Cap. 15
Evolução de estrelas massivas

(até *Stellar Remnants of a Core-Collapse Supernova*)

AGA0293

Jorge Meléndez

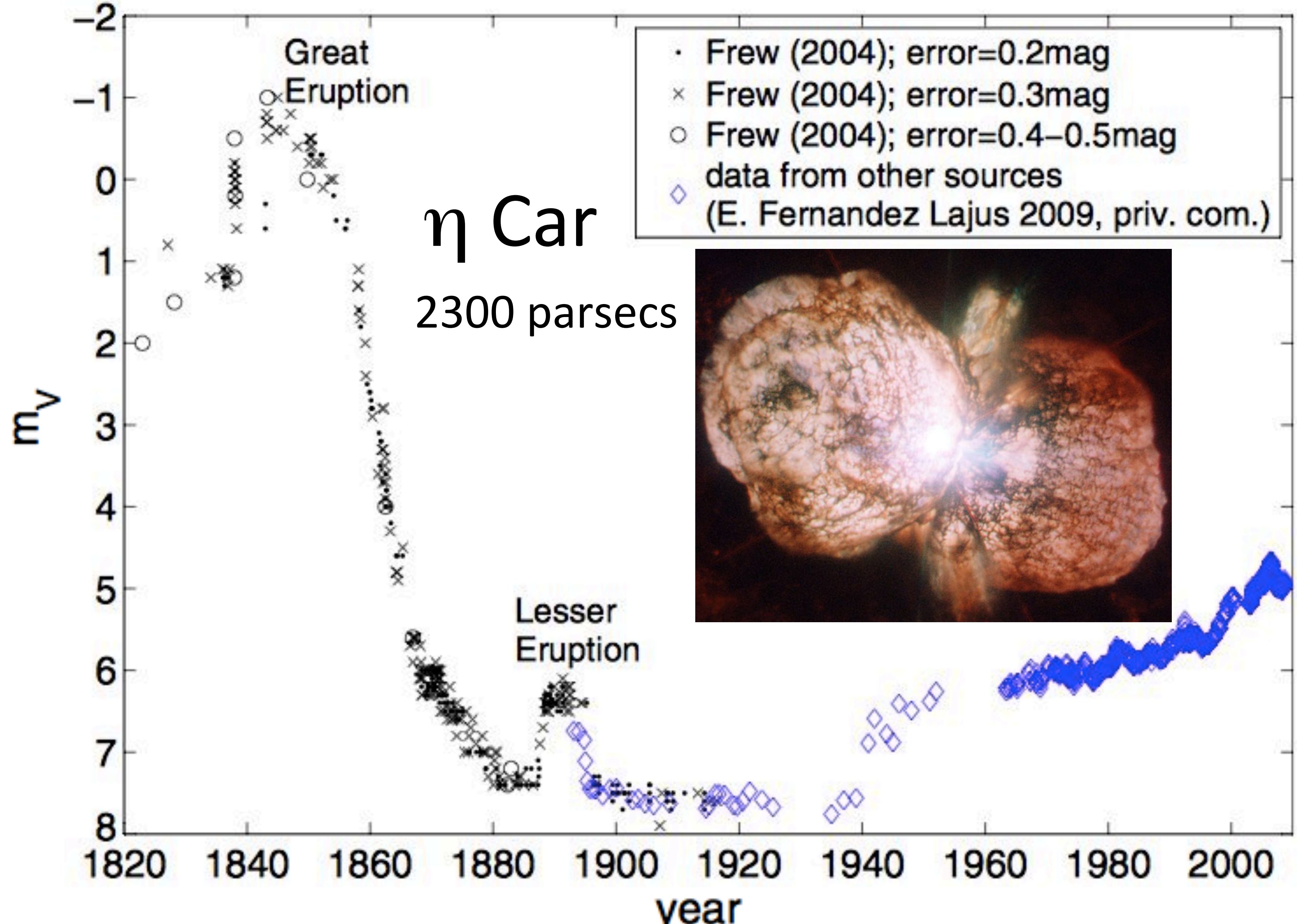
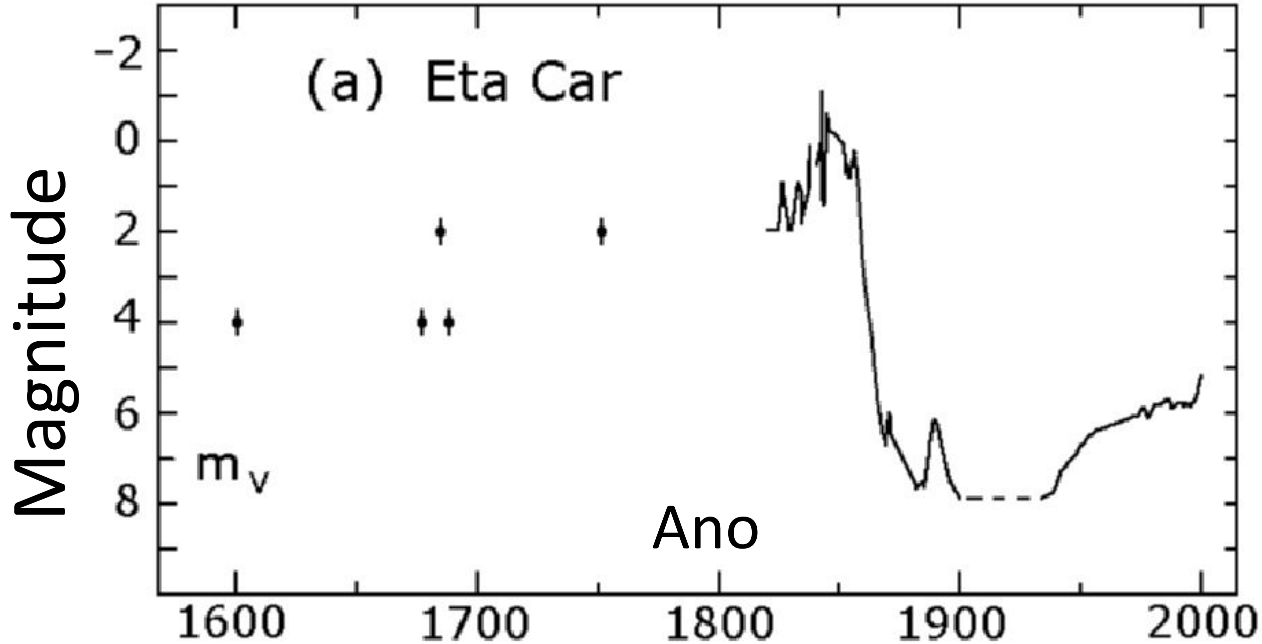
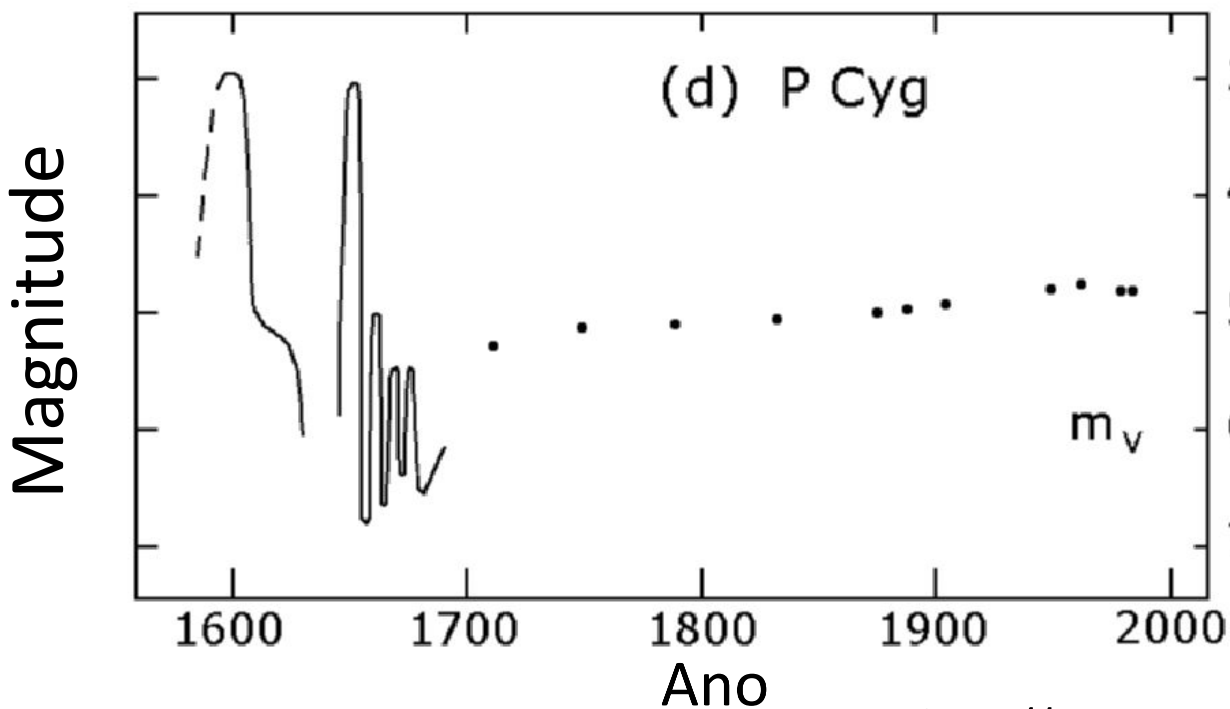


Figure 1. Historical *V* magnitude light curve

Kashi & Soker 2010 ApJ 723, 602



2300 parsecs

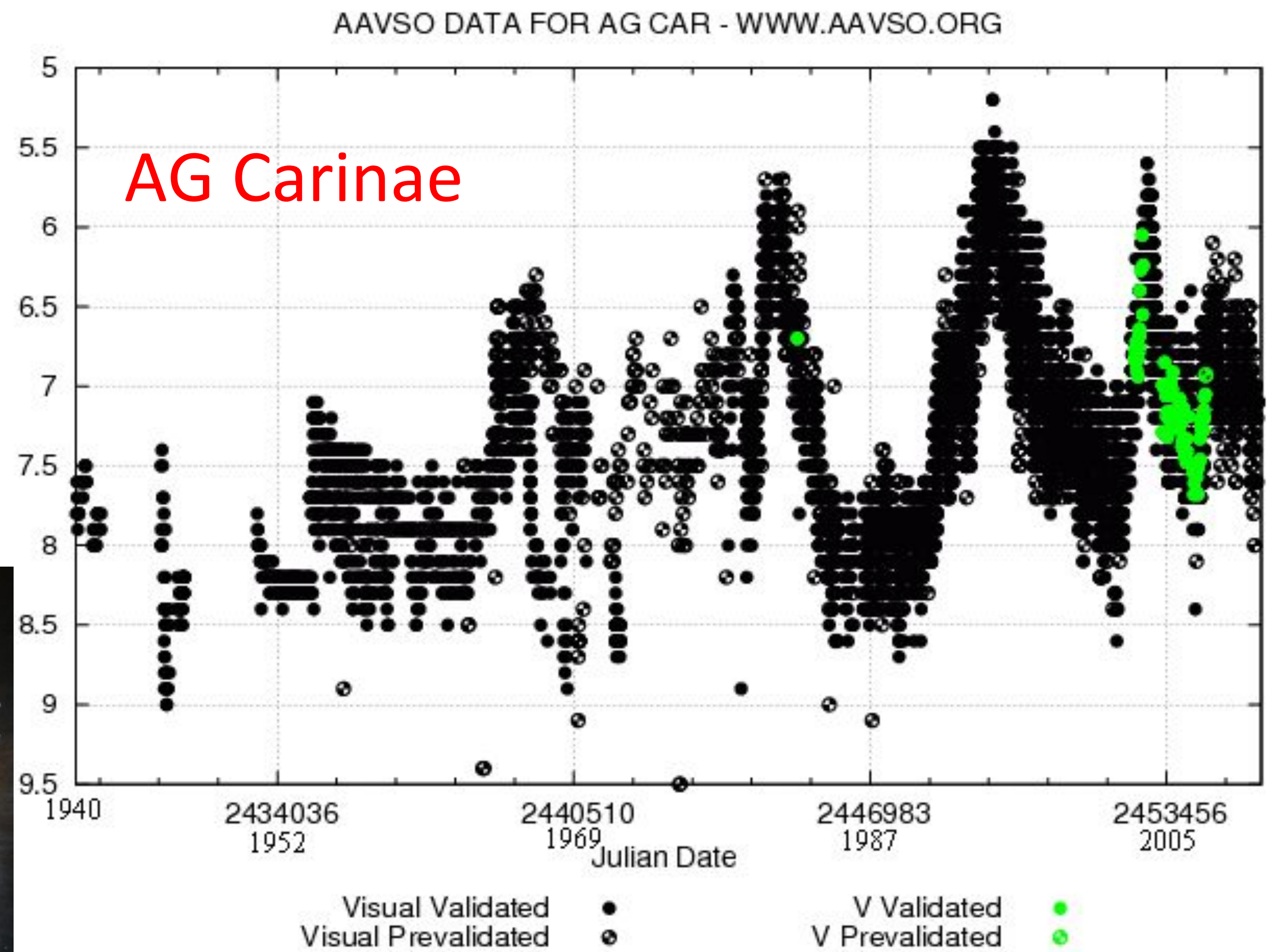


1700 parsecs

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

Existem outras estrelas massivas com variações, porem menores que em Eta Carinae e P-Cygni

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



AG Carinae © HST

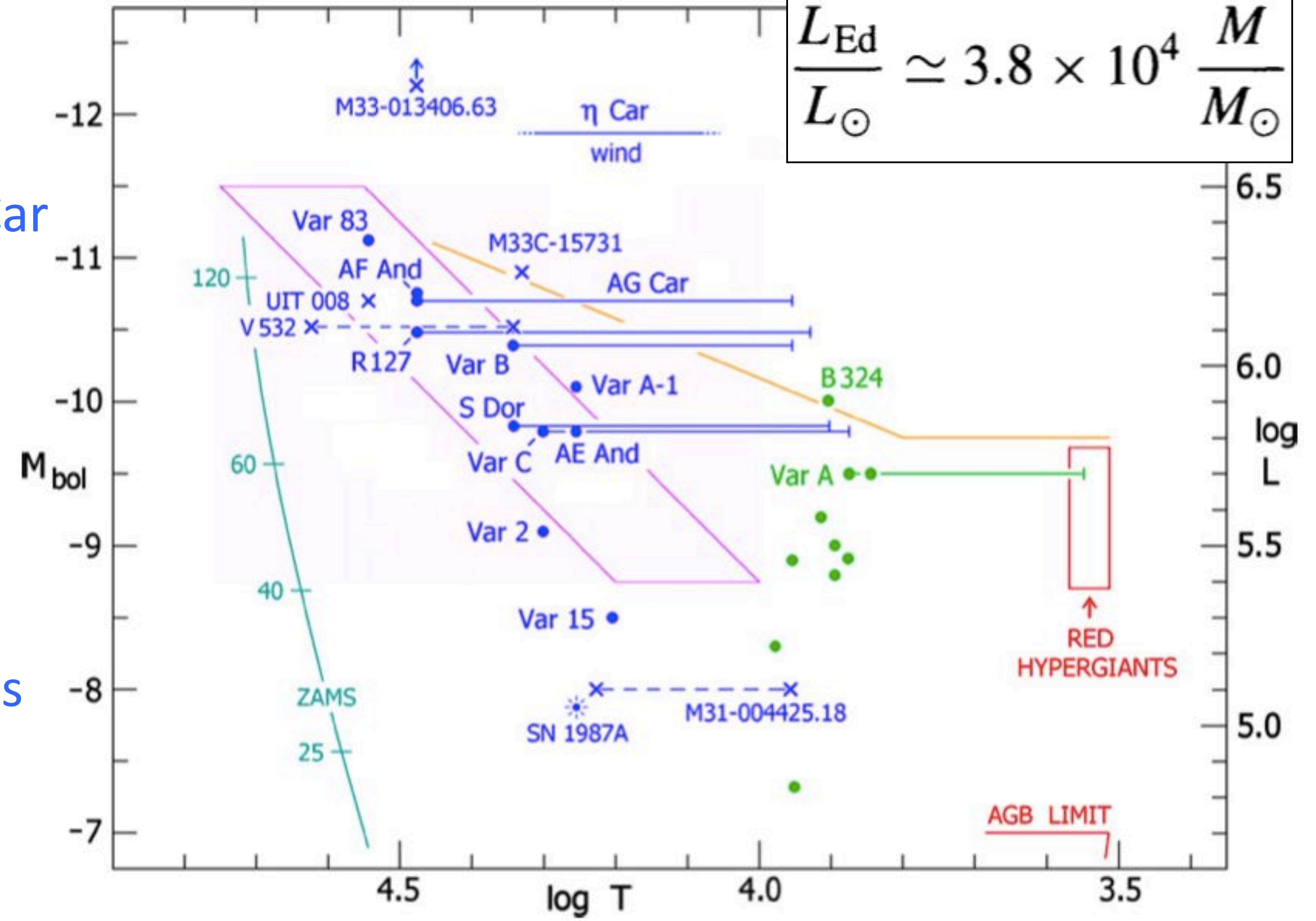
Luminous blue variables (LBVs)

