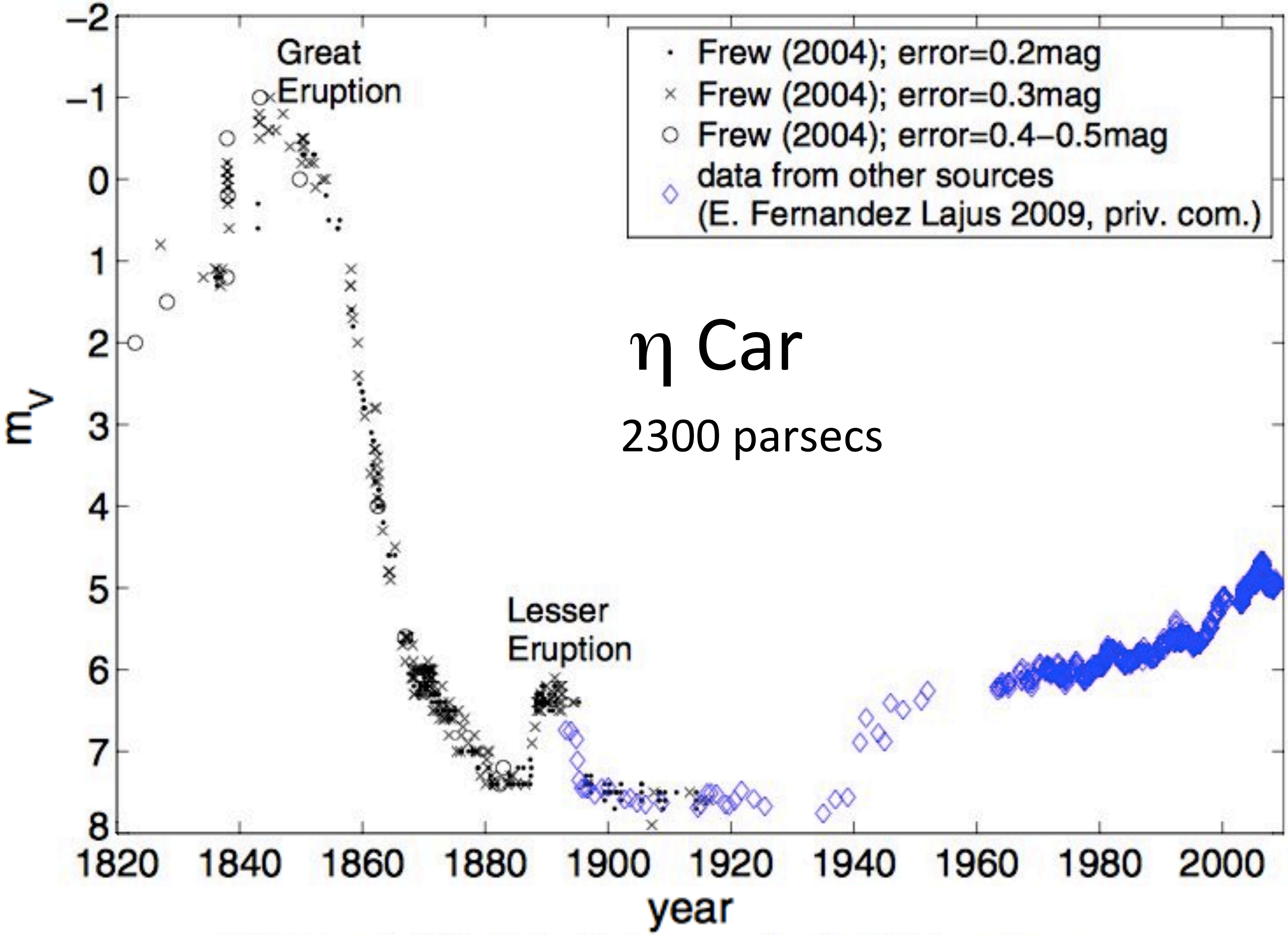
Evolução de estrelas massivas

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

AGA293

Jorge Meléndez

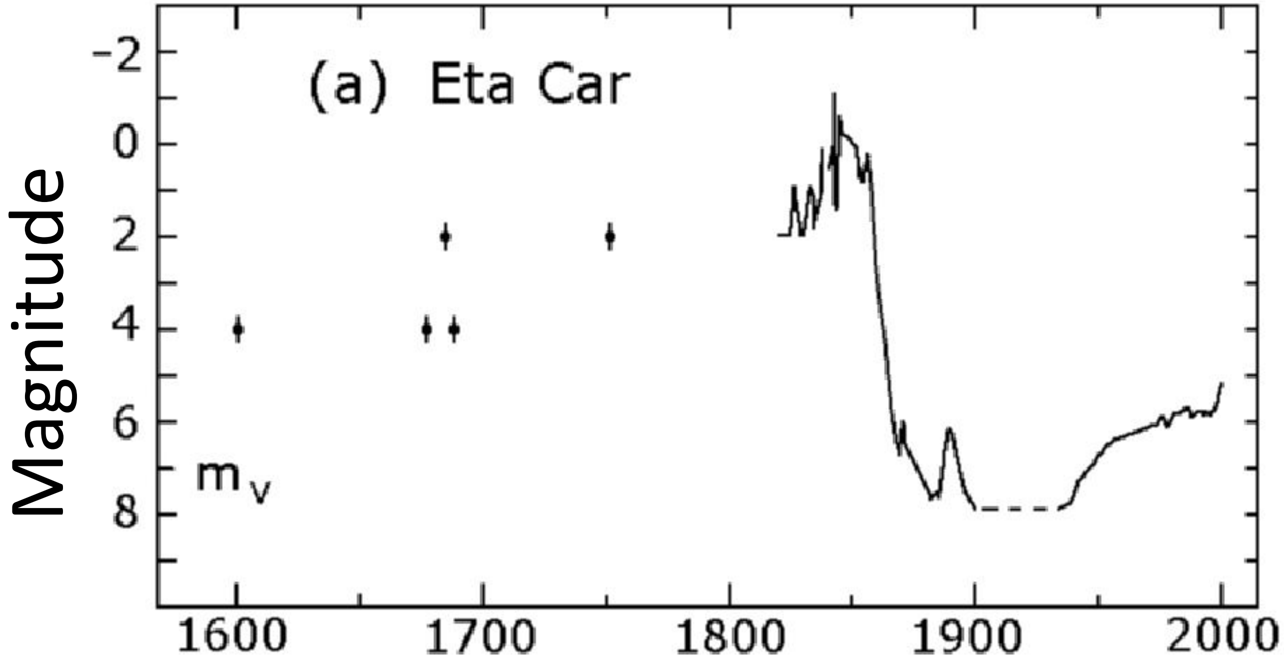


η Car

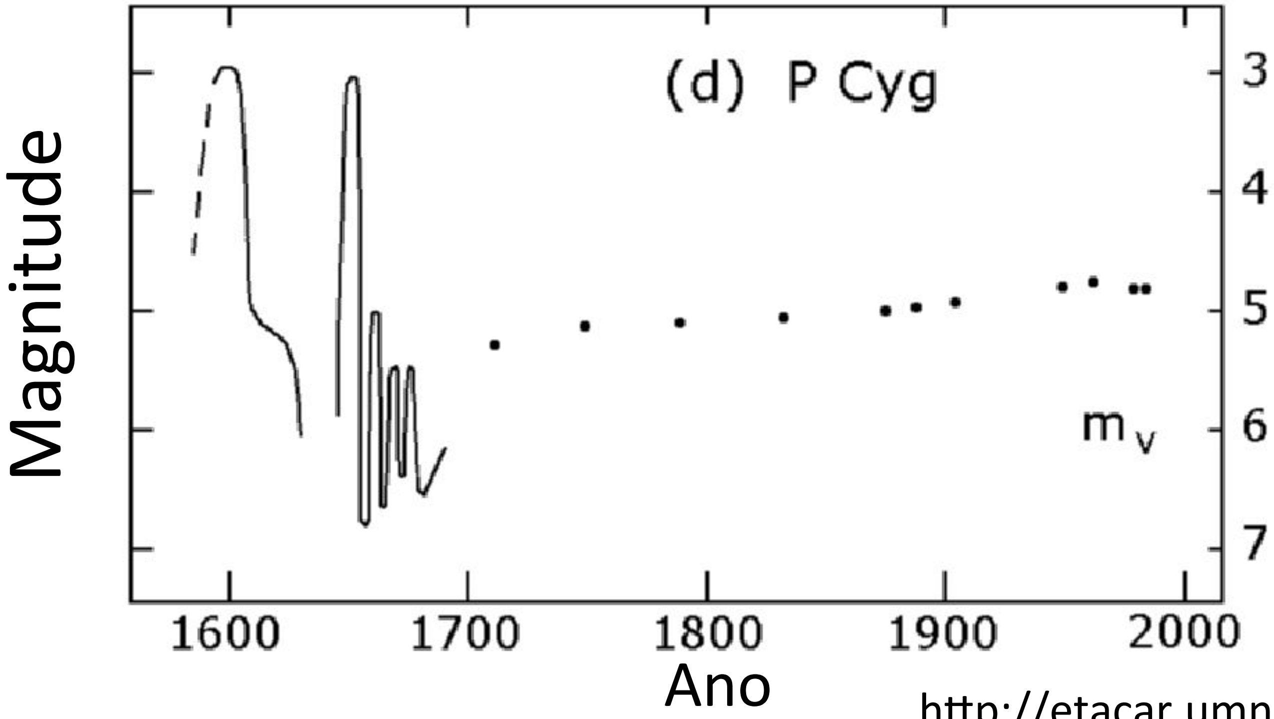
2300 parsecs

Figure 1. Historical *V* magnitude light curve

Kashi & Soker 2010 ApJ 723, 602



2300 parsecs



1700 parsecs

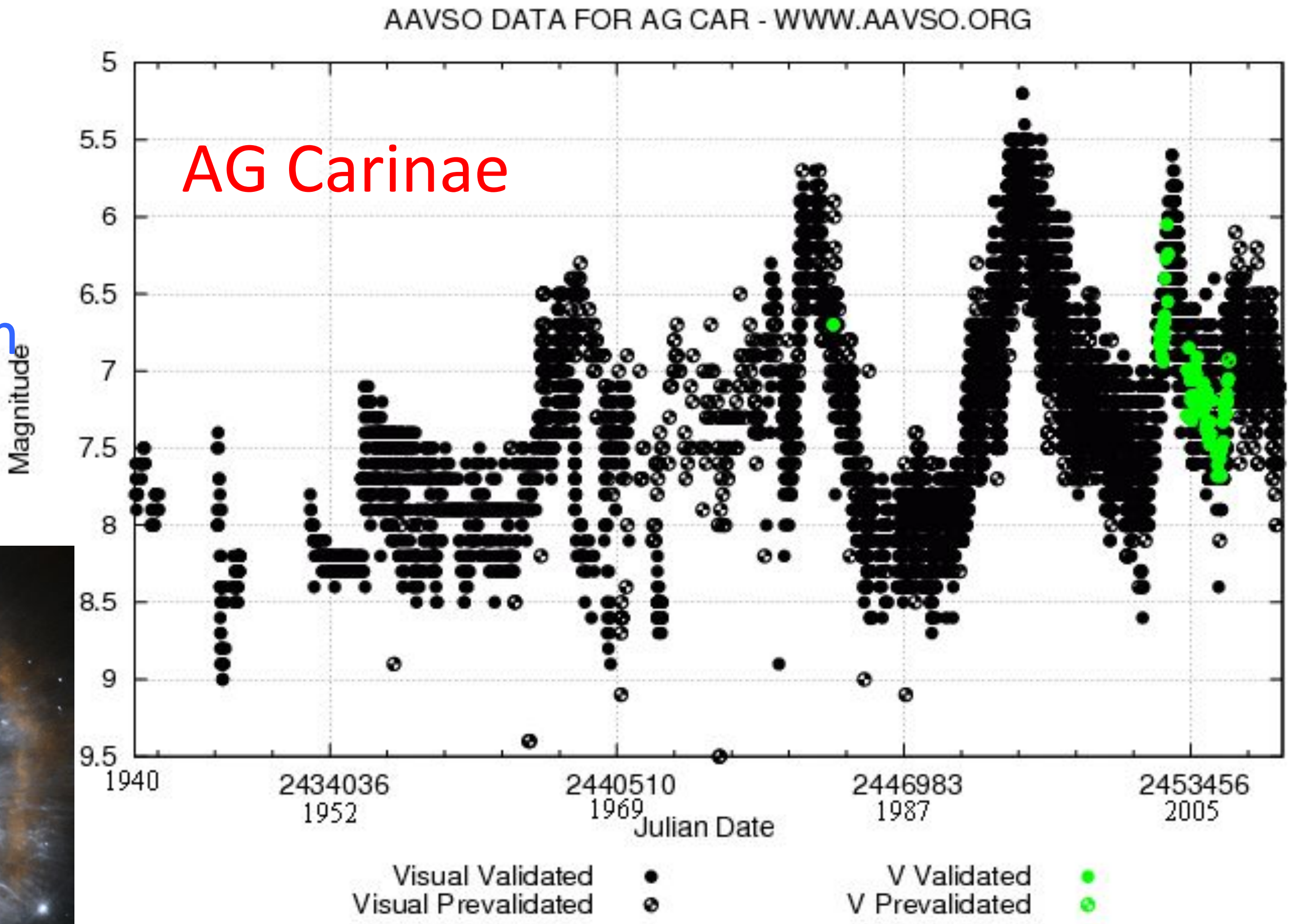
http://etacar.umn.edu/LuminousStars/

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

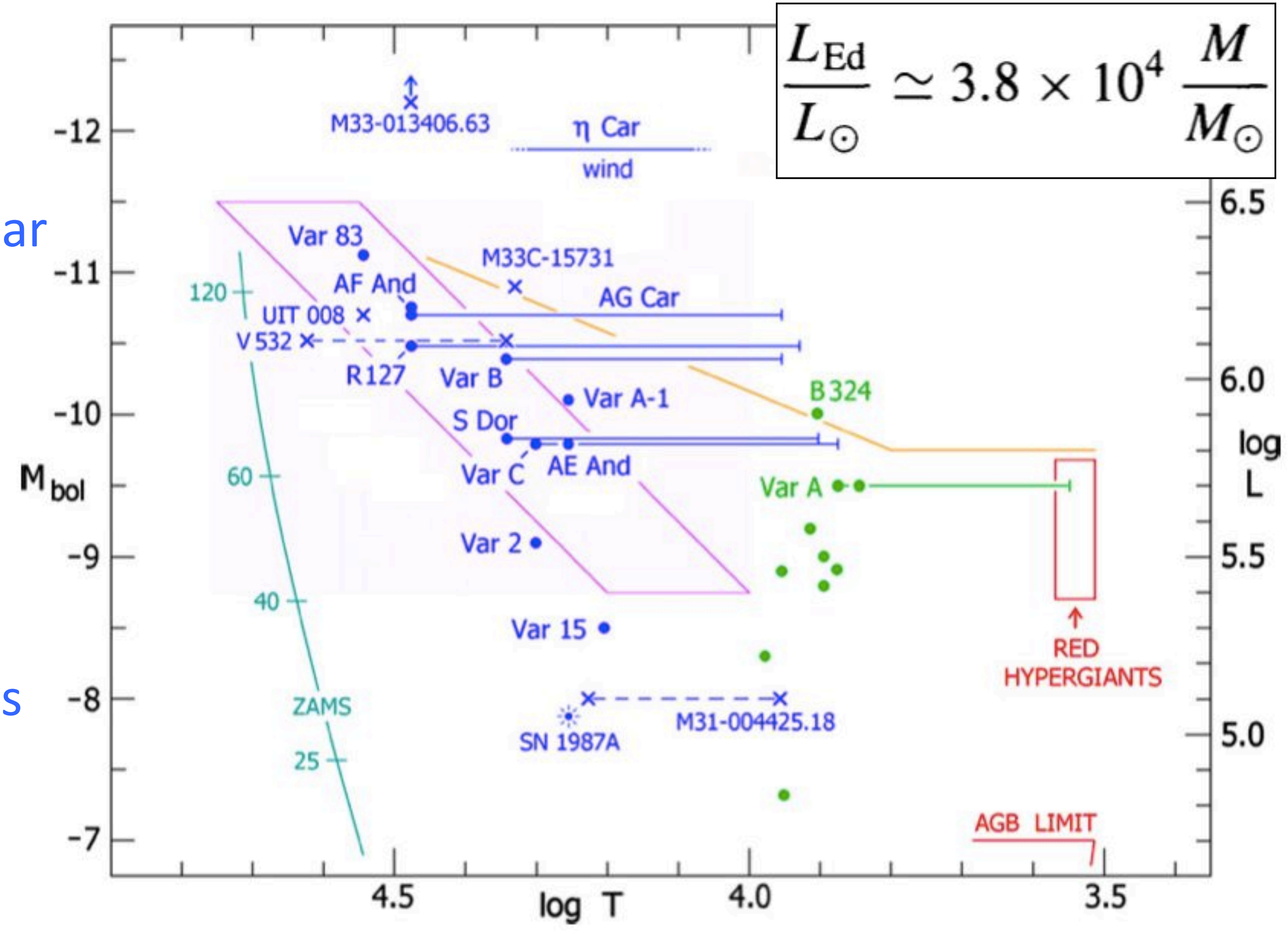
Luminous blue variables (LBVs)

