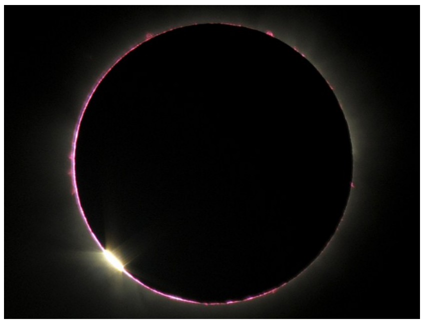
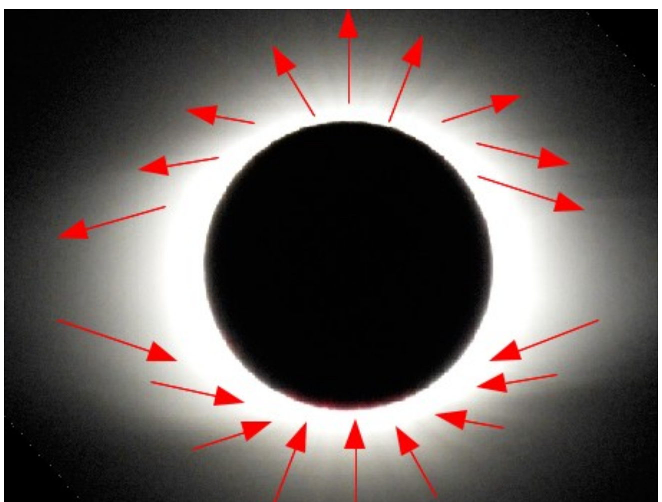
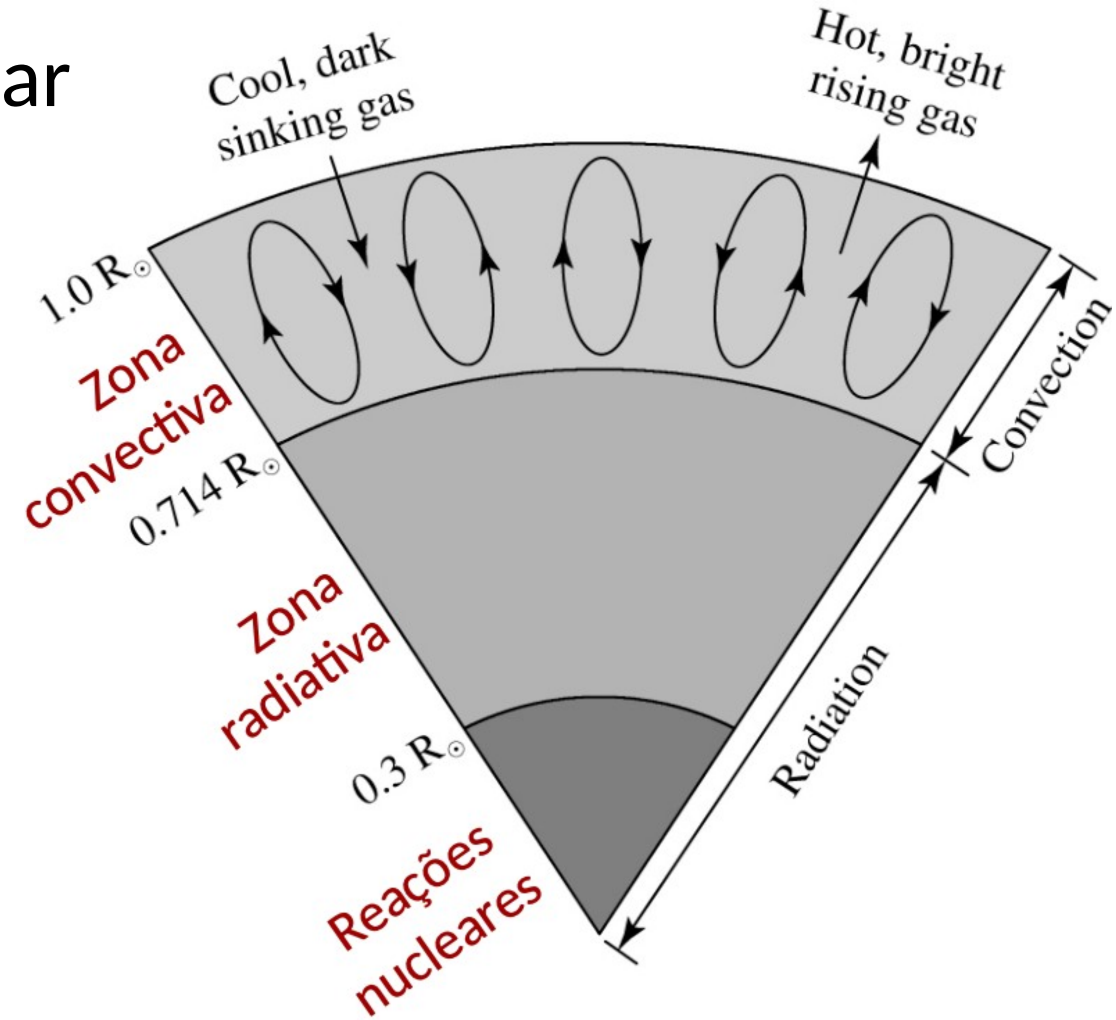
Cap. 11 – O Sol

11.1 O interior solar

11.2 A atmosfera solar







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

11.1 O interior solar

Estrela mais importante.
Devido à sua proximidade conhecemos em detalhe:

- Composição química
- Temperatura
- Luminosidade
- Raio
- Rotação; Campos magnéticos; Frequências de oscilação; Fluxo de neutrinos

Idade do Sol: 4,57±0,01 bilhões de anos

Livro-Texto: 4,5672 Gyr

[2]Radioactive dating of the oldest known objects in the Solar System, calcium-aluminum-rich inclusions (CAIs) in meteorites, leads to a determination of the age of the Solar System of 4.5672 ± 0.0006 Gyr.

Artigo mais recente em Nature Geoscience: 4,5682 Gyr

Nature Geoscience **3**, 637 - 641 (2010)
Published online: 22 August 2010 | doi:10.1038/ngeo941

Audrey Bouvier[1] & Meenakshi Wadhwa[1]

The age of the Solar System redefined by the oldest Pb–Pb age of a meteoritic inclusion

Chondrite meteorite with calcium–aluminium-rich inclusions seen as white specks. From the collection of the American Museum of Natural History.

Propriedades básicas do Sol

- Tipo espectral: G2V
- Idade: $t_\odot$ = 4,5682 Gyr
- Raio: $R_\odot = 6.96\times10^5$ km
- Massa: $M_\odot = 1.99\times10^{30}$ kg

1048 massa de Júpiter, 332 946 massa da Terra

- Luminosidade: $L_\odot = 3.828\times10^{26}$ W

(mais a luminosidade de neutrinos = 0.023 $L_\odot$)

- Temperatura efetiva ("superficial"): $T_{eff,\odot}$ = 5777 K
- Composição química: X = 0.74, Y = 0.24, Z = 0.02

Frações da massa do Sol (X: hidrogênio, Y: hélio, Z: metais)

No livro-texto, são apresentados resultados de um modelo “padrão” do Sol, por **Bahcall, Pinsonneault & Basu 2001, ApJ, 555, 990**

THE ASTROPHYSICAL JOURNAL, 555:990–1012, 2001 July 10

SOLAR MODELS: CURRENT EPOCH AND TIME DEPENDENCES, NEUTRINOS, AND HELIOSEISMOLOGICAL PROPERTIES

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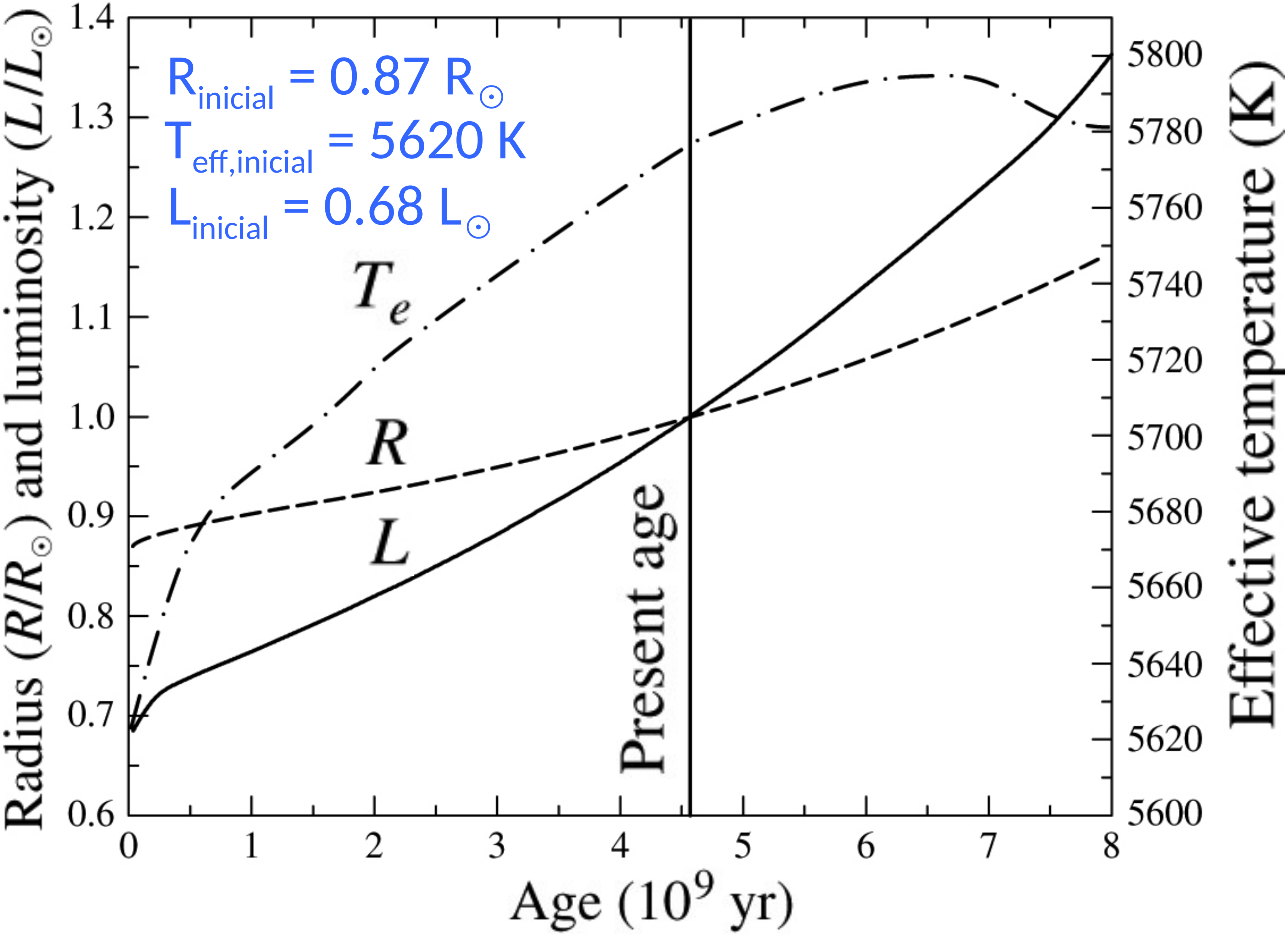
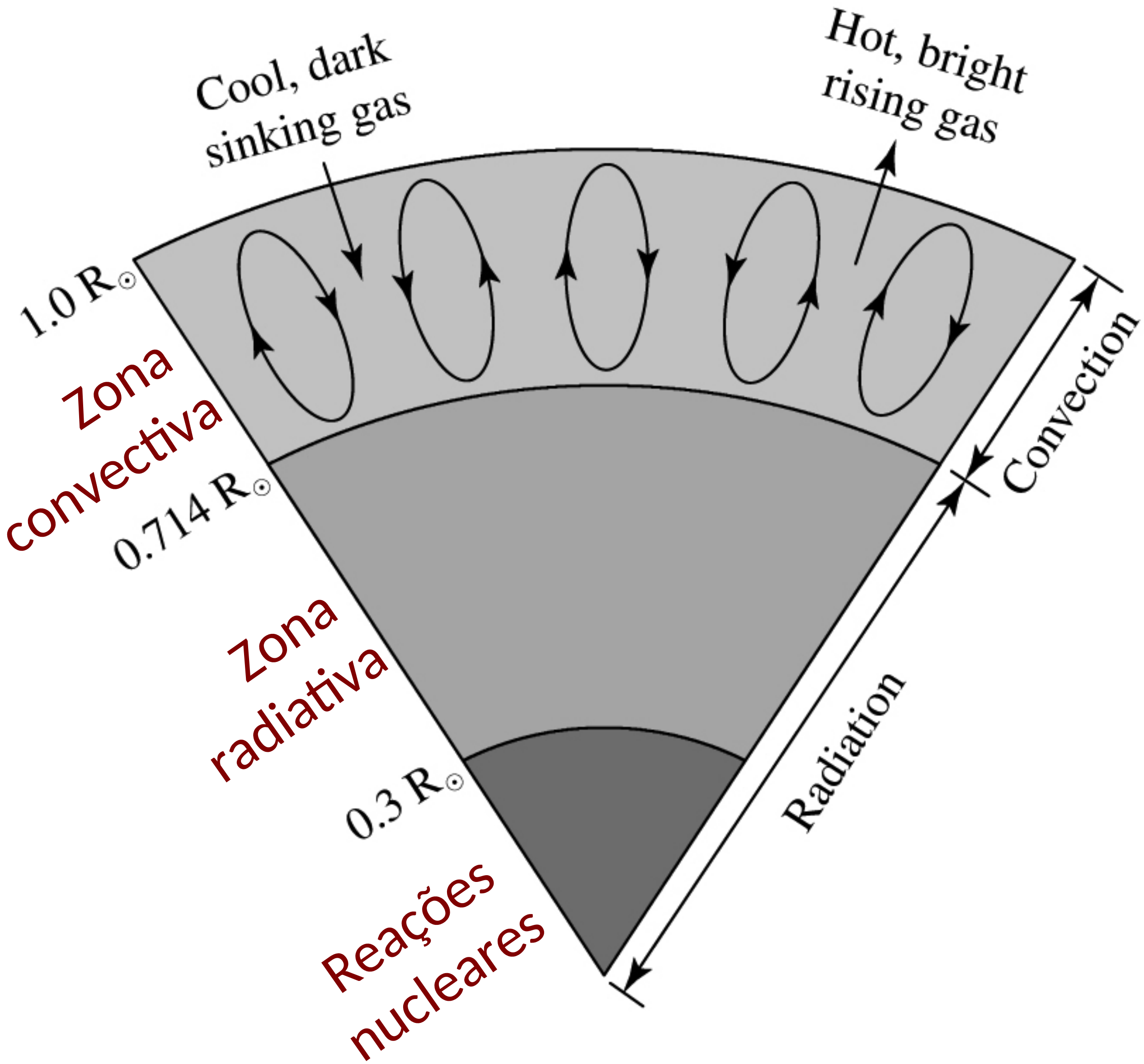
Received 2000 October 29; accepted 2001 March 12

História evolucionária do Sol



Aumento de luminosidade do Sol: fim dos oceanos na Terra (daqui a 1 a 2 bilhões de anos)

A estrutura interna do Sol **hoje**



No centro do Sol:

$\mathbf{X_c = 0.34}$ ($X_i = 0.71$)

$\mathbf{Y_c = 0.64}$ ($Y_i = 0.27$)

$T_c = 1{,}57\ 10^6 K$

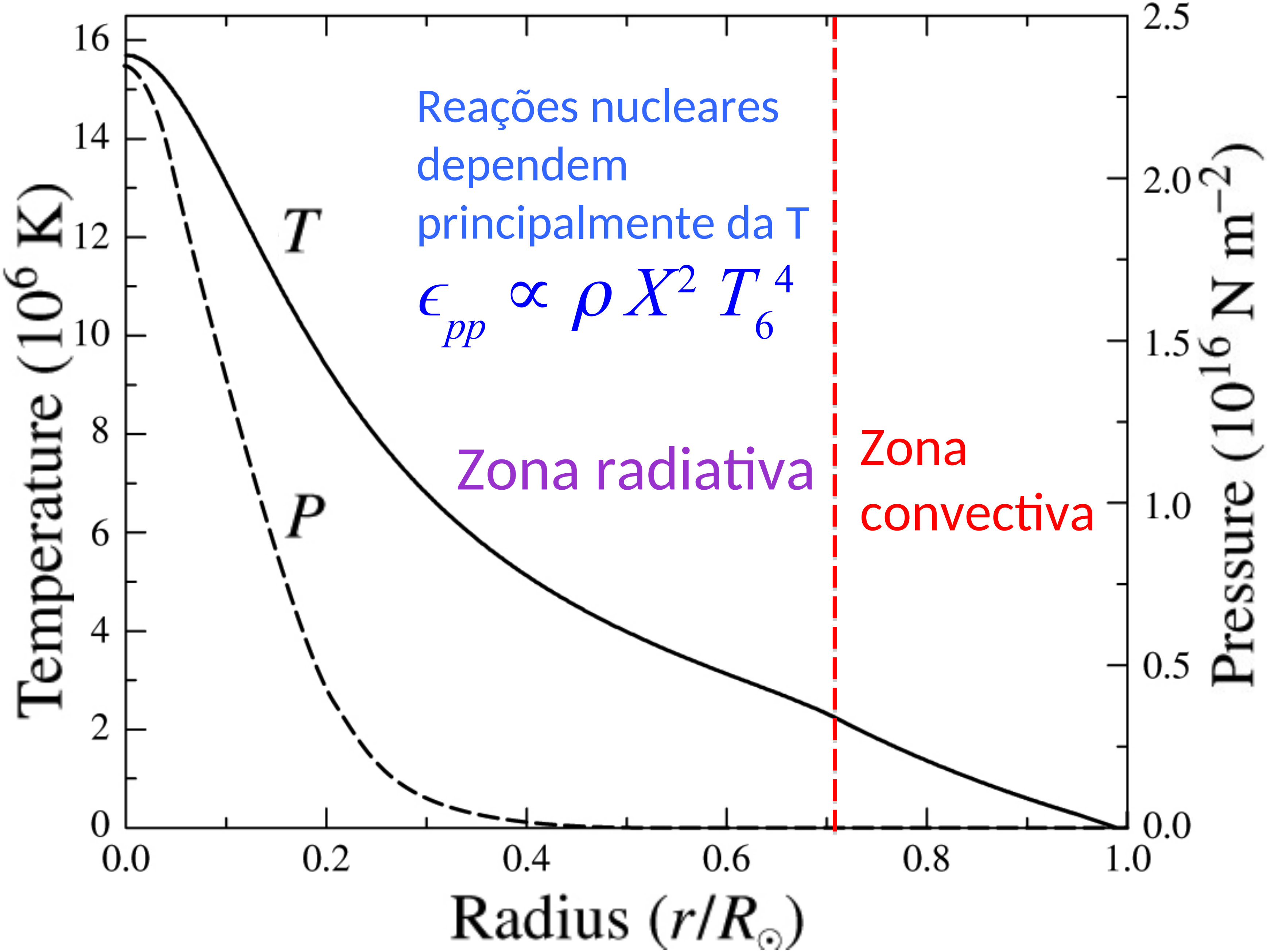
$P_c = 2{,}34\ 10^{16}\ Nm^{-2}$

$\rho_C = 1{,}5\ 10^5\ kg\ m^{-3}$

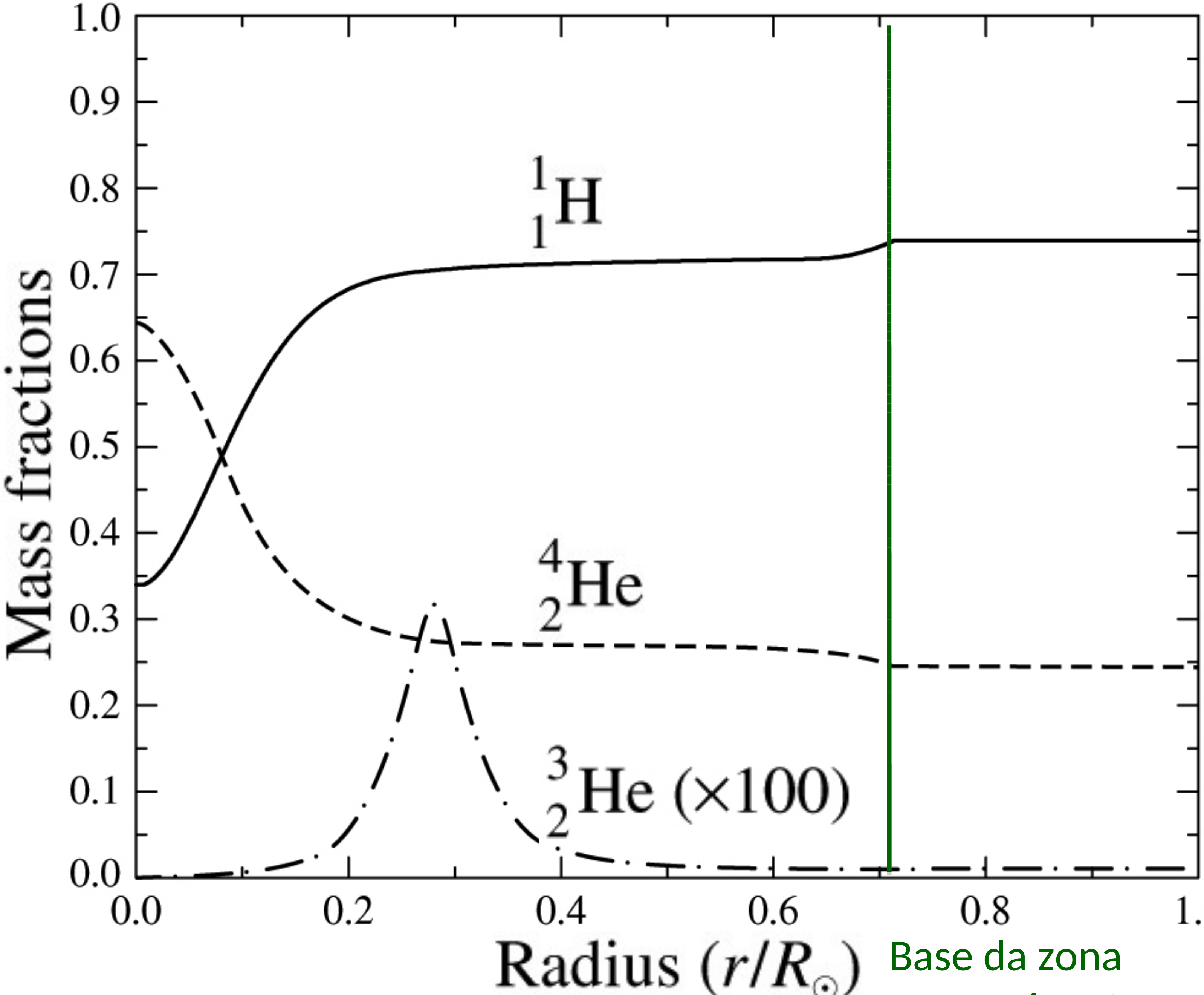
Superfície:

$\mathbf{X_s = 0.74}$ ($X_i = 0.71$)

$\mathbf{Y_s = 0.24}$ ($Y_i = 0.27$)



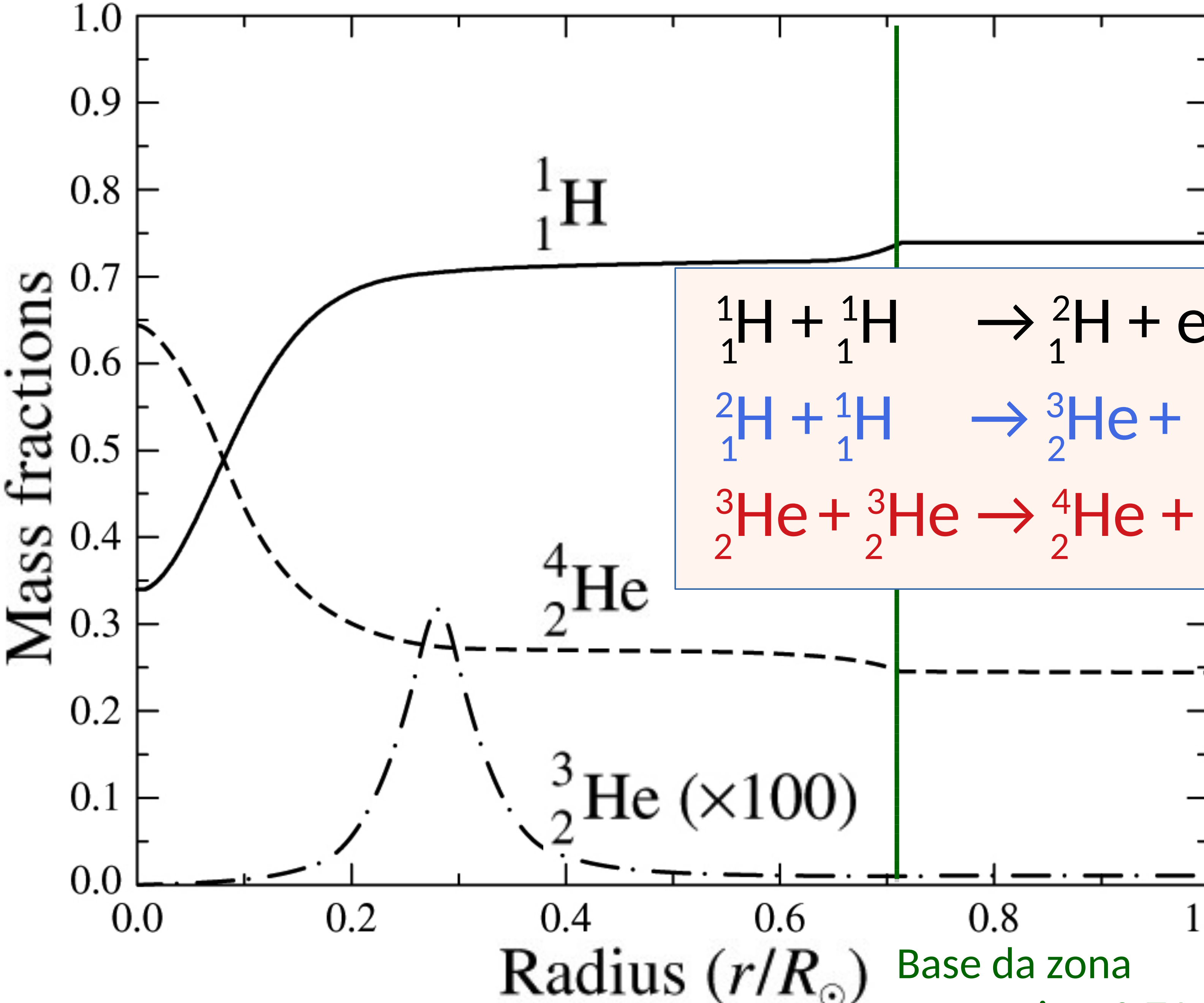
Reações nucleares
dependem
principalmente da T
$\epsilon_{pp} \propto \rho X^2 T_6^4$
Zona radiativa
Zona
convectiva
T
P
Temperature (10^6 K)
Pressure (10^{16} N m^{-2})
Radius ($r/R_\odot$)
0
2
4
6
8
10
12
14
16
0.0
0.5
1.0
1.5
2.0
2.5
0.0
0.2
0.4
0.6
0.8
1.0



