GEO-DEEP9509

The Sun and stars

Image: M. Kornmesser, spaceengine.org/ESO

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2022

Introduction

What is a star?

- We define a star as an **astronomical object** that
  1. consists of **gas** that is (partially) ionised (plasma) and
  2. is held together and formed into a sphere due to its **own gravity** and
  3. is **luminous** and
  4. releases energy due to **nuclear fusion** in its interior.
- Important: A star is **shining** by itself!
  ➡ An energy source is required.
  ➡ Brown Dwarfs satisfy the three first criteria but not #4 (no (hydrogen) fusion in their cores)

Stars in the sky – Distances and apparent sizes

The distance to the Sun

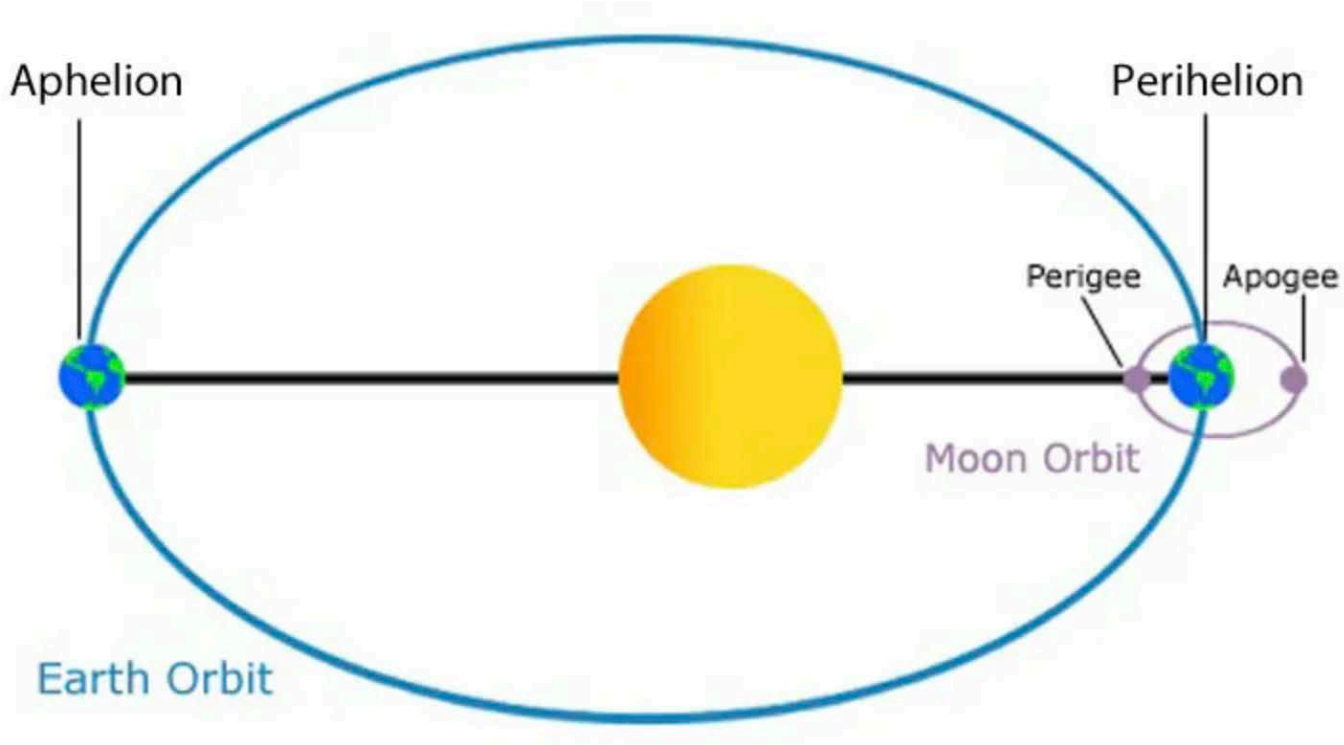
- Average distance to the Sun is defined as **one astronomical unit**

$$1\,\text{AU} = 149597870700\ \text{m}$$

- Easier to remember: **1 AU ≈ 150 × 10⁶ km**.

- Light needs **~ 8 min** from the Sun's surface to Earth's orbit

- **Earth's orbit** is not a perfect circle, **varies** by about 3% during the year
  - Maximum distance (aphelion): 152.1×10^6 km
  - Minimum distance (perihelion): 147.1×10^6 km



Aphelion versus Perihelion. (Orbits exaggerated). Image credit: NOAA/NASA.