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

Na Galáxia:
Eta Car, AG Car

Na LMC:
S Dor, R127

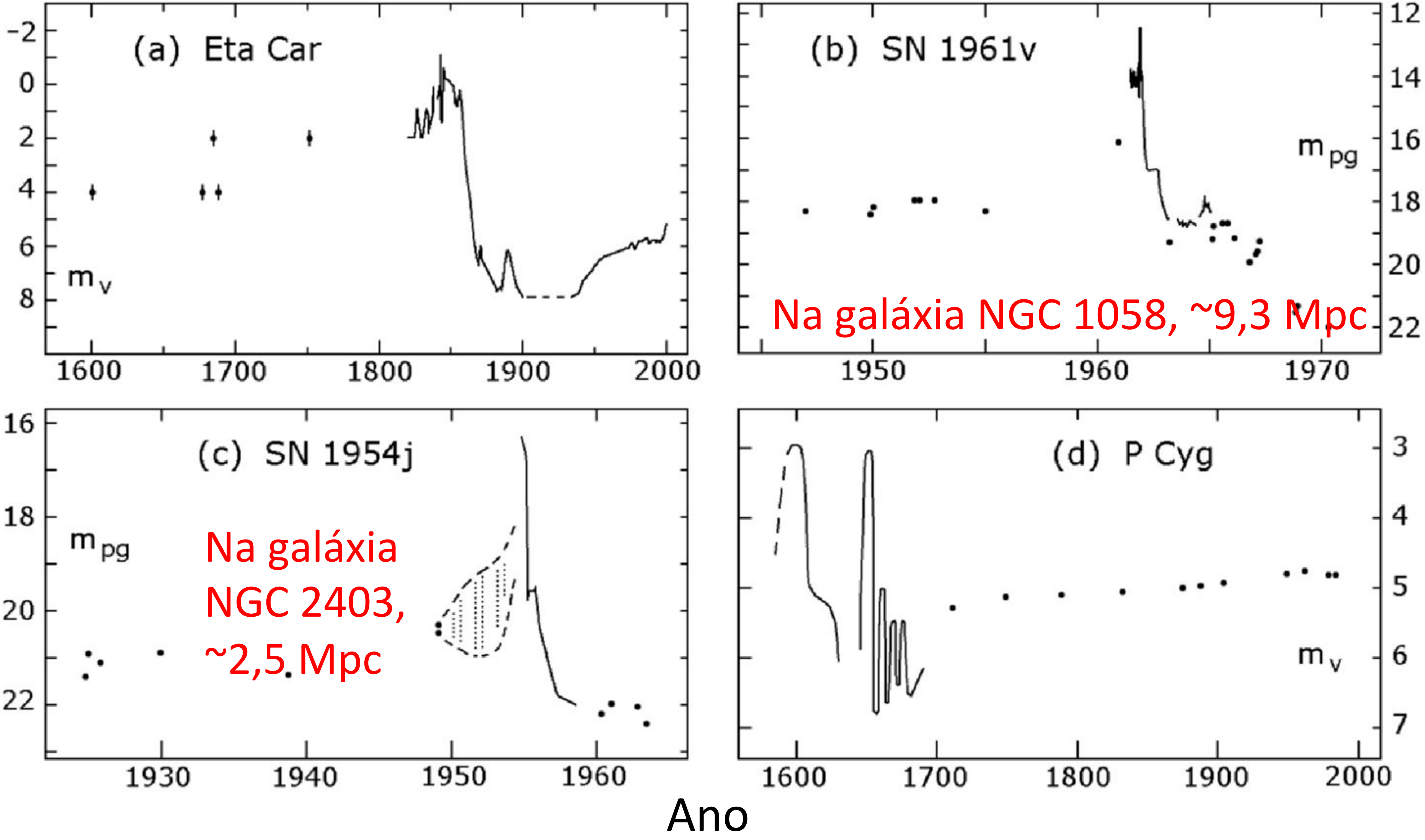
Nas galáxias
M31 e M33:
outros pontos
em azul



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.

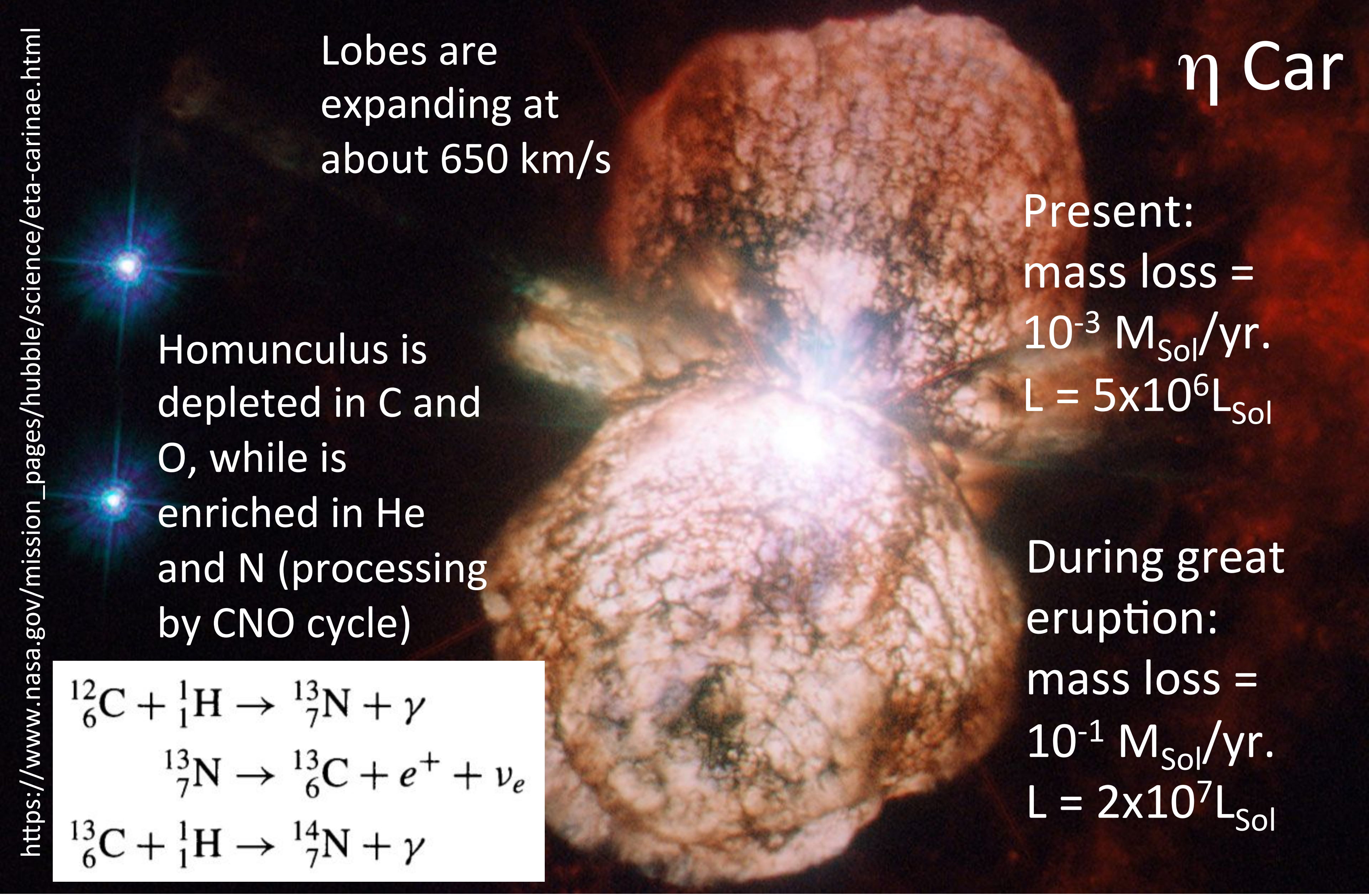
Quando apresentam grandes variações, as LBVs são chamadas de *Eta Carina Variables*, "Giant Eruption" LBVs, ou *Supernova Impostors*



Na galáxia NGC 1058, ~9,3 Mpc

Na galáxia NGC 2403, ~2,5 Mpc

η Car



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

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

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

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}

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

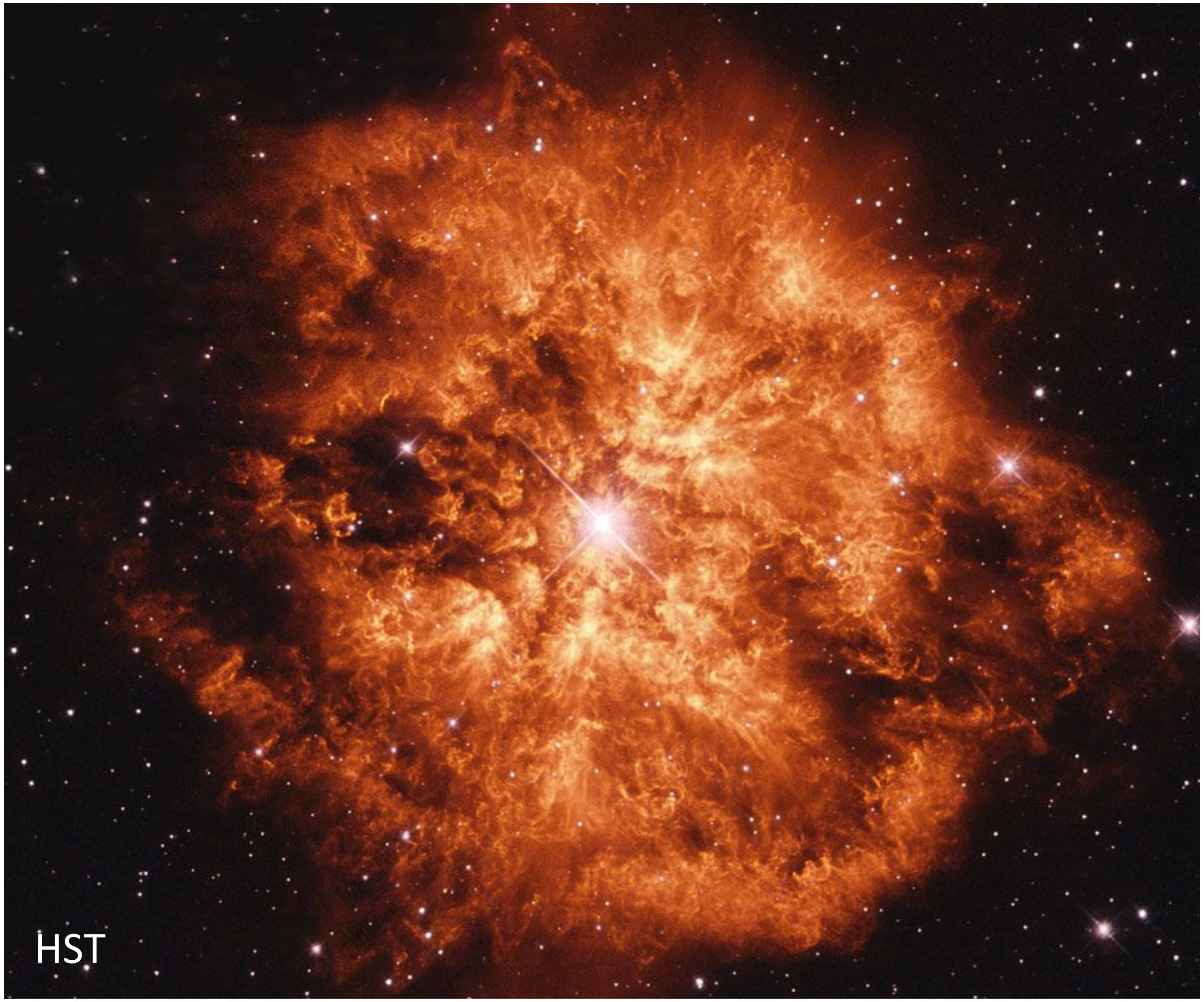
$$L_{\rm Ed} = \frac{4\pi G c}{\overline{\kappa}} M$$

Binarity in LBVs?

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

Estrelas Wolf-Rayet

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



mass loss > 10^{-5} M_{Sun}/yr.

winds
800 – 3000 km/s

Rotation 300 km/s

Masses > 20 M_{Sun}

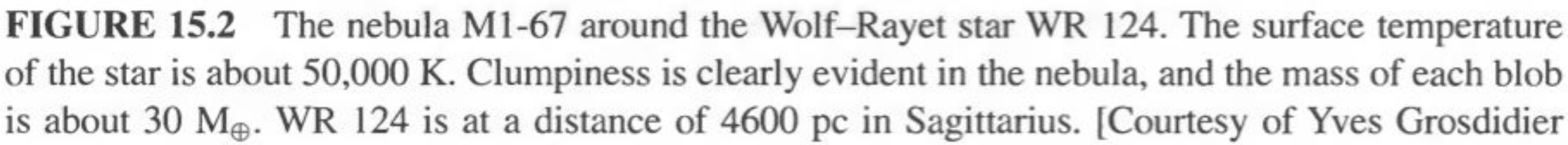
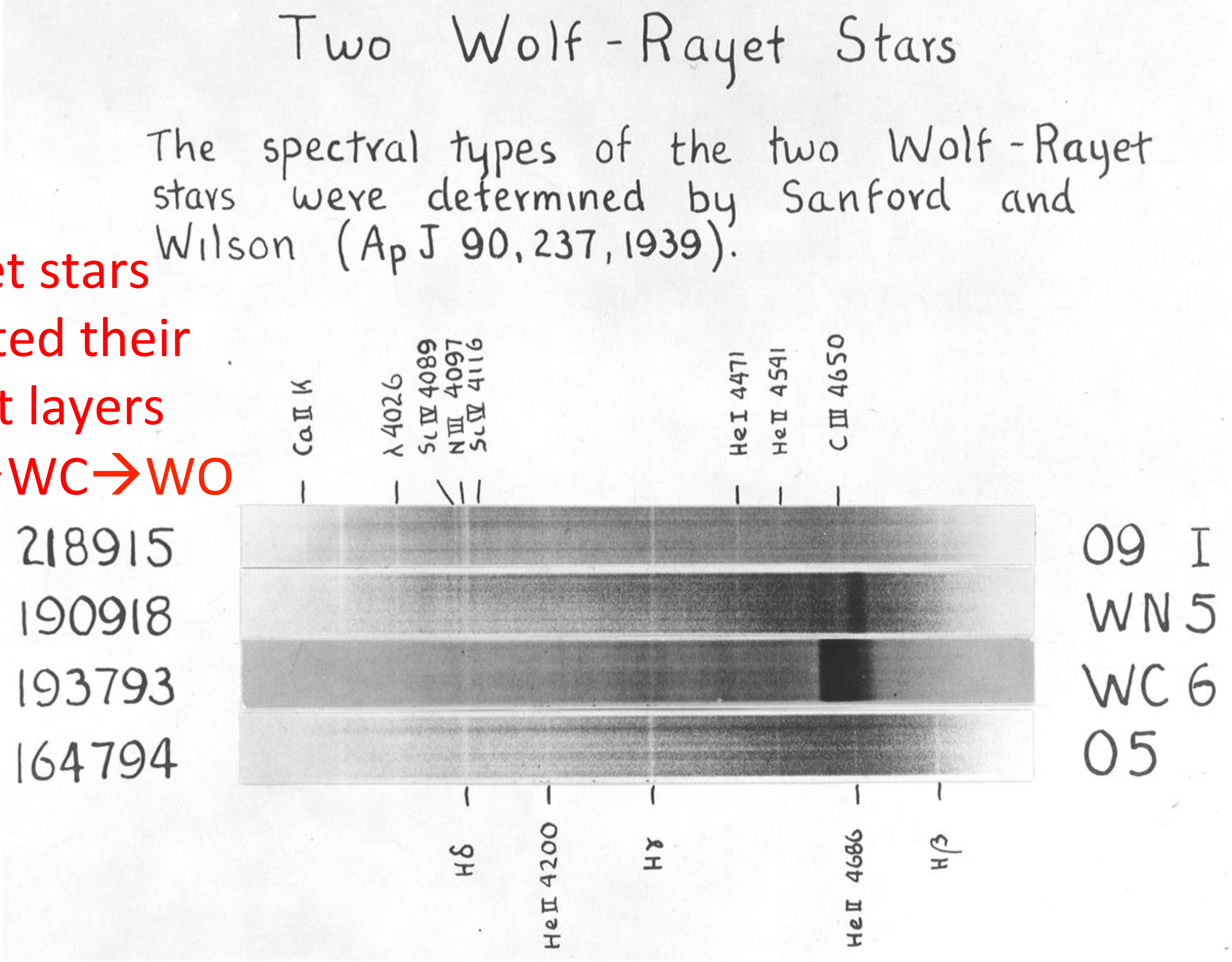