Sol
hoje

Base da zona
convectiva: 0.714 $R_\odot$

Sol hoje

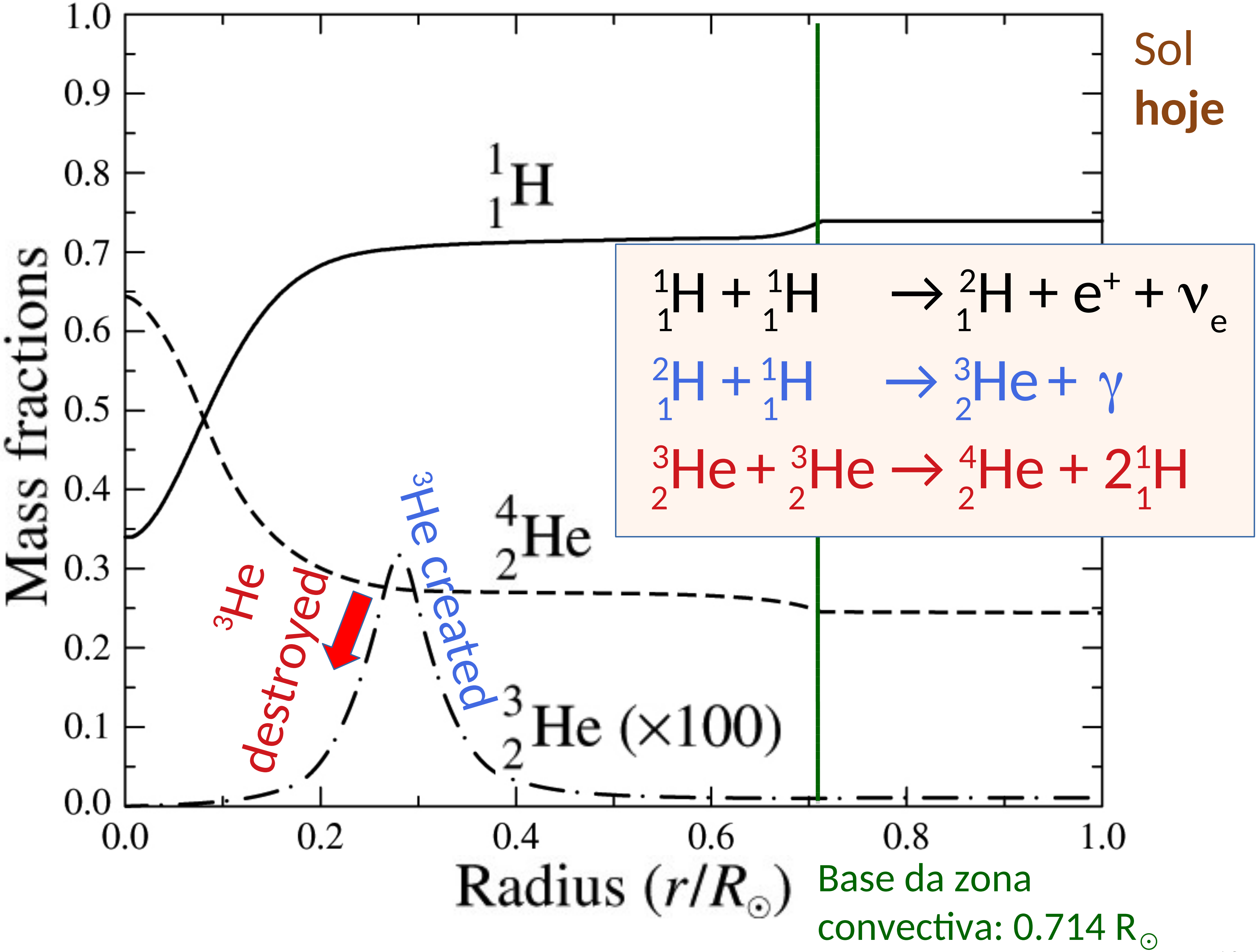


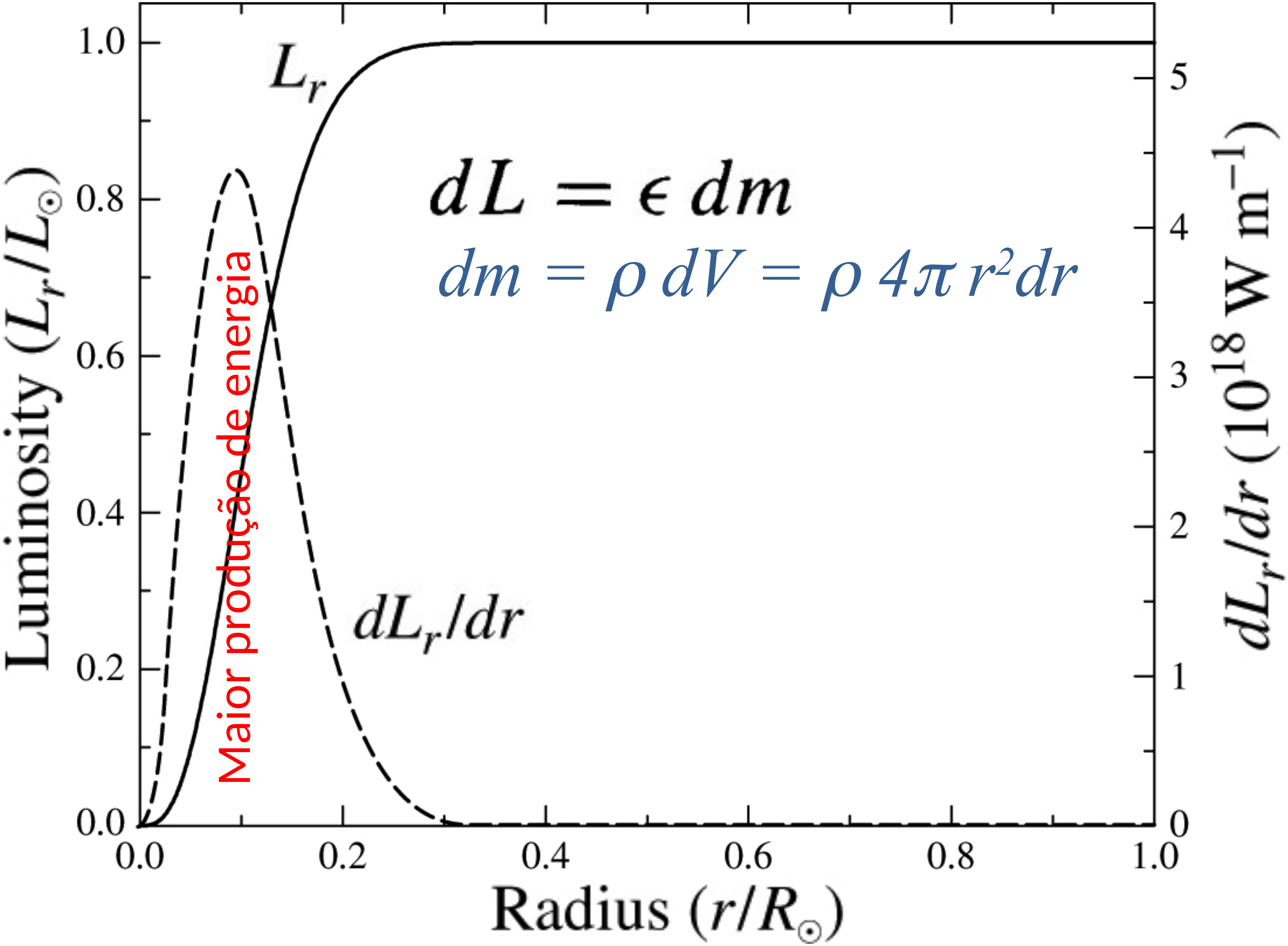
$$^1_1H + ^1_1H \rightarrow ^2_1H + e^+ + \nu_e$$

$$^2_1H + ^1_1H \rightarrow ^3_2He + \gamma$$

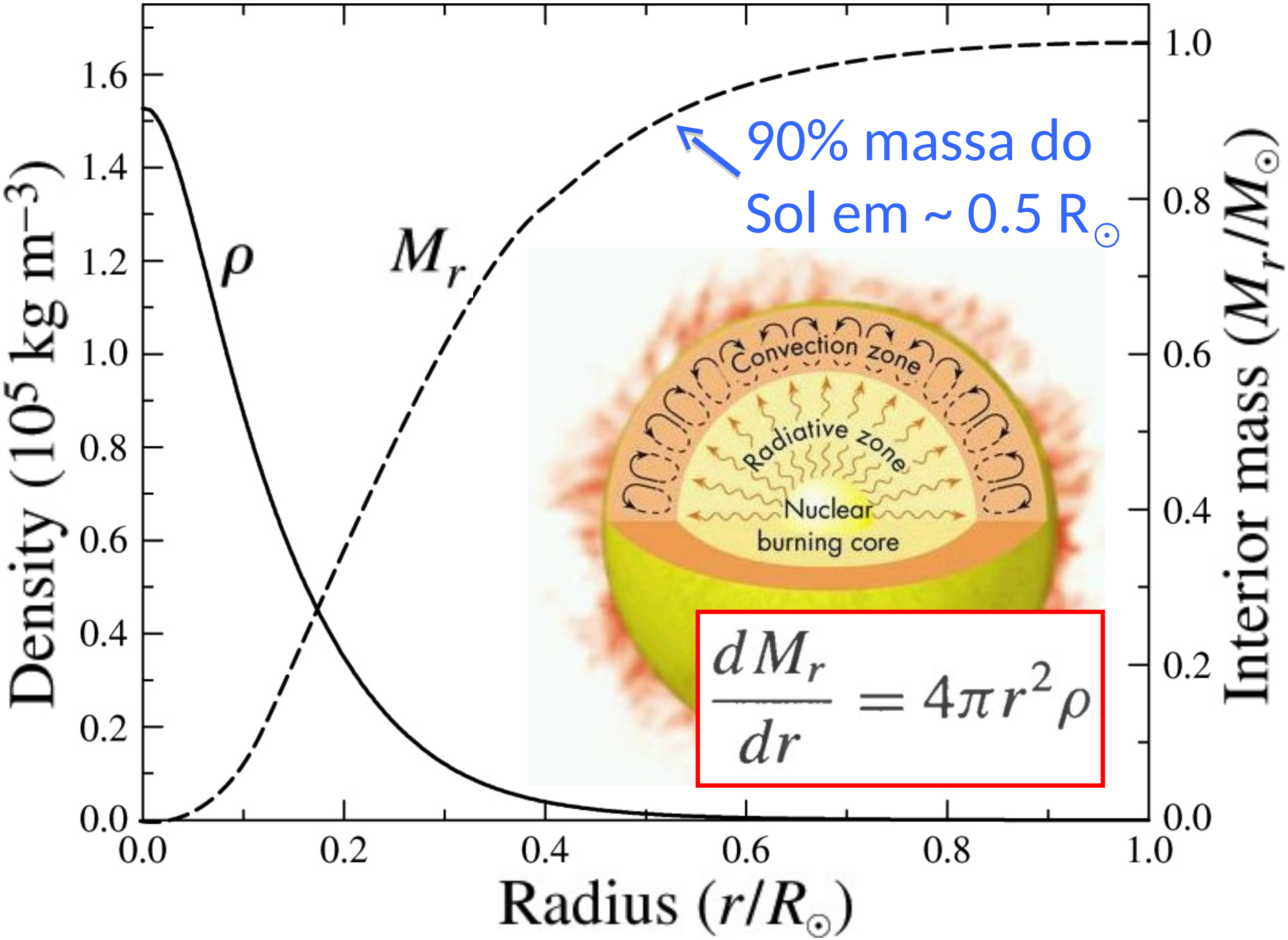
$$^3_2He + ^3_2He \rightarrow ^4_2He + 2\,^1_1H$$

Base da zona convectiva: 0.714 $R_\odot$


Sol
hoje
Mass fractions
Radius $(r/R_\odot)$
^1_1H
^4_2He
^3_2He (×100)
^{3}He destroyed
^{3}He created
$^1_1H + ^1_1H \rightarrow ^2_1H + e^+ + \nu_e$
$^2_1H + ^1_1H \rightarrow ^3_2He + \gamma$
$^3_2He + ^3_2He \rightarrow ^4_2He + 2^1_1H$
Base da zona convectiva: 0.714 $R_\odot$

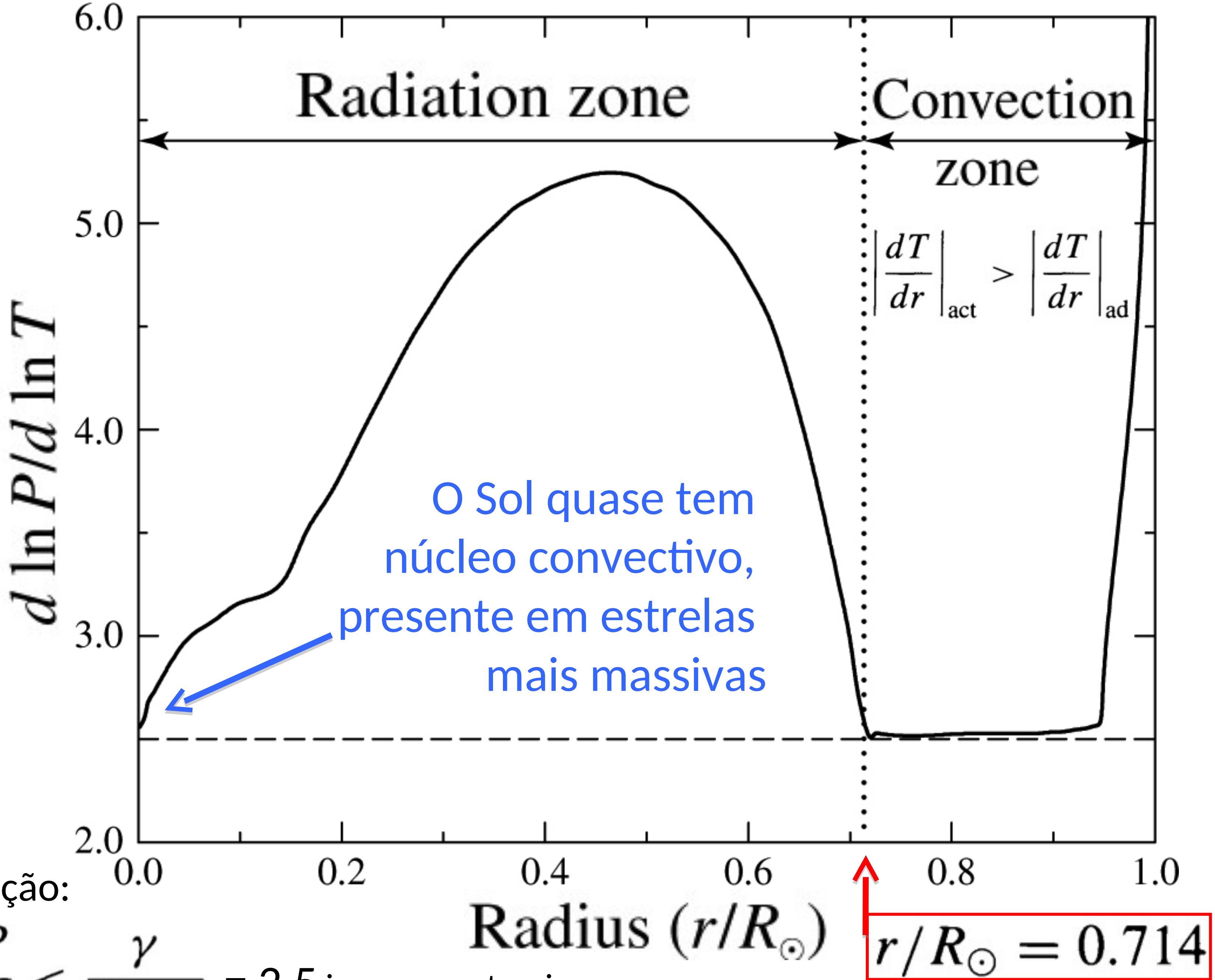


Luminosity ($L_r/L_\odot$)
dL_r/dr (10^{18} W m^{-1})
Radius ($r/R_\odot$)
L_r
dL_r/dr
$dL = \epsilon\, dm$
$dm = \rho\, dV = \rho\, 4\pi\, r^2 dr$
Maior produção de energia


Density (10^5 kg m^{-3})
Interior mass ($M_r/M_\odot$)
Radius ($r/R_\odot$)
ρ
M_r
90% massa do Sol em ~ 0.5 $R_\odot$
Convection zone
Radiative zone
Nuclear burning core
$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

Critério de convecção: $$\frac{d \ln P}{d \ln T} < \frac{\gamma}{\gamma - 1} = 2{,}5$$

Gás neutro ou completamente ionizado monoatômico: $\gamma = 5/3 = 1{,}67$

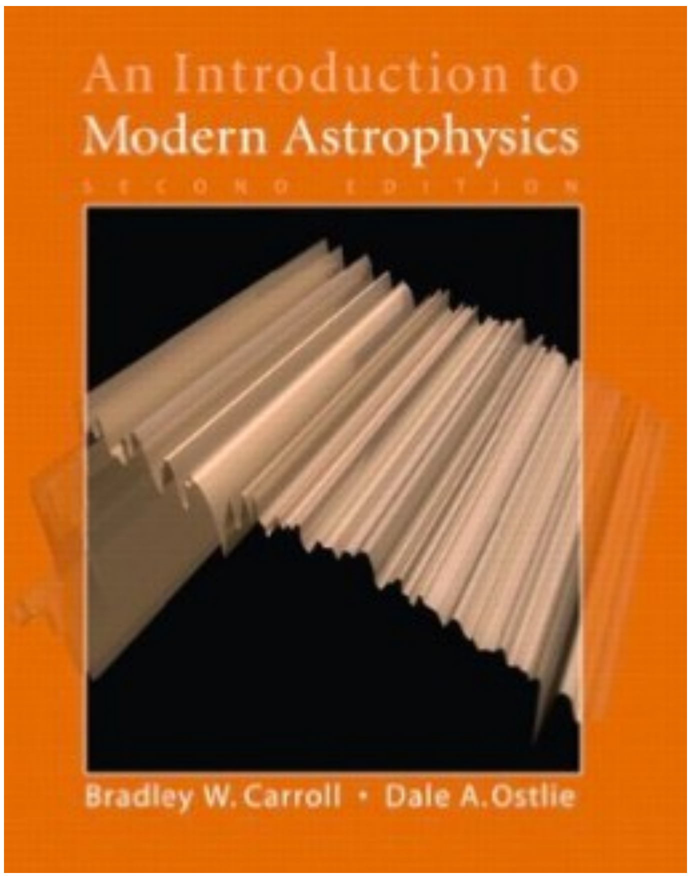


Convecção:

$$\frac{d \ln P}{d \ln T} < \frac{\gamma}{\gamma - 1}$$ = 2,5 in a monoatomic gas

Mistério do lítio no Sol: mais de 60 anos!

One aspect of the observed Sun that is not yet fully consistent with the current solar model is the abundance of lithium. The observed lithium abundance at the Sun's surface is actually somewhat less than expected and may imply some need for adjustments in the model through refined treatments of convection, rotation, and/or mass loss. The lithium problem will be discussed further in Chapter 13.



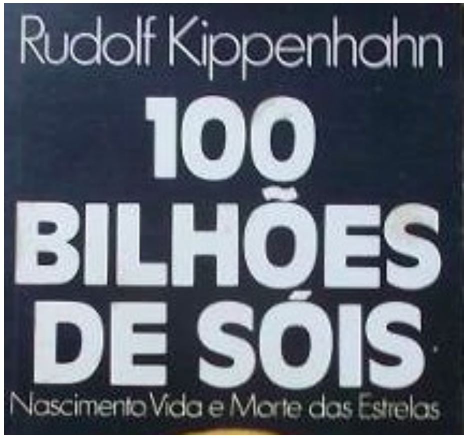
An Introduction to Modern Astrophysics, 2nd Edition, by Bradley W. Carroll, Dale A. Ostlie
2007

Mistério de mais de 60 anos!

O Problema do Lítio

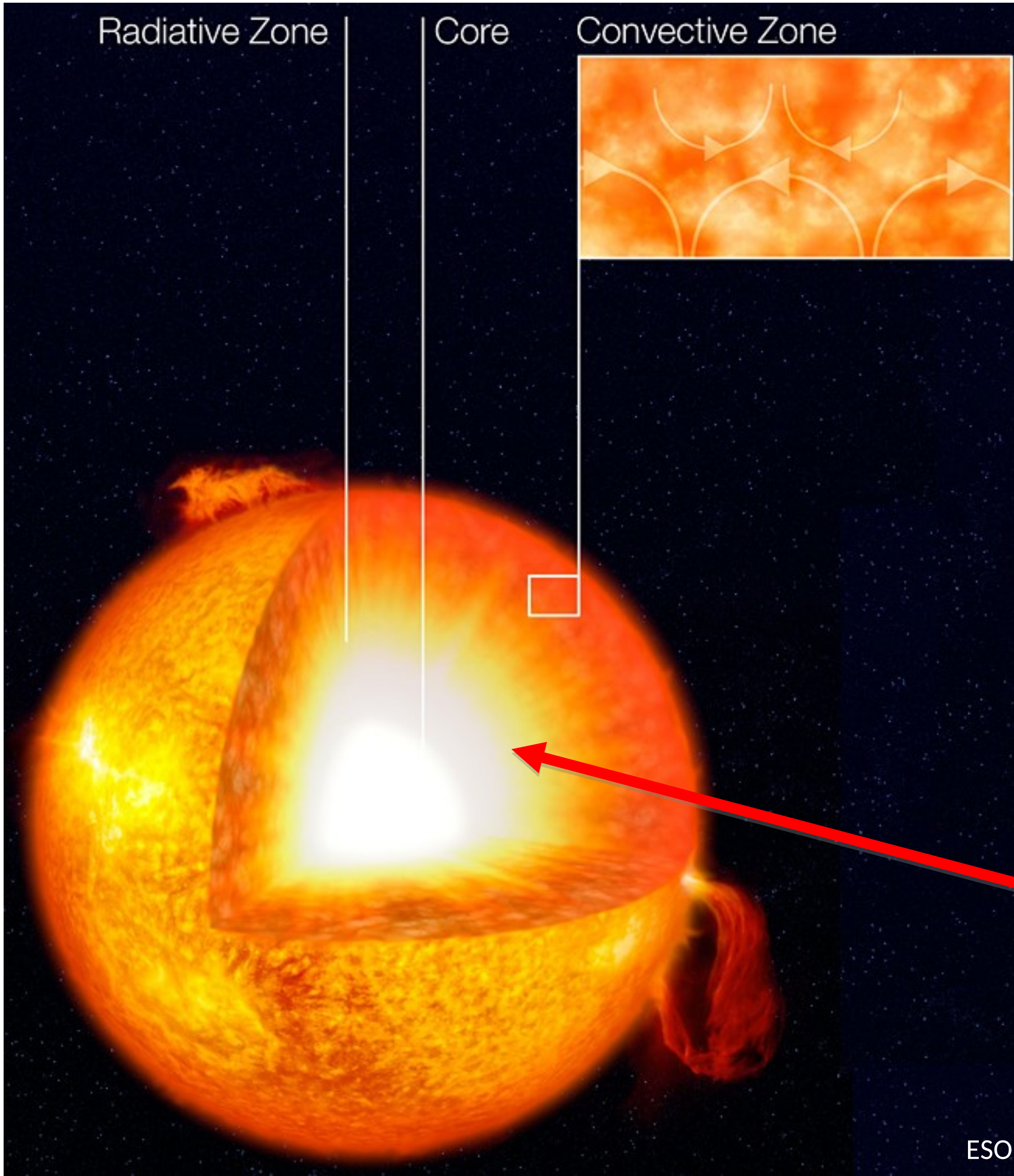
Os nossos modelos de computador não conseguem explicar tudo. Ao estudar a composição química da superfície solar, nota-se que — em comparação com aquilo que nos é familiar aqui na Terra — ainda há um outro elemento muito raro, ou seja, o lítio. Esta substância pertence aos elementos mais leves, com três prótons e quatro nêutrons formando normalmente seu núcleo atômico; é muito raro no Sol. Em comparação com sua ocorrência na Terra, mas mesmo com a matéria proveniente do universo e que se precipita sobre o globo terrestre na forma de meteoritos, o quilograma de matéria solar contém lítio em quantidade cem vezes menor. Será que também este elemento teria sido destruído pelas temperaturas elevadas no fundo da camada de propagação?

Efetivamente, o lítio pode receber um núcleo de hidrogênio e, com isto, dividir-se em dois átomos de hélio, conforme mostra a fig. 5-3. No entanto, a temperatura de 1 milhão de graus centígrados, à qual os átomos de lítio se misturam e confundem na superfície solar, não daria para destruí-los; isto aconteceria tão-somente nas camadas mais internas, onde a temperatura é três vezes mais elevada. Como todos os modelos



1981

O Problema do lítio solar

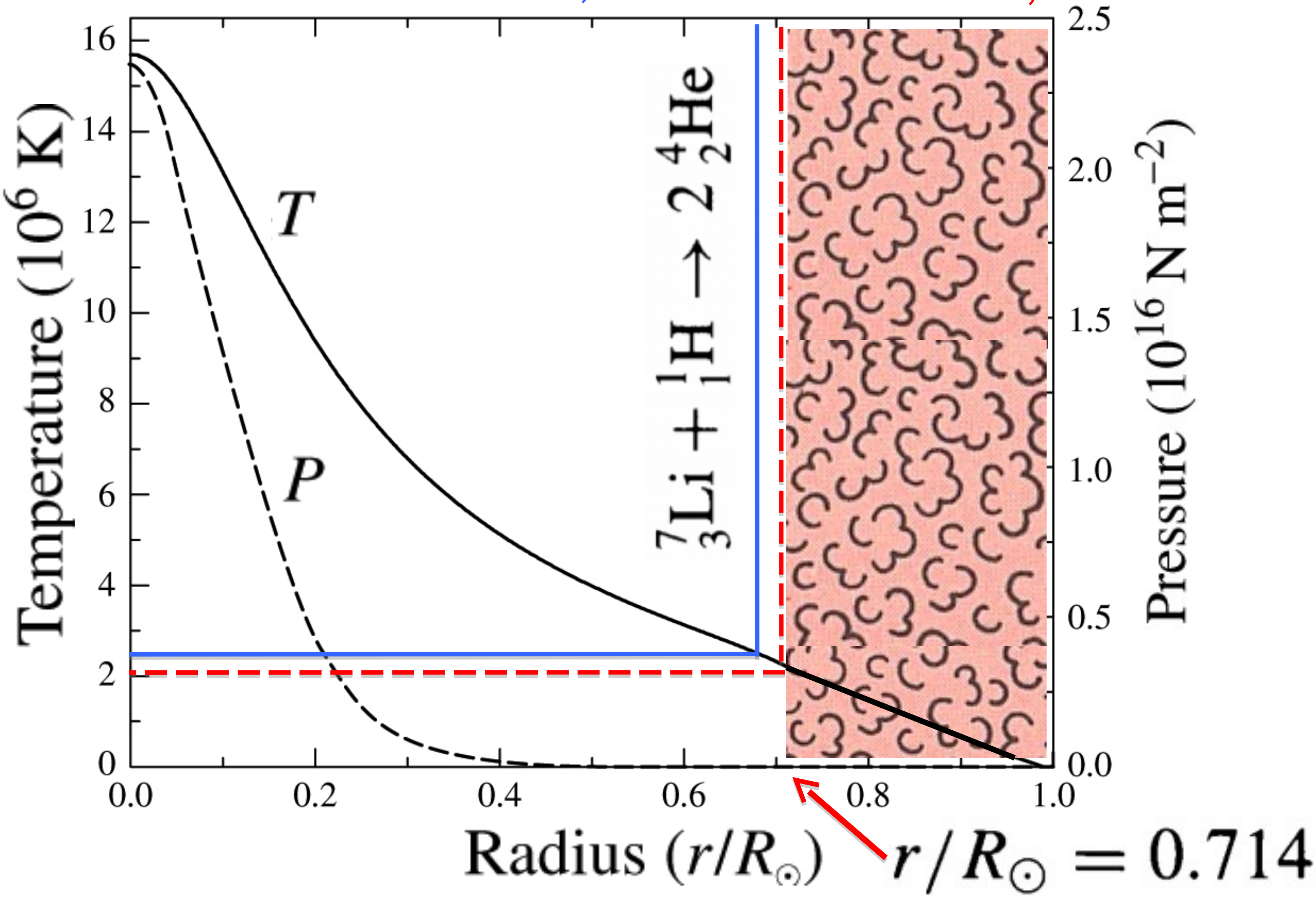


A abundância de Li observada no Sol é 160 vezes menor à de meteoritos

*Li queima a T=2,5x10^6 K, **sob** a zona convectiva (base, T=2x10^6 K) → não seria observada a destruição do lítio!*

Queima do lítio solar a T = $2,5 \times 10^6$ K

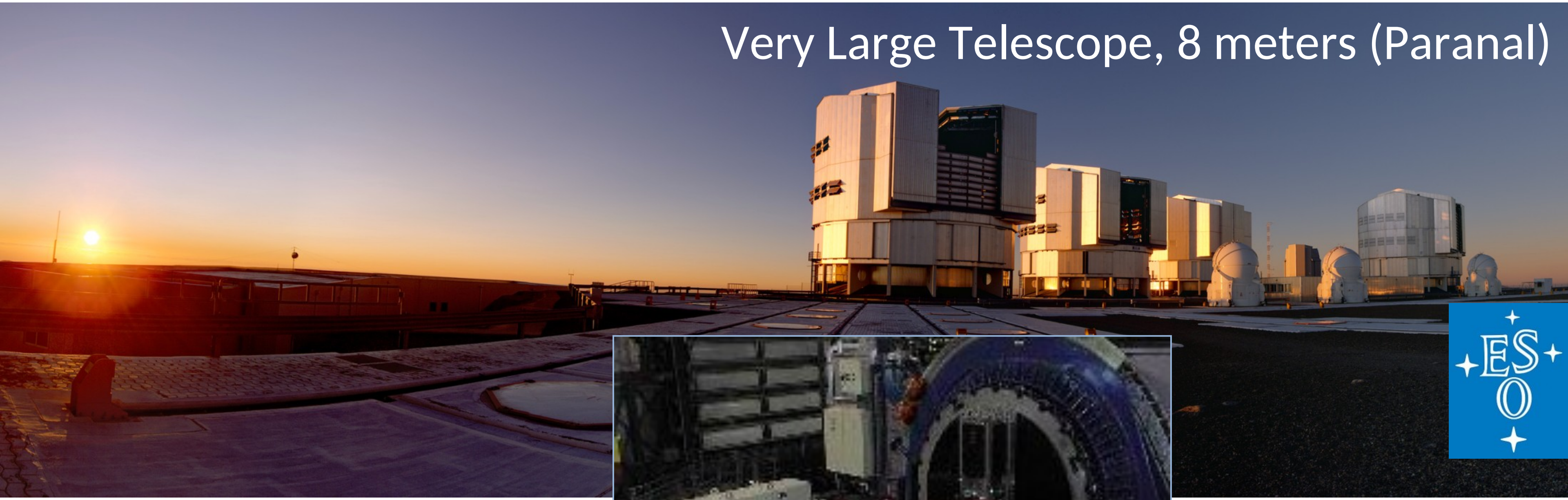
Base da ZC, T = 2×10^6 K



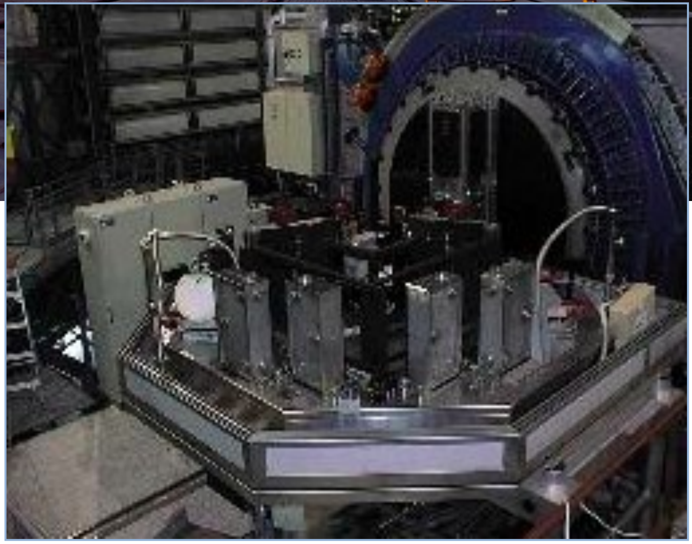
Resolvendo o mistério do lítio usando gêmeas solares de diferentes idades

