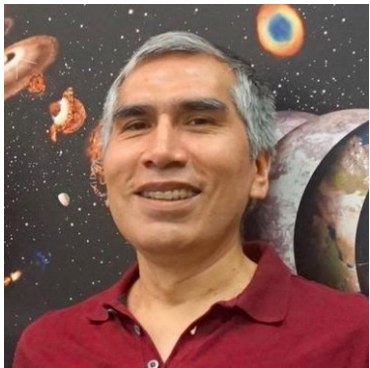
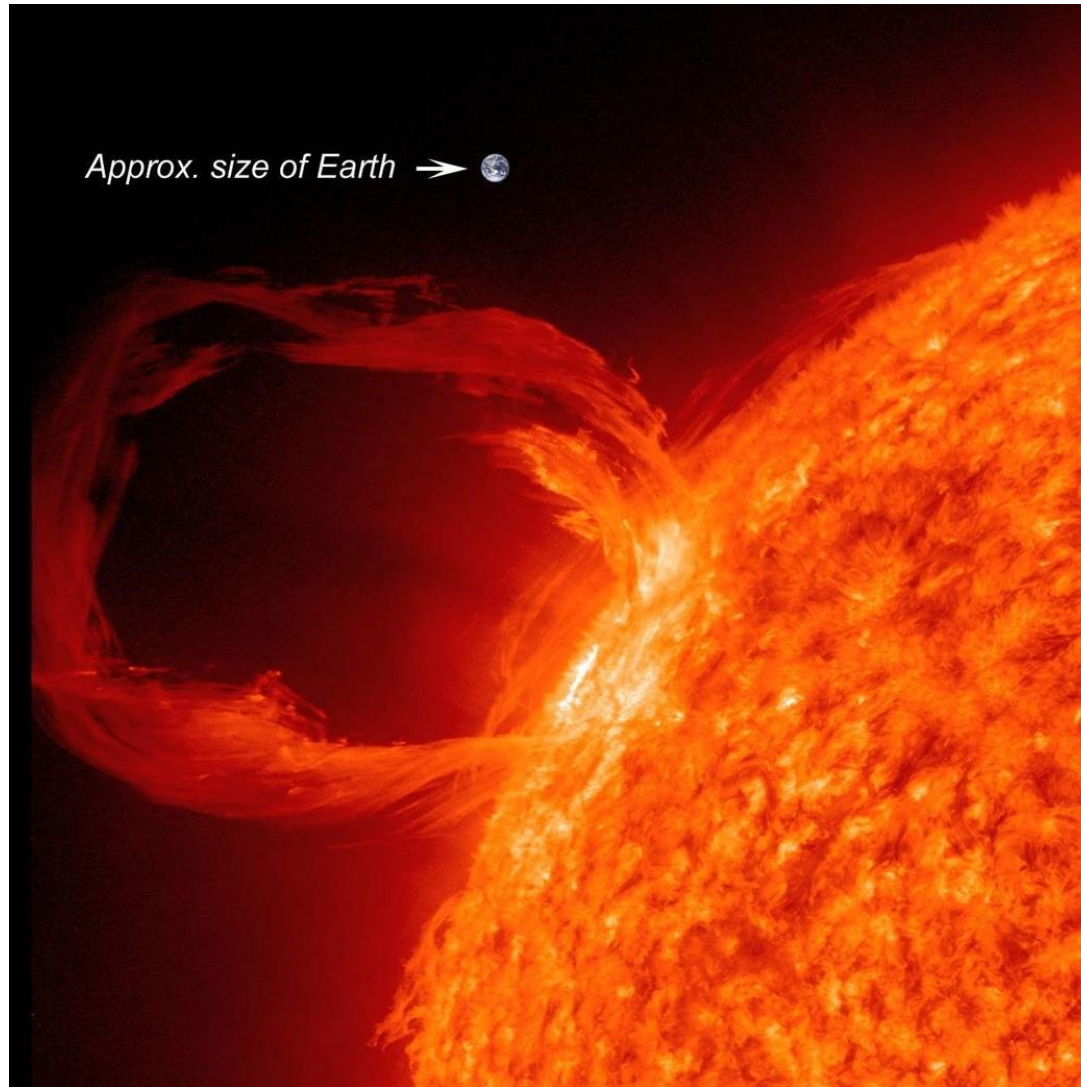


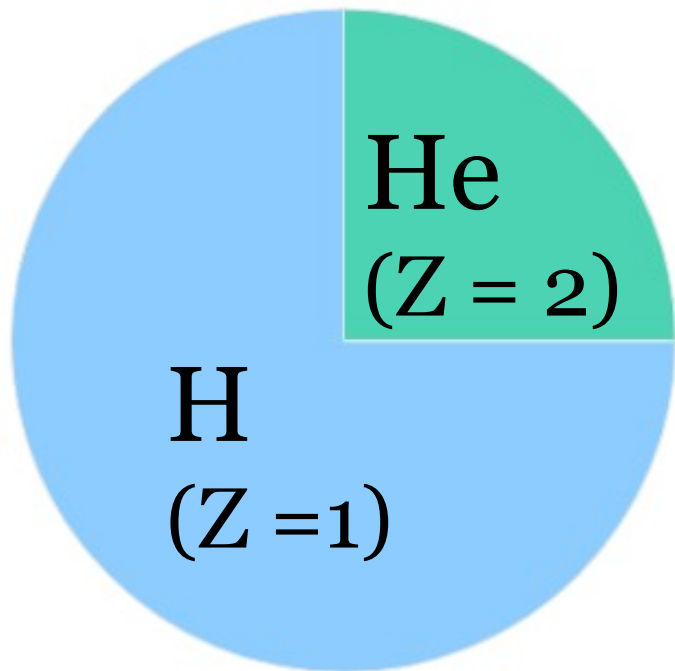
1. O Sol: Estrutura e Evolução



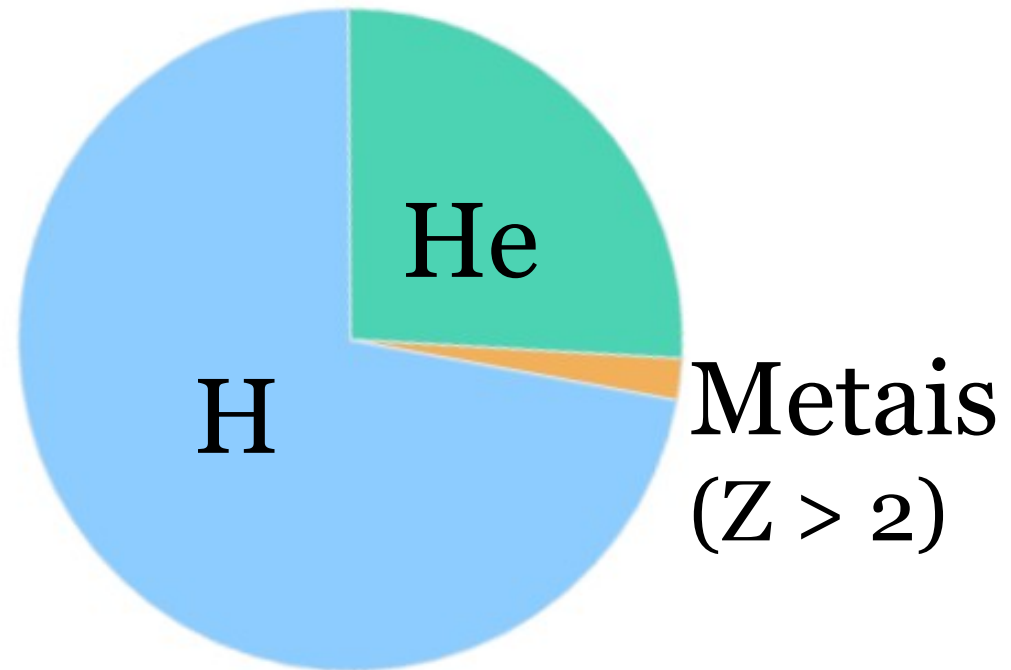
AGA0502, Planetas e Sistemas Planetários
Prof. Jorge Meléndez, IAG-USP

Composição química da matéria no universo (em fração de massa)

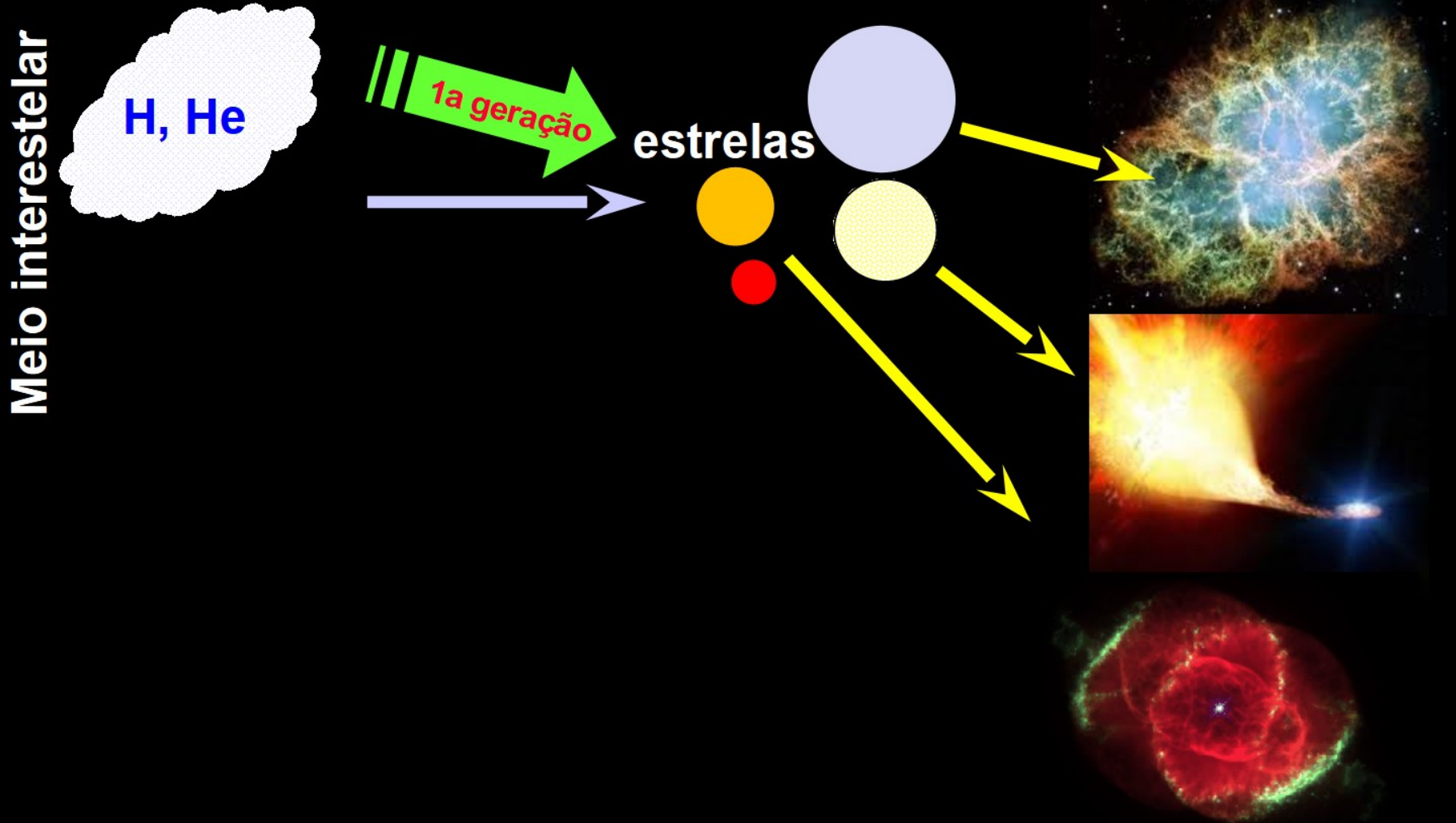
Big Bang
13,8 Bilhões de anos



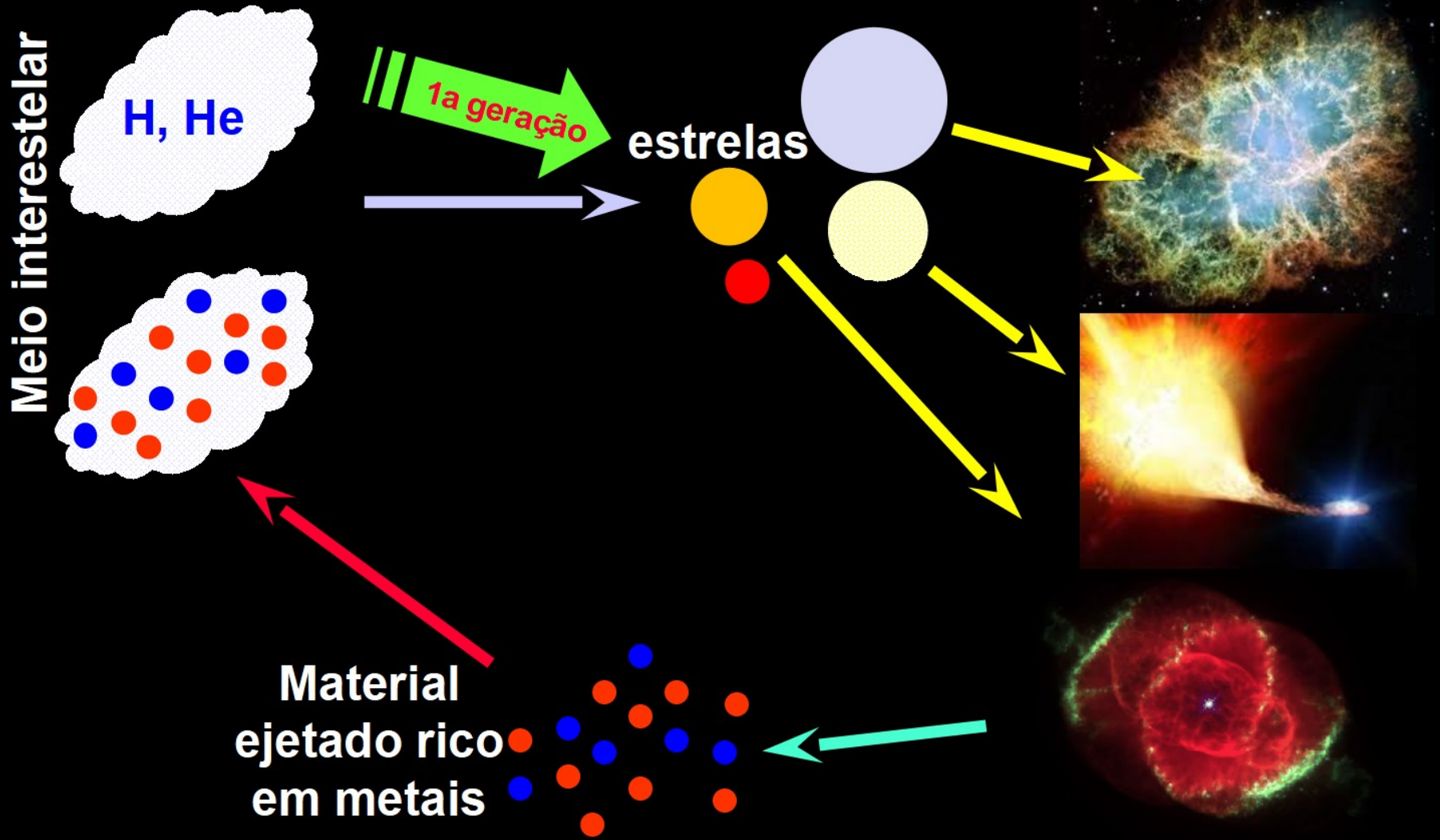
Via Láctea
Hoje



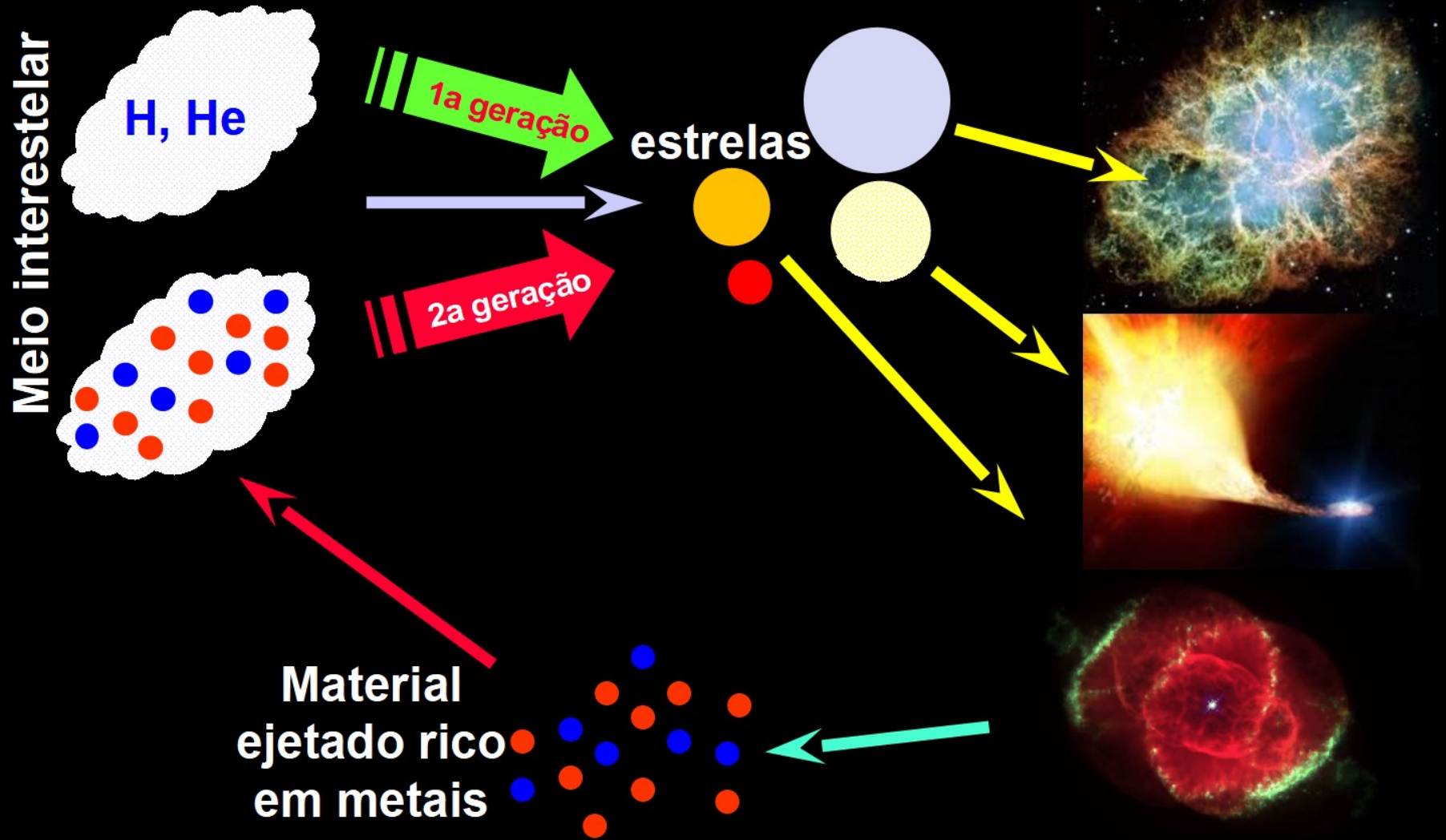
Evolução dos elementos químicos na Galáxia