FIGURE 15.2 The nebula M1-67 around the Wolf–Rayet star WR 124. The surface temperature of the star is about 50,000 K. Clumpiness is clearly evident in the nebula, and the mass of each blob is about 30 $M_\oplus$. WR 124 is at a distance of 4600 pc in Sagittarius. [Courtesy of Yves Grosdidier

Wolf Rayet: WN, WC, WO

Wolf Rayet stars have ejected their outermost layers

O→WN→WC→WO

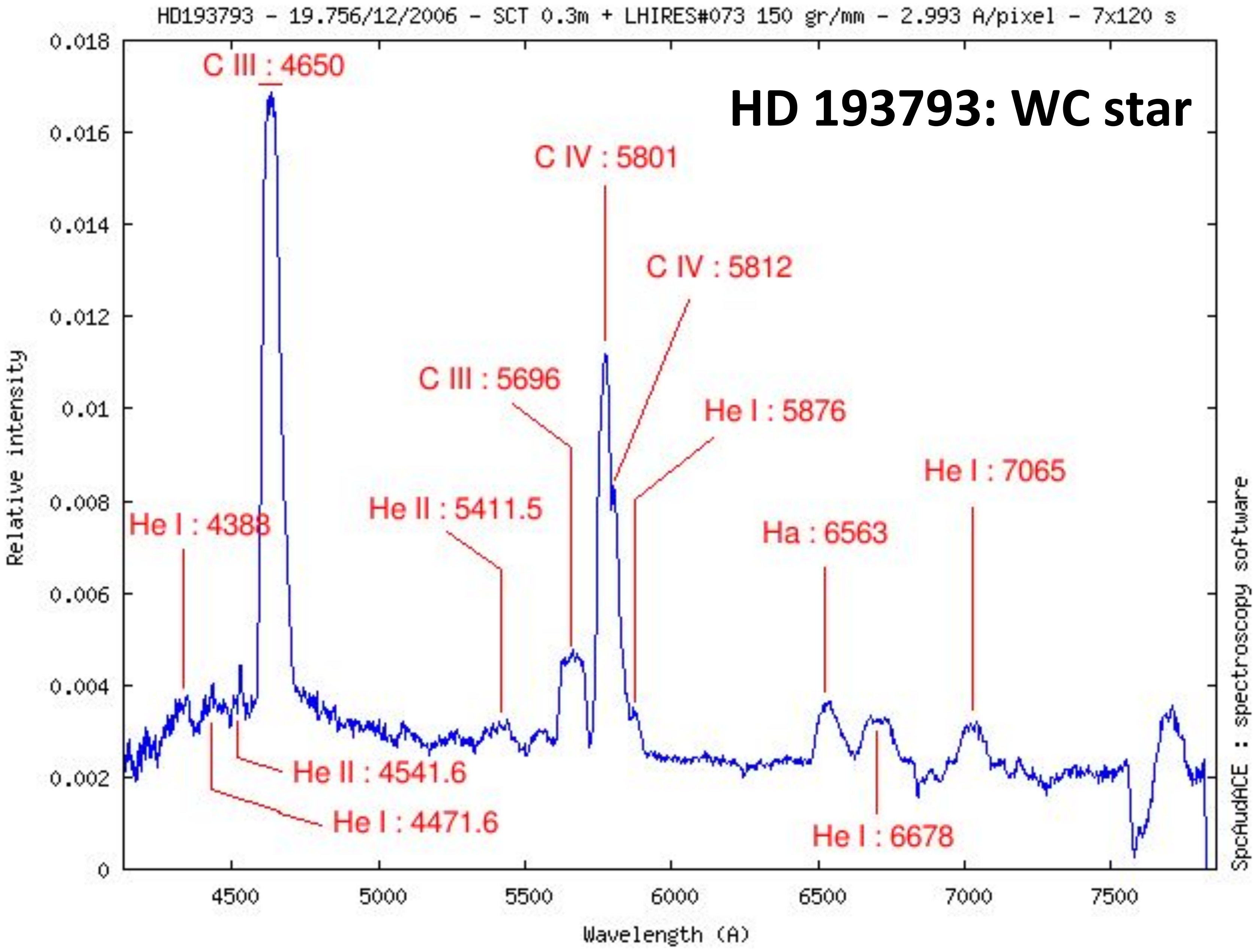


Two Wolf-Rayet Stars

The spectral types of the two Wolf-Rayet stars were determined by Sanford and Wilson (ApJ 90, 237, 1939).

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

HD 193793: WC star

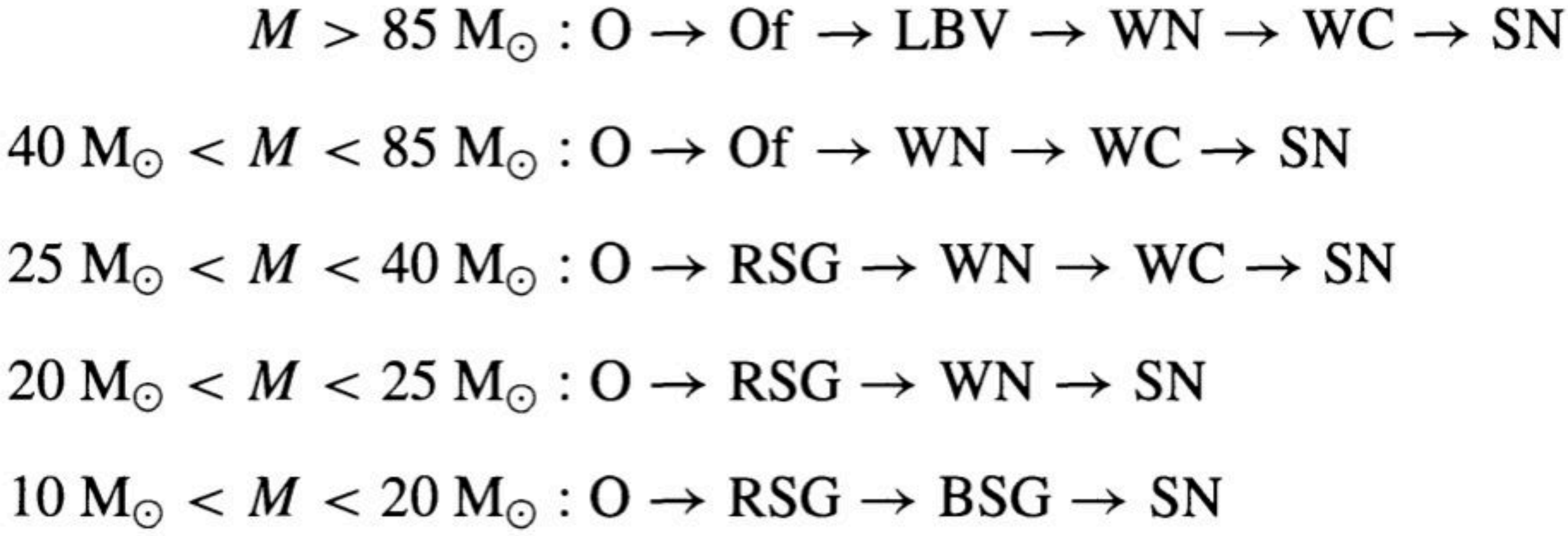


http://wsdiscovery.free.fr/astronomie/spectro/pedagogie/identite/index.html

Outros tipos de estrelas na parte superior do diagrama HR

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

Evolução (tentativa) de estrelas massivas



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

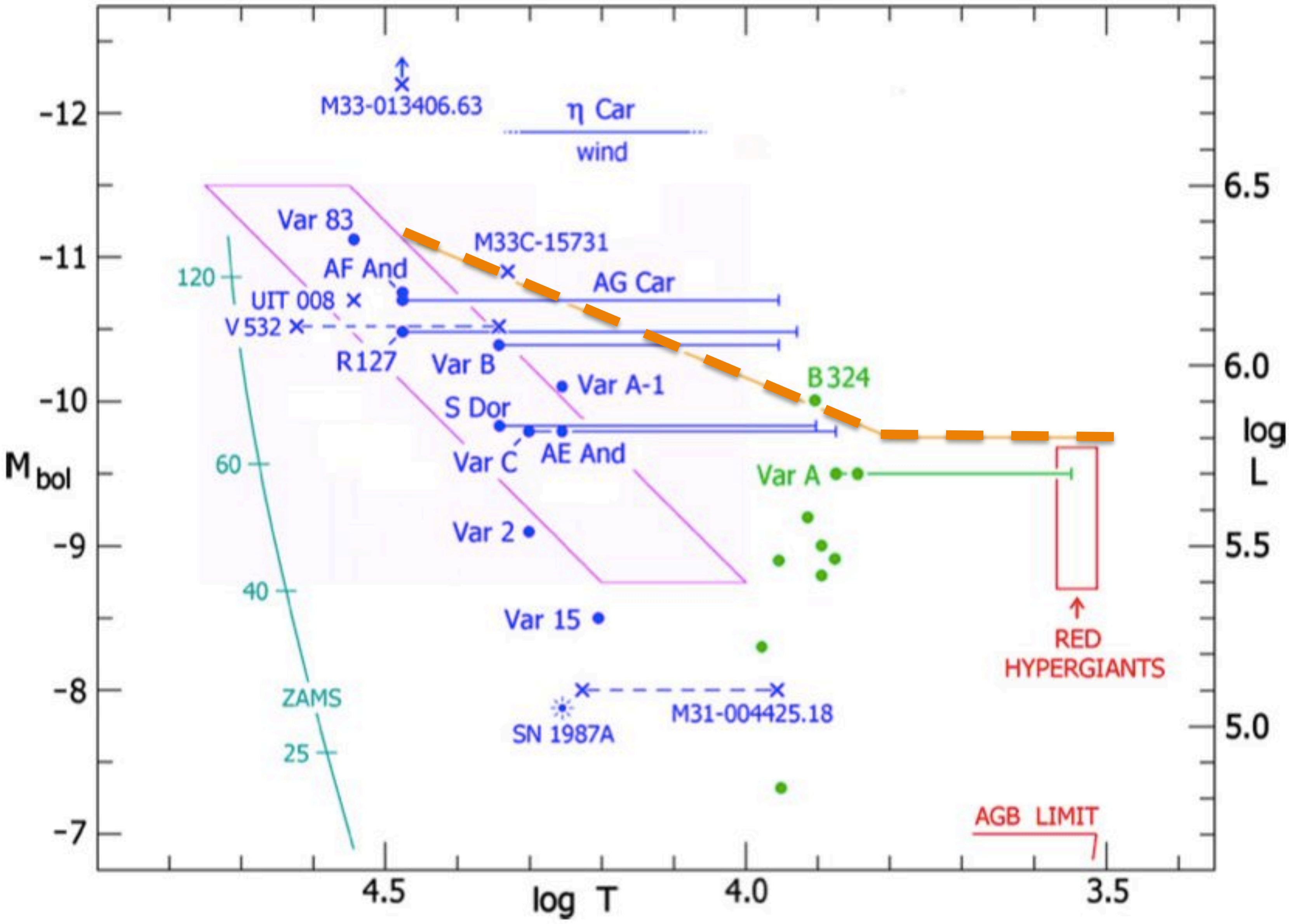
$$40\,\mathrm{M}_\odot < M < 85\,\mathrm{M}_\odot : \mathrm{O} \rightarrow \mathrm{Of} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN}$$

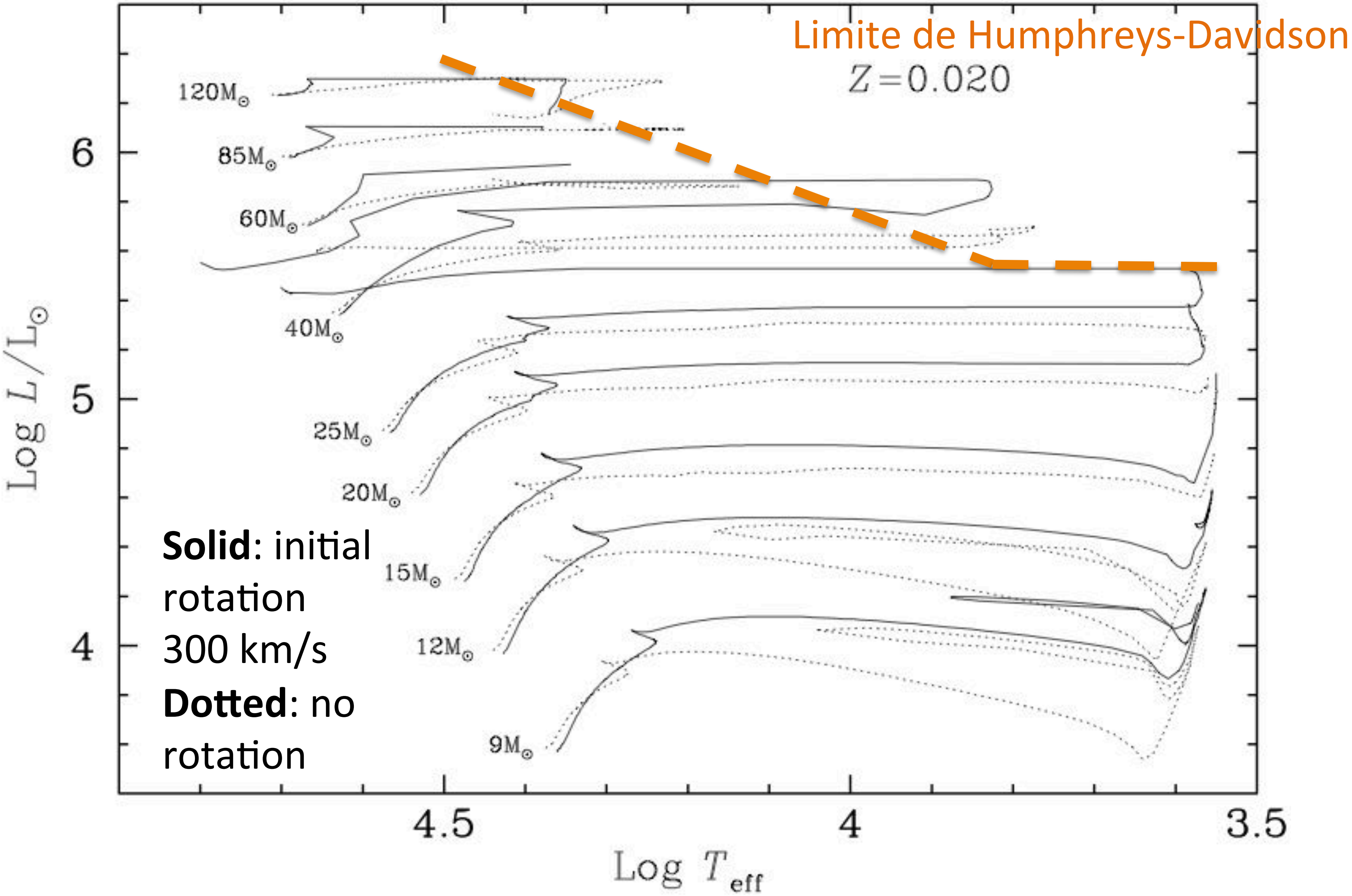
$$25\,\mathrm{M}_\odot < M < 40\,\mathrm{M}_\odot : \mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN}$$