Telescópio VLT (8 metros) + UVES

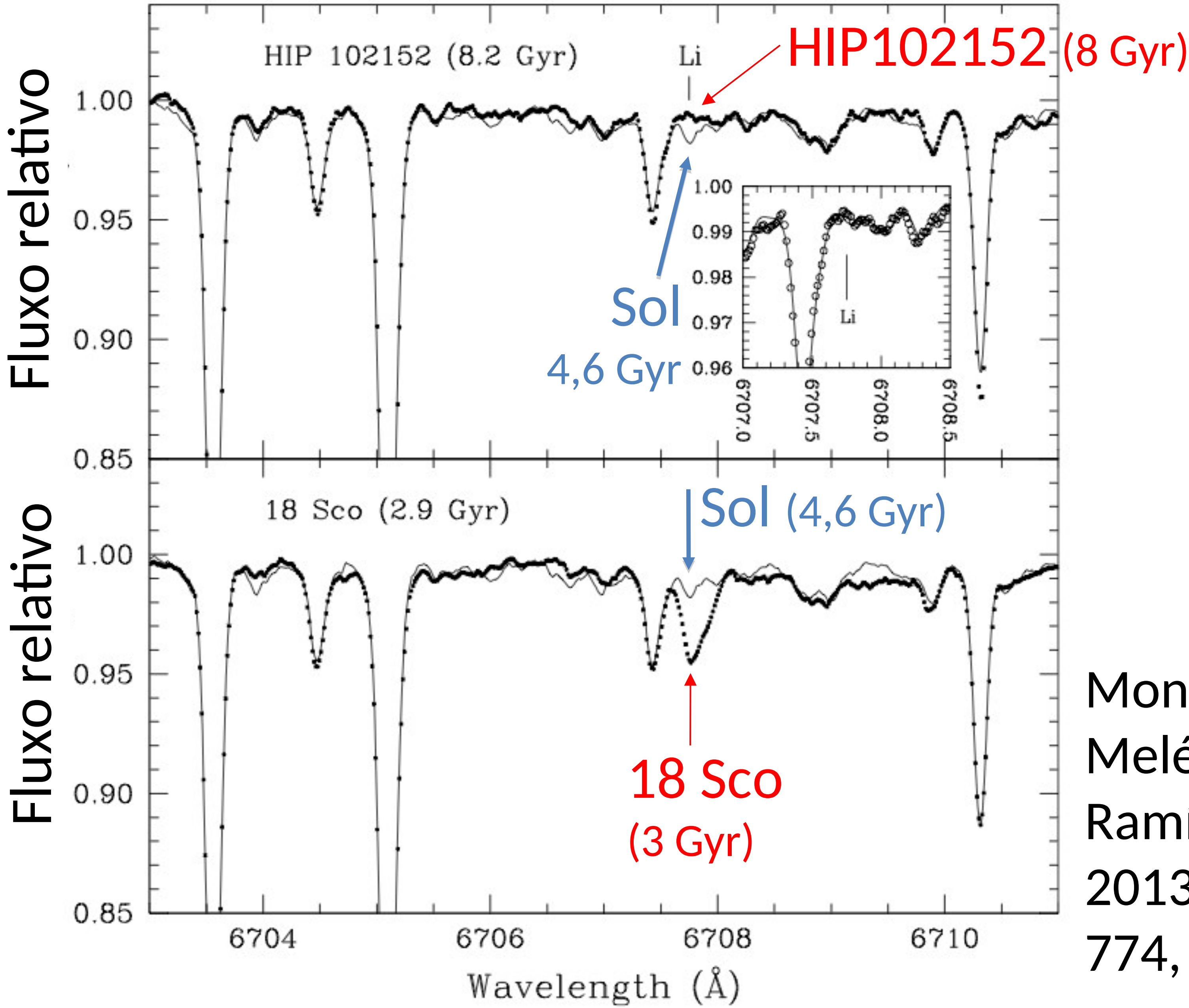
R = 110 000, S/N ~ 500 - 1000 perto da linha de Li



Espectrógrafo UVES

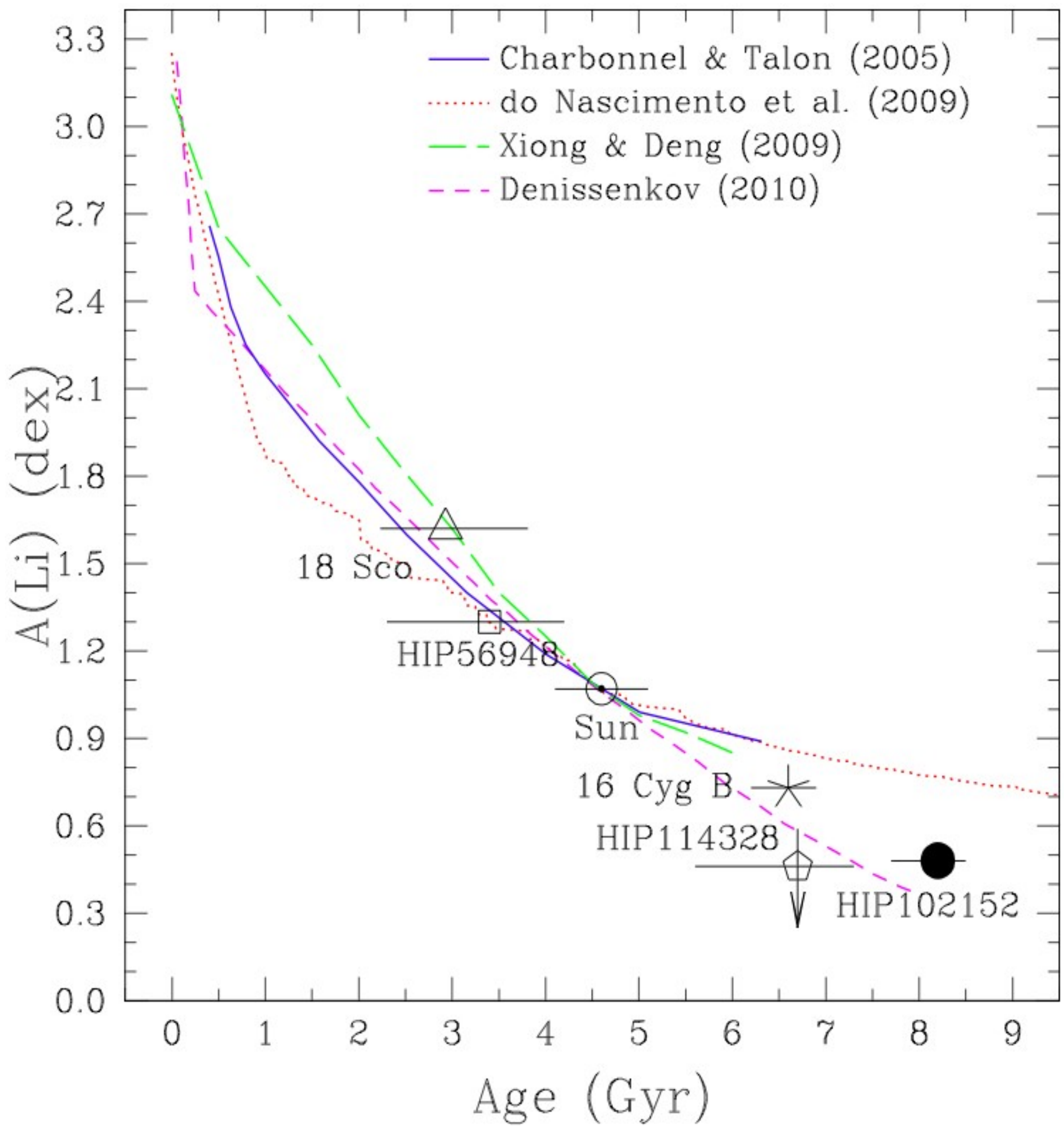


HIGH PRECISION ABUNDANCES OF THE OLD SOLAR TWIN HIP 102152: INSIGHTS ON Li DEPLETION FROM THE OLDEST SUN*



Monroe, Meléndez, Ramírez et al. 2013, ApJ, 774, L32

HIP 114328 e HIP102152: gêmeas solares velhas com pouco lítio → existem mecanismos de transporte que atingem a região de queima de lítio



Monroe et al. 2013

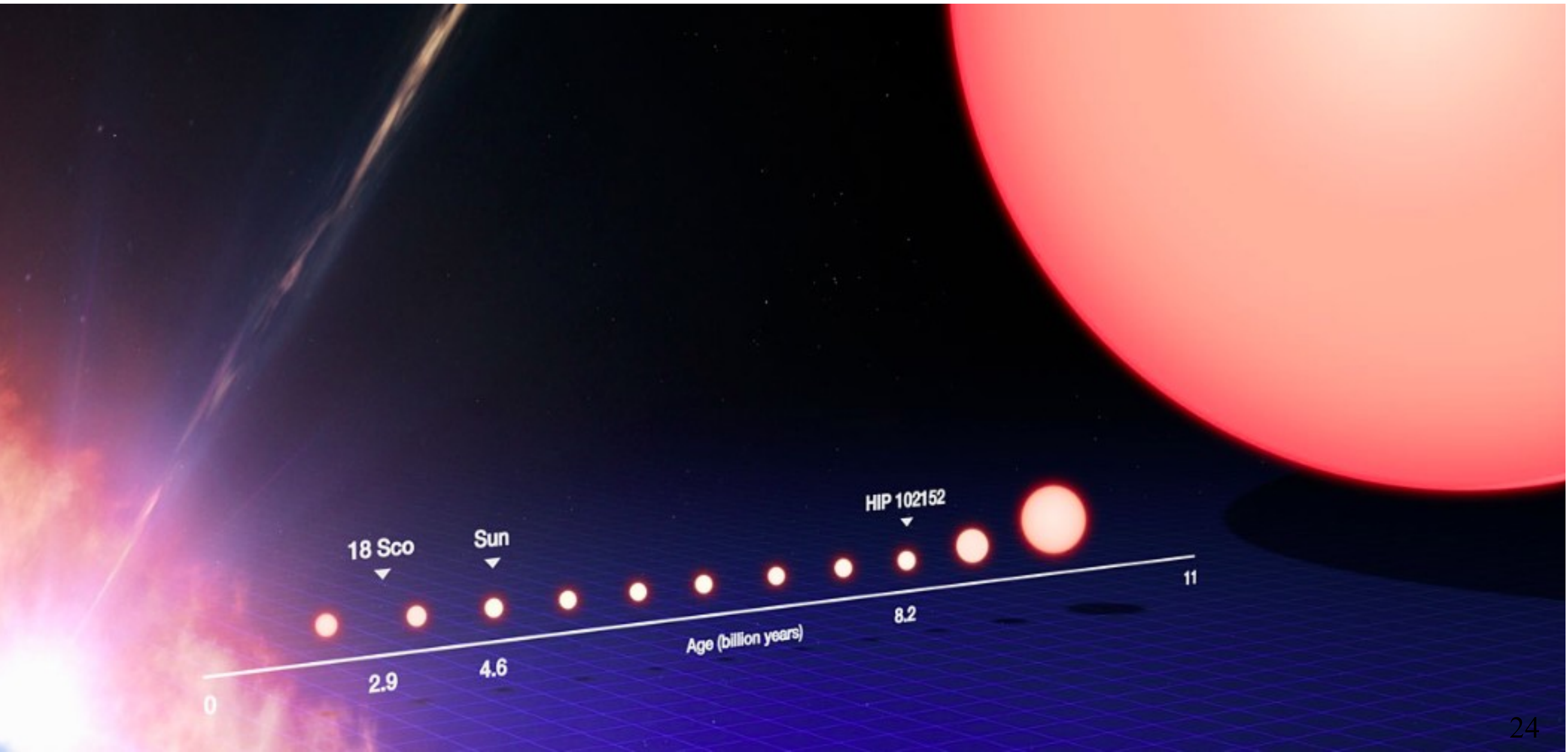
Jorge Meléndez, Lucas Schirbel, Tala Monroe et al. 2014 eso1337pt-br — Nota de imprensa científica

Identificada a estrela gêmea do Sol mais velha conhecida até hoje

O VLT do ESO fornece novas pistas que ajudam a solucionar o mistério do lítio

28 de Agosto de 2013

European Southern Observatory



Press release mais coletiva de imprensa, IAG/USP, 28/8/2013, 10h30m

Globo

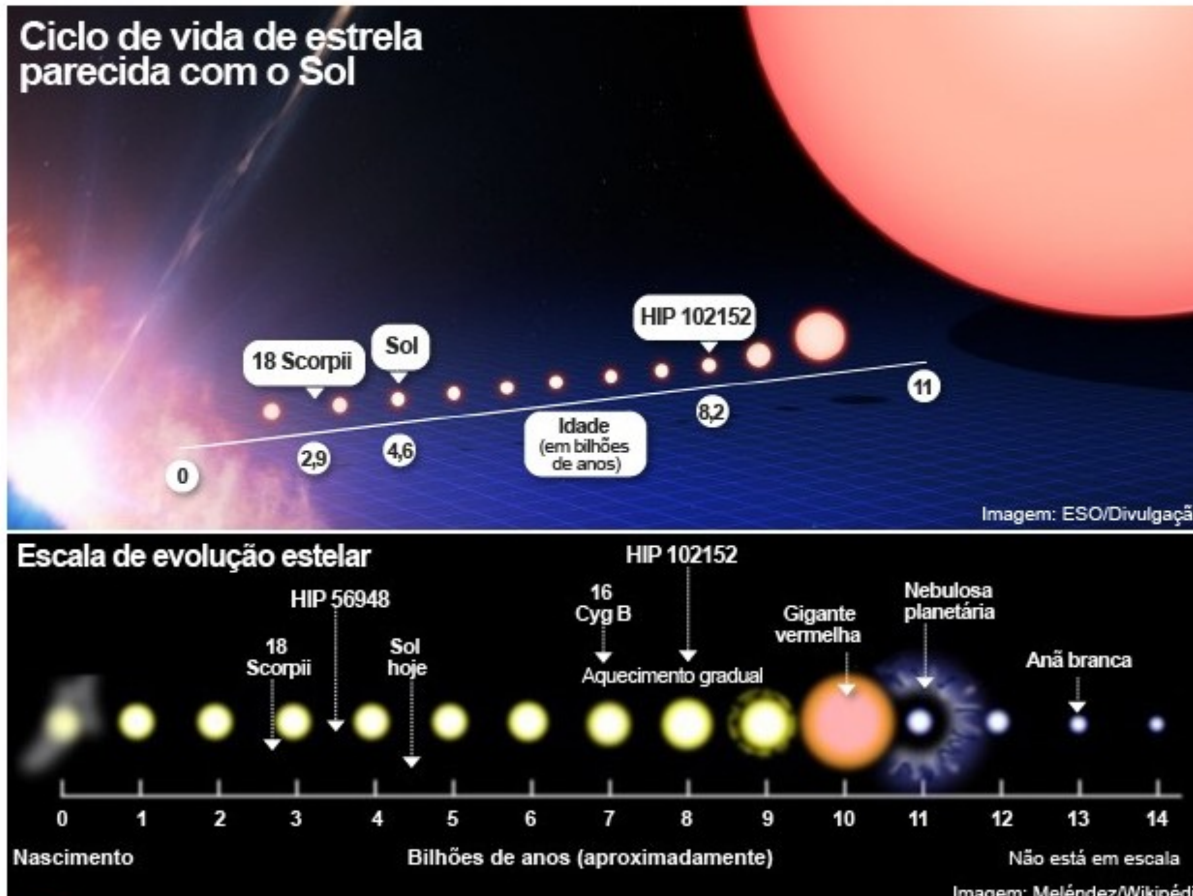
http://g1.globo.com/ciencia-e-saude/noticia/2013/08/equipe-da-usp-ajuda-descobrir-mais-velha-estrela-gemea-do-sol.html

28/08/2013 10h29 - Atualizado em 29/08/2013 11h18

Equipe da USP ajuda a descobrir mais velha estrela 'gêmea' do Sol

HIP 102152 tem 8,2 bilhões de anos e fica a 250 anos-luz da Terra.
Estudo foi feito em parceria com o Observatório Europeu do Sul (ESO).

Luna D'Alama
Do G1, em São Paulo



G1.com.br

http://www.skyandtelescope.com/news/Sun-Loses-Lithium-with-Age-221836221.html

NEWS by Camille Carlisle

Sun Loses Lithium with Age

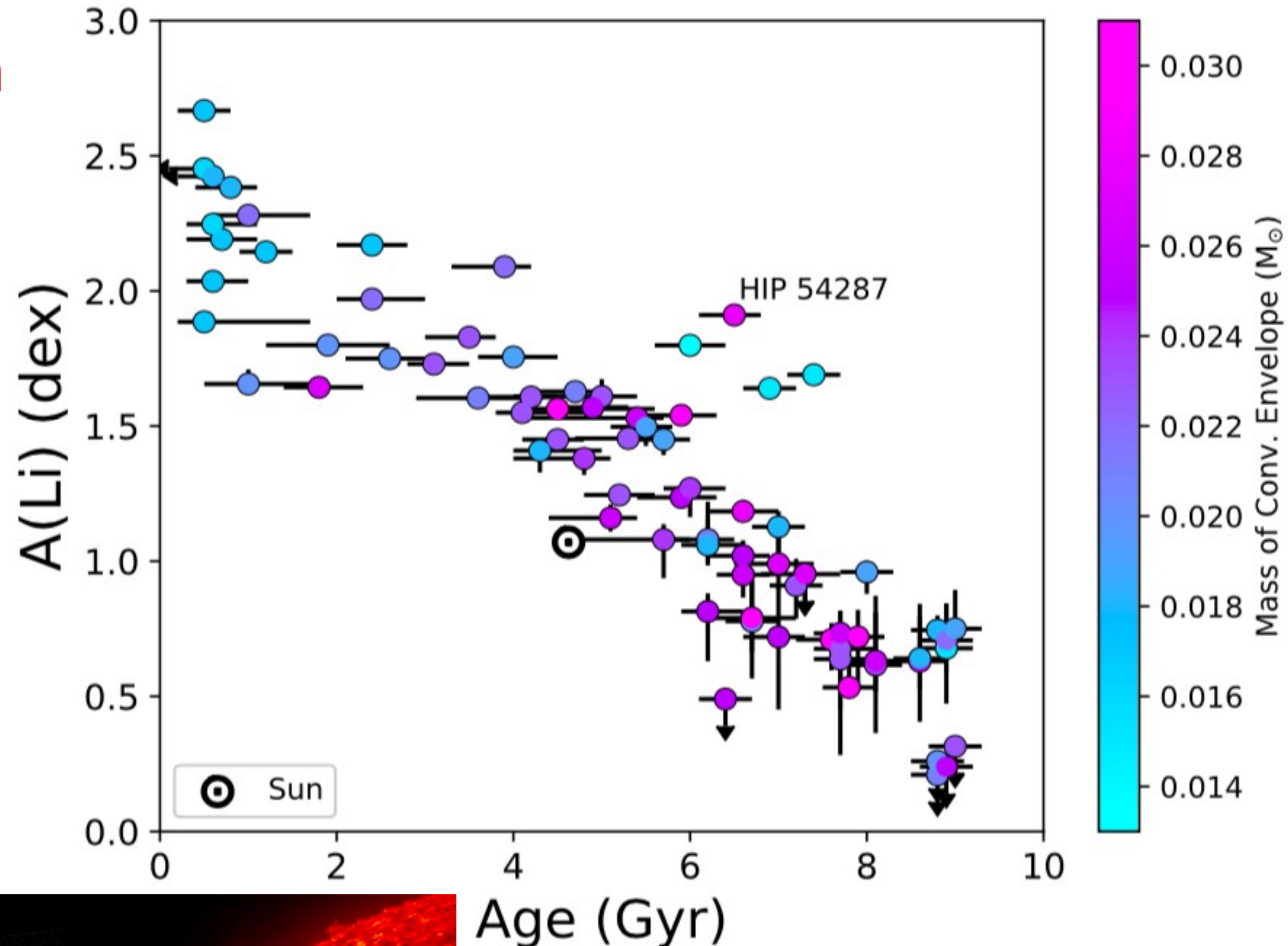
Observations of two solar twins — one old and one young — confirm that the Sun has probably destroyed its lithium over time.

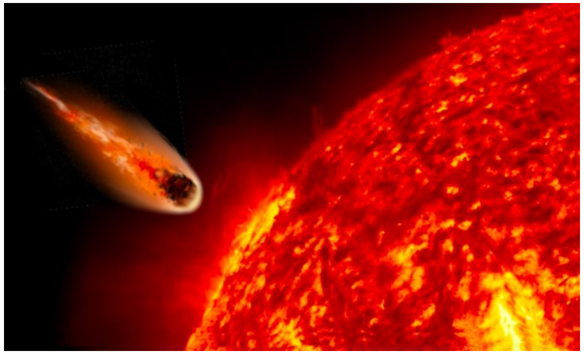
I've blogged repeatedly here about the universe's missing lithium. But lithium is also a troublemaker in the solar system. Based on primitive meteorites that record the makeup of the nebula from which the solar system formed, the Sun seems to have destroyed more than 99% of its initial lithium.

Questões ainda em aberto sobre o lítio:

- Por que o Sol é mais pobre em Li que estrelas da mesma idade?

- Engolimento de planetas por estrelas ricas em lítio?

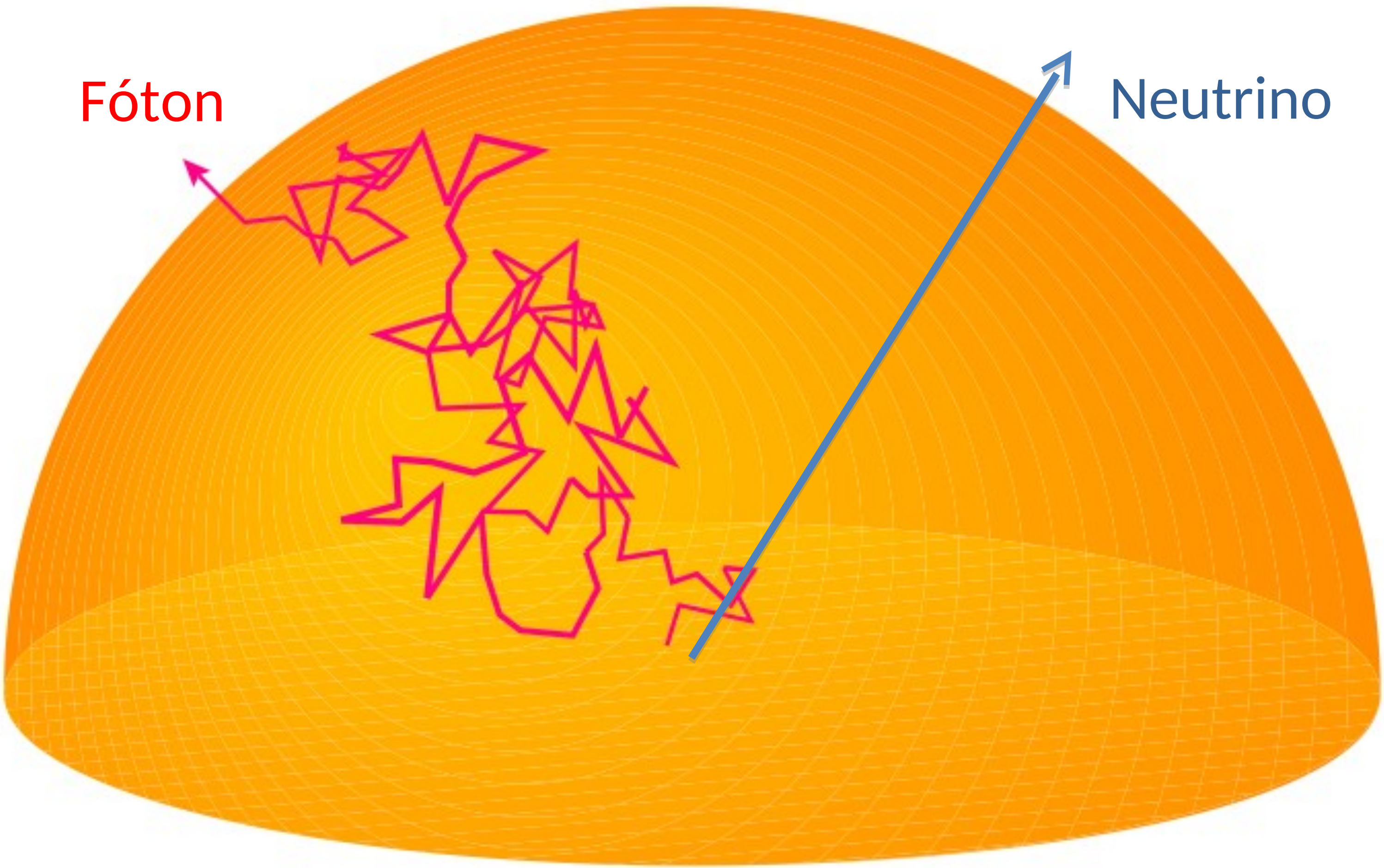




Marília Carlos, Jorge Meléndez, Lorenzo Spina et al. (2019, MNRAS)

O Problema do neutrino solar

São detectados menos neutrinos do que os preditos pelo modelo padrão do Sol

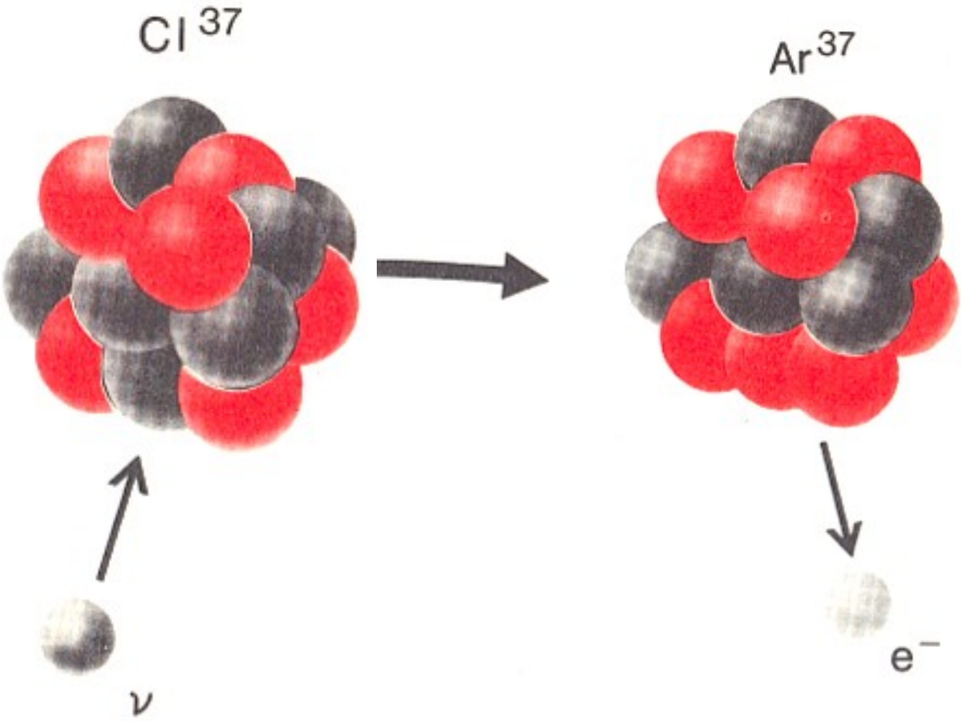


Detector de neutrinos de Raymond Davis Jr. (~1970)
377 000 litros de tetracloroeteno, C_2Cl_4

