

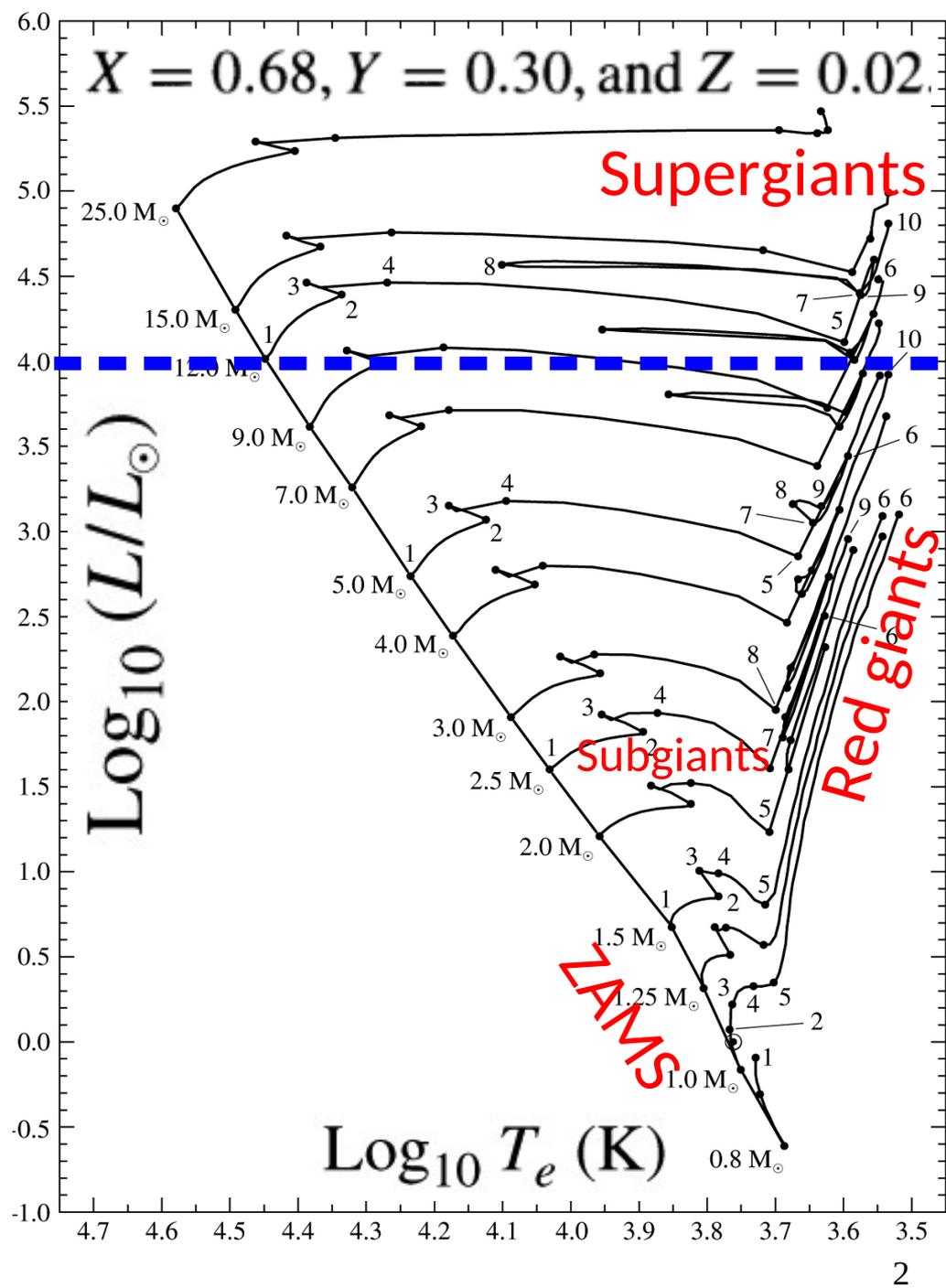
13 - Evolução na Sequência Principal e estágios avançados da evolução estelar

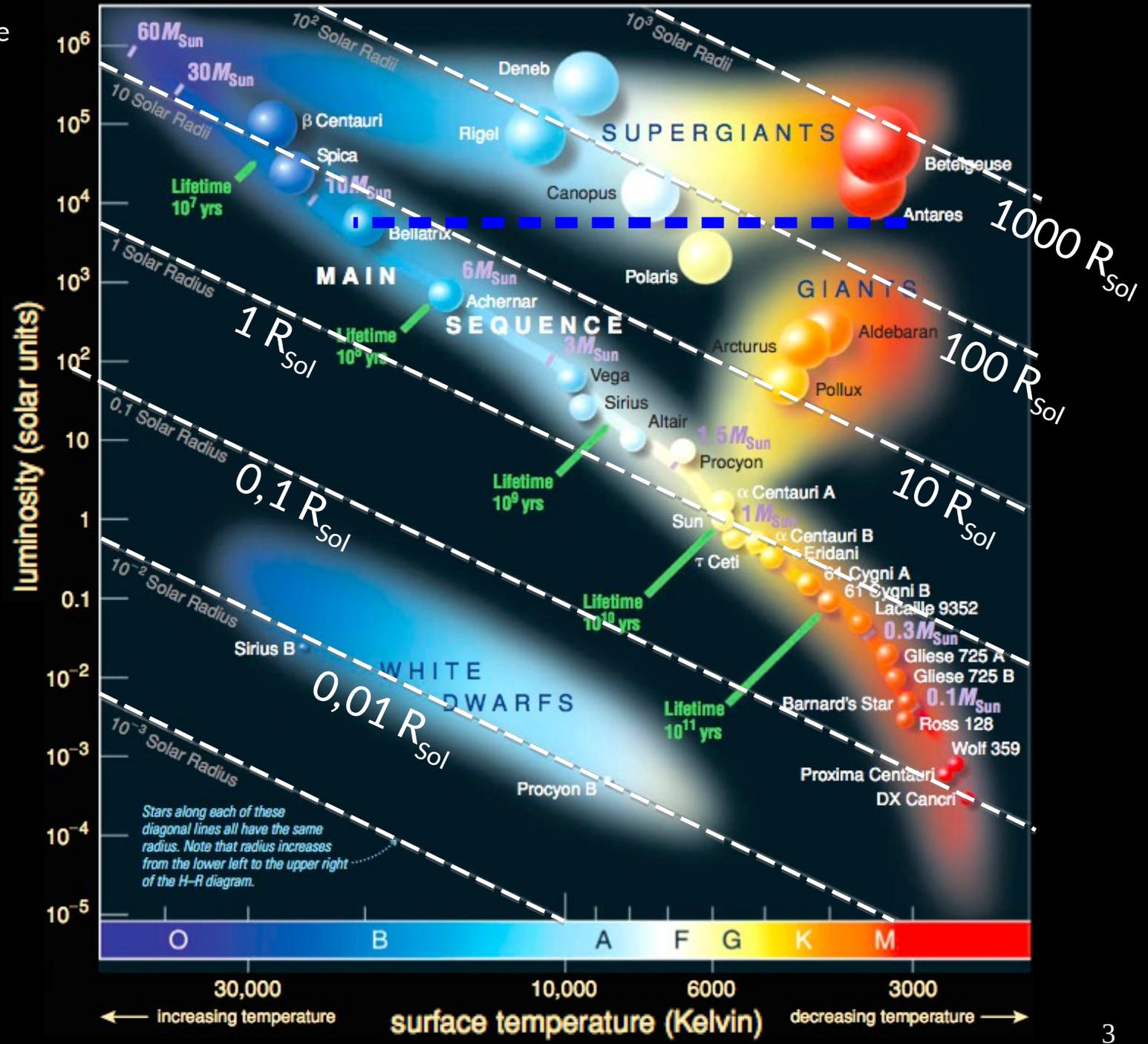
- 13.2 Estágios avançados de evolução estelar (a partir do Ramo Horizontal)
- 13.3 Aglomerados estelares
- Parte do Cap. 14 (estrelas pulsantes)



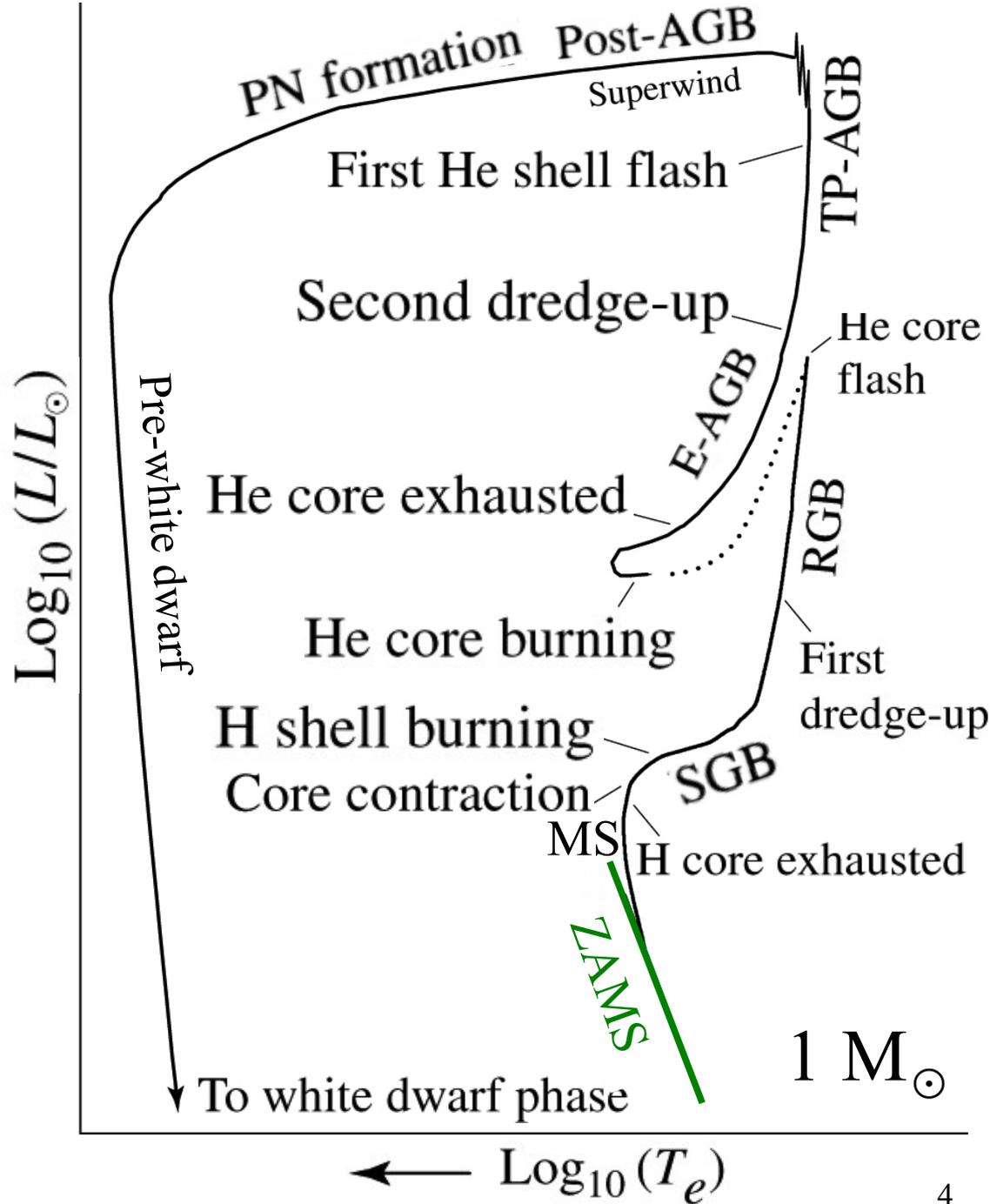
Tempo (Myr) a partir da ZAMS

Initial Mass (M_{\odot})	1	2	3	4	5
25	0 6.51783	6.33044 7.04971	6.40774 7.0591	6.41337 6.41337	6.43767 6.43767
15	0 11.6135	11.4099 11.6991	11.5842 12.7554	11.5986 11.5986	11.6118 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	355.018 355.018
2.5	0 595.476	574.337 607.356	584.916 710.235	586.165 757.056	589.786 589.786
2	0 1148.10	1094.08 1160.96	1115.94 1379.94	1117.74 1411.25	1129.12 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		





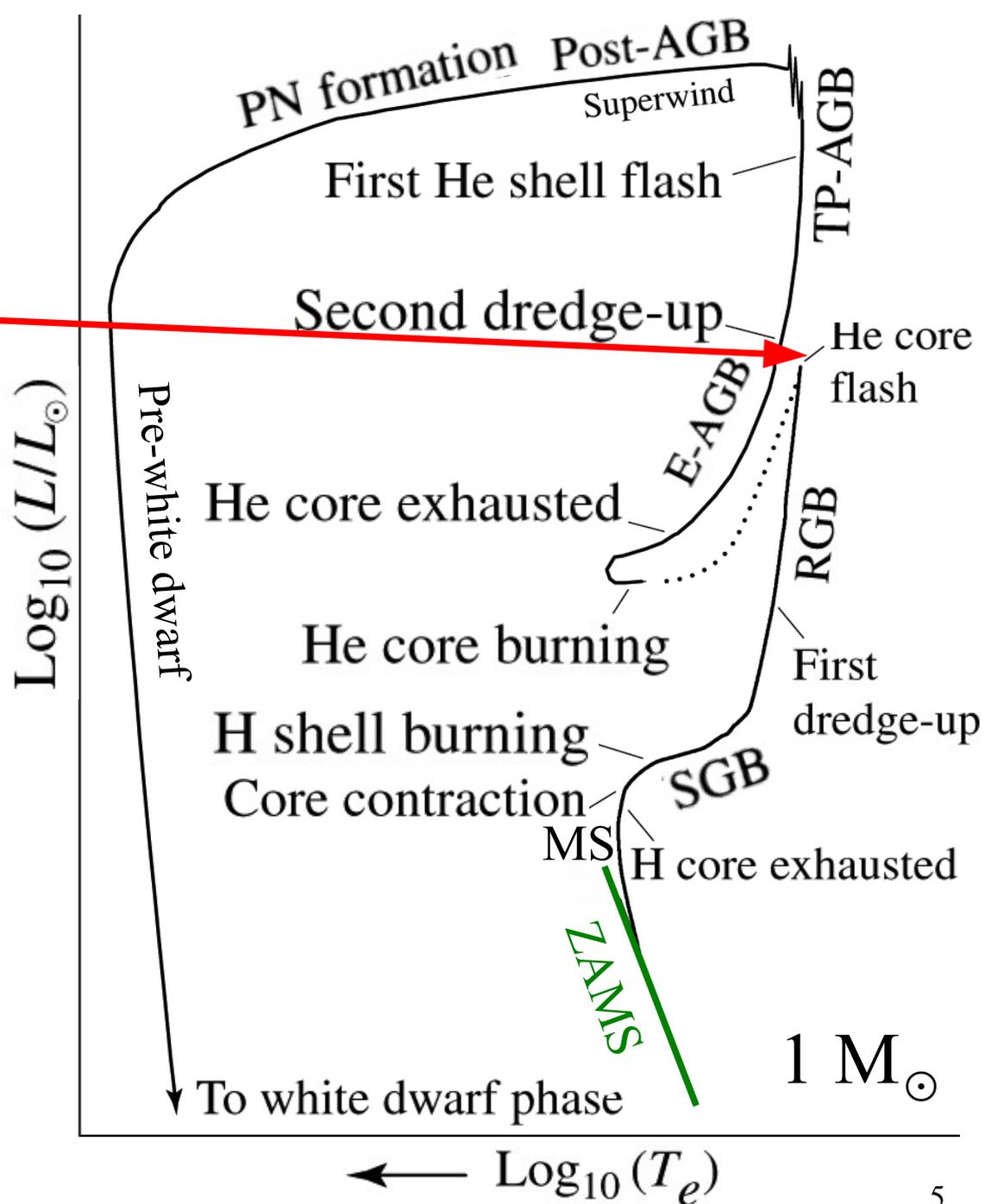
Evolução de $1 M_{\odot}$

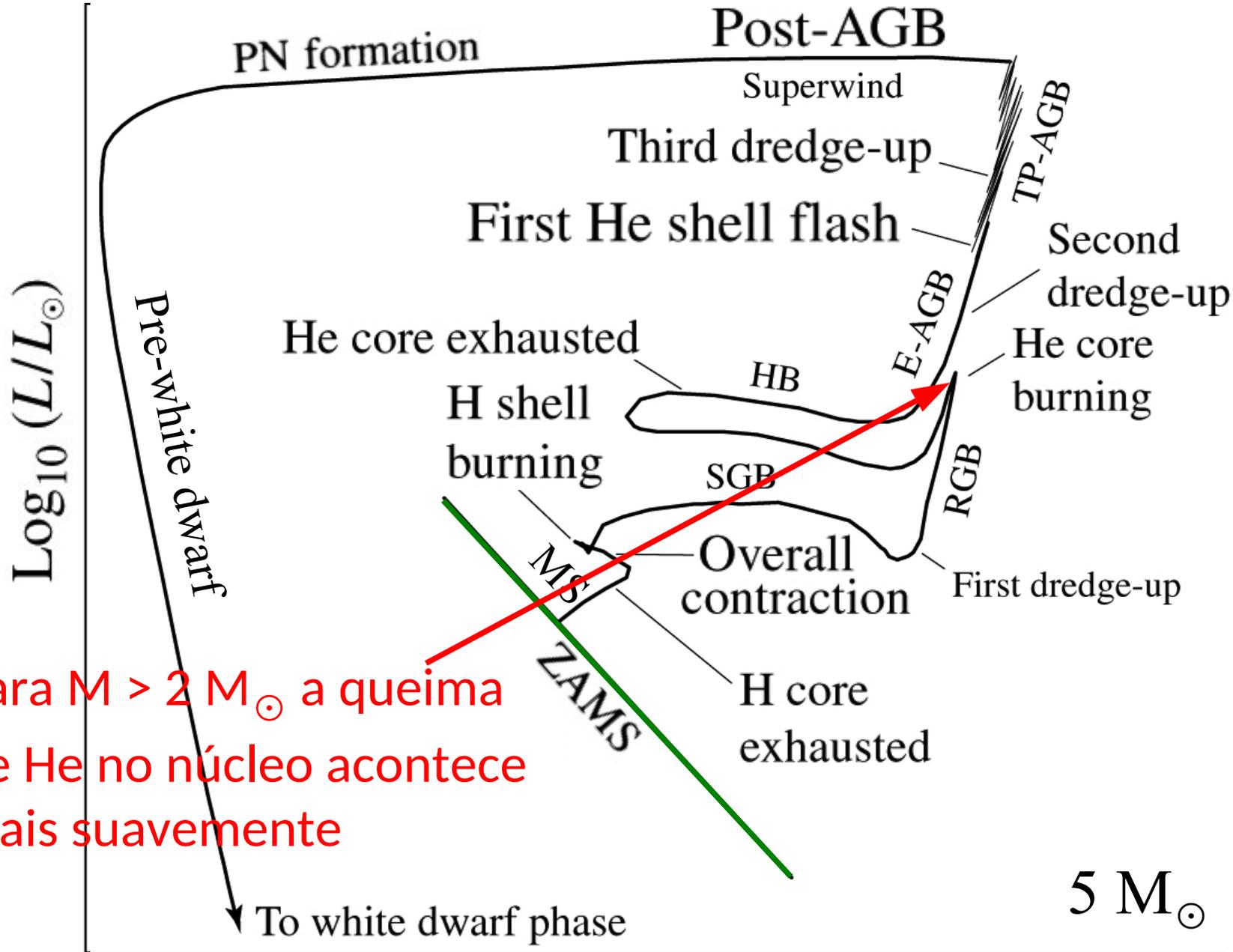


Para $M < 2 M_{\odot}$:
núcleo de He muito degenerado:

Início da queima
começa com o flash
de He, e depois em
equilíbrio

Evolução de $1 M_{\odot}$



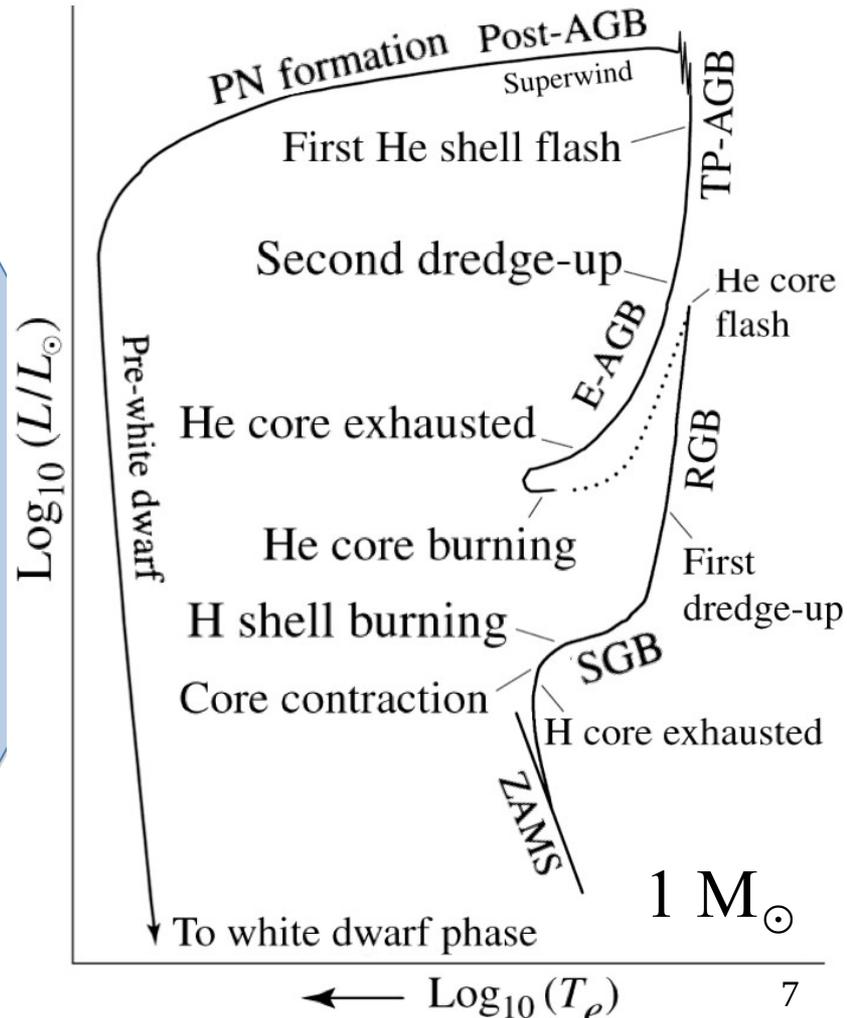
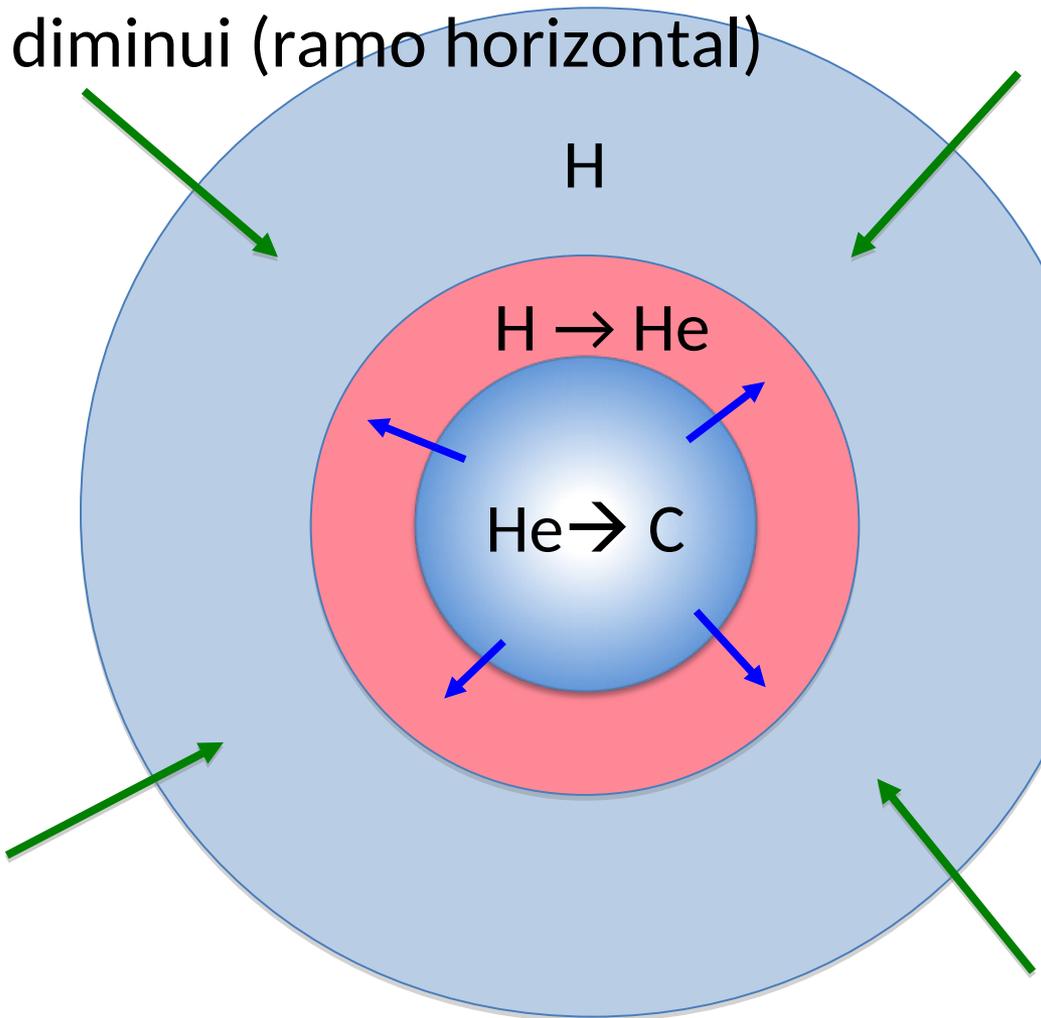


Para $M > 2 M_{\odot}$ a queima de He no núcleo acontece mais suavemente

Evolução de $5 M_{\odot}$ ← $\text{Log}_{10}(T_e)$

Do topo do RGB ao HB

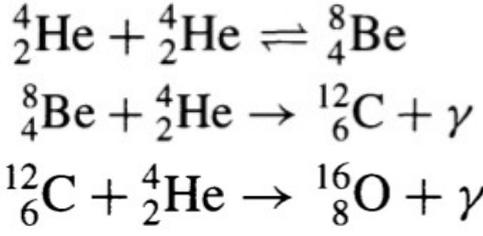
Energia do flash de He \rightarrow tira a degenerescência do núcleo de He. A energia produzida faz *shell* de queima de H expandir e esfriar (já não produz He) \rightarrow envelope em contração \rightarrow L diminui (ramo horizontal)



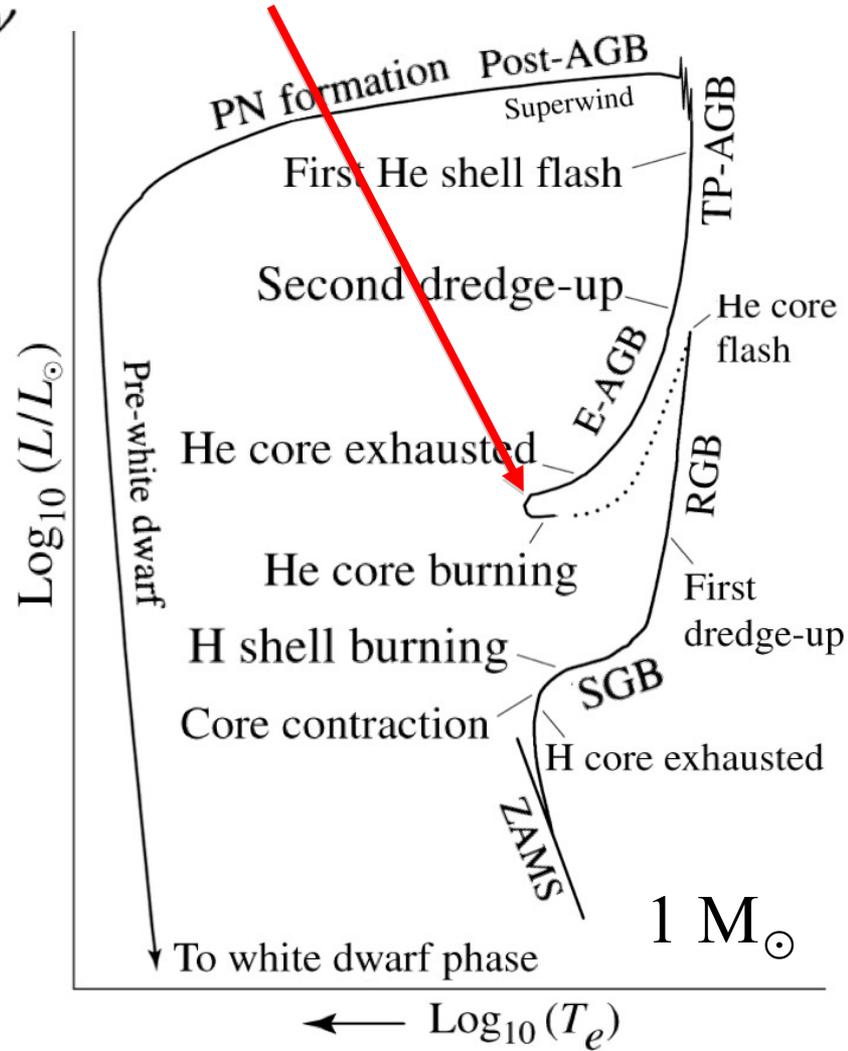
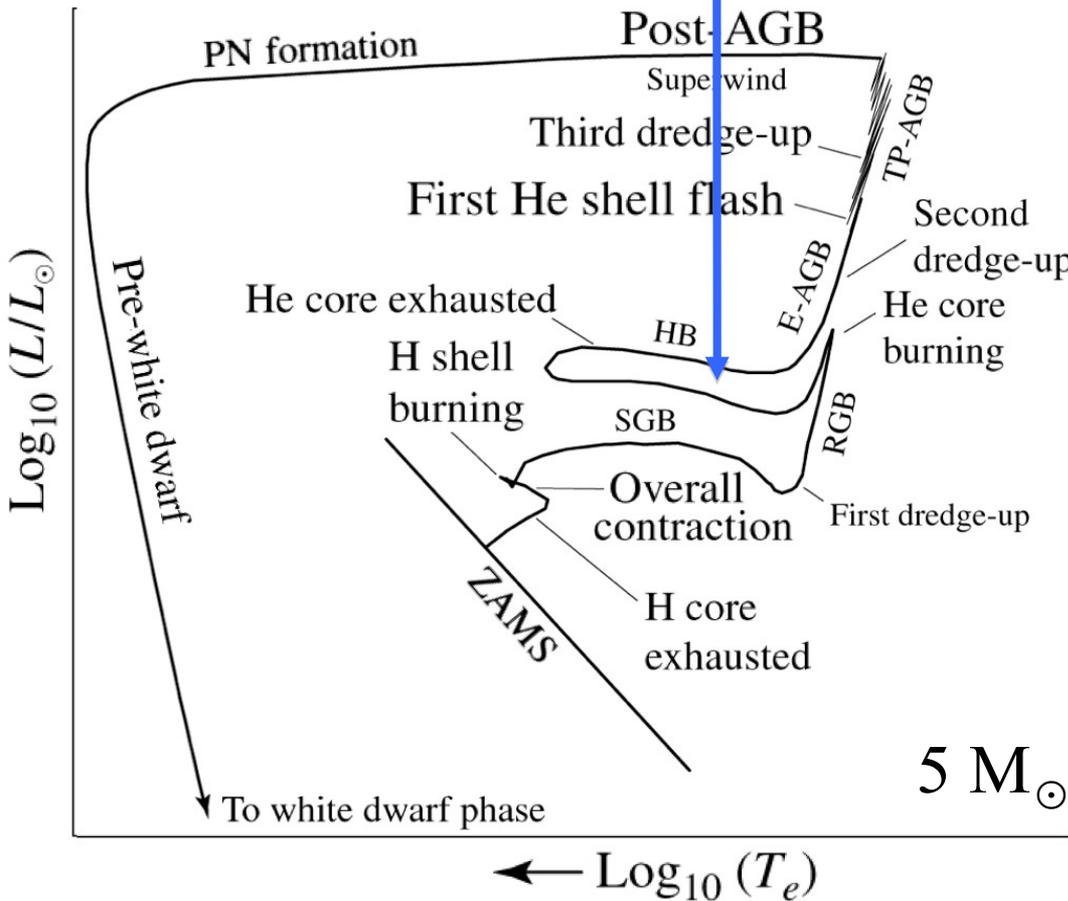
O ramo horizontal:

