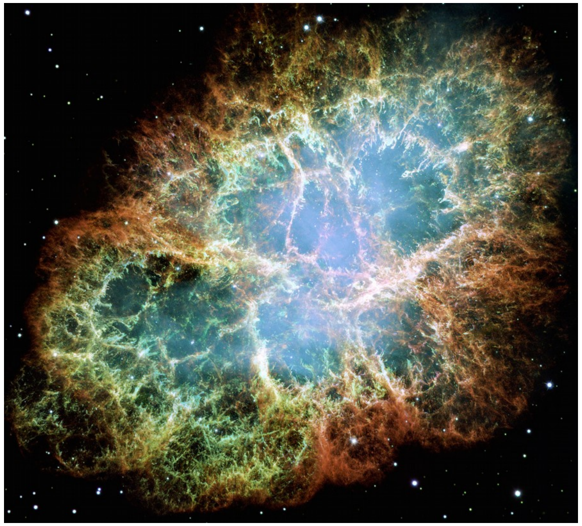
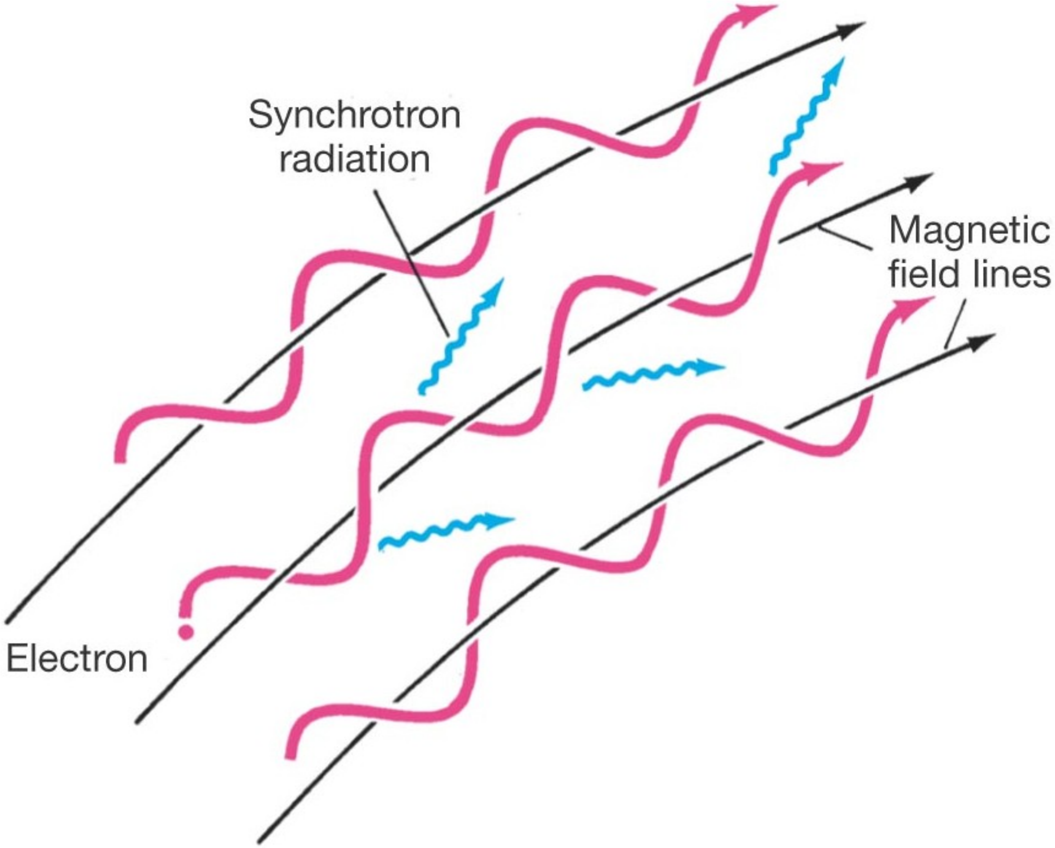
Cap. 15: Evolução de estrelas massivas

15.3 Supernovas de colapso do núcleo
(a partir de decaimento radioativo das curvas de luz de supernova)
15.4 Gamma-ray bursts
15.5 raios cósmicos



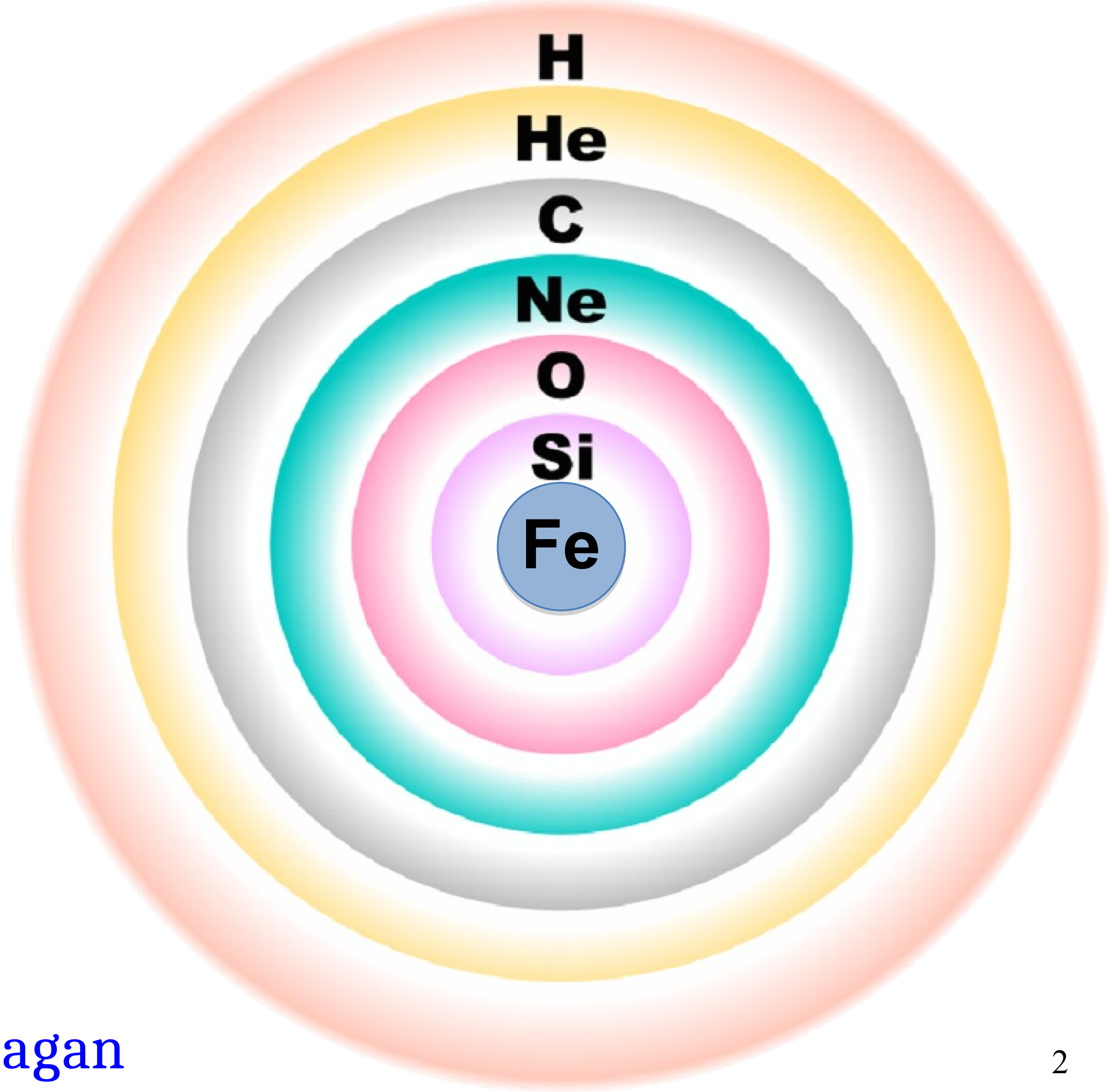


Prof. Jorge Meléndez, AGA0293, Astrofísica Estelar, IAG-USP

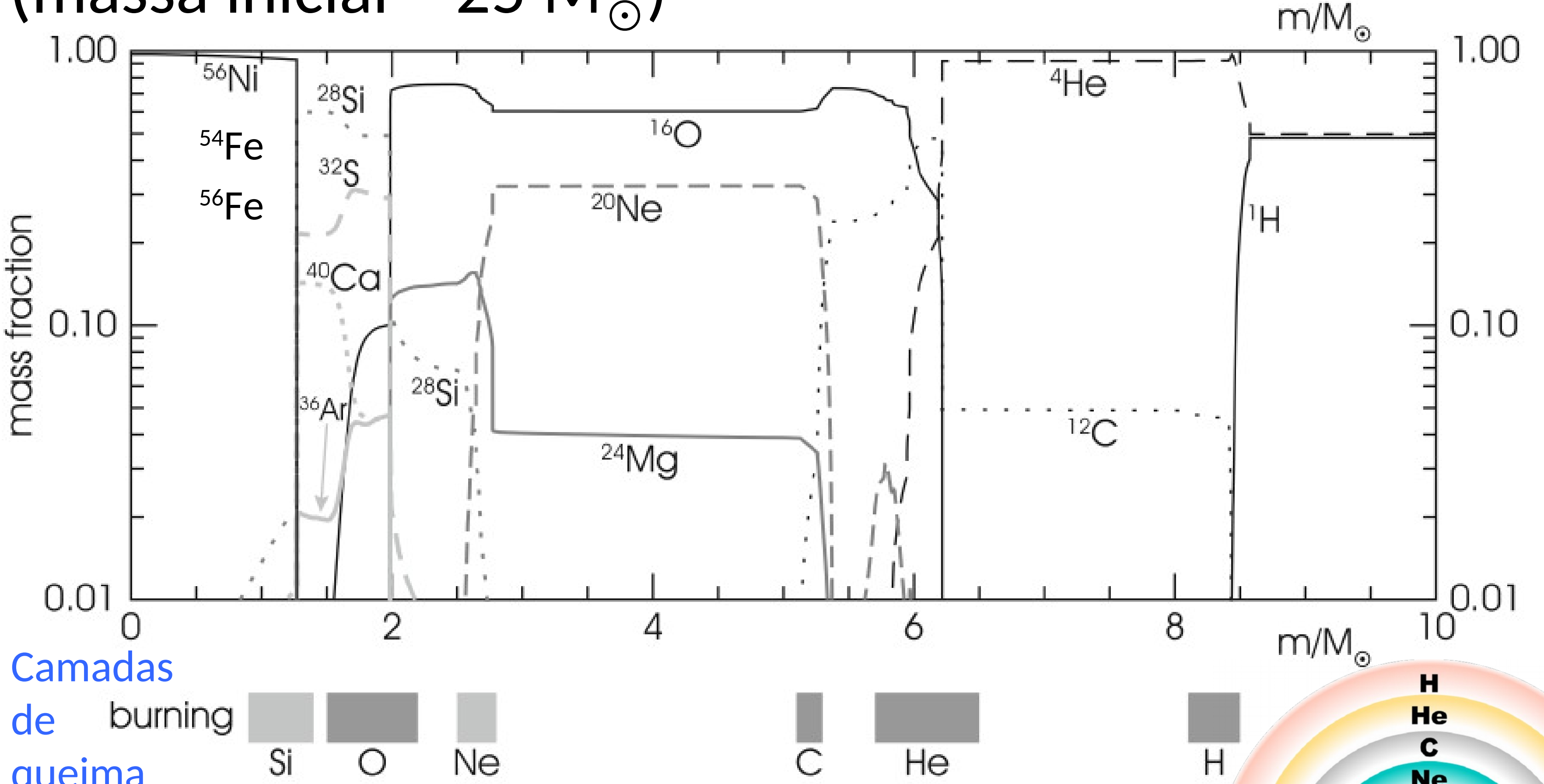
Estrutura de estrela massiva ($\text{Massa}_{\text{inicial}} > 8\ M_\odot$) antes do colapso do núcleo e explosão supernova

Uma estrela é uma espécie de cozinha cósmica dentro da qual átomos de hidrogênio são cozinhados e viram átomos mais pesados

Carl Sagan



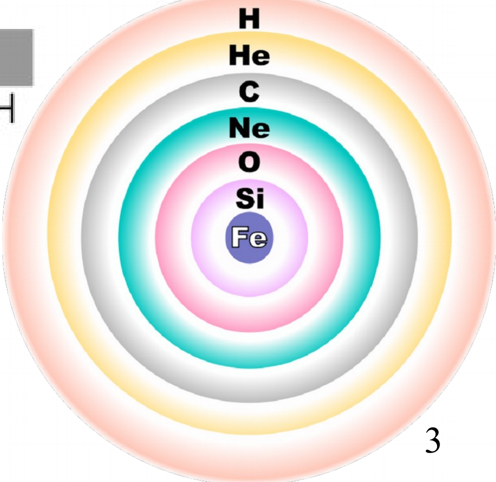
Estrutura pre-colapso de estrela massiva (massa inicial = 25 M$_\odot$)



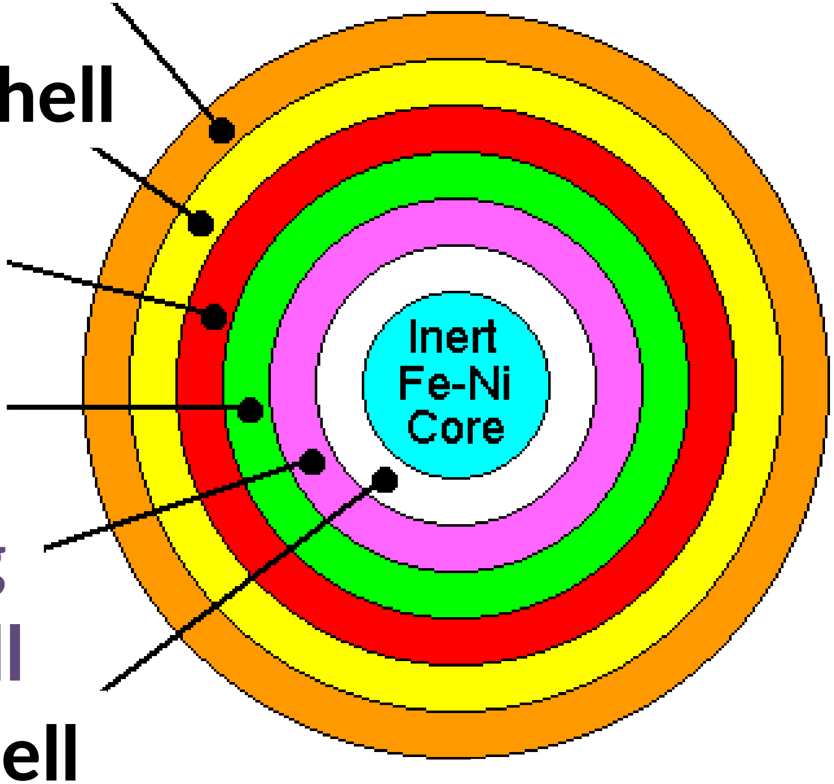
Camadas de queima

Fig. 36.4 The chemical composition in the interior of a highly evolved model of a population I star with an initial mass of 25$M_\odot$, close to the end of hydrostatic nuclear burning. The mass at this time is reduced to 16$M_\odot$ due to mass loss. In the *upper panel* the mass concentrations of important elements are plotted against the mass variable *m*. *Below* the abscissa, in the *middle* of the figure, the approximate location of shell sources in different nuclear burning phases is indicated by the *grey rectangles*.

Kippenhahn et al. 2012: Stellar Structure & Evolution, 2nd Ed.



Estrutura pre-colapso de estrela massiva (massa inicial > 8 $M_\odot$)



H burning shell

He burning shell

C burning shell

Ne burning shell

O burning shell

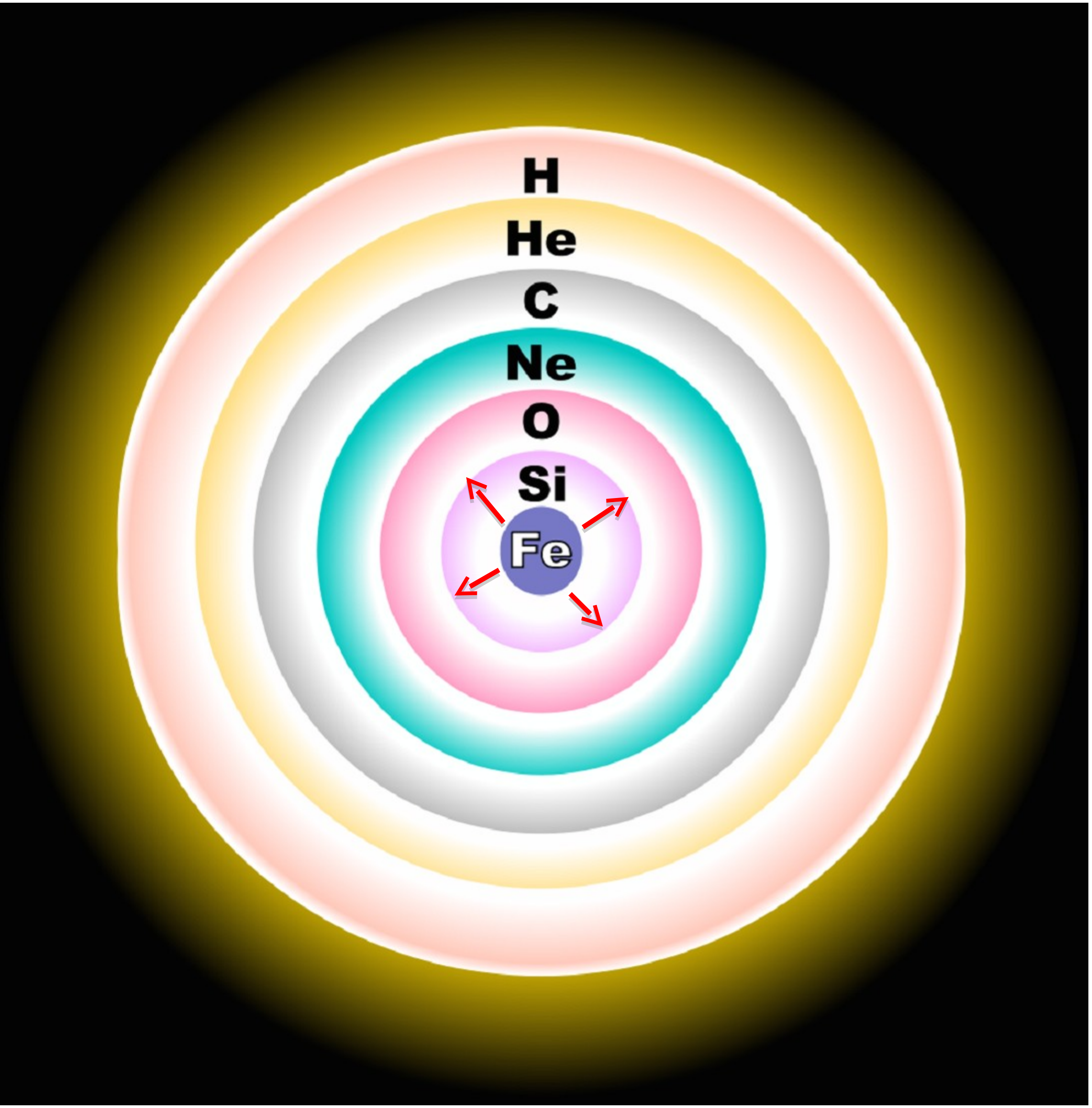
Si burning shell

Raio do núcleo ~ 1000 km

Raio do envelope ~ 5 U.A.

http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit3/supernova.html

Nucleossíntese no rebote



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

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

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

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

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

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

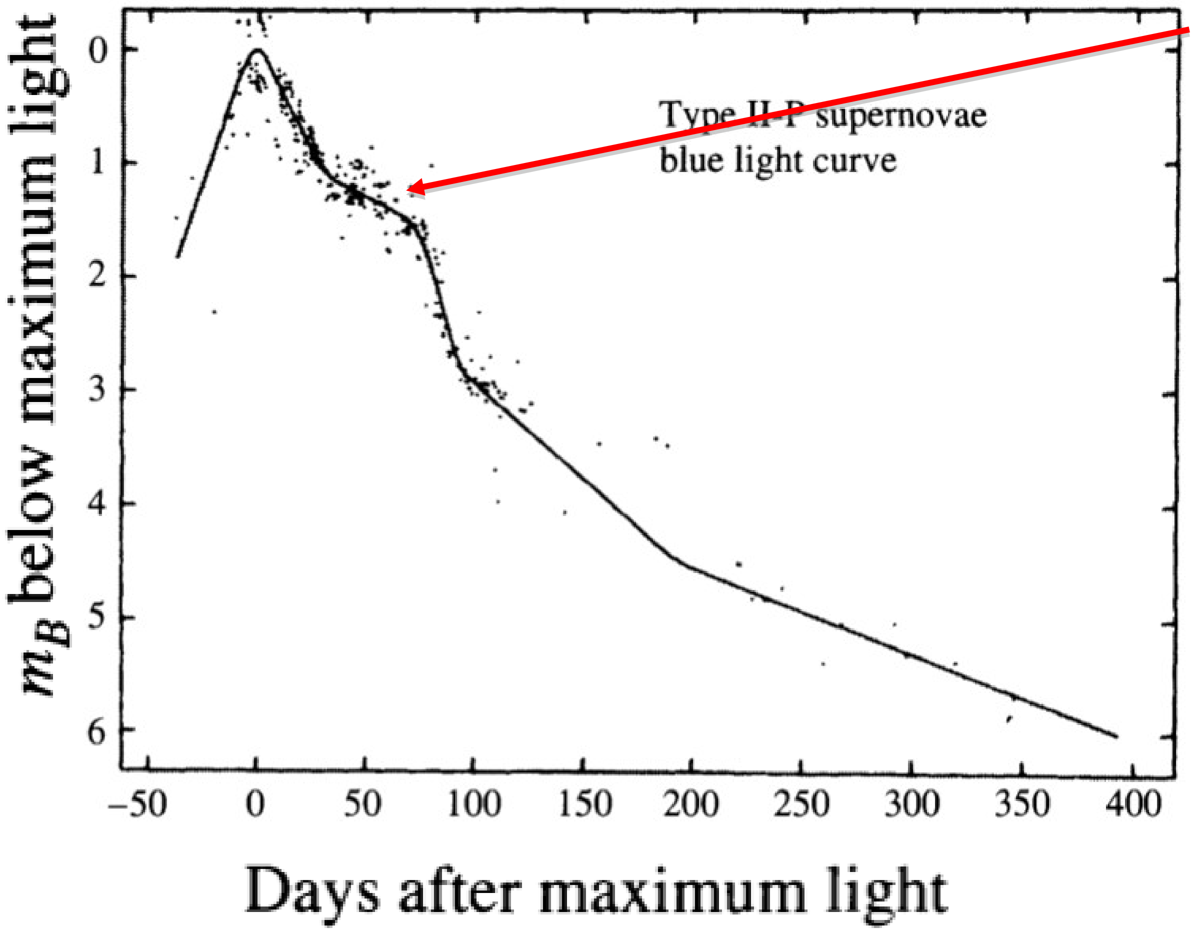
$${}^{52}_{26}\mathrm{Fe} + {}^{4}_{2}\mathrm{He} \rightarrow \boxed{{}^{56}_{28}\mathrm{Ni}}$$

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

E outras reações, por ex. :

$${}^{52}_{24}\mathrm{Cr} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{56}_{26}\mathrm{Fe}$$

As supernovas mais comuns de colapso de núcleo são as tipo II-P (*Plateau*)

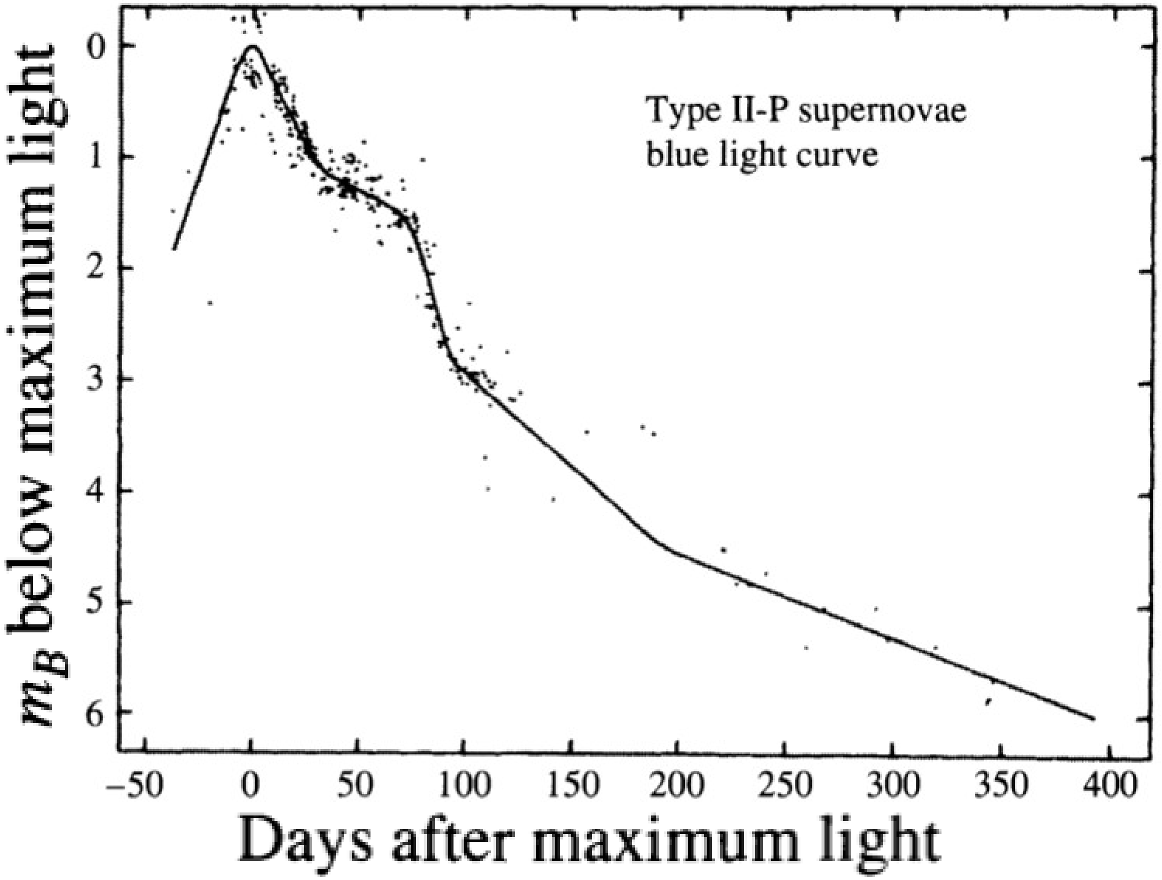


O *Plateau* (platô) é pela energia do frente de choque no envelope rico em hidrogênio → ionização → recombinação, liberando energia a T ~ 5000 K

Também energia do decaimento radioativo do Ni-56 ($\tau_{½}$ = 6,1 dias)

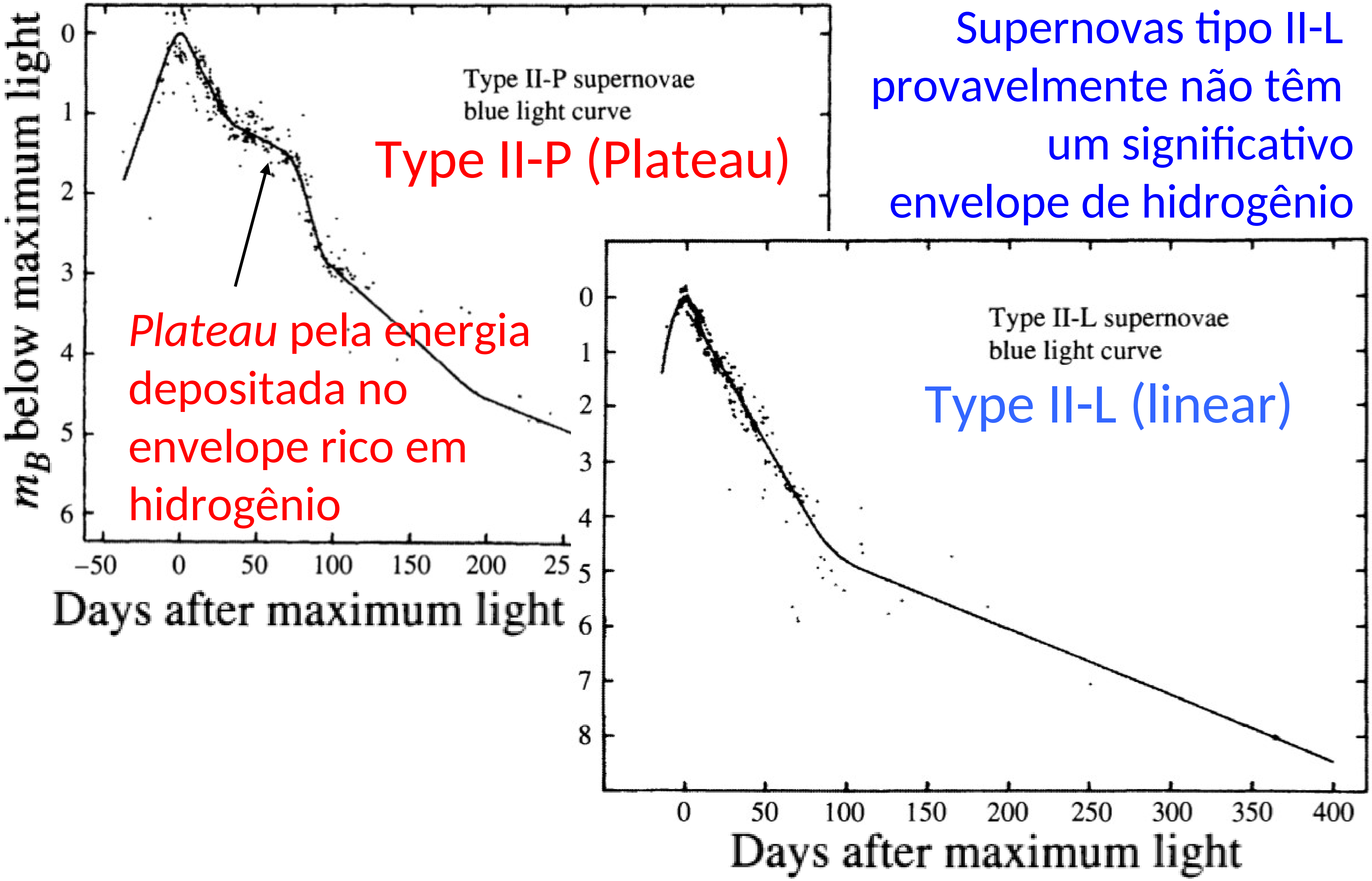
Na expansão do frente de choque da SN, diferentes isótopos (vários deles radioativos) podem ser formados.

