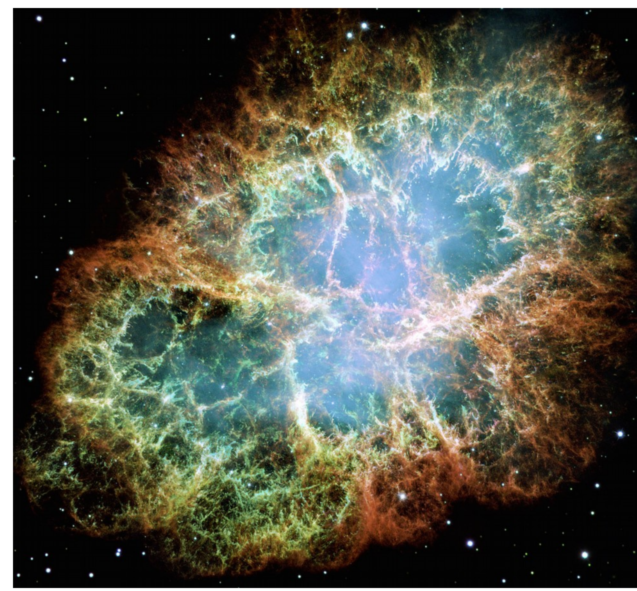
Cap. 15: evolução de estrelas massivas

15.1 Evolução Pós-Sequência Principal

15.2 A Classificação de Supernovas

15.3 Supernovas de colapso do núcleo
(até Remanescentes Estelares de Supernovas de colapso do núcleo)



Prof. Jorge Meléndez, AGA0293, Astrofísica Estelar, IAG-USP

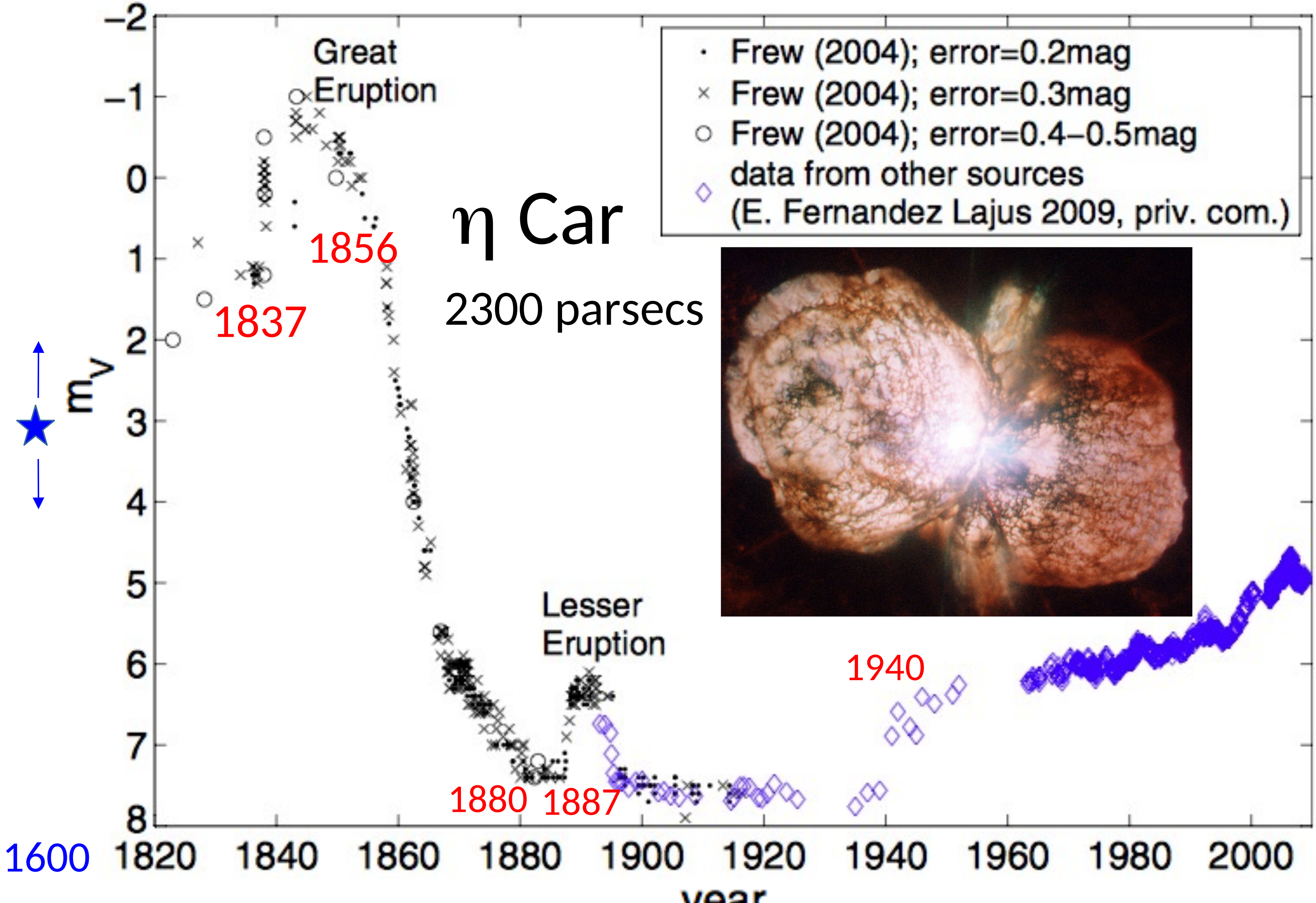
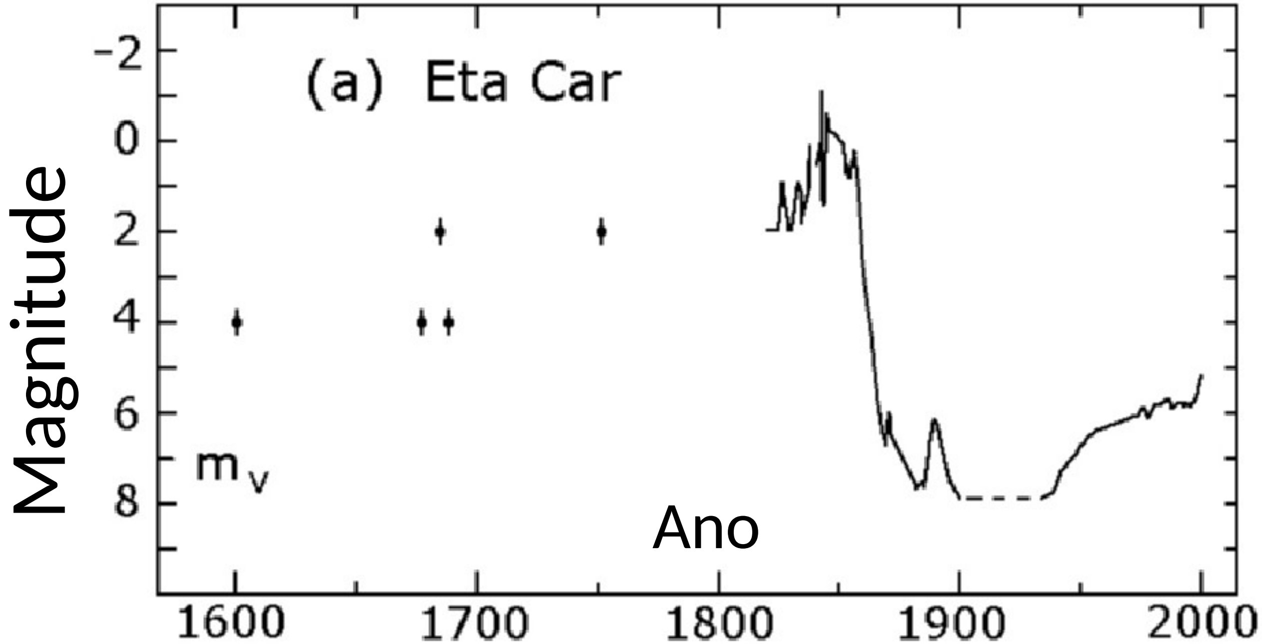


Figure 1. Historical *V* magnitude light curve

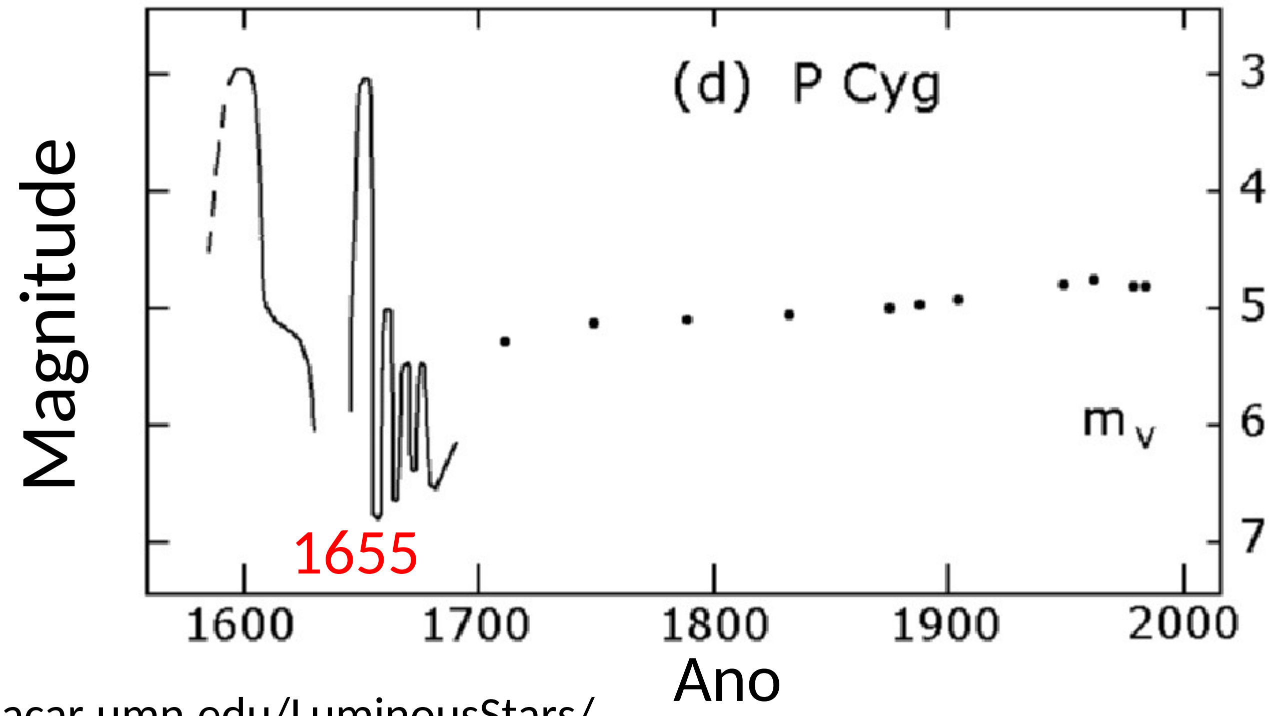
Sirius

V=-1,5, d = 2,6 pc

Kashi & Soker 2010 ApJ 723, 602



2300 parsecs

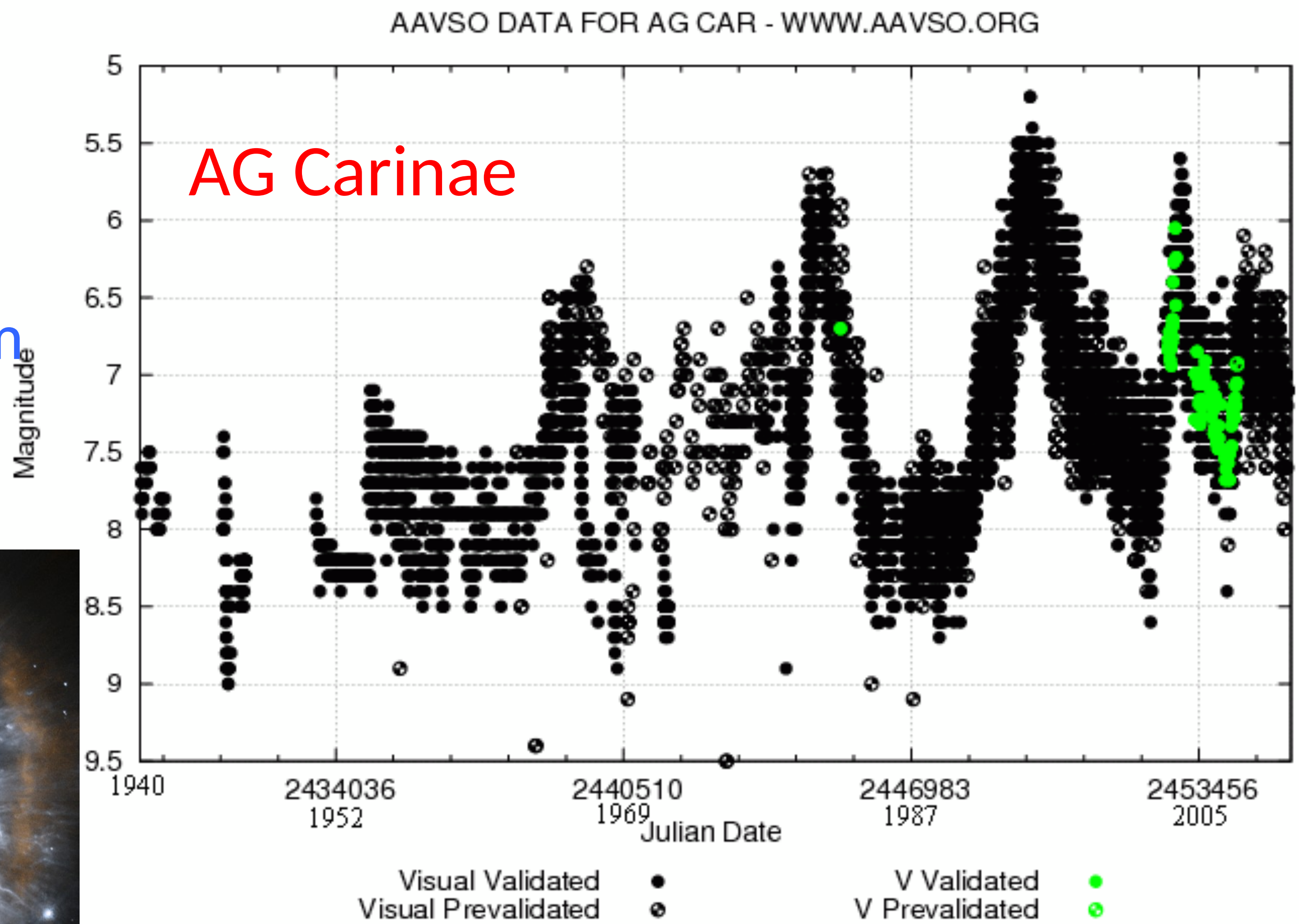


1700 parsecs

http://etacar.umn.edu/LuminousStars/

Existem outras estrelas massivas com variações imprevisíveis, mas de amplitude menor que η Car

Por exemplo:
AG Carinae na Galáxia e
S Doradus na Grande Nuvem de Magalhães (LMC)



AG Carinae © HST

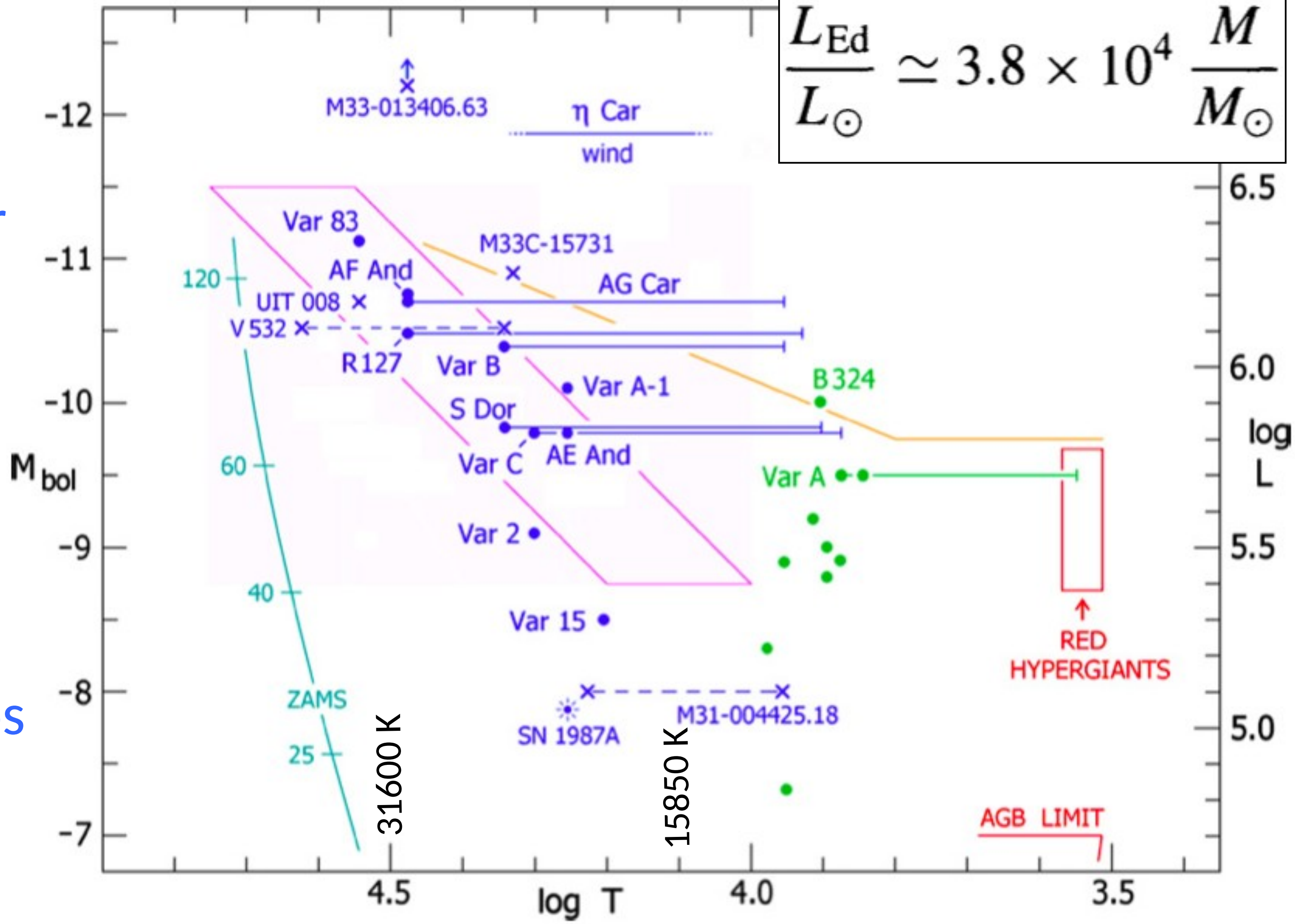
Luminous blue variables (LBVs)

$$\frac{L_{\rm Ed}}{L_\odot} \simeq 3.8 \times 10^4 \frac{M}{M_\odot}$$

Na Galáxia:
η Car, AG Car

Na LMC:
S Dor, R127

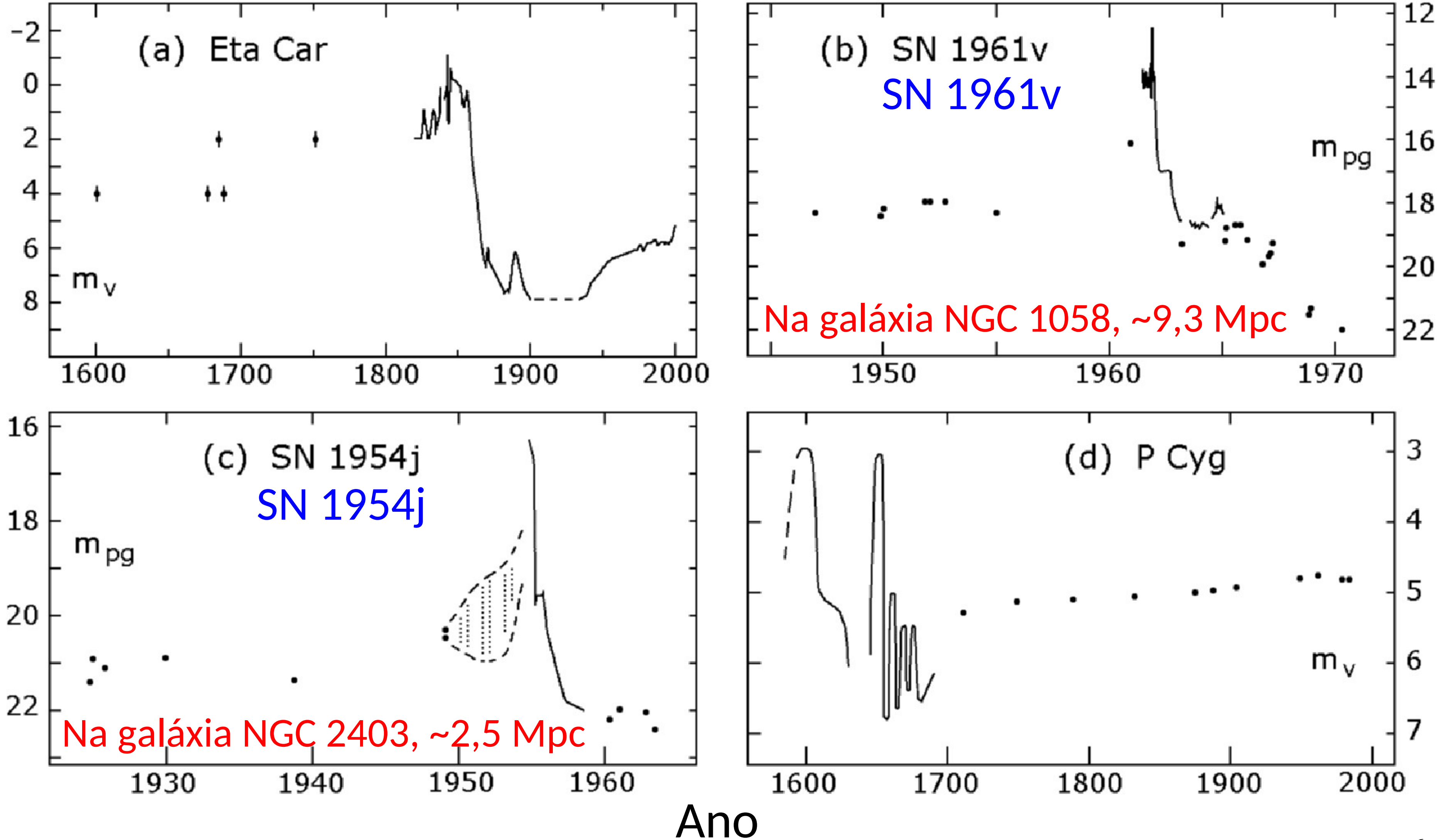
Nas galáxias M31 e M33: outros pontos em azul

