

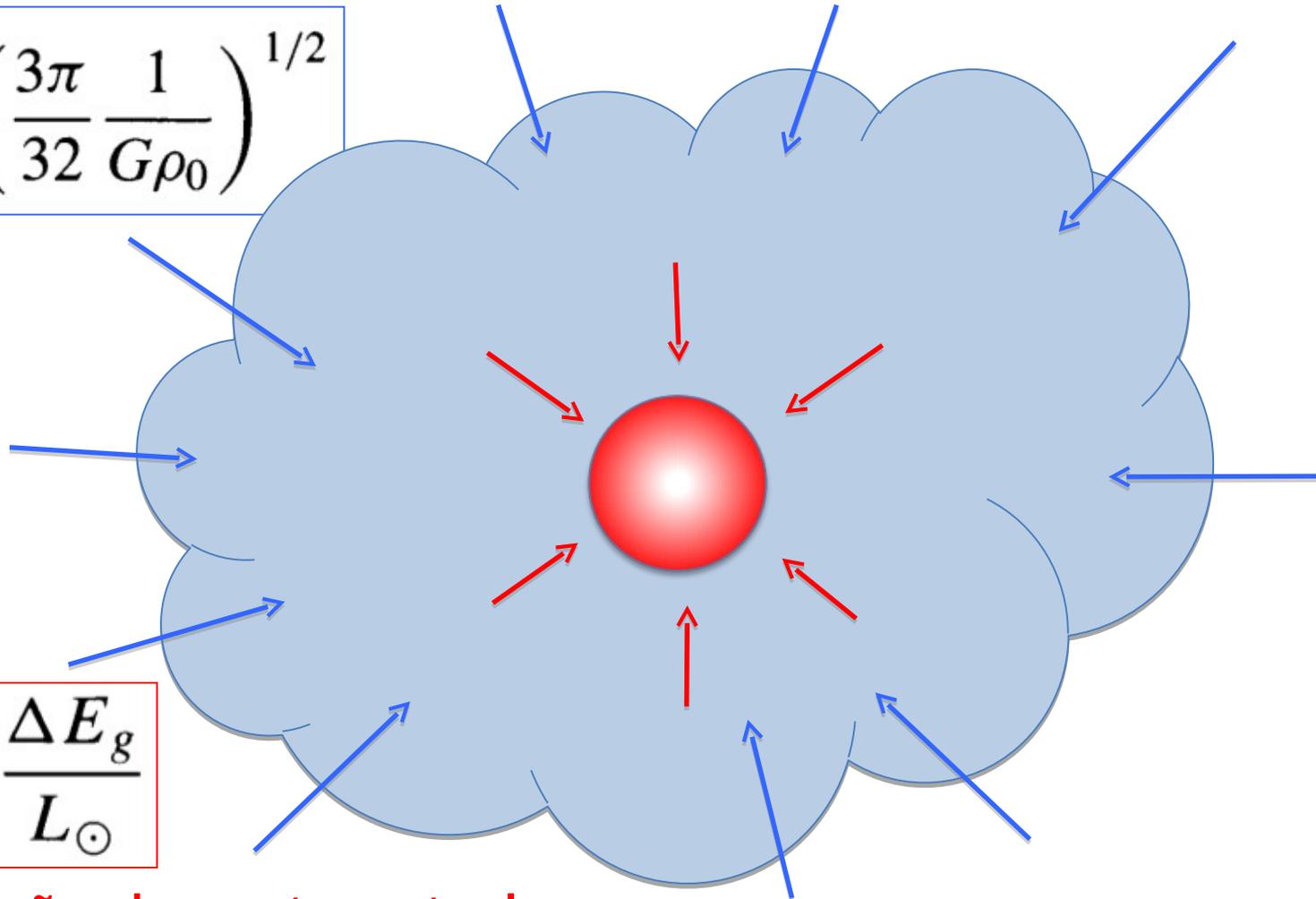
12 - O Meio Interestelar (ISM) e a Formação de Estrelas

12.3 Evolução pre-sequência principal (PMS) + parte do 12.2 (colapso da nuvem a proto-estrela)



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

$$t_{\text{ff}} = \left(\frac{3\pi}{32} \frac{1}{G\rho_0} \right)^{1/2}$$



$$t_{\text{KH}} = \frac{\Delta E_g}{L_\odot}$$

Contração da proto-estrela (começando na trilha de Hayashi):
escala de tempo de Kelvin-Helmholtz $\sim 10^7$ de anos

Colapso homólogo

Escala de tempo de *free fall* para o colapso da nuvem:

$$t_{\text{ff}} = \left(\frac{3\pi}{32} \frac{1}{G\rho_0} \right)^{1/2}$$

O tempo de *free fall* não depende do raio da nuvem → colapso homólogo (todas as partes da nuvem colapsam no mesmo tempo)

Exemplo 12.2.2

Usando os dados do Exemplo 12.2.1, estimar o tempo de colapso da nuvem para uma proto-estrela.

$$\rho_0 = 3 \times 10^{-17} \text{kgm}^{-3} \rightarrow t_{\text{ff}} = 3,8 \times 10^5 \text{ anos}$$

Exemplo 10.3.1. Quanto tempo pode brilhar o Sol no colapso de proto-estrela a partir de um raio inicial muito maior ao atual?

$$E \sim -\frac{3}{10} \frac{GM^2}{R} \quad (\text{metade da energia potencial pode ser radiada})$$

Assumindo que uma proto-estrela tem $R_i \gg R_\odot$:

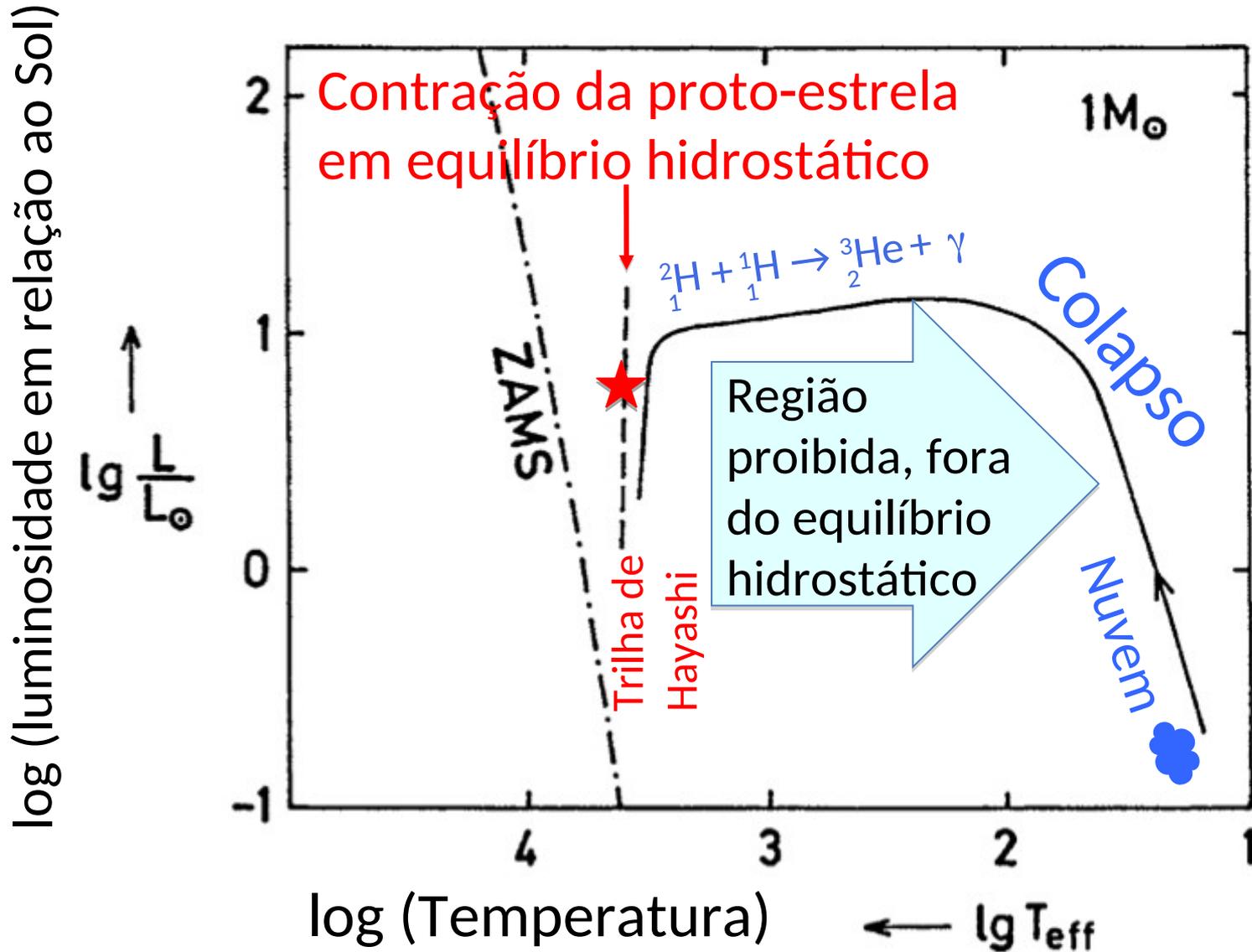
$$\Delta E_g = -(E_f - E_i) \simeq -E_f \simeq \frac{3}{10} \frac{GM_\odot^2}{R_\odot} \simeq 1.1 \times 10^{41} \text{ J.}$$

Supondo luminosidade aprox. constante para o Sol:

$$t_{KH} = \frac{\Delta E_g}{L_\odot} \sim 10^7 \text{ anos} \quad t_{KH} \text{ é a escala de tempo Kelvin-Helmholtz}$$

$t_{KH} \gg t_{ff} \rightarrow$ a evolução da proto-estrela acontece lentamente (comparada ao colapso da nuvem)

Colapso de nuvem a proto-estrela



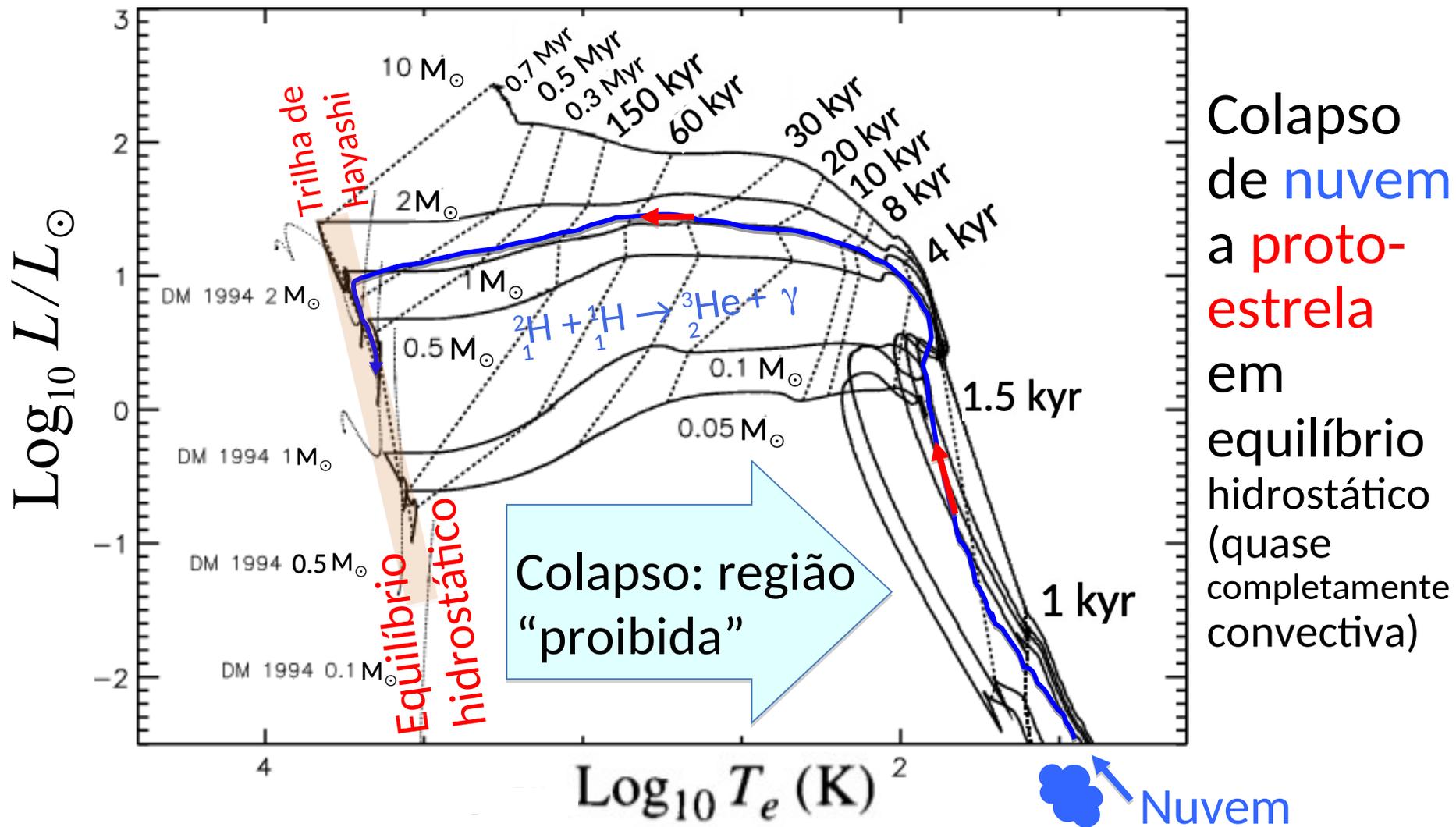


FIGURE 12.9 Theoretical evolutionary tracks of the gravitational collapse of 0.05, 0.1, 0.5, 1, 2, and 10 M_⊙ clouds through the protostar phase (solid lines). The dashed lines show the times since collapse began. The light dotted lines are pre-main-sequence evolutionary tracks of 0.1, 0.5, 1, and 2 M_⊙ stars from D'Antona and Mazzitelli, *Ap. J. Suppl.*, 90, 457, 1994. Note that the horizontal axis is plotted with effective temperature increasing to the left, as is characteristic of all H–R diagrams. (Figure adapted from Wuchterl and Tscharnuter, *Astron. Astrophys.*, 398, 1081, 2003.)

Cálculos clássicos de evolução na pré-Sequência Principal (**PMS: Pre-Main-Sequence**)

■ Início da queima de deutério (quase não afeta o colapso pois há pouco deutério)

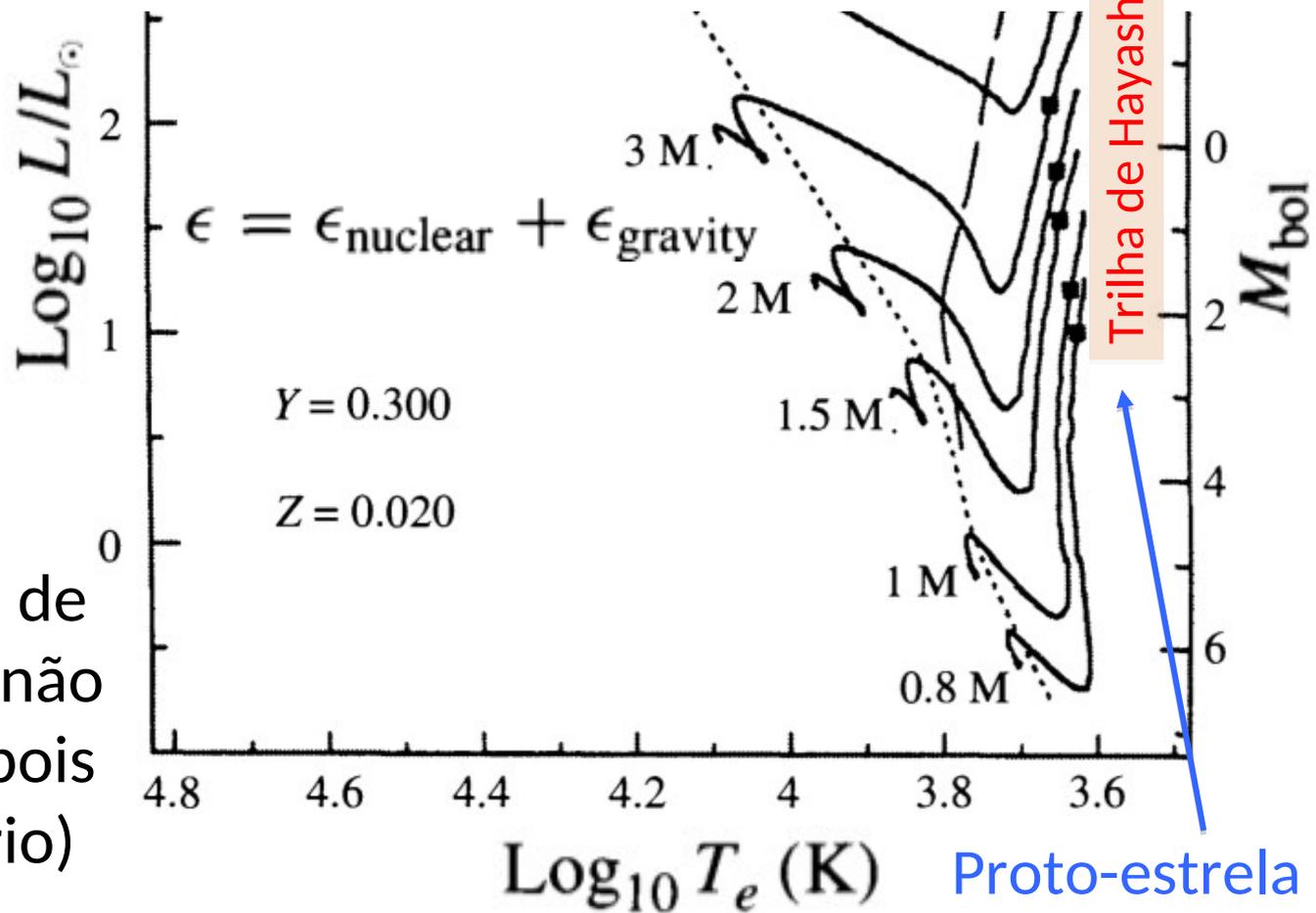
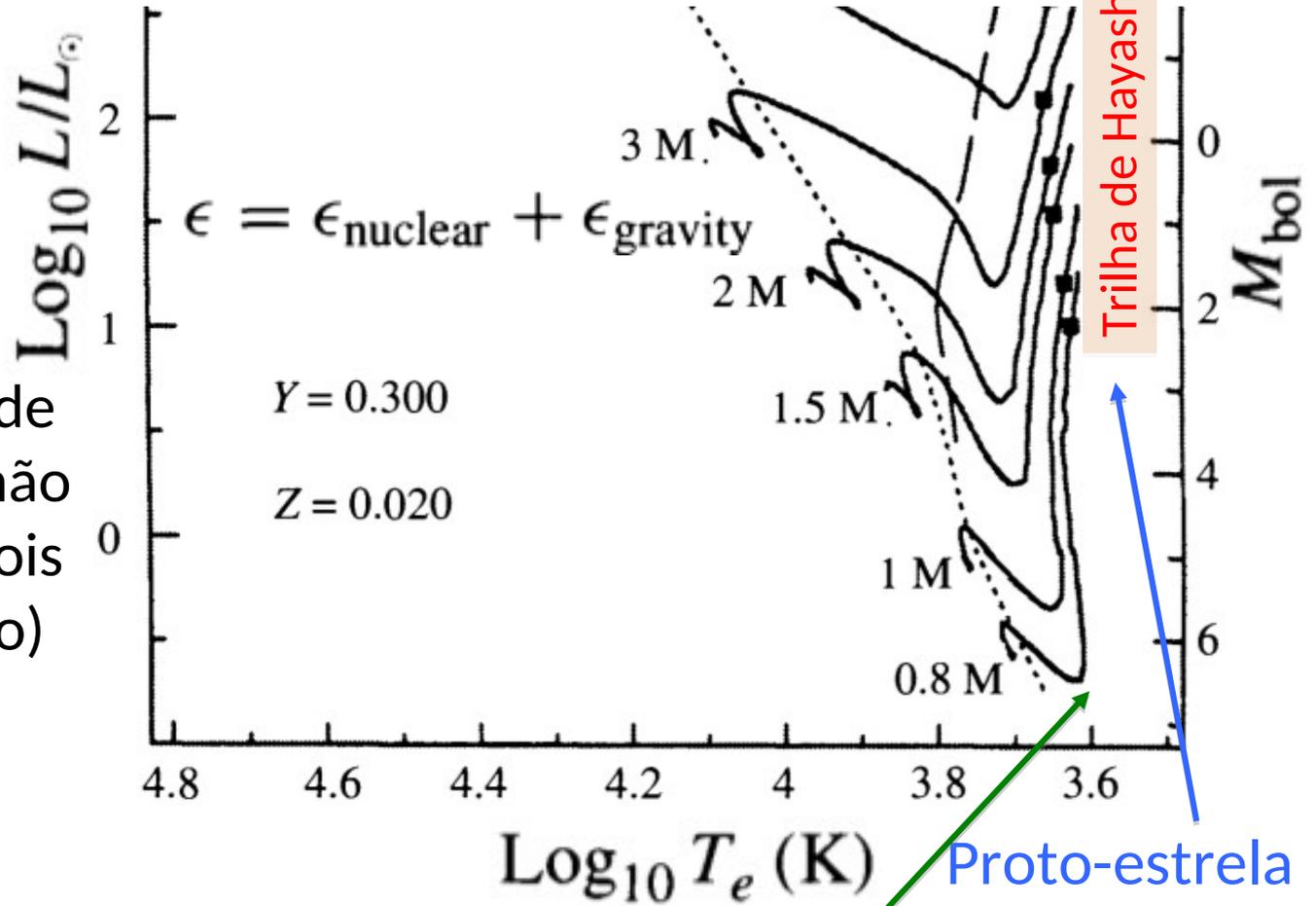