Evolução dos elementos químicos na Galáxia



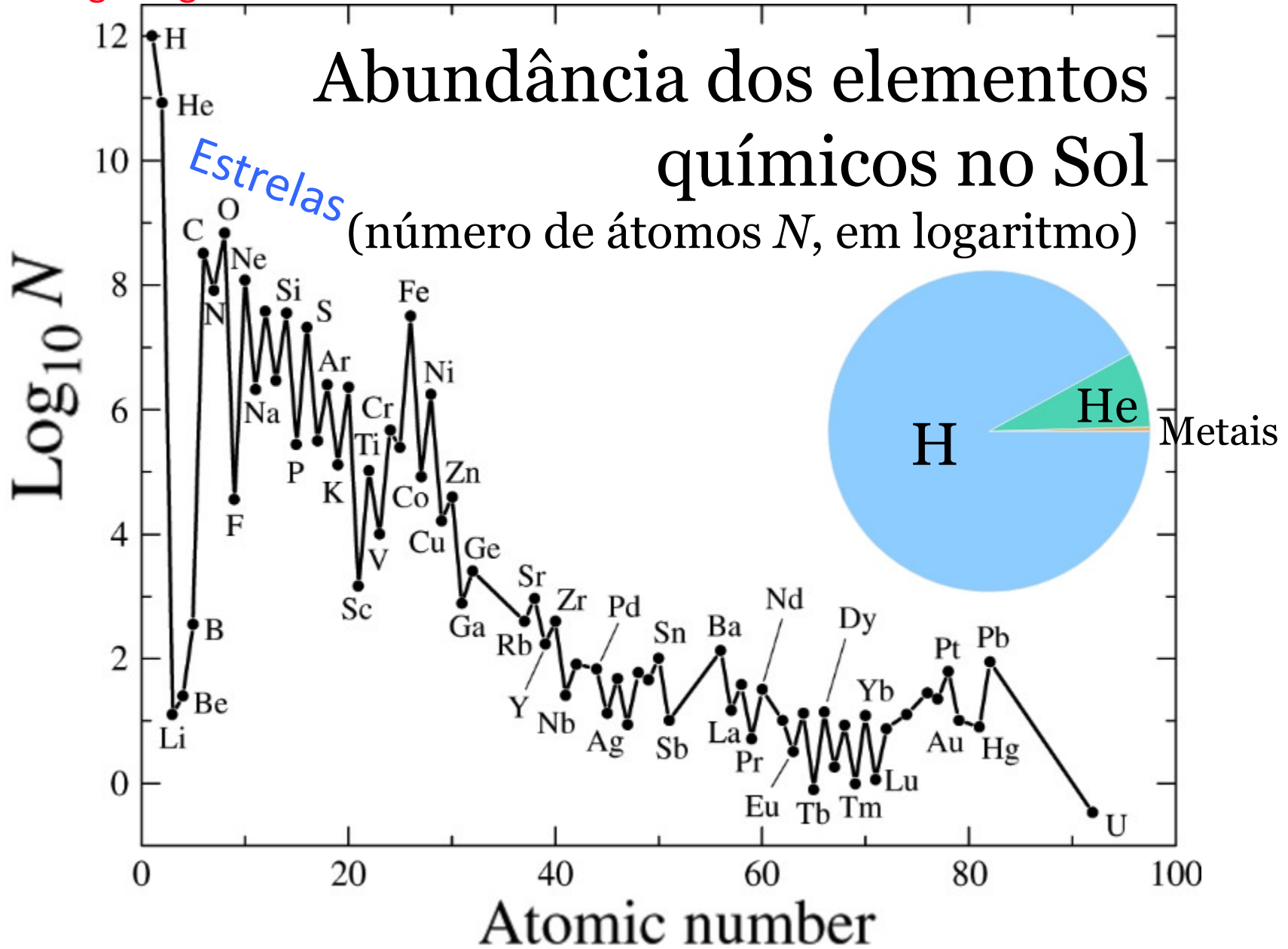
Evolução dos elementos químicos na Galáxia



Big Bang

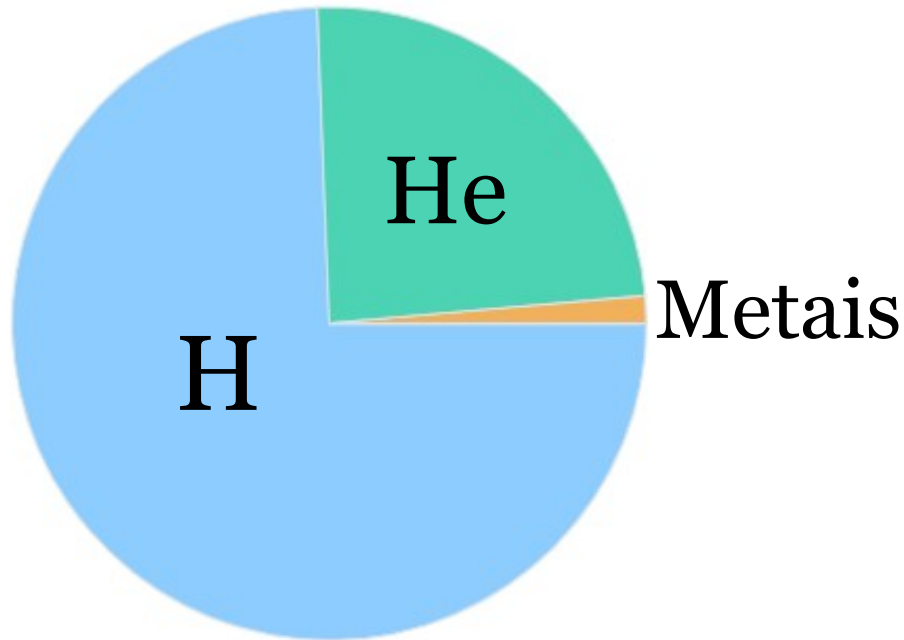
Abundância dos elementos químicos no Sol

(número de átomos N , em logaritmo)



Abundância dos elementos no Sol (hoje)

Fração de massa
do Sol

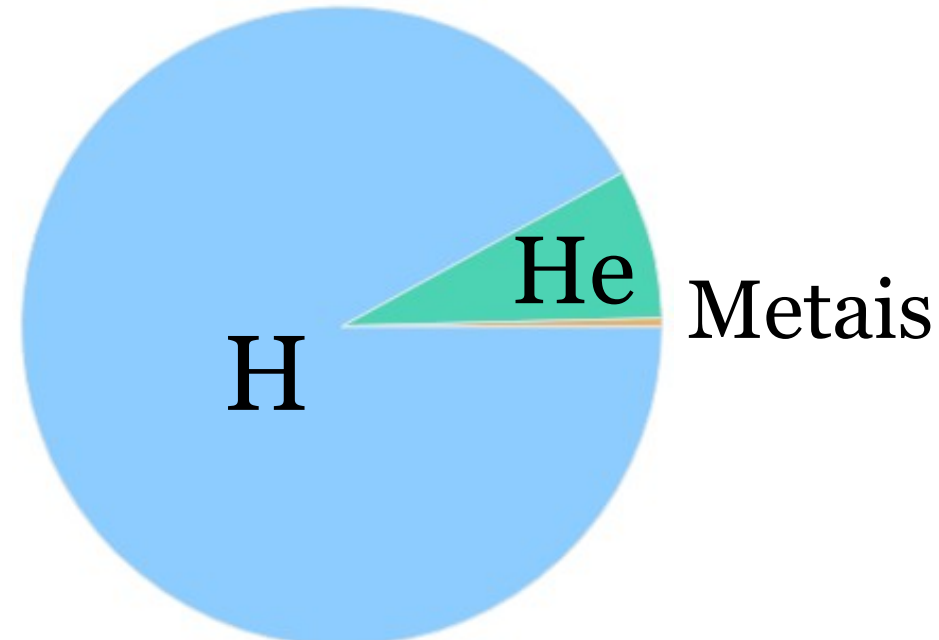


H ($Z = 1$): 74,4 %

He ($Z = 2$): 24,2 %

Metais ($Z > 2$): 1,4 %

Número de átomos



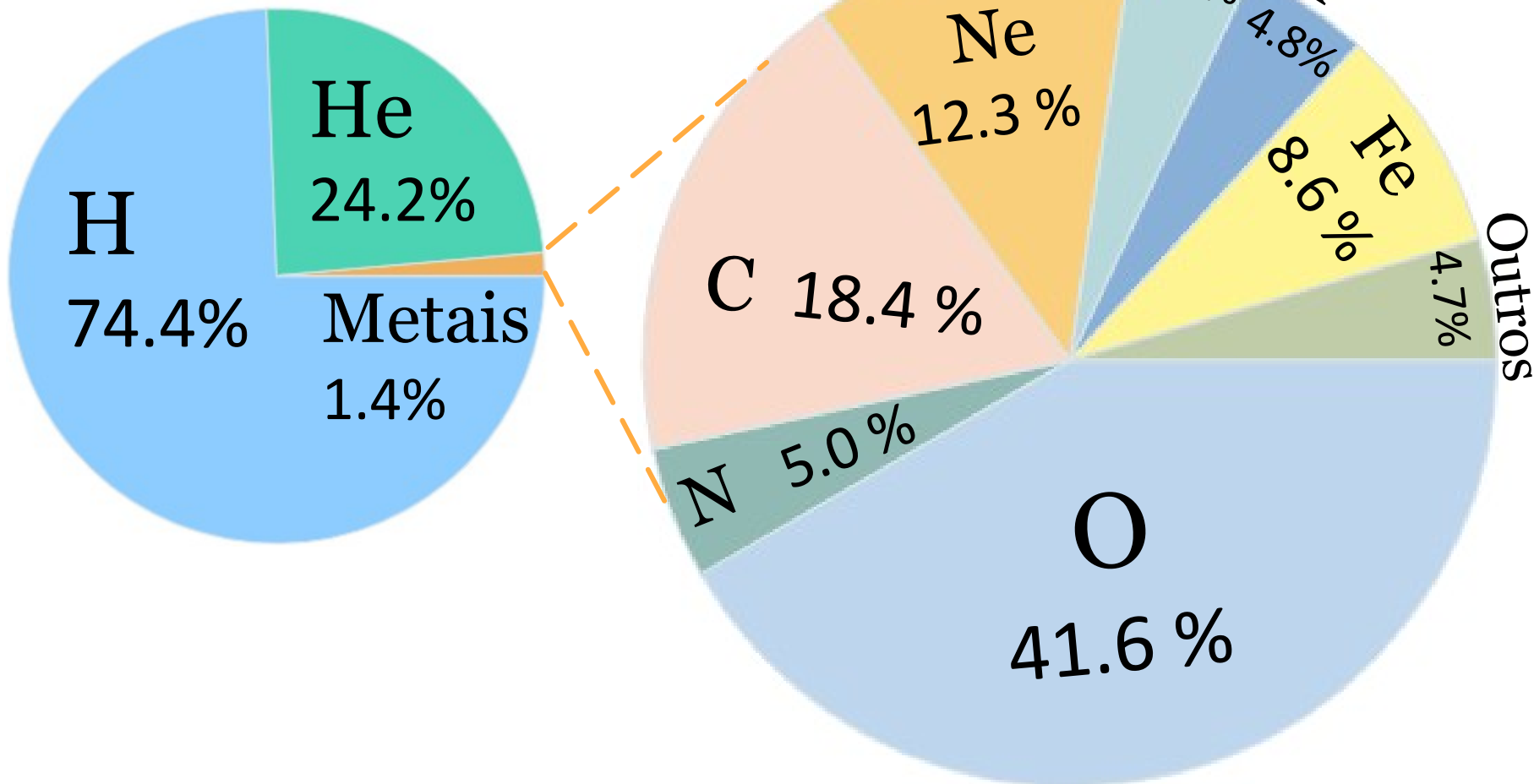
H: 92 %

He: 7,6 %

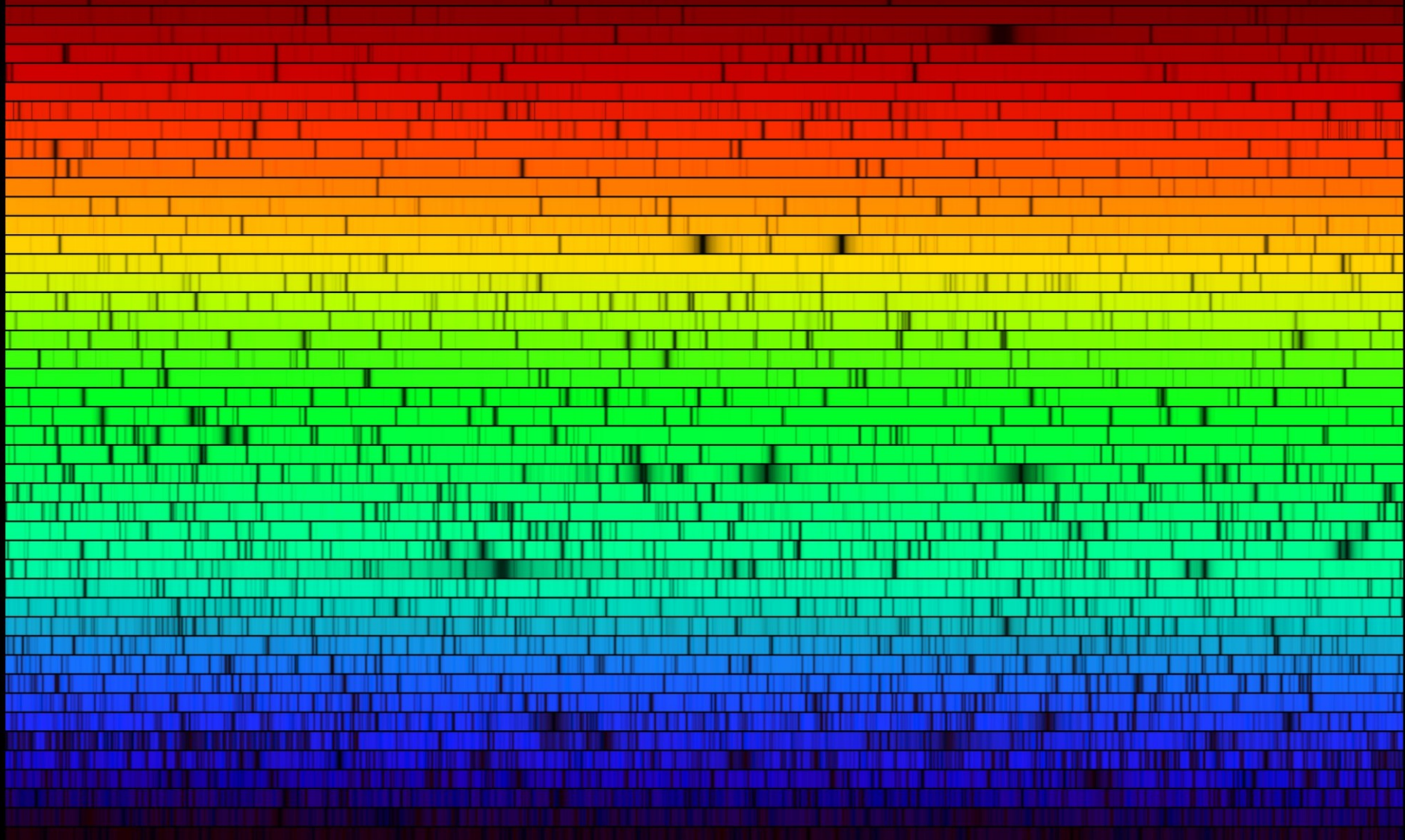
Metais: 0,4 %

Abundância dos elementos no Sol (hoje)

Fração de massa
do Sol



A composição química do Sol e as estrelas é determinada via a análise do espectro. As linhas escuras são devidas à absorção de diversos elementos químicos na atmosfera estelar