Stars in the sky – Distances and apparent sizes

Parallax

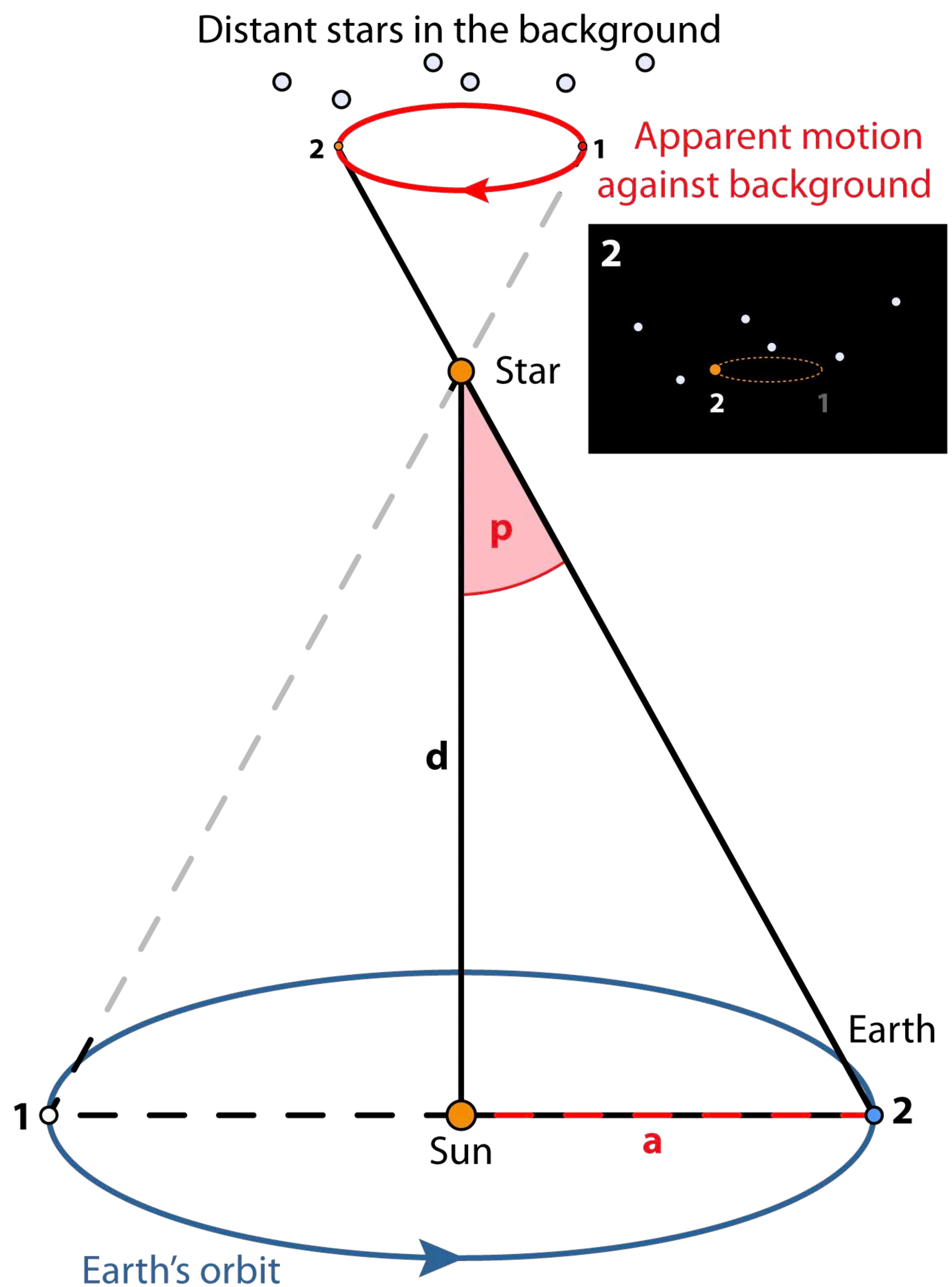
- Star closer to us seen at different angle against more distant stars during the course of a year.

➡ A star seems to be displaced periodically with respect to other stars.

- Caused by motion of the Earth around the Sun.