Além do Ni-56 ($\tau_{½}$ = 6,1 dias), temos o decaimento de isótopos como Co-57 ($\tau_{½}$ = 271 d), Na-22 ($\tau_{½}$ = 2,6 anos), Ti-44 ($\tau_{½}$ = 47 anos)



Isótopos abundantes dão forma à curva de luz da SN

Supernovas tipo II-L provavelmente não têm um significativo envelope de hidrogênio



Type II-P (Plateau)

Plateau pela energia depositada no envelope rico em hidrogênio

Type II-L (linear)

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

$${}^{56}_{28}\mathrm{Ni} \rightarrow {}^{56}_{27}\mathrm{Co} + e^{+} + \nu_e + \gamma$$ $\tau_{½}$ = 6,1 dias

$${}^{56}_{27}\mathrm{Co} \rightarrow {}^{56}_{26}\mathrm{Fe} + e^{+} + \nu_e + \gamma$$ $\tau_{½}$ = 77,7 dias

Taxa de Decaimento radioativo:

$$\boxed{\frac{dN}{dt} = -\lambda N}$$

N: número de átomos

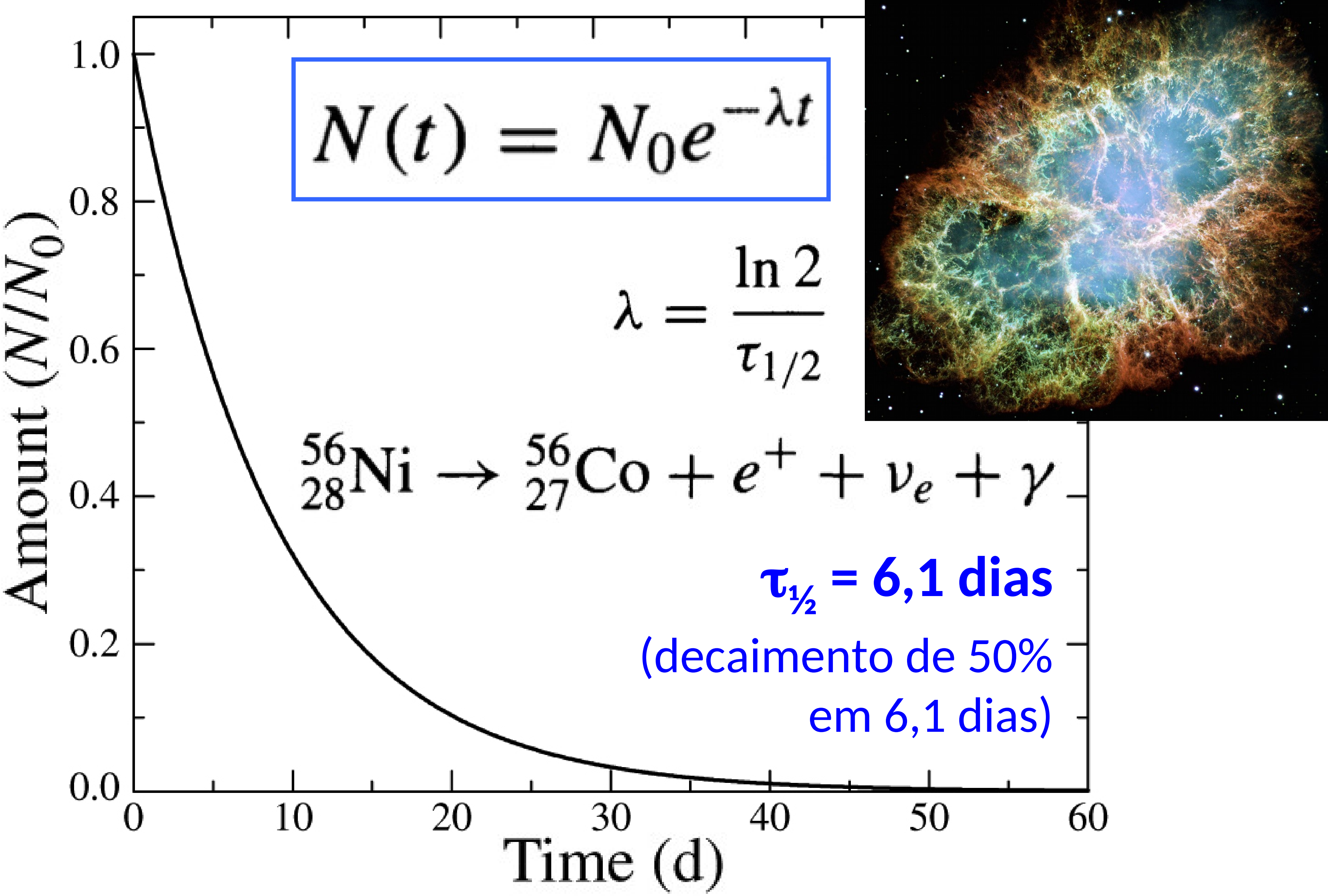
λ: constante de desintegração

$$\boxed{N(t) = N_0 e^{-\lambda t}}$$

$$\lambda = \frac{\ln 2}{\tau_{1/2}}$$

N_0: número inicial de átomos na amostra

$\tau_{½}$: tempo de vida média



$$\boxed{N(t) = N_0 e^{-\lambda t}}$$

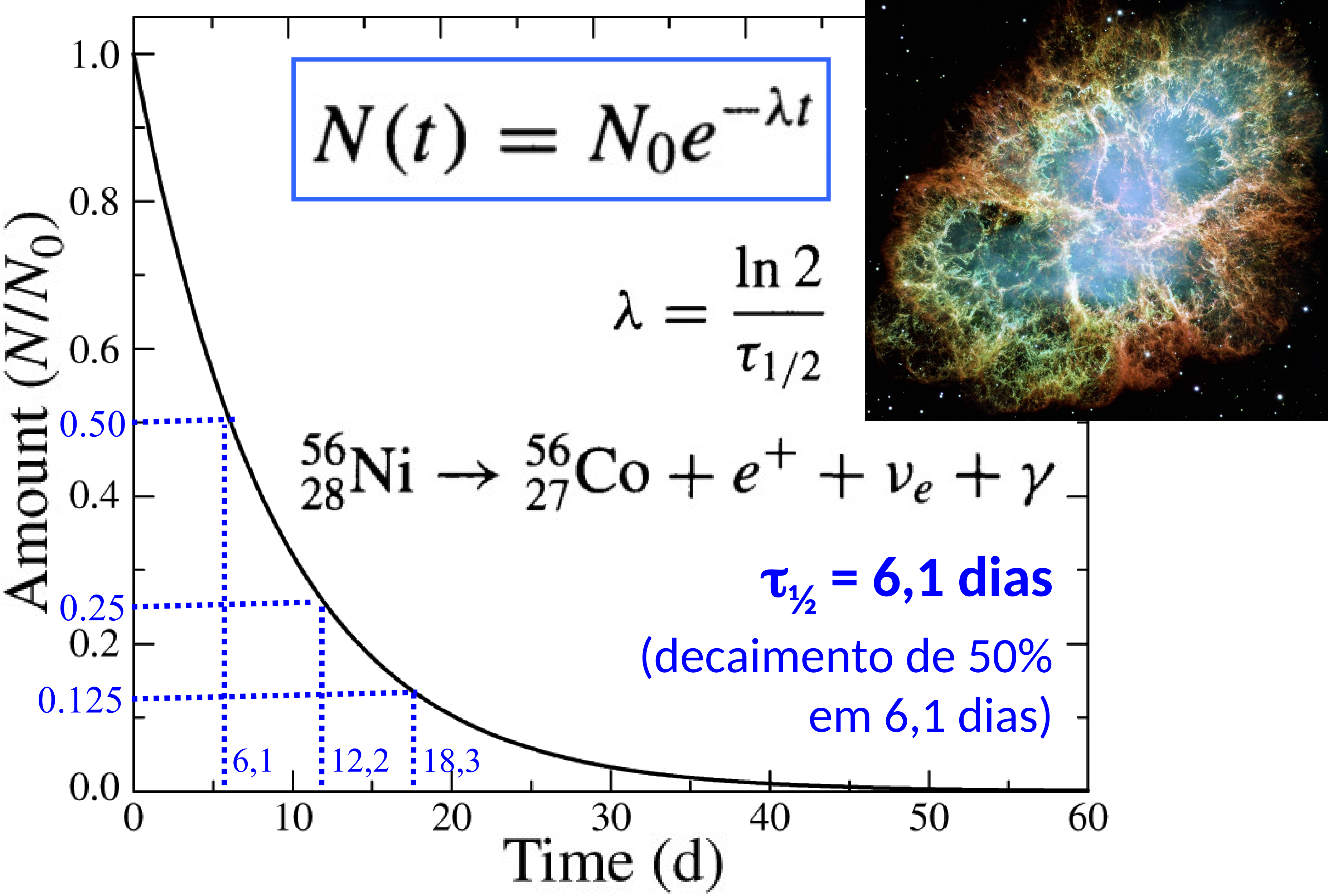
$$\lambda = \frac{\ln 2}{\tau_{1/2}}$$

$$^{56}_{28}\mathrm{Ni} \rightarrow {}^{56}_{27}\mathrm{Co} + e^{+} + \nu_e + \gamma$$

$\tau_{½}$ = 6,1 dias

(decaimento de 50% em 6,1 dias)

FIGURE 15.11 The radioactive decay of $^{56}_{28}$Ni, with a half-life of $\tau_{1/2} = 6.1$ days. There is a 50% chance that any given $^{56}_{28}$Ni atom will decay during a time interval of 6.1 days. If the original sample is entirely composed of $^{56}_{28}$Ni, after n successive half-lives the fraction of Ni atoms remaining is 2^{-n}.



$$N(t) = N_0 e^{-\lambda t}$$

$$\lambda = \frac{\ln 2}{\tau_{1/2}}$$

$$^{56}_{28}\text{Ni} \rightarrow {}^{56}_{27}\text{Co} + e^+ + \nu_e + \gamma$$

$\tau_{½}$ = 6,1 dias

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FIGURE 15.11 The radioactive decay of $^{56}_{28}$Ni, with a half-life of $\tau_{1/2} = 6.1$ days. There is a 50% chance that any given $^{56}_{28}$Ni atom will decay during a time interval of 6.1 days. If the original sample is entirely composed of $^{56}_{28}$Ni, after n successive half-lives the fraction of Ni atoms remaining is 2^{-n}.

A taxa de variação da luminosidade (curva de luz):

$$\frac{d\log_{10} L}{dt} = -0.434\lambda$$

Variação da luminosidade *dL/dt* é proporcional a *dN/dt*:

$$\rightarrow d \log L/dt = \log_{10}e\,(dN/dt)\ /\ N$$

$$= 0{,}434\,(dN/dt)/N = 0{,}434\,(-\lambda) = -0{,}434\lambda$$

$$\frac{dN}{dt} = -\lambda N$$

$$\frac{d\log_{10} L}{dt} = -\log_{10} e \cdot \lambda = -0.434\lambda$$

$u = f(x)$ is a function of x,

$$y = \log_b u$$

$$\frac{dy}{dx} = (\log_b e)\frac{u'}{u}$$

A taxa de variação da luminosidade (curva de luz):

$$\frac{d\log_{10}L}{dt} = -0.434\lambda$$

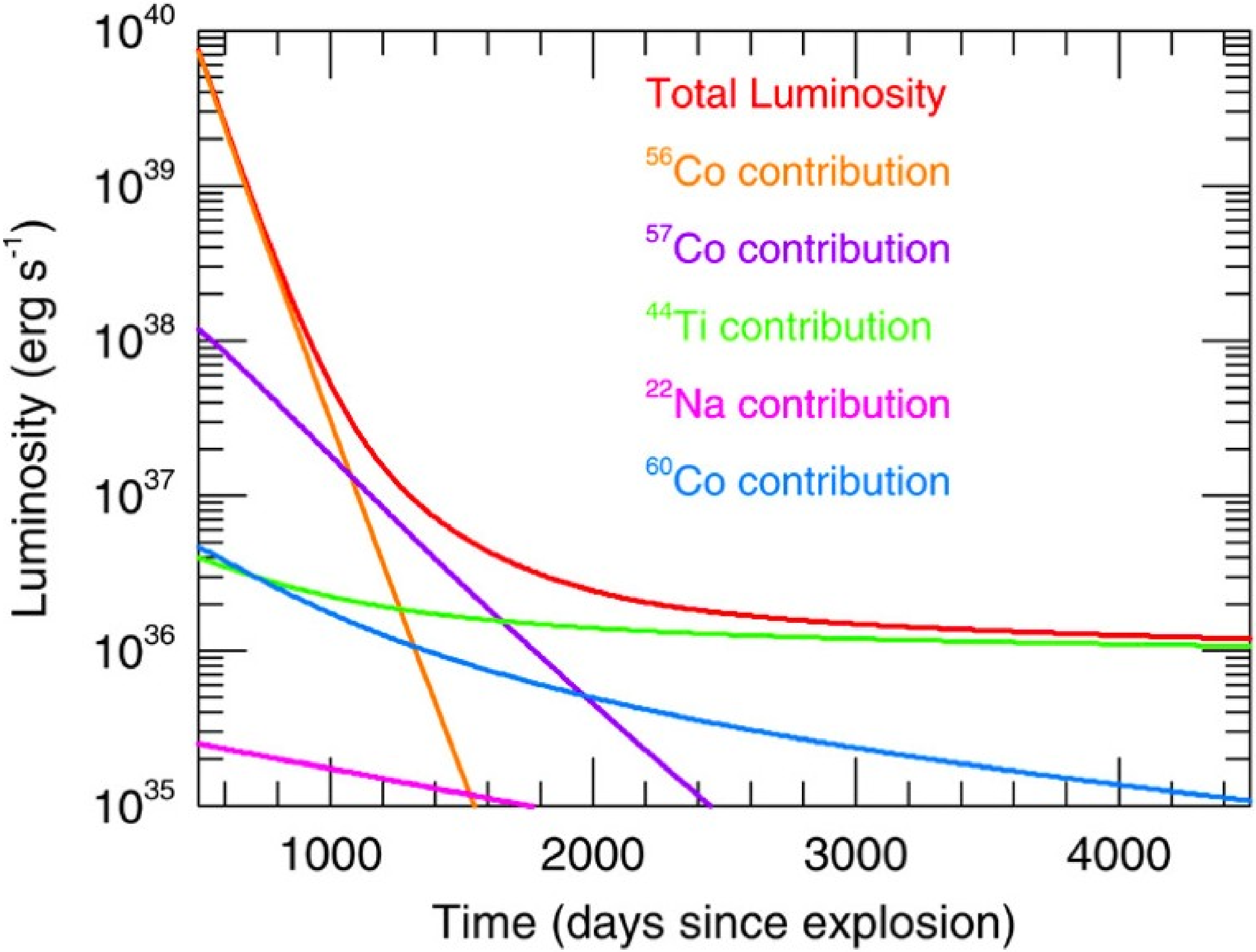
Ou:

$$\frac{dM_{\mathrm{bol}}}{dt} = 1.086\lambda$$

Medindo a inclinação da curva de luz podemos determinar λ → determinar a origem

$$\boxed{\lambda = \frac{\ln 2}{\tau_{1/2}}}$$

$$\boxed{\frac{dN}{dt} = -\lambda N}$$



Radioactive decays contributing to supernova light curves.

(From http://cococubed.asu.edu, Frank Timmes’s pages at Arizona State University)

M_{bol} (pico) = -15,5, mas geralmente as tipo II têm -18

Demorou muito (80 dias) em chegar ao máximo

Curva de luz da SN 1987A (SN de tipo II)

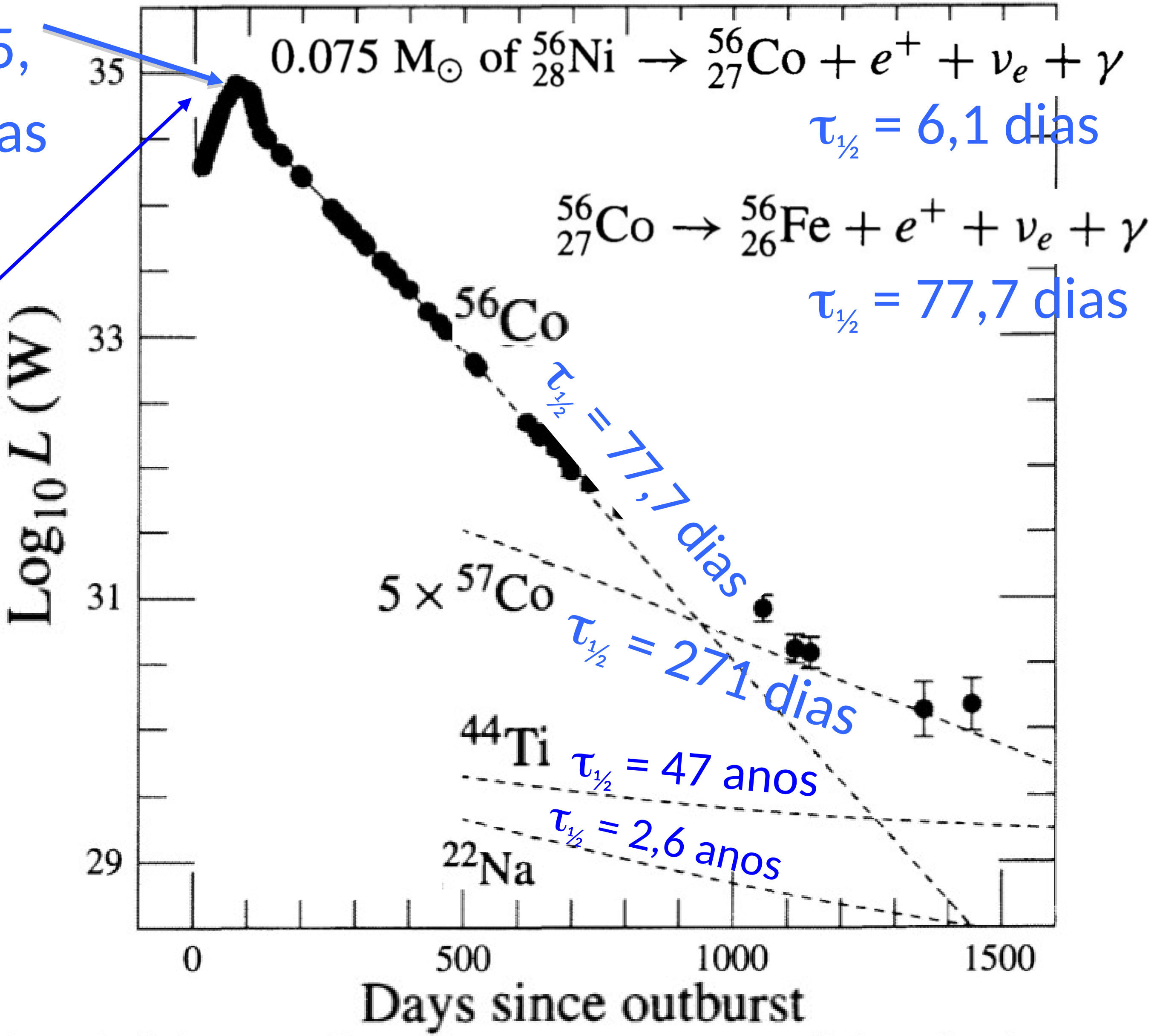
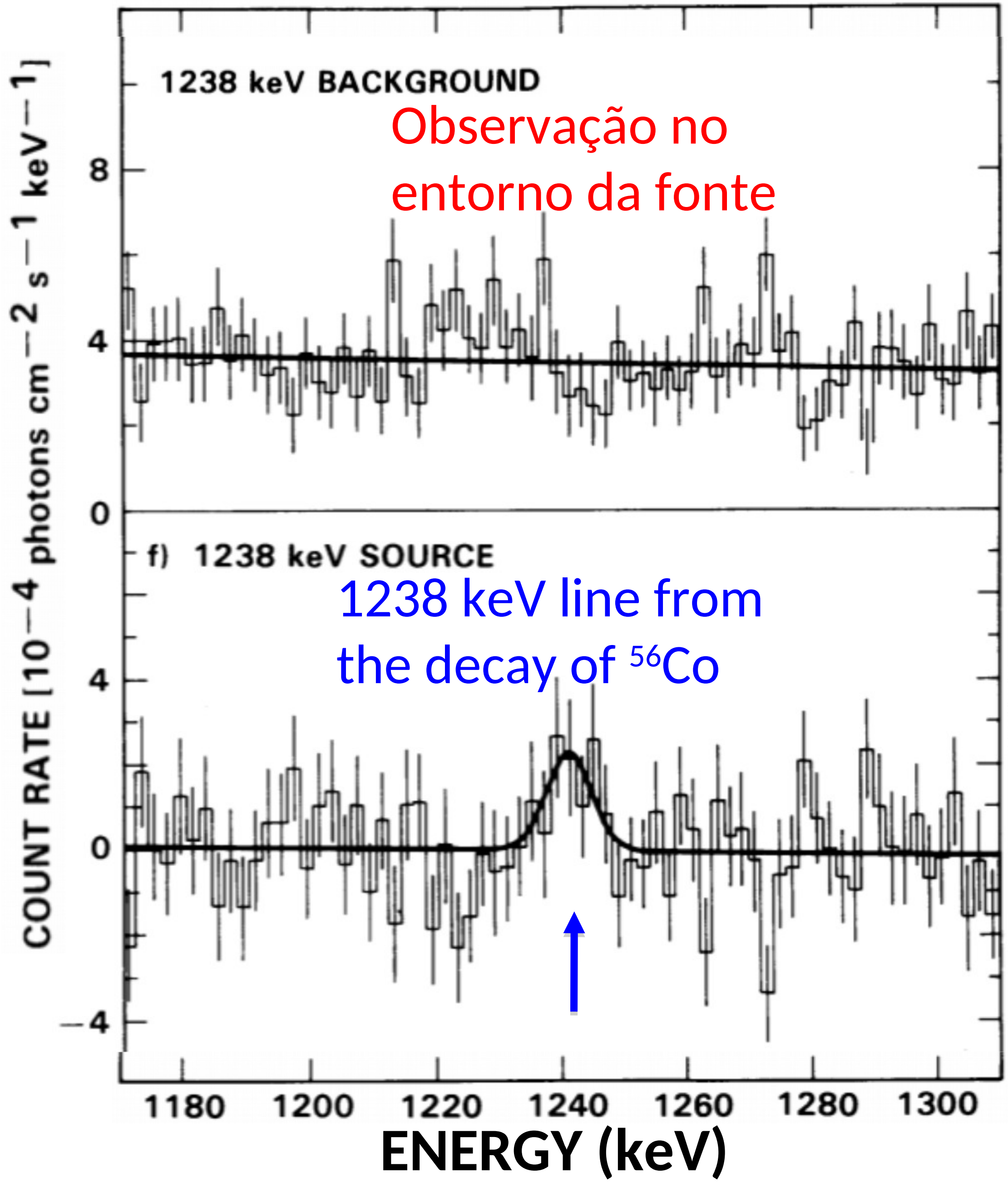


FIGURE 15.12 The bolometric light curve of SN 1987A through the first 1444 days after the explosion. The dashed lines show the contributions expected from the radioactive isotopes produced by the shock wave. The initial masses are estimated to be $^{56}_{28}$Ni (and later $^{56}_{27}$Co), 0.075 $M_\odot$; $^{57}_{27}$Co, 0.009 $M_\odot$ (five times the solar abundance); $^{44}_{22}$Ti, 1 × 10^{-4} $M_\odot$; and $^{22}_{11}$Na, 2 × 10^{-6} $M_\odot$. (Figure