FIGURE 12.11 Classical pre-main-sequence evolutionary tracks computed for stars of various masses with the composition $X = 0.68$, $Y = 0.30$, and $Z = 0.02$. The direction of evolution on each track is generally from low effective temperature to high effective temperature (right to left). The mass of each model is indicated beside its evolutionary track. The square on each track indicates the onset of deuterium burning in these calculations. The long-dash line represents the point on each track where convection in the envelope stops and the envelope becomes purely radiative. The short-dash line marks the onset of convection in the core of the star. Contraction times for each track are given in Table 12.1. (Figure adapted from Bernasconi and Maeder, *Astron. Astrophys.*, 307, 829, 1996.)

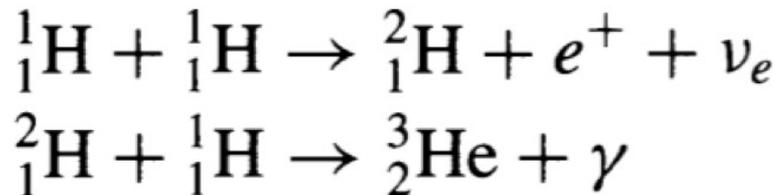
Cálculos clássicos de evolução na pré-Sequência Principal

- ${}^2_1\text{H} + {}^1_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$
 Início da queima de deutério (quase não afeta o colapso pois há pouco deutério)



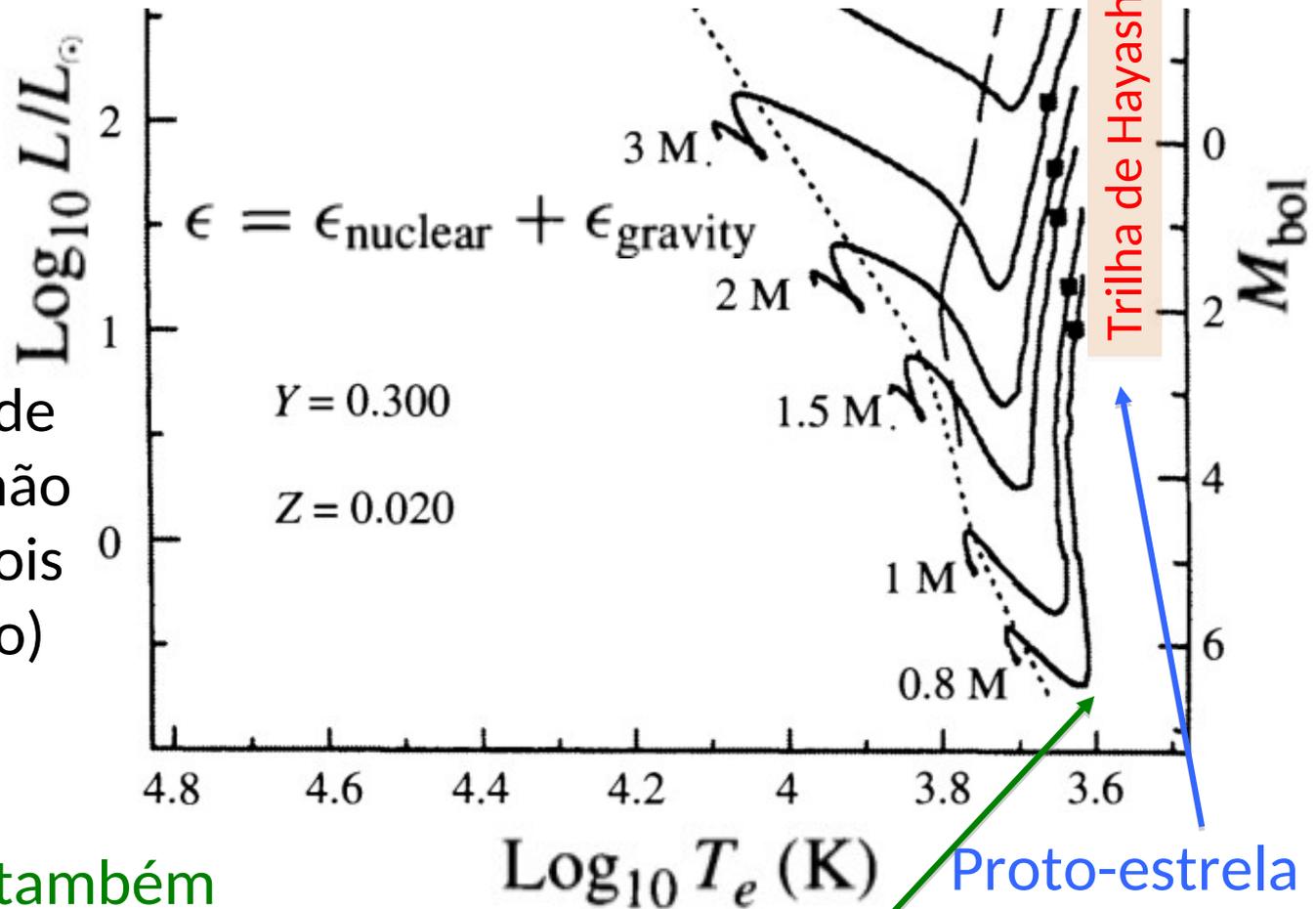
Núcleo radiativo.

Começa p-p

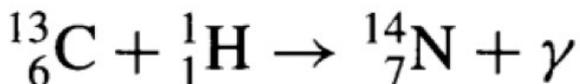
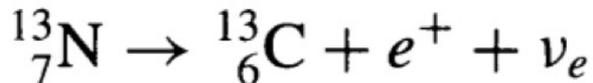
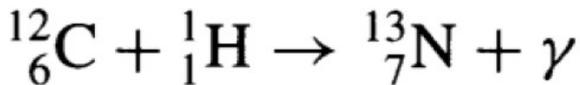


Cálculos clássicos de evolução na pré-Sequência Principal

- ${}^2_1\text{H} + {}^1_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$
Início da queima de deutério (quase não afeta o colapso pois há pouco deutério)

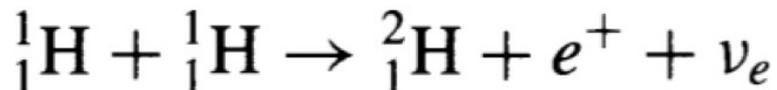


Para $M > 0,5 M_{\text{sol}}$ também temos ${}^{12}\text{C} \rightarrow {}^{14}\text{N}$



Núcleo radiativo.

Começa p-p



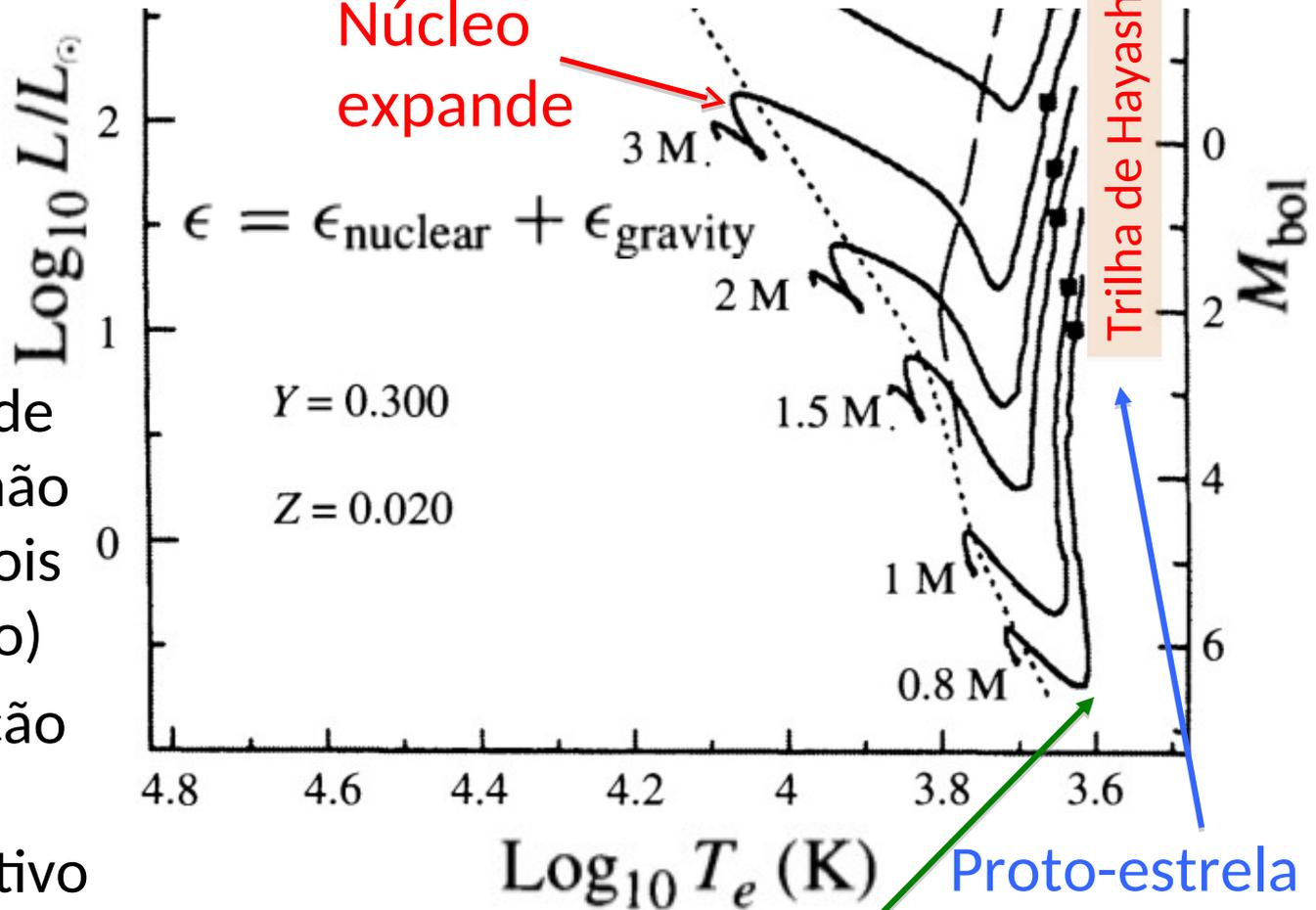
Proto-estrela completamente convectiva

Cálculos clássicos de evolução na pré-Sequência Principal

■ ${}^2_1\text{H} + {}^1_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$
 Início da queima de deutério (quase não afeta o colapso pois há pouco deutério)

— Fim da convecção no envelope → envelope radiativo

..... Começo da convecção no núcleo da estrela



Núcleo convectivo radiativo.

Começa p-p

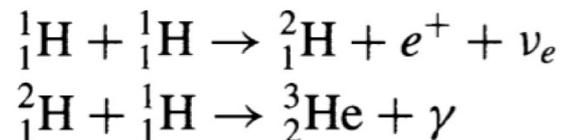


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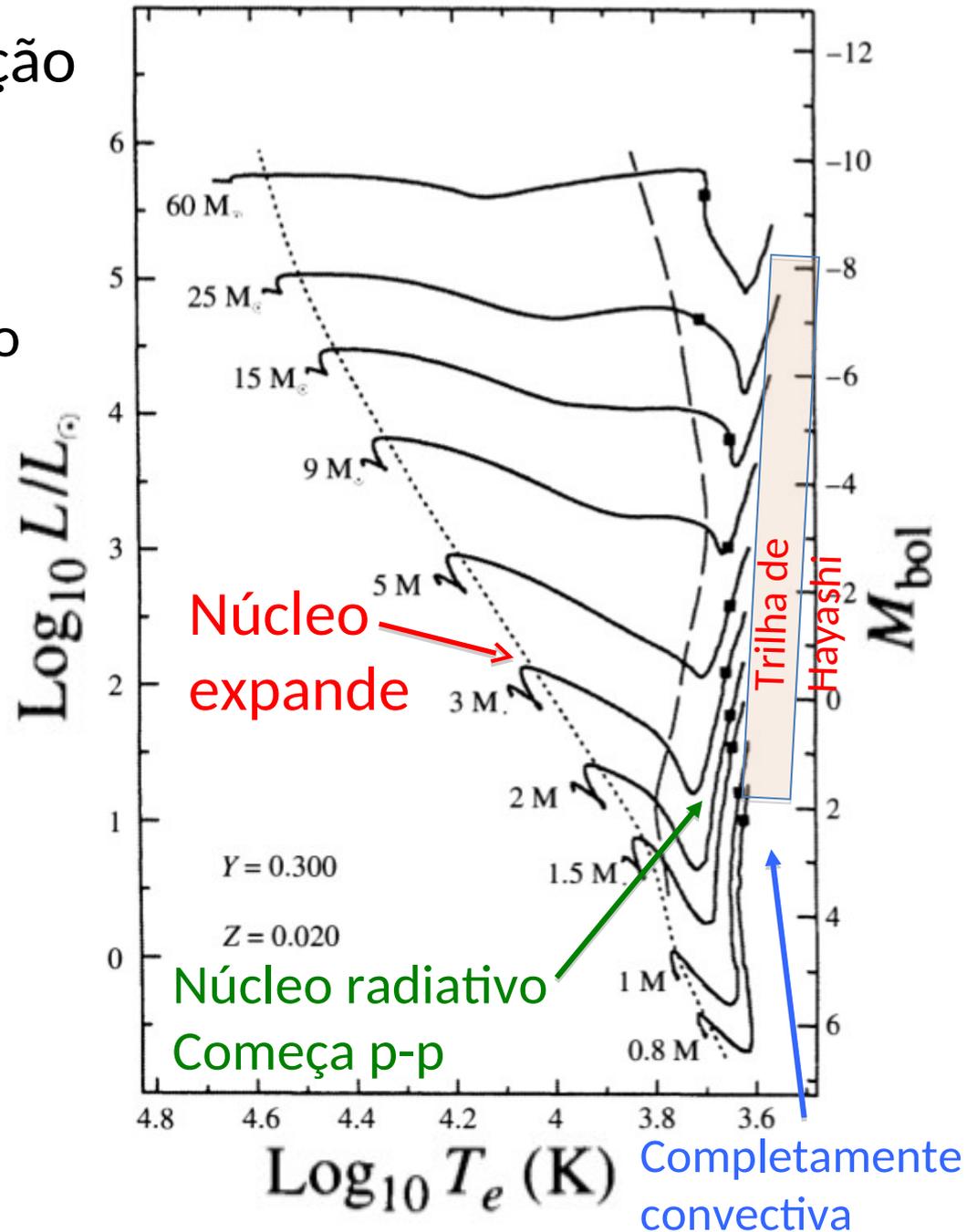
Cálculos clássicos de evolução na pré-Sequência Principal (contração da proto-estrela)

■ Início da queima de deutério (quase não afeta o colapso pois há pouco deutério)