He \rightarrow C, O

Estrelas de massa intermediária têm HB extenso

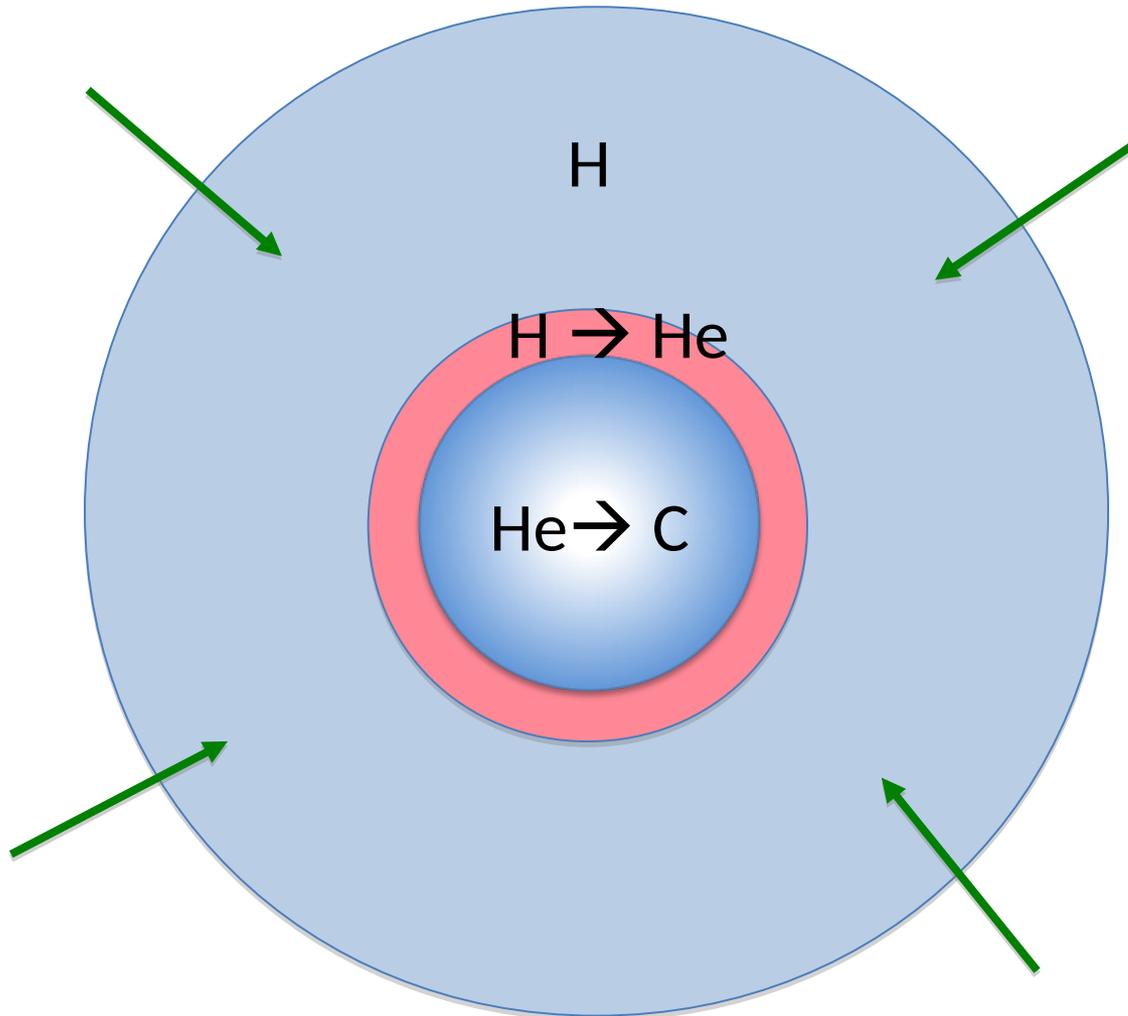


Estrelas de baixa massa como o Sol têm um ramo horizontal curto



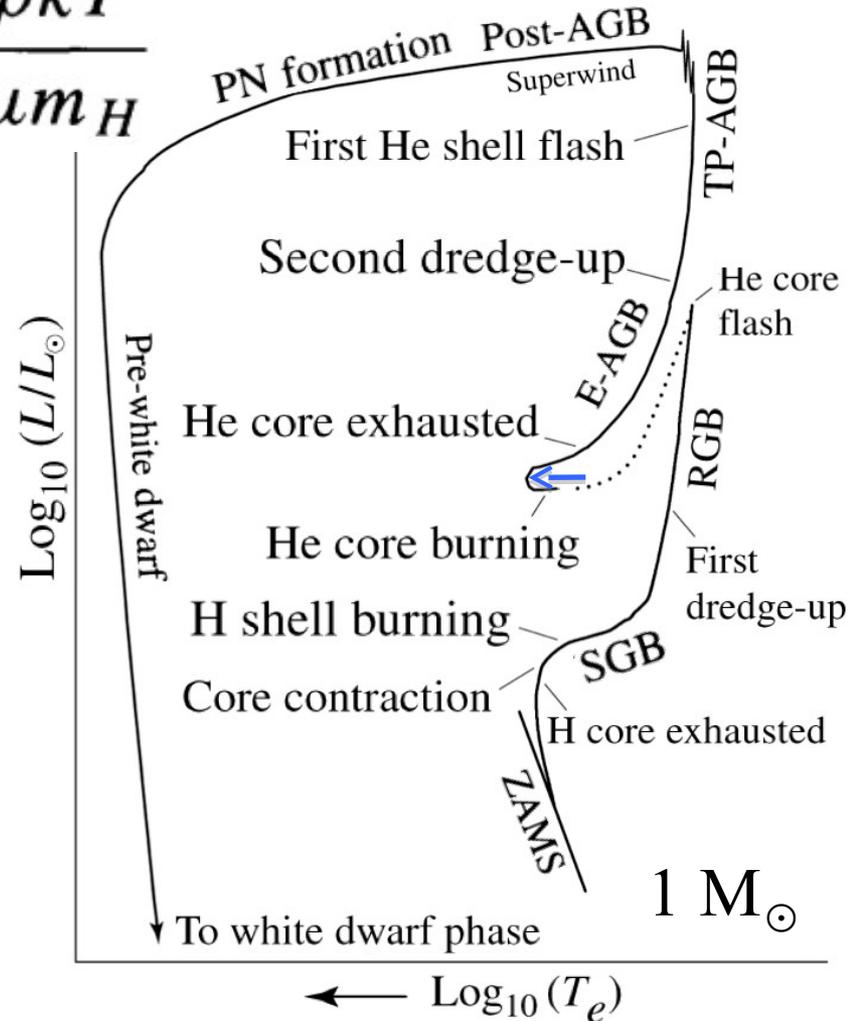
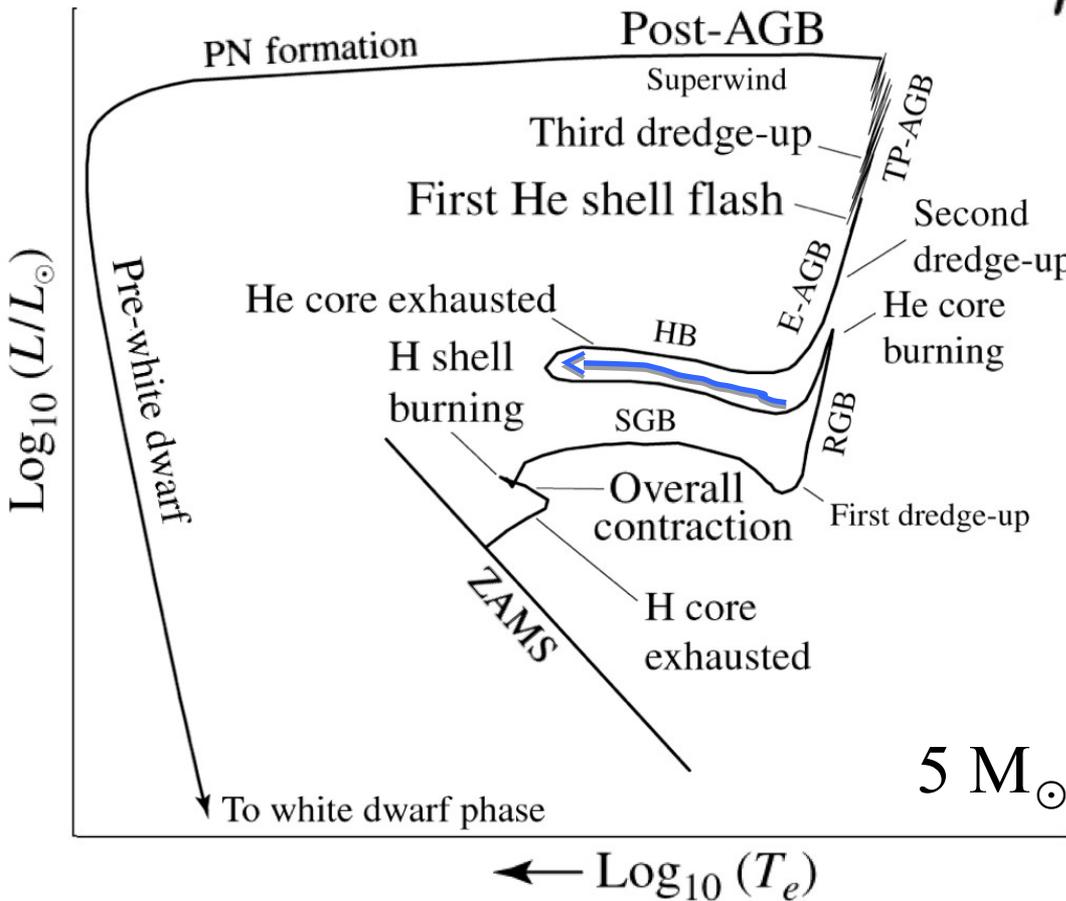
Estrela no lado azul do ramo horizontal

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 de maneira estável. No ponto mais azul, peso molecular é muito alto \rightarrow núcleo de He entra em contração.

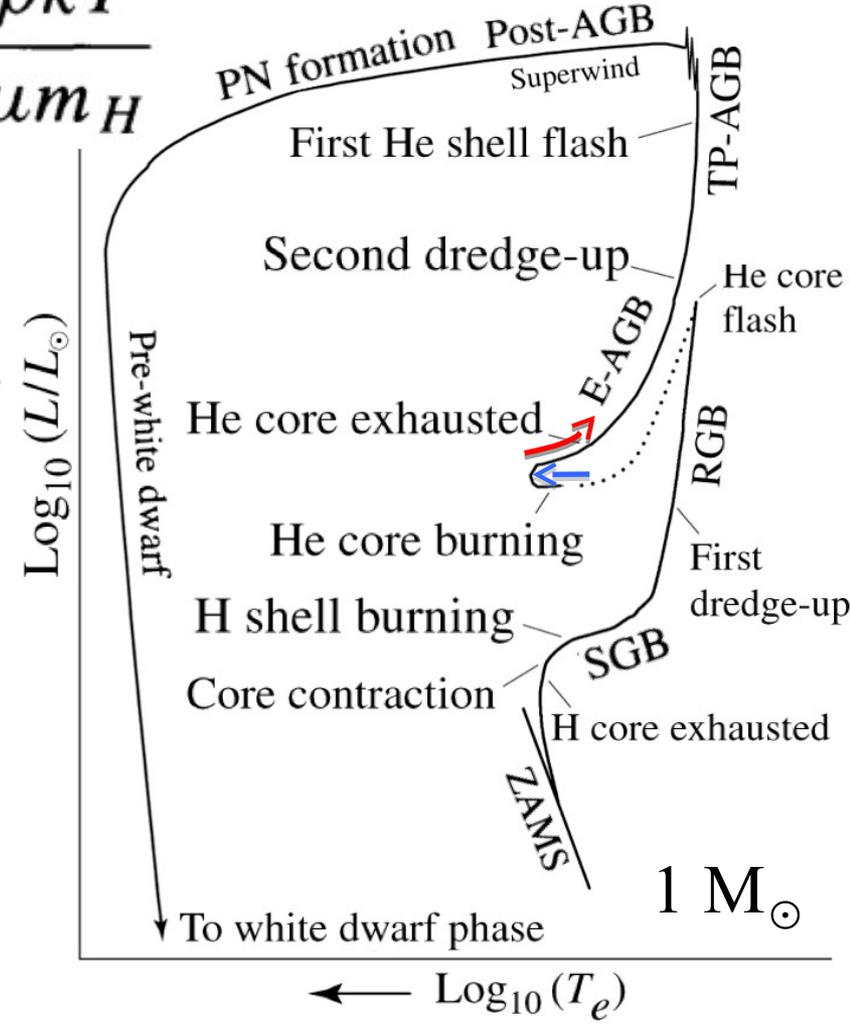
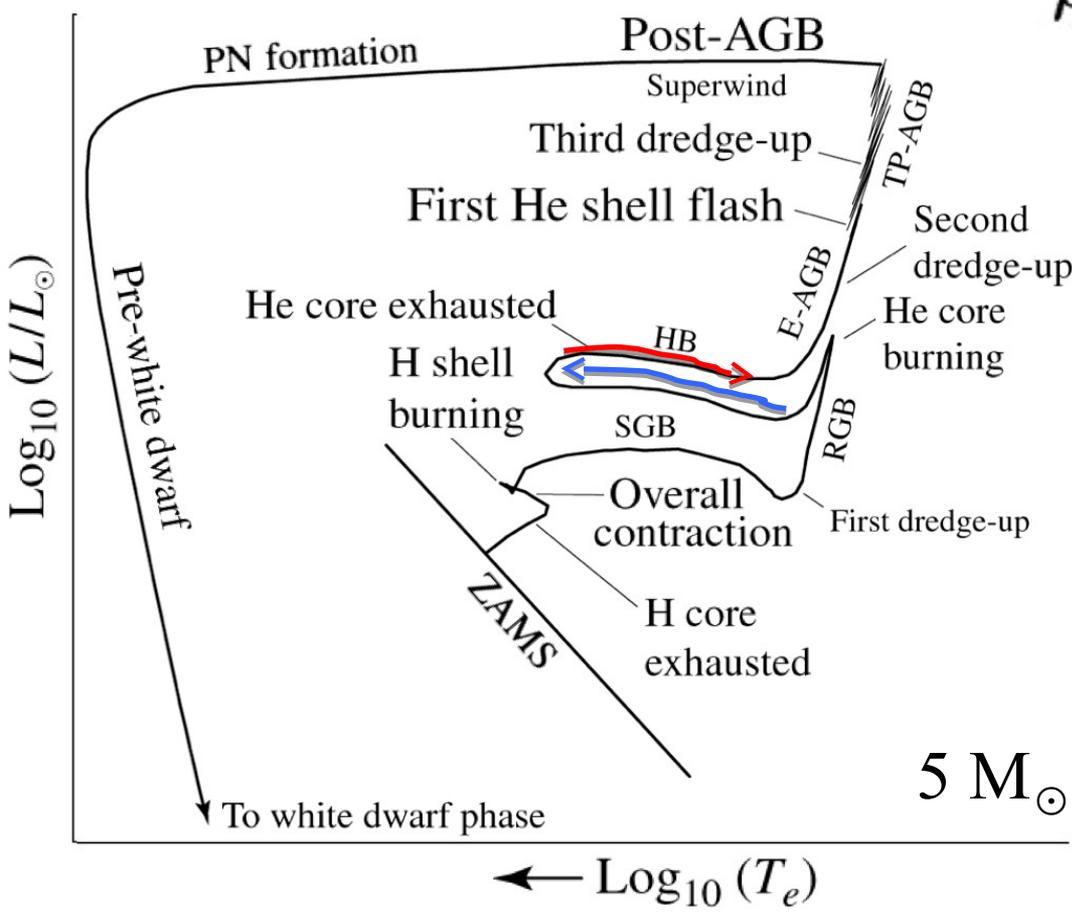
$$P_g = \frac{\rho k T}{\mu m_H}$$



No percurso para o lado azul (quente) do ramo horizontal, temos queima do He de maneira estável. 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

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

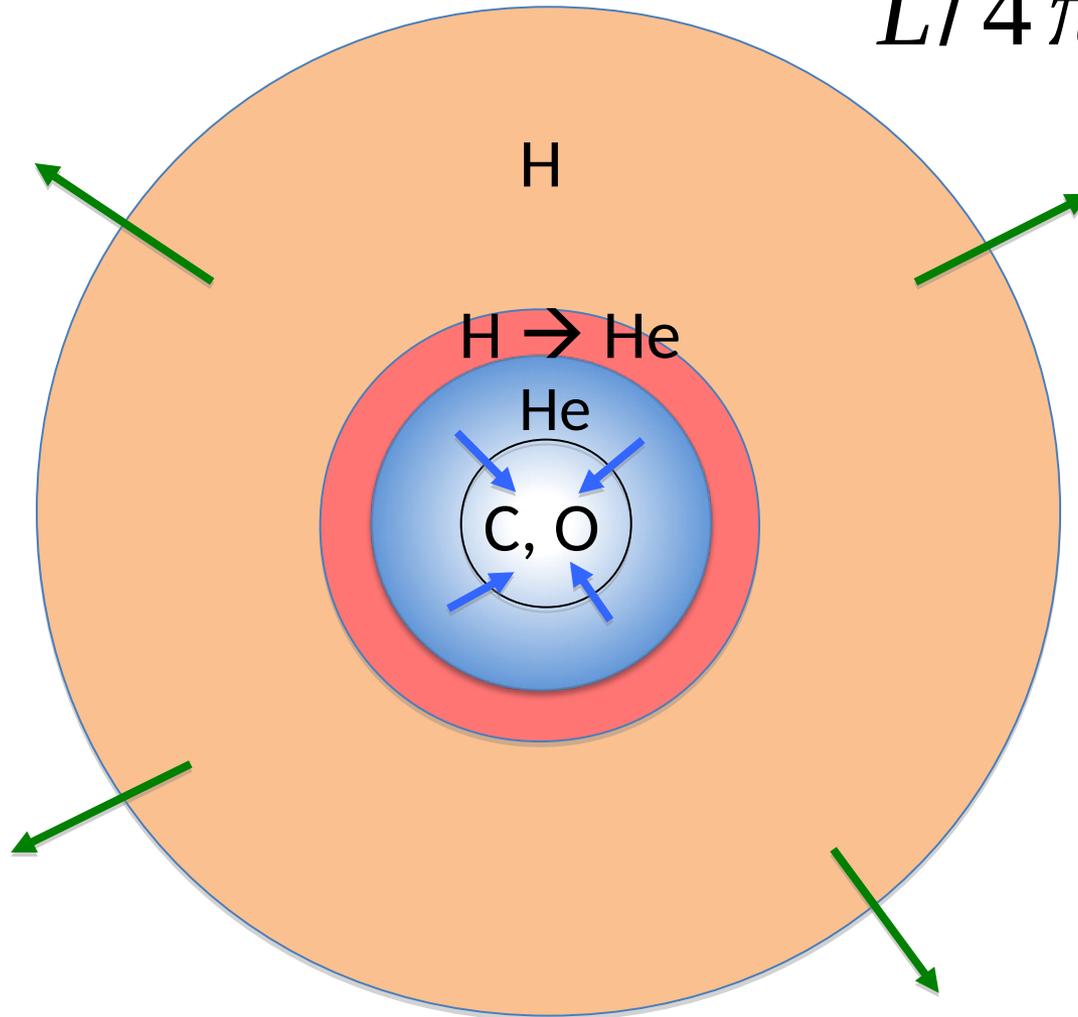


Estrela no lado vermelho do ramo horizontal

Peso molecular alto \rightarrow núcleo de CO em contração.

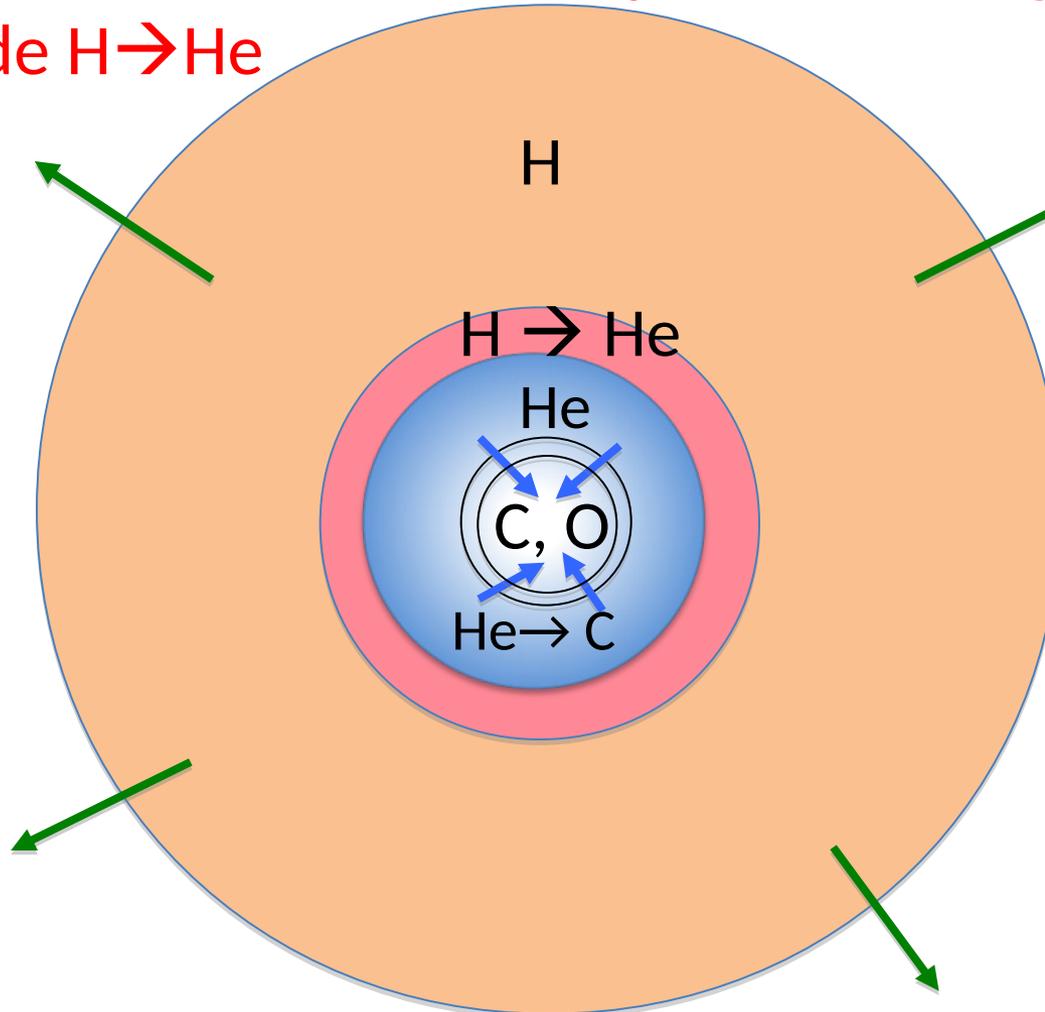
Envelope em expansão \rightarrow temperatura diminui

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



Estrela no lado vermelho do ramo horizontal

Núcleo de CO em contração → desenvolve casca de queima de $\text{He} \rightarrow \text{C}$. Aumento de luminosidade força material acima a se expandir e resfriar. A diminuição da T desliga a camada de queima de $\text{H} \rightarrow \text{He}$



Junto com a contração do núcleo de CO, são emitidos muitos ν e o núcleo resfria um pouco e fica mais denso e degenerado

