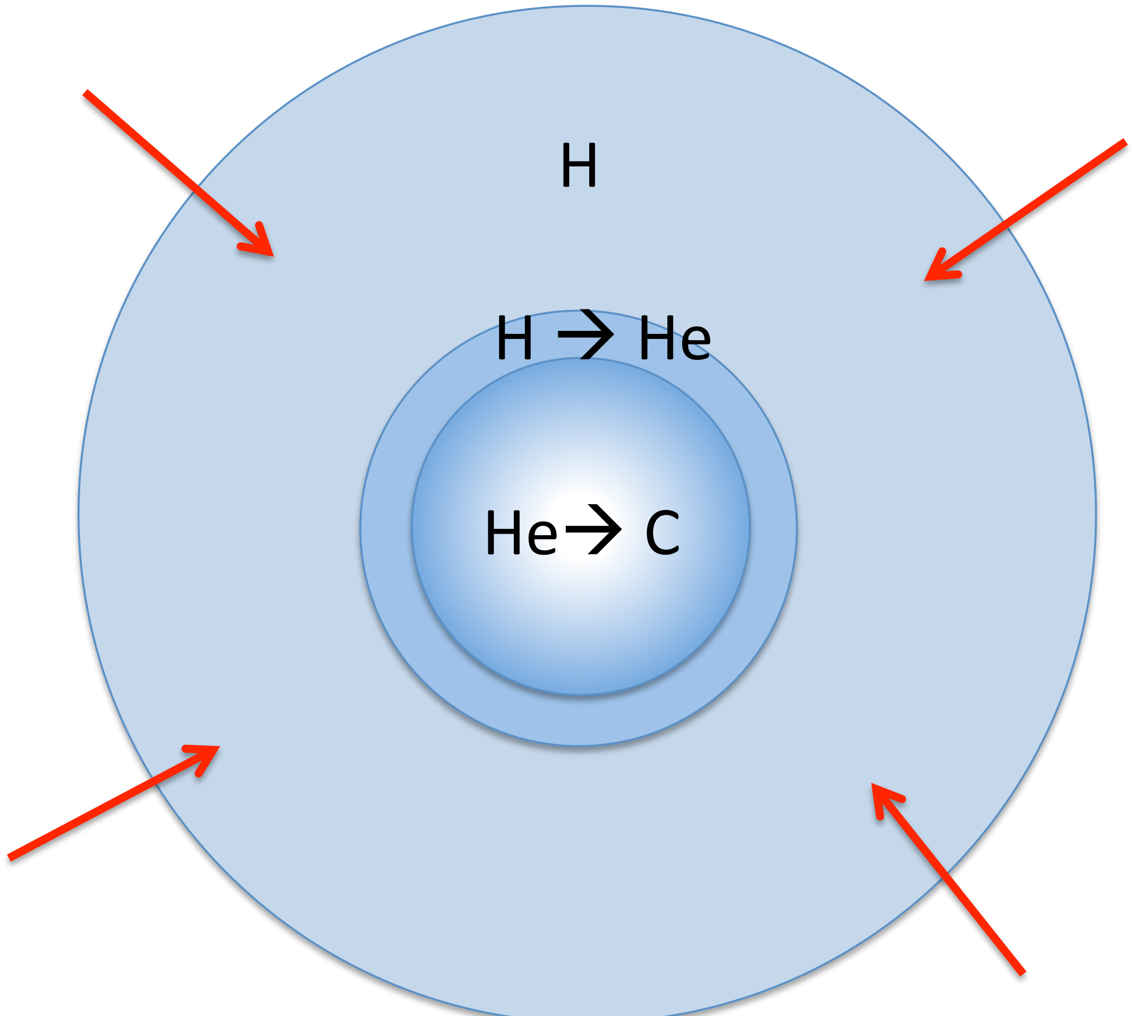
Estrelas de baixa massa como o Sol tem um ramo horizontal pequeno

Estrelas de massa intermediaria tem um ramo horizontal extenso



Estrela no lado azul do ramo horizontal

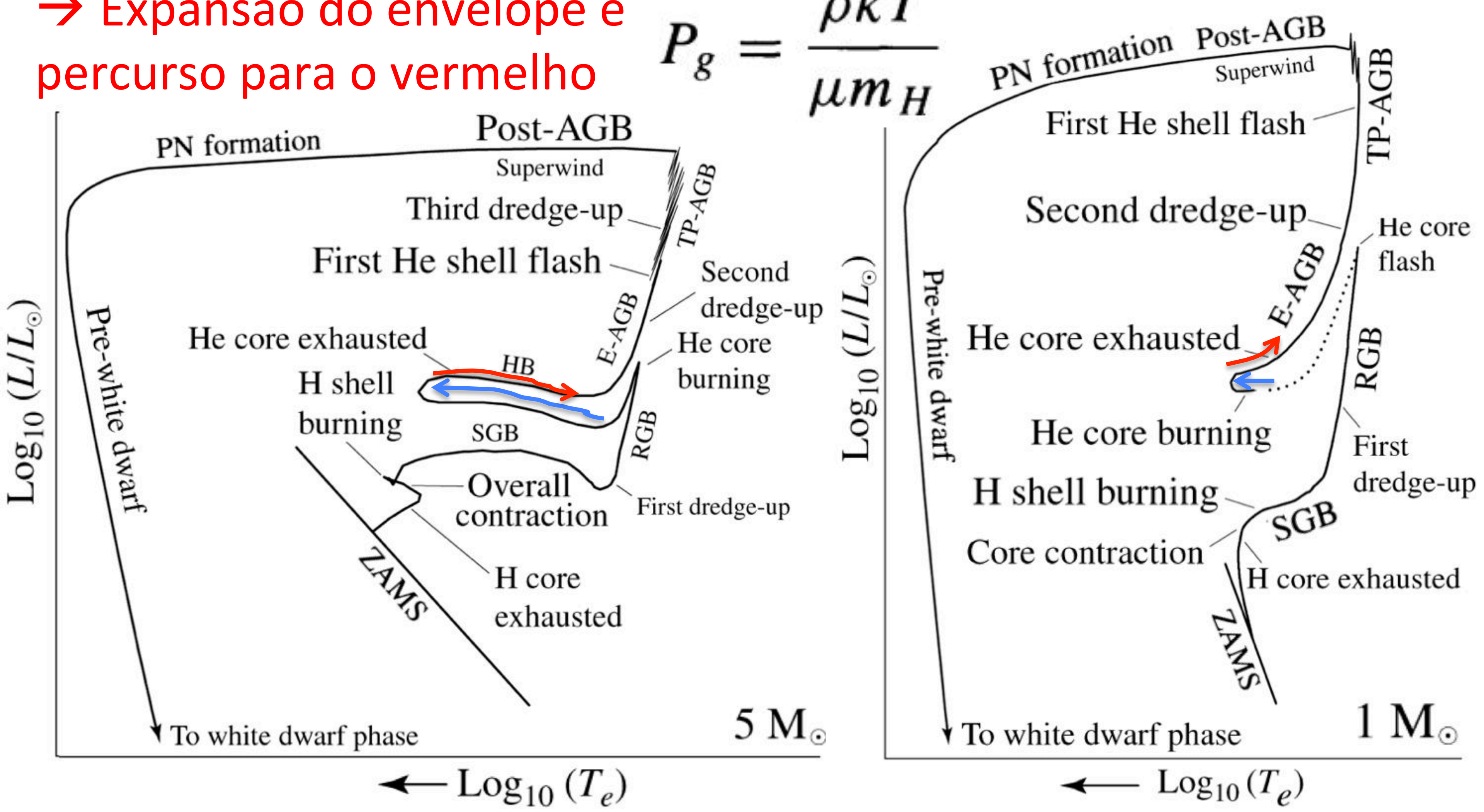
O envelope ainda estão em contração → aumenta a produção de energia pela *shell* (H → He). No centro do núcleo de He temos a queima de He em C e O, e se desenvolve uma zona convectiva



No percurso para o lado azul (quente) do ramo horizontal, temos queima do He similar à queima de H na SP. No ponto mais azul, peso molecular é muito alto → núcleo de He entra em contração.

→ Expansão do envelope e percurso para o vermelho

$$P_g = \frac{\rho k T}{\mu m_H}$$



Estrela no lado vermelho do ramo horizontal

Peso molecular é muito alto → núcleo de He entra em contração e o envelope em expansão → temperatura diminui

$$L / 4\pi R^2 = \sigma T^4$$

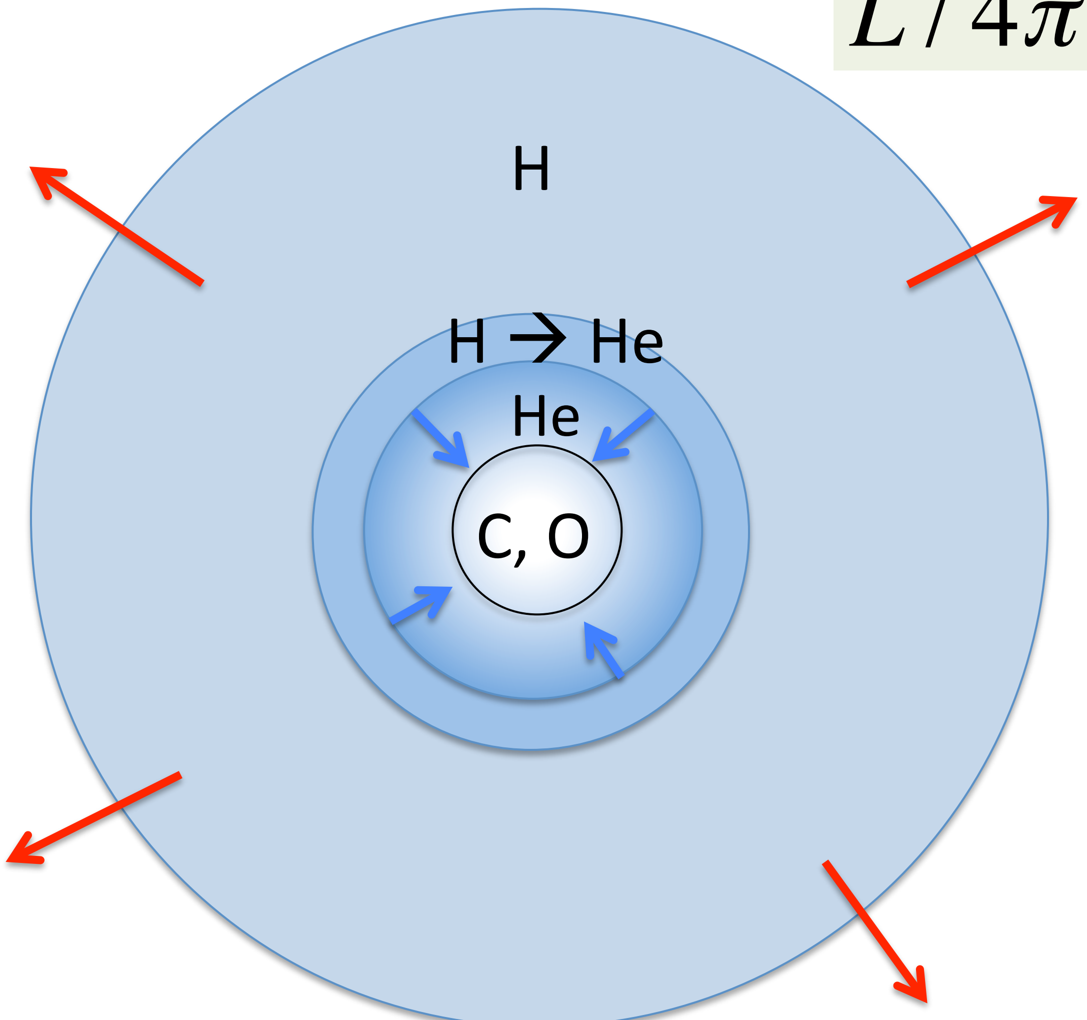
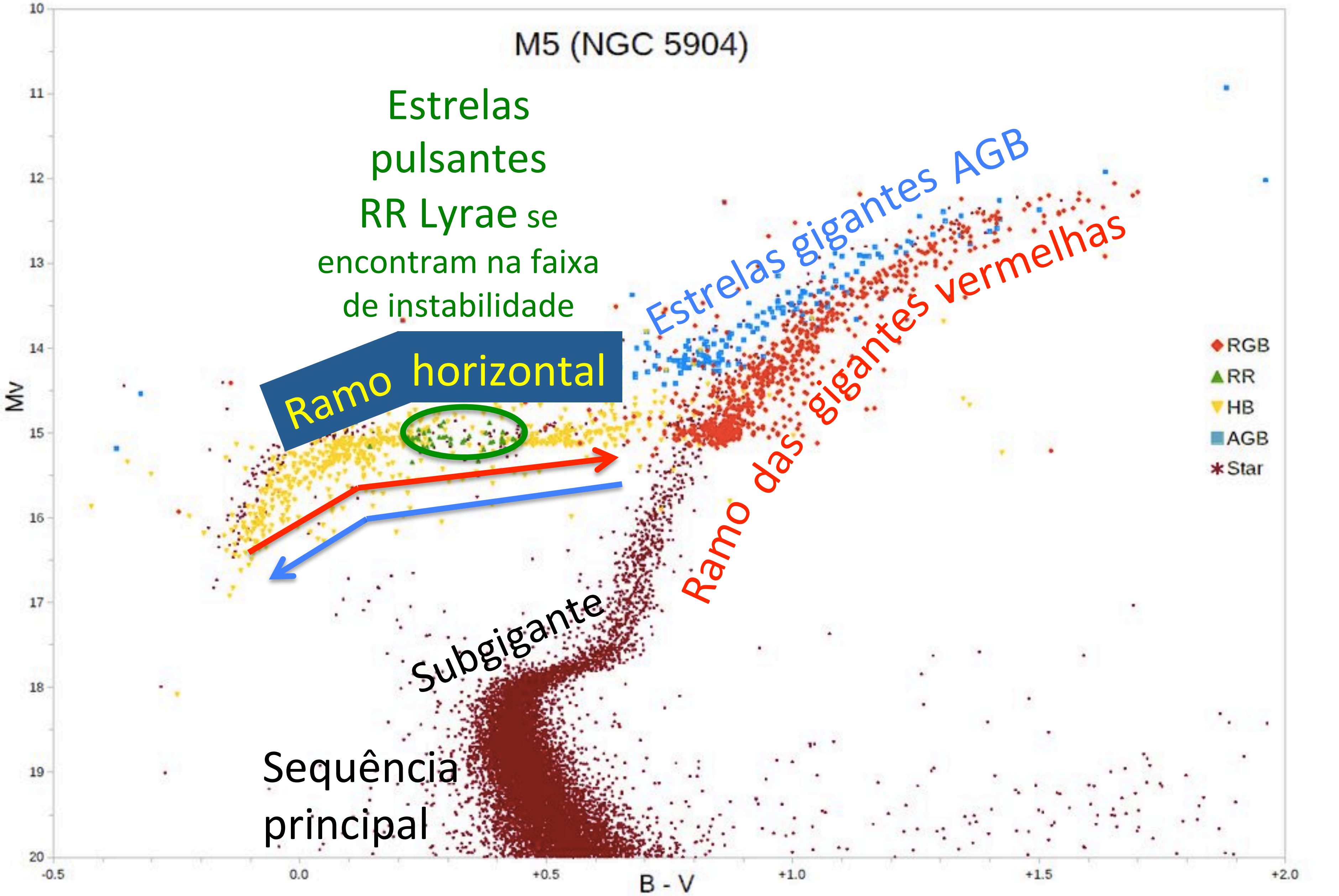
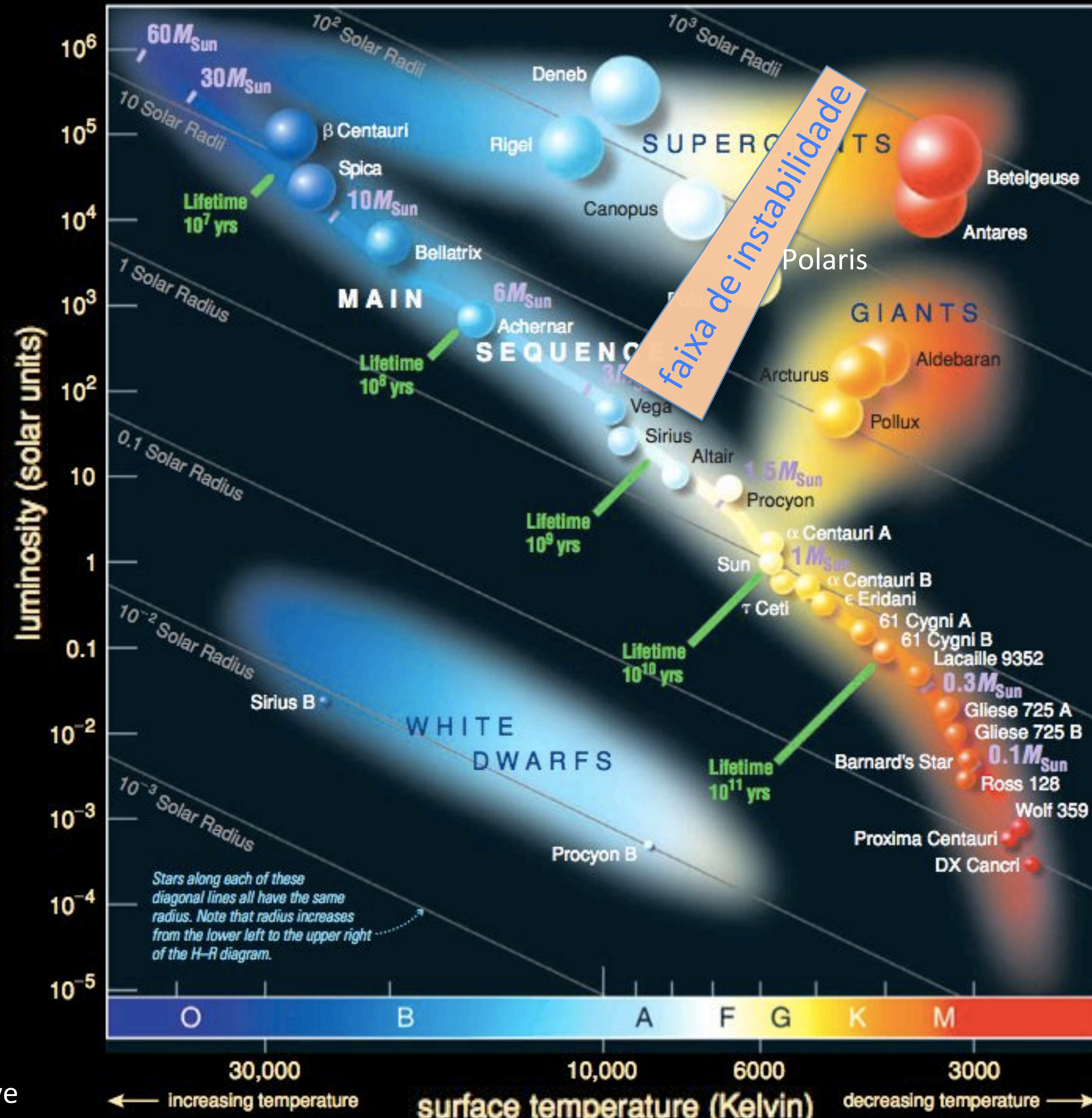
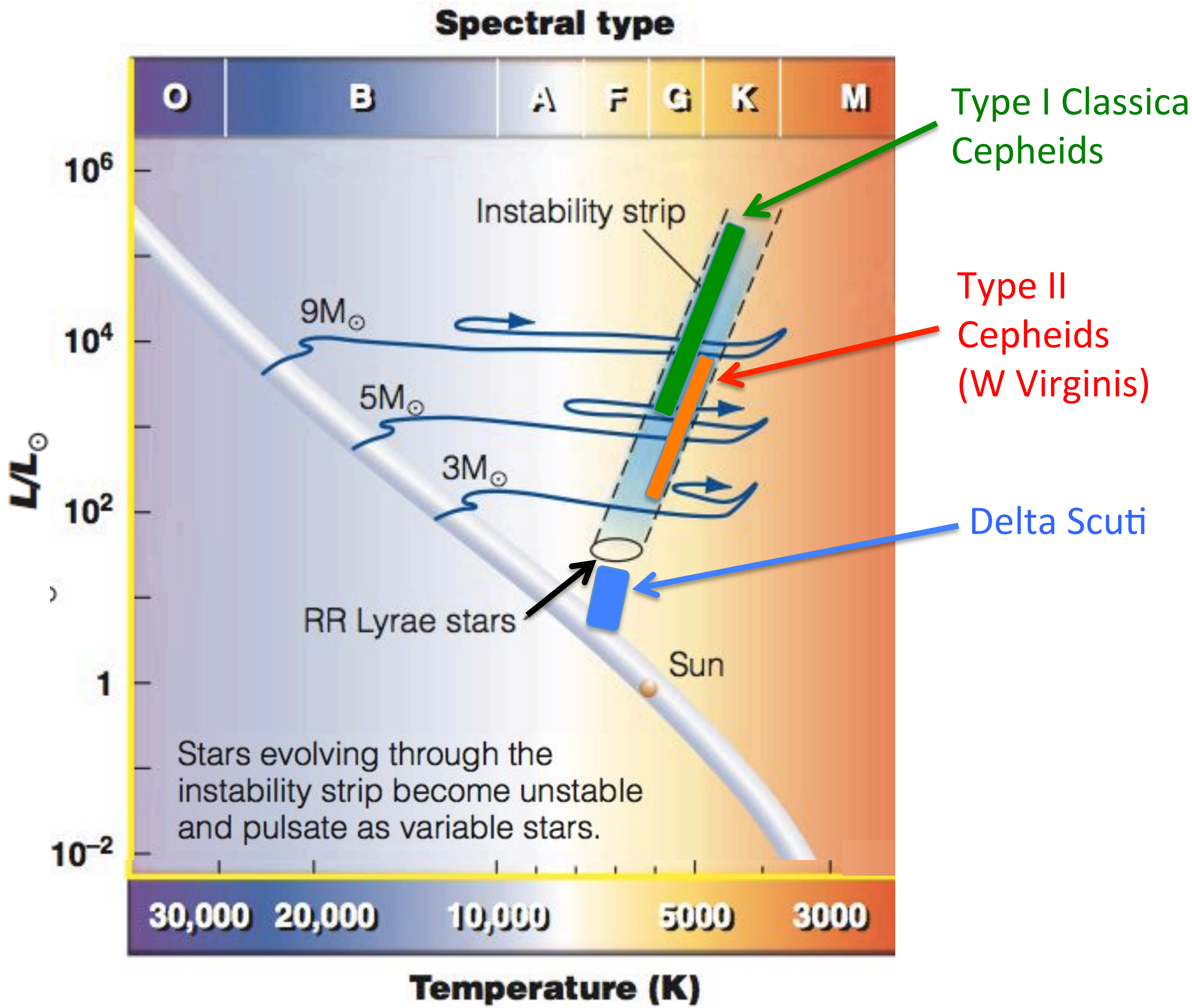