Formação de linhas espectrais (AGA0293)

Equações de Boltzmann: $e^{-E_{nível} / kT}$ e Saha: $e^{-E_{ion} / kT}$

$$\frac{N_b}{N_a} = \frac{g_b e^{-E_b/kT}}{g_a e^{-E_a/kT}} = \frac{g_b}{g_a} e^{-(E_b-E_a)/kT}$$

$$\frac{N_{i+1}}{N_i} = \frac{2kT Z_{i+1}}{P_e Z_i} \left(\frac{2\pi m_e kT}{h^2} \right)^{3/2} e^{-\chi_i/kT}$$

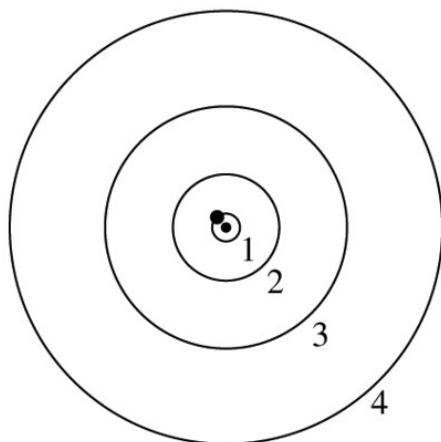
(c) Bruna Barroso



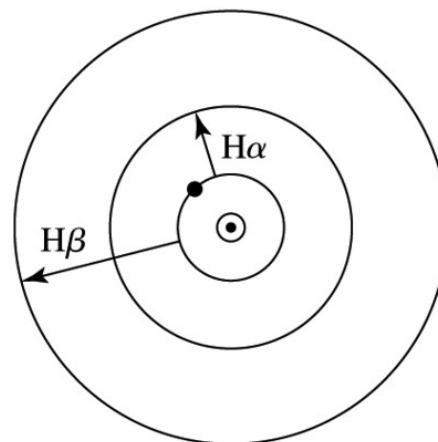
Hydrogen
atom

Excitation
Boltzmann equation

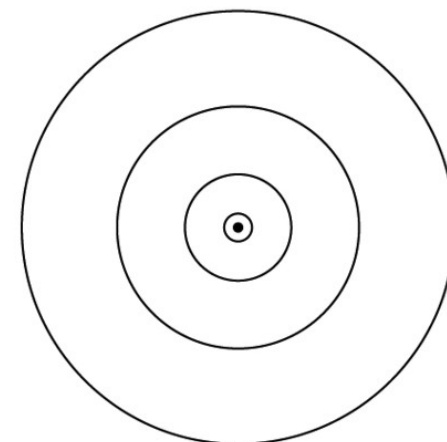
Ionization
Saha equation



(a) $T < 9900$ K



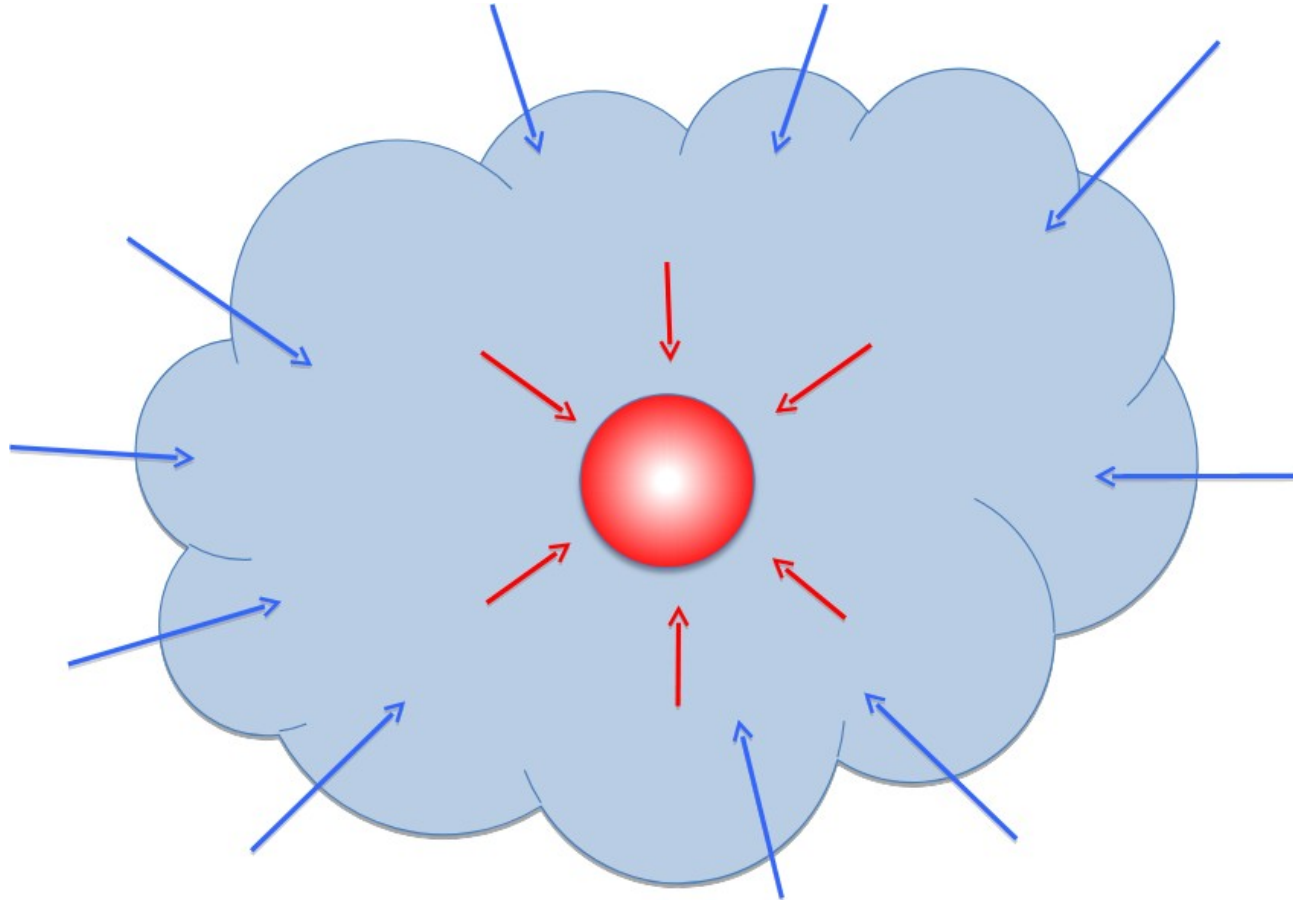
(b) $T = 9900$ K



(c) $T > 9900$ K

Formação do Sol

Colapso da nuvem: escala de tempo $\sim 10^5$ anos



Contração da proto-estrela $\sim 40 \times 10^6$ anos

A contração do proto-Sol termina quando a temperatura central $T_c \sim 15 \times 10^6$ K.

Nessa temperatura temos a fusão nuclear estável de hidrogênio em hélio, via a cadeia próton-próton.

O Sol passará a maior parte da sua vida na “Sequência Principal”.

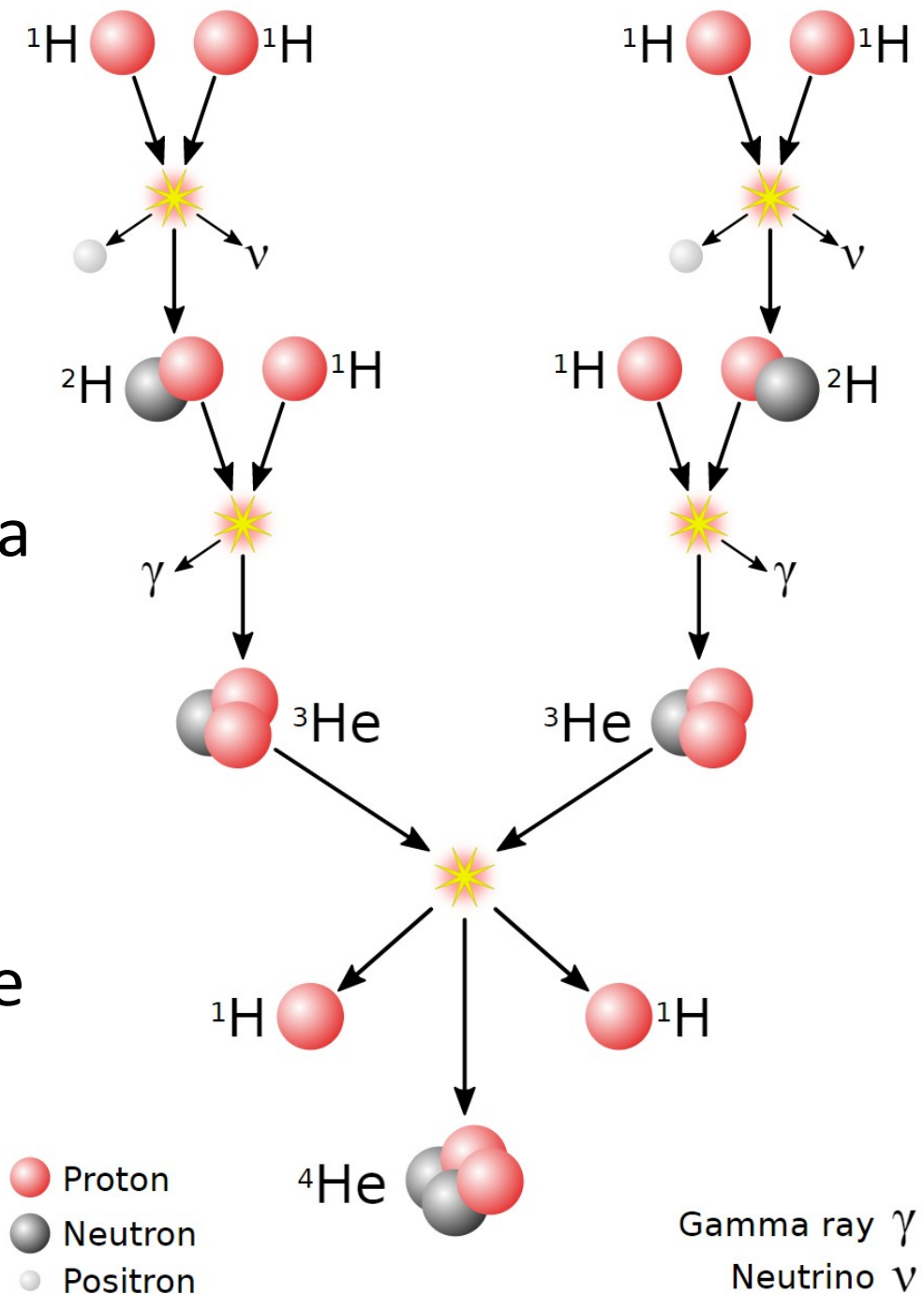
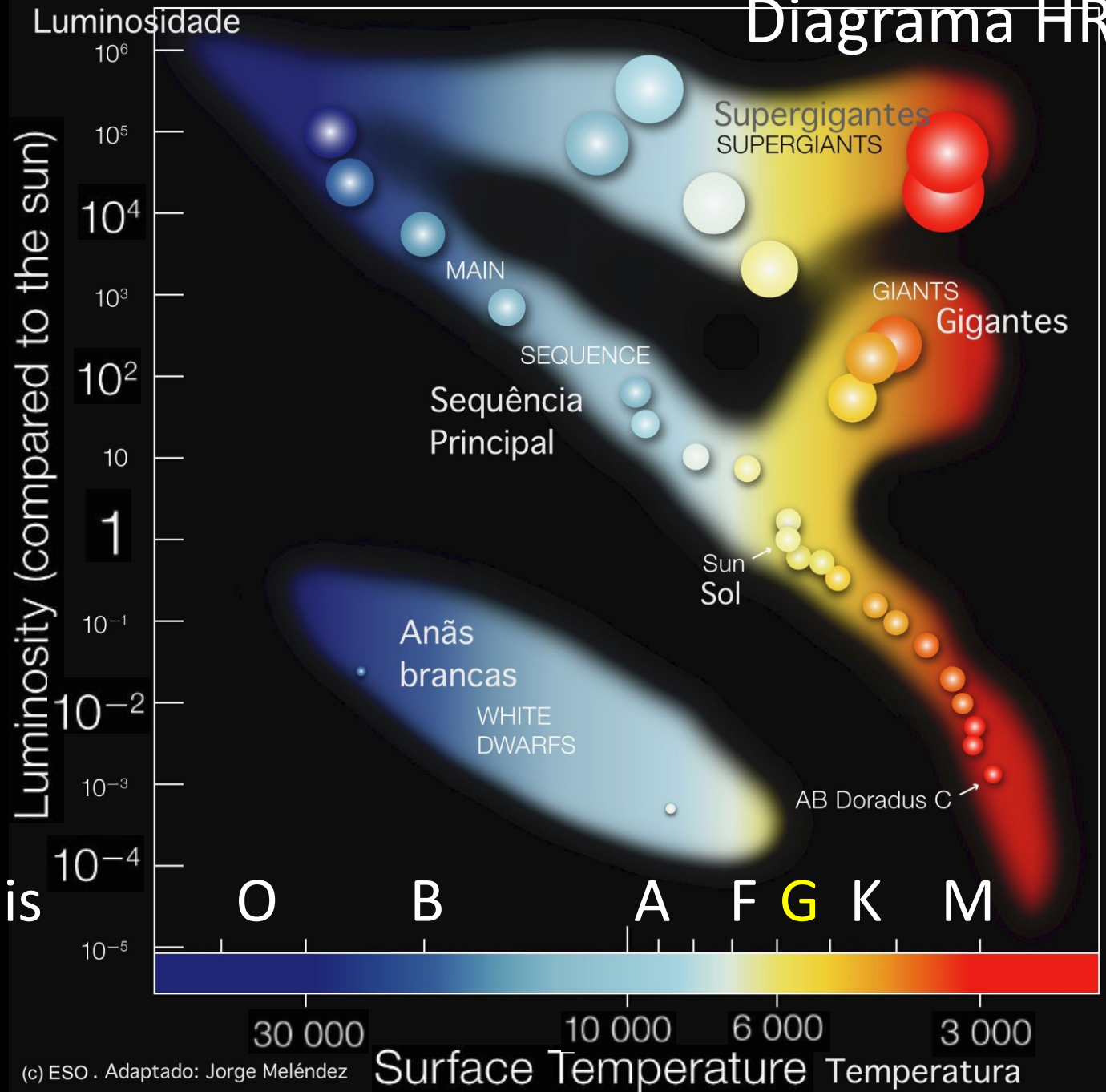