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

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

- - - - Limite de Humphreys-Davidson



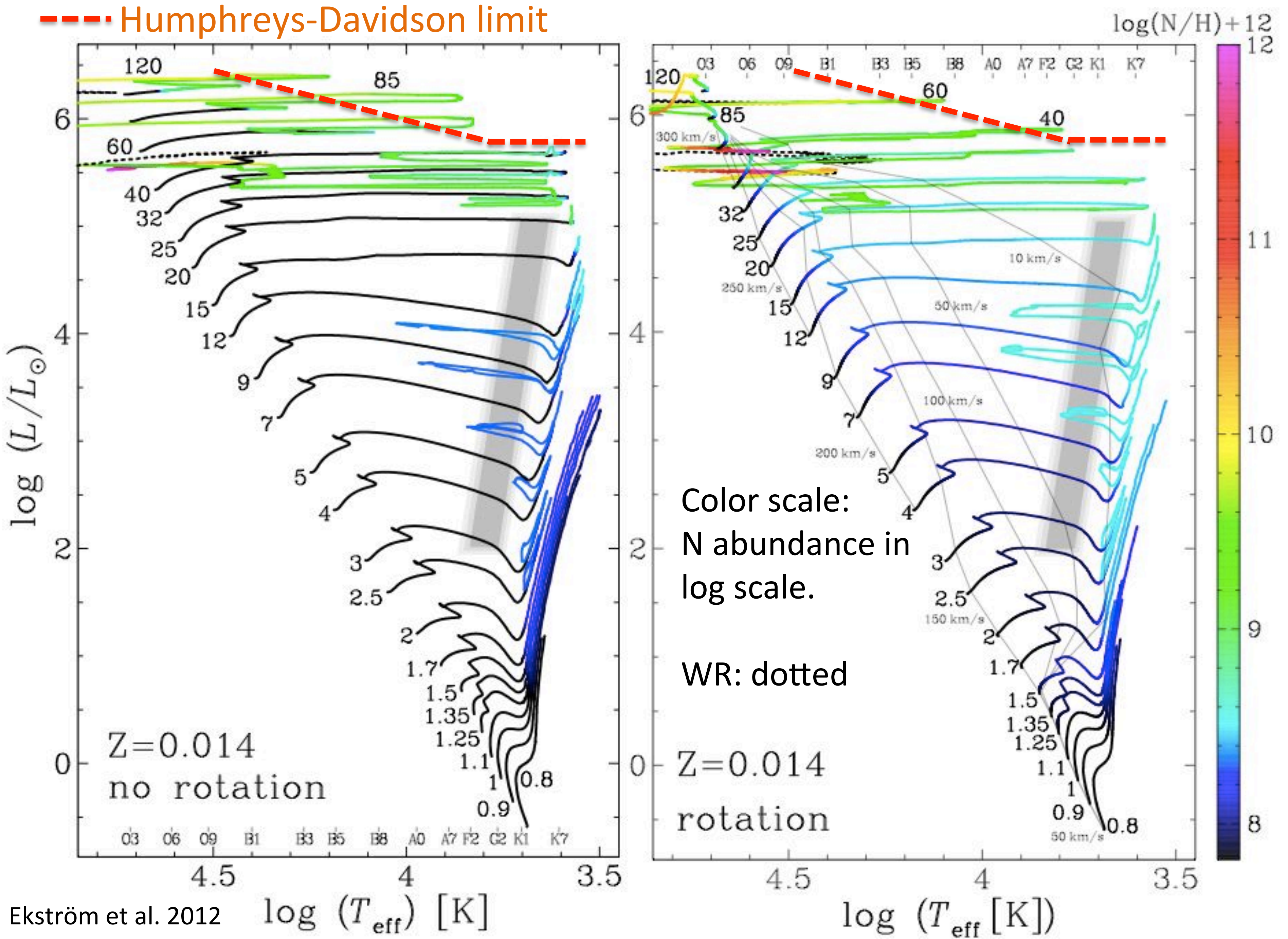


Limite de Humphreys-Davidson

Solid: initial rotation 300 km/s

Dotted: no rotation

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.)



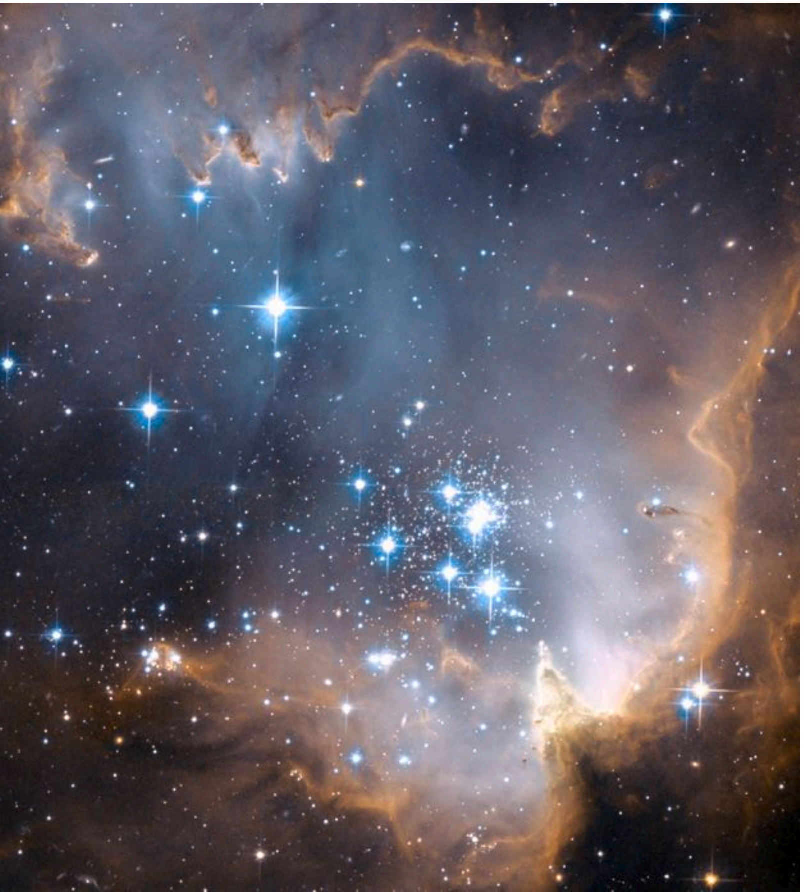
Color scale:
N abundance in log scale.

WR: dotted

Ekström et al. 2012
A&A 537, A146

Importância das estrelas massivas

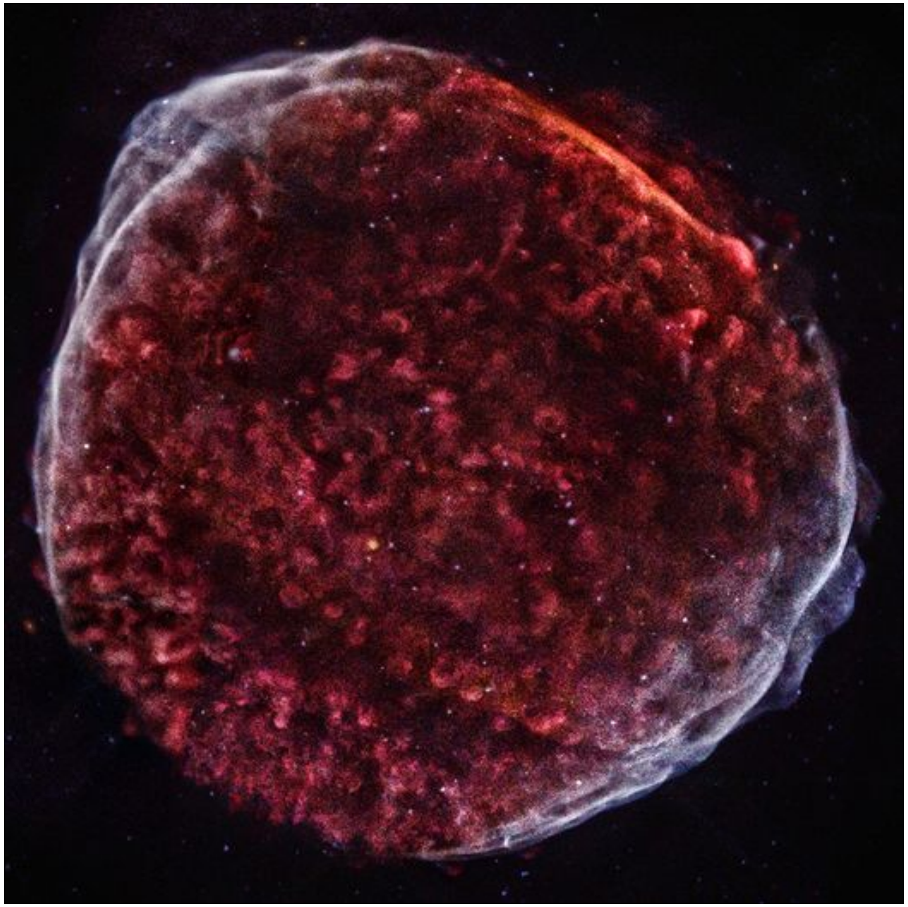
NGC 602, HST



- São poucas: 1 de 100 M_{Sol} por cada 1 milhão de 1 M_{Sol}
- Porem 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, desestabiliza nuvens moleculares → enriquecimento químico e formação de estrelas

Classificação de supernovas

X-rays, Chandra @NASA



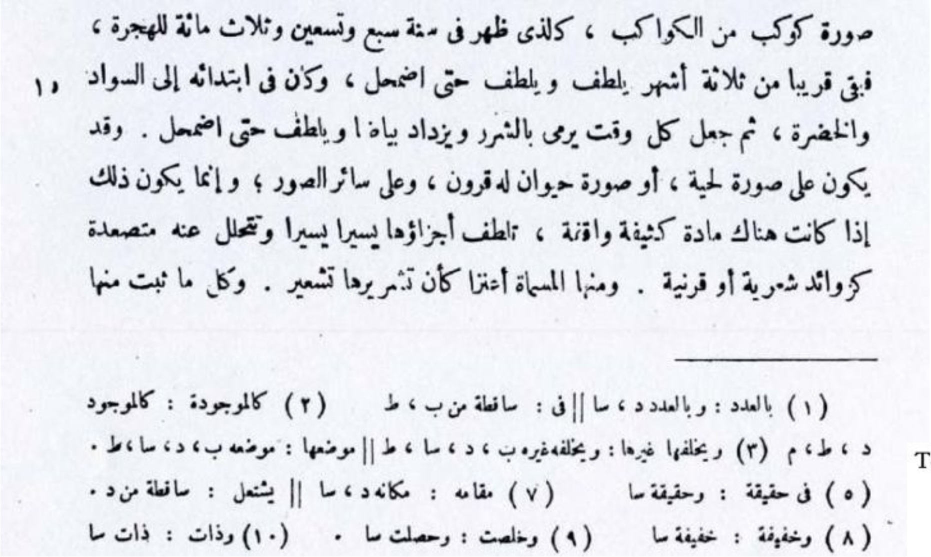
Supernova 1006

V ~ -7,5 (a mais brilhante já observada)

d = 2,2 kpc

Coordenadas:

A.R.= 15 02 22.1 Dec =-42 05 49

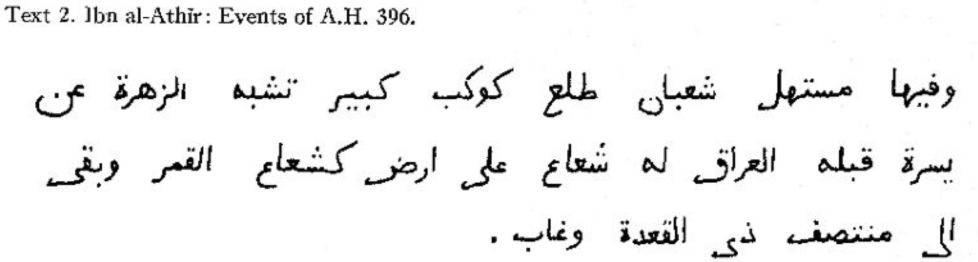


صورة كوكب من الكواكب ، كالذى ظهر فى سنة سبع وتسعين وثلاث مائة للهجرة ،
فبقى قريبا من ثلاثة أشهر يلطف ويلطف حتى اضمحل ، وكان فى ابتدائه إلى السواد
والخضرة ، ثم جعل كل وقت يرمى بالشرر ويزداد بياضا ويلطف حتى اضمحل . وقد
يكون على صورة لحية ، أو صورة حيوان له قرون ، وعلى سائر الصور ؛ وإنما يكون ذلك
إذا كانت 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 || ف : 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)



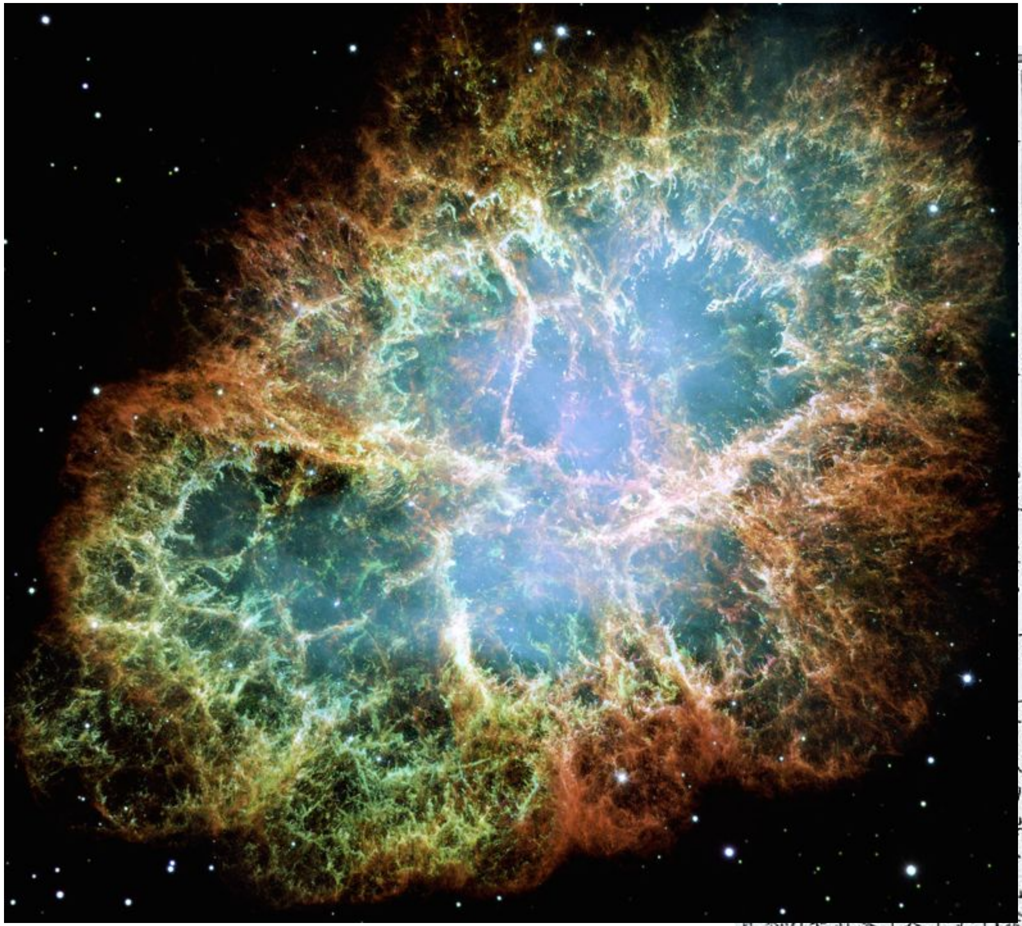
Text 2. Ibn al-Athīr: Events of A.H. 396.

