

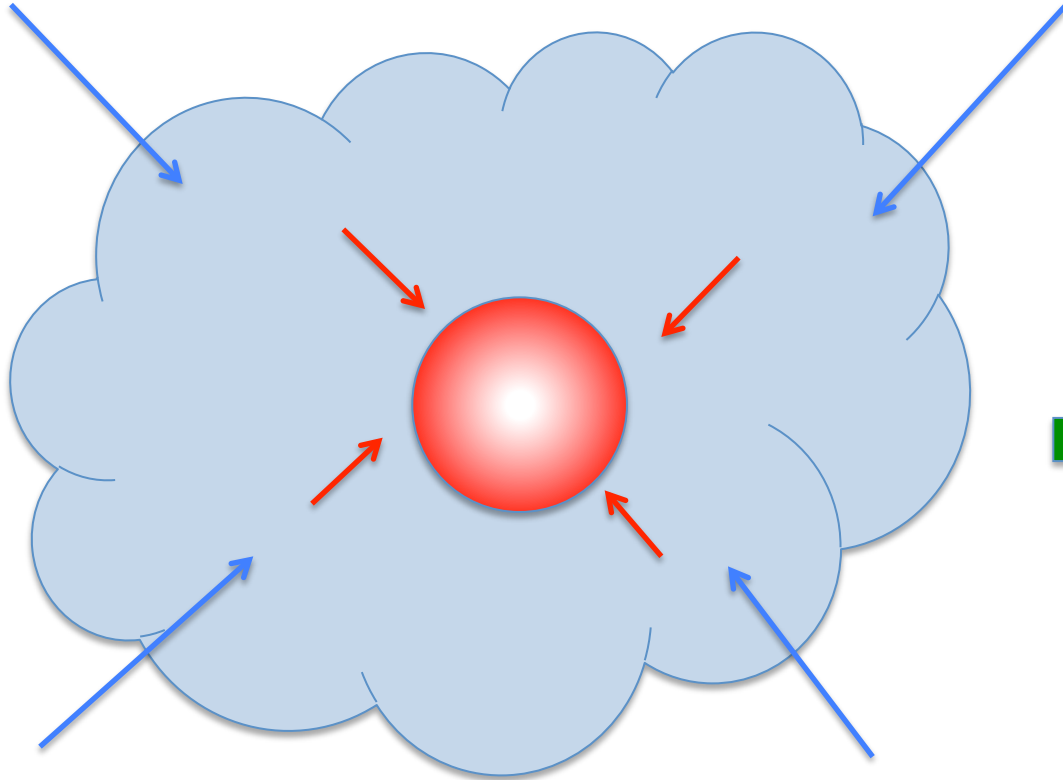
13 - Estágios avançados da evolução estelar (a partir de *The Horizontal Branch*) e Aglomerados estelares + parte do Cap. 14

J. Meléndez

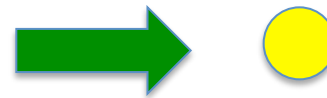
AGA293

Escalas de tempo de evolução estelar

Colapso da nuvem: escala de tempo *free-fall* $\sim 10^5$ anos



Escala de tempo da fusão nuclear. Para o Sol $\sim 10^{10}$ anos

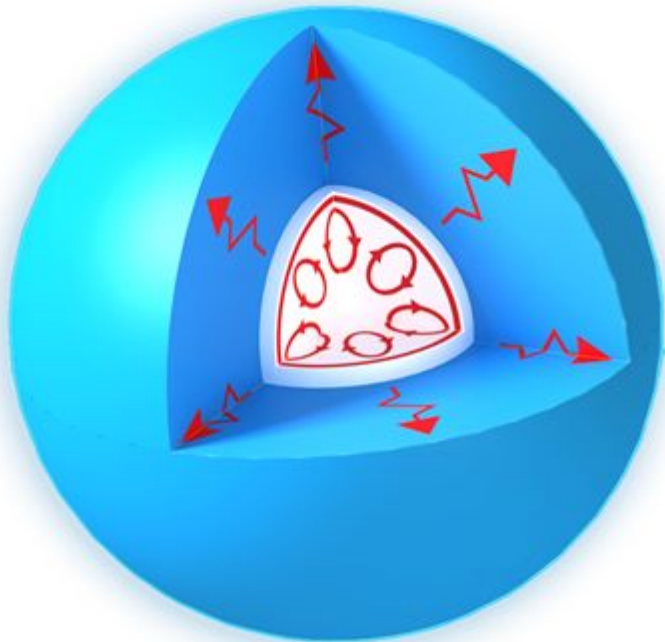


Colapso da proto-estrela: escala de tempo de Kelvin-Helmholtz $\sim 10^7$ anos

A estrutura e tamanho das estrelas muda durante a sua evolução

$$M > 1.2 M_{\odot}$$

Queima de hidrogênio
pelo ciclo CNO →
núcleo convectivo



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

$$M < 0.3 M_{\odot}$$

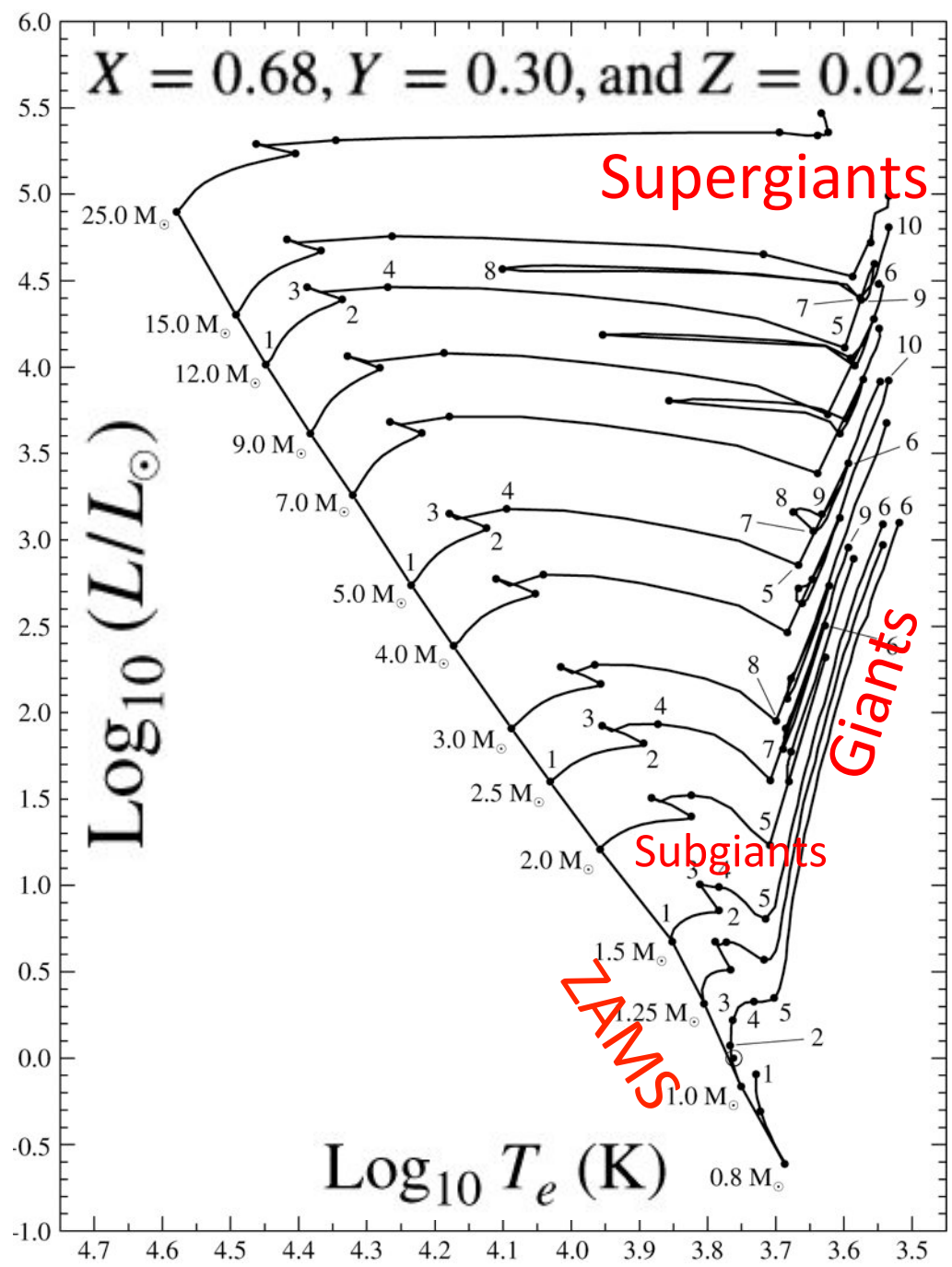
$0.3 M_{\odot} < M < 1.2 M_{\odot}$
Envelope convectivo

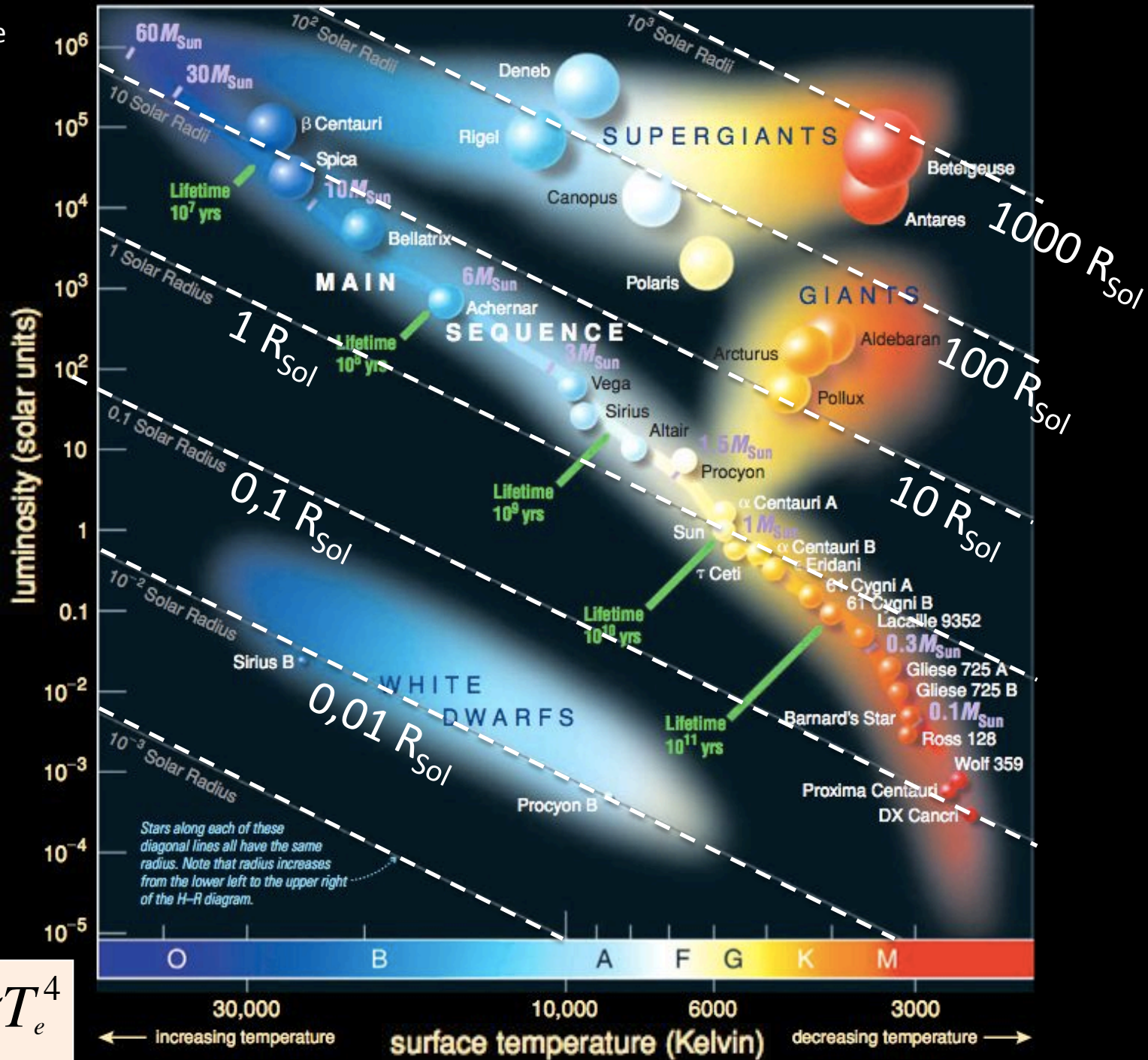
Totalmente
convectivas
devido à alta
opacidade