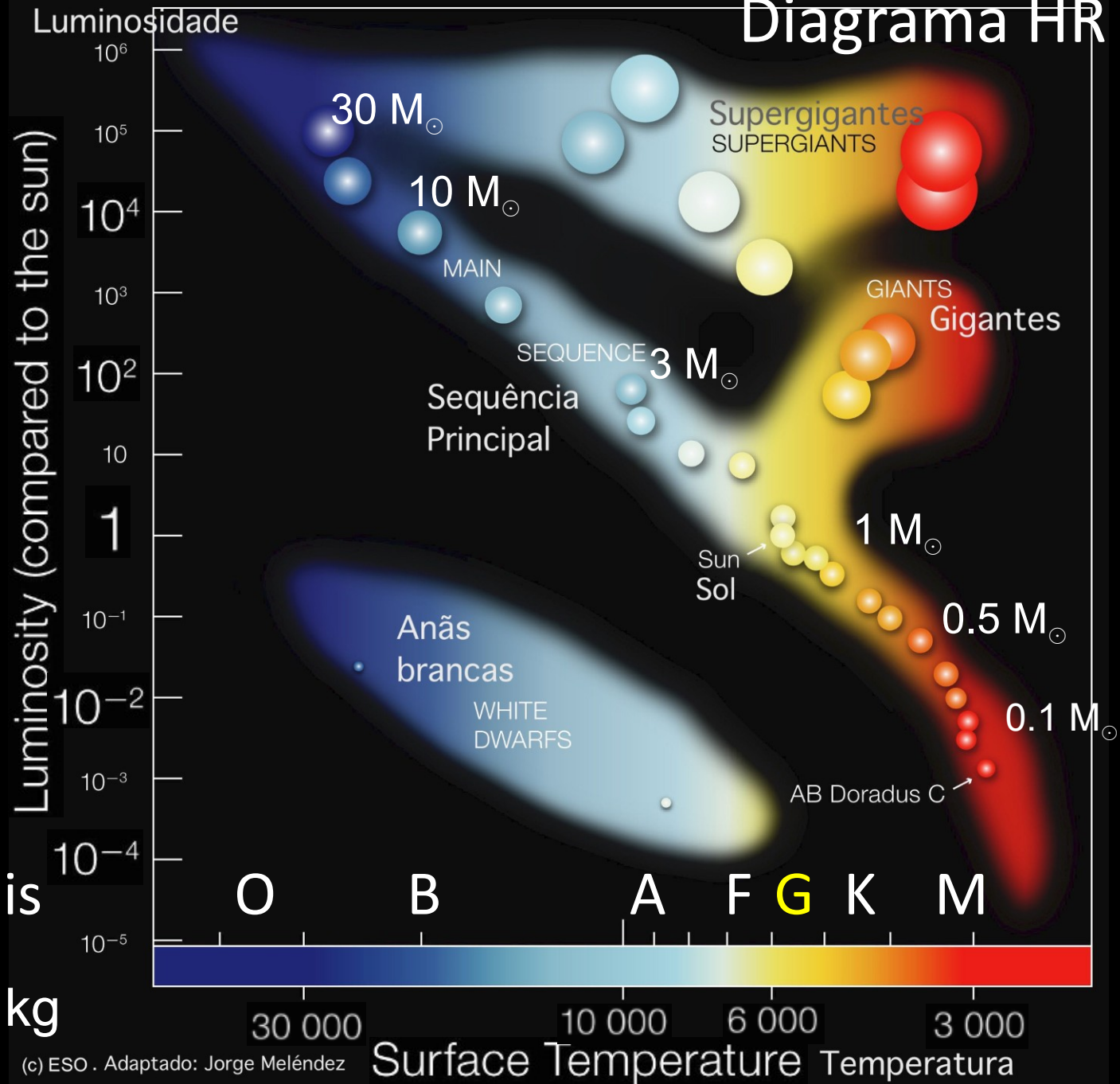
Diagrama HR



Tipos espectrais

Sol: tipo G2

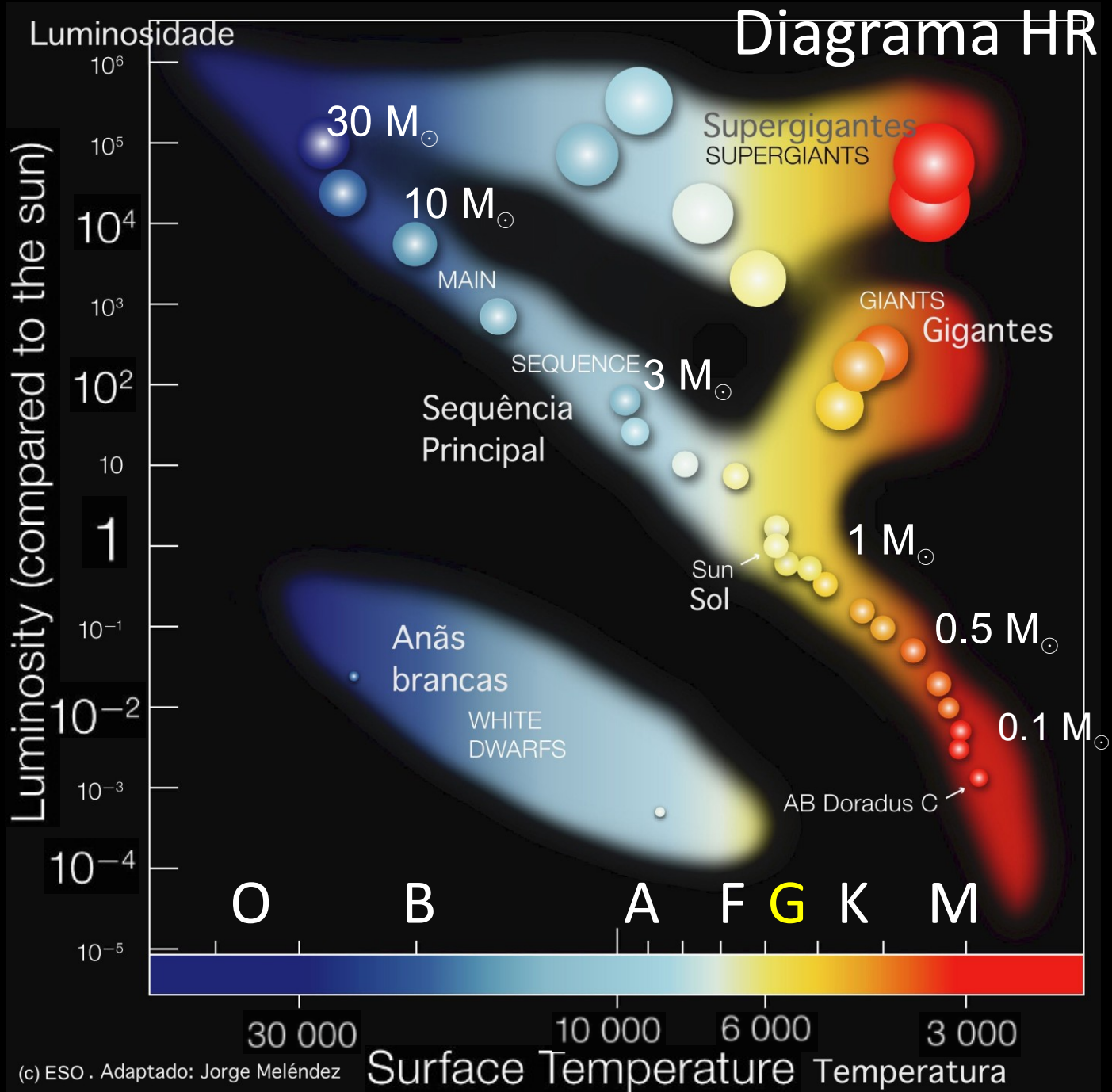
Diagrama HR



(c) ESO . Adaptado: Jorge Meléndez

Tempo de vida na sequência principal

30 M _☉	5 Myr
10 M _☉	27 Myr
3 M _☉	350 Myr
1.5 M _☉	2.7 Gyr
1.25 M _☉	5 Gyr
1.0 M _☉	10 Gyr
0.75 M _☉	30 Gyr
0.5 M _☉	200 Gyr



As estrelas costumam nascer em aglomerados. As estrelas mais antigas da Galáxia nasceram em **aglomerados globulares (à esquerda)** e as mais jovens (do disco Galáctico) em **aglomerados abertos (exemplo à direita)**

M80



Plêiades



O Sol se formou com outras estrelas a partir de colapso de nuvem, mas o aglomerado aberto do Sol se dispersou

NGC 602, aglomerado aberto jovem (5 Myr)



M67, aglomerado aberto de ~4 Gyr (similar à idade do Sol [4,6 Gyr])



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

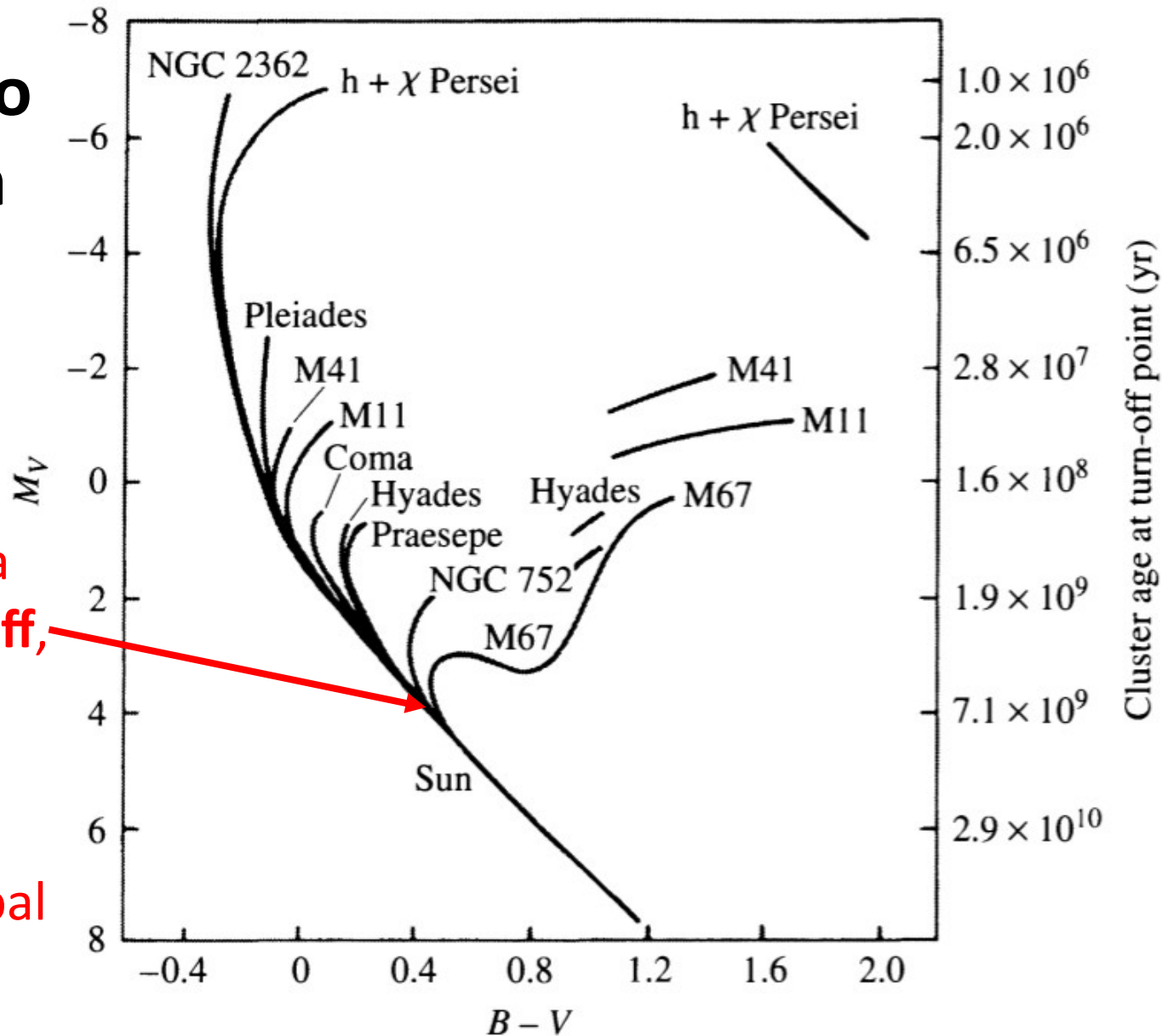
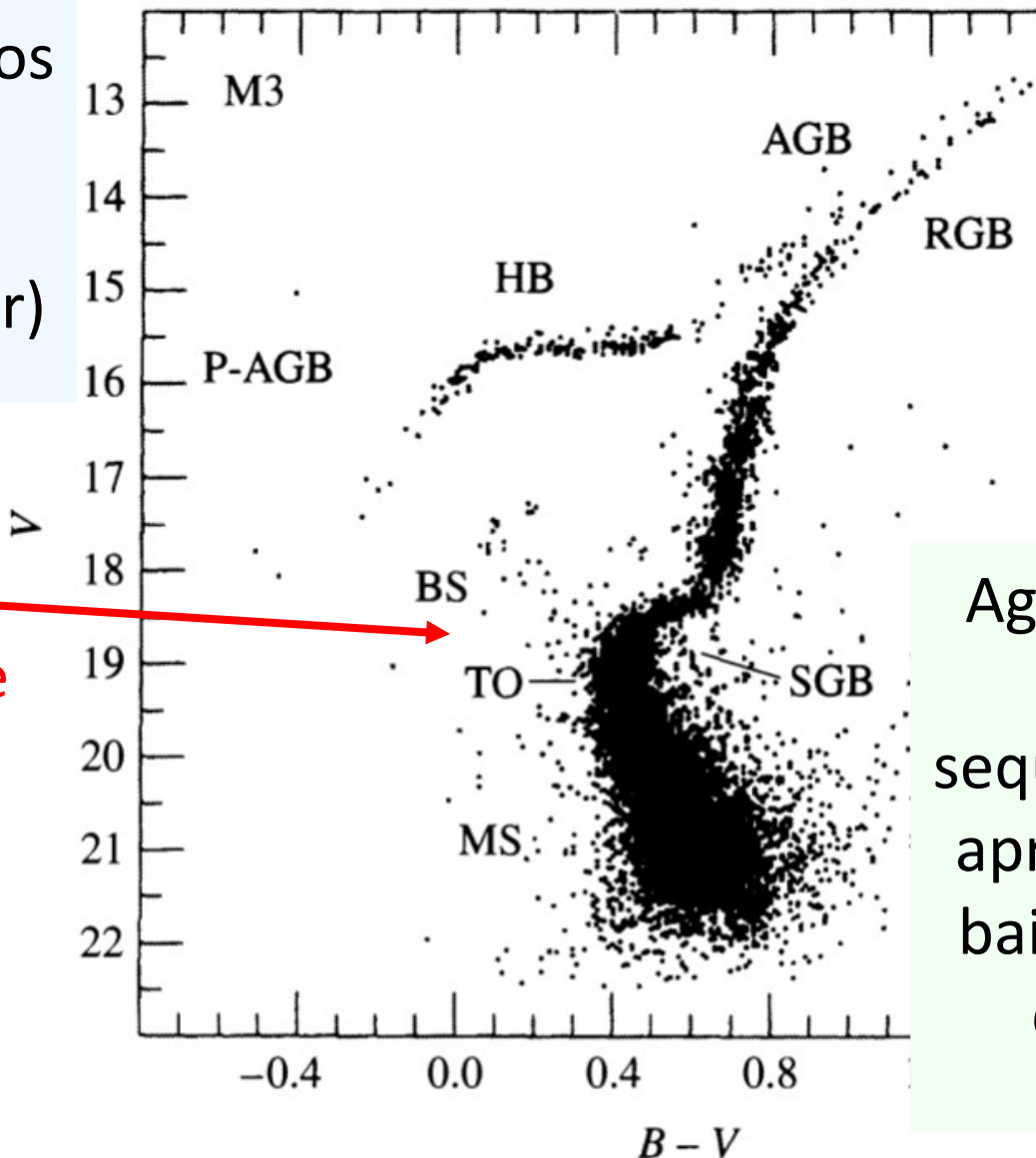


FIGURE 13.19 A composite color–magnitude diagram for a set of Population I galactic clusters. The absolute visual magnitude is indicated on the left-hand vertical axis, and the age of the cluster, based on the location of its turn-off point, is labeled on the right-hand side. (Figure adapted from an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

Aglomerados globulares são velhos (10 – 12 Gyr)

Turnoff, ponto onde as estrelas deixam a sequência principal



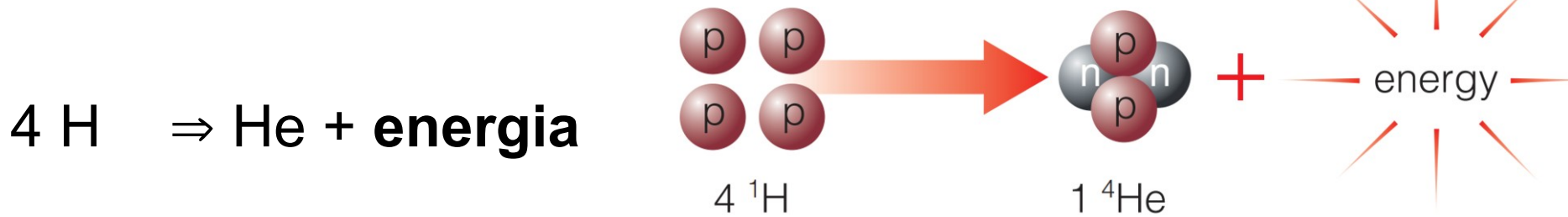
Aglomerado globular M3 (11 Gyr). A sequência principal só apresenta estrelas de baixa massa. 2 ramos de gigantes (RGB e AGB) são visíveis;

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

Fusão nuclear como fonte de energia

massa próton p+ (núcleo de H): $1,6726 \times 10^{-27}$ kg

massa do núcleo de He: $6,6426 \times 10^{-27}$ kg



$$4 (1,6726 \times 10^{-27} \text{ kg}) \Rightarrow 6,6426 \times 10^{-27} \text{ kg} + \text{energia}$$

$$6,6904 \times 10^{-27} \text{ kg} \Rightarrow 6,6426 \times 10^{-27} \text{ kg} + \text{energia}$$

$$\Delta \text{ massa } (4\text{H} - \text{He}) = 0,0478 \times 10^{-27} \text{ kg}$$

$$\text{energia } E = mc^2 = 0,0478 \times 10^{-27} \text{ kg} \times c^2 = \mathbf{26,8 \text{ MeV}}$$

$$0,0478 \times 10^{-27} / 6,6904 \times 10^{-27} = 0,7\% \text{ da massa de } 4 \text{ p+}$$

Exemplo. É a energia nuclear suficiente para manter o Sol brilhando durante sua vida na sequência principal?