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

Na Galáxia:
Eta Car, AG Car

Na LMC:
S Dor, R127

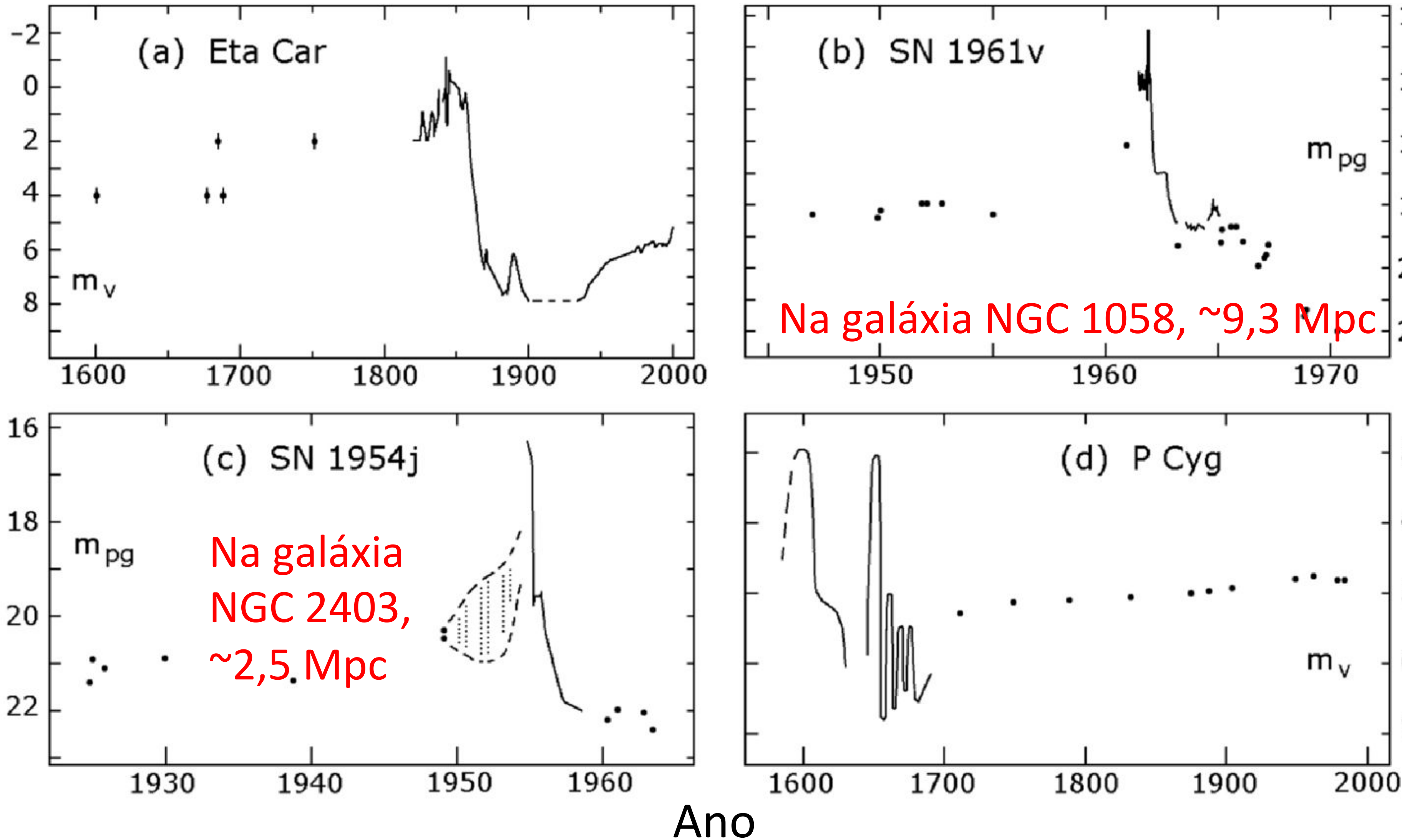
Nas galáxias M31 e M33: outros pontos em azul



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*



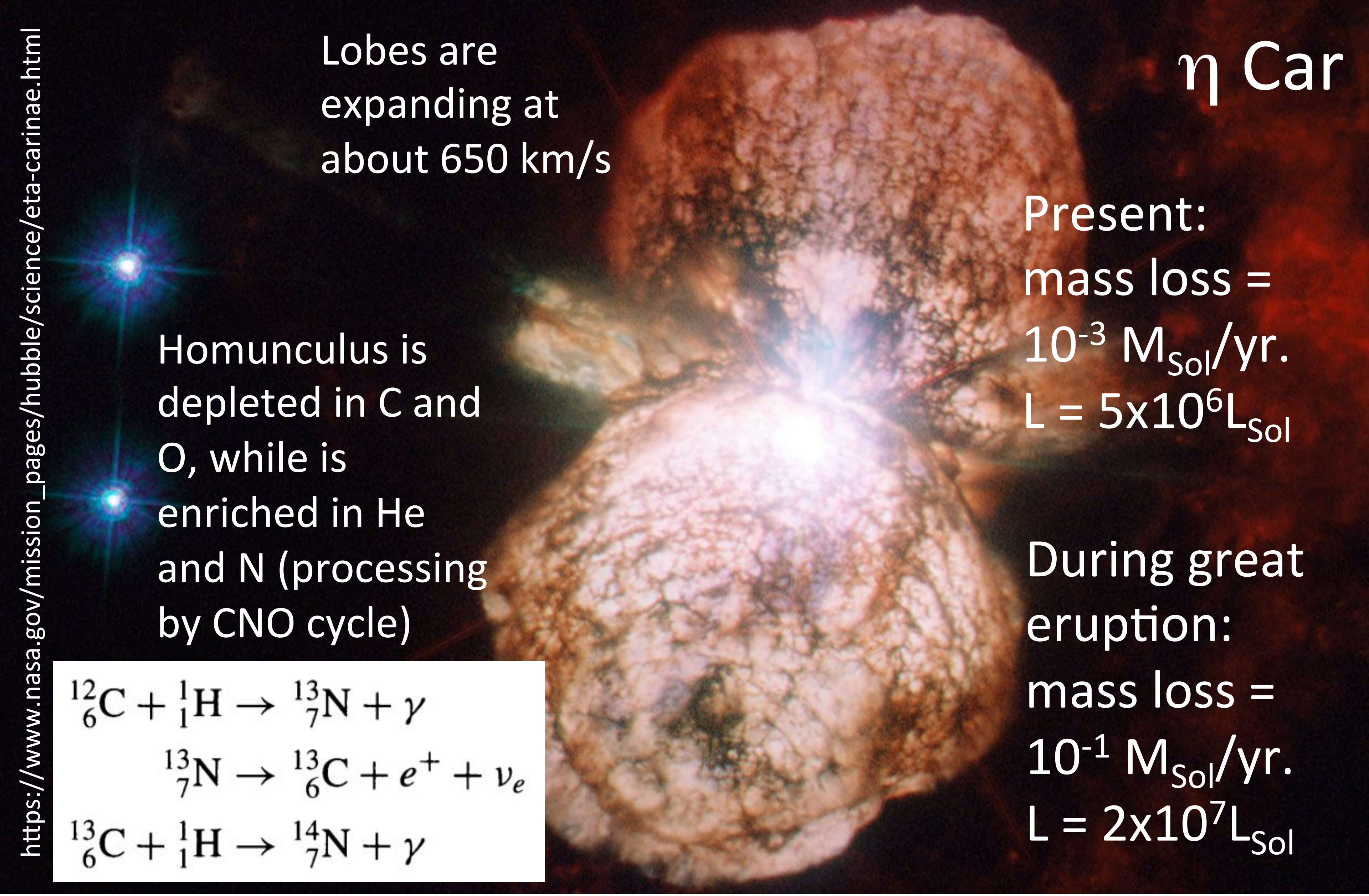


FIGURE 15.1 η Carinae is a luminous blue variable that is estimated to have a mass of 120 $M_\odot$ and is rapidly losing mass. Each lobe has a diameter of approximately 0.1 pc. [Courtesy of Jon Morse (University of Colorado) and NASA.]

Luminous blue variables (LBVs)

$T_e \sim 15\,000 - 30\,000$ K
$L \sim 10^6\ L_{Sol}$

Massas > 85 M_{Sol}

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

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

Instabilities?

Binarity in LBVs?

For η Car, 5,54 years periodicity, Prof. Augusto Damineli (IAG)

Luminous blue variables (LBVs)

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

Na Galáxia:
Eta Car, AG Car

Na LMC:
S Dor, R127

Nas galáxias M31 e M33: outros pontos em azul

Humphreys et al. 2014, ApJ 790, 48

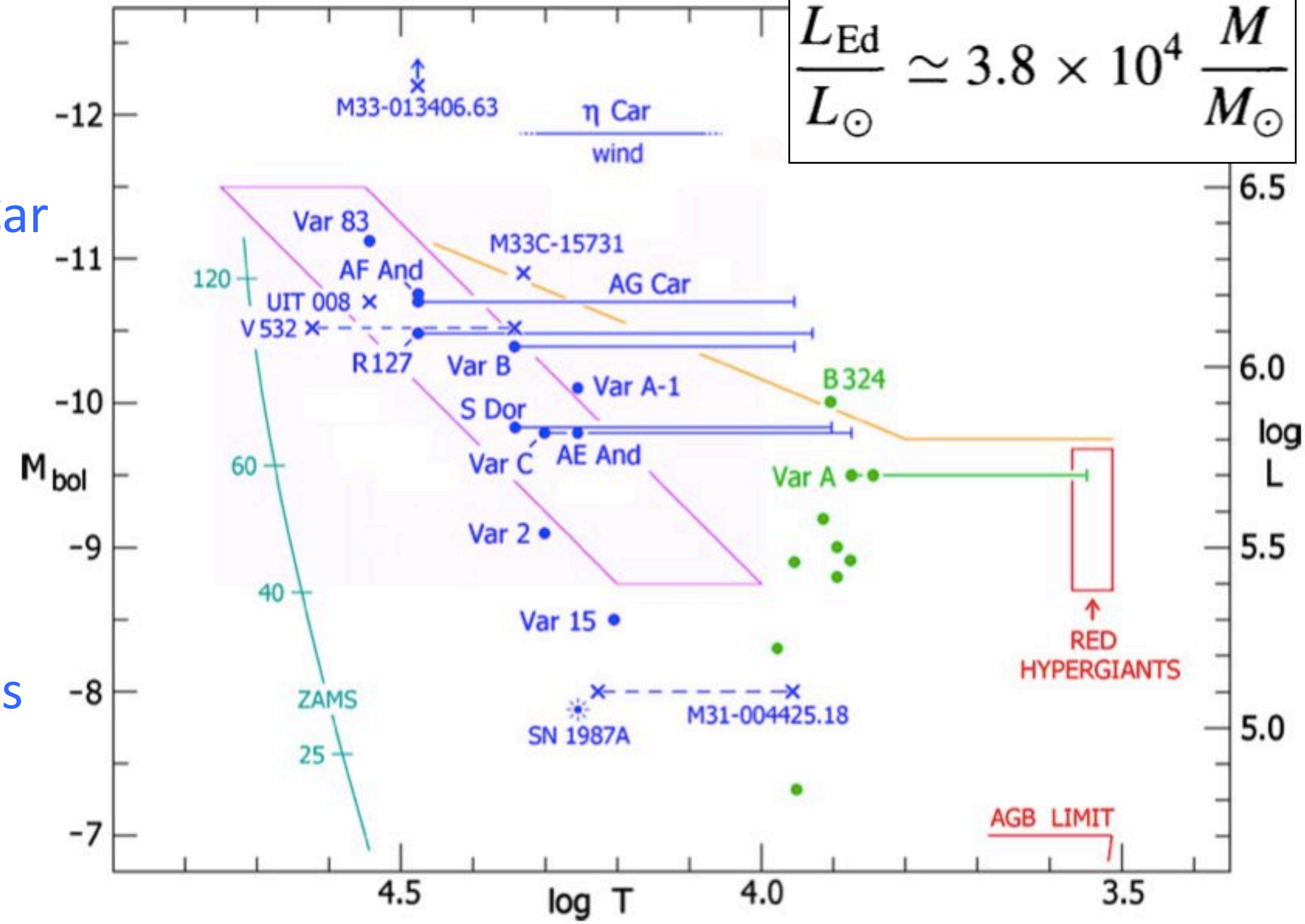
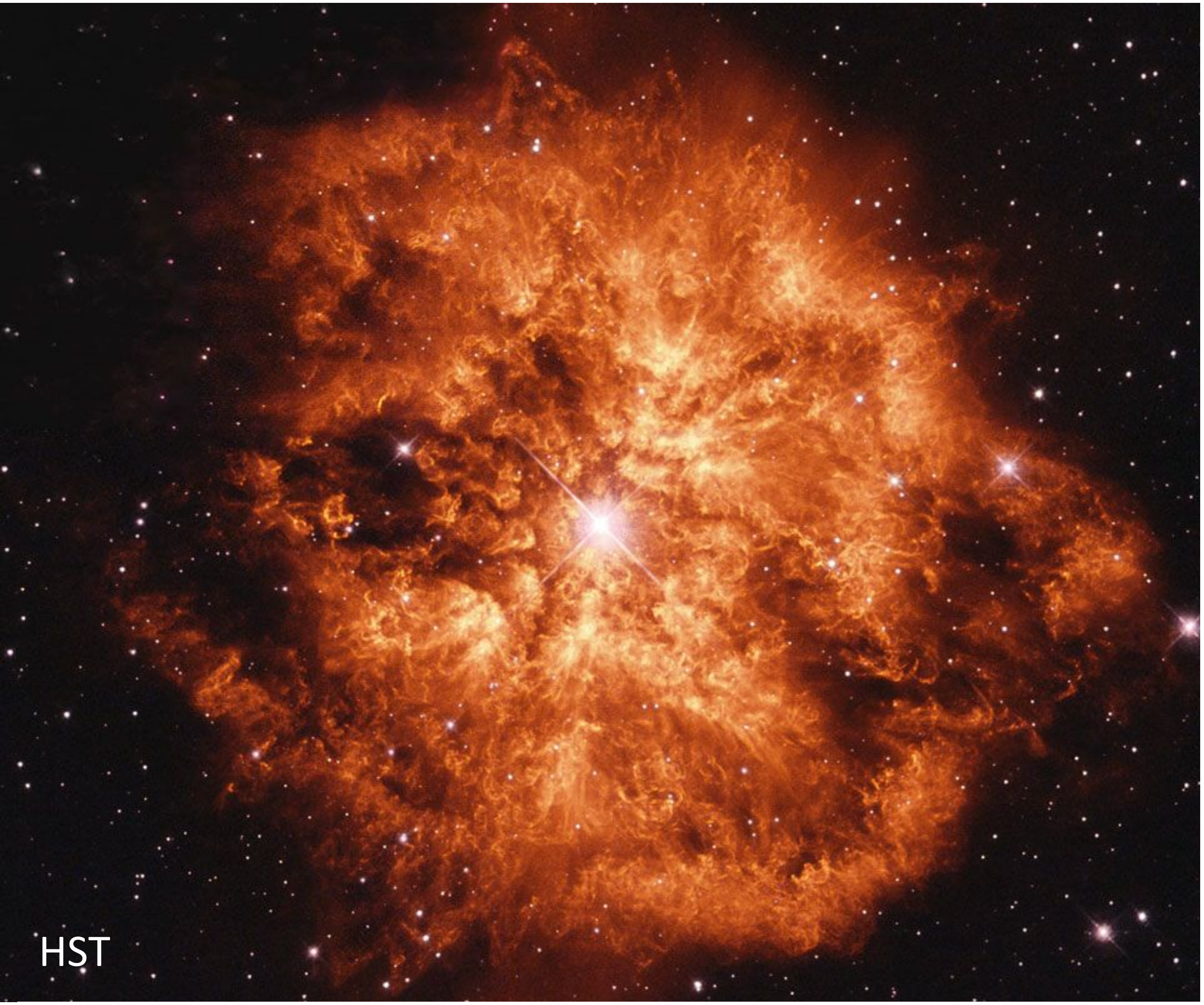


Figure 12. Schematic upper HR Diagram with the locations of the confirmed LBVs (blue dots), the warm hypergiants (Paper I) and candidate post-red supergiants (green dots), and other stars discussed in Section 4 (blue ×'s). The outline of the LBV/S Dor instability strip (pink) and the empirical upper 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.

Estrelas Wolf-Rayet

$T_e \sim 25\,000 – 100\,000$ K
$L \sim 10^5 - 10^6\ L_{Sol}$



Mass loss
$> 10^{-5}\ M_{Sun}$/yr.