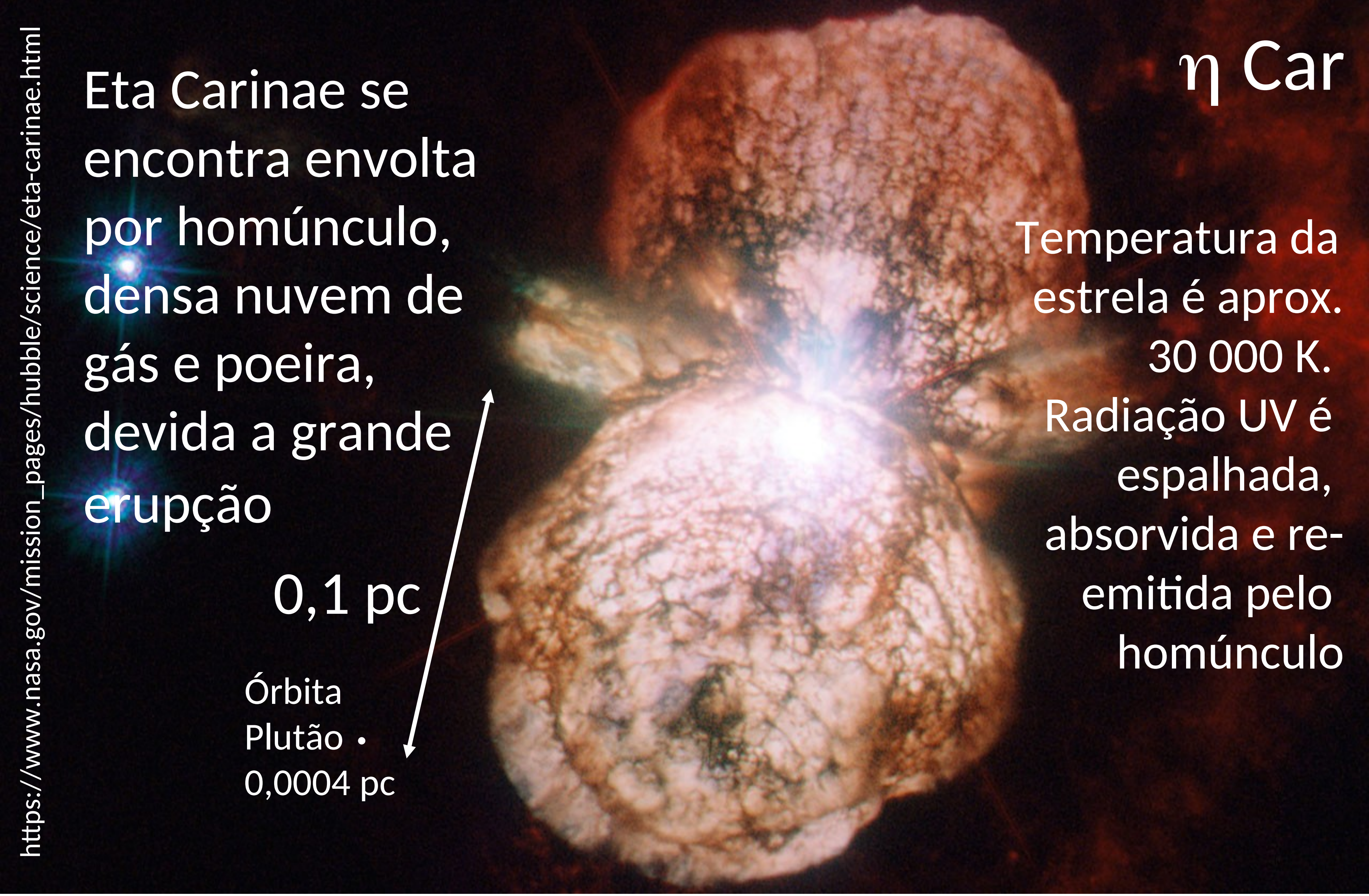


Humphreys et al. 2014, ApJ 790, 48

Figure 12. Schematic upper HR Diagram with the locations of the confirmed LBVs (blue dots), the warm hypergiants (Paper I) and candidate post-red supergiants (green dots), and other stars discussed in Section 4 (blue ×'s). The outline of the LBV/S Dor instability strip (pink) and the empirical upper luminosity boundary (gold) (Humphreys & Davidson 1994) are also shown. The LBV/S Dor transits to the cool dense wind state are shown as solid blue lines and those for V532/GR290 (Romano's star) and M31-004425.18 are dashed blue lines. The positions of η Car and the well-studied Galactic and LMC LBVs, AG Car, S Dor, and R 127 are shown for comparison. The apparent temperatures of Var 2, Var 15 and Var A-1 are estimates and their positions on the HRD are uncertain. Note that the solid blue transit line for Var C passes through the position of AE And.

Quando apresentam grandes variações, as LBVs são chamadas de *Eta Carina Variables*, "Giant Eruption" LBVs, ou *Supernova Impostors*





η Car

Eta Carinae se encontra envolta por homúnculo, densa nuvem de gás e poeira, devida a grande erupção

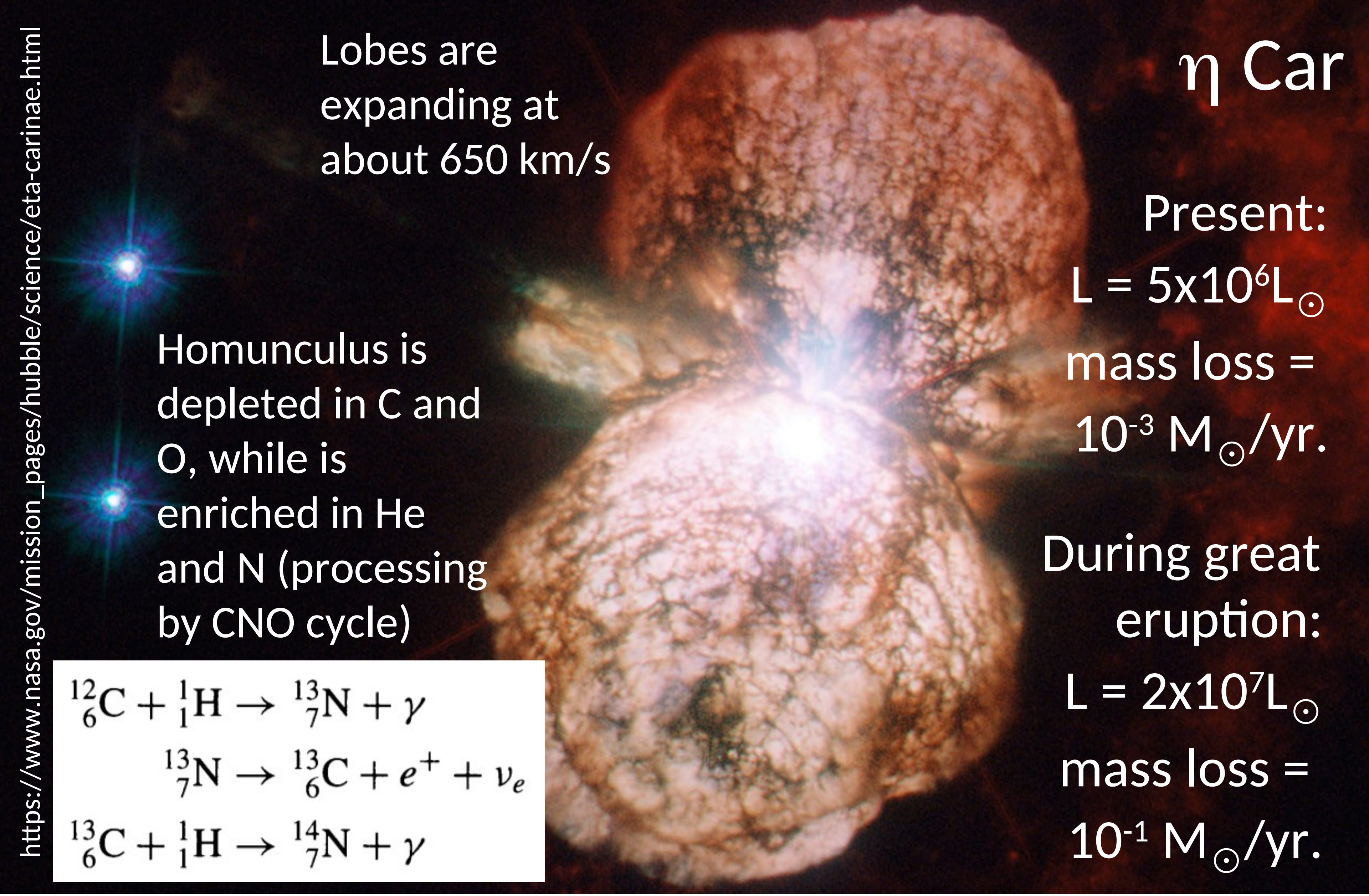
0,1 pc

Órbita Plutão • 0,0004 pc

Temperatura da estrela é aprox. 30 000 K. Radiação UV é espalhada, absorvida e re-emitida pelo homúnculo

https://www.nasa.gov/mission_pages/hubble/science/eta-carinae.html

FIGURE 15.1 η Carinae is a luminous blue variable that is estimated to have a mass of 120 $M_\odot$ and is rapidly losing mass. Each lobe has a diameter of approximately 0.1 pc. [Courtesy of Jon Morse (University of Colorado) and NASA.]



η Car

Lobes are expanding at about 650 km/s

Homunculus is depleted in C and O, while is enriched in He and N (processing by CNO cycle)

$$
\begin{aligned}
{}^{12}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{13}_{7}\mathrm{N} + \gamma \\
{}^{13}_{7}\mathrm{N} &\rightarrow {}^{13}_{6}\mathrm{C} + e^{+} + \nu_e \\
{}^{13}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{14}_{7}\mathrm{N} + \gamma
\end{aligned}
$$

Present:
$L = 5\text{x}10^{6} L_{\odot}$
mass loss = $10^{-3}\ M_{\odot}$/yr.

During great eruption:
$L = 2\text{x}10^{7} L_{\odot}$
mass loss = $10^{-1}\ M_{\odot}$/yr.

https://www.nasa.gov/mission_pages/hubble/science/eta-carinae.html

FIGURE 15.1 η Carinae is a luminous blue variable that is estimated to have a mass of 120 $M_{\odot}$ and is rapidly losing mass. Each lobe has a diameter of approximately 0.1 pc. [Courtesy of Jon Morse (University of Colorado) and NASA.]

Luminous blue variables (LBVs)

$T_e \sim 15\,000 - 30\,000$ K

$L \sim 10^6 L_\odot$

$Massa_{inicial} > 60 M_\odot$ (?)

$$\frac{L_{Ed}}{L_\odot} \simeq 3.8 \times 10^4 \frac{M}{M_\odot}$$

$$L_{Ed} = \frac{4\pi Gc}{\bar{\kappa}} M$$

Instabilidades:
- pressão de radiação
- oscilações
- alta rotação
- binariedade

η Carinae: periodicidade de 5,54 anos
(descoberta em 1996 pelo Prof. Augusto Damineli, IAG-USP)

THE ASTROPHYSICAL JOURNAL, 460: L49–L52, 1996 March 20

THE 5.52 YEAR CYCLE OF ETA CARINAE[1]

AUGUSTO DAMINELI

I have discovered spectroscopic variations correlated with the photometric near-infrared (NIR) light curve in η Carinae. The fading of the high-excitation lines is coincident with the peaks in the NIR light curve, strongly resembling an S Doradus type of variability. The cycle, however, is highly stable, and the 5.52 yr period fits well all the shell episodes reported in the last 50 years. This period also recovers the three historical bursts of the last century, in phase with the present low-amplitude oscillations, which suggests a connection between the S Doradus cycle and the giant bursts. The present data reveal that η Car is continuously varying in the He I λ10830 line by thousands of solar luminosities. The last spectra in this line show that the low-excitation phase is already in progress. A test for the strict periodicity will be the confirmation of the central phase epoch of the next shell event, predicted to occur in 1997 December. A very sensitive mapping technique is also proposed for this occasion, in order to prove Homunculus geometry.

Prof. Augusto Damineli

(c) Léo Ramos Chaves

Sistema binário:

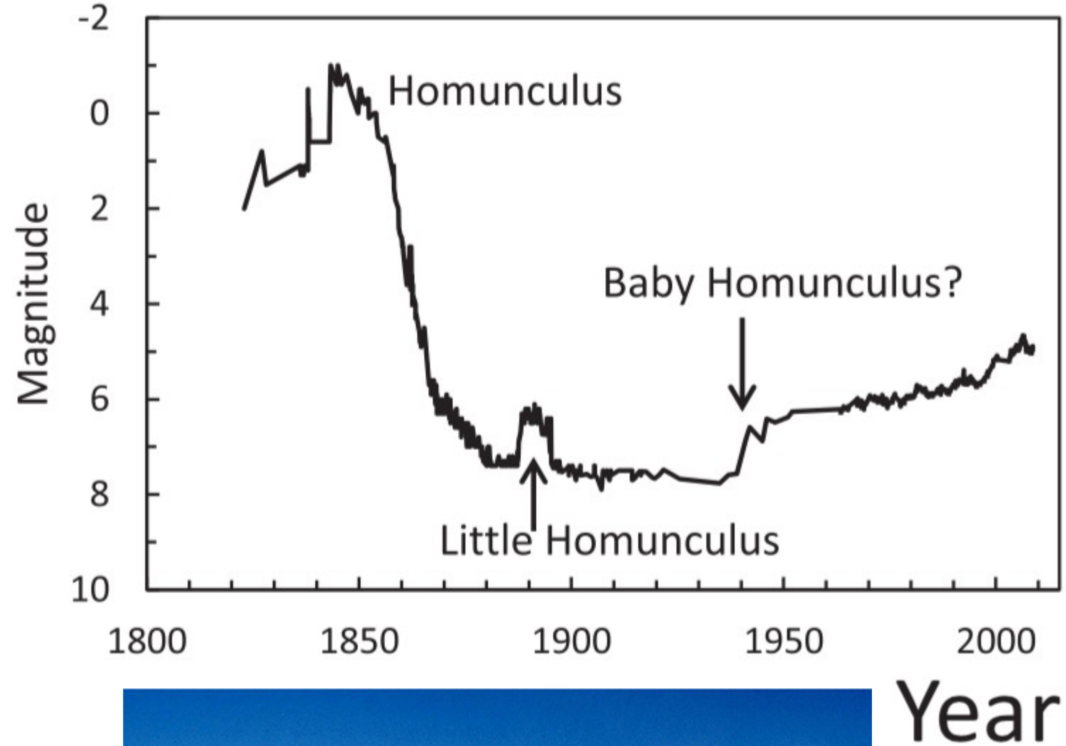
$90\ M_{\odot} + 30\ M_{\odot}$

The Astrophysical Journal, 791:95 (10pp), 2014 August 20

η CARINAE BABY HOMUNCULUS UNCOVERED BY ALMA

Zulema Abraham[1], Diego Falceta-Gonçalves[2,3], and Pedro P. B. Beaklini[1,4]
[1] Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, R. do Matão 1226, Cidade Universitária, CEP 05508-900 São Paulo, SP, Brazil; zulema.abraham@iag.usp.br
[2] Escola de Artes, Ciências e Humanidades, Universidade de São Paulo, R. Arlindo Bettio 1000, 03828-000 São Paulo, SP, Brazil

Profa. Zulema Abraham (IAG-USP)

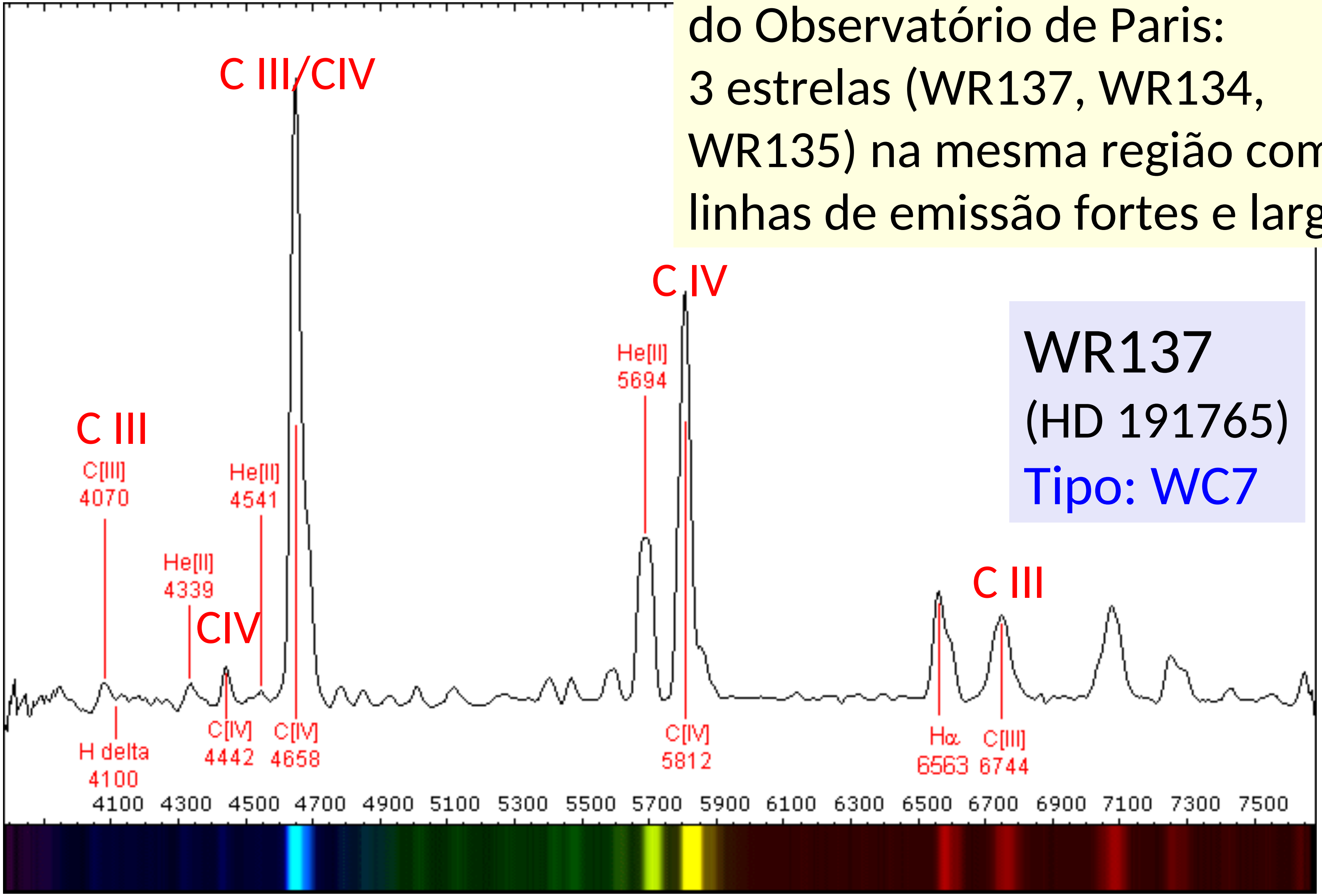


η Car no UV, HST

RadioObservatório ALMA @ESO

Estrelas Wolf-Rayet

Descobertas em 1867 por Charles Wolf e Georges Rayet, do Observatório de Paris: 3 estrelas (WR137, WR134, WR135) na mesma região com linhas de emissão fortes e largas



WR137

(HD 191765)

Tipo: WC7

Estrelas Wolf-Rayet

$T_e \sim 25\,000 - 100\,000$ K

$L \sim 10^5 - 10^6\ L_\odot$

Perda de massa
$> 10^{-5}\ M_\odot$/yr.