Gamma-ray observations of ^{56}Co in SN 1987A



Observação no entorno da fonte

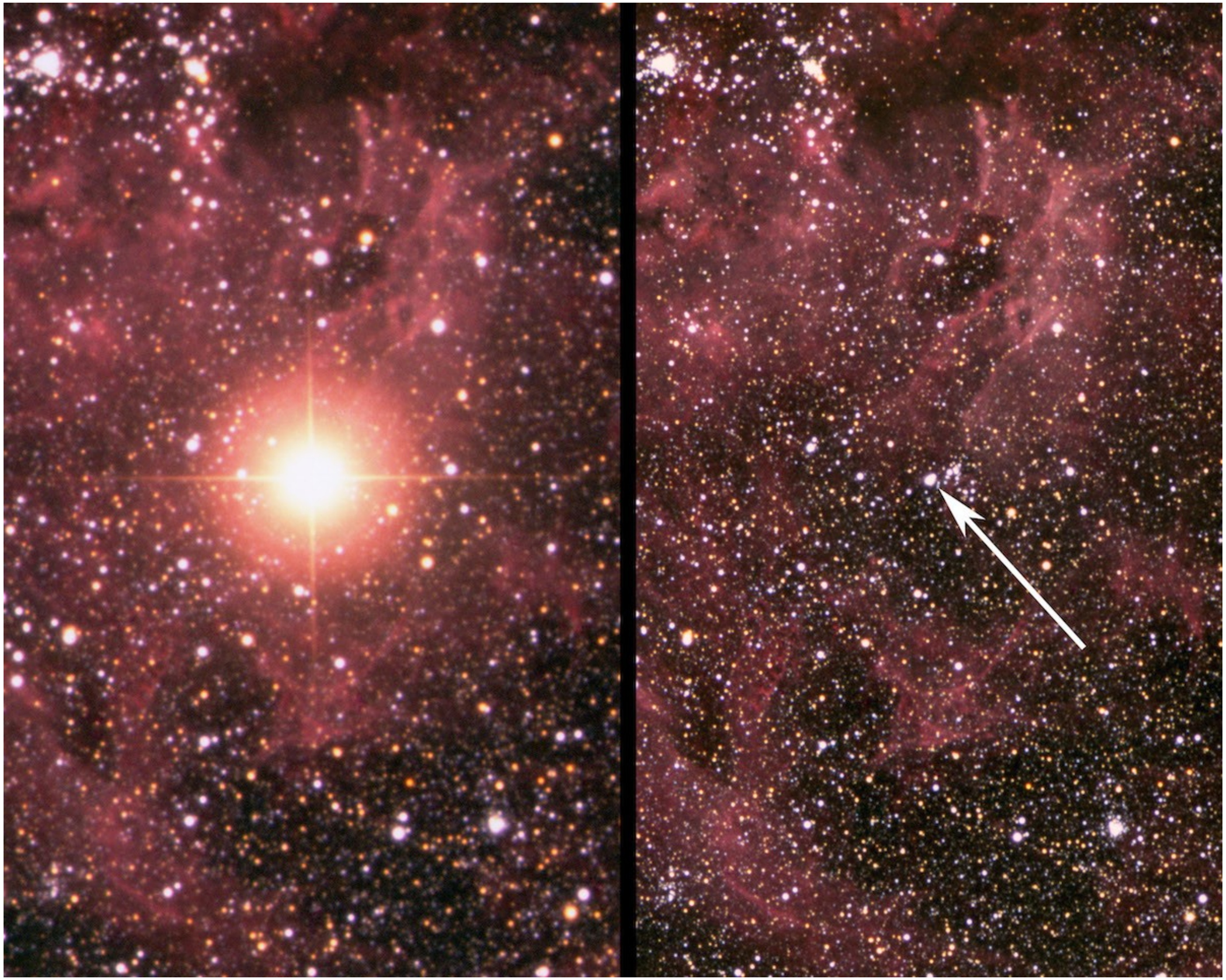
1238 keV line from the decay of ^{56}Co

$$^{56}_{27}\mathrm{Co} \rightarrow\, ^{56}_{26}\mathrm{Fe} + e^{+} + \nu_e + \gamma$$

Mahoney et al. 1988, ApJ, 334, L81

Supernova 1987A,

V ~ 2,9; d ~ 51,4 kpc



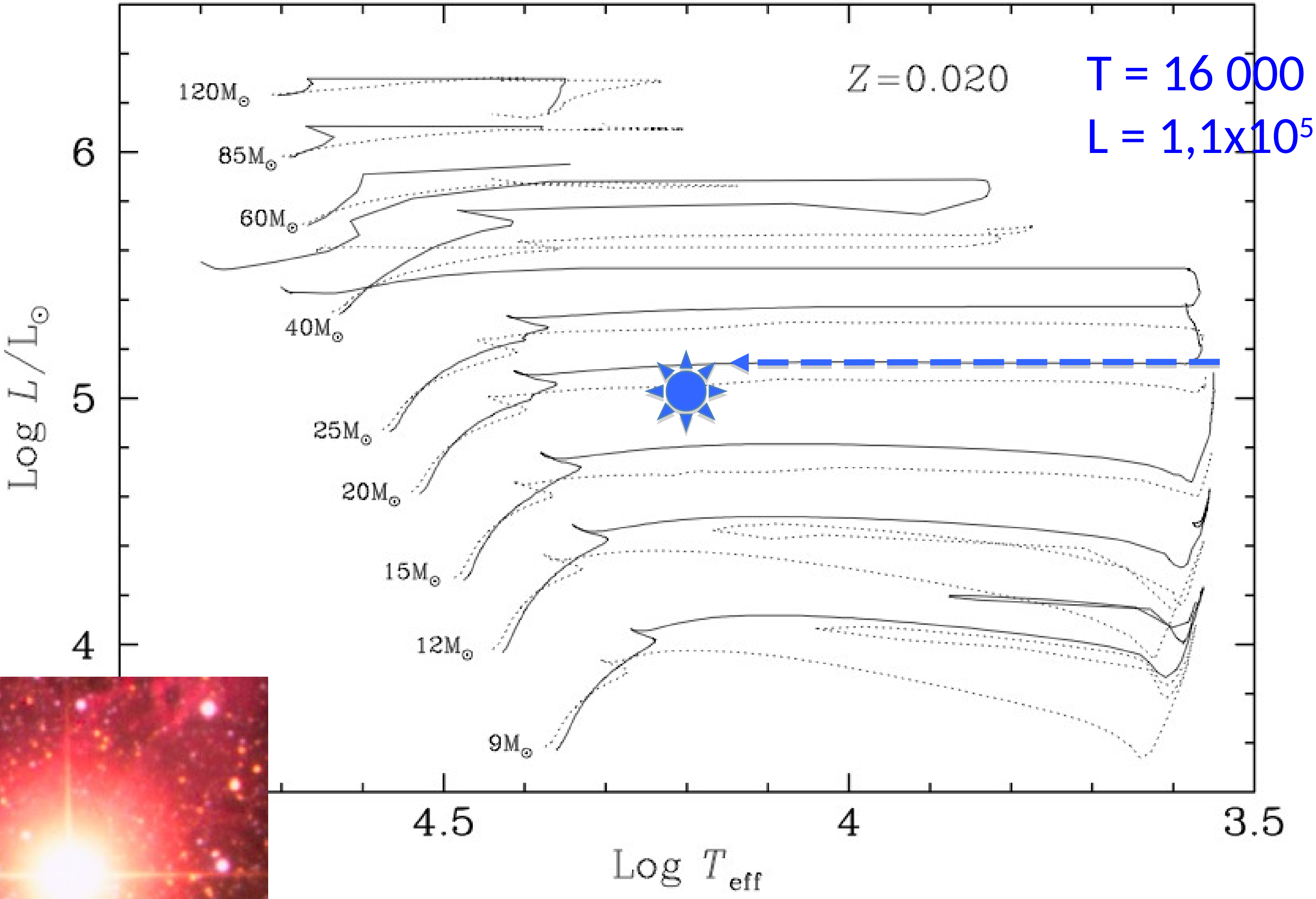
The progenitor star was identified as Sanduleak −69° 202, a blue supergiant, B3I (V = 12)

T = 16 000 K

L = 1,1x10^5 $L_\odot$

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

Estrela progenitora da Supernova 1987A



T = 16 000 K

L = 1,1x10^5 L☉

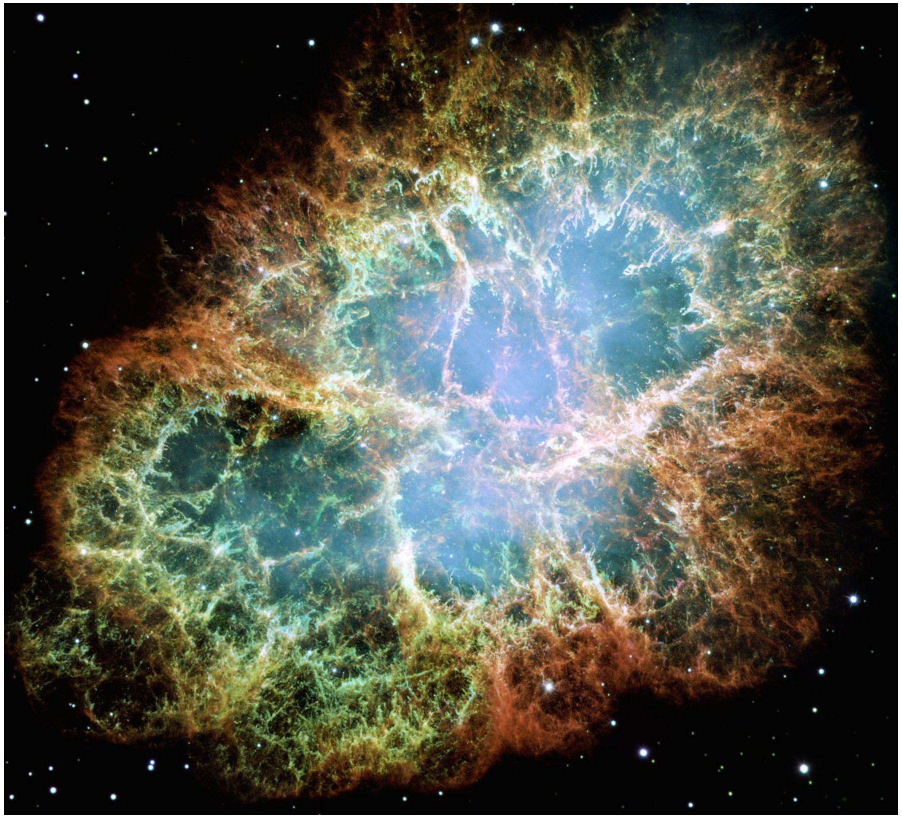
Massa inicial ~ 20 M☉

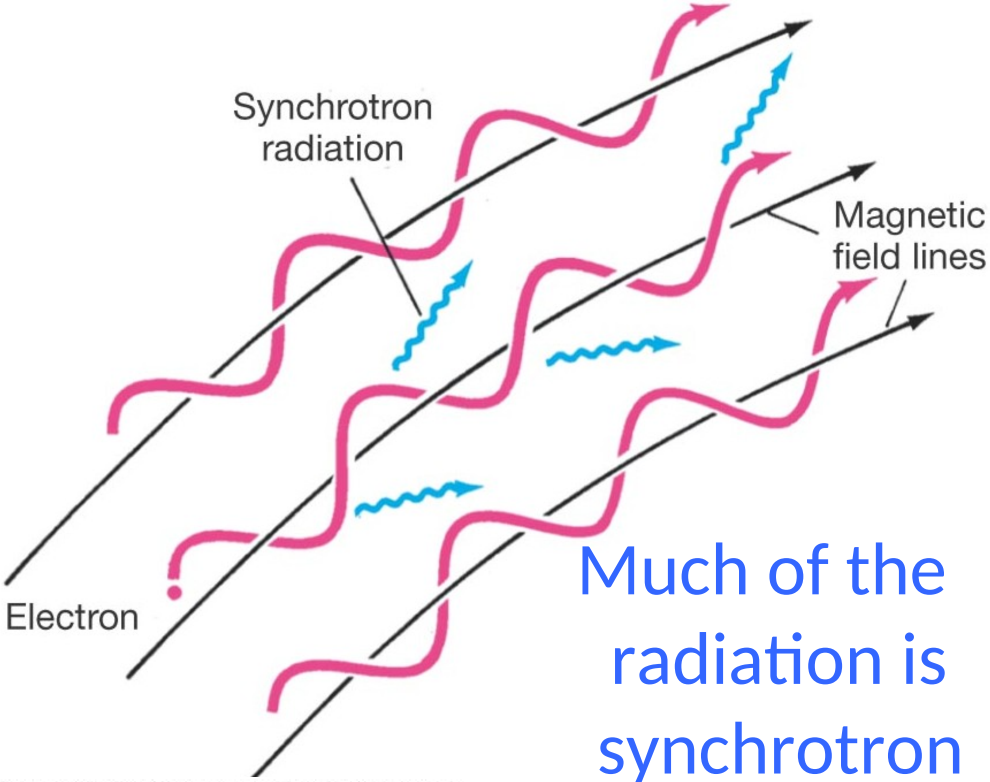
Supernova 1987A

Remanescente de supernova

Supernova 1054

Still expanding at rate of 1450 km/s





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Much of the radiation is synchrotron

There are now many examples of **supernova remnants** (SNR), including the Crab Nebula, located in the constellation of Taurus (recall Fig. 15.4). Today, nearly 1000 years since the SN 1054 explosion, the Crab is still expanding at a rate of almost 1450 km s^{-1} and it has a luminosity of 8×10^4 $L_\odot$. Much of the radiation being emitted is in the form of highly polarized synchrotron radiation (see Section 4.3), indicating the presence of relativistic electrons that are spiraling around magnetic field lines.

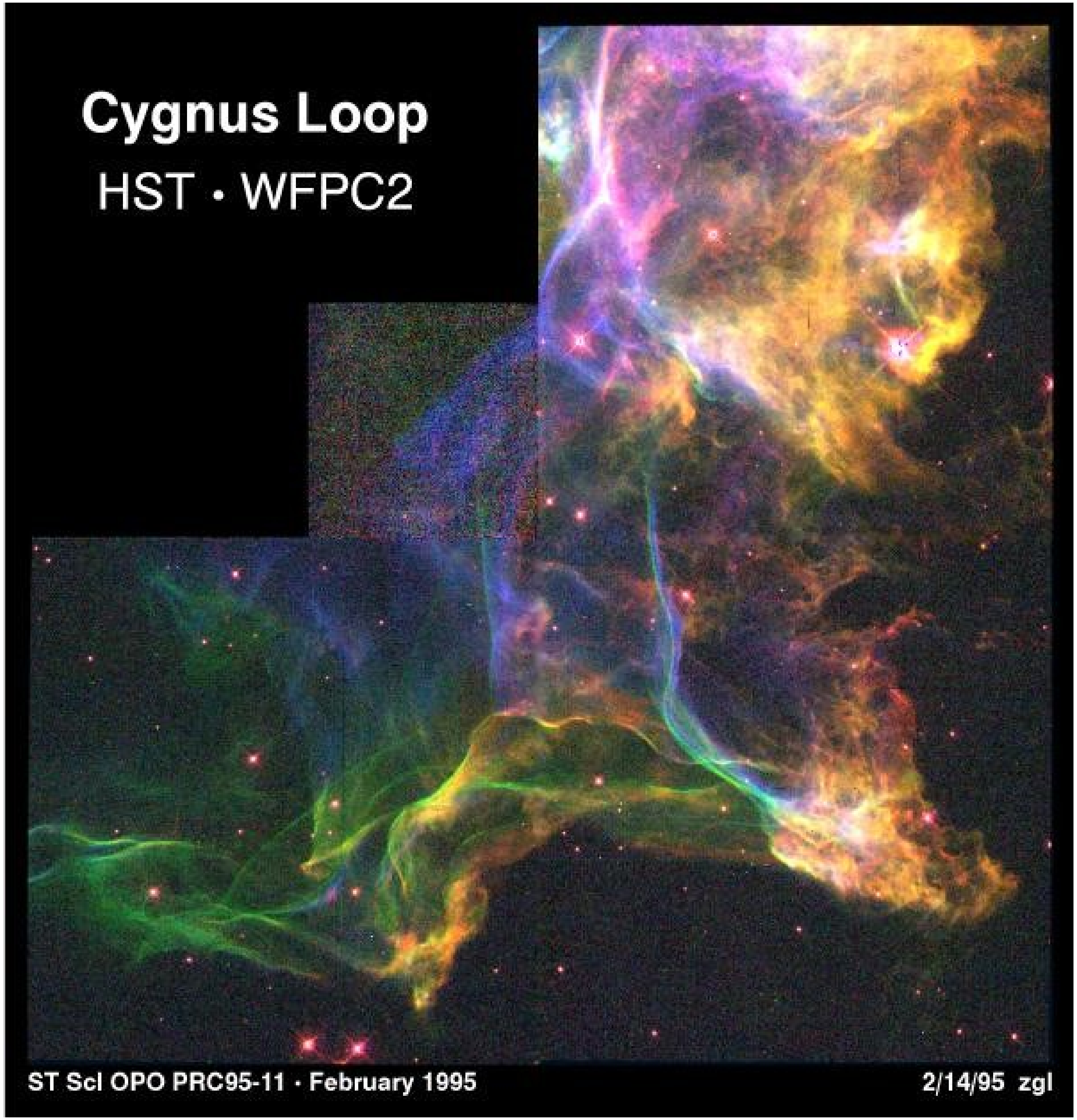


FIGURE 15.13 An HST WF/PC 2 image of a portion of the Cygnus Loop, 800 pc away.

Pequena parte do Cygnus loop (laço do Cisne), nebulosa de 15 000 anos

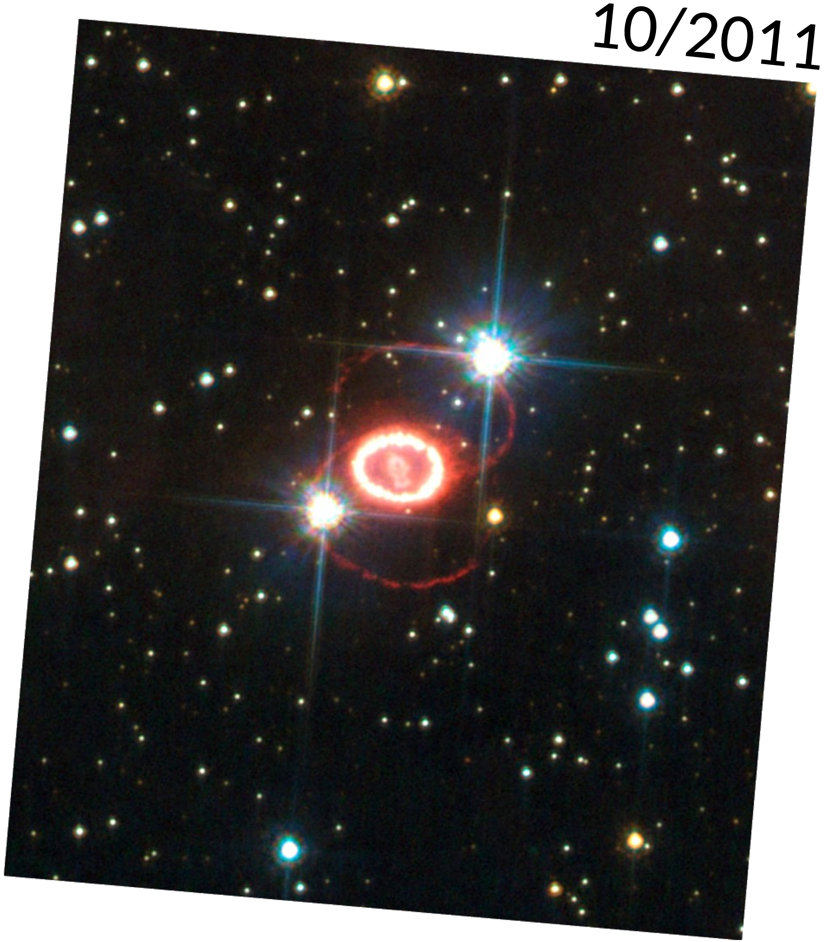
Ionização do ISM quando o remanescente SN encontra o ISM

THREE RINGS OF GAS SURROUND SUPERNOVA 1987A

(c) Hubble

02/1994

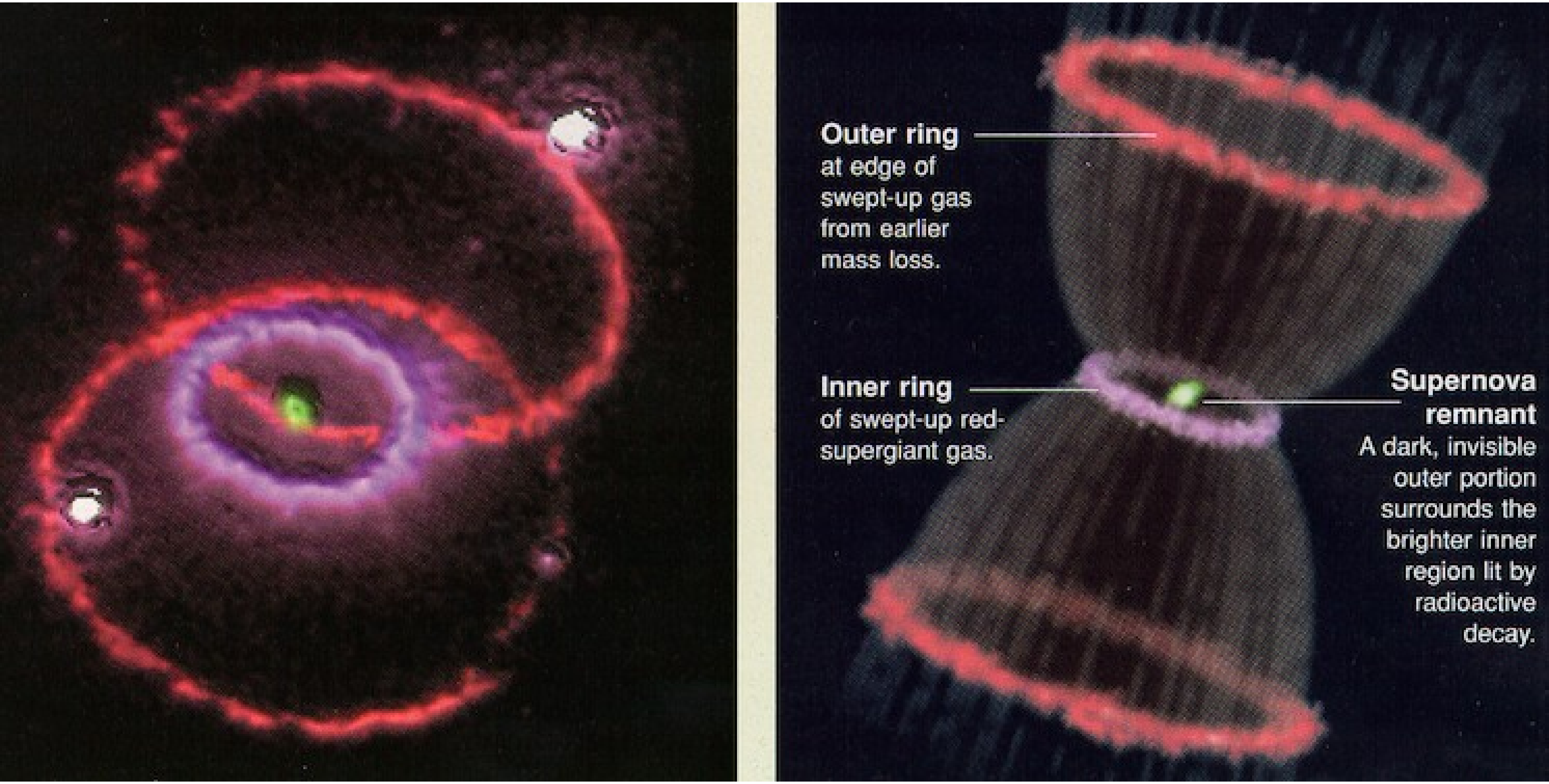
10/2011



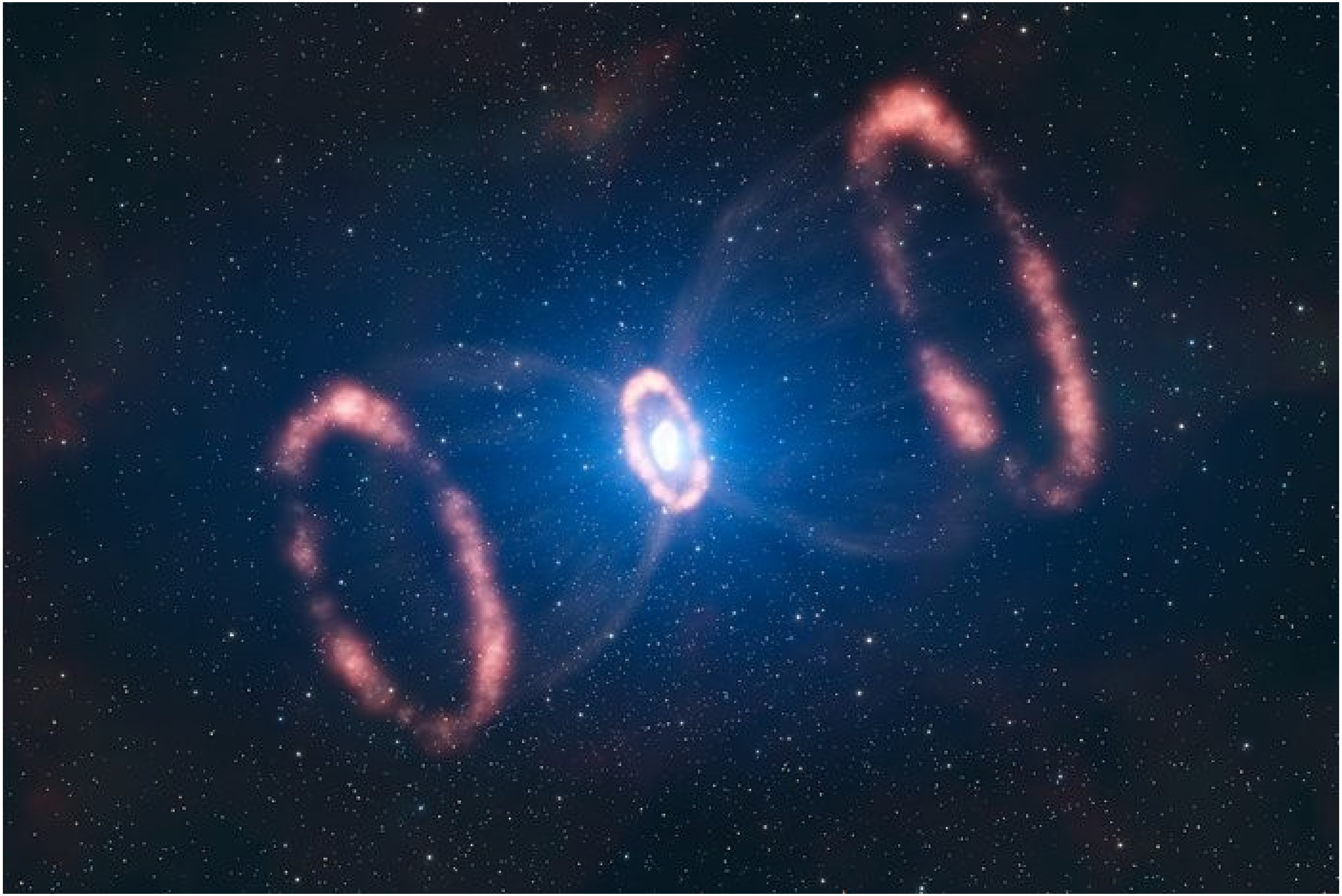
Inner ring (0,42 pc in diameter): ejected by slower winds 20 000 years ago from red supergiant phase?

Outer rings: faster & more energetic stellar winds from blue supergiant?