Isótopo $^{37}_{17}Cl$ pode interagir com neutrino

FIGURE 11.8 Raymond Davis's solar neutrino detector. The tank was located 1478 m (4850 ft) below ground in the Homestake Gold Mine in Lead, South Dakota, and was filled with 615,000 kg of C_2Cl_4 in a volume of 377,000 liters (100,000 gallons). (Courtesy of Brookhaven National Laboratory.)

$$^{37}_{17}\mathrm{Cl} + \nu_e \rightleftharpoons {}^{37}_{18}\mathrm{Ar} + e^-$$



Os neutrinos que interagem com o ^{37}Cl são de alta energia, na maioria (77%) da rara reação da cadeia pp-III:

$$^{8}_{5}\mathrm{B} \rightarrow {}^{8}_{4}\mathrm{Be} + e^+ + \nu_e$$

Também parcialmente com neutrinos da cadeia pp-I:

$$^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + e^+ + \nu_e$$

Um neutrino é capaz de transformar um átomo de cloro em um átomo de argônio, liberando um elétron durante o processo

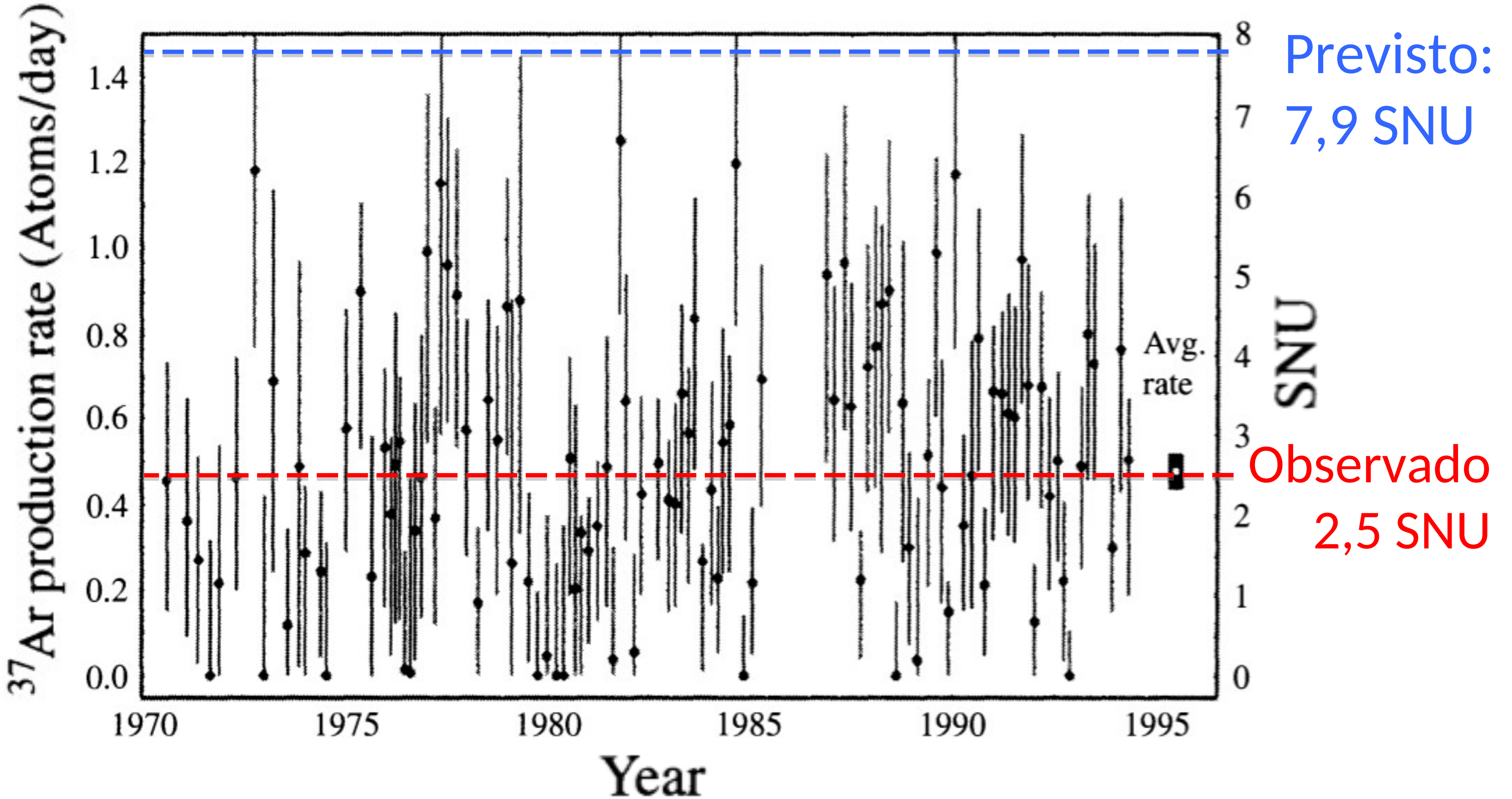
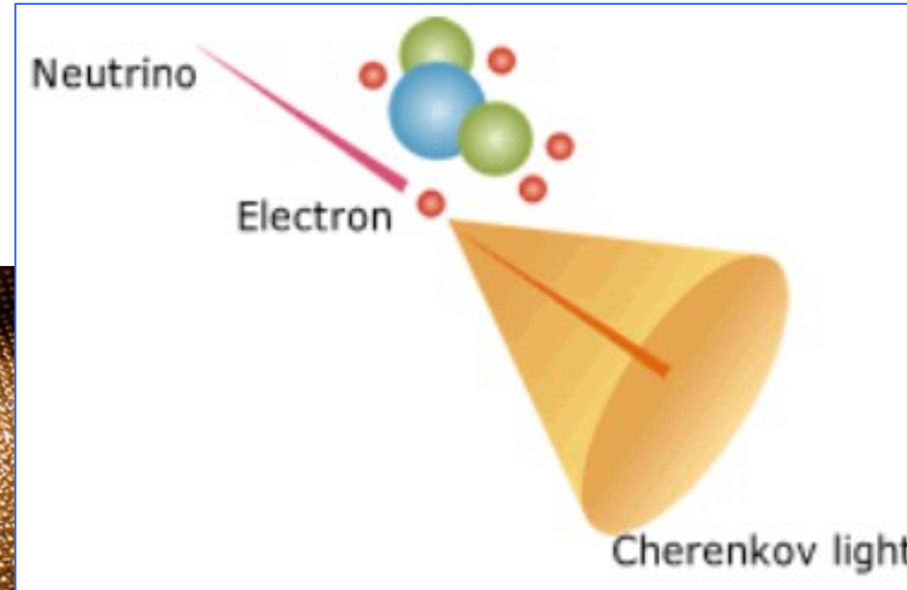
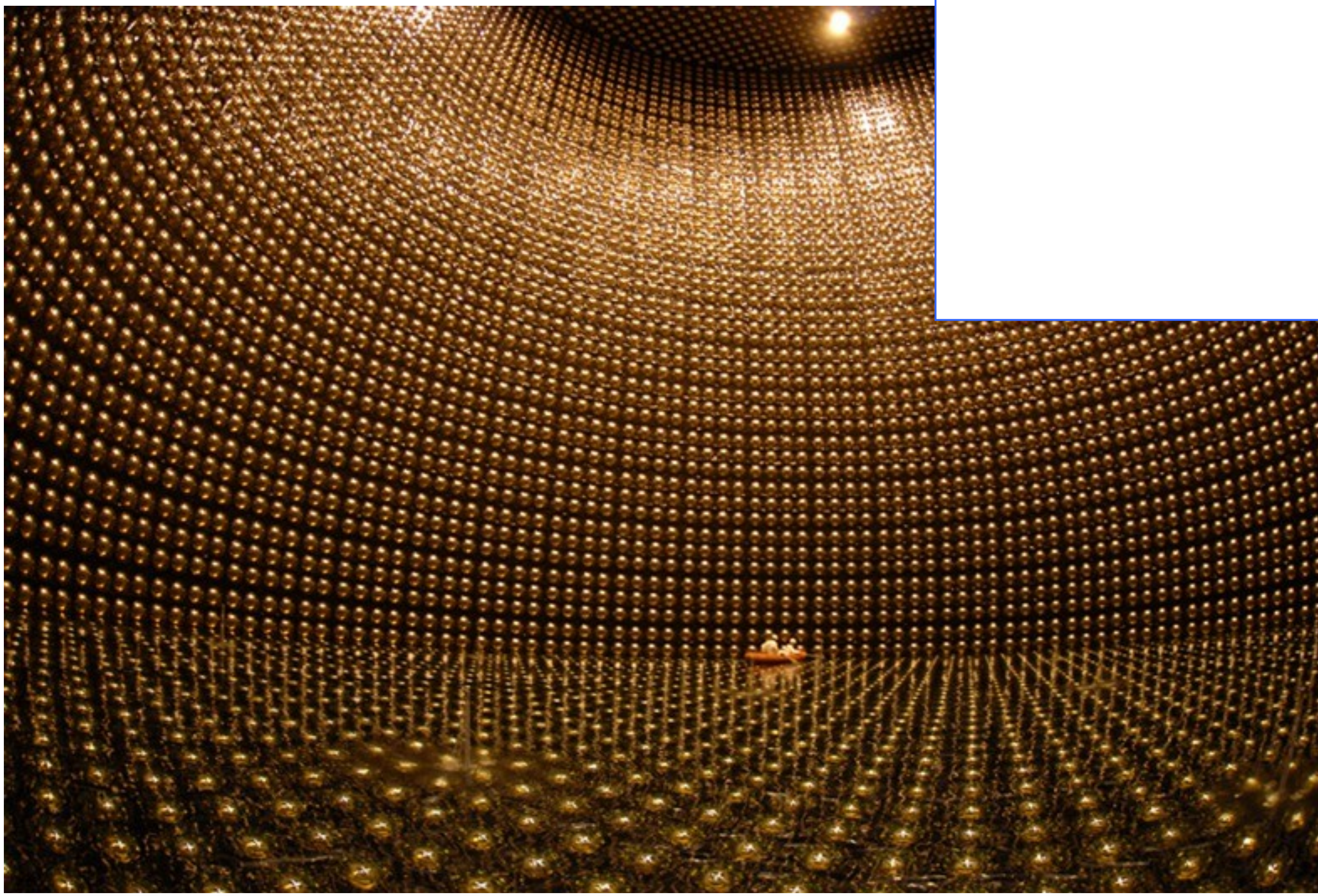


FIGURE 11.9 Results of the Davis solar neutrino experiment from 1970 to 1994. The uncertainties in the experimental data are shown by vertical error bars associated with each run. The predicted solar neutrino capture rate for the $^{37}_{17}$Cl detector was 7.9 SNU based on solar models without neutrino oscillations. (Figure adapted from Cleveland, et al., *Ap. J.*, *496*, 505, 1998.)

1 SNU = 10^{-36} reações por átomo alvo por segundo





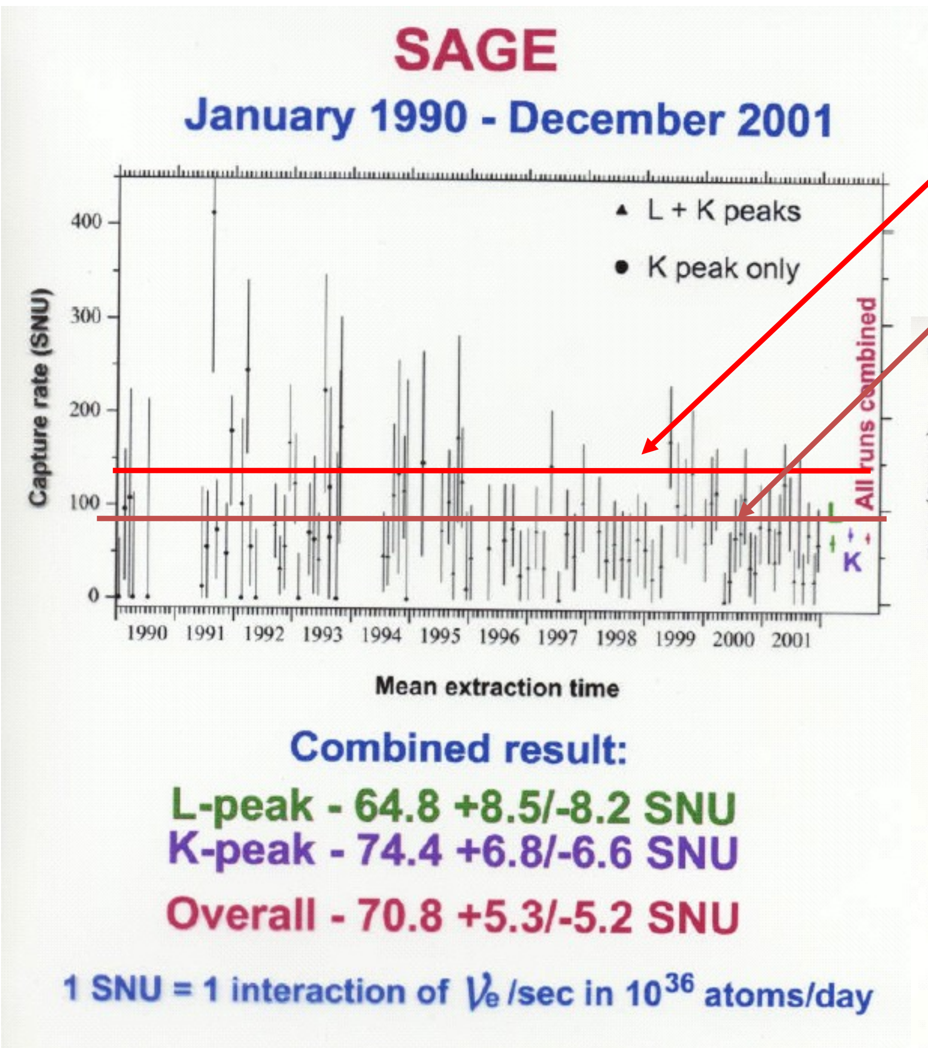
Super-Kamiokande is underground inside a mine in Japan to shield it from cosmic rays.

FIGURE 11.10 Super-Kamiokande neutrino observatory in Japan contains 4.5×10^7 kg (50,000 tons) of pure water. As neutrinos pass through the water, they scatter electrons at speeds greater than the speed of light through water. The pale blue Cerenkov light that is produced is detected by the 11,200 inwardly-directed photomultiplier tubes, signaling the presence of the passing neutrino.

Gallium experiments $\nu_e + {}^{71}_{31}\mathrm{Ga} \rightarrow {}^{71}_{32}\mathrm{Ge} + e^-$

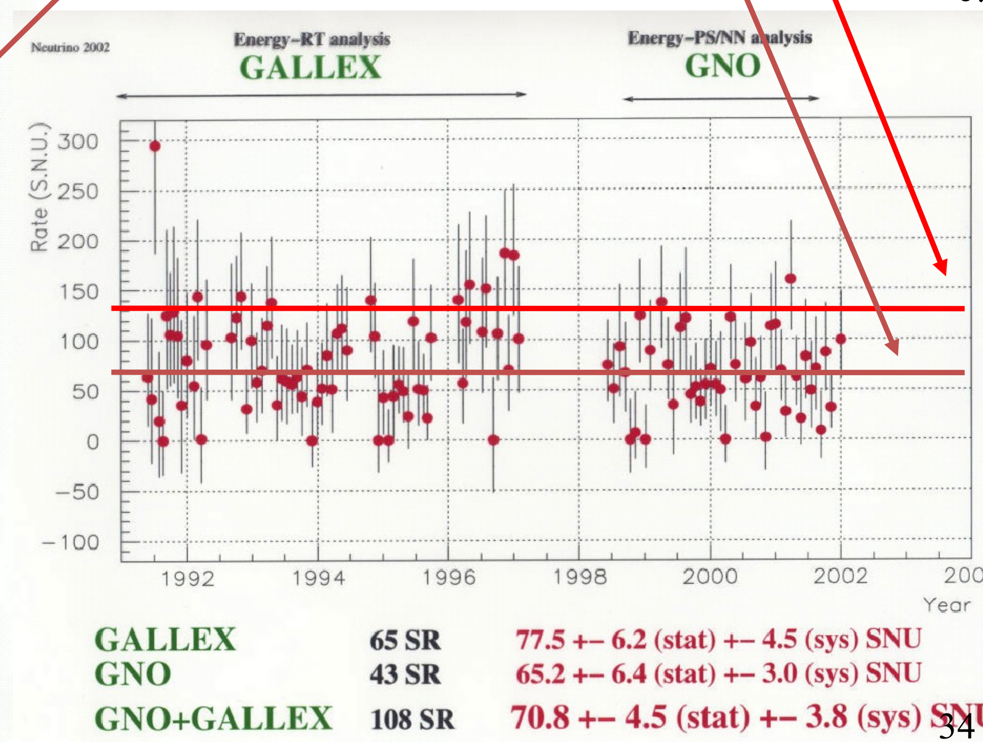
Similar experiments to chlorine but with gallium:

- Lower threshold (0.233 MeV) so sensitive to the lower end of the pp chain
- Further evidence of missing solar neutrinos (55% of expectation)



Expectation: 129+-8 SNU

Observed: 70.8+-6 SNU



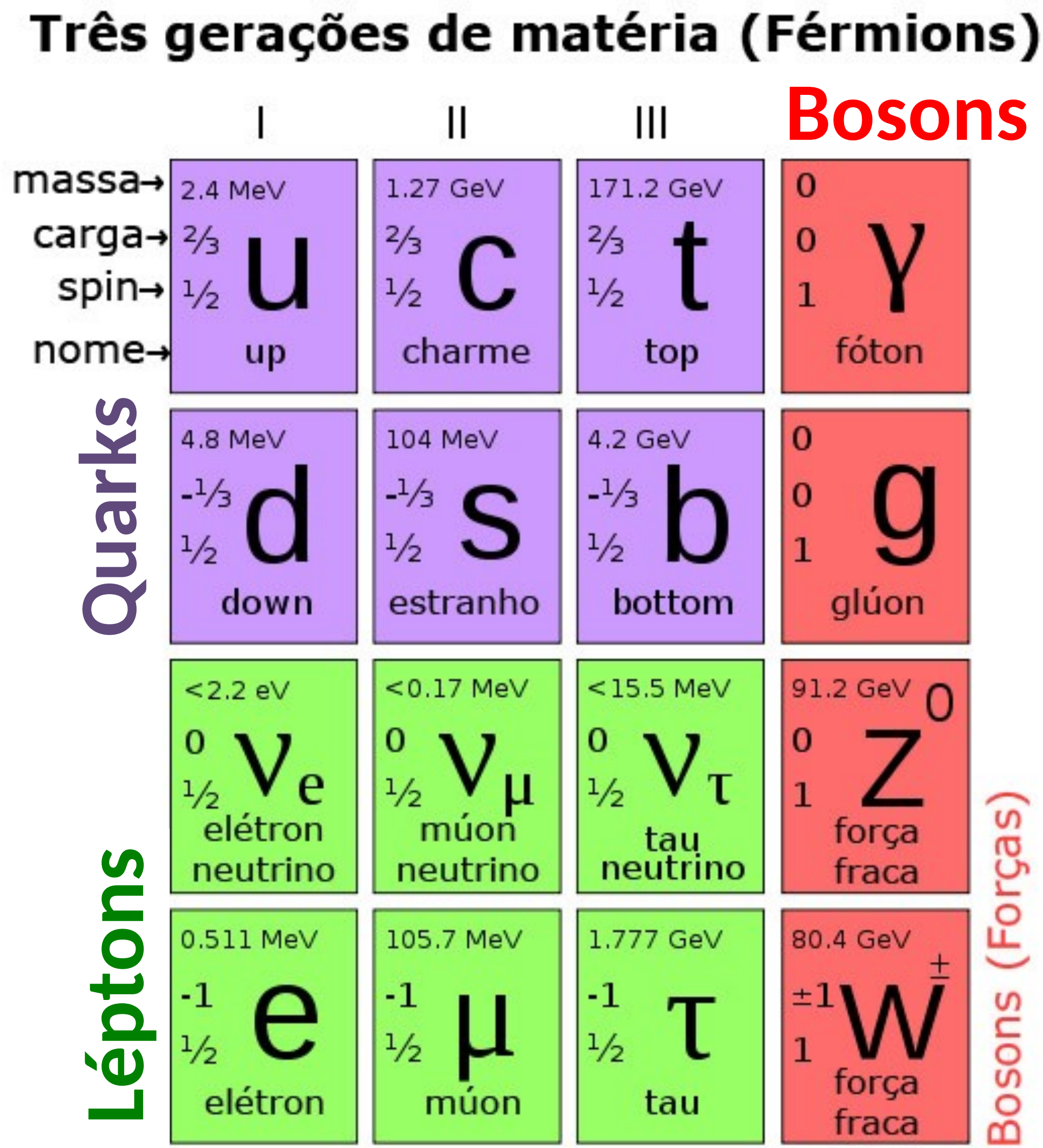
Slide: Dr Paul Soler, Univ.Glasgow

Solução ao problema do neutrino solar

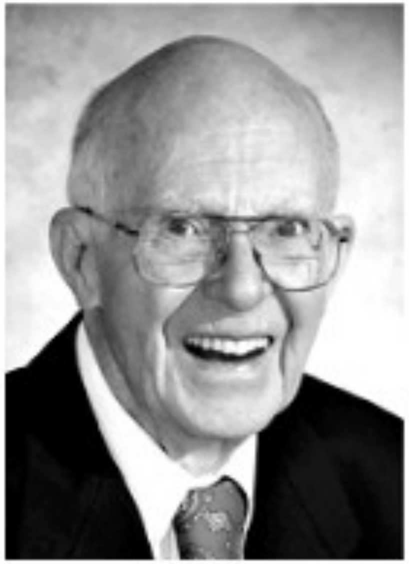
Se os neutrinos têm massa, eles podem oscilar entre diferentes tipos, por exemplo:

$$\nu_e \rightarrow \nu_\mu$$

→ ν original não é necessariamente detectado



Nobel Prize in Physics 2002



Raymond Davis Jr.
Prize share: 1/4

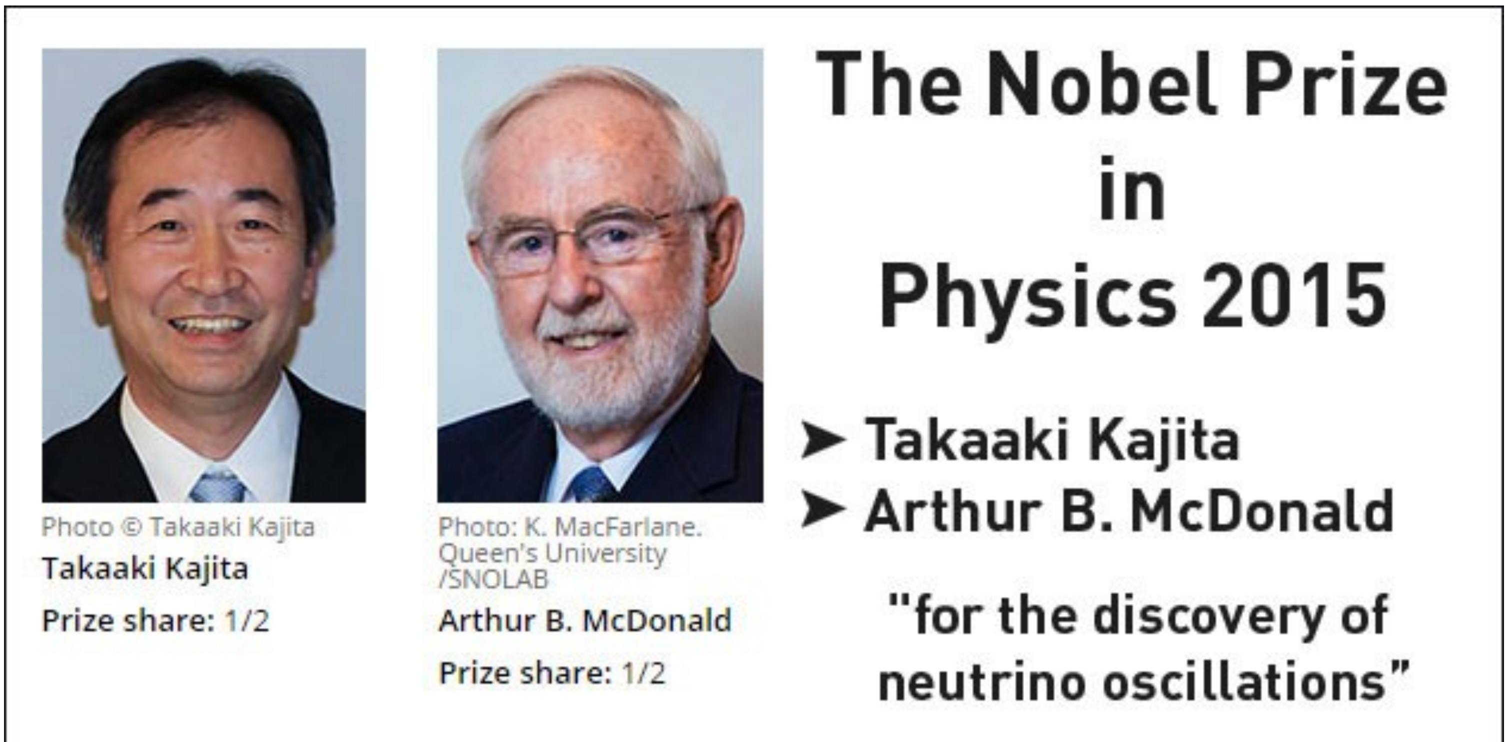
Masatoshi Koshiba
Prize share: 1/4

Riccardo Giacconi
Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to **Raymond Davis Jr.** and **Masatoshi Koshiba** *"for pioneering contributions to astrophysics, in particular for the* ***detection of cosmic neutrinos****"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to
Takaaki Kajita (Super-Kamiokande Collaboration) &
Arthur B. McDonald (Sudbury Neutrino Observatory Collab.)