Vento
800 – 3000 km/s

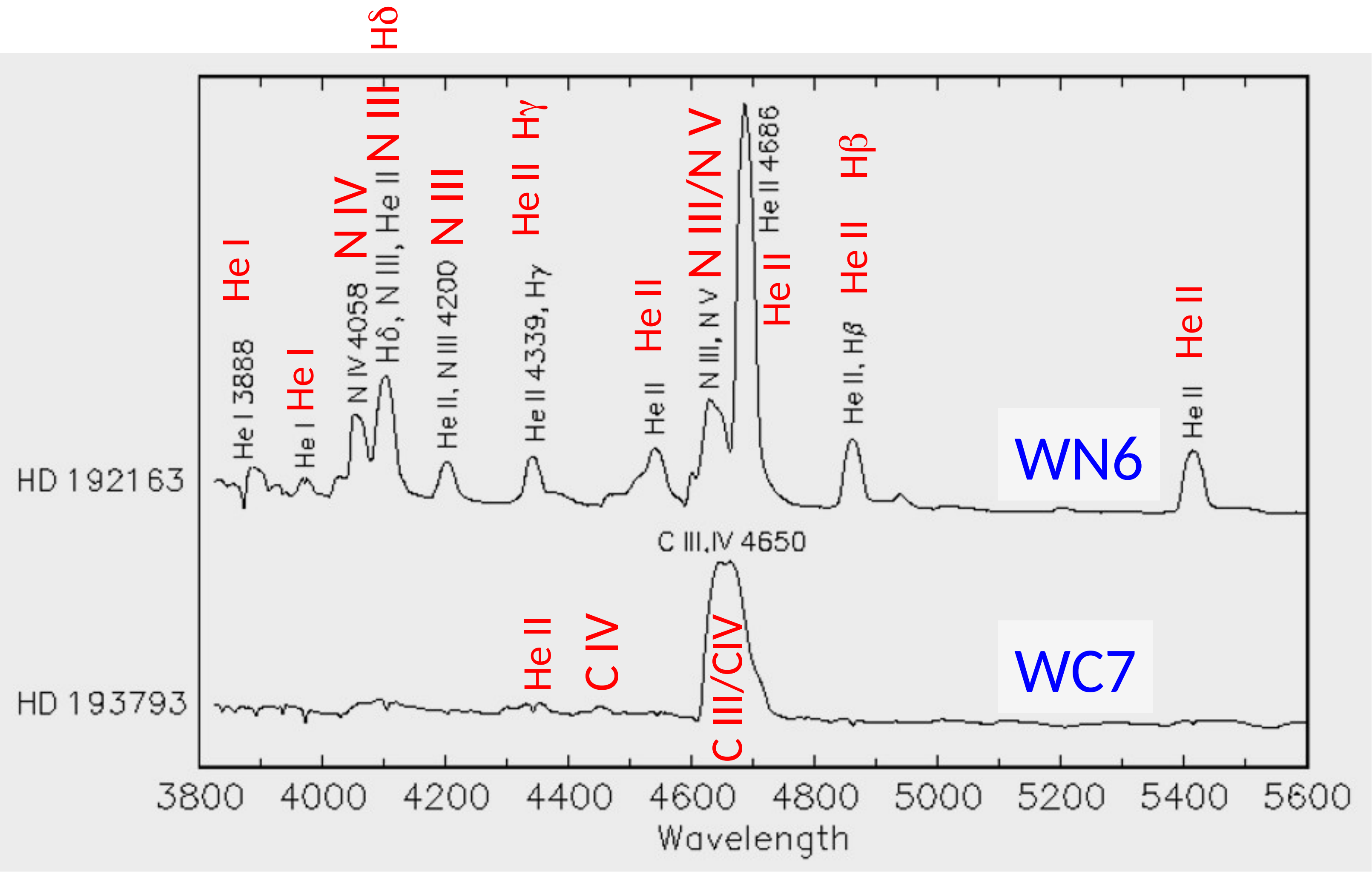
Rotação 300 km/s

$\text{Massa}_{\text{inicial}} > 20\ M_\odot$

Não apresentam grandes variações como as LBVs

FIGURE 15.2 The nebula M1-67 around the Wolf–Rayet star WR 124. The surface temperature of the star is about 50,000 K. Clumpiness is clearly evident in the nebula, and the mass of each blob is about 30 $M_\oplus$. WR 124 is at a distance of 4600 pc in Sagittarius. [Courtesy of Yves Grosdidier

Wolf Rayet: tipos WN, WC, WO



https://ned.ipac.caltech.edu/level5/Gray/Gray3.html

Wolf Rayet: tipos WN, WC, WO

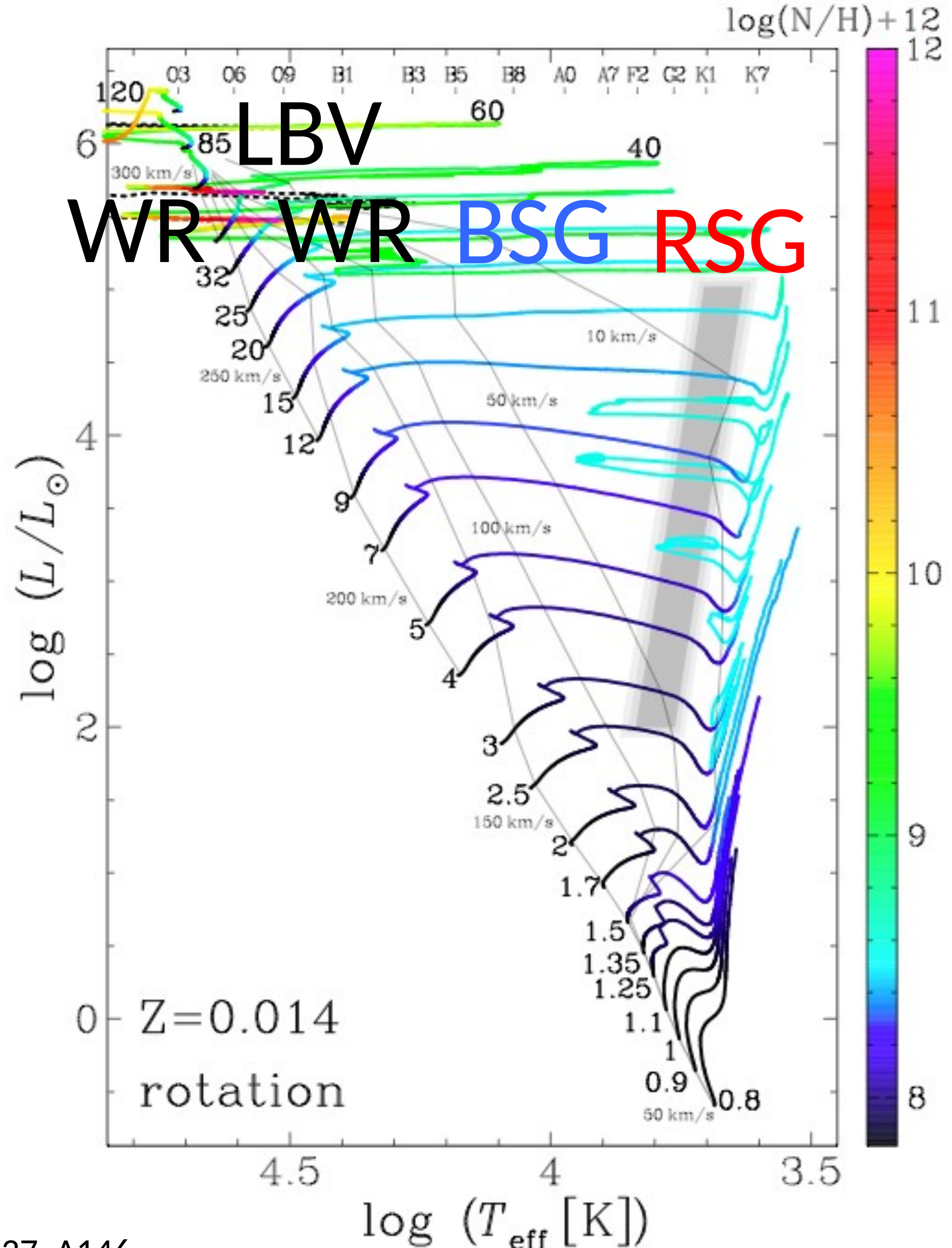
WN: perdeu envelope de H, deixando produtos do ciclo CNO
WC: ejeção de produtos do ciclo CNO, deixando material do triplo-α
WO: ejeção de produtos triplo-α, deixando o oxigênio residual

Wolf Rayet stars have ejected their outermost layers
O→WN→WC→WO

http://www.ulo.ucl.ac.uk/library/catalogues/mkkatlas/xhtml/index.html

Outros tipos de estrelas na parte superior do diagrama HR

- BSG: blue supergiants
- RSG: red supergiants
- Of: O supergiants with pronounced emission lines



Ekström et al. 2012 A&A 537, A146

Evolução (tentativa) de estrelas massivas

$$M > 85\,M_\odot : O \rightarrow Of \rightarrow LBV \rightarrow WN \rightarrow WC \rightarrow SN$$

$$40\,M_\odot < M < 85\,M_\odot : O \rightarrow Of \rightarrow WN \rightarrow WC \rightarrow SN$$

$$25\,M_\odot < M < 40\,M_\odot : O \rightarrow RSG \rightarrow WN \rightarrow WC \rightarrow SN$$

$$20\,M_\odot < M < 25\,M_\odot : O \rightarrow RSG \rightarrow WN \rightarrow SN$$

$$10\,M_\odot < M < 20\,M_\odot : O \rightarrow RSG \rightarrow BSG \rightarrow SN$$

Evolução (tentativa) de estrelas massivas

60
$M > 85\ M_\odot : \mathrm{O} \rightarrow \mathrm{Of} \rightarrow \mathrm{LBV} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN}$

60 LBV?
$40\ M_\odot < M < 85\ M_\odot : \mathrm{O} \rightarrow \mathrm{Of} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN}$

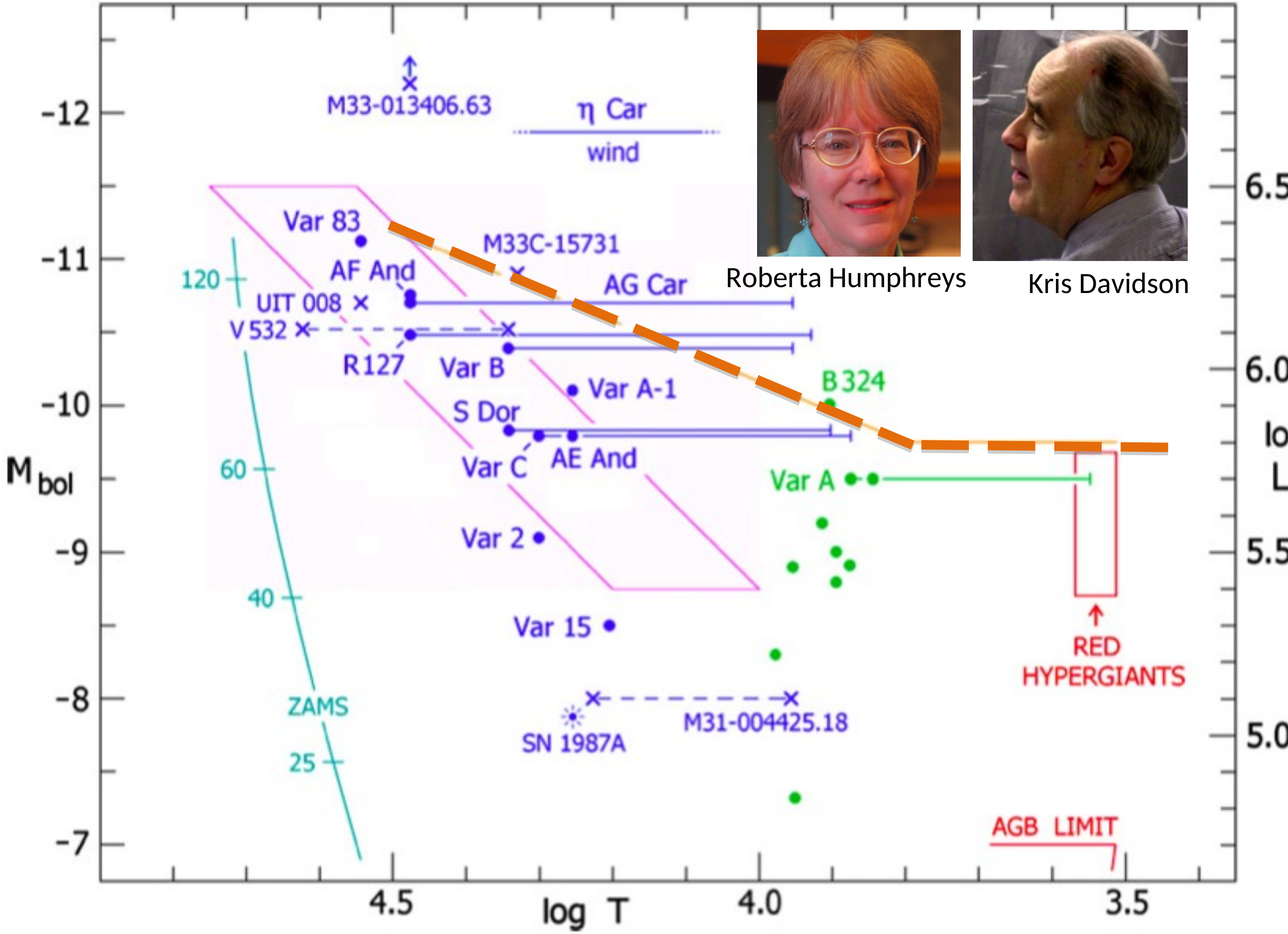
BSG
$25\ M_\odot < M < 40\ M_\odot : \mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN}$

BSG BSG → RSG
$20\ M_\odot < M < 25\ M_\odot : \mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{WN} \rightarrow \mathrm{SN}$

RSG
$10\ M_\odot < M < 20\ M_\odot : \mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{BSG} \rightarrow \mathrm{SN}$

Blue loop,
mas volta
para RSG

Limite de Humphreys-Davidson



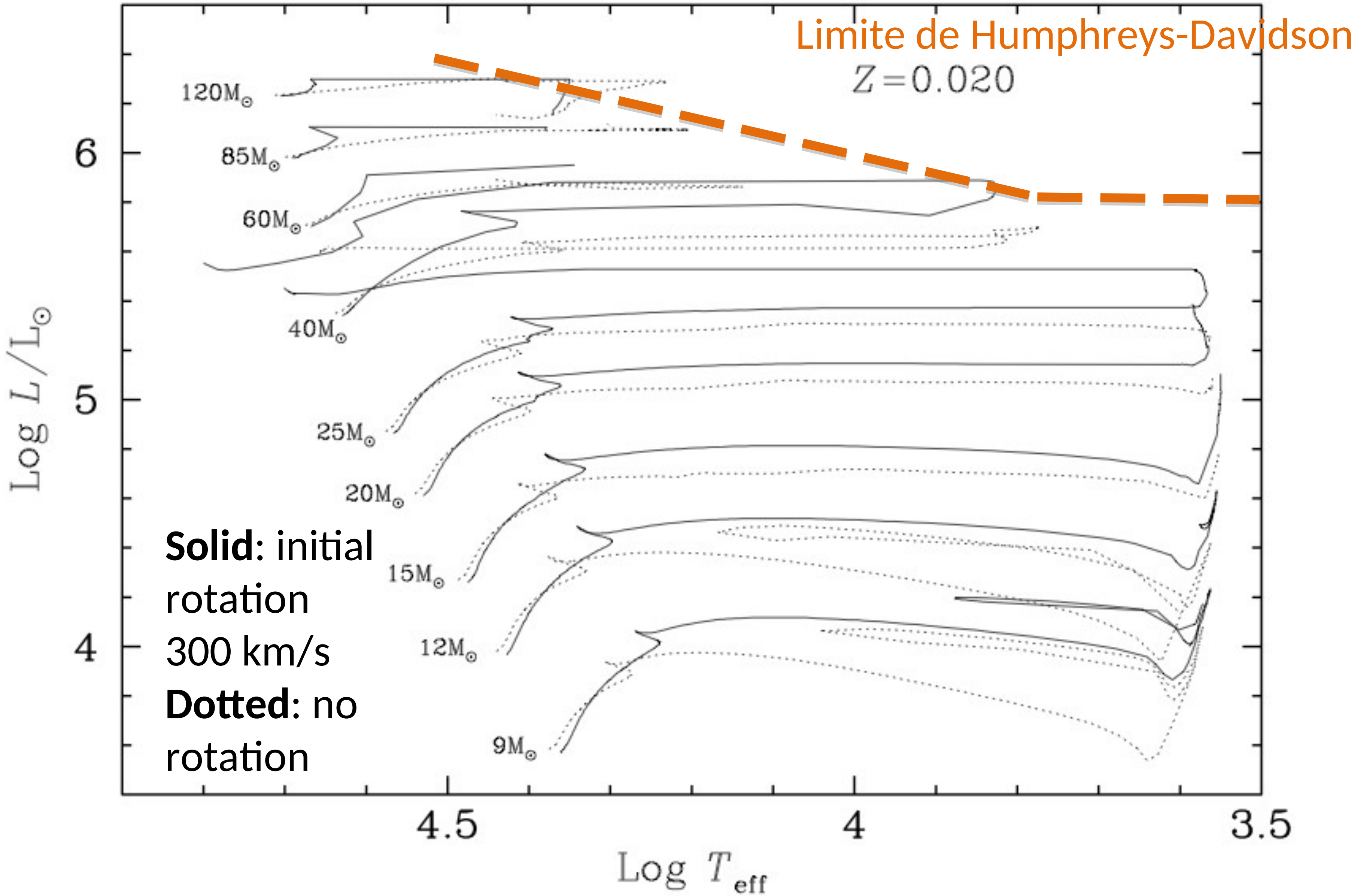
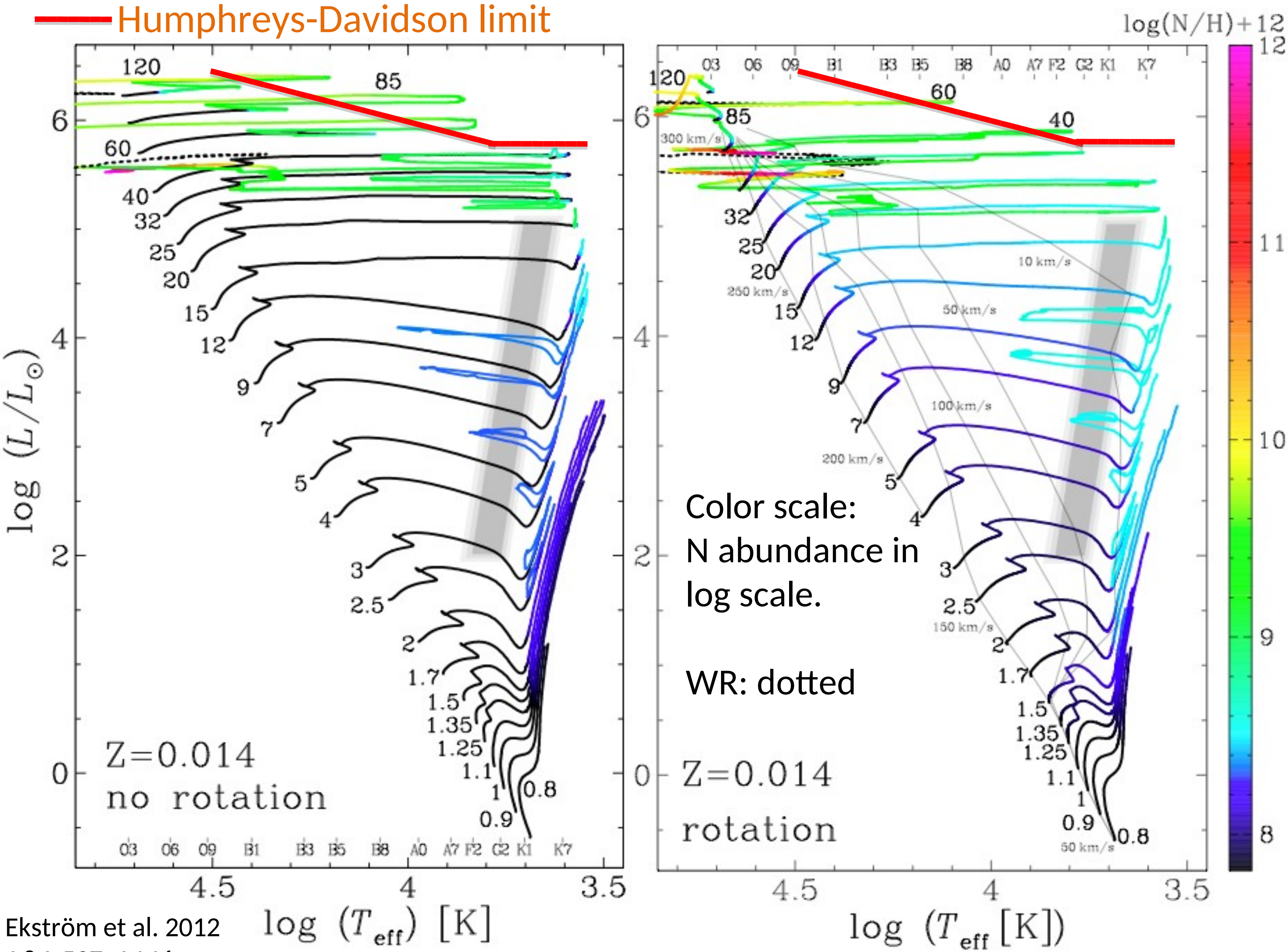


FIGURE 15.3 The evolution of massive stars with $Z = 0.02$. The solid lines are evolutionary tracks computed with initial rotation velocities of 300 km s^{-1}, and the dotted lines are evolutionary tracks for stars without rotation. Mass loss has been included in the models and significantly impacts the evolution of these stars. (Figure from Meynet and Maeder, *Astron. Astrophys.*, *404*, 975, 2003.)