--- Fim da convecção no envelope → envelope puramente radiativo

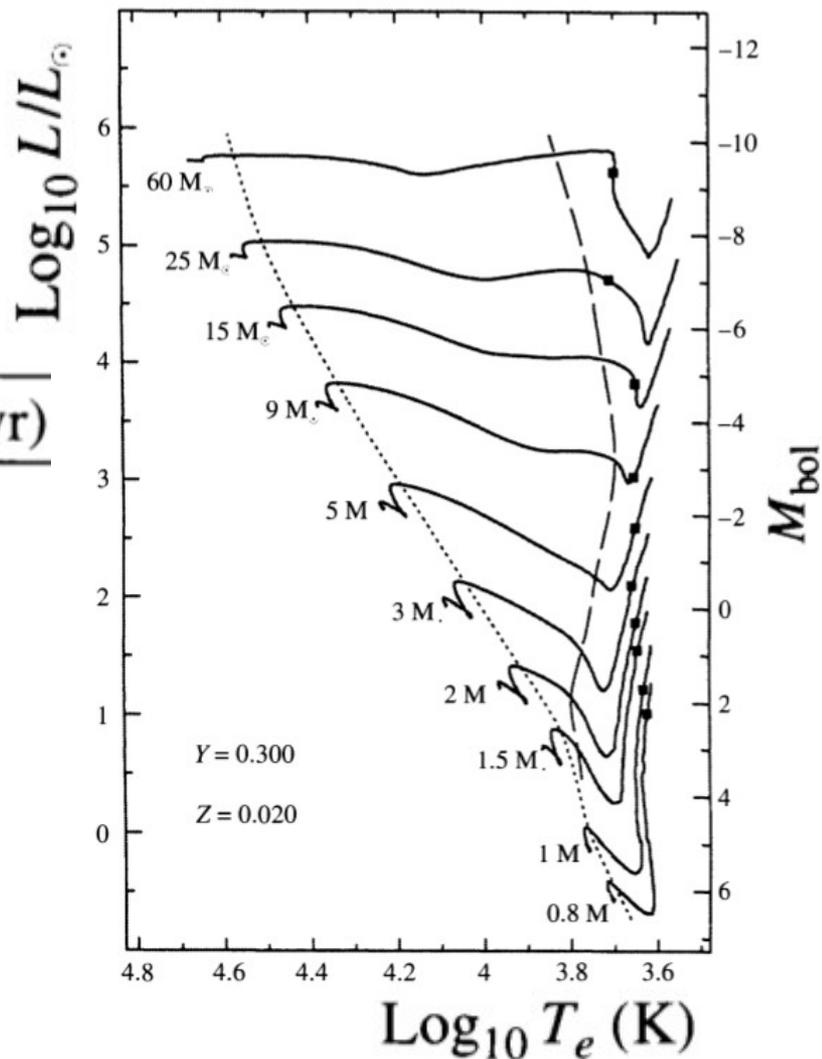
..... Começo da convecção no núcleo da estrela

$$\epsilon = \epsilon_{\text{nuclear}} + \epsilon_{\text{gravity}}$$



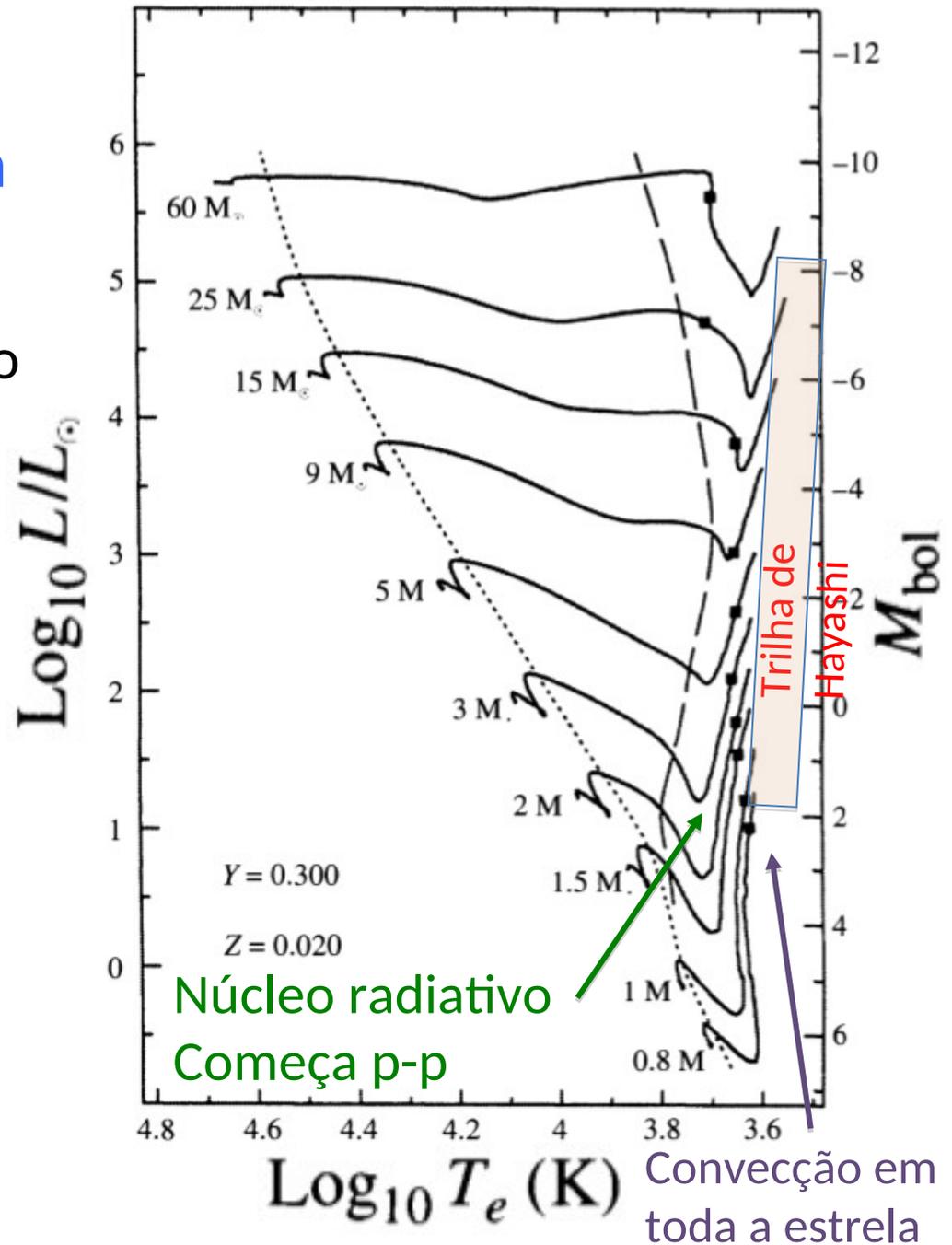
Cálculos clássicos de evolução na pré-Sequência Principal (contração da proto-estrela)

Initial Mass (M_{\odot})	Contraction Time (Myr)
60	0.0282
25	0.0708
15	0.117
9	0.288
5	1.15
3	7.24
2	23.4
1.5	35.4
1	38.9
0.8	68.4

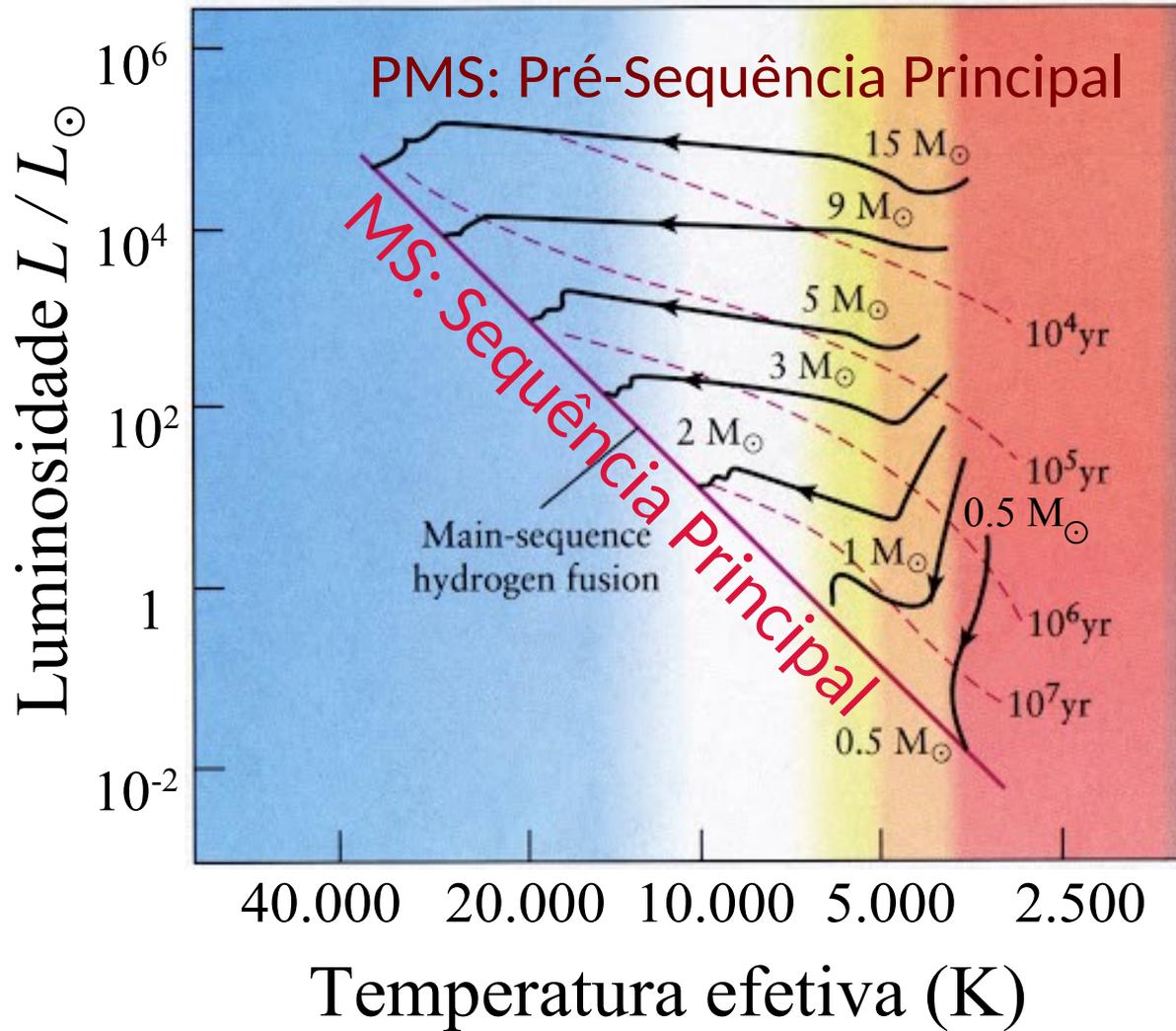


Estrelas massivas: núcleo convectivo mesmo após a pré-Sequência principal

- Início da queima de deutério (quase não afeta o colapso pois há pouco deutério)
- Fim da convecção no envelope → envelope puramente radiativo
- Começo da convecção no núcleo da estrela



Evolução na pré-Sequência Principal para $M \leq 0,5 M_{\odot}$



São completamente convectivas na PMS e na MS.

Não têm temperatura suficiente para queimar $^{12}\text{C} \rightarrow ^{14}\text{N}$

Portanto, não apresentam a subida de luminosidade, como em estrelas de maior massa.

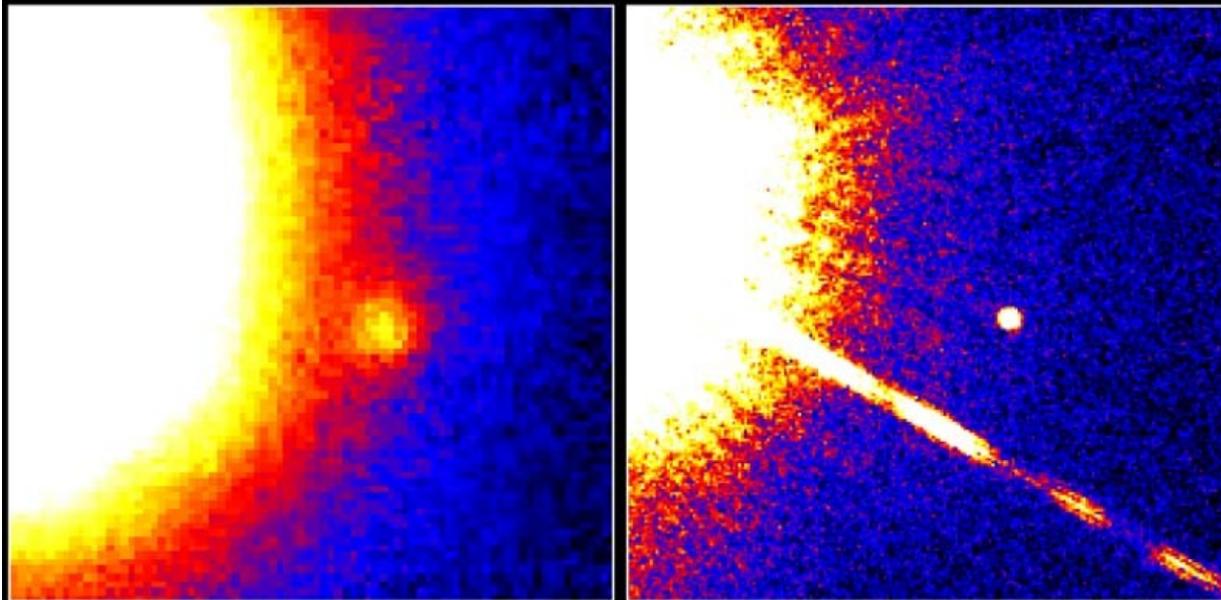
Se M da proto-estrela $< 0,072 M_{\odot} \rightarrow$ temperatura baixa demais para a queima de H

$M > 0,06 M_{\odot} \rightarrow$ queima de Li

$M > 0,013 M_{\odot} \rightarrow$ queima de deutério

Anãs marrons: $0,013 < M/M_{\odot} < 0,072$

Brown Dwarf Gliese 229B



Palomar Observatory
Discovery Image
October 27, 1994

Hubble Space Telescope
Wide Field Planetary Camera 2
November 17, 1995

Tipos espectrais
L e T

Planetas:

$M < 0,013 M_{\odot}$

($13 M_{Jup}$)

----- Sequência Principal de Idade Zero

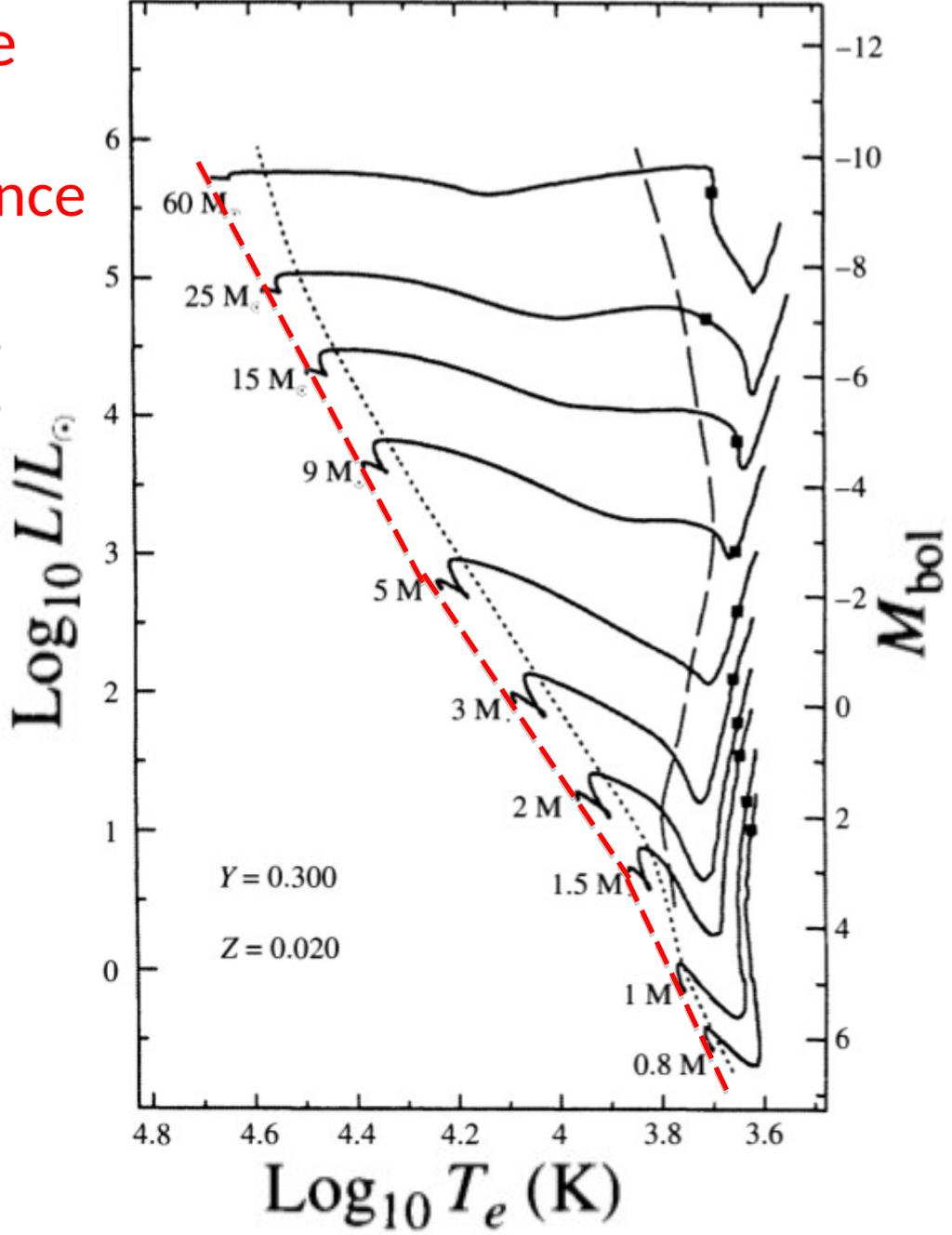
ZAMS: Zero-Age Main Sequence

Começa queima estável de H

Initial Mass (M_{\odot})	Contraction Time (Myr)
------------------------------	------------------------

60	0.0282
25	0.0708
15	0.117
9	0.288
5	1.15
3	7.24
2	23.4
1.5	35.4
1	38.9
0.8	68.4

Estrelas massivas se formam muito mais rapidamente do que estrelas de baixa massa



Near the outskirts of the Small Magellanic Cloud, lies the young star cluster NGC 602, surrounded by natal gas and dust. Fantastic ridges and undulating shapes strongly suggest that energetic radiation and shock waves from NGC 602's massive young stars have eroded the dusty material and triggered a progression of star formation moving away from the cluster's center.