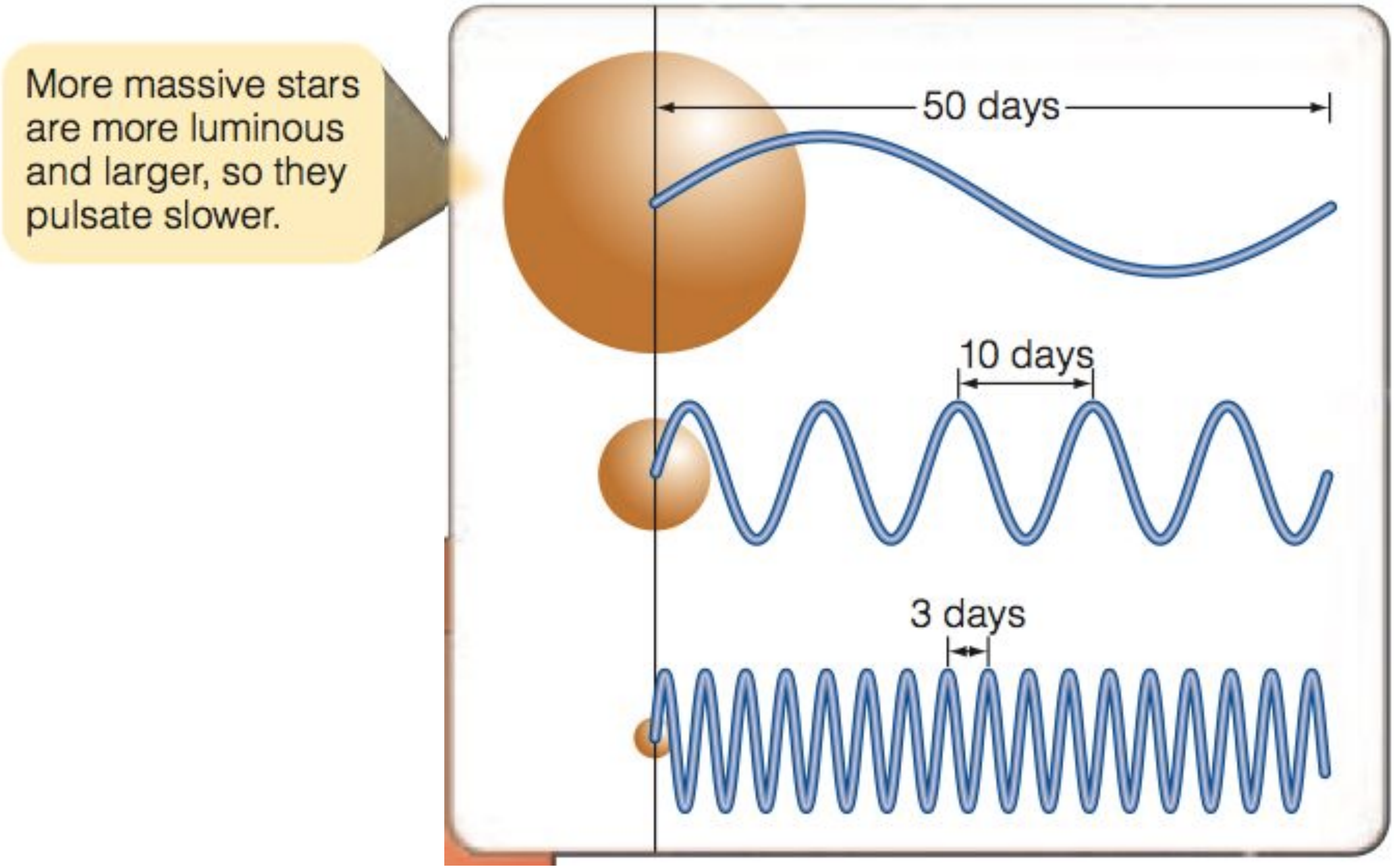
Diagrama HR do aglomerado globular M5

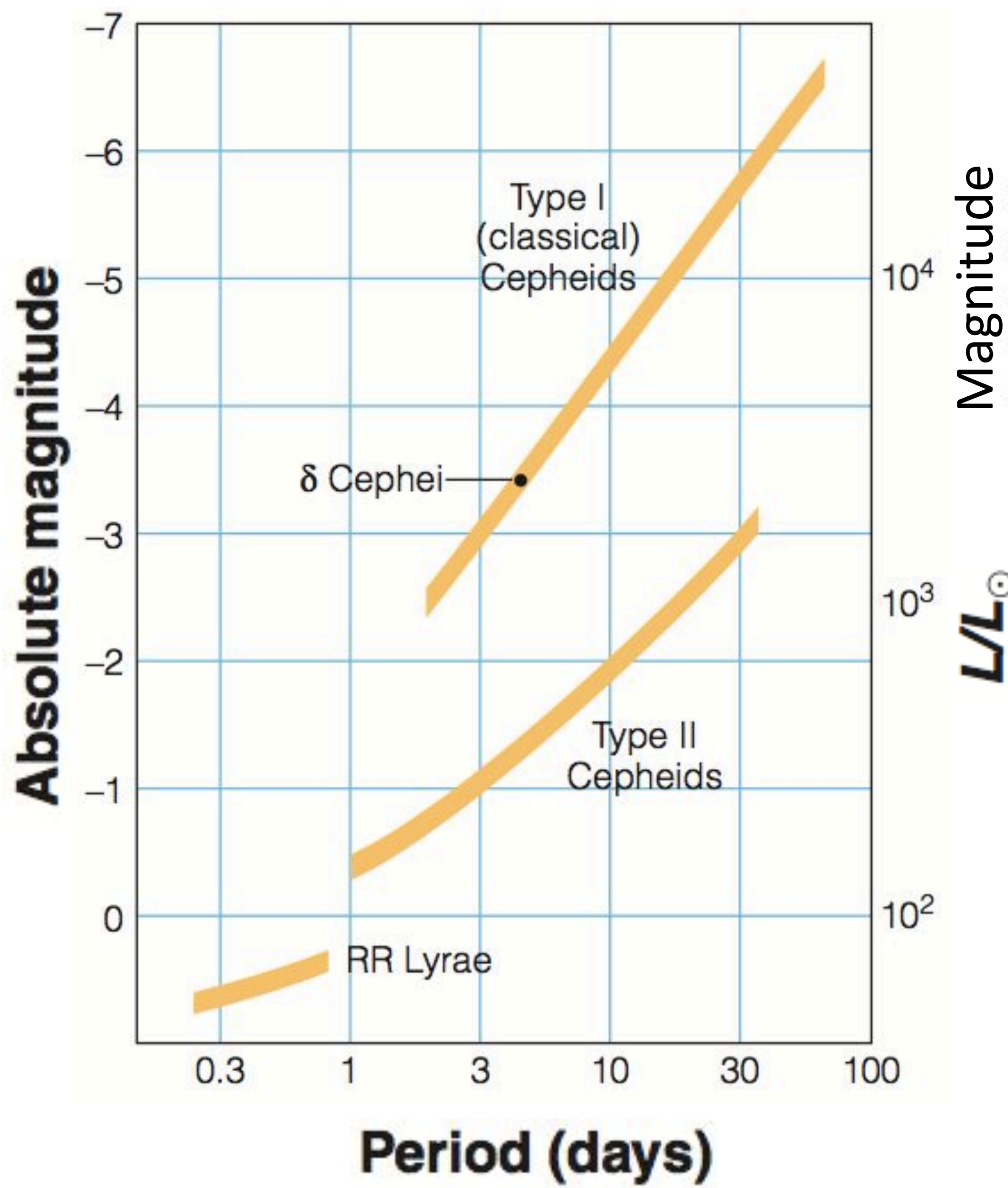




luminosity (solar units)
surface temperature (Kelvin)
increasing temperature
decreasing temperature
30,000
10,000
6000
3000
O
B
A
F
G
K
M
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
faixa de instabilidade
Polaris
Deneb
Rigel
Canopus
Betelgeuse
Antares
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Altair
Procyon
Arcturus
Aldebaran
Pollux
α Centauri A
Sun
α Centauri B
ε Eridani
τ Ceti
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
1.5 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
Stars along each of these diagonal lines all have the same radius. Note that radius increases from the lower left to the upper right of the H–R diagram.