Por simplicidade, podemos supor que o Sol é 100% hidrogênio. Adotar que somente 10% da massa mais interna do Sol é quente o suficiente para fusão nuclear

$$E_{\text{nuclear}} = 0.1 \times 0.007 \times M_{\odot} c^2 = 1.3 \times 10^{44} \text{ J}$$

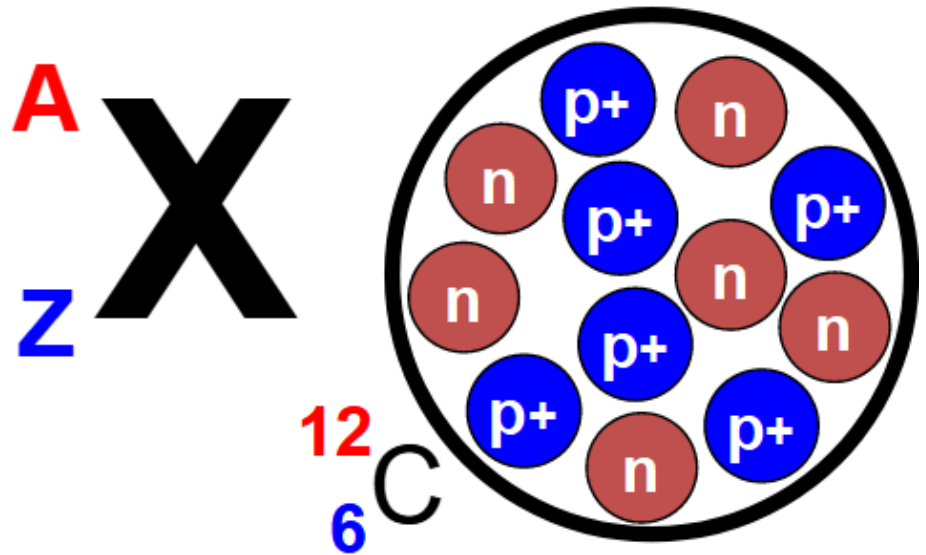
$1 M_{\odot} = 1,9891 \times 10^{30} \text{ kg}$ \uparrow 0,7% de 4H

$$t_{\text{nuclear}} = \frac{E_{\text{nuclear}}}{L_{\odot}} \sim 10^{10} \text{ anos}$$

$1 L_{\odot} = 3,828 \times 10^{26} \text{ W}$

Representação do elemento químico X

A = Número de núcleons = Z + Nêutrons



Z : Número de Prótons
(número atômico)

A : Número de massa

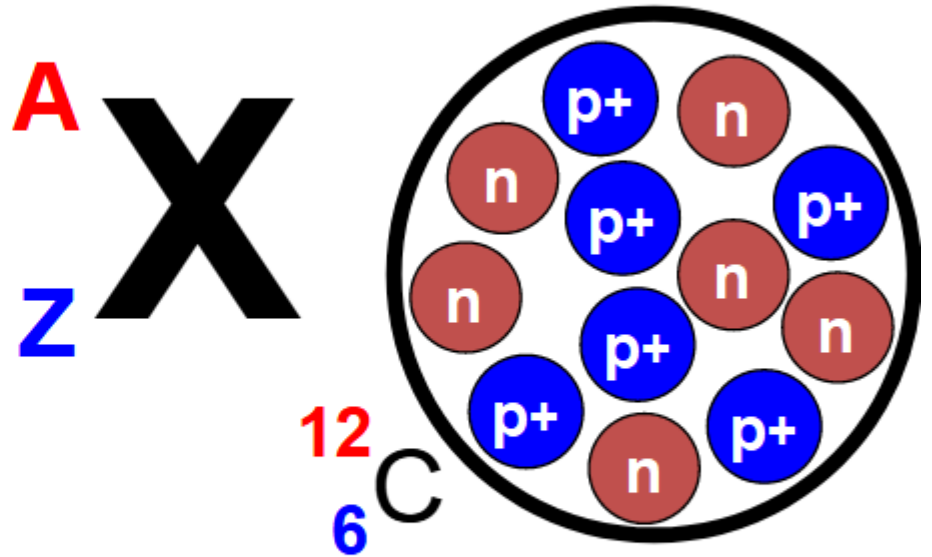
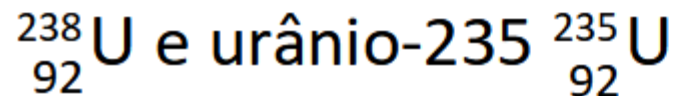
Representação do elemento químico X

$$A = \text{Número de núcleons} = Z + \text{Nêutrons}$$

Isótopo de um elemento químico:

igual número de prótons (Z) mas diferente número de nêutrons \rightarrow diferente A .

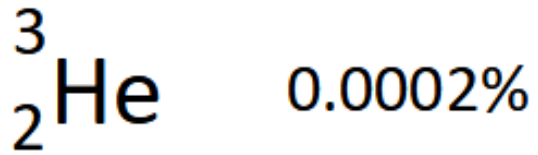
Exemplo: urânio ($Z = 92$) tem como isótopos mais abundantes o urânio-238



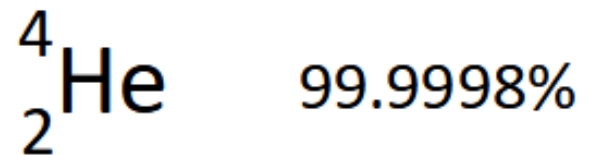
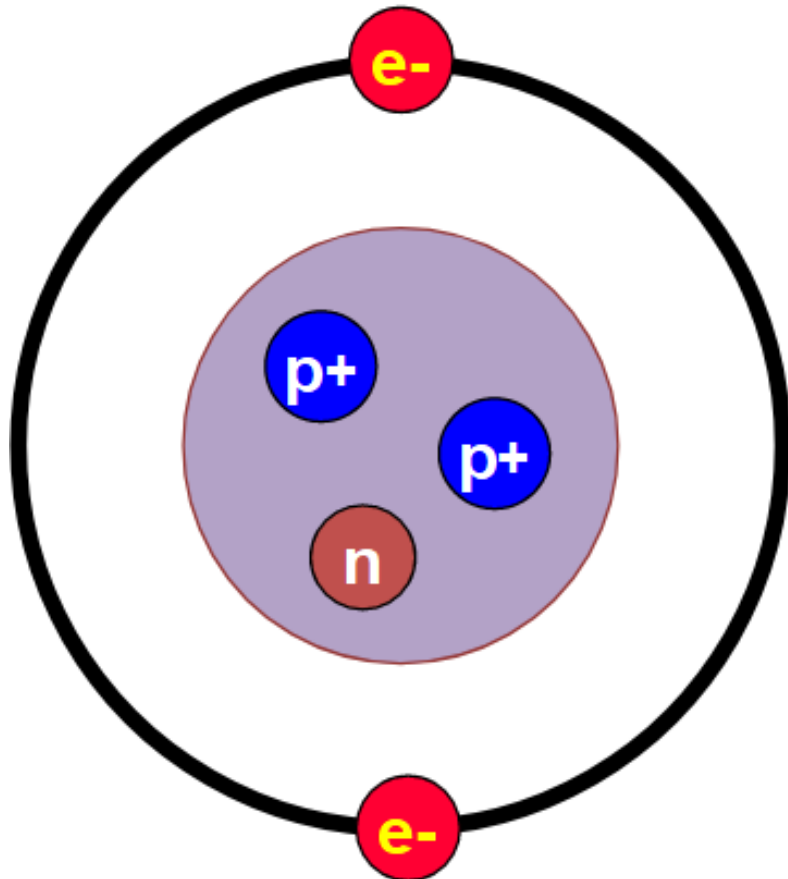
Z : Número de Prótons
(número atômico)

A : Número de massa

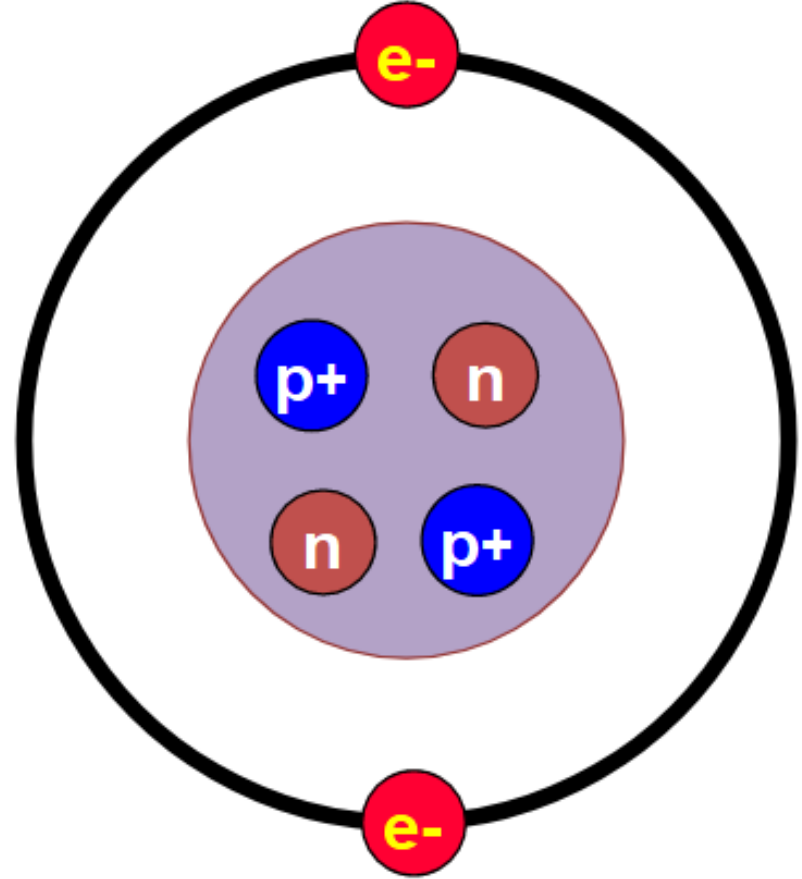
Isótopos estáveis do hélio



Hélio 3 (trítium)



Hélio 4 (núcleo=partícula α)

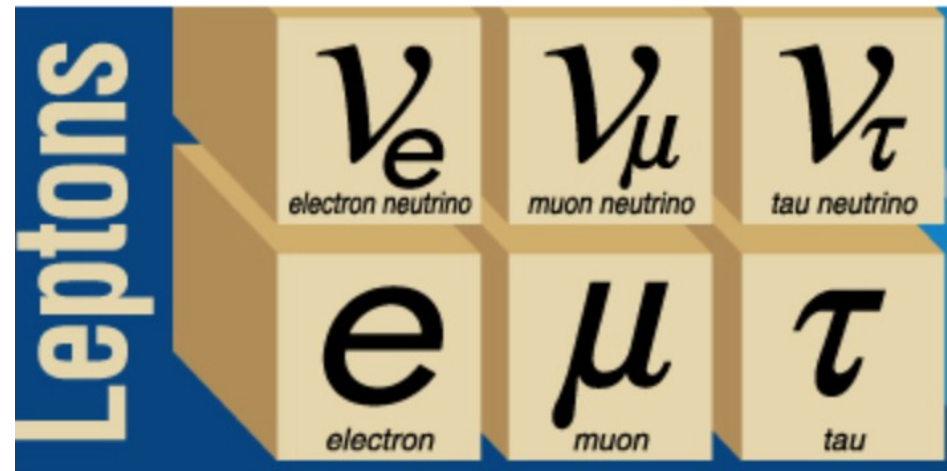


Também aparecem nas reações nucleares os **elétrons** [e^-] e **neutrinos** [ν_e], assim como suas antipartículas: **pósitron** [e^+] e **antineutrino** [$\bar{\nu}_e$]

Neutrinos ν

São partículas que quase não interagem com a matéria, $\sigma_\nu \sim 10^{-48} \text{ m}^2$

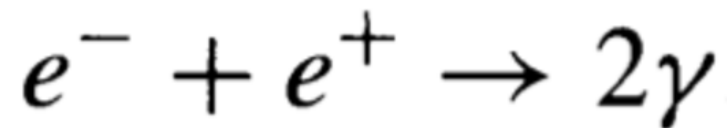
Percurso livre médio do neutrino 'dentro' do Sol é de $\sim 10^{18} \text{ m}$, ou ~ 100 anos-luz, ou $\sim 1,4 \times 10^9 R_\odot$



Antimatéria

- Mistura da matéria e antimatéria → aniquilamento.
- Colisão de uma partícula e antipartícula → energia

Por exemplo, colisão de elétron e antielétron (pósitron) resulta em fótons de alta energia (radiação gama γ):

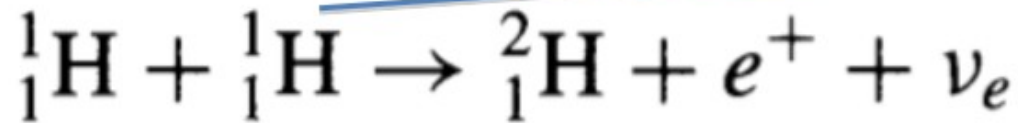
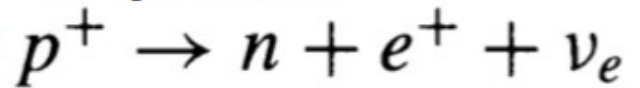


São necessários 2 fótons para a conservação da quantidade de movimento (*momento*)

A **X** A: Número de massa (p + n)
Z Z: Número de prótons (carga positiva)

Cadeia próton-próton, PP-I

Força fraca



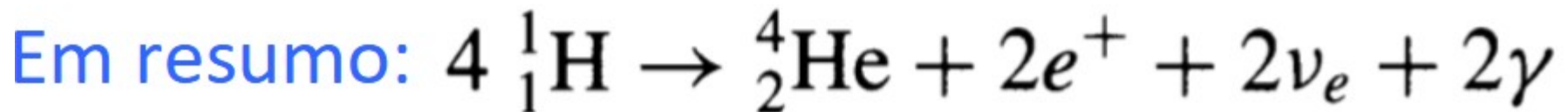
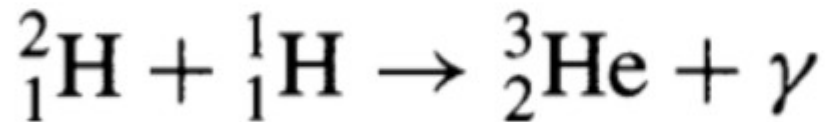
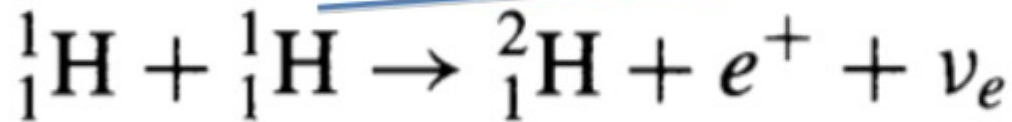
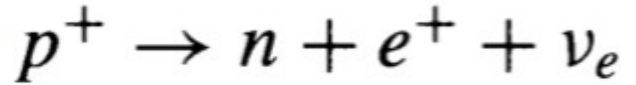
A
Z **X**

A: Número de massa (p + n)

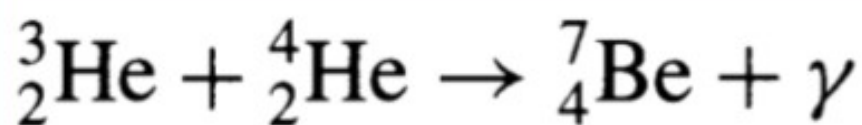
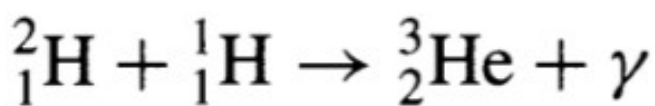
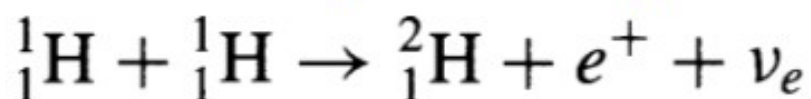
Z: Número de prótons (carga positiva)

Cadeia próton-próton, PP-I

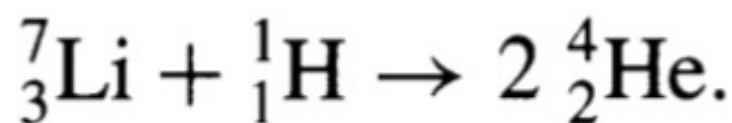
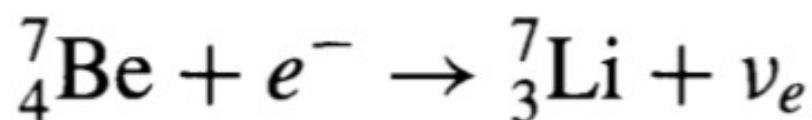
Força fraca



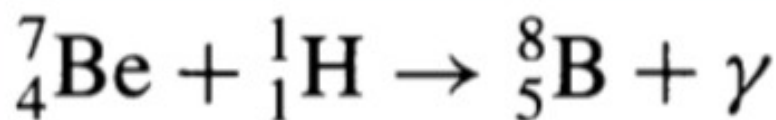
Cadeia próton-próton, PP-II



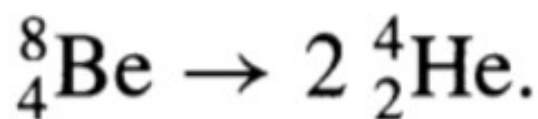
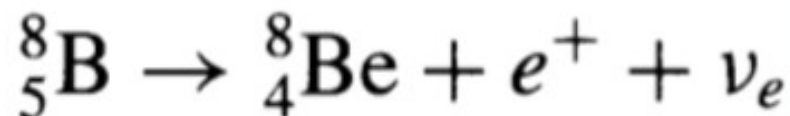
31%

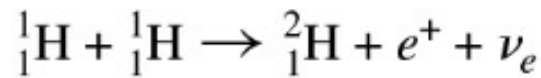


PP-III



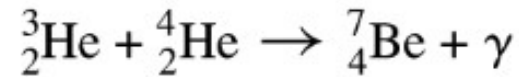
0,3%





69%

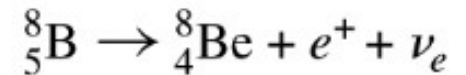
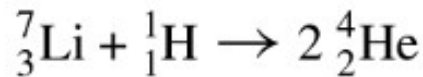
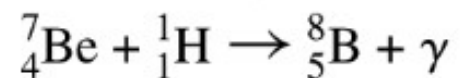
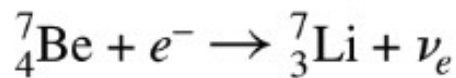
31%



PP-I

99,7%

0,3%

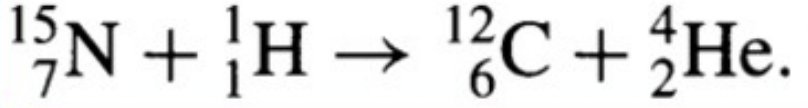
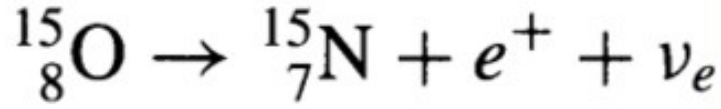
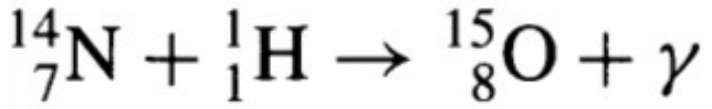
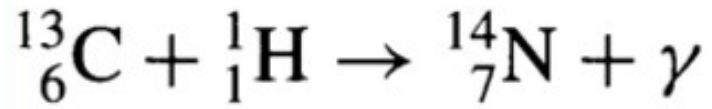
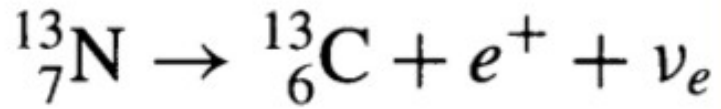
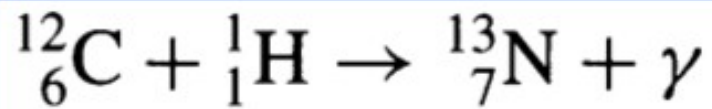