A Função de Massa Inicial (IMF)

Initial Mass Function

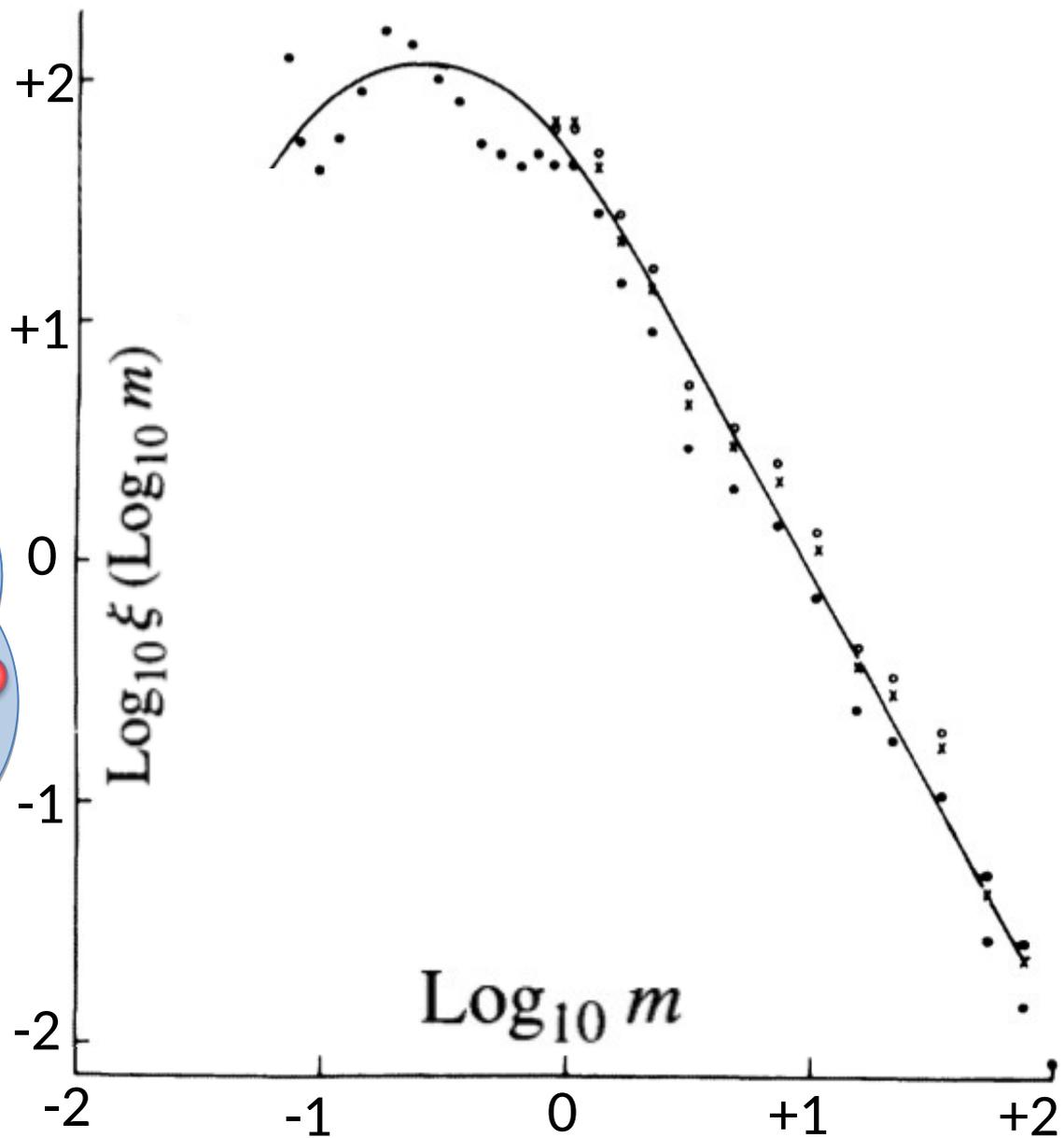
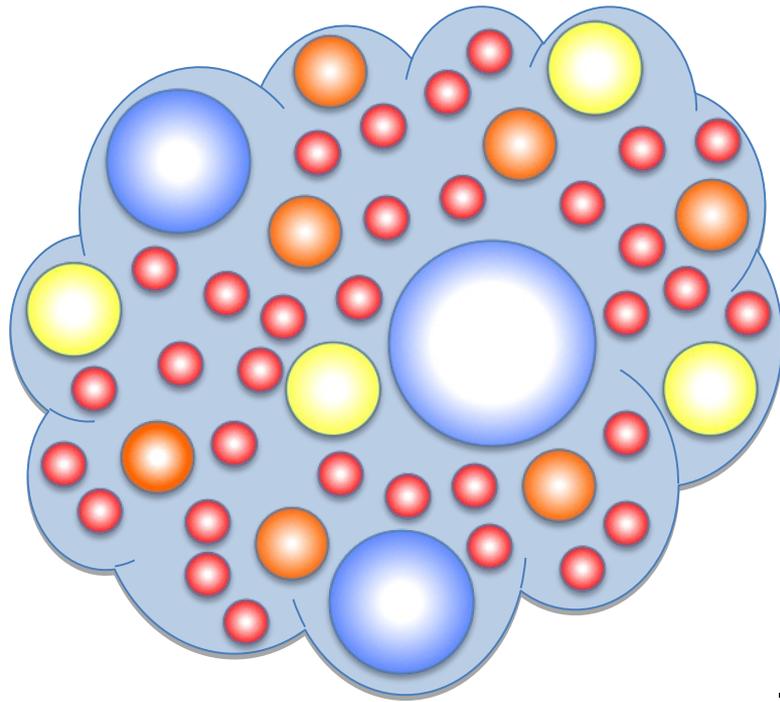


FIGURE 12.12 The initial mass function, ξ , shows the number of stars per unit area of the Milky Way's disk per unit interval of logarithmic mass that is produced in different mass intervals. The individual points represent observational data and the solid line is a theoretical estimate. Masses are in solar units. (Figure adapted from Rana, *Astron. Astrophys.*, 184, 104, 1987.)

A Função de Massa Inicial (IMF)

Initial Mass Function

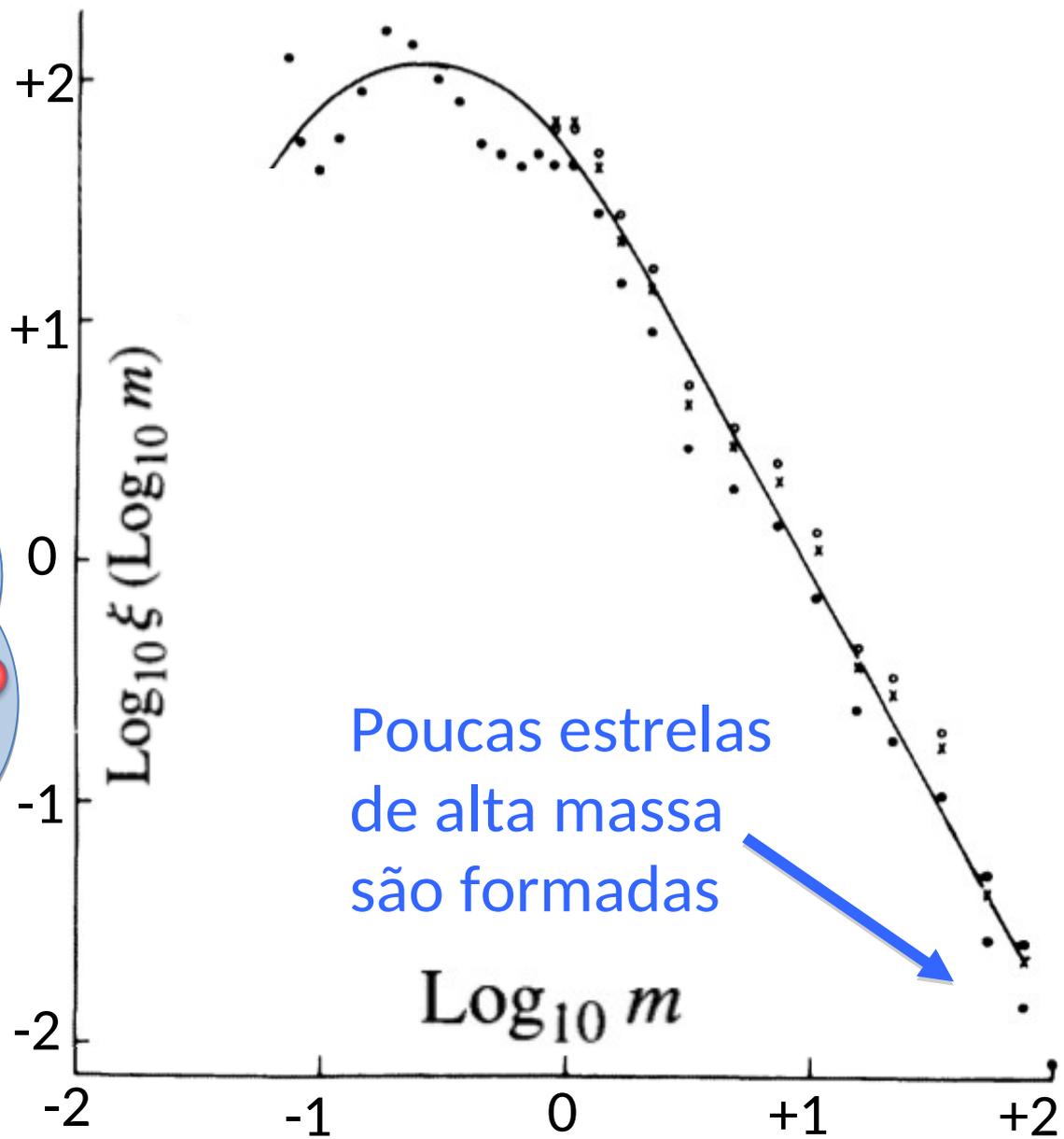
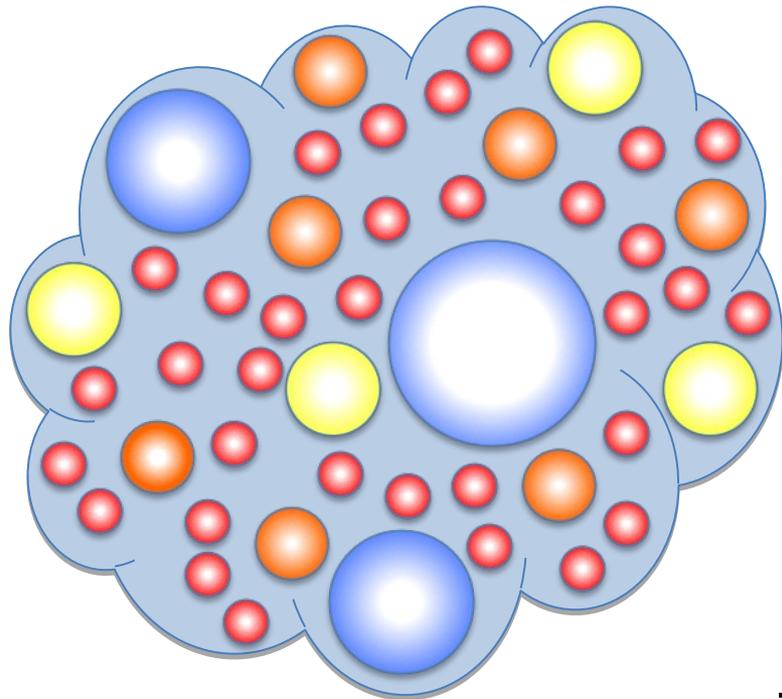


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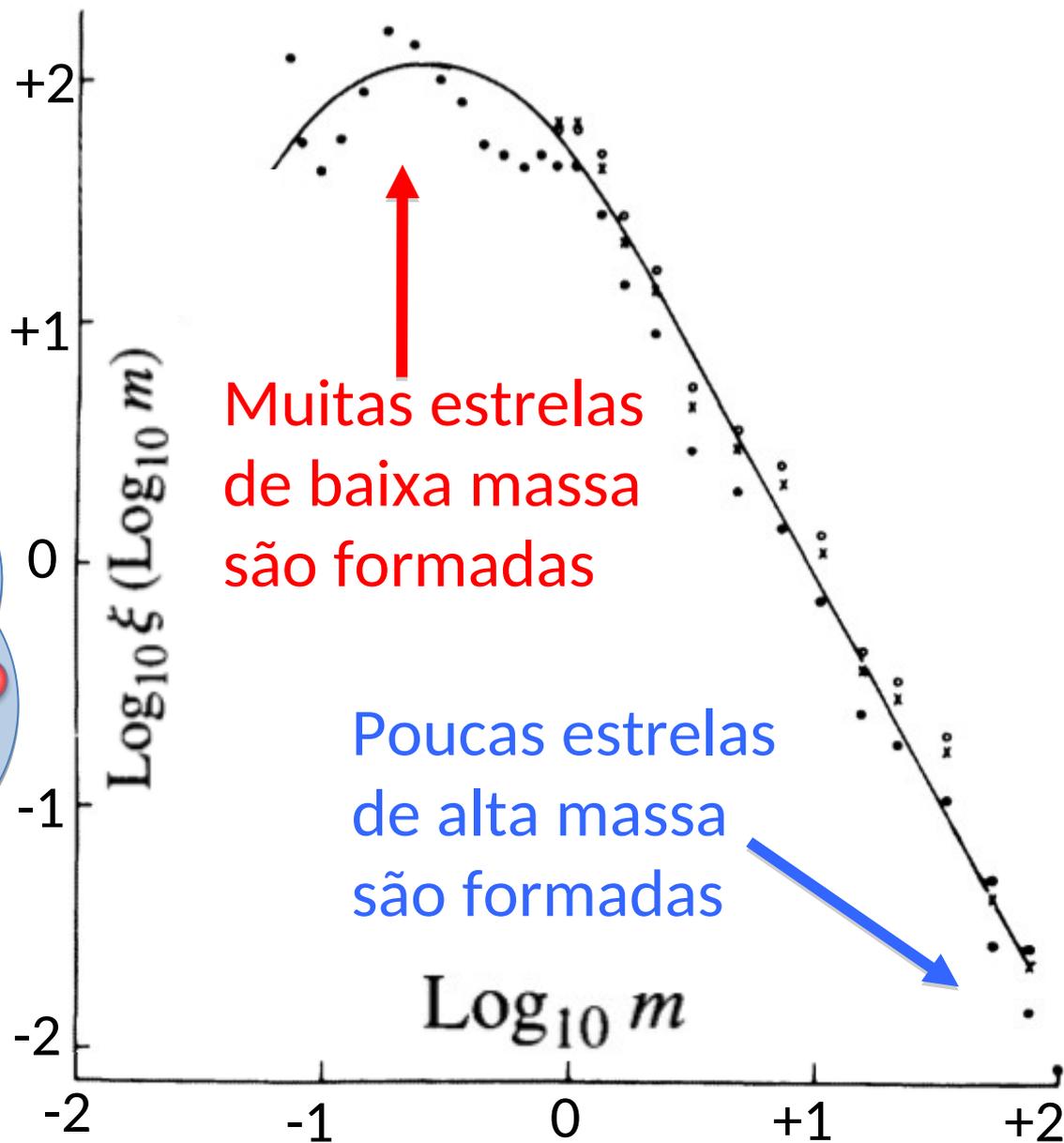
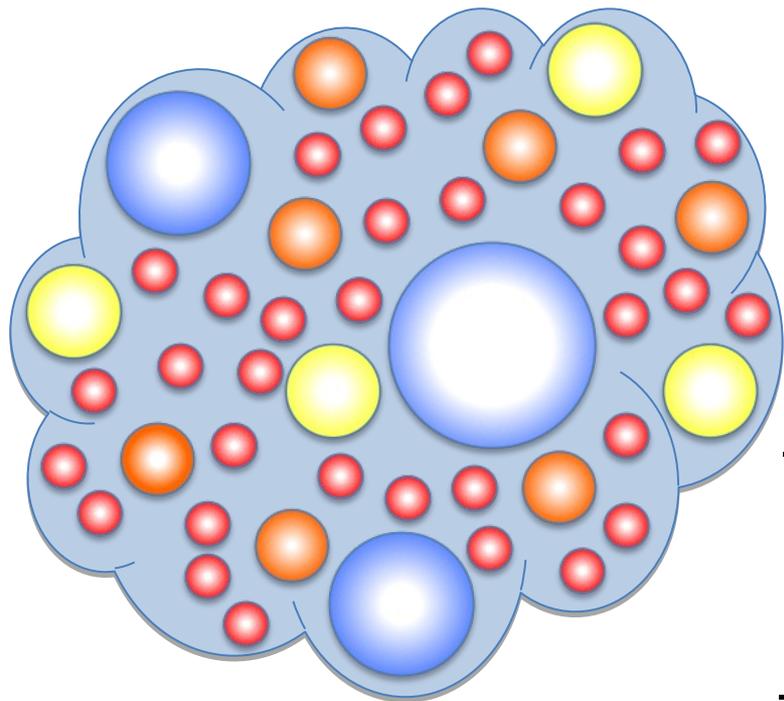


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A Função de Massa Inicial (IMF)