Tempo (Myr) a partir da ZAMS

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

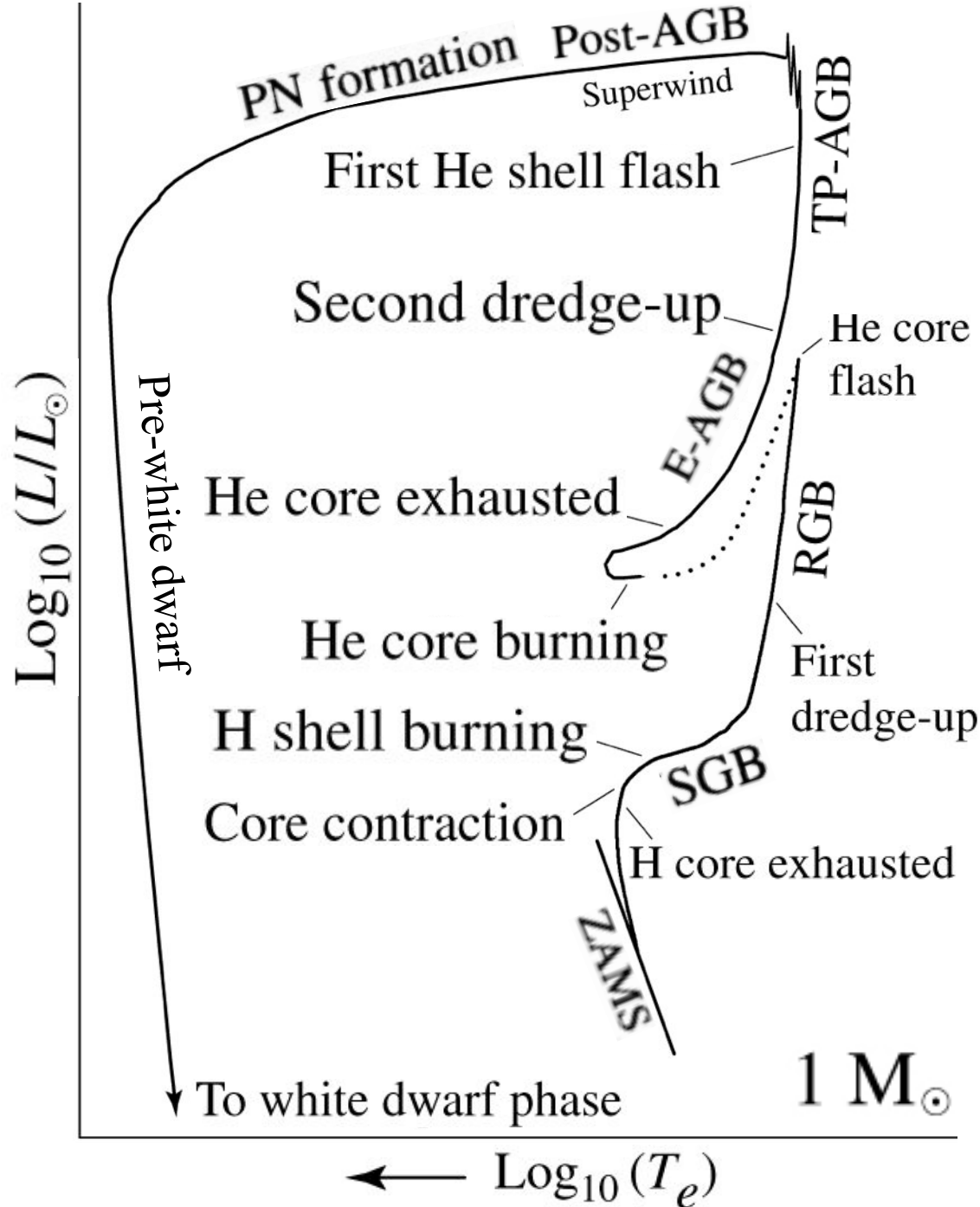
E-AGB: Early Asymptotic Giant Branch

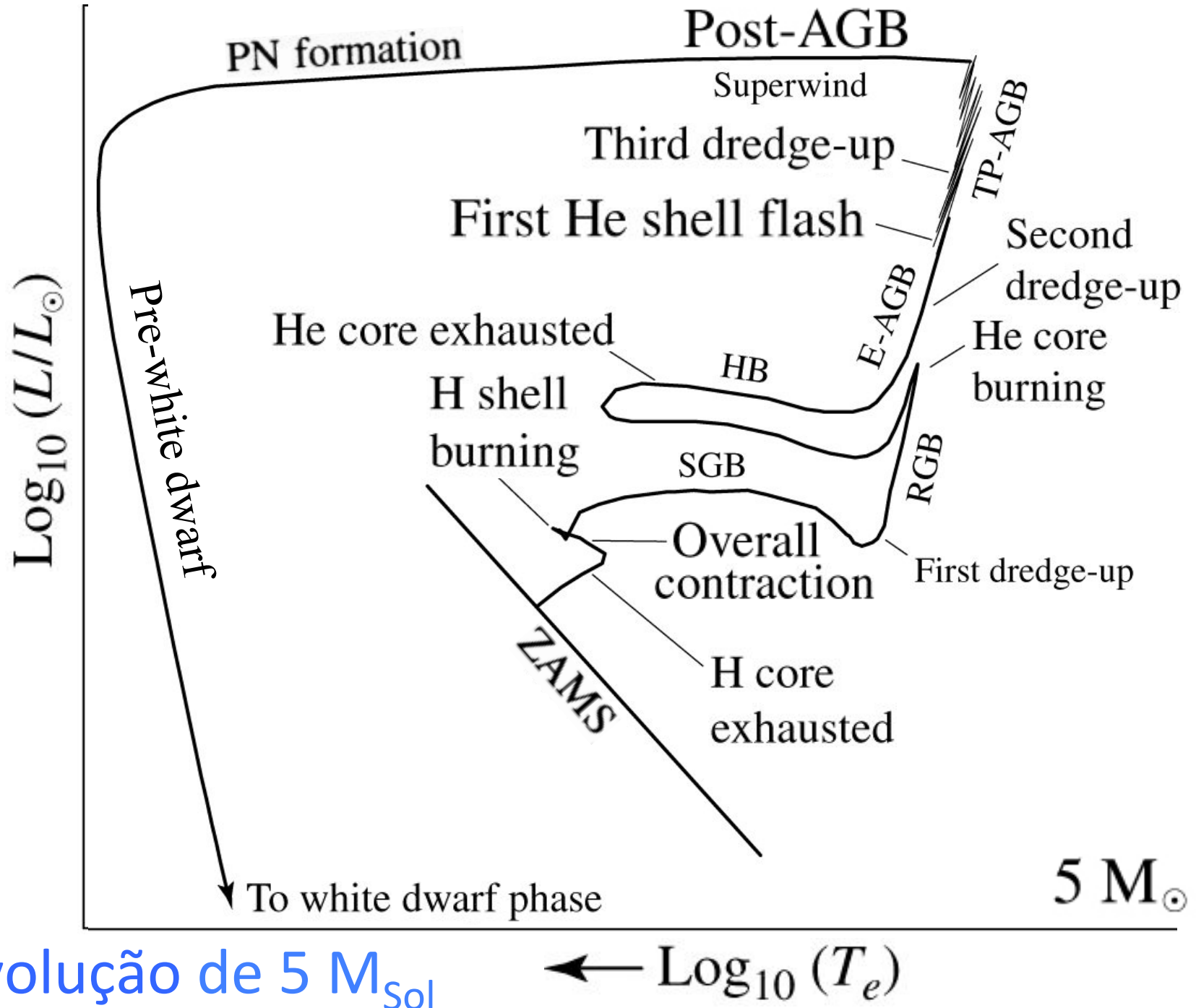
TP-AGB: Thermal Pulse AGB

Post-AGB: Post-AGB

PN-formation: Planetary Nebula formation

Evolução de $1 M_{\text{Sol}}$





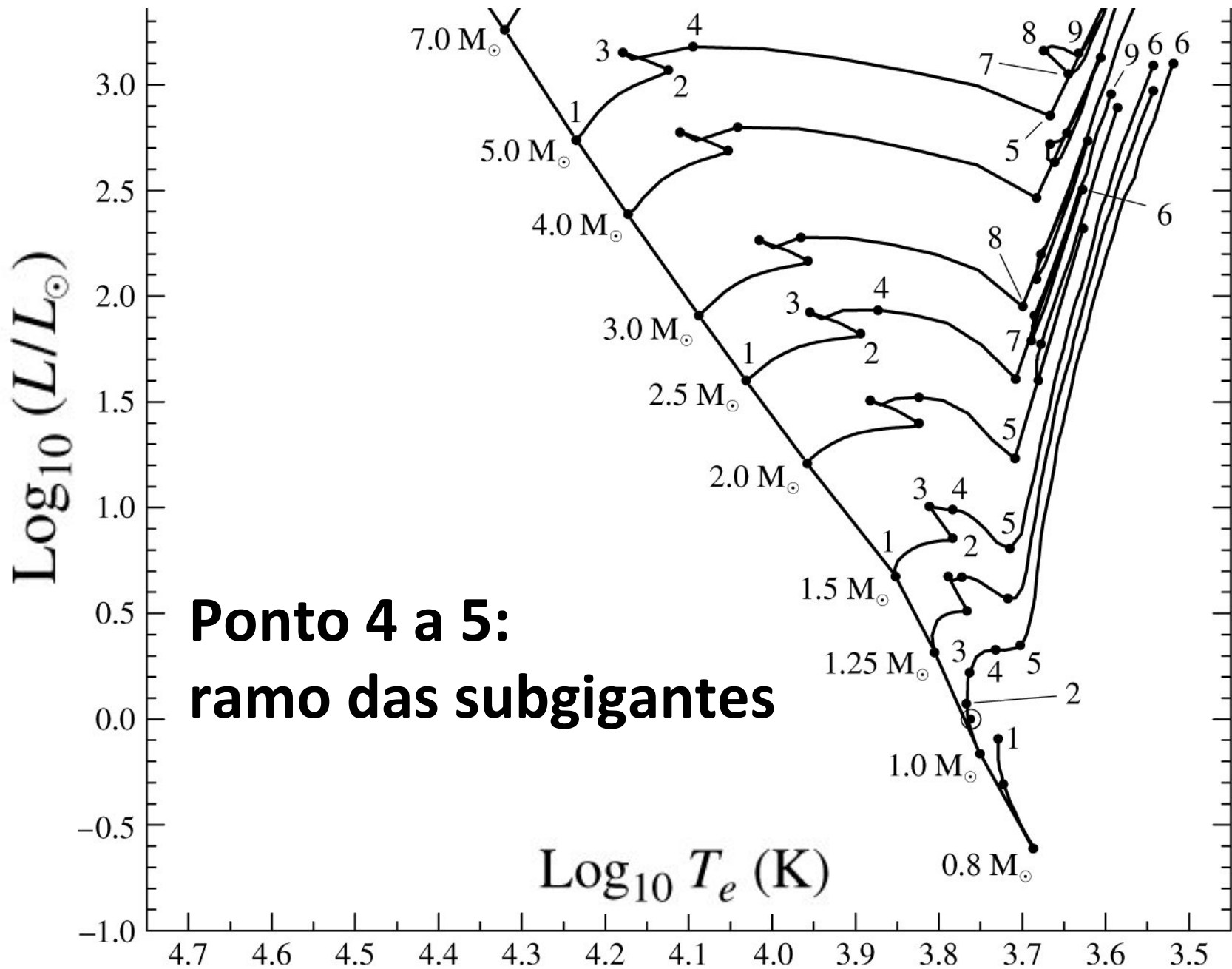
Evolução de $5 M_{\text{Sol}}$

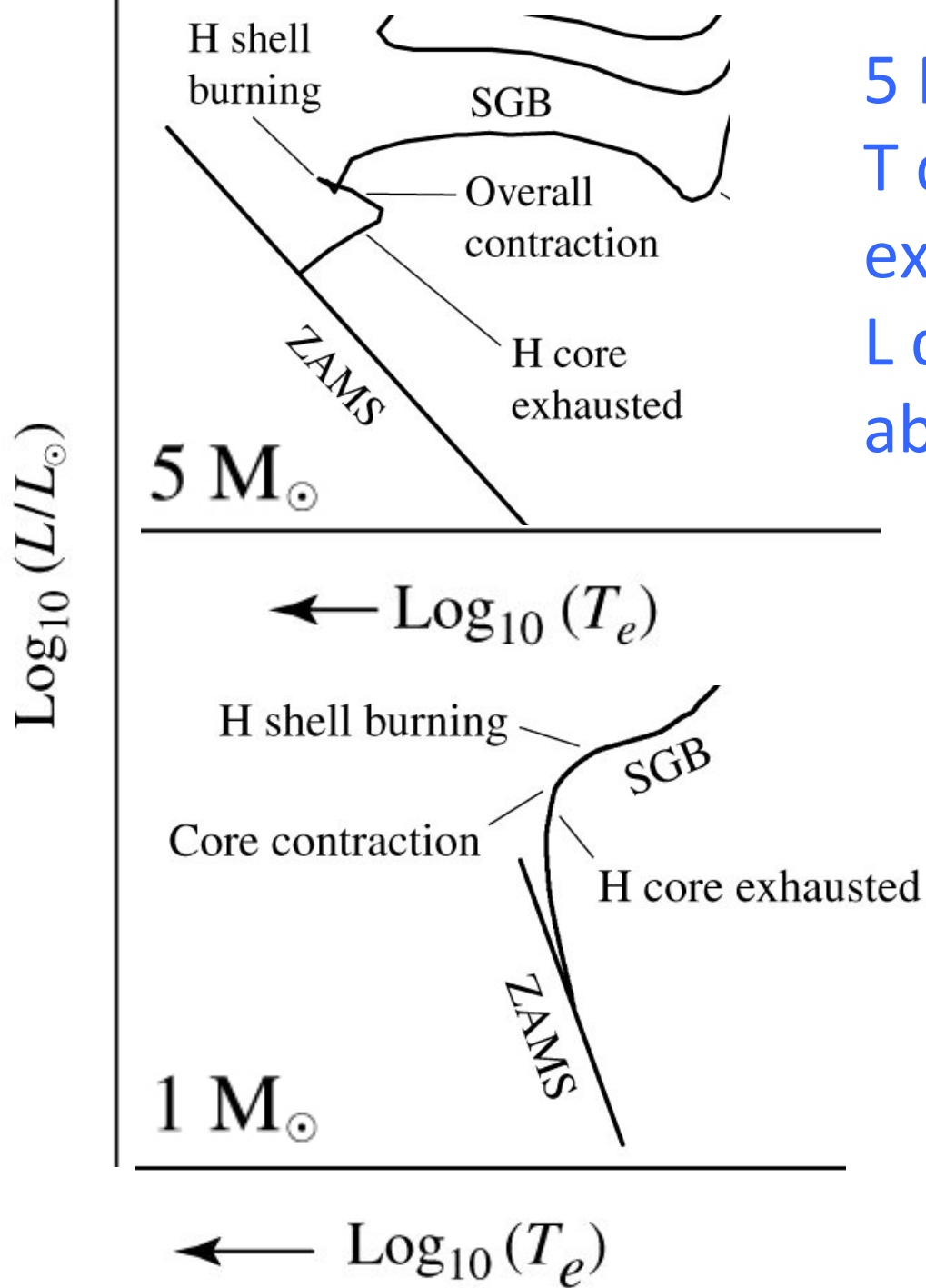
O ramo das subgigantes

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

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





$5 M_{\text{Sol}}$:

T decresce devido à expansão do envelope.

L decresce pois envelope absorve muita energia

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

$1 M_{\text{sol}}$:

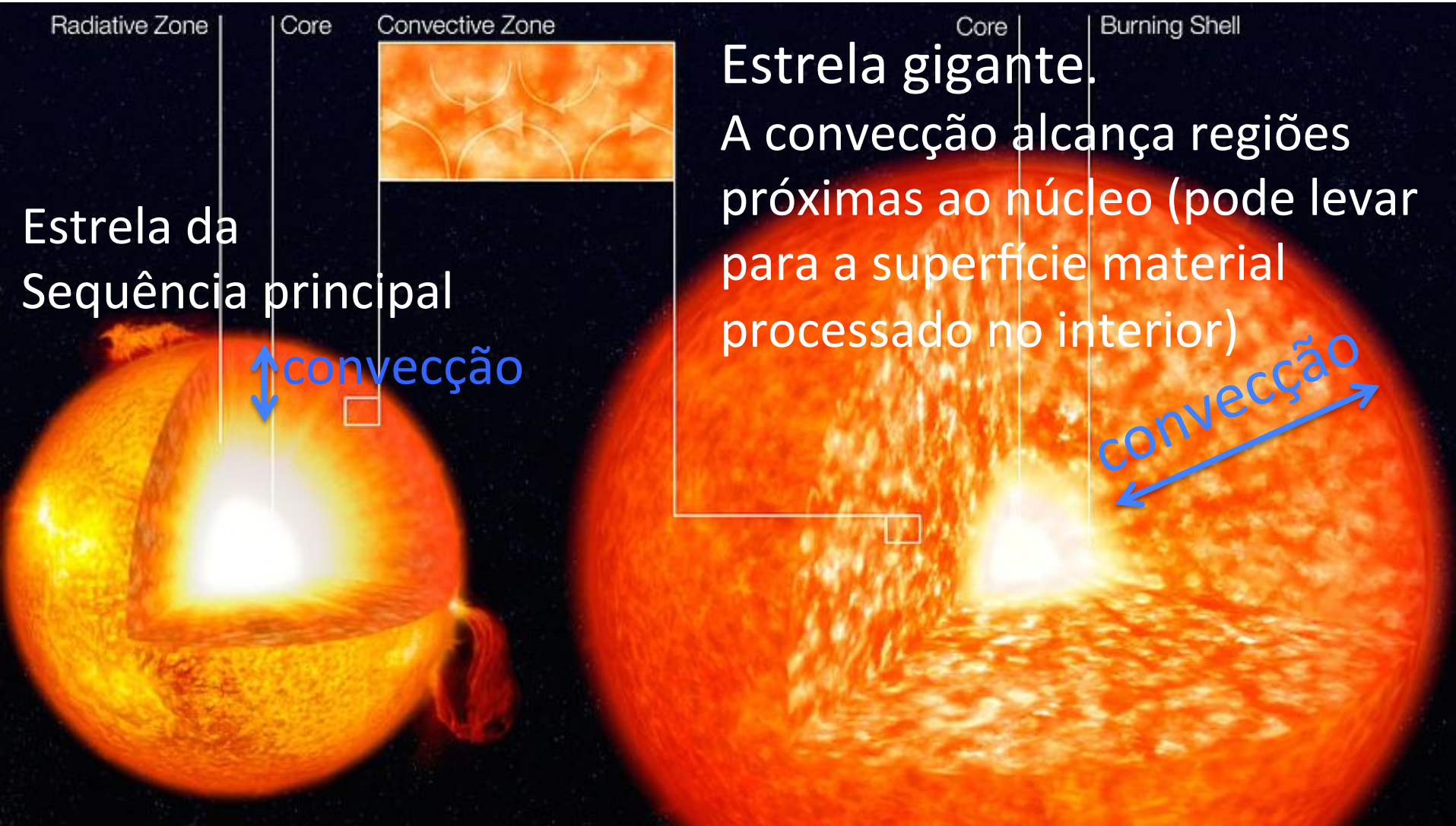
L pequeno aumento.

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 $\rightarrow$ opacidade interior aumenta (H^-)
 $\rightarrow$ Convecção

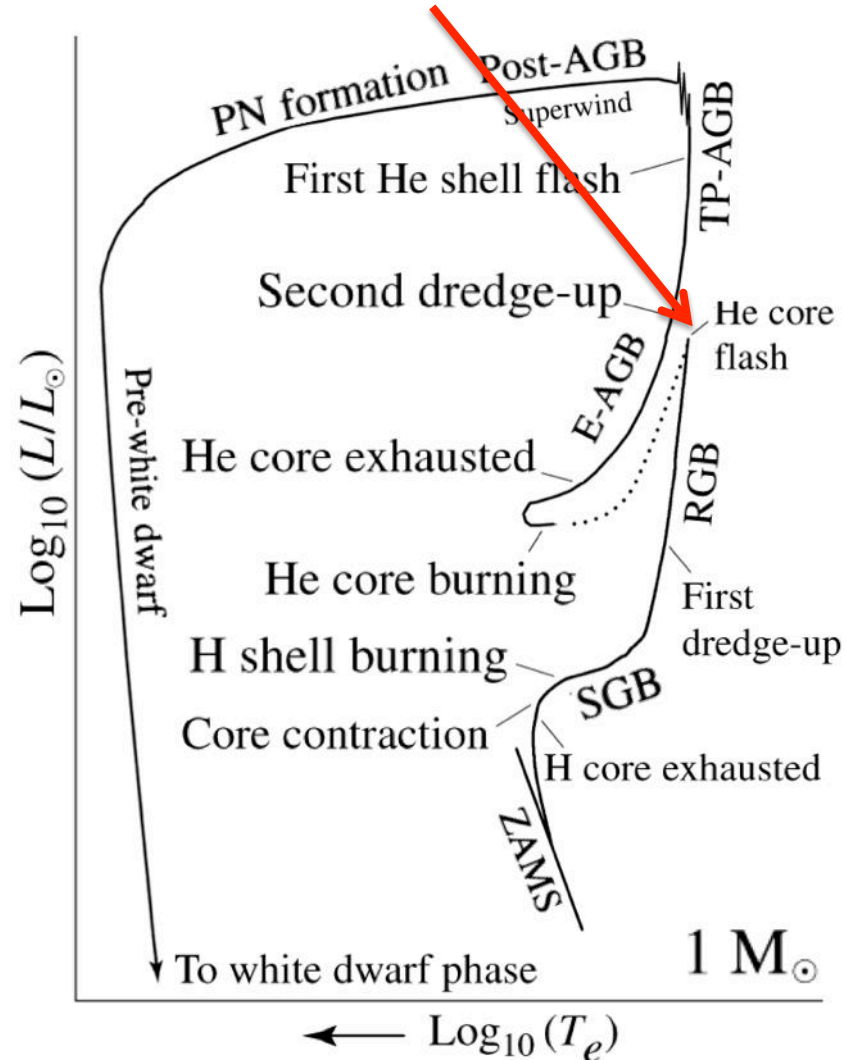
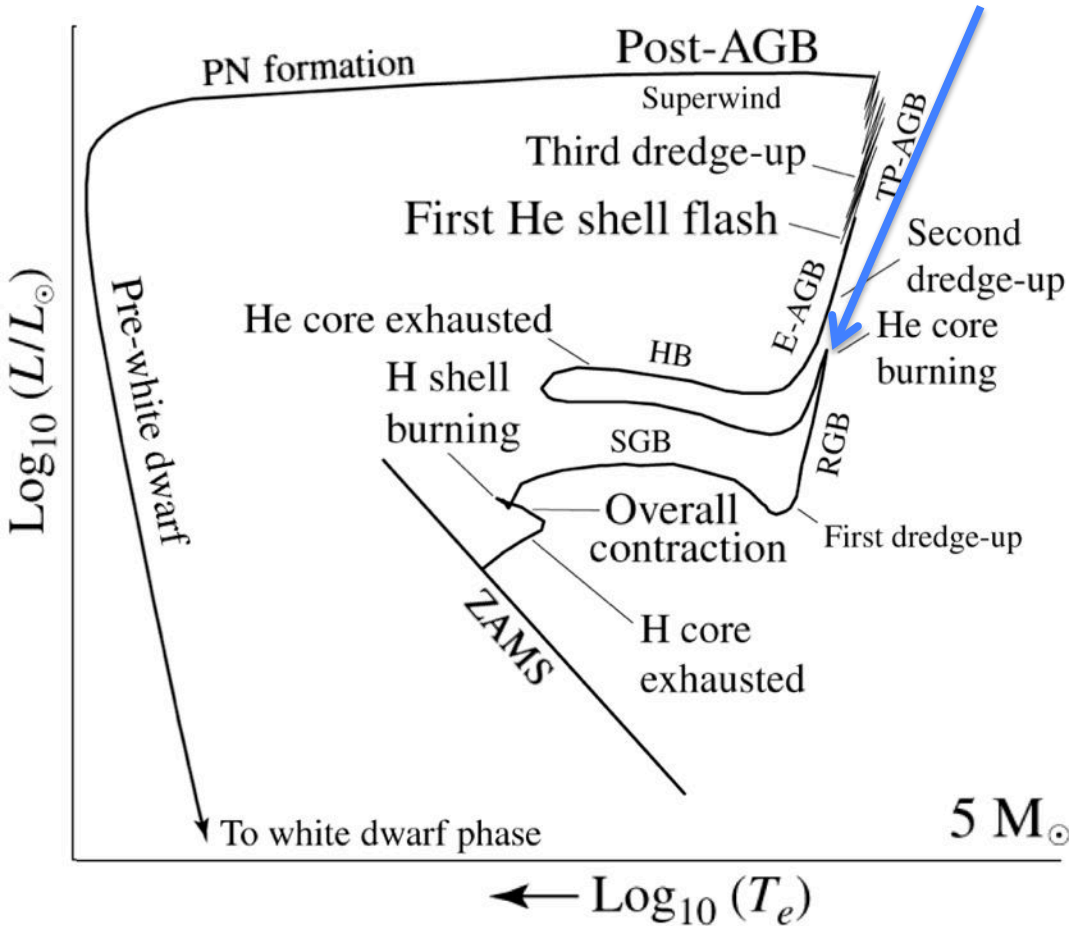


Fim do ramo das gigantes (RGB):

início da queima de He

Para $M < 2 M_{\text{sol}}$ o início da queima de He é explosiva

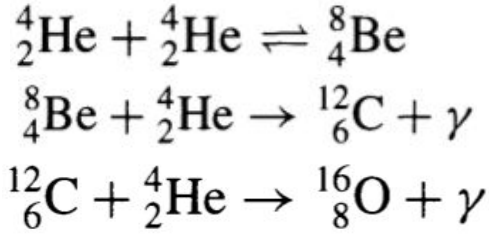
Para $M > 2 M_{\text{sol}}$ a queima de He no núcleo acontece mais suavemente



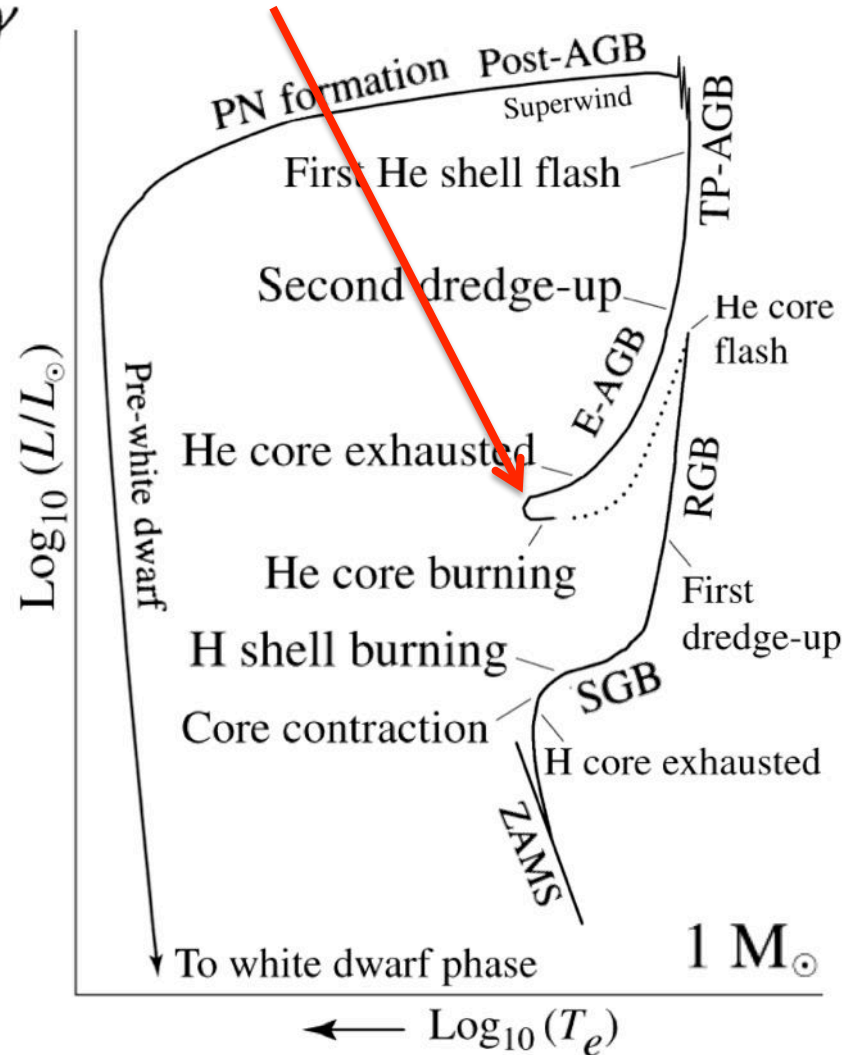
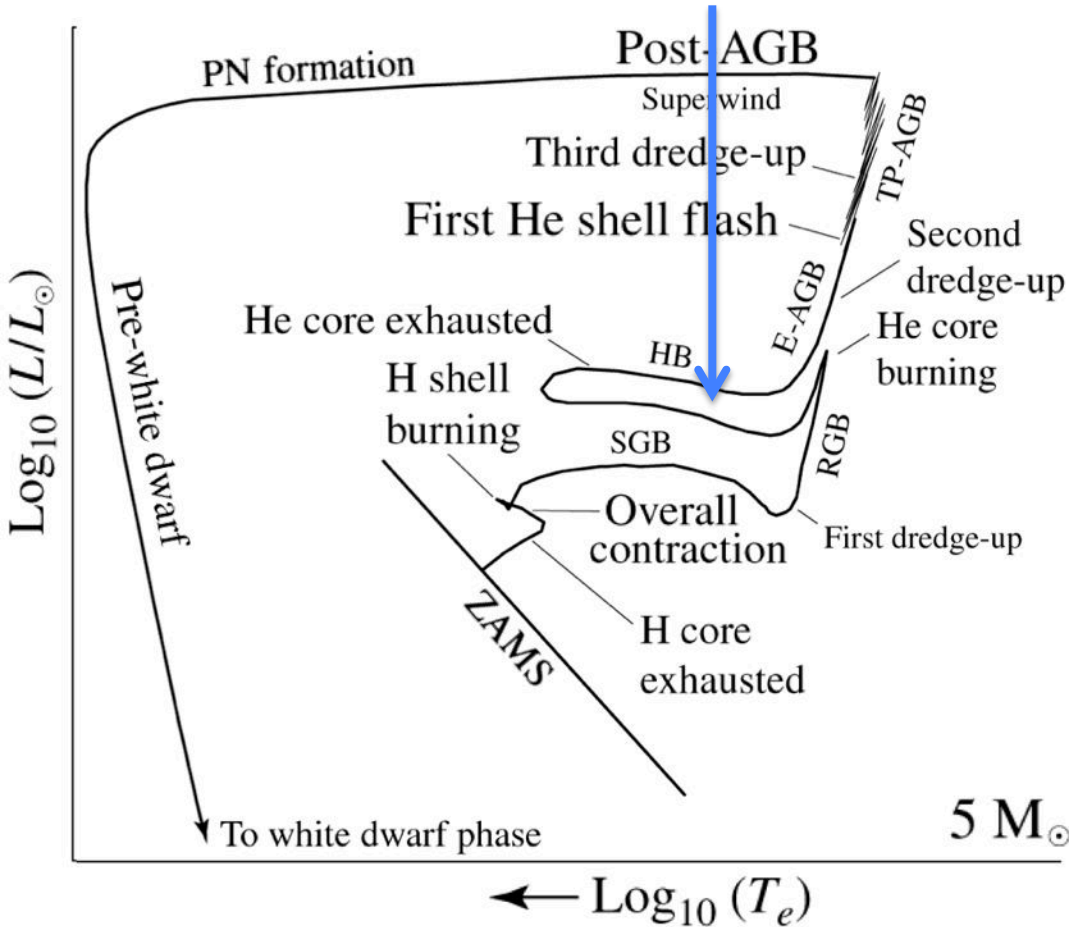
O ramo horizontal:

$\text{He} \rightarrow \text{C, O}$

Estrelas de massa intermediária têm HB extenso

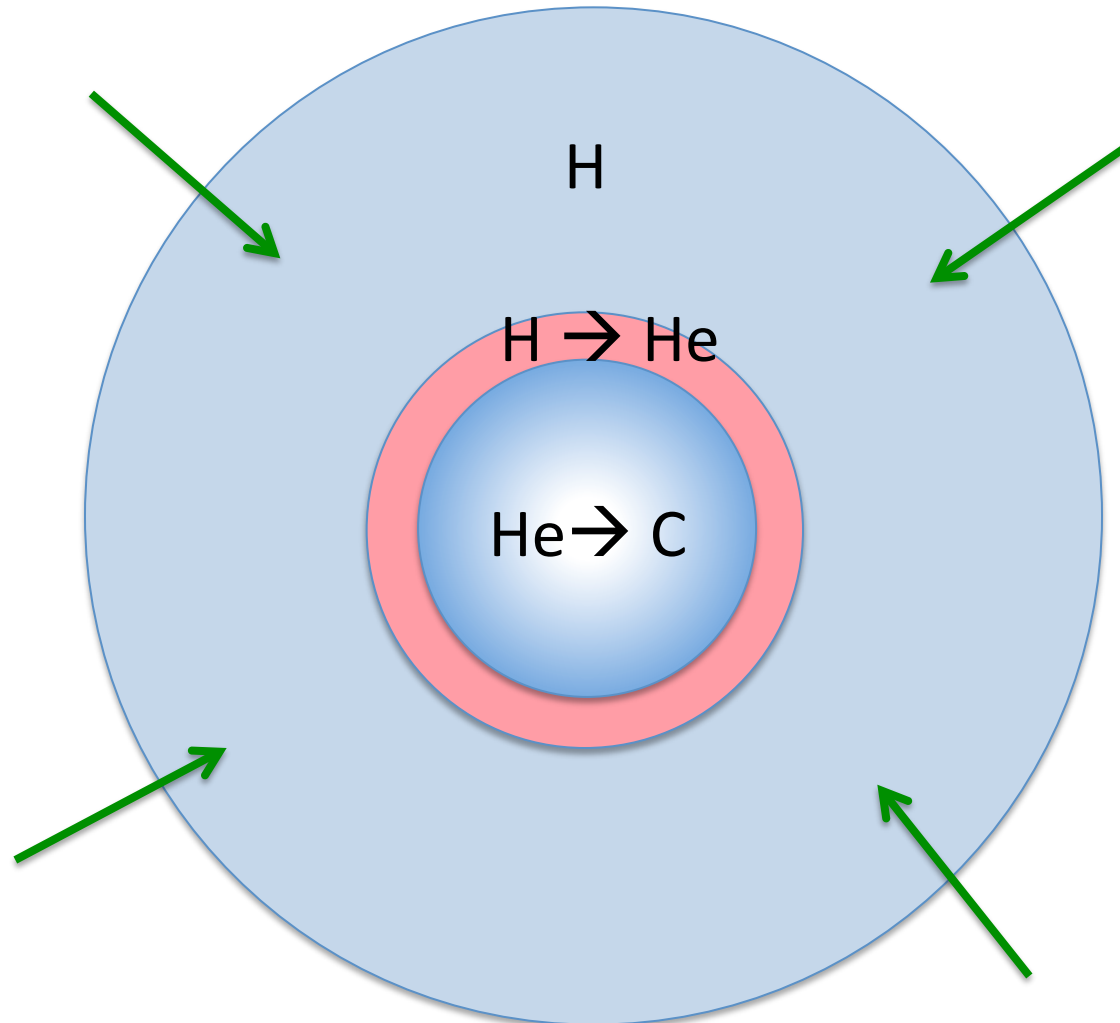


Estrelas de baixa massa como o Sol têm um ramo horizontal curto



Estrela no lado azul do ramo horizontal

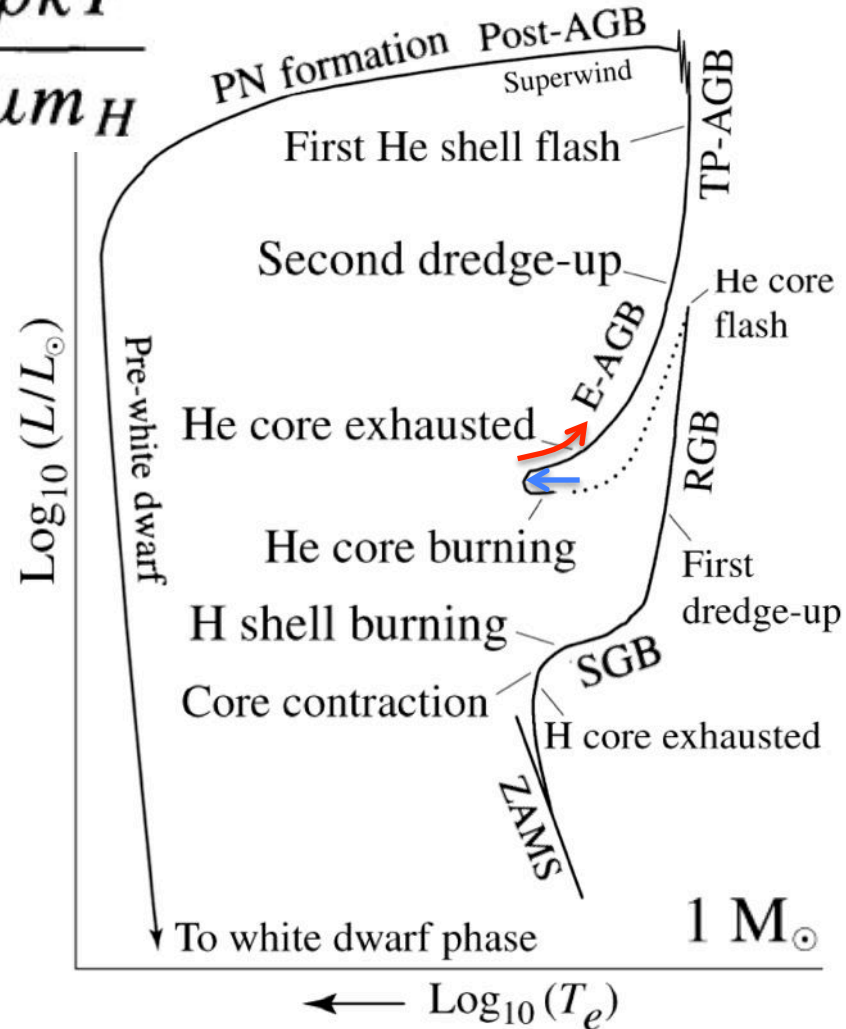
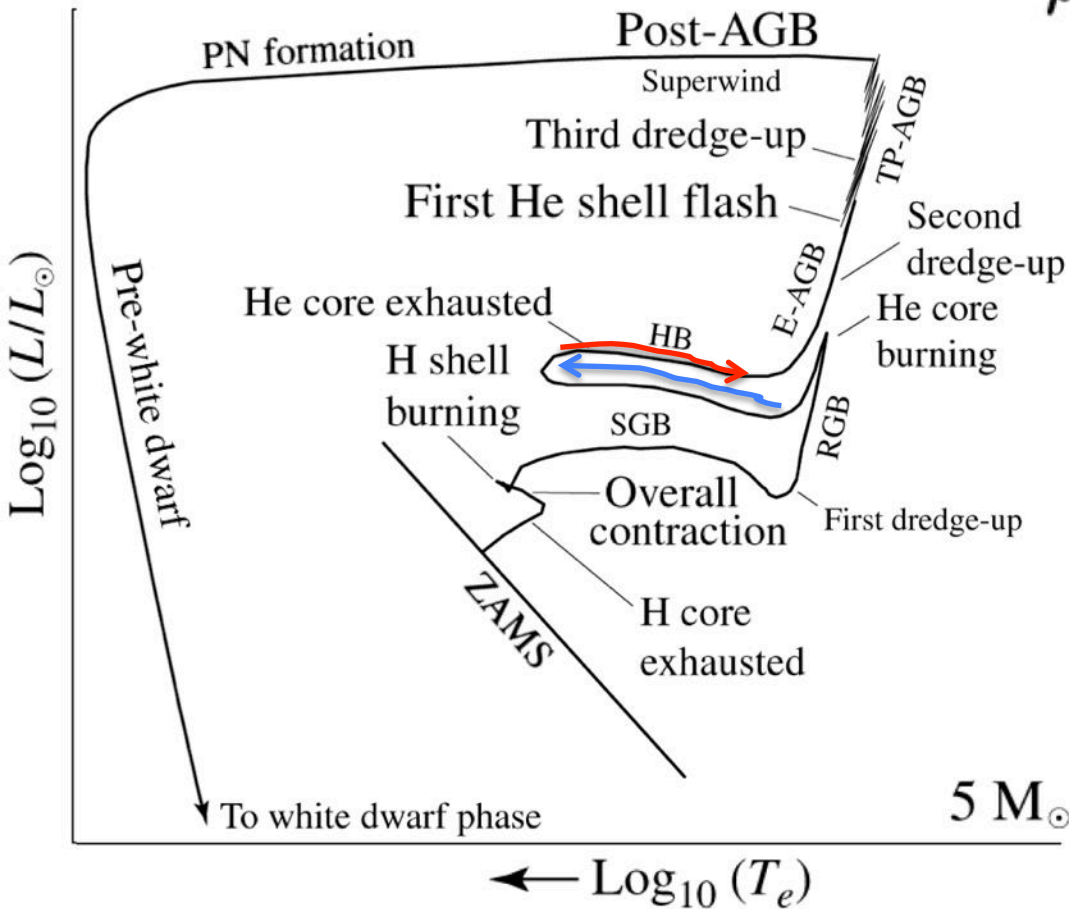
O envelope ainda estão em contração $\rightarrow$ aumenta a produção de energia pela *shell* ($H \rightarrow He$). No núcleo: queima de He em C e O $\rightarrow$ se desenvolve uma zona convectiva



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 $\rightarrow$ núcleo de He entra em contração.

$\rightarrow$ Expansão do envelope e percurso para o vermelho

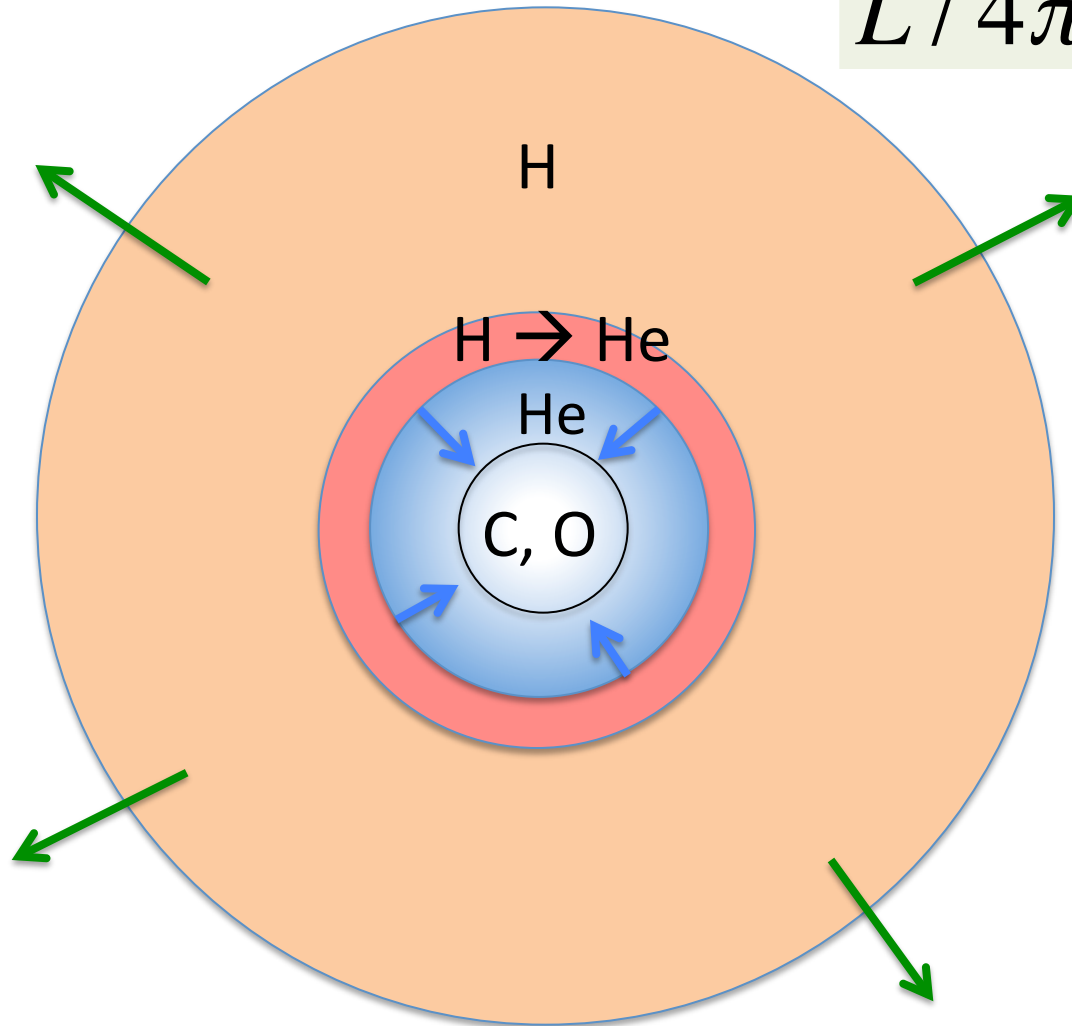
$$P_g = \frac{\rho k T}{\mu m_H}$$



Estrela no lado vermelho do ramo horizontal

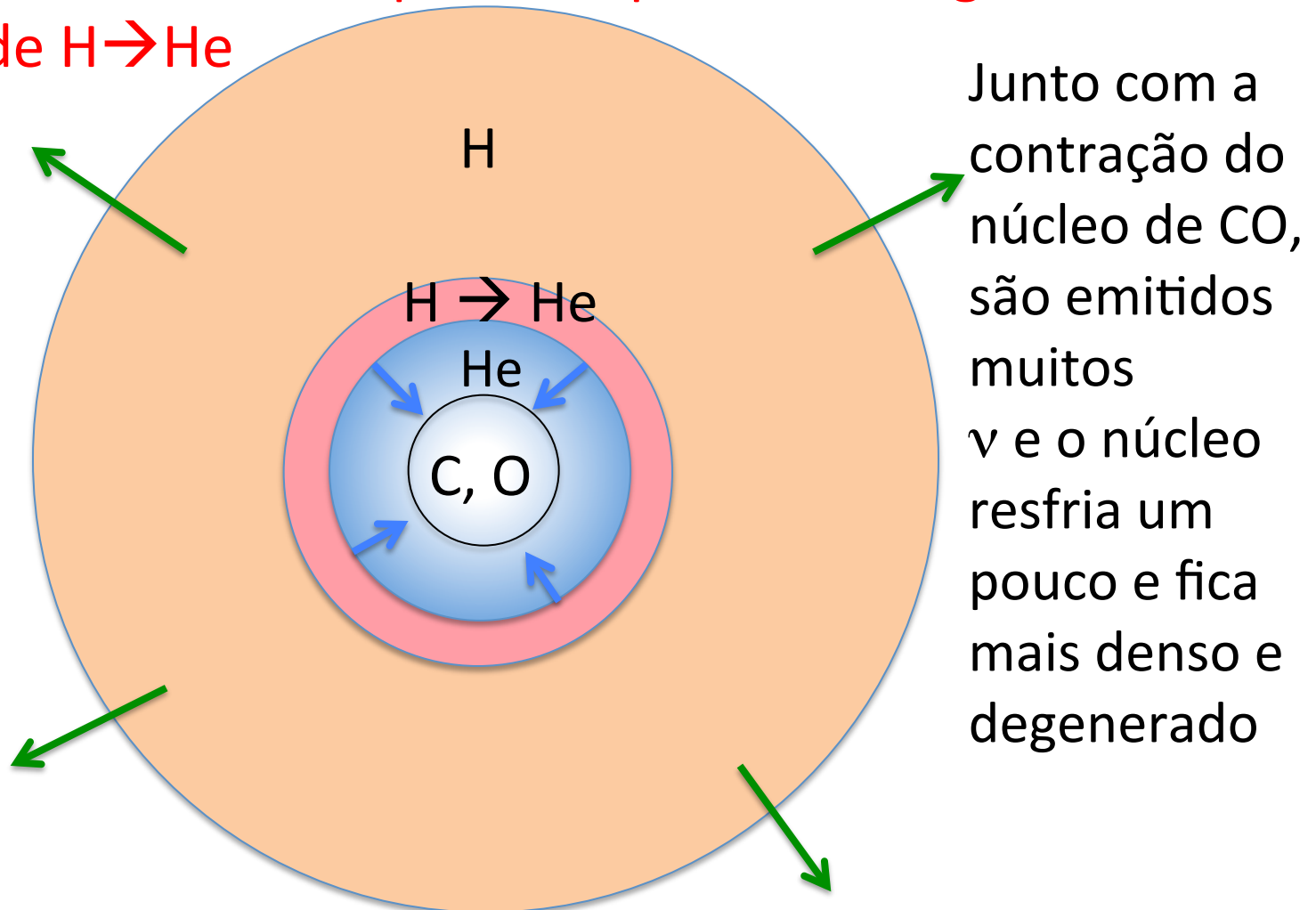
Peso molecular é muito alto → núcleo de He entra em contração e o envelope em expansão → temperatura diminui

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



Estrela no lado vermelho do ramo horizontal

Peso molecular alto $\rightarrow$ núcleo de He em contração e a casca de queima de $\text{He} \rightarrow \text{C}$ fica mais fina e luminosa. A diminuição da T no envelope em expansão desliga a camada de queima de $\text{H} \rightarrow \text{He}$



Durante a passagem pelo **ramo horizontal**,
estrelas podem desenvolver instabilidades