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

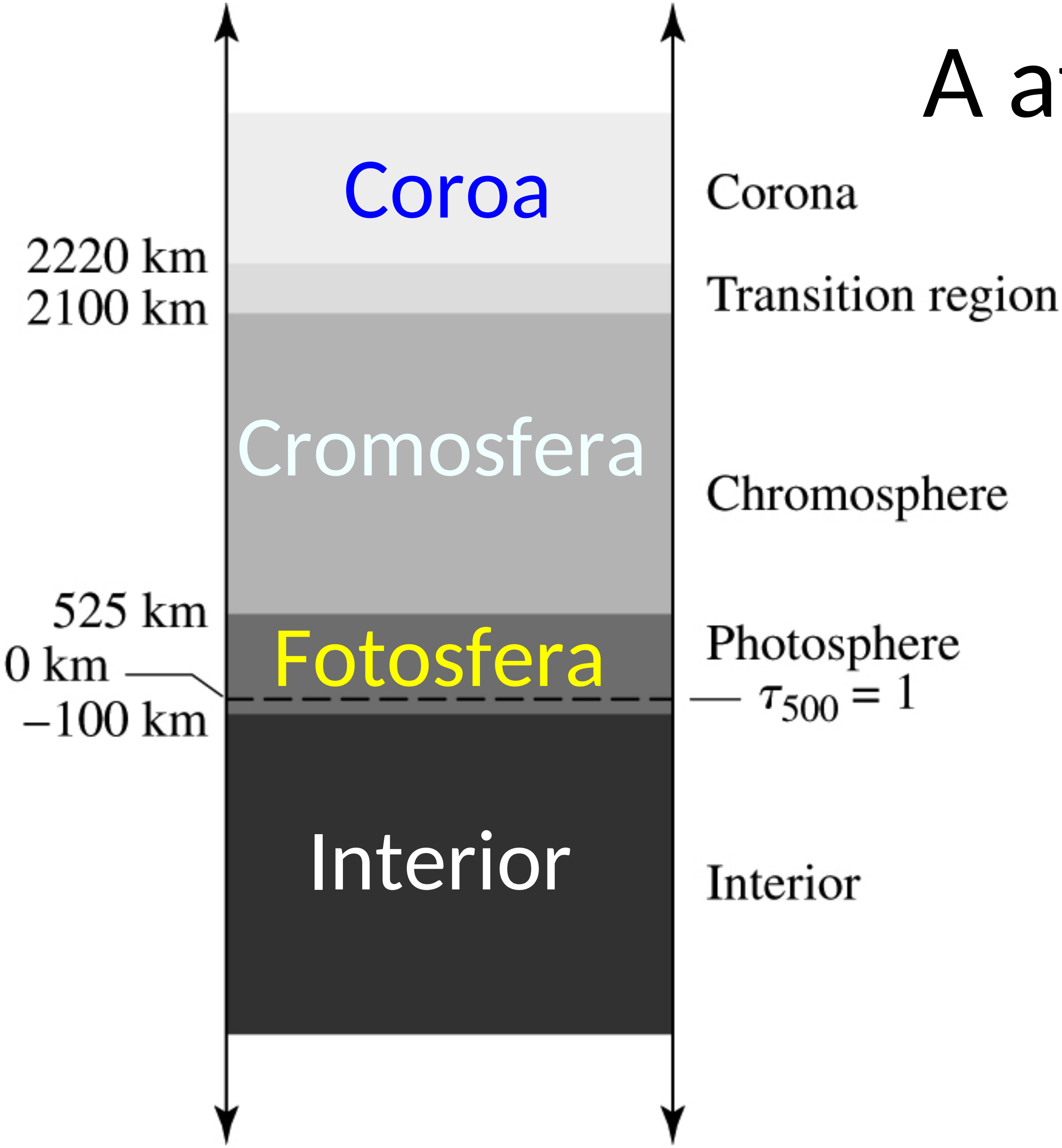


11.2 A atmosfera solar

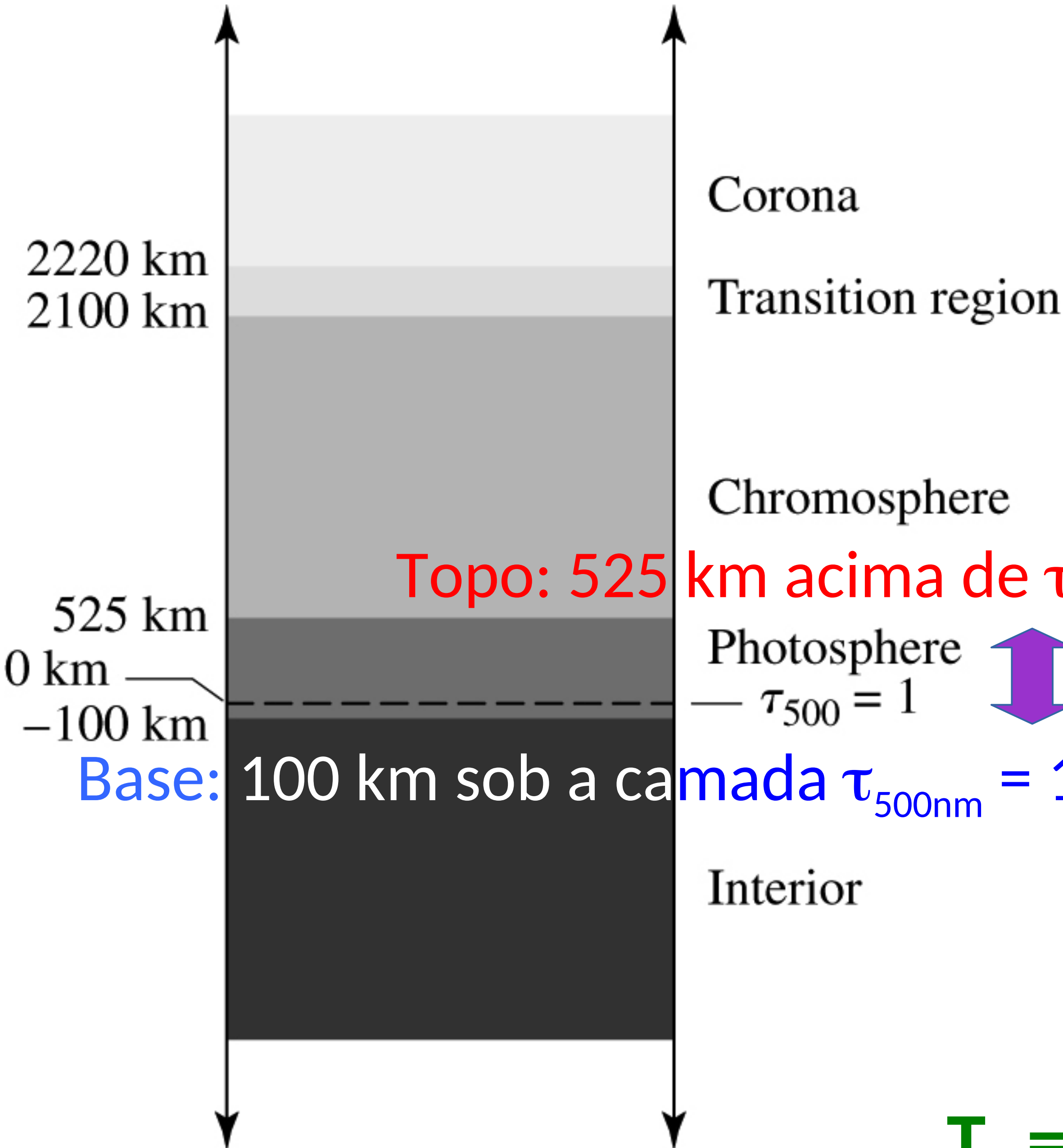
Disco solar aparece bem definido pela rápida mudança da profundidade óptica.

A atmosfera muda de opaca para transparente em apenas 600 km (0,09% do raio solar)

A atmosfera solar



A fotosfera



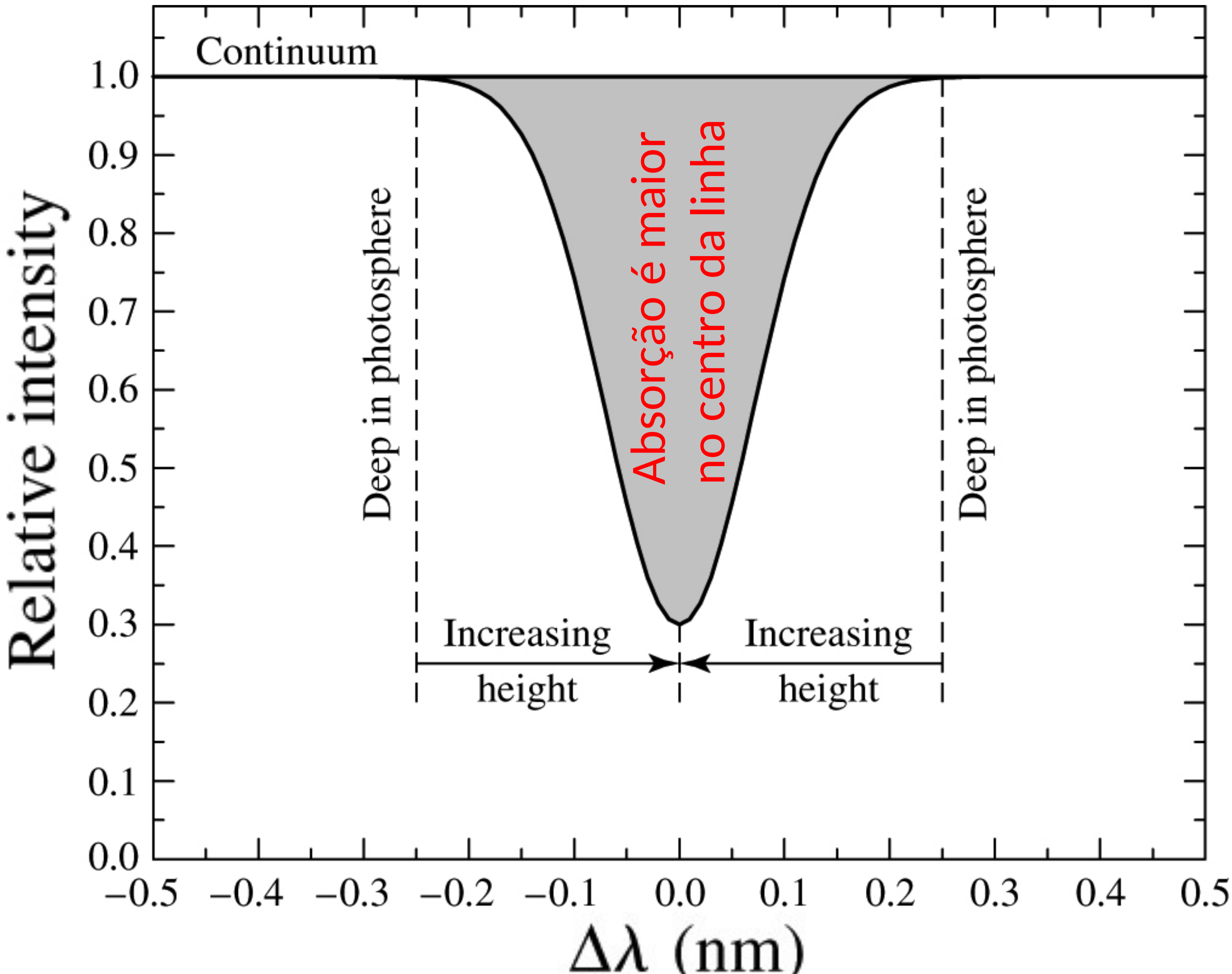
Topo: 525 km acima de $\tau_{500nm} = 1 \rightarrow T \sim 4400$ K

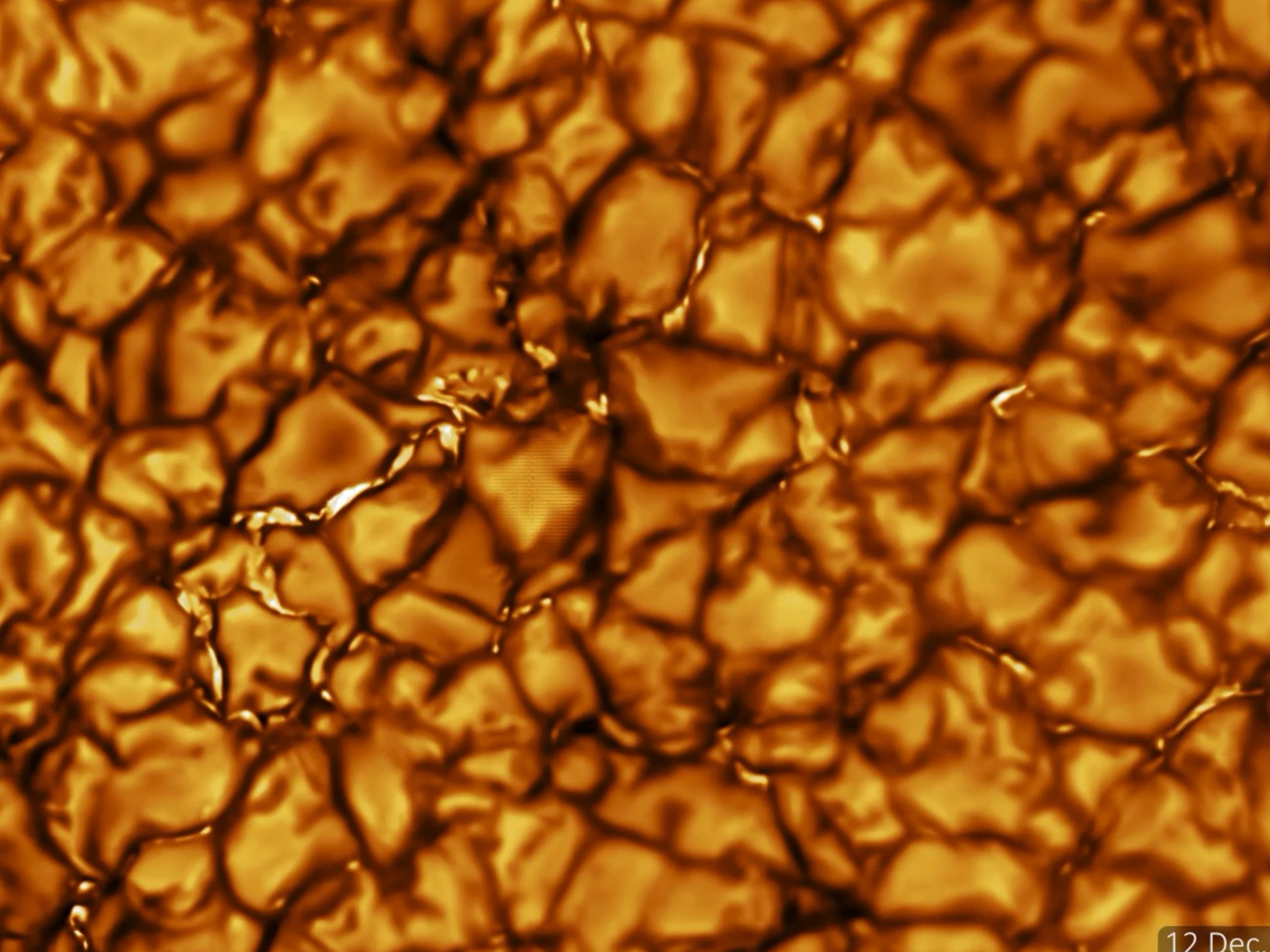
Espessura: 600 km

Base: 100 km sob a camada $\tau_{500nm} = 1 \rightarrow \tau \sim 24$ e $T \sim 9400$ K

$T_e = 5777$ K em $\tau \sim 2/3$

Formação das linhas de absorção na fotosfera




12 Dec

Granulação no Sol

Observação Simulação

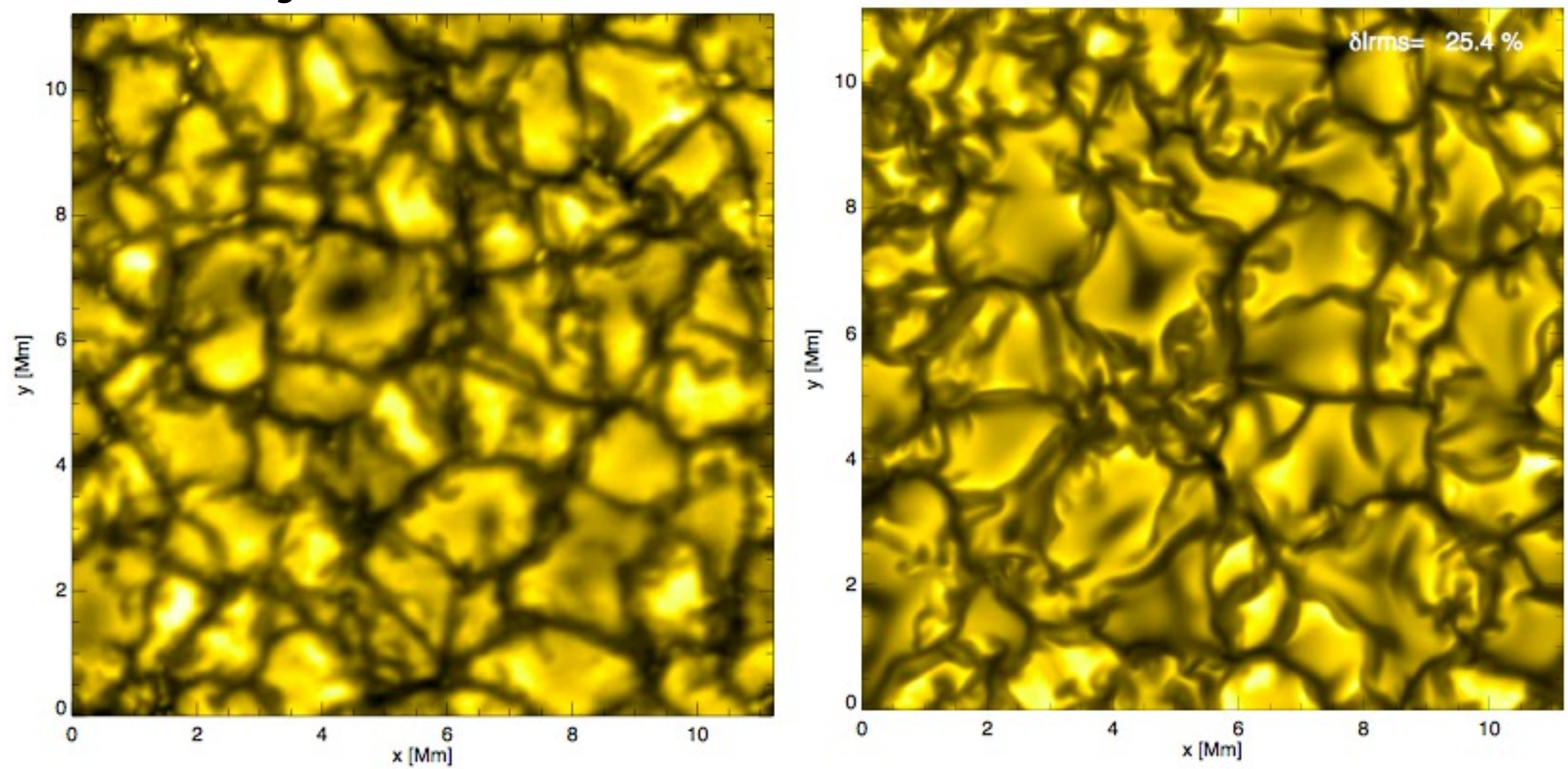


Figure 1: **Left:** Quiet solar granulation as observed with the 1m Swedish Solar Telescope (courtesy Mats Carlsson 2004). **Right:** High-resolution CO^5BOLD simulation of solar surface convection. Both images show the emergent continuum intensity (using identical scaling) at λ 4364 Å in a field measuring $15'' \times 15''$ $(11 \times 11$ Mm).

Tamanho do granulo ~ 1500 km
(1,5 Mm)

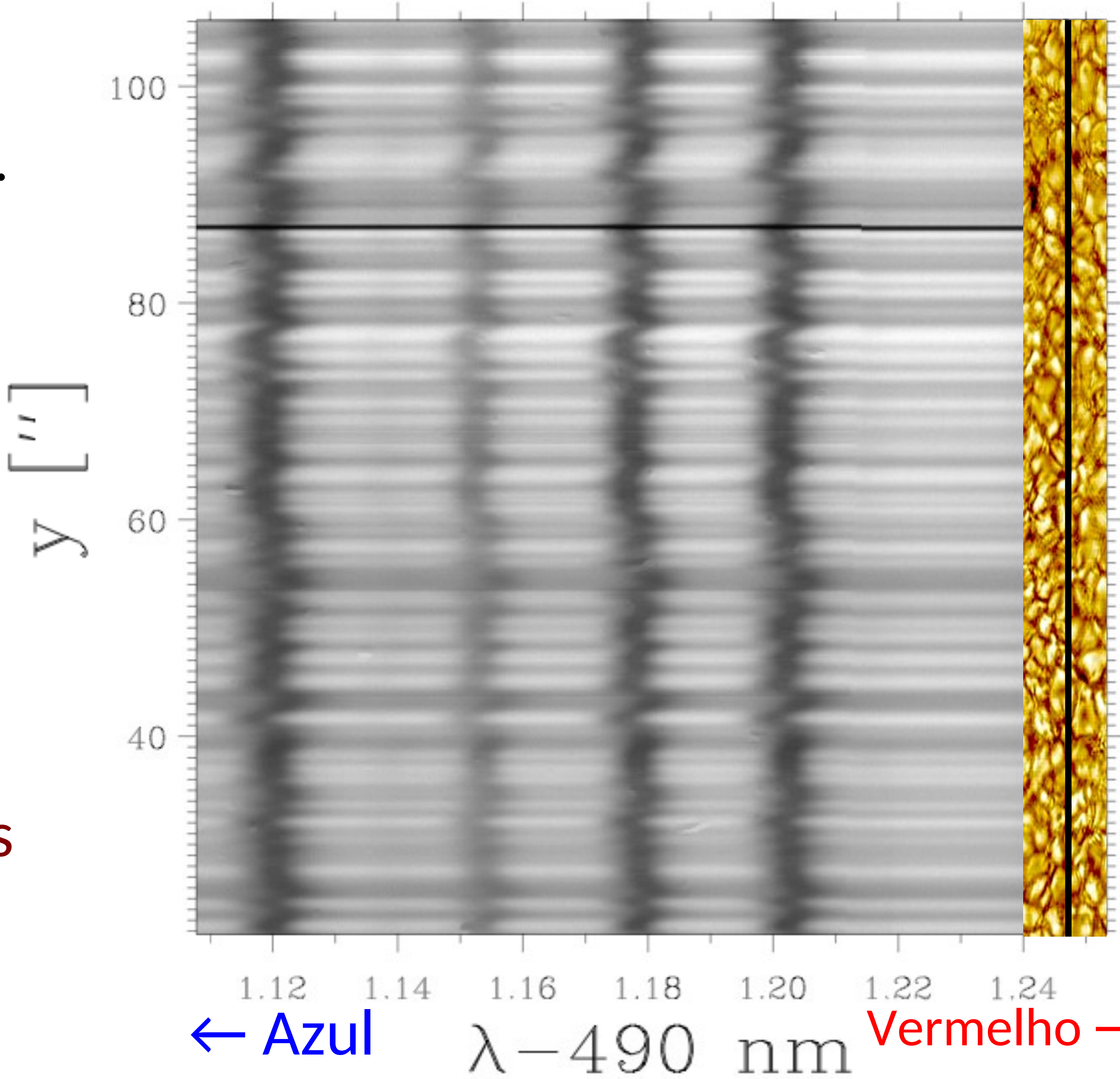
The Solar Photospheric Nitrogen Abundance. Determination with 3D and 1D model atmospheres.

E.Maiorca[A], *E.Caffau*[B], *P.Bonifacio*[C,B,D], *M.Busso*[A,H], *R.Faraggiana*[E], *M.Steffen*[F], *H.-G.Ludwig*[C,B], *I.Kamp*[G]

Dynamics of the solar granulation. VII. A nonlinear approach.

Nesis et al. 2001, A&A, 373, 307

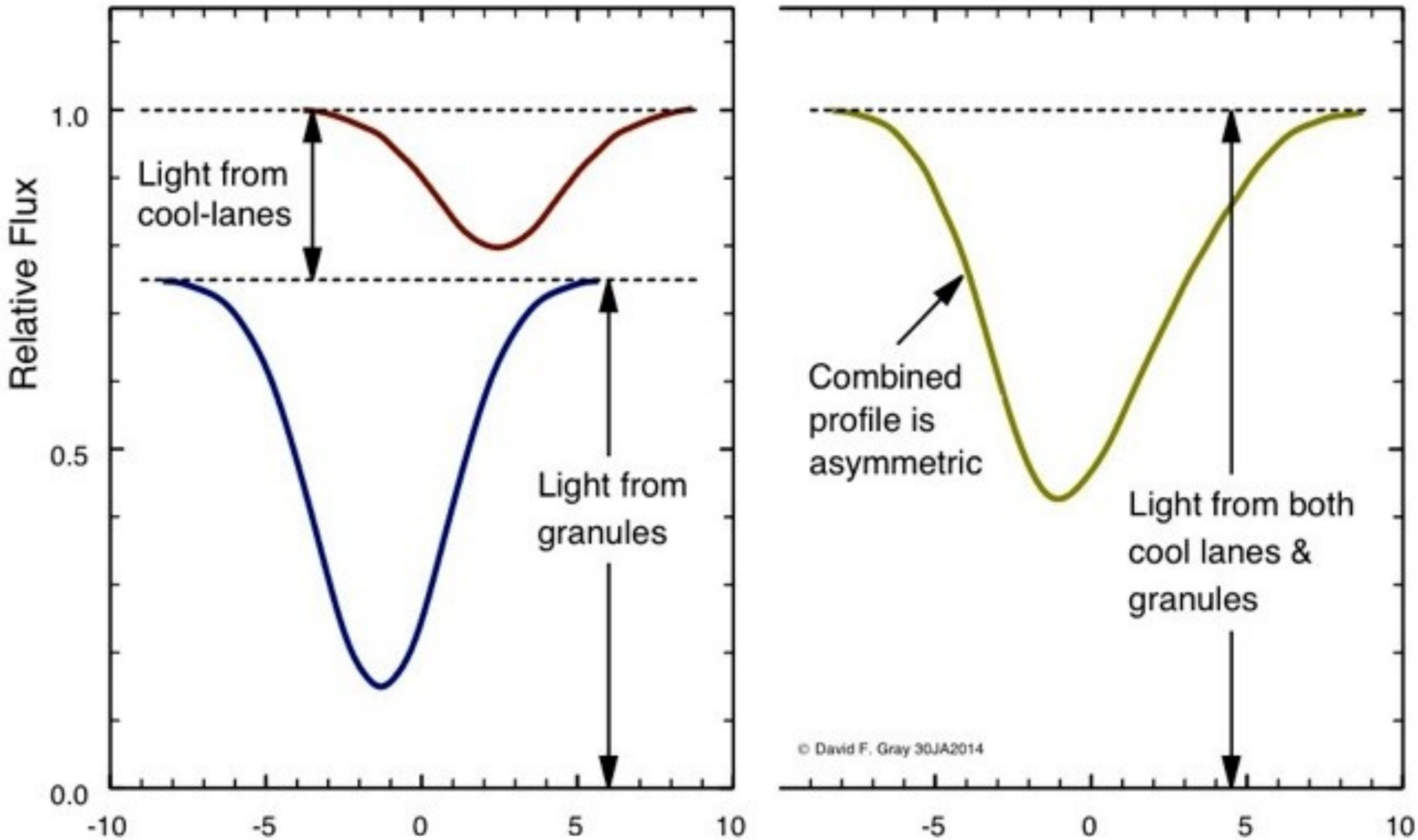
Livro-texto: Radial velocities ~ 0,4 km/s



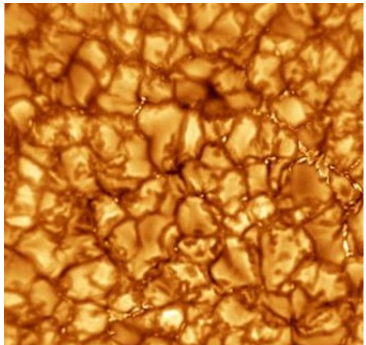
← Azul

Vermelho →

Fig. 1. Part of our best spectrogram 99S4.Sp66, in the wavelength region λλ: 491.11–491.24 nm with the corresponding slit-jaw white light picture attached at the right border. The dark line parallel to the x-axis, at 87 arcsec on the y-axis, is due to a calibration hair across the spectrograph slit. The dark line parallel to the y-axis corresponds to the spectrograph slit.