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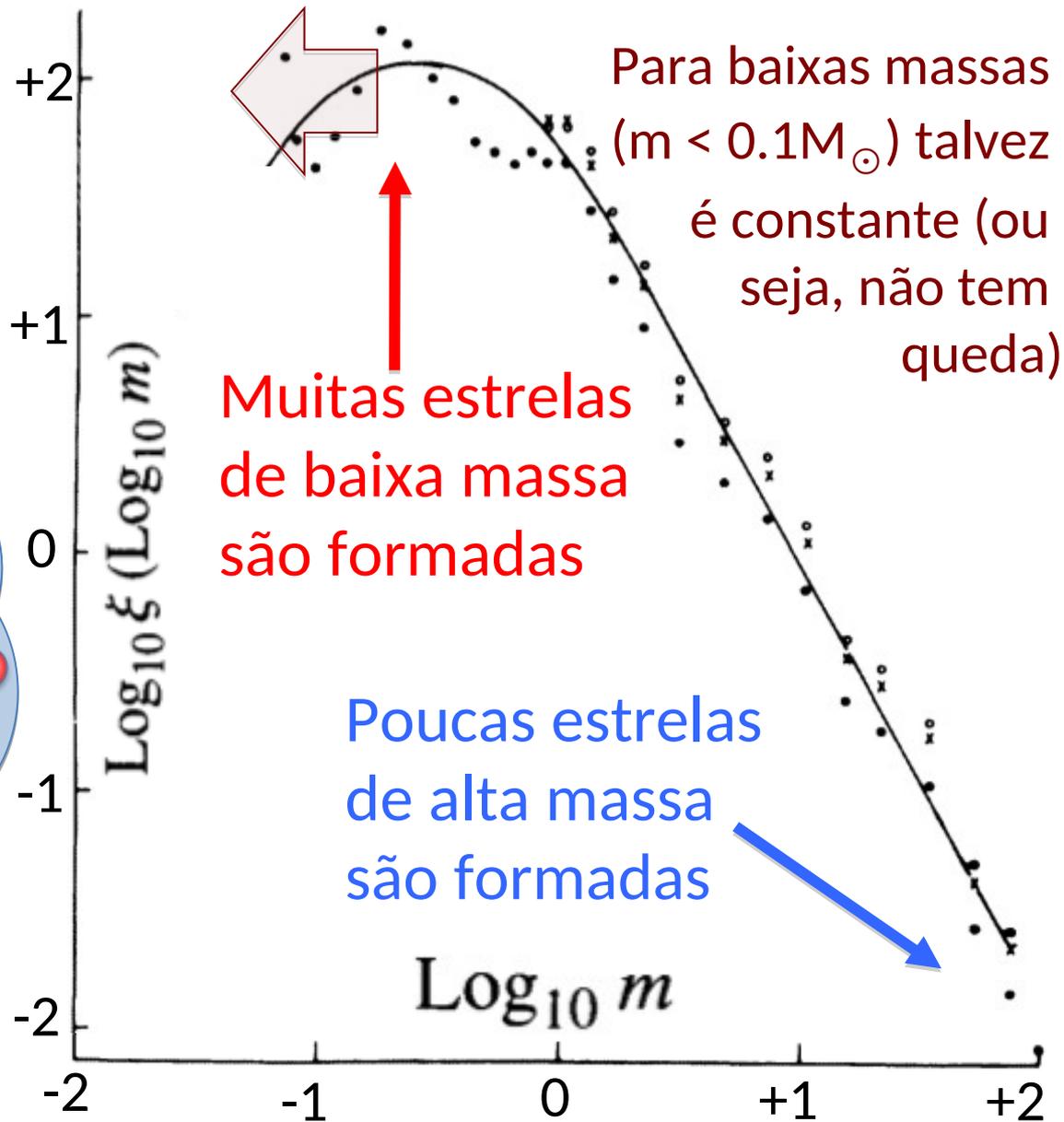
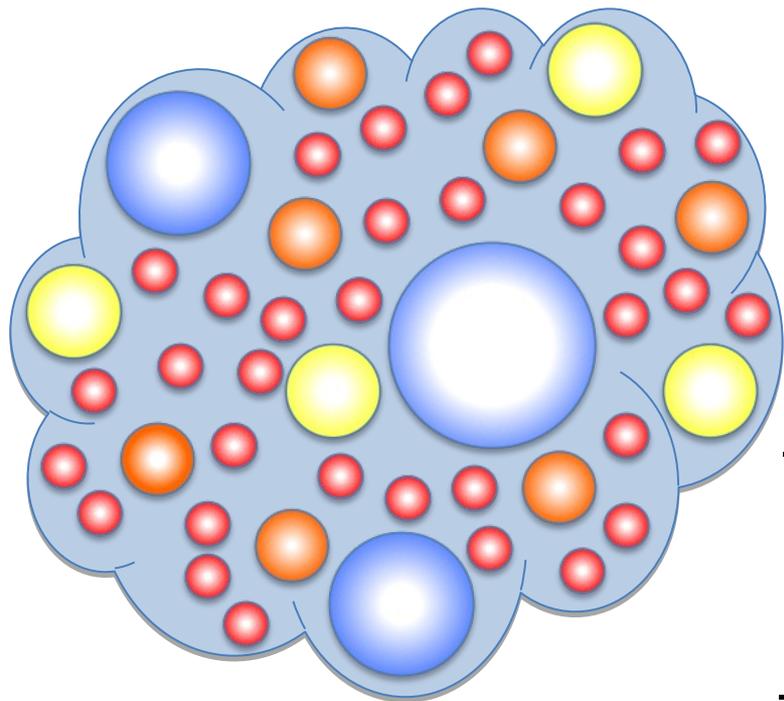
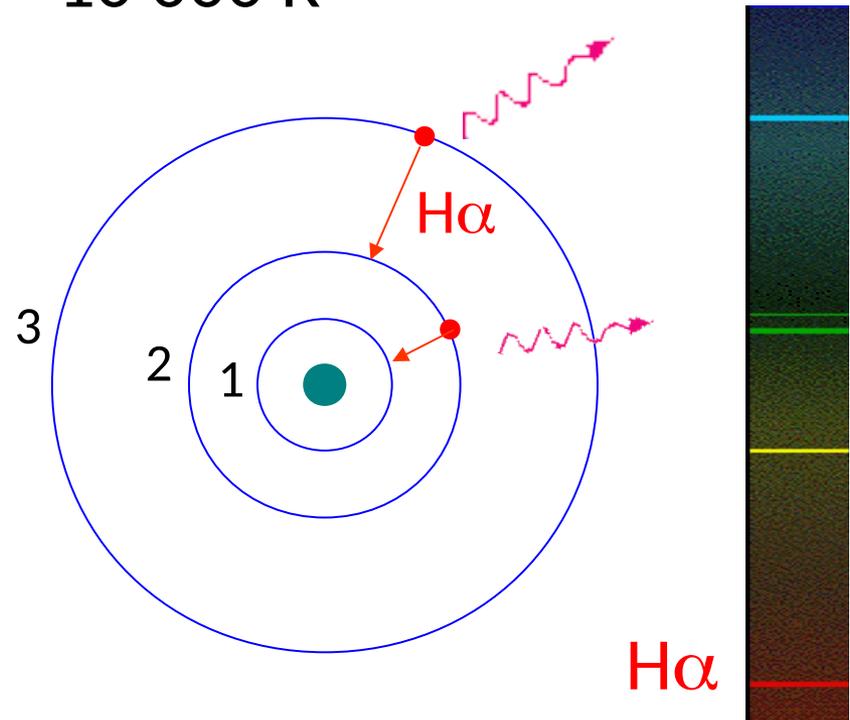


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Regiões H II

- Luz UV de estrelas O e B pode ionizar nuvens de gás de hidrogênio neutro ($E > 13,6 \text{ eV}$ para ionizar H do estado base)
- Elétrons recombinam e decaem a estados menos excitados. No visível, a radiação dominante é devida à transição $n=3 \rightarrow 2$, o que dá a cor vermelha (**$H\alpha$: 656,3 \text{ nm})**
- Temperatura das regiões H II $\sim 10\,000 \text{ K}$



The Temperature Scale and the Classification of Stars

Bruna Barroso Gomes*, Jorge Meléndez*

$$\lambda_{\max} \text{ (nm)} = 2\,897\,755 / T(K)$$

$$E = h\nu = hc/\lambda$$

$$hc = 1240 \text{ nm eV}$$

Precisamos $E \geq 13,6 \text{ eV}$ ($\lambda \leq 91,2 \text{ nm}$) para ionizar as regiões H II

	T_{eff}	λ (nm)	E (eV)
A0	9565		
B5	–		
B3	–		
B2	21931		
B0	–		
O9	31542		
O6	45000		



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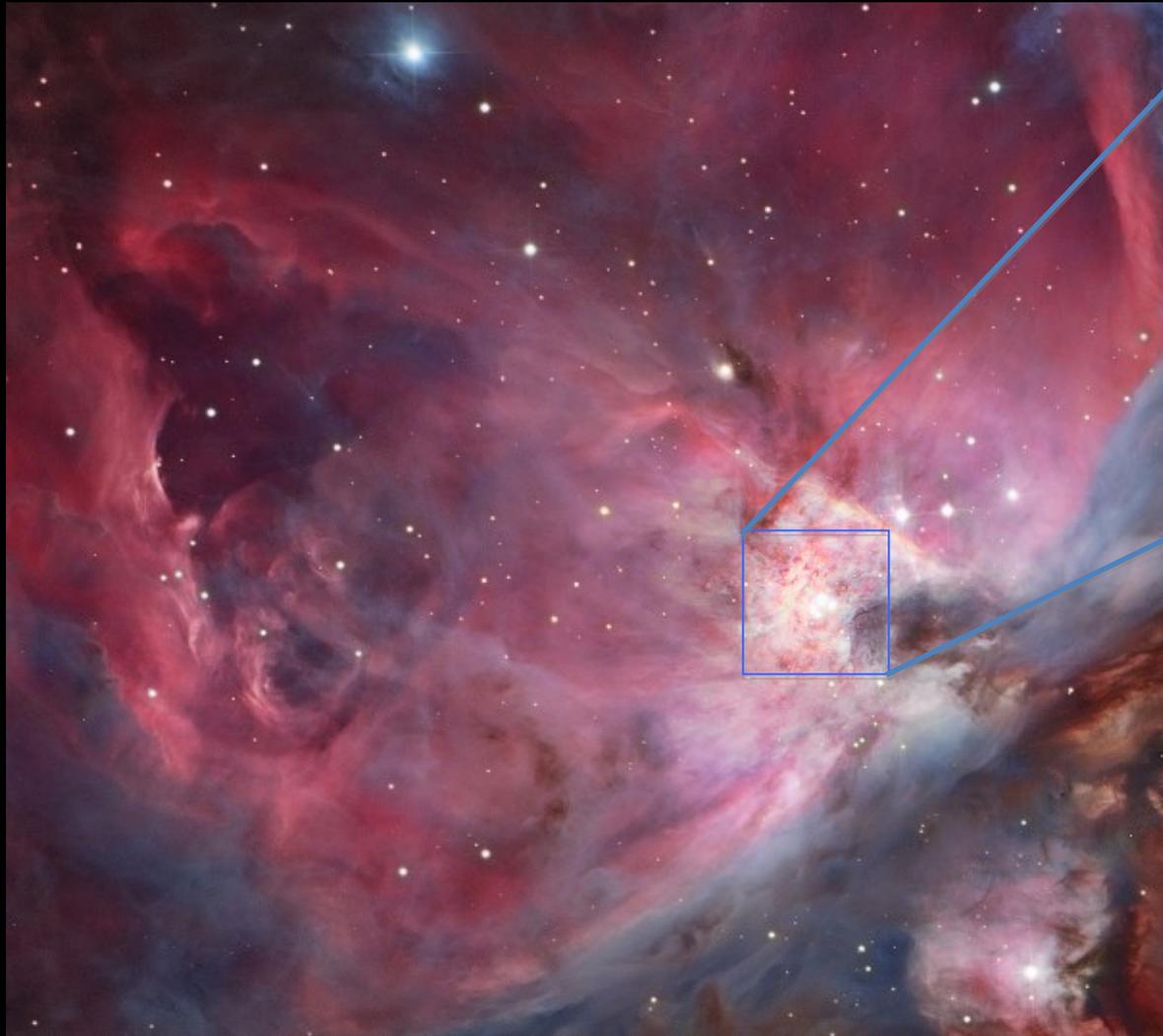
	T_{eff}	λ (nm)	E (eV)
A0	9565	303	4,1
B5	—		
B3	—		
B2	21931	132	9,4
B0	—		
O9	31542	92	13,5
O6	45000	64	19 eV



Nebulosa de Orion: região H II (hidrogênio ionizado)



Trapezium cluster @ Orion Nebula



Hubble, infrared



Tamanho de Regiões H II

$\alpha n_e n_H$: número de recombinações por unidade de V por segundo

α : coeficiente de recombinação (probabilidade de $e + p \rightarrow H$)

Para cada íon de H, um e^- é liberado: $n_e = n_H$

Em equilíbrio, o número total de fótons ionizantes por segundo, N , deve ser igual ao número de recombinações por segundo:

$$N = \alpha n_H^2 V$$

Supondo região

HII esférica: $V = \frac{4}{3} \pi r^3$

Raio de Strömngren:

$$r_S \simeq \left(\frac{3N}{4\pi\alpha} \right)^{1/3} n_H^{-2/3}$$

N : número total de fótons ionizantes ($\lambda < 91,2$ nm) por segundo

n_H : densidade numérica de H

α : coeficiente de recombinação. $\sim 3,1 \times 10^{-19} \text{ m}^3 \text{ s}^{-1}$ ($T = 8000$ K)

Example 12.3.1. From Appendix G, the effective temperature and luminosity of an O6 star are $T_e \simeq 45,000$ K and $L \simeq 1.3 \times 10^5 L_\odot$, respectively. According to Wien's law (Eq. 3.15), the peak wavelength of the blackbody spectrum is given by

$$\lambda_{\max} = \frac{0.0029 \text{ m K}}{T_e} = 64 \text{ nm}$$

Since this is significantly shorter than the 91.2-nm limit necessary to produce ionization from the hydrogen ground state, it can be assumed that most of the photons created by an O6 star are capable of causing ionization.

The energy of one 64-nm photon can be calculated from Eq. (5.3), giving

$$E_\gamma = \frac{hc}{\lambda} = 19 \text{ eV}$$

Now, assuming for simplicity that all of the emitted photons have the same (peak) wavelength, the total number of photons produced by the star per second is just

$$N \simeq L/E_\gamma \simeq 1.6 \times 10^{49} \text{ photons s}^{-1}$$

taking $n_H \sim 10^8 \text{ m}^{-3}$ to be a typical value in an H II region, we find

$$r_S \simeq 3.5 \text{ pc} \quad r_S \simeq \left(\frac{3N}{4\pi\alpha} \right)^{1/3} n_H^{-2/3}$$

Values of r_S range from less than 0.1 pc to greater than 100 pc.

Imagem no infravermelho da Nebulosa Carina (@ESO)

- Estrelas massivas podem dispersar o resto da nuvem, dificultando a formação de novas estrelas
- Se a nuvem estava fracamente ligada no início, a perda de massa da nuvem diminui a energia potencial, e as estrelas e proto-estrelas do aglomerado podem ficar desassociadas

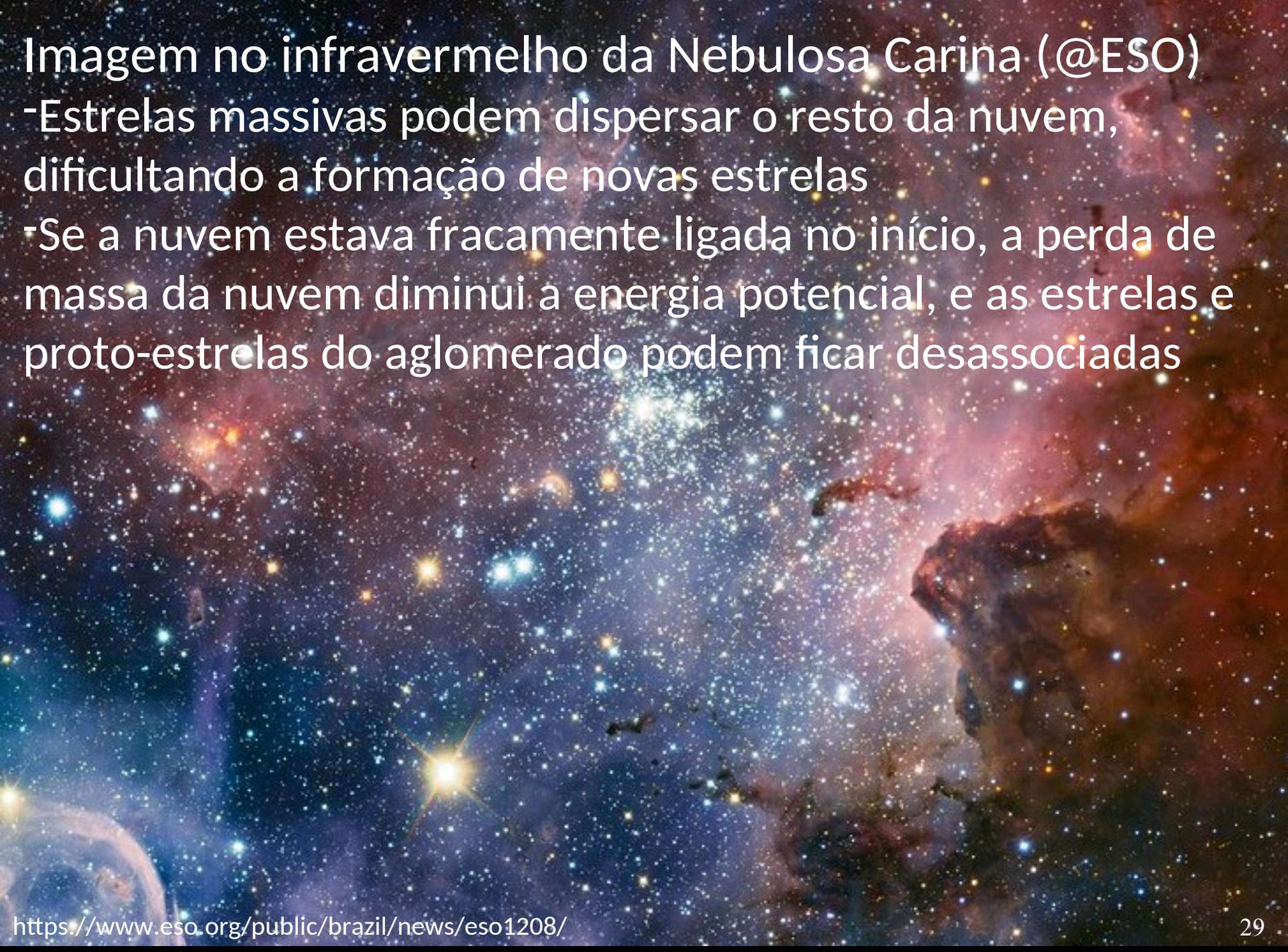




FIGURE 12.15 The giant gas pillars of the Eagle Nebula (M16). The left most pillar is more than 1 pc long from base to top. Ionizing radiation from massive newborn stars off the top edge of the image are causing the gas in the cloud to photoevaporate. [Courtesy of NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University).]

Associações OB

- São grupos dominados por estrelas O e B
- De acordo a diferentes estudos essas estrelas estão no processo de ser dispersadas

Exemplo.

Aglomerado do Trapézio

- Idade < 10 milhões de anos
- Densamente populado (densidade $\sim 2000 \text{ pc}^{-3}$)
- Medidas da velocidade do gás sugerem que o gás está sendo dispersado \rightarrow *cluster unbound*



Trapezium cluster in the infrared

© Hubble

Estrelas T Tauri

- Estrelas de baixa massa ($0,5 - 2 M_{\text{sol}}$) da pré-Sequência Principal
- Variabilidade
- Alta rotação
- Muitas apresentam fortes linhas de emissão em $H\alpha$ e $CaII$
- Algumas linhas proibidas
→ gás em baixa densidade
- Forte absorção em Li

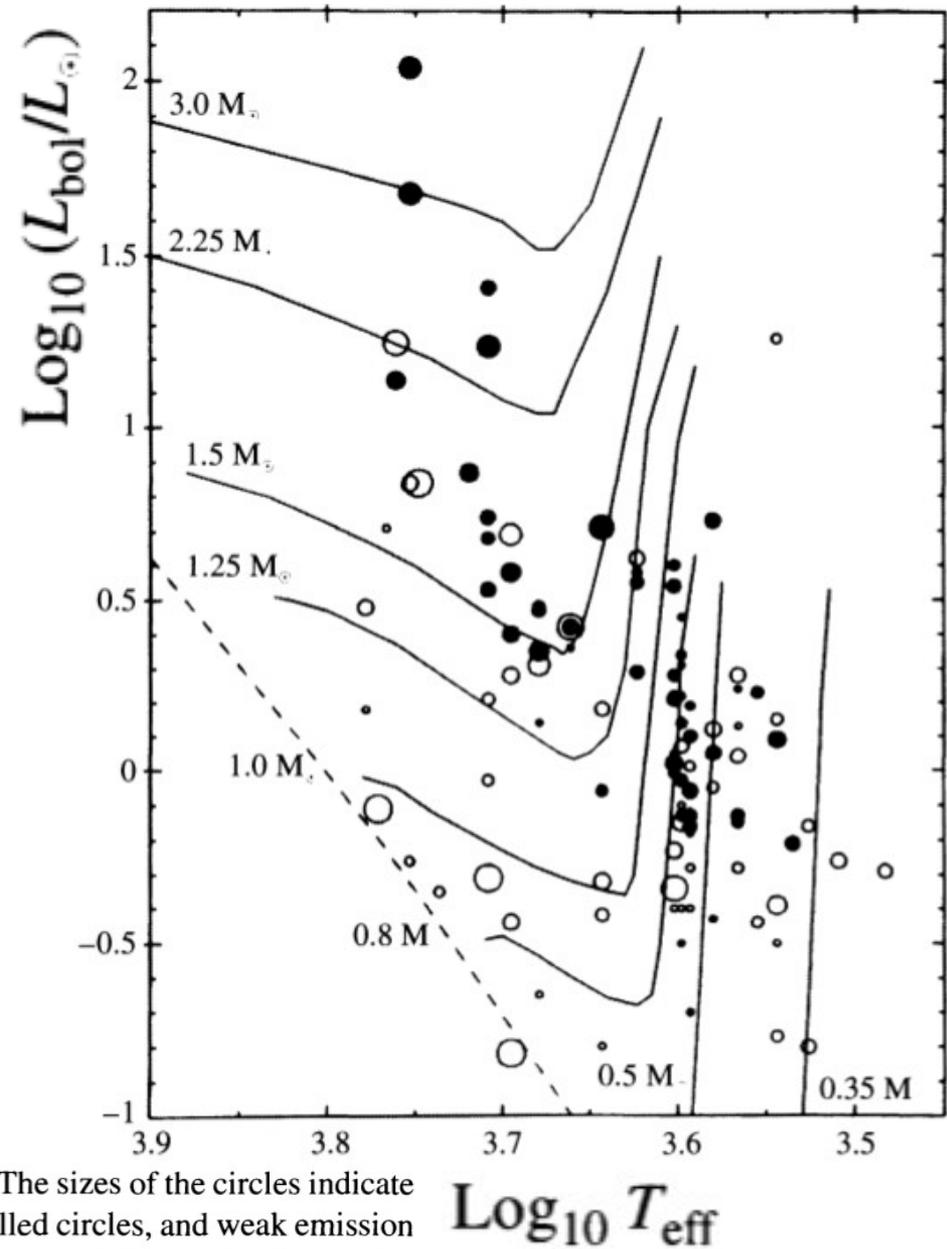


FIGURE 12.16 The positions of T Tauri stars on the H-R diagram. The sizes of the circles indicate the rate of rotation. Stars with strong emission lines are indicated by filled circles, and weak emission line stars are represented by open circles. Theoretical pre-main-sequence evolutionary tracks are also included. (Figure adapted from Bertout, *Annu. Rev. Astron. Astrophys.*, 27, 351, 1989. Reproduced with permission from the *Annual Review of Astronomy and Astrophysics*, Volume 27, ©1989 by Annual Reviews Inc.)