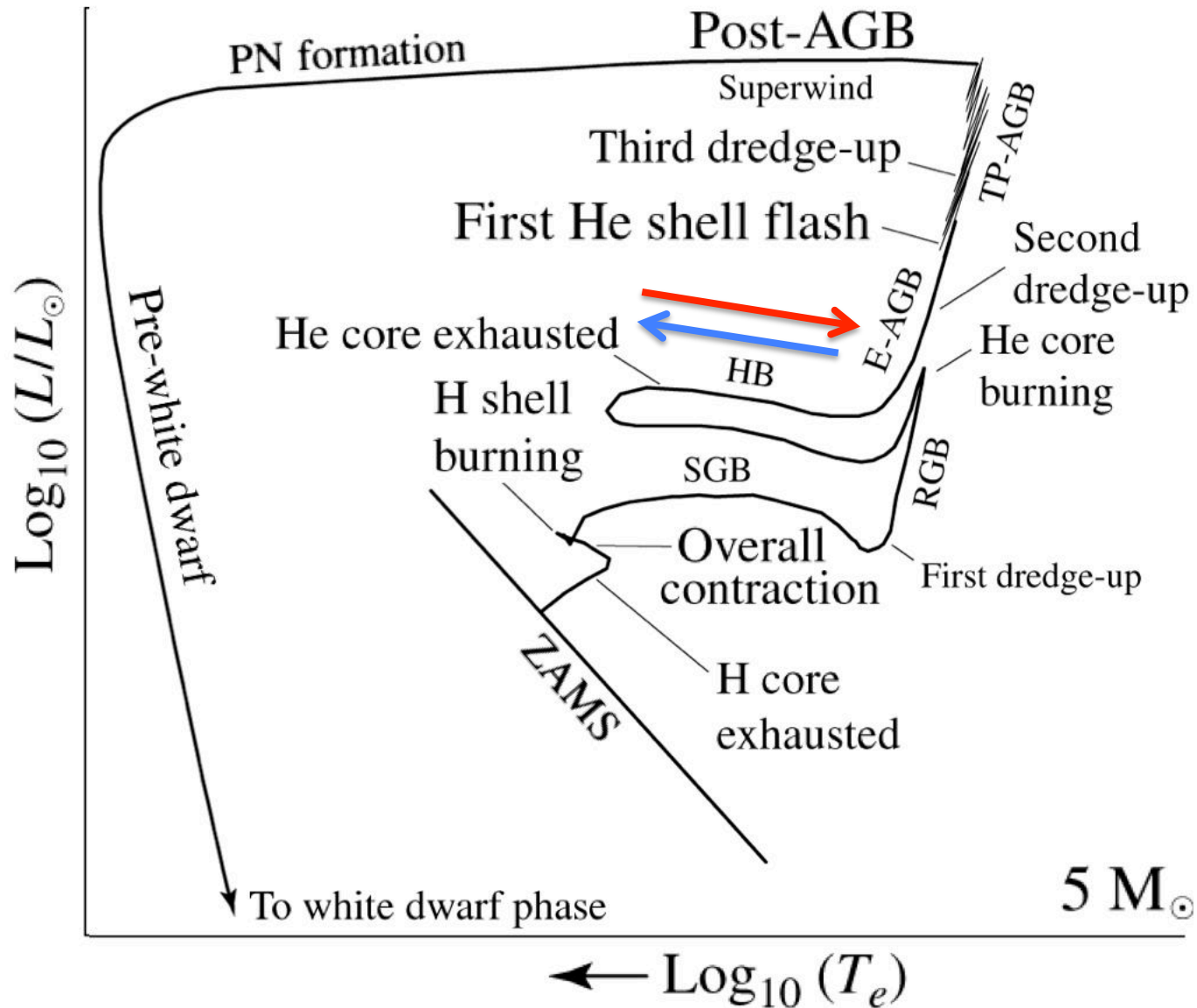
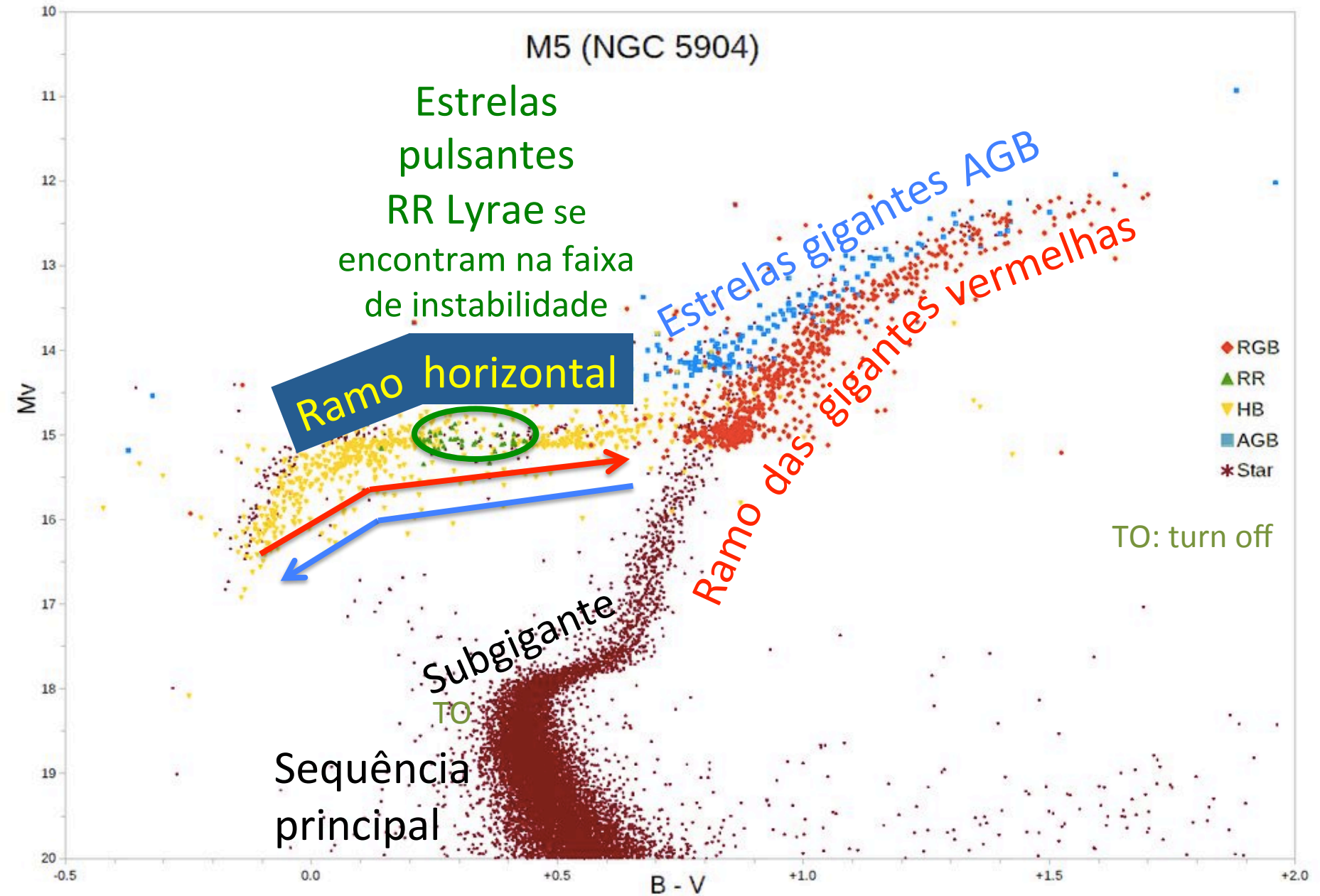
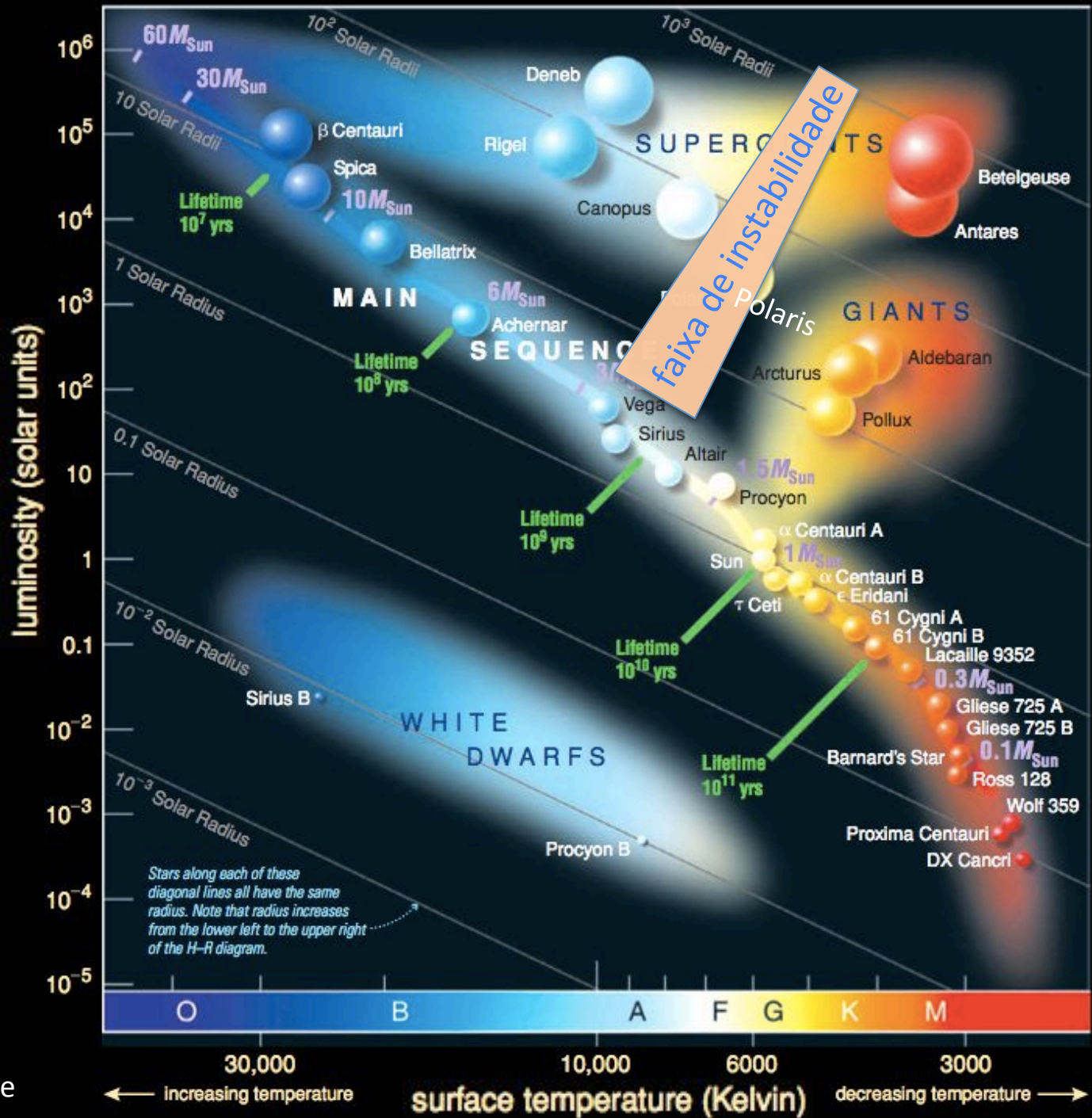
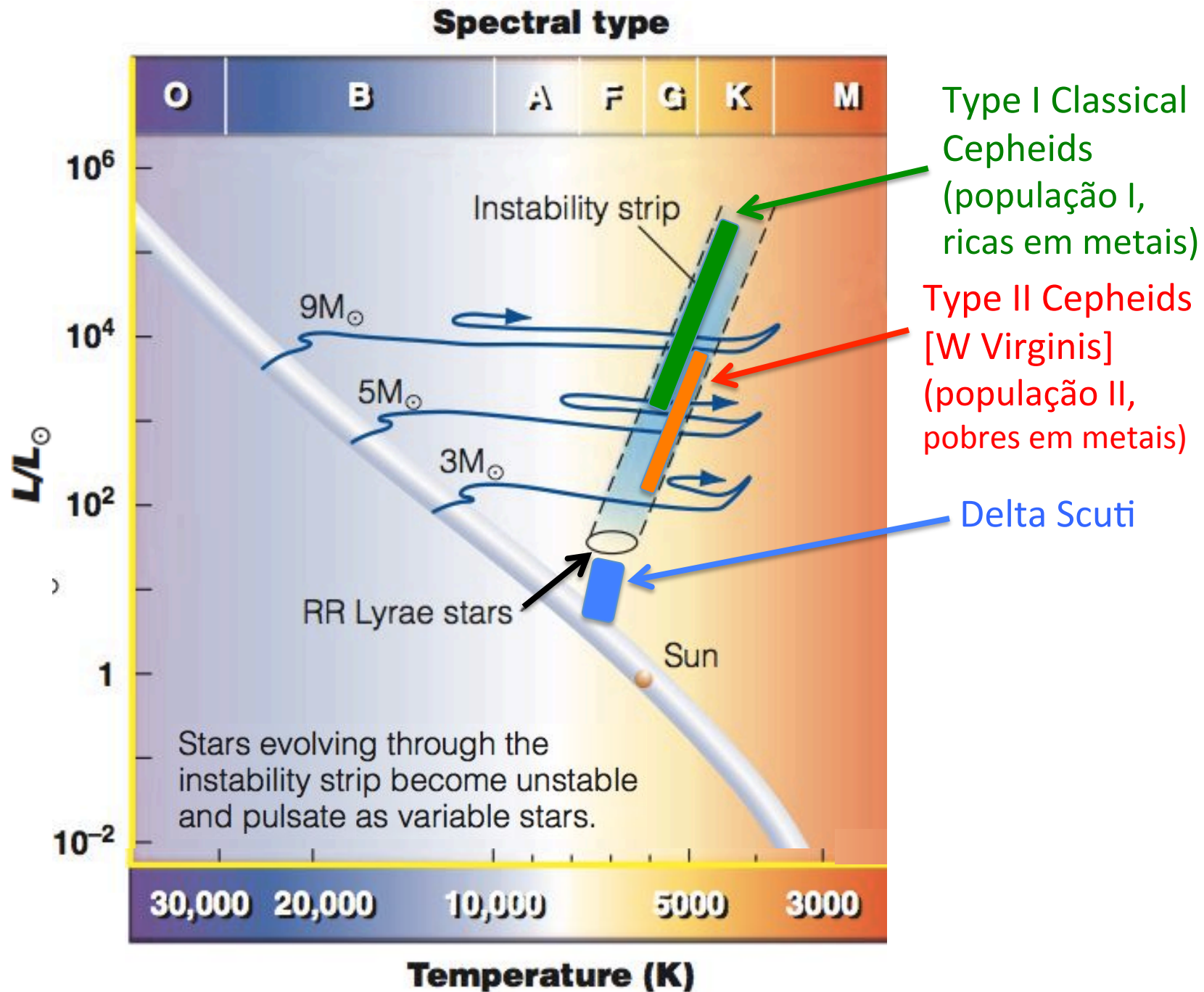


Diagrama HR do aglomerado globular M5







Curva de luz de δ Cephei

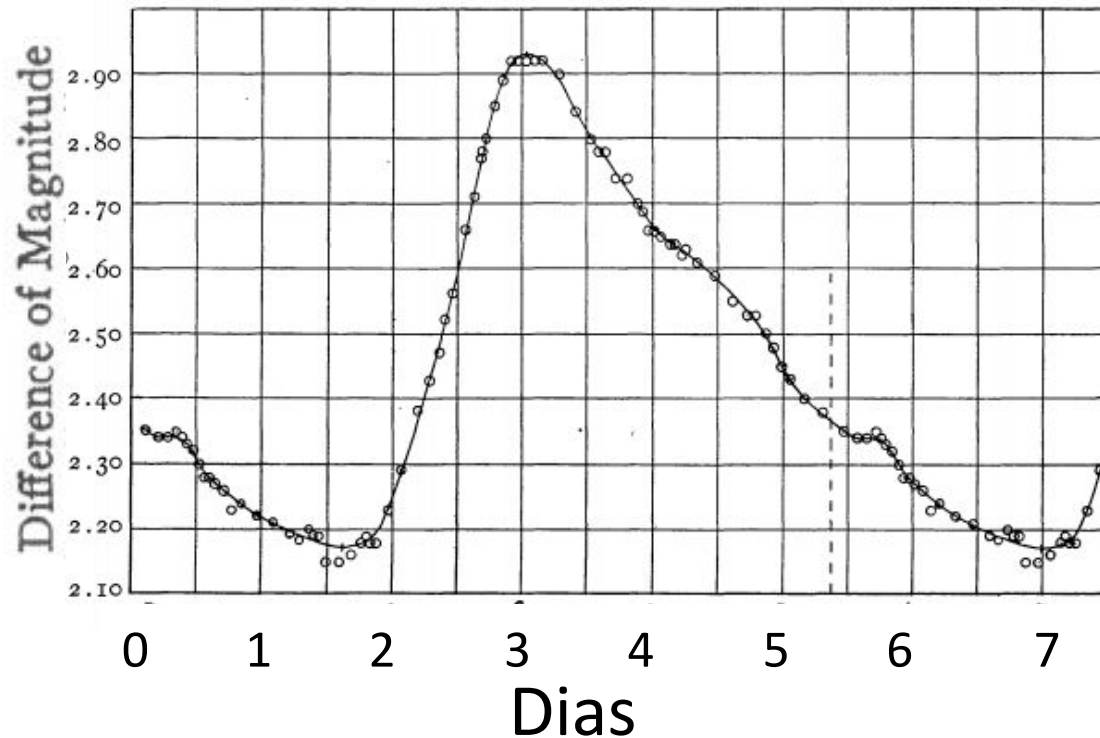


Fig. 14.2. The light curve of δ Cephei. Its pulsation period is 5.37 days.

Figure from Joel Stebbings (1908, ApJ, 27, 188)

From a window in Treasurer's House near this
tablet, the young deaf and dumb astronomer

JOHN GOODRICKE

1764 - 1786

who was elected a Fellow of the Royal Society
at the age of 21, observed the periodicity of
the star ALGOL and discovered the variation
of δ CEPHEI and other stars thus laying the
foundation of modern measurement of the Universe.





Henrietta
Leavitt
Relação brilho –
luminosidade
em 1912,
usando cefeídas
da Pequena
Nuvem de
Magalhães

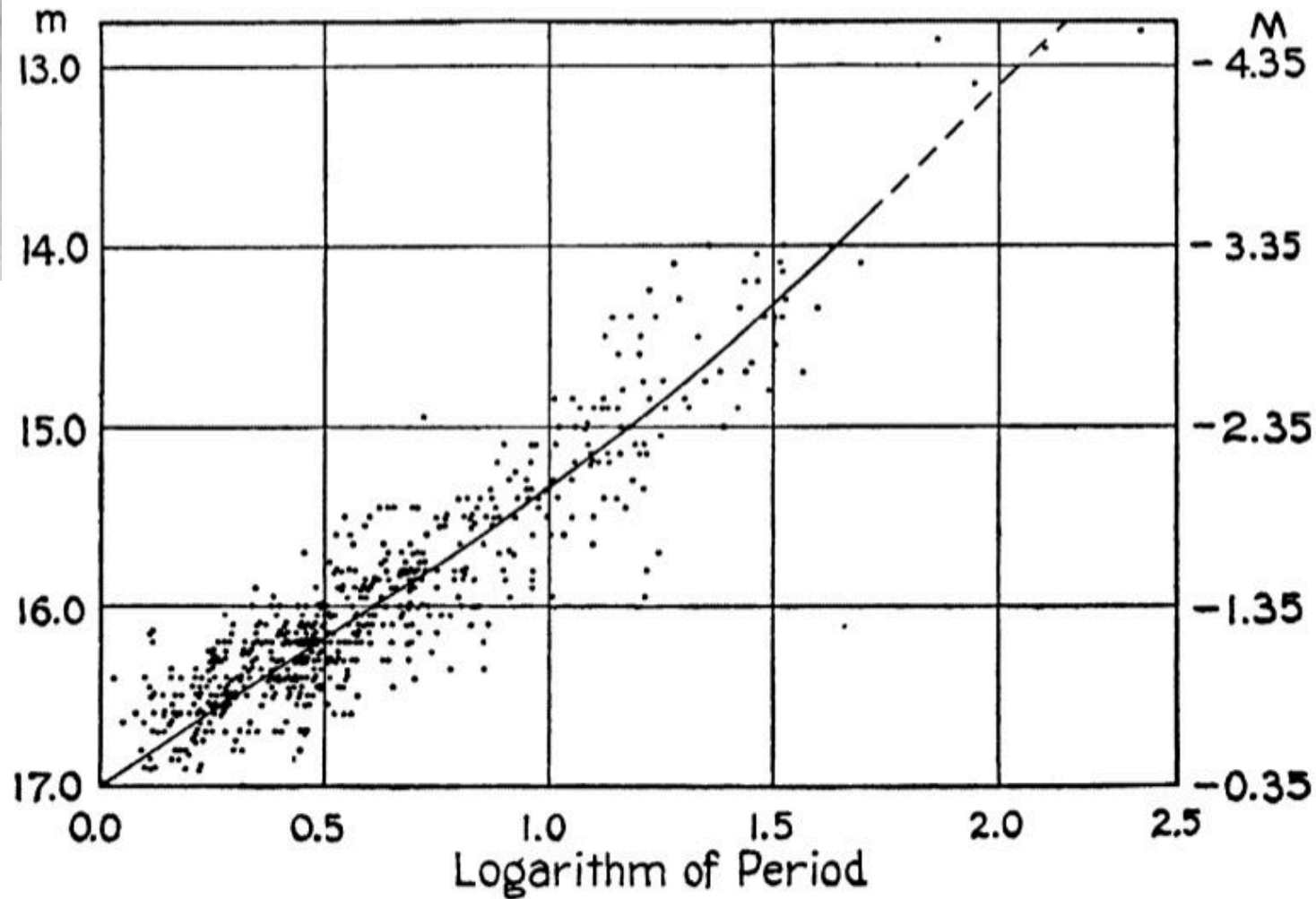


FIGURE 14.4 Classical Cepheids in the Small Magellanic Cloud, with the period in units of days. (Figure from Shapley, *Galaxies*, Harvard University Press, Cambridge, MA, 1961.)

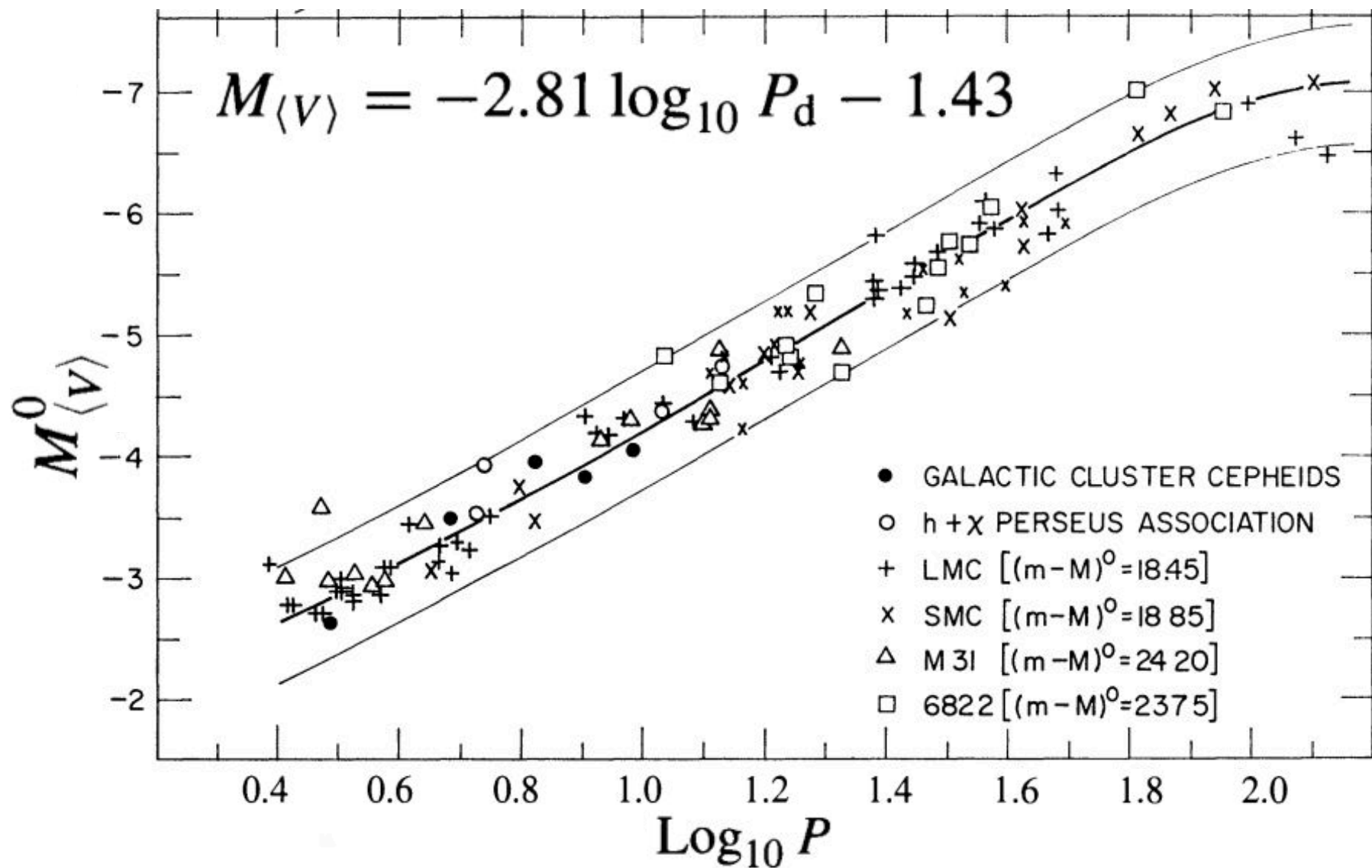


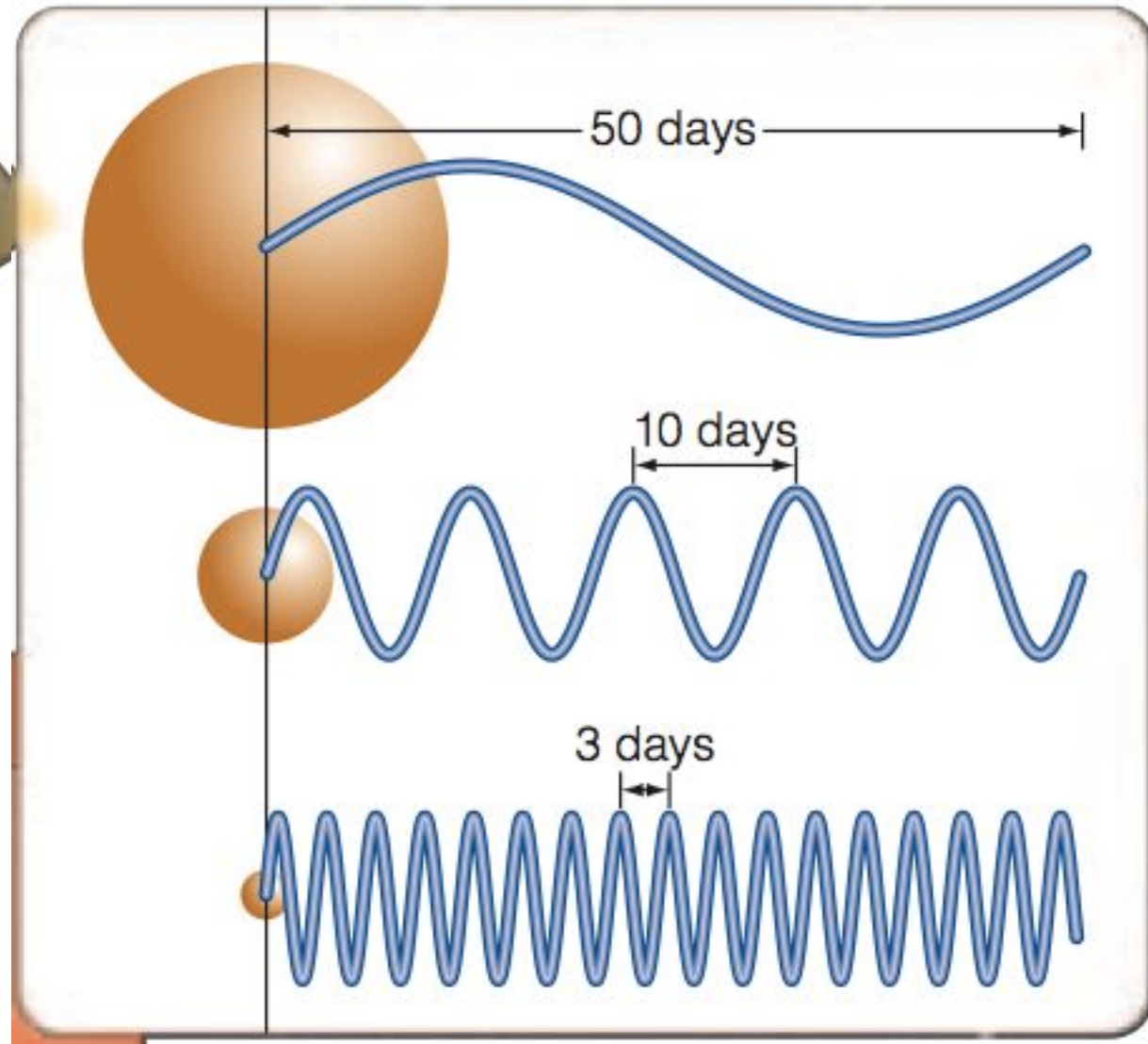
FIGURE 14.5 The period–luminosity relation for classical Cepheids. (Figure adapted from Sandage and Tammann, *Ap. J.*, 151, 531, 1968.)