Both rings (inner ring and 2 outer rings) may be due to previous mass loss

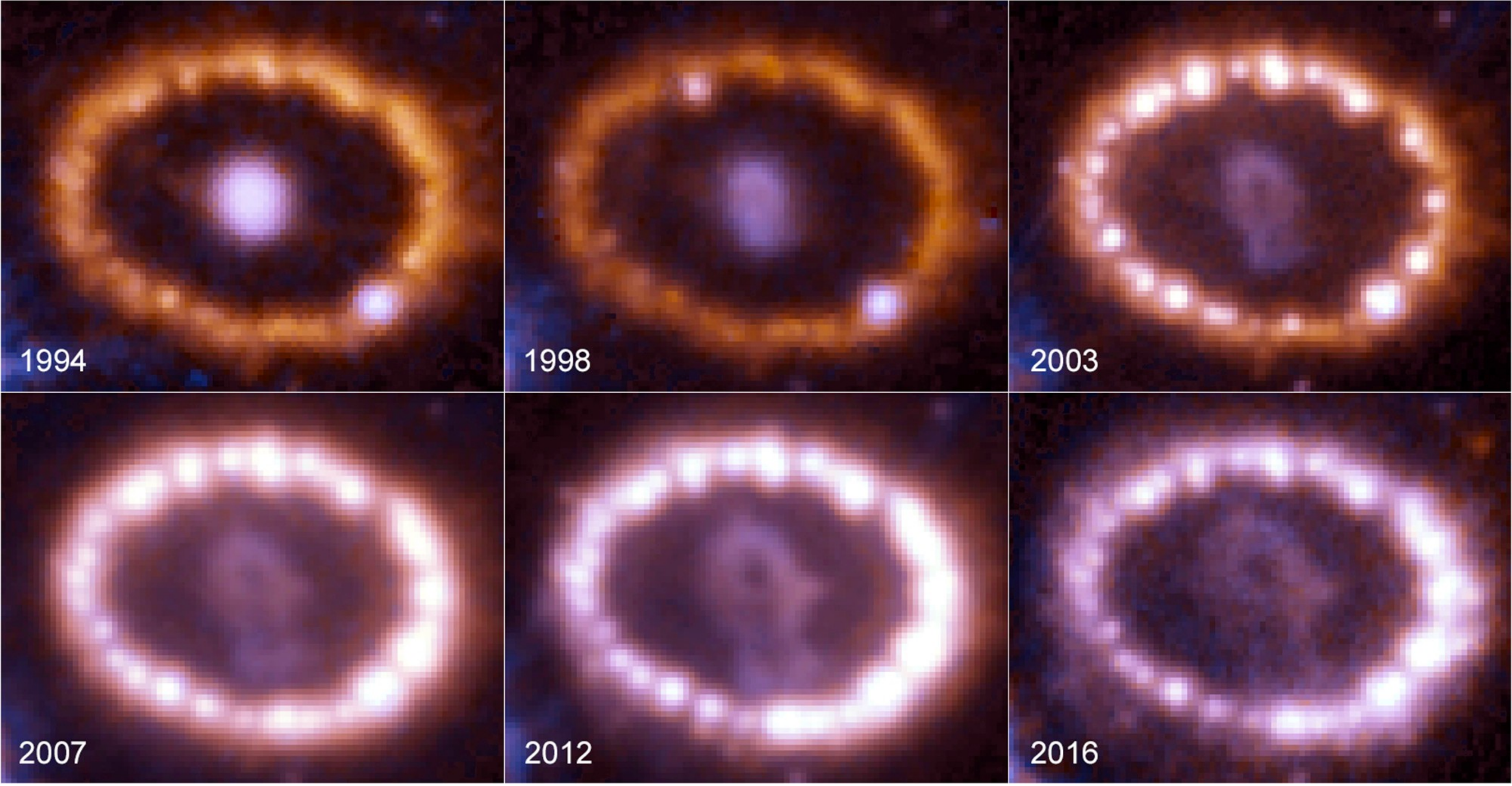


© Sky & Telescope



Artist’s impression of SN 1987A. © ESO

http://www.eso.org/public/brazil/news/eso1032/



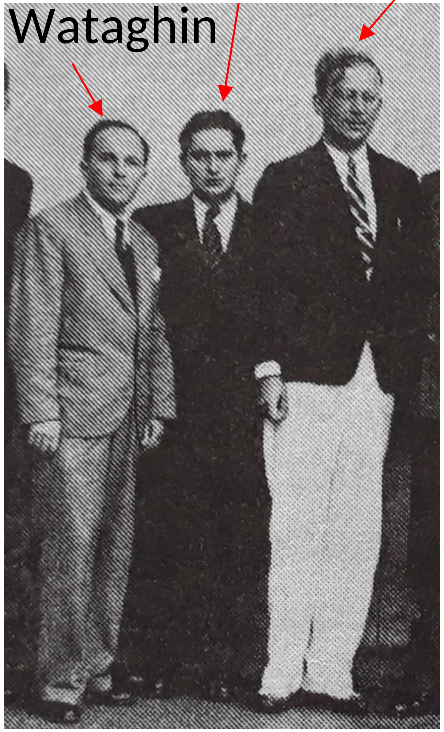
HST/NASA images (between 1994 and 2016) chronicle the brightening and fading of a ring of gas around an exploded star.

https://www.nasa.gov/feature/goddard/2017/the-dawn-of-a-new-era-for-supernova-1987a

Evolution of the ring collision from 1994 to 2014 (days 2270–9975) from a combination of *HST* B- and R-band images. Fransson et al. (2015)

1934/8/22: Mario Schenberg (ainda na graduação na Poli) ouviu falar pela 1a vez em neutrinos, em seminário do Enrico Fermi em Sampa

1940: Desenvolve com Gamow a teoria de neutrinos nas supernovas de colapso do núcleo estelar



Wataghin Schenberg Gamow

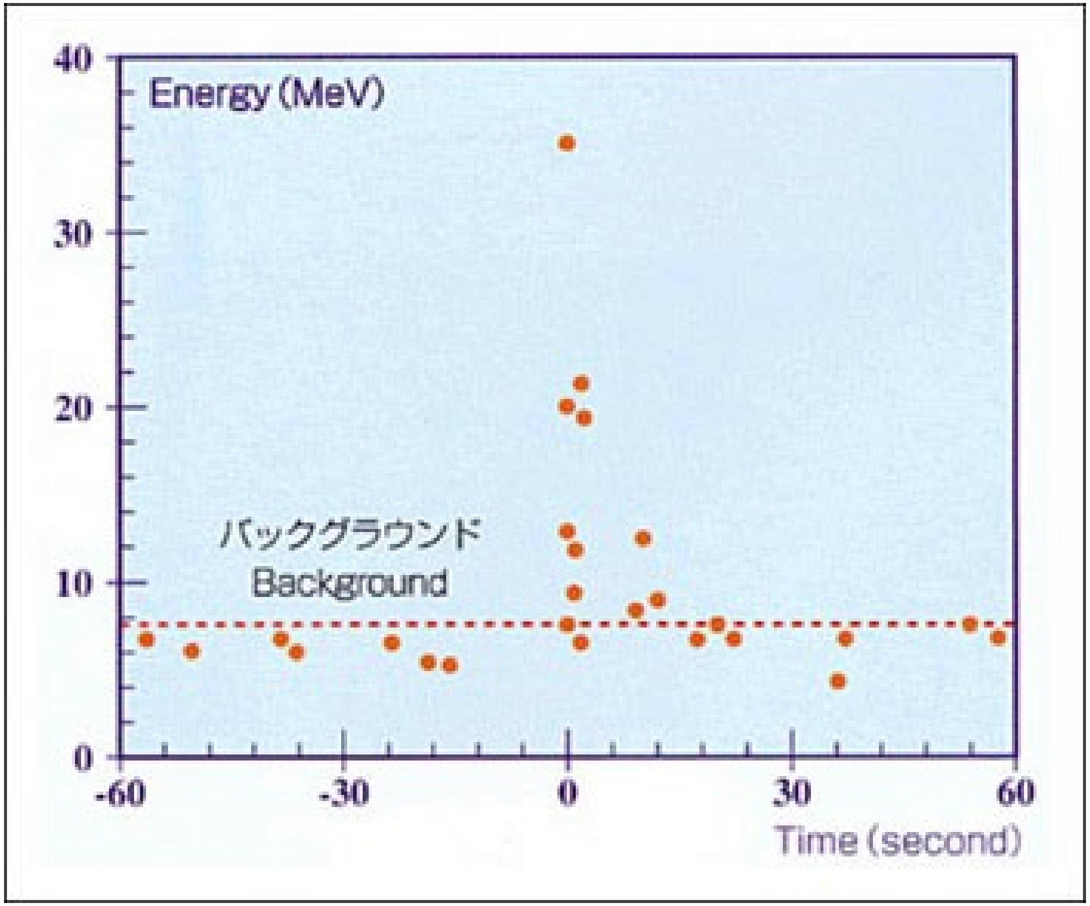
Foto tirada quando Gamow veio ao Brasil, em 1939.

Gamow Pauli Schenberg Chandrasekhar

Foto tirada nos EUA em 1942, quando Schenberg estava trabalhando com Gamow e Chandrasekhar.

https://www.comciencia.br/schenberg-e -os-neutrinos-do-processo-urca/

Neutrinos da SN1987A confirmaram teoria de Gamow e Schönberg

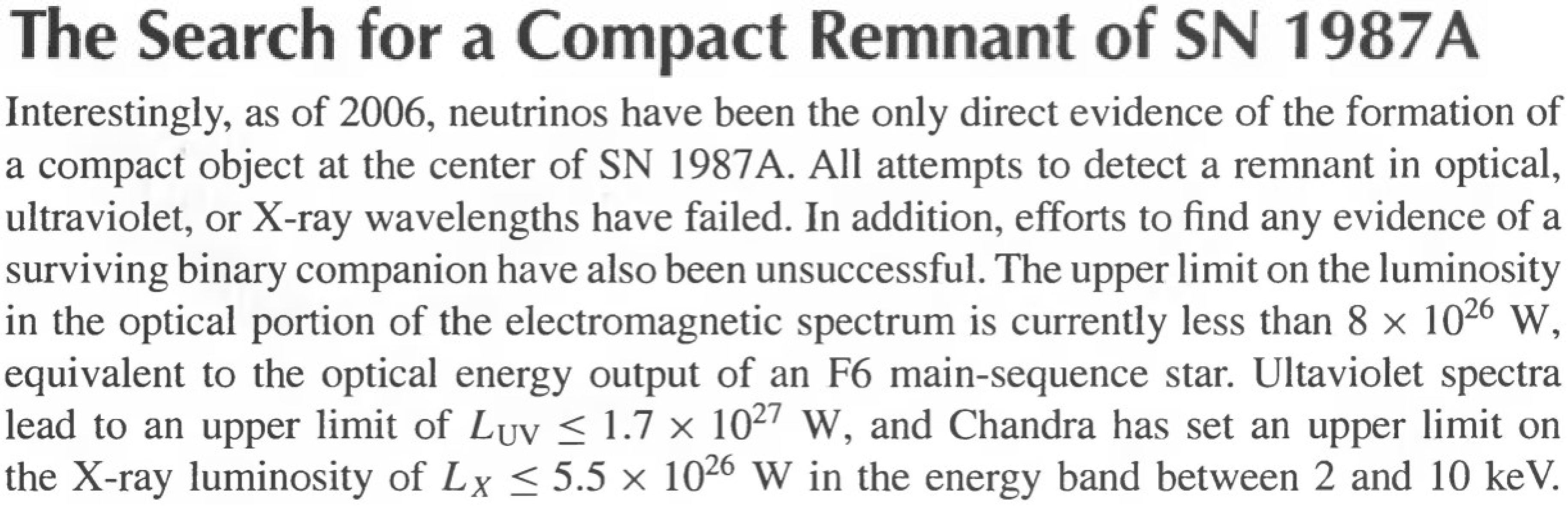


Kamiokande (large water Cherenkov detector) detected 11 events of neutrinos from the SN 1987A

http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/supernova-e.html

8 events were also detected in the USA.

Both neutrino detections occurred hours before the optical detection → neutrinos must have travelled close to c.



The Search for a Compact Remnant of SN 1987A

Interestingly, as of 2006, neutrinos have been the only direct evidence of the formation of a compact object at the center of SN 1987A. All attempts to detect a remnant in optical, ultraviolet, or X-ray wavelengths have failed. In addition, efforts to find any evidence of a surviving binary companion have also been unsuccessful. The upper limit on the luminosity in the optical portion of the electromagnetic spectrum is currently less than 8×10^{26} W, equivalent to the optical energy output of an F6 main-sequence star. Ultaviolet spectra lead to an upper limit of $L_{\mathrm{UV}} \leq 1.7 \times 10^{27}$ W, and Chandra has set an upper limit on the X-ray luminosity of $L_X \leq 5.5 \times 10^{26}$ W in the energy band between 2 and 10 keV.

11/2019: objeto compacto ainda não encontrado

The Remnant of Supernova 1987A

Annual Review of Astronomy and Astrophysics

Vol. 54:19-52 (Volume publication date September 2016)
First published online as a Review in Advance on June 27, 2016
https://doi.org/10.1146/annurev-astro-082615-105405

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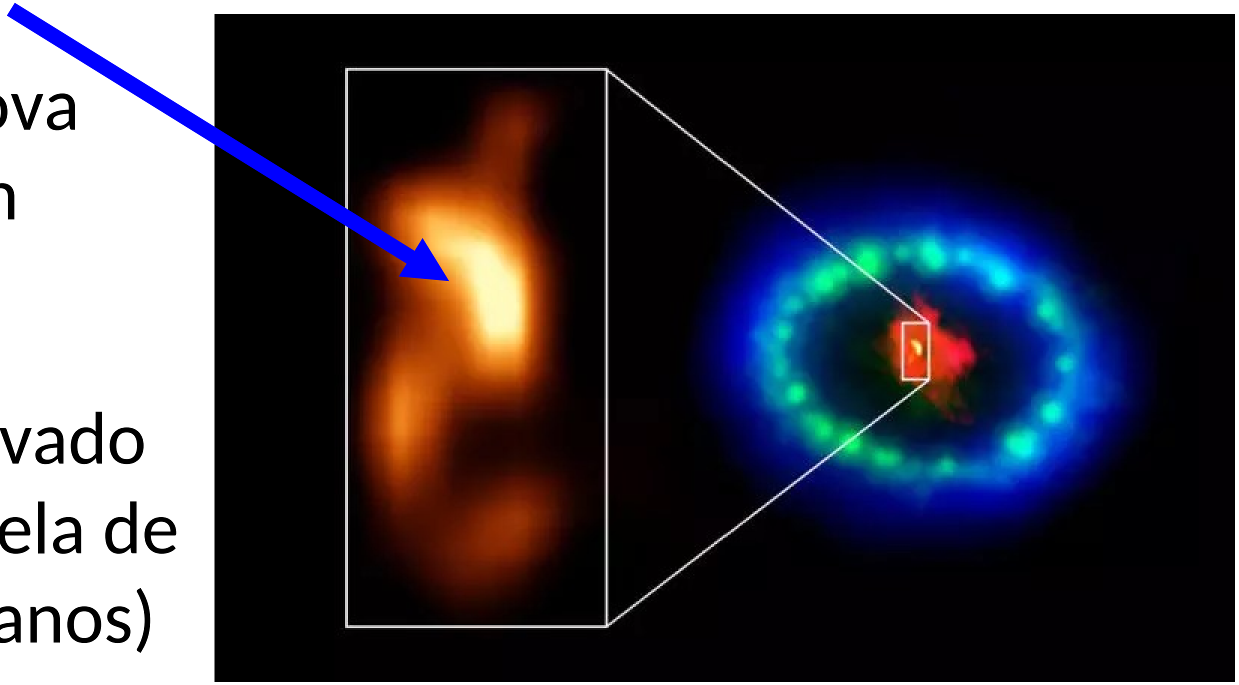
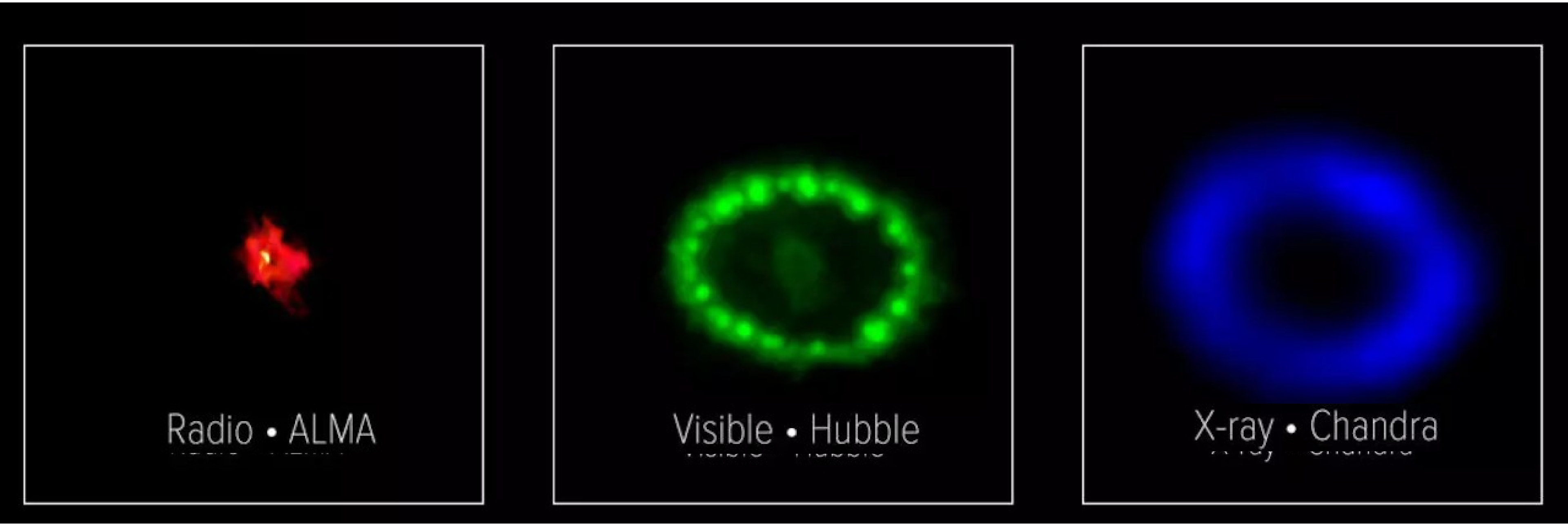
12/2019: estrela de nêutrons da supernova 1987A observada em rádio pelo ALMA?

7/2020: brilho observado compatível com estrela de nêutrons jovem (33 anos)

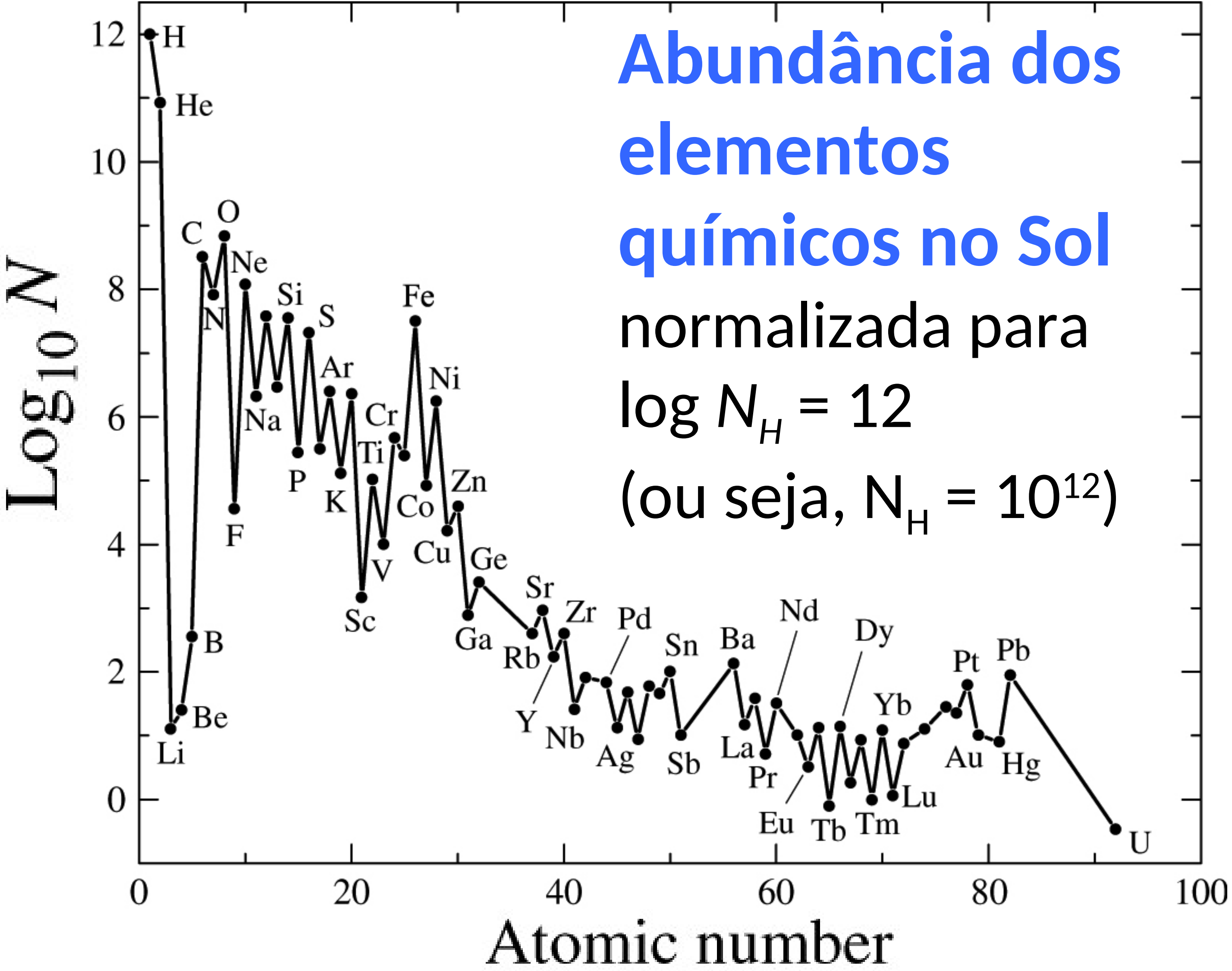




https://www.almaobservatory.org /en/press-releases/alma-finds-possible-sign-of-neutron-star-in-supernova-1987a/

Abundâncias químicas no universo

Big Bang



Abundância dos elementos químicos no Sol

normalizada para

log N_H = 12

(ou seja, $N_H = 10^{12}$)

H, He: muito abundantes (Big Bang)

Li, Be, B: pouco abundantes

FIGURE 15.16 The relative abundances of elements in the Sun's photosphere. All abundances are normalized relative to 10^{12} hydrogen atoms. (Data from Grevesse and Sauval, *Space Sci. Rev.*, *85*, 161, 1998.)

Li e Be são facilmente destruídos em interiores estelares.
Li queima a $2,7 \times 10^6$ K e Be a $3,6 \times 10^6$ K

$$p + {}^6_3Li \rightarrow {}^7_4Be$$

$${}^7_4Be + e^- \rightarrow {}^7_3Li + \nu$$

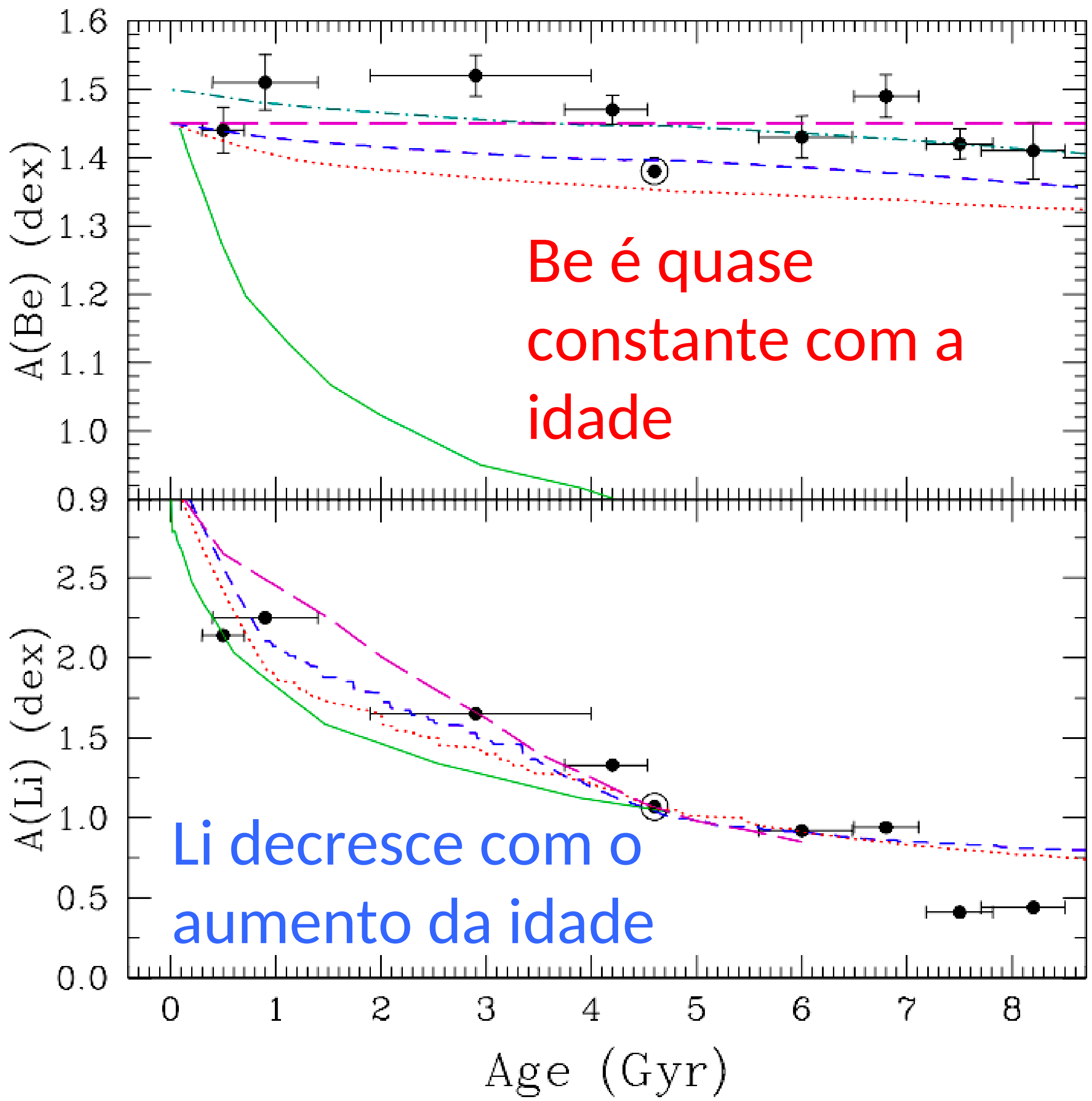
$$p + {}^7_3Li \rightarrow {}^8_4Be$$

$${}^8_4Be \rightarrow 2\,{}^4_2He + energia$$

De fato, a abundância de Li no Sol é 150 vezes menor do que em meteoritos, porem o Be no Sol é similar ao dos meteoritos.