$\text{Log}_{10} T_{\text{eff}}$

Estrelas T Tauri: perfis de linha P-Cygni

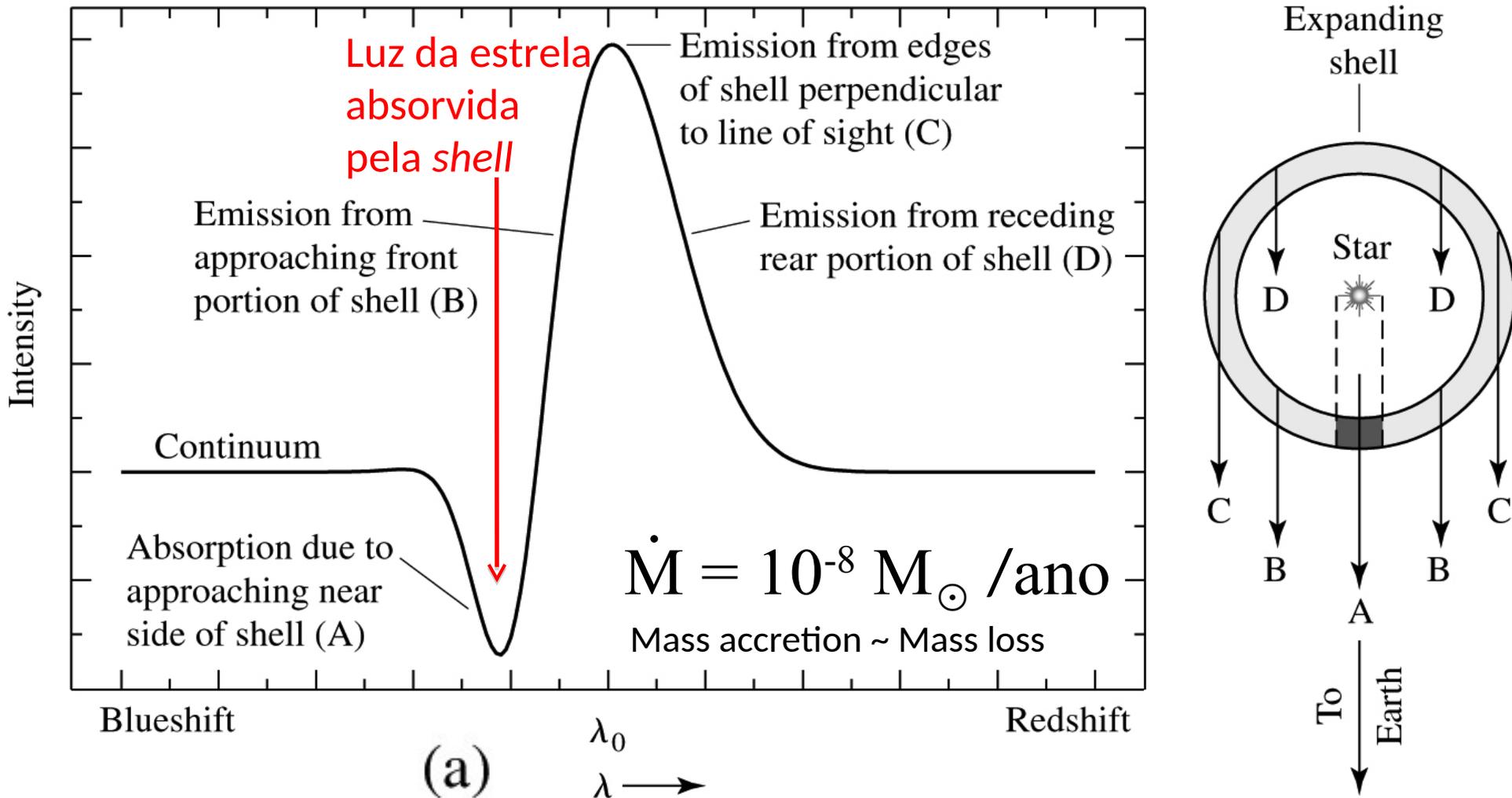


FIGURE 12.17 (a) A spectral line exhibiting a P Cygni profile is characterized by a broad emission peak with a superimposed blueshifted absorption trough. (b) A P Cygni profile is produced by an expanding mass shell. The emission peak is due to the outward movement of material perpendicular to the line of sight, whereas the blueshifted absorption feature is caused by the approaching matter in the shaded region, intercepting photons coming from the central star.

Estrelas FU Orionis

- Às vezes as estrelas T Tauri podem sofrer um aumento na acreção de massa $\dot{M} = 10^{-4} M_{\odot} / \text{ano}$
- Luminosidade incrementa em ~ 4 ordens de grandeza. Isso pode durar décadas.
- Essa instabilidade pode ser devida a uma grande acreção de massa ($\sim 0,01 M_{\odot}$)
- Estrelas T Tauri podem passar por vários episódios FU Orionis

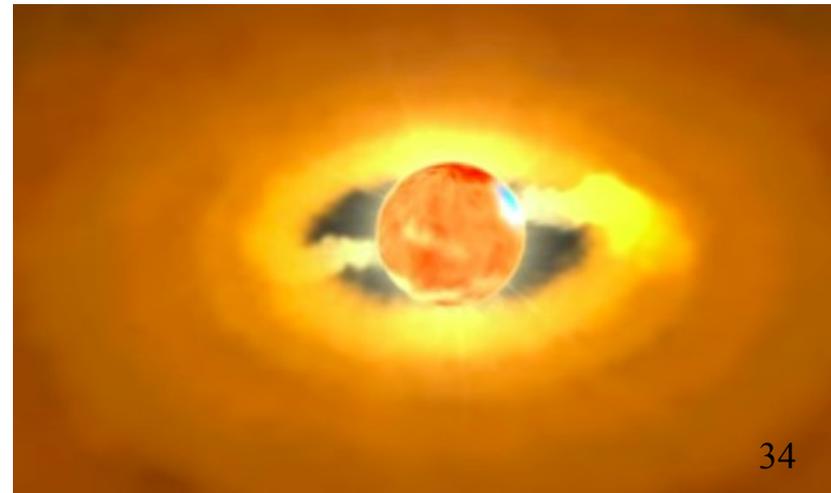


Imagem artística, NASA.
V1647 Orionis

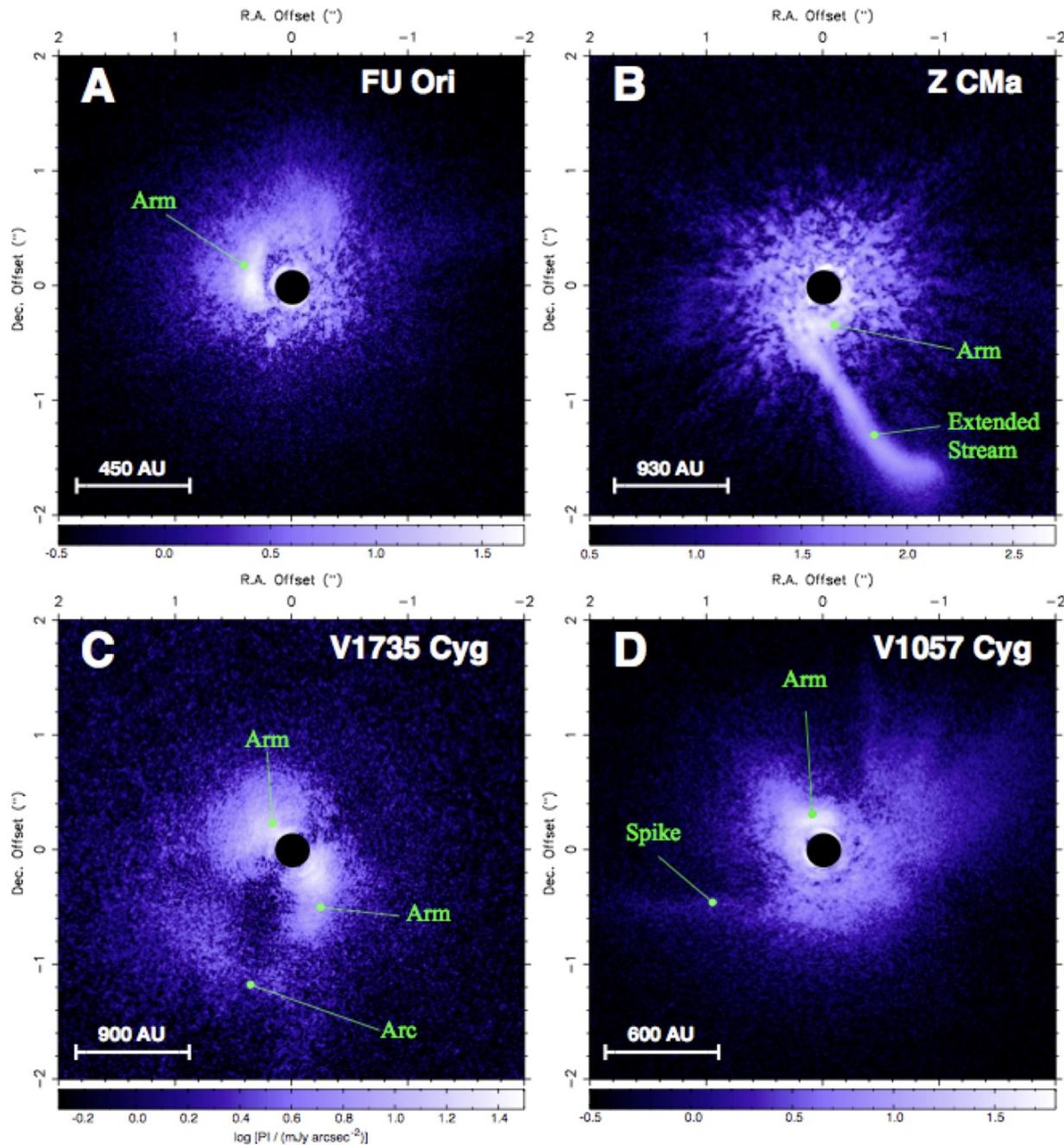
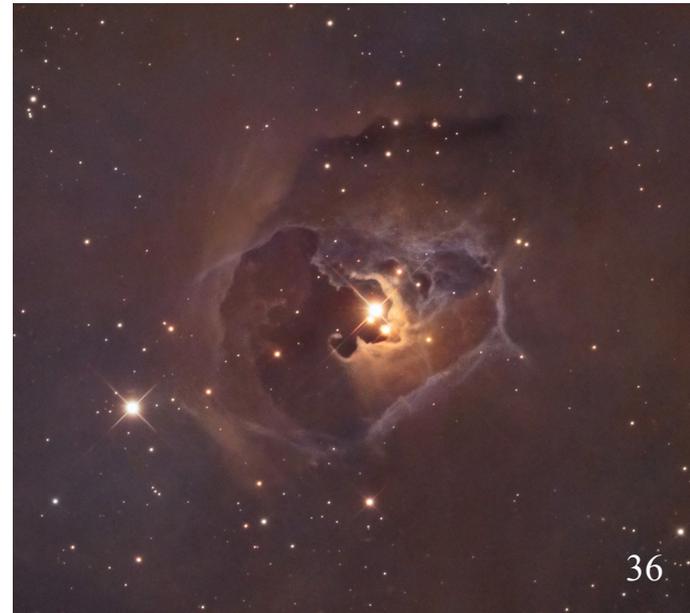


Figure 1: Circumstellar structures revealed by Subaru-HiCIAO. The scale bars are shown in AUs (astronomical units). One AU is the average distance from the sun to the earth. The gas and dust surrounding baby stars (their food) are significantly more extended than our solar system. Here we show the first observations of such complex structures around active young stars.

Estrelas Herbig Ae/Be

- A versão mais massiva de estrelas T Tauri
- Têm fortes linhas de emissão → designação Ae/Be
- Massa $\sim 2 - 10 M_{\odot}$
- Tempo de vida curto → pouco estudadas

Estrela V1025 Tauri, de tipo Herbig Ae/Be.
(c) Mount Lemmon SkyCenter



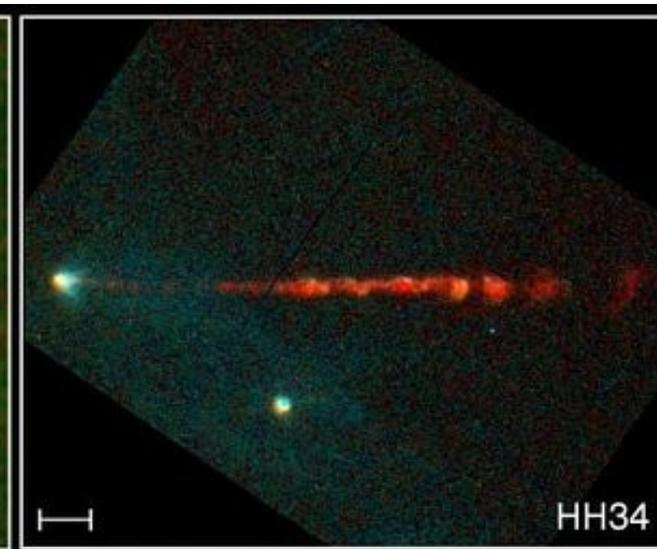
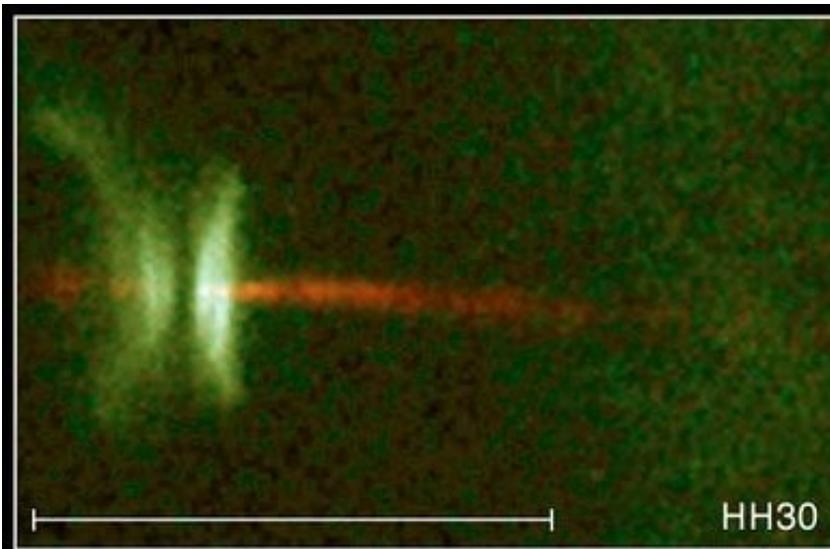
Objetos Herbig-Haro

- Relacionados a jatos produzidos por proto-estrelas como as T Tauri



Jets from Young Stars • HH1/HH2 **HST • WFPC2**
PRC95-24c • ST ScI OPO • June 6, 1995 • J. Hester (AZ State U.), NASA

FIGURE 12.18 (a) The Herbig–Haro objects HH 1 and HH 2 are located just south of the Orion nebula and are moving away from a young protostar hidden inside a dust cloud near the center of the image. [Courtesy of J. Hester (Arizona State University), the WF/PC 2 Investigation Definition



Upper left image: Protostellar object called HH-30 reveals an edge-on disk of dust encircling a newly forming star. Light from the forming star illuminates the top and bottom surfaces of the disk, making them visible, while the star itself is hidden behind the densest parts of the disk.

Jets from Young Stars

PRC95-24a · ST Scl OPO · June 6, 1995

C. Burrows (ST Scl), J. Hester (AZ State U.), J. Morse (ST Scl), NASA

HST · WFPC2

Upper right: A more distant jet in object HH-34 shows a beaded structure, produced by a blast of 'bullets' of dense gas ejected from the star at speeds of ~220 km/s.

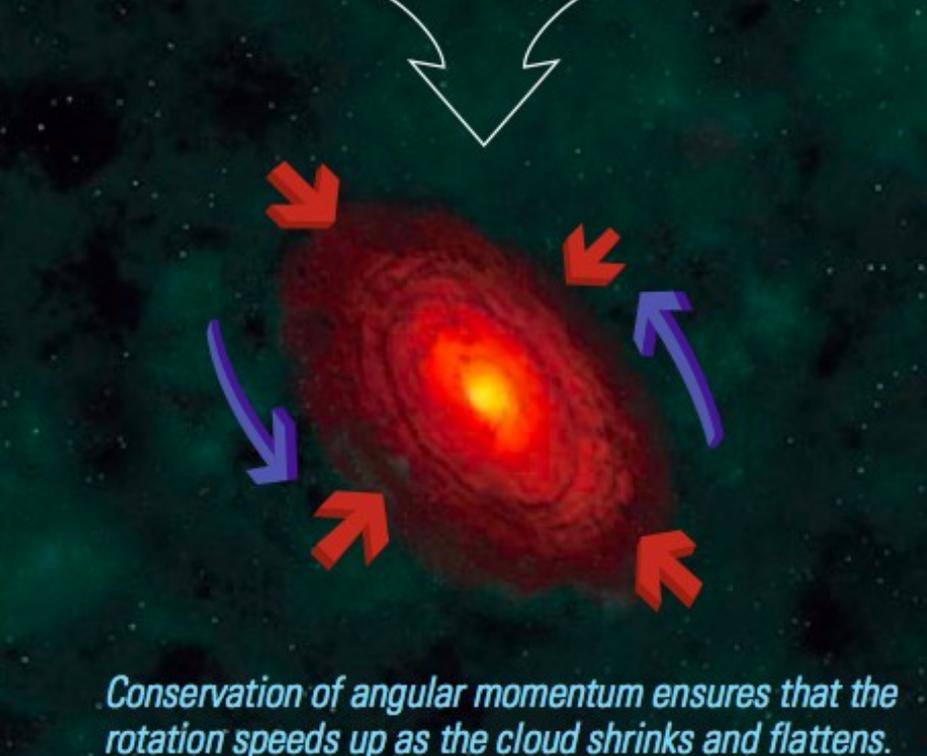
Bottom image: This view of a 5 trillion km-long jet called HH-47 reveals a very complicated jet pattern that indicates the star (hidden inside a dust cloud near the left edge of the image) might be wobbling, possibly caused by the gravitational pull of a companion star.