PP-II



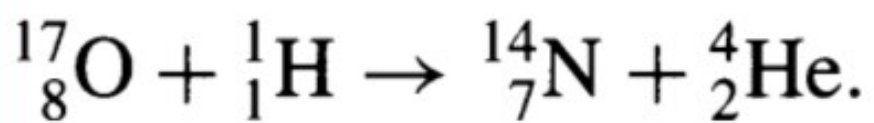
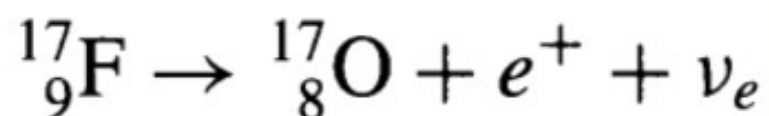
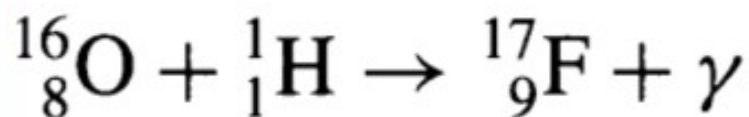
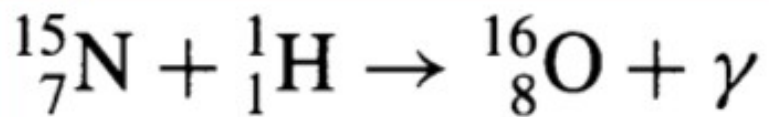
PP-III

O Ciclo CNO



99,96%

0,04%

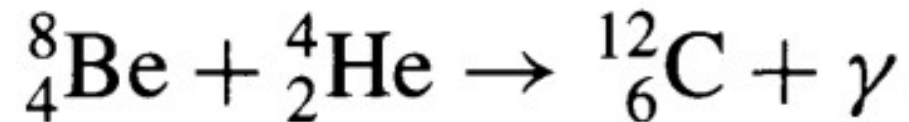


O Sol queima He no fim da fase gigante vermelha, nas fases 'ramo horizontal' e 'gigante AGB' (asymptotic giant branch):

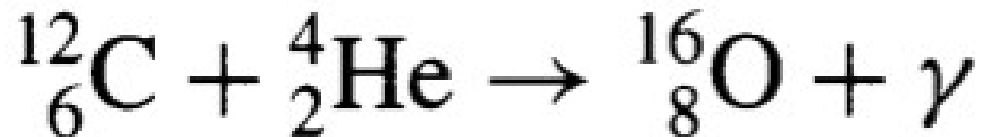


Processo triplo-alfa

$$T \sim 10^8 \text{ K}$$



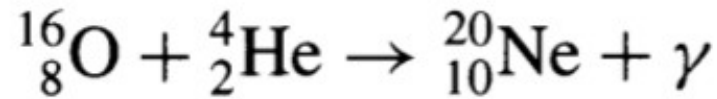
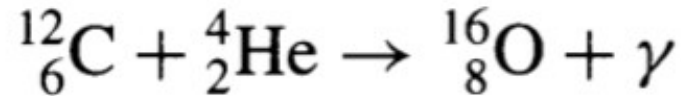
$$T \sim 10^8 \text{ K}$$



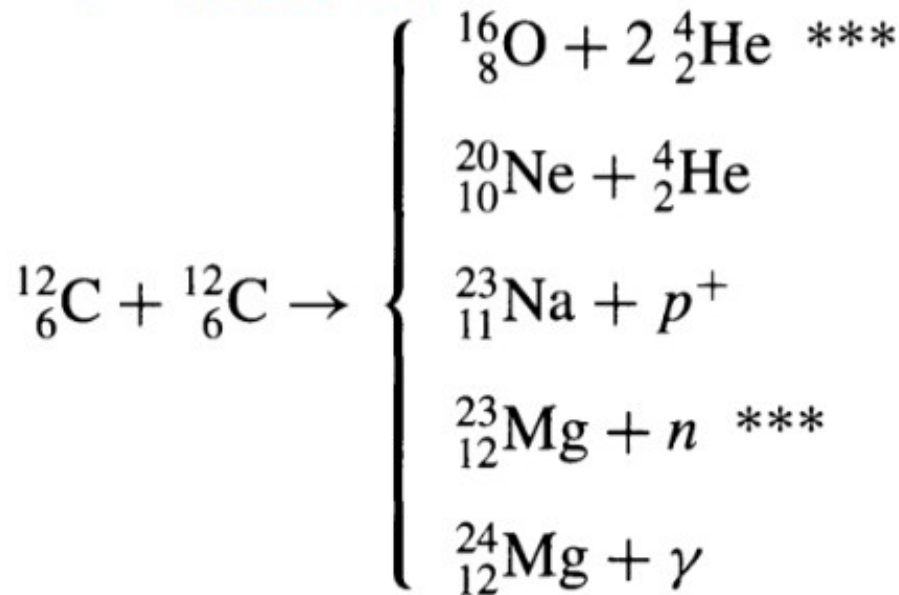
Outras reações em estrelas mais massivas que o Sol

Queima de C e O

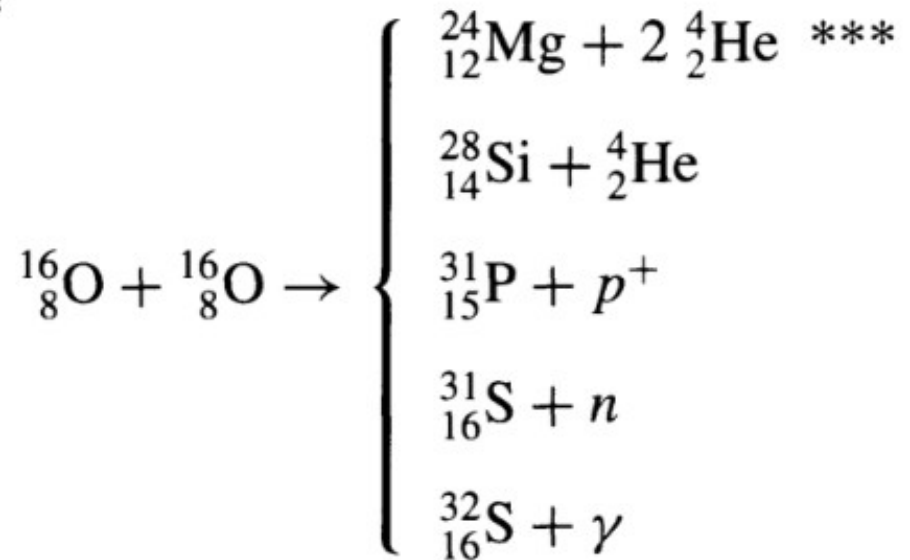
$$T \sim 10^8 \text{ K}$$



$$T \sim 6 \times 10^8 \text{ K}$$



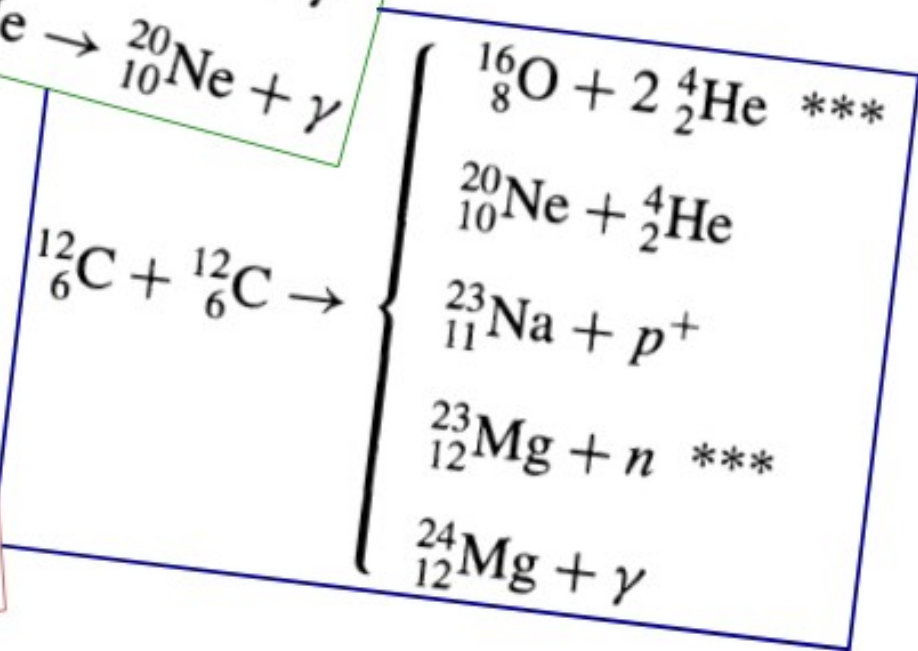
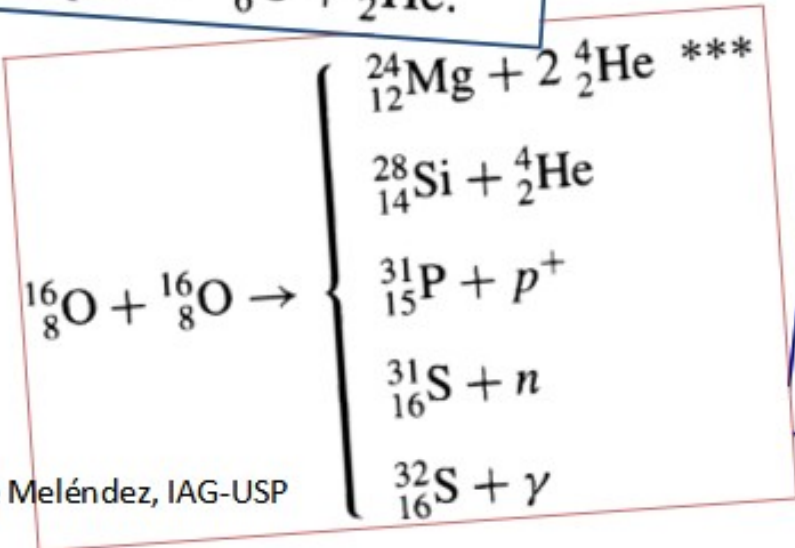
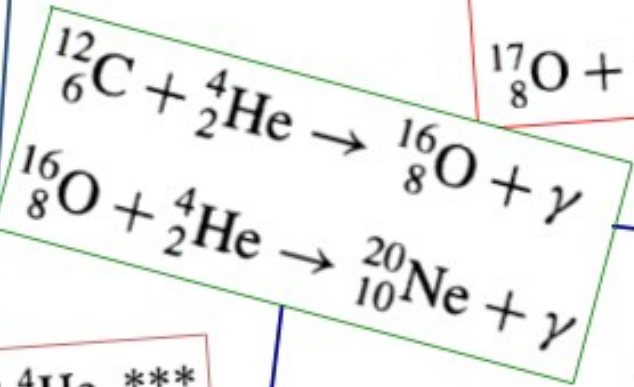
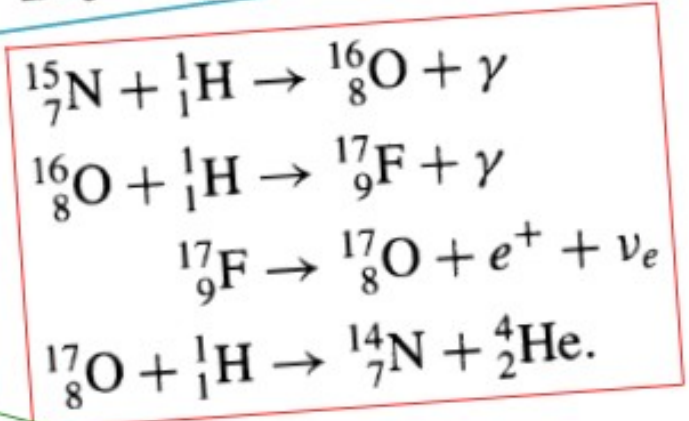
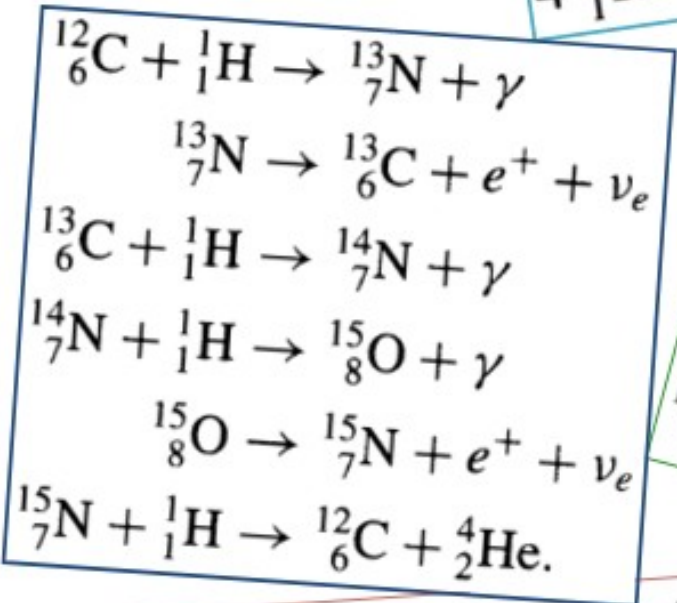
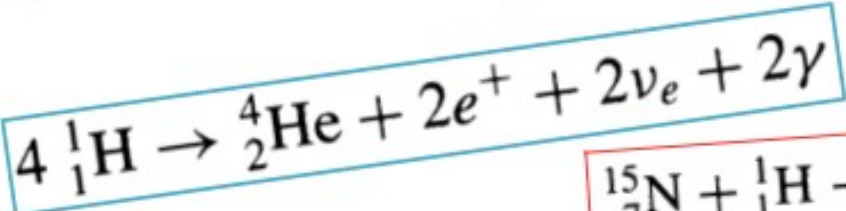
$$T \sim 10^9 \text{ K}$$