Ekström et al. 2012
A&A 537, A146

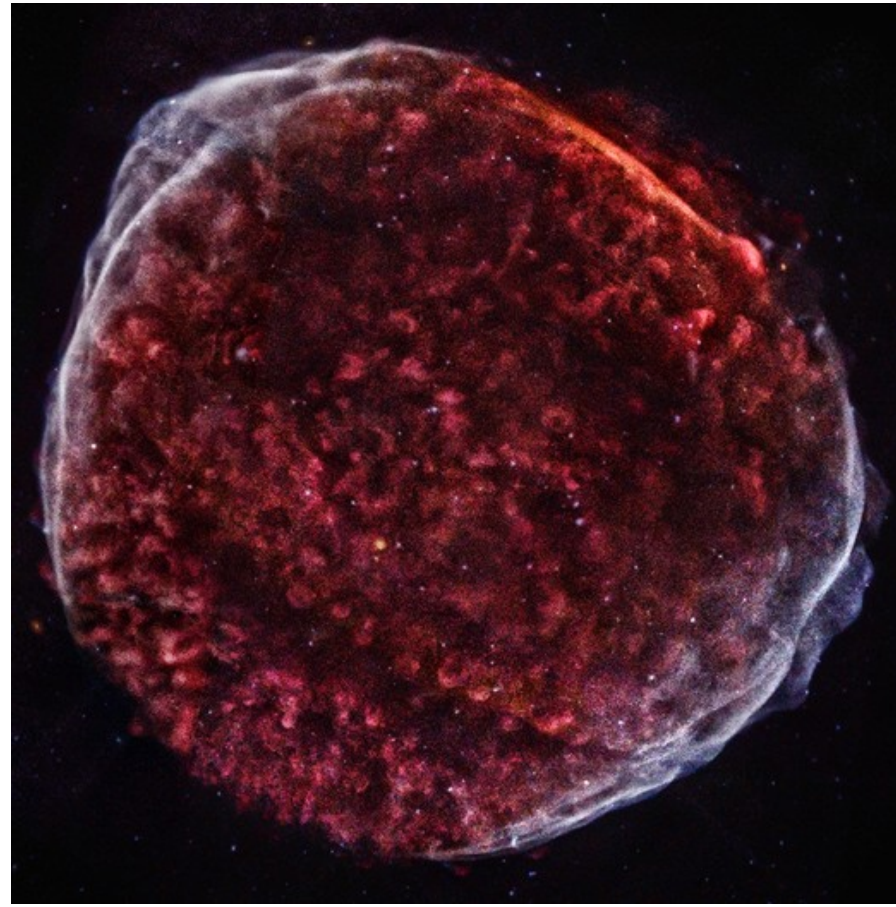
Importância das estrelas massivas

NGC 602, HST

- São poucas: 1 de 100 $M_\odot$ por cada 1 milhão de 1 $M_\odot$
- Os ventos podem afetar as nuvens moleculares, cessando a formação estelar
- Os ventos são ricos em metais processados no interior→ enriquecimento químico do ISM
- Explodem como supernovas, desestabilizando nuvens moleculares → formação de estrelas e enriquecimento químico do ISM

Classificação de supernovas

X-rays, Chandra @NASA



Supernova 1006

V ~ -8 (a mais brilhante já observada)

d = 2,2 kpc

Coordenadas:

A.R. = 15 02 22 Dec = -42 05 49

صورة كوكب من الكواكب ، كالذى ظهر فى سنة سبع وتسعين وثلاث مائة للهجرة ،
فبقى قريبا من ثلاثة أشهر يلطف ويلطف حتى اضمحل ، وكان فى ابتدائه إلى السواد
والخضرة ، ثم جعل كل وقت يرمى بالشرر ويزداد بياضا ويلطف حتى اضمحل . وقد
يكون على صورة لحية ، أو صورة حيوان له قرون ، وعلى سائر الصور ؛ وإنما يكون ذلك
إذا كانت هناك مادة كثيفة واقفة ، تلطف أجزاؤها يسيرا يسيرا وتتحلل عنه متصعدة
كزوائد شعرية أو قرنية . ومنها المسماة أعنزا كأن تشعيرها تشعير . وكل ما ثبت منها

---

(١) بالعدد : وبالعدد د ، سا || فى : ساقطة من ب ، ط (٢) كالموجودة : كالموجود
د ، ط ، م (٣) ويخلفها غيرها : ويخلفه غيره ب ، د ، سا ، ط || موضعها : موضعه ب ، د ، سا ، ط .
(٥) فى حقيقة : وحقيقة سا (٧) مقامه : مكانه د ، سا || يشتعل : ساقطة من د .
(٨) وخفيفة : خفيفة سا (٩) وخلصت : وحصلت سا . (١٠) وذات : ذات سا

Arabic text from the report of SN 1006 of Ibn Sina in al-Shifa from the Arabic edition by Madkur et al. (1965)

Text 2. Ibn al-Athīr: Events of A.H. 396.

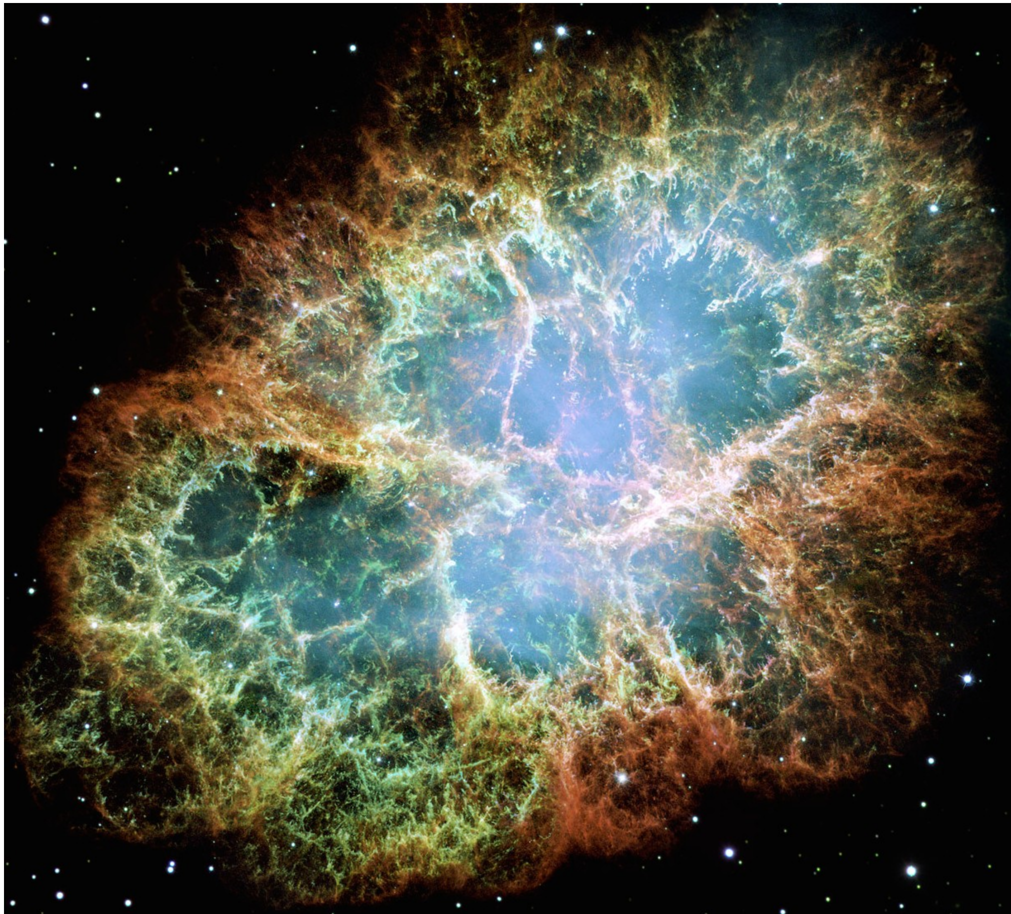
وفيها مستهل شعبان طلع كوكب كبير تشبه الزهرة عن
يسرة قبله العراق له شعاع على ارض كشعاع القمر وبقى
الى منتصف ذى القعدة وغاب .

Goldstein (1965, ApJ 70, 105)

Supernova 1054

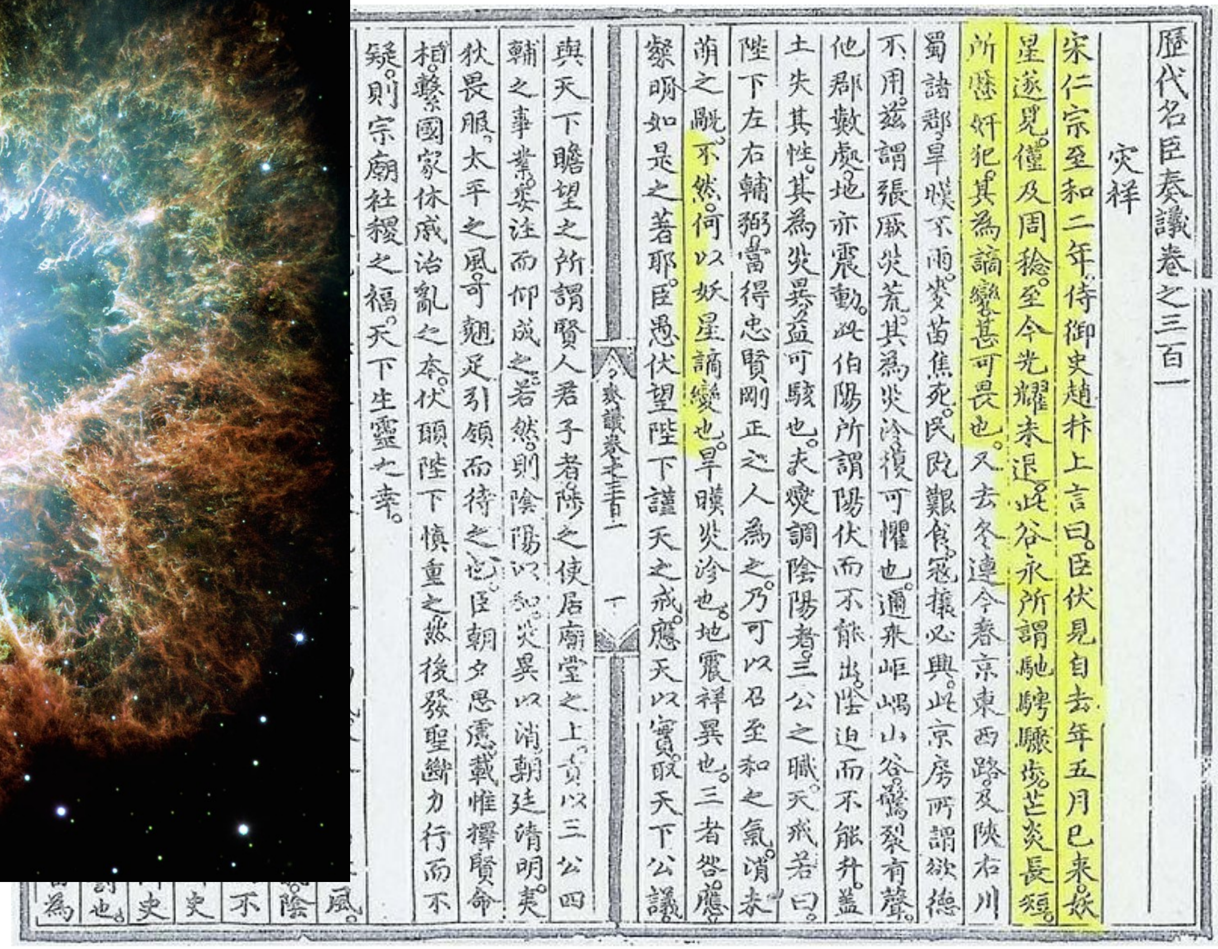
V ~ -6, d ~ 2 kpc

The Crab Nebula is the remnant of SN 1054, reported by Chinese, Japanese & Arab astronomers



Crab nebula

© HST



歷代名臣奏議卷之三百一

災祥

宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖星遂見僅及周歲至今光耀未退此谷永所謂馳騁驟步芒炎長短所歷奸犯其爲譎變甚可畏也又去冬連今春京東西路及陝右川蜀諸郡旱暵不雨麥苗焦死民旣艱食寇攘必興此京房所謂欲德不用茲謂張厥災荒其爲災沴復可懼也通衆峰嵎山谷驚裂有聲他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋土失其性其爲災異益可駭也夫燮調陰陽者三公之職天若曰陛下左右輔弼當得忠賢剛正之人爲之乃可以召至和之氣消未萌之戾不然何以妖星譎變也旱暵災沴也地震祥異也三者咎應粲明如是之著耶臣愚伏望陛下謹天之戒應天以實敢天下公議

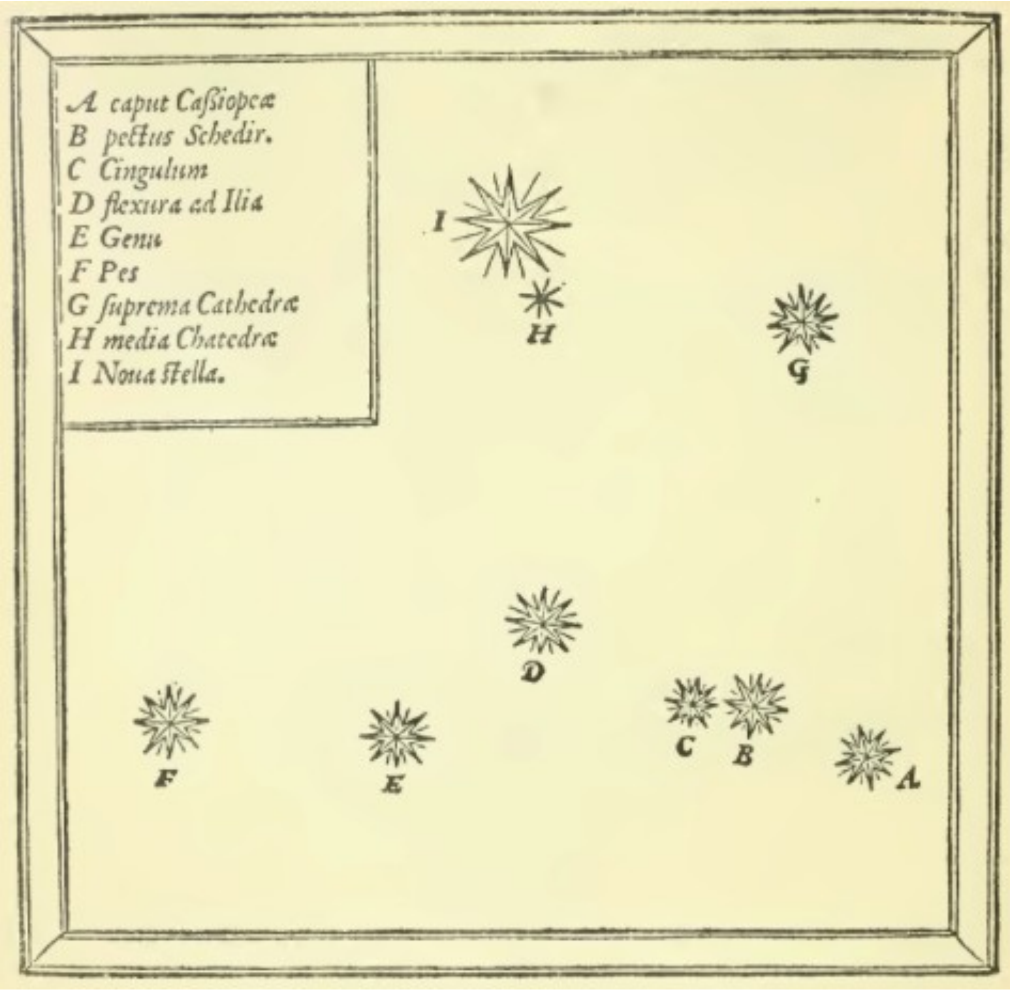
歷代名臣奏議卷三百一 一

與天下瞻望之所謂賢人君子者陟之使居廟堂之上責以三公四輔之事業要注而仰成之若然則陰陽以和災異以消朝廷清明矣狀畏服太平之風可翹足引領而待之也臣朝夕思慮載惟擇賢命相繫國家休戚治亂之本伏願陛下慎重之然後發聖斷力行而不疑則宗廟社稷之福天下生靈之幸

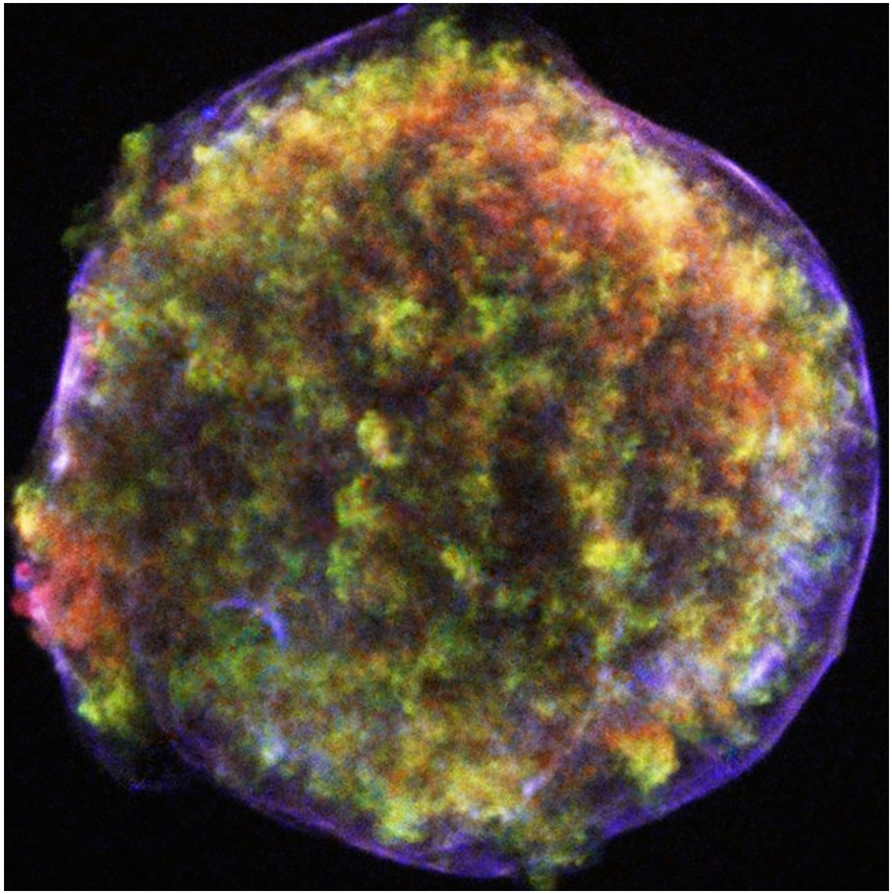
The highlighted passages refer to SN 1054, a guest star reported by Chinese astronomers in 1054