Winds
800 – 3000 km/s

Rotation 300 km/s

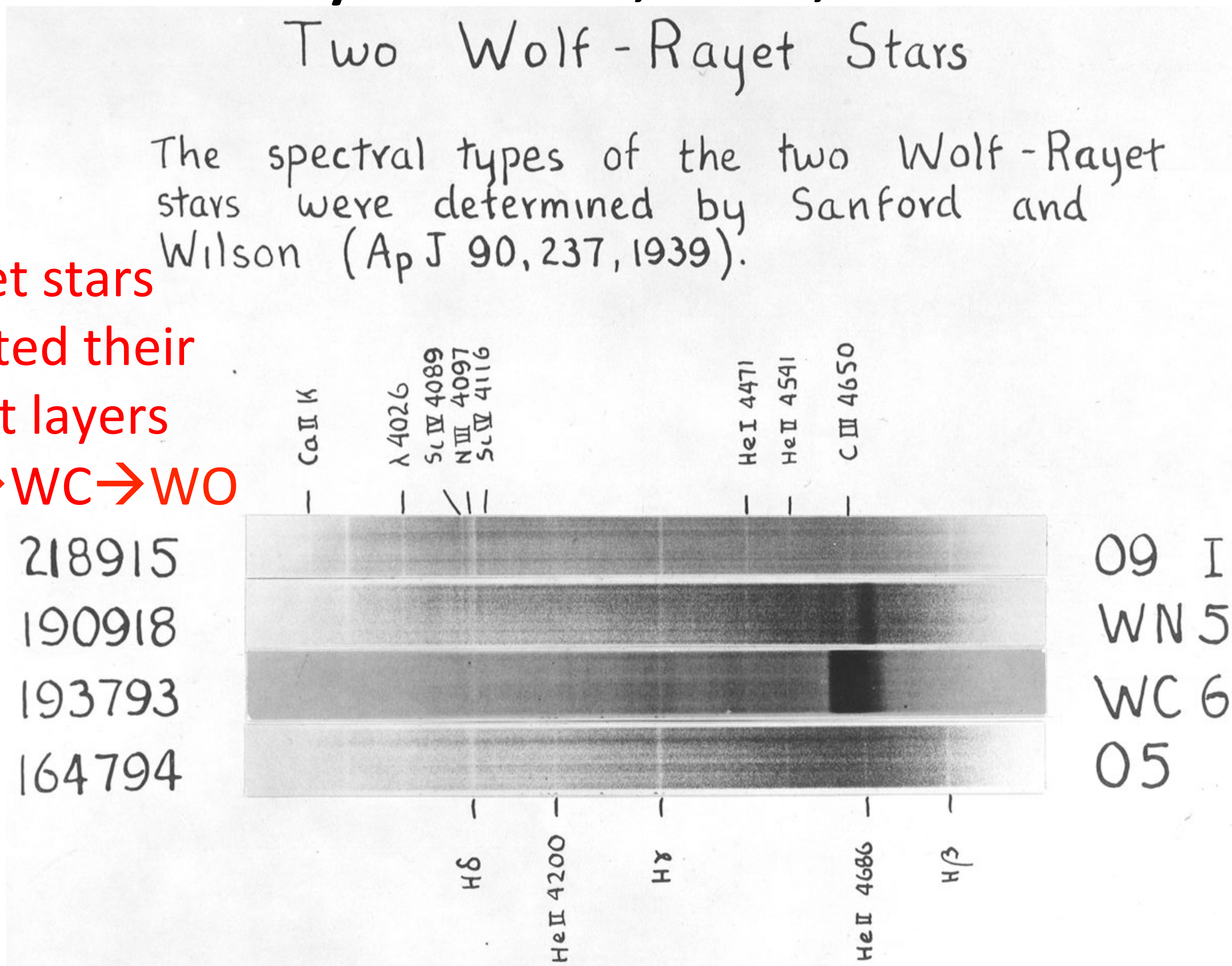
Masses $> 20\ M_{sun}$

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

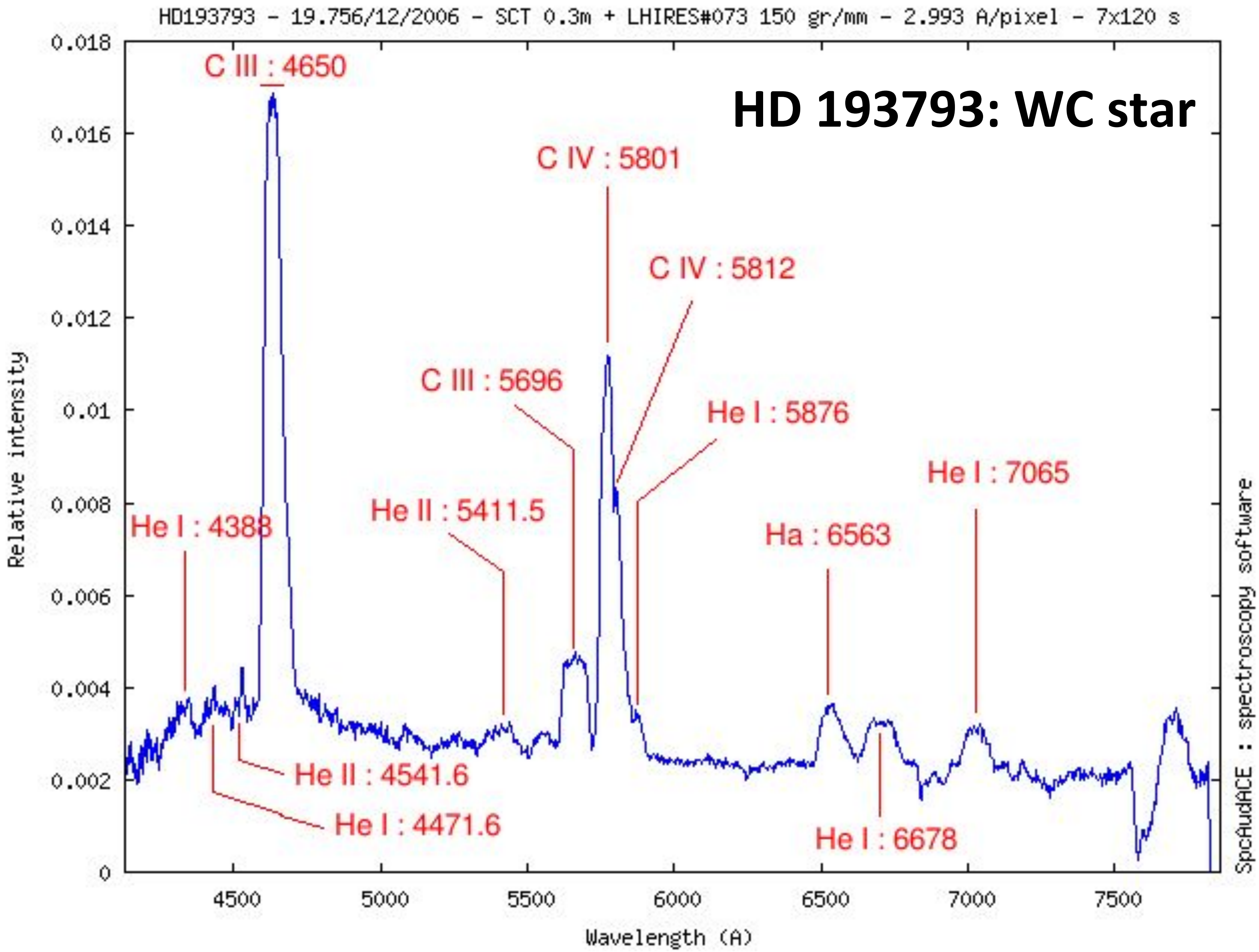
Wolf Rayet: WN, WC, WO

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



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

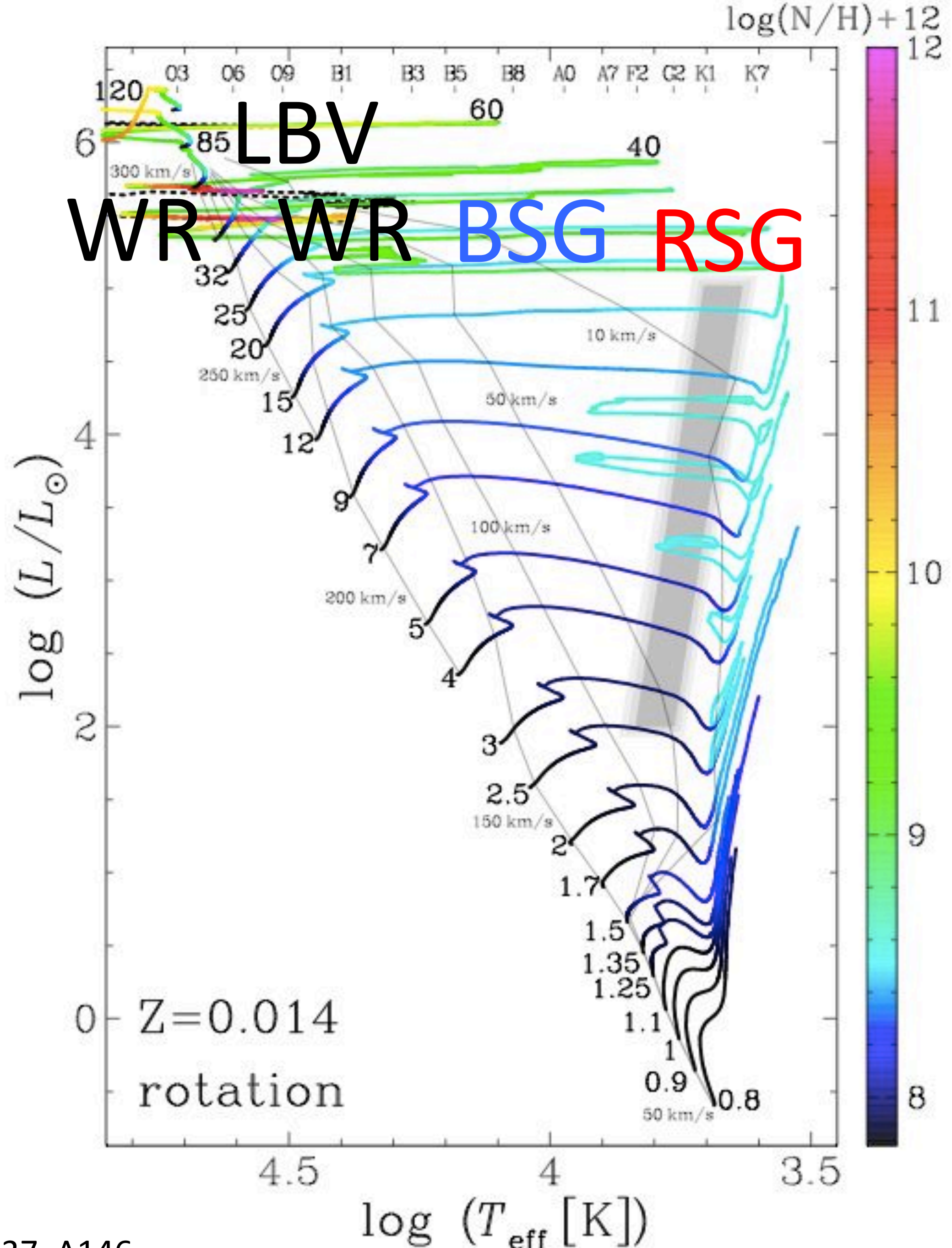
HD 193793: WC star



http://wsdiscovery.free.fr/astronomie/spectro/pedagogie/identite/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

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

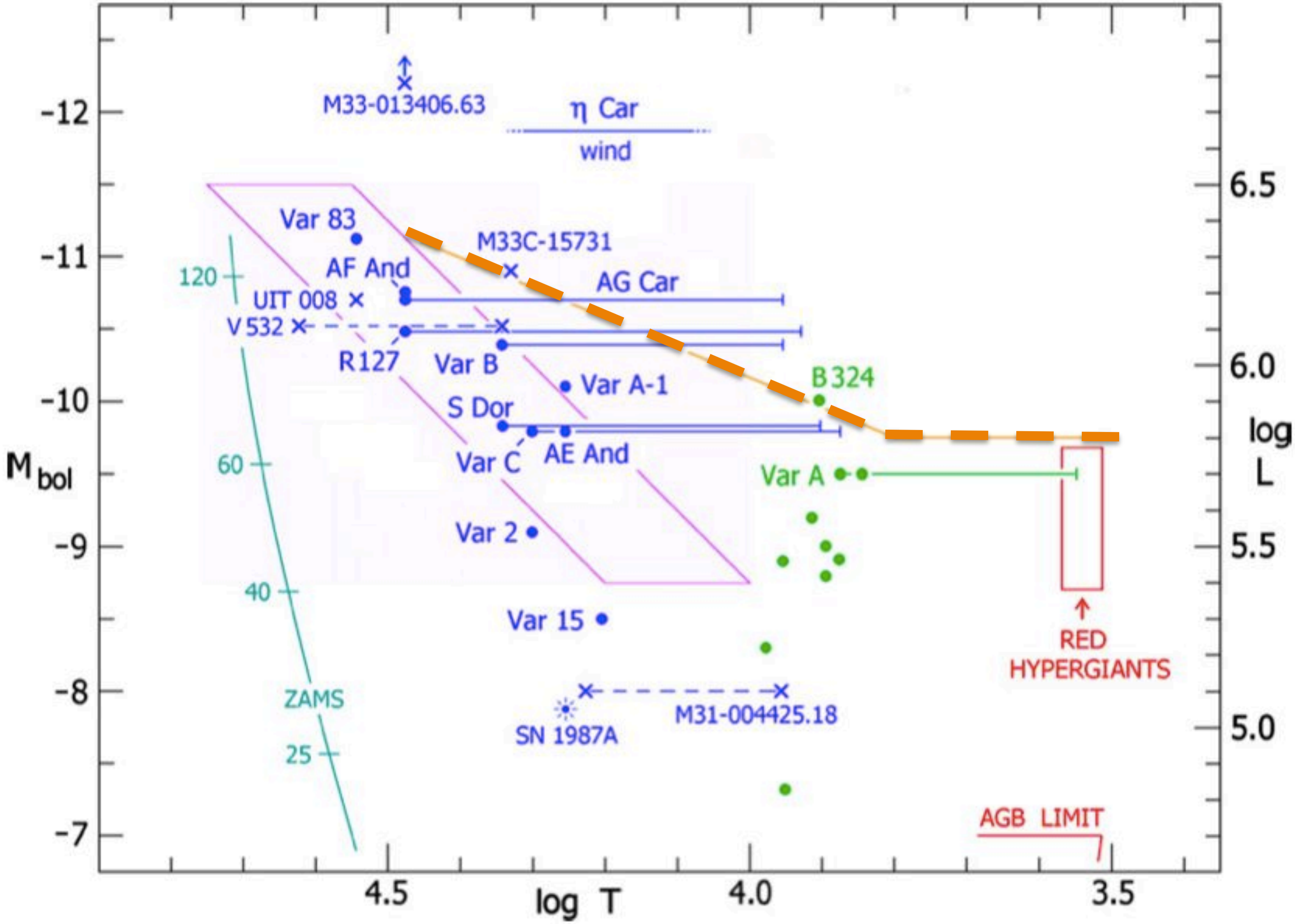
$$40\ \mathrm{M}_\odot < M < 85\ \mathrm{M}_\odot : \mathrm{O} \rightarrow \mathrm{Of} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN}$$