***: endotérmica



Carl Sagan: somos poeira de estrelas



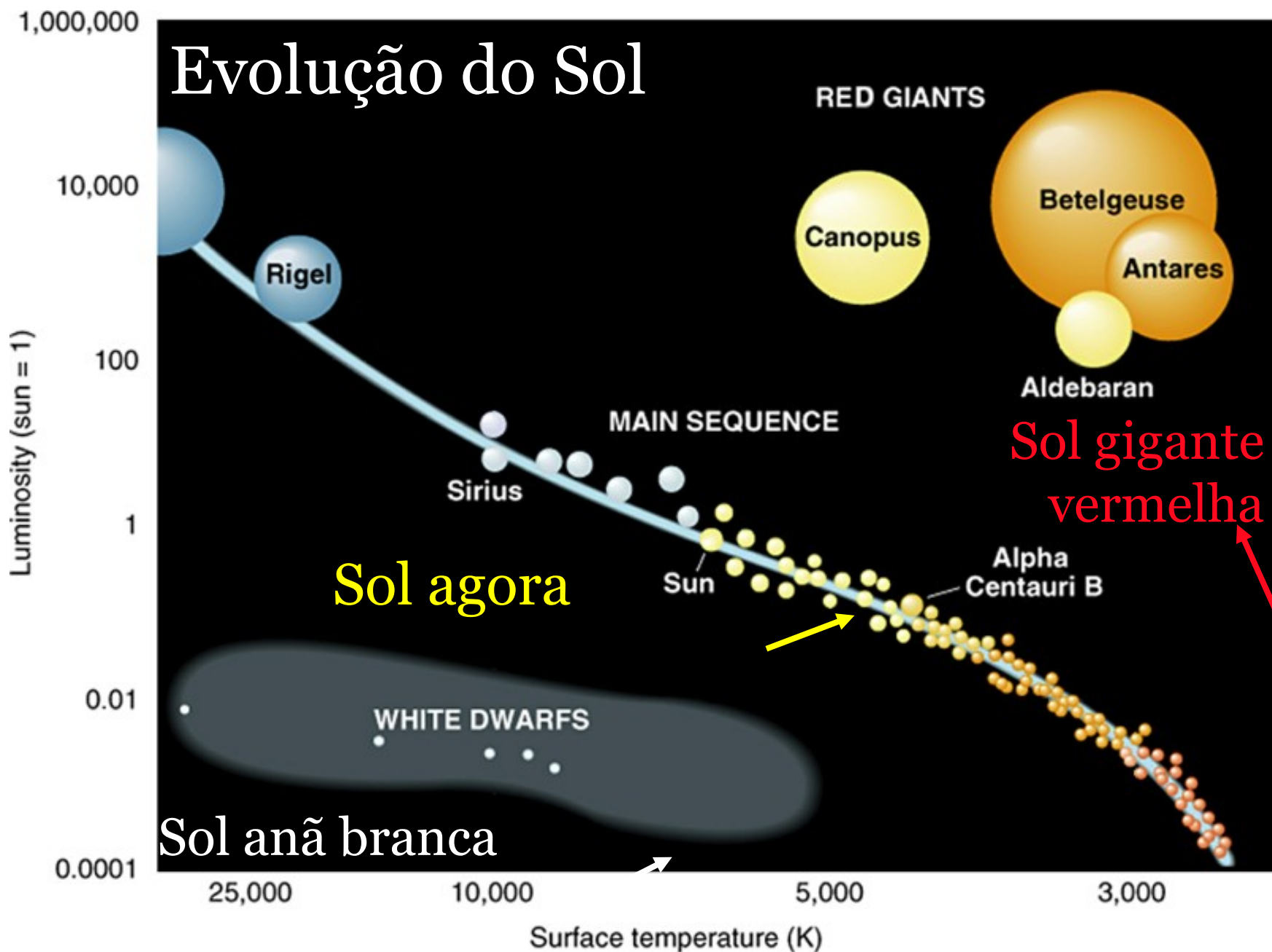
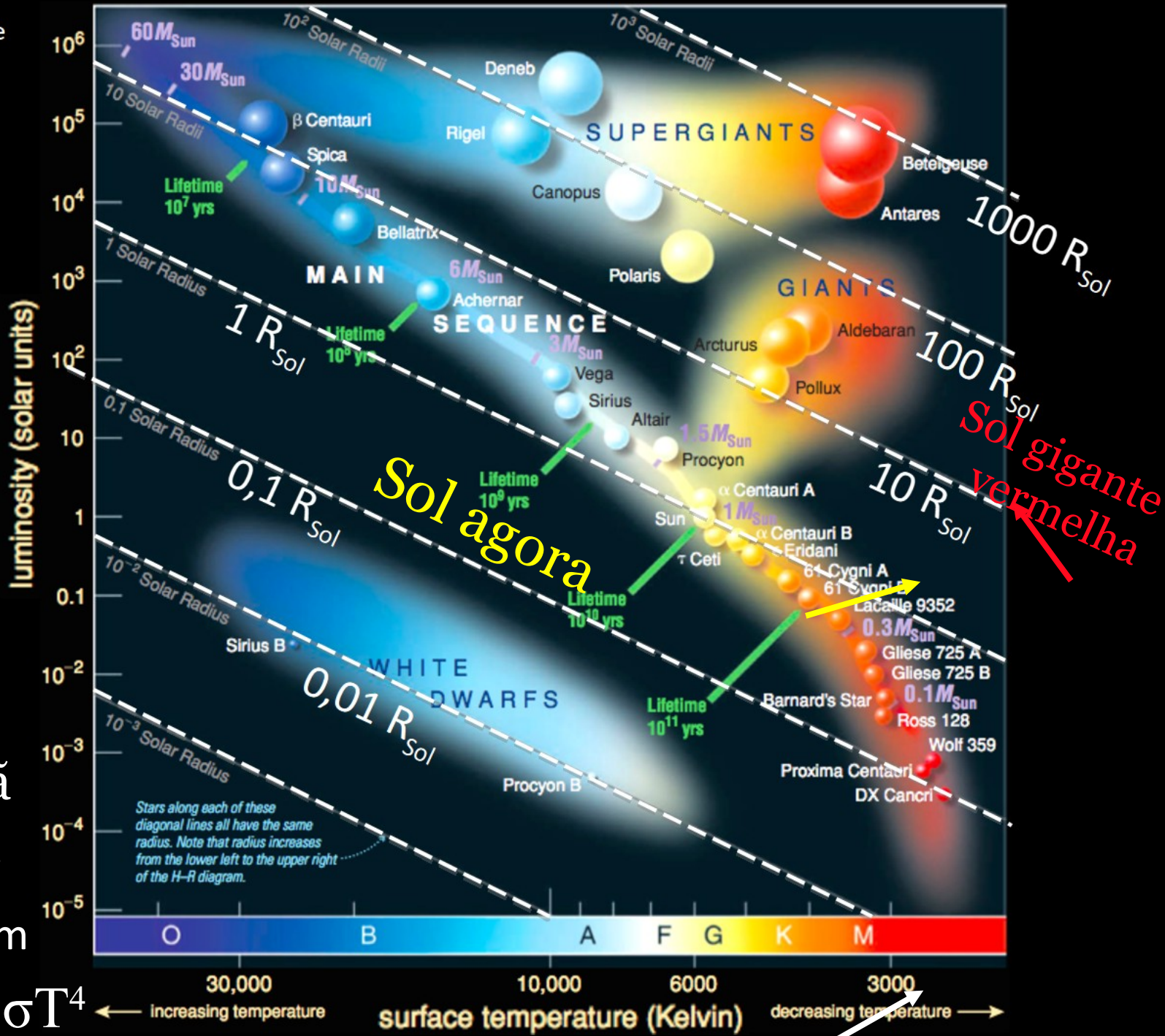


Figure 1 - The Hertzsprung-Russell Diagram. Dim cool stars are at the lower-right, bright hot stars are at the upper-left. The sizes shown for the stars are suggestive, not exact.

Cosmic Perspective



Sol anã
branca

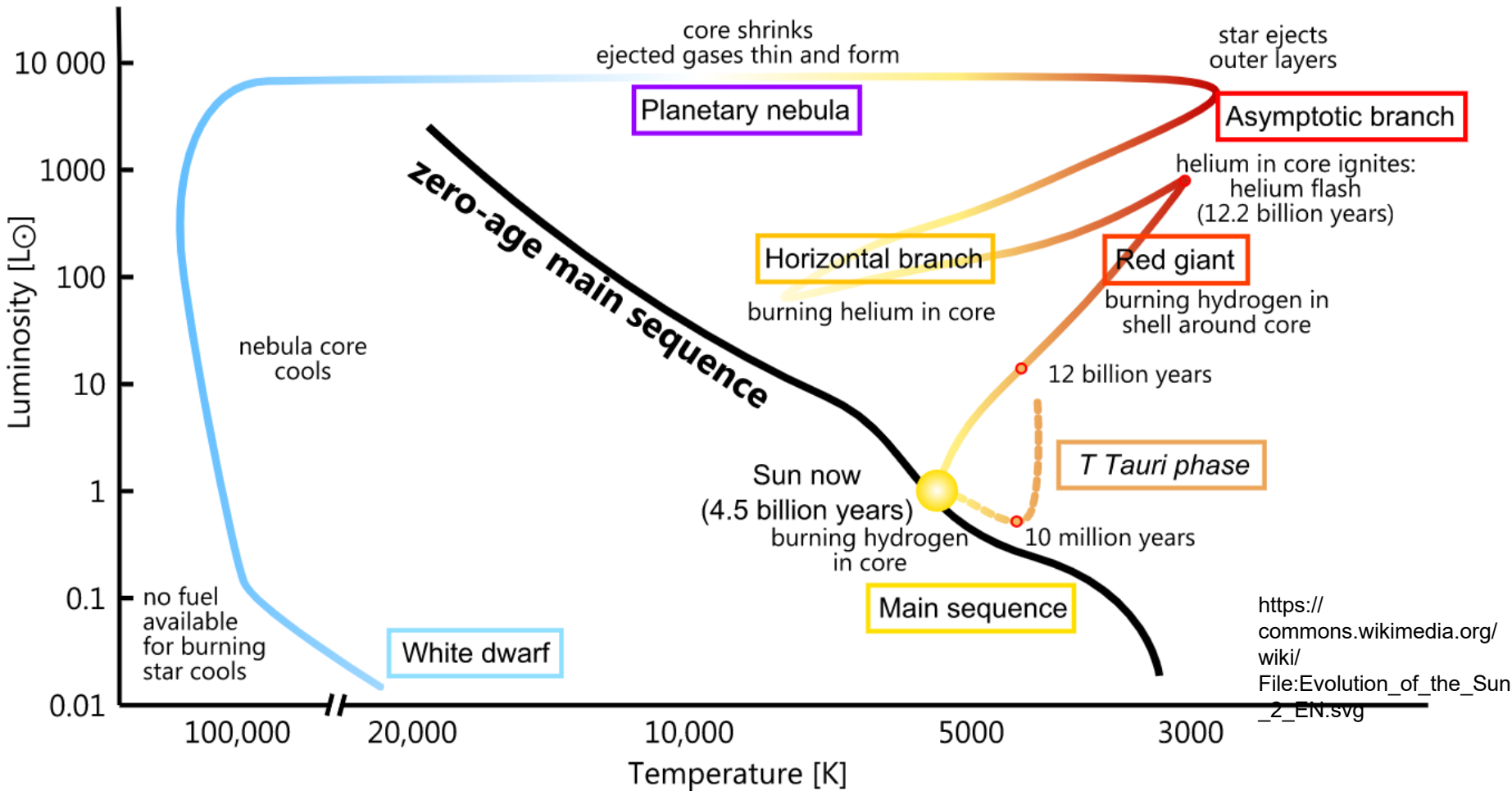
$$R_{\odot} \sim 7 \times 10^8 \text{ m}$$

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

← increasing temperature surface temperature (Kelvin) decreasing temperature →

Evolução do Sol: sequência principal, gigante vermelha, ramo horizontal, gigante assintótica (AGB), nebulosa planetária, anã branca

	~9 Ga	>	~1 Ga	>	~100 Ma	>	~10 000 a	>	
Stage:	Main sequence		Red giant		Horizontal branch		Planetary nebula		White dwarf
Sun's age:	4.5 Ga (now)		12.2 Ga		12.3 Ga		12.3305 Ga		12.3306 Ga





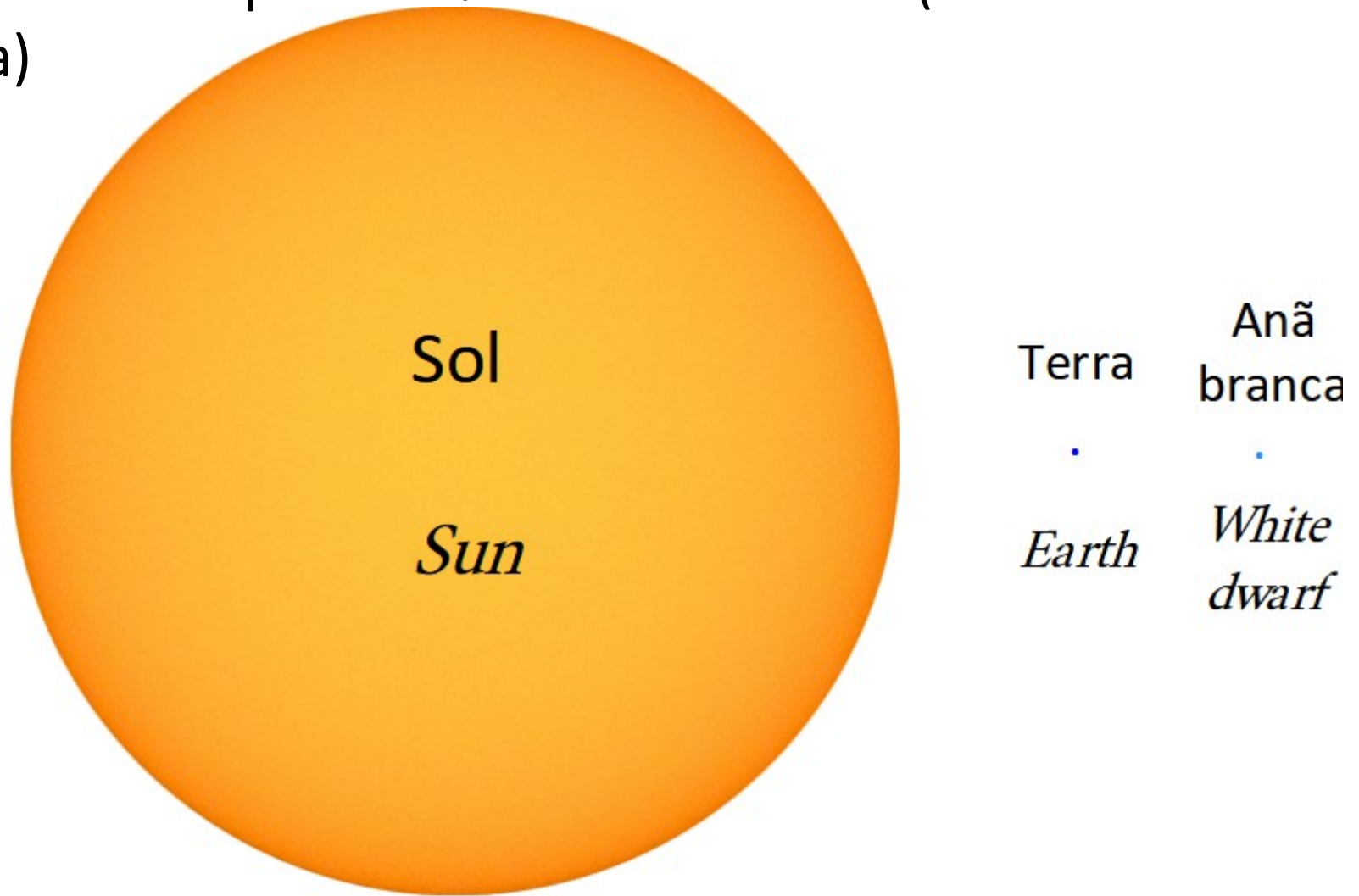
Helix Planetary Nebula (NGC 7293). [O III] + H α
74h com telescópio pequeno (20cm)

© Andrew Campbell 2018

NGC 6543. Nebulosa Olho de gato



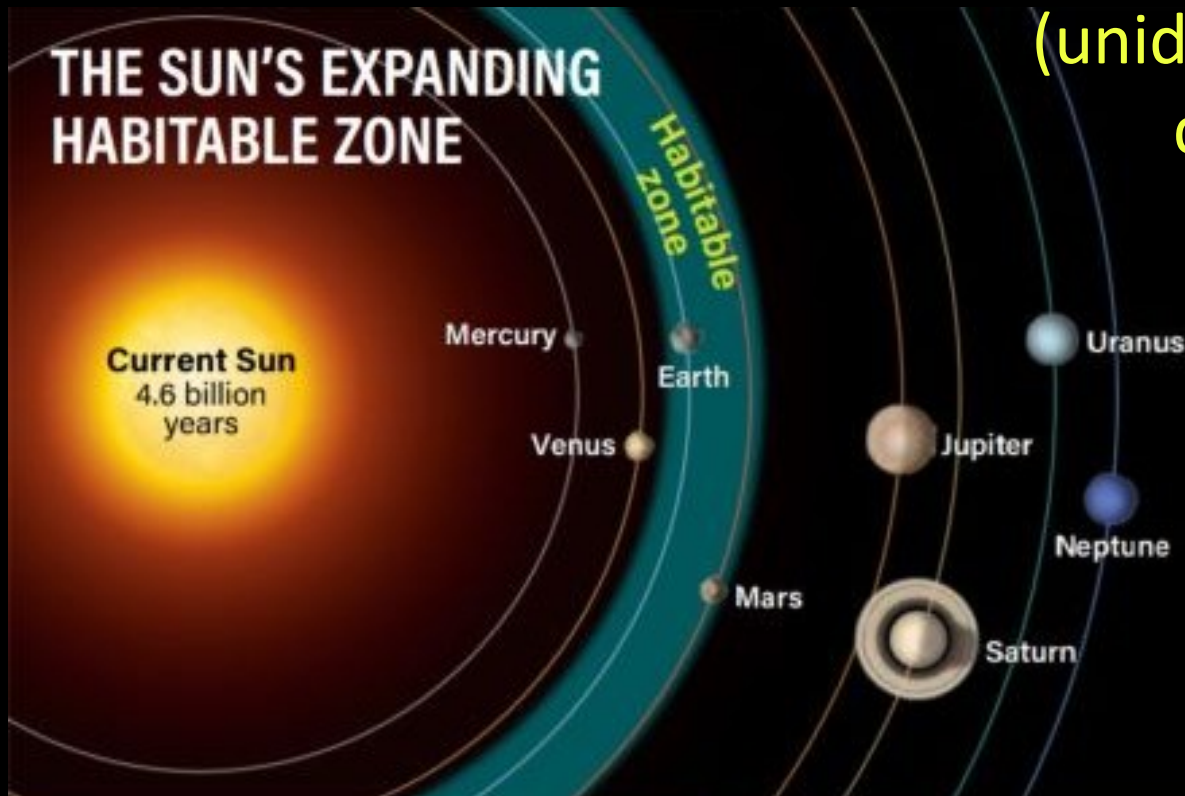
Estágio final da evolução do Sol é uma anã branca, um objeto com apenas 1% do raio do Sol (~ tamanho da Terra)



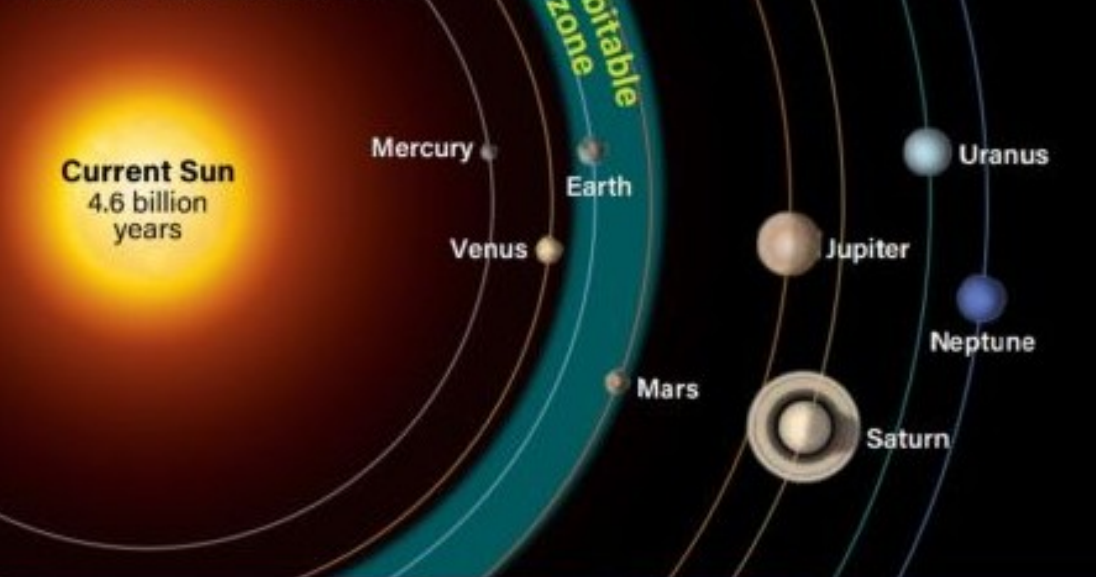
Zona habitável: região ao redor da estrela onde pode existir água líquida