- Measuring the “displacement angle” accurately allows for **determination of the star’s distance d**

$$p = \tan\frac{a}{d} \quad \Rightarrow \quad p \approx \frac{1\,\mathrm{AU}}{d}$$



Stars in the sky – Distances and apparent sizes

Parallax

- The other way around: Earth's orbit seen from a distance d

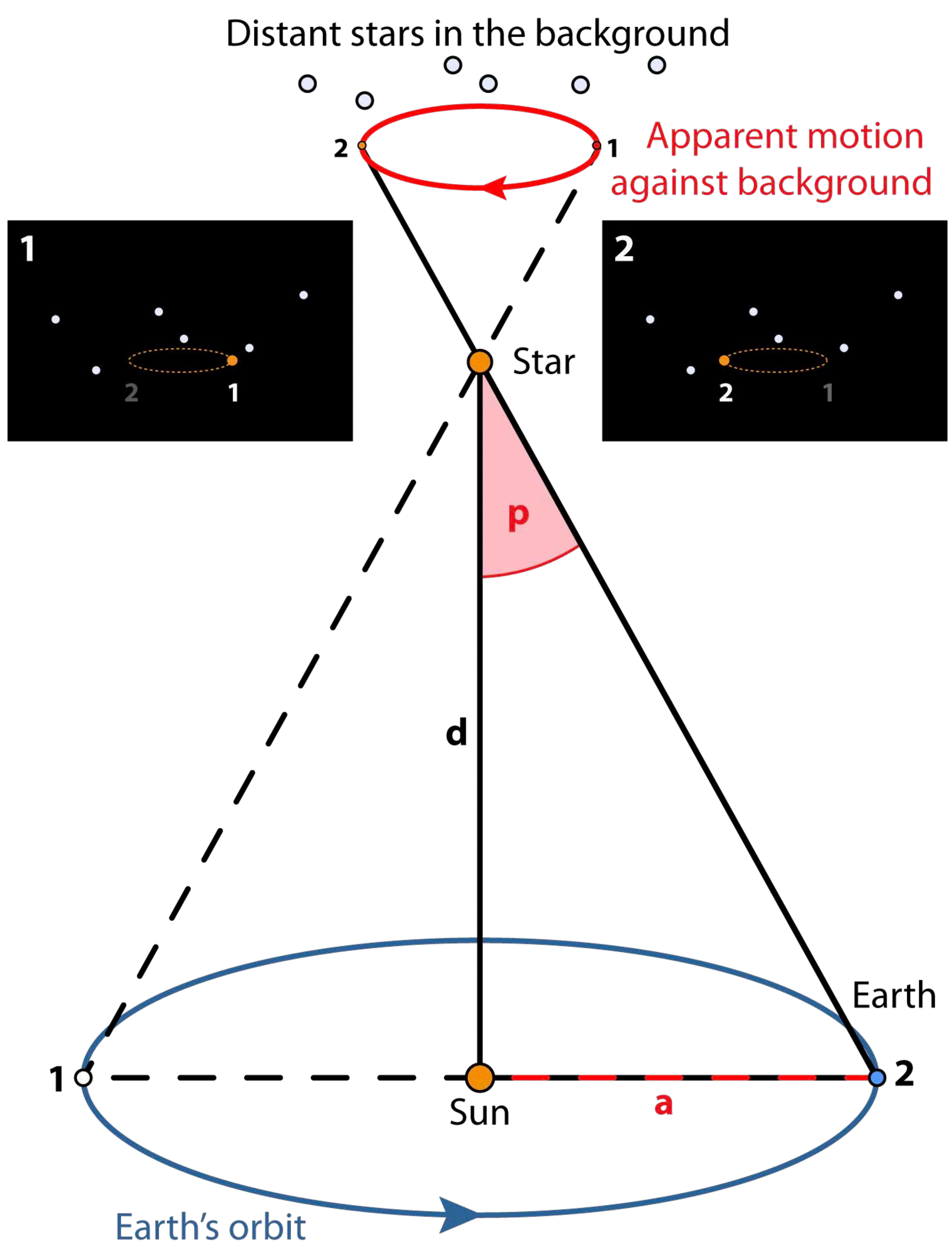
➡ The length **a** appears as **p = 1"** from a distance of d=206265 AU.

➡ This unit is called **parsec** (pc, from parallax and arcsecond).