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

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

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

- - - - Limite de Humphreys-Davidson



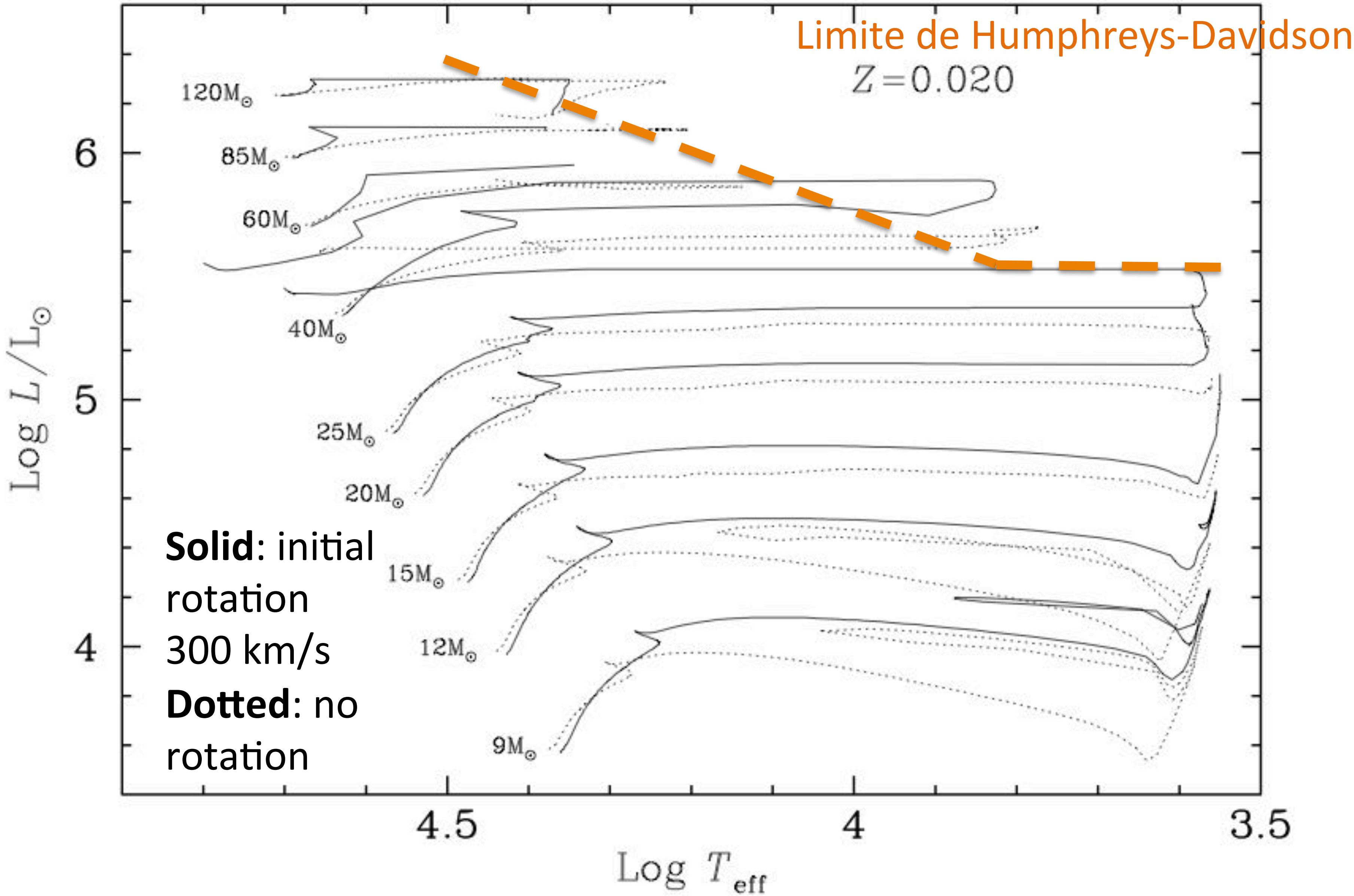
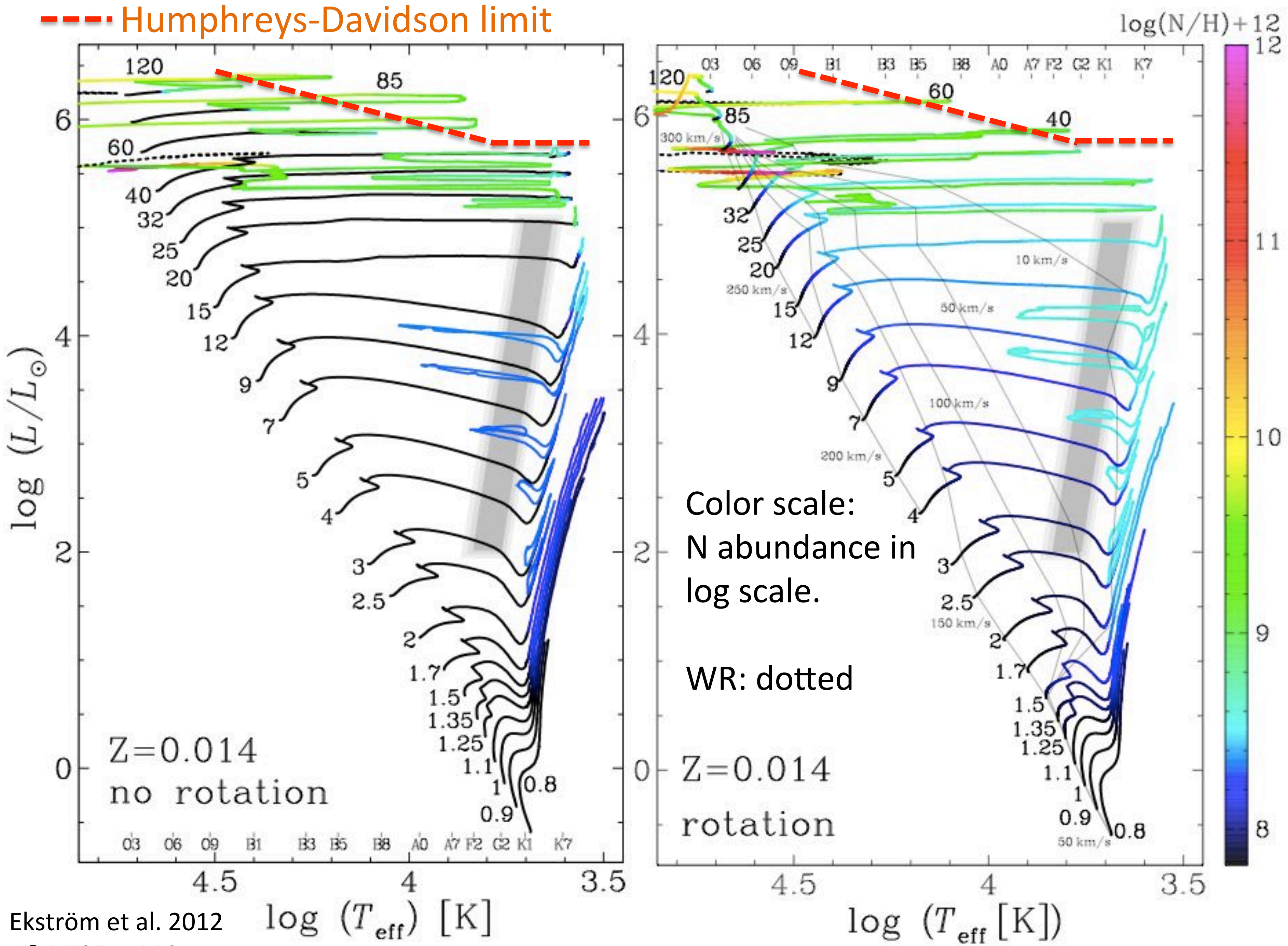


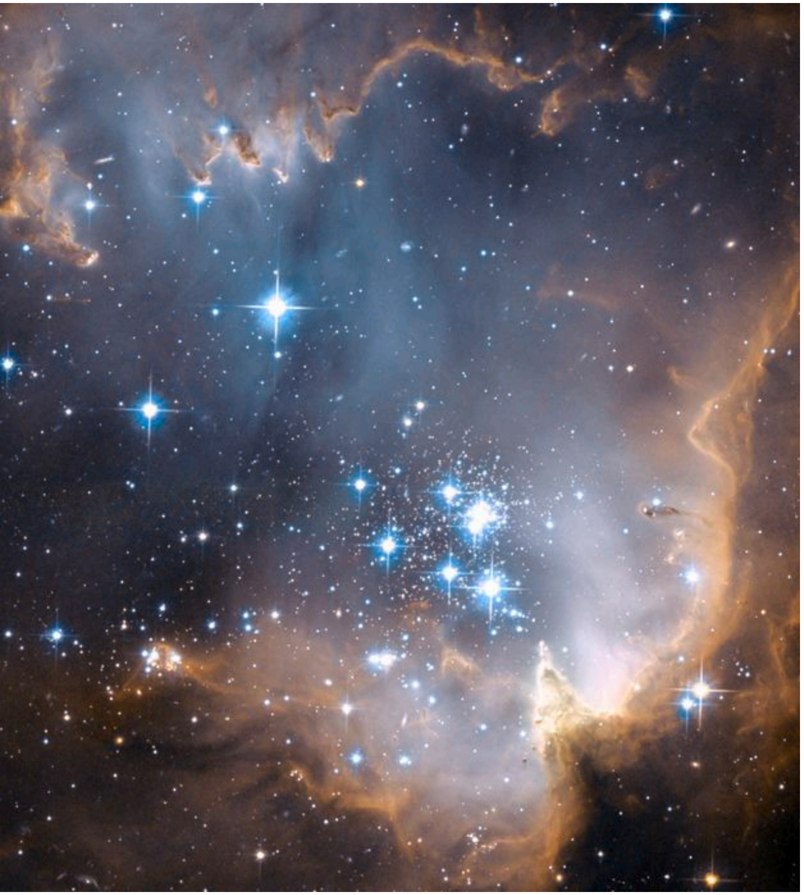
FIGURE 15.3 The evolution of massive stars with $Z = 0.02$. The solid lines are evolutionary tracks computed with initial rotation velocities of 300 km s^{-1}, and the dotted lines are evolutionary tracks for stars without rotation. Mass loss has been included in the models and significantly impacts 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_{Sol} por cada 1 milhão de 1 M_{sol}
- Os ventos podem afetar as nuvens moleculares, cessando a formação estelar
- Os ventos são ricos em metais processados no interior → enriquecimento químico do ISM
- Podem explodir como supernovas, desestabilizando nuvens moleculares → enriquecimento químico e formação de estrelas

Classificação de supernovas

X-rays, Chandra @NASA

Supernova 1006

V ~ -7,5 (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 و يلطف حتى اضمحل ، وكان فى ابتدائه إلى السواد
والخضرة ، ثم جعل كل وقت يرمى بالشرر ويزداد بياضا و يلطف حتى اضمحل . وقد
يكون على صورة لحية ، أو صورة حيوان له قرون ، وعلى سائر الصور ؛ و إنما يكون ذلك
إذا كانت هناك مادة كثيفة واقفة ، تلطف أجزاؤها يسيرا يسيرا وتتحلل عنه متصعدة
كزوائد شعرية أو قرنية . ومنها المسماة أعنزا كأن تشريرها 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.

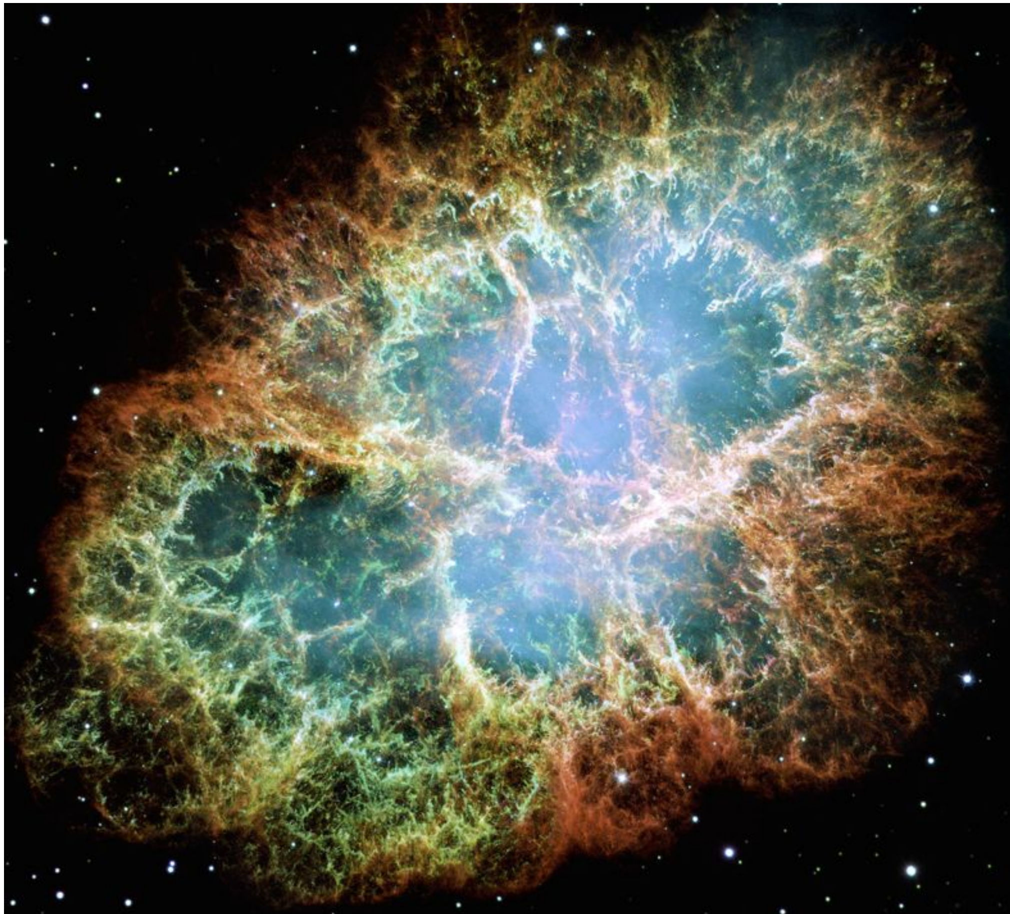
وفيها مستهل شعبان طلع كوكب كبير تشبه الزهرة عن
يسرة قبلة العراق له شعاع على ارض كشعاع القمر وبقى
الى منتصف ذى القعدة وغاب .

Goldstein (1965, ApJ 70, 105)

Supernova 1054

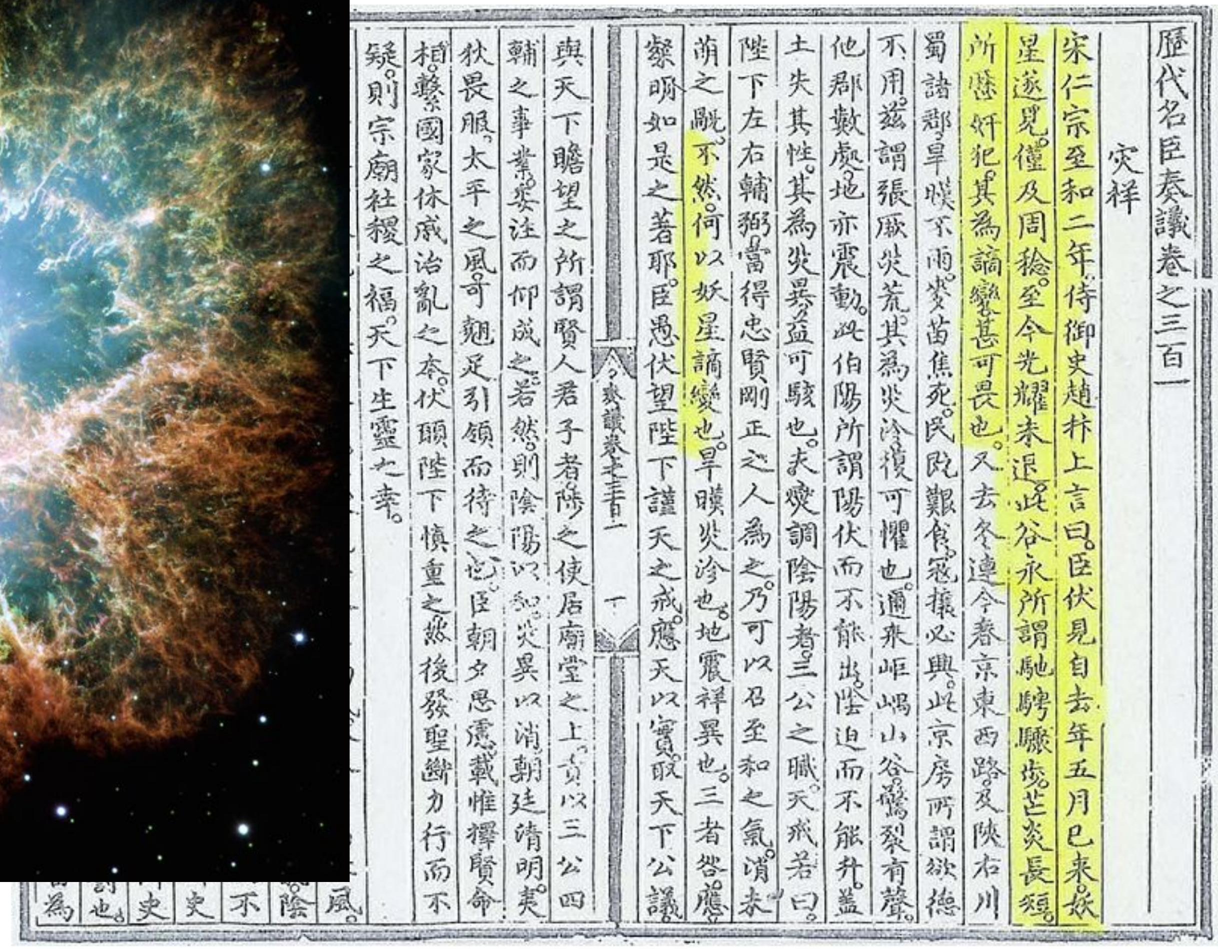
V ~ -6, d ~ 2 kpc

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



Crab nebula

© HST

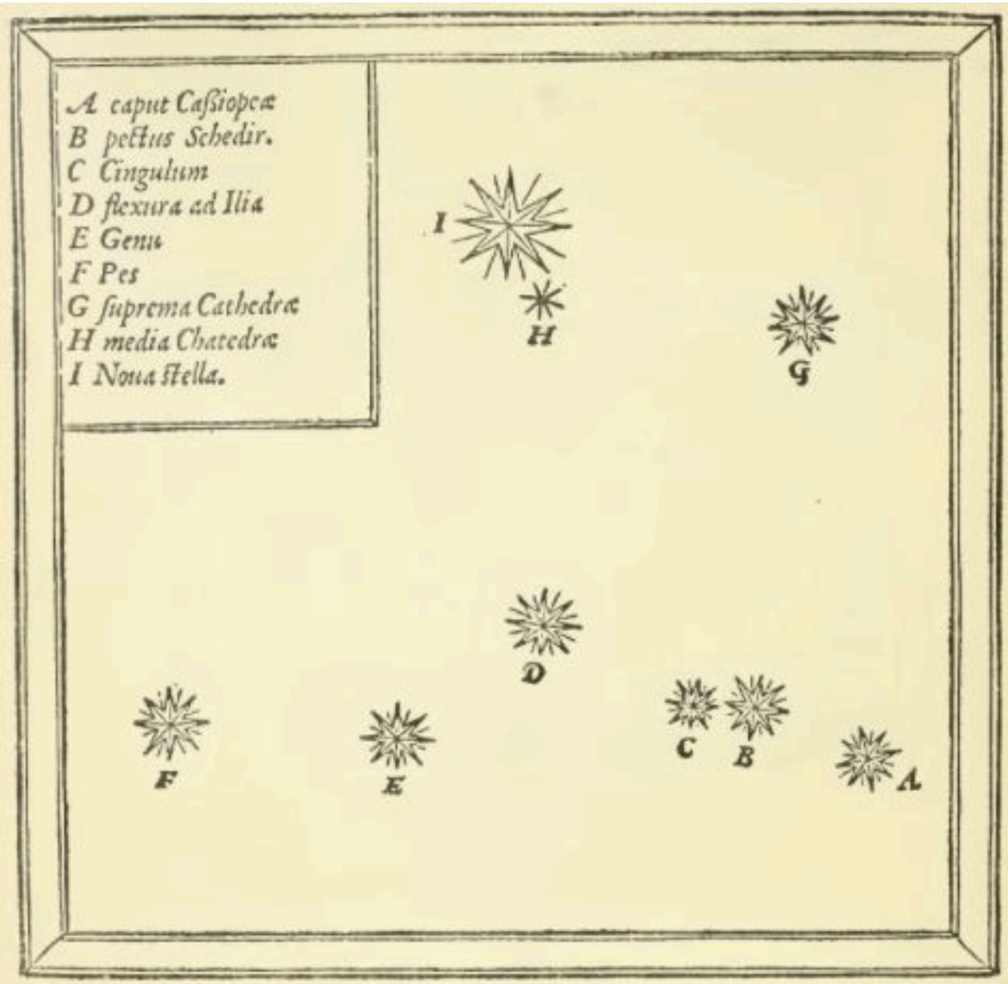


歷代名臣奏議卷之三百一
災祥
宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖
星遂見僅及周稔至今光耀未退此谷永所謂馳騁驟步芒炎長緩
所懸奸犯其為譴變甚可畏也又去冬迄今春京東西路及陝右川
蜀諸郡旱暵不雨麥苗焦死民既艱食寇攘必興此京房所謂欲德
不用茲謂張厥災荒其為災沴復可懼也邇來岠嵎山谷驚裂有聲
他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋
土失其性其為災異益可駭也夫燮調陰陽者三公之職天戒若曰
陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消去
萌之眦不然何以妖星譴變也旱暵災沴也地震祥異也三者咎應
粲明如是之著耶臣愚伏望陛下謹天之戒應天以實敢天下公議
奏議卷之三百一 一
與天下瞻望之所謂賢人君子者陟之使居廟堂之上責以三公四
輔之事業委注而仰成之若然則陰陽以和災異以消朝廷清明矣
狄晏眠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