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

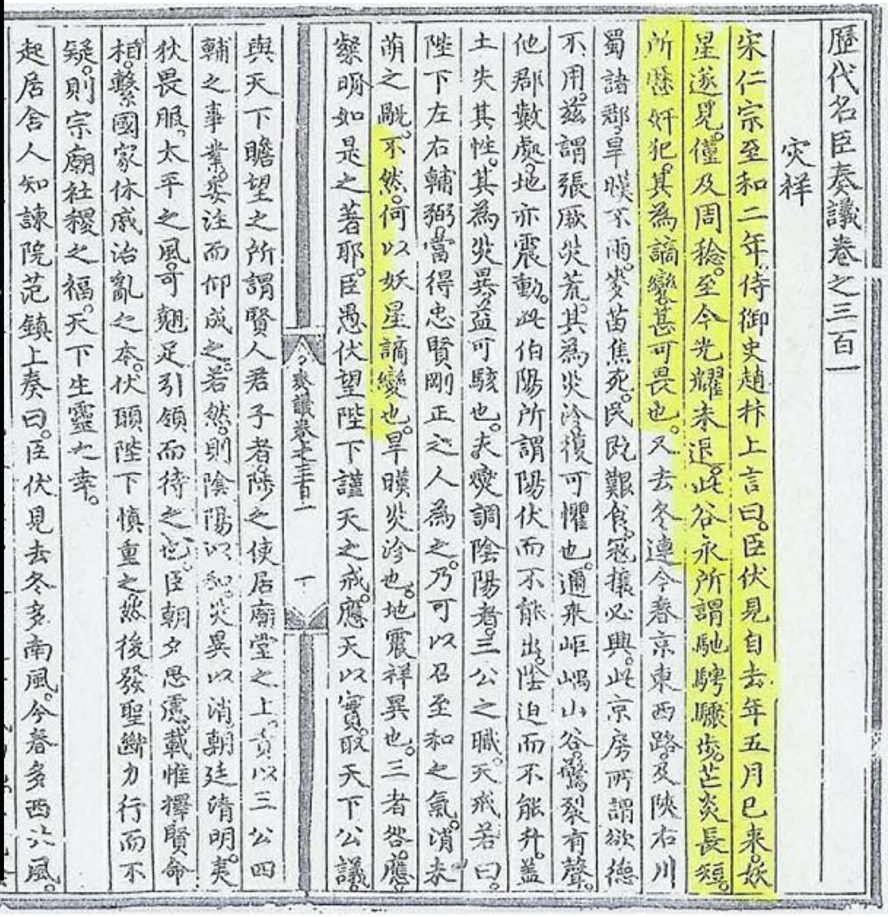
Goldstein (1965, ApJ 70, 105)

Supernova 1054

$V \sim -6$, $d \sim 2$ kpc



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。芒炎長短。所歷奸犯。其爲讁變甚可畏也。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。民既艱食。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。邇來岷峨山谷。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。天戒若曰。陛下左右輔弼。當得忠賢剛正之人爲之。乃可以召至和之氣。消未萌之亂。不然。何以妖星讁變也。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。取天下公議。

奏議卷之三百一　十

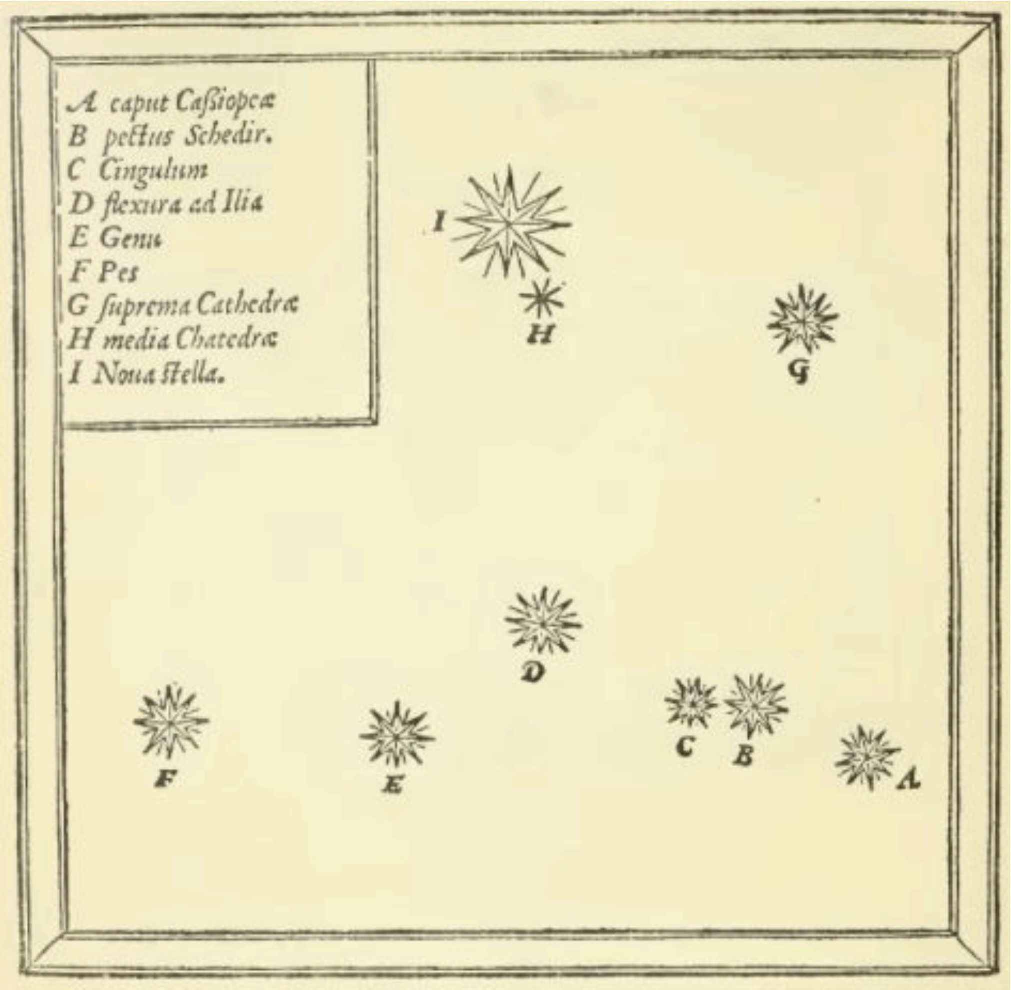
與天下瞻望之所謂賢人君子者。陟之使居廟堂之上。責以三公四輔之事。業委注而仰成之。若然。則陰陽以和。災異以消。朝廷清明。夷狄畏服。太平之風。可翹足引領而待之也。臣朝夕思慮。載惟擇賢命相。繫國家休戚治亂之本。伏願陛下慎重之。然後發聖斷。力行而不疑。則宗廟社稷之福。天下生靈之幸。

起居舍人知諫院范鎮上奏曰。臣伏見去冬多南風。今春多西北風。

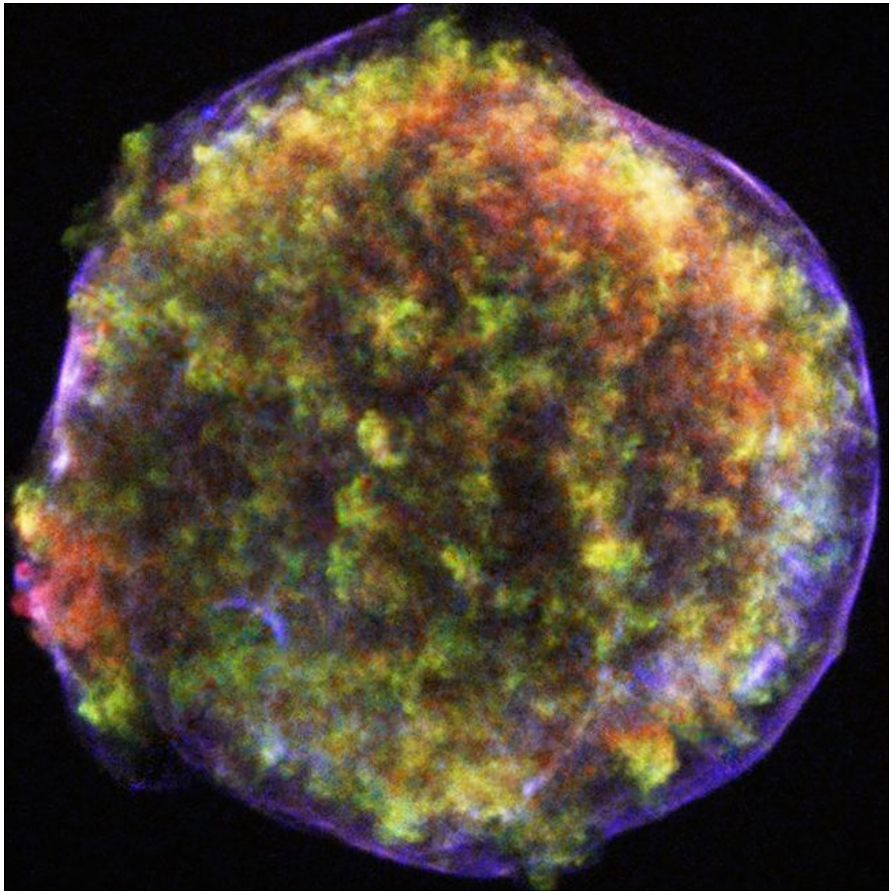
The guest star reported by Chinese astronomers in 1054 is identified as SN 1054. The highlighted passages refer to the supernova.

Supernova 1572

V ~ -4, d ~ 2,7 kpc



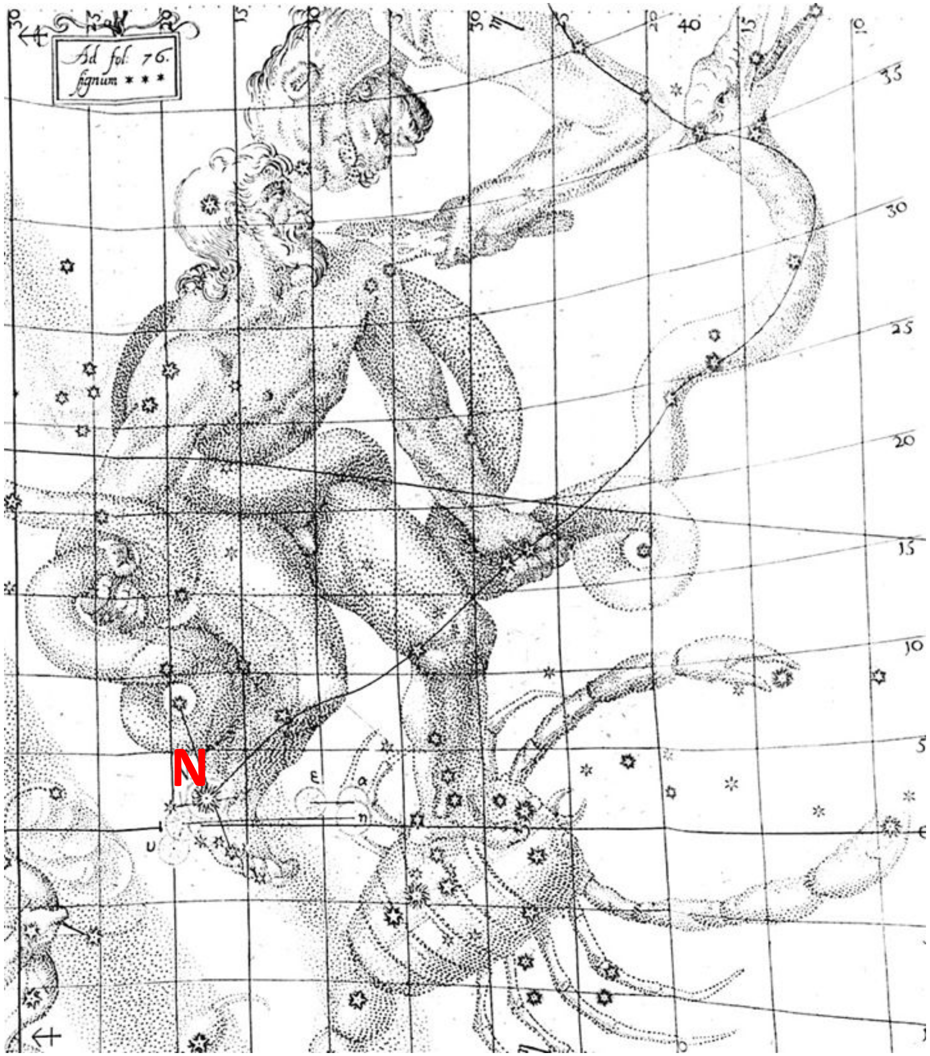
Tycho's notes on SN 1572



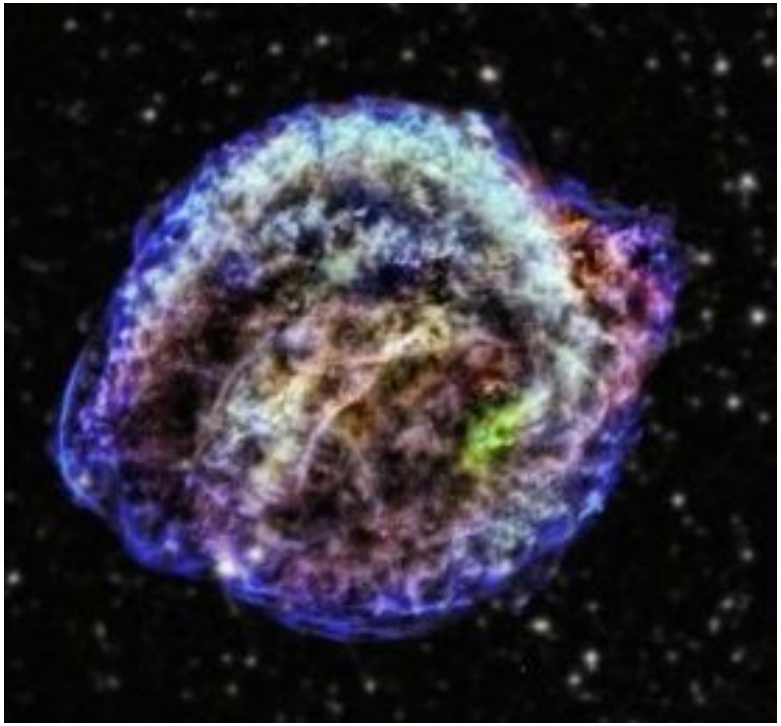
Tycho's Supernova Remnant. Chandra's image of the supernova remnant shows an expanding bubble of multimillion degree debris (green and red) inside a more rapidly moving shell of extremely high energy electrons (filamentary blue).