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

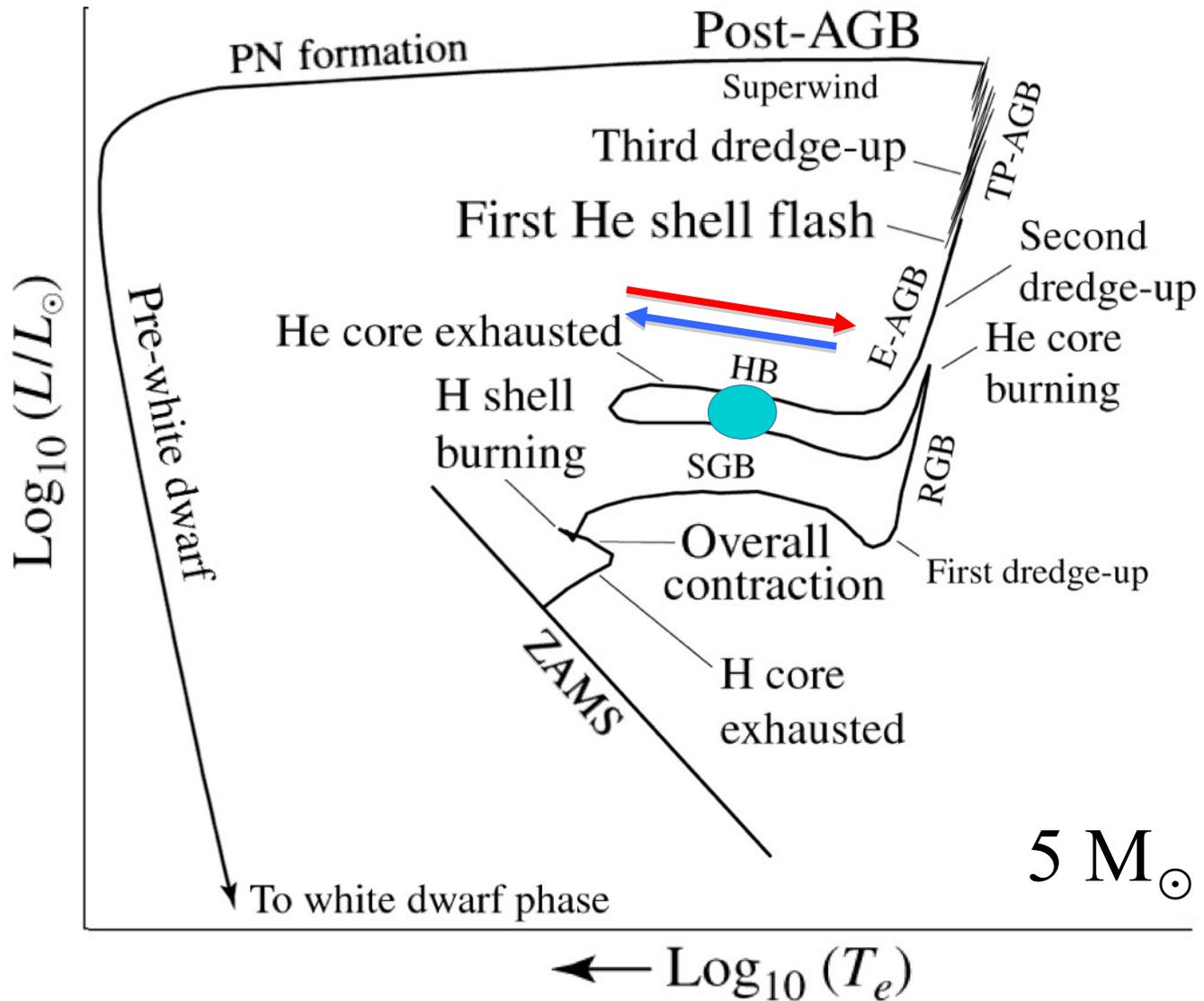


Diagrama HR do aglomerado globular M5

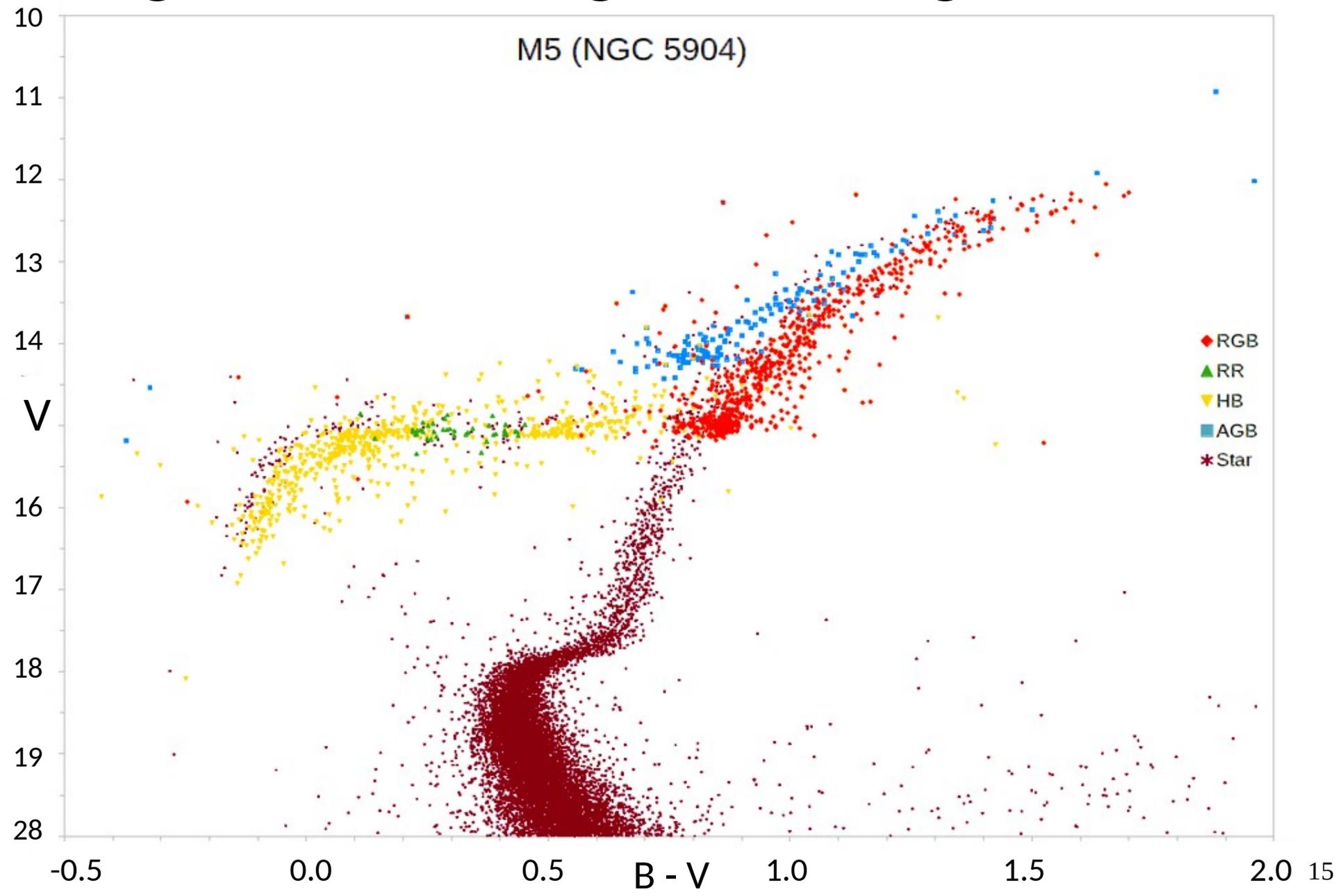


Diagrama HR do aglomerado globular M5

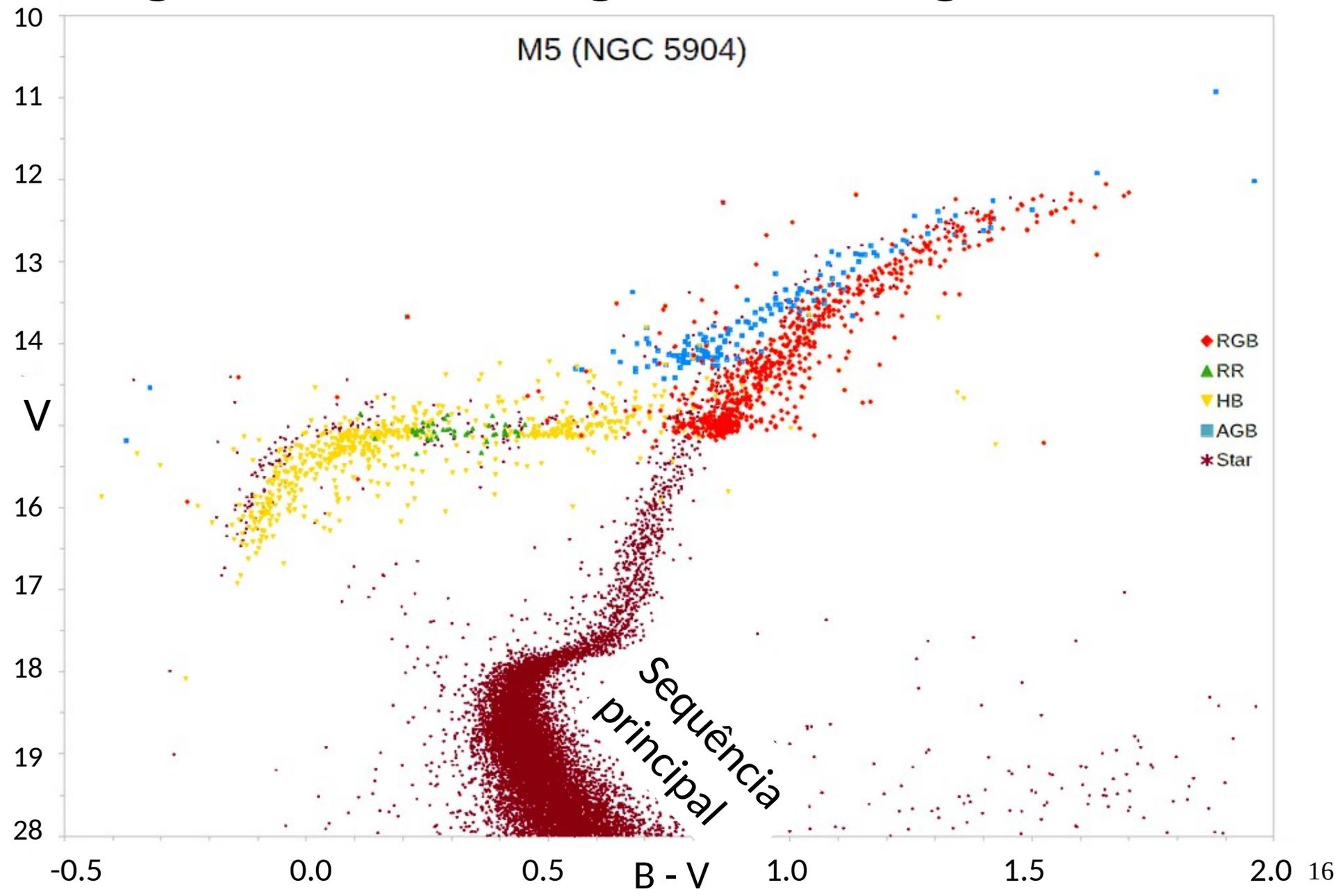


Diagrama HR do aglomerado globular M5

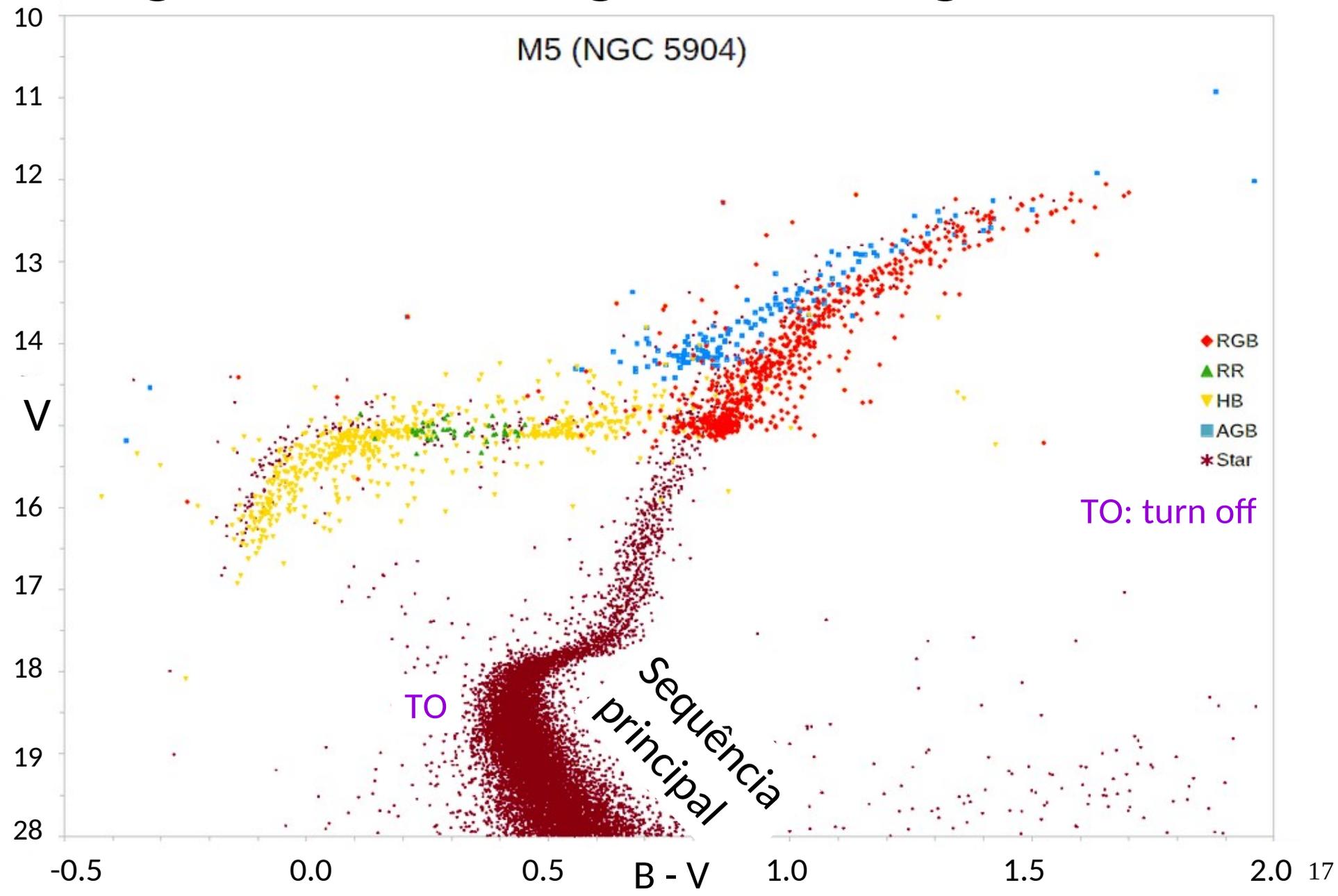


Diagrama HR do aglomerado globular M5

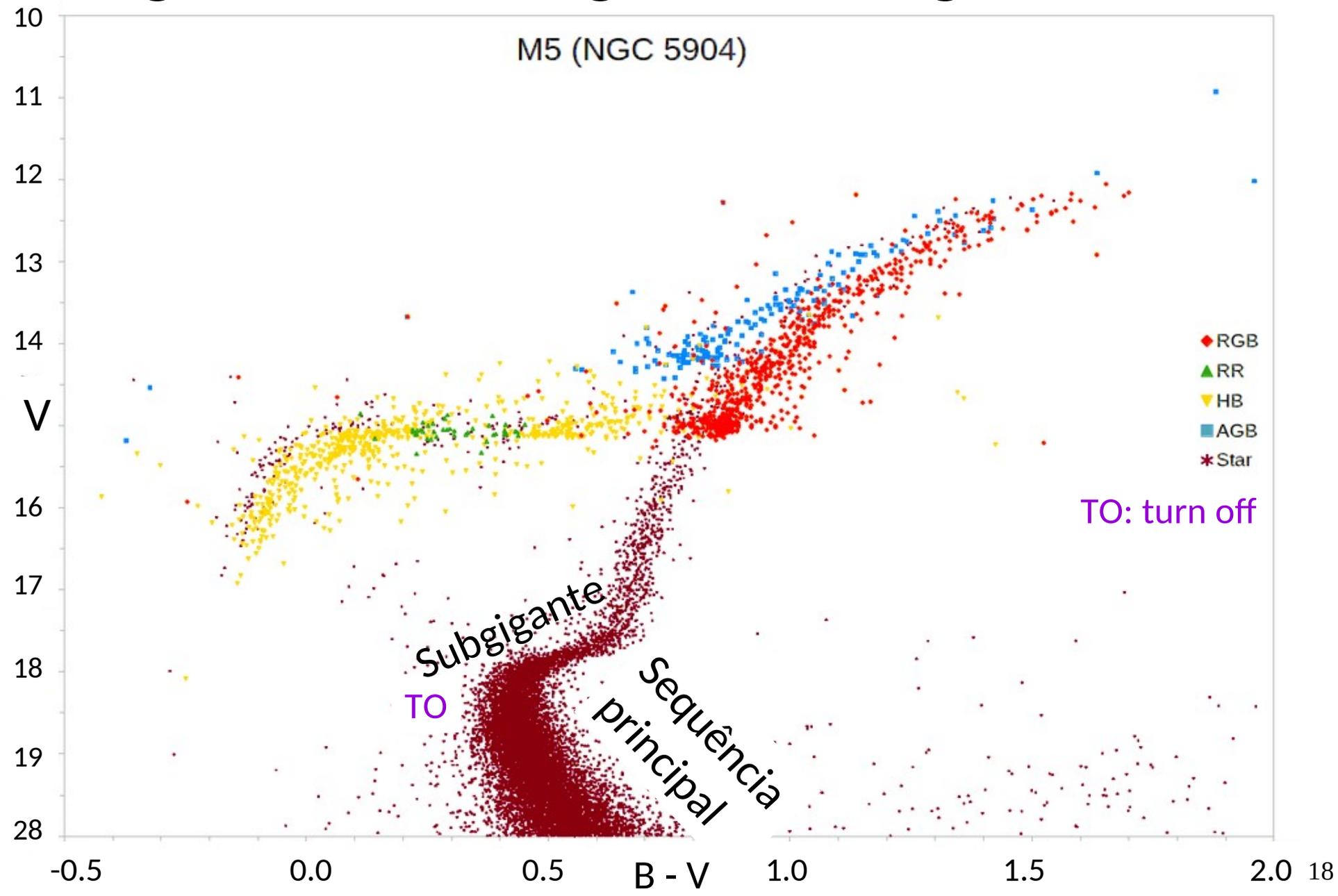


Diagrama HR do aglomerado globular M5

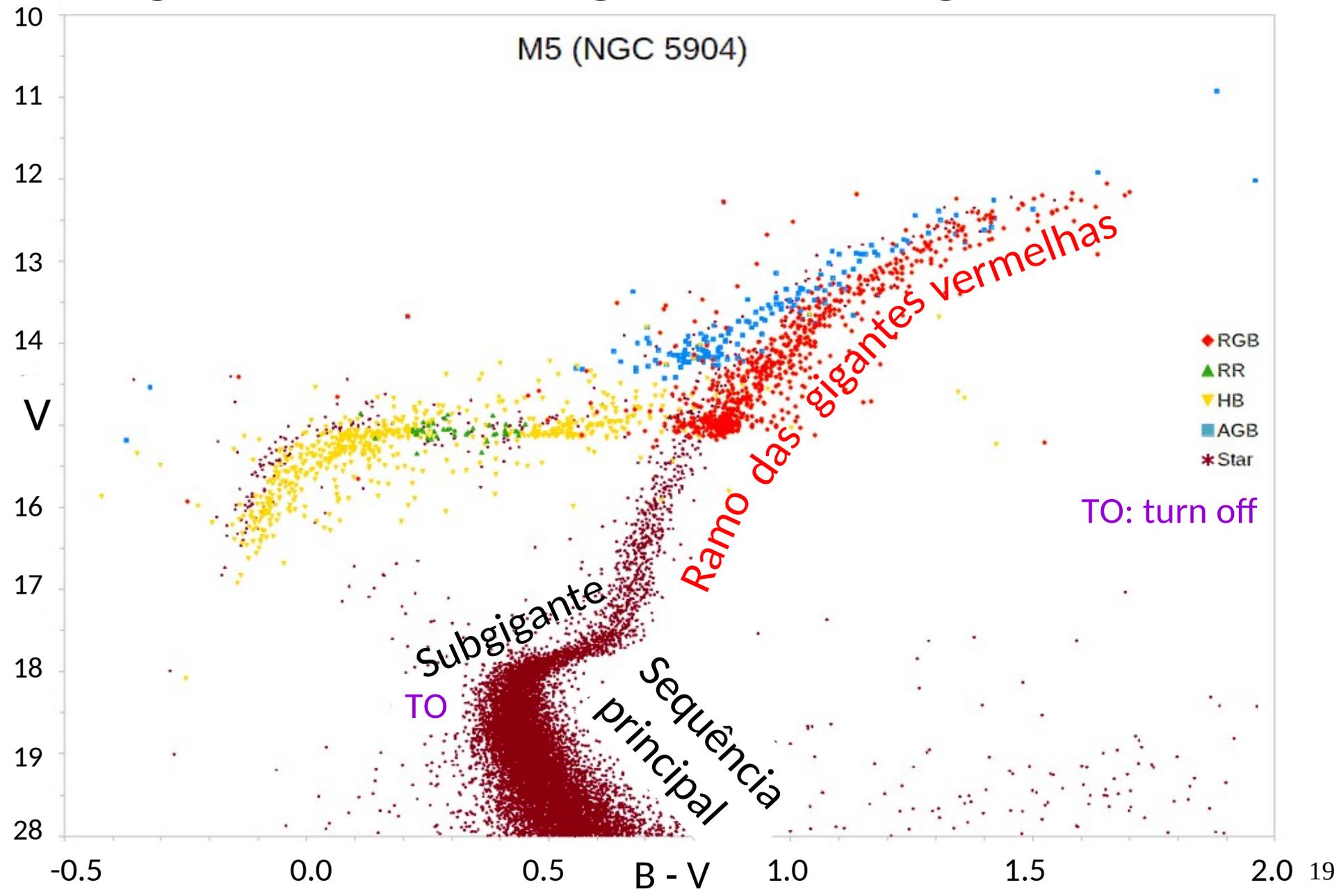


Diagrama HR do aglomerado globular M5

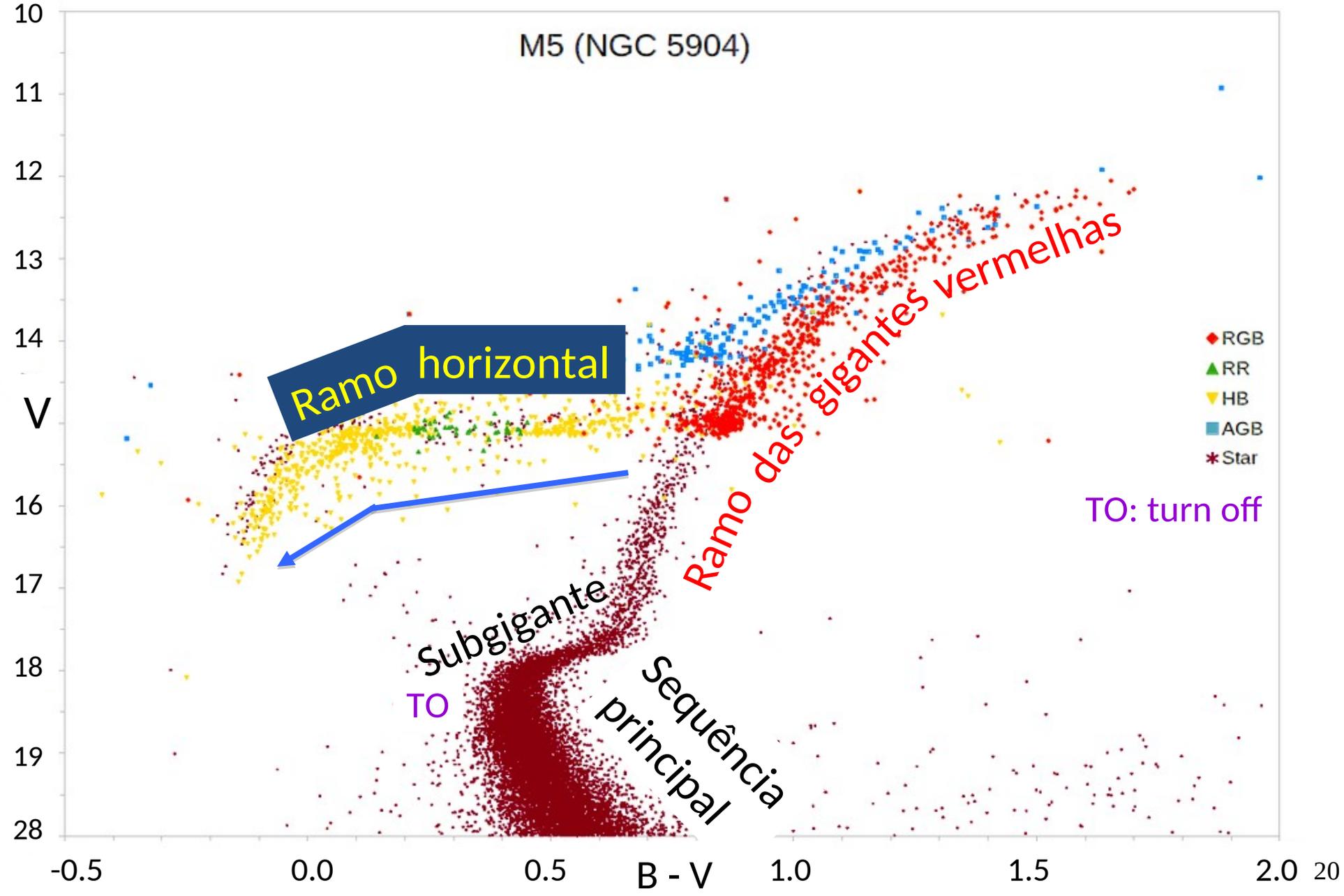


Diagrama HR do aglomerado globular M5

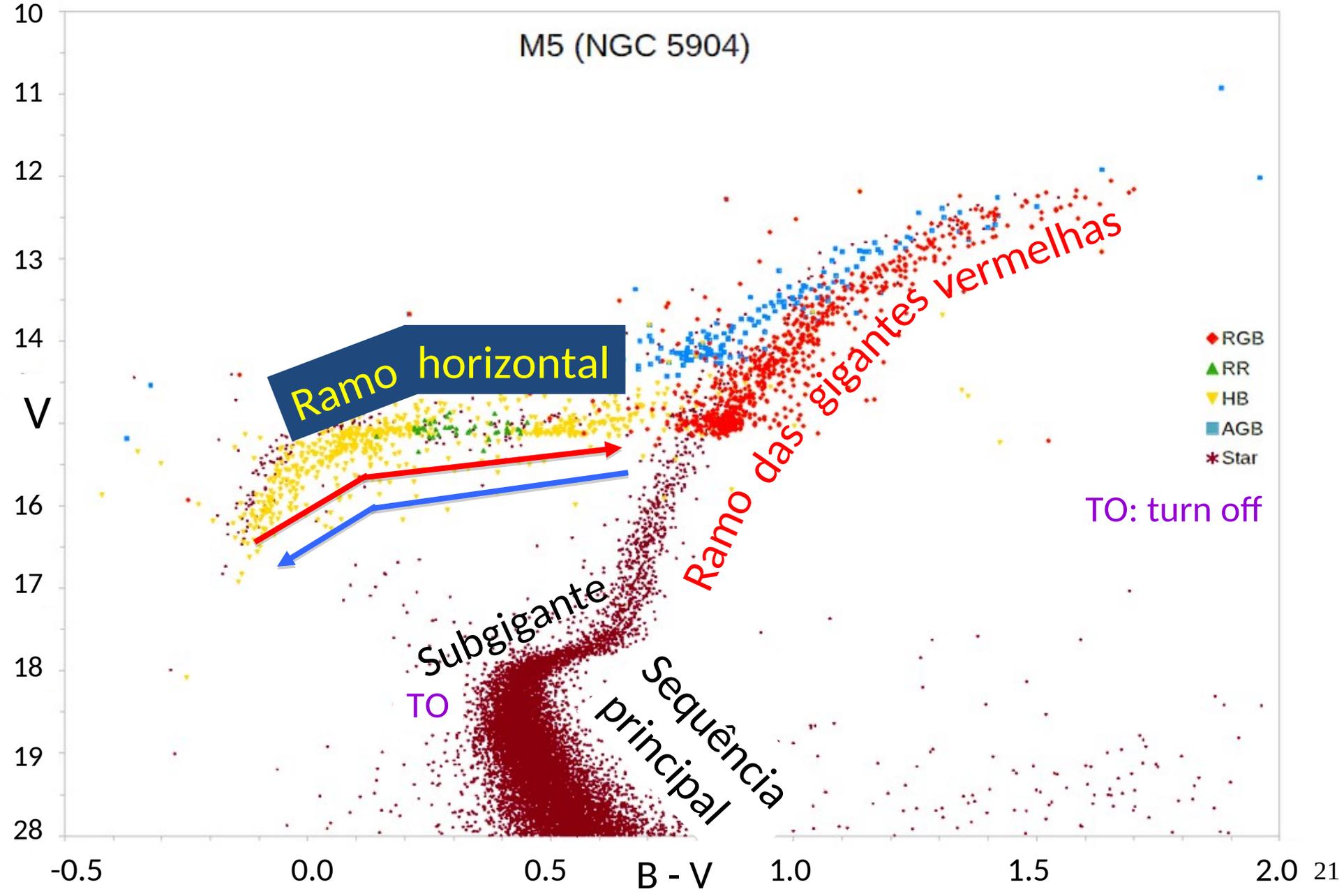


Diagrama HR do aglomerado globular M5

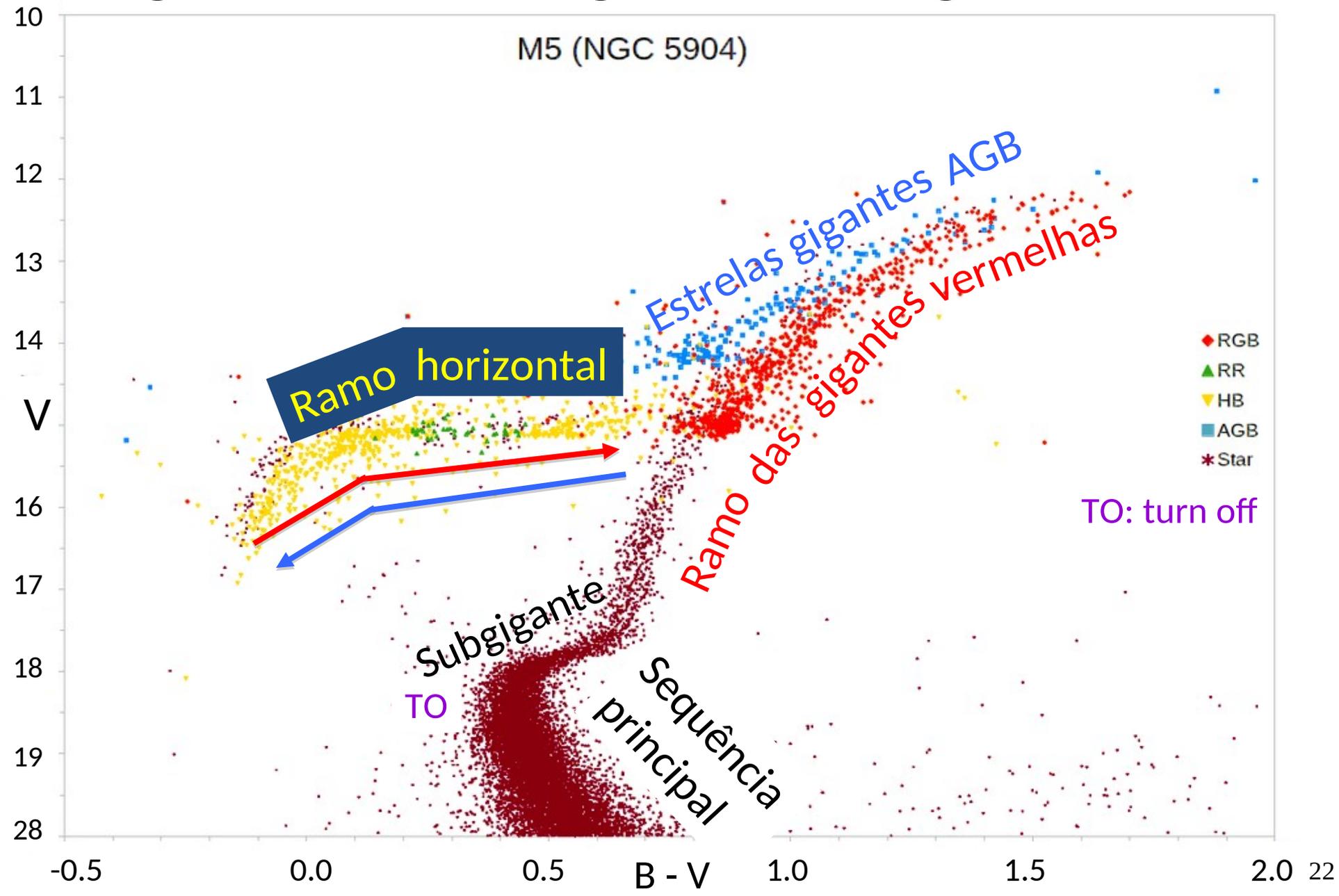
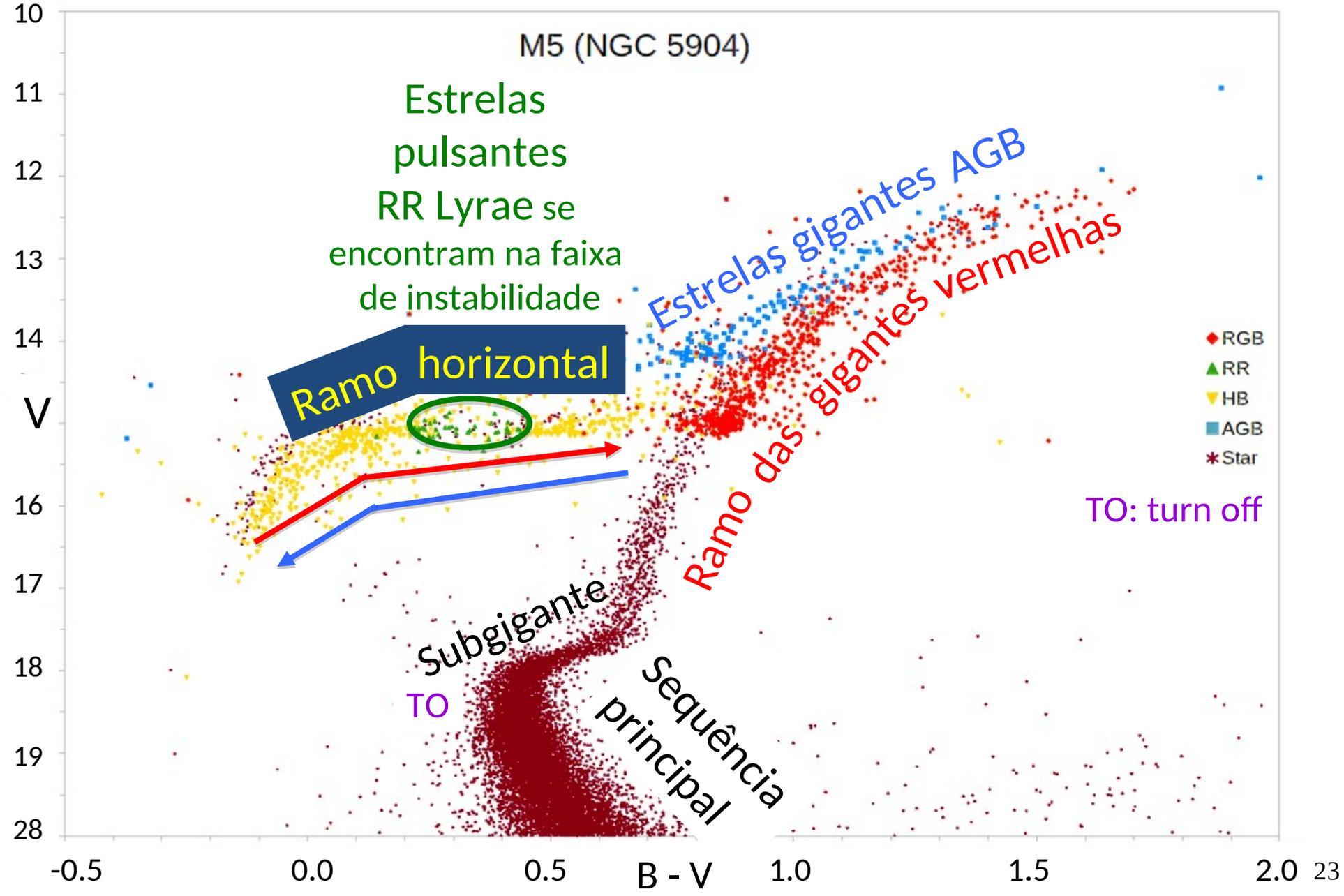
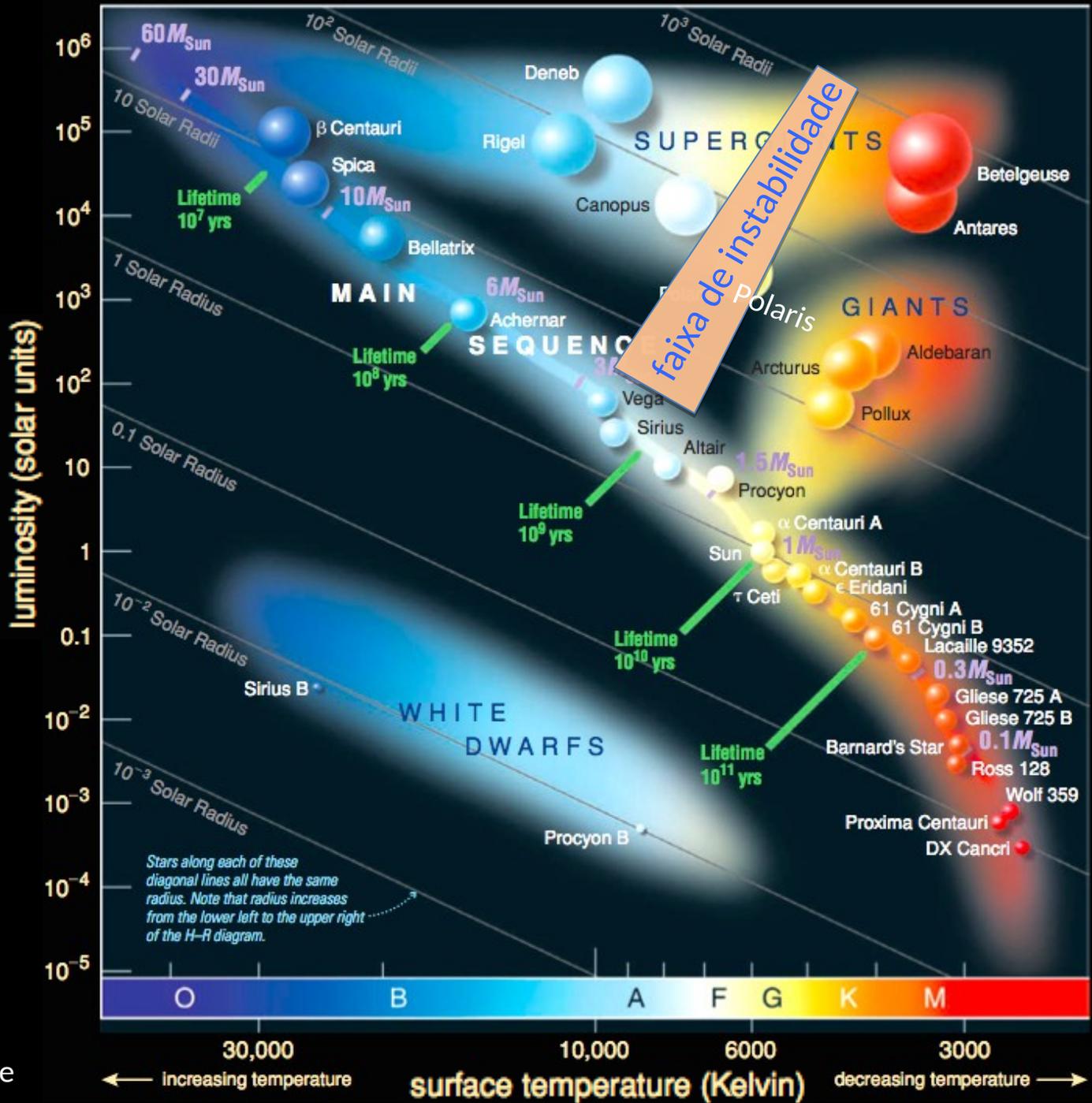
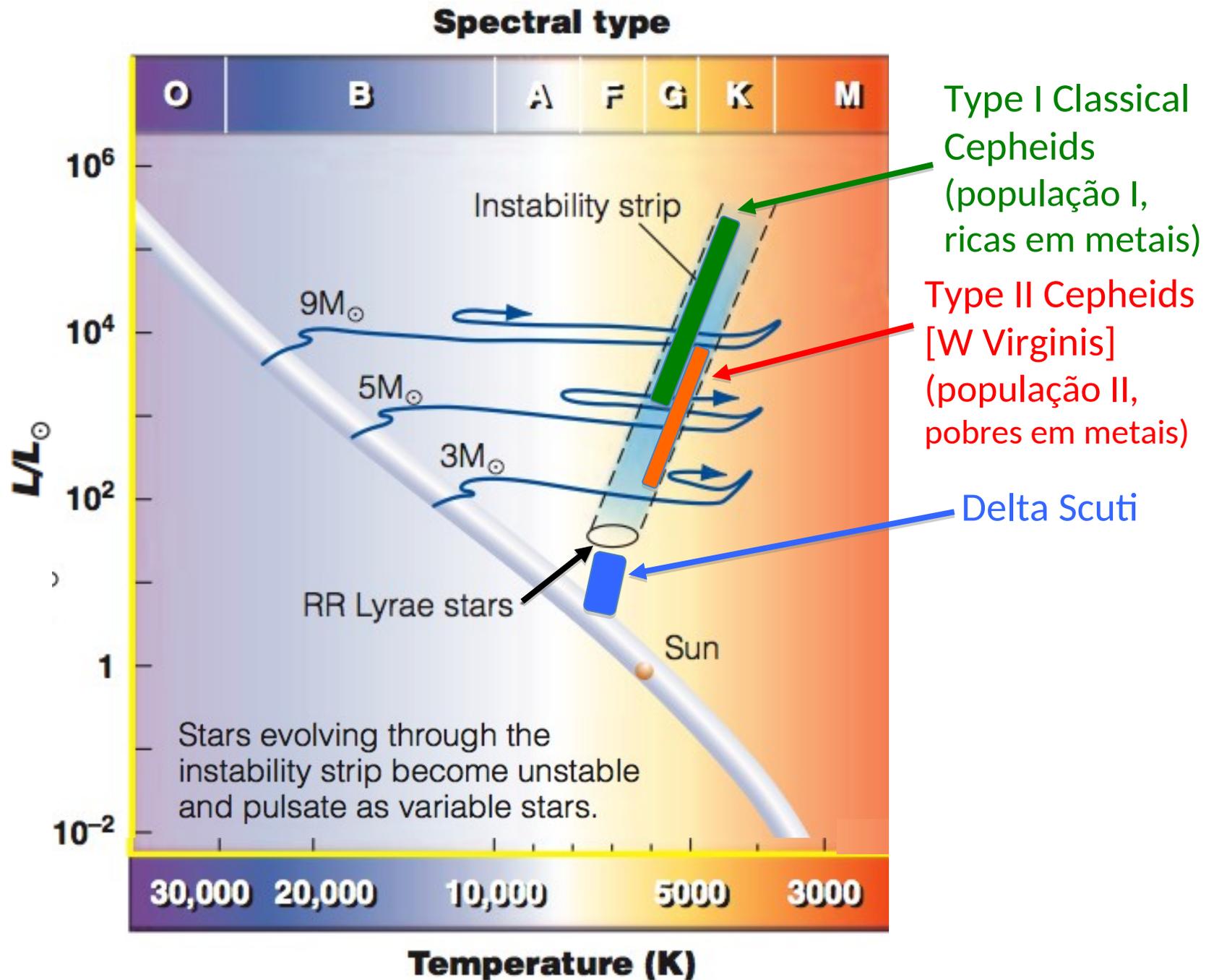


Diagrama HR do aglomerado globular M5







Curva de luz de δ Cephei

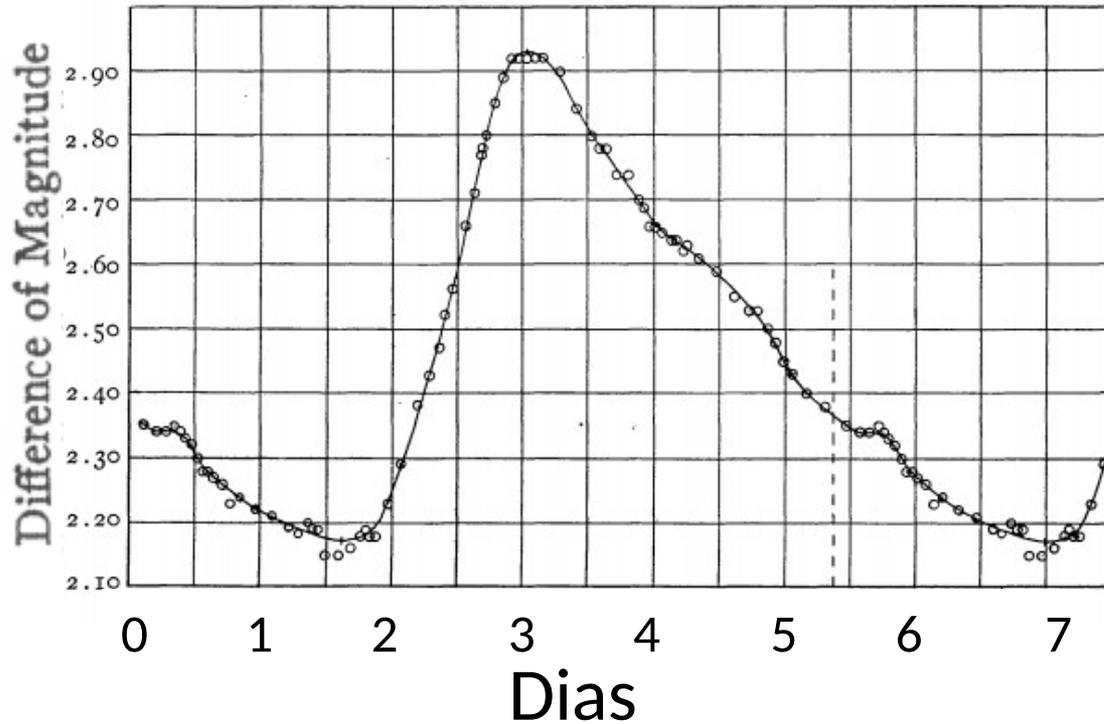


Fig. 14.2. The light curve of δ Cephei. Its pulsation period is 5.37 days.

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

XXIVth IAU General Assembly

Start date/time

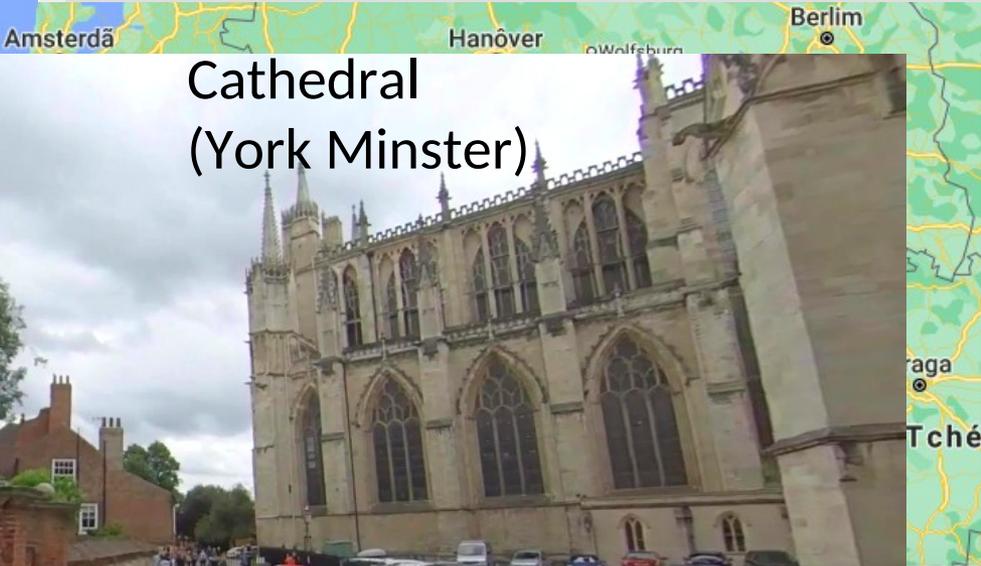
August 7, 2000

End date/time

August 19, 2000

Place

Manchester,
United Kingdom



Cathedral
(York Minster)

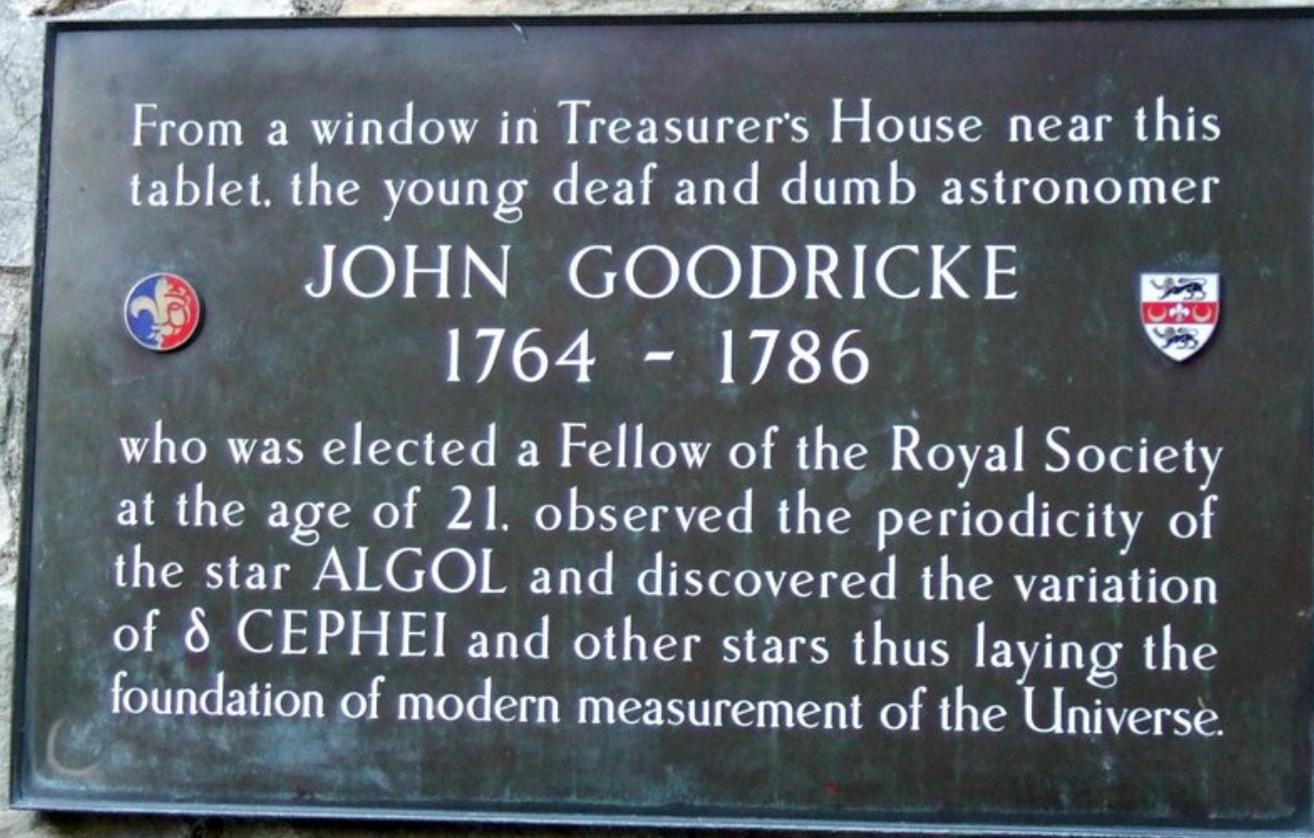


Treasurer's
house

Minster
Yard

Google

York, Inglaterra



John Goodricke
1764 - 1786

Edward Pigott: observação de possível estrela variável em 1781

Edward Pigott + John Goodricke: procura de estrelas variáveis em 1782