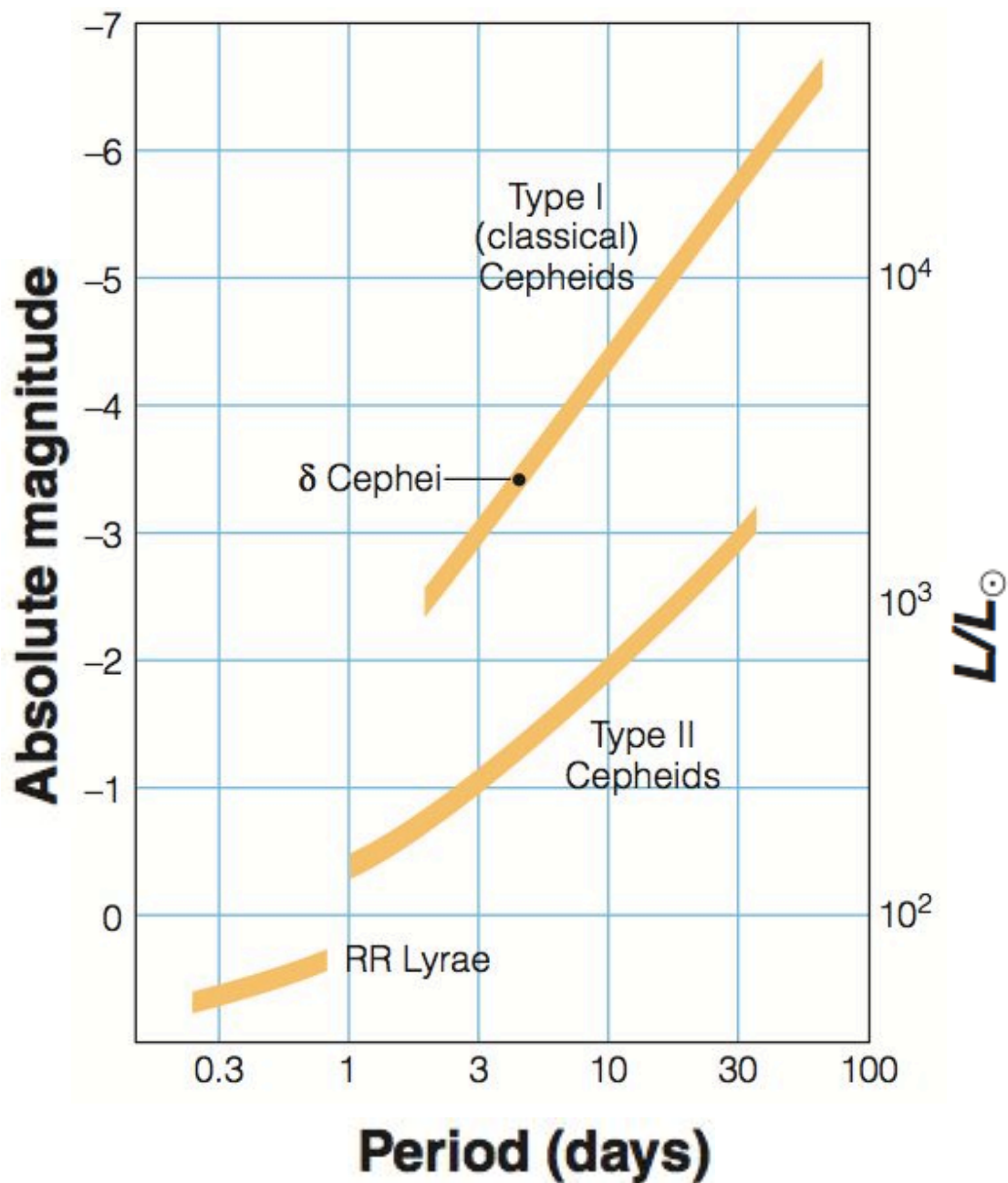
More massive stars are more luminous and larger, so they pulsate slower.

Período de
oscilação: (14.6)

$$\Pi \approx \sqrt{\frac{3\pi}{2\gamma G\rho}}$$

$$\gamma \equiv \frac{C_P}{C_V}$$





Período de oscilação: $\Pi \approx \sqrt{\frac{3\pi}{2\gamma G\rho}}$
(14.6)

$$\gamma \equiv \frac{C_P}{C_V}$$

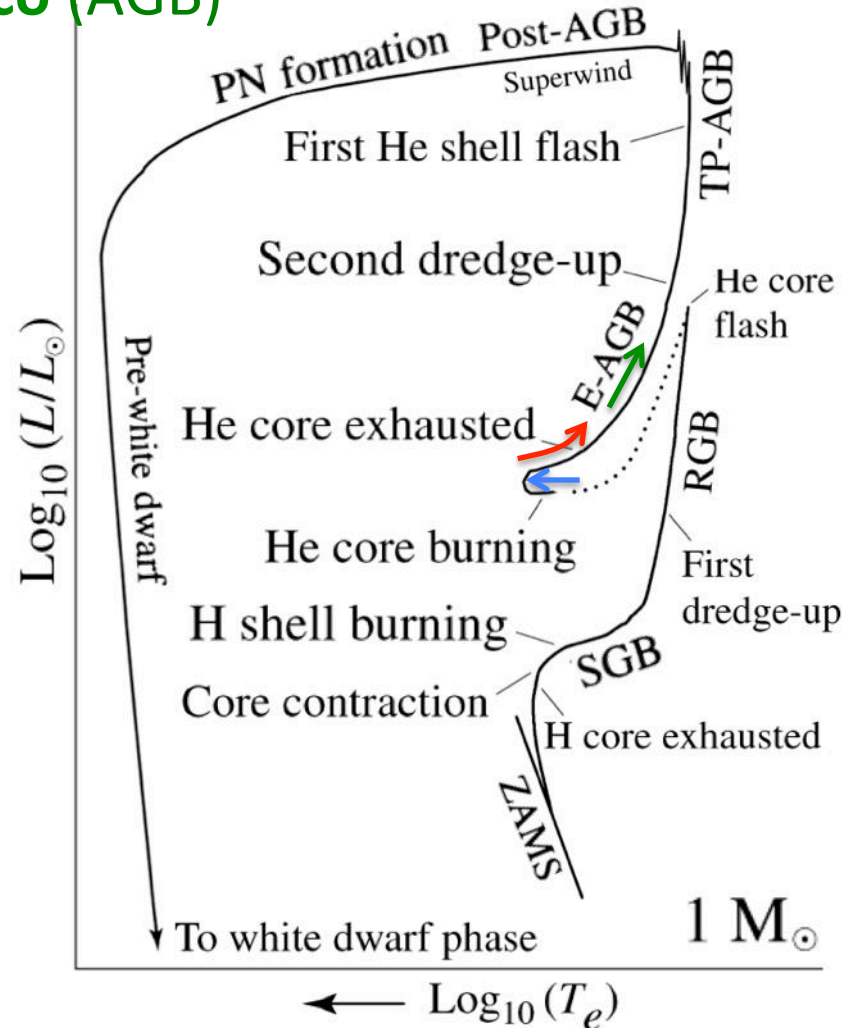
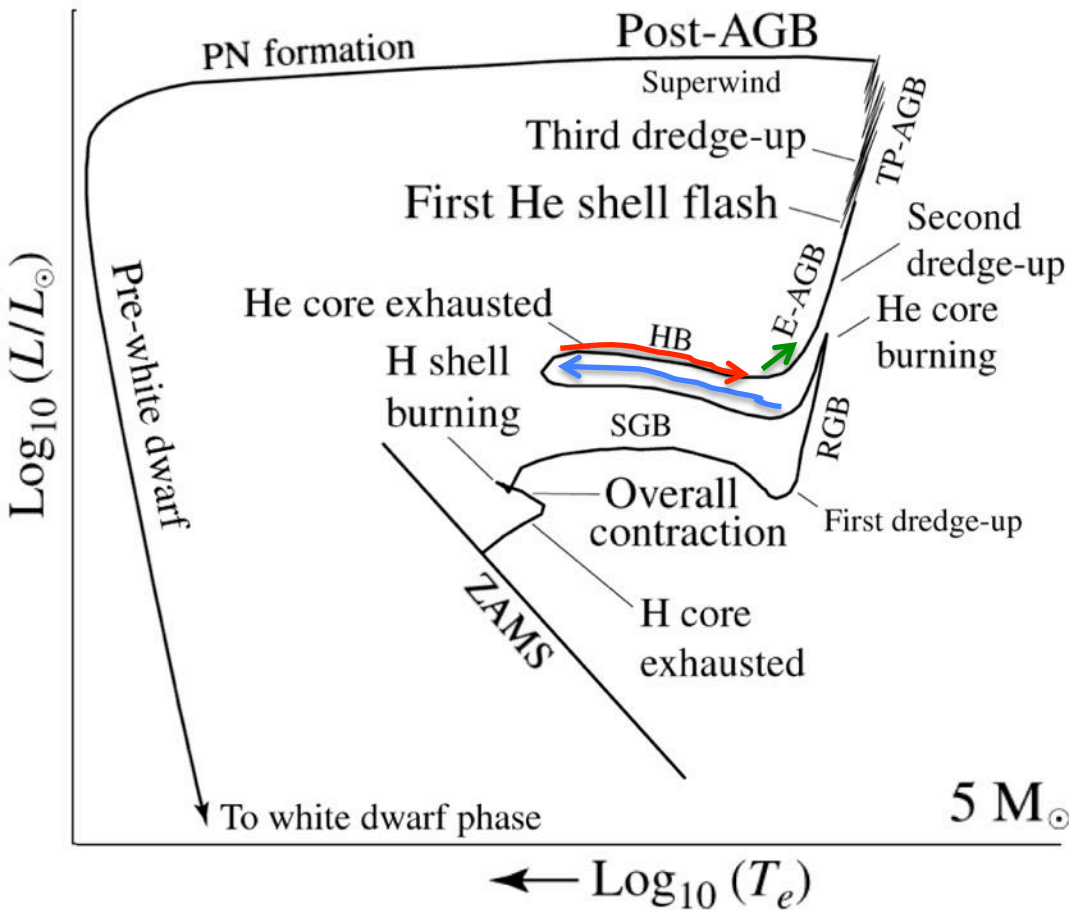
No lado azul “sequência principal” de queima do He,
depois μ muito alto $\rightarrow$ núcleo He em contração.

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

$\rightarrow$ Expansão do envelope e percurso para o vermelho

Estrela sobe **ramo gigante assintótico (AGB)**

e temos um “*second dredge-up*”



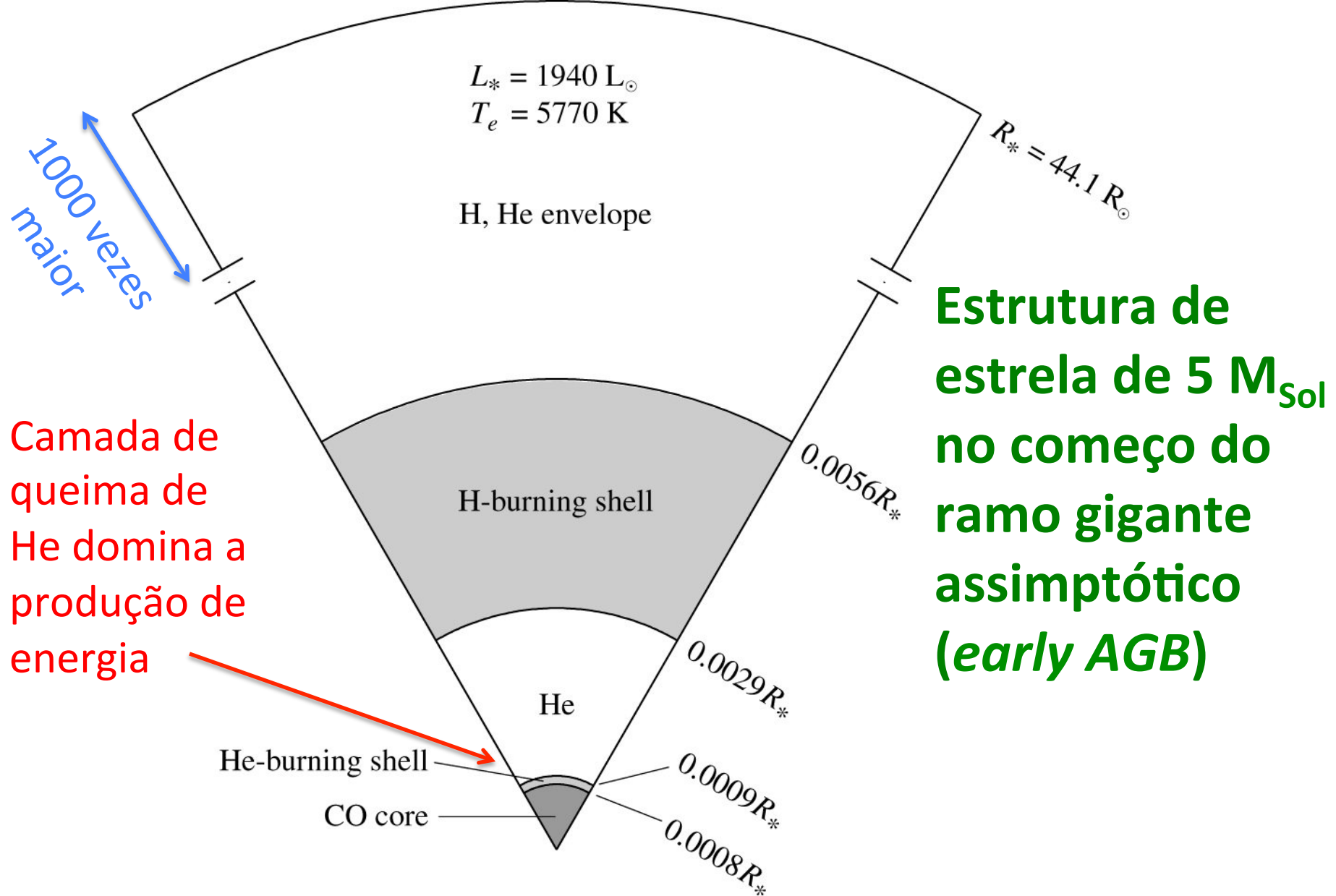
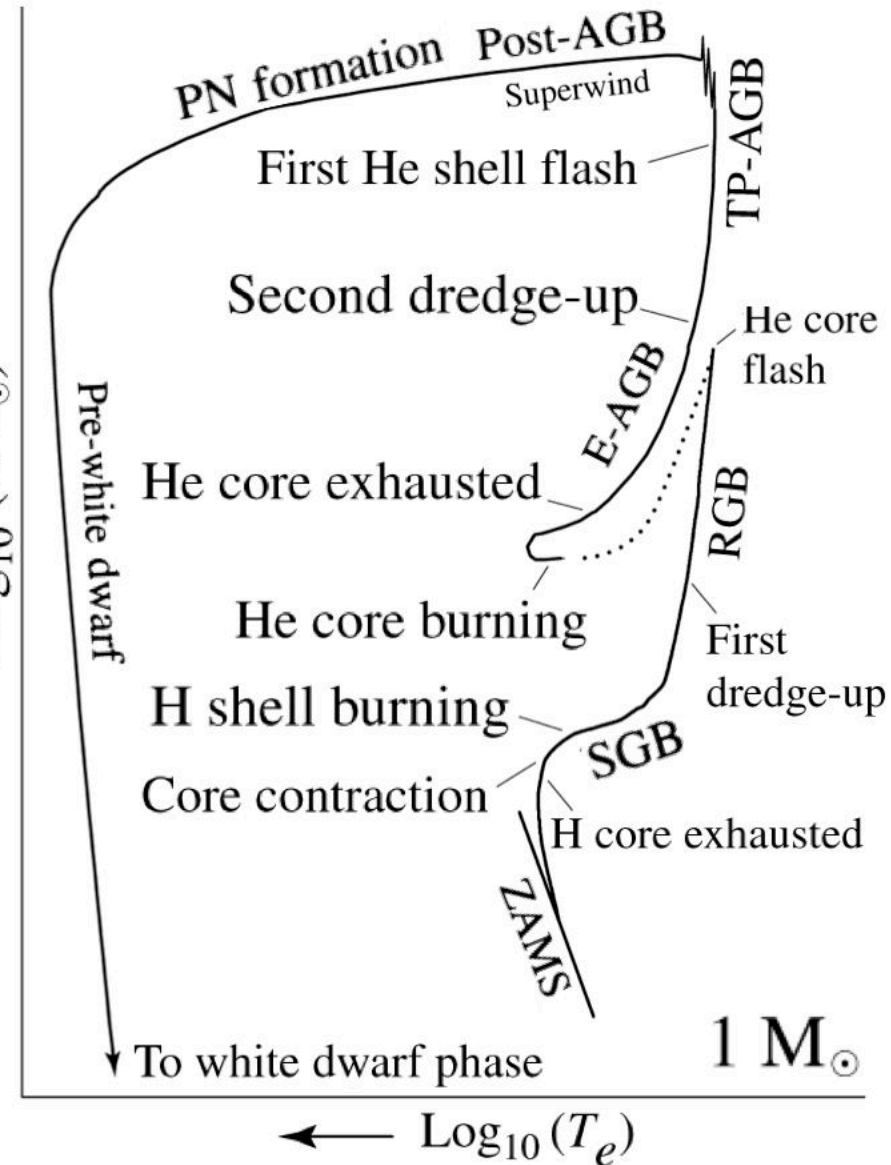
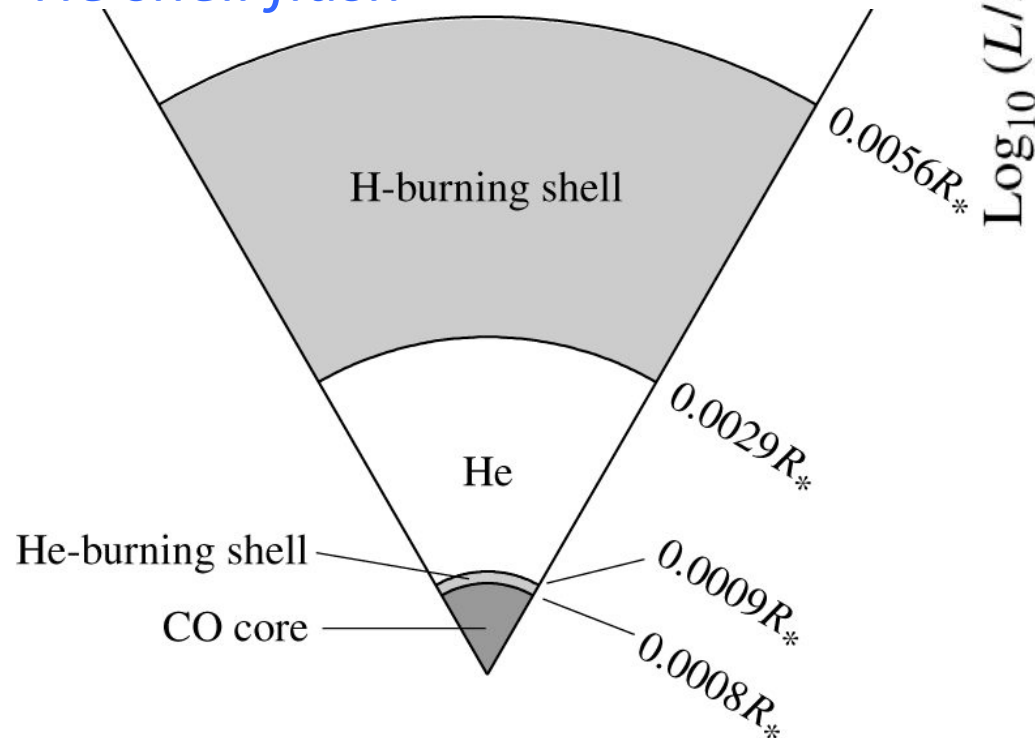
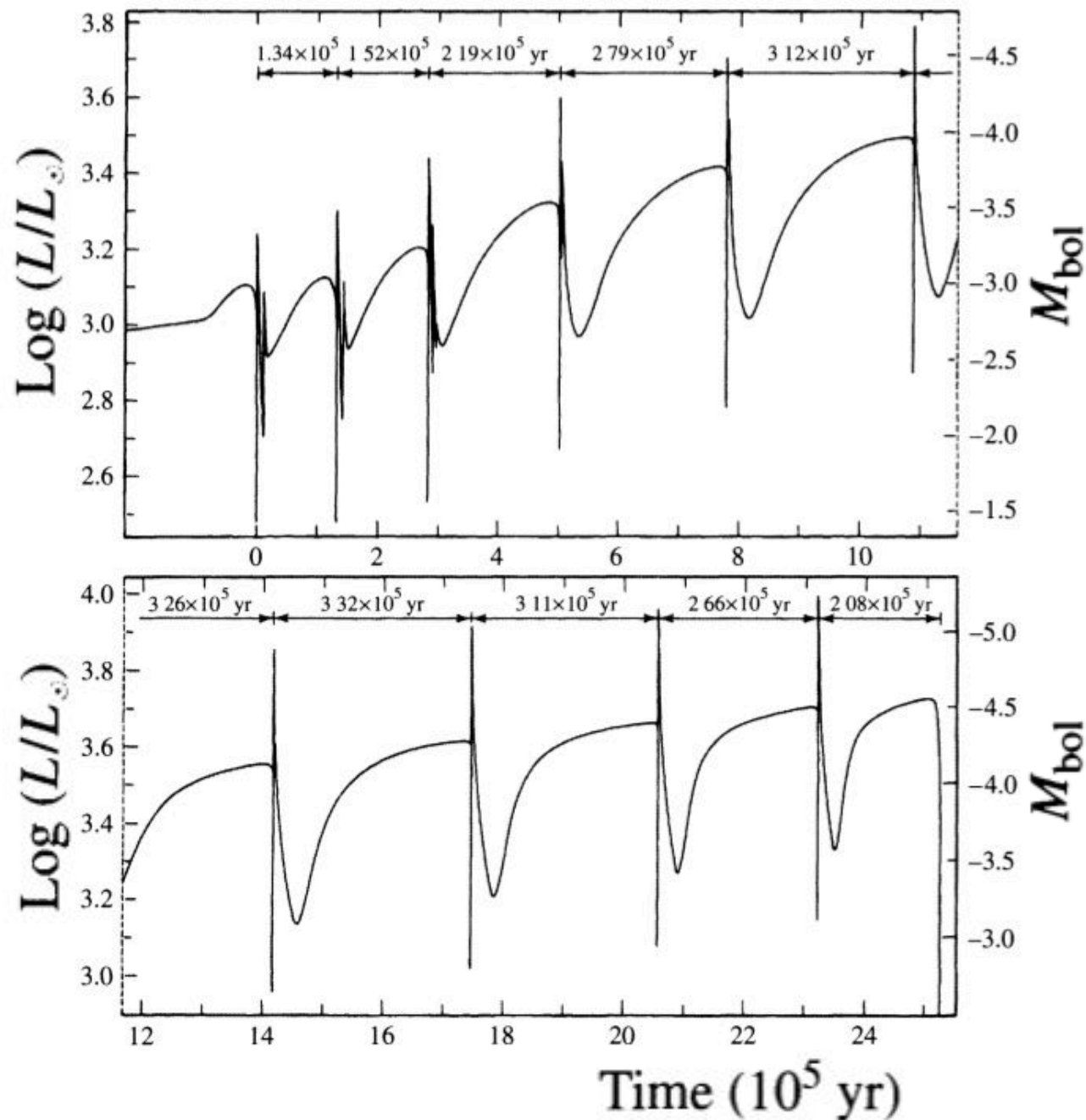


FIGURE 13.8 A $5 M_{\odot}$ star on the early asymptotic giant branch with a carbon–oxygen core and hydrogen- and helium-burning shells. Note that relative to the surface radius, the scale of the shells and core has been increased by a factor of 100 for clarity. (Data from Iben, *Ap. J.*, 143, 483, 1966.)