Zona habitável
do Sol agora

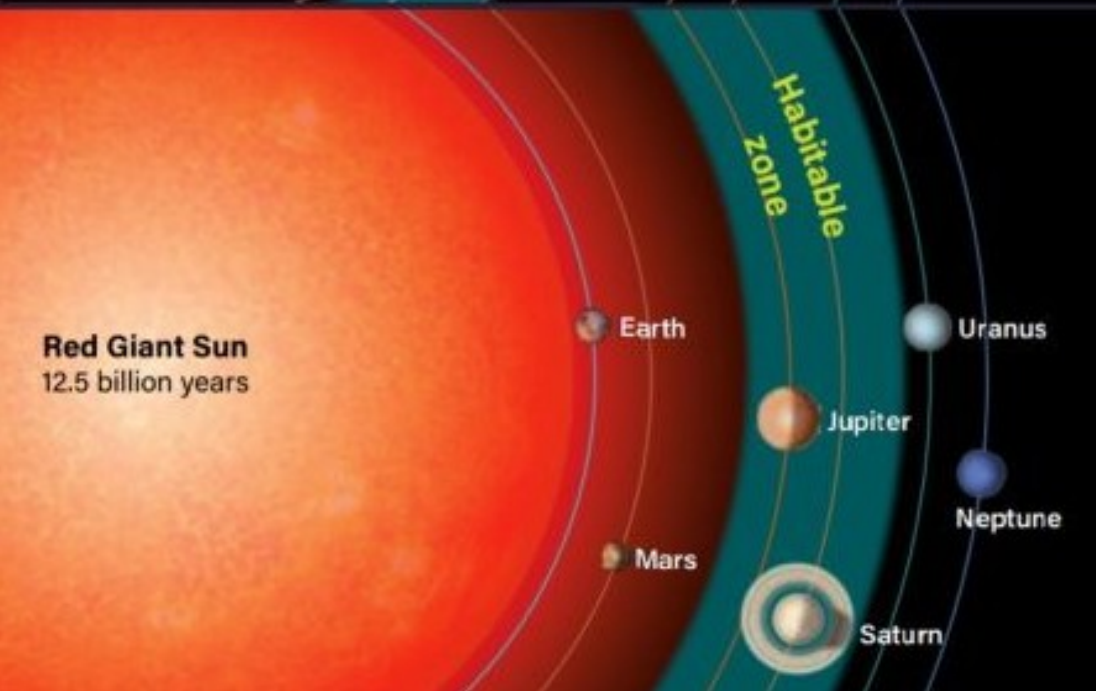
A zona habitável agora
se encontra ~ 1 UA
(unidade astronômica =
distância Terra-Sol)



THE SUN'S EXPANDING HABITABLE ZONE



Zona habitável
do Sol agora



Zona habitável
do Sol gigante
vermelha

<https://astronomy.com/magazine/ask-astro/2020/09/what-will-happen-to-the-planets-when-the-sun-becomes-a-red-giant>

Interior solar

$R_{\odot} = 696\,000\text{ km}$

Núcleo: $0,0 - 0,25 R_{\odot}$

Zona radiativa: $0,25 - 0,71 R_{\odot}$

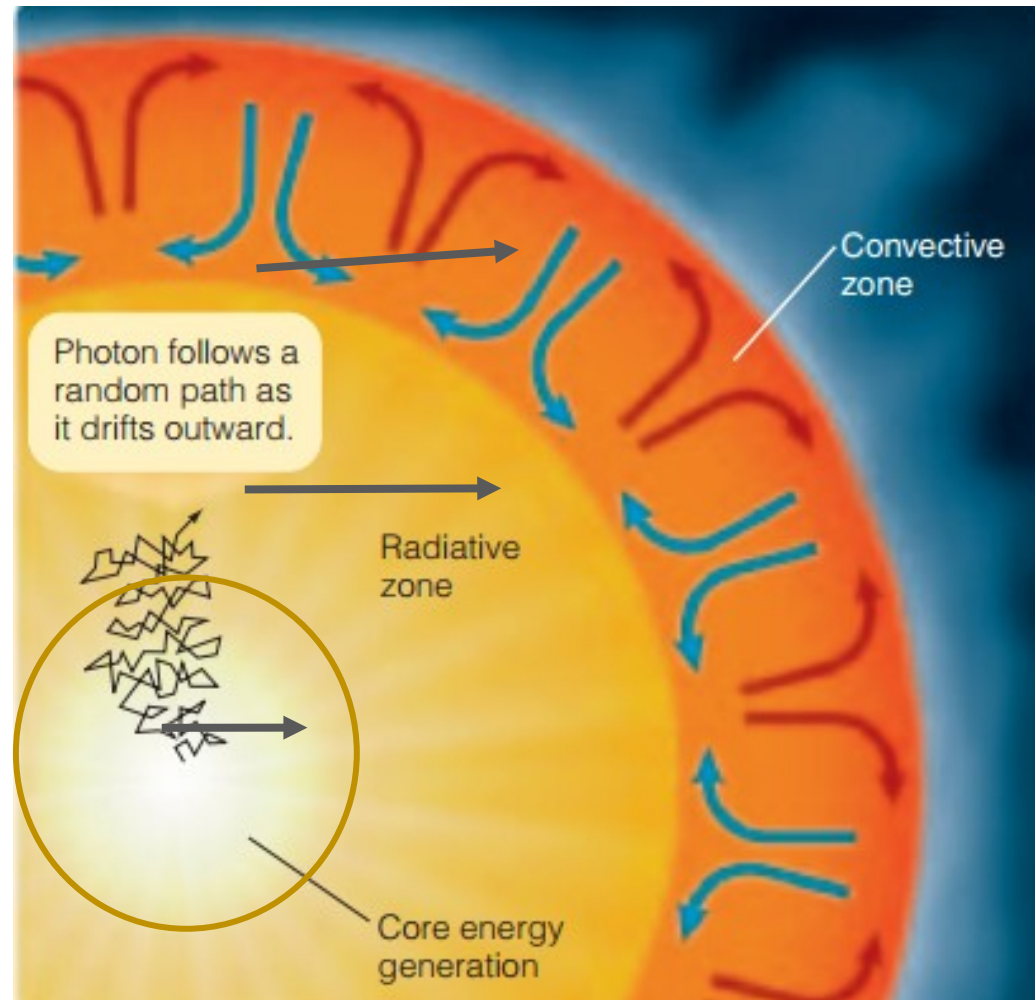
Zona convectiva: $0,71 - 1,0 R_{\odot}$

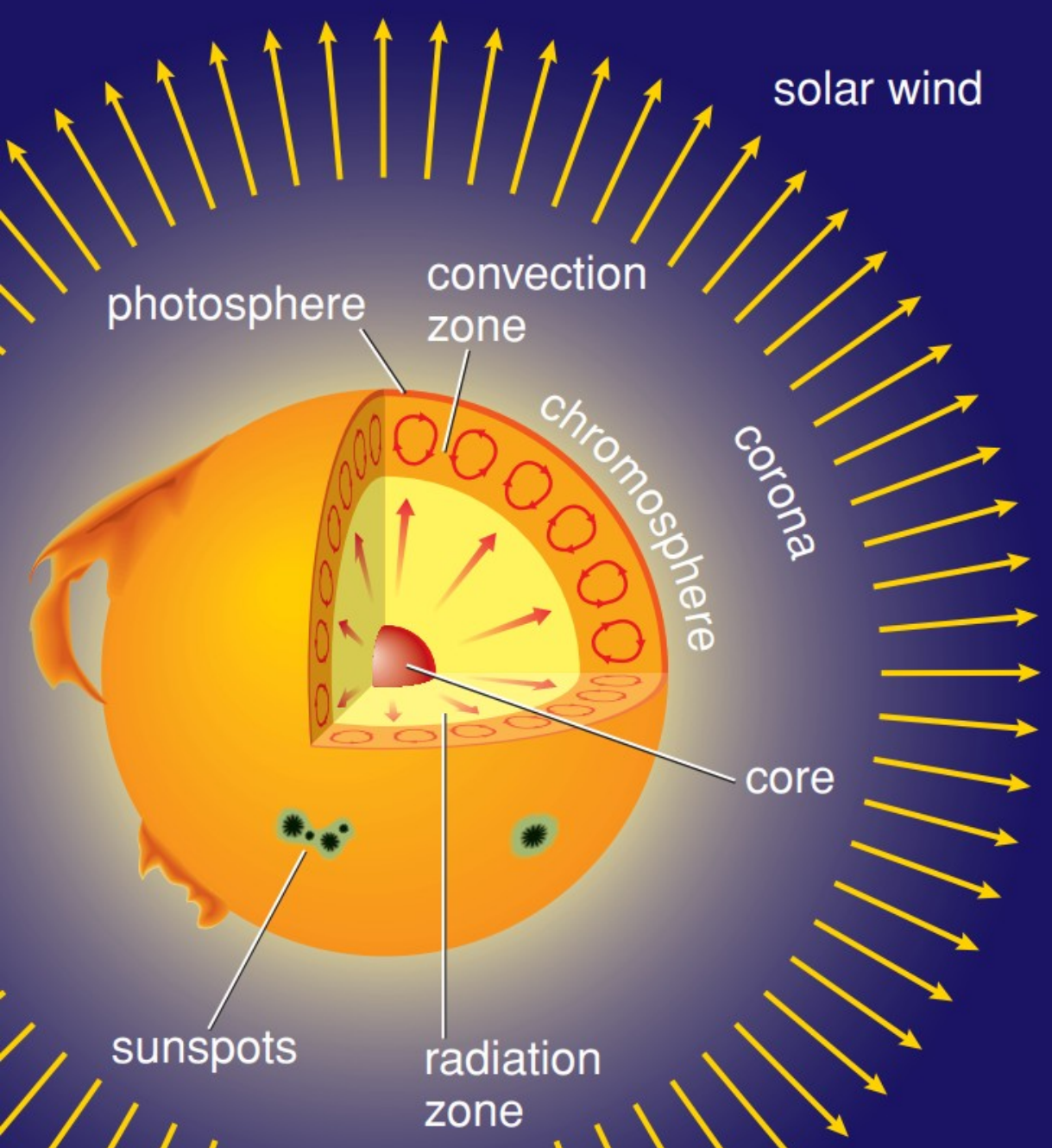
Fluxo de energia

Transporte de energia via convecção

Transporte de energia via radiação

Núcleo: geração de energia (fusão nuclear)





Atmosfera solar

Fotosfera:

-100 a 500 km

Cromosfera:

500 a 2000 km

Coroa:

2000 a $\sim 8 \times 10^6$ km

Vento solar:

até ~ 100 U.A.?

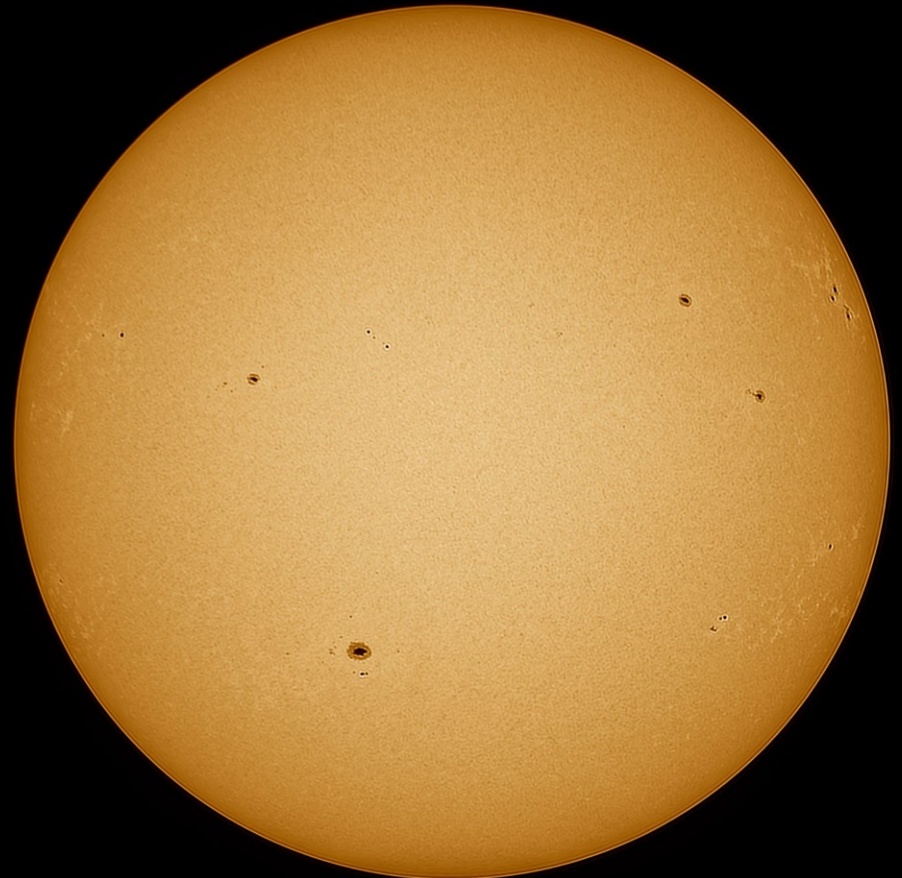
Geralmente apenas podemos observar a fotosfera (“superfície”) do Sol

<https://twitter.com/CarbonRobot/>

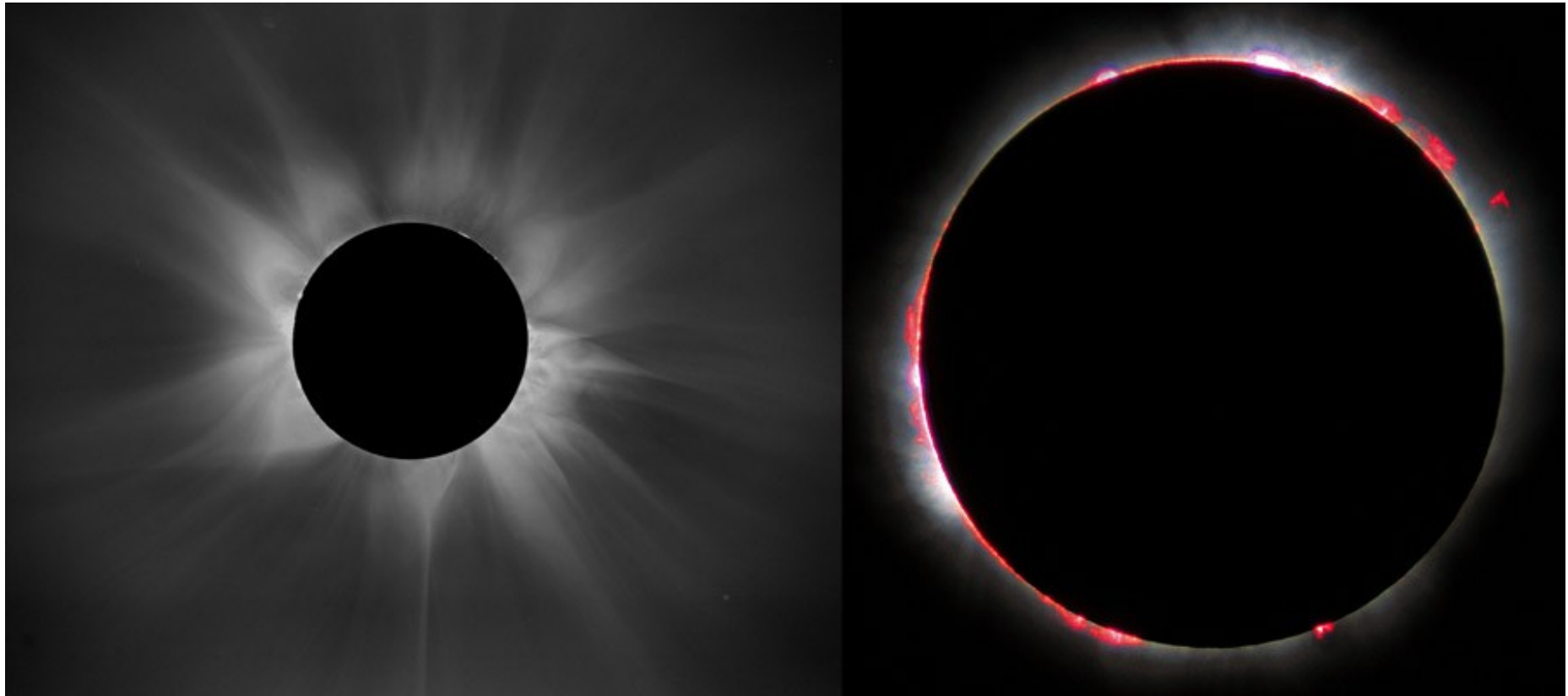
6 de agosto de 2023



7 de agosto de 2023



Durante eclipse solar total podemos observar a cromosfera (direita) e coroa (esquerda) solar



<https://scied.ucar.edu/image/suns-atmosphere-corona-and-chromosphere>