John: variações periódicas de Algol em 11/1782. δ Cephei em 6/1785 28

Artigo da descoberta da δ Cephei, por John Goodricke
 $P = 5,359$ d, bem próximo do período atualmente aceito (5,366 d)

II. *A Series of Observations on, and a Discovery of, the Period of the Variation of the Light of the Star marked δ by Bayer, near the Head of Cepheus. In a Letter from John Goodricke, Esq. to Nevil Maskelyne, D. D. F. R. S. and Astronomer Royal.*

Read November 24, 1785.

S I R,

York, June 28, 1785.

Having now delivered the observations, from whence I have deduced the preceding conclusions, nothing more relative to this subject remains to be mentioned, except the determination of the period; in the doing of which I must follow nearly the same methods as have been used in some preceding papers.

D. H. M.

5 8 37 $\frac{1}{2}$

If you think this account worthy of notice, I beg you will be so kind as to communicate it to the Royal Society.

I remain, with great regard, &c.

JOHN GOODRICKE.



Henrietta
Leavitt
Relação brilho -
luminosidade
em 1912,
usando cefeidas
da Pequena
Nuvem de
Magalhães

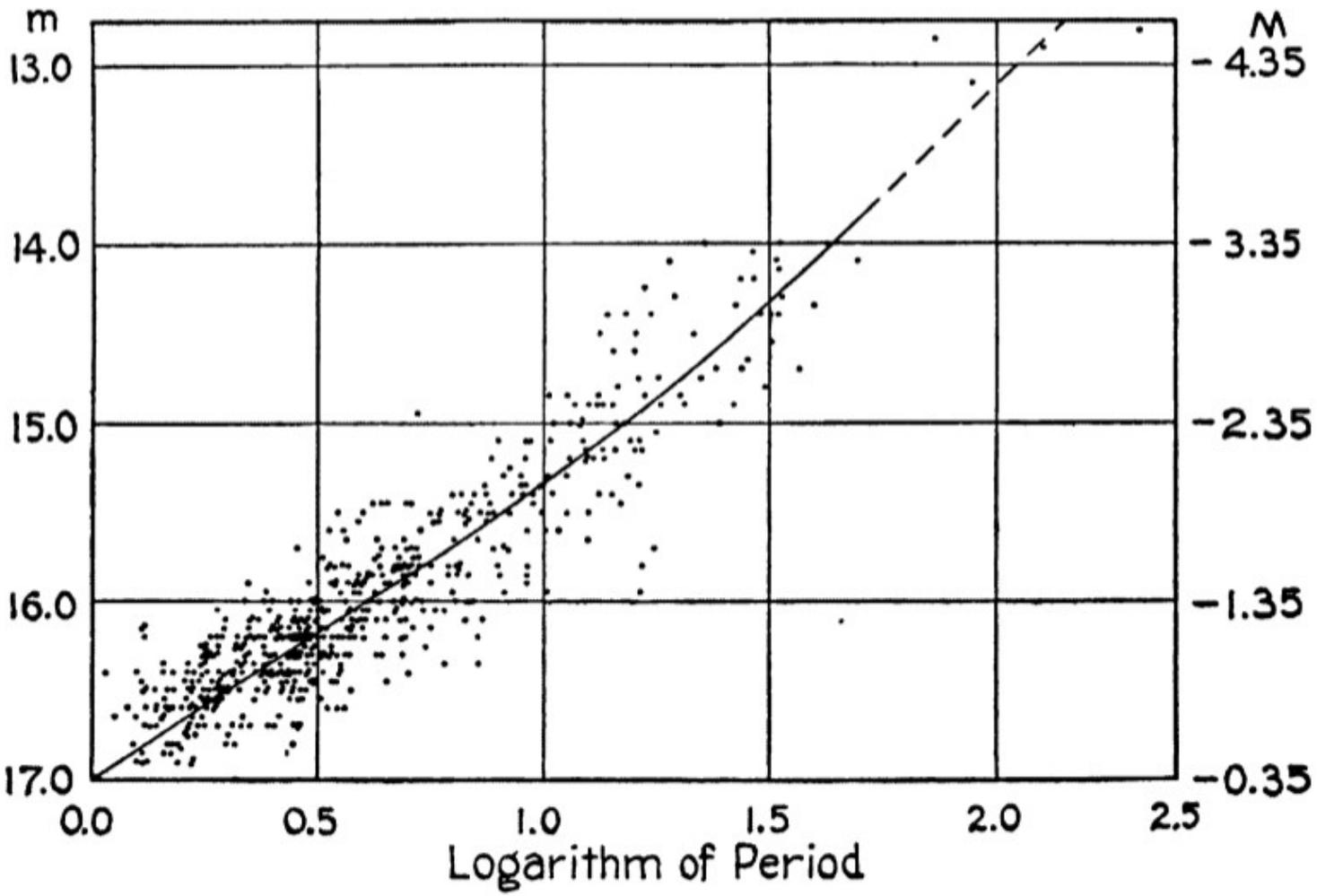


FIGURE 14.4 Classical Cepheids in the Small Magellanic Cloud, with the period in units of days. (Figure from Shapley, *Galaxies*, Harvard University Press, Cambridge, MA, 1961.)

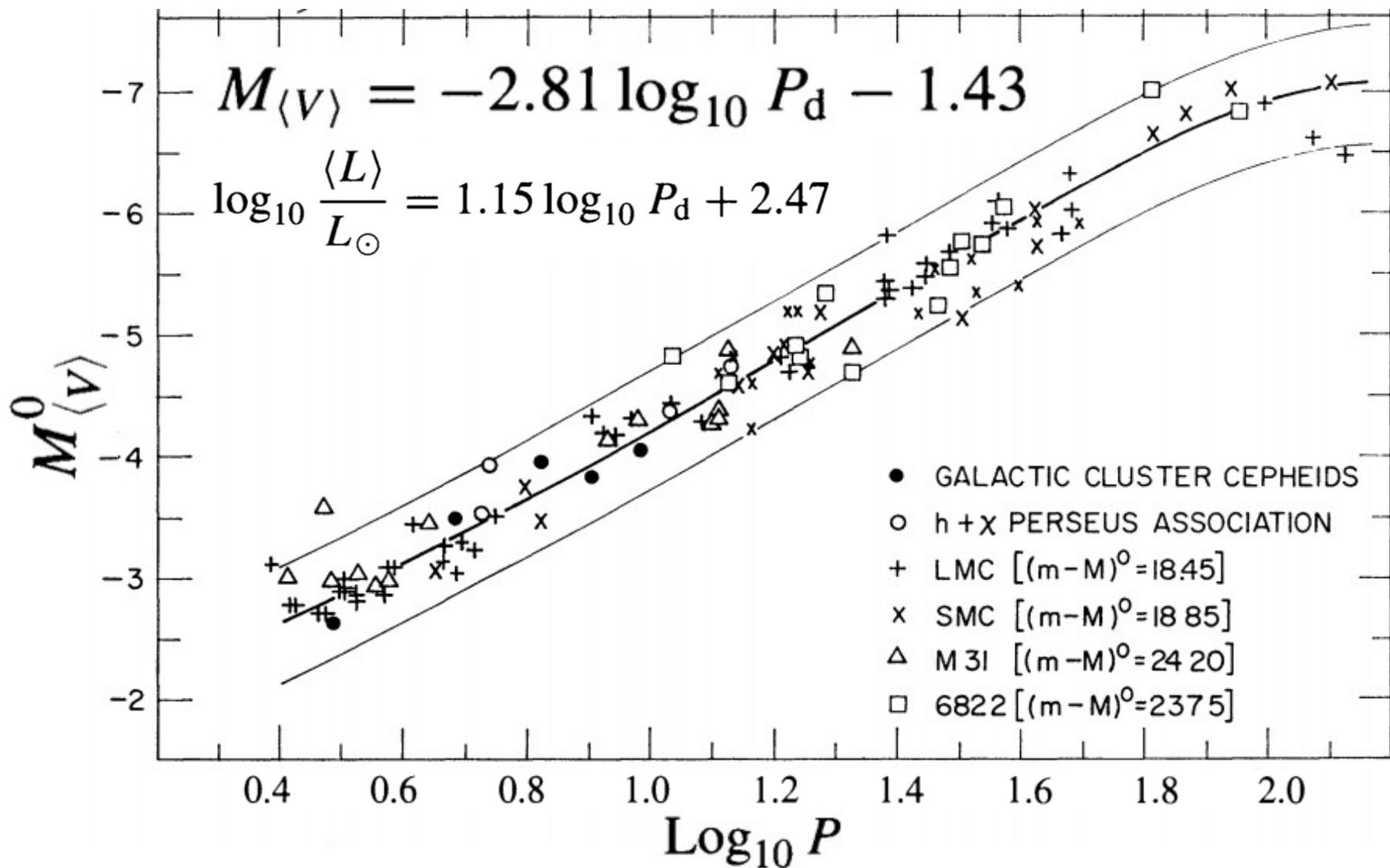


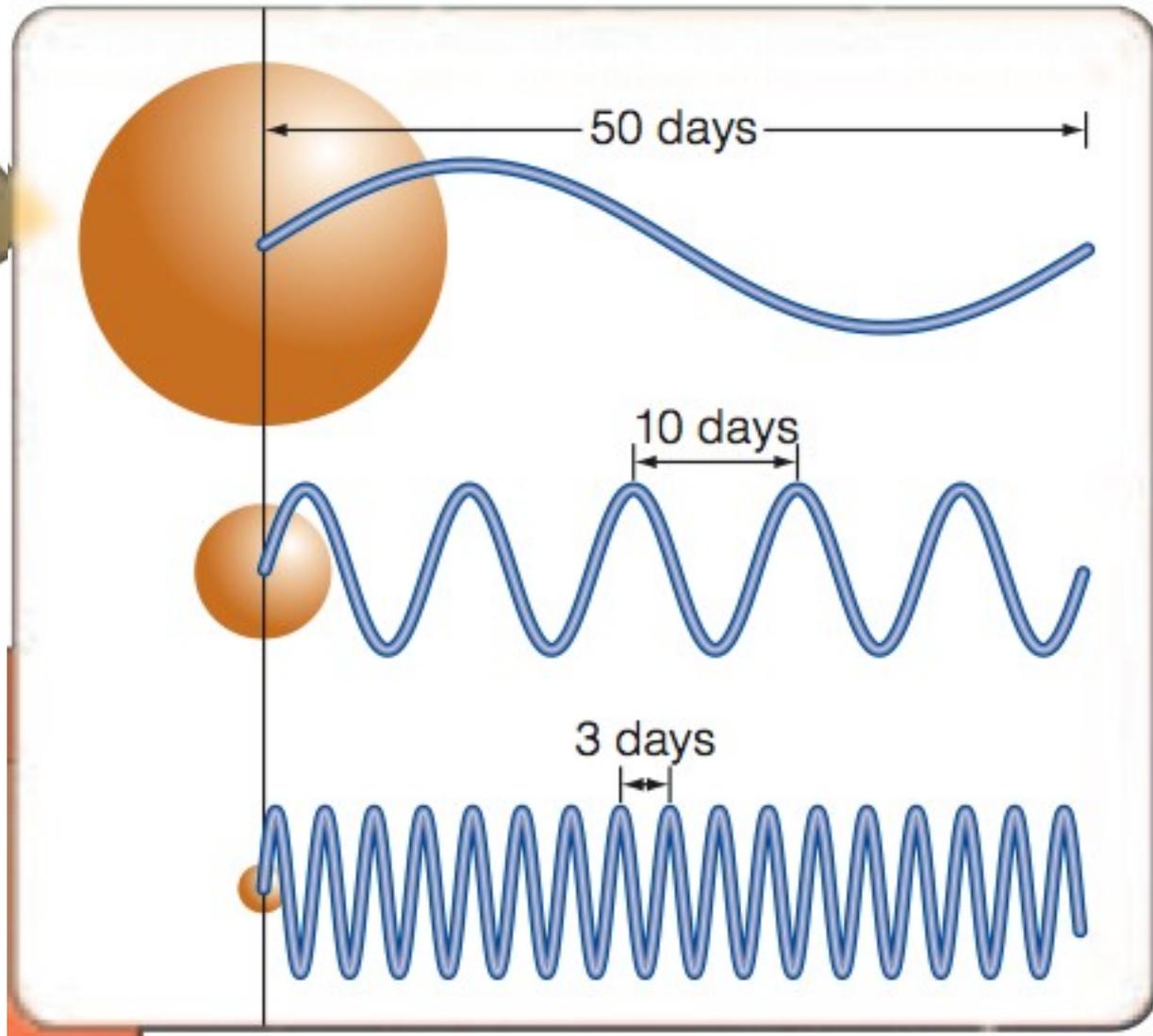
FIGURE 14.5 The period–luminosity relation for classical Cepheids. (Figure adapted from Sandage and Tammann, *Ap. J.*, 151, 531, 1968.)