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*

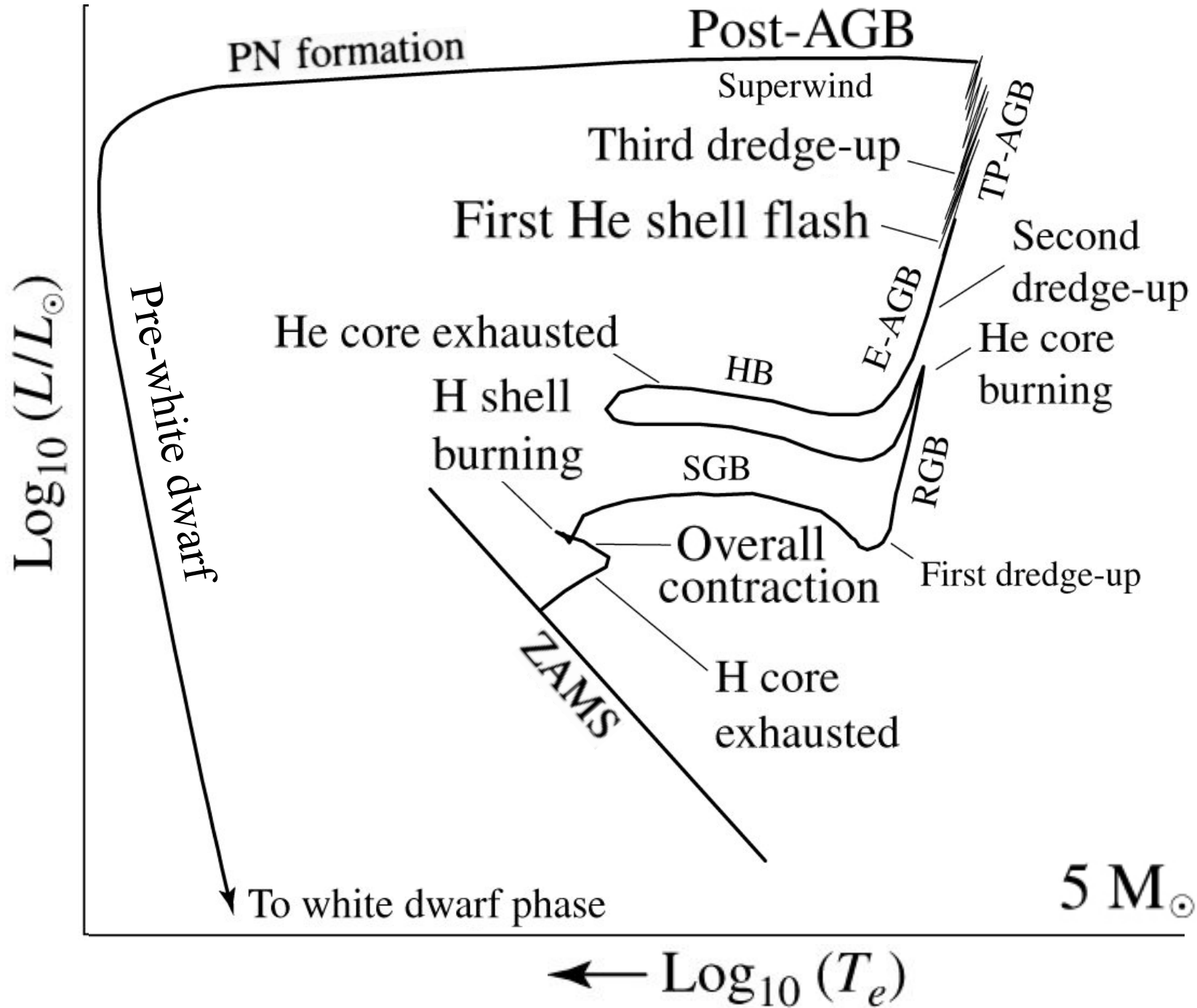
Pulsos térmicos no AGB: The Thermal-Pulse AGB

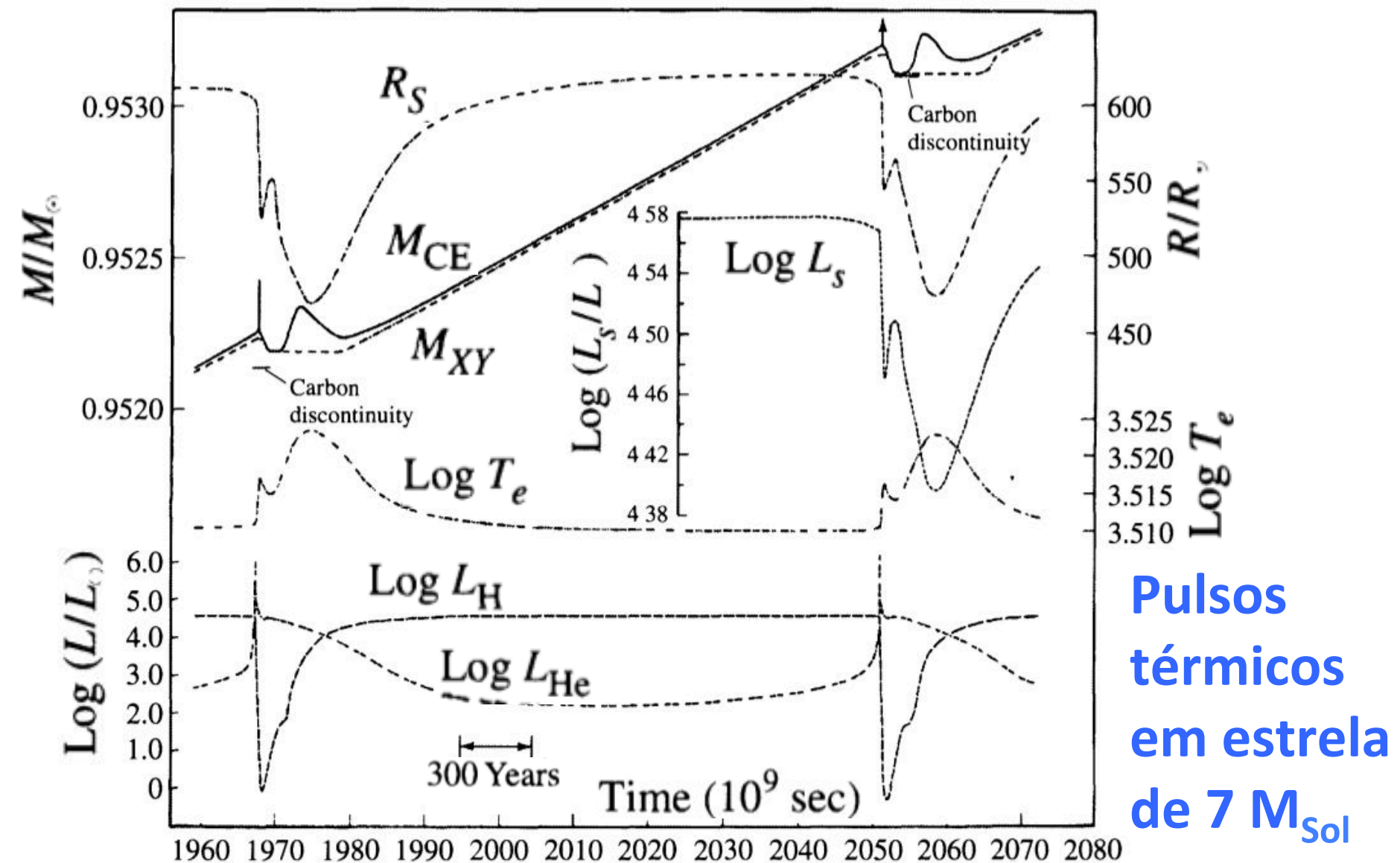




Pulsos térmicos:
 Da ordem de
 100 mil anos
 para estrelas de
 $\sim 1 M_{\text{Sol}}$
 e de 10^3 anos
 para $\sim 5 M_{\text{Sol}}$

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.)

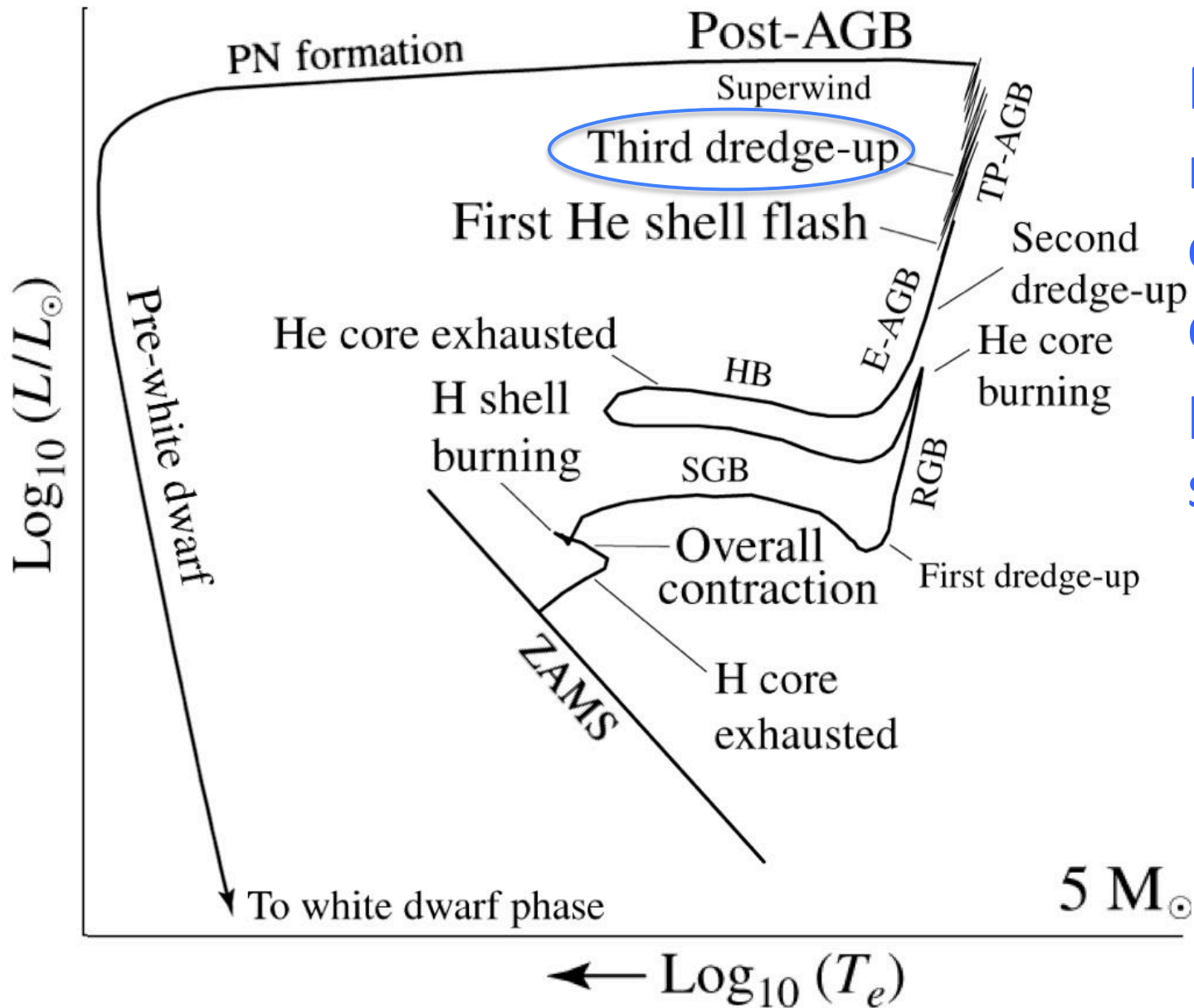




**Pulsos
térmicos
em estrela
de $7 M_{\text{Sol}}$**

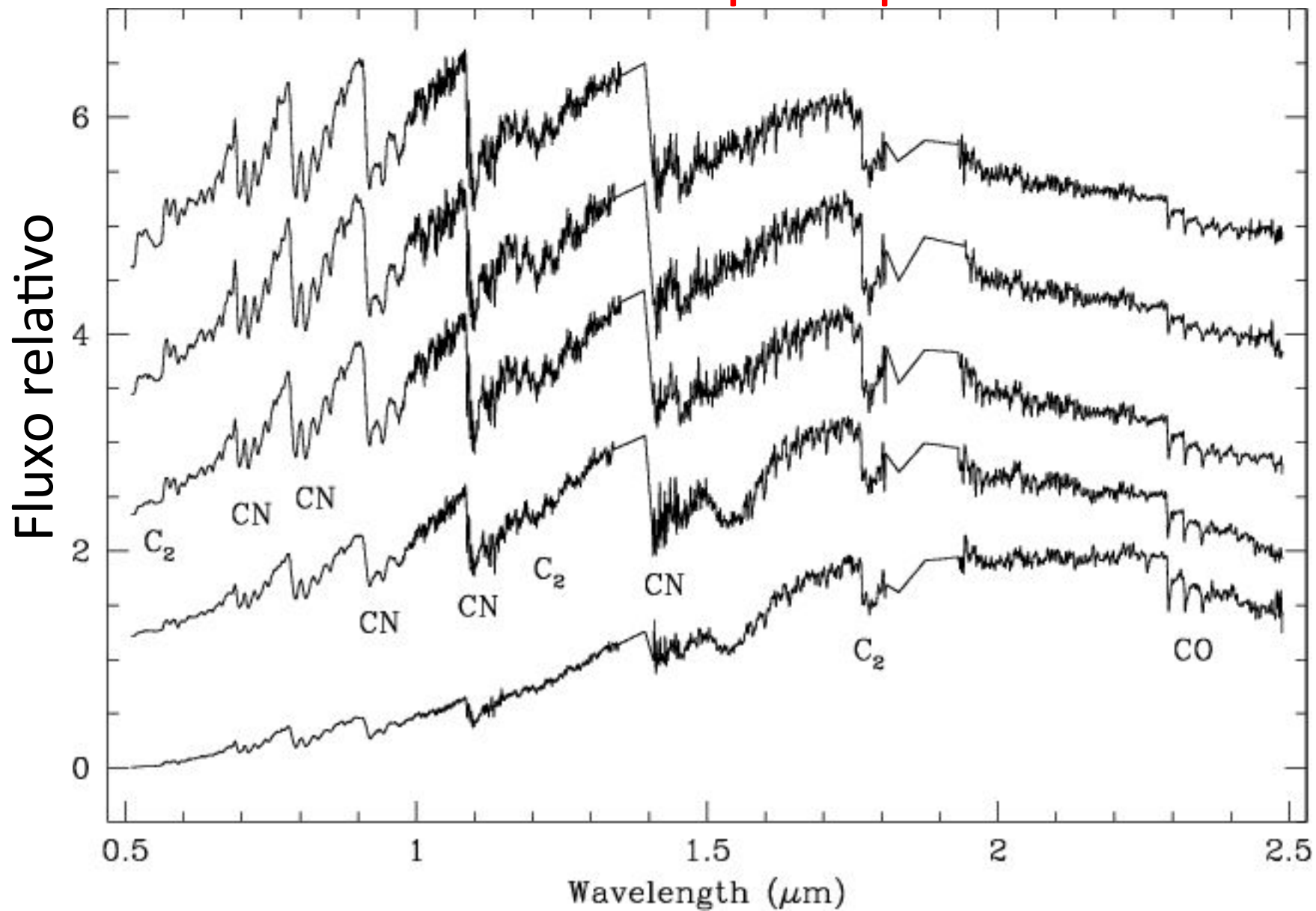
FIGURE 13.10 Time-dependent changes in the properties of a $7 M_{\odot}$ AGB star produced by helium shell flashes on the TP-AGB. The quantities shown are the surface radius (R_S), the interior mass fractions of the base of the convective envelope (M_{CE}) and the hydrogen–helium discontinuity (M_{XY}), 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*



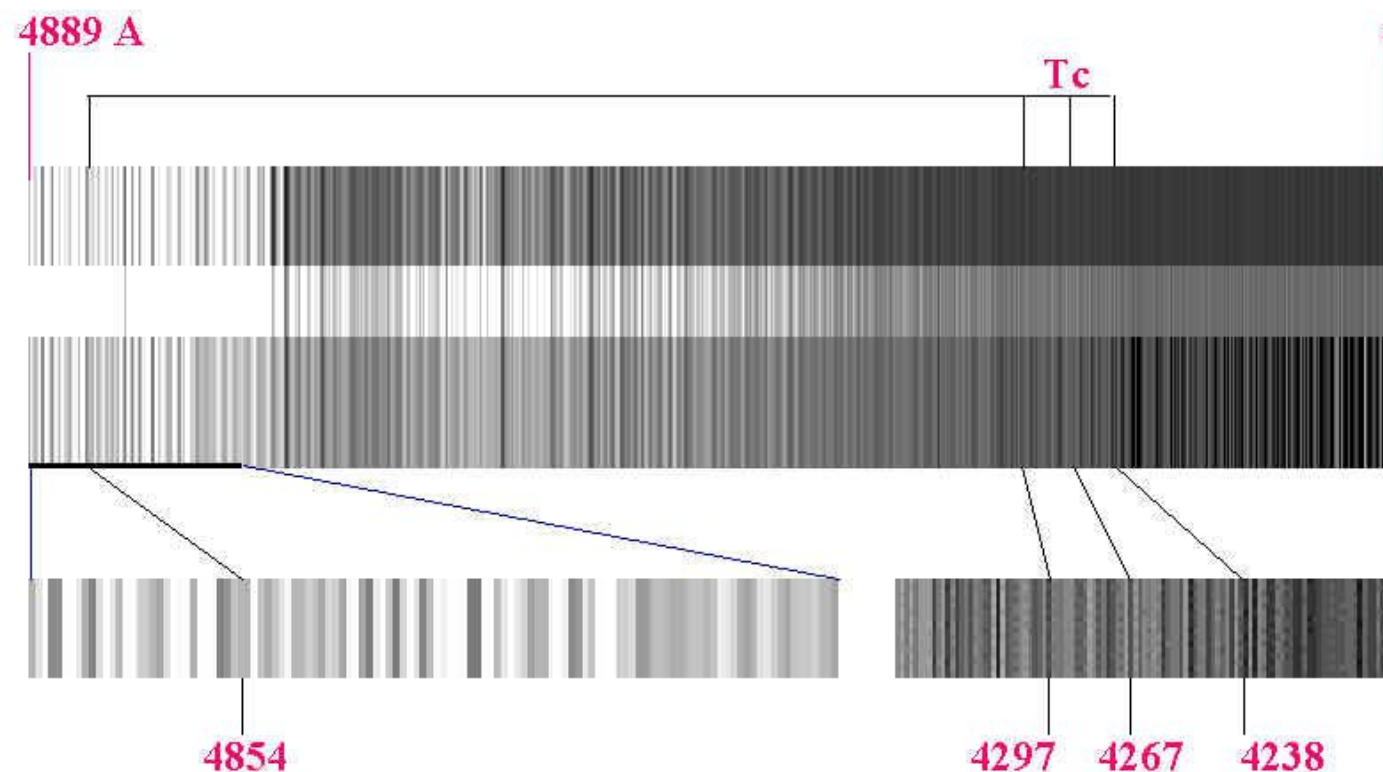
Material
rico em
carbono é
dragado
para a
superfície