➡ **1 pc = 206265 AU = 3.26 ly**

(1ly = 9.46×10^{12} km)

➡ **d [pc] = 1/p ["]**



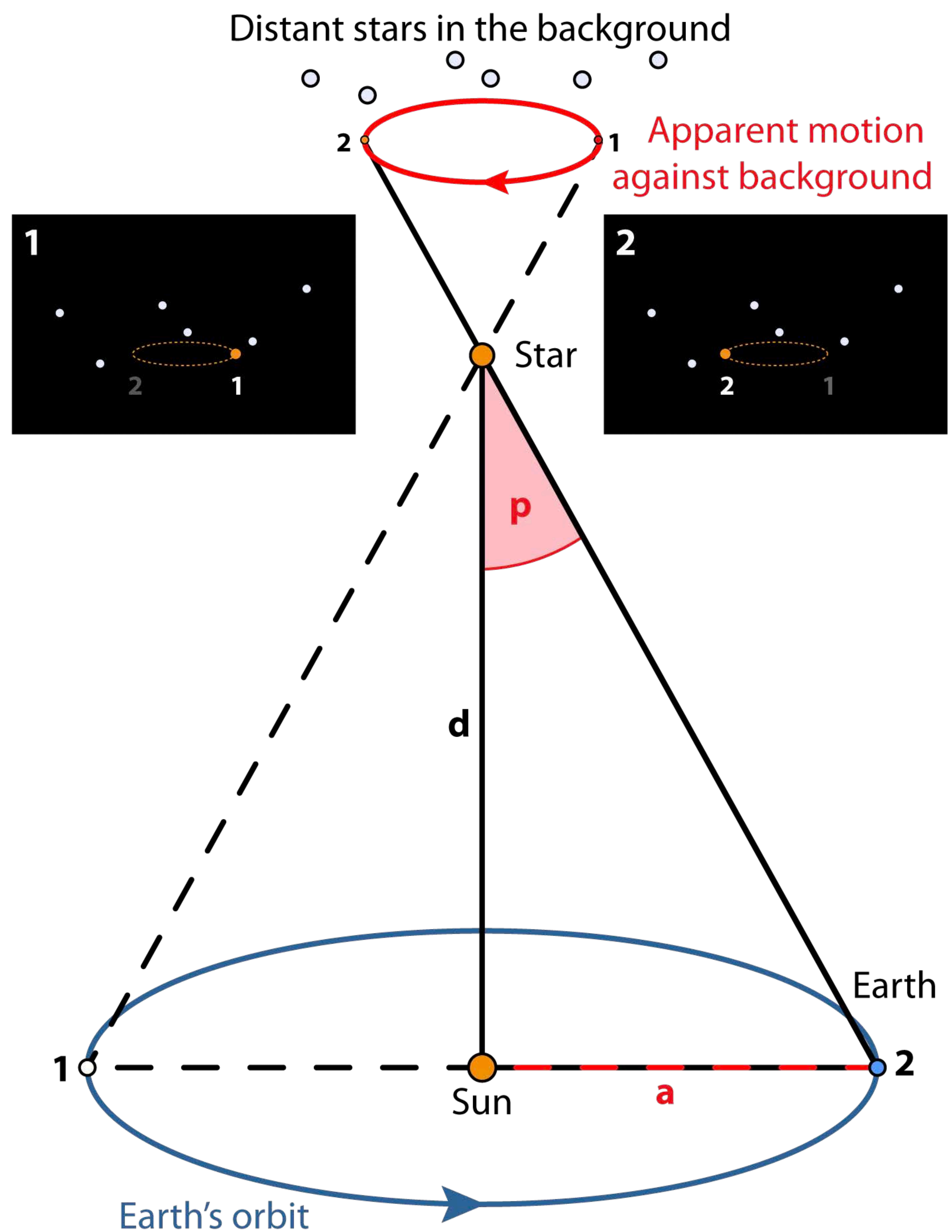
Stars in the sky – Distances and apparent sizes

Parallax

- **Example: Proxima Centauri**
- Measured parallax = 0.768″

➡ d [pc] = 1 / 0.768″ = 1.302 pc = **4.243 ly**

- First parallax measured: Bessel 1838
- **Hipparcos satellite** (1989-1993)
  - Accuracy of 0.001″ for 120,000 stars (+ ~2.5 million stars with lower accuracy.)
- **Gaia mission** (2013-2022)
  - Accuracy of ~ 10^{-4}″
  - Mapping billions of stars in the Milky Way



Stars in the sky – Distances and apparent sizes

Apparent sizes of stars