Supernova 1604,

V ~ -2,4, d ~ 6 kpc



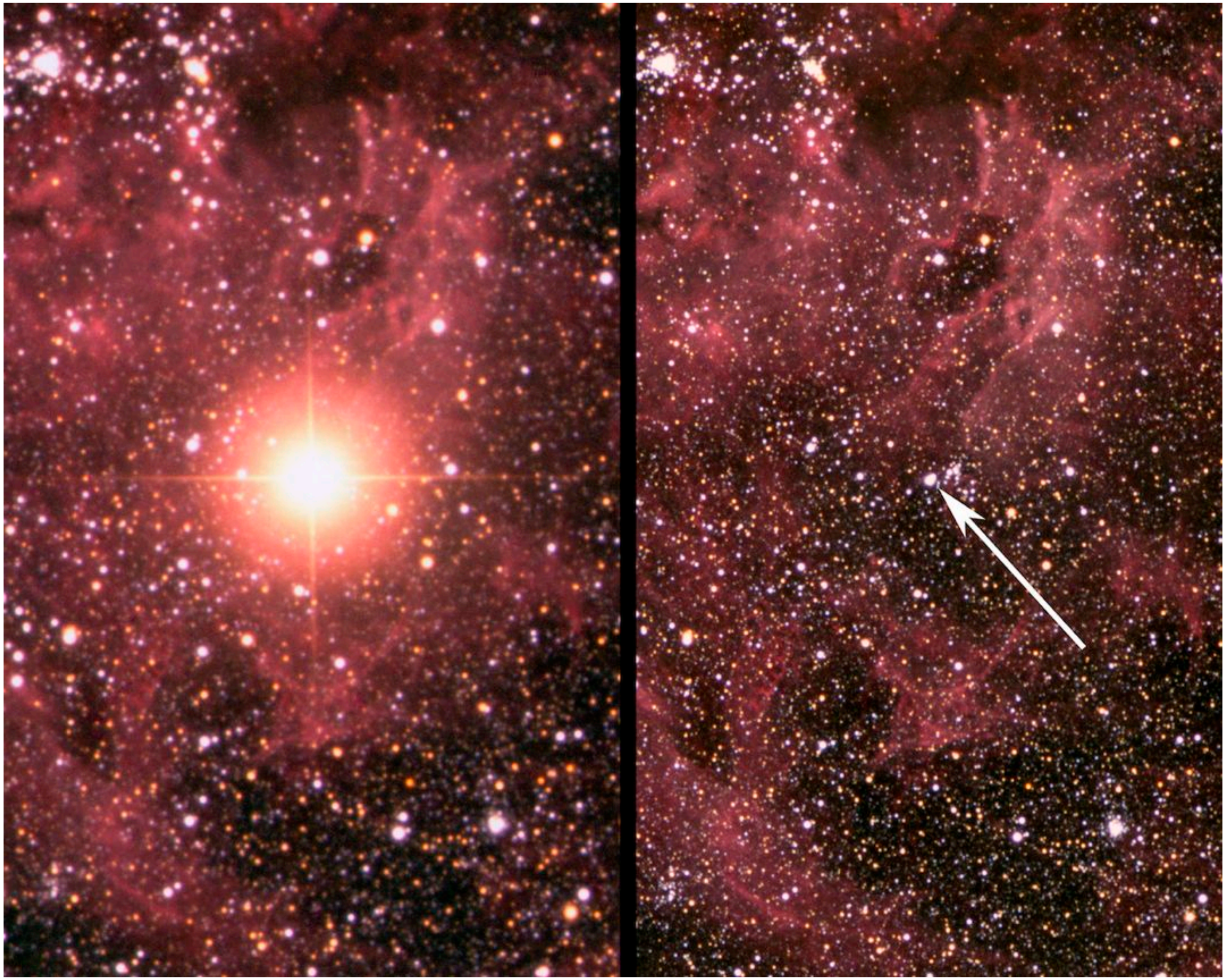
Kepler's original drawing depicting the location of the stella nova (**N**)



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.

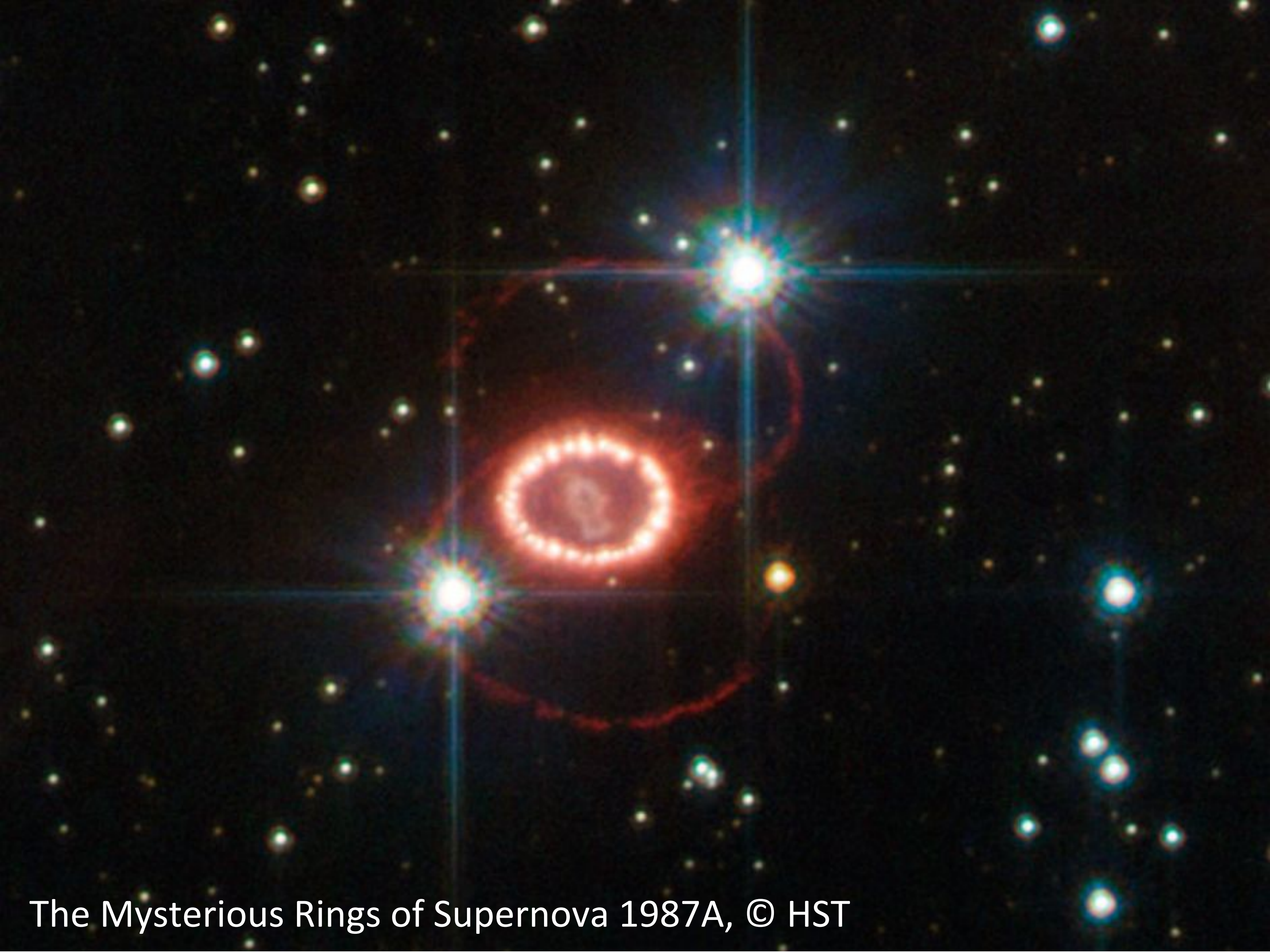
Supernova 1987A, V ~ 2,9; d ~ 51,4 kpc

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



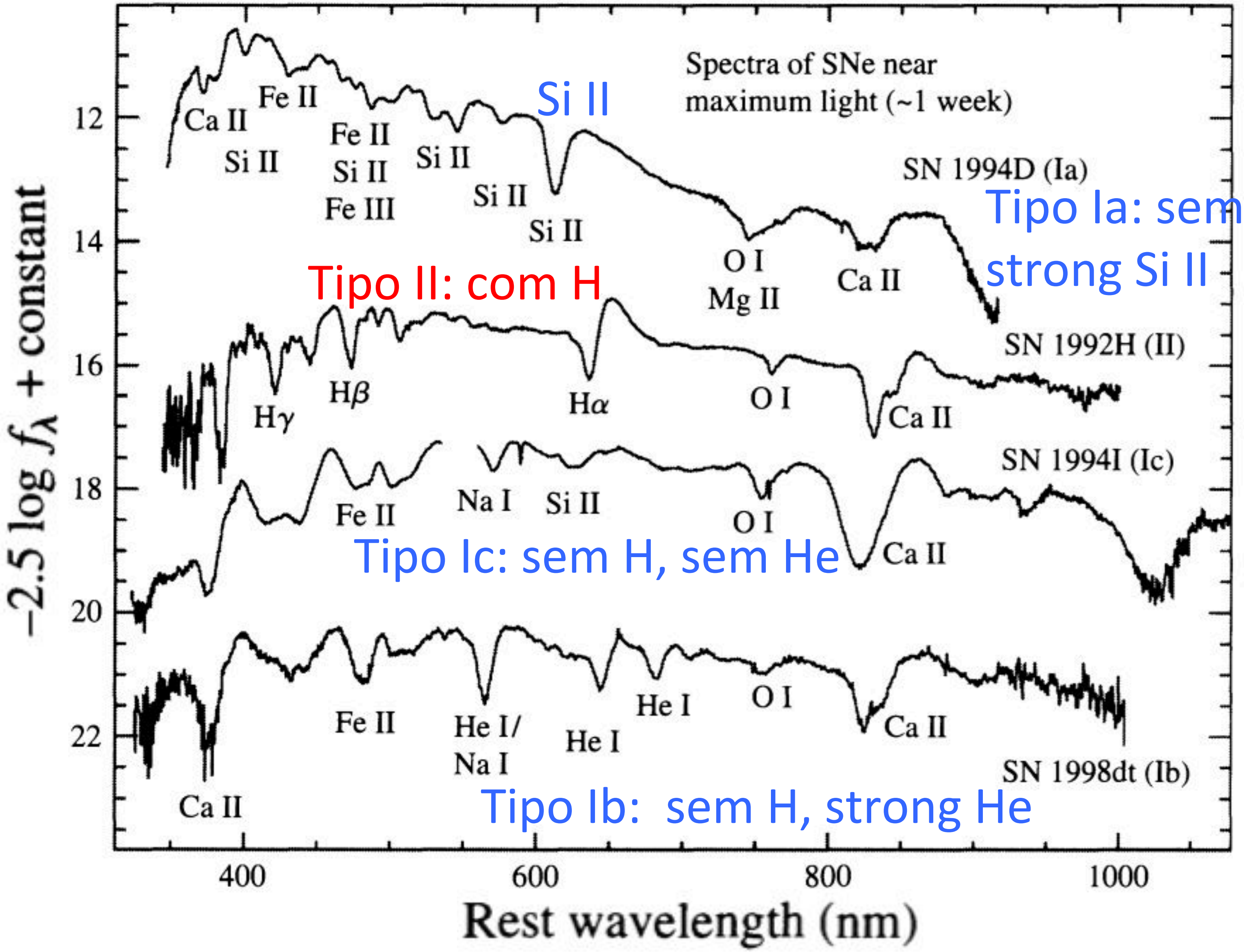
The progenitor star was identified as Sanduleak −69° 202, a blue supergiant