Spectral type
O
B
A
F
G
K
M
Type I Classical Cepheids
Type II Cepheids (W Virginis)
Delta Scuti
10^6
10^4
10^2
1
10^{-2}
$L/L_\odot$
Instability strip
$9M_\odot$
$5M_\odot$
$3M_\odot$
RR Lyrae stars
Sun
Stars evolving through the instability strip become unstable and pulsate as variable stars.
30,000
20,000
10,000
5000
3000
Temperature (K)


More massive stars are more luminous and larger, so they pulsate slower.
50 days
10 days
3 days



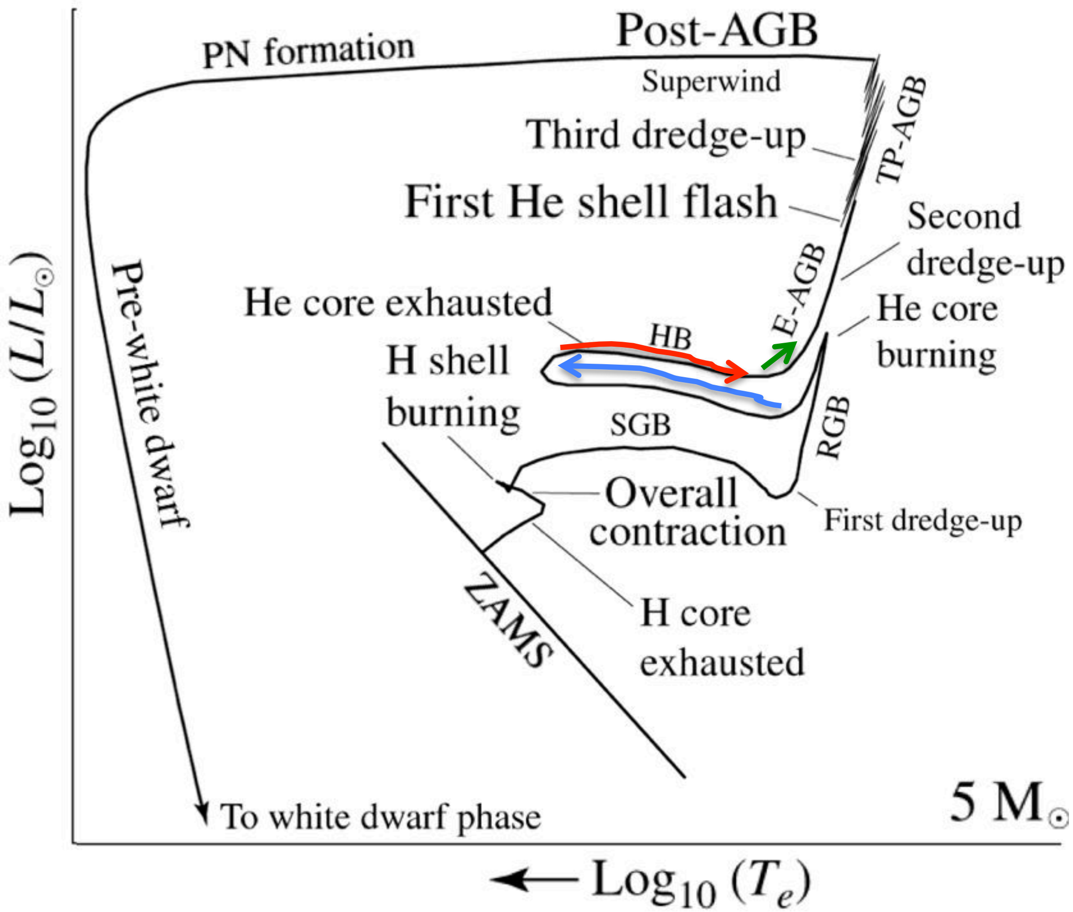
Curva de luz de Delta Cephei

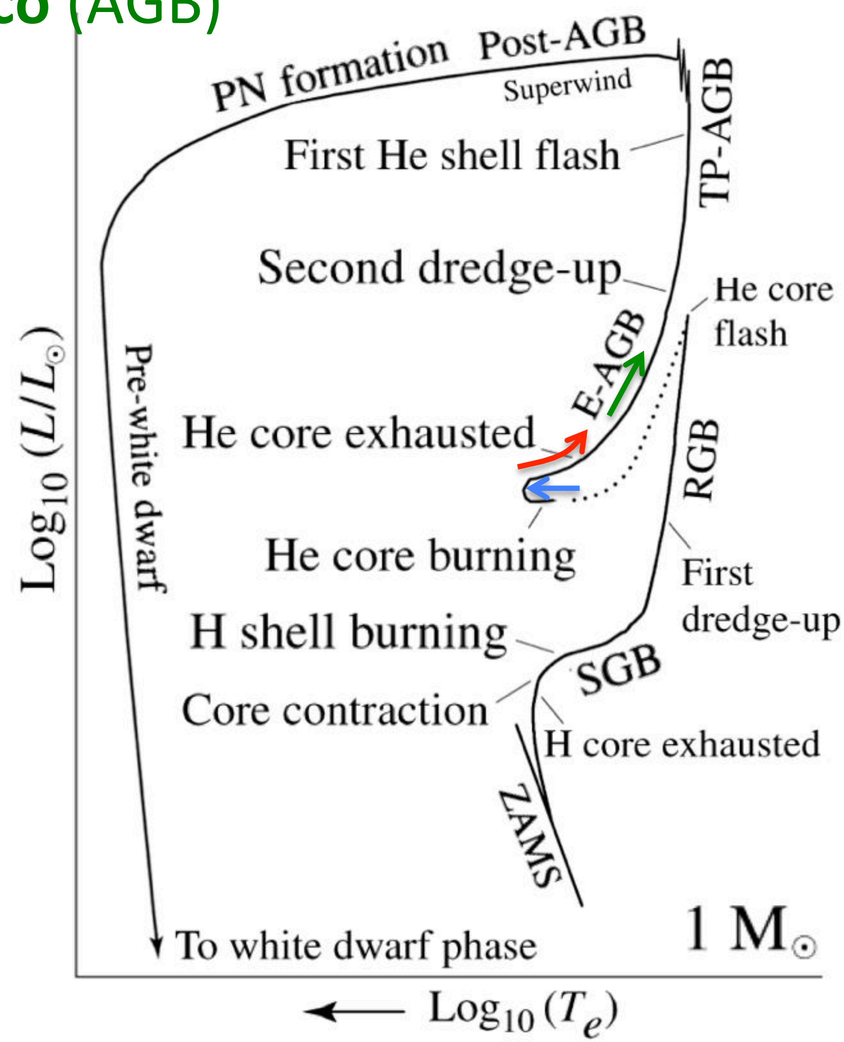
No lado azul “sequência principal” de queima do He, depois μ muito alto → núcleo He em contração.

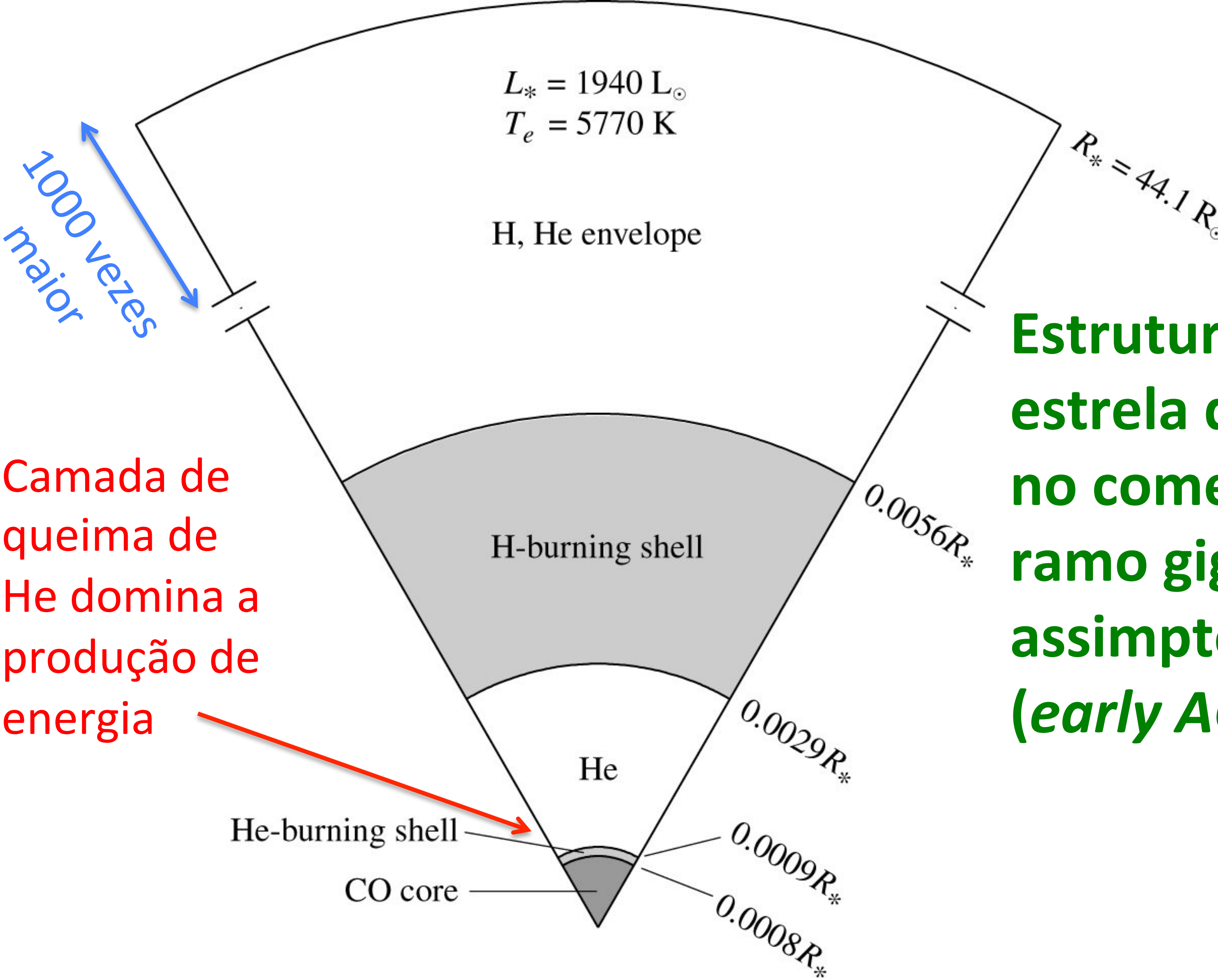
$$P_g = \frac{\rho k T}{\mu m_H}$$

→ Expansão do envelope e percurso para o vermelho

Estrela sobe **ramo gigante assimptótico** (AGB) e temos um “*second dredge-up*”







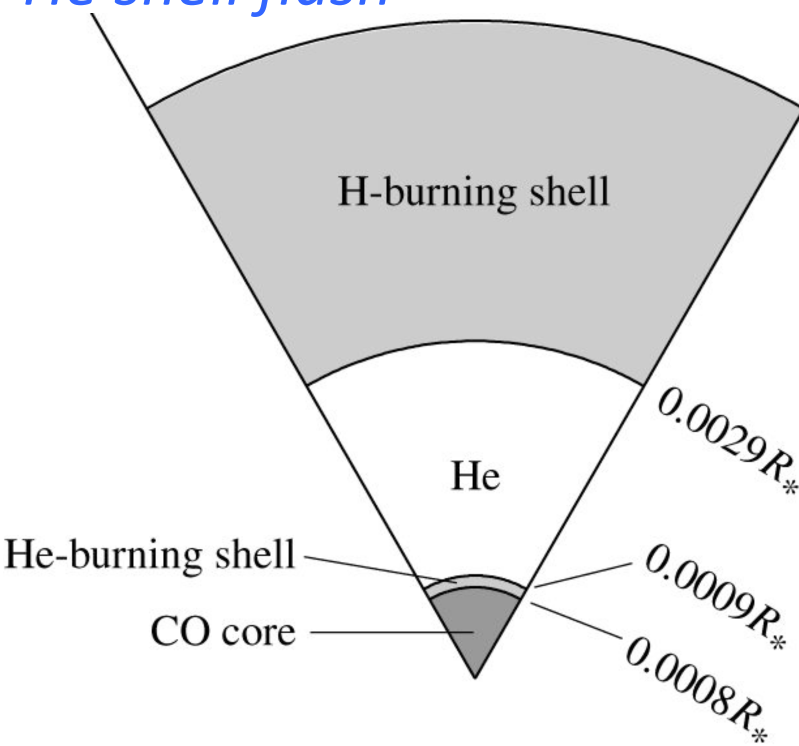
Camada de queima de He domina a produção de energia

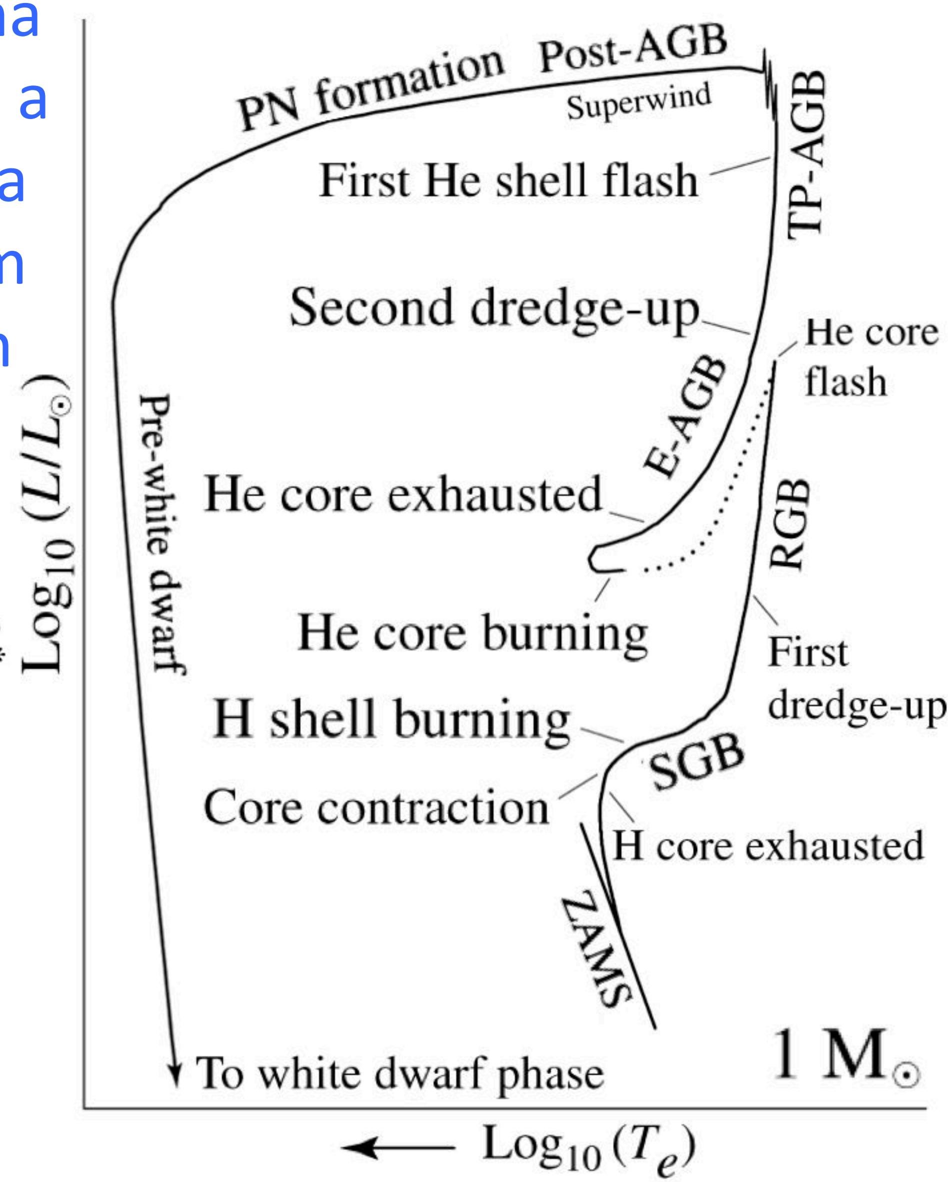
Estrutura de estrela de 5 M_{Sol} no começo do ramo gigante assimptótico (*early AGB*)