Supernova 1572

V ~ -4, d ~ 2,7 kpc

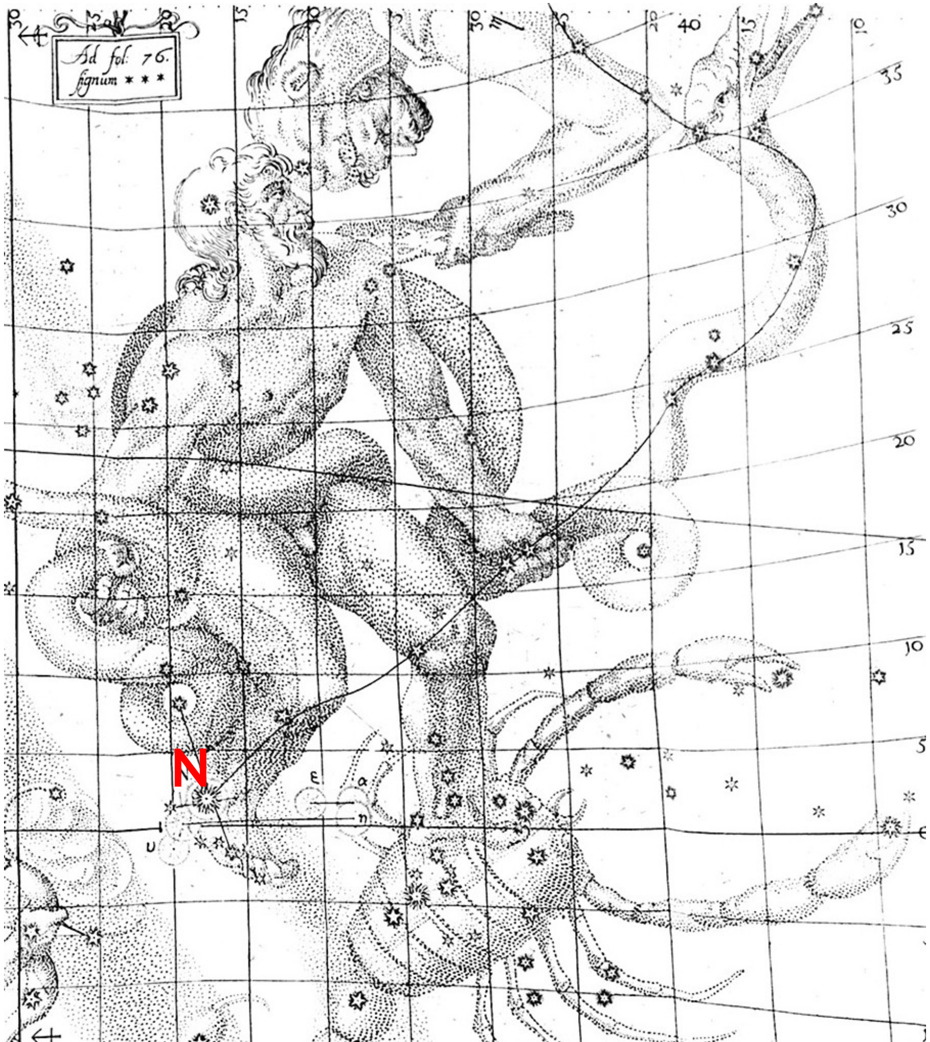


Tycho's notes on SN 1572

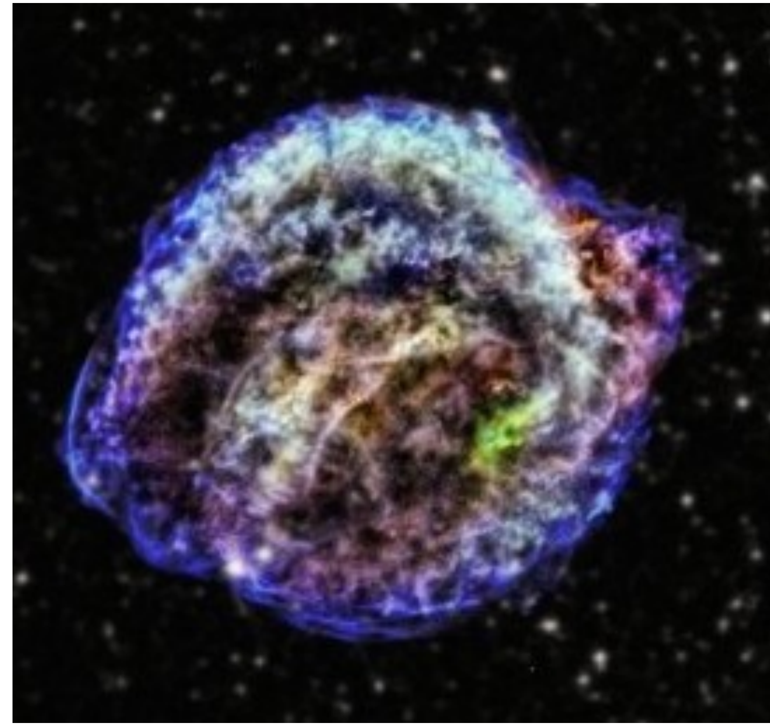


Tycho's Supernova Remnant. Chandra's image of the supernova remnant shows an expanding bubble of multimillion degree debris (green and red) inside a more rapidly moving shell of extremely high energy electrons (filamentary blue).

Supernova 1604, V ~ -2,4, d ~ 6 kpc



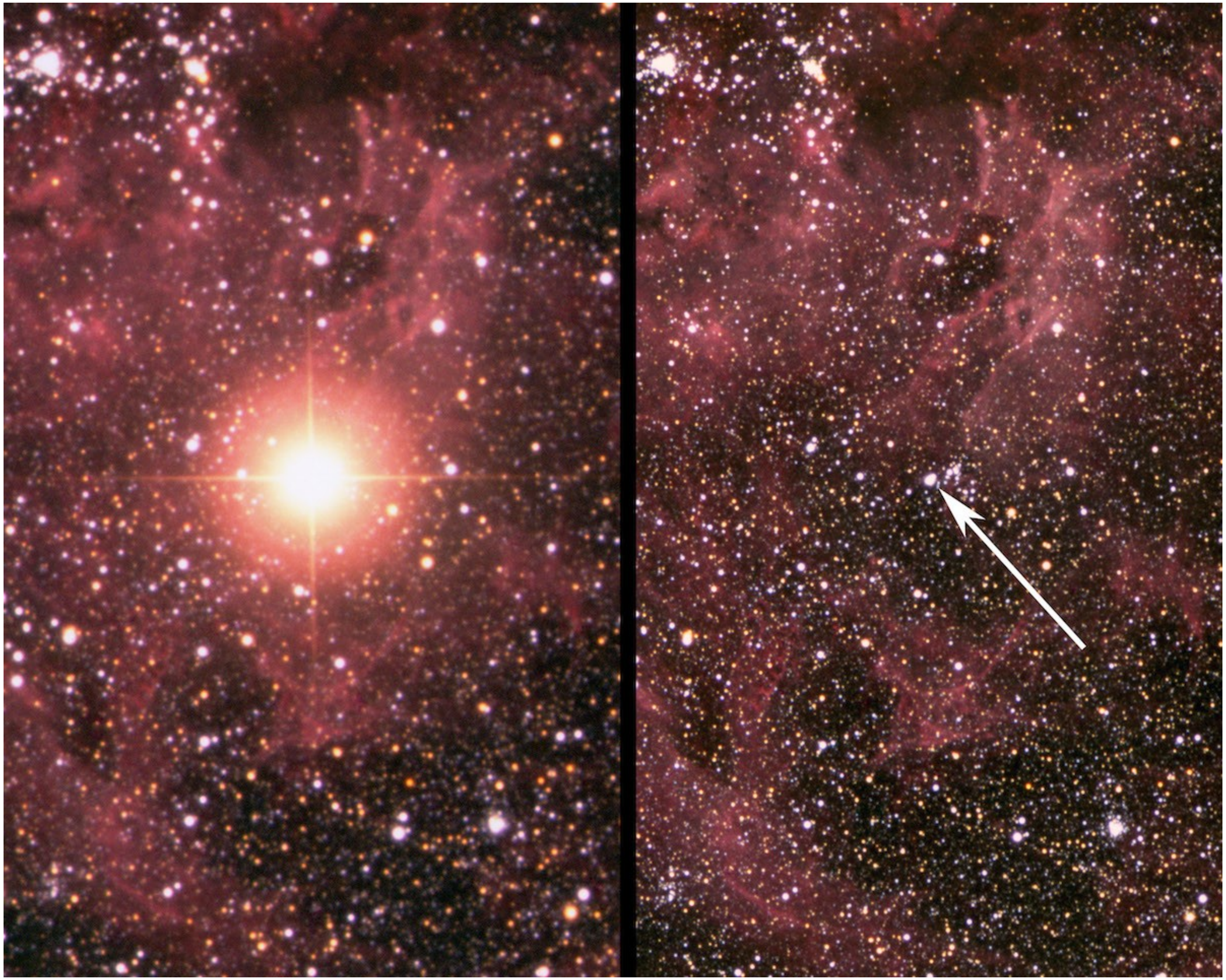
Kepler's original drawing depicting the location of the stella nova (**N**)



Remnant of Kepler's supernova, the famous explosion that was discovered by Johannes Kepler in 1604. The red, green and blue colors show low, intermediate and high energy X-rays observed with NASA's Chandra X-ray Observatory, and the star field is from the Digitized Sky Survey.

Supernova 1987A, V ~ 2,9; d ~ 51,4 kpc

SN 1987A was discovered by Ian Shelton & Oscar Duhalde at the Las Campanas Observatory in Chile on Feb 24, 1987

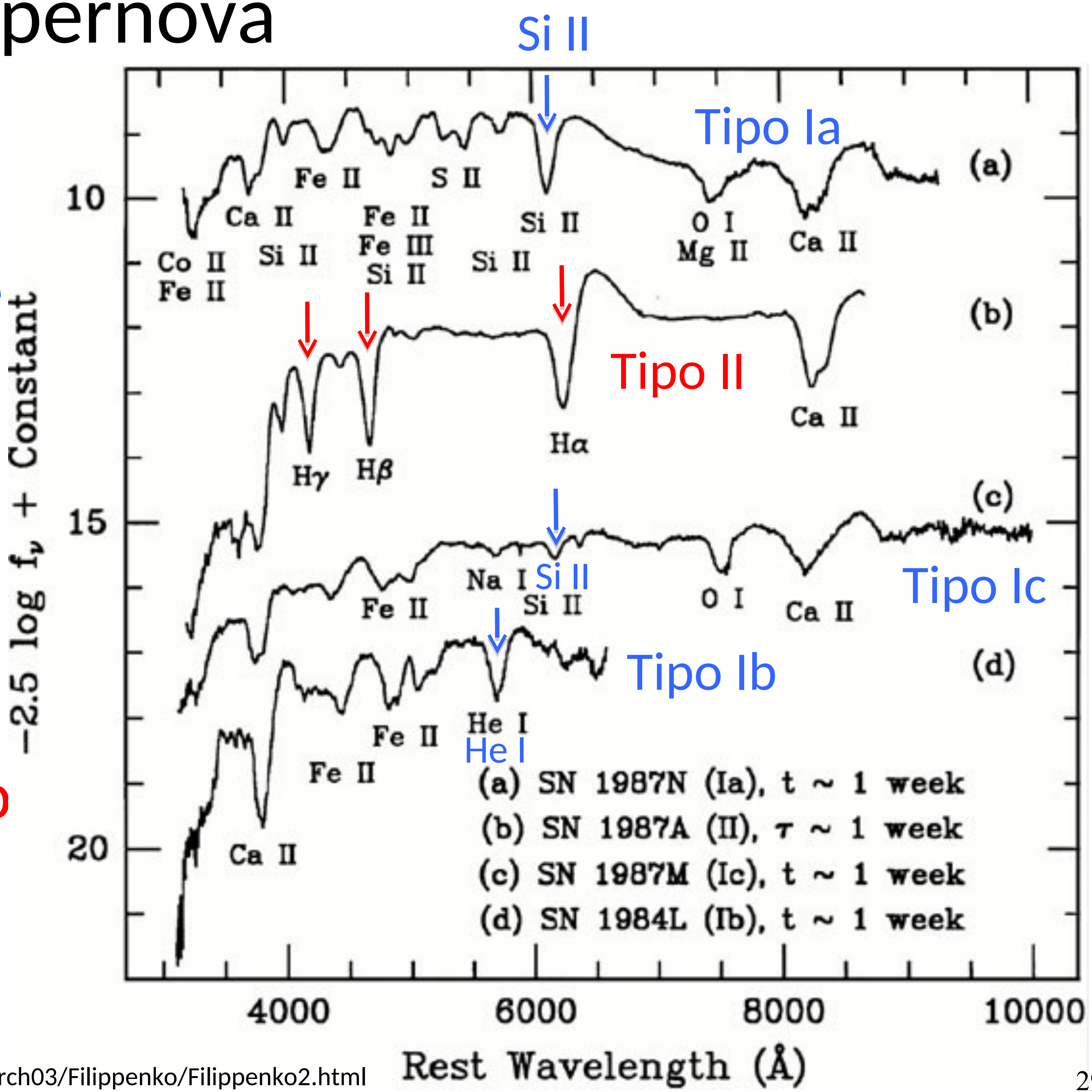


The progenitor star was identified as Sanduleak −69° 202, a blue supergiant in the LMC

Supernova 1987A after exploding & an image before the explosion. (c) David Malin / AAO

Tipos de Supernova

- Tipo I: sem linhas de hidrogênio no espectro
- Tipo II: com linhas de hidrogênio



https://ned.ipac.caltech.edu/level5/March03/Filippenko/Filippenko2.html

Tipos de supernova. Tipo I: sem linhas de H, Tipo II: com H

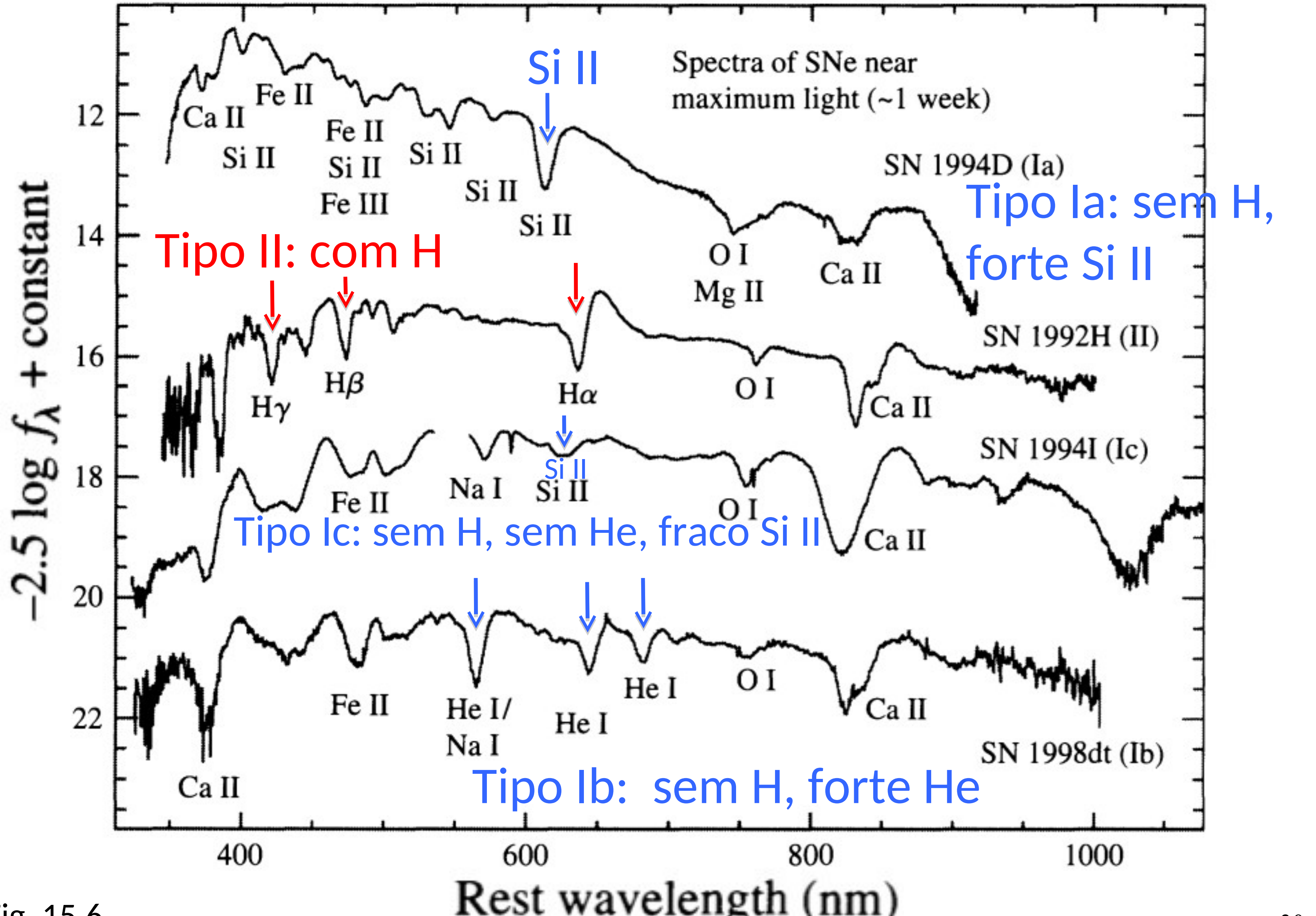
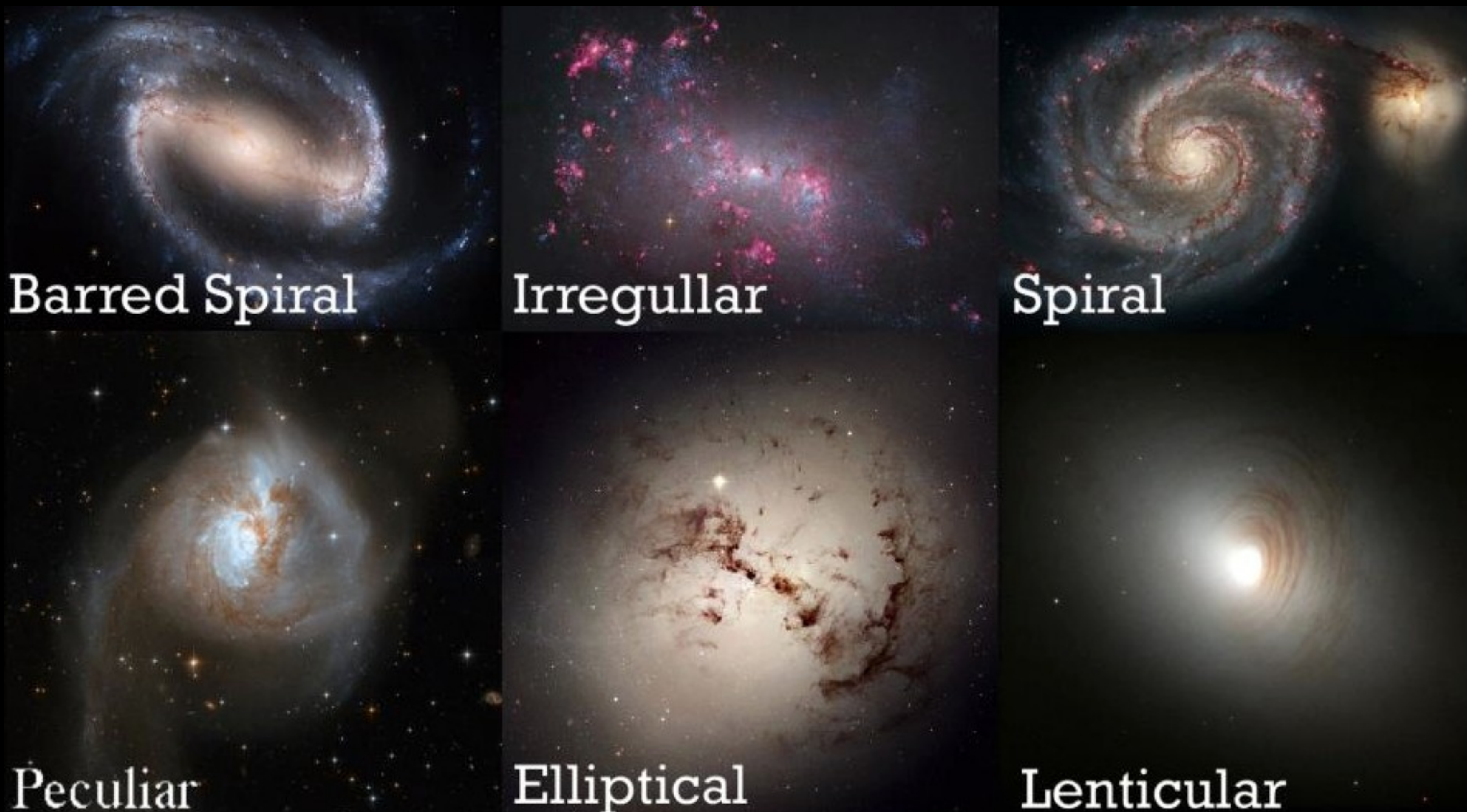