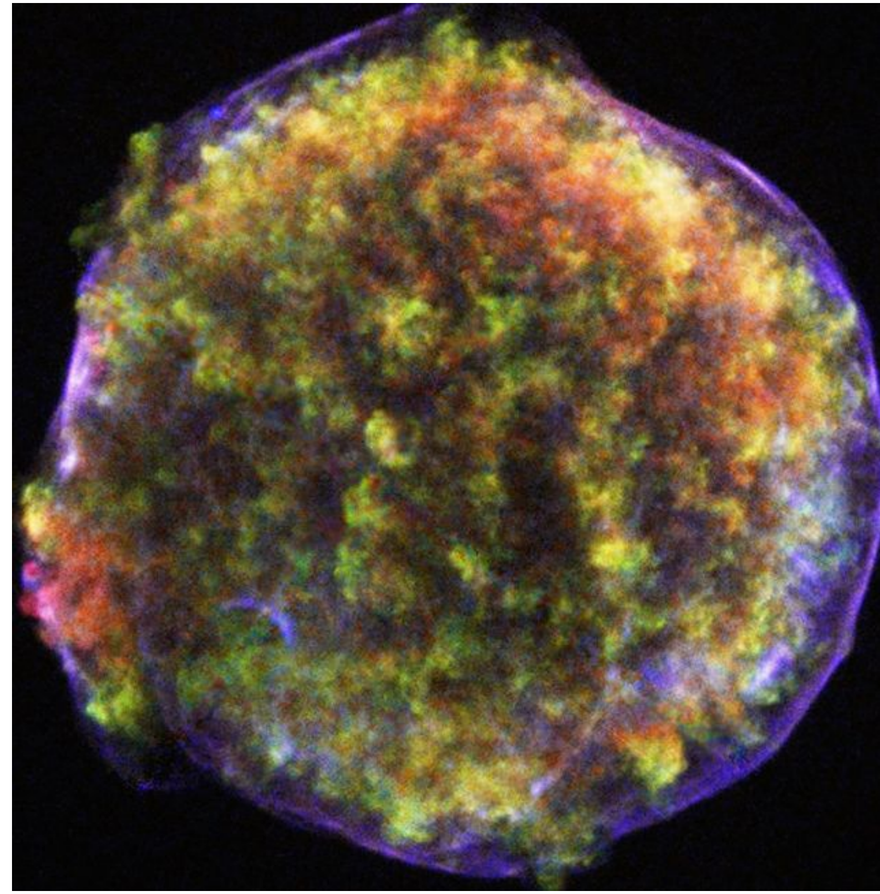
The highlighted passages refer to SN 1054, a guest star reported by Chinese astronomers in 1054

Supernova 1572

V ~ -4, d ~ 2,7 kpc



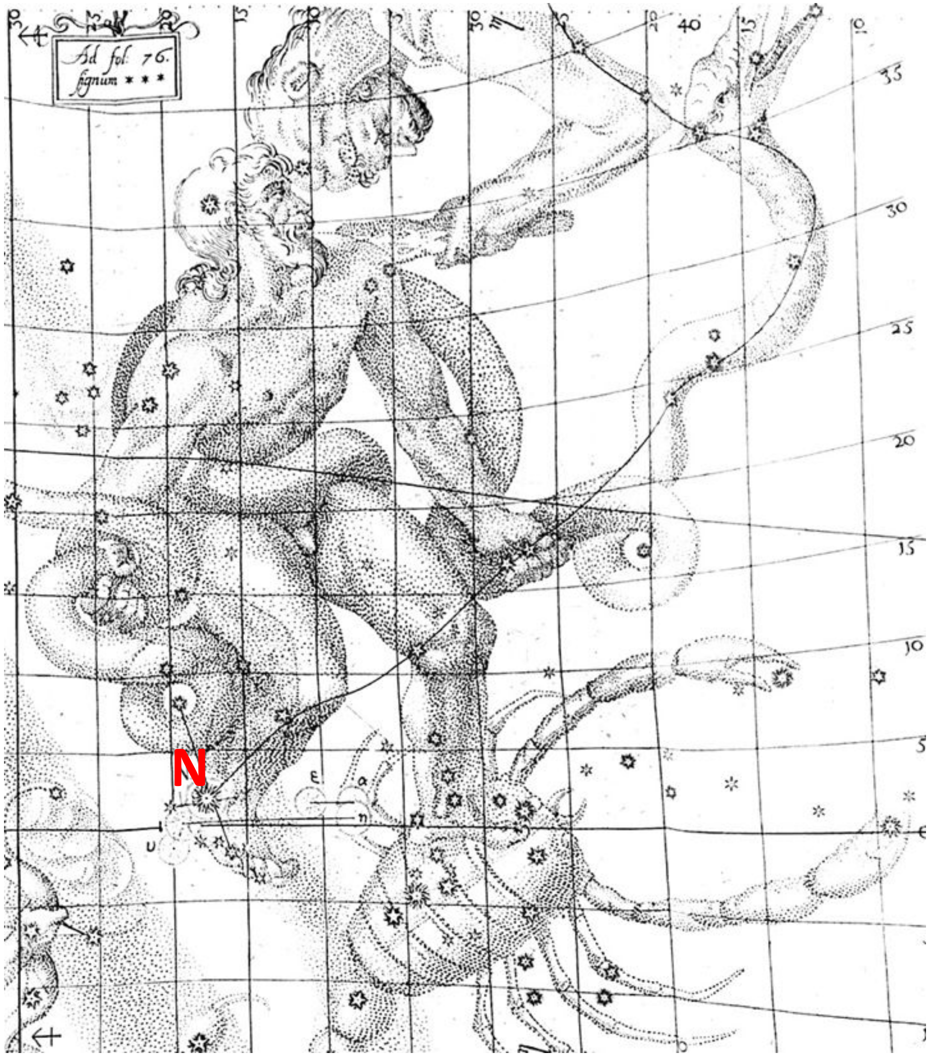
Tycho's notes on SN 1572



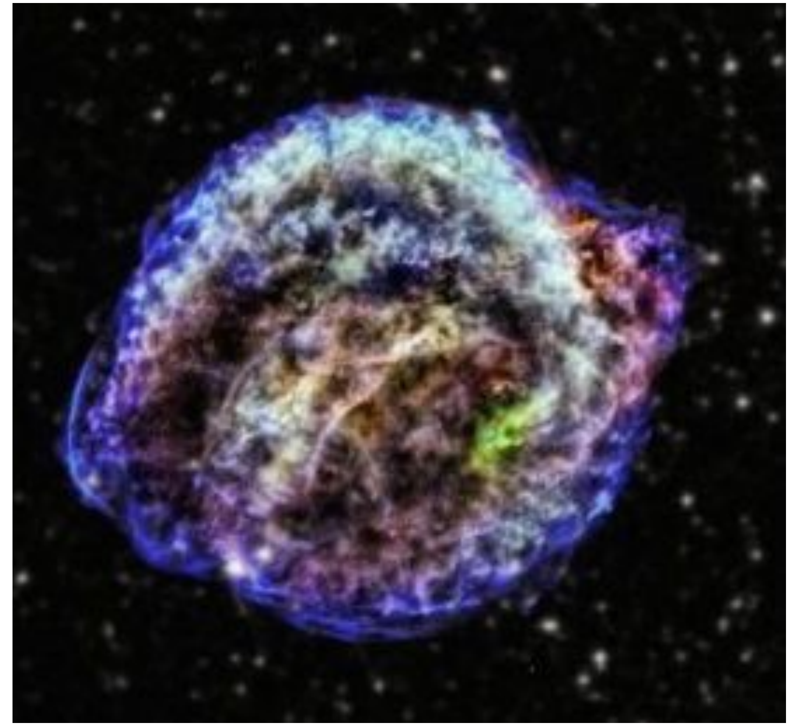
Tycho's Supernova Remnant. Chandra's image of the supernova remnant shows an expanding bubble of multimillion degree debris (green and red) inside a more rapidly moving shell of extremely high energy electrons (filamentary blue).

Supernova 1604,

V ~ -2,4, d ~ 6 kpc



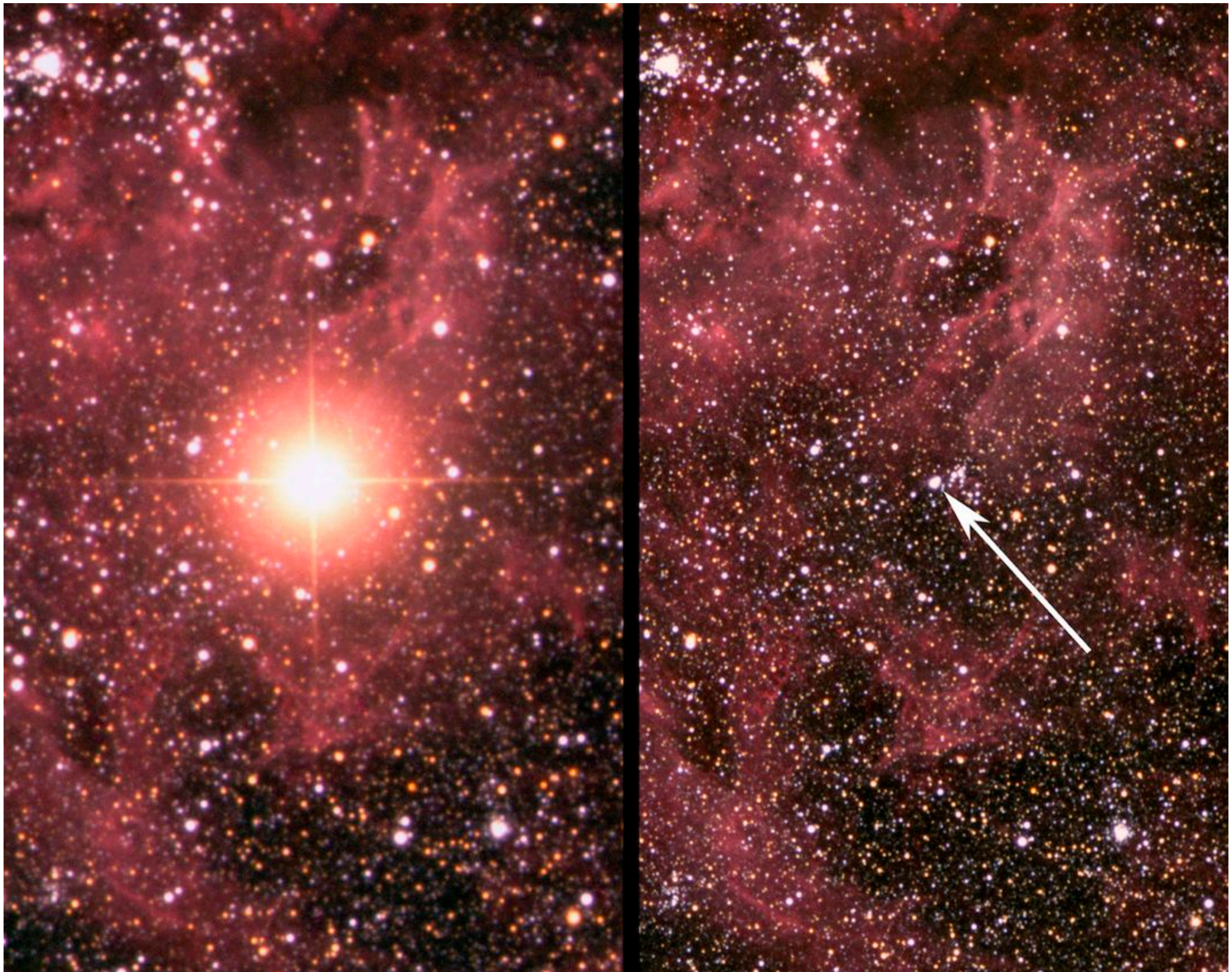
Kepler's original drawing depicting the location of the stella nova (**N**)



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.