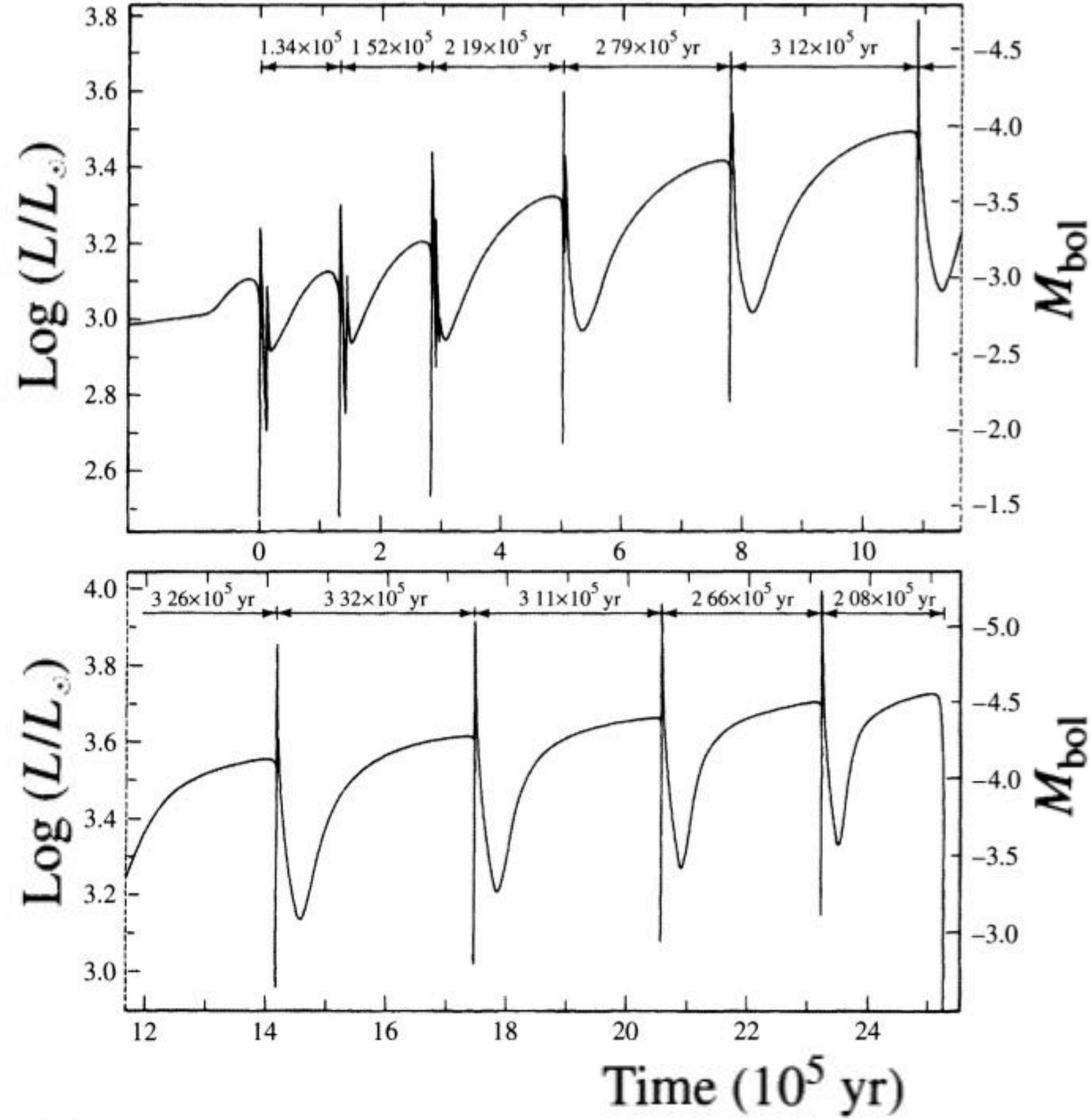
FIGURE 13.8 A 5 $M_\odot$ star on the early asymptotic giant branch with a carbon–oxygen core and hydrogen- and helium-burning shells. Note that relative to the surface radius, the scale of the shells and core has been increased by a factor of 100 for clarity. (Data from Iben, *Ap. J.*, *143*, 483, 1966.)

Pulsos térmicos no AGB: The Thermal-Pulse AGB

No começo do AGB a produção de energia é dominada pela camada de queima de He, porem ela pode desligar e a queima de H ser ativada. Depois a camada de He é reativada (porem com He degenerado) e temos um *He shell flash*





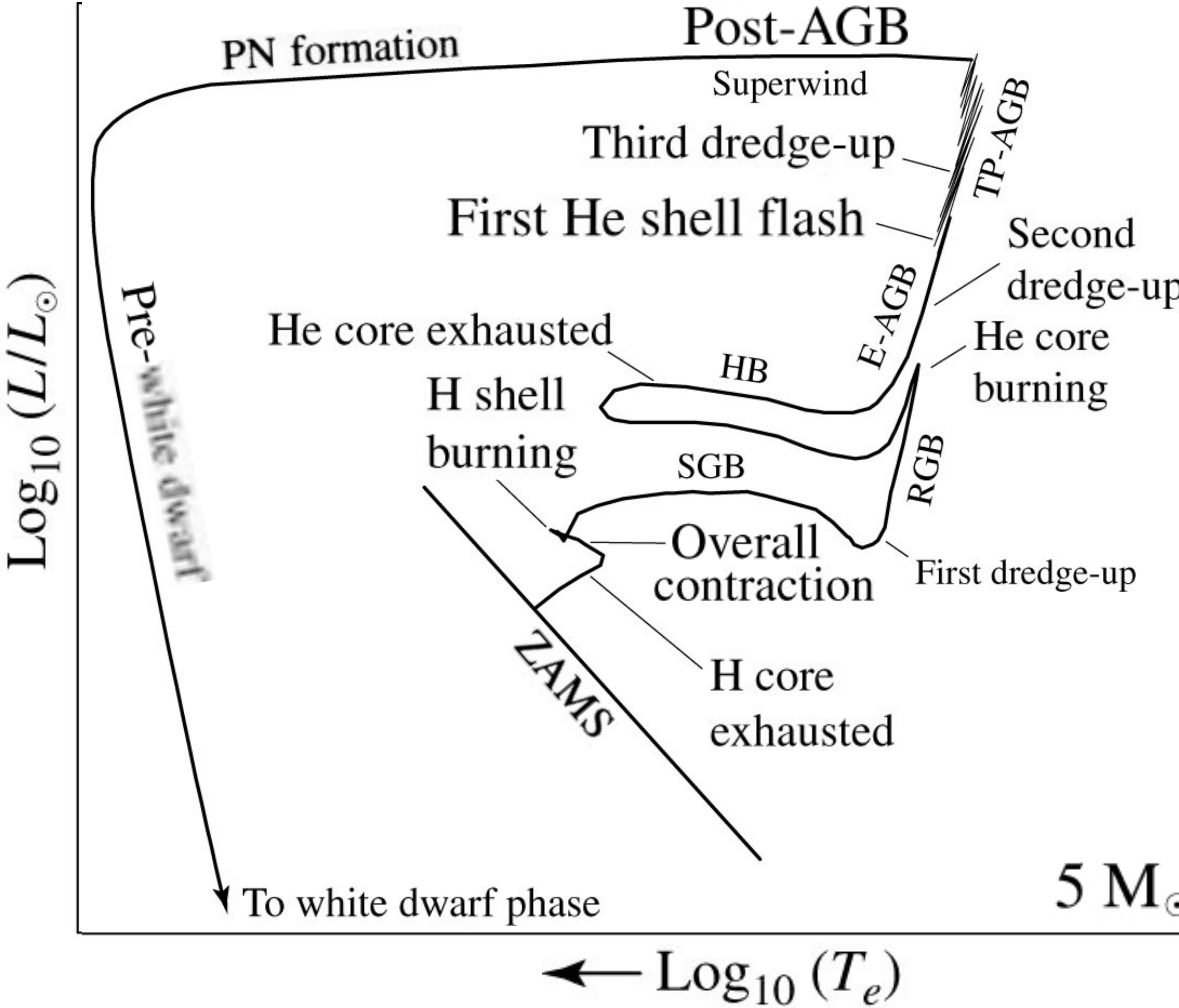


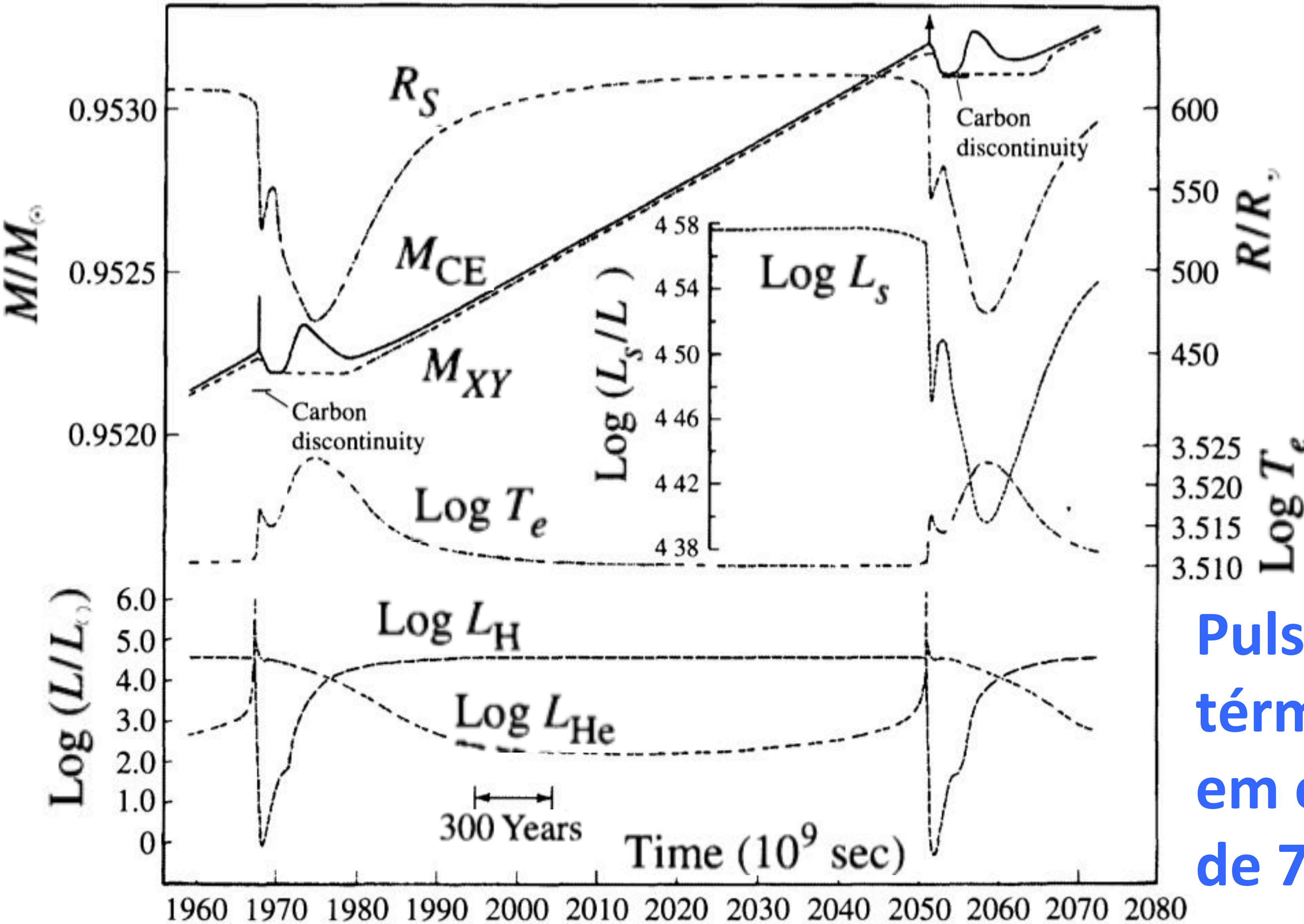
Pulsos térmicos:

Da ordem de 100 mil anos para estrelas de ~1 M_{Sol}

e de 10^3 anos para ~5 M_{Sol}

FIGURE 13.9 The surface luminosity as a function of time for a 0.6 $M_\odot$ stellar model that is undergoing helium shell flashes on the TP-AGB. (Figure adapted from Iben, *Ap. J.*, *260*, 821, 1982.)

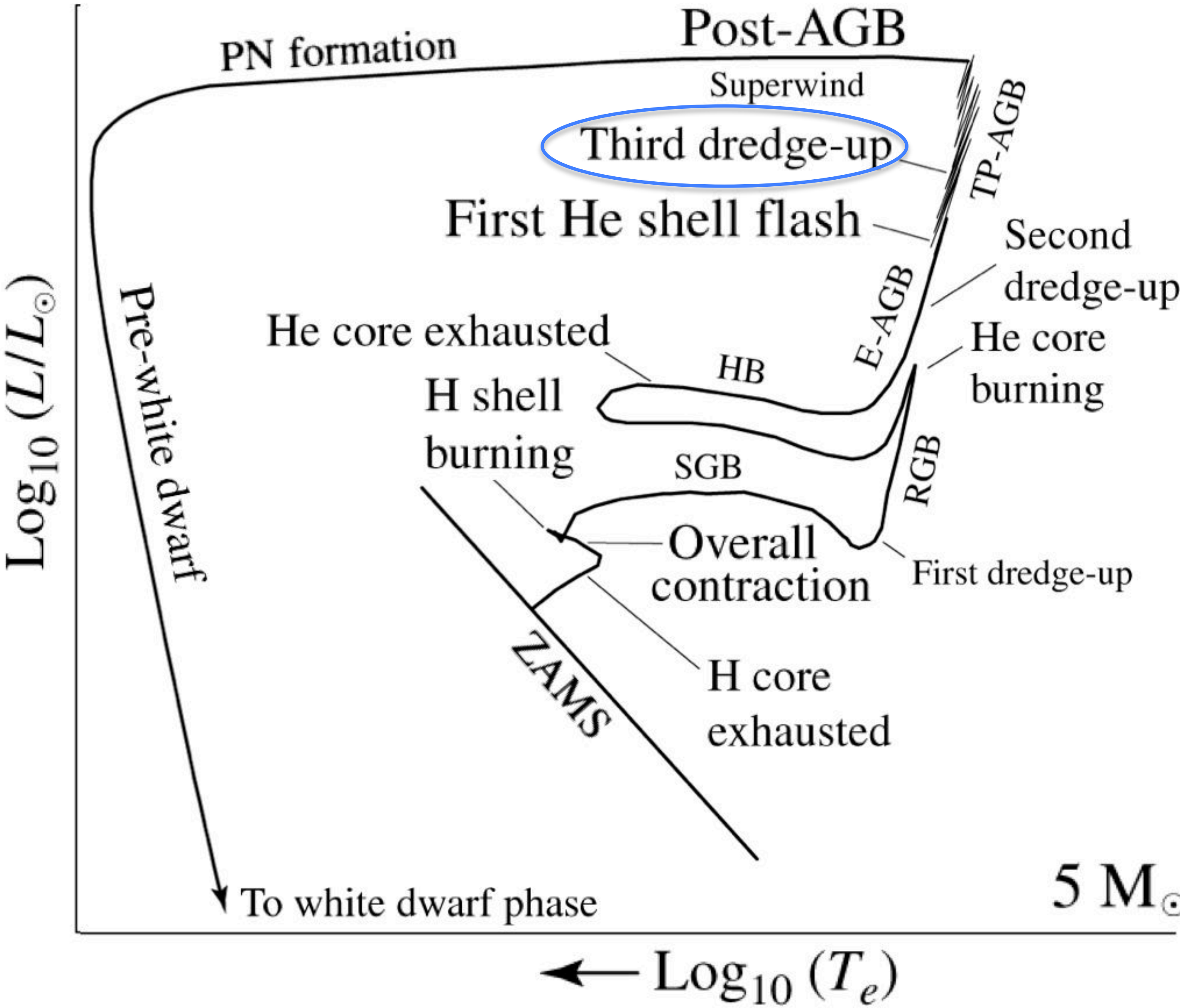

Post-AGB
PN formation
Superwind
Third dredge-up
TP-AGB
First He shell flash
Second dredge-up
E-AGB
He core exhausted
HB
He core burning
H shell burning
SGB
RGB
Pre-white dwarf
Overall contraction
First dredge-up
ZAMS
H core exhausted
To white dwarf phase
5 M$_\odot$
$\log_{10}(L/L_\odot)$
$\leftarrow \log_{10}(T_e)$