Carbon stars: tipo espectral C



Identification of Technetium in 19 Piscium

C5II star, 4.95 magnitude



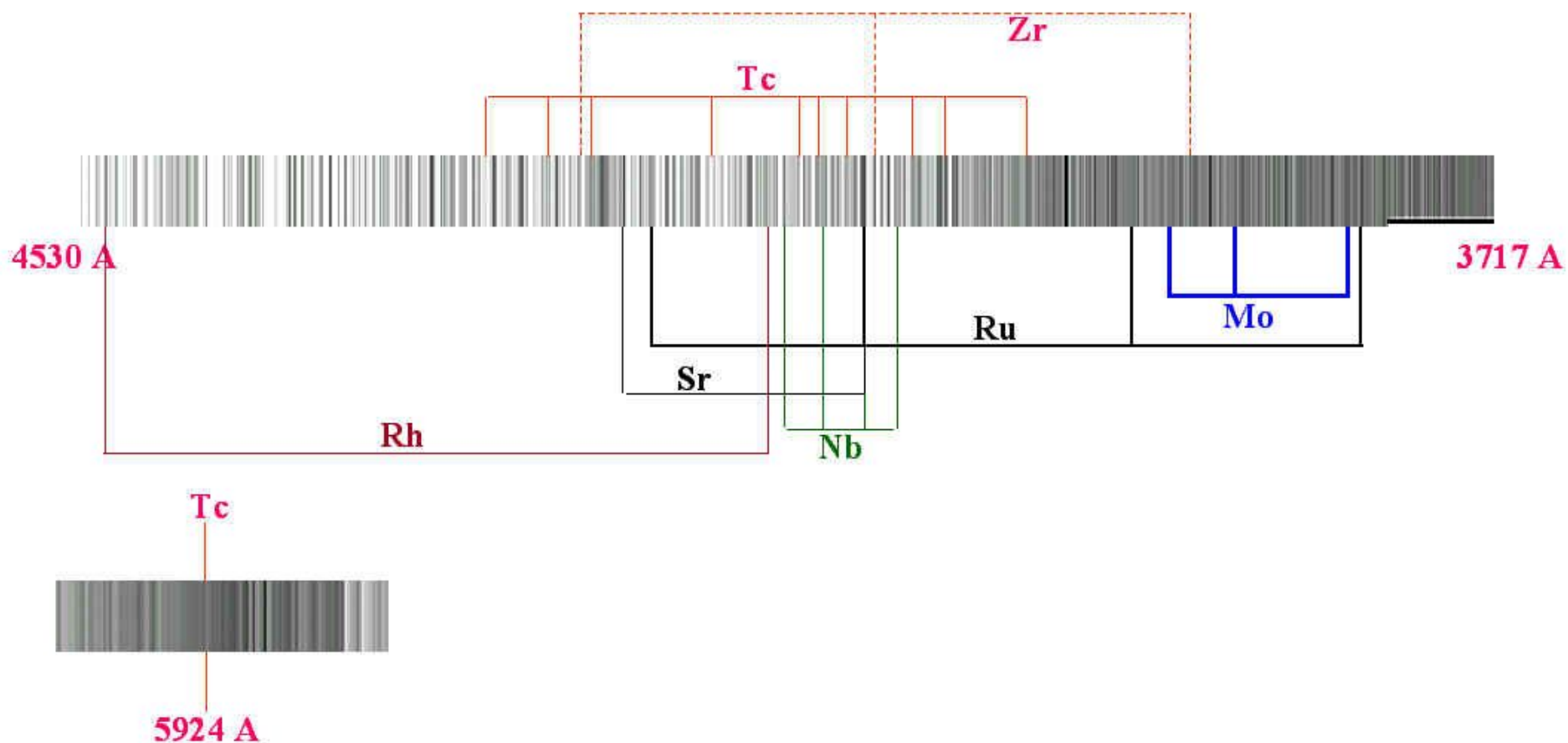
4073 A

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”

⁴³Tc : no stable isotopes
^{Tc}⁹⁷ $t_{1/2} = 2.6 \times 10^6$ years
^{Tc}⁹⁸ $t_{1/2} = 1.5 \times 10^6$ years
^{Tc}⁹⁹ $t_{1/2} = 2.1 \times 10^5$ years
 + various short lived isotopes

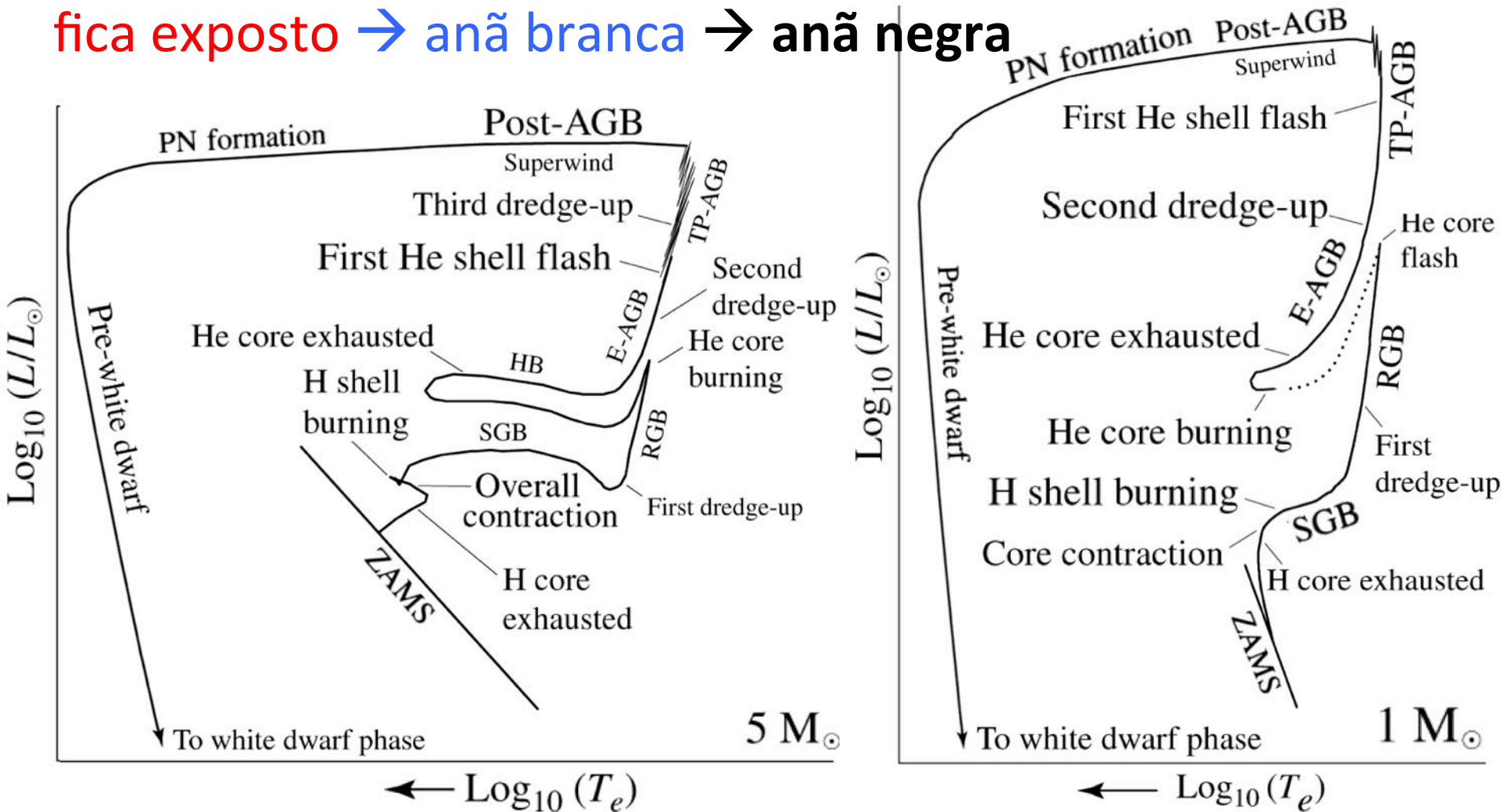
Produção de outros elementos pesados por captura de nêutrons (processo-s [slow]) em estrelas AGB

Presence of Neutron Capture Heavy Metals near Technetium in RS Cnc



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**



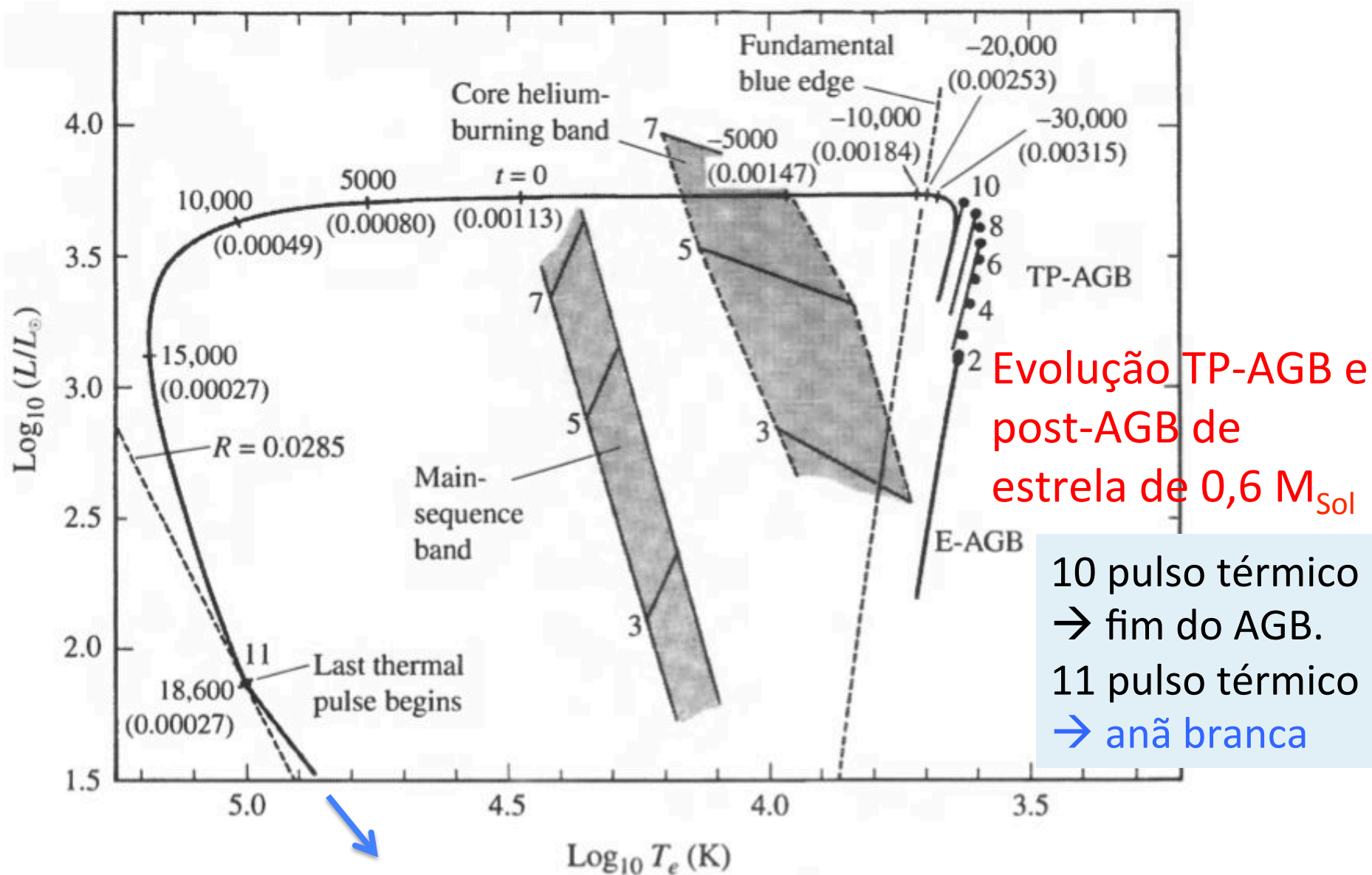


FIGURE 13.12 The AGB and post-AGB evolution of a $0.6 M_{\odot}$ star undergoing mass loss. The initial composition of the model is $X = 0.749$, $Y = 0.25$, and $Z = 0.001$. The main-sequence and horizontal branches of 3, 5, and 7 $M_{\odot}$ stars are shown for reference. Details of the figure are discussed 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 ($Z \lll 0,02$). Estrelas do Halo da Galáxia. **Aglomerados globulares.**
- População I: estrelas mais jovens e com metalicidade próxima da solar ($Z \sim 0,02$). Estrelas do disco da Galáxia. **Aglomerados abertos.**

Aglomerados globulares e abertos

M80



Plêiades



Turnoff,
ponto onde
as estrelas
deixam a
sequência
principal

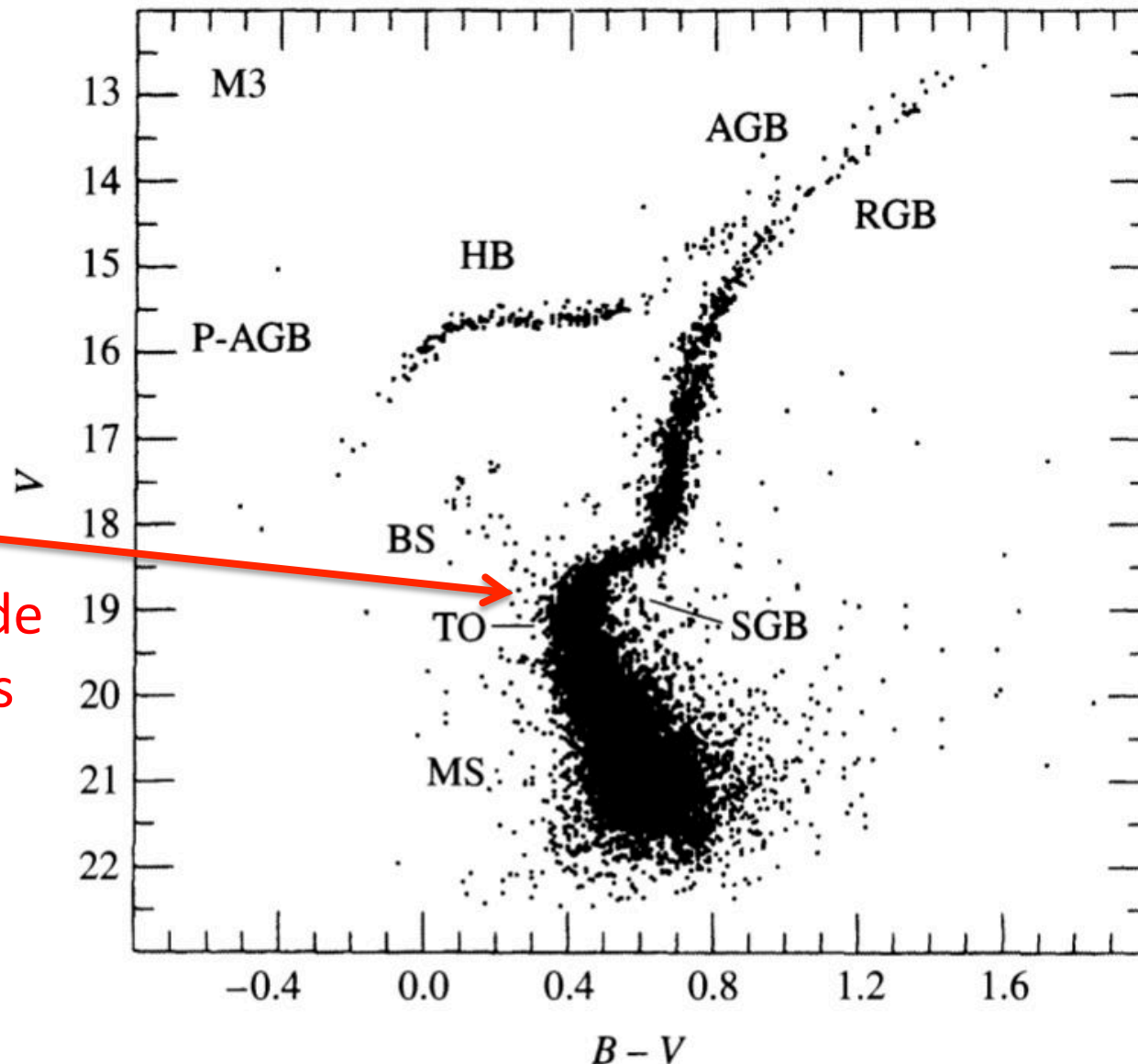


FIGURE 13.17 A color-magnitude diagram for M3, an old globular cluster. The major phases of stellar evolution are indicated: main sequence (MS); blue stragglers (BS); the main-sequence turn-off point (TO); the subgiant branch of hydrogen shell burning (SGB); the red giant branch along the Hayashi track, 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 em aglomerados abertos

A idade por ser determinada pela posição do **Turnoff**, ou seja o ponto onde as estrelas deixam a sequência principal

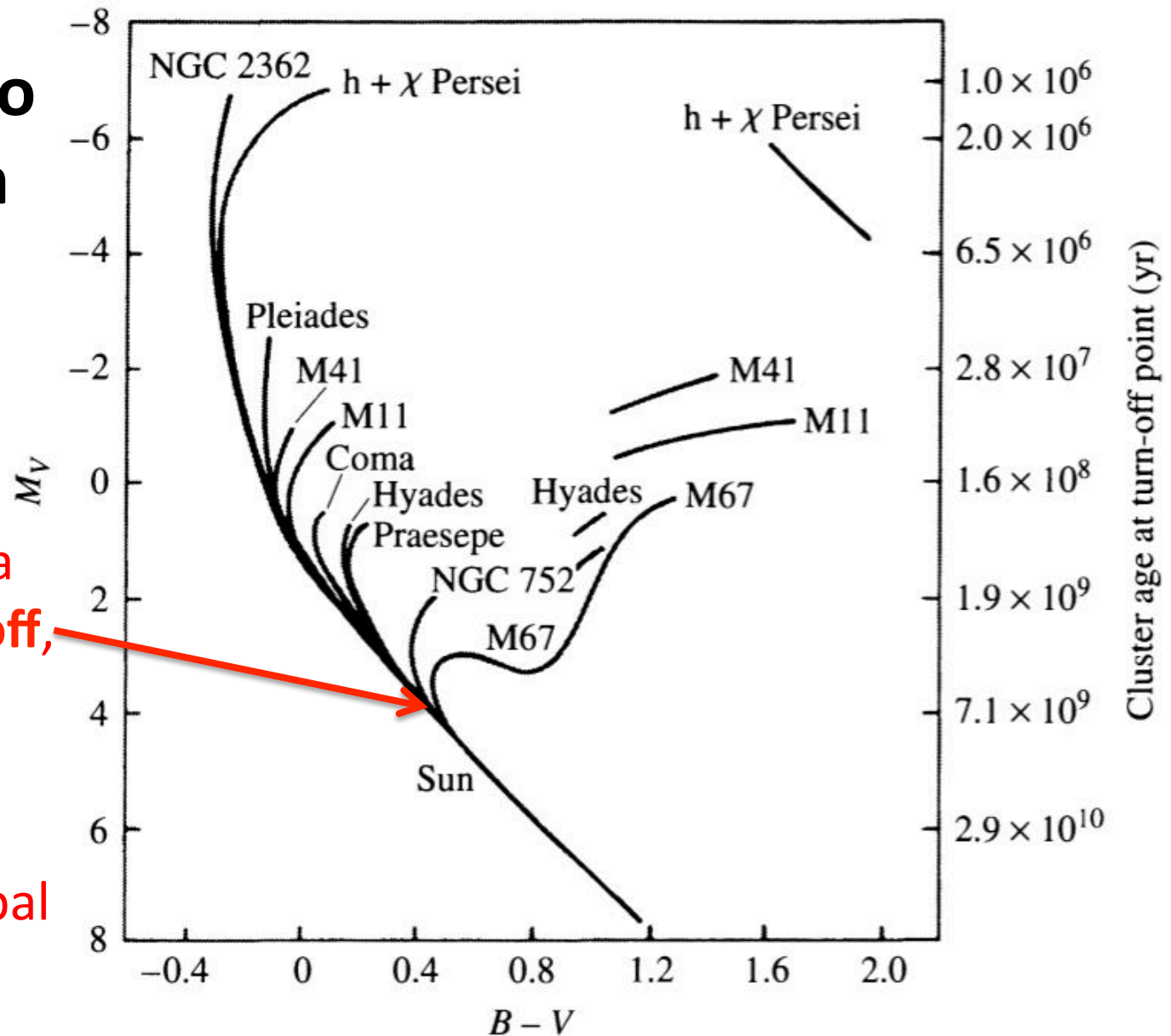
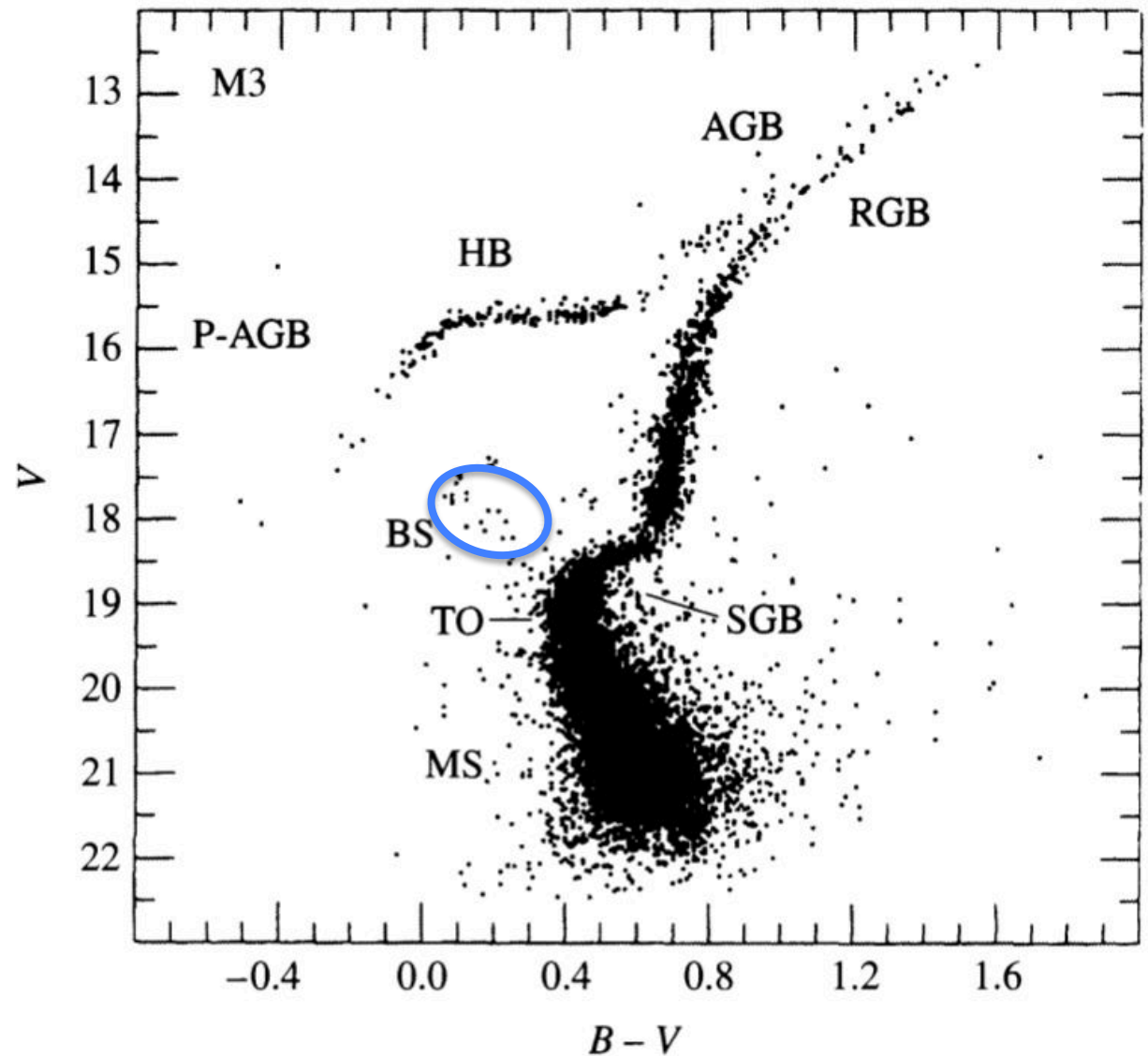