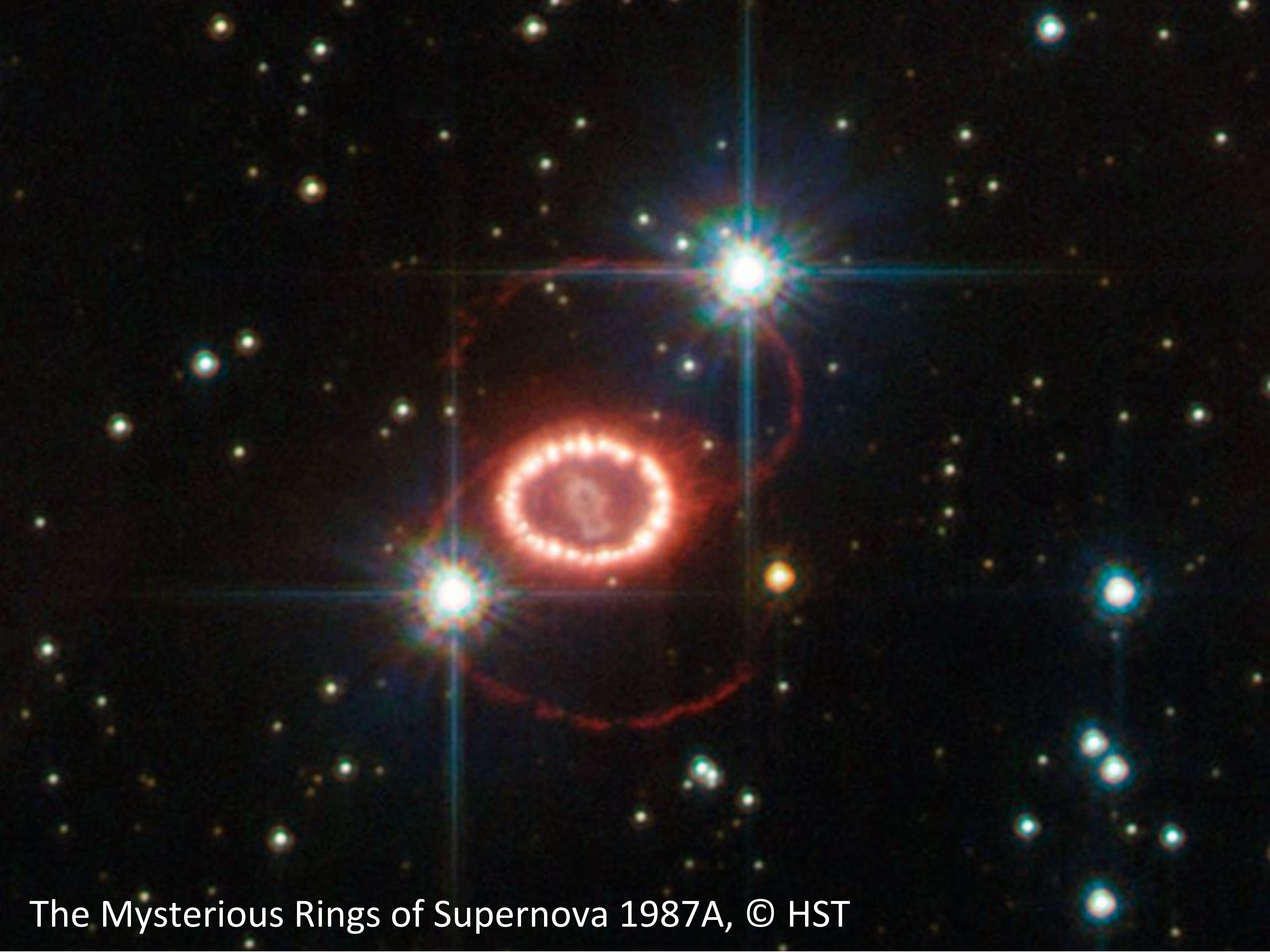
Supernova 1987A, V ~ 2,9; d ~ 51,4 kpc

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



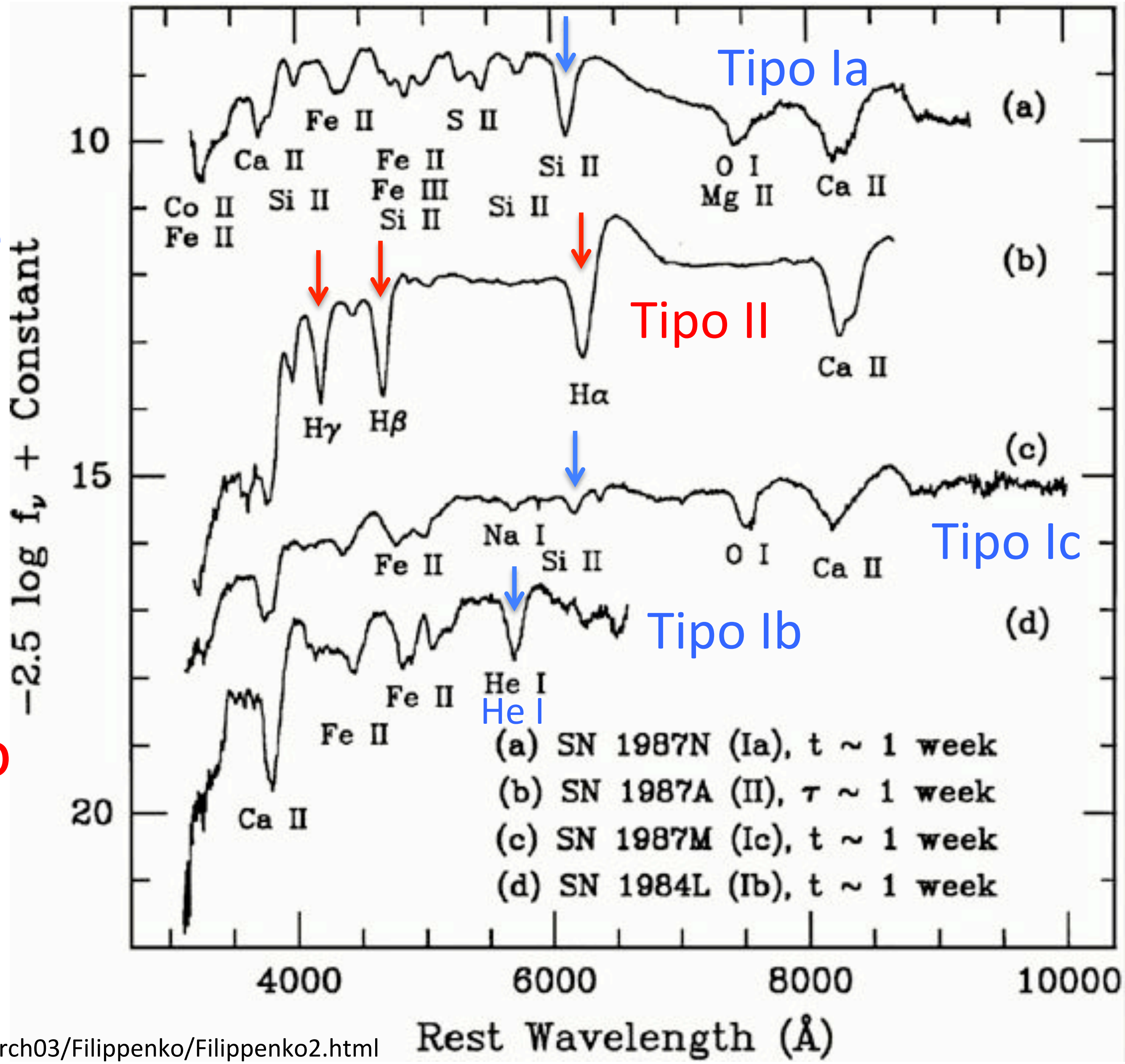
Supernova 1987A after exploding & an image before the explosion. (c) David Malin / AAO

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


The Mysterious Rings of Supernova 1987A, © HST

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

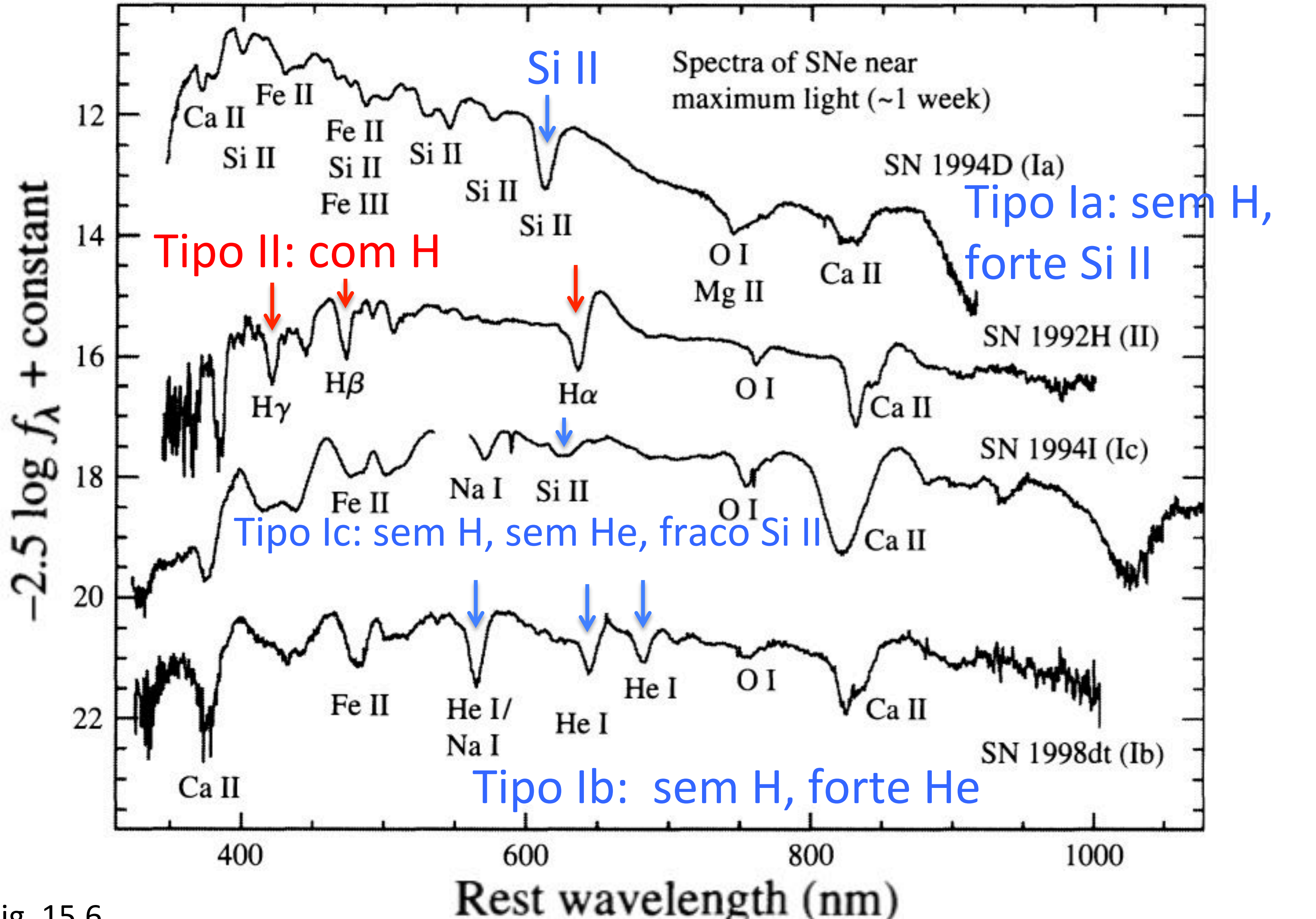
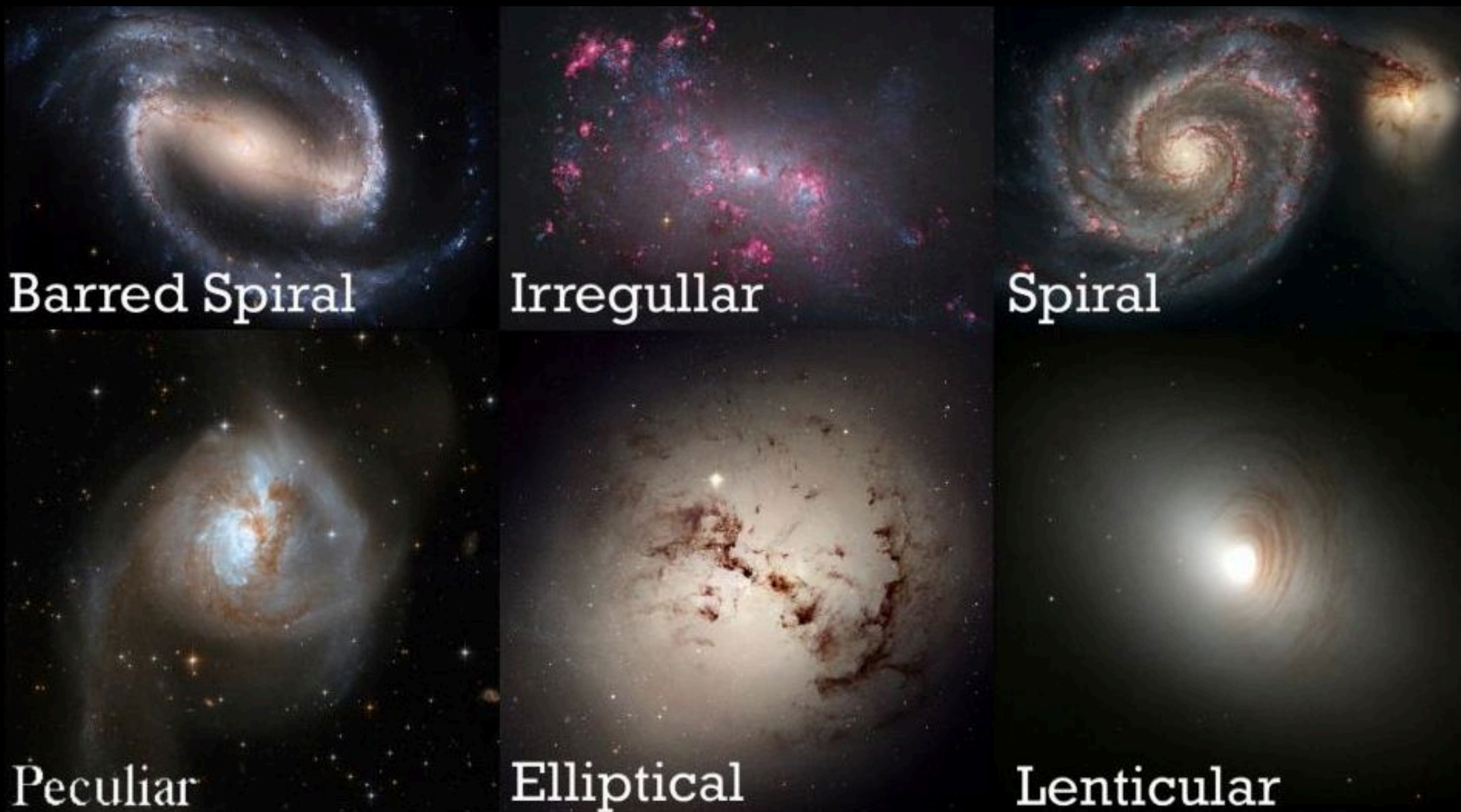


Fig. 15.6

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



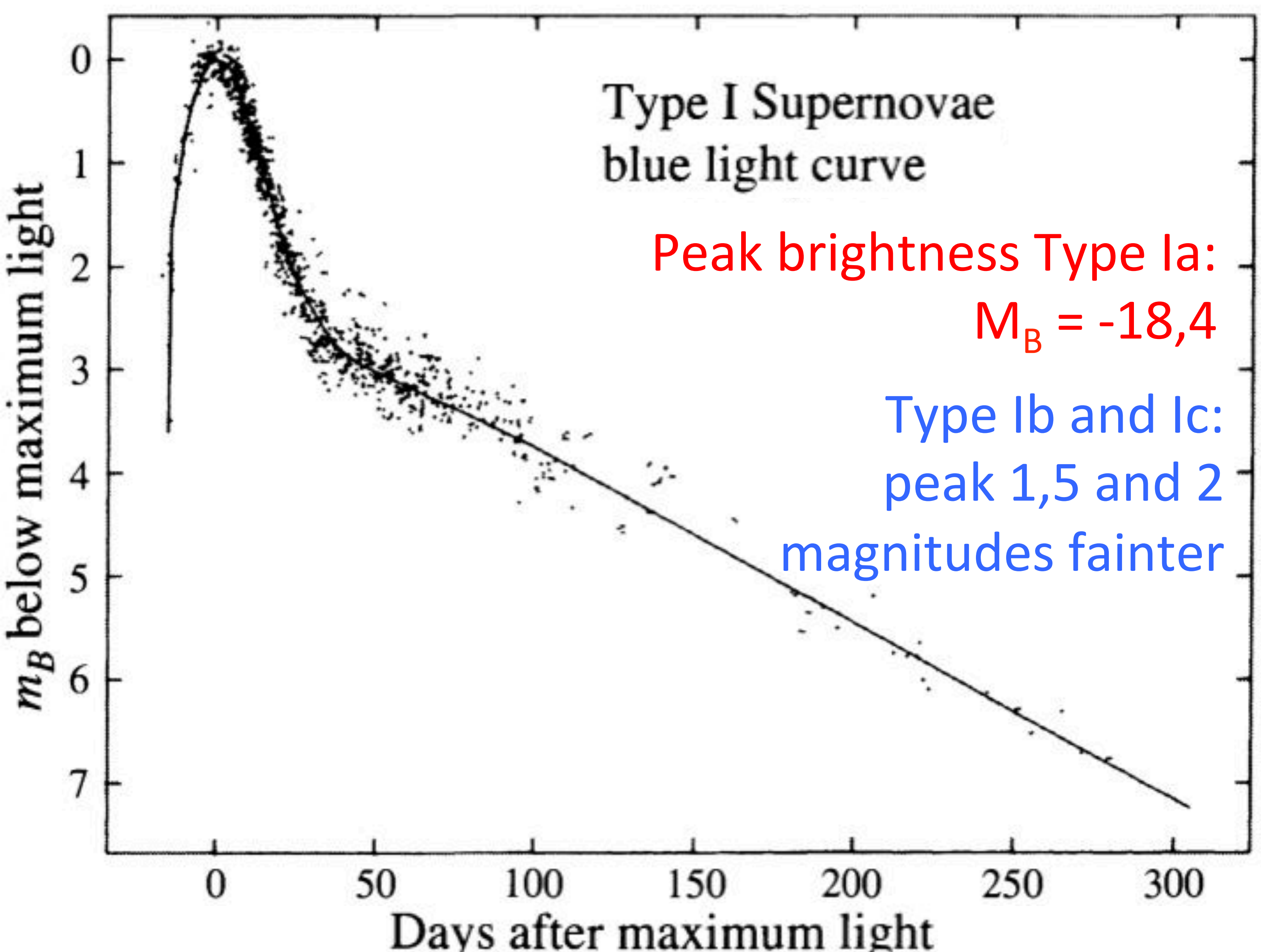
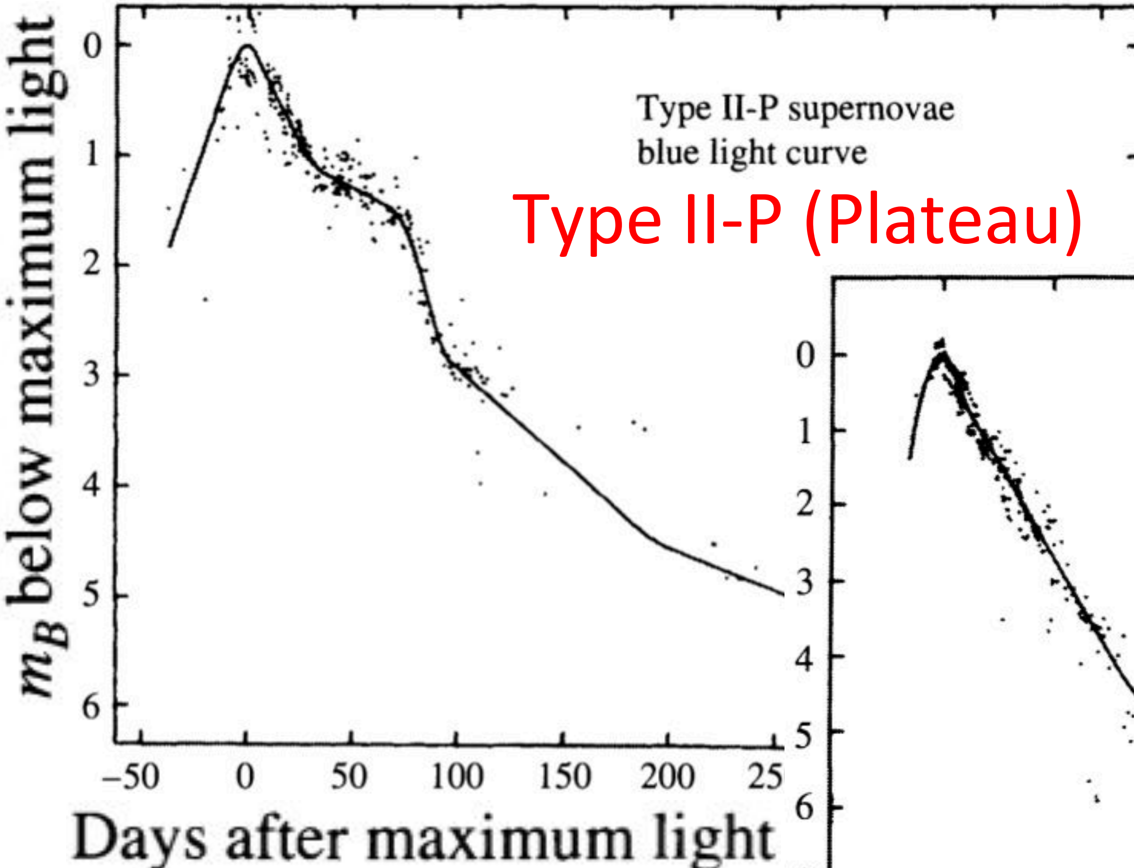
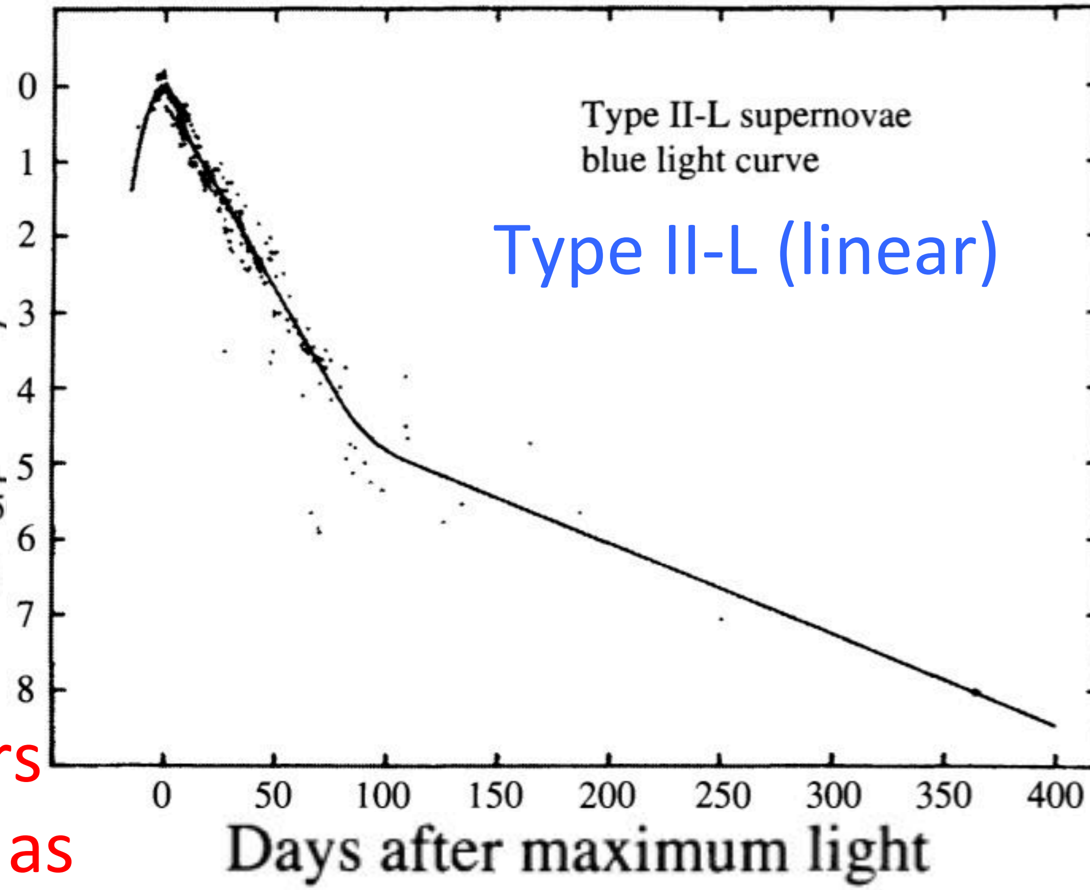