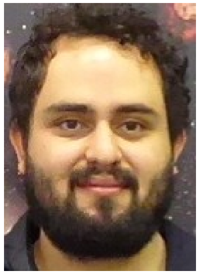
→ processos de transporte no envelope convectivo atingem a região de queima de Li mas não atingem a região onde Be é queimado

Be & Li no Sol e em estrelas gêmeas do Sol



Be é quase constante com a idade

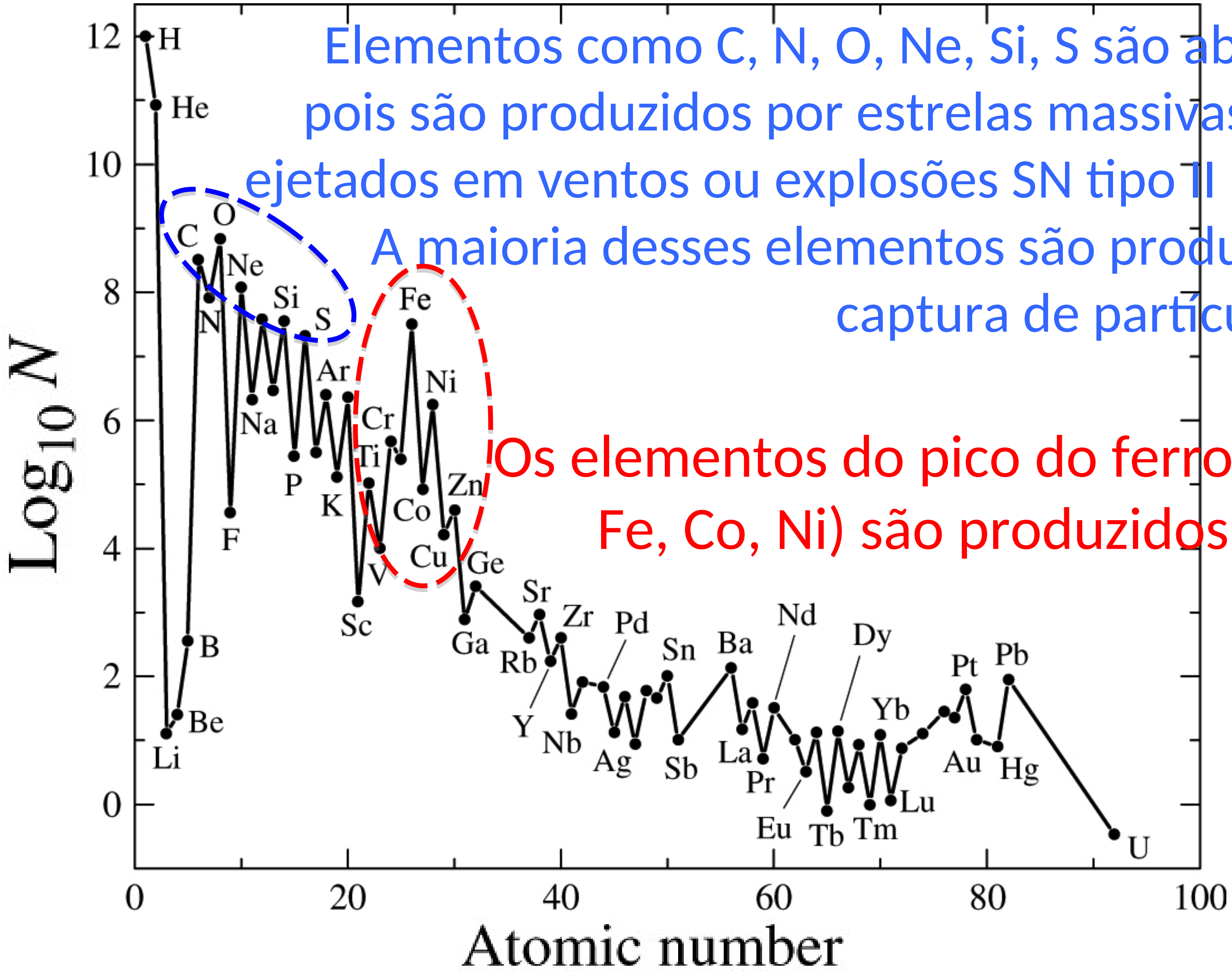
Li decresce com o aumento da idade



Marcelo Tucci Maia et al. 2015, A&A 576, L10

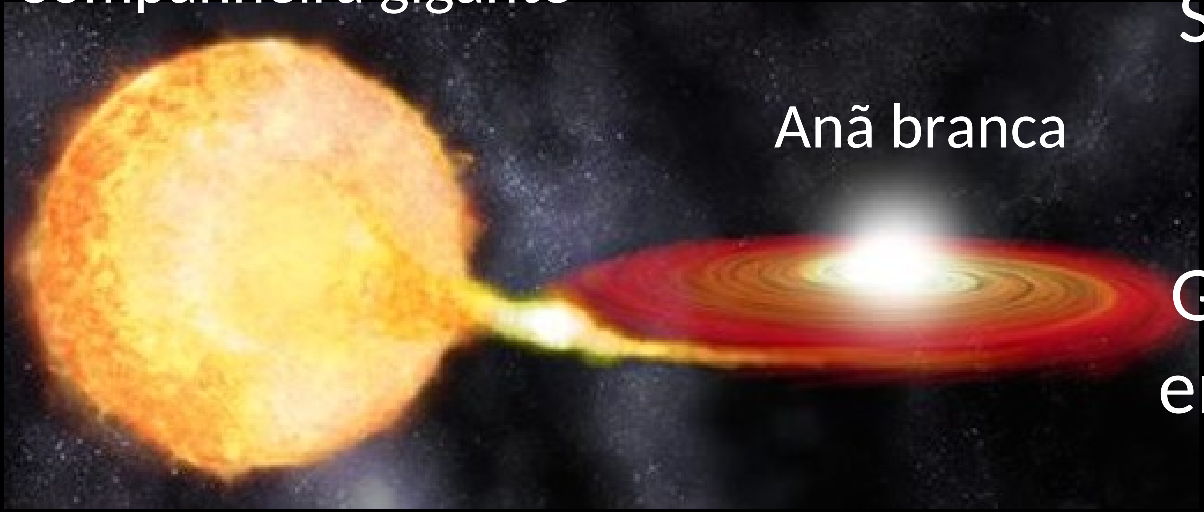
Os processos de transporte atingem apenas a camada de queima do Li, logo abaixo da zona convectiva (não chegam à camada de queima de Be que é mais interna)

Abundâncias químicas no Sol

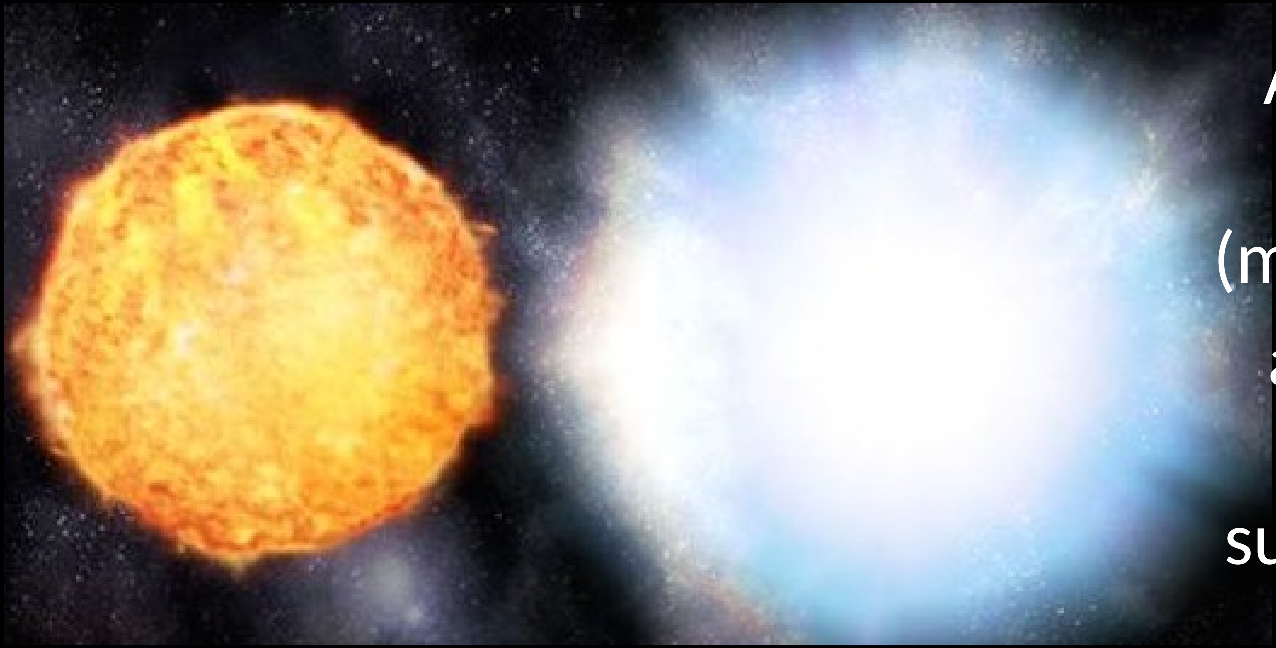


Elementos como C, N, O, Ne, Si, S são abundantes pois são produzidos por estrelas massivas e depois ejetados em ventos ou explosões SN tipo II (ou Ib/Ic). A maioria desses elementos são produzidos por captura de partícula α (^{4}He)

Os elementos do pico do ferro (e.g., Cr, Fe, Co, Ni) são produzidos por SN Ia



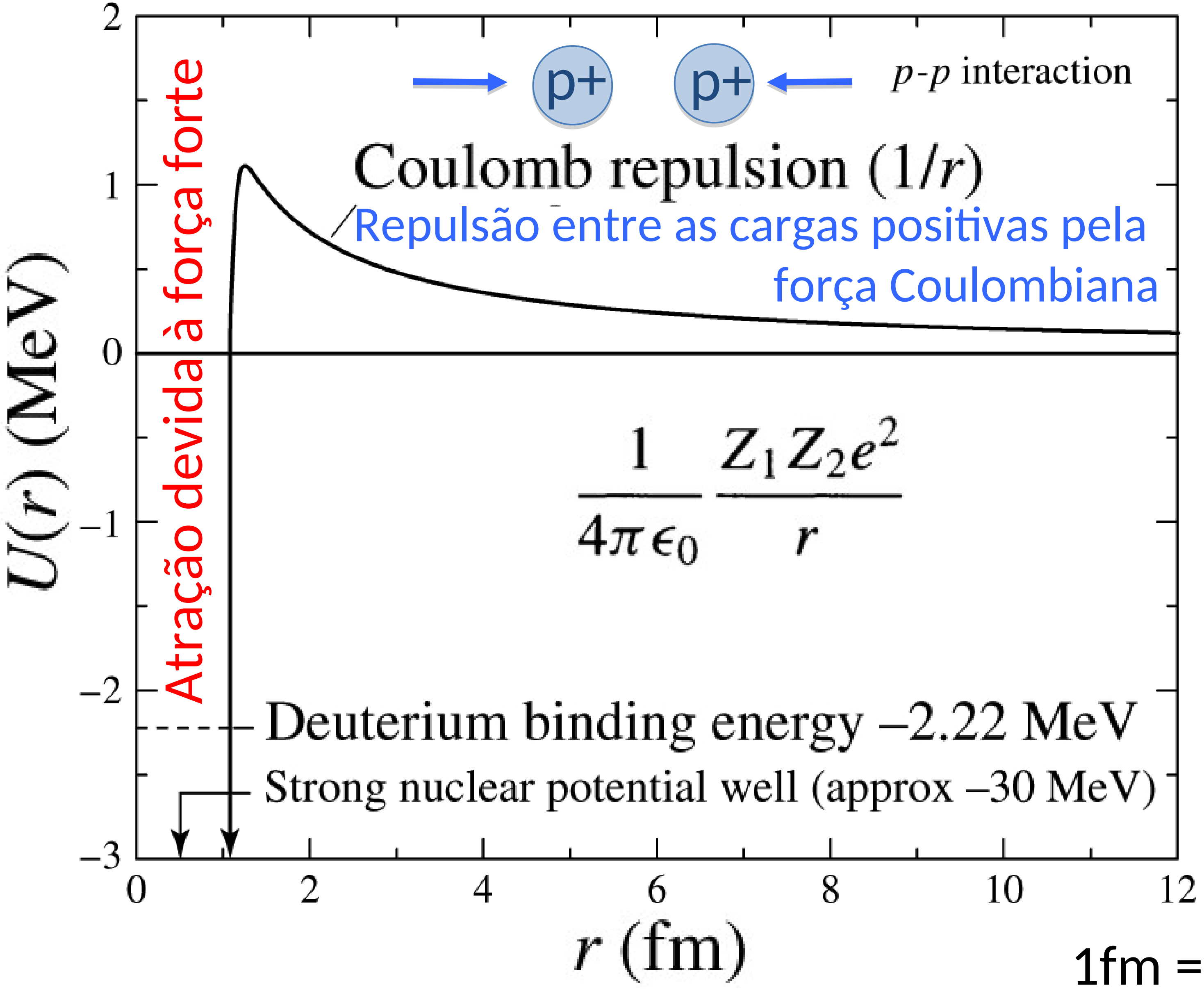
Supernovas de tipo Ia enriquecem quimicamente a Galáxia, em particular em elementos do pico do Fe.



Acontecem quando anãs brancas (massa inicial < 8$M_\odot$) acrescem massa de companheiras e superam certo limite (~1,4 $M_\odot$)

https://phys.org/news/2014-08-ia-supernovae-stem-explosion-white.html

Para núcleos com alto Z fica mais difícil a fusão nuclear devido à maior barreira Coulombiana



$$\frac{1}{4\pi\epsilon_0}\frac{Z_1Z_2e^2}{r}$$

Repulsão entre as cargas positivas pela força Coulombiana

Atração devida à força forte

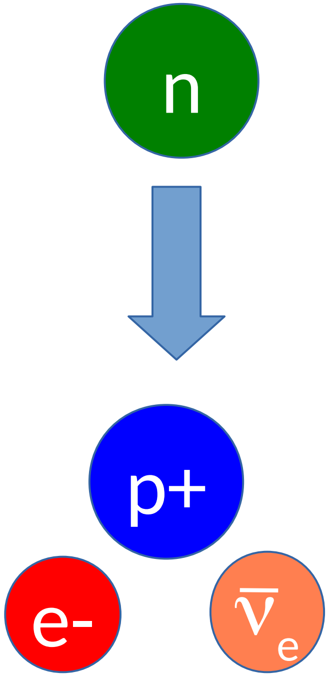
$1\text{fm} = 10^{-15}\text{m}$

Nucleossíntese por captura de nêutrons:
processo-s e **processo-r**

Nêutrons não são afetados pela barreira Coulombiana.

$$ {}^{A}_{Z}\mathrm{X} + n \rightarrow {}^{A+1}_{Z}\mathrm{X} + \gamma $$

O Nêutron capturado pode decair → elemento químico com Z = Z+1



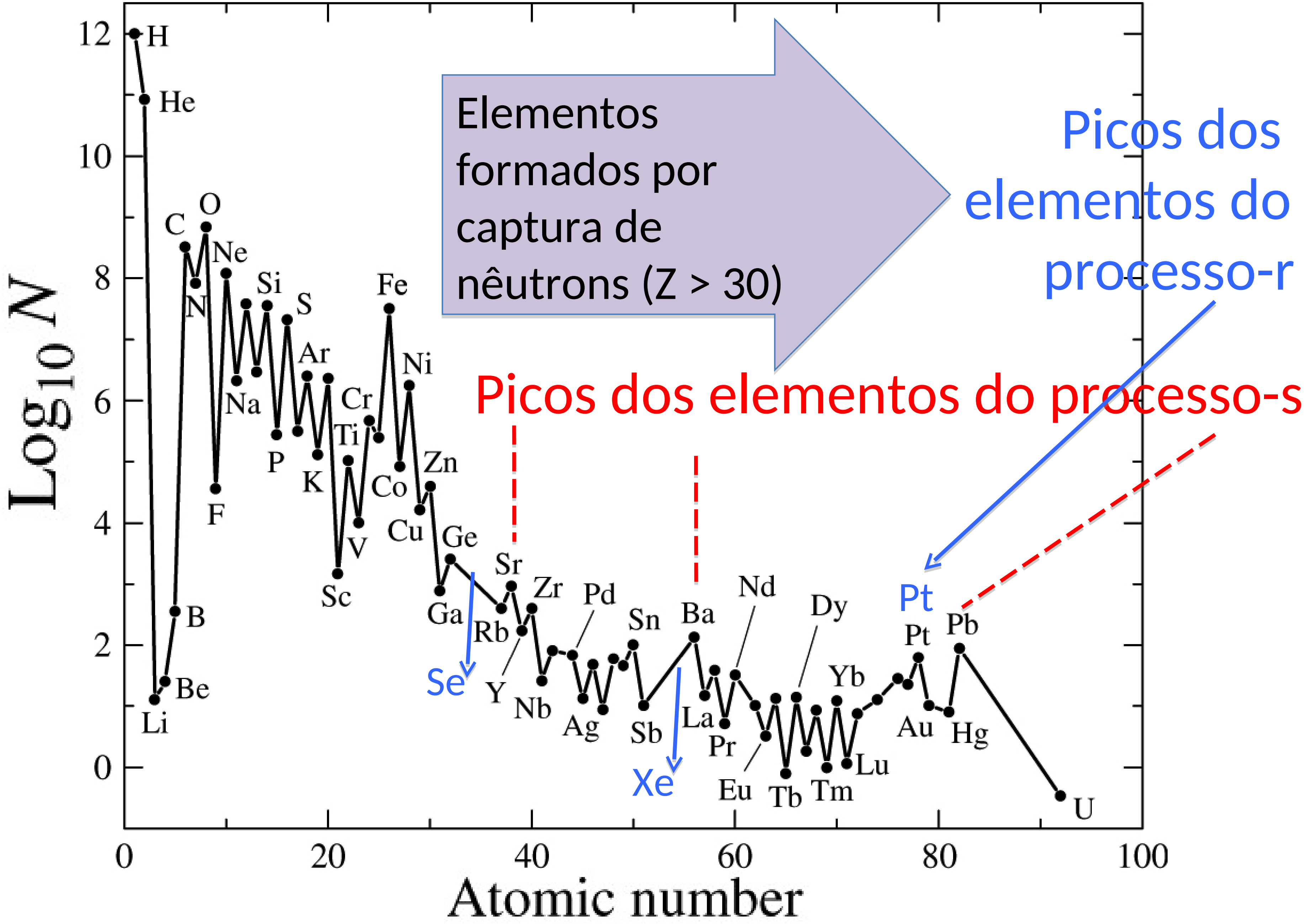
$$ {}^{A+1}_{Z}\mathrm{X} \rightarrow {}^{A+1}_{Z+1}\mathrm{X} + e^{-} + \bar{\nu}_e + \gamma $$

Alto fluxo de nêutrons: processo-*r* (rapid)

P.ex., SN II ou fusão de estrelas de nêutrons

Baixo fluxo de nêutrons: processo-*s* (slow)

Estrelas AGB



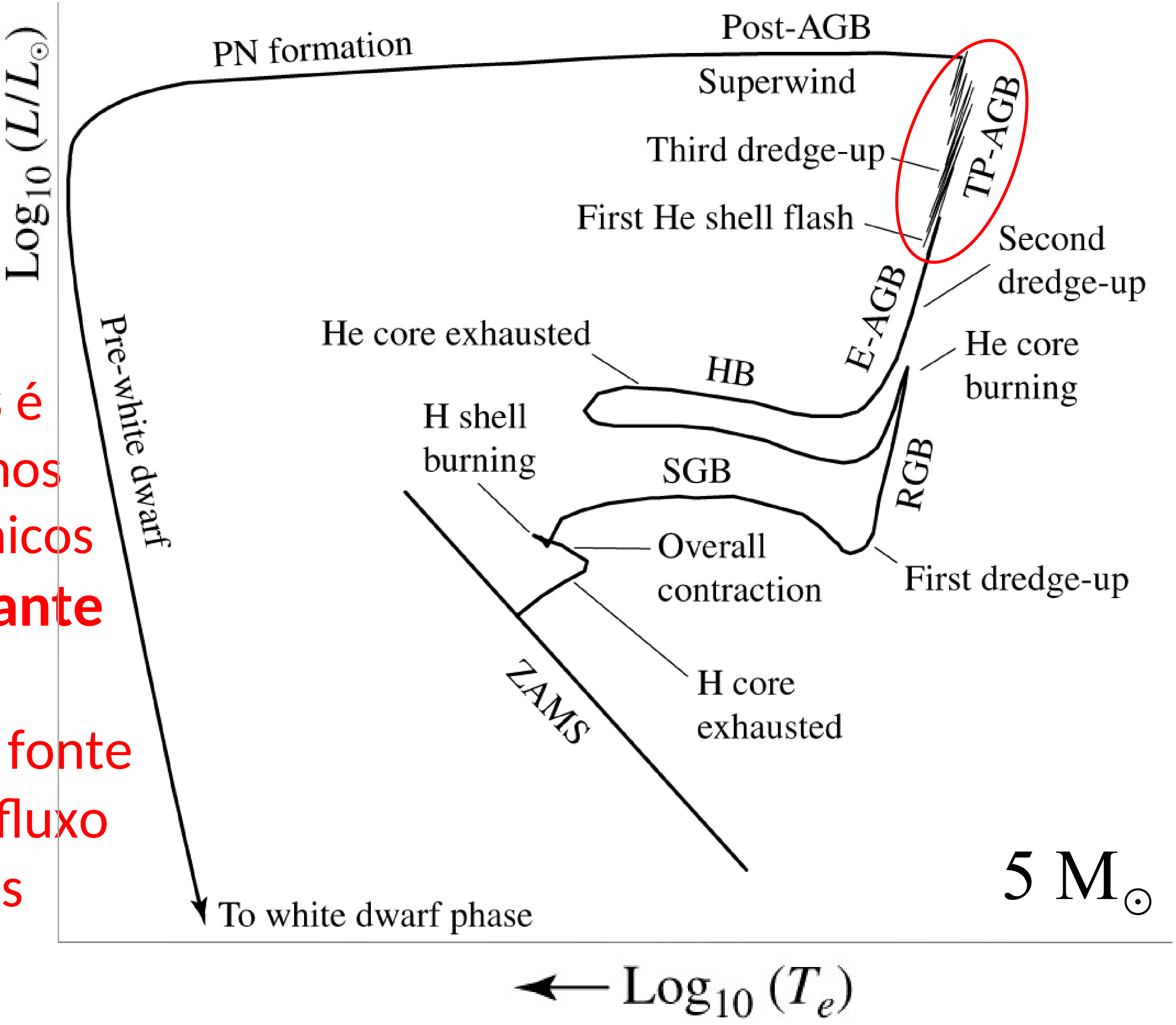
Elementos formados por captura de nêutrons (Z > 30)

Picos dos elementos do processo-r

Picos dos elementos do processo-s

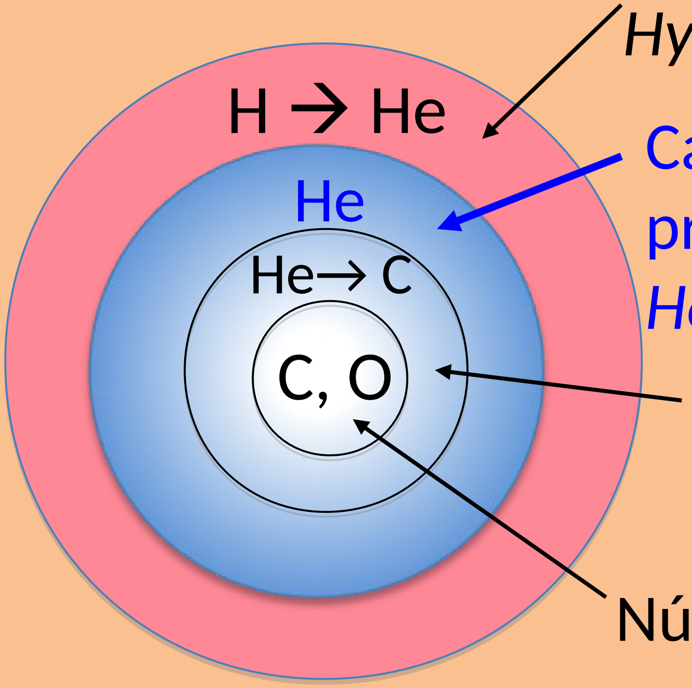
Abundância dos elementos químicos no Sol

Processo-s é produzido nos pulsos térmicos da fase **gigante AGB**, onde existe uma fonte com baixo fluxo de nêutrons



Os elementos do processo-s são produzidos na fase de gigante AGB (durante os pulsos térmicos)

Envelope de hidrogênio
(não está em escala) x 1000



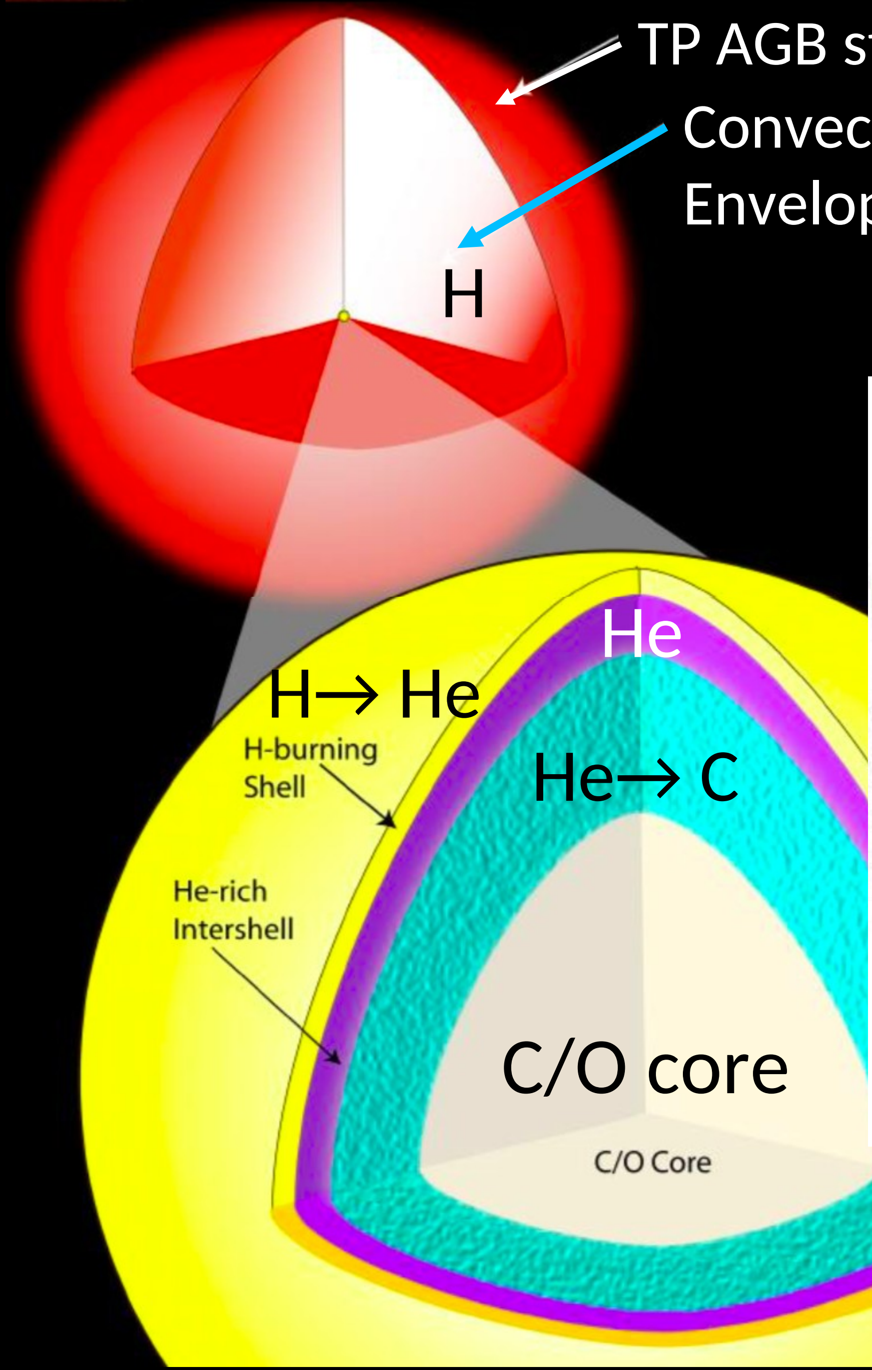
Casca de queima de H
Hydrogen-burning shell

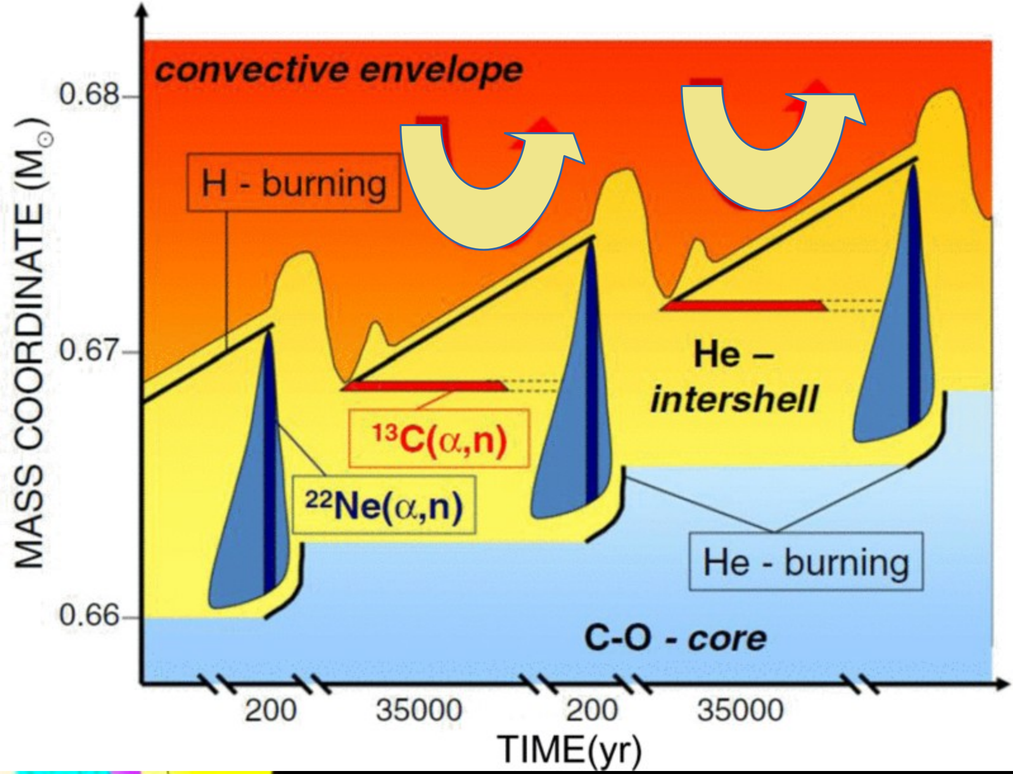
Casca de He, onde é produzido o processo-s
Helium intershell