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



The Mysterious Rings of Supernova 1987A, © HST

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



Si II

Tipo Ia: sem H,
strong Si II

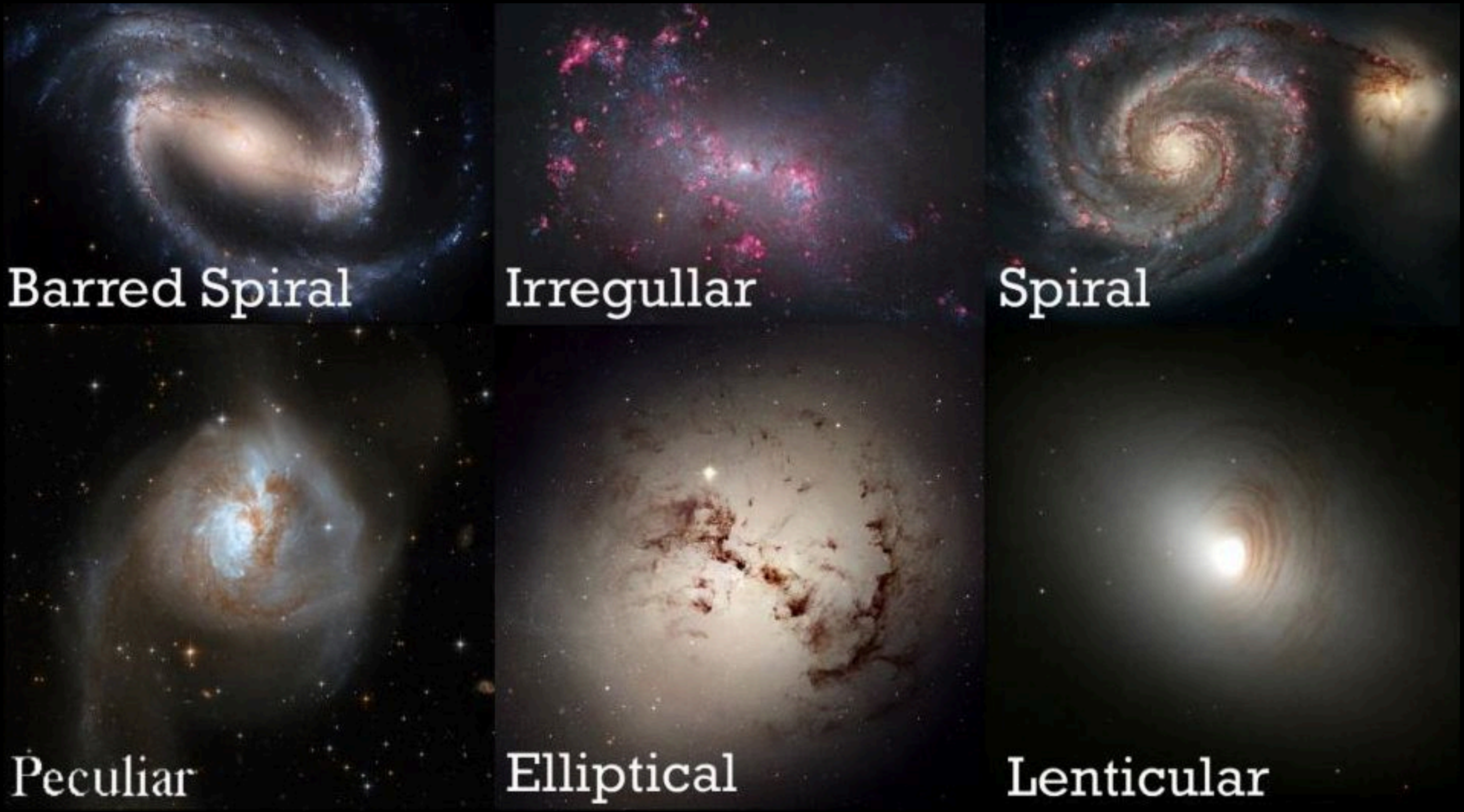
Tipo II: com H

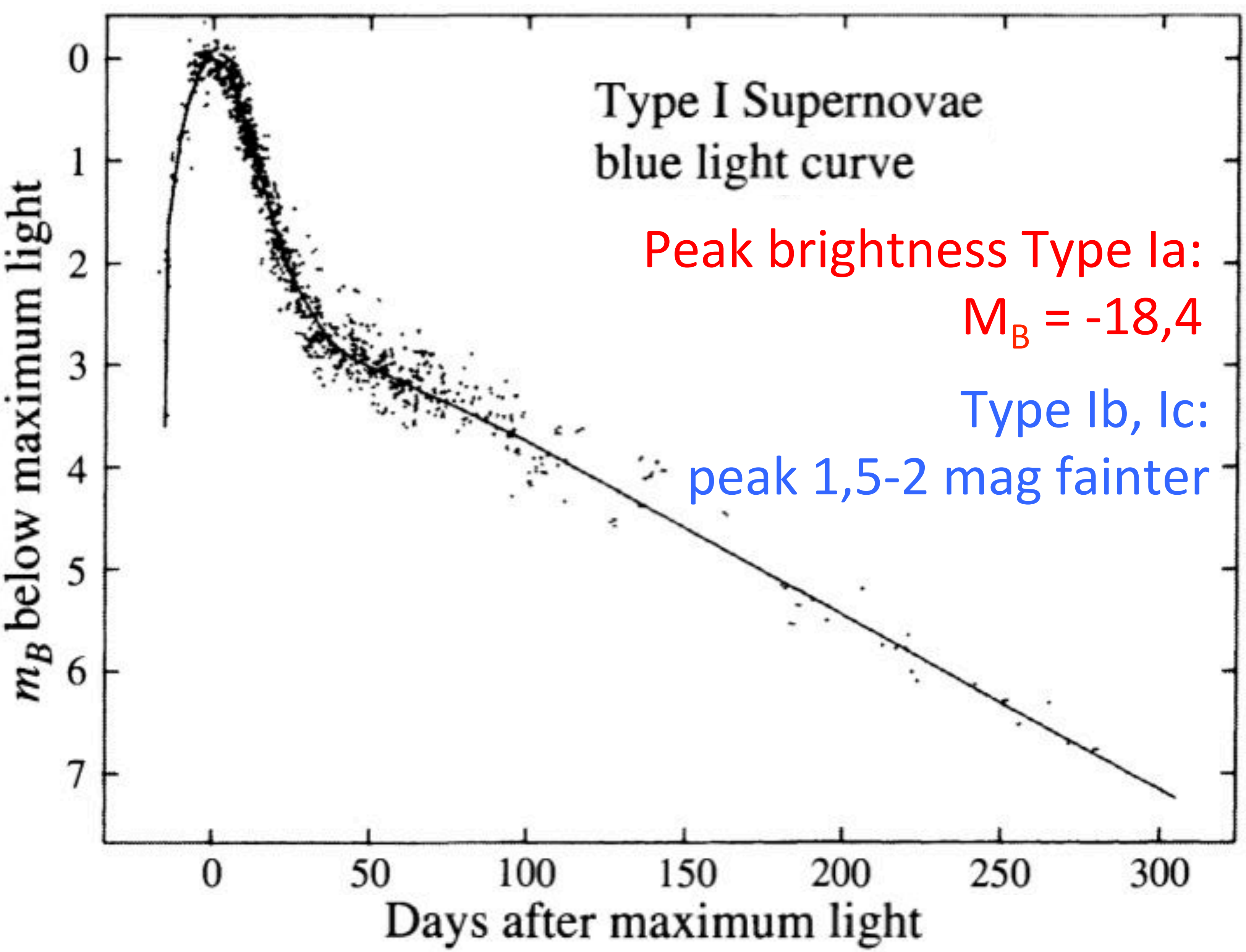
Tipo Ic: sem H, sem He

Tipo Ib: sem H, strong He

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

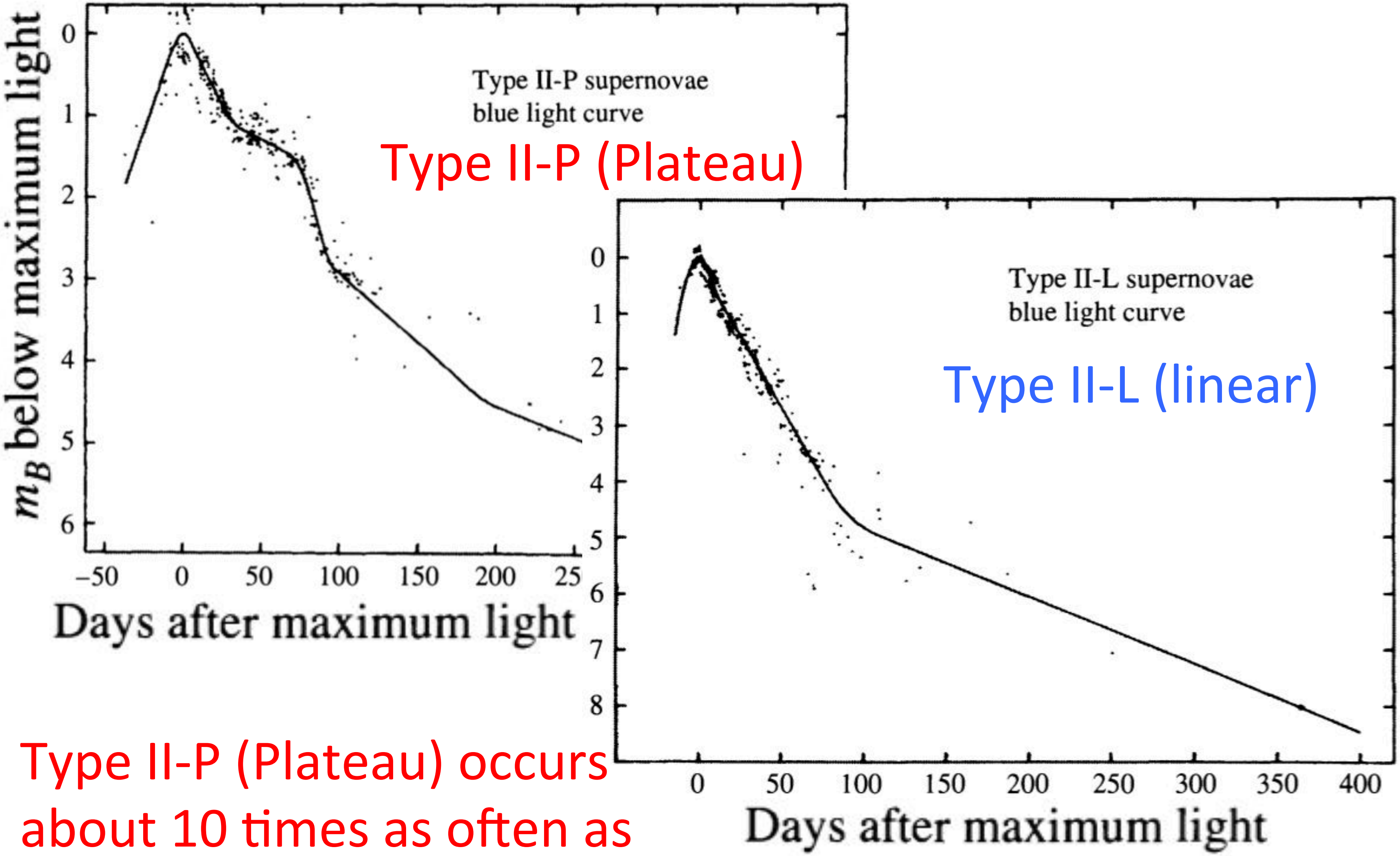




Peak brightness Type Ia:
$M_B = -18,4$

Type Ib, Ic:
peak 1,5-2 mag fainter

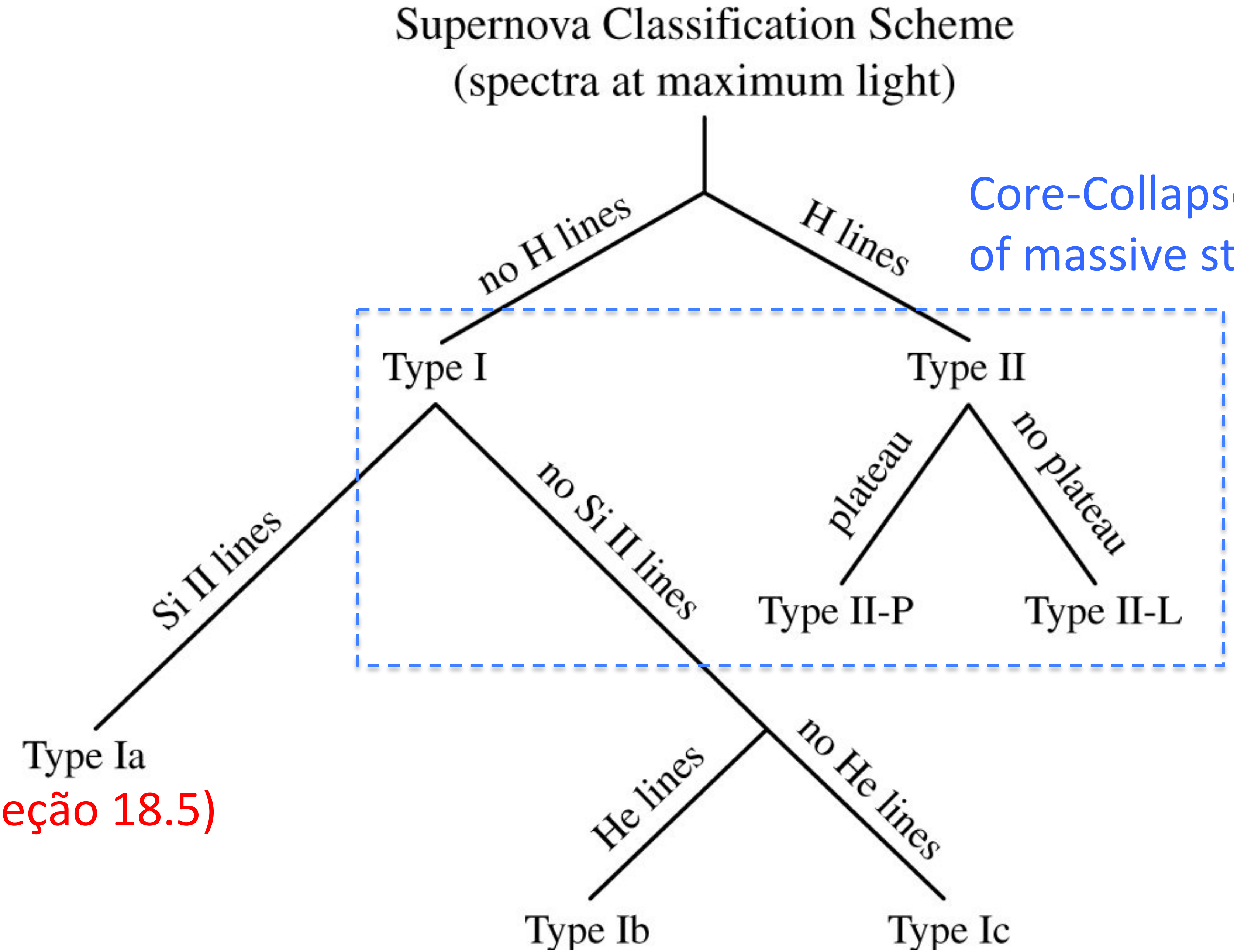
FIGURE 15.7 Composite light curve for Type I supernovae at blue wavelengths. All magnitudes are relative to m_B at maximum. (Figure adapted from Doggett and Branch, *Astron. J.*, *90*, 2303, 1985.)



Type II-P (Plateau)

Type II-L (linear)

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



Core-Collapse
of massive stars

(Seção 18.5)

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

Após queima de He
→ Queima de C e O

T ~ 10^8 K

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

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

T ~ $6\text{x}10^8$ K

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

T ~ 10^9 K

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

***: endotérmica

Silicon burning

T ~ 3×10^9 K

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

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

$$\vdots$$

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

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

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

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

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

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

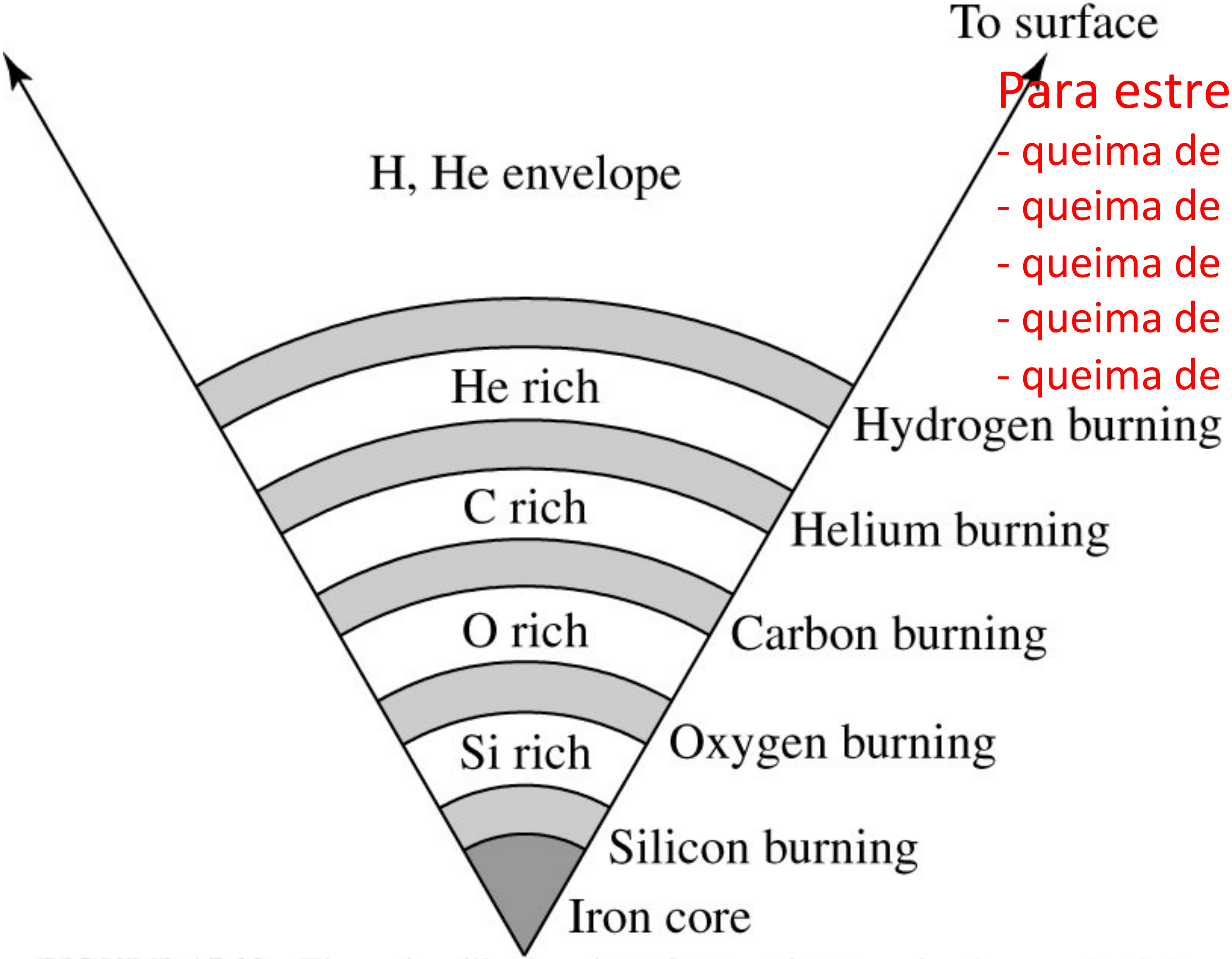
$$^{48}_{24}\mathrm{Cr} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{52}_{26}\mathrm{Fe}$$

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

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

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

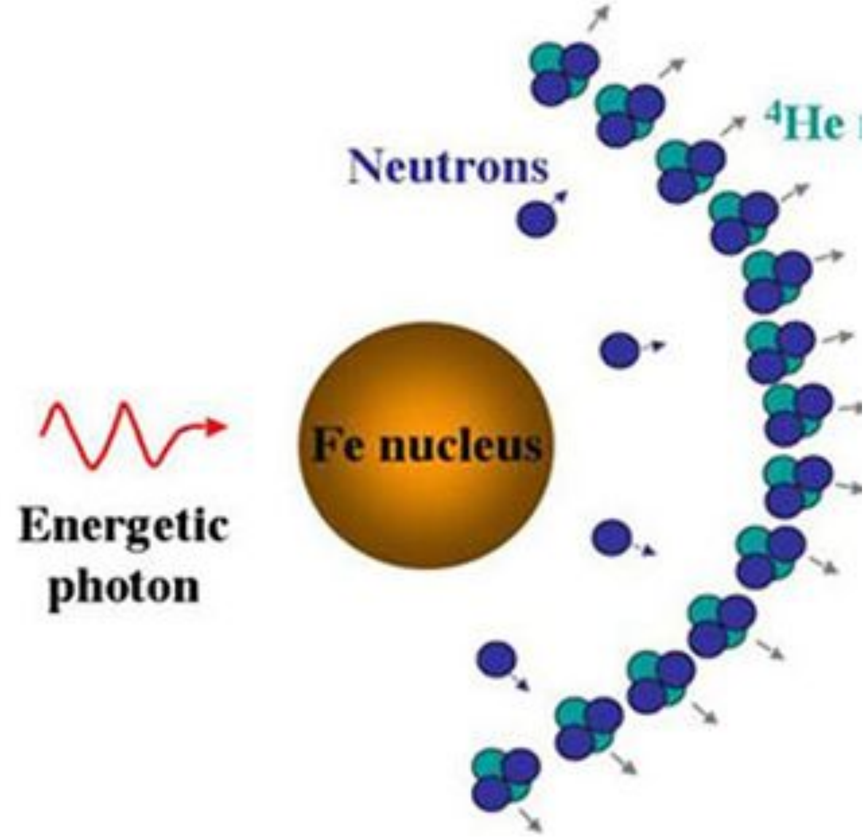
Também temos fotodesintegração do Si → contração



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.