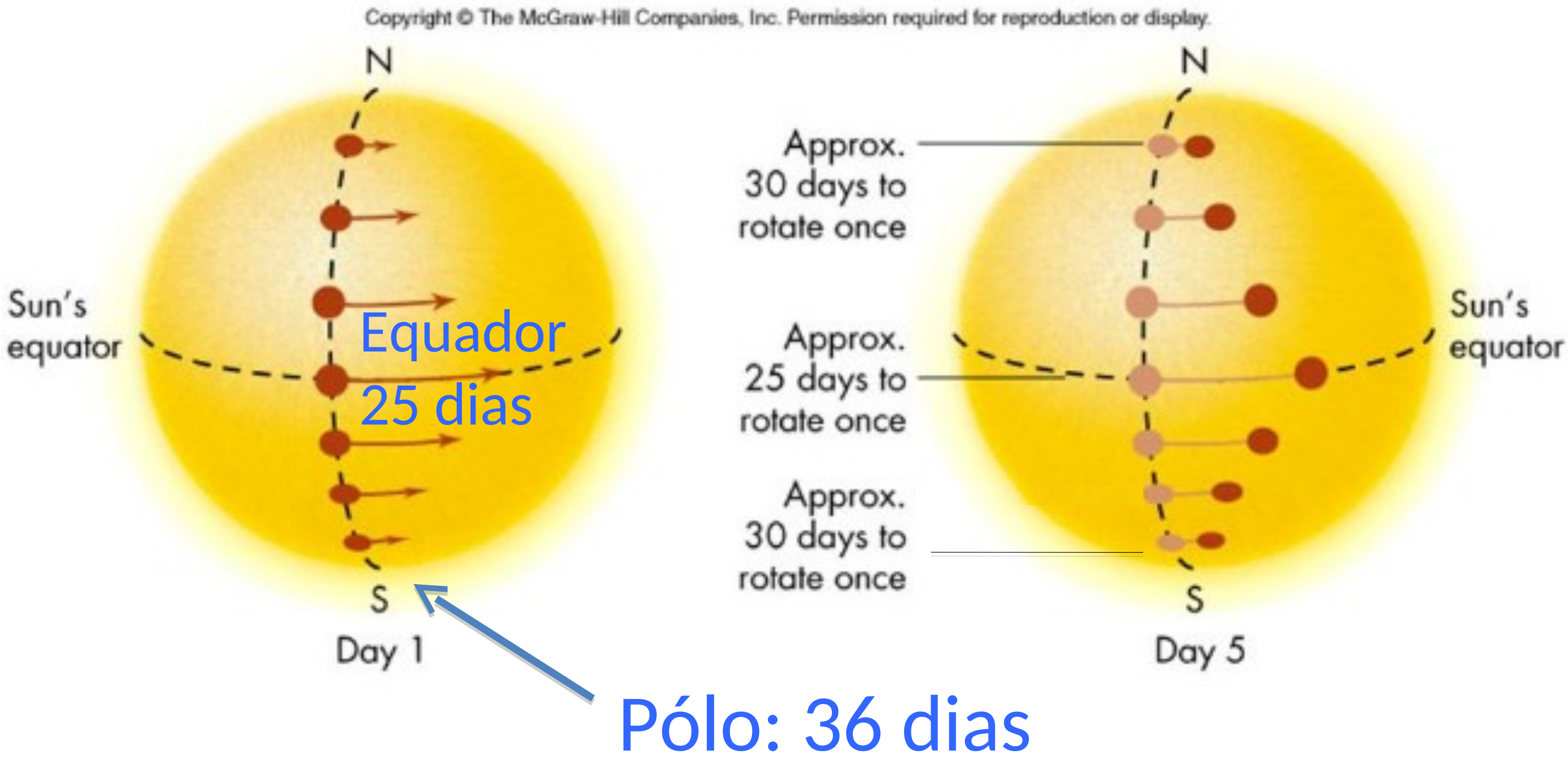
Δλ (km/s) Δλ (km/s)



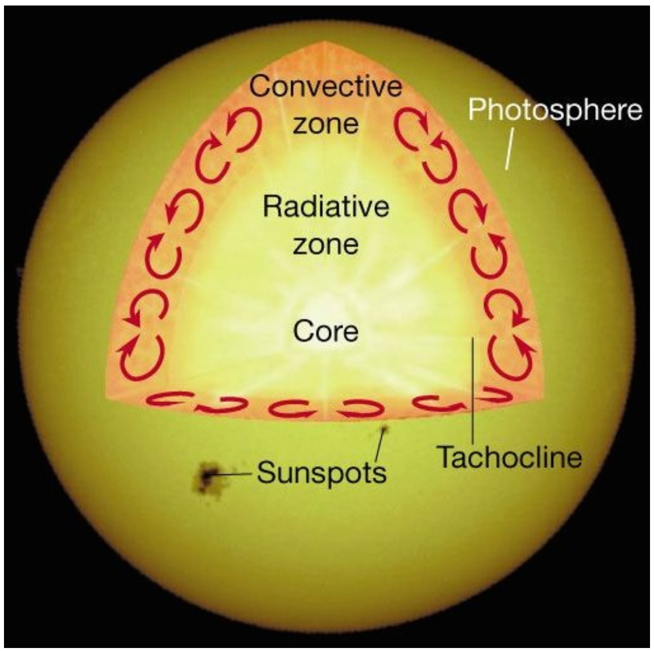
Em estrelas não observamos grânulos individuais, mas o efeito médio: **perfil assimétrico**

http://astro.uwo.ca/~dfgray/Granulation.html

Rotação diferencial



A rotação solar também varia com o raio, convergendo sob a camada convectiva, na região 'tacoclina'



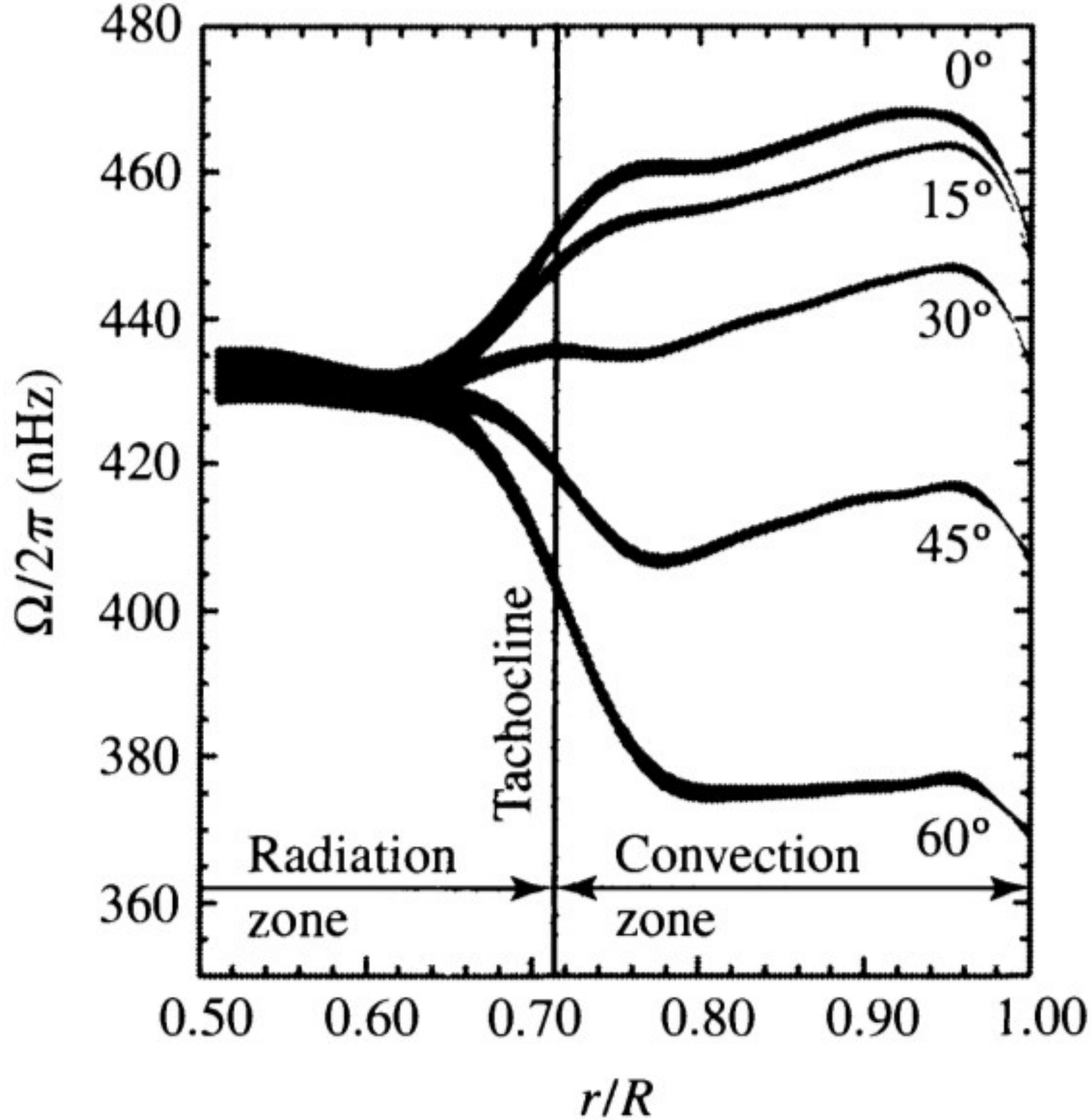
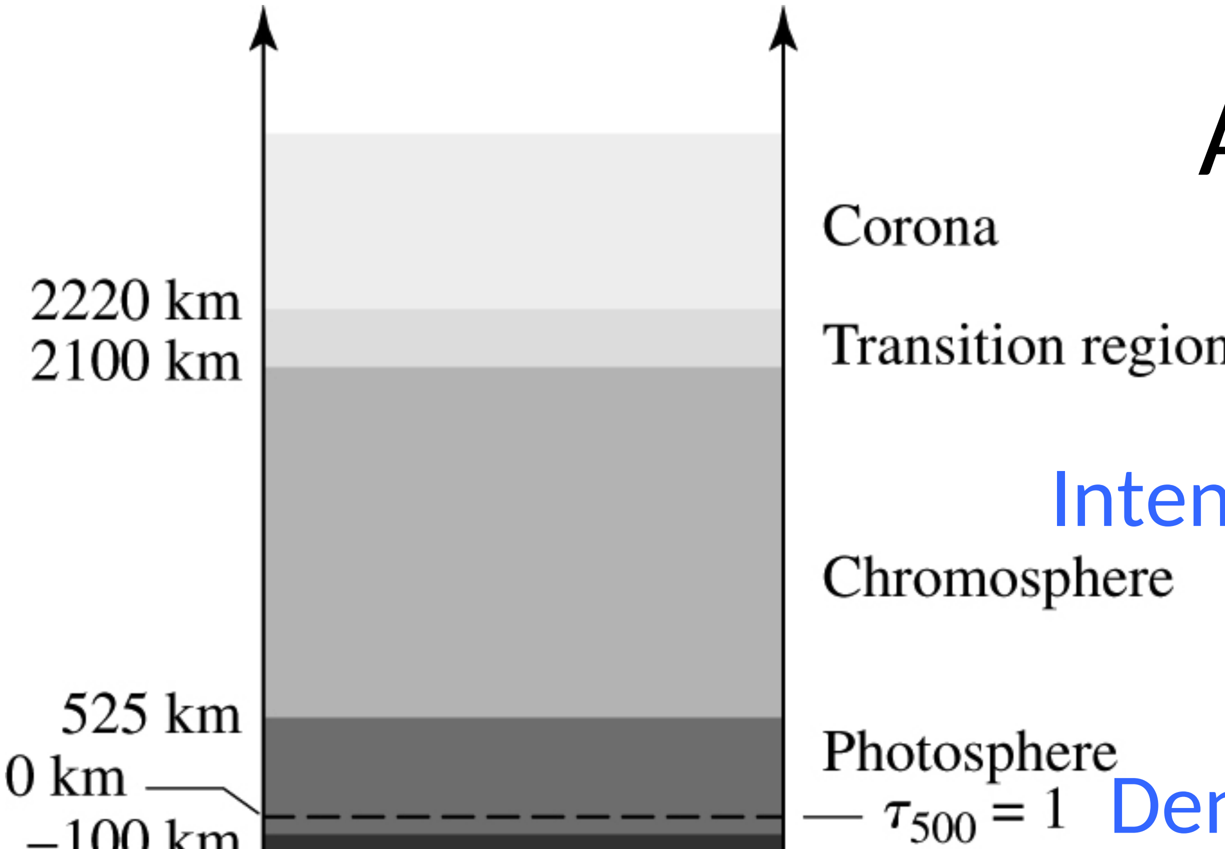


FIGURE 11.16 The rotation period of the Sun varies with latitude and depth. Ω, the angular frequency, has units of radians per second. (Adapted from a figure courtesy of NSF's National Solar Observatory.)

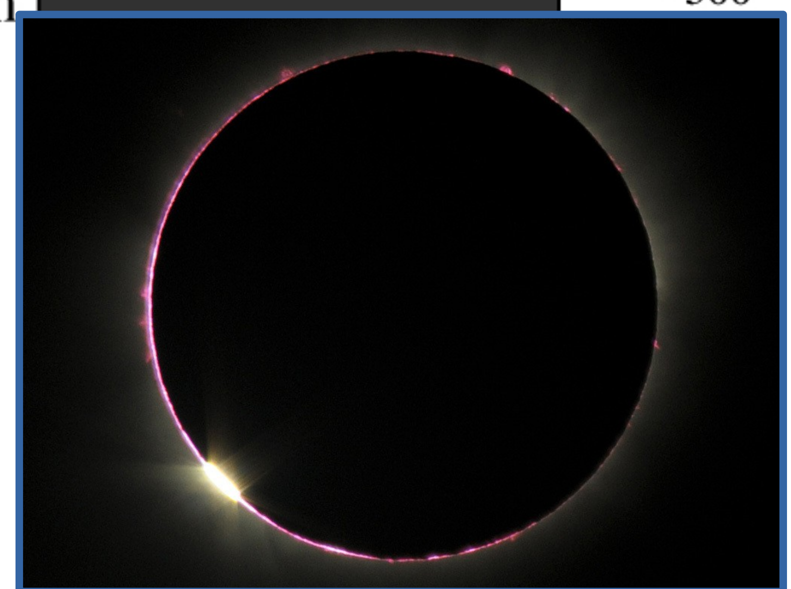
A cromosfera



Intensidade de apenas 10^{-4} da fotosfera

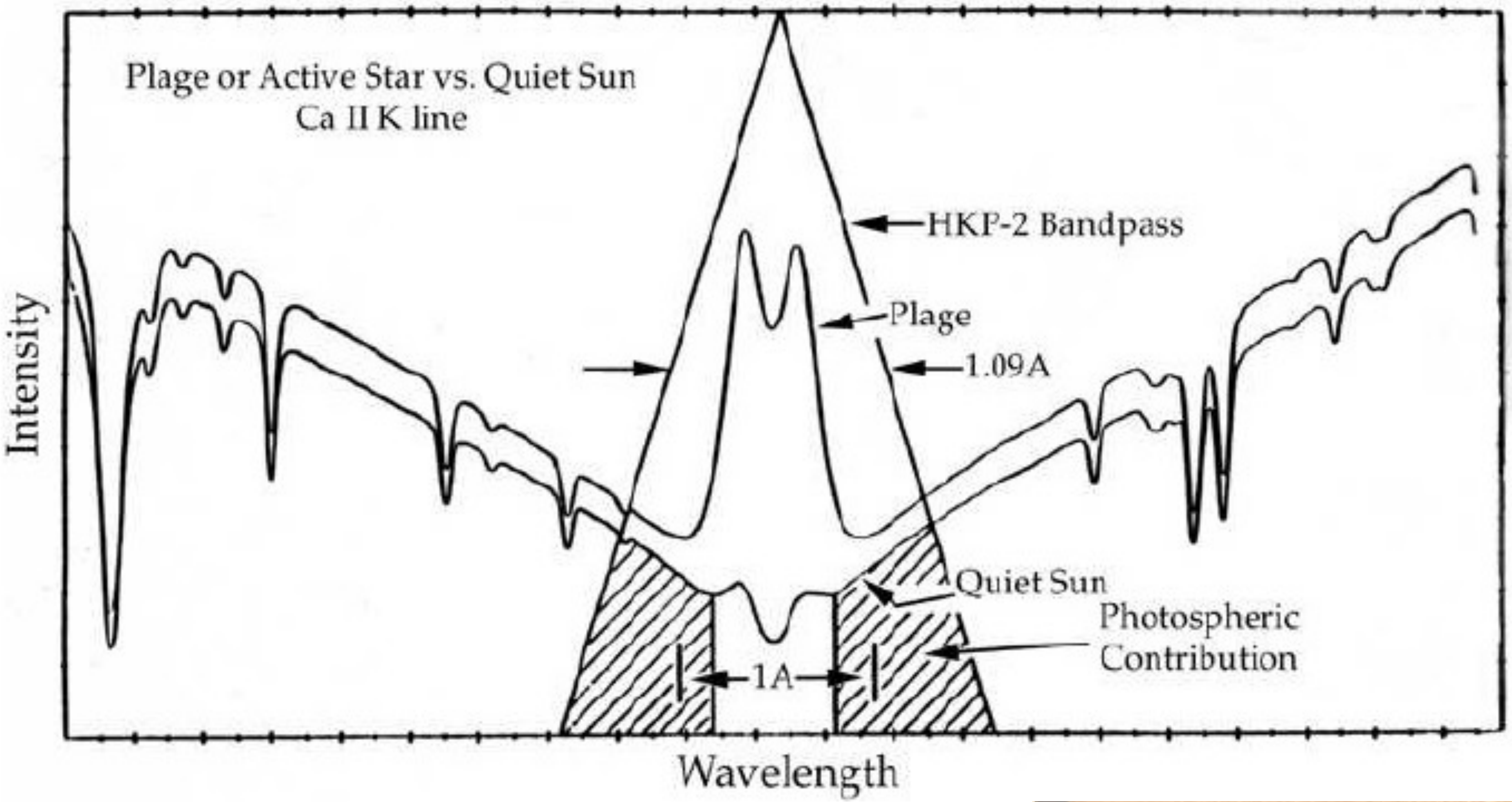
Densidade cai em 10^{4}

Temperatura aumenta de 4400 a 10 000 K

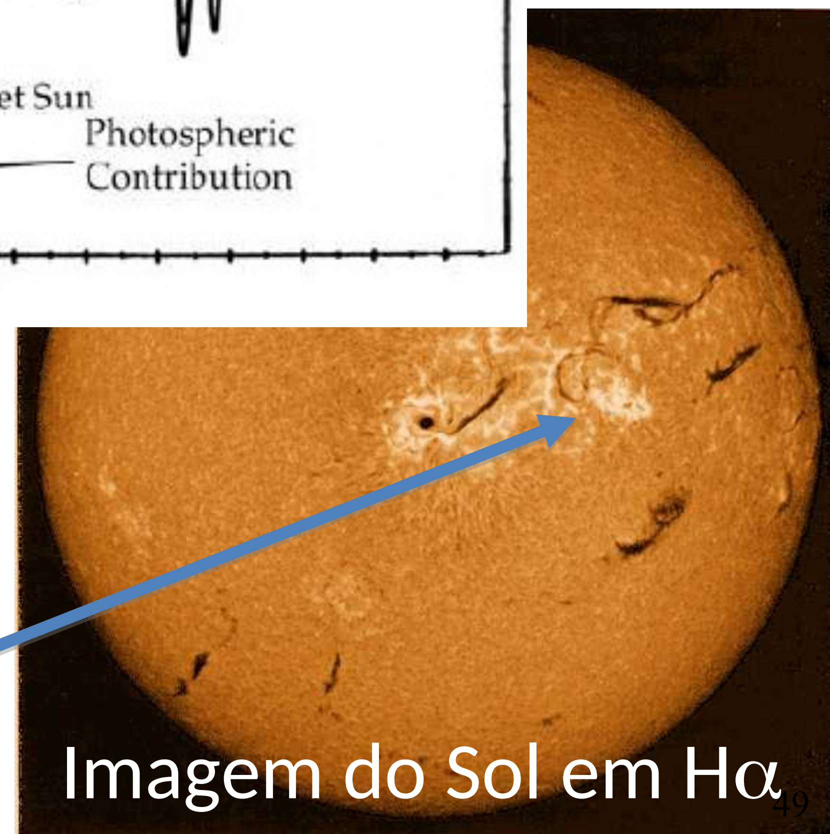


Alson Wong, 3/nov/2013, Uganda

Linha de absorção (fotosfera) e emissão (plage) da linha K do Ca II

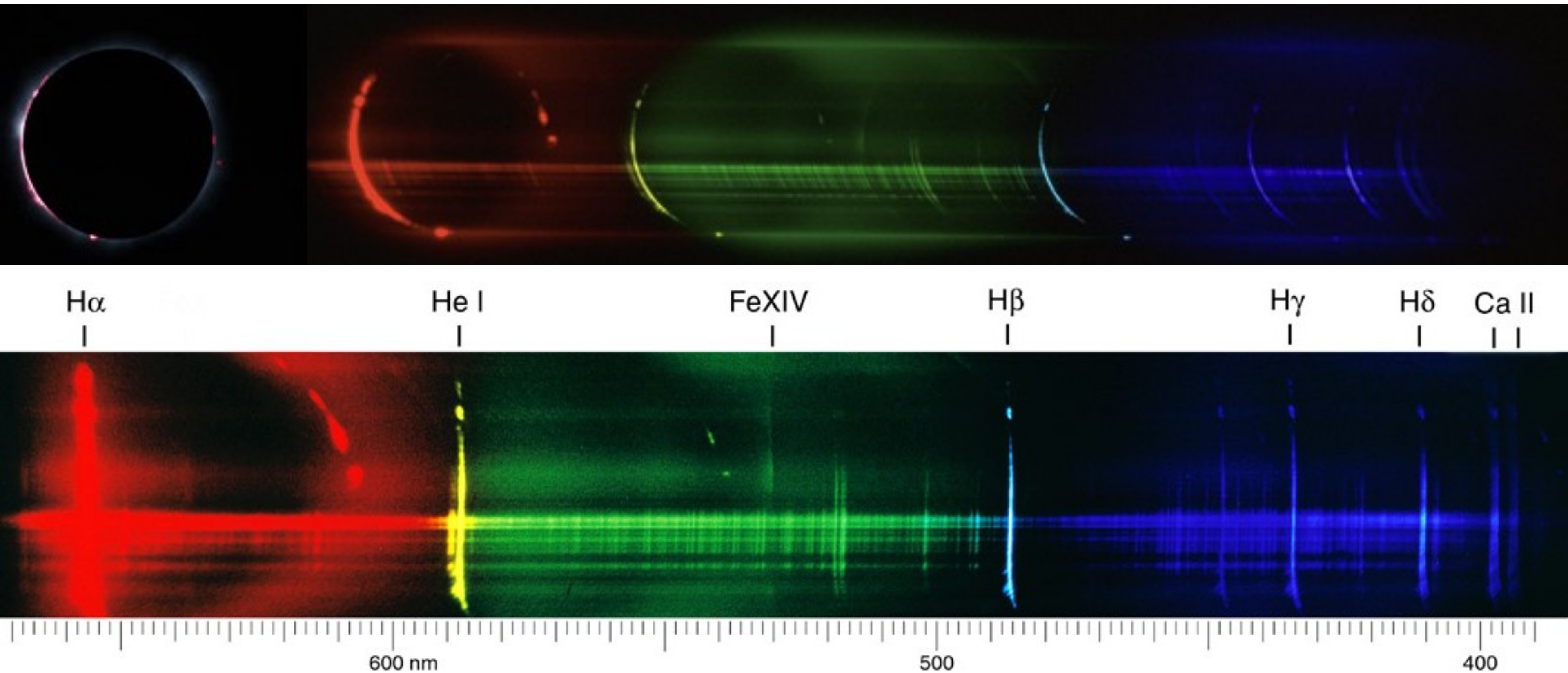


Plage: emissão brilhante na cromosfera



Espectro da cromosfera durante eclipse de 1999 na Hungria

É chamado espectro *flash* pois as linhas de emissão aparecem por apenas alguns segundos



http://www.eurastro.de/webpages/MRSPECT.HTM

O Hélio foi descoberto primeiro no Sol, usando espectros do eclipse solar de 18/8/1868.

Supergranulação no Sol
(“imagens” em datas diferentes)

- Escala horizontal de ~30 000 km
- velocidades r.m.s. 350 m/s horizontal e 25 m/s vertical

Fig. 6 A view of the chromospheric network at the CaII K3 line at 393.37 nm. (c) Meudon Observatory

https://link.springer.com/article/10.1007/s41116-018-0013-5

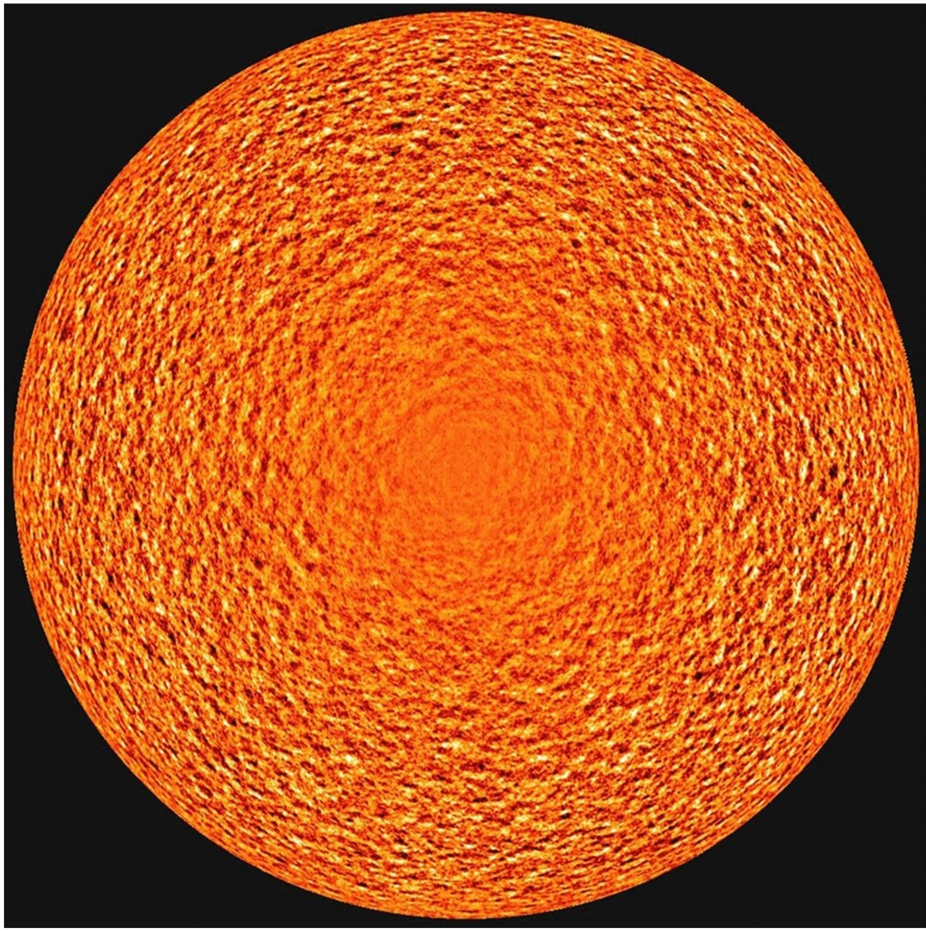
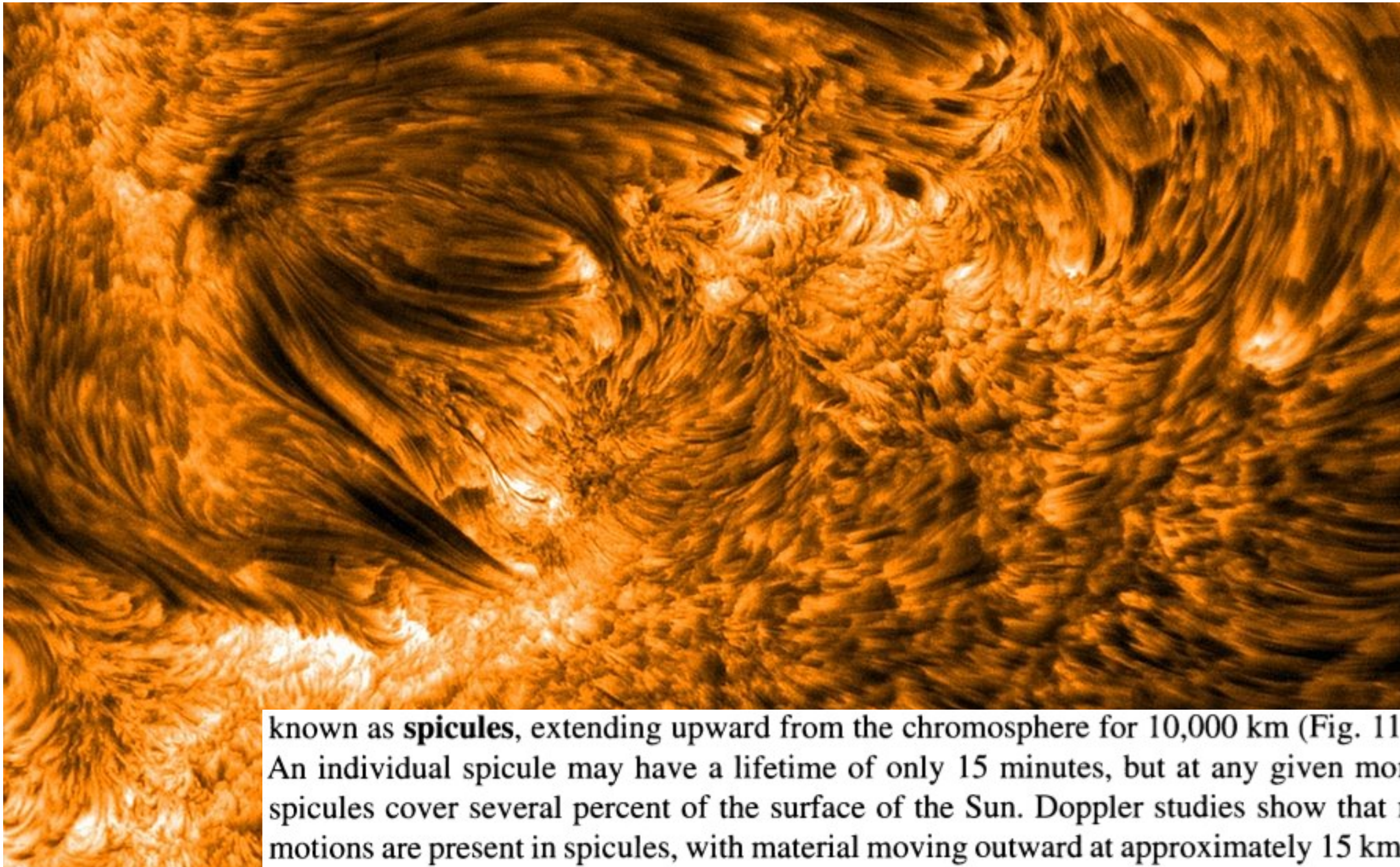