Formação de disco e jatos em proto-estrelas



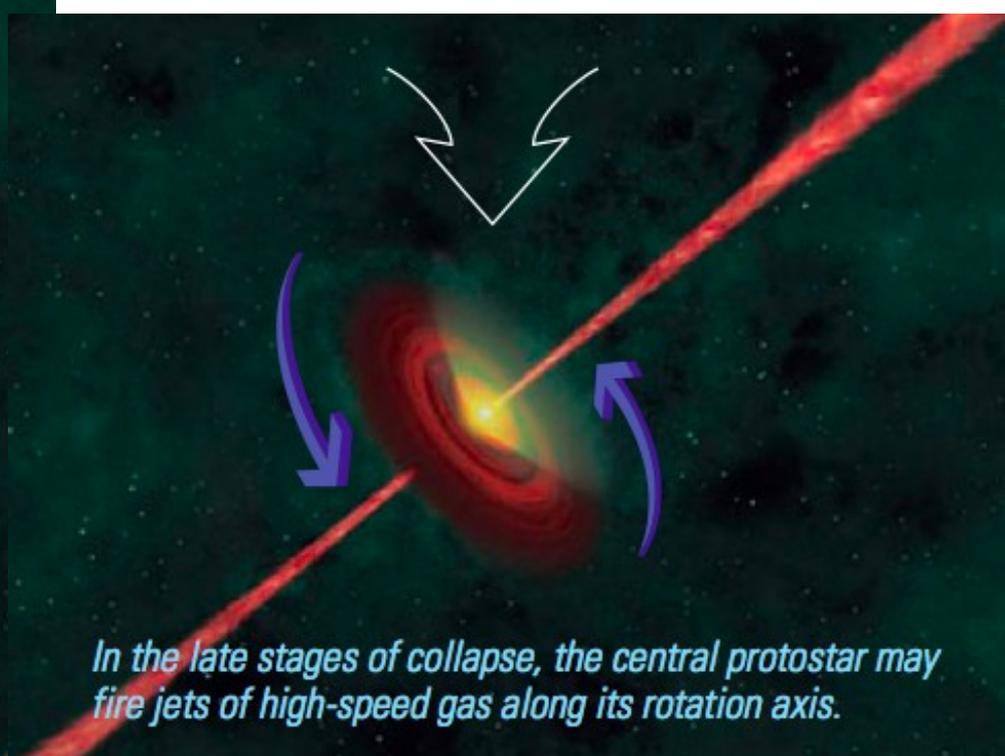
A contracting cloud fragment always has some small, overall rotation.

The image shows a dark, reddish-brown cloud fragment against a dark green background. Several arrows of different colors (red and purple) point inward from the edges, indicating the cloud is contracting. A white arrow points from the text below to this cloud.



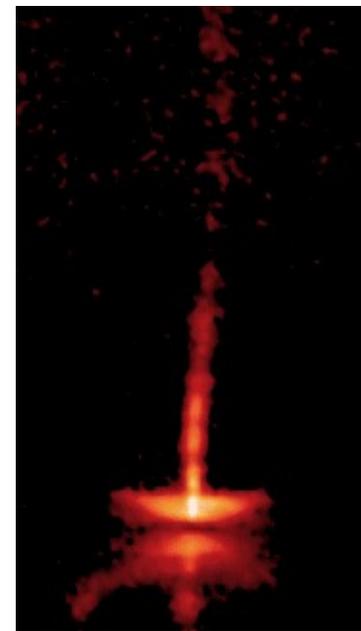
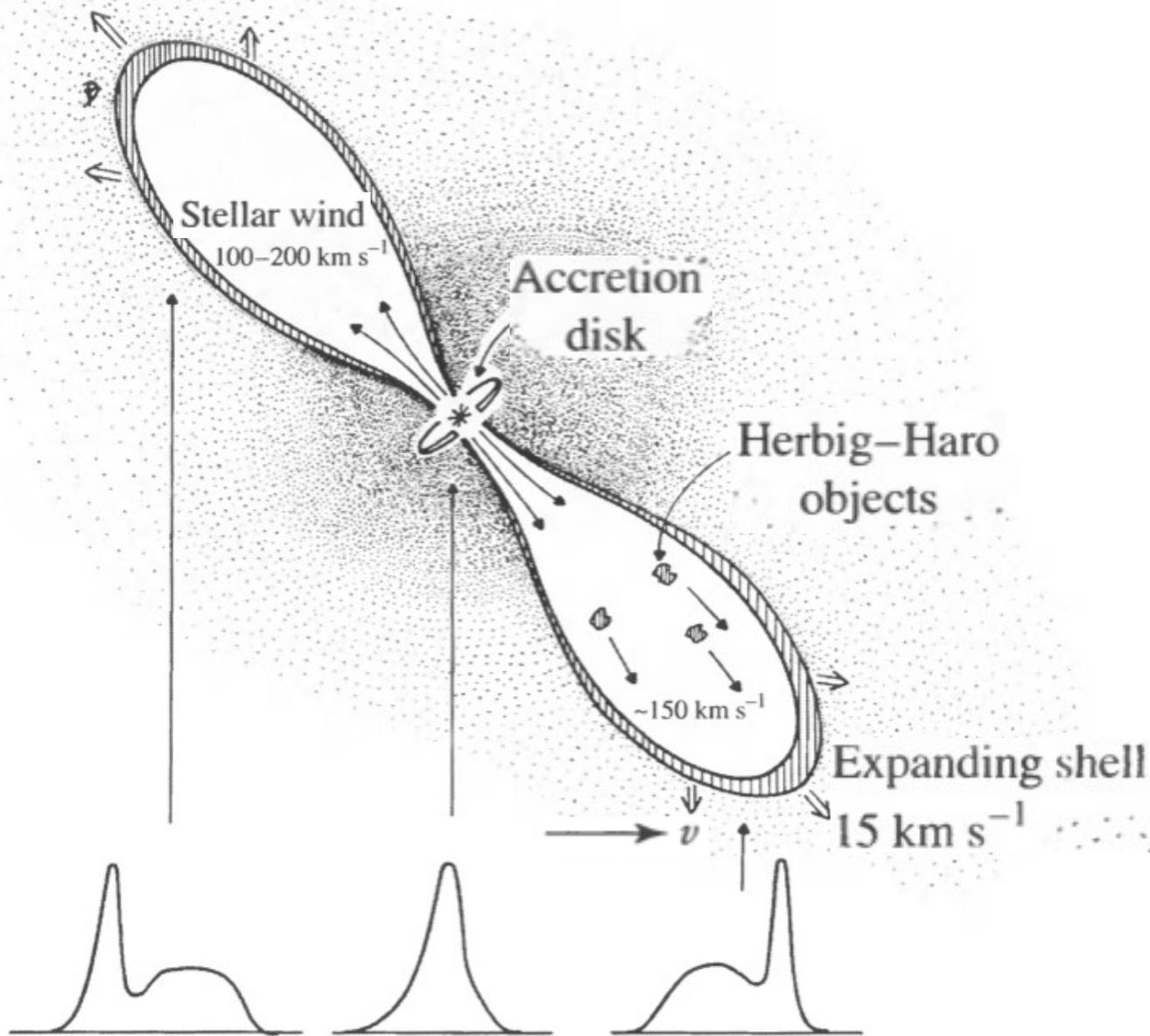
Conservation of angular momentum ensures that the rotation speeds up as the cloud shrinks and flattens.

The image shows a more compact, flattened protostar with a bright yellow-orange core. It is surrounded by a dark, reddish-brown disk. Several arrows (red and purple) point inward, indicating rotation. A white arrow points from the text above to this protostar.



In the late stages of collapse, the central protostar may fire jets of high-speed gas along its rotation axis.

The image shows the protostar from the previous stage, now with two bright red jets of gas extending outwards along its rotation axis. The central core is very bright yellow-orange. Several arrows (red and purple) indicate rotation. A white arrow points from the text above to this protostar.



HH-30,
de 1995 a 2000
(c) Hubble

FIGURE 12.20 An early model of a T Tauri star with an accretion disk. The disk powers and collimates jets that expand into the interstellar medium, producing Herbig-Haro objects. (Figure adapted from Snell, Loren, and Plambeck, *Ap. J. Lett.*, 239, L17, 1980.)

Estrelas jovens com discos circumestelares

Disco de detritos
em estrela jovem

Material para
formar planetas?

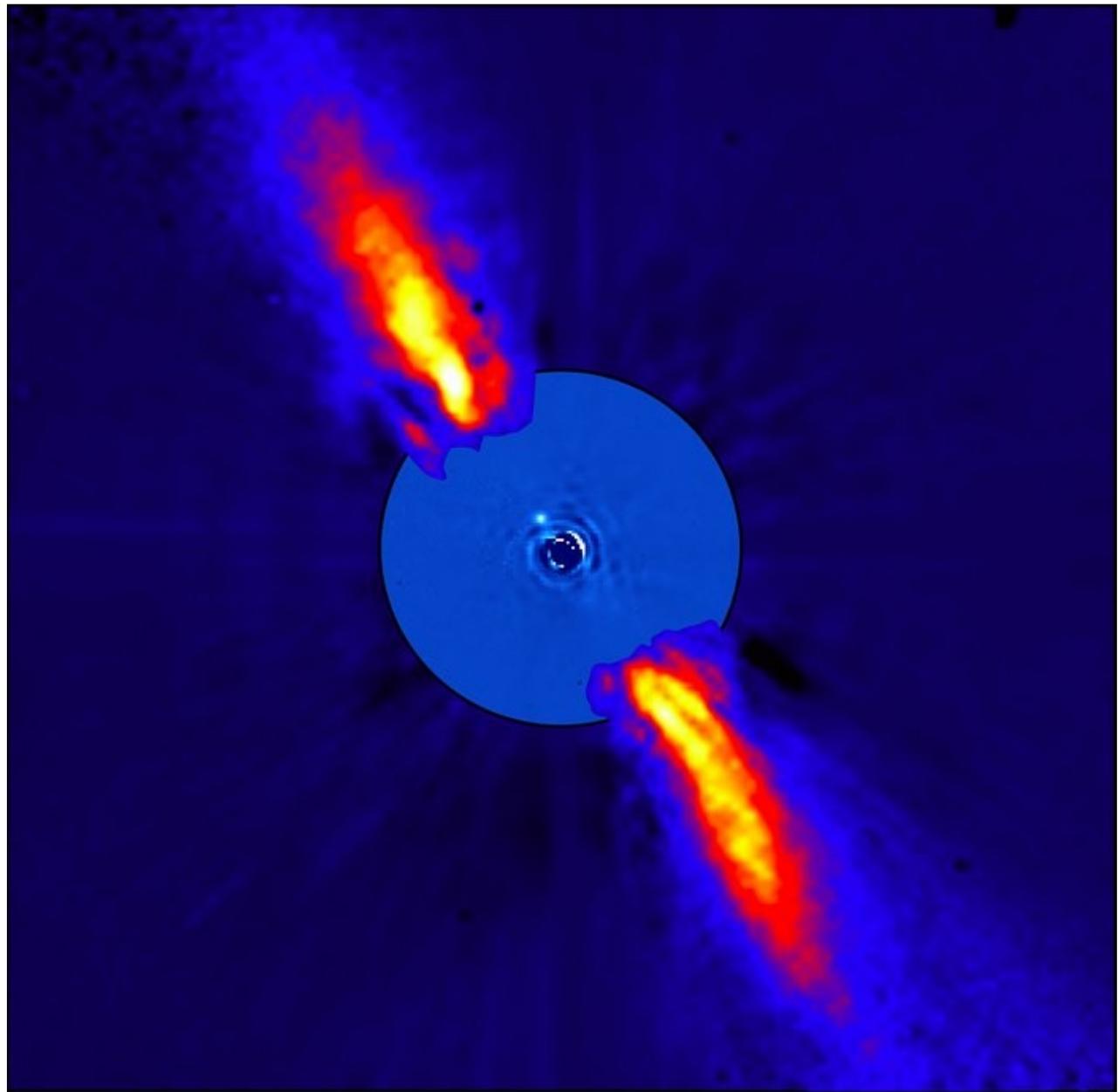
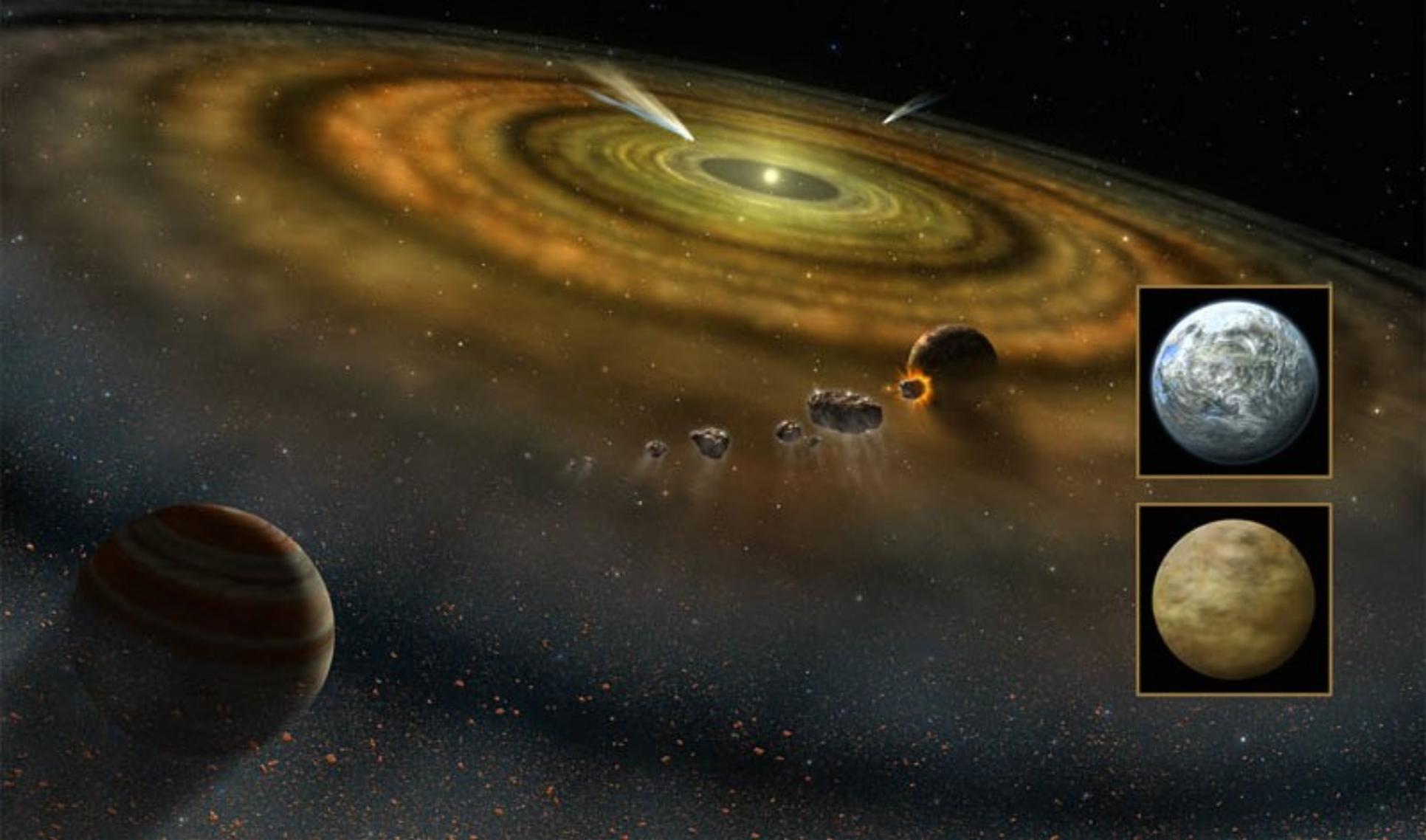
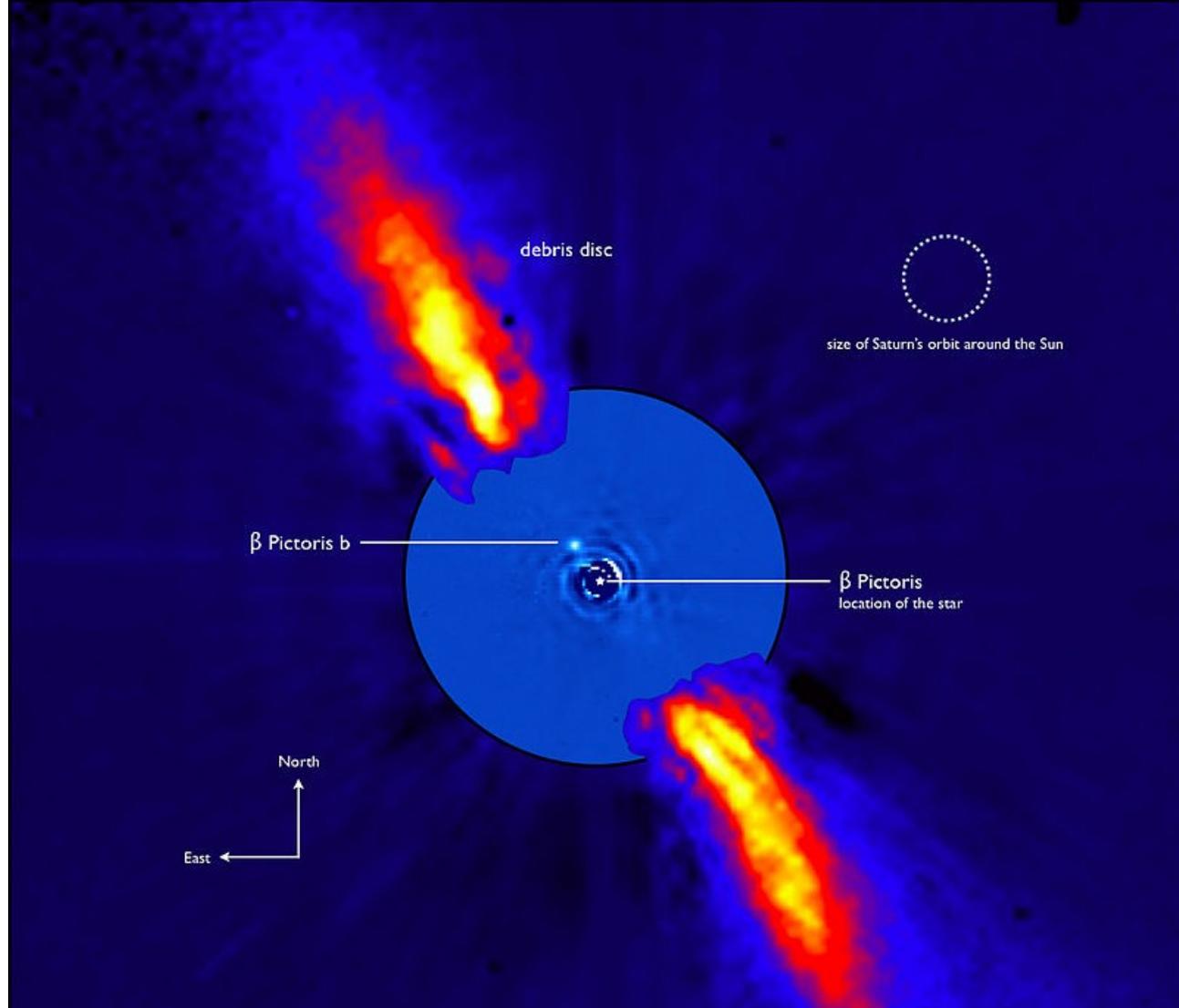