Casca queima de He
Helium burning shell

Núcleo de C, O

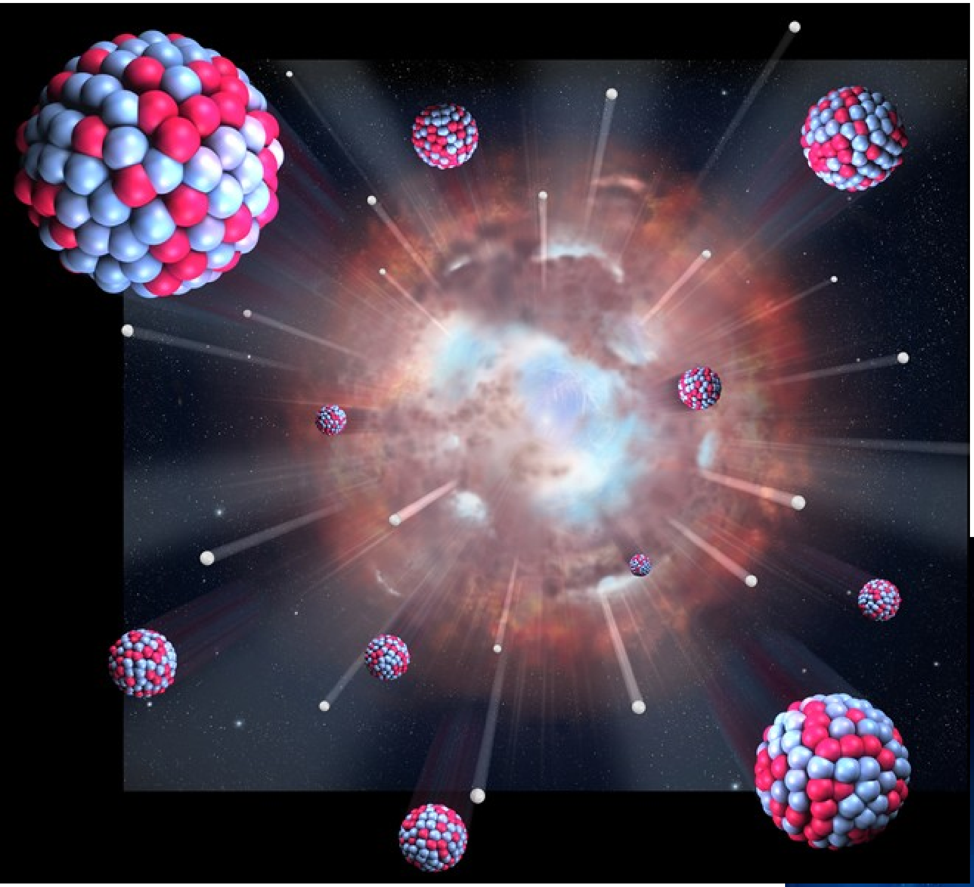
Elementos do processo-s são dragados para a superfície via o envelope convectivo





Slide adaptado de Amanda Karakas

Processo-r: captura de nêutrons em alto fluxo de nêutrons



(c) Akihiro Ikeshita/Naotsugu Mikami

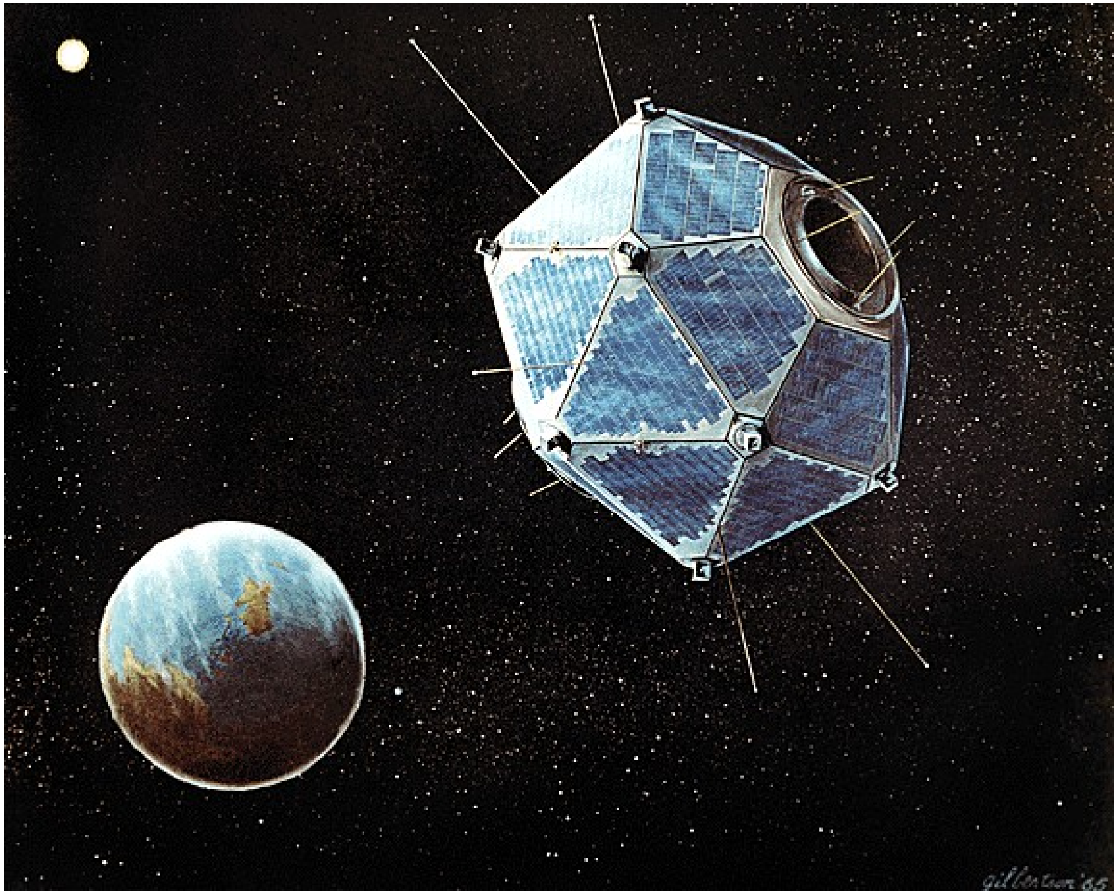
Explosões supernovas tipo II

(c) Mark Garlick

Fusão de estrelas de nêutrons

15.4 Gamma ray bursts (GRB)

Primeiros *gamma ray bursts* detectados nos anos 1960s



Satellite Vela that detected Gamma Ray Bursts

The Vela spacecrafts monitored the compliance of the Soviet Union to the 1963 Partial Test Ban Treaty, by looking for sudden bursts of gamma rays from nuclear weapons.

Em 1967 era clara a origem astronômica, porem GRB publicados apenas em 1973

https://en.wikibooks.org/wiki/General_Astronomy/Introduction_and_Brief_History_of_Gamma-Ray_Bursts

Gamma ray bursts

(c) NASA/M. Kornmesser

- Aproximadamente 1 por dia aleatoriamente no céu
- Energia de keV a GeV
- Duração de 10^{-2} a 10^{3} segundos (*short GRB* [curto] < 2 s; *long GRB* [longo] > 2 s)
- Tempo de subida rápido (~10^{-4}s a alguns segundos), seguido de queda exponencial.
- Geralmente podem existir vários picos

Curvas de luz de 2 *Gamma ray bursts* observados pelo BATSE/Compton Gamma-Ray Observatory [CGRO]

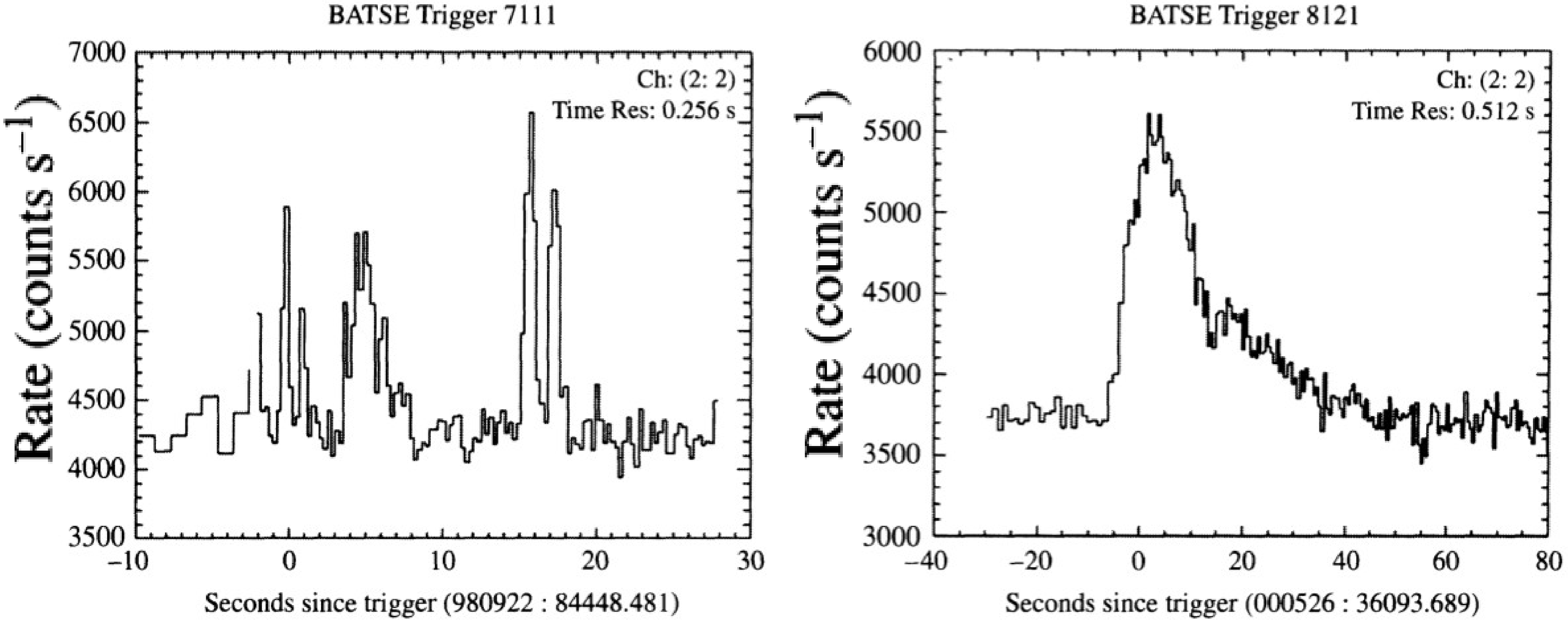
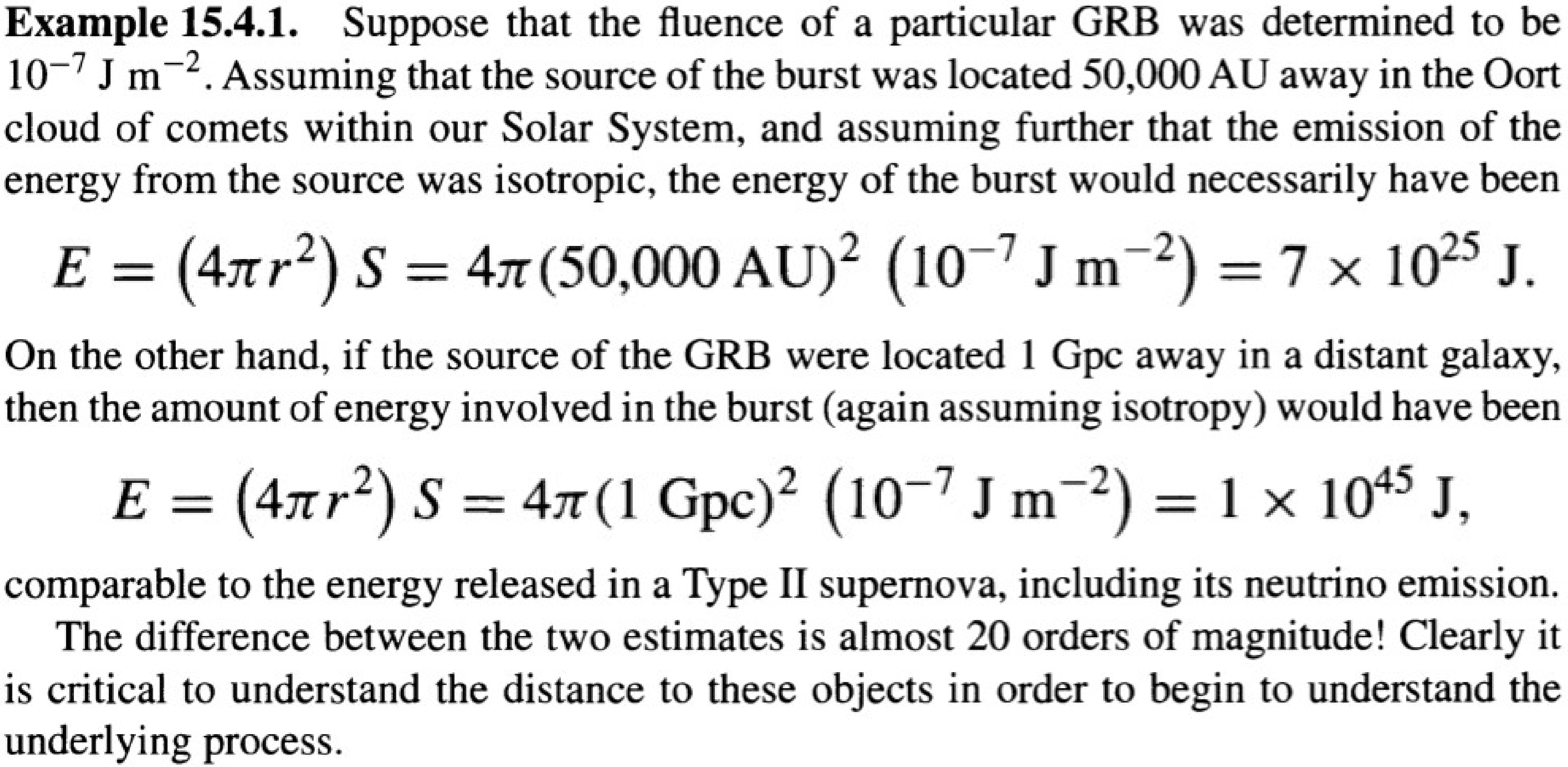


FIGURE 15.17 Light curves of two gamma-ray bursts, GRB 980922 and GRB 000526, in the energy range between 50 keV and 100 keV. The data were obtained by BATSE onboard the Compton Gamma-Ray Observatory. The dates of the two events are recorded in their designations; GRB 980922 occurred on September 22, 1998, and GRB 000526 occurred on May 26, 2000. GRB 0000526 was the last gamma-ray burst recorded by BATSE before the Compton Gamma-Ray Observatory was deorbited. (Courtesy of the BATSE Team – NASA.)

Energia liberada



Example 15.4.1. Suppose that the fluence of a particular GRB was determined to be 10^{-7} J m^{-2}. Assuming that the source of the burst was located 50,000 AU away in the Oort cloud of comets within our Solar System, and assuming further that the emission of the energy from the source was isotropic, the energy of the burst would necessarily have been

$$E = \left(4\pi r^2\right) S = 4\pi (50{,}000\ \mathrm{AU})^2\ \left(10^{-7}\ \mathrm{J\ m^{-2}}\right) = 7 \times 10^{25}\ \mathrm{J}.$$

On the other hand, if the source of the GRB were located 1 Gpc away in a distant galaxy, then the amount of energy involved in the burst (again assuming isotropy) would have been

$$E = \left(4\pi r^2\right) S = 4\pi (1\ \mathrm{Gpc})^2\ \left(10^{-7}\ \mathrm{J\ m^{-2}}\right) = 1 \times 10^{45}\ \mathrm{J},$$

comparable to the energy released in a Type II supernova, including its neutrino emission.

The difference between the two estimates is almost 20 orders of magnitude! Clearly it is critical to understand the distance to these objects in order to begin to understand the underlying process.

Distâncias desconhecidas. Proposta inicial: estrelas de nêutrons no disco espesso da nossa galáxia.

Problema: distribuição é isotrópica

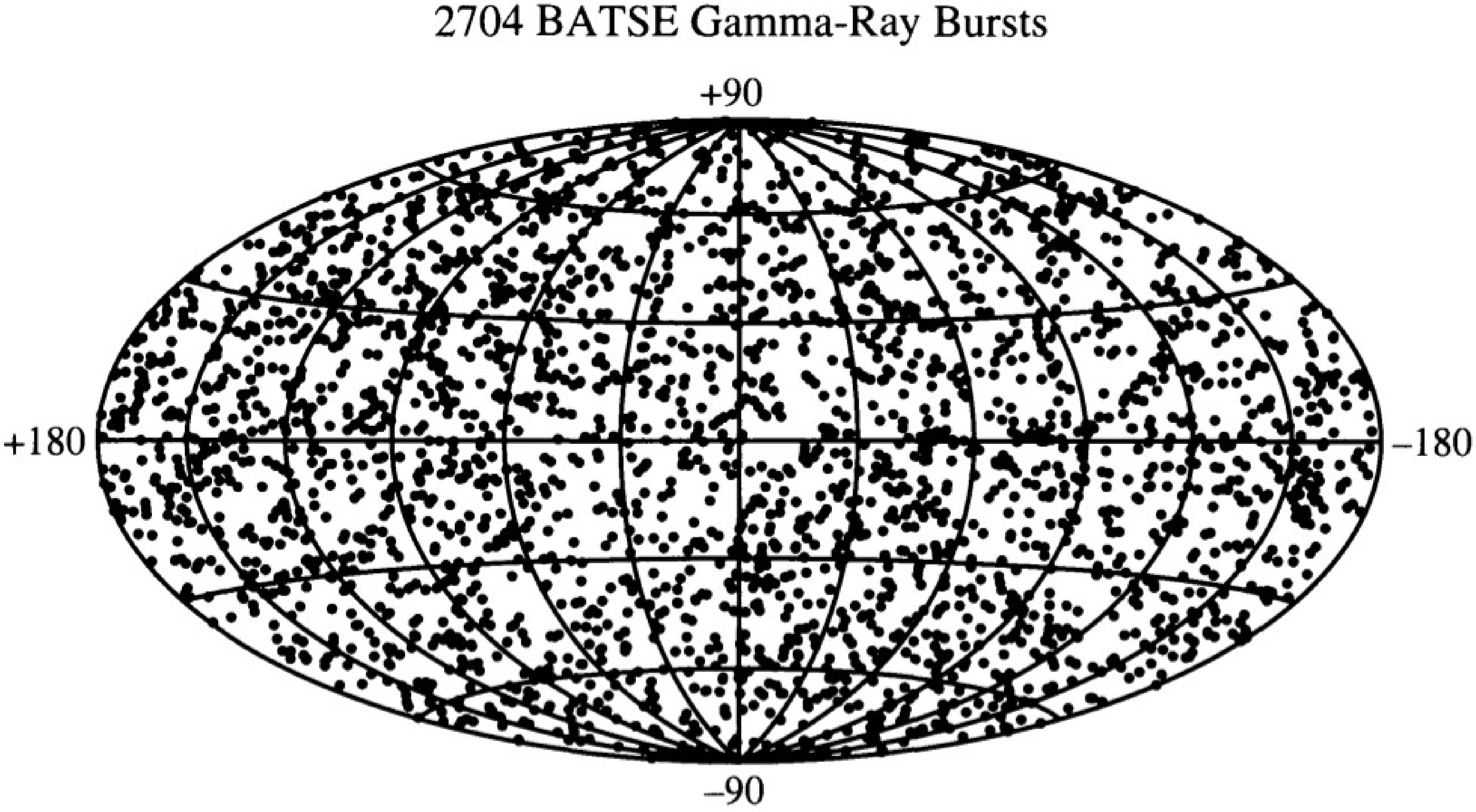
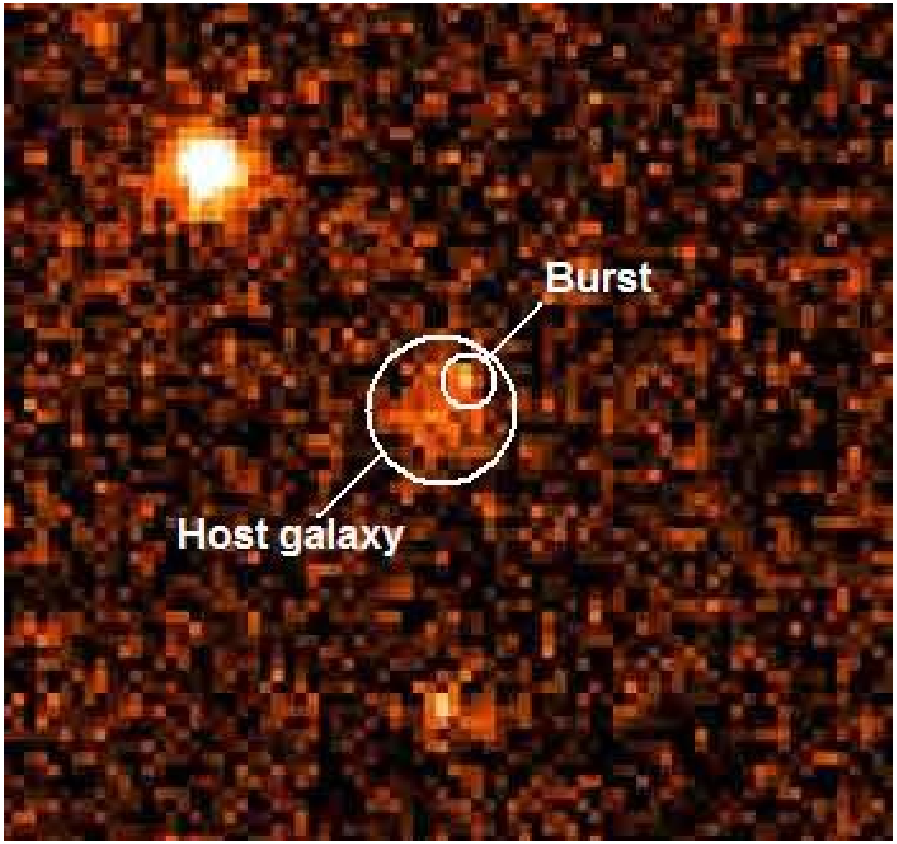


FIGURE 15.18 The isotropic angular distribution of 2704 gamma-ray bursts seen by the BATSE detector onboard the CGRO. (Courtesy of the BATSE Team – NASA.)

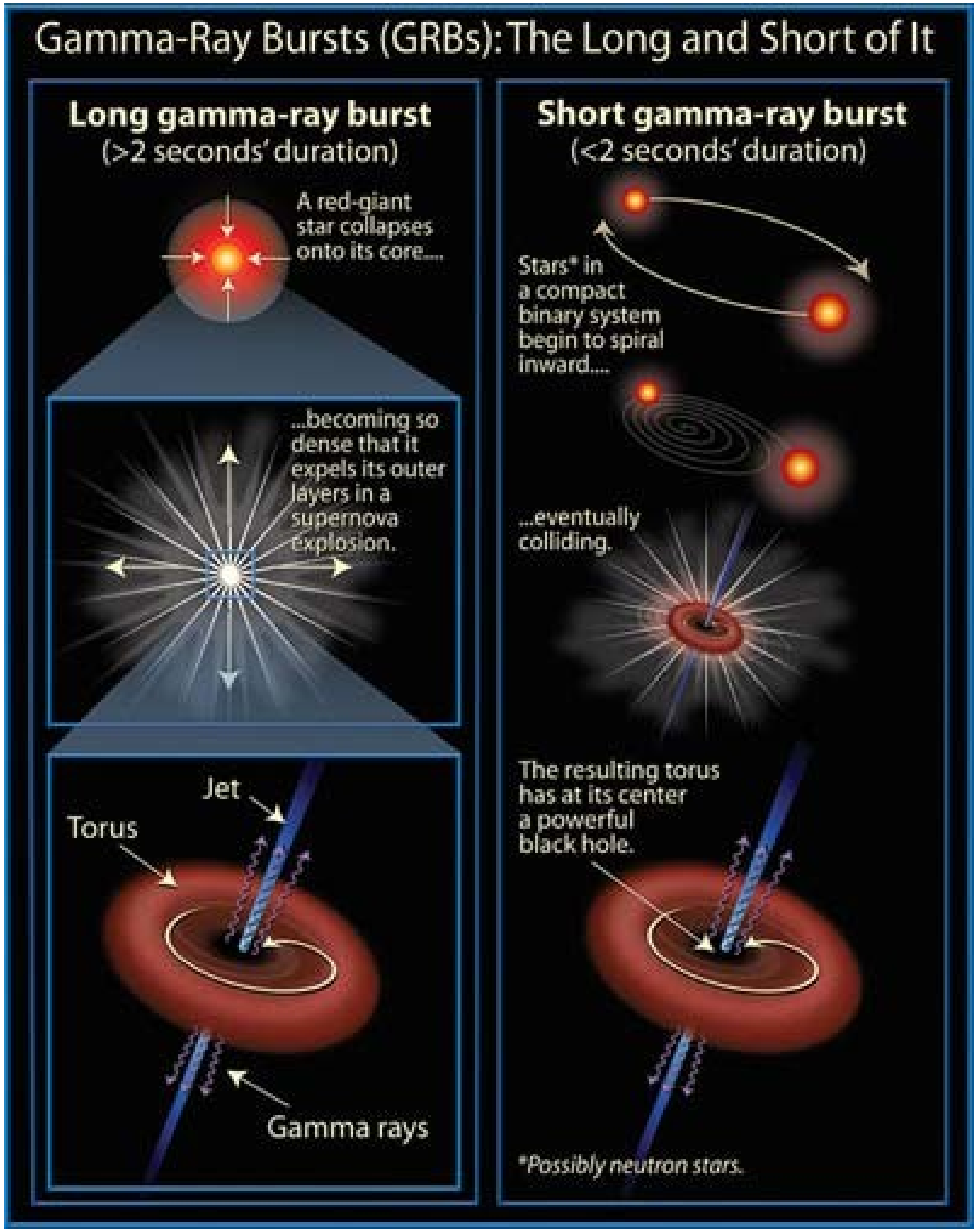
BeppoSAX (satélite Itália/Holanda) observou no 28 fev 1997 o GRB 970228, localizando a fonte dentro de 3 arcmin com a câmera da grande campo. Depois, telescópios de raios-X do observatório com melhor resolução angular, conseguiram localizaram a fonte.