FIGURE 15.7 Composite light curve for Type I supernovae at blue wavelengths. All magnitudes are relative to m_B at maximum. (Figure adapted from Doggett and Branch, *Astron. J.*, *90*, 2303, 1985.)

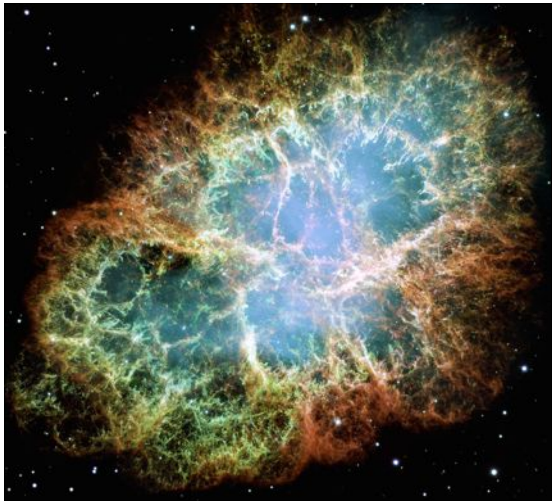
Peak brightness Type II: 1,5 magnitudes fainter than Type Ia

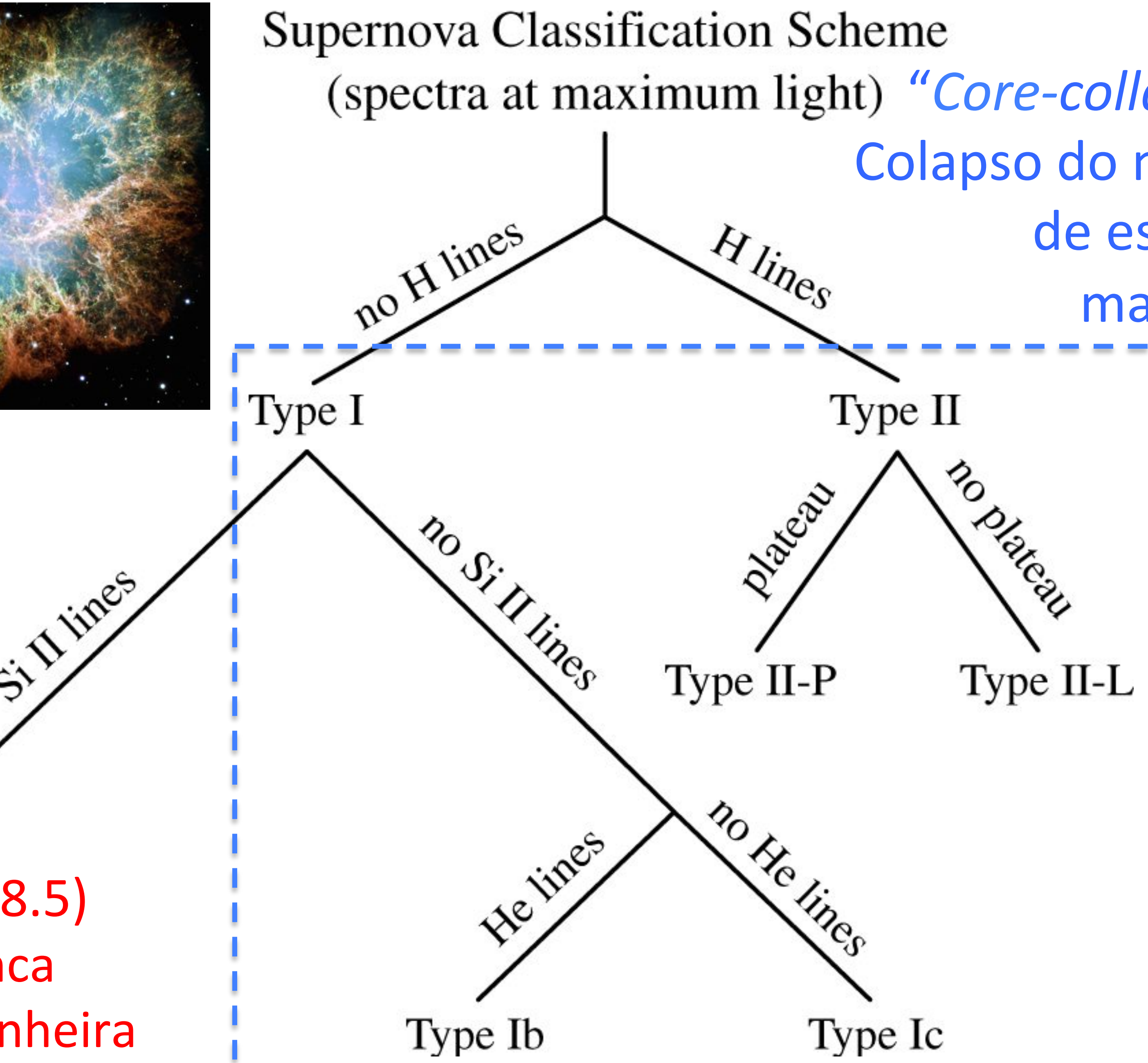




Type II-P (Plateau) occurs about 10 times as often as Type II-L (linear)

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

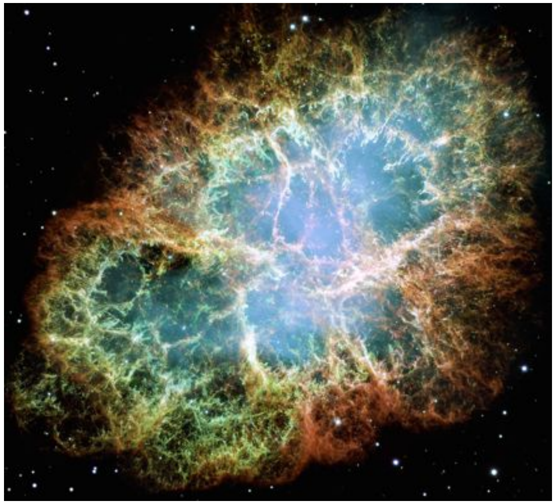




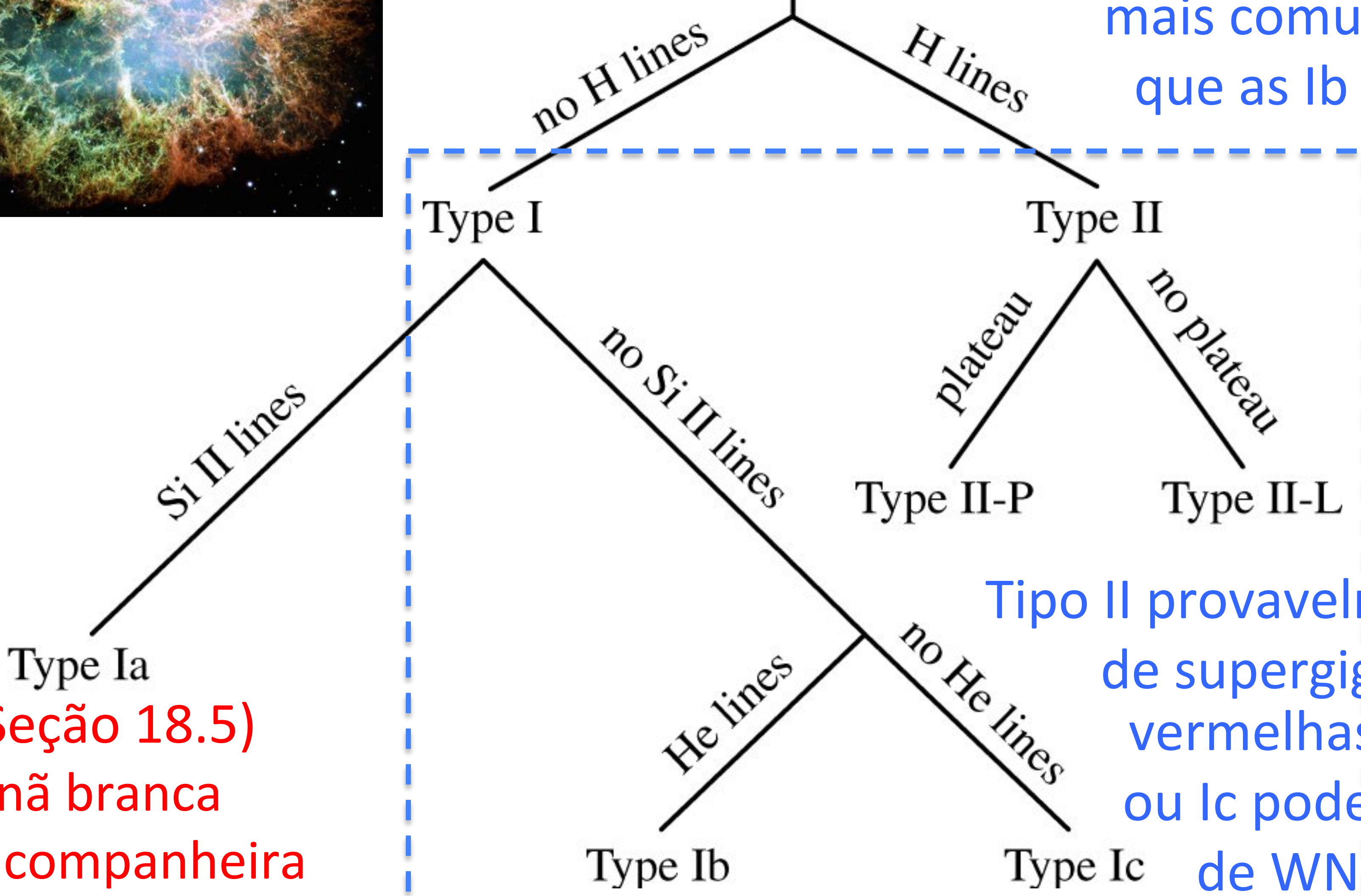
"Core-collapse": Colapso do núcleo de estrelas massivas

(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.



Supernova Classification Scheme
(spectra at maximum light)



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

Tipo II provavelmente de supergigantes vermelhas, já Ib ou Ic podem ser de WN e WN

(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.