Pulsos térmicos em estrela de 7 M_{Sol}

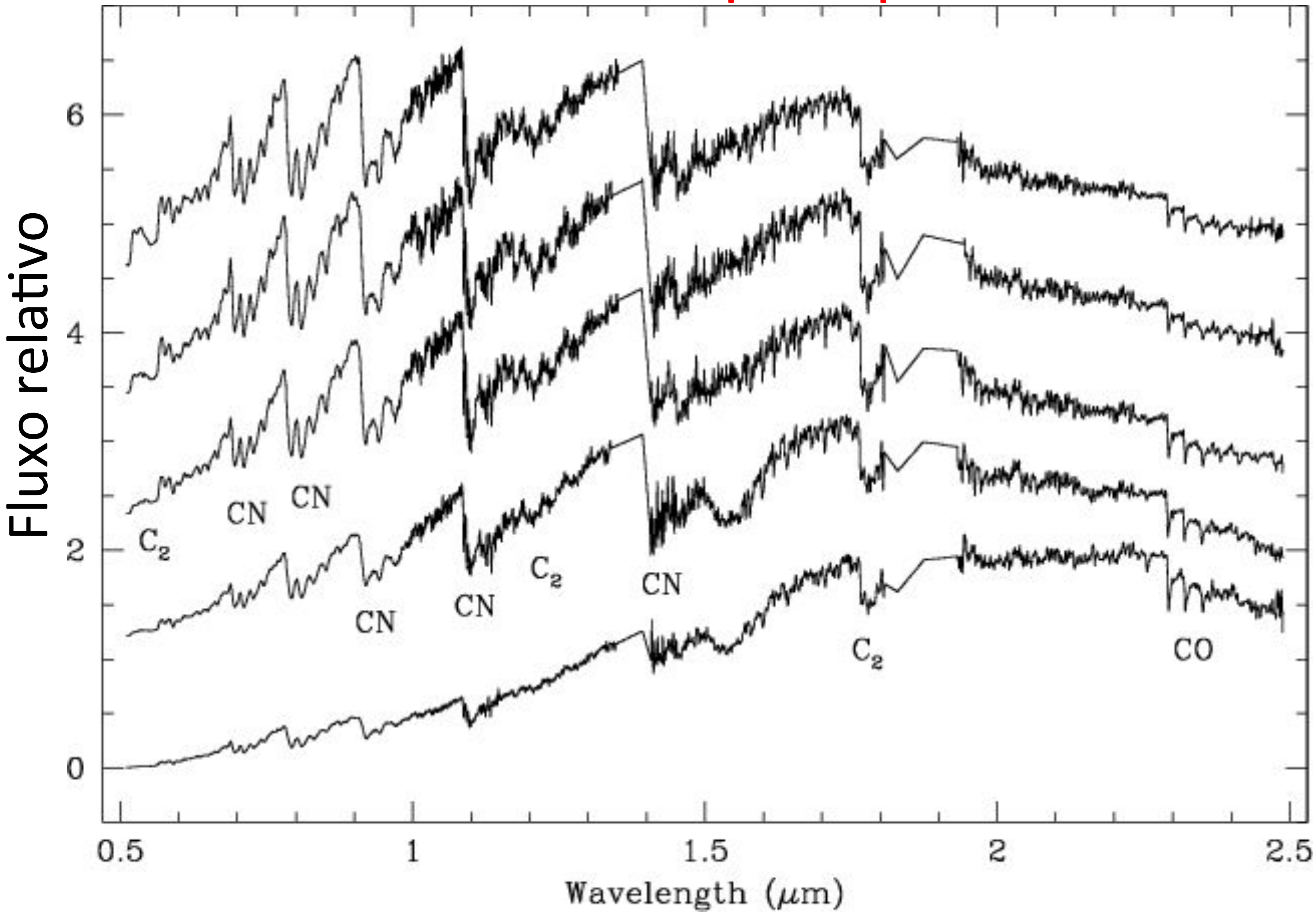
FIGURE 13.10 Time-dependent changes in the properties of a 7 $M_\odot$ AGB star produced by helium shell flashes on the TP-AGB. The quantities shown are the surface radius (R_S), the interior mass fractions of the base of the convective envelope (M_{CE}) and the hydrogen–helium discontinuity (M_{XY}), the star's luminosity and effective temperature (L_s and T_e, respectively), and the luminosities of the hydrogen- and helium-burning shells (L_H and L_{He}, respectively). (Figure adapted from Iben, *Ap. J.*,

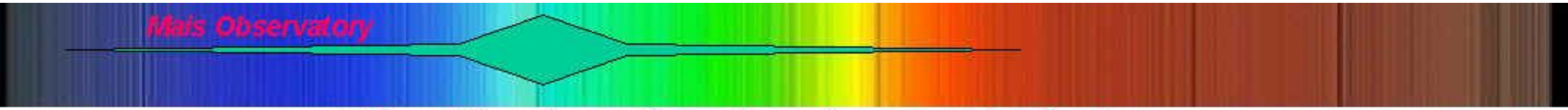
Terceira dragagem: *Third dredge-up*



Material rico em carbono é dragado para a superfície

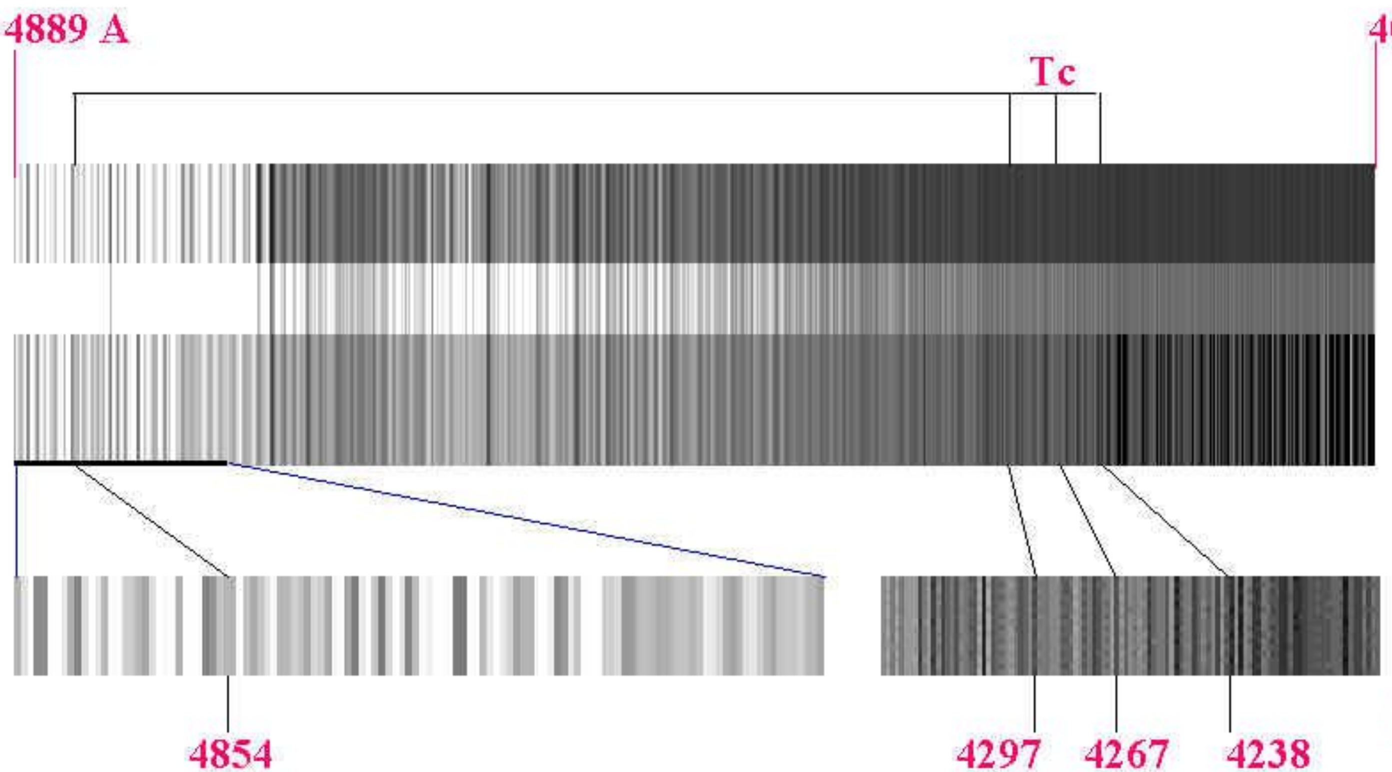
Carbon stars: tipo espectral C





Identification of Technetium in 19 Piscium

C5II star, 4.95 magnitude



Tc-99 é o isótopo mais abundante de Tc. Tempo de vida é de apenas ~ 200 000 anos.

Tc é observado em estrelas AGB → foi produzido "recentemente"

^{43}Tc : no stable isotopes

Tc^{97} $t_{1/2} = 2.6\times10^6$ years

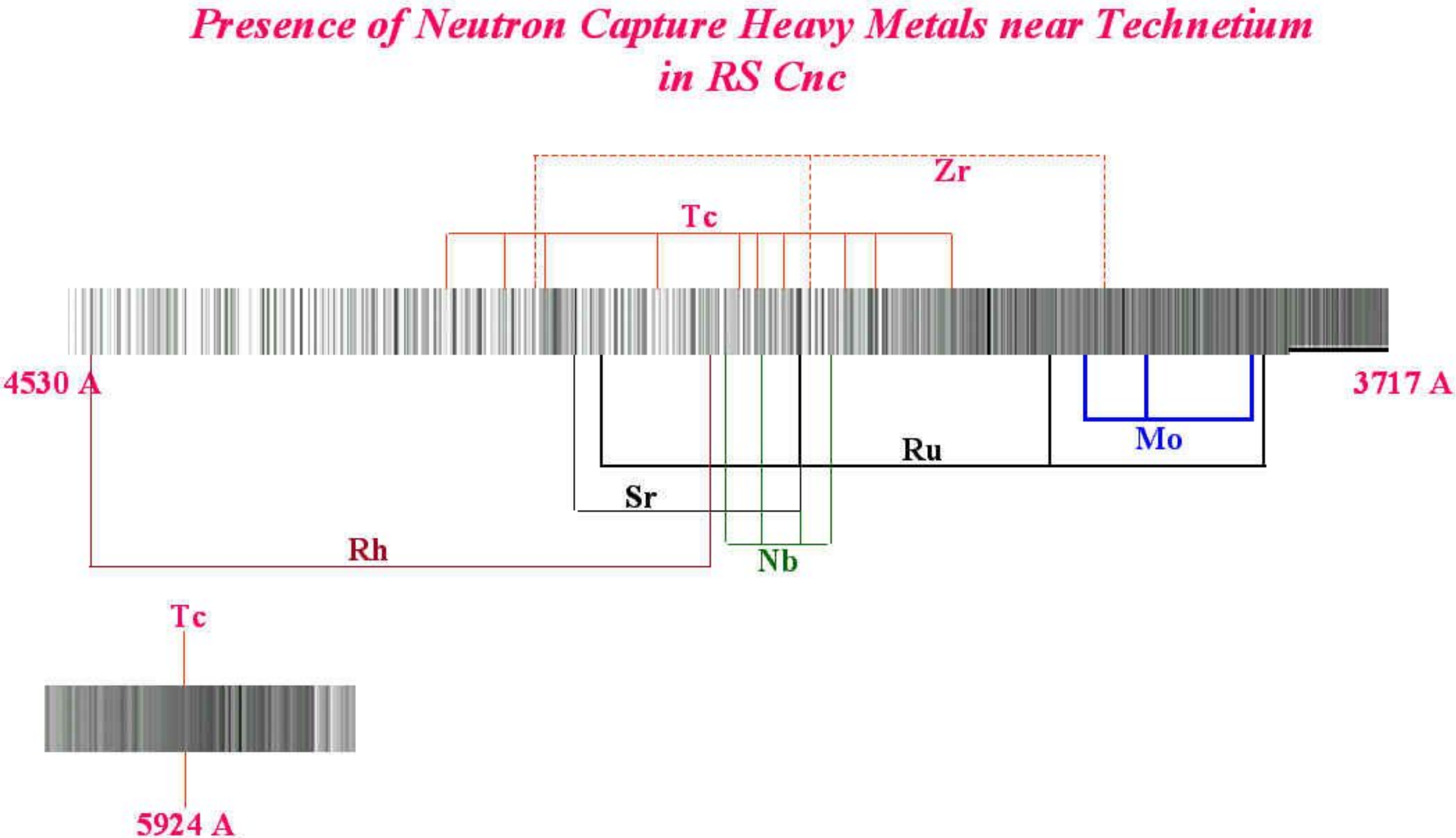
Tc^{98} $t_{1/2} = 1.5\times10^6$ years

Tc^{99} $t_{1/2} = 2.1\times10^5$ years

+ various short lived isotopes

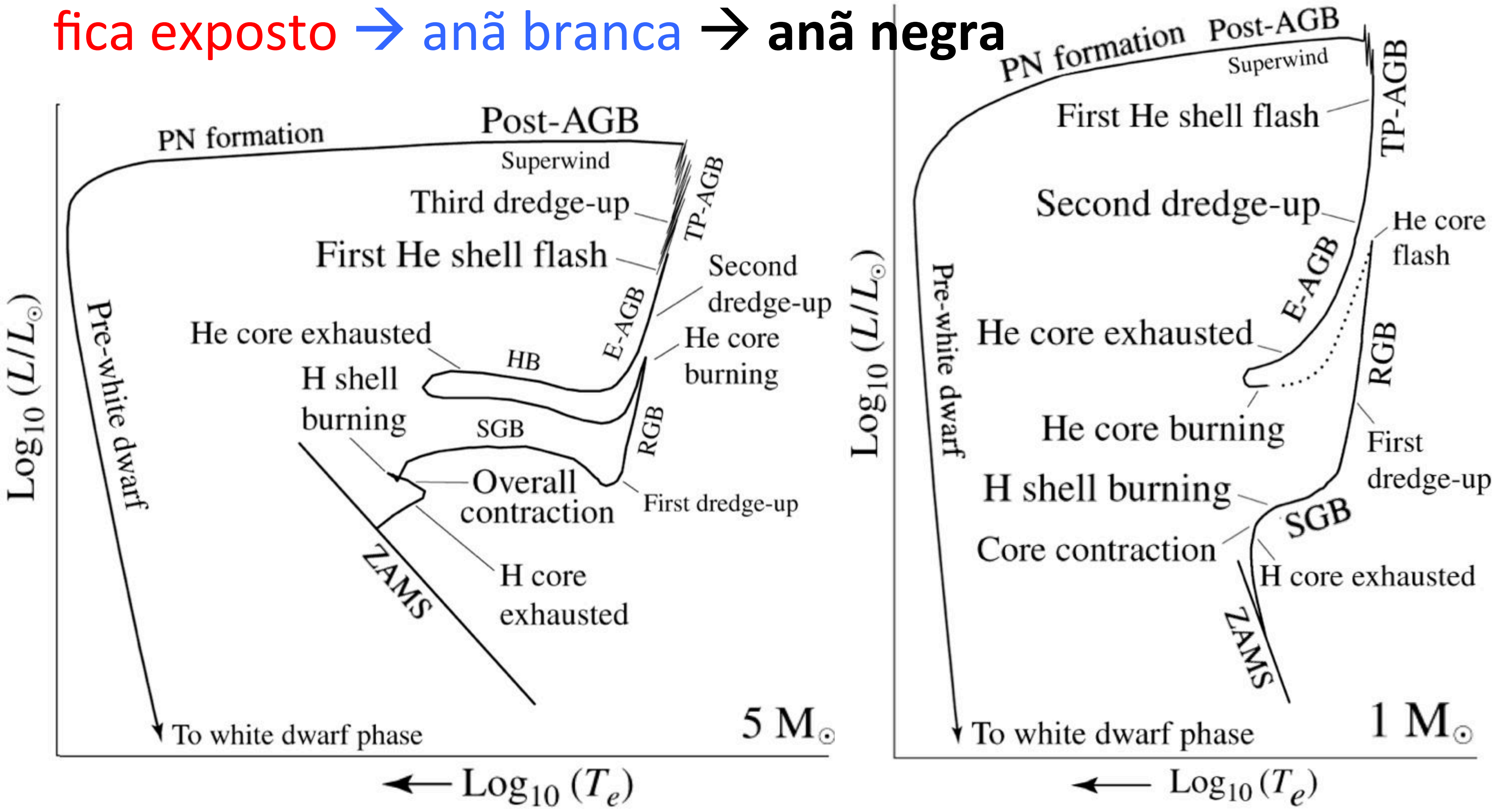
http://mais-ccd-spectroscopy.com/Stellar.htm