FIGURE 12.21 An infrared image of β Pictoris, showing its circumstellar debris disk. (European Southern Observatory)



Impressão artística do disco de detritos ao redor de Beta Pictoris, mostrando formação planetária, exocometas e planetesimais

Imagem infravermelha tirada pelo Observatório Europeu do Sul, mostrando o disco de detritos e o planeta Beta Pictoris b



Planeta (a partir da estrela)	Massa	Semieixo maior (UA)	Período orbital (d)	Excentricidade orbital	Inclinação ($^{\circ}$)	Raio
b	$12_{-3}^{+4} M_J$	$9,2_{-1,5}^{+0,4}$	7890 ± 1000	$\sim 0,1$	$89,01 + 0,36$	$1,65 R_J$

nature astronomy

Article | Published: 19 August 2019

Evidence for an additional planet in the β Pictoris system

A.-M. Lagrange , Nadège Meunier, Pascal Rubini, Miriam Keppler, Franck Galland, Eric Chapellier,

Novo planeta descoberto em Agosto de 2019, Beta Pictoris c, usando o método de velocidades radiais, com 10 anos de observações obtidas com o HARPS/ESO

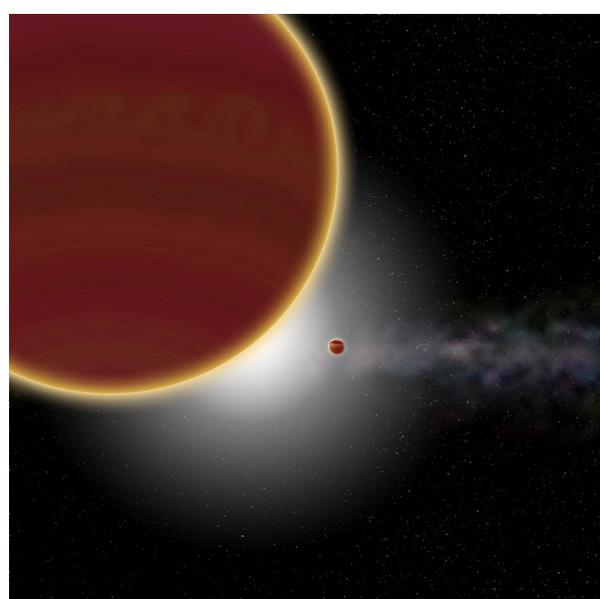


Imagem artística do planeta Beta Pictoris c
(c) Pascal Rubini / A-M Lagrange

The Beta Pictoris planetary system

Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity	Inclination	Radius
c	$9 M_J$	2.7	1200	0.24	—	—
Inner belt	6.4 AU			~89°	—	
b	$12_{-3}^{+4} M_J$	$9.2_{-1.5}^{+0.4}$	7890 ± 1000	~0.1	$89.01 + 0.36^\circ$	$1.65 R_J$
secondary disk	130+ AU			$89 \pm 1^\circ$	—	
main disk	16–1450/1835 AU			$89 \pm 1^\circ$	—	

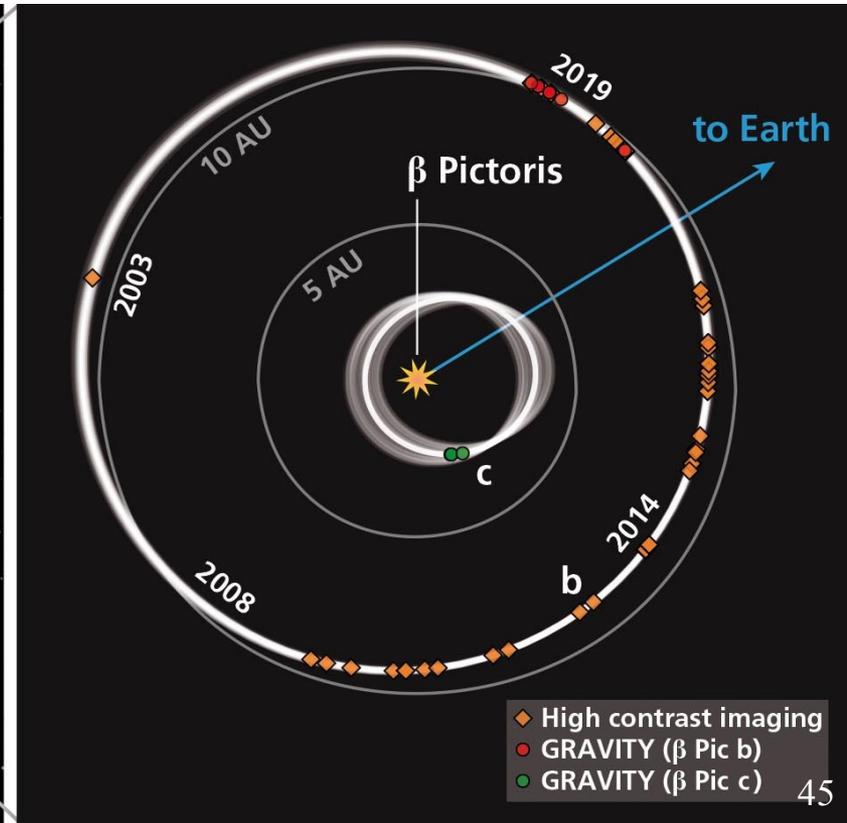
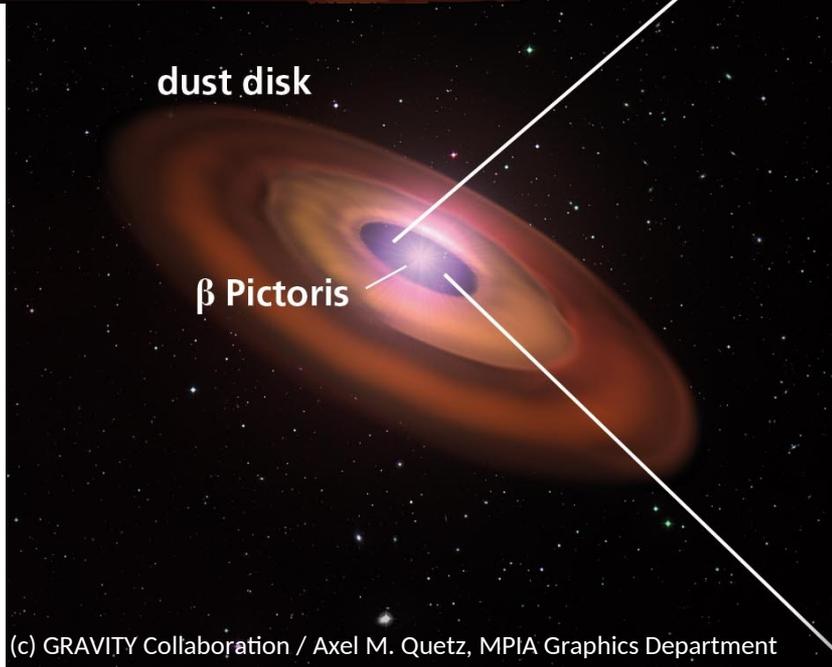
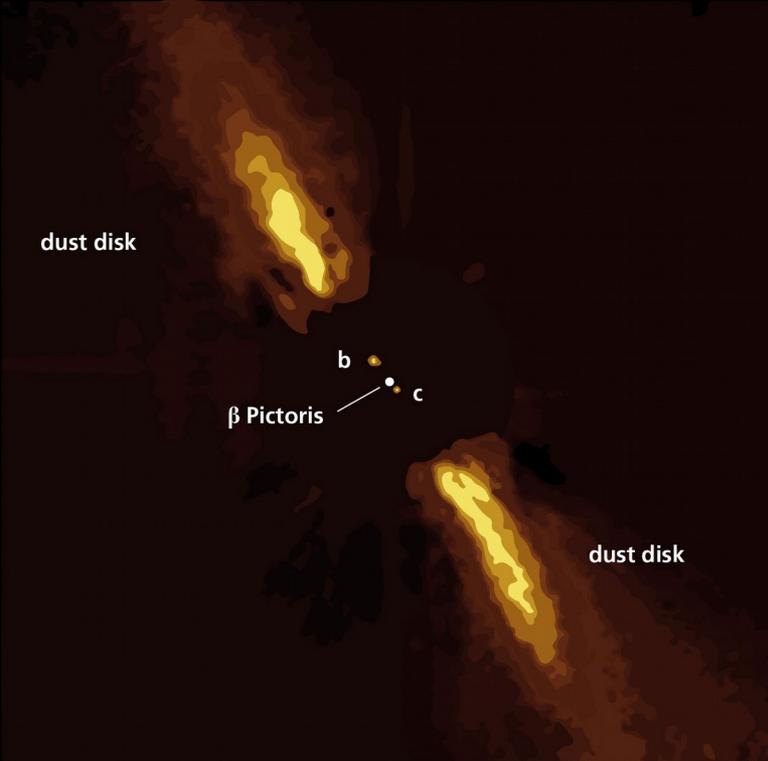
Direct confirmation of the radial-velocity planet β Pictoris c

M. Nowak^{1,2}, S. Lacour^{3,7}, A.-M. Lagrange⁴, P. Rubini²⁴, J. Wang¹⁰, T. Stolker²⁷, R. Abuter⁷, A. Amorim⁷

Atualização (2020) para as massas:

β Pictoris c: $8.2 \pm 0.8 M_{\text{jup}}$,

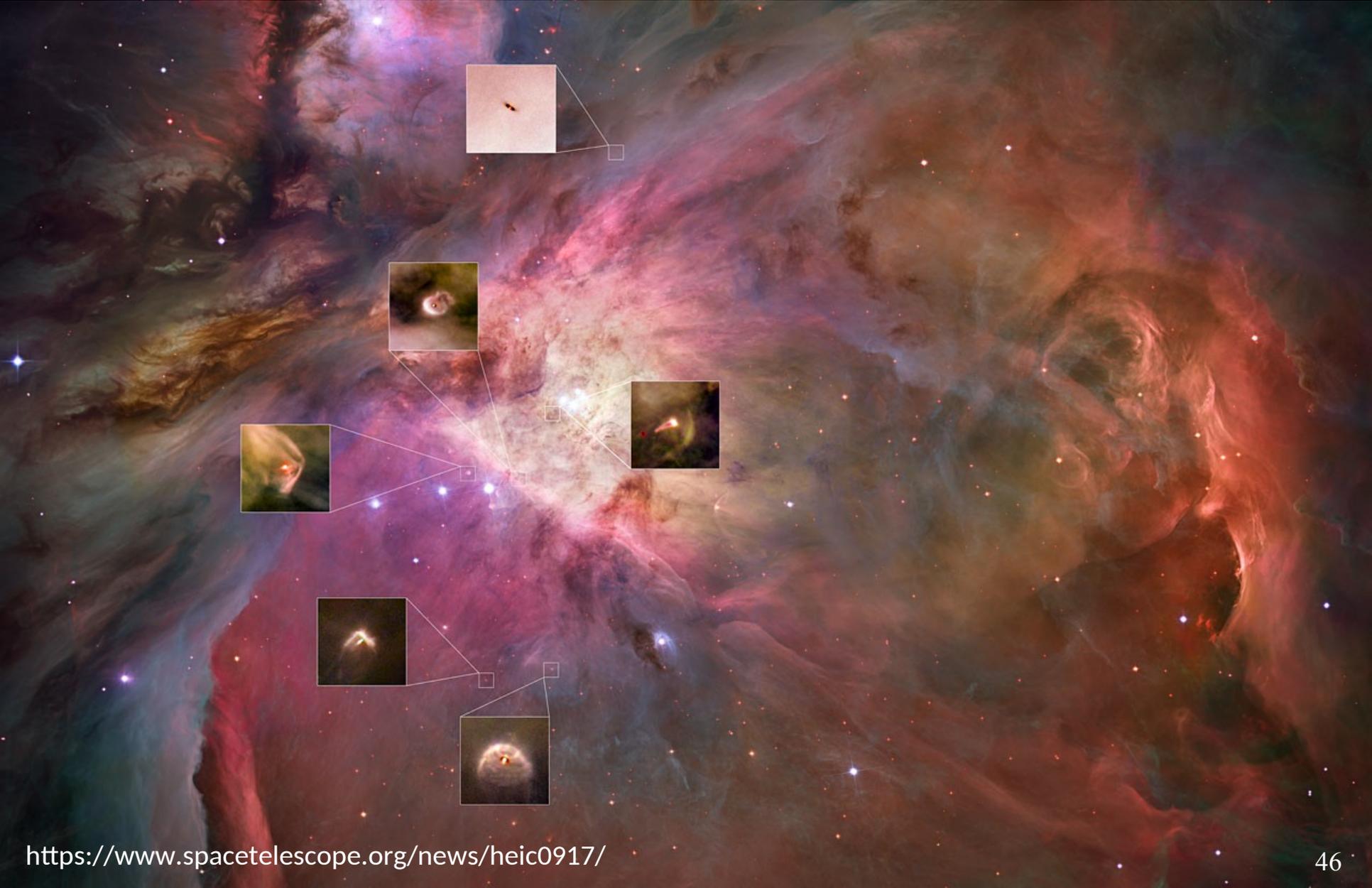
β Pictoris b: $9.0 \pm 1.6 M_{\text{Jup}}$



Proplyds in Orion

Discos protoplanetários em Orion

Massa $> 2 \times 10^{25}$ kg ($M_{\text{Terra}} \sim 6 \times 10^{24}$ kg)



Proplyds in Orion

(c) HST

Discos protoplanetários em Orion

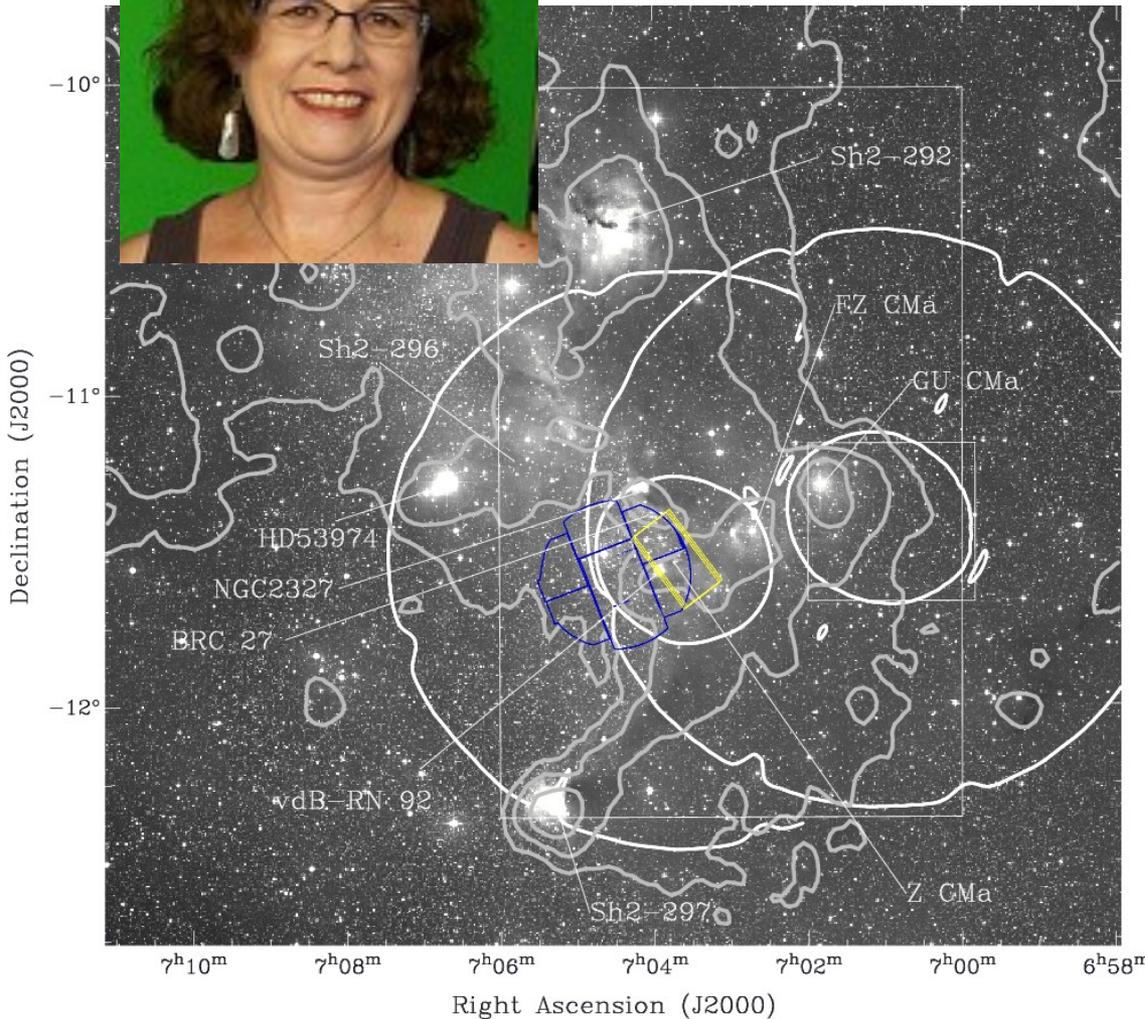


Estudo de estrelas pre sequência principal no Brasil



Profa. Jane Gregorio
Hetem (IAG/USP)

Profa. Silvia Alencar
(UFMG)



V 830 Tau, estrela T Tauri

Região de formação de estrelas CMa R1