Fig. 15.6

SN tipo Ia: qualquer tipo de galáxias
SN tipo Ib, Ic: só em regiões de formação de estrelas em galáxias espirais → provavelmente relacionadas a estrelas de alta massa



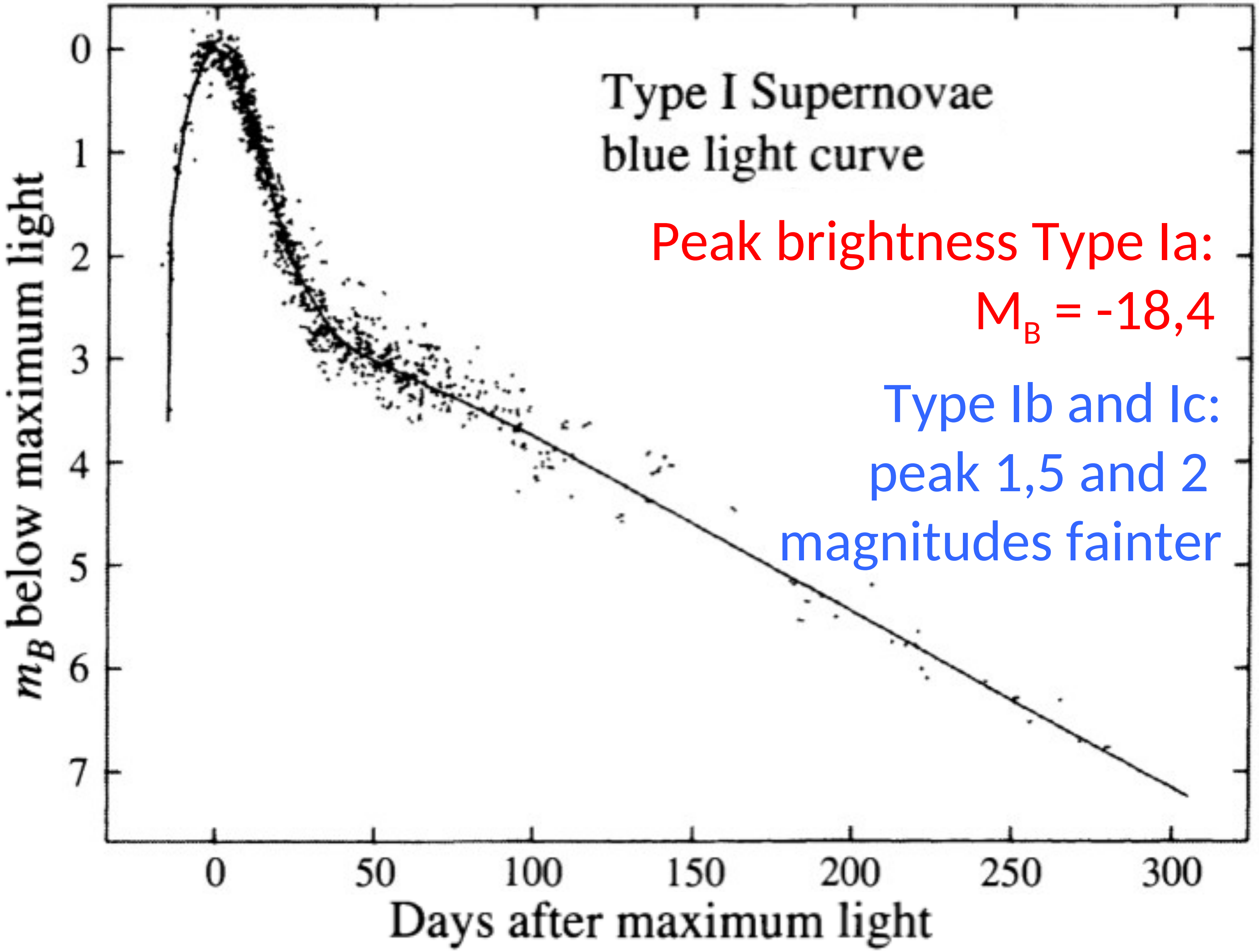
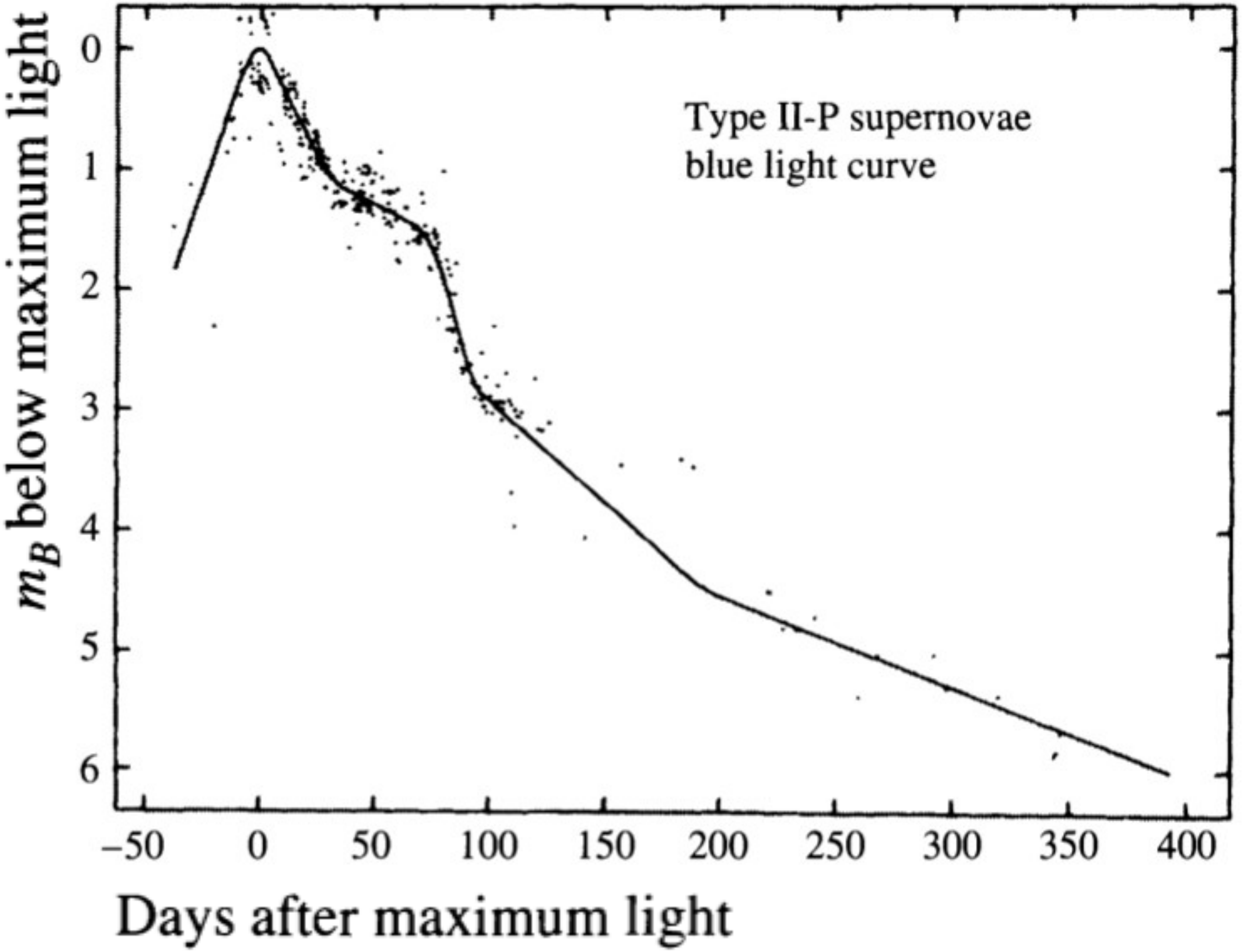
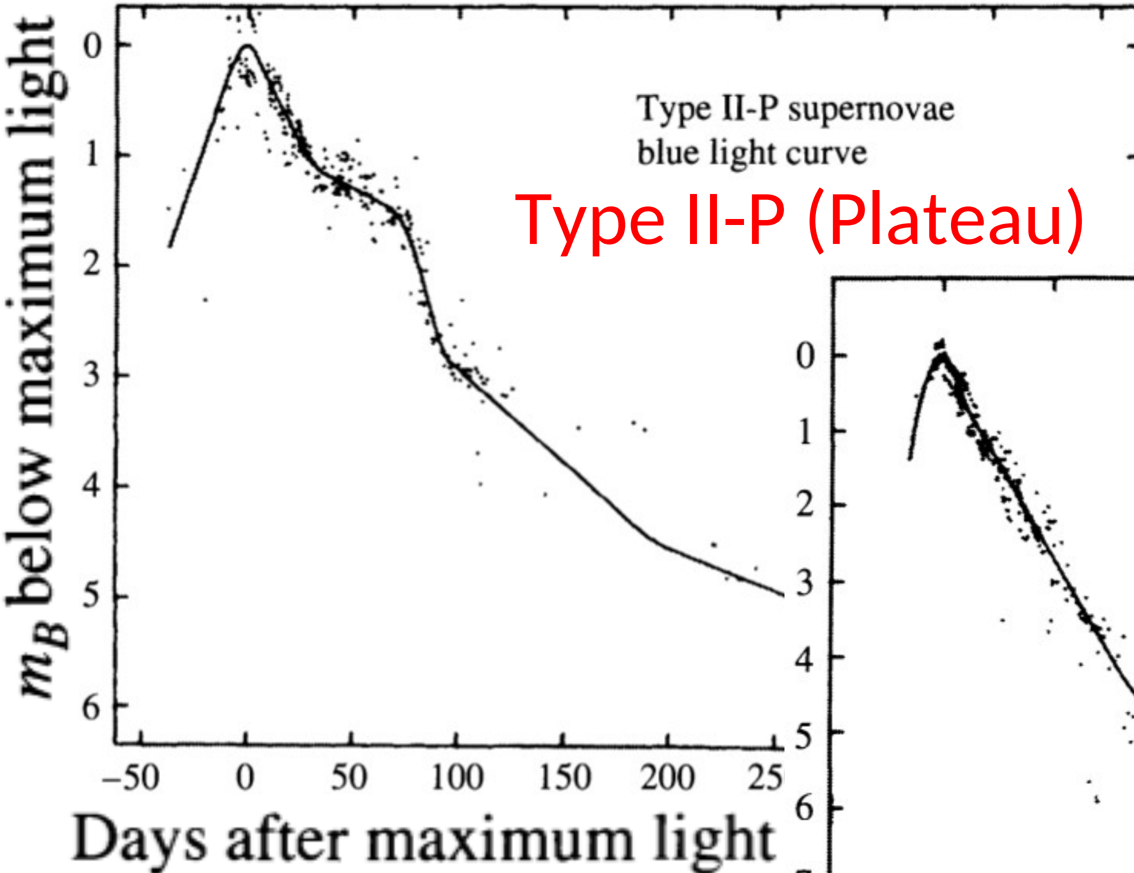


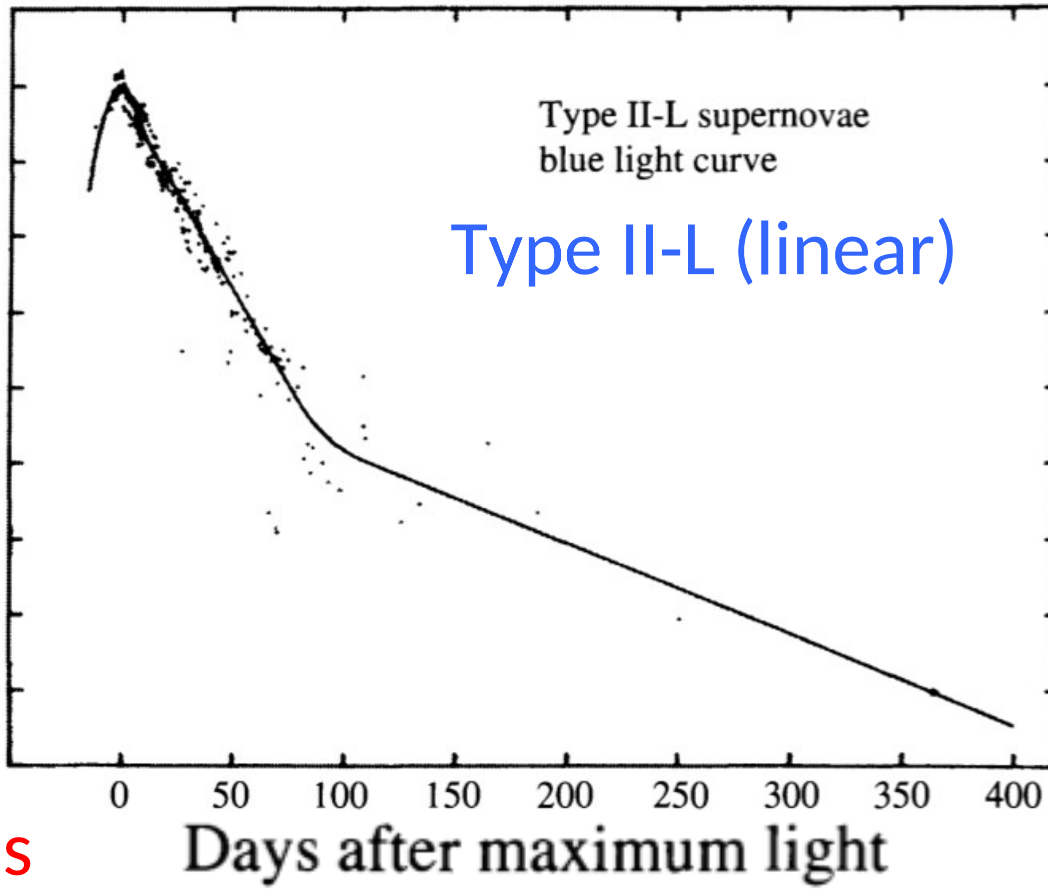
FIGURE 15.7 Composite light curve for Type I supernovae at blue wavelengths. All magnitudes are relative to m_B at maximum. (Figure adapted from Doggett and Branch, *Astron. J.*, *90*, 2303, 1985.)

Peak brightness Type II: 1,5 magnitudes fainter than Type Ia

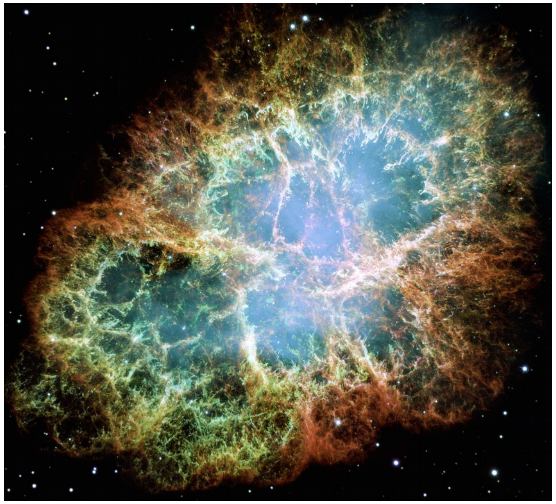


The Crab supernova (SN 1054) and SN 1987A were Type II's.





Type II-P (Plateau) occurs about 10 times as often as Type II-L (linear)



Supernova Classification Scheme (spectra at maximum light)

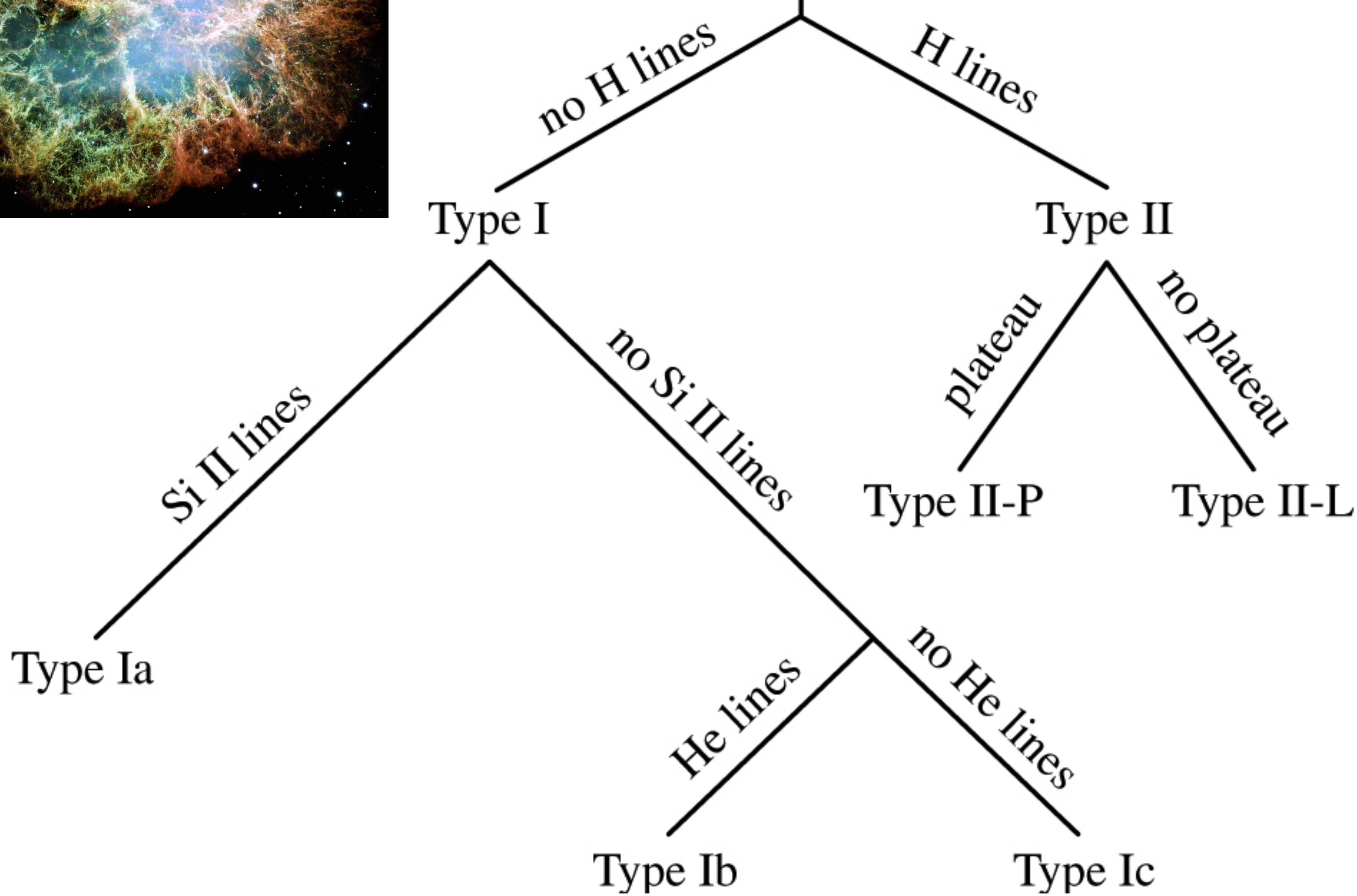
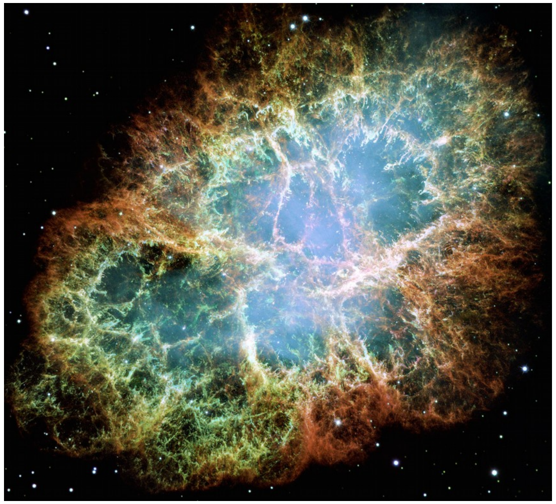
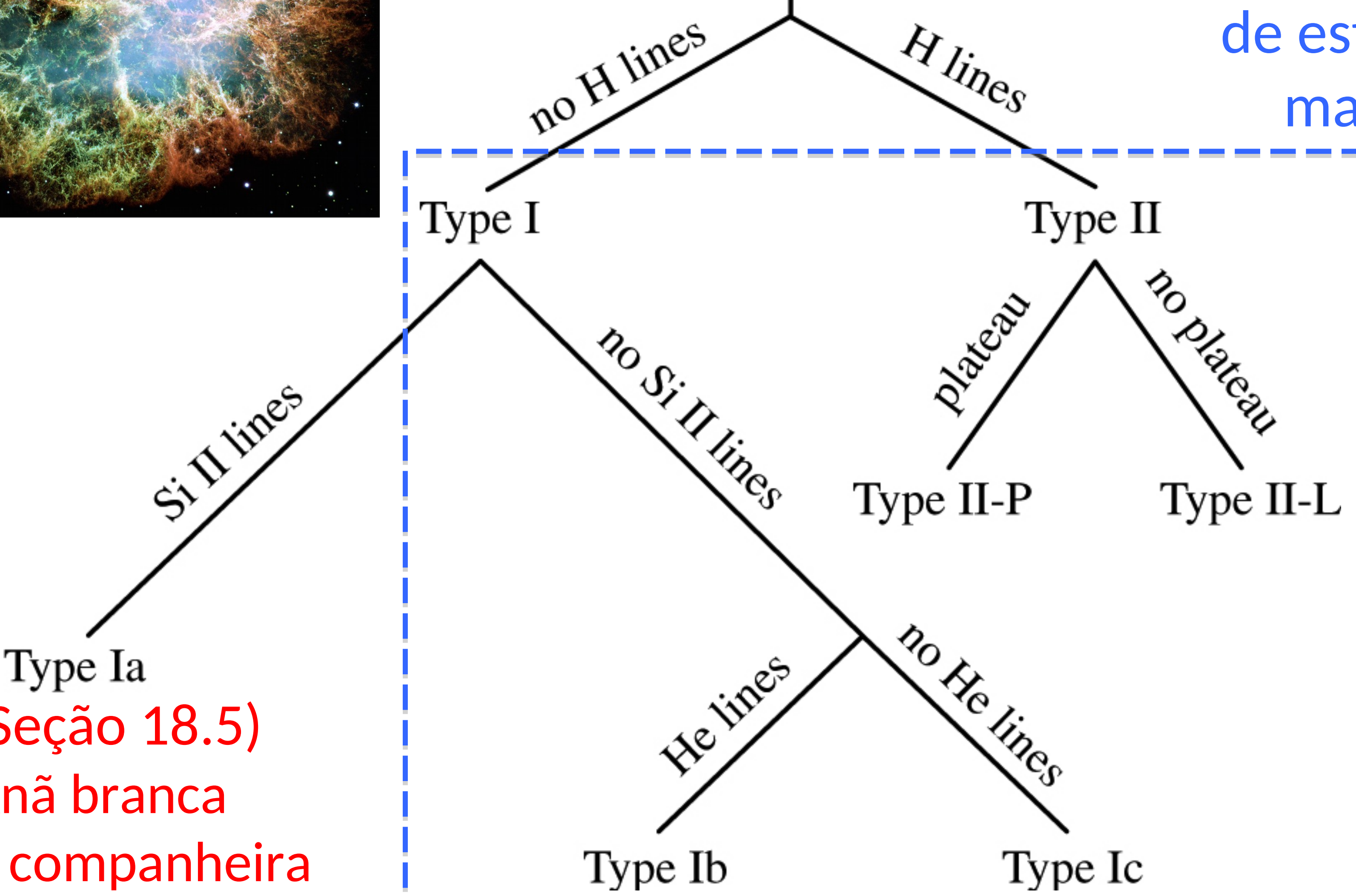