Produção de outros elementos pesados por captura de nêutrons (processo-s [*slow*]) em estrelas AGB



Perda de massa na fase AGB

A perda de massa é acentuada nos pulsos térmicos → formação de nebulosa planetária e núcleo degenerado fica exposto → anã branca → **anã negra**



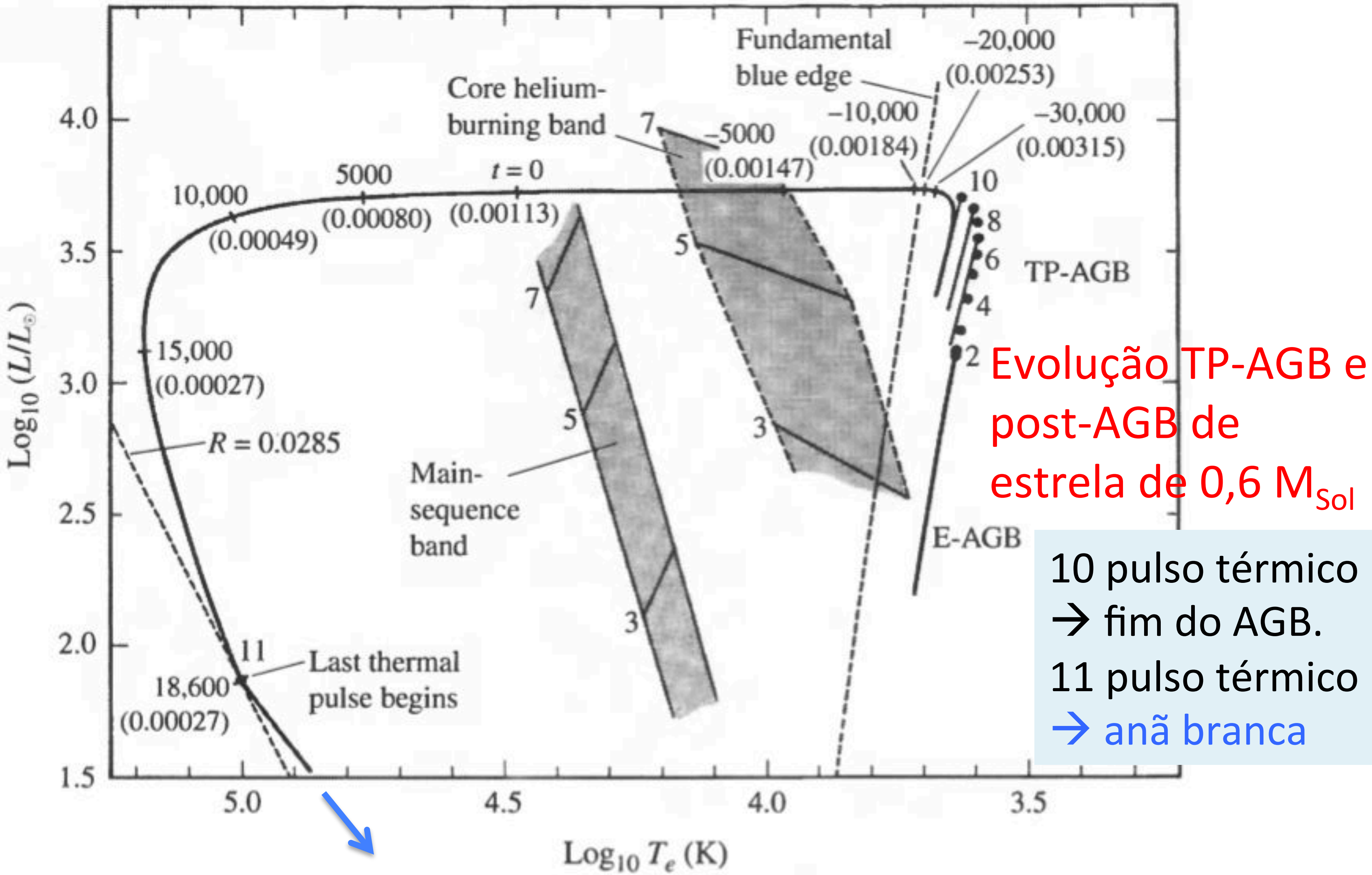


FIGURE 13.12 The AGB and post-AGB evolution of a 0.6 $M_\odot$ star undergoing mass loss. The initial composition of the model is $X = 0.749$, $Y = 0.25$, and $Z = 0.001$. The main-sequence and horizontal branches of 3, 5, and 7 $M_\odot$ stars are shown for reference. Details of the figure are discussed in the body of the text. (Figure adapted from Iben, *Ap. J.*, *260*, 821, 1982.)

Helix Planetary Nebula

Cat's eye Planetary Nebula

The bluish-green coloration of many planetary nebulae is due to the 500.68-nm and 495.89-nm forbidden lines of [O III] (forbidden lines of [O II] and [Ne III] are also common), and the reddish coloration comes from ionized hydrogen and nitrogen. Characteristic temperatures of these objects are in the range of the ionization temperature of hydrogen, 10^4 K.

The image from Hubble's Advanced Camera for Surveys (ACS) shows a bull's eye pattern of eleven or even more concentric shells around the Cat's Eye. Each 'ring' is actually the edge of a spherical bubble seen projected onto the sky. Pulses ~1500 years

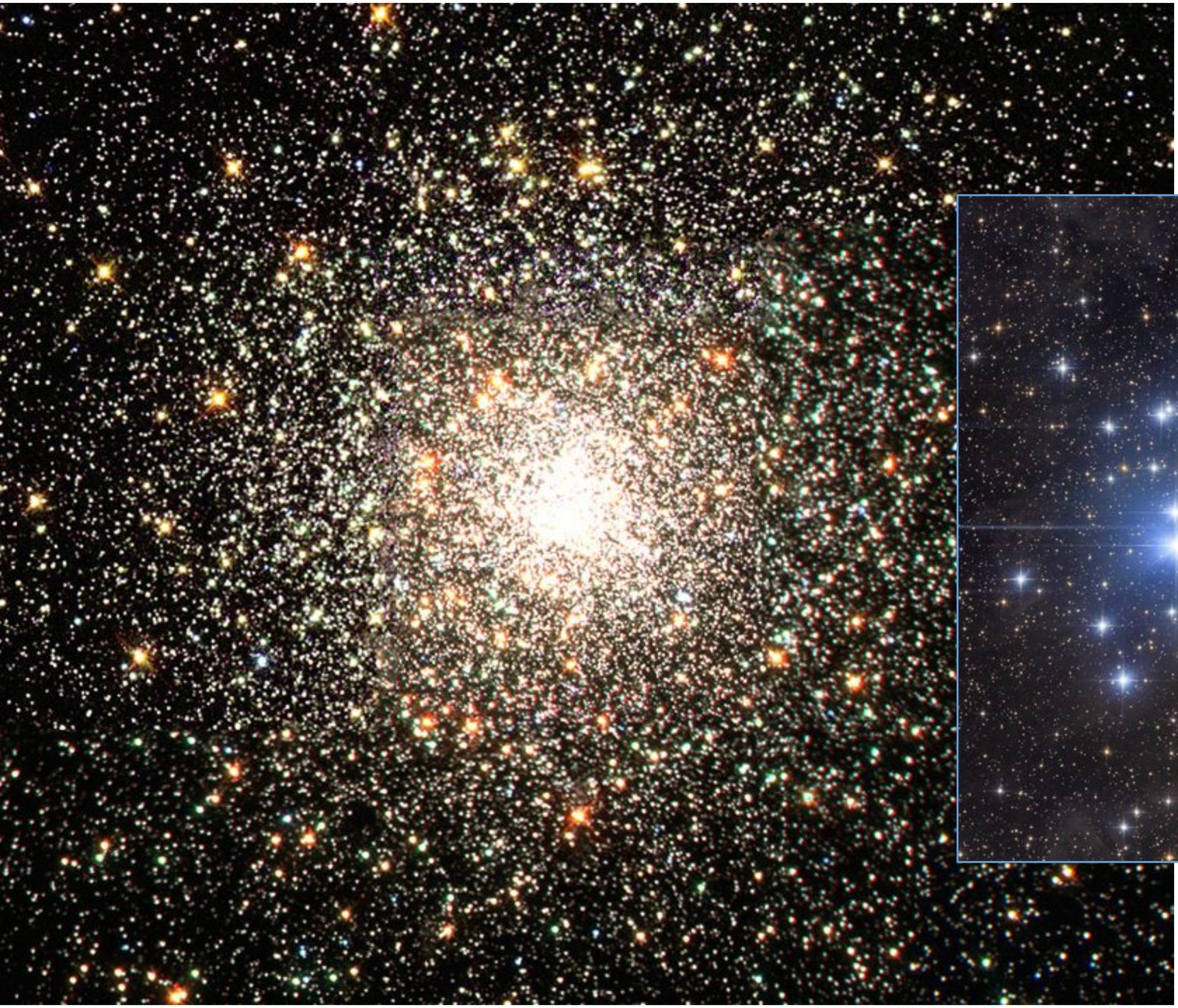
Cat's Eye Nebula (NGC 6543) by HST

Aglomerados estelares e Populações estelares

- População III: Z = 0 (hypothetical)
- População II: estrelas muito antigas e pobres em metais (Z <<< 0,02). Estrelas do Halo da Galáxia. Aglomerados globulares.
- População I: estrelas mais jovens e com metalicidade próxima da solar (Z ~ 0,02). Estrelas do disco da Galáxia. Aglomerados abertos.

Aglomerado globular e aberto

M80



Pleiades

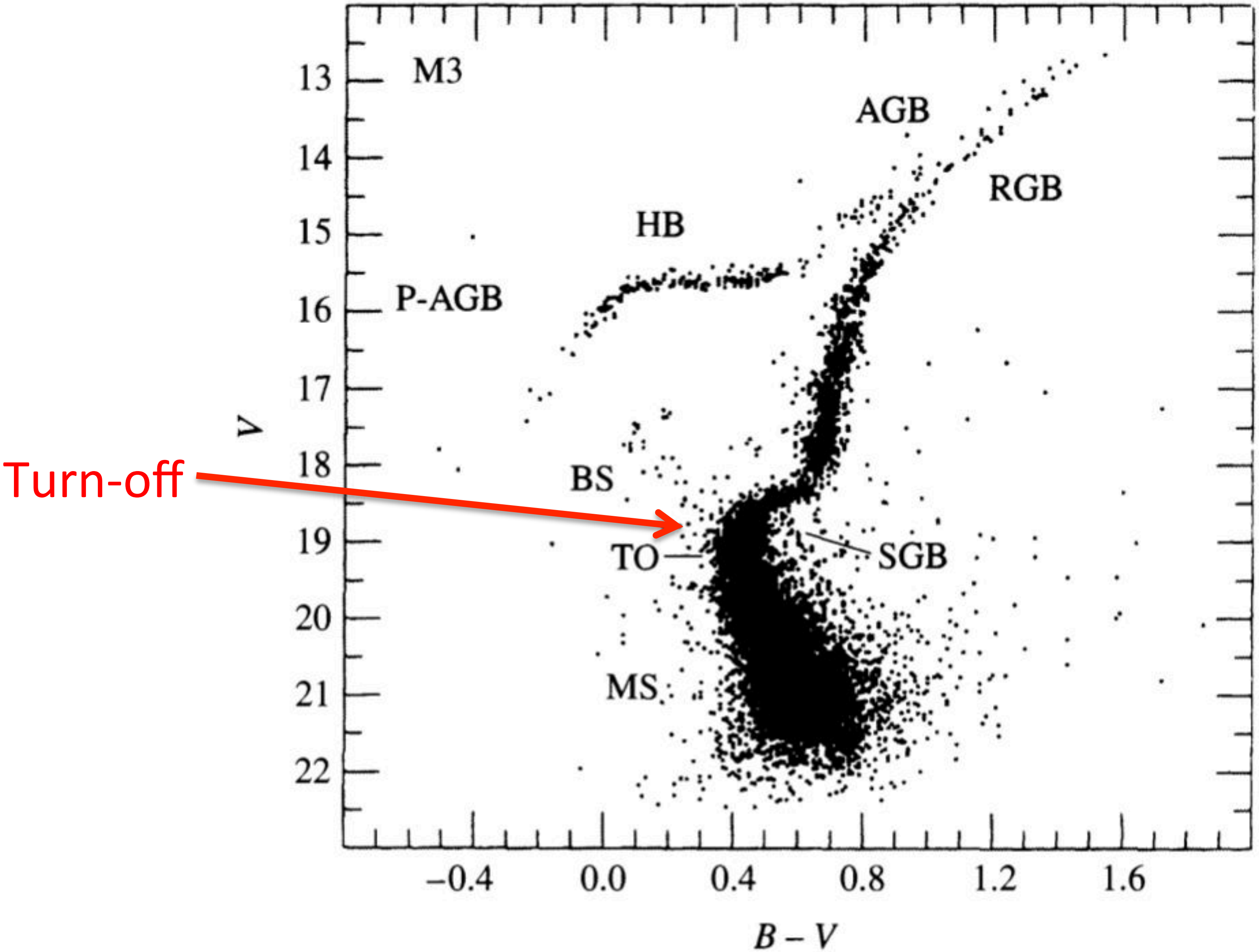


FIGURE 13.17 A color–magnitude diagram for M3, an old globular cluster. The major phases of stellar evolution are indicated: main sequence (MS); blue stragglers (BS); the main-sequence turn-off point (TO); the subgiant branch of hydrogen shell burning (SGB); the red giant branch along the Hayashi track, prior to helium core burning (RGB); the horizontal branch during helium core burning (HB); the asymptotic giant branch during hydrogen and helium shell burning (AGB); post-AGB evolution proceeding to the white dwarf phase (P-AGB). (Figure adapted from Renzini and Fusi