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

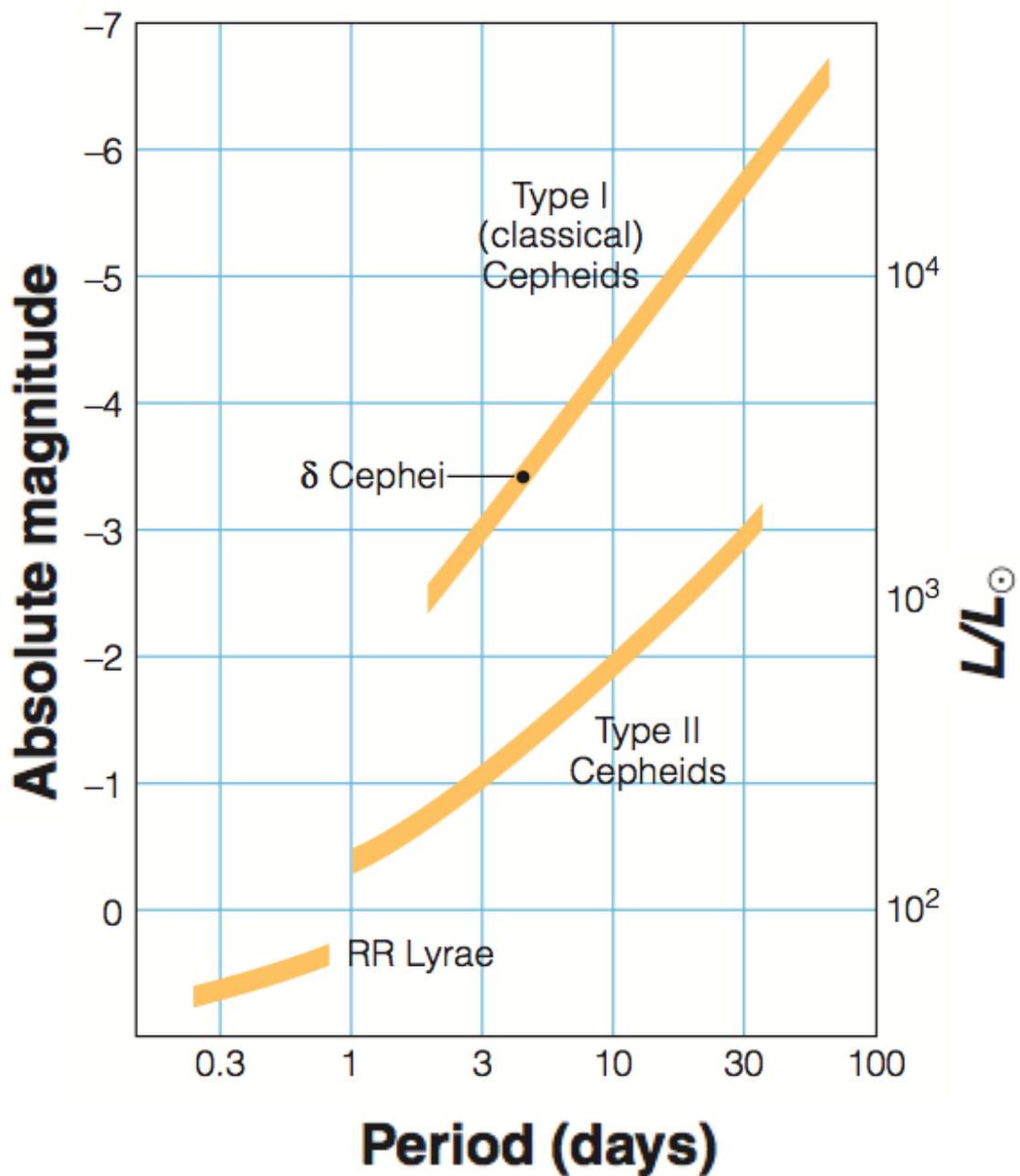
Período de oscilação: (14.6)

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

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



© Foundations of Astronomy

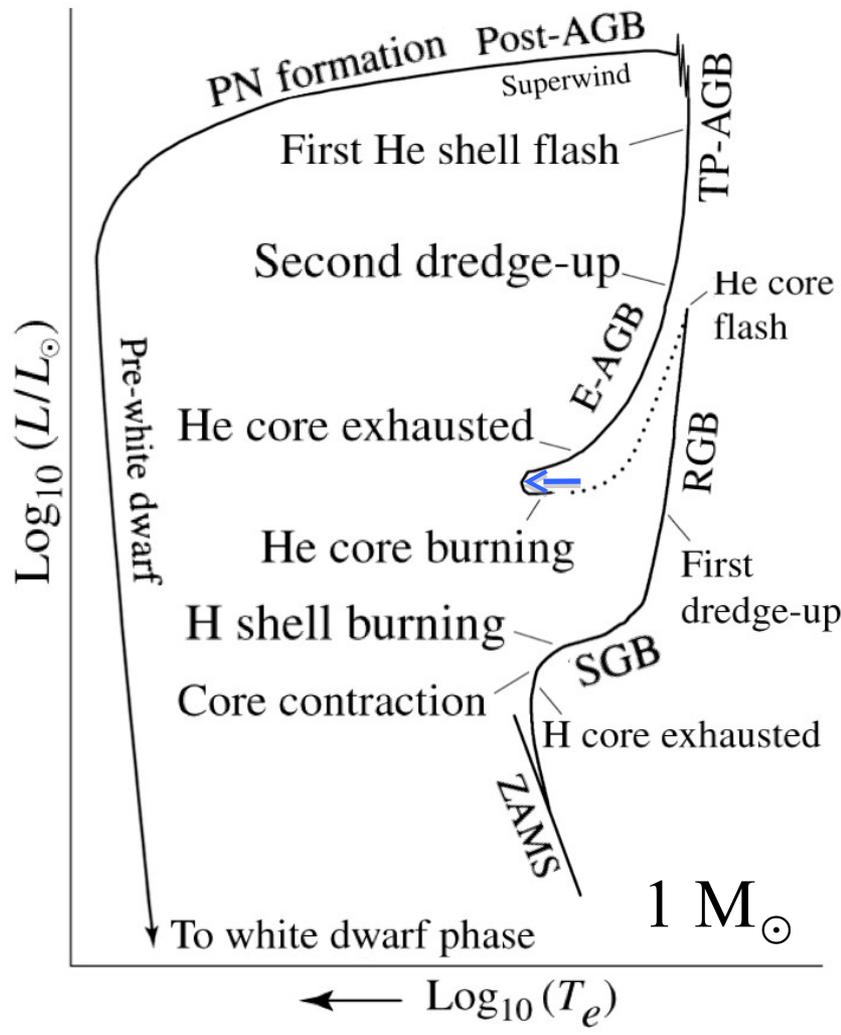
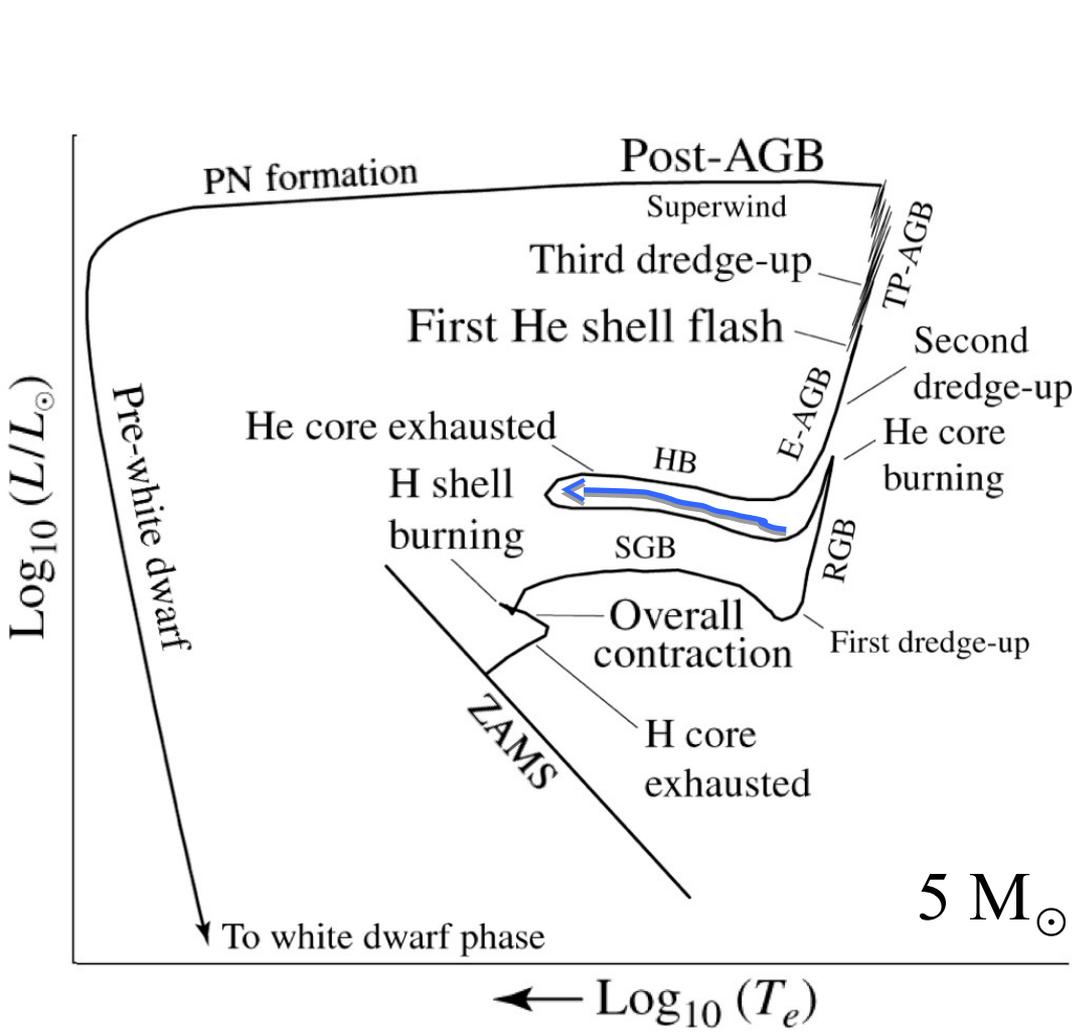


Período de oscilação: $\Pi \approx \sqrt{\frac{3\pi}{2\gamma G\rho}}$ (14.6)

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

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

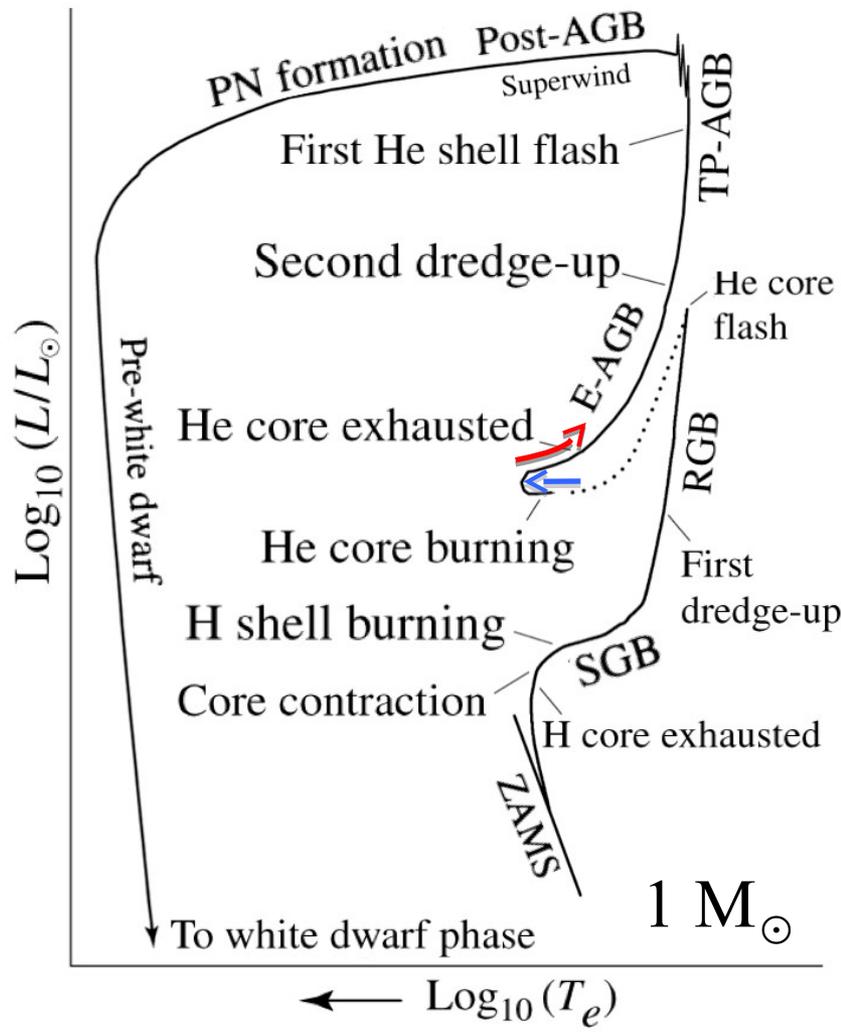
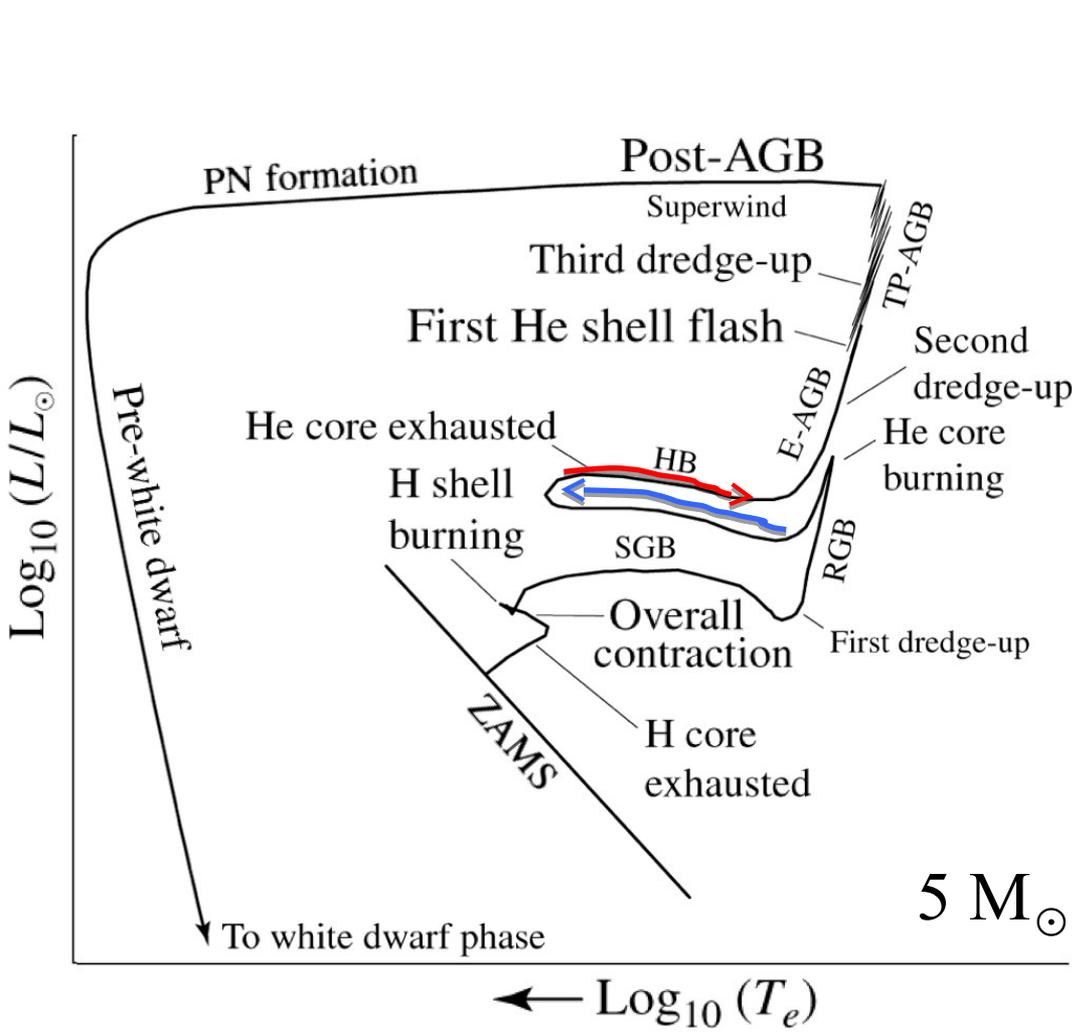
$$P_g = \frac{\rho k T}{\mu m_H}$$



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

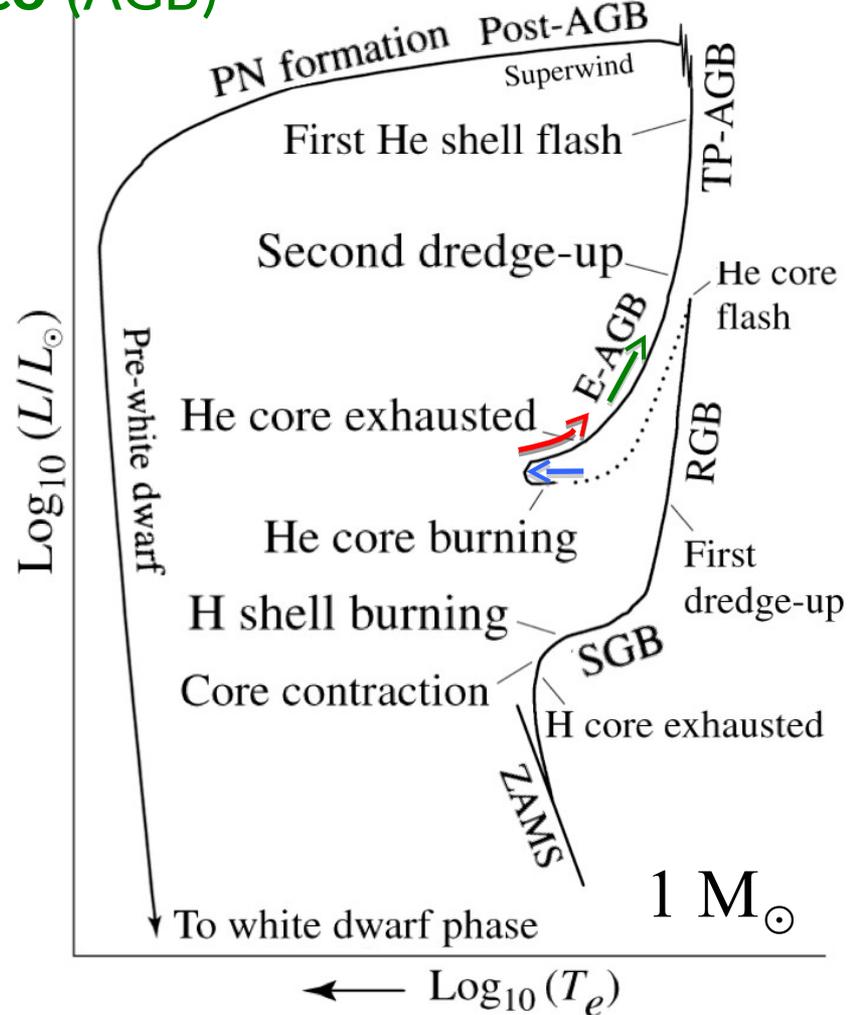
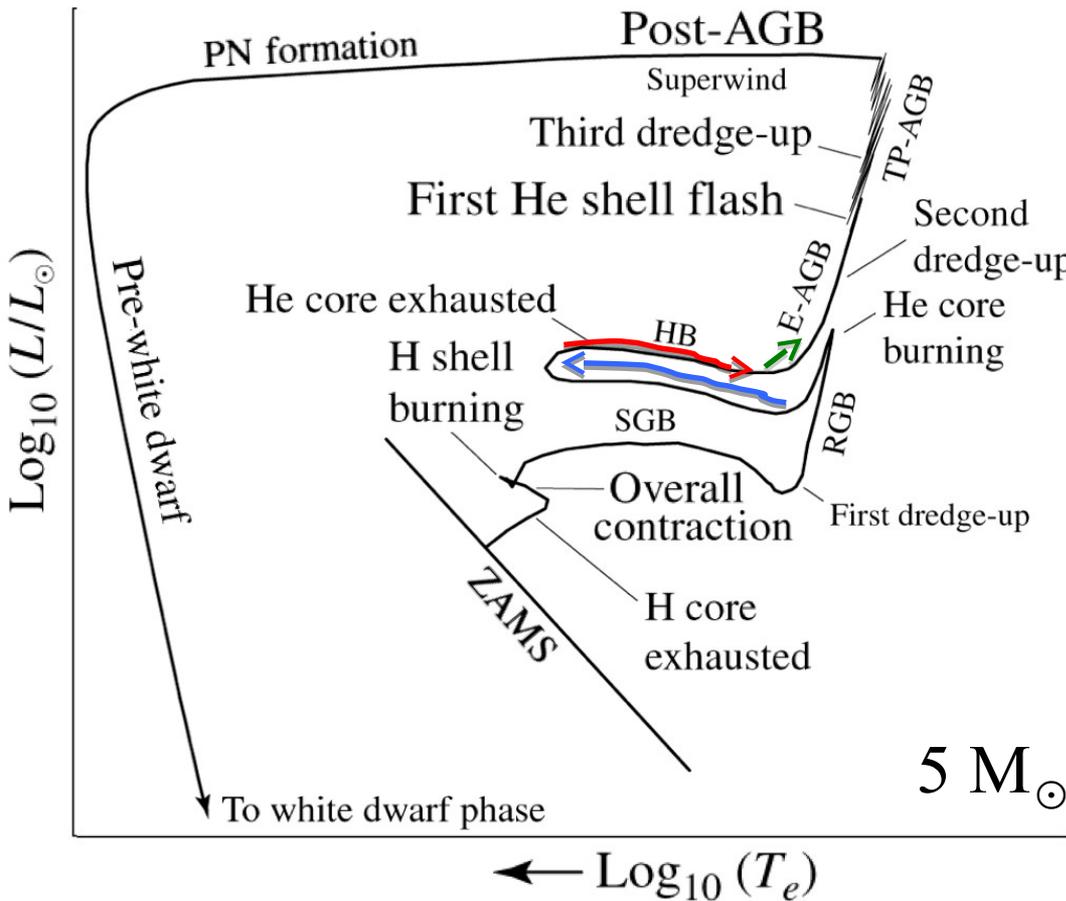


No lado azul “sequência principal” de queima do He, depois μ muito alto \rightarrow núcleo He em contração.

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

\rightarrow Expansão do envelope e percurso para o vermelho

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



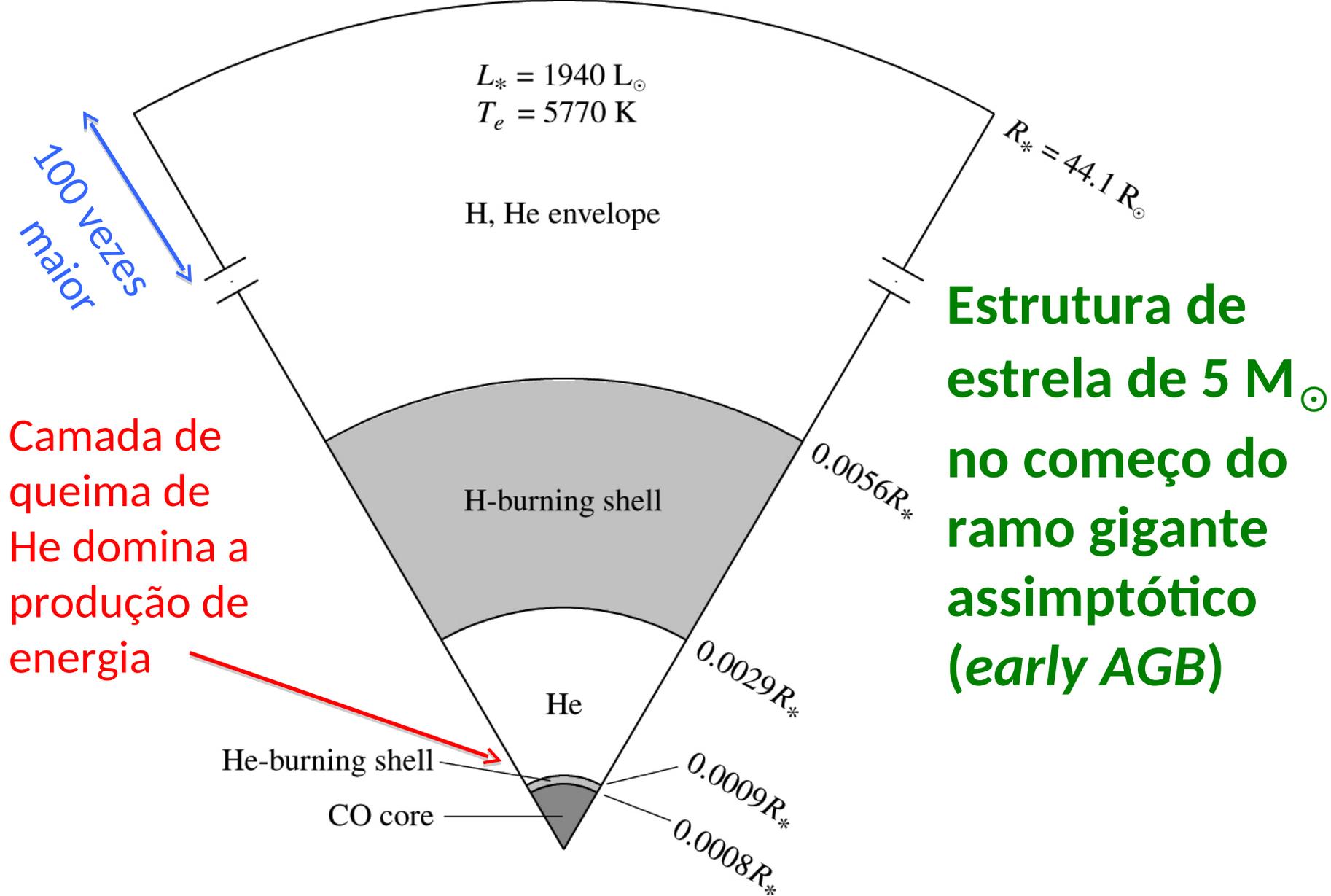
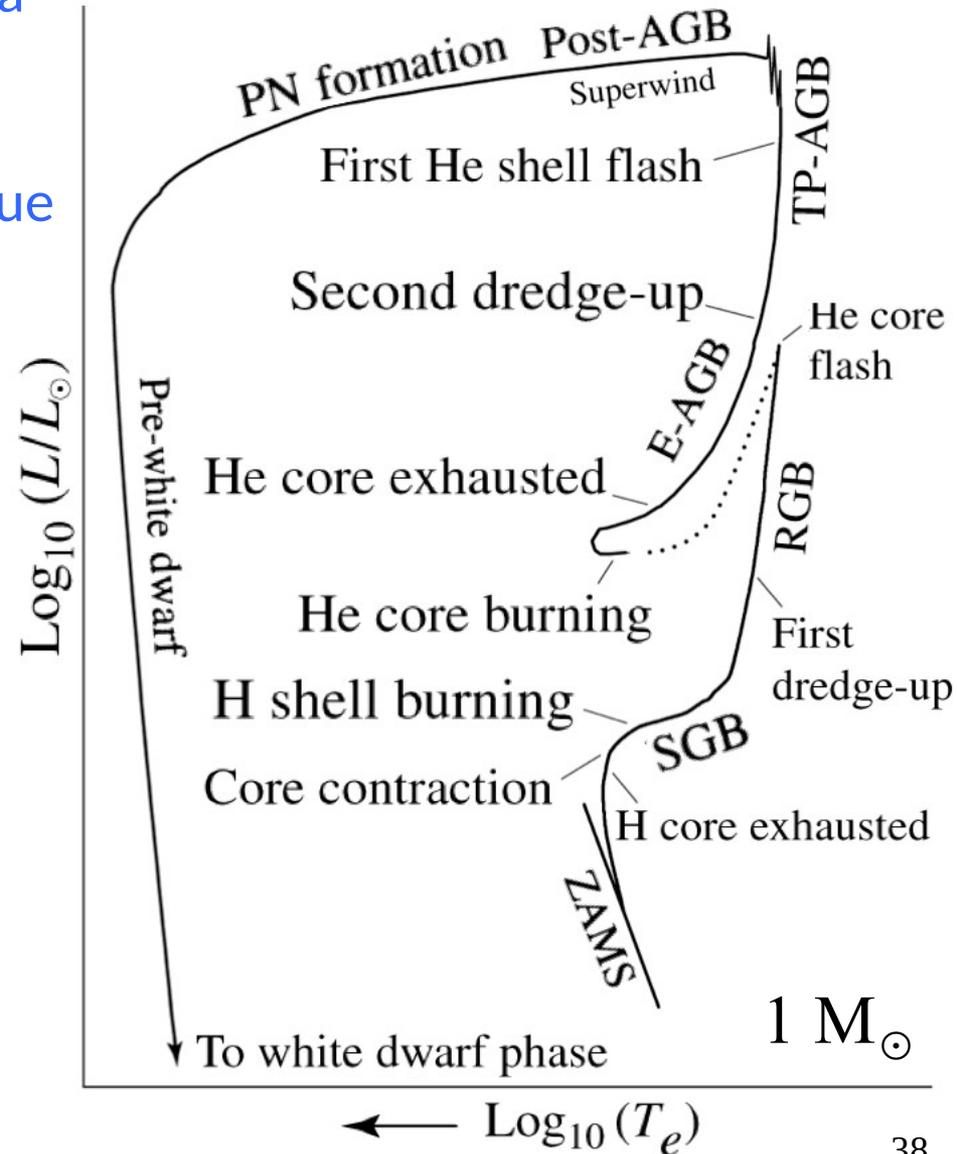
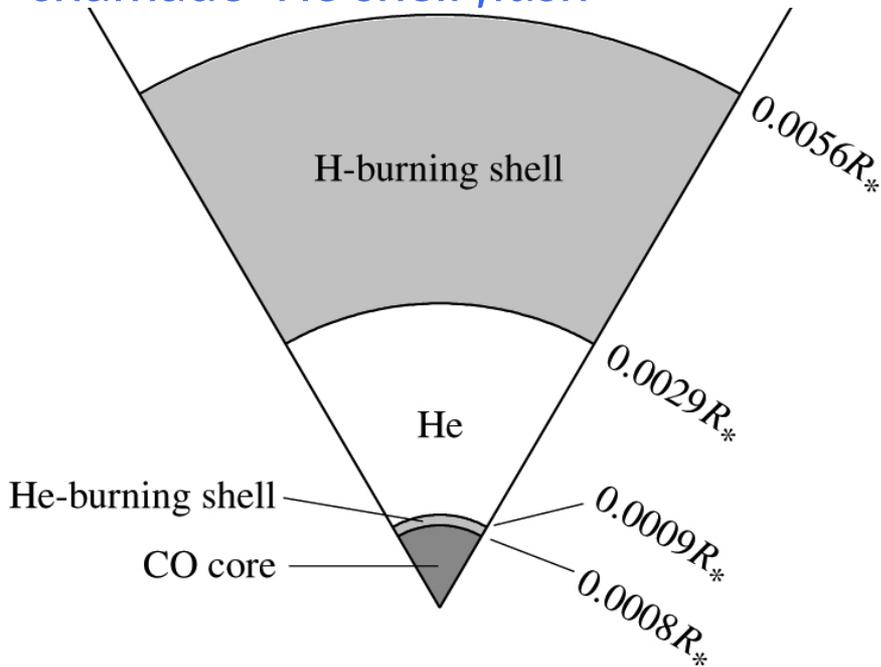
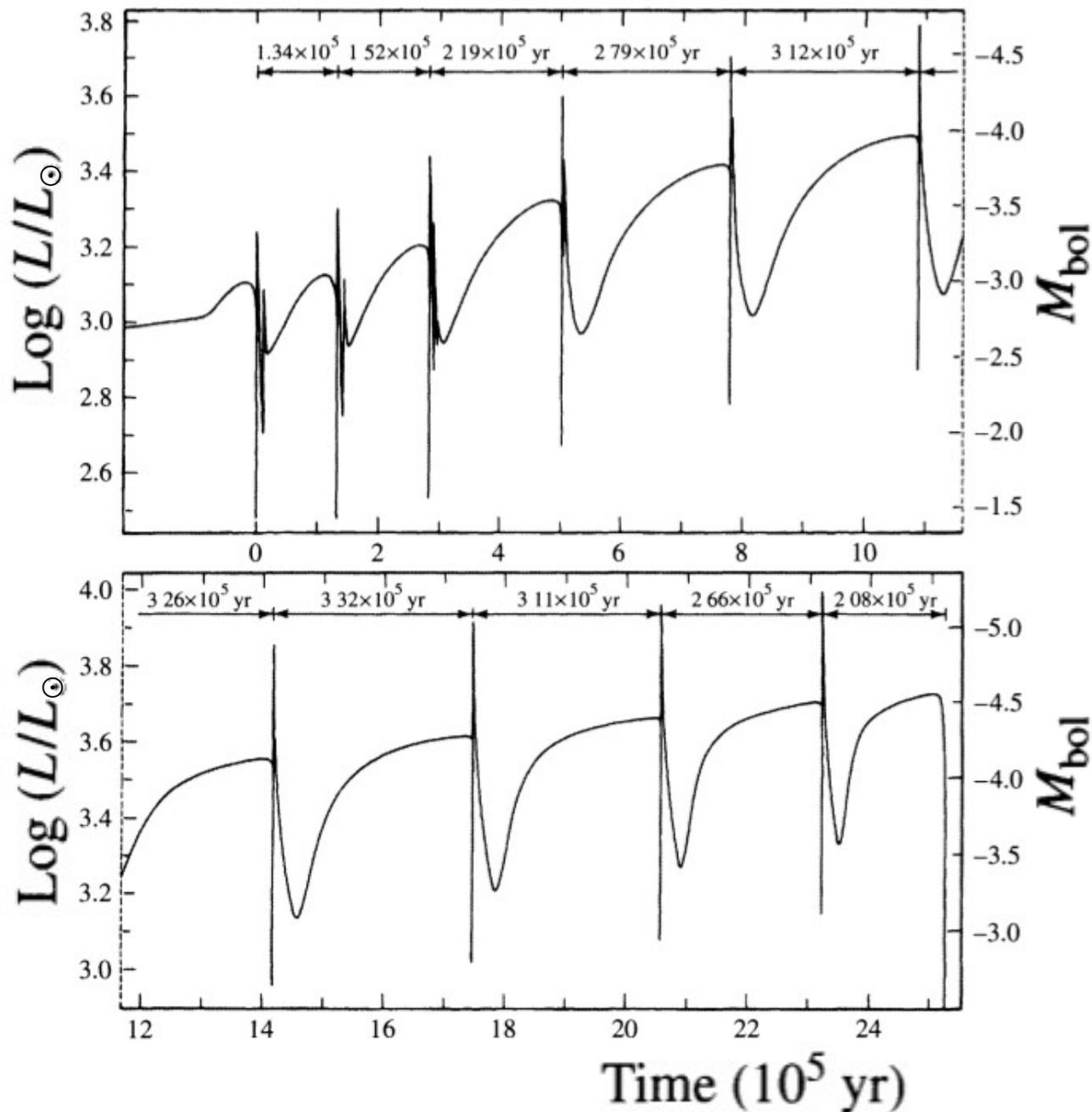