FIGURE 15.9 The classification of supernovae based on their spectra at maximum light and the existence or absence of a plateau in the Type II light curve.

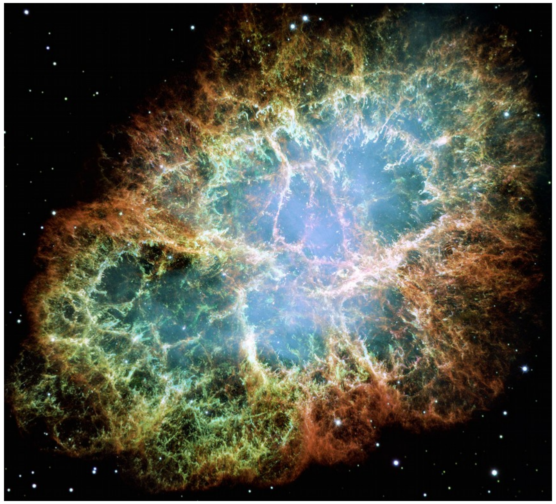


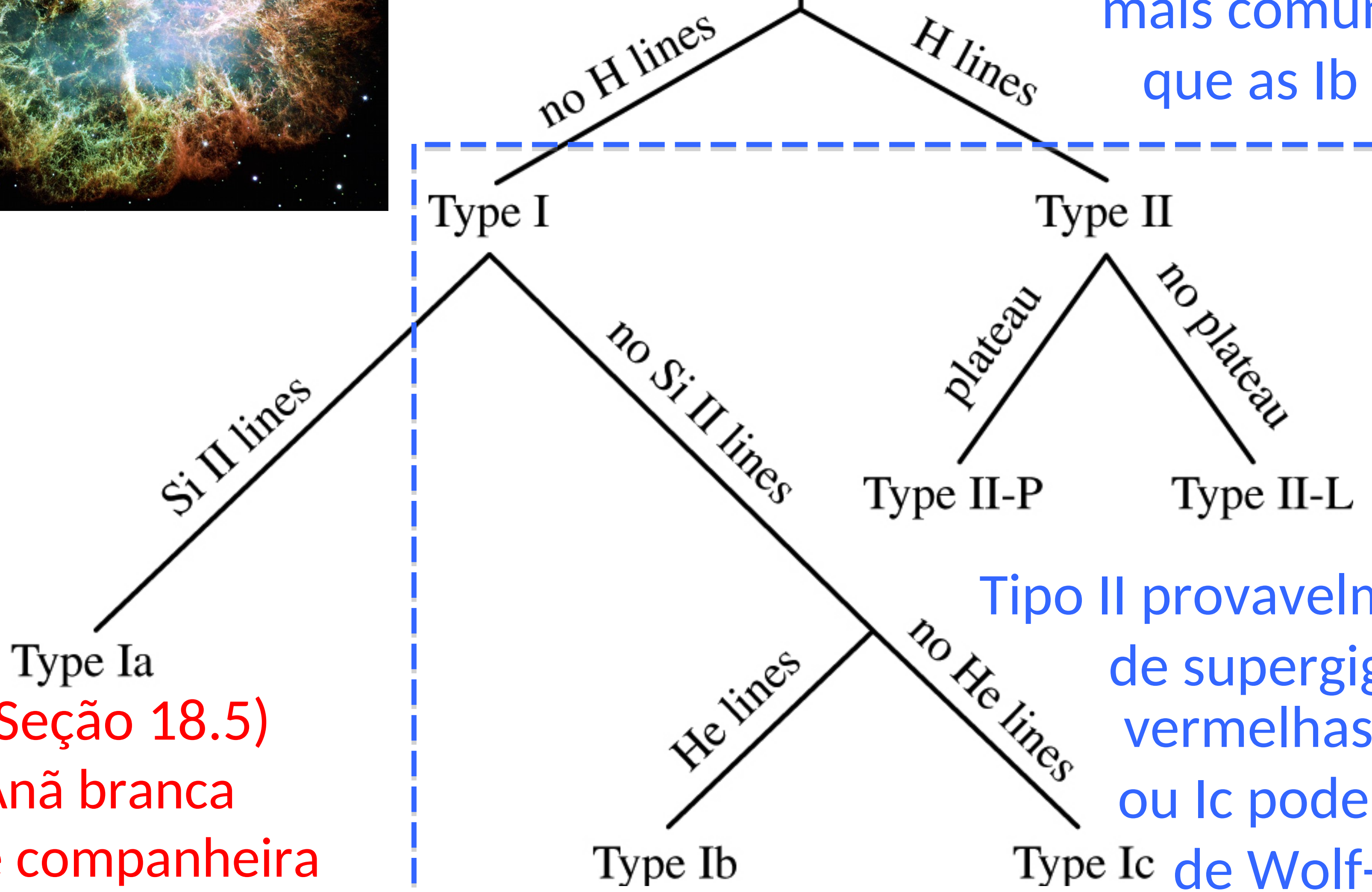


"*Core-collapse*": Colapso do núcleo de estrelas massivas

(Seção 18.5)
Anã branca
e companheira

FIGURE 15.9 The classification of supernovae based on their spectra at maximum light and the existence or absence of a plateau in the Type II light curve.





Core-Collapse. As Tipo II são mais comuns do que as Ib ou Ic.

(Seção 18.5) Anã branca e companheira

Tipo II provavelmente de supergigantes vermelhas, já Ib ou Ic podem ser de Wolf-Rayet

FIGURE 15.9 The classification of supernovae based on their spectra at maximum light and the existence or absence of a plateau in the Type II light curve.

15.3 Supernovas de colapso do núcleo

Estrelas com massa inicial < 8 $M_\odot$:

H → He, He → C e O → Nebulosa Planetária

Estrelas com massa inicial > 8 $M_\odot$:

Supernova: tipo II, Ib, Ic

SN tipo II libera 10^{46} J de energia:

- 1% energia cinética do material ejetado
- 0,01% fótons
- resto: neutrinos

Mário Schenberg (Schönberg)

Neutrino Theory of Stellar Collapse

G. Gamow and M. Schoenberg

Phys. Rev. **59**, 539 – Published 1 April 1941

Após queima de He → Queima de C e O

T ~ 10^8 K

$$^{12}_{6}C + ^{4}_{2}He \rightarrow ^{16}_{8}O + \gamma$$

$$^{16}_{8}O + ^{4}_{2}He \rightarrow ^{20}_{10}Ne + \gamma$$

T ~ $6x10^8$ K

$$^{12}_{6}C + ^{12}_{6}C \rightarrow \begin{cases} ^{16}_{8}O + 2\,^{4}_{2}He \quad *** \\ ^{20}_{10}Ne + ^{4}_{2}He \\ ^{23}_{11}Na + p^{+} \\ ^{23}_{12}Mg + n \quad *** \\ ^{24}_{12}Mg + \gamma \end{cases}$$

T ~ 10^9 K

$$^{16}_{8}O + ^{16}_{8}O \rightarrow \begin{cases} ^{24}_{12}Mg + 2\,^{4}_{2}He \quad *** \\ ^{28}_{14}Si + ^{4}_{2}He \\ ^{31}_{15}P + p^{+} \\ ^{31}_{16}S + n \\ ^{32}_{16}S + \gamma \end{cases}$$

***: endotérmica

Silicon burning

T ~ $3x10^9$ K

$$^{28}_{14}\mathrm{Si} + ^{4}_{2}\mathrm{He} \rightleftharpoons ^{32}_{16}\mathrm{S} + \gamma$$

$$^{32}_{16}\mathrm{S} + ^{4}_{2}\mathrm{He} \rightleftharpoons ^{36}_{18}\mathrm{Ar} + \gamma$$

$$\vdots$$

$$^{52}_{24}\mathrm{Cr} + ^{4}_{2}\mathrm{He} \rightleftharpoons ^{56}_{28}\mathrm{Ni} + \gamma$$

Reações acima do pico do ferro são endotérmicas →é necessária energia

$$^{28}_{14}\mathrm{Si} + ^{4}_{2}\mathrm{He} \rightarrow ^{32}_{16}\mathrm{S}$$

$$^{32}_{16}\mathrm{S} + ^{4}_{2}\mathrm{He} \rightarrow ^{36}_{18}\mathrm{Ar}$$

$$^{36}_{18}\mathrm{Ar} + ^{4}_{2}\mathrm{He} \rightarrow ^{40}_{20}\mathrm{Ca}$$

$$^{40}_{20}\mathrm{Ca} + ^{4}_{2}\mathrm{He} \rightarrow ^{44}_{22}\mathrm{Ti}$$

$$^{44}_{22}\mathrm{Ti} + ^{4}_{2}\mathrm{He} \rightarrow ^{48}_{24}\mathrm{Cr}$$

$$^{48}_{24}\mathrm{Cr} + ^{4}_{2}\mathrm{He} \rightarrow ^{52}_{26}\mathrm{Fe}$$

$$^{52}_{26}\mathrm{Fe} + ^{4}_{2}\mathrm{He} \rightarrow ^{56}_{28}\mathrm{Ni}$$

$$^{56}_{28}\mathrm{Ni} + ^{4}_{2}\mathrm{He} \rightarrow ^{60}_{30}\mathrm{Zn}$$

Para estrela 20 $M_{\odot}$

- queima de H: 10^7 anos
- queima de He: 10^6 anos
- queima de C: 300 anos
- queima de O: 200 dias
- queima de Si: 2 dias

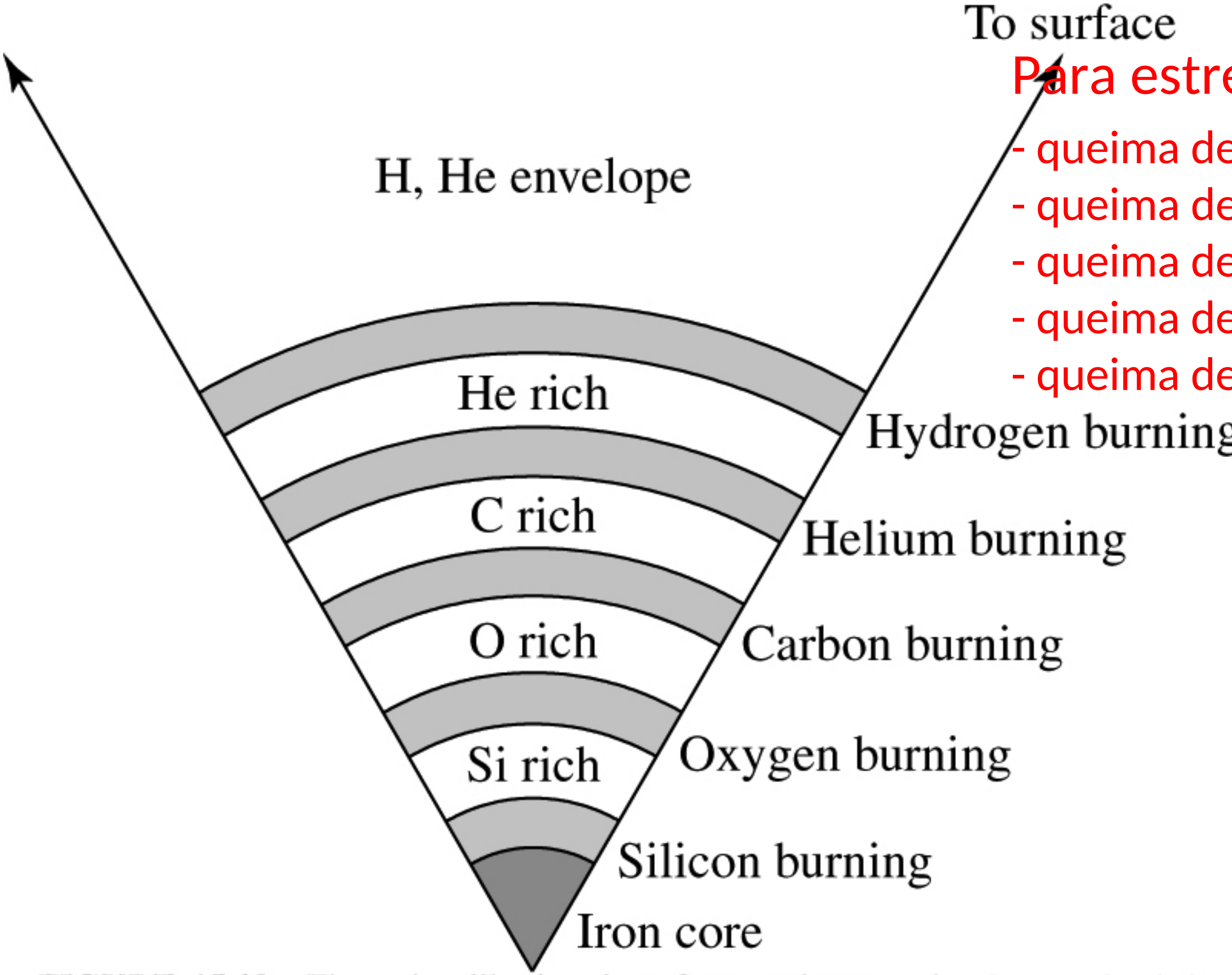
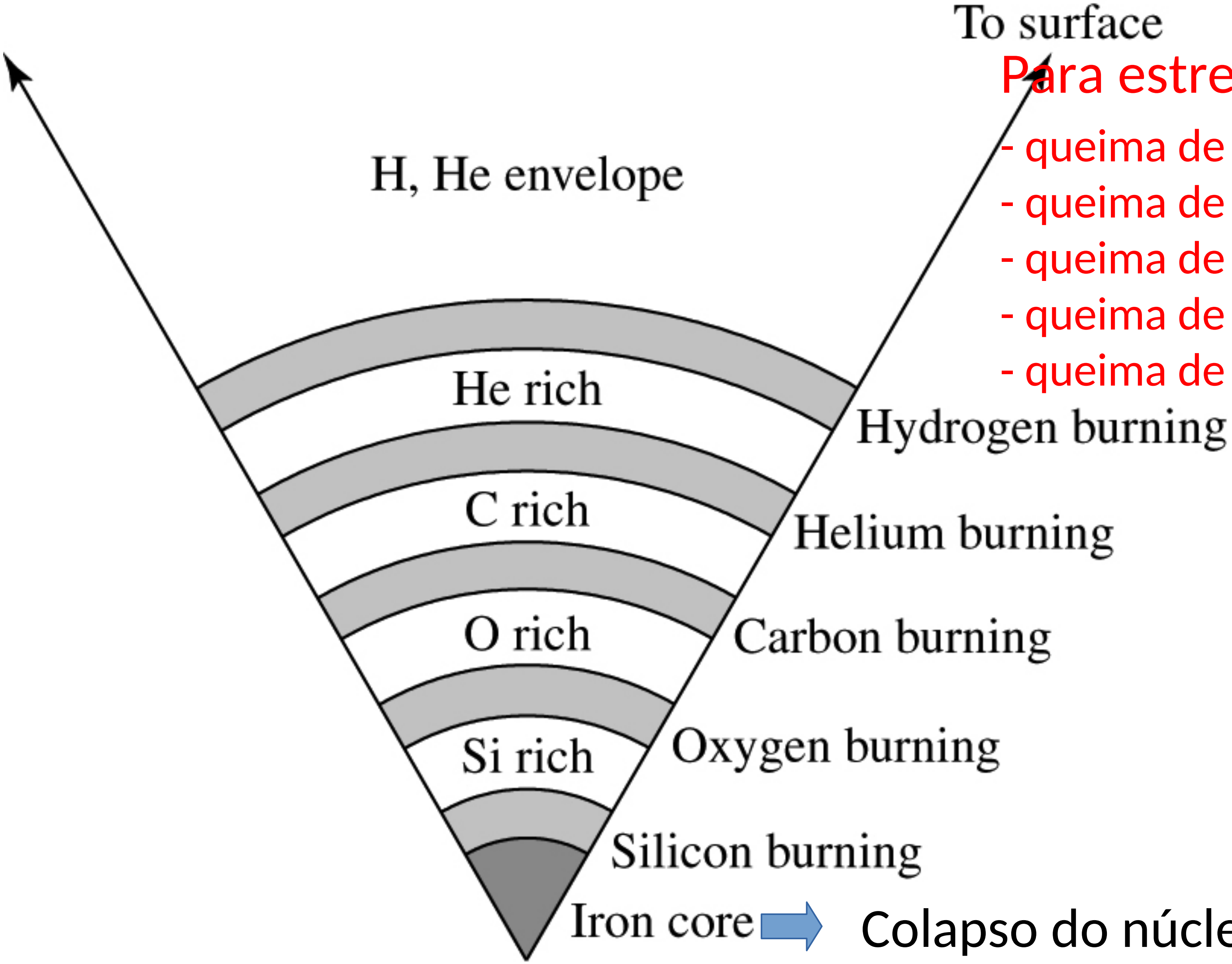


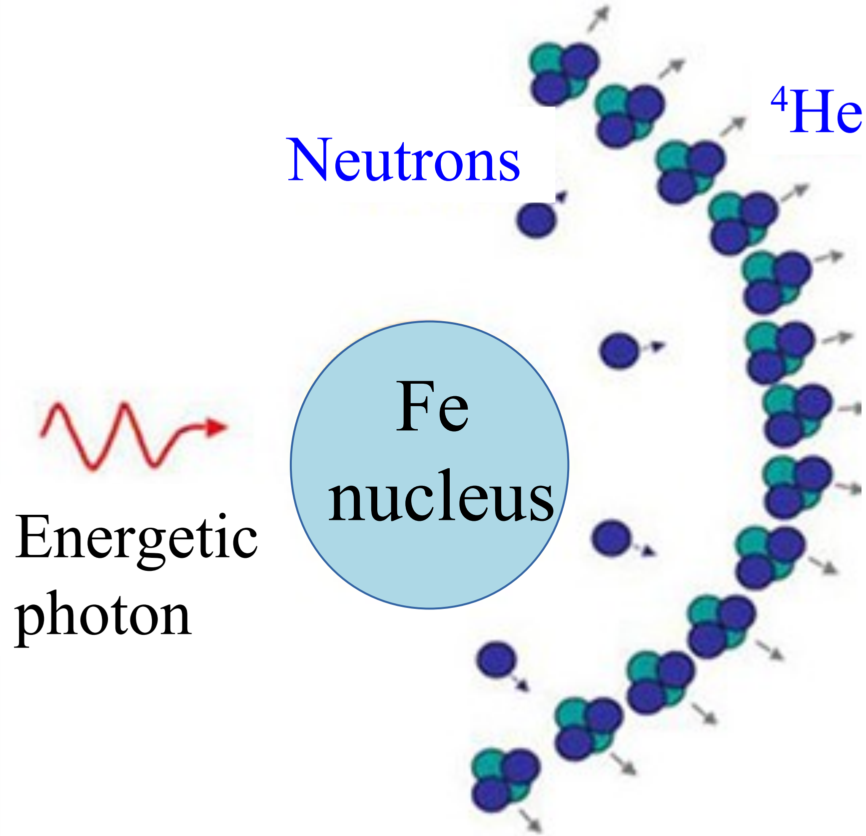
FIGURE 15.10 The onion-like interior of a massive star that has evolved through core silicon burning. Inert regions of processed material are sandwiched between the nuclear burning shells. The inert regions exist because the temperature and density are not sufficient to cause nuclear reactions to occur with that composition. (This drawing is not to scale.)