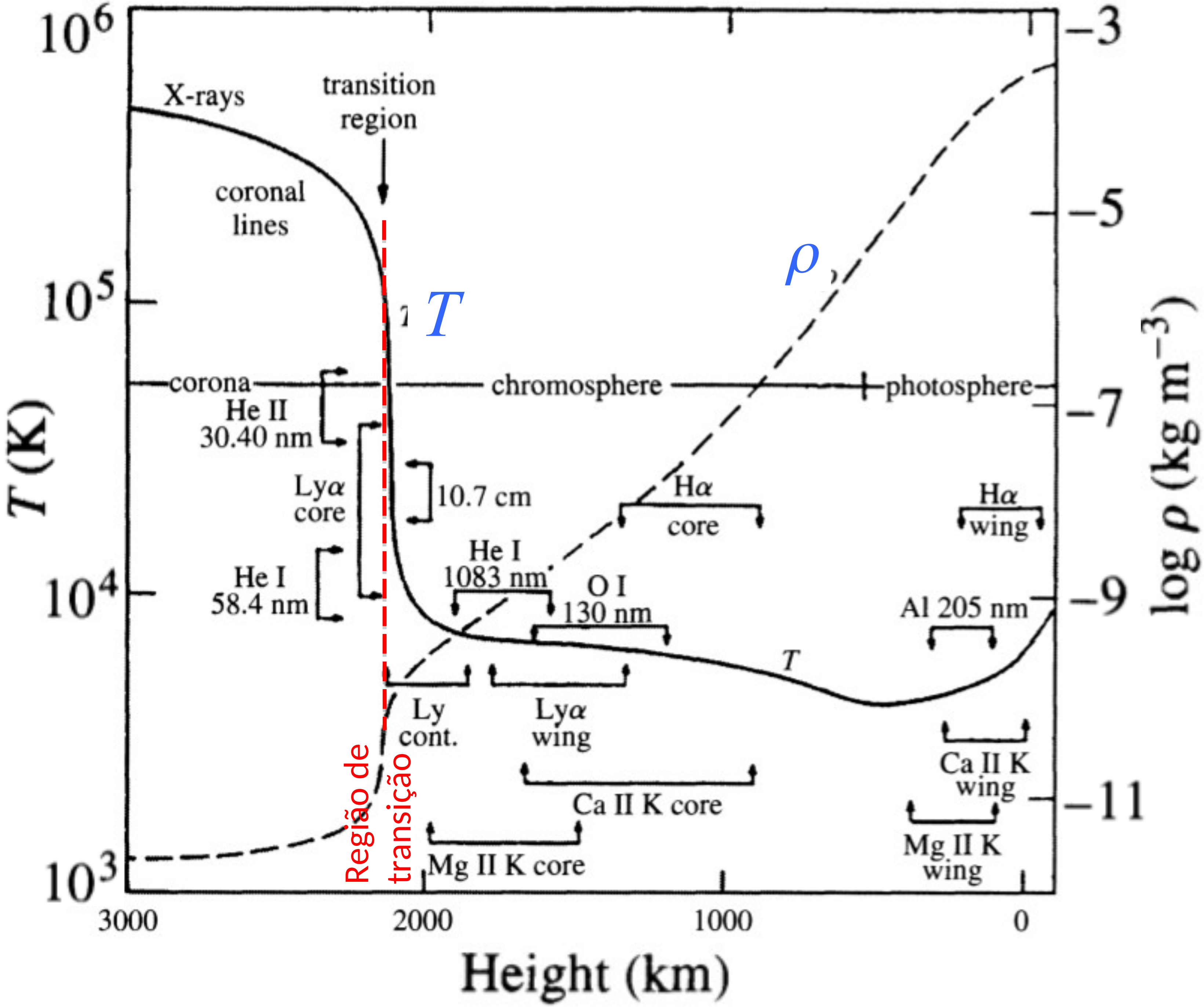
Fig. 1 The supergranulation pattern as revealed by Doppler imaging of the full solar disc obtained with the MDI instrument onboard the SOHO satellite. (c) SOHO/MDI/ESA

Solar active region 10380, in June 2004. Spicules (solar flux tubes) are visible, particularly evident as a carpet of dark tubes on the right. (c) Royal Swedish Academy of Sciences

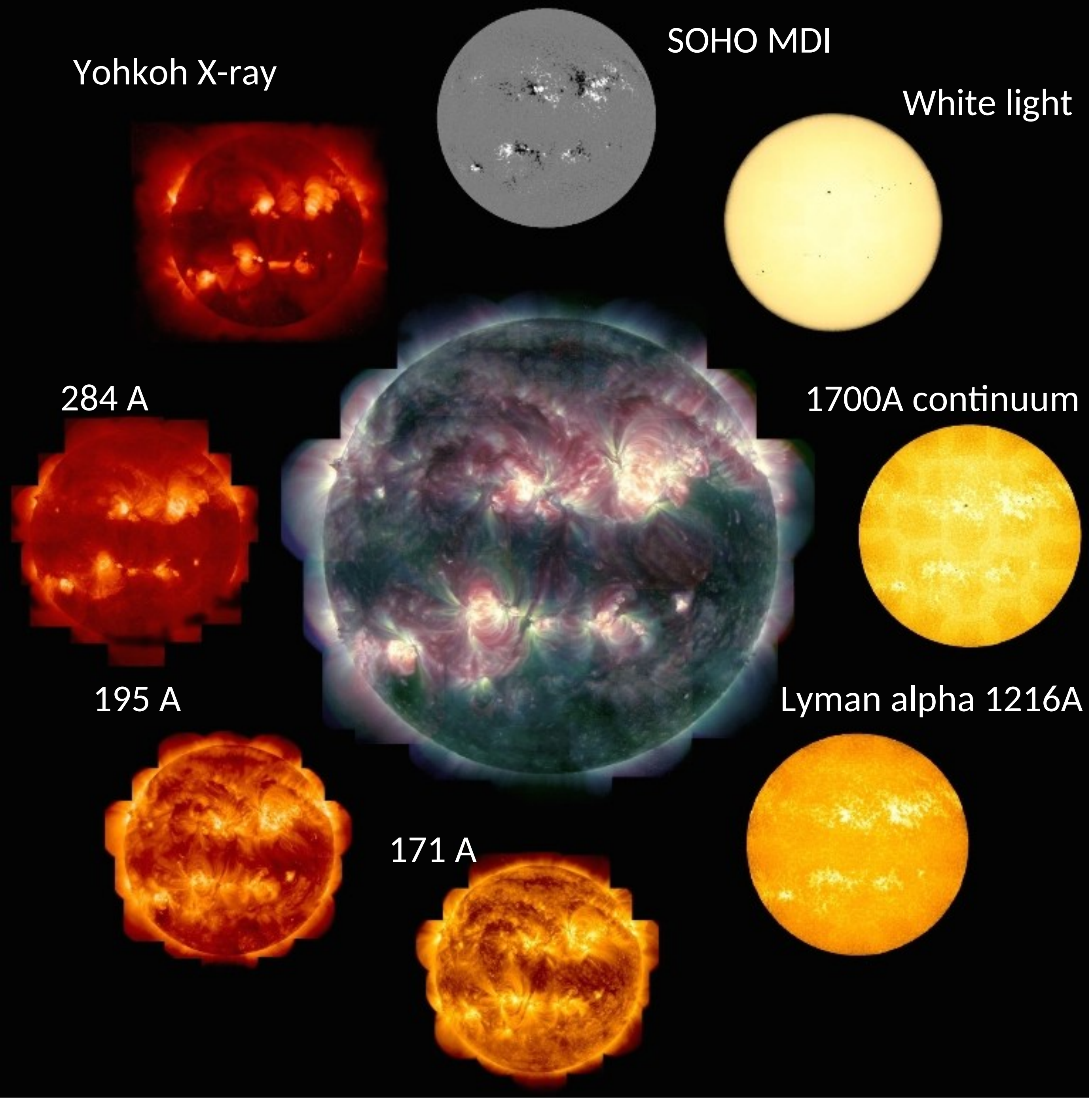


known as **spicules**, extending upward from the chromosphere for 10,000 km (Fig. 11.17). An individual spicule may have a lifetime of only 15 minutes, but at any given moment spicules cover several percent of the surface of the Sun. Doppler studies show that mass motions are present in spicules, with material moving outward at approximately 15 km s^{-1}.

FIGURE 11.17 Spicules in the chromosphere of the Sun. In addition, small sunspots are visible in the upper left quadrant of the image, and brighter areas known as plage regions are also visible. The observations were made using the Hα emission line. Features as small as 130 km are evident in this image. (Courtesy of the Royal Swedish Academy of Sciences.)



X-rays
transition region
coronal lines
T
ρ
corona
chromosphere
photosphere
He II 30.40 nm
Lyα core
10.7 cm
He I 58.4 nm
He I 1083 nm
O I 130 nm
Hα core
Hα wing
Al 205 nm
Ly cont.
Lyα wing
Ca II K core
Ca II K wing
Mg II K core
Mg II K wing
Região de transição
T (K)
log ρ (kg m⁻³)
Height (km)



Looking through the solar atmosphere. The central image is a 3-color composite of the solar corona, with the NASA Transition Region & Coronal Explorer. This mosaic is made up of 3 exposures; the green, blue, and red color tables in this ``true color'' image represent the 171Å (1 MK), 195Å (1.5 MK), and 284Å (2 MK) channels. The surrounding images are, clockwise starting from the top: SOHO/MDI magnetic map, white light, TRACE 1700A continuum,TRACE Lyman alpha, TRACE 171Å, TRACE 195Å, TRACE 284Å, YOHKOH/SXT X-ray image.

http://www.lmsal.com/TRACE/POD/TRACEpodarchive4.html

Coroa solar

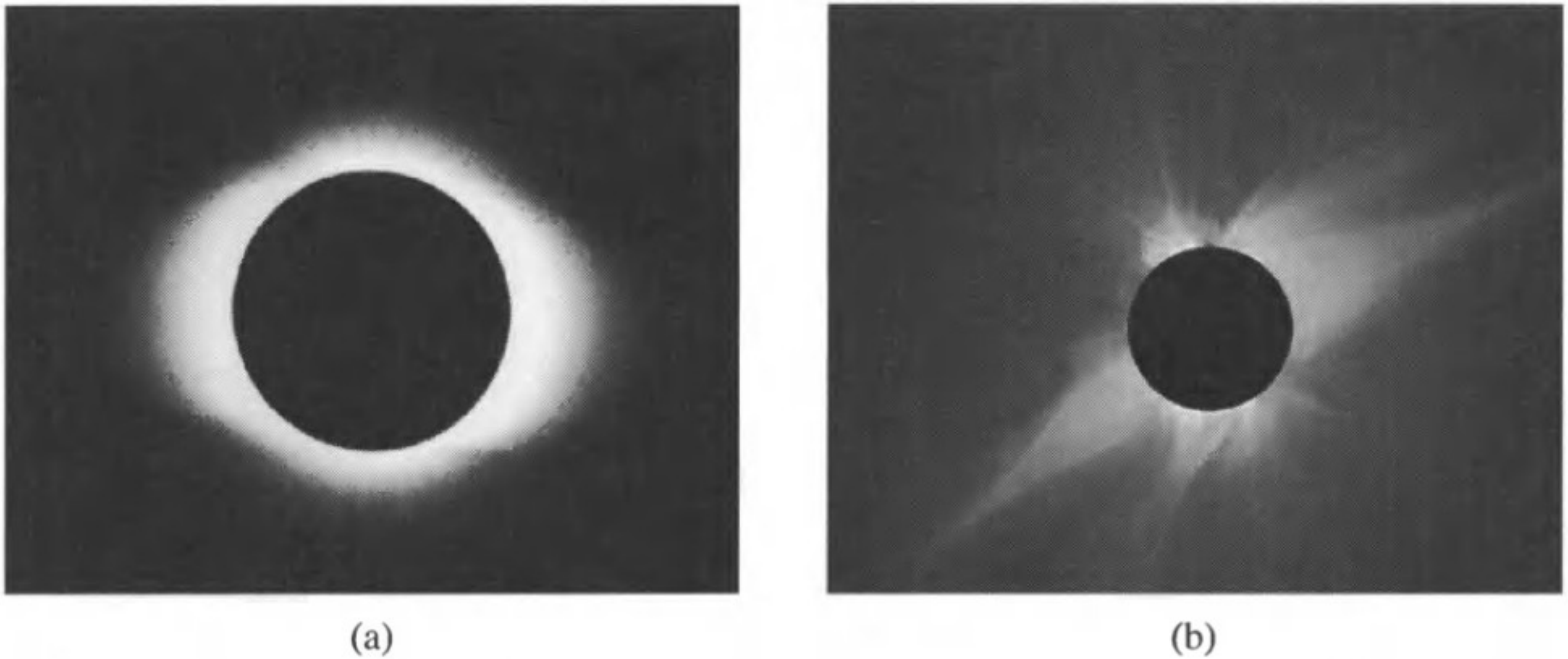


FIGURE 11.20 (a) The quiet solar corona seen during a total solar eclipse in 1954. The shape of the corona is elongated along the Sun's equator. (Courtesy of J. D. R. Bahng and K. L. Hallam.) (b) The active corona tends to have a very complex structure. This image of the July 11, 1991, eclipse is a composite of five photographs that was processed electronically. (Courtesy of S. Albers.)


(c) Jorge Meléndez, 2/jul/2019, Incahuasi, Deserto do Atacama, Chile

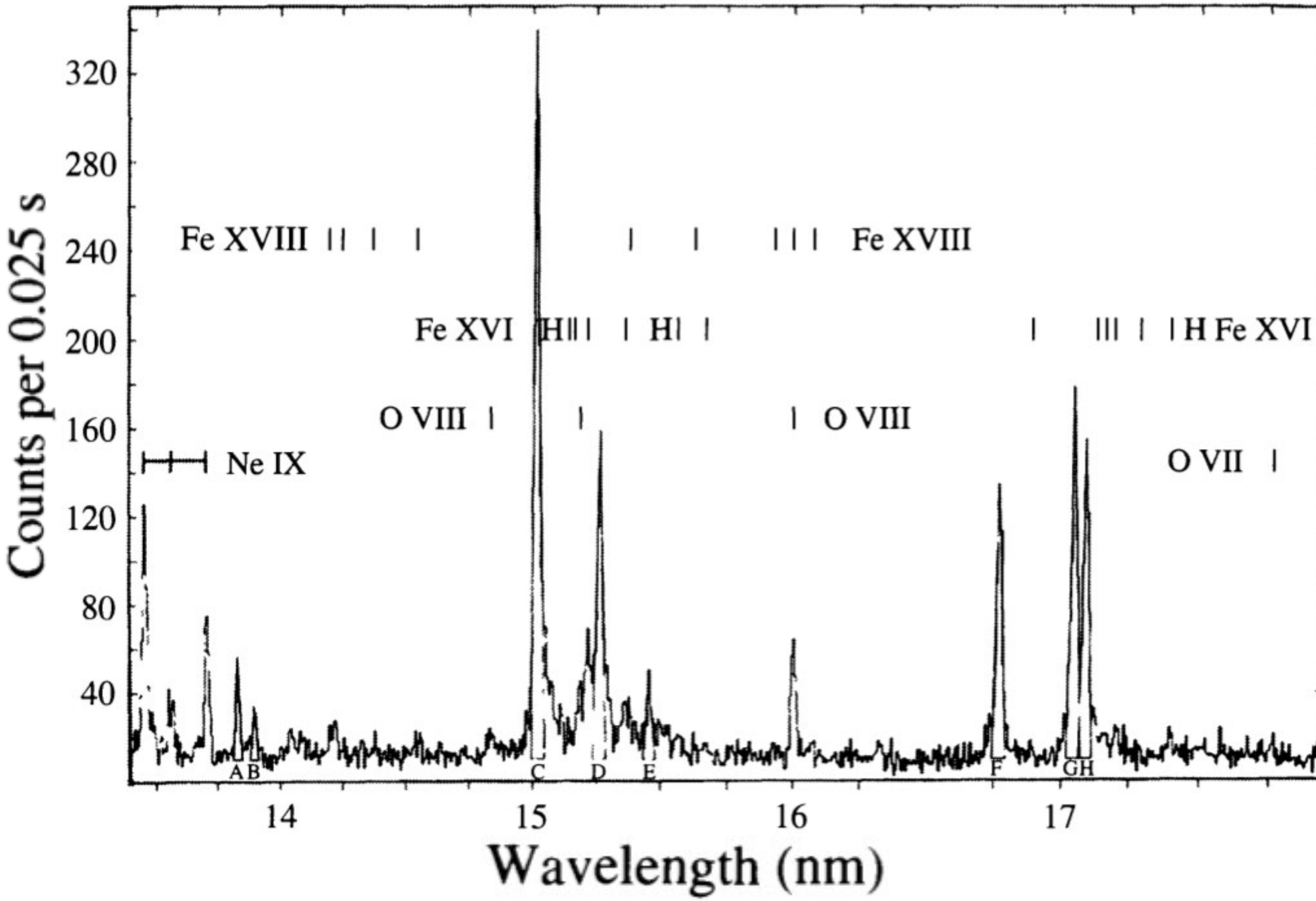
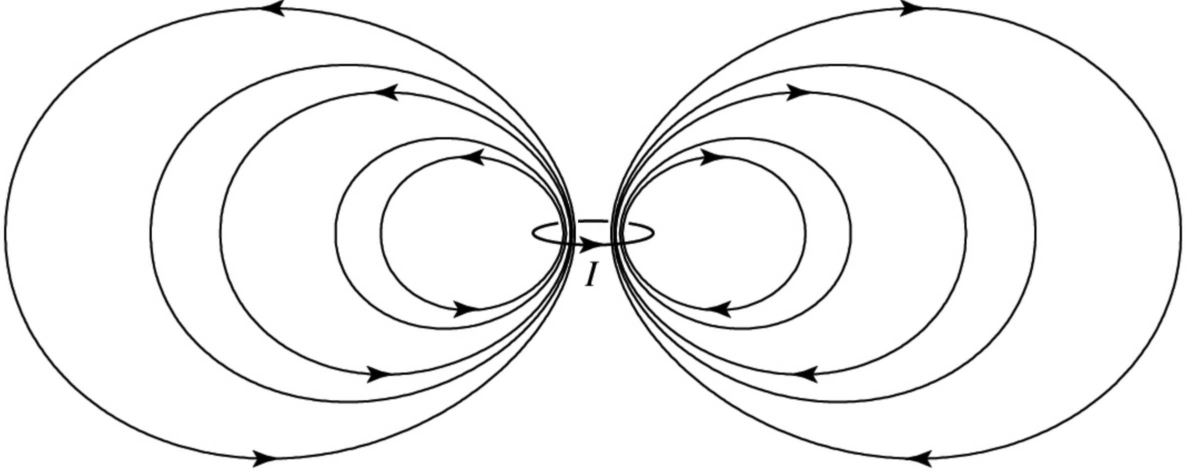
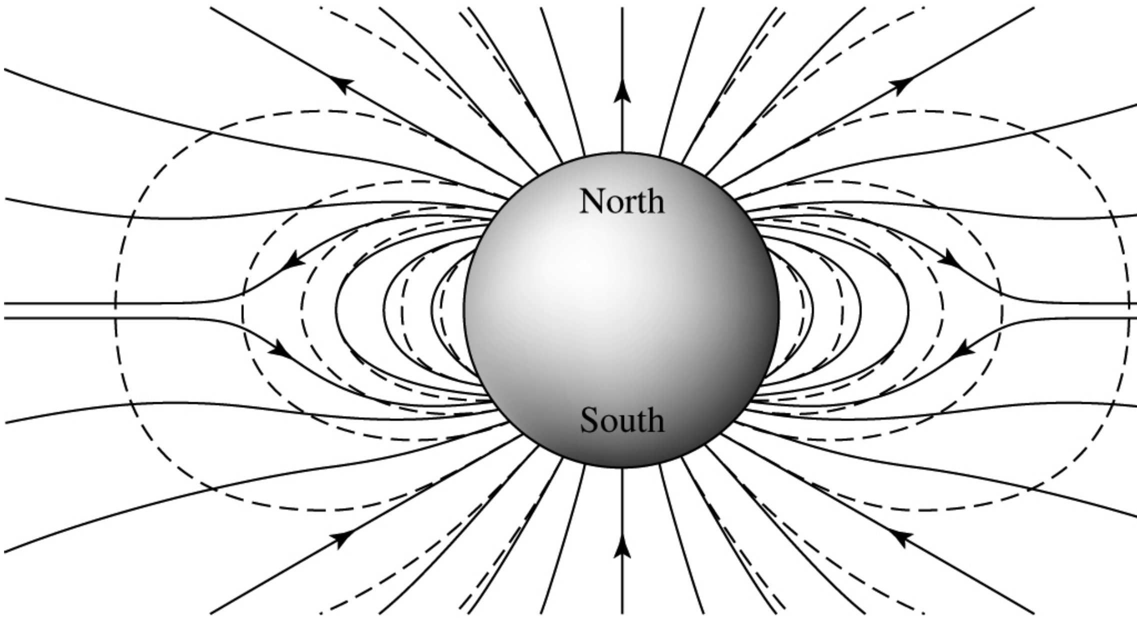


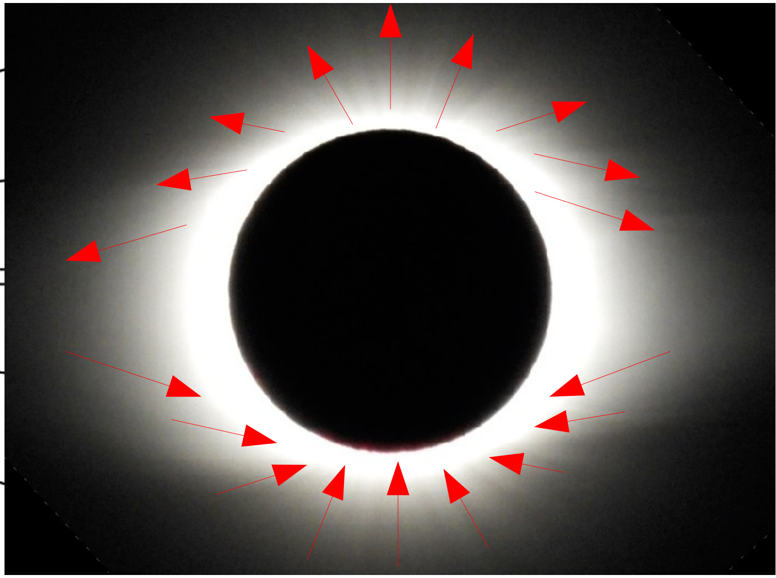
FIGURE 11.21 A section of the X-ray emission spectrum of the solar corona. (Figure adapted from Parkinson, *Astron. Astrophys.*, *24*, 215, 1973.)



(a)

(c) Jorge Meléndez, 2/Jul/2019

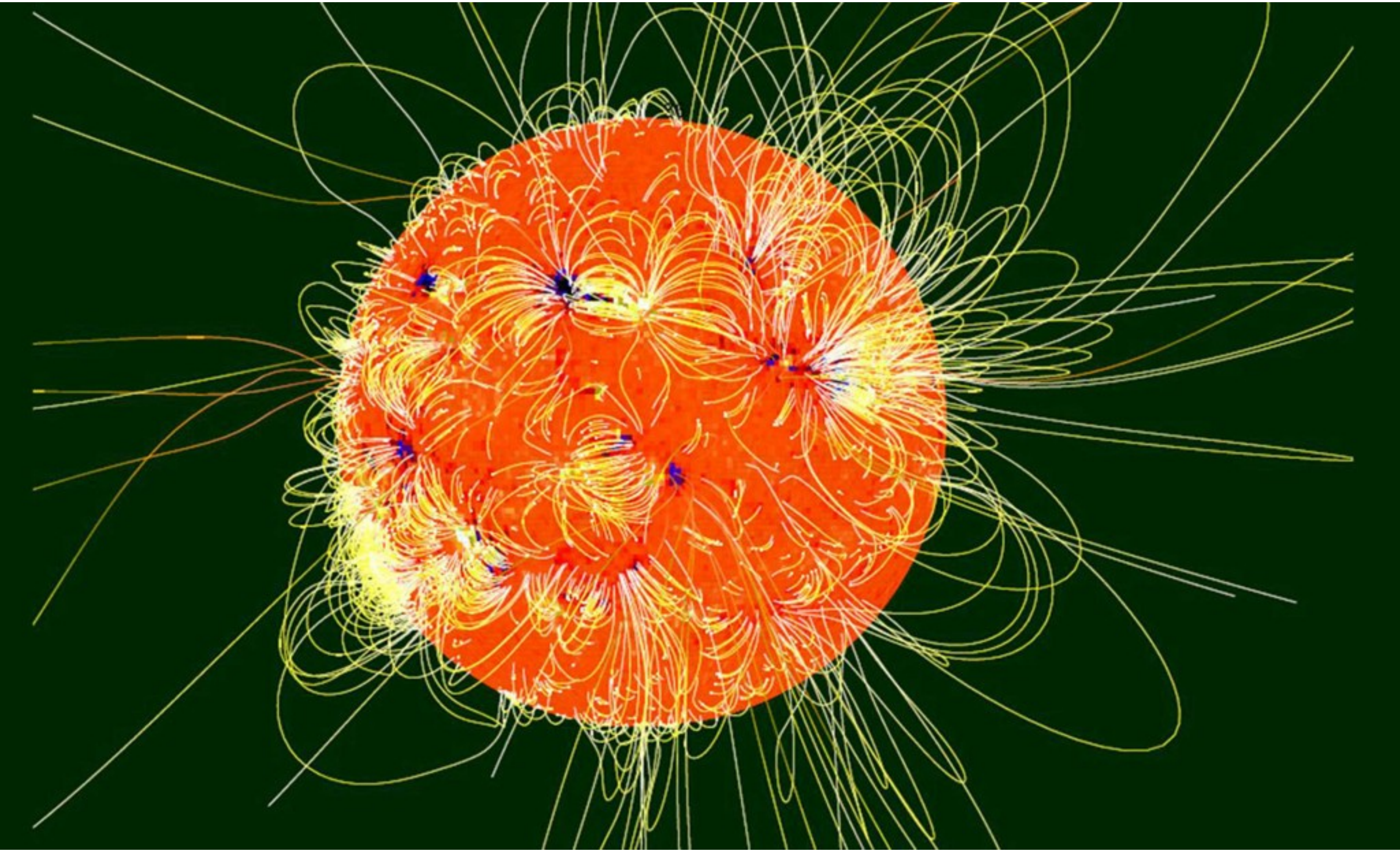




(b)

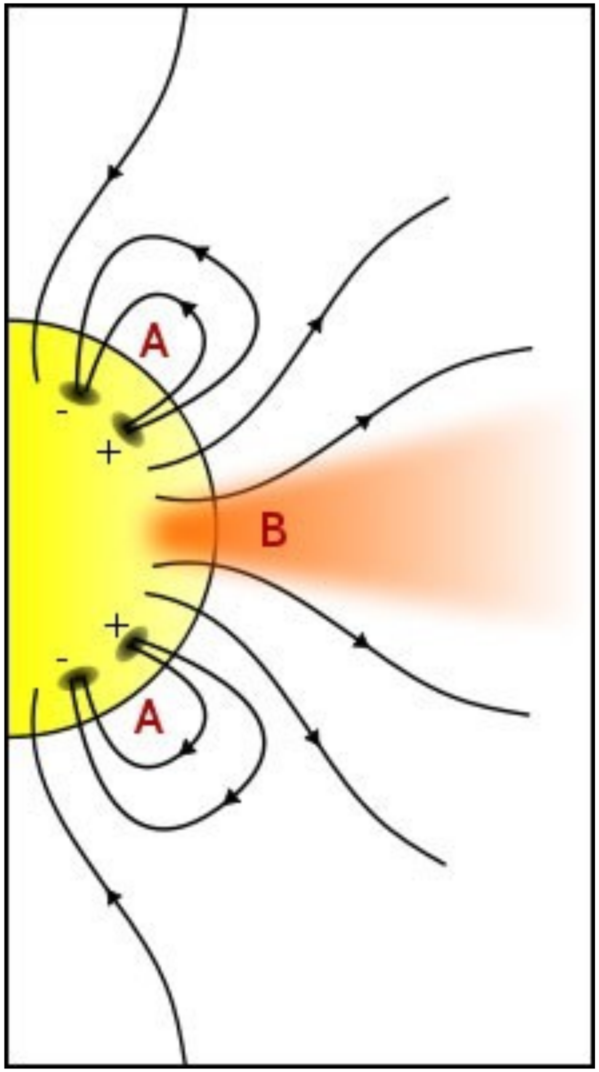
FIGURE 11.23 (a) The characteristic dipole magnetic field of a current loop. (b) A generalized depiction of the global magnetic field of the Sun. The dashed lines show the field of a perfect magnetic dipole.