Observações posteriores no óptico descobriram que a fonte está localizada em uma galáxia → origem extragaláctica dos GRBs

Gamma Ray Burst GRB 970228 Appears To Originate Outside Our Galaxy.

https://en.wikipedia.org/wiki/GRB_970228

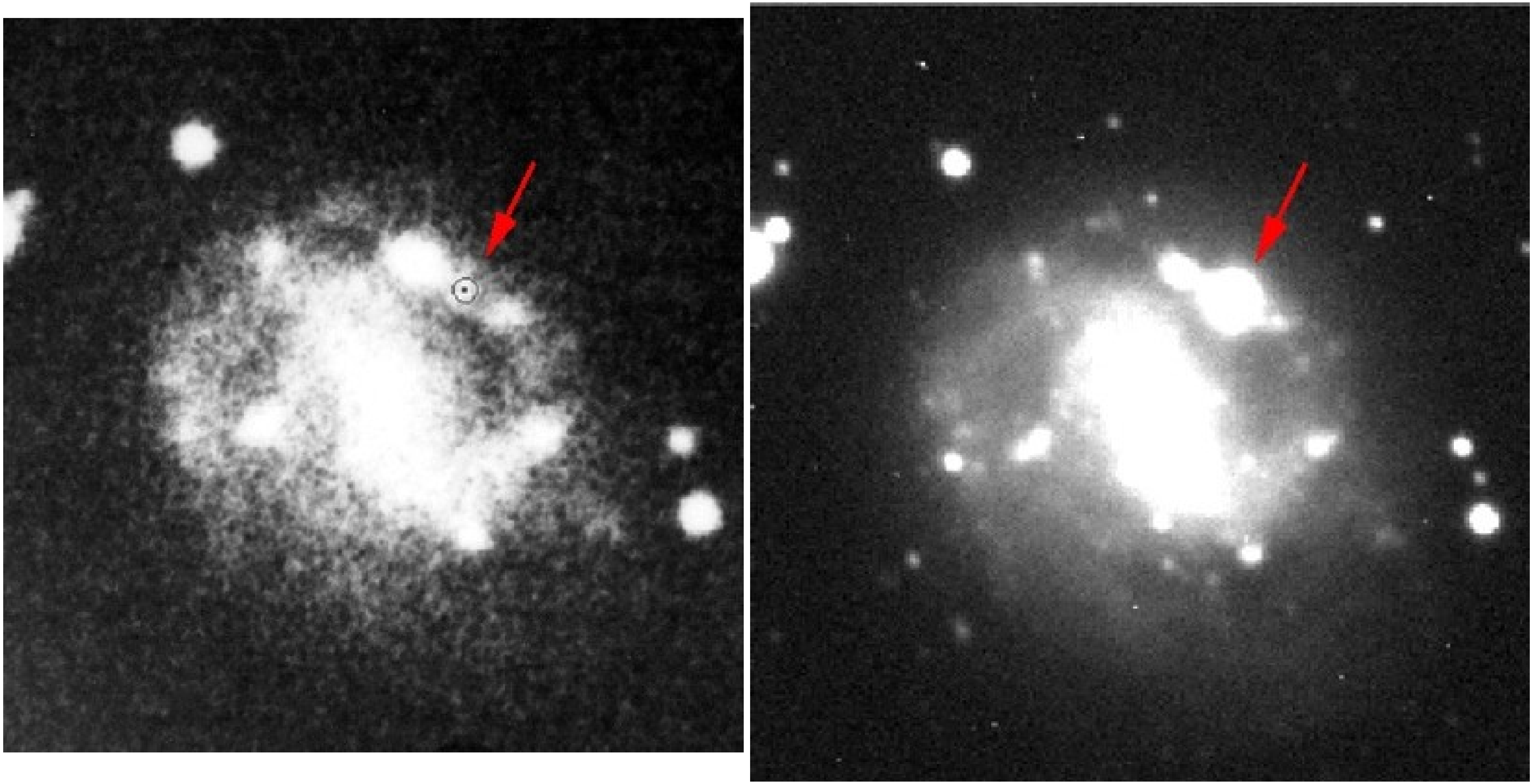


Dois tipos de GRBs.

Long-soft (> 2 segundos)
Menor energia.
Supernova de colapso de núcleo.

Short-hard (< 2 segundos)
Maior energia.
Colisão de 2 estrelas de nêutrons

Conexão entre GRB Long-Soft e supernovas de colapso do núcleo foi bem estabelecida com o GRB 980425

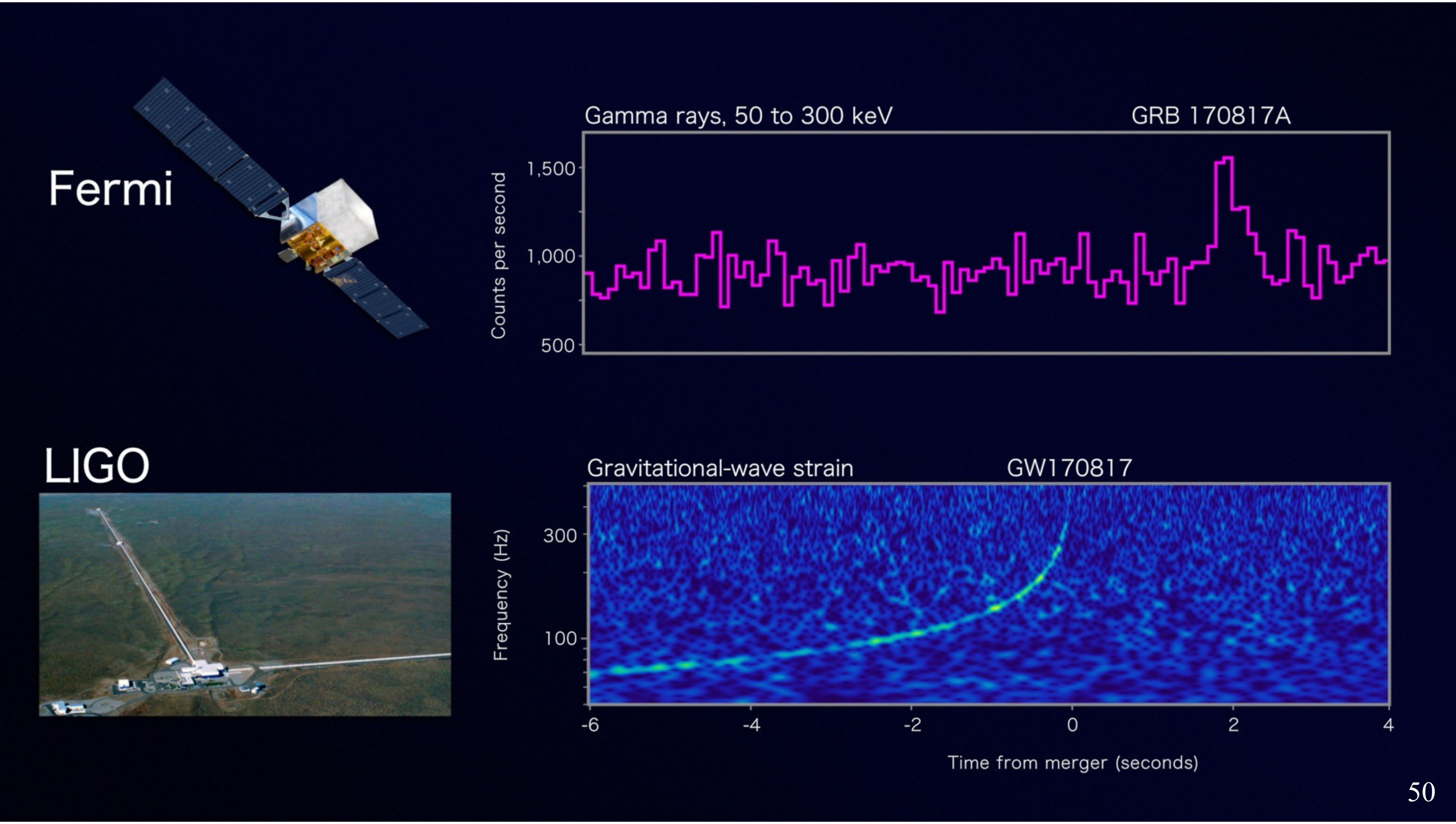


Discovery of SN 1998bw associated with GRB 980425.

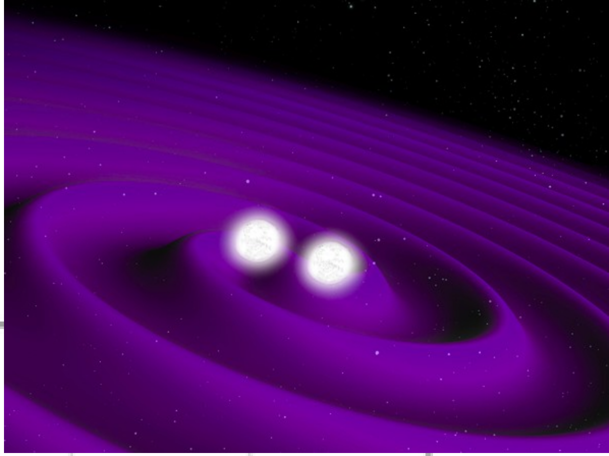
GW170817 Press Release

LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars

Discovery marks first cosmic event observed in both gravitational waves and light.



Raios-gama pela colisão de 2 estrelas de nêutrons



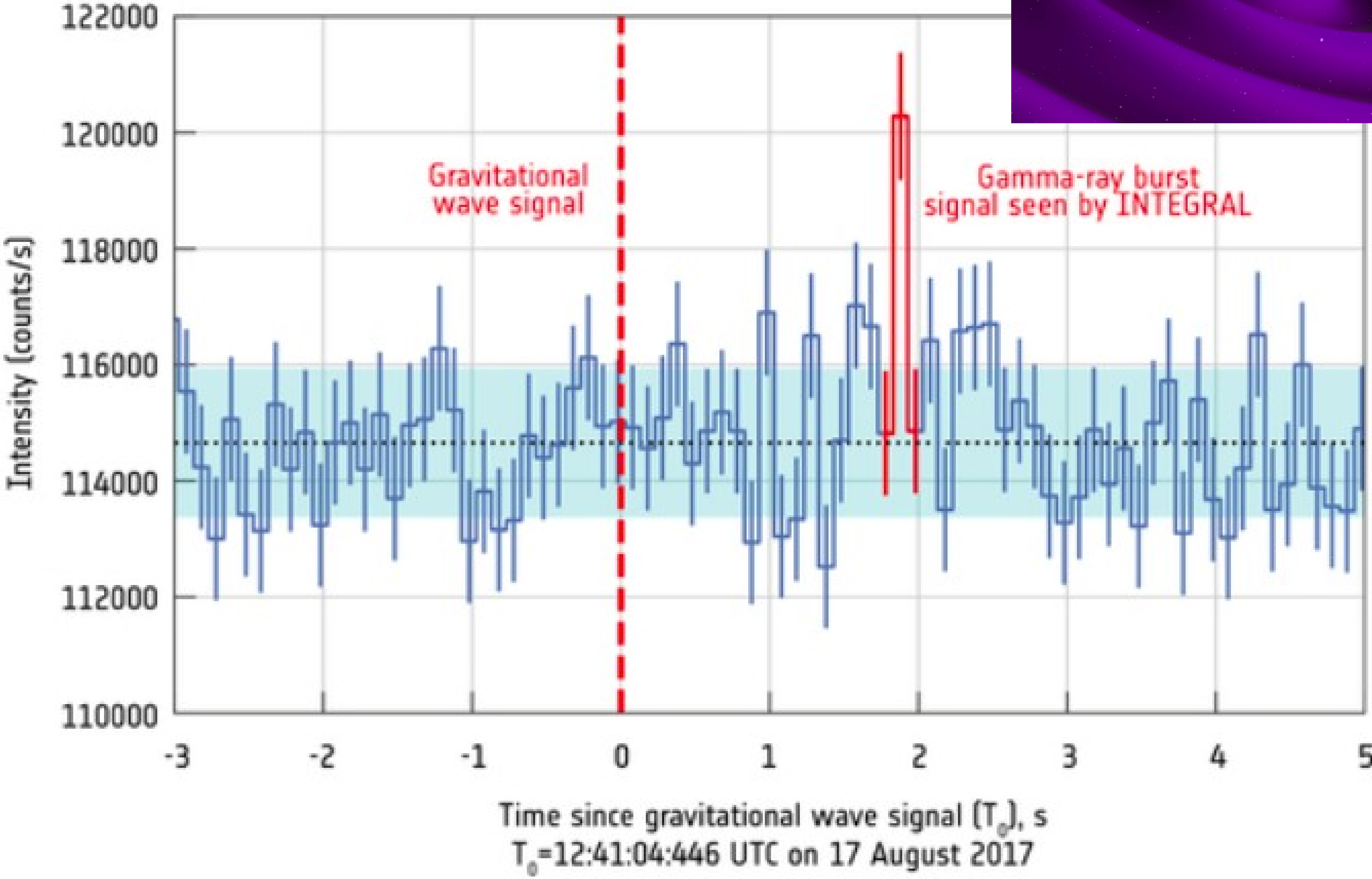
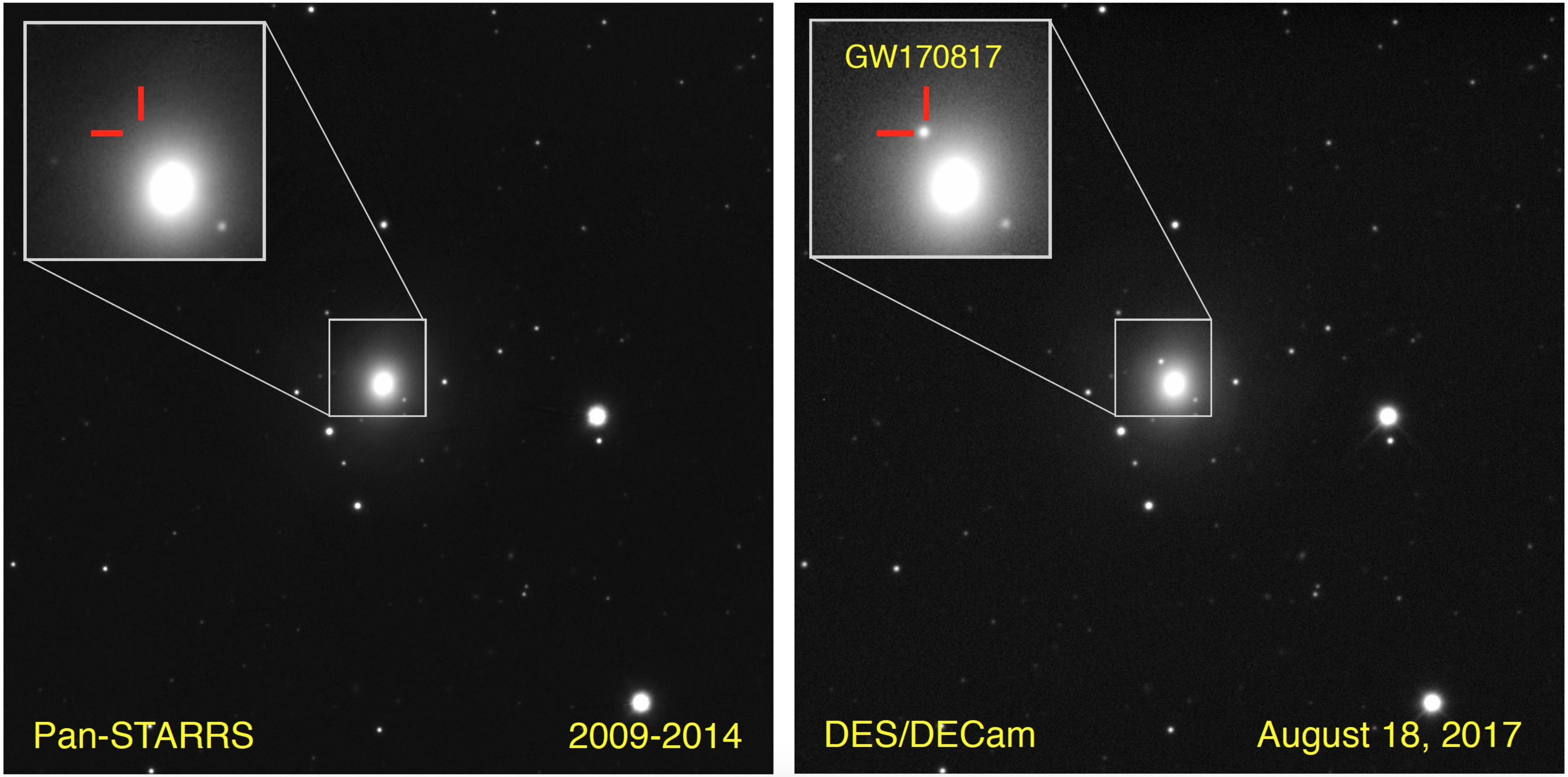


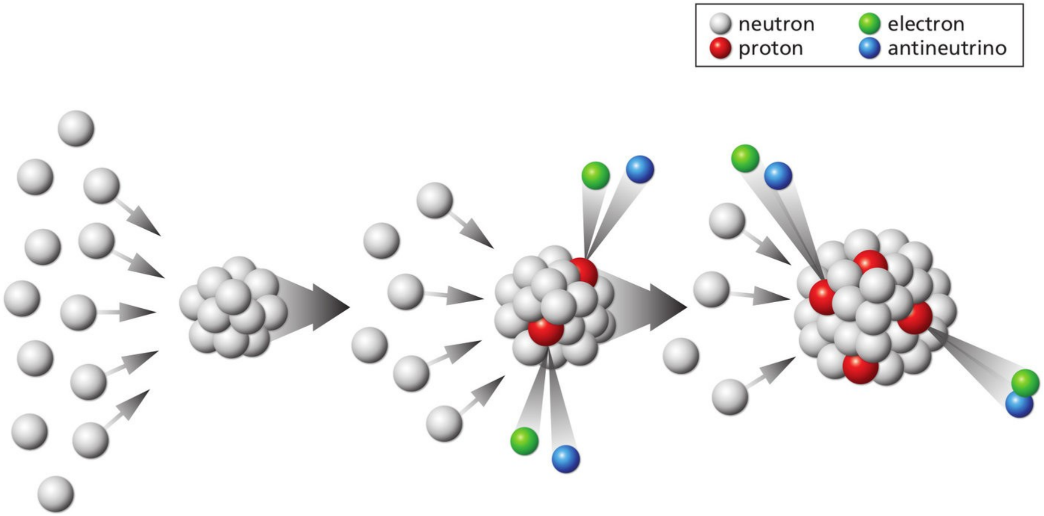
Imagem no visível da kilonova, resultado da colisão de duas estrelas de nêutrons



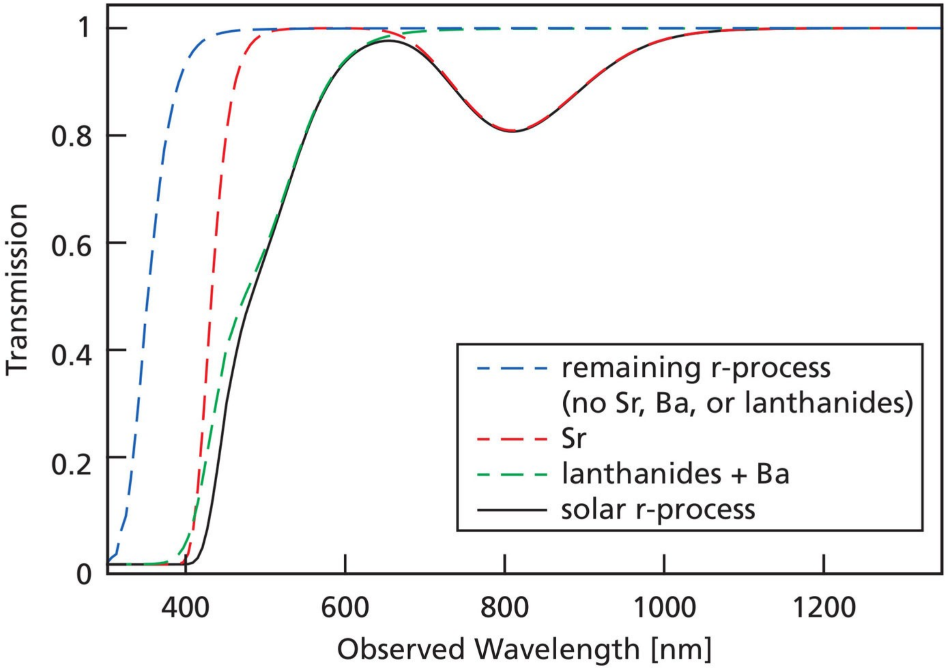
The alchemy of neutron stars

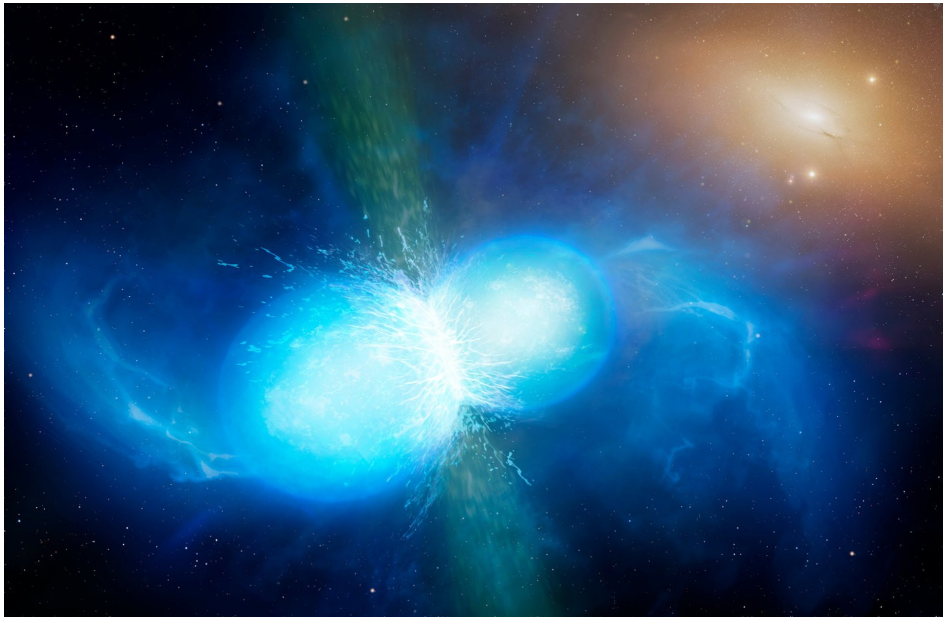
Astronomers find out that the collision of these cosmic objects actually produces heavy elements

OCTOBER 23, 2019



Now astronomers, including those from the Max Planck Institute for Astronomy, have identified such an element in the spectra of that time: **strontium**, which was apparently produced in the so-called r-process.

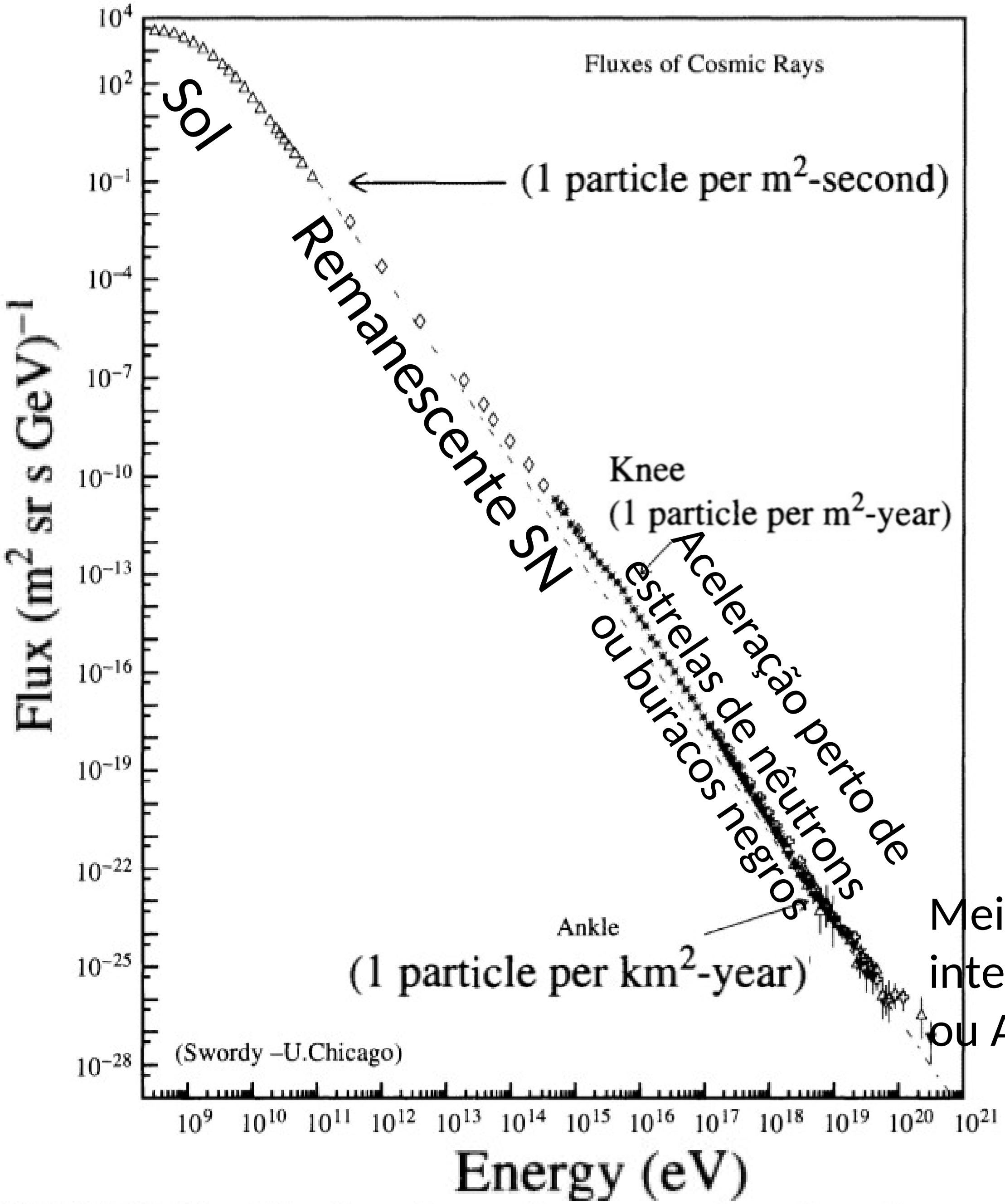




15.5 Raios cósmicos

Descobertos em 1912 por Victor Hess.

"Raios" cósmicos são na verdade partículas de várias massas (p+, e-, núcleos de C, O, Mg, Si, …)



Sol

Remanescente SN

Aceleração perto de estrelas de nêutrons ou buracos negros

Meio intergaláctico ou AGNs

Energias:
10^7 – $3x10^{20}$ eV

FIGURE 15.22 The flux of cosmic rays as a function of energy. (Ref: J. Cronin, T. K. Gaisser, and S. P. Swordy, *Sci. Amer.*, *276*, 44, 1997.)

Raio de Larmor (ou raio de giro)

Força em partícula carregada de velocidade v em campo magnético B

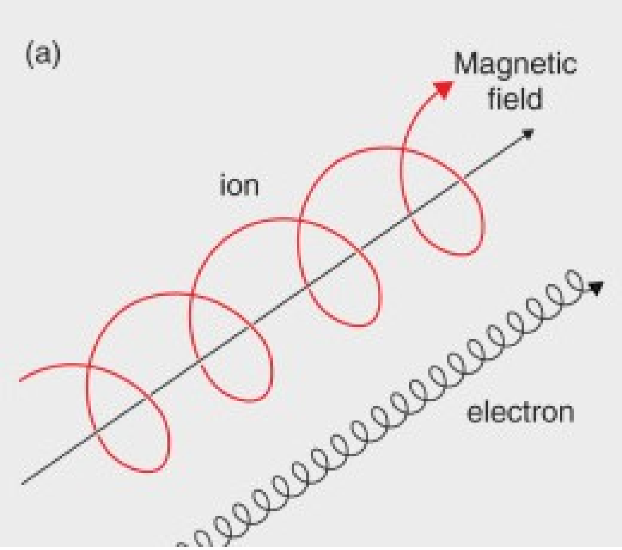
$$F_B = qvB$$

Força centrípeta no caso relativístico: $$\frac{\gamma m v^2}{r} = qvB$$

$$r = \frac{\gamma m v}{qB}$$

γ is the Lorentz factor.