FIGURE 13.8 A $5 M_{\odot}$ star on the early asymptotic giant branch with a carbon–oxygen core and hydrogen- and helium-burning shells. Note that relative to the surface radius, the scale of the shells and core has been increased by a factor of 100 for clarity. (Data from Iben, *Ap. J.*, 143, 483, 1966.) 37

Pulsos térmicos no AGB: The Thermal-Pulse AGB

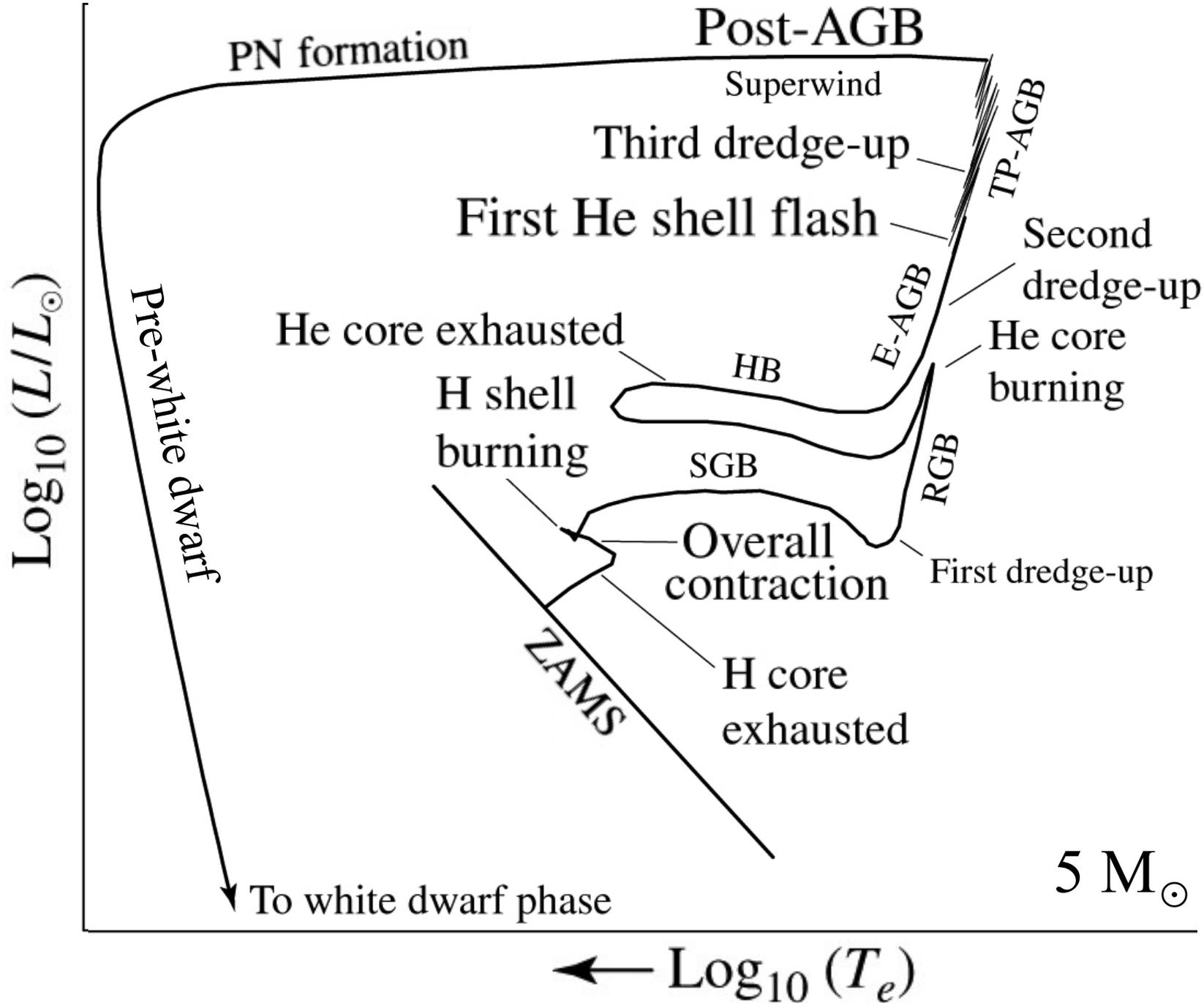
Devido à energia pela queima de hélio → expansão da camada de He → a casca de queima de H desliga → estrela em contração, reativando a camada de queima de H, que despeja cinza de He na camada de He abaixo, que vai se tornando degenerada. Quando T na base da camada de He aumenta o suficiente → queima explosiva, o chamado 'He shell flash'





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

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.) 39



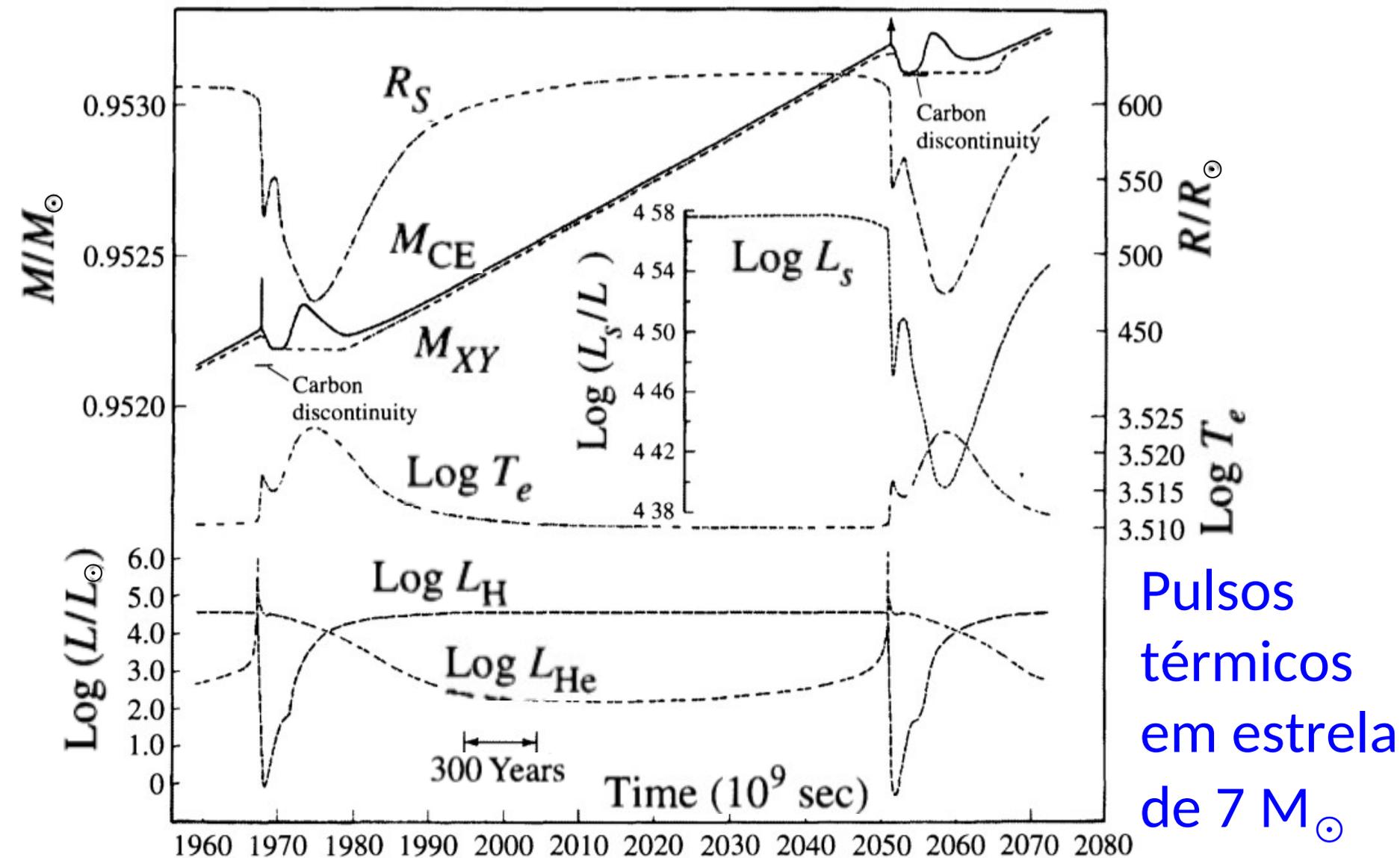
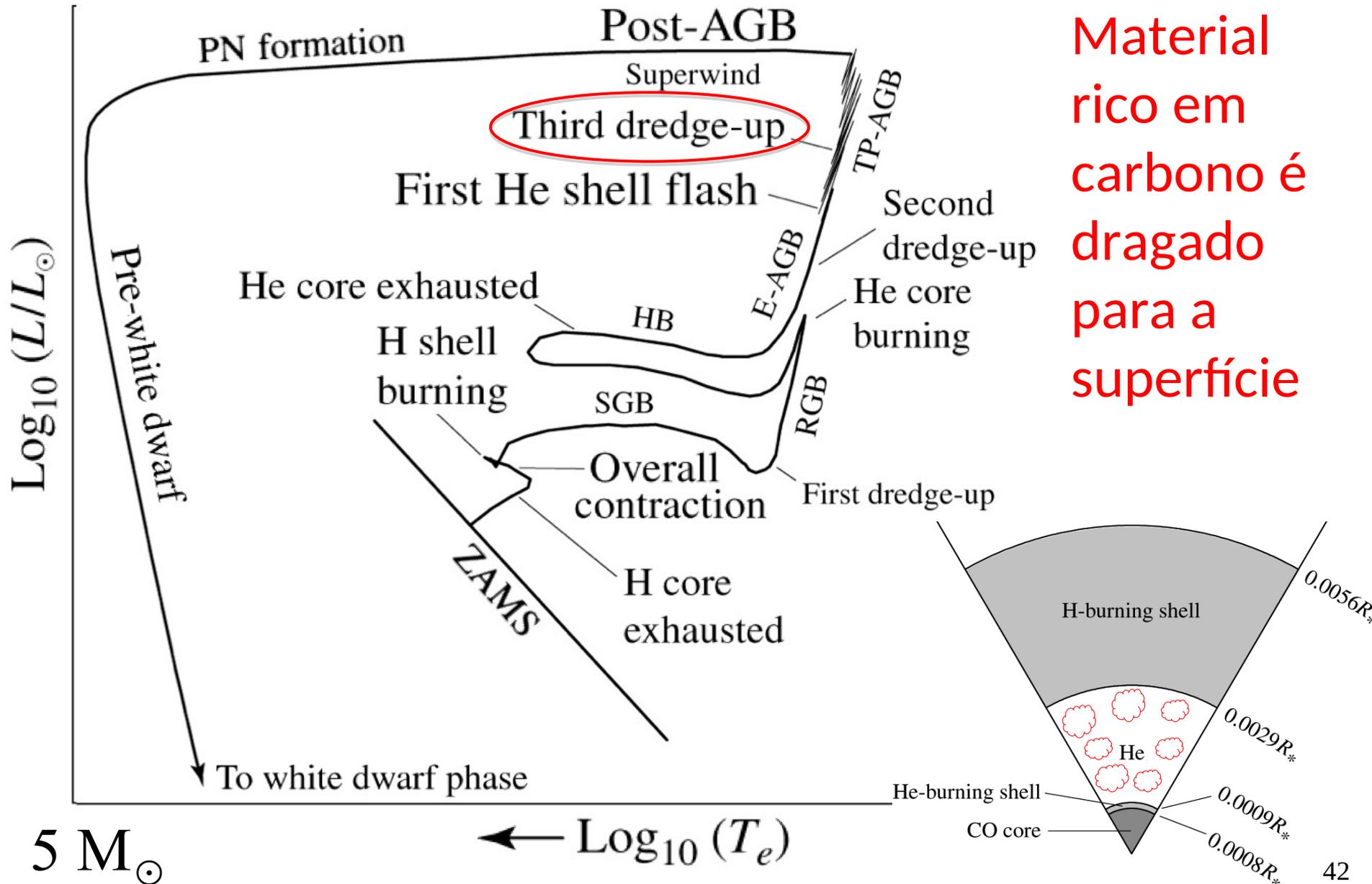
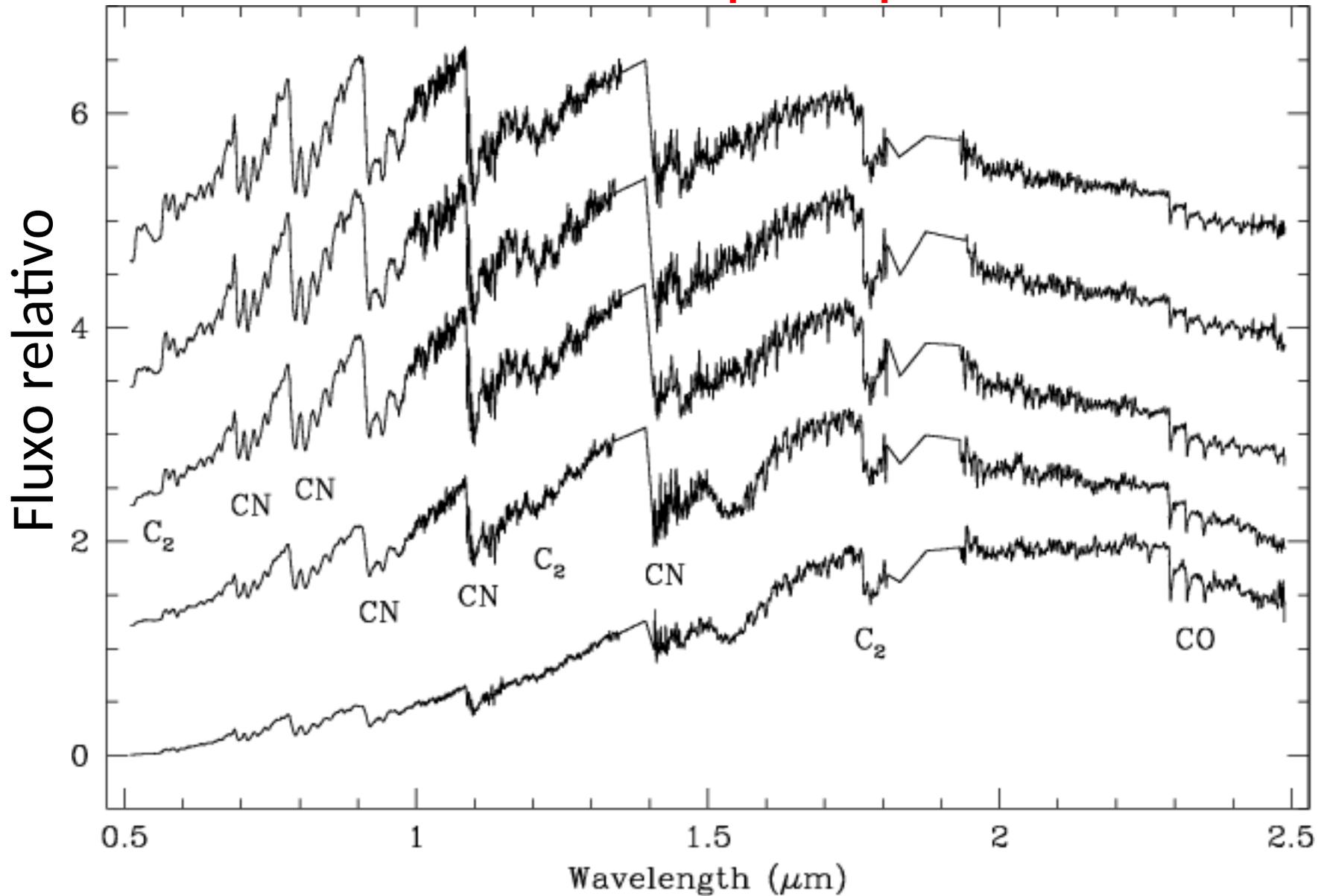


FIGURE 13.10 Time-dependent changes in the properties of a $7 M_{\odot}$ AGB star produced by helium shell flashes on the TP-AGB. The quantities shown are the surface radius (R_S), the interior mass fractions of the base of the convective envelope (M_{CE}) and the hydrogen–helium discontinuity (M_{XY}),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

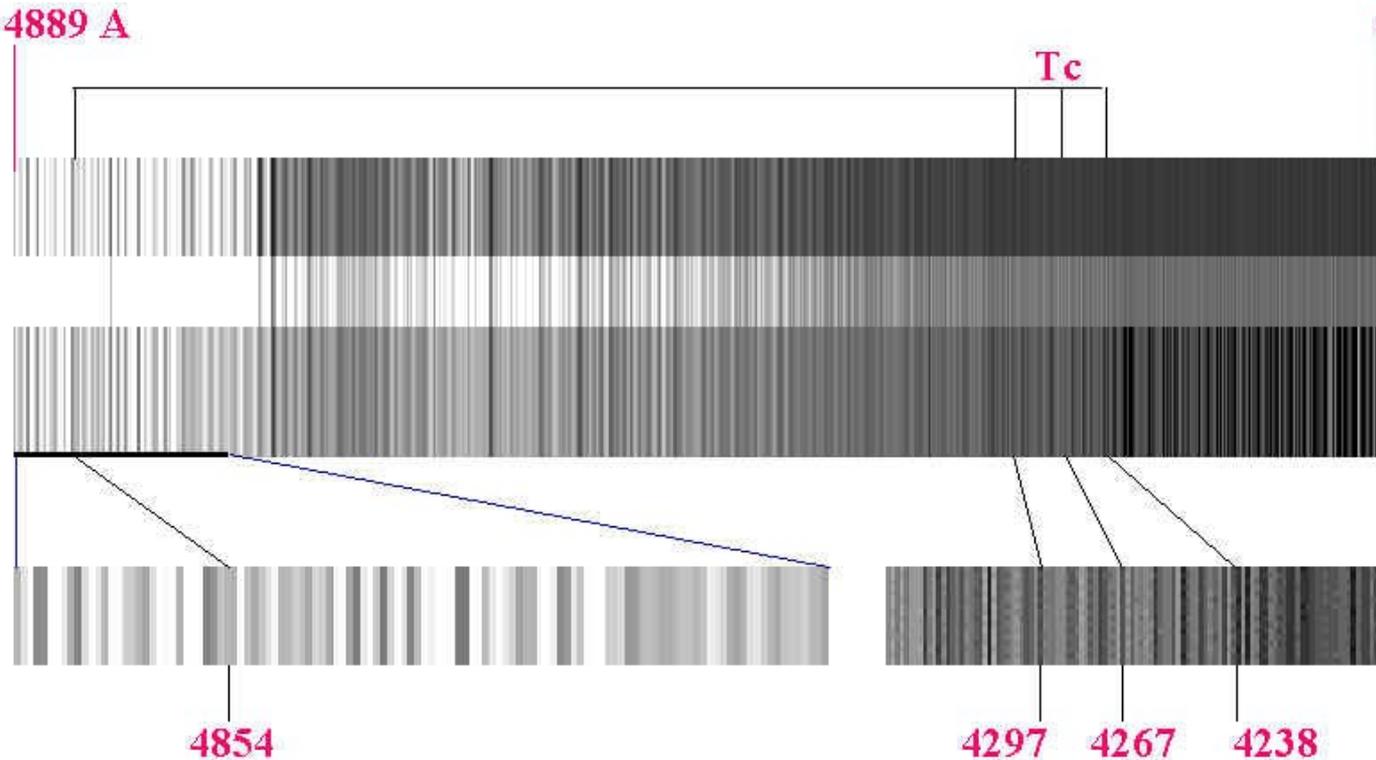
Terceira dragagem: *Third dredge-up*



Carbon stars: tipo espectral C



Identification of Technetium in 19 Piscium C5 II star, 4.95 magnitude

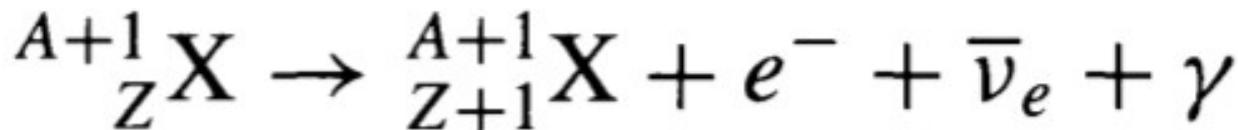
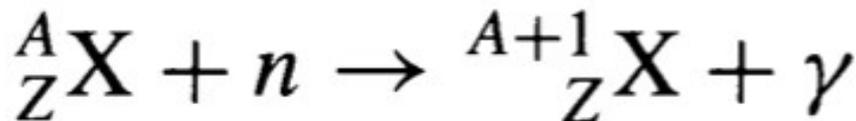
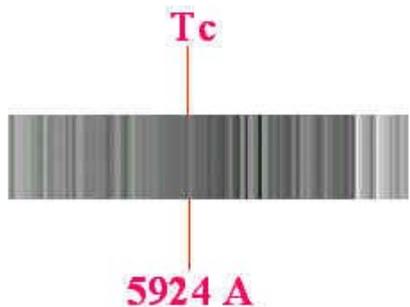
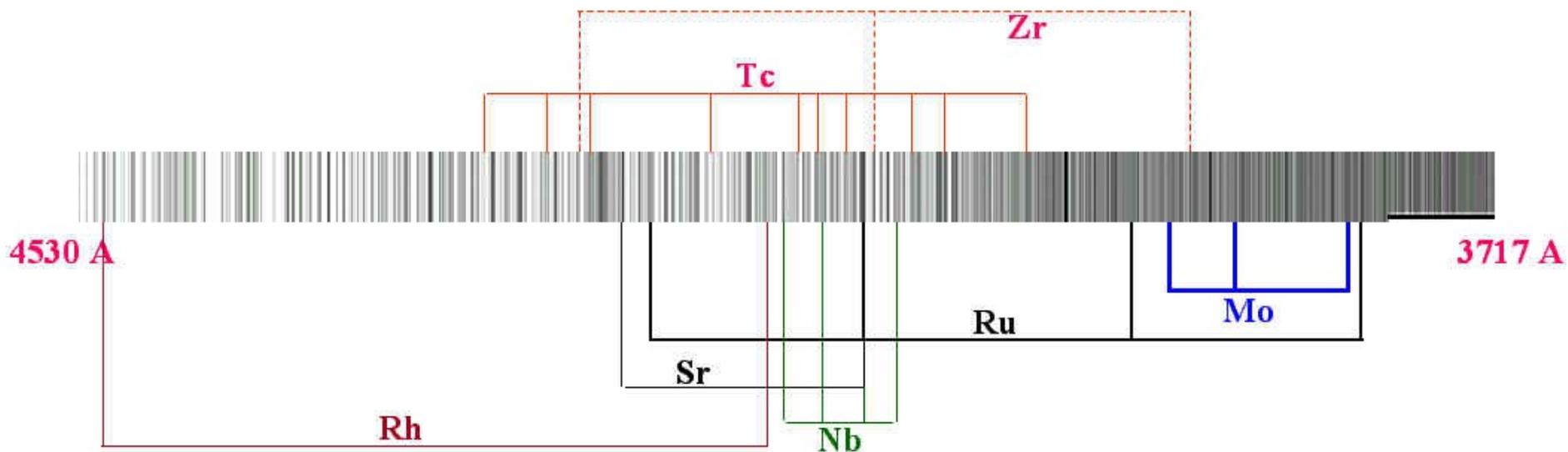


Tc-99 é o isótopo mais abundante de Tc. Tempo de vida é de apenas ~ 200 000 anos. Tc é observado em estrelas AGB → foi produzido “recentemente”

⁴³Tc : no stable isotopes
 Tc⁹⁷ $t_{1/2} = 2.6 \times 10^6$ years
 Tc⁹⁸ $t_{1/2} = 1.5 \times 10^6$ years
 Tc⁹⁹ $t_{1/2} = 2.1 \times 10^5$ years
 + various short lived isotopes

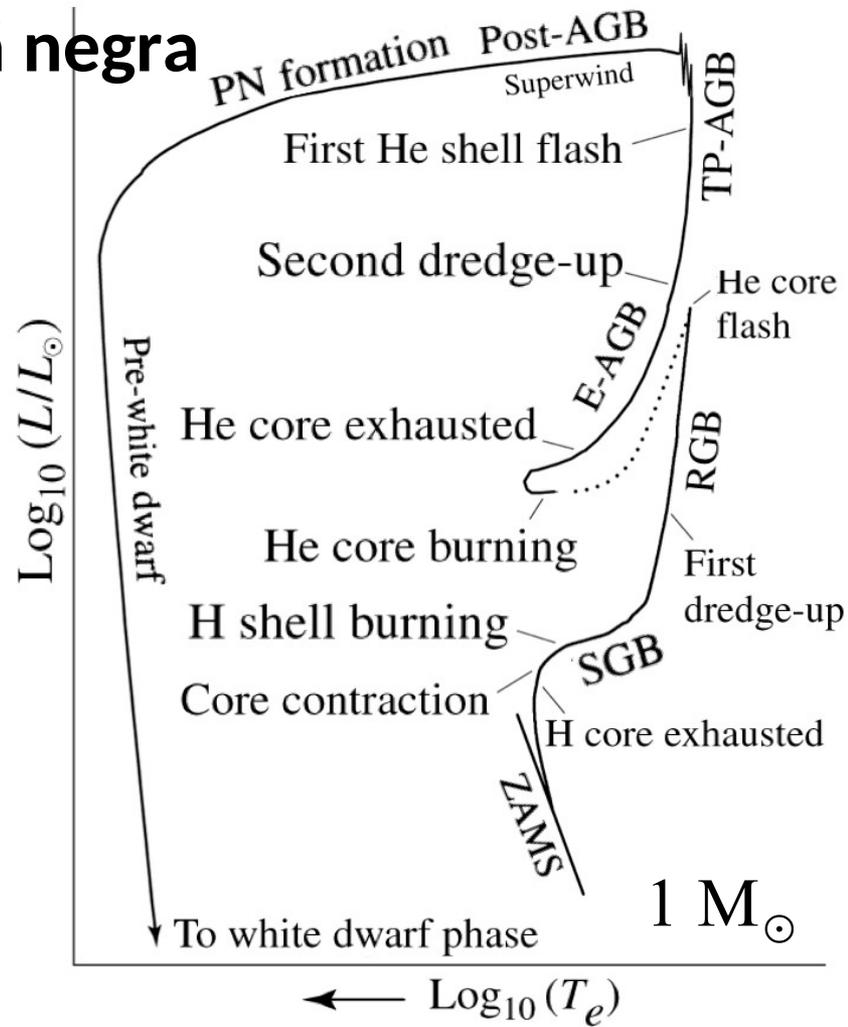
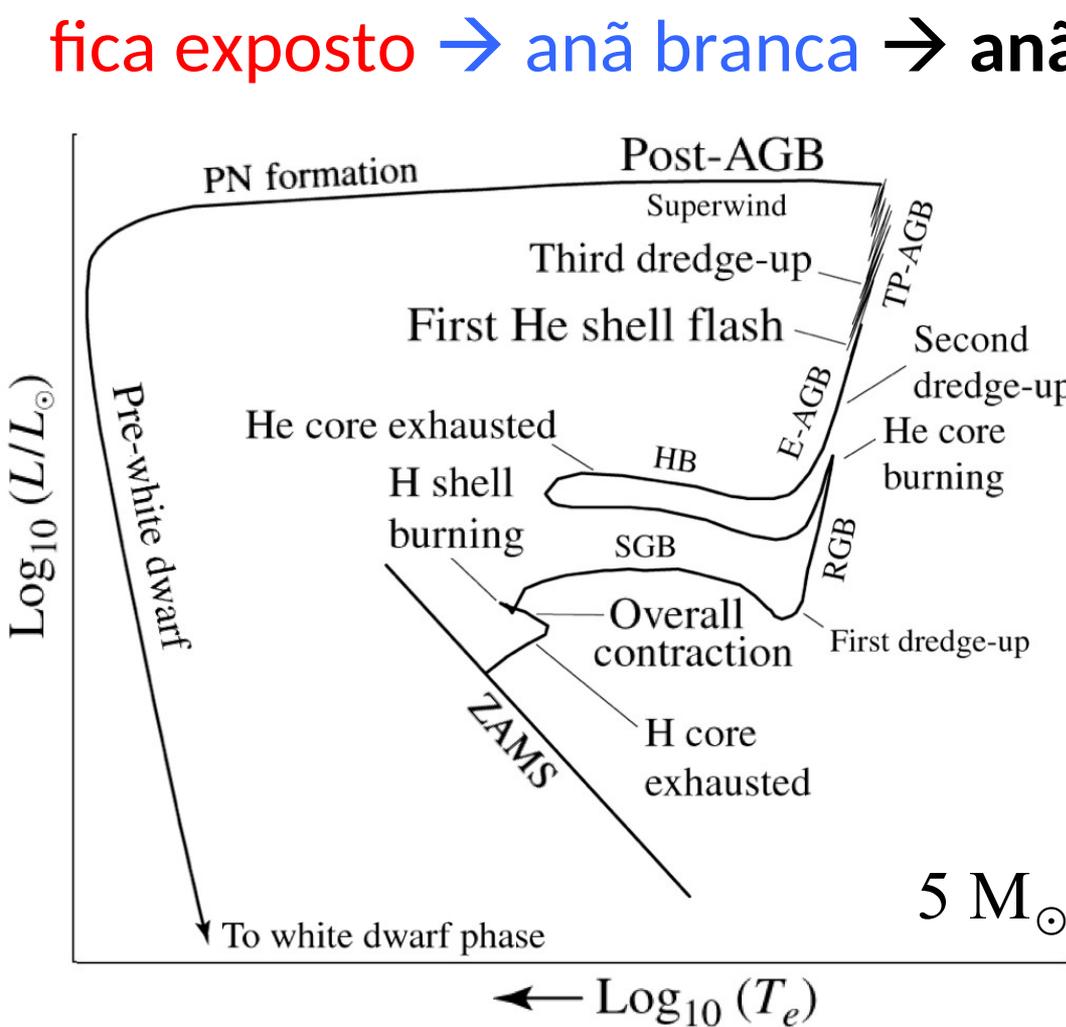
Produção de outros elementos pesados por captura de nêutrons (processo-s [slow]) em estrelas AGB