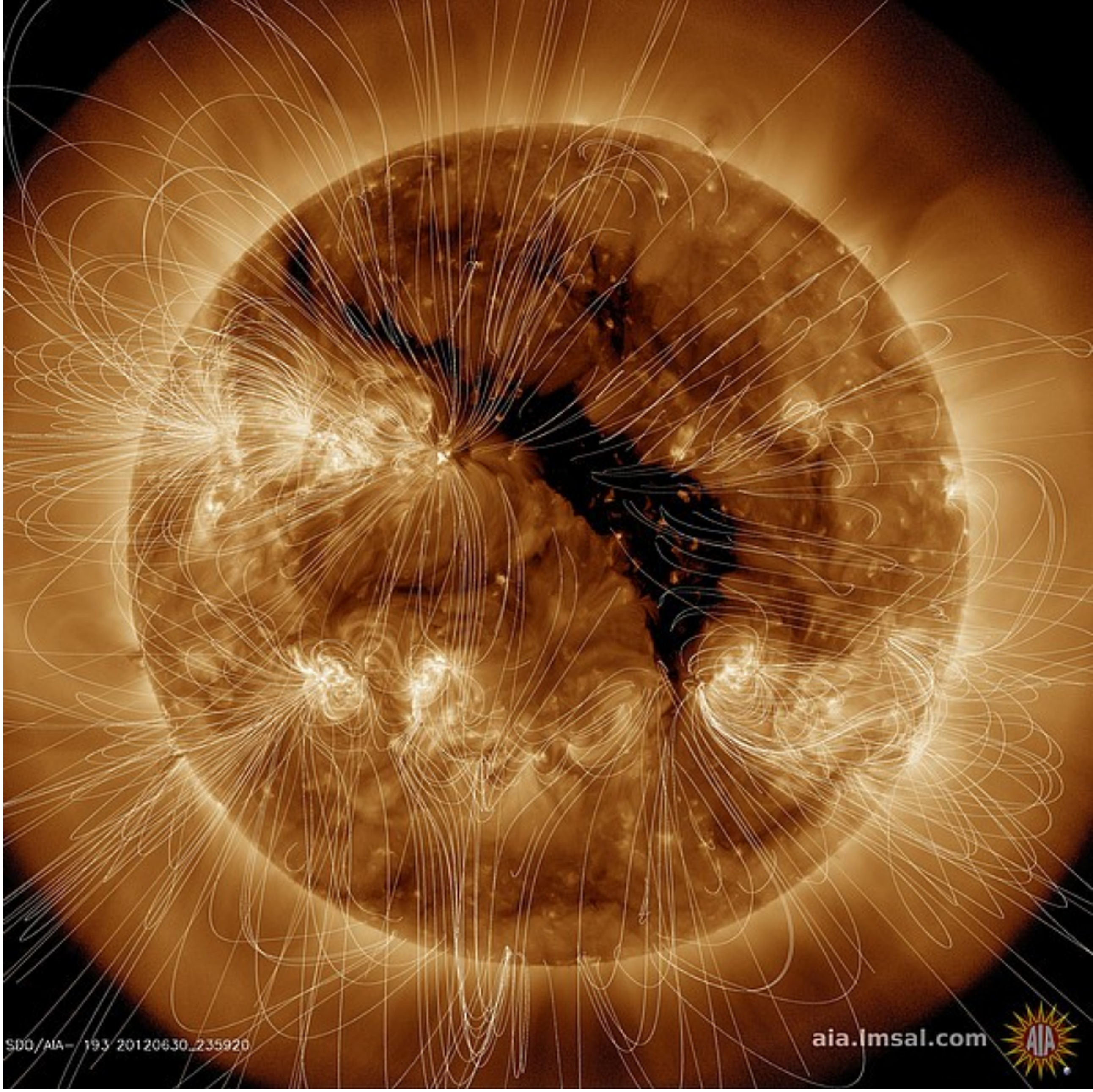
Reconstrução do campo magnético coronal



https://www2.mps.mpg.de/de/projekte/solar-corona3d/index_print.html

Coronal holes
fast solar wind





https://physik.uni-graz.at/en/astrophysics/research/solar-and-heliospheric-physics/coronal-holes-and-their-relation-to-the-solar-wind/

Equação de força de Lorentz:

$$\mathbf{F} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

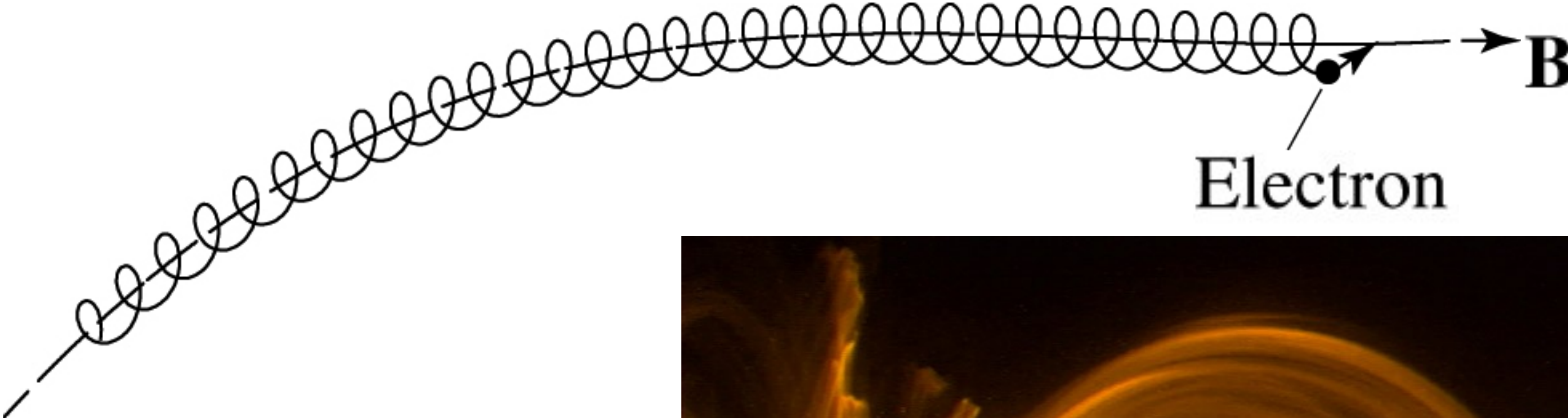
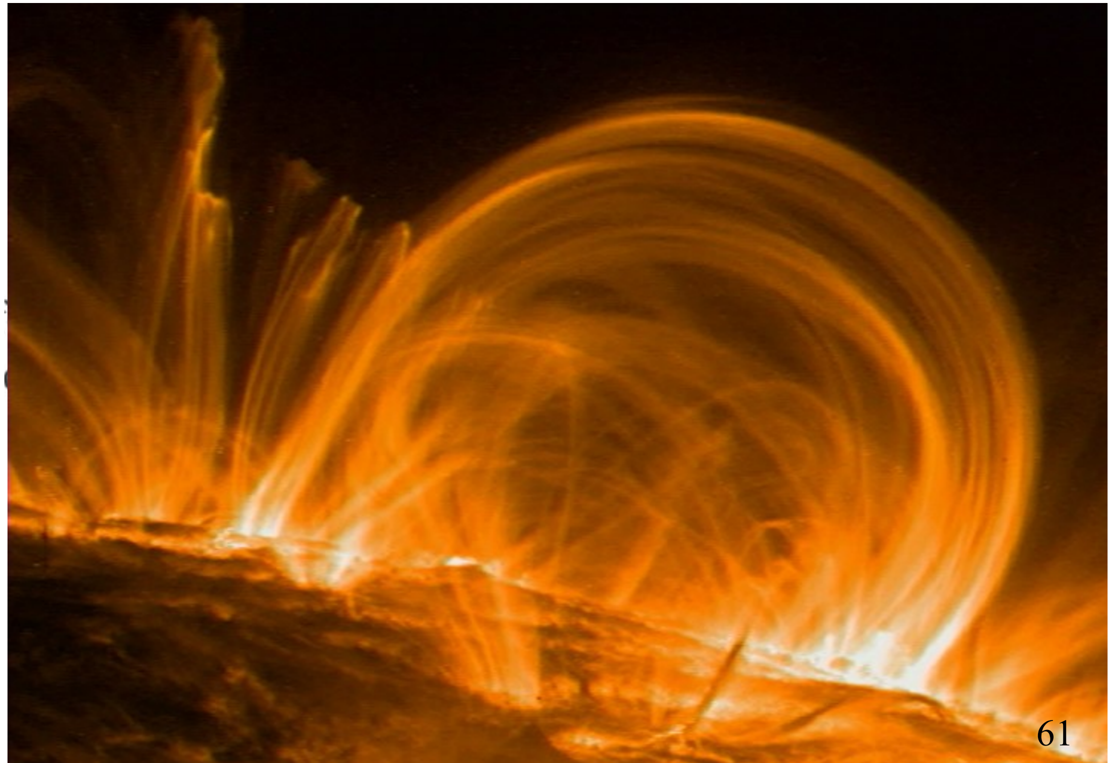
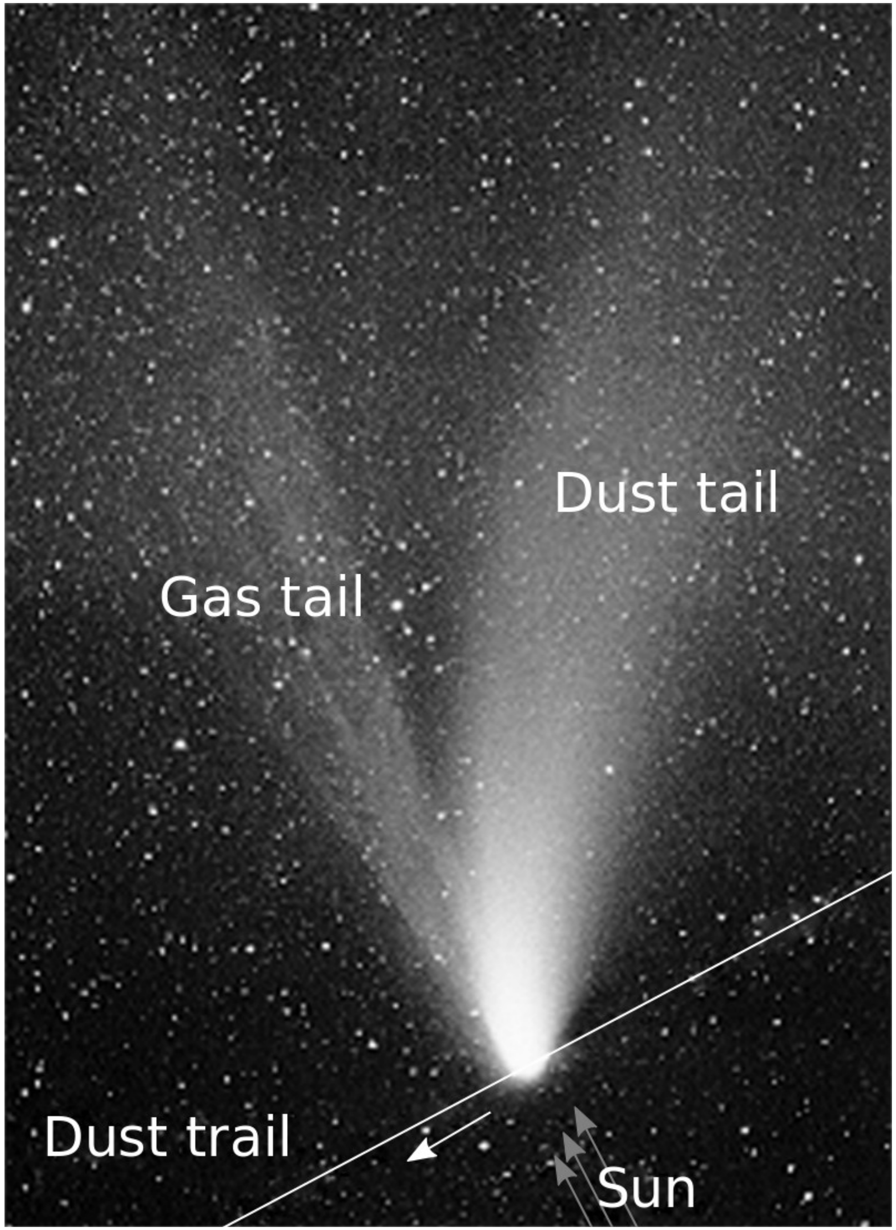


Fig. 11.24. A charged particle is forced to spiral around a magnetic field line because the Lorentz force is mutually perpendicular to both the velocity of the particle and the direction of the magnetic field





Proximidade Sol: liberação de partículas.

Radiação solar: dust tail (reflete a luz do Sol)

Vento solar (partículas) interage com partículas do cometa ionizadas pela radiação UV do Sol

Evidência de vento solar: *ion tail* em cometas

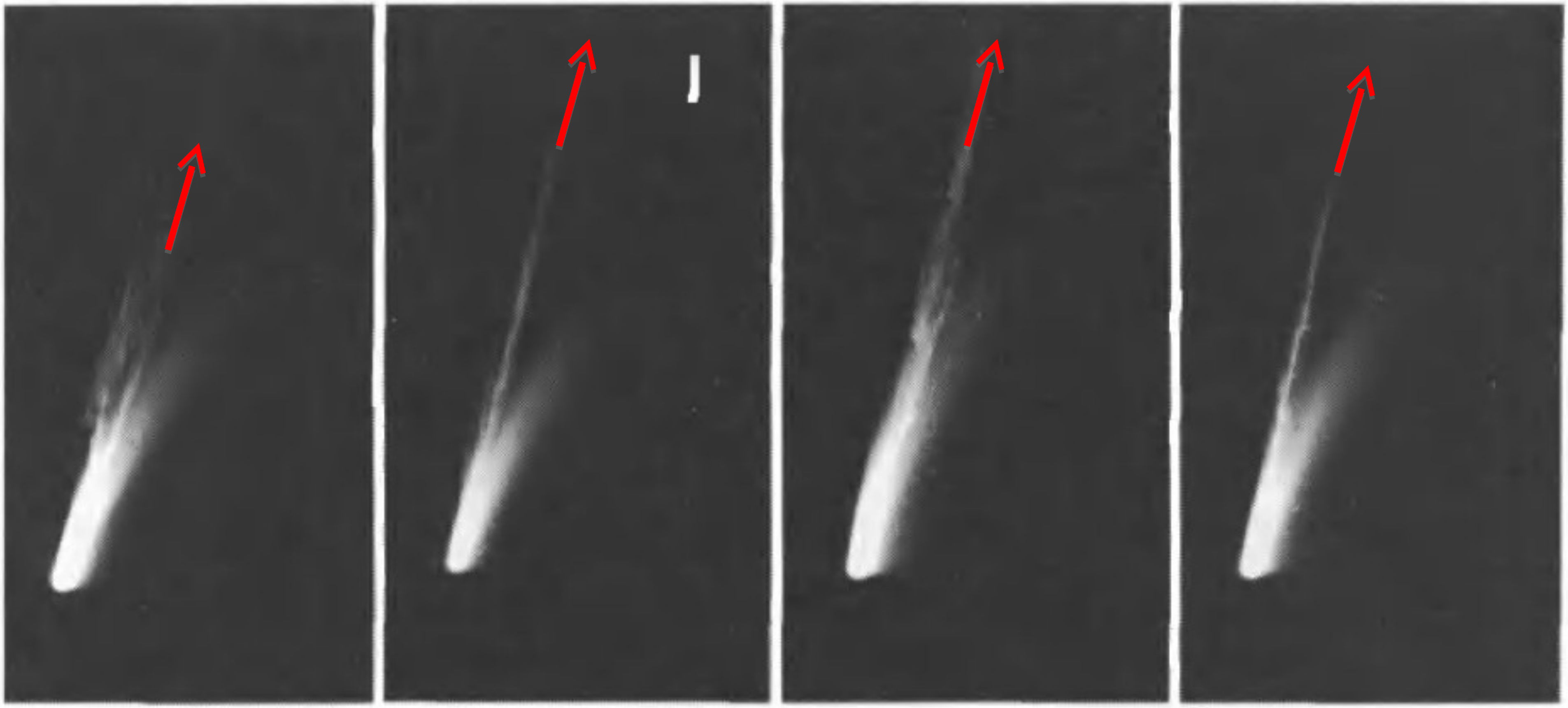
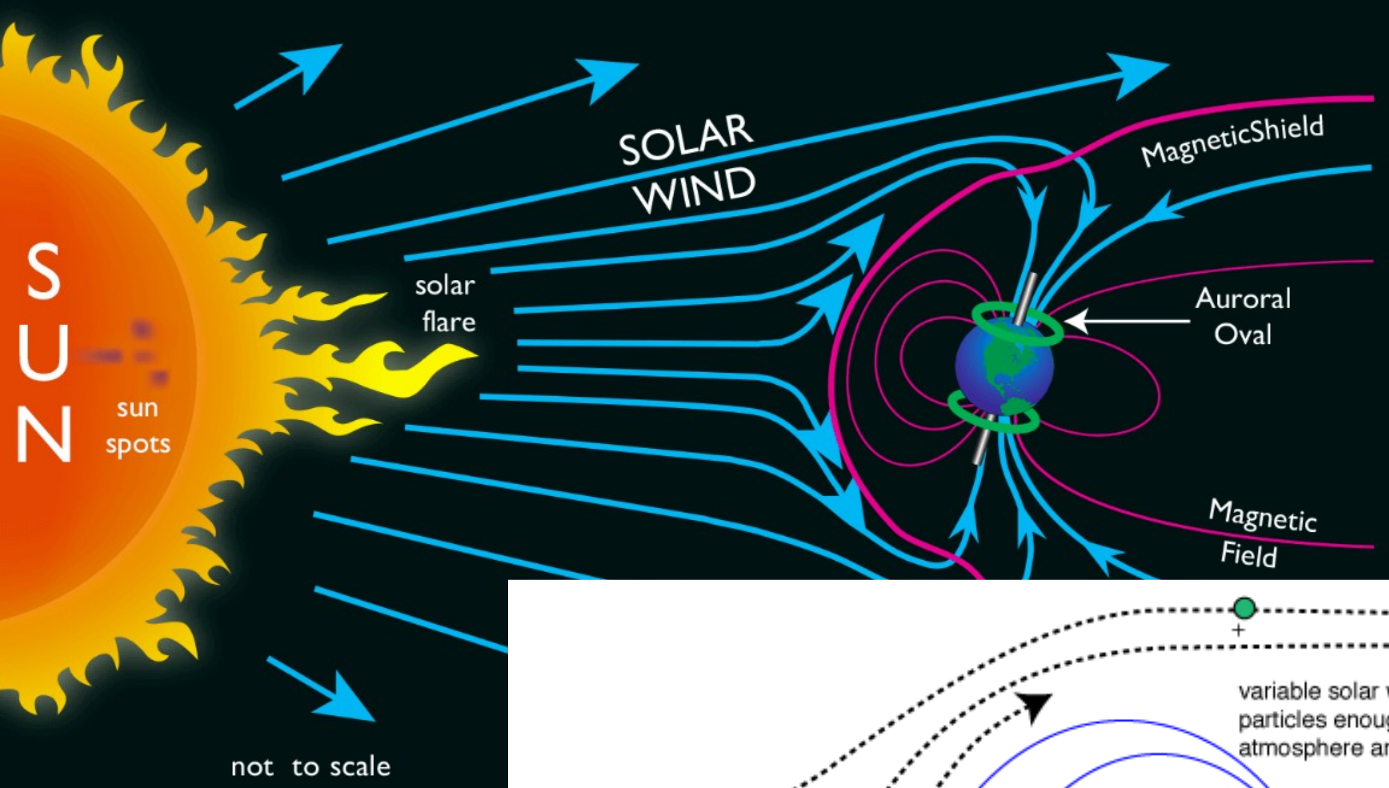
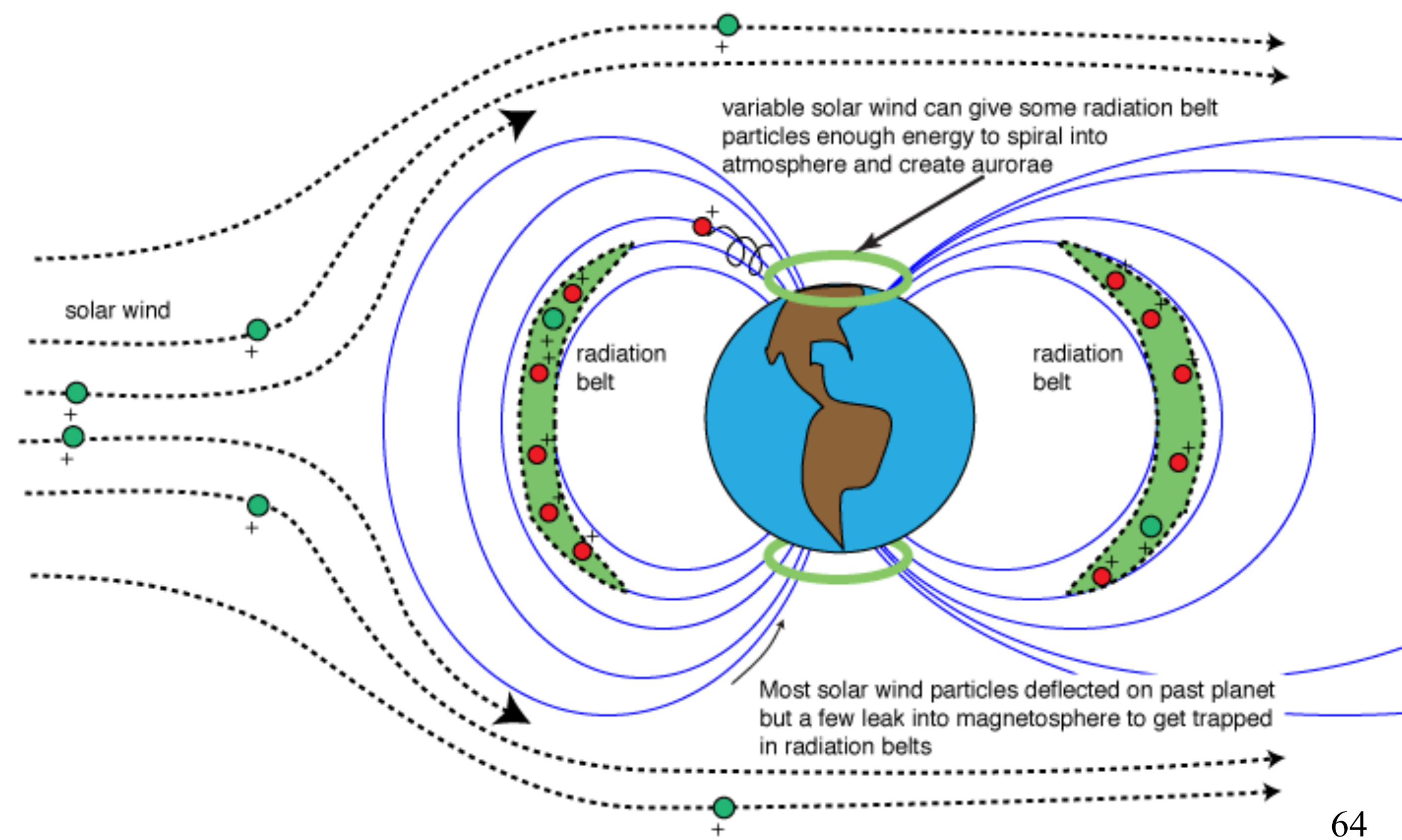


FIGURE 11.25 Comet Mrkos in 1957. The dust tail of a comet is curved and its ion tail is straight. (Courtesy of Palomar/Caltech.)

Vento solar: Auroras






Suécia
Aurora em Kiruna, 28/2/2019
(c) Mia Stålnacke


Noruega
www.arcticphoto.no 1/2012

Medições do vento solar a 1 U.A.

- velocidade v ~ 500 km/s (de 200 km/s a 750 km/s)

- densidade de 7×10^6 íons / m^3

- temperaturas cinéticas de 4×10^4 K para prótons e 10^5 K para elétrons

- composição: principalmente prótons e elétrons, uma fração de partículas α (núcleos de He) e uma quantidade pequena de íons mais pesados

Example 11.2.1. The mass loss rate of the Sun may be estimated from the data given above. We know that all of the mass leaving the Sun must also pass through a sphere of radius 1 AU centered on the Sun; otherwise it would collect at some location in space. If we further assume (for simplicity) that the mass loss rate is spherically symmetric, then the amount of mass crossing a spherical surface of radius r in an amount of time t is just the mass density of the gas multiplied by the volume of the shell of gas that can travel across the sphere during that time interval, or

$$dM = \rho\, dV = (n m_H)(4\pi r^2 v\, dt)$$

where n is the number density of ions (mostly hydrogen), m_H is approximately the mass of a hydrogen ion, v is the ion velocity, and $dV = A\,dr \simeq 4\pi r^2 v\, dt$ is the volume of a shell that crosses a spherical surface in an amount of time dt. Dividing both sides by dt, we obtain the mass loss rate,

$$\frac{dM}{dt} = 4\pi r^2 n m_H v = 4\pi r^2 \rho v \qquad (11.3)$$

By convention, stellar mass loss rates are generally given in *solar masses per year* and symbolized by $\dot{M} \equiv dM/dt$. Using $v = 500\ \mathrm{km\ s^{-1}}$, $r = 1$ AU, and $n = 7 \times 10^6$ protons $\mathrm{m^{-3}}$, we find that

$$\dot{M}_\odot \simeq 3 \times 10^{-14}\ \mathrm{M_\odot\ yr^{-1}}$$

A rotação do Sol cria uma estrutura espiral no campo magnético solar no meio interplanetário. Torque (atrito) faz o Sol mais lento

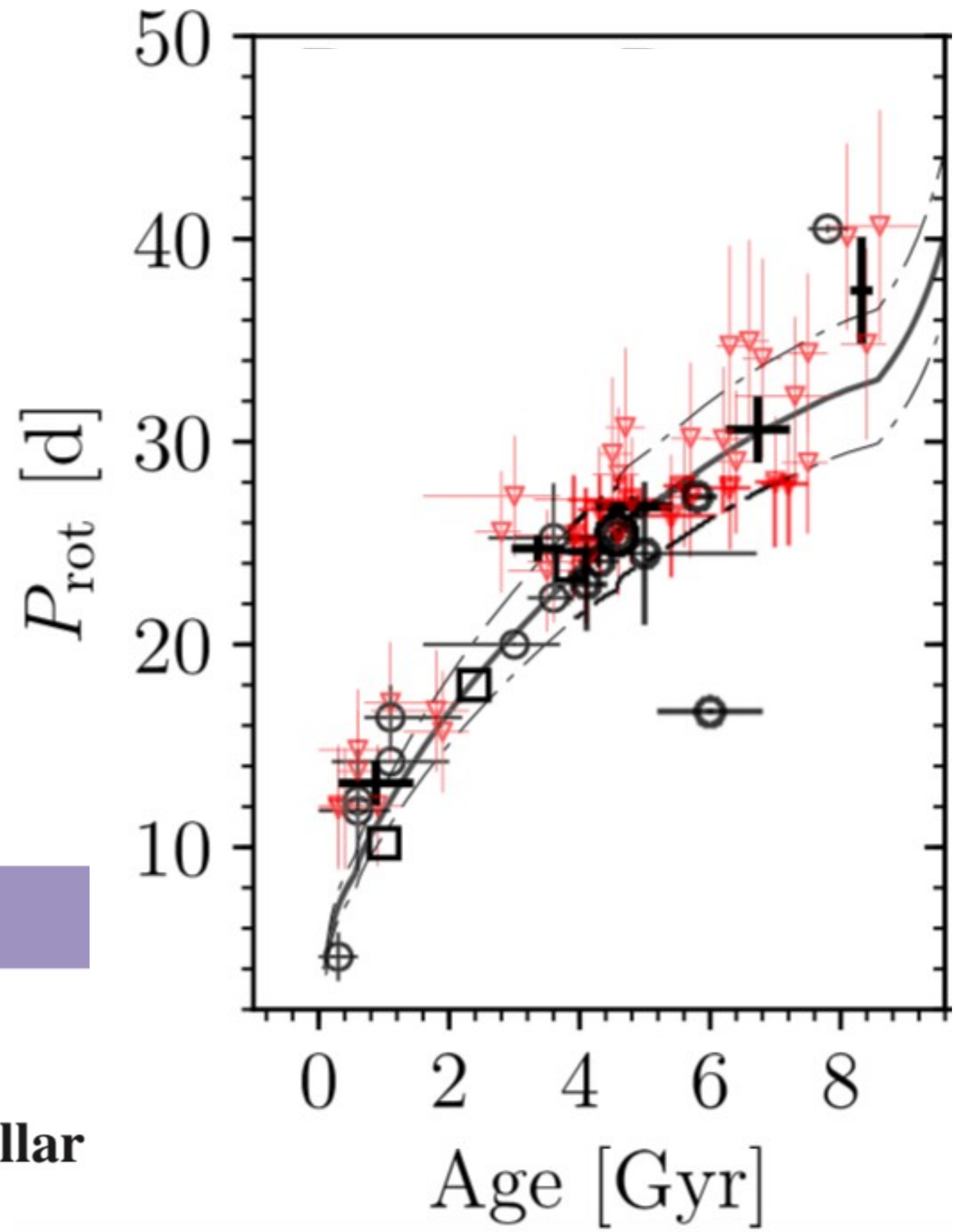
→ girocronologia

Espiral de Parker

FIGURE 11.27 The Sun's rotation creates a spiral pattern in the solar magnetic field in interplanetary space, known as the Parker spiral. The drag produced by the spiraling magnetic field causes angular momentum to be transferred away from the Sun. This diagram shows the heliospheric current sheet that separates regions of space where the magnetic field points toward or away from the Sun. The orbits of the planets out to Jupiter are depicted. (Courtesy of Prof. John M. Wilcox and NASA artist Werner Heil.)

A evolução do período de rotação do Sol e estrelas gêmeas solares

A rotação pode ser usada para estimar a idade das estrelas!



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **485,** L68–L72 (2019)
Advance Access publication 2019 March 19

Constraining the evolution of stellar rotation using solar twins

Diego Lorenzo-Oliveira,[1★] Jorge Meléndez,[1] Jhon Yana Galarza,[1] Geisa Ponte,[2] Leonardo A. dos Santos,[3] Lorenzo Spina,[4] Megan Bedell,[5] Iván Ramírez,[6] Jacob L. Bean[7] and Martin Asplund[8]

NASA's Parker Solar Probe: Humanity's First Visit to a Star (~10 $R_\odot$), 2018 - 2025