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

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

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}

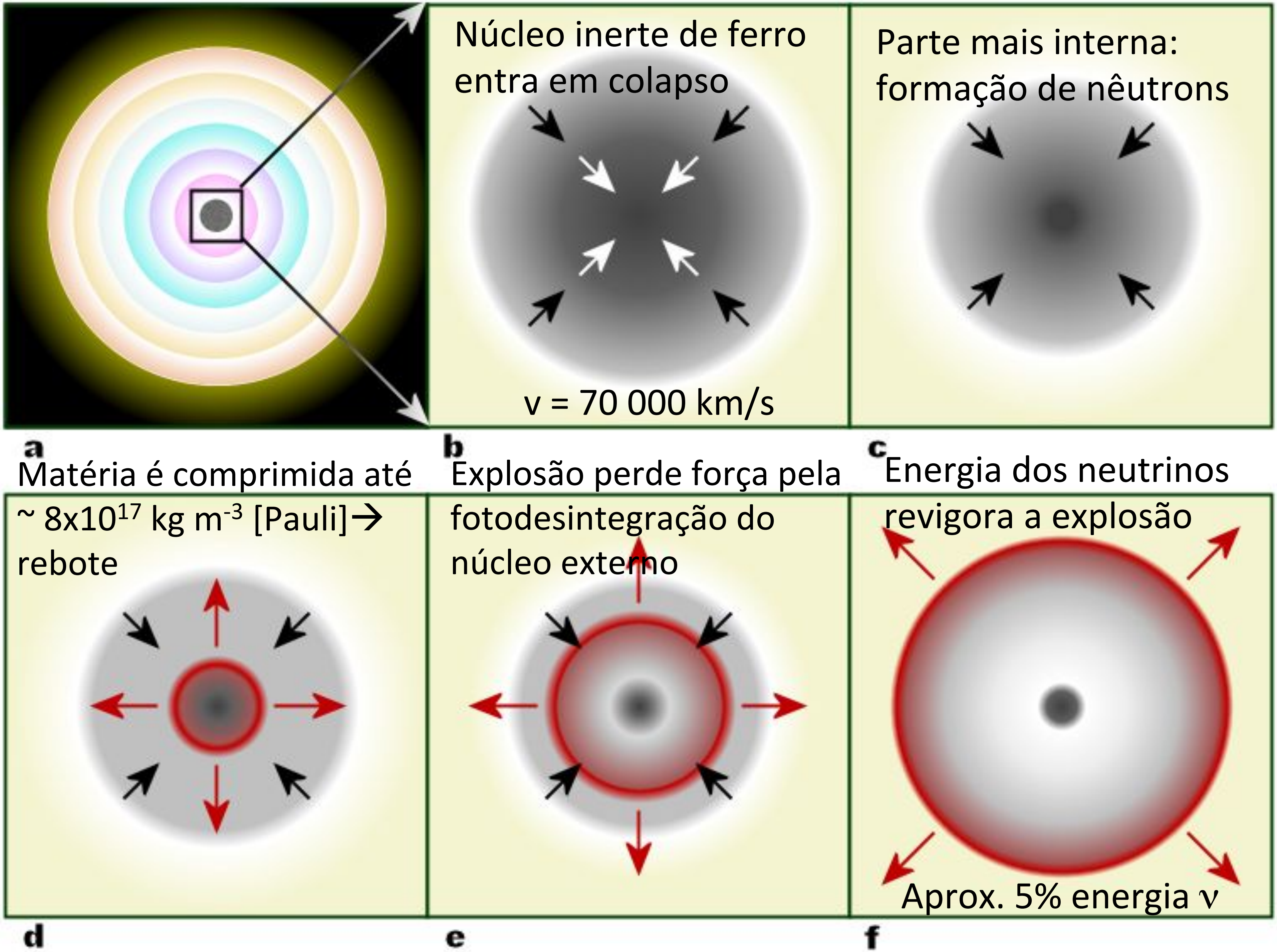
Condições extremas no núcleo inerte de ferro.
Para estrela de 15 M_{Sol}:
T ~ $8x10^9$ K
R ~ 10^{13} kg m^{-3}

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}: $L_{fótons} = 4x10^{31}$ W, $L_{\nu} = 3x10^{38}$W

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



Núcleo inerte de ferro entra em colapso

v = 70 000 km/s

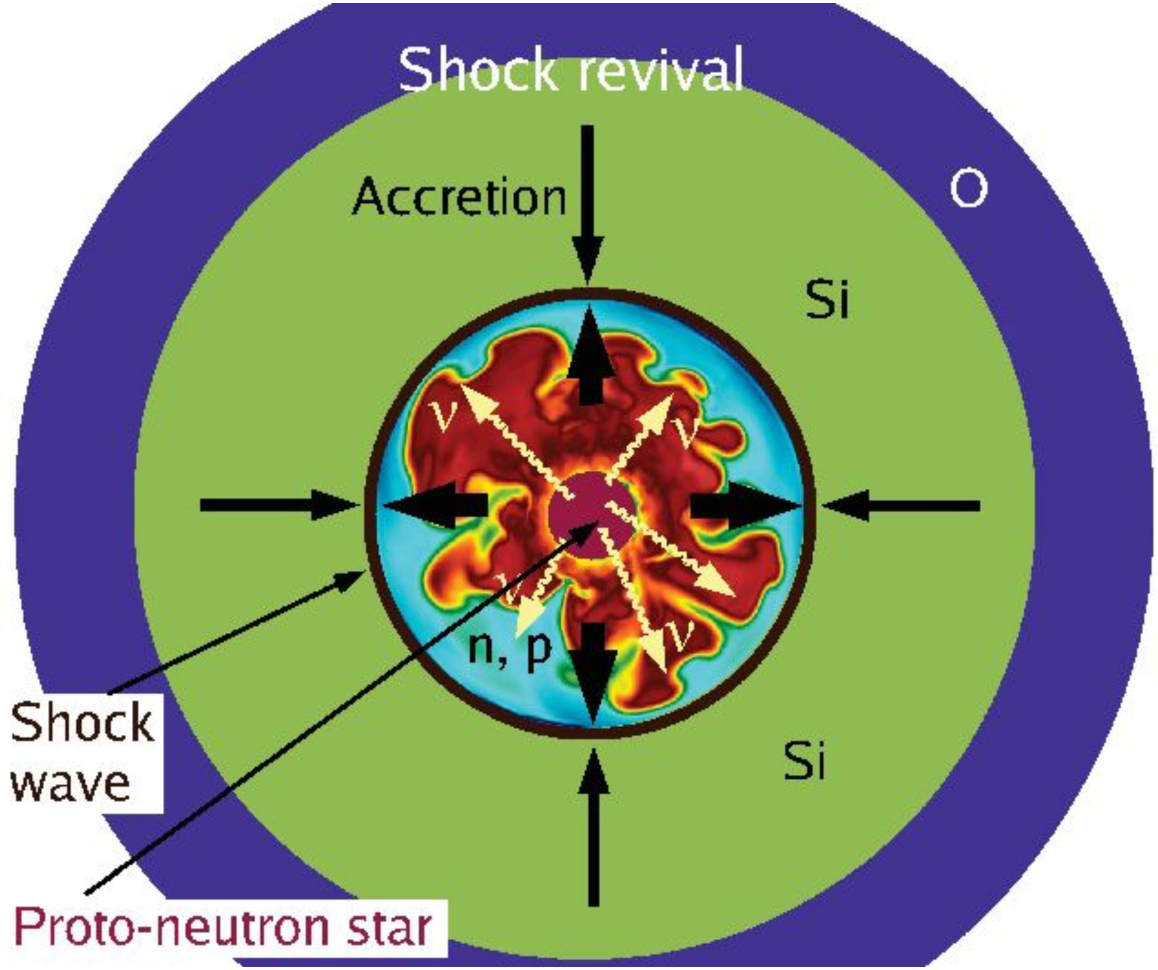
Parte mais interna: formação de nêutrons

Matéria é comprimida até ~ $8x10^{17}$ kg m^{-3} [Pauli]→ rebote

Explosão perde força pela fotodesintegração do núcleo externo

Energia dos neutrinos revigora a explosão

Aprox. 5% energia ν

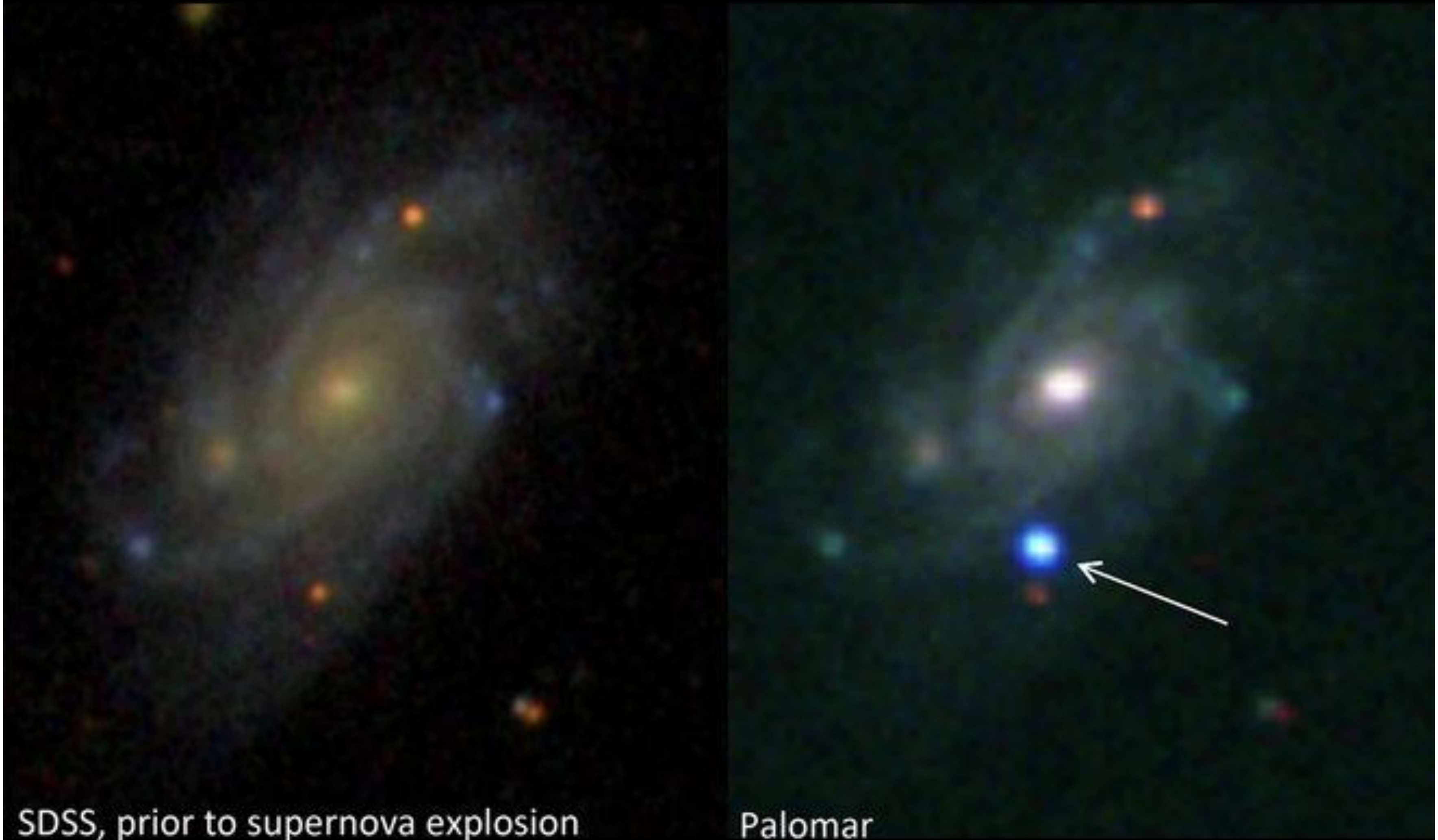


Energia cinética total do material em expansão ~ 10^{44} J (~1% da energia liberada por neutrinos).

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})

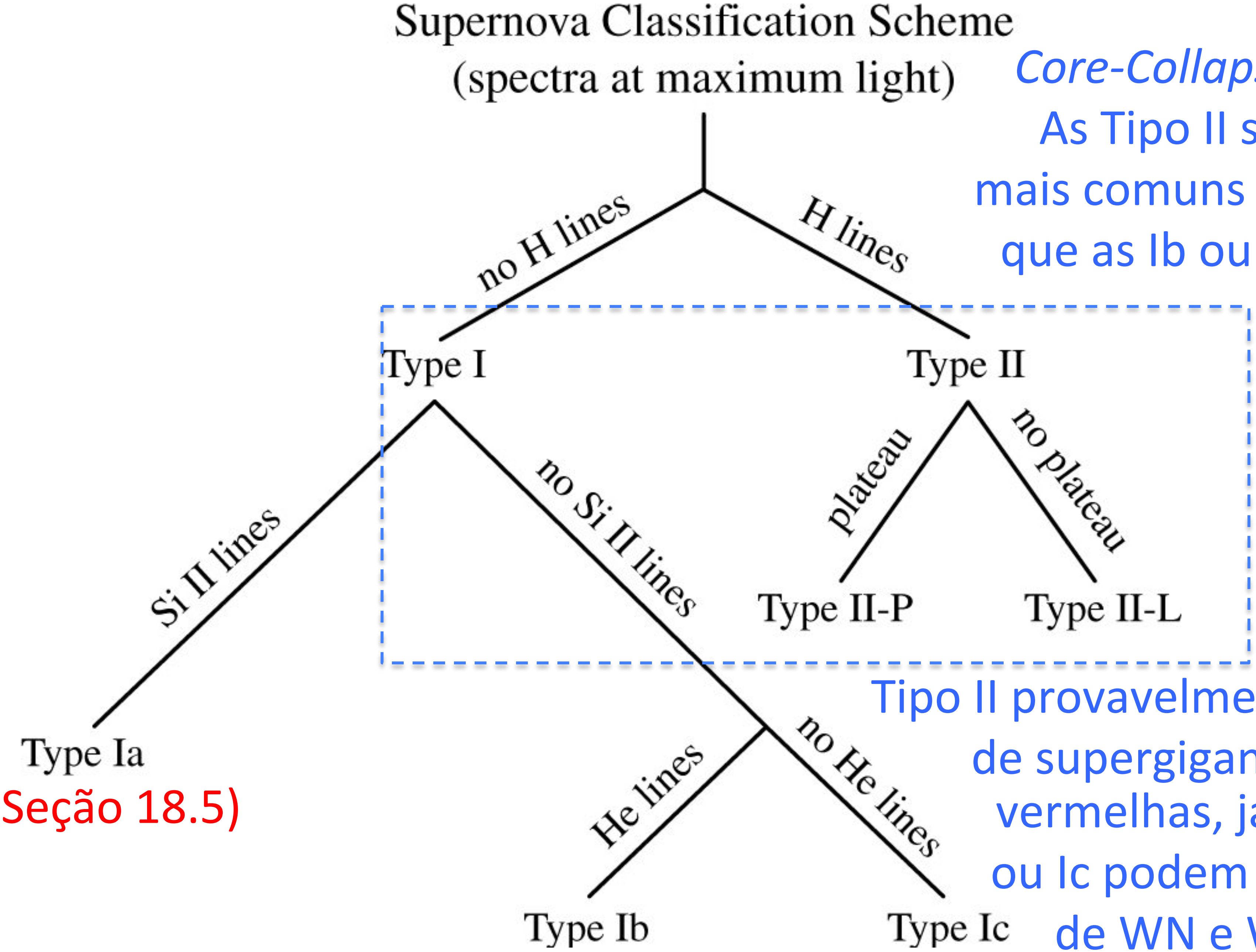
SN 2013cu (iPTF13ast)



SDSS, prior to supernova explosion

Palomar

Gal-Yam et al. 2014; Nature, May 22, 2014



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

(Seção 18.5)

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

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.

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

- *Binding energy* da estrela de nêutrons

~ 3×10^{46} J (100 vezes mais energia do que o Sol produzira na sequência principal)

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 $R_f = 50\ \mathrm{km} \ll R_\oplus$, 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.