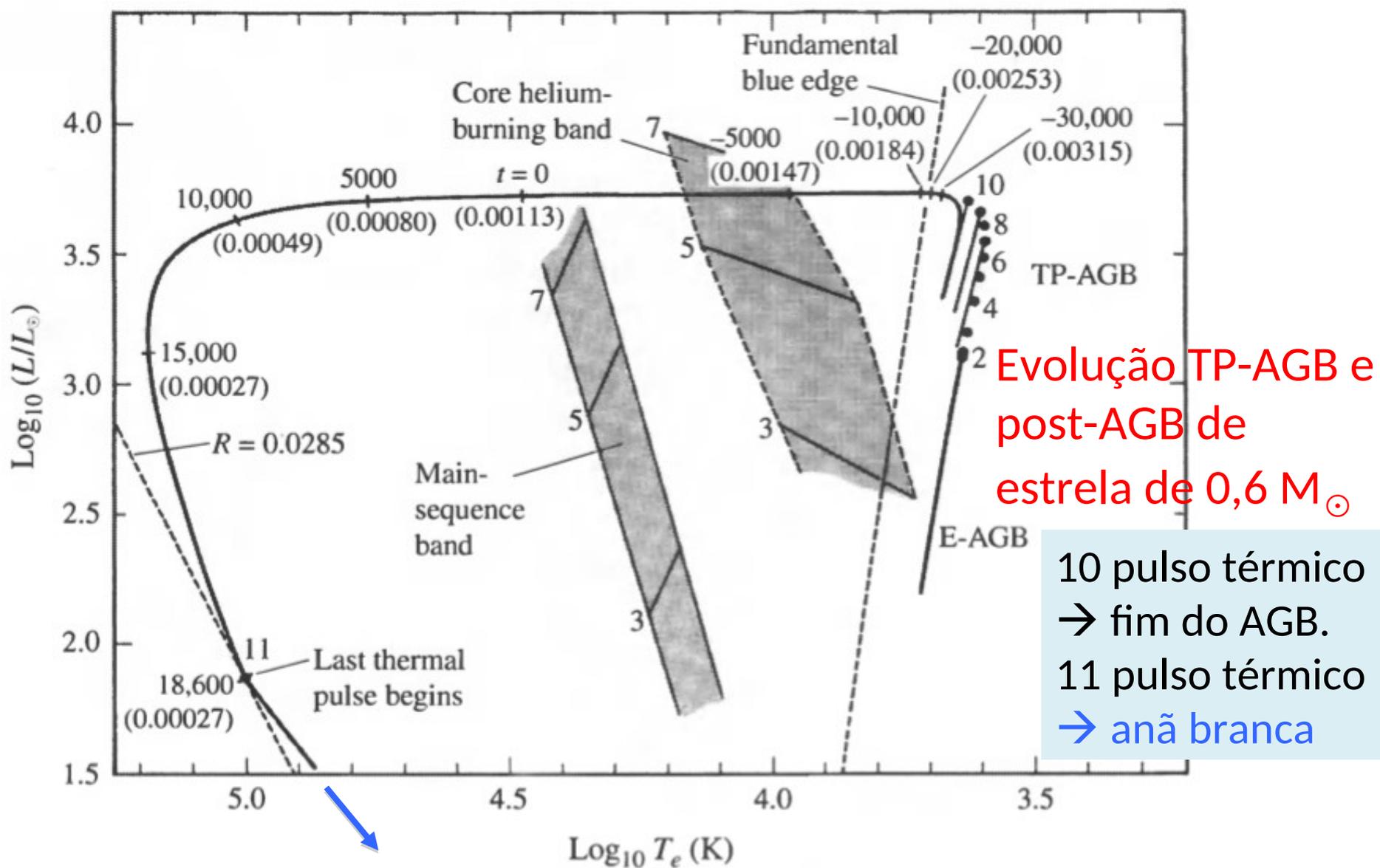
Presence of neutron-capture heavy metals near Technetium in RS Cnc



Evolução final da AGB para massa inicial $\leq 8M_{\odot}$

A perda de massa é acentuada nos pulsos térmicos: $10^{-4}M_{\odot}/\text{ano}$
 → formação de nebulosa planetária e núcleo degenerado
 fica exposto → anã branca → anã negra

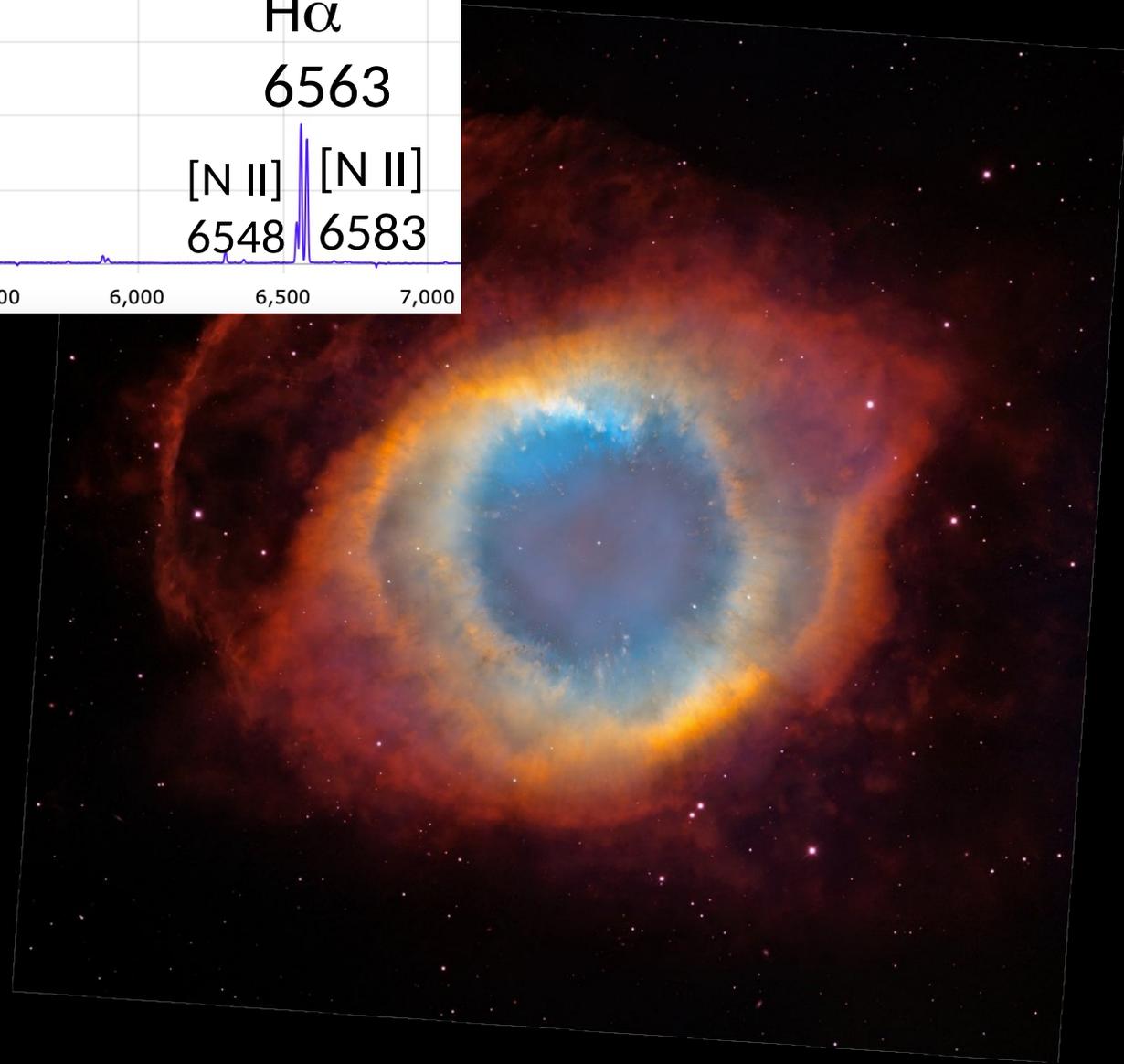
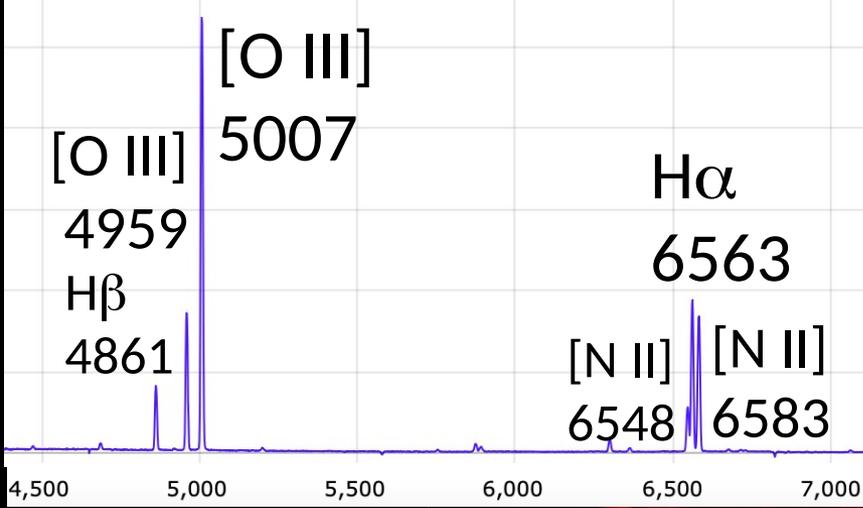




Evolução TP-AGB e post-AGB de estrela de $0,6 M_{\odot}$

10 pulso térmico → fim do AGB.
 11 pulso térmico → anã branca

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 (NGC 7293)

(c) Hubble + CTIO 4m 48



74h com telescópio pequeno (20cm)

<https://apod.nasa.gov/apod/ap190213.html>

Helix Planetary Nebula (NGC 7293). [O III] + H α © Andrew Campbell 2018 49

NGC 6543. Nebulosa Olho de gato Cat's eye Planetary Nebula



(c) NASA/ESA Hubble

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

Filters: F502N [O III], FR505N [O III], F658N (H α + [N II])

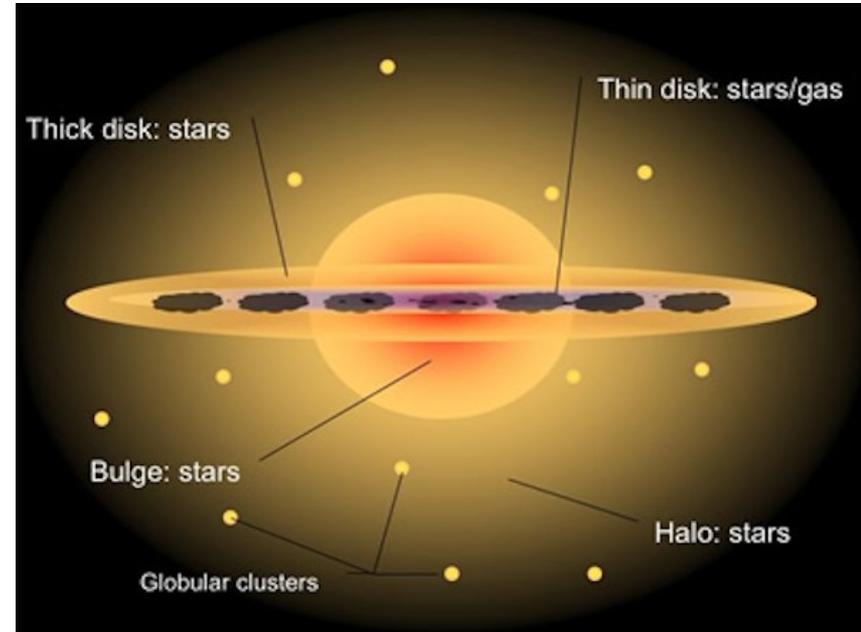
Aglomerados estelares e Populações estelares

- **População III:** $Z = 0$ (hypothetical)
- **População II:** estrelas muito antigas e pobres em metais ($Z < 0,002$). 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

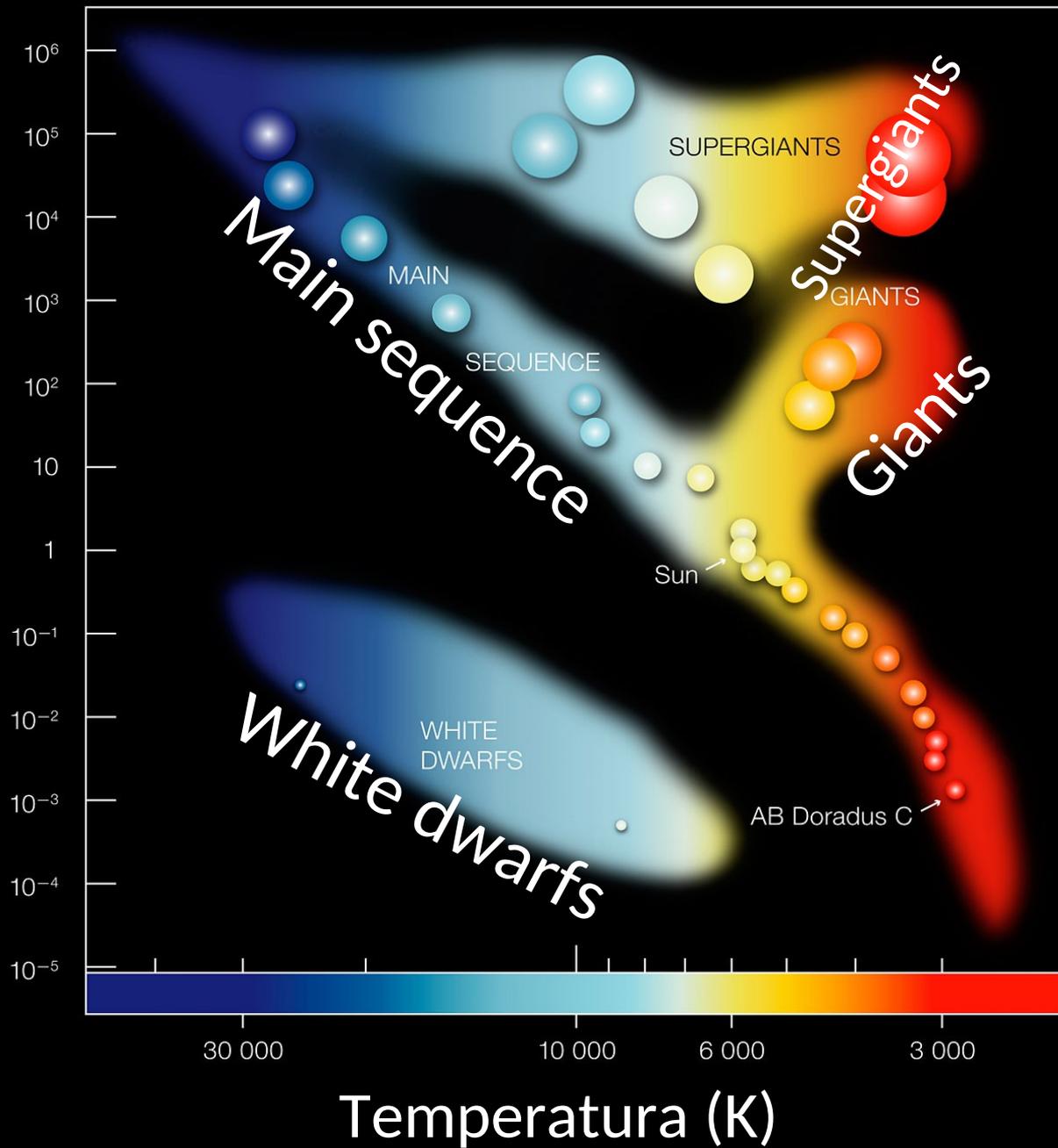


Plêiades

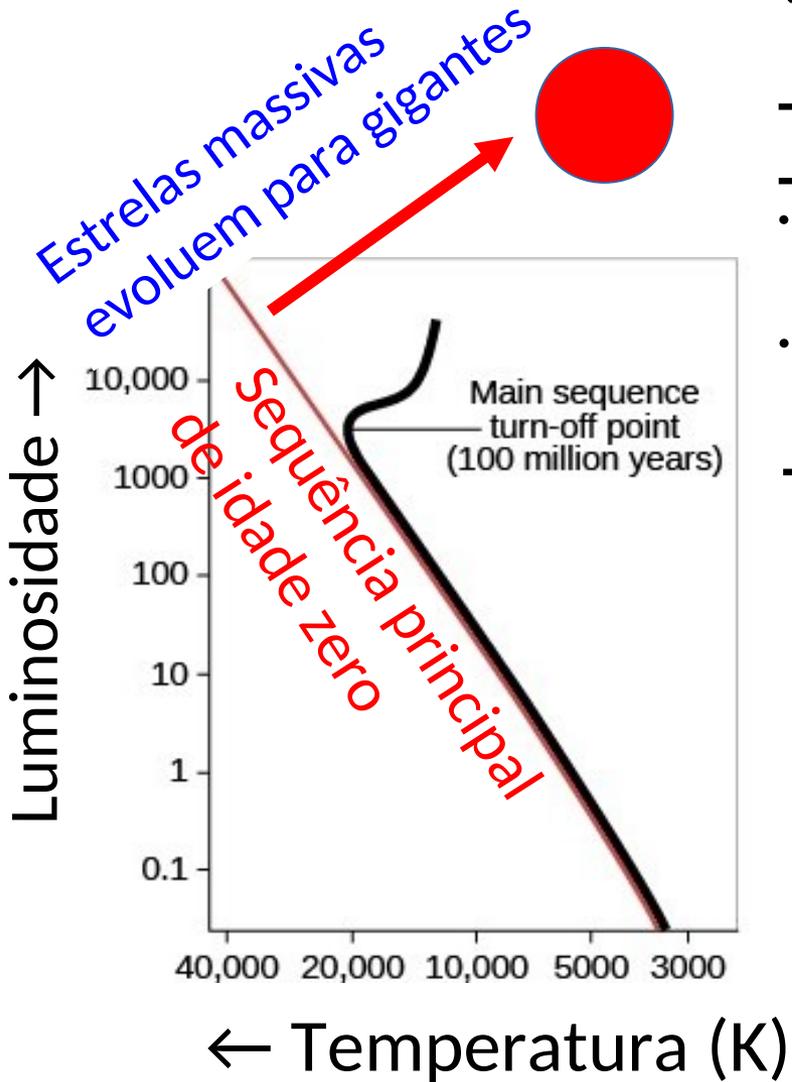


Luminosidade (L_{\odot})

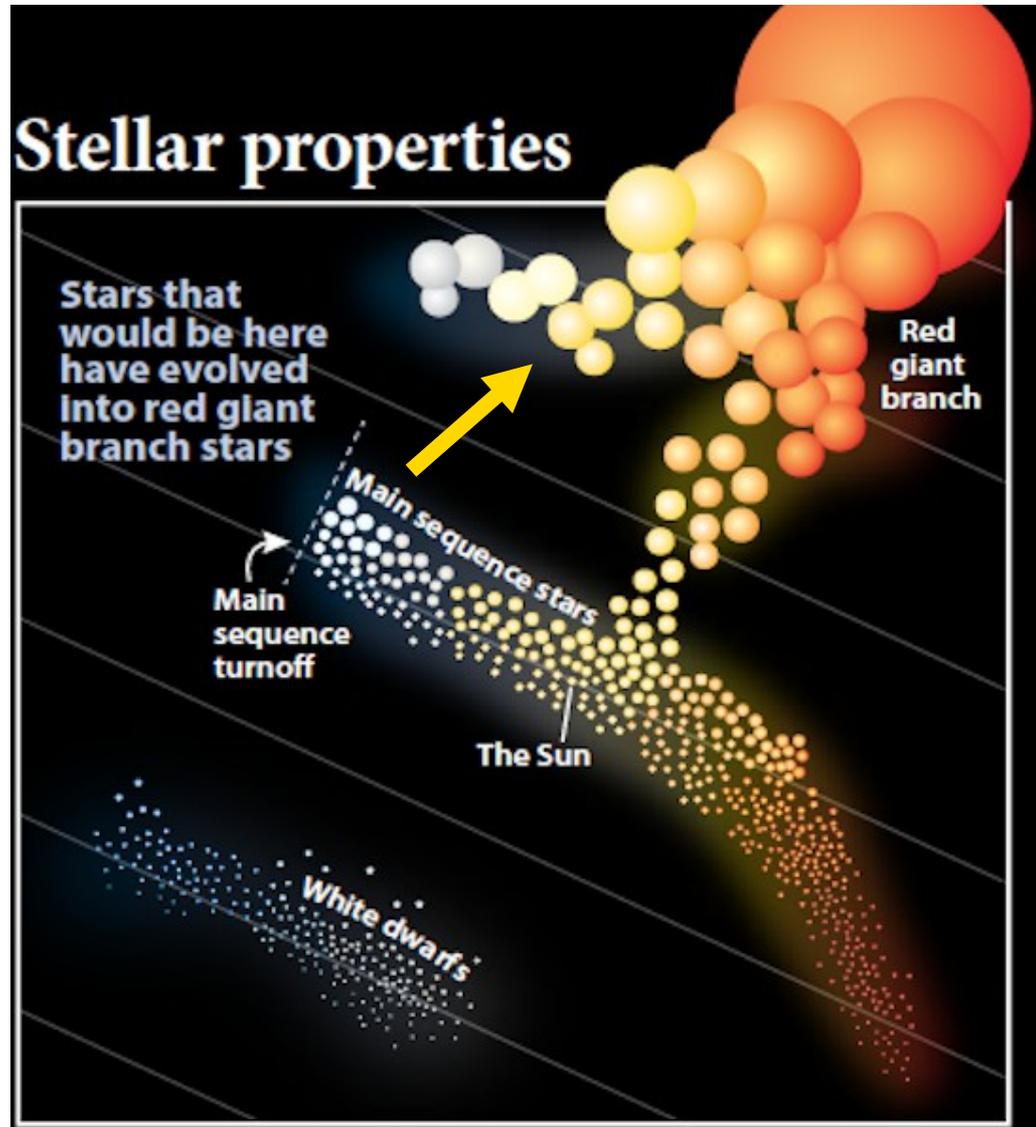
Luminosity (compared to the sun)



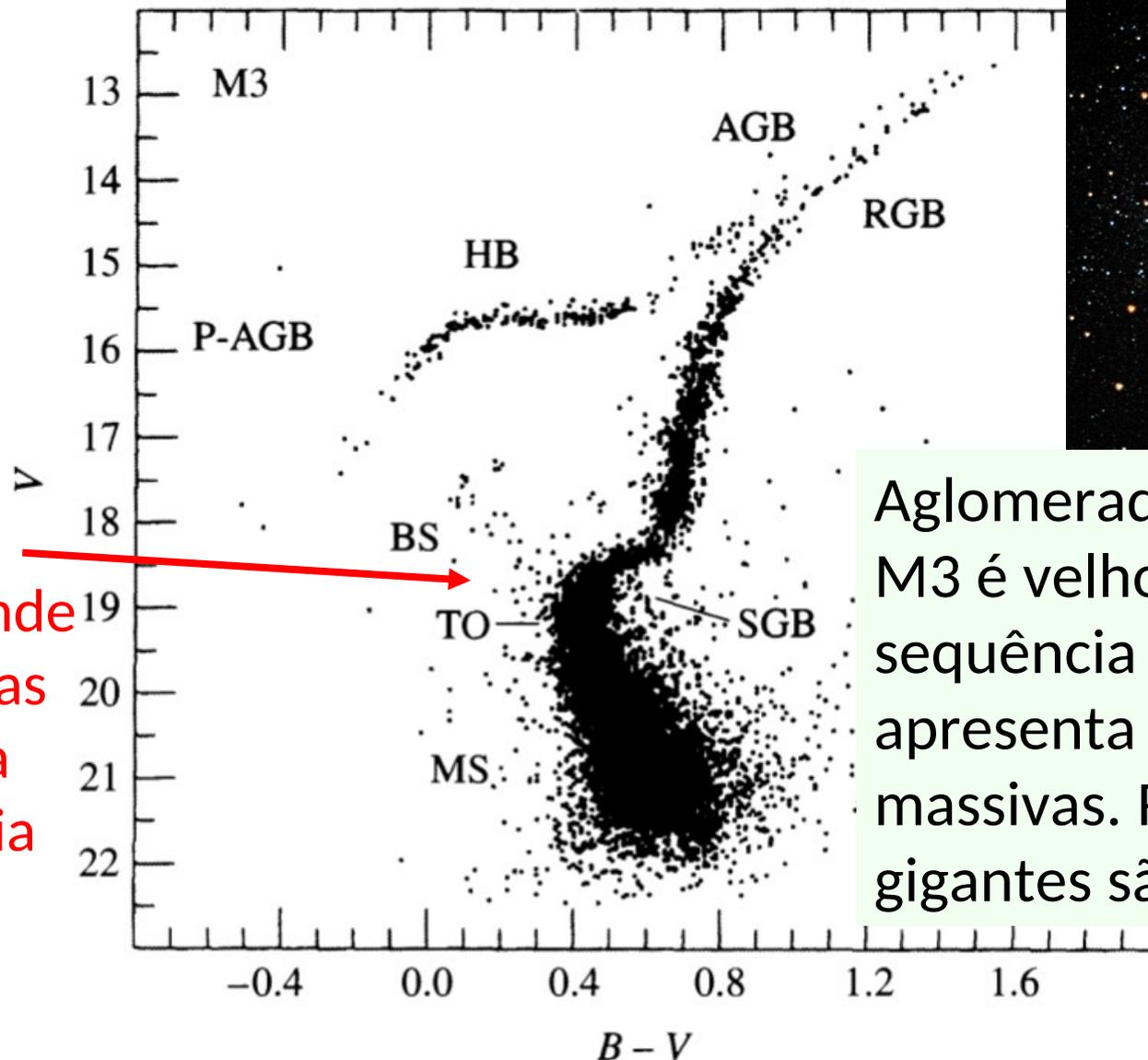
Evolução de aglomerados estelares



Luminosidade ↑



← Temperatura (K)



Turnoff, ponto onde as estrelas deixam a sequência principal

Aglomerado globular M3 é velho (11 Gyr). A sequência principal não apresenta estrelas massivas. Ramos de gigantes são evidentes