Para estrela 20 $M_{\odot}$

- queima de H: 10^7 anos
- queima de He: 10^6 anos
- queima de C: 300 anos
- queima de O: 200 dias
- queima de Si: 2 dias



Colapso do núcleo, aumento da ρ e T (~10^{10} K)



Temperatura muito alta ($\sim 10^{10}$K) do núcleo em colapso → fotodesintegração

$$^{56}_{26}Fe + \gamma \rightarrow 13\ ^{4}_{2}He + 4n$$

$$^{4}_{2}He + \gamma \rightarrow 2p^{+} + 2n$$

Para estrela de 10 $M_{\odot}$ → núcleo de ferro ~ 1,3 $M_{\odot}$

Para estrela de 50 $M_{\odot}$ → núcleo de ferro ~ 2,5 $M_{\odot}$

Condições extremas no núcleo após fotodesintegração. Para estrela de 15 $M_\odot$: T ~ 8×10^9 K, ρ ~ 10^{13} kg m^{-3}

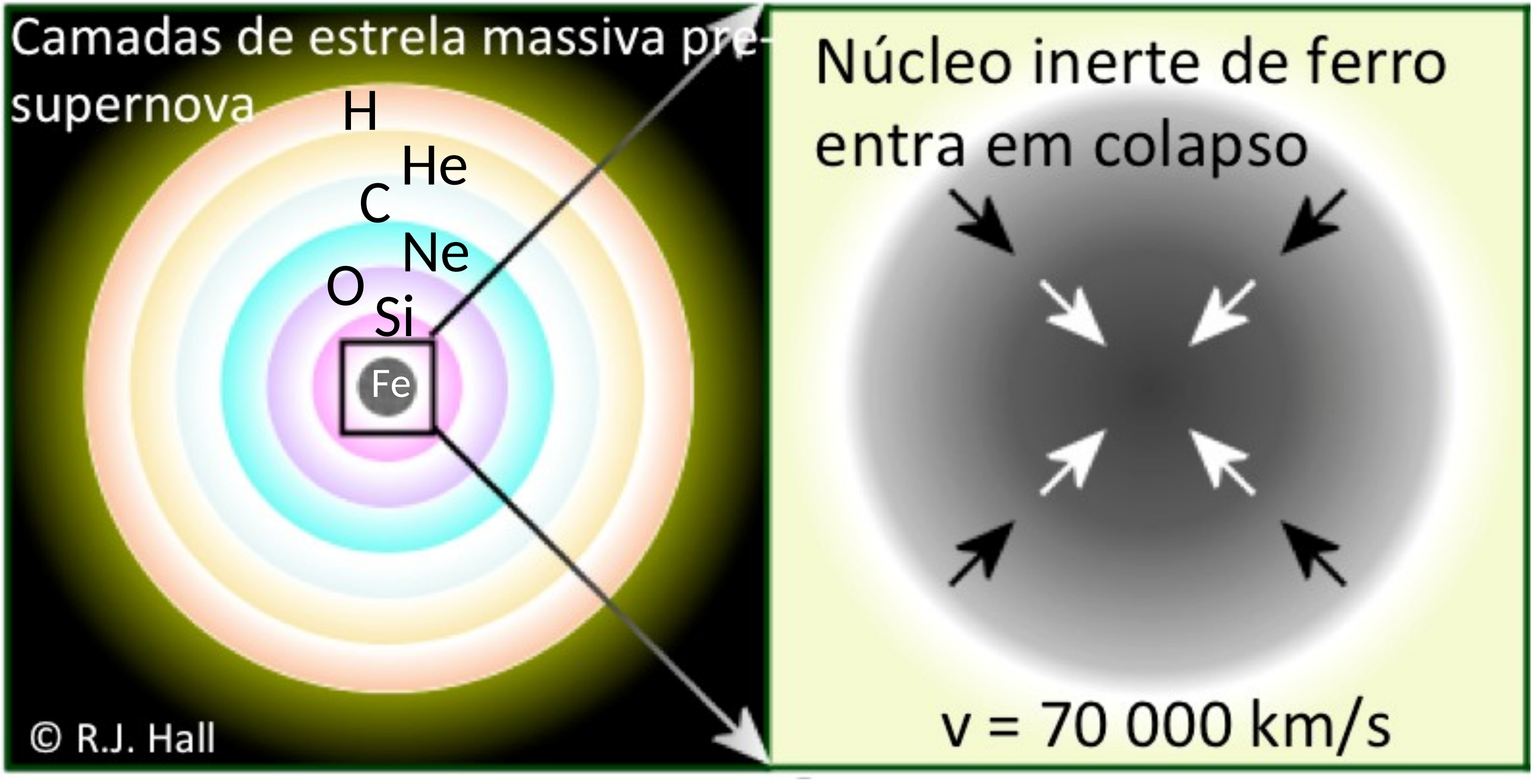
Elétrons livres são capturados pelos núcleos que foram produzidos na fotodesintegração. Por exemplo:

$$p^+ + e^- \rightarrow n + \nu_e$$

Muita energia escapa da estrela em forma de neutrinos. Para estrela de 20 $M_\odot$ na queima de Si $L_{fótons} = 4 \times 10^{31}$W. Já a $L_\nu = 3 \times 10^{38}$W

Núcleo da estrela fica sem suporte pois fótons são usados para fotodesintegração. Também, pressão de degenerescência de *e*- diminui devido à sua captura.

Em apenas 1 segundo, núcleo de aprox. o raio da Terra colapsa para um raio ~ 50 km



Example 15.3.2. If a mass with the radius of Earth ($R_\oplus$) collapses to a radius of only 50 km, a tremendous amount of gravitational potential energy would be released. Can this energy release be responsible for the energy of a core-collapse supernova?

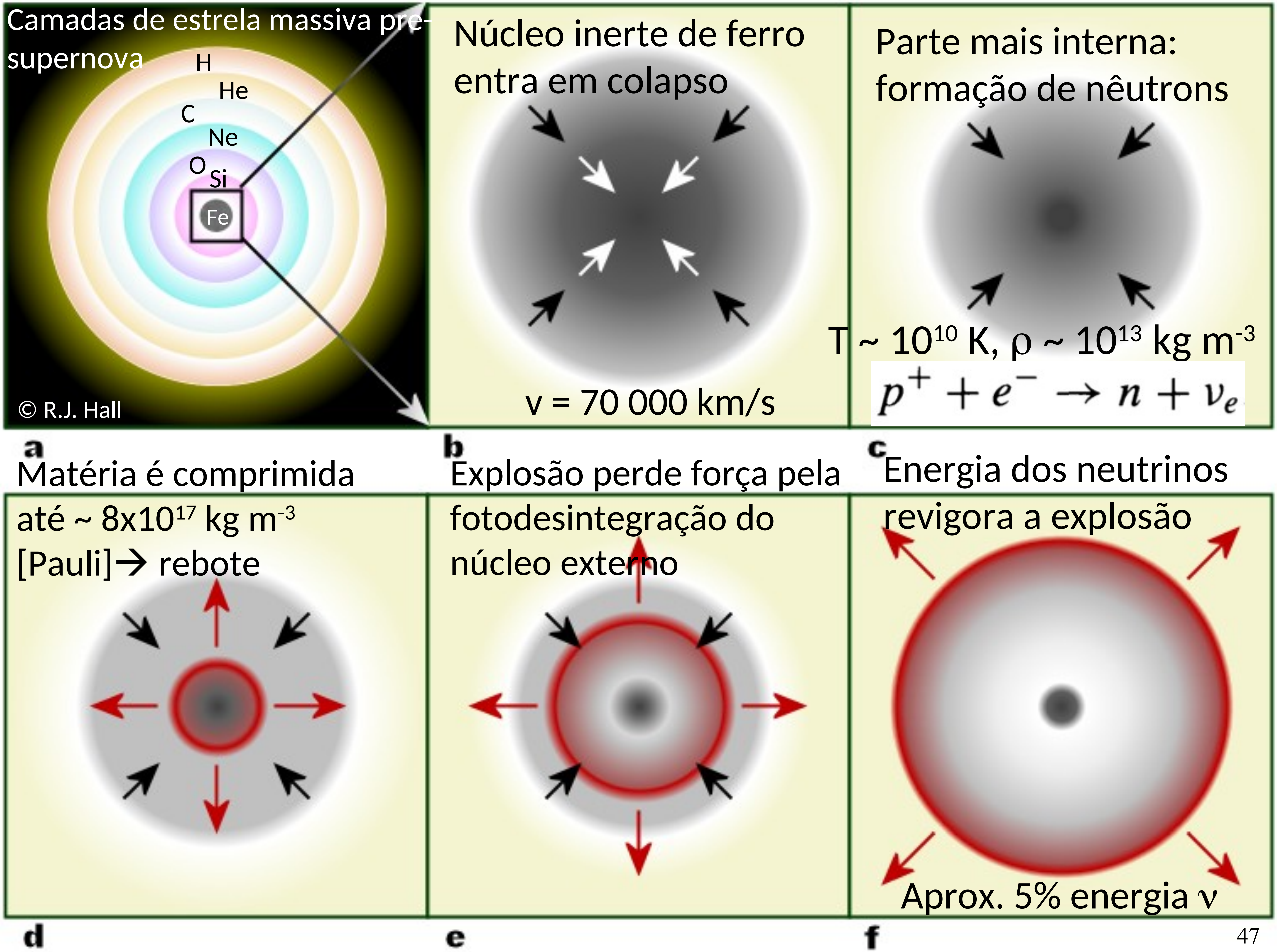
Assume for simplicity that we can use Newtonian physics to estimate the amount of energy released during the collapse. From the virial theorem (see Eq. 10.23), the energy released in the formation of a spherically symmetric star of constant density is

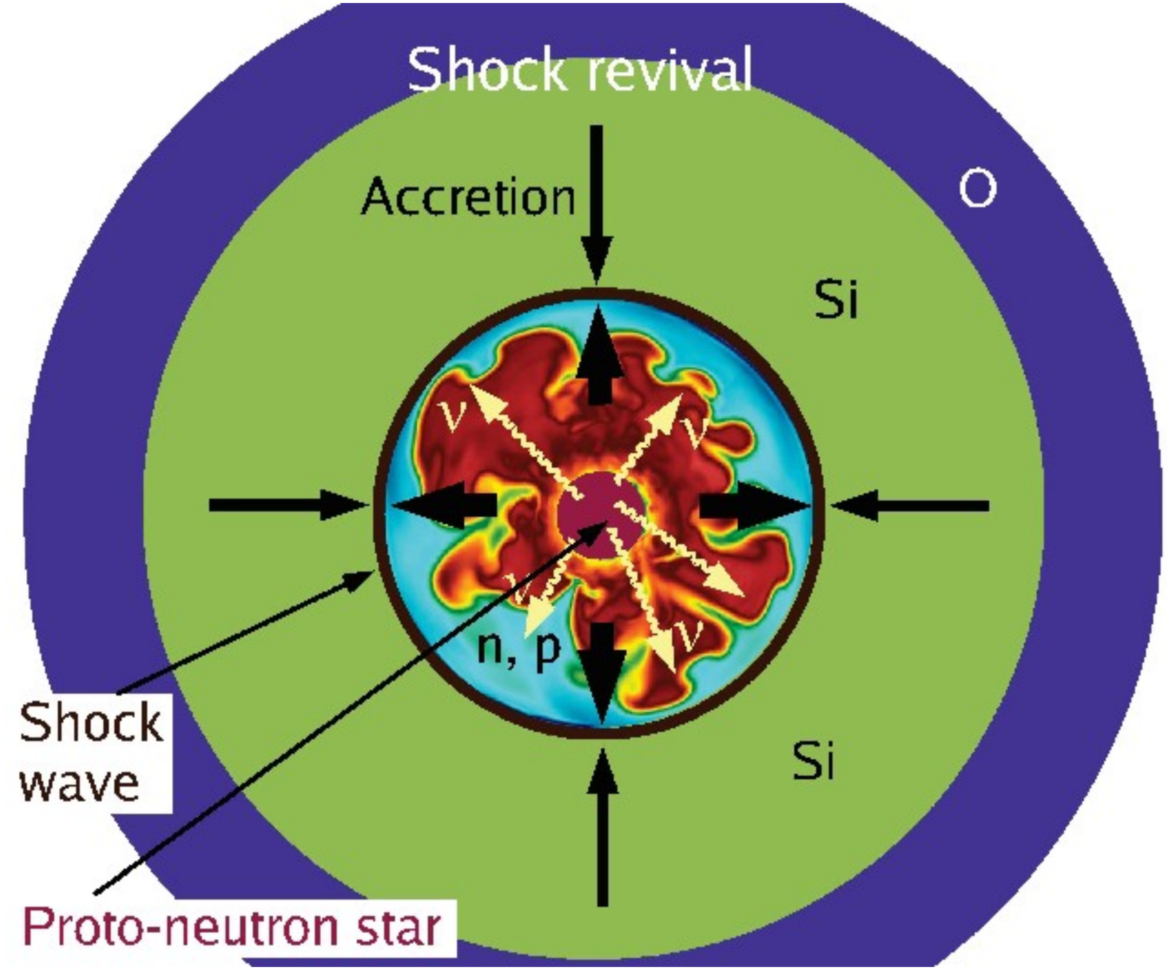
$$E \sim -\frac{3}{10}\frac{GM^2}{R}.$$

Equating the energy of a Type II supernova, $E_{\mathrm{II}} = 10^{46}$ J, to the gravitational energy released during the collapse, and given that $R_f = 50 \text{ km} \ll R_\oplus$, the amount of mass required to produce the supernova would be

$$M \simeq \sqrt{\frac{10}{3}\frac{E_{\mathrm{II}} R_f}{G}} \simeq 5 \times 10^{30}\ \text{kg} \simeq 2.5\ \mathrm{M}_\odot.$$

This value is characteristic of the core masses mentioned earlier.


Camadas de estrela massiva pre-supernova
H
He
C
Ne
O
Si
Fe
© R.J. Hall
a
Núcleo inerte de ferro entra em colapso
v = 70 000 km/s
b
Parte mais interna: formação de nêutrons
$T \sim 10^{10}$ K, $\rho \sim 10^{13}$ kg m^{-3}
$p^+ + e^- \rightarrow n + \nu_e$
c
Matéria é comprimida até ~ 8x10^{17} kg m^{-3} [Pauli]→ rebote
d
Explosão perde força pela fotodesintegração do núcleo externo
e
Energia dos neutrinos revigora a explosão
Aprox. 5% energia ν
f

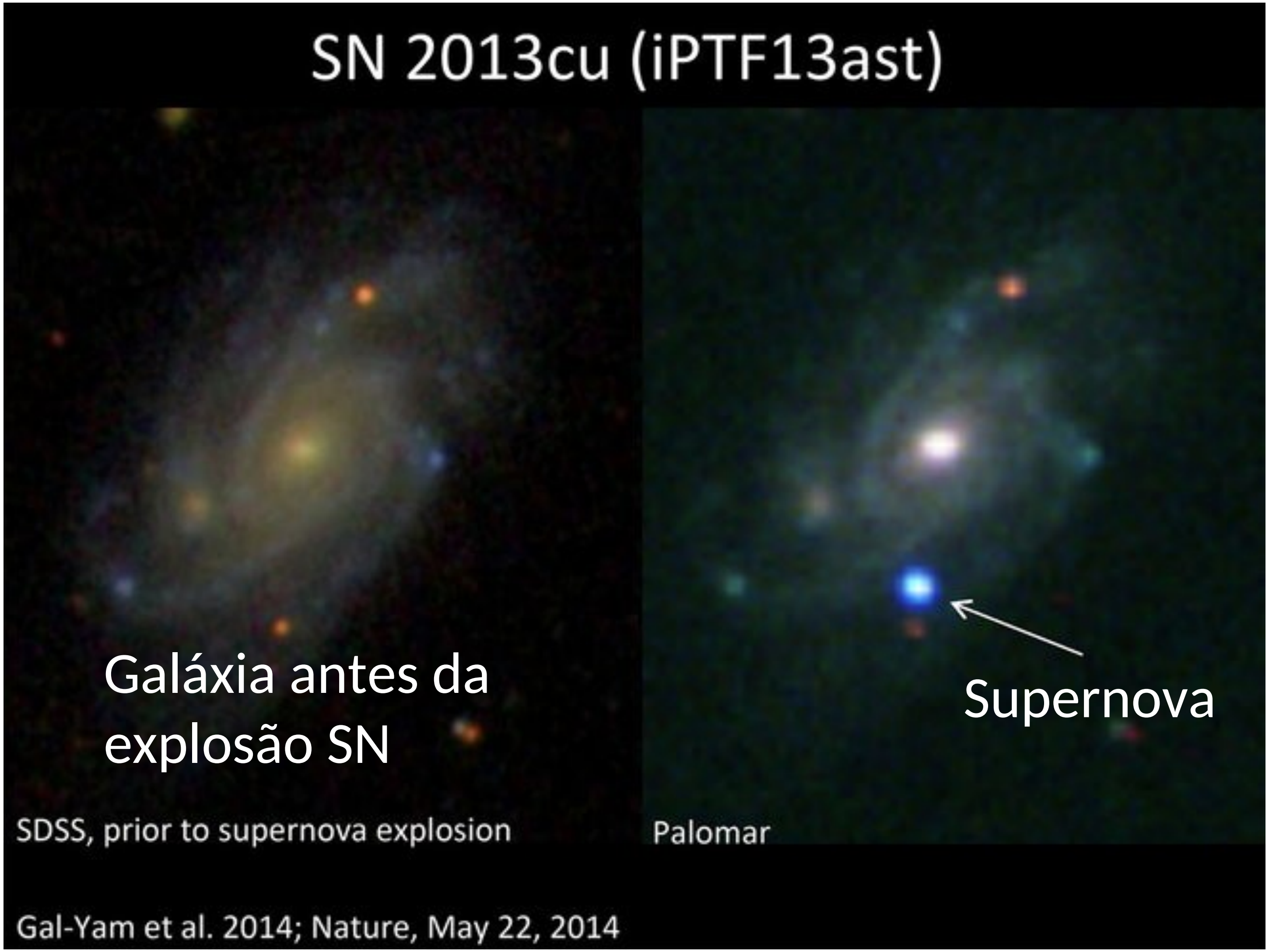


Energia cinética total do material em expansão ~ 10^{44} J (~1% da energia liberada por neutrinos).

Quando o material é oticamente fino (~100 AU) observamos a explosão no visível (~10^{42} J energia em fótons).

Luminosidade no pico ~ 10^{36} W (10^9 $L_\odot$)

A luminosidade no pico da supernova é ~$10^9 L_\odot$ (quase o brilho de uma galáxia!)



Stellar Remnants of a Core-Collapse Supernova

Neutron star or black hole?

$Massa_{inicial} < 25\ M_{\odot}$ → estrela de nêutrons

(suportada pela pressão de degenerescência de nêutrons)

$Massa_{inicial} > 25\ M_{\odot}$ → buraco negro

A massa final do núcleo para ser buraco negro é de no mínimo ~3 $M_{\odot}$ (Cap. 17).

Energia ν liberada na supernova ~ $3x10^{46}$ J (100 x mais energia do que o Sol produzira na sequência principal).

Evolução de estrelas massivas

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[Teoria e Observações, estrelas Be]

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