FIGURE 13.19 A composite color-magnitude diagram for a set of Population I galactic clusters. The absolute visual magnitude is indicated on the left-hand vertical axis, and the age of the cluster, based on the location of its turn-off point, is labeled on the right-hand side. (Figure adapted from an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



Blue Stragglers

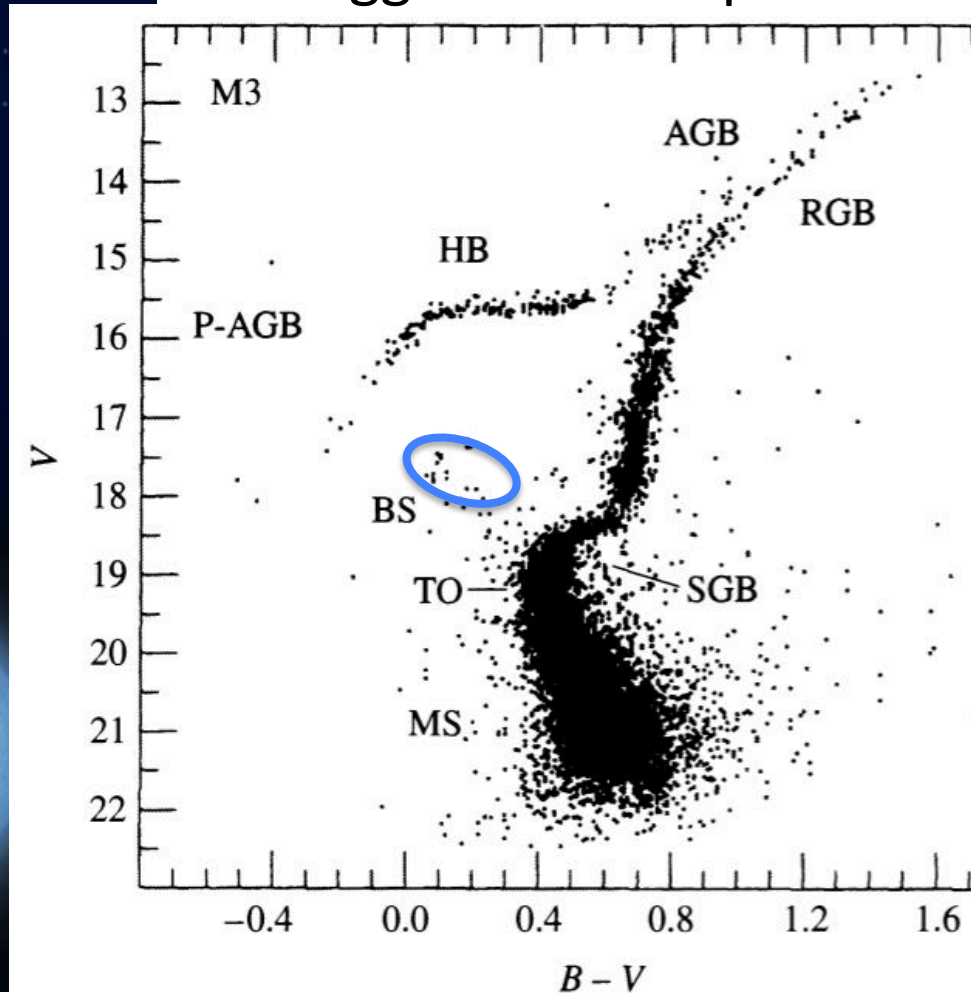
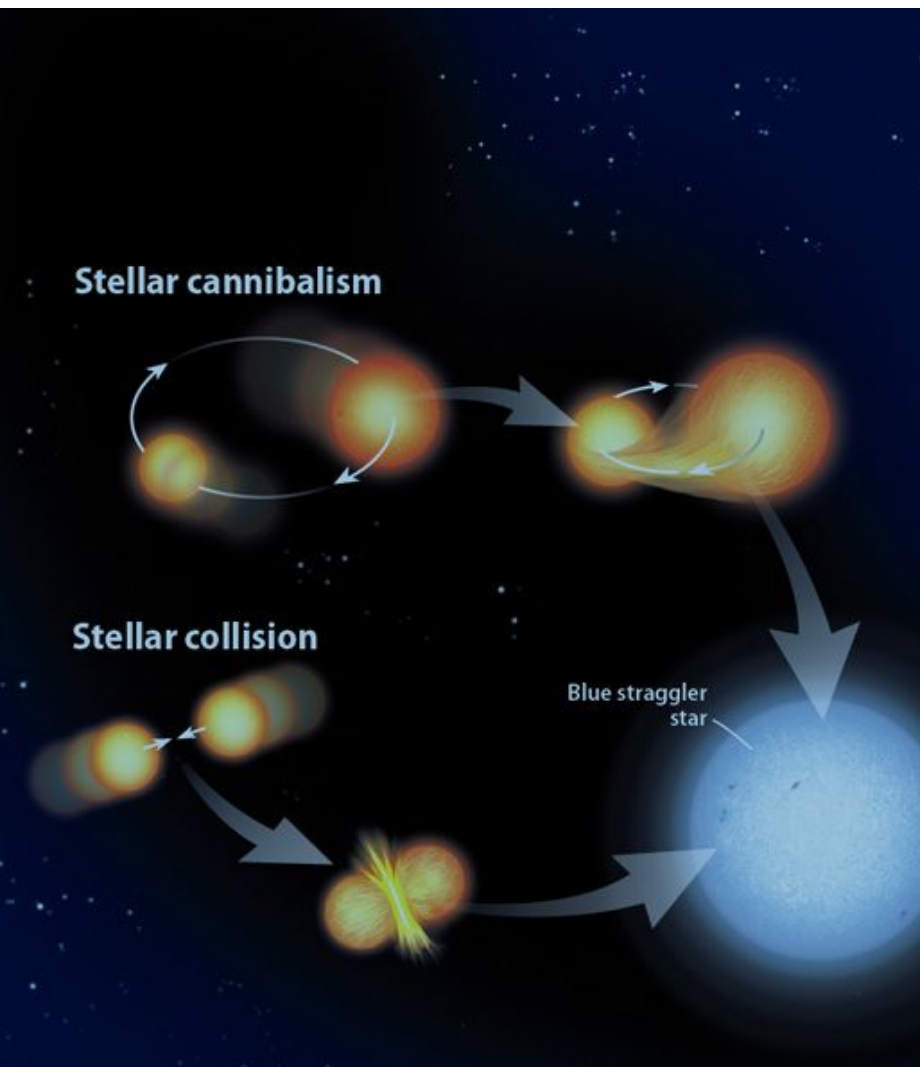
It should be pointed out that a group of stars, known as **blue stragglers**, can be found above the turn-off point of M3. Although our understanding of these stars is incomplete, it appears that their tardiness in leaving the main sequence is due to some unusual aspect of their evolution. The most likely 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?



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^{★,★★}

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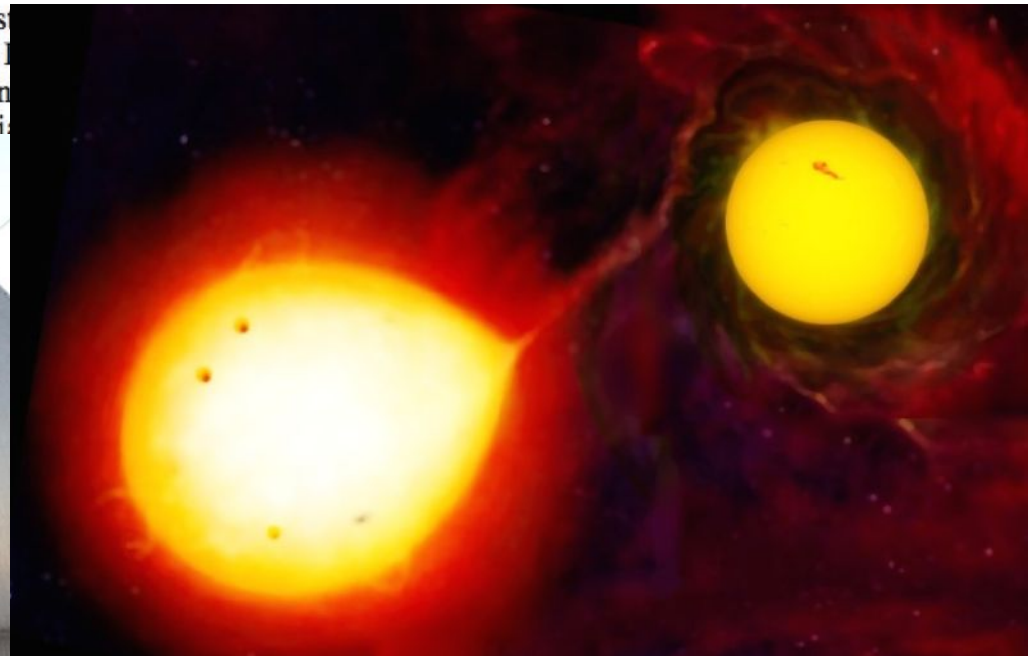
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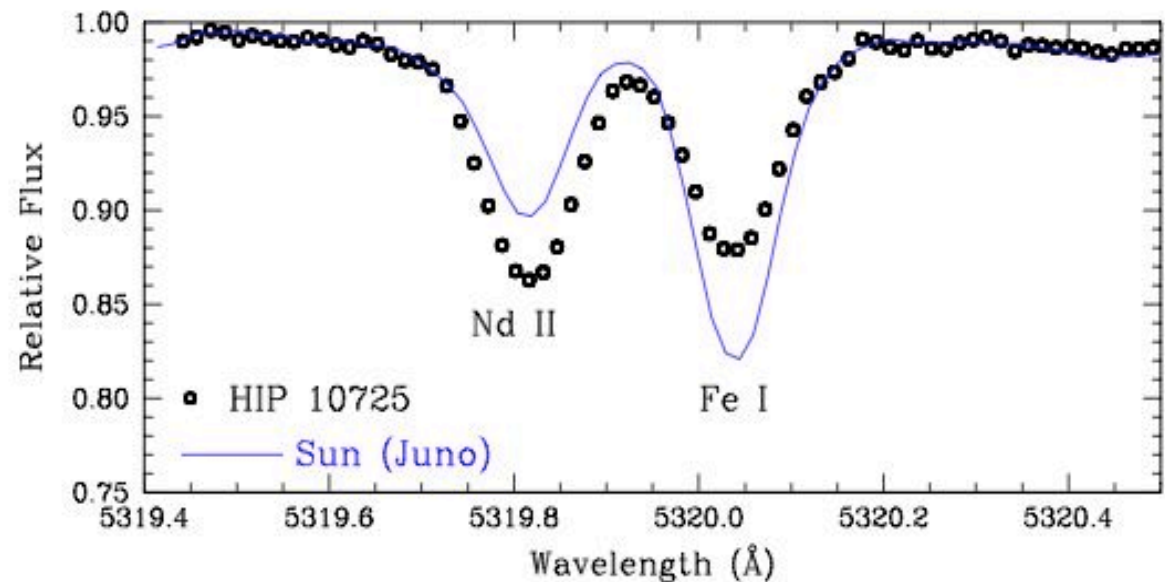
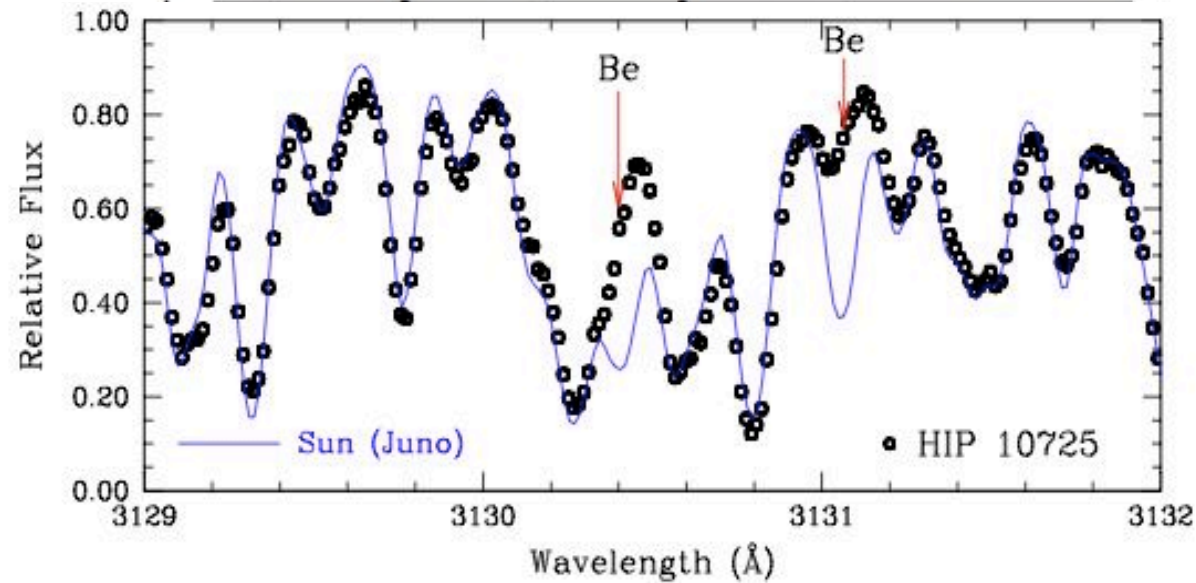


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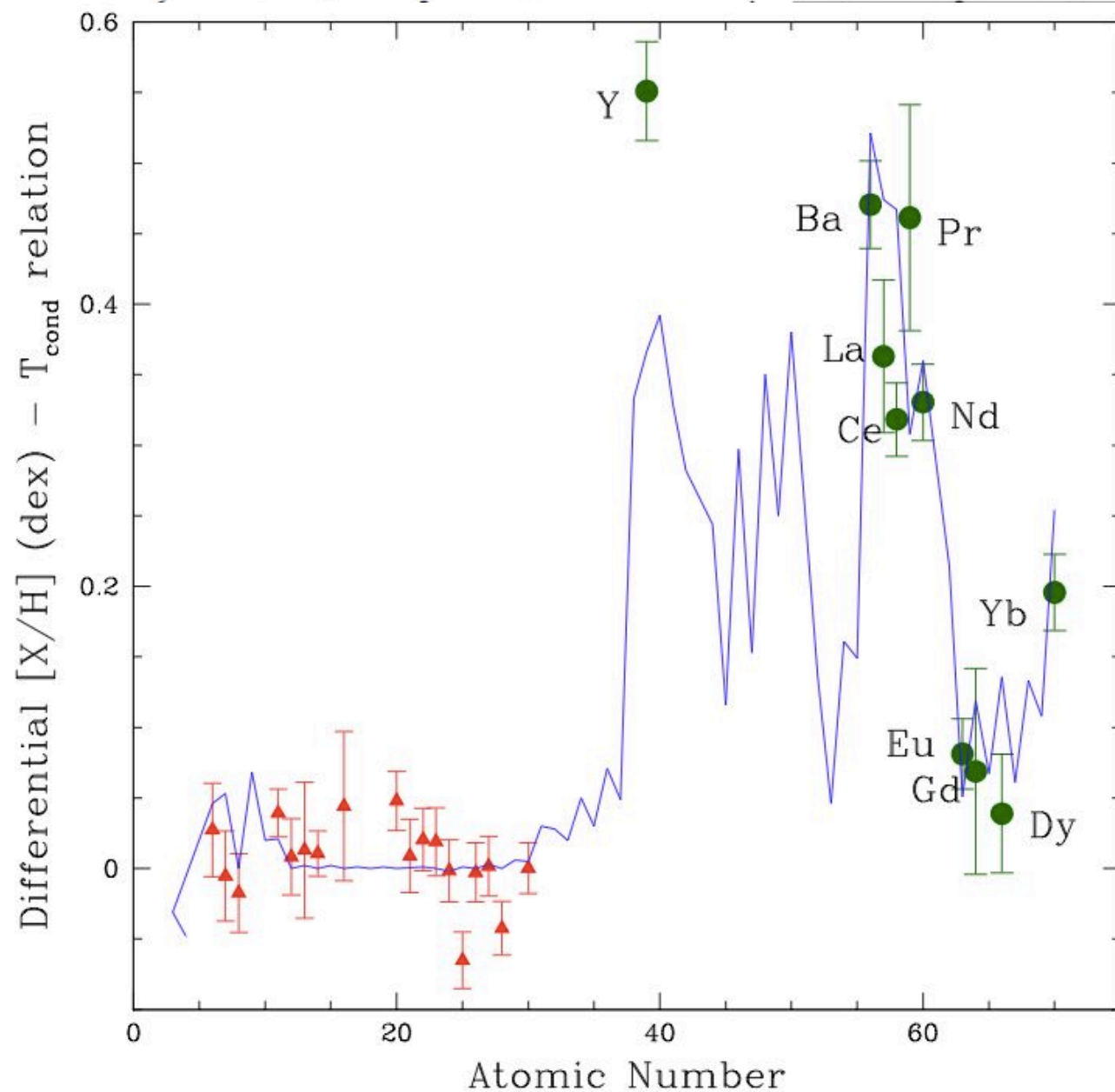
A gêmea solar HIP 10725 tem uma rotação maior à esperada para a idade dela. A alta rotação talvez é devida à transferência de momento angular da antiga companheira AGB.

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



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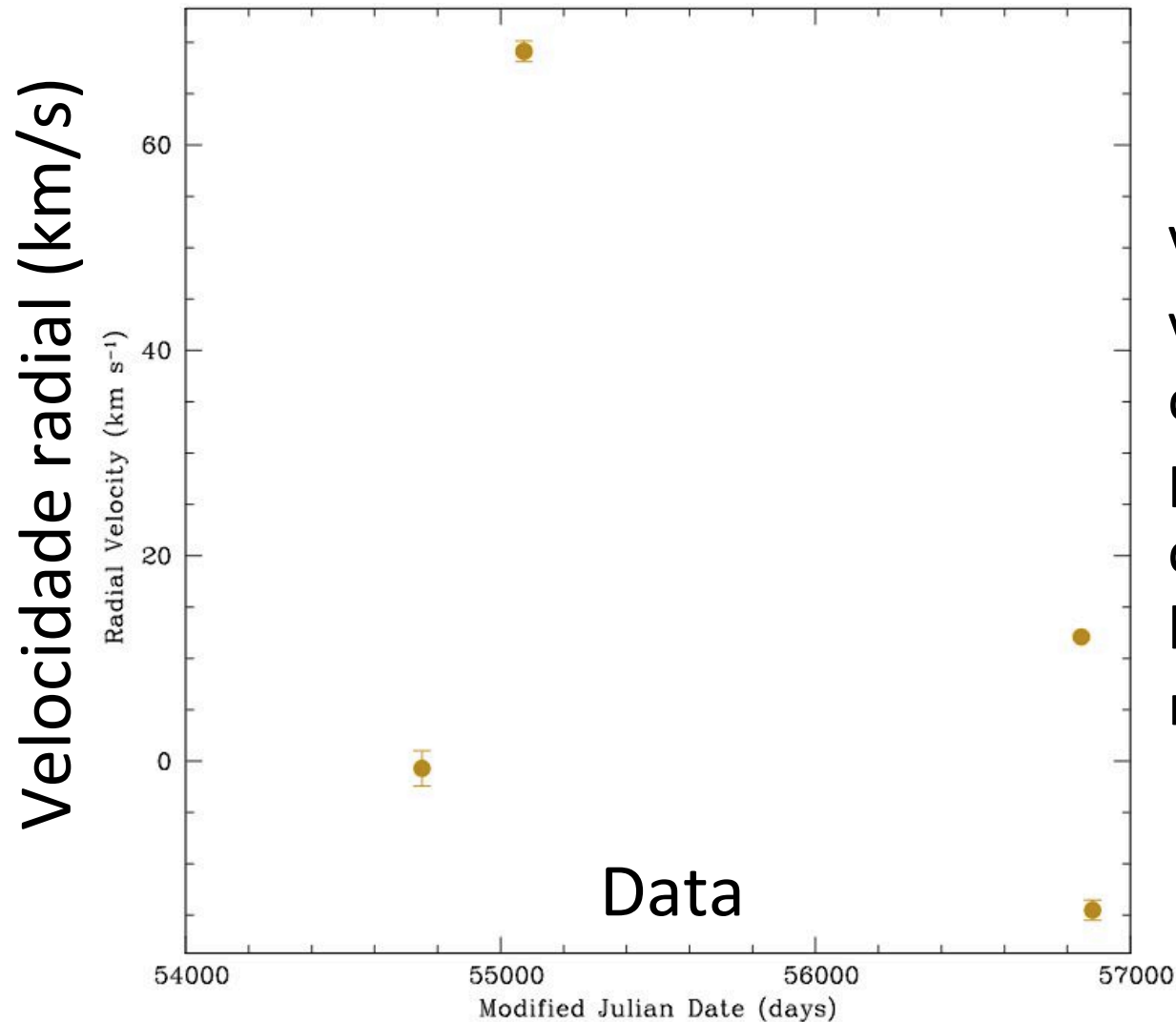
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Gêmea solar rica
em elementos
de captura de
nêutrons
(processo-s) →
provavelmente a
antiga
companheira
AGB pode ter
transferido
material rico em
elementos do
processo-s

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

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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.

Algumas áreas de Evolução Estelar no Brasil

Estrutura e evolução estelar (anãs brancas)

- Kepler Oliveira, Alejandra Romero (UFRGS)

Cálculo de evolução do Li e Be em gêmeas do Sol:

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

Assinaturas químicas de evolução estelar:

- Estrelas: Beatriz Barbuy, Jorge Meléndez (IAG/USP), Claudio Pereira (ON)
- Nebulosas Planetárias: Roberto Costa (IAG/USP)

Estrelas massivas:

- Alex Carciofi (IAG/USP), Marcelo Borges Fernandes (ON)

Provinha

- 1) Para uma estrela de $5M_{\text{sol}}$, explique o motivo para a virada do lado azul ao vermelho do ramo horizontal
- 2) O que é uma estrela Cefeída e qual a utilidade dessas estrelas?
- 3) Quando acontece o segundo *dredge-up*?
- 4) Desenhar *grosso modo* a estrutura interna de uma estrela AGB, indicando as 2 camadas (“*shells*”) de queima de H e de He
- 5) Por que acontecem os pulsos térmicos?