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

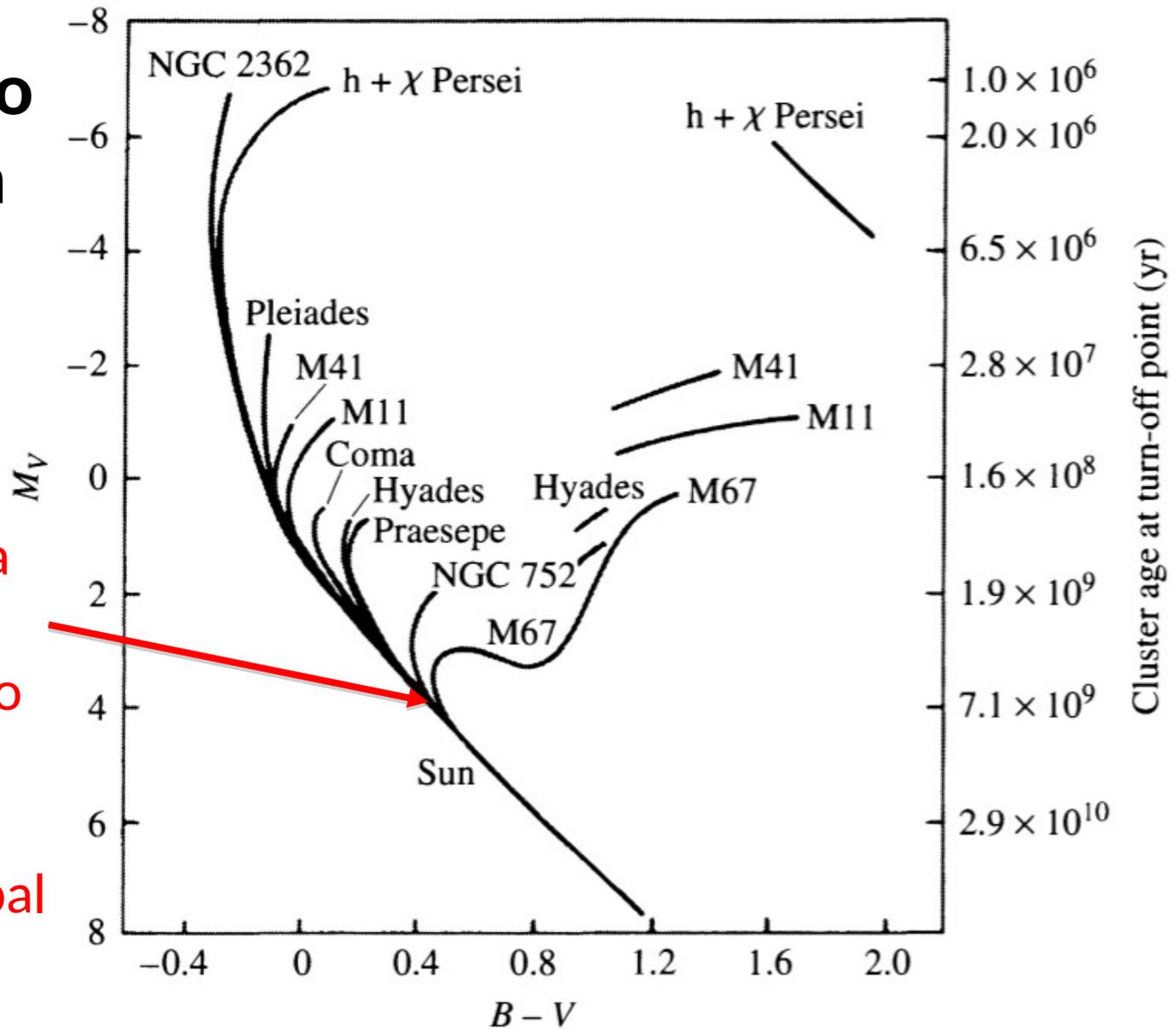
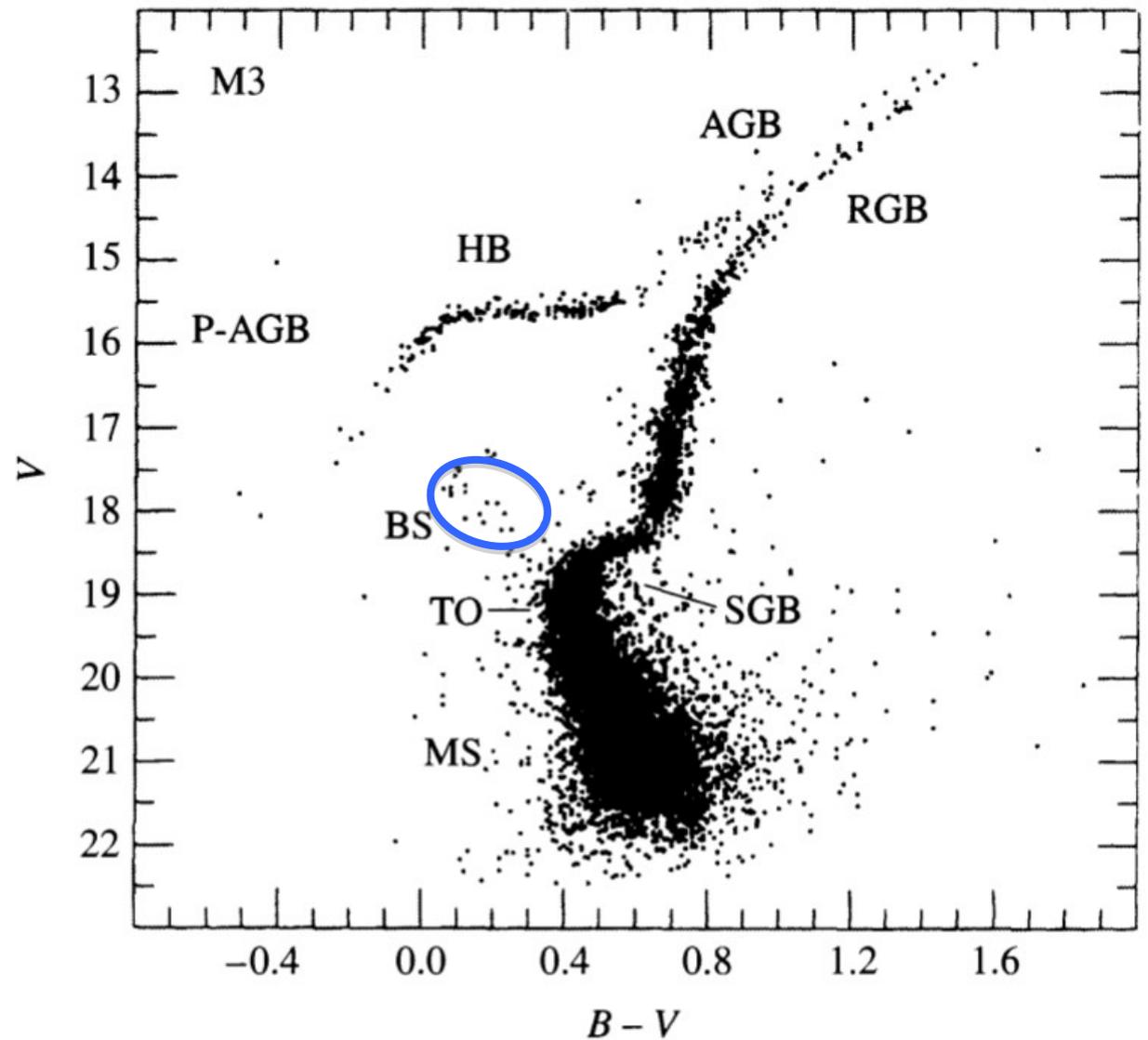


FIGURE 13.19 A composite color–magnitude diagram for a set of Population I galactic clusters. The absolute visual magnitude is indicated on the left-hand vertical axis, and the age of the cluster, based on the location of its turn-off point, is labeled on the right-hand side. (Figure adapted from an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

Blue Stragglers (BS)



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. 58

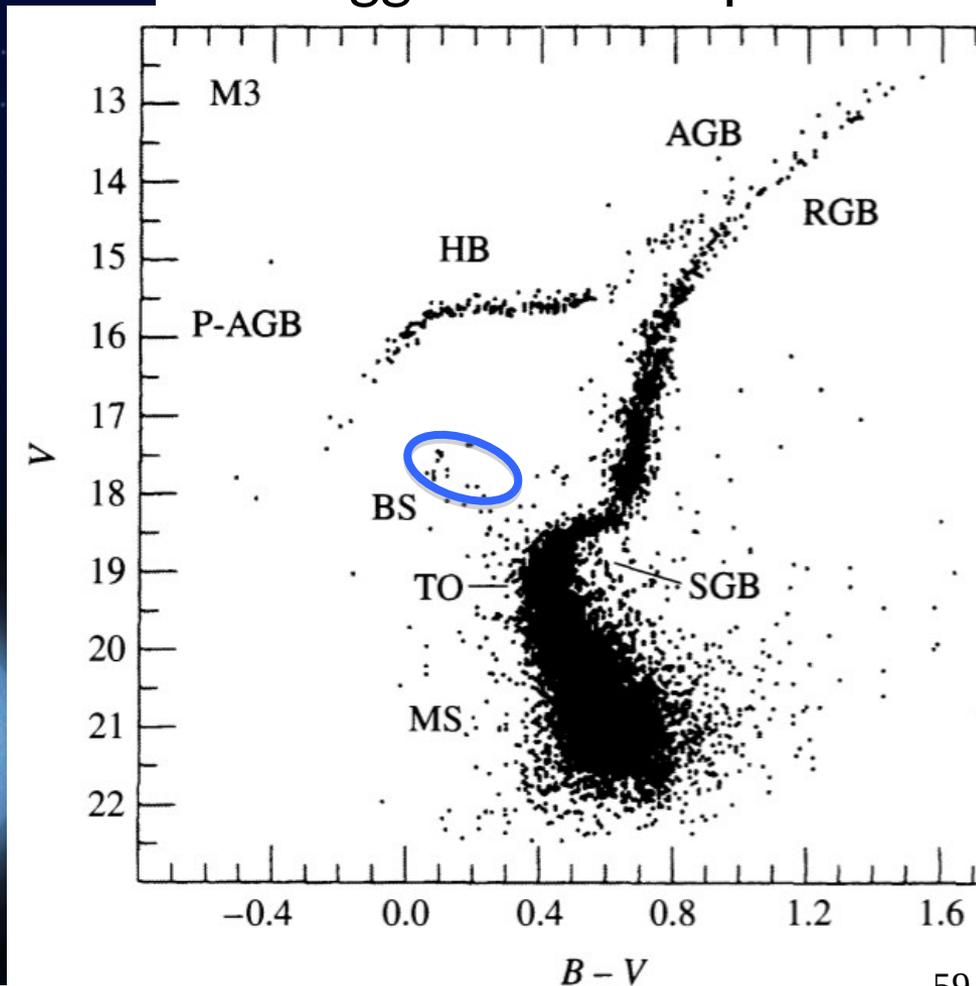
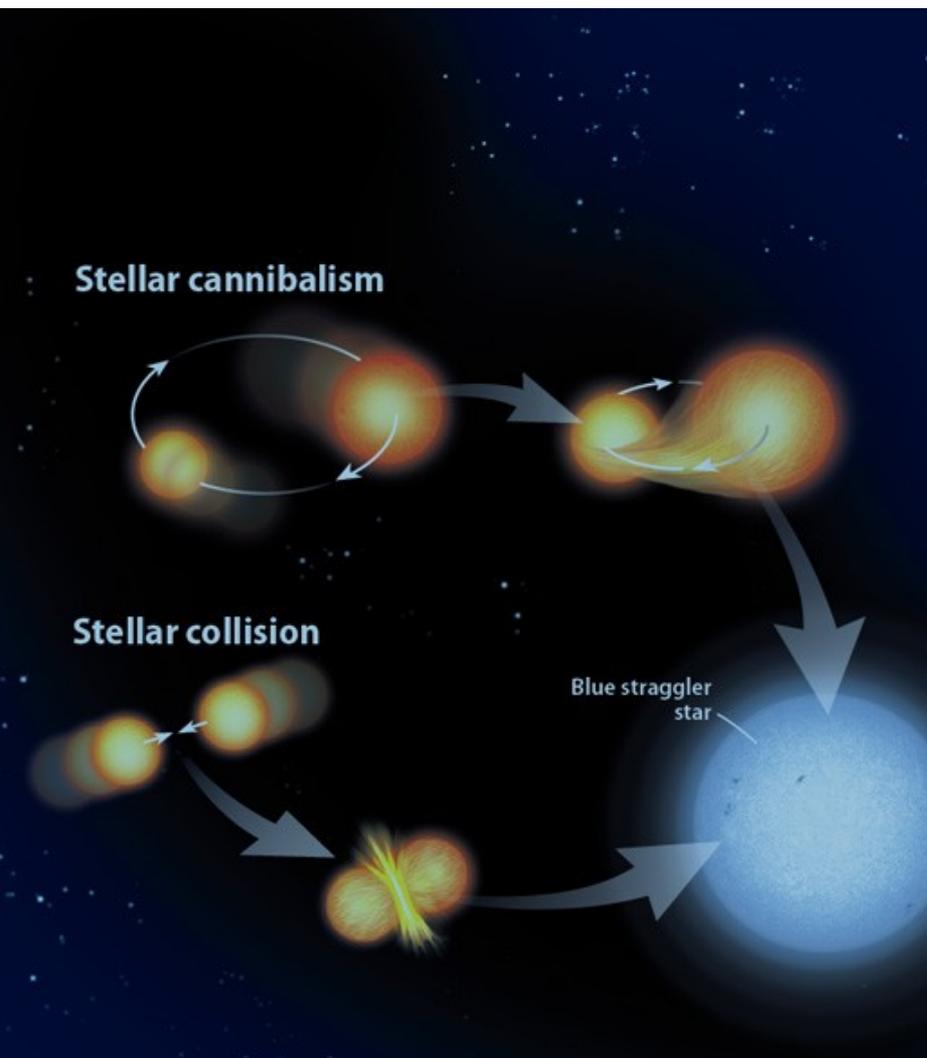
Blue Straggler: two channels:

-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^{★,★★}

Lucas Schirbel¹, Jorge Meléndez¹, Amanda I. Karakas², Iván Ramírez³, Matthieu Castro⁴, Marcos A. Faria⁵, Maria Lugaro⁶, Martin Asplund², Marcelo Tucci Maia¹, David Yong², Louise Howes², and José D. do Nascimento Jr.^{4,7}

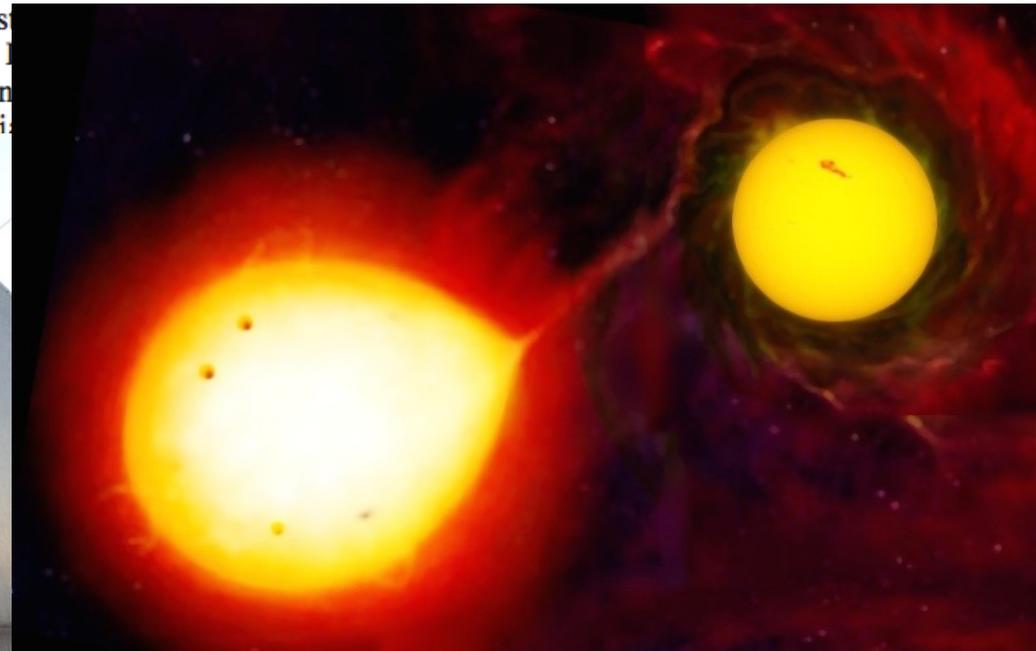
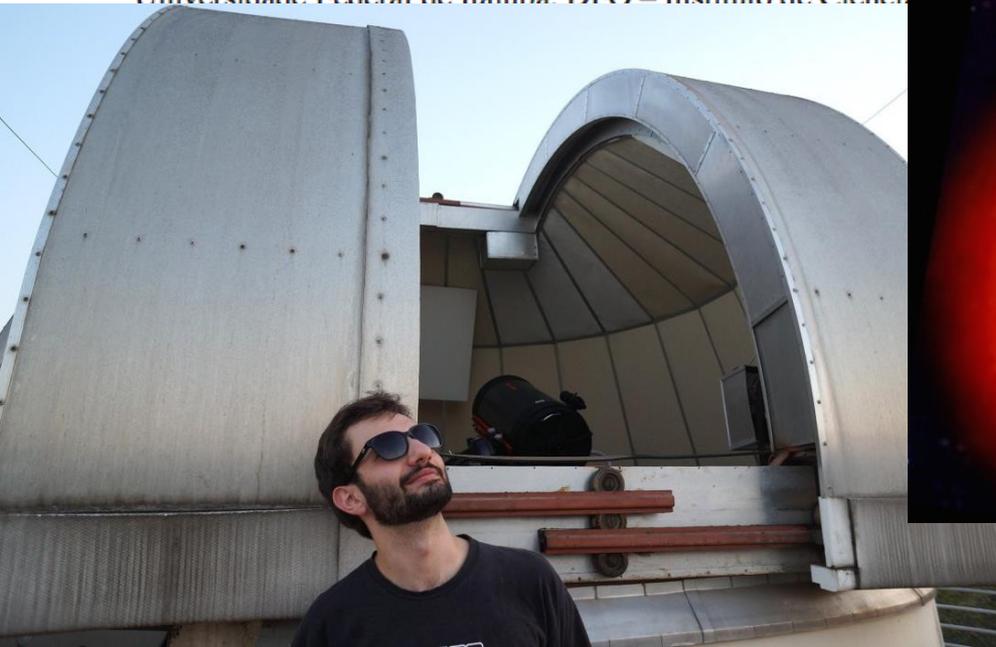
¹ Universidade de São Paulo, Departamento de Astronomia do IAG/USP, Rua do Matão 1226, Cidade Universitária, 05508-900 São Paulo, SP, Brazil
e-mail: lucas.schirbel@usp.br

² The Australian National University, Research School of Astronomy and Astrophysics

³ University of Texas at Austin, McDonald Observatory and Lick Observatory

⁴ Universidade Federal do Rio Grande do Norte, Departamento de Física

⁵ Universidade Federal de Itaipubá, DFO – Instituto de Ciências

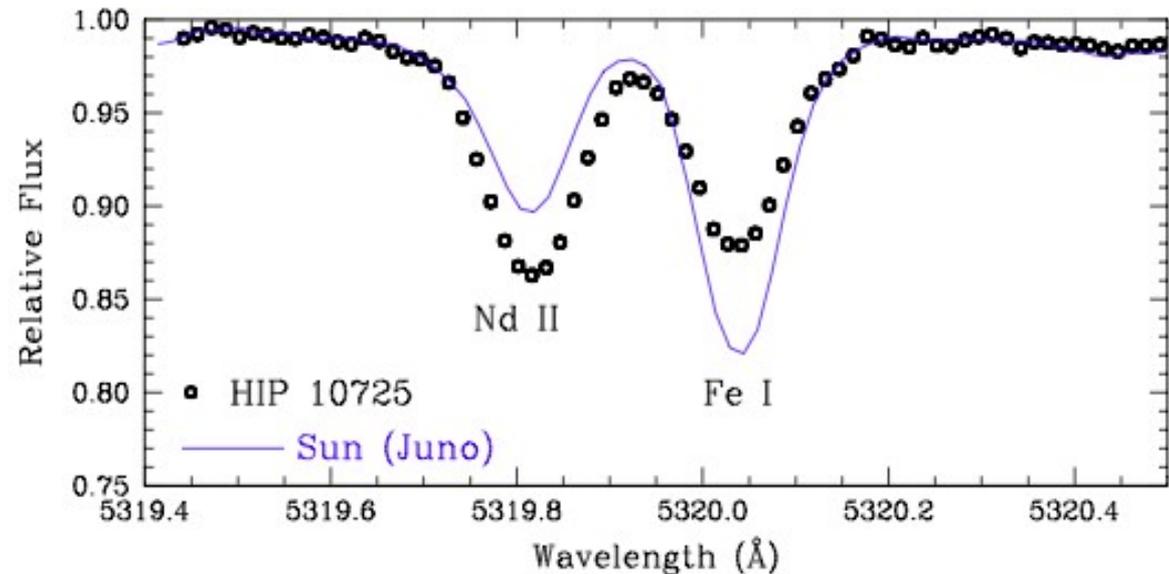
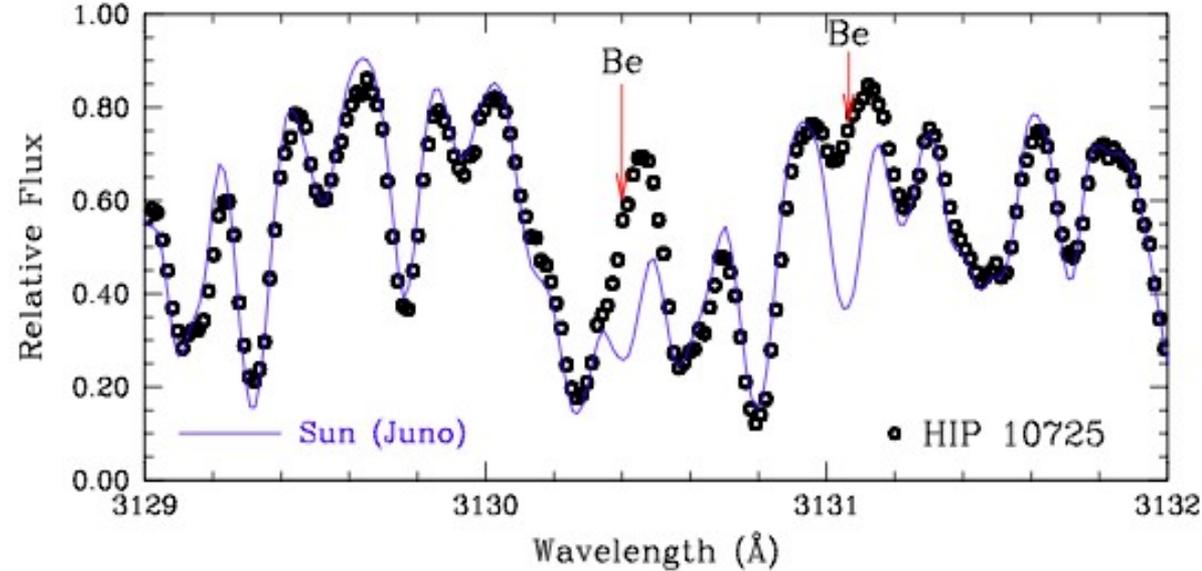


HIP 10725: The first solar twin/analogue field blue straggler^{★,★★}

Lucas Schirbel¹, Jorge Meléndez¹, Amanda I. Karakas², Iván Ramírez³, Matthieu Castro⁴, Marcos A. Faria⁵,

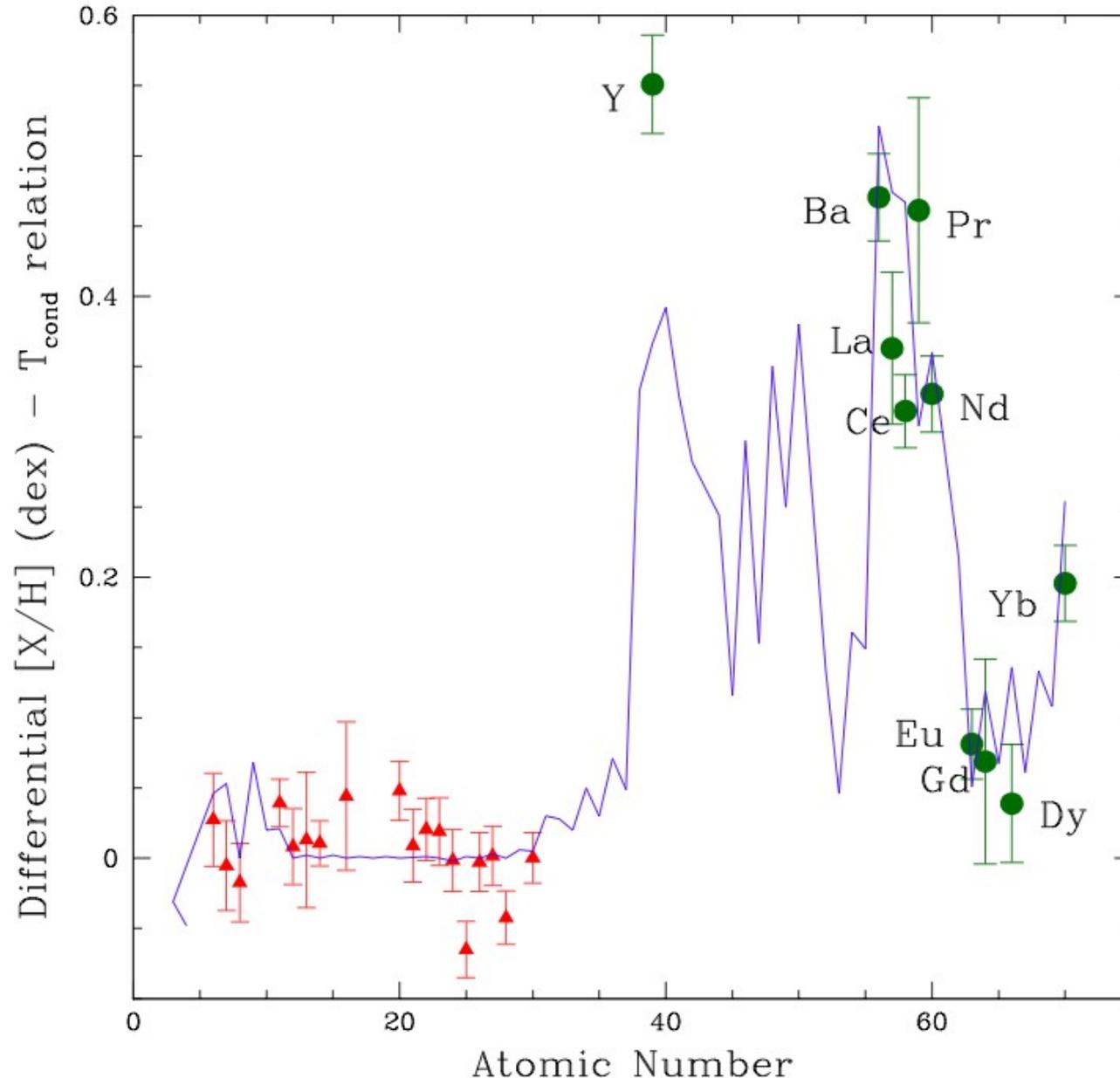
A gêmea solar HIP 10725 tem uma rotação maior à esperada para a idade dela. A alta rotação talvez é devida à transferência de momento angular da antiga companheira AGB.

HIP 10725 não apresenta berílio. O aumento da rotação pode ter resultado em dragagem de Be para o interior, onde é queimado



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

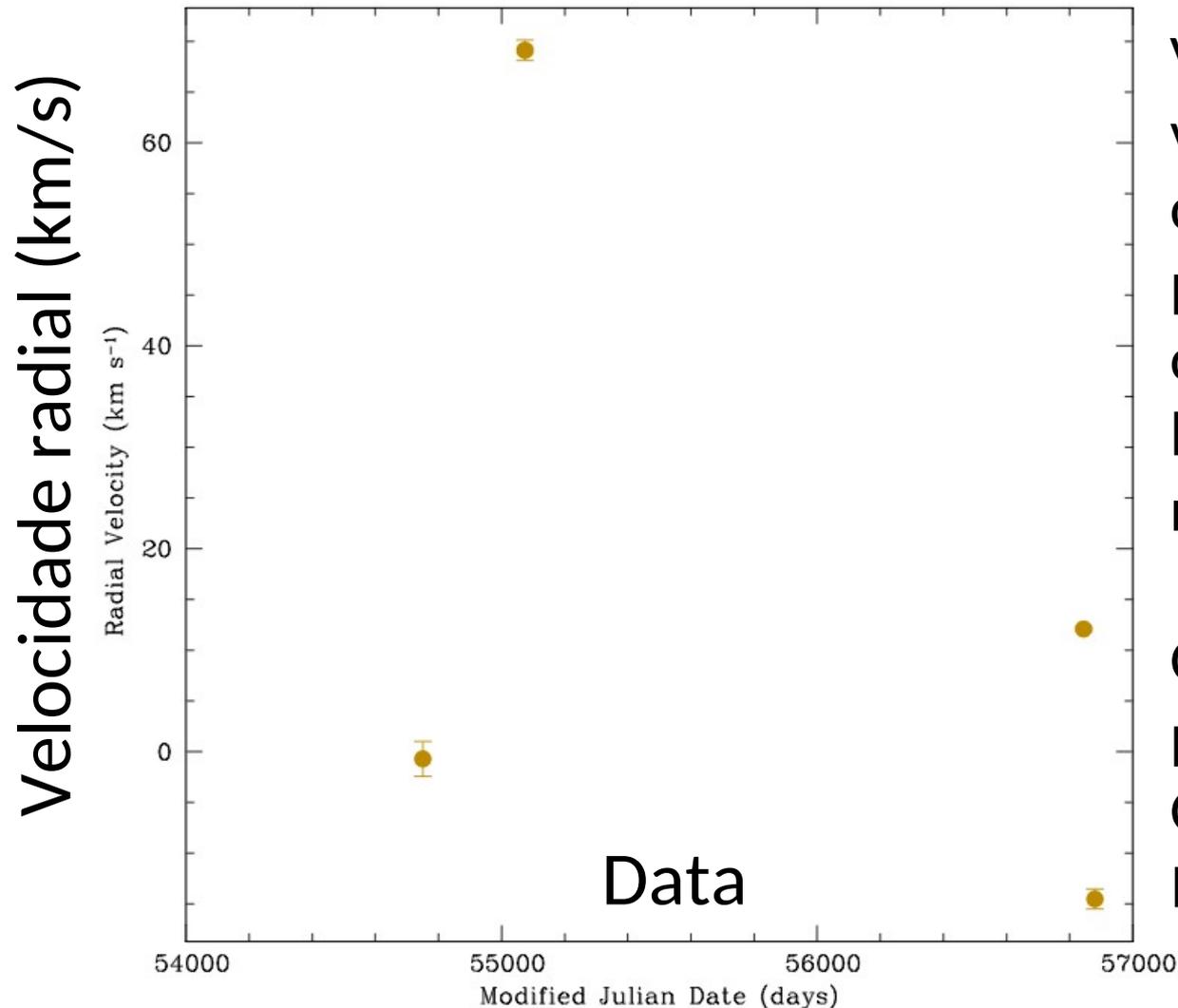
Lucas Schirbel¹, Jorge Meléndez¹, Amanda I. Karakas², Iván Ramírez³, Matthieu Castro⁴, Marcos A. Faria⁵,



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 Schirbel¹, Jorge Meléndez¹, Amanda I. Karakas², Iván Ramírez³, Matthieu Castro⁴, Marcos A. Faria⁵,



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

Observação parcialmente no OPD/LNA em Minas Gerais

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:

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

Assinaturas químicas de evolução estelar:

- Estrelas: Beatriz Barbuy, Jorge Meléndez (IAG/USP), Claudio Pereira (ON), Alan Alves-Brito (UFRGS), Diogo Souto (UFS)
- Nebulosas Planetárias: Roberto Costa, W.Maciel (IAG/USP)

Estrelas massivas:

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