Determinação de idades

Idade por ser determinada pela posição to Turn-off

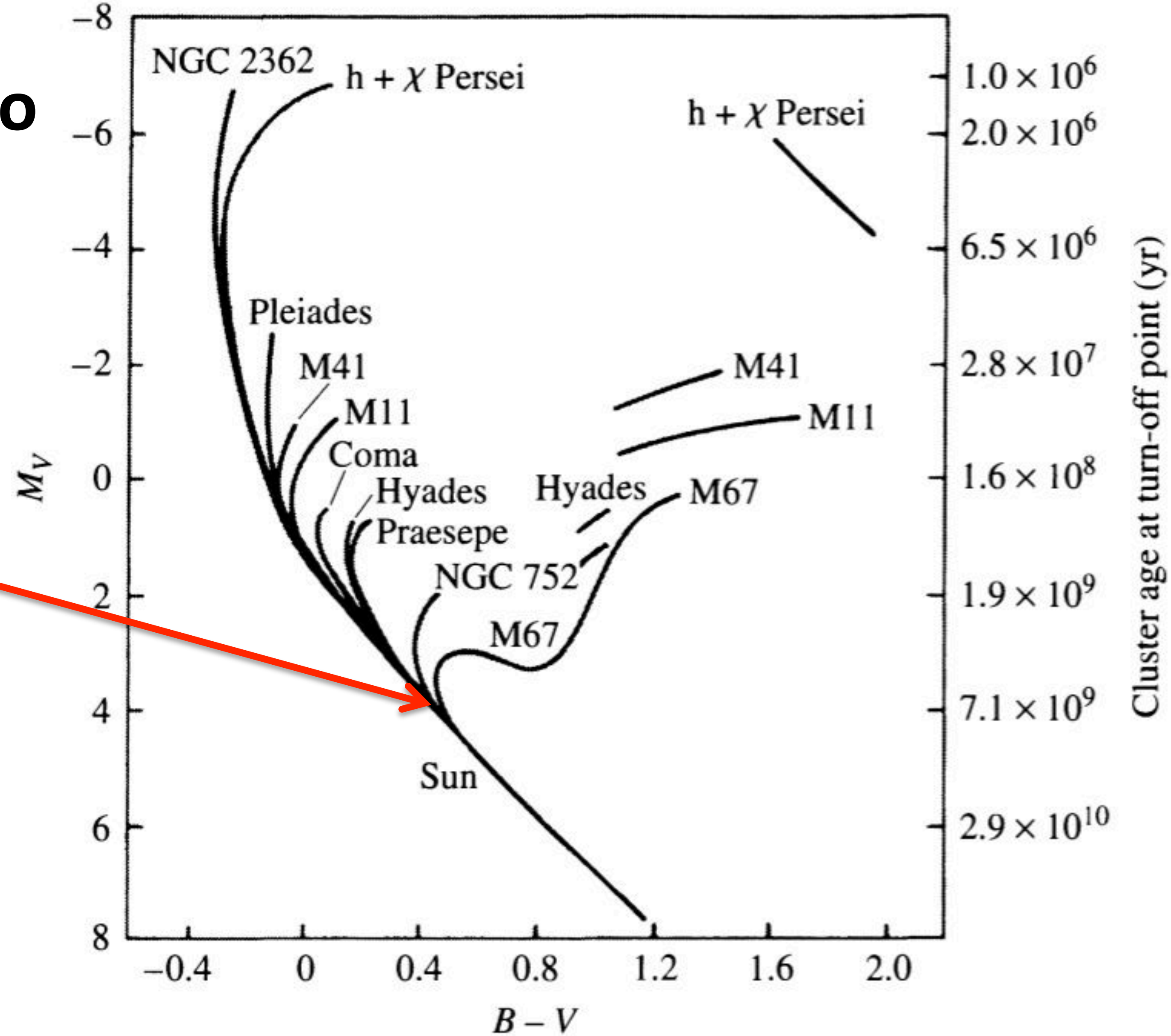
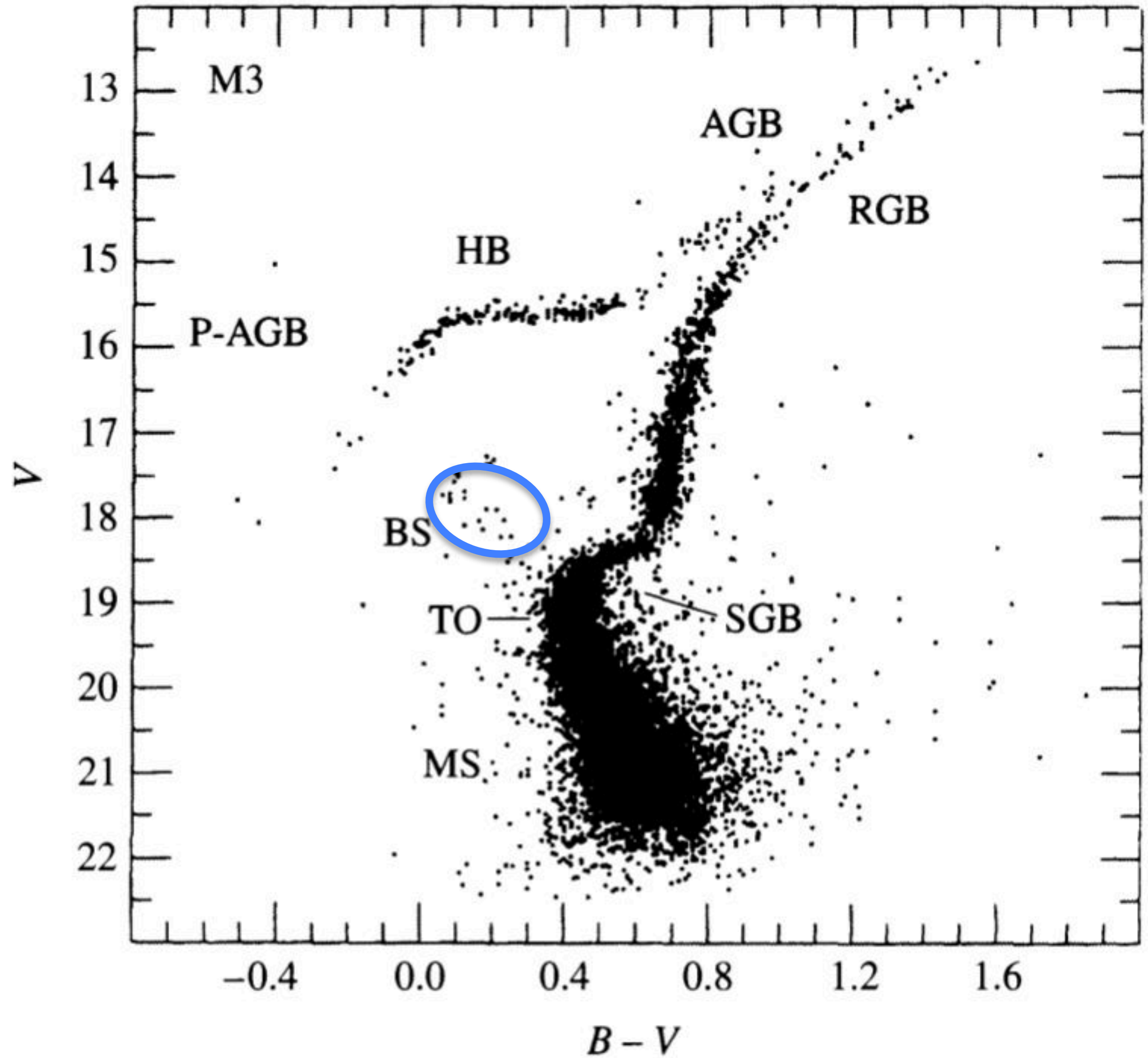


FIGURE 13.19 A composite color–magnitude diagram for a set of Population I galactic clusters. The absolute visual magnitude is indicated on the left-hand vertical axis, and the age of the cluster, based on the location of its turn-off point, is labeled on the right-hand side. (Figure adapted from an original diagram by A. Sandage.)



Blue Stragglers

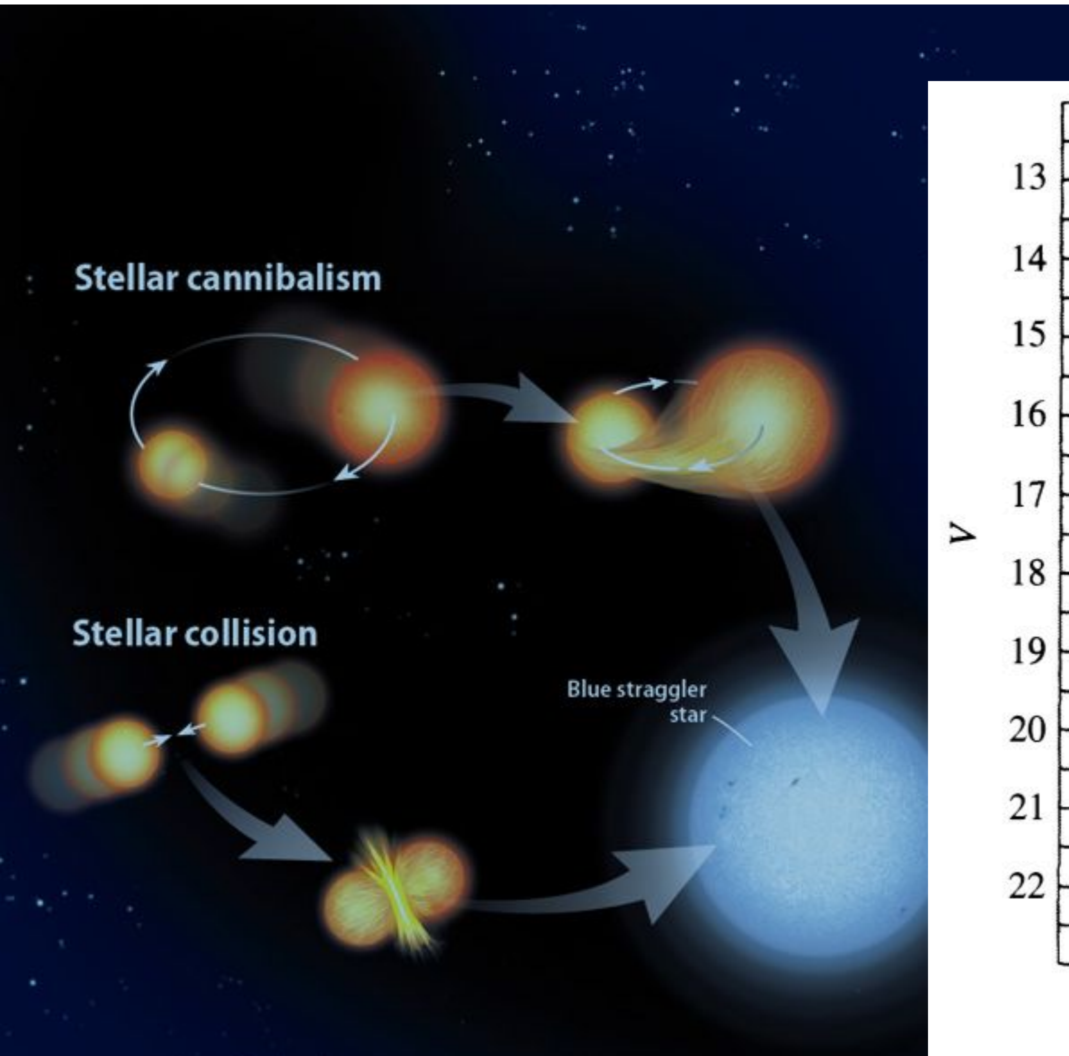
It should be pointed out that a group of stars, known as **blue stragglers**, can be found above the turn-off point of M3. Although our understanding of these stars is incomplete, it appears that their tardiness in leaving the main sequence is due to some unusual aspect of their evolution. The most likely scenarios appear to be mass exchange with a binary star companion,[14] or collisions between two stars, extending the star's main-sequence lifetime.

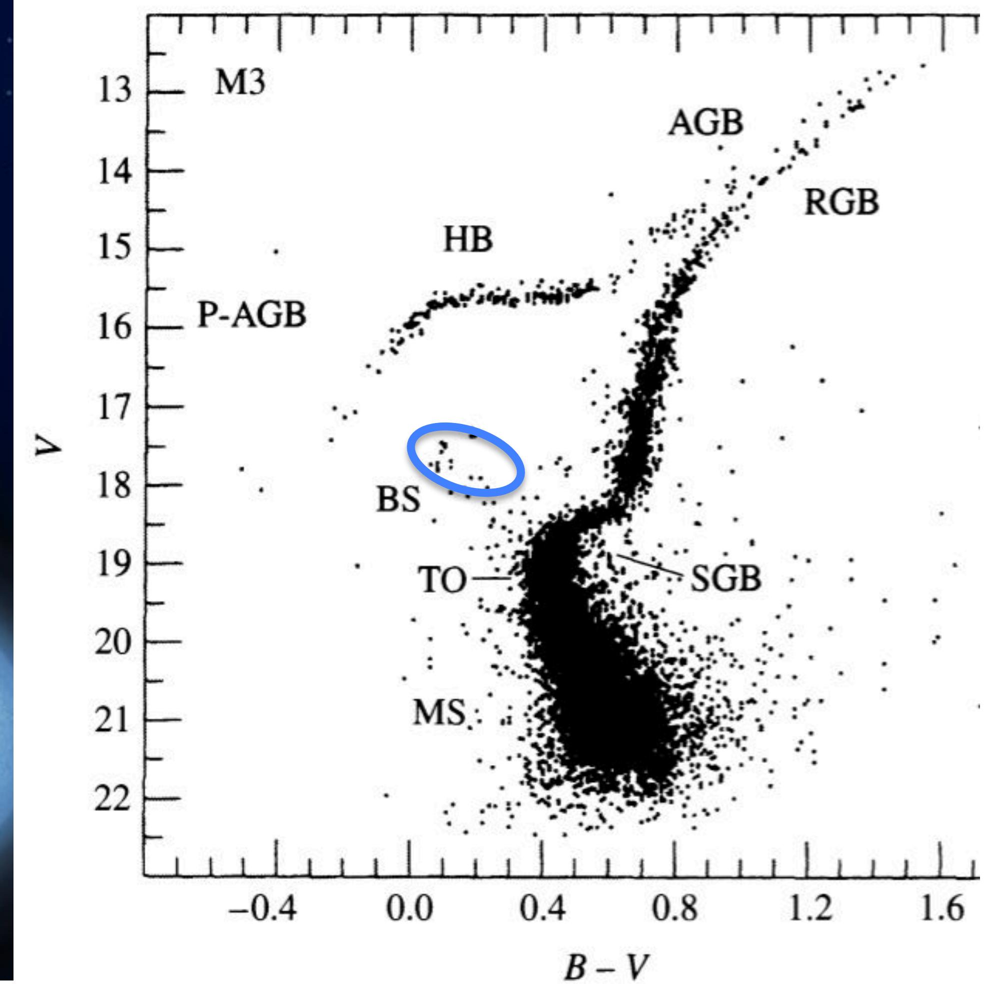
Blue Straggler: two channels:

- Collision or
- Mass transfer ("cannibalism")

Em aglomerado é fácil identificar Blue Stragglers.

Como identificar Blue Stragglers de campo?