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

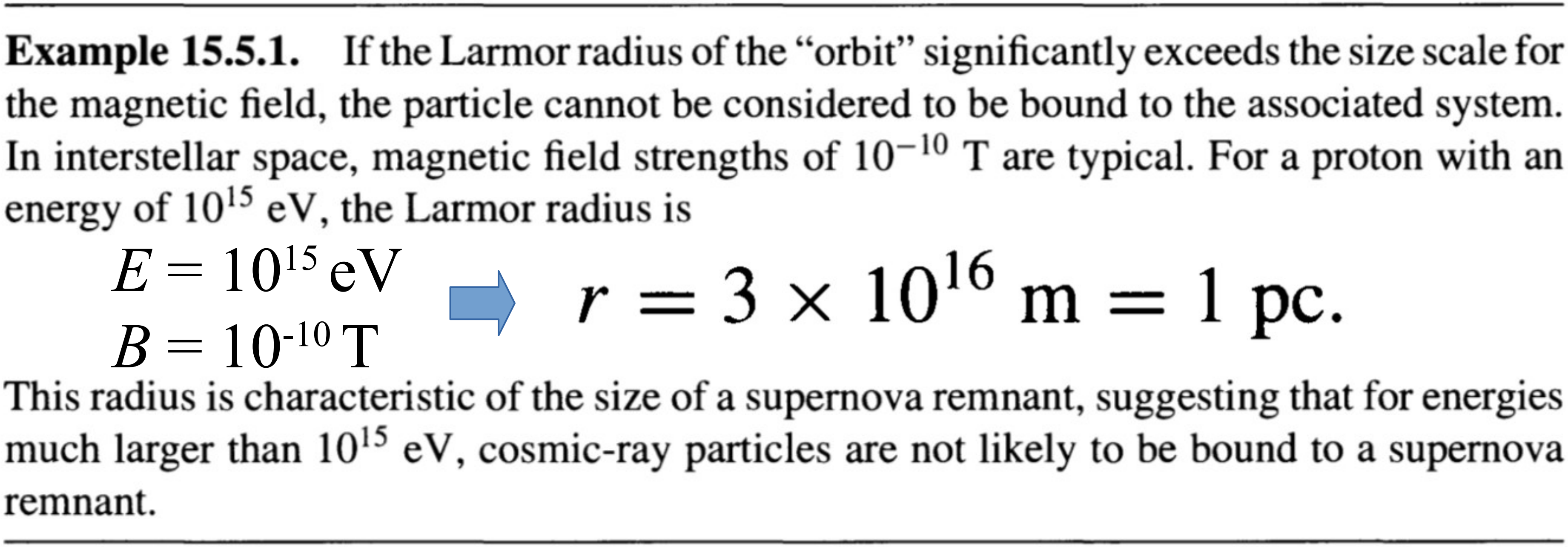


Se v ~ c, então:

$$r = \frac{\gamma m c^2}{qcB} = \frac{E}{qcB}$$

Raio de Larmor (ou raio de giro)

$$r = \frac{\gamma mc^2}{qcB} = \frac{E}{qcB}$$



Example 15.5.1. If the Larmor radius of the "orbit" significantly exceeds the size scale for the magnetic field, the particle cannot be considered to be bound to the associated system. In interstellar space, magnetic field strengths of 10^{-10} T are typical. For a proton with an energy of 10^{15} eV, the Larmor radius is

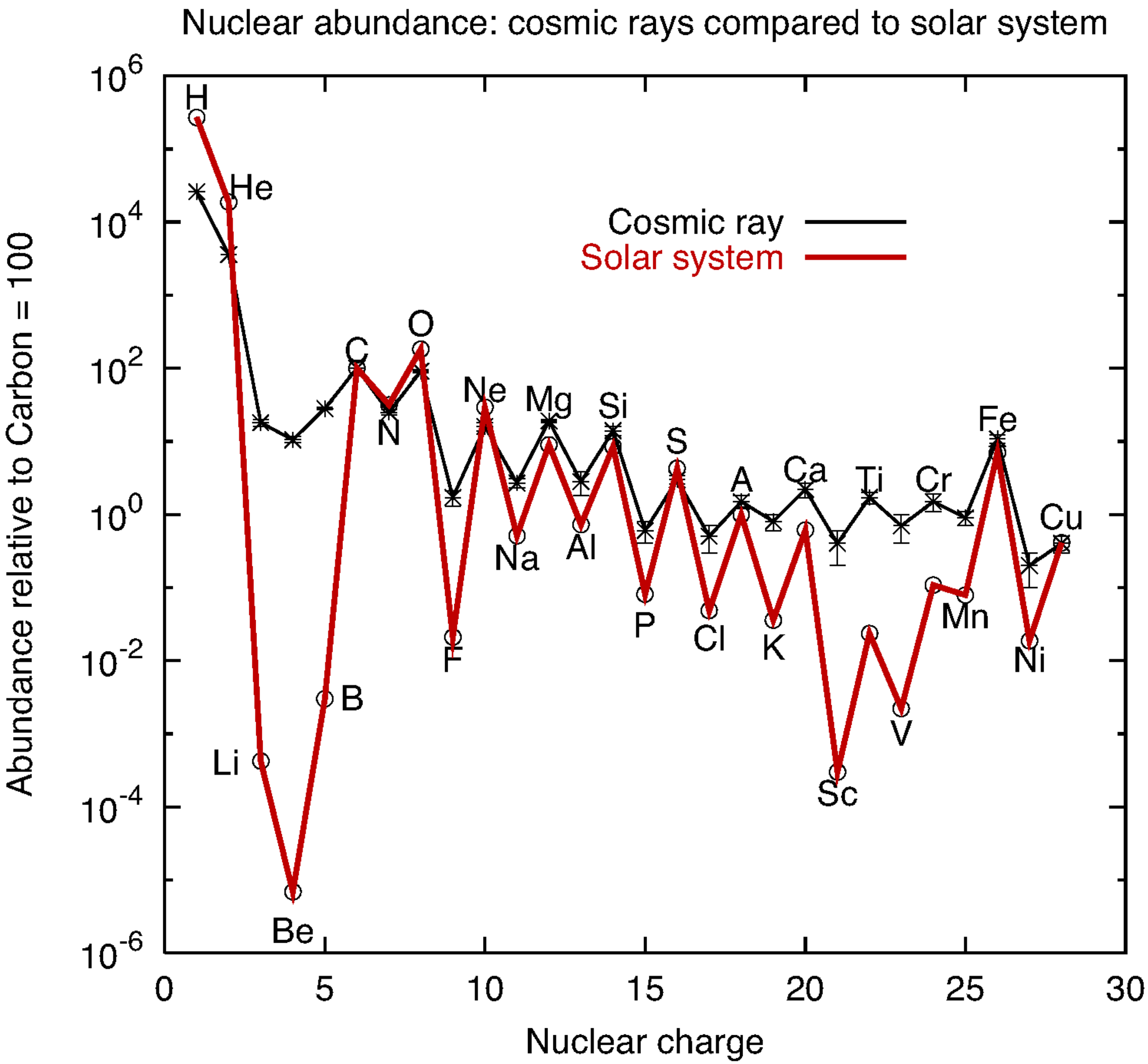
$E = 10^{15}$ eV

$B = 10^{-10}$ T

$$r = 3 \times 10^{16} \text{ m} = 1 \text{ pc}.$$

This radius is characteristic of the size of a supernova remnant, suggesting that for energies much larger than 10^{15} eV, cosmic-ray particles are not likely to be bound to a supernova remnant.

15.5 Raios cósmicos. Composição



Li, Be e B podem ser produzidos no ISM devido ao processo de “*spallation*”, que é a quebra de átomos de C, N e O, pelo bombardeio de raios cósmicos (p. ex., prótons)

Exemplo: *spallation* (espalação; quebra/fissão) do carbono, por por bombardeio de raio cósmico de próton

$${}^{12}_{6}\text{C} + {}^{1}_{1}\text{H} \rightarrow {}^{11}_{5}\text{B} + 2\,{}^{1}_{1}\text{H}$$

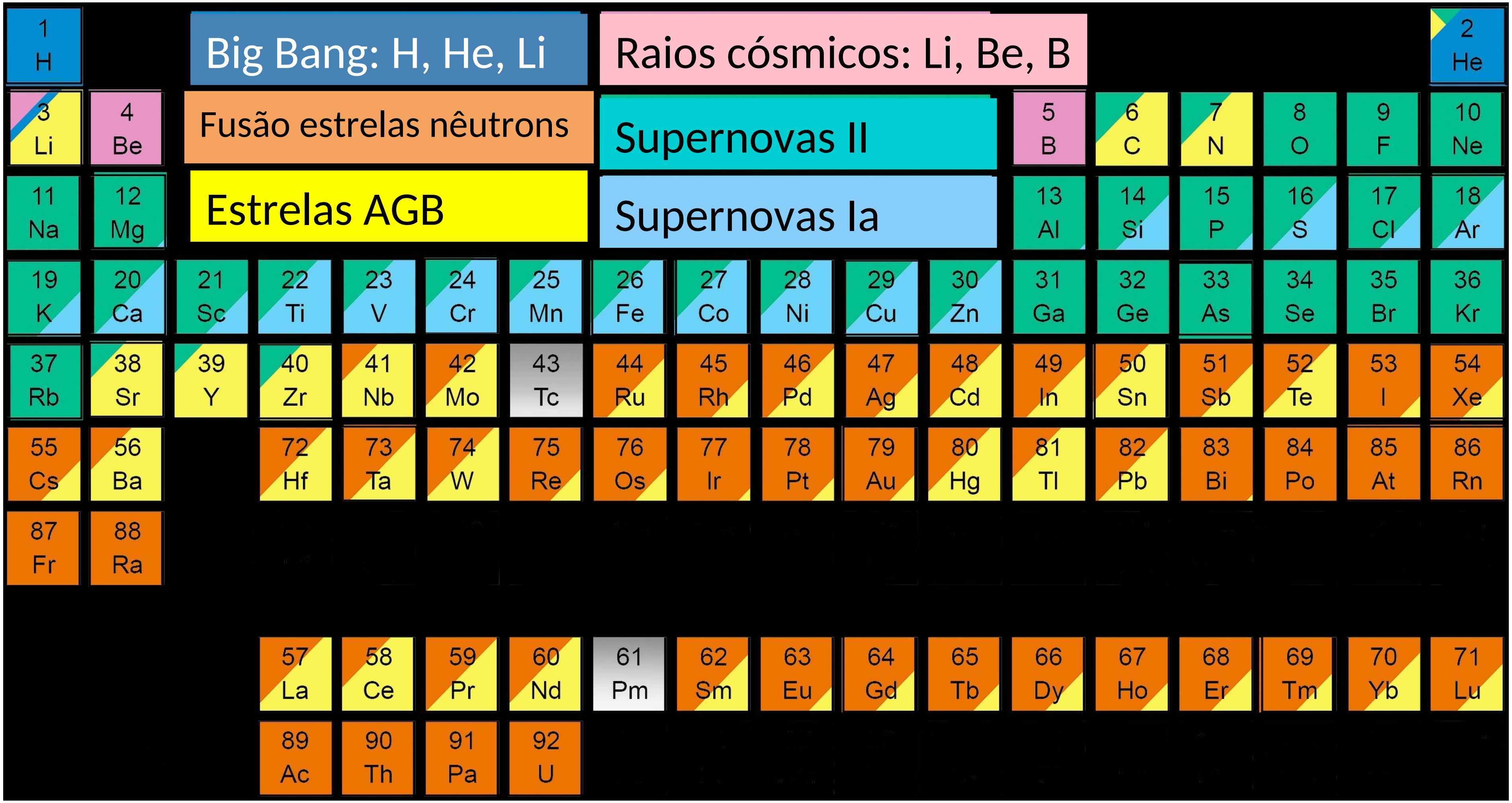
$$\rightarrow {}^{10}_{5}\text{B} + {}^{3}_{2}\text{He}$$

$$\rightarrow {}^{9}_{4}\text{Be} + {}^{3}_{2}\text{He} + {}^{1}_{1}\text{H}$$

A origem dos elementos no Sistema Solar

Processo-s: estrelas AGB (fase de pulsos térmicos)

Processo-r: fusão de estrelas de nêutrons (e SN II?)



Big Bang: H, He, Li

Raios cósmicos: Li, Be, B

Fusão estrelas nêutrons

Supernovas II

Estrelas AGB

Supernovas Ia

Adaptado de Jennifer Johnson

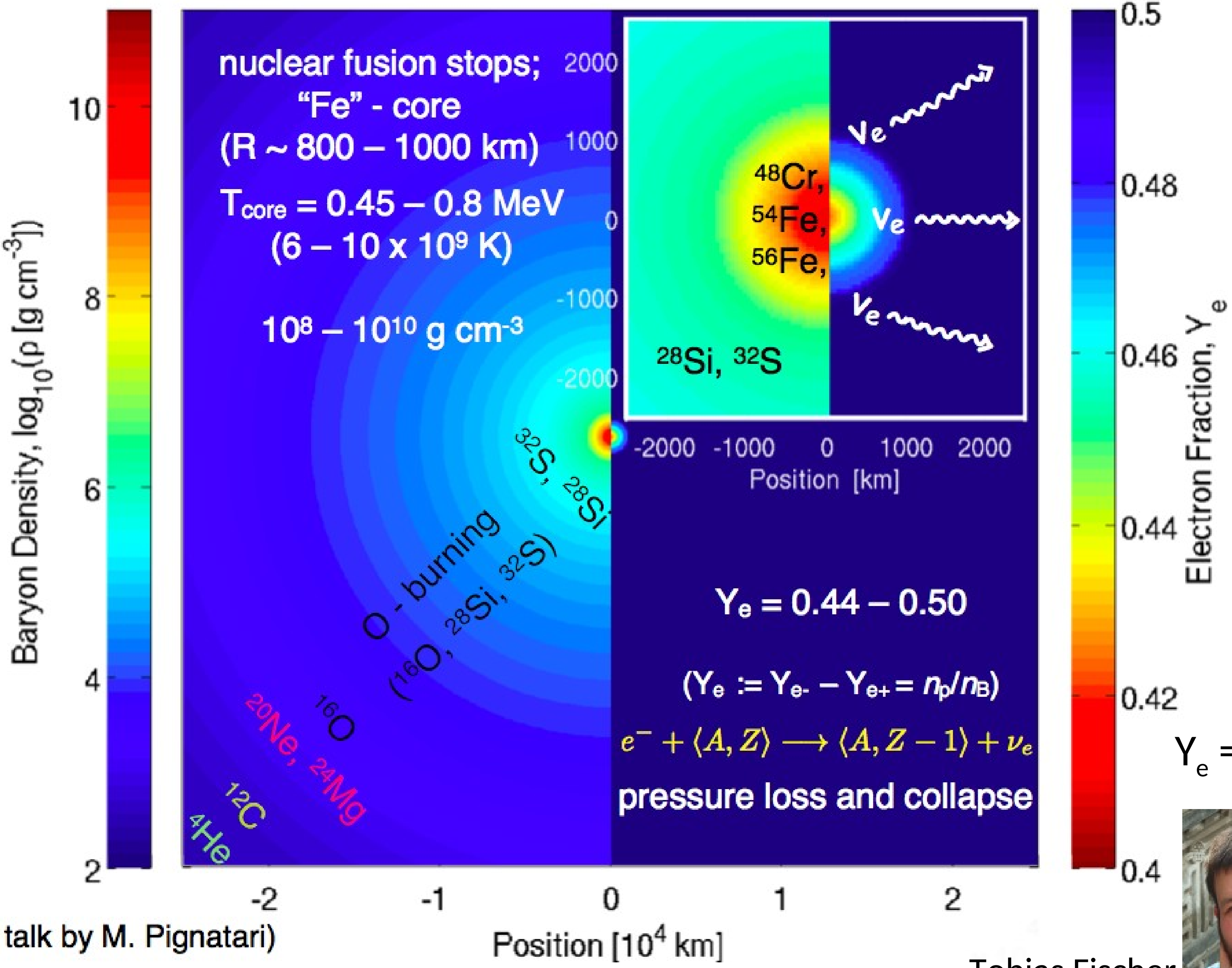
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Provinha 16, 2018

1. É possível produzir Li-6 a partir de *spallation* de núcleo de ^{12}C, ^{14}N ou ^{16}O? Se sim, propor uma possível reação?

2. Qual a fração de Ni-56 que sobrevive após 12,2 dias da explosão supernova?

Estrutura pre-colapso de estrela massiva

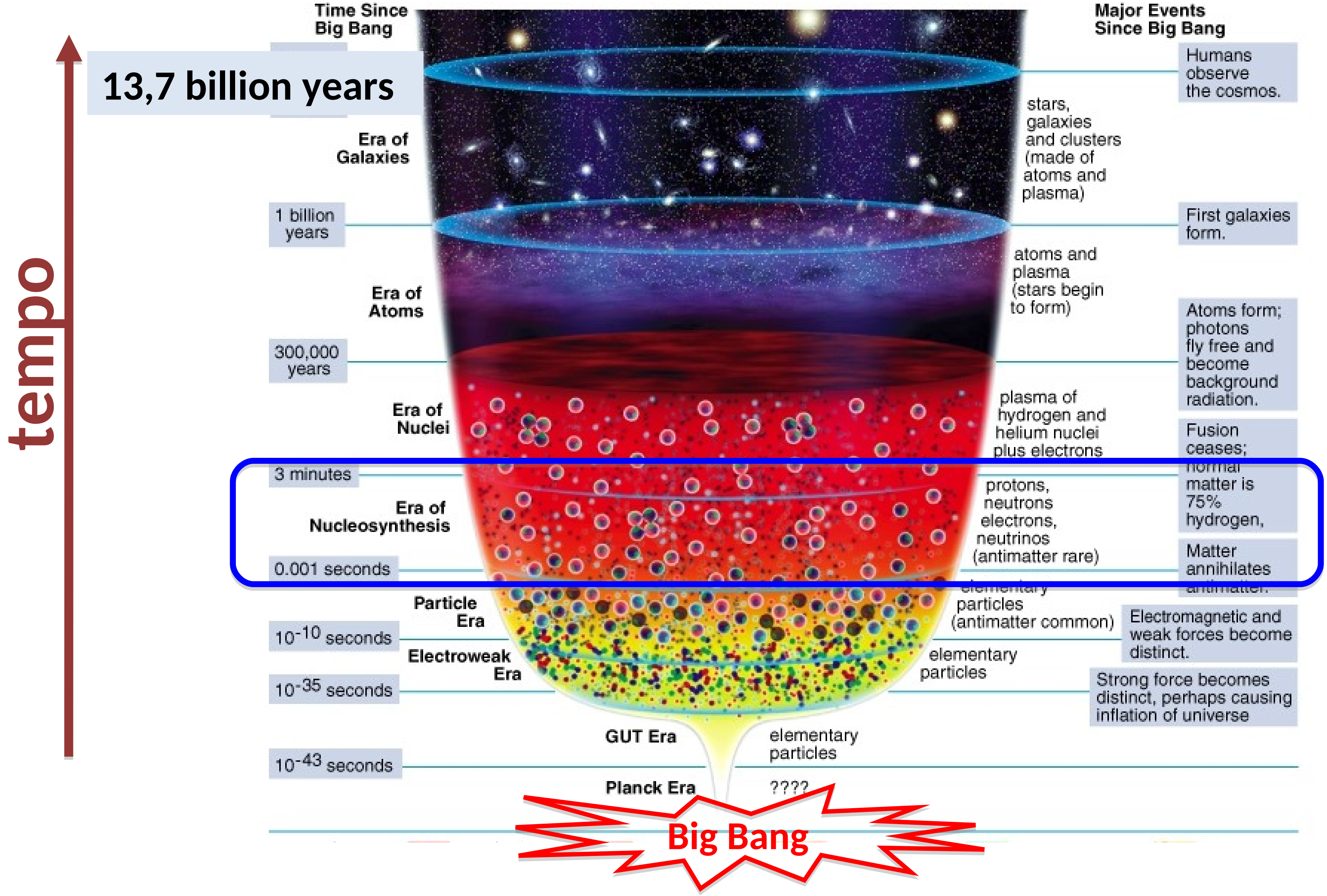


(see talk by M. Pignatari)

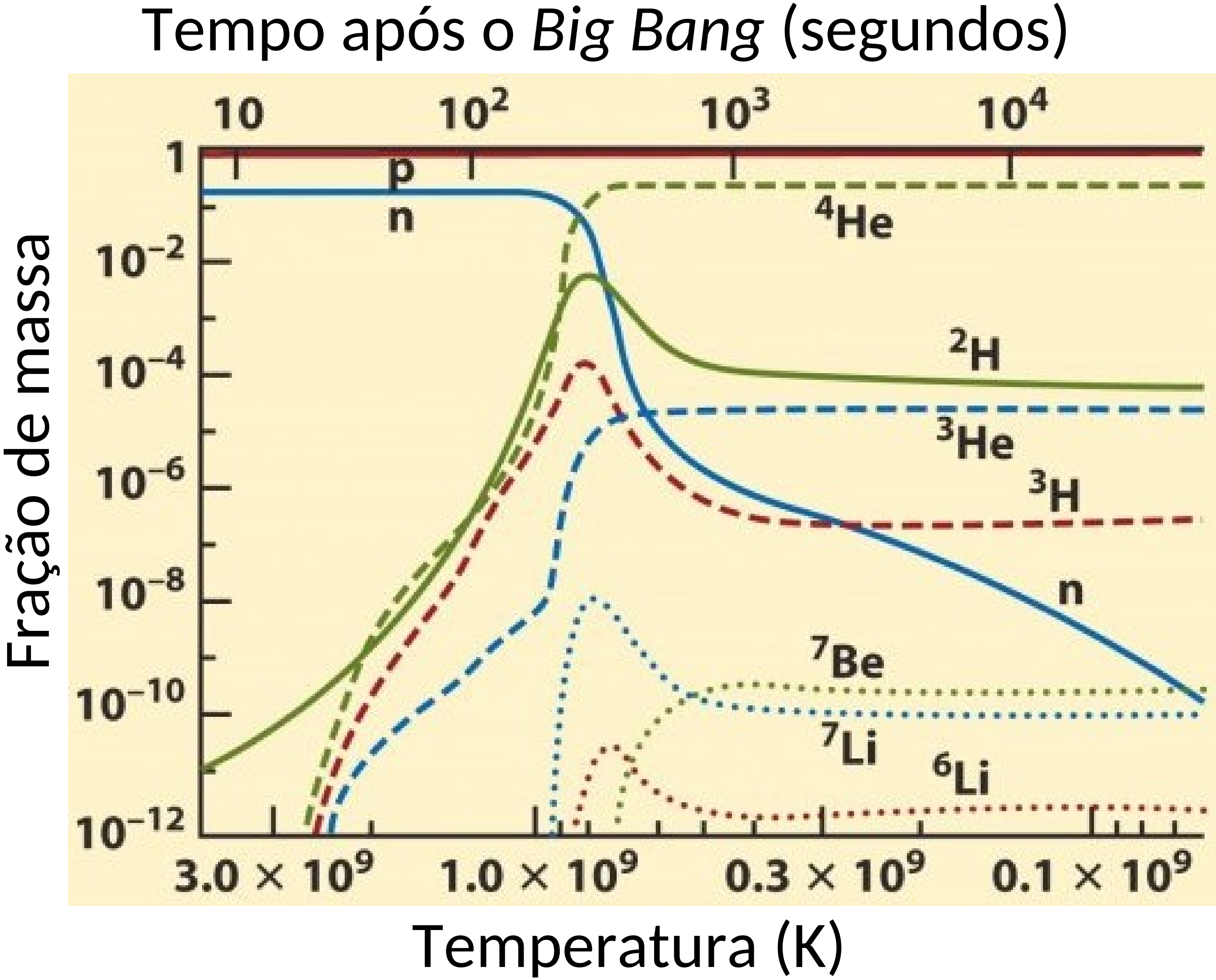
$Y_e = X_p$

Tobias Fischer

Evolução de nosso universo
Primeiros minutos: H, He (e pouco Li)



Nucleossíntese primordial



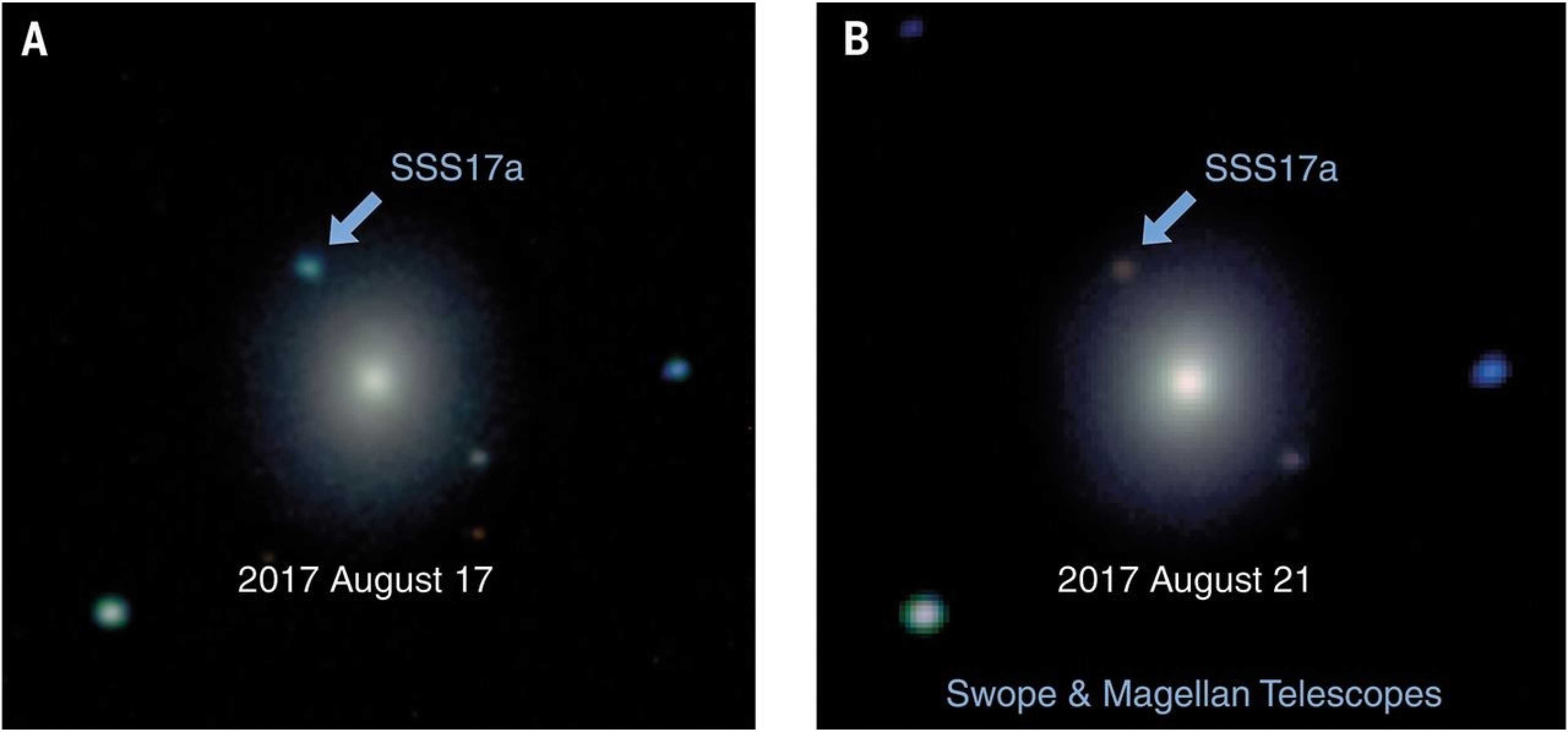
^3H e ^7Be não sobrevivem

^3H (trítio) decai → ^3He ($\tau_{½}$ = 2,6 anos)

^7Be decai → ^7Li ($\tau_{½}$ = 53 d)

https://universe-review.ca/F02-cosmicbg01.htm

Evolução da curva de luz



Light curves of the neutron star merger GW170817/SSS17a: Implications for r-process nucleosynthesis

M. R. Drout[1,*], A. L. Piro[1], B. J. Shappee[1,2], C. D. Kilpatrick[3], J. D. Simon[1], C. Contreras[4], D. A. Coulter[3], R. J. Foley[3], …

+ See all authors and affiliations

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