15.3 Supernovas de colapso do núcleo

Estrelas < 8 M_{Sol}:
H → He, He → C e O → Nebulosa Planetária

Estrelas > 8 M_{Sol}:
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 ~ 3×10^9 K

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

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

$$\vdots$$

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

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

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

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

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

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

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

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

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

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

Também temos fotodesintegração do Si → contração

Para estrela 20 M_{sol}

- 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

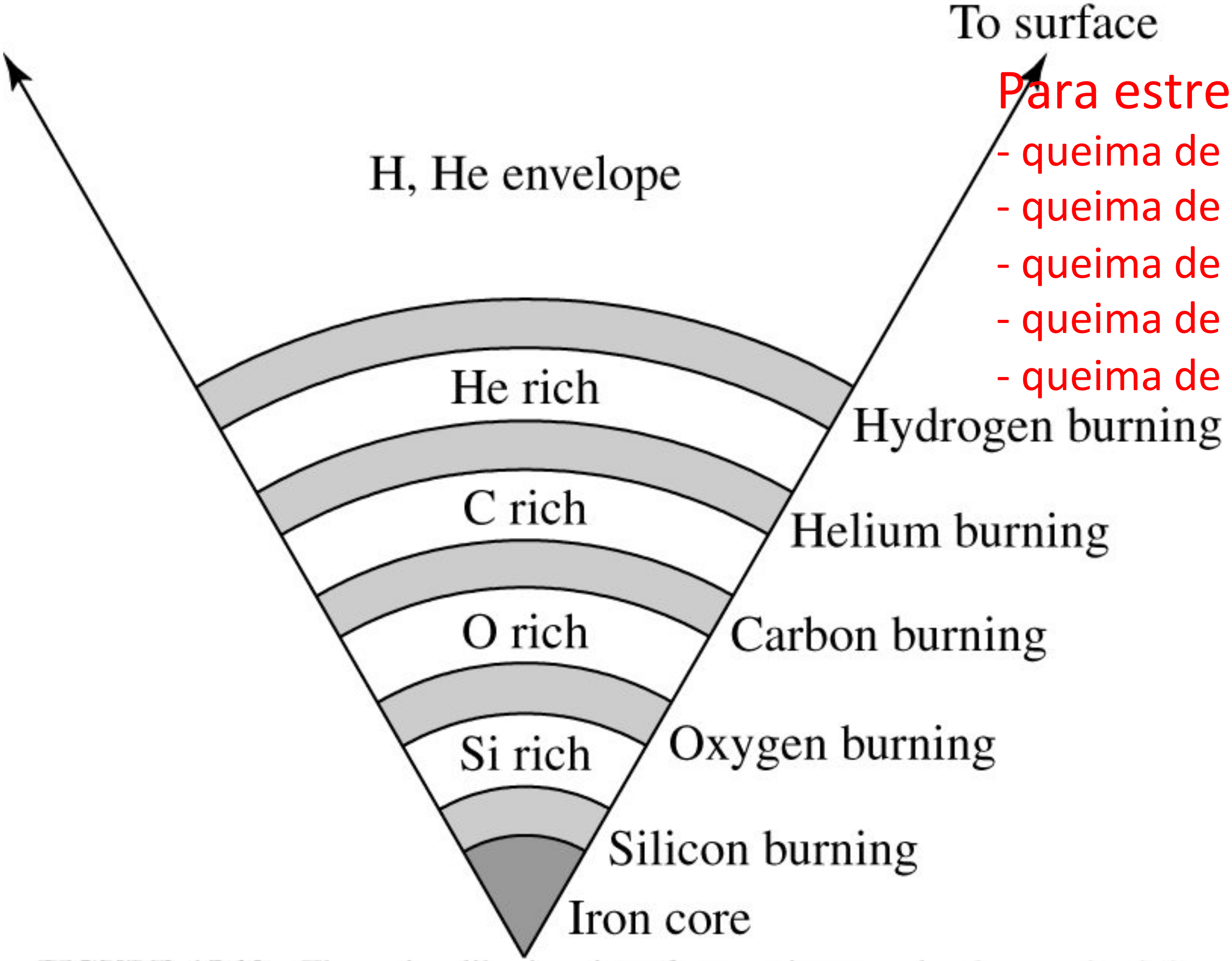
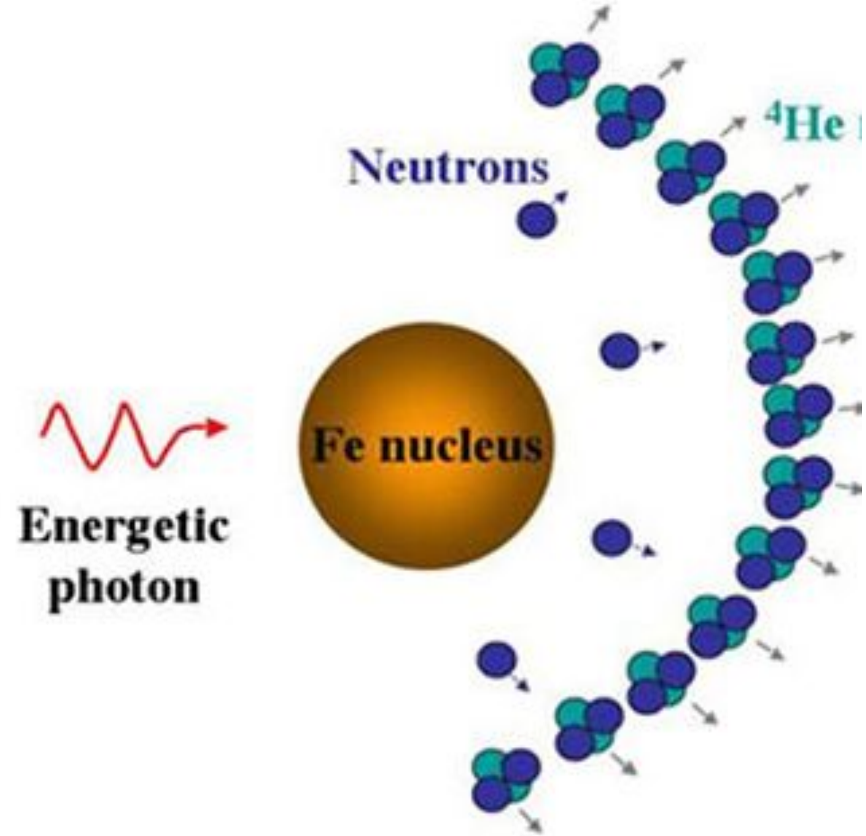


FIGURE 15.10 The onion-like interior of a massive star that has evolved through core silicon burning. Inert regions of processed material are sandwiched between the nuclear burning shells. The inert regions exist because the temperature and density are not sufficient to cause nuclear reactions to occur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



Temperaturas muito altas no núcleo → fotodesintegração.

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

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

Para estrela de 10 M_{Sol} → núcleo de ferro ~ 1,3 M_{Sol}

Para estrela de 50 M_{Sol} → núcleo de ferro ~ 2,5 M_{Sol}

Condições extremas no núcleo inerte de ferro.
Para estrela de 15 M_{sol}: T ~ $8x10^9$ K, ρ ~ 10^{13} kg m^{-3}

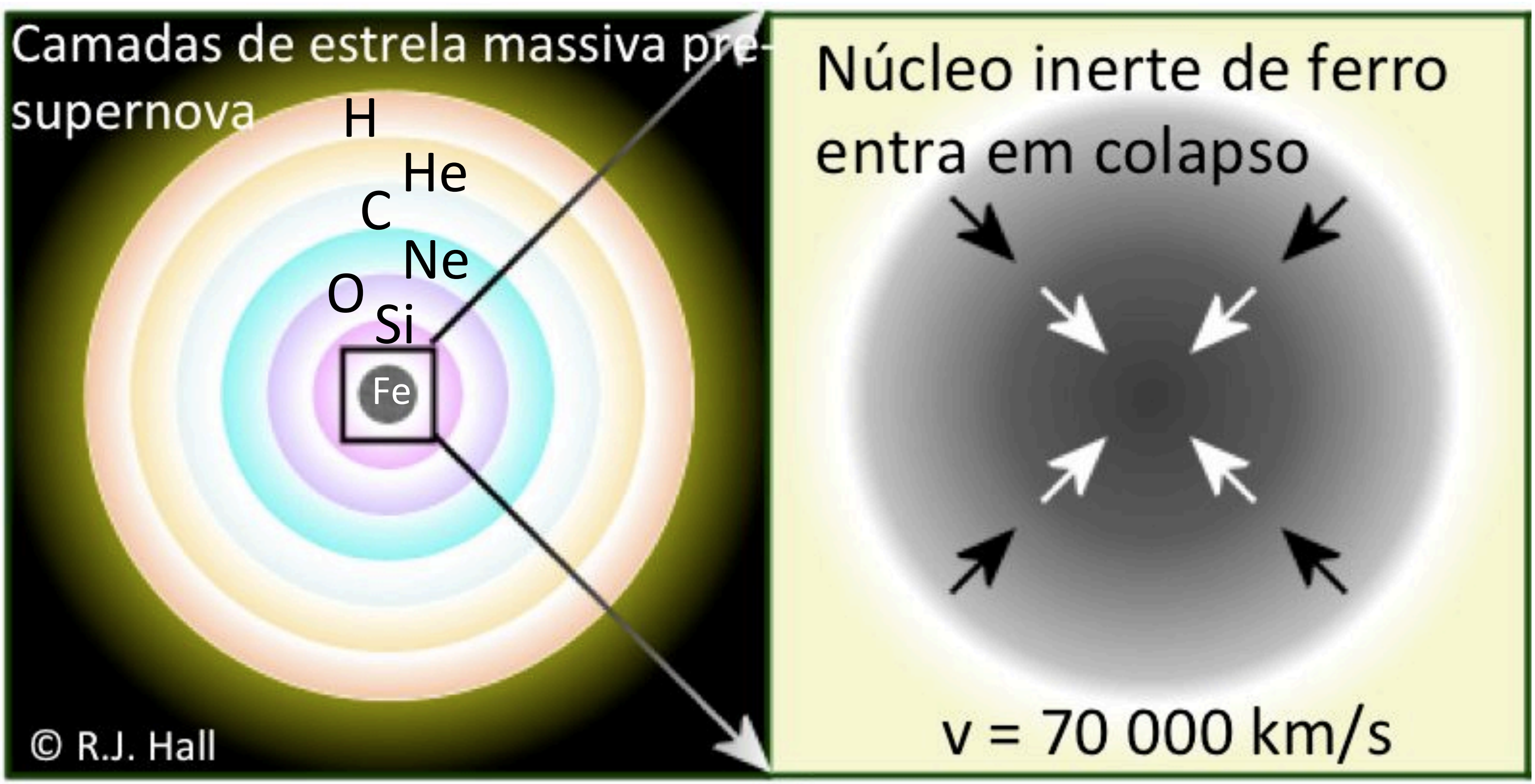
Elétrons livres são capturados pelos núcleos que foram produzidos na fotodesintegração. Por exemplo:

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

Muita energia escapa da estrela em forma de neutrinos.
Para estrela de 20 M_{sol} na queima de Si $L_{fótons} = 4x10^{31}$W.
Já a L_ν = $3x10^{38}$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?

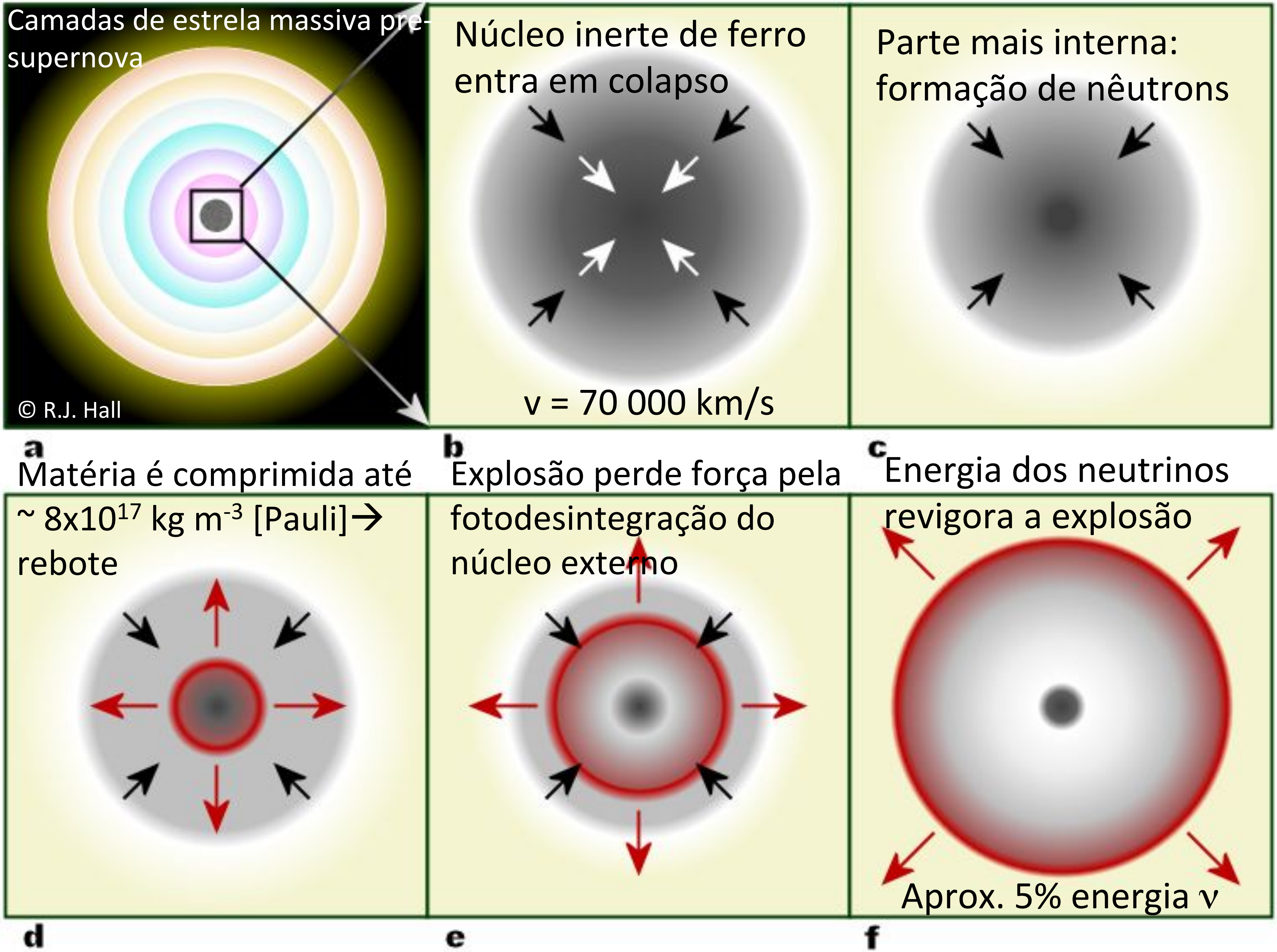
Assume for simplicity that we can use Newtonian physics to estimate the amount of energy released during the collapse. From the virial theorem (see Eq. 10.23), the energy released in the formation of a spherically symmetric star of constant density is

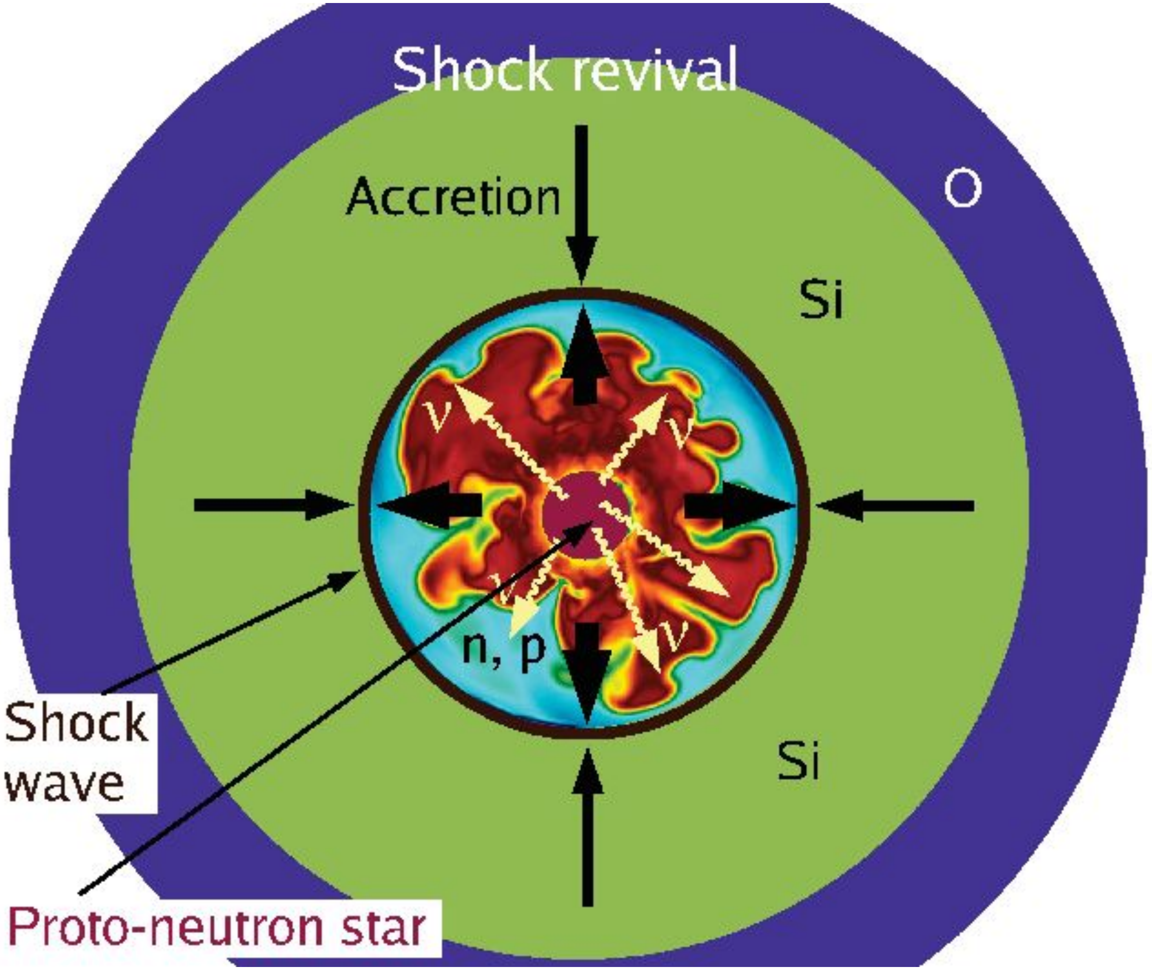
$$\mathrm{E} \sim -\frac{3}{10}\frac{GM^2}{R}.$$

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 $R_f = 50$ km $\ll R_\oplus$, the amount of mass required to produce the supernova would be

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

This value is characteristic of the core masses mentioned earlier.


Camadas de estrela massiva pre-supernova
© R.J. Hall
a
Núcleo inerte de ferro entra em colapso
v = 70 000 km/s
b
Parte mais interna: formação de nêutrons
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_{Sol})

Stellar Remnants of a Core-Collapse Supernova

Neutron star or black hole?

- Massa inicial < 25 M_{Sol} → estrela de nêutrons (suportada pela pressão de degenerescência de nêutrons)
- Massa inicial > 25 M_{Sol} → buraco negro

A massa final do núcleo para ser buraco negro é de no mínimo umas 3 M_{sol} (Cap. 17).

Energia liberada ~ $3x10^{46}$ J (100 vezes mais energia do que o Sol produzira na sequência principal), ou 10^9 L_{Sol} (quase o brilho de uma galáxia!)