A&A 584, A116 (2015)
DOI: 10.1051/0004-6361/201527303

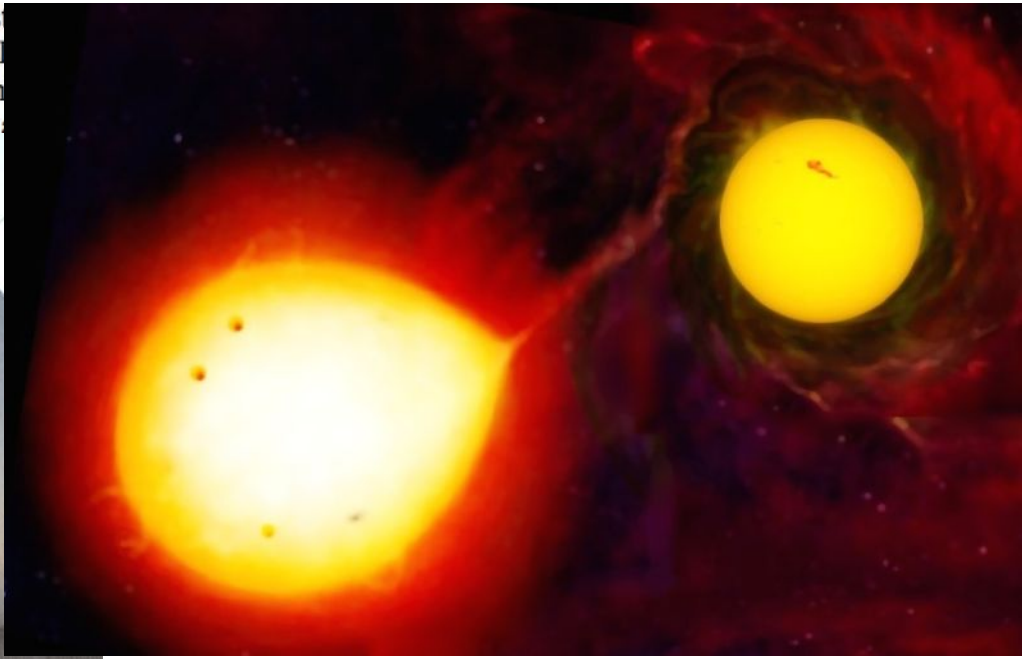
Astronomy & Astrophysics

Trabalho de IC de Lucas Schirbel: identificar sistema Blue Straggler em estrela gêmea do Sol

HIP 10725: The first solar twin/analogue field blue straggler★,★★

Lucas Schirbel[1], Jorge Meléndez[1], Amanda I. Karakas[2], Iván Ramírez[3], Matthieu Castro[4], Marcos A. Faria[5], Maria Lugaro[6], Martin Asplund[2], Marcelo Tucci Maia[1], David Yong[2], Louise Howes[2], and José D. do Nascimento Jr.[4,7]

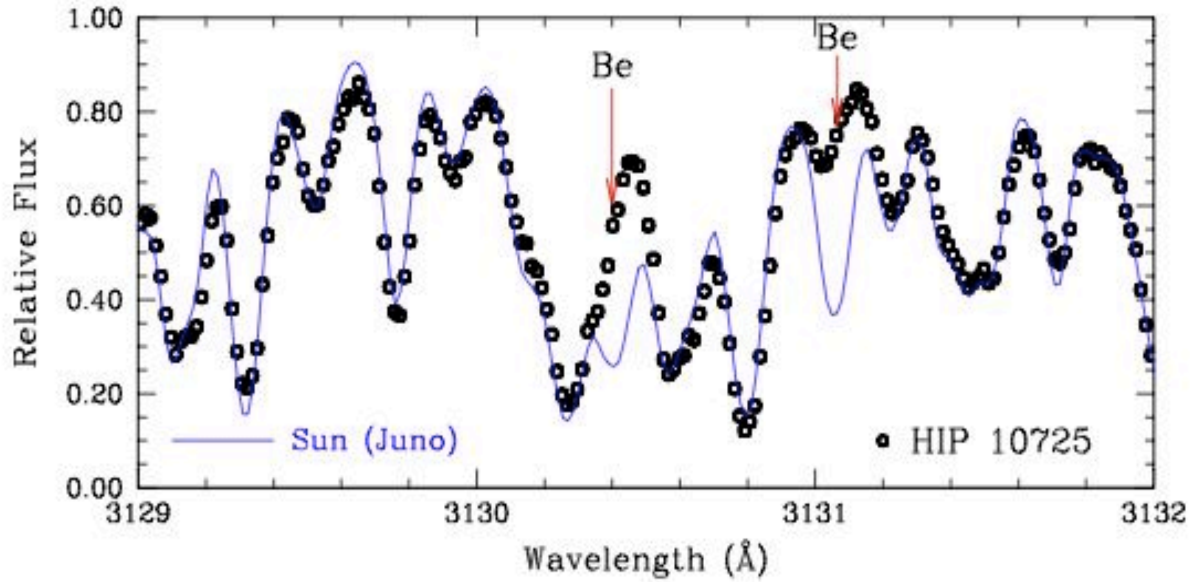
[1] Universidade de São Paulo, Departamento de Astronomia do IAG/USP, Rua do Matão 1226, Cidade Universitária, 05508-900 São Paulo, SP, Brazil
e-mail: lucas.schirbel@usp.br
[2] The Australian National University, Research School of As
[3] University of Texas at Austin, McDonald Observatory and
[4] Universidade Federal do Rio Grande do Norte, Departamen
[5] Universidade Federal de Itajubá, DFQ – Instituto de Ciênci



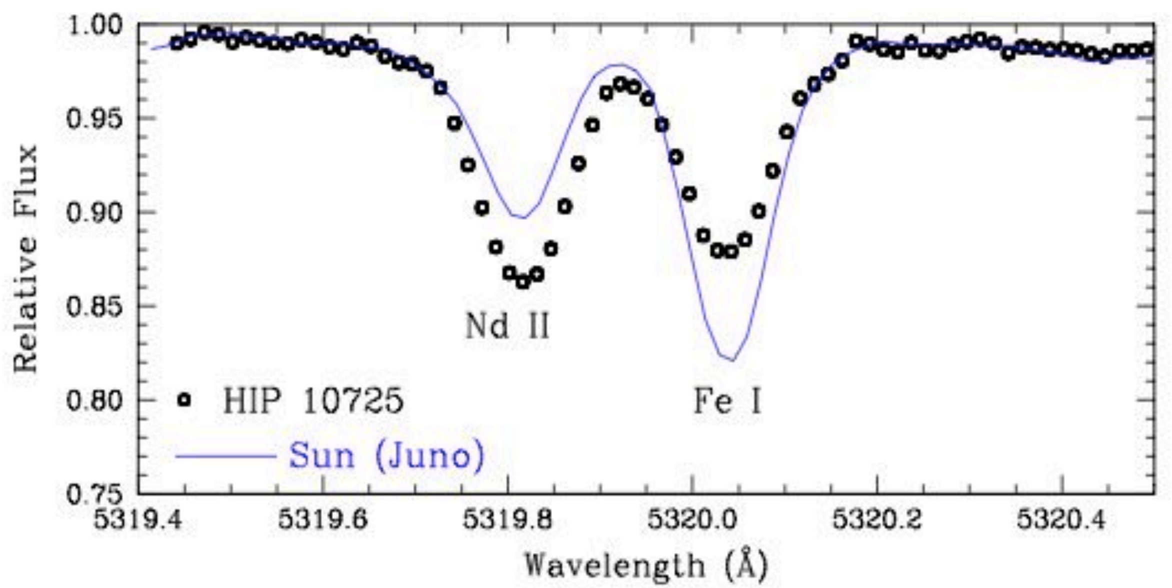
HIP 10725: The first solar twin/analogue field blue straggler*,**

Lucas Schirbel[1], Jorge Meléndez[1], Amanda I. Karakas[2], Iván Ramírez[3], Matthieu Castro[4], Marcos A. Faria[5],

A gêmea solar HIP 10725 tem uma rotação maior à esperada para a idade dela. A alta rotação talvez é devida à transferência de momento angular da antiga companheira AGB.

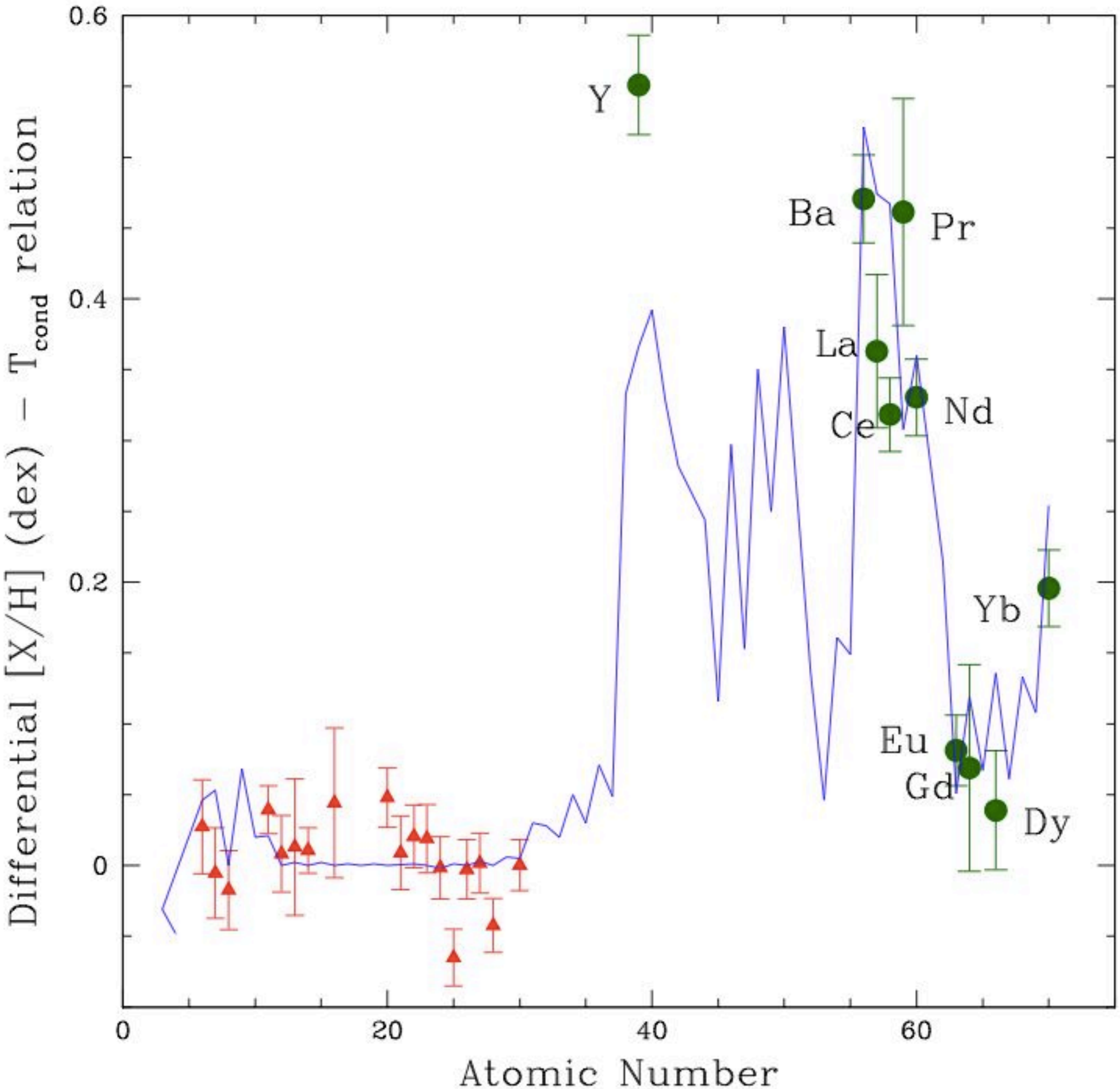


A estrela HIP 10725 não apresenta berílio. O aumento da rotação pode ter resultado em dragagem de material pobre em Be



HIP 10725: The first solar twin/analogue field blue straggler★,★★

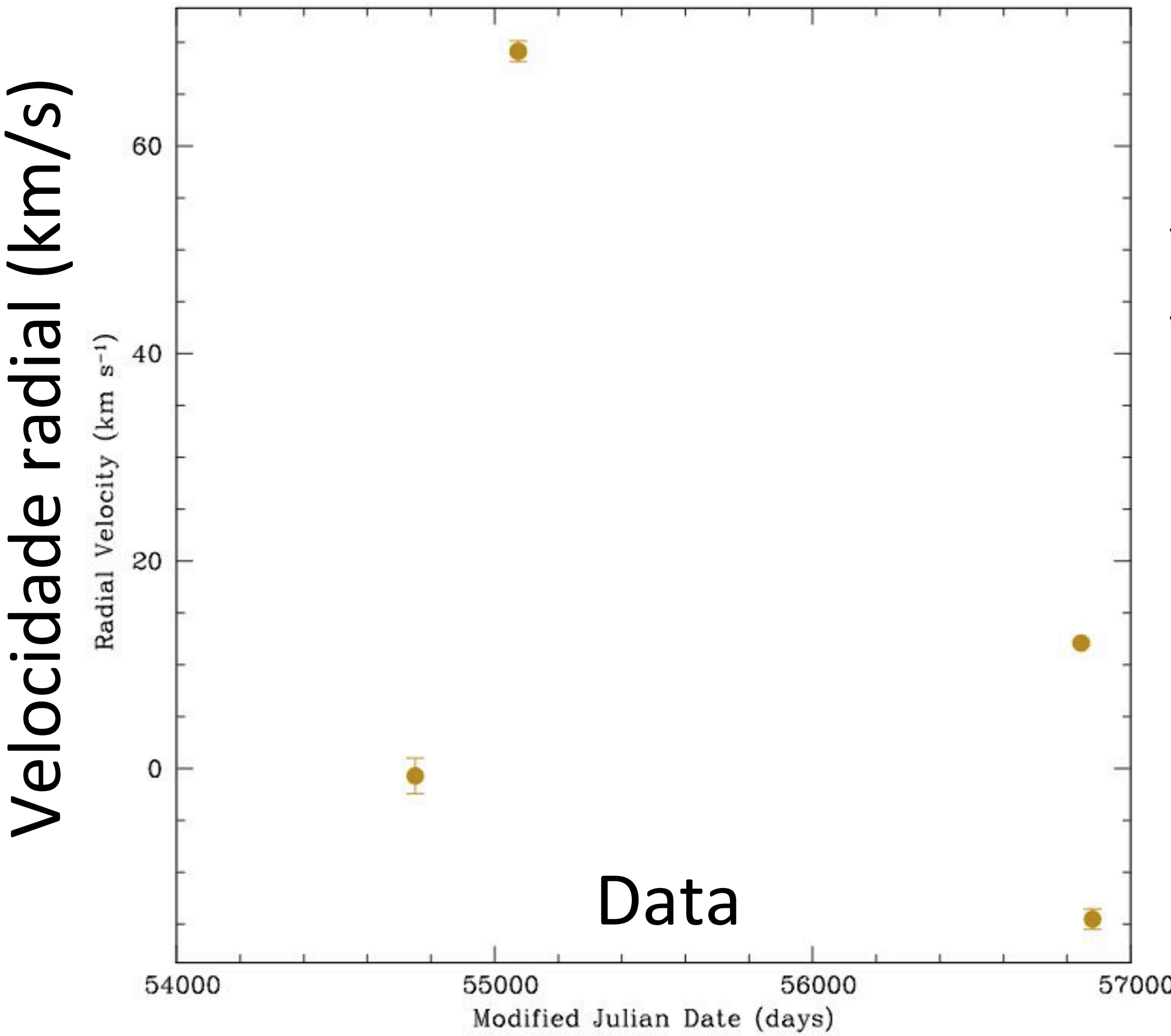
Lucas Schirbel[1], Jorge Meléndez[1], Amanda I. Karakas[2], Iván Ramírez[3], Matthieu Castro[4], Marcos A. Faria[5],



Gêmea solar rica em elementos de captura de nêutrons (processo-s) → provavelmente a antiga companheira AGB pode ter transferido material rico em elementos do processo-s

HIP 10725: The first solar twin/analogue field blue straggler⋆,⋆⋆

Lucas Schirbel[1], Jorge Meléndez[1], Amanda I. Karakas[2], Iván Ramírez[3], Matthieu Castro[4], Marcos A. Faria[5],



Variação em velocidade radial causada provavelmente por companheira anã branca (o que restou da AGB).

Fig. 4. Radial velocity data obtained for HIP 10725 over the course of several years, evidence for the presence of the unseen white dwarf companion.

Evolução Estelar no Brasil

Estrutura e evolução estelar (em particular anãs brancas)

- Kepler Oliveira (UFRGS)
- Alejandra Romero (UFRGS)

Estrutura e evolução estelar (em particular nucleossíntese de Li e Be em estrelas de tipo solar):

- José-Dias do Nascimento (UFRN)
- Matthieu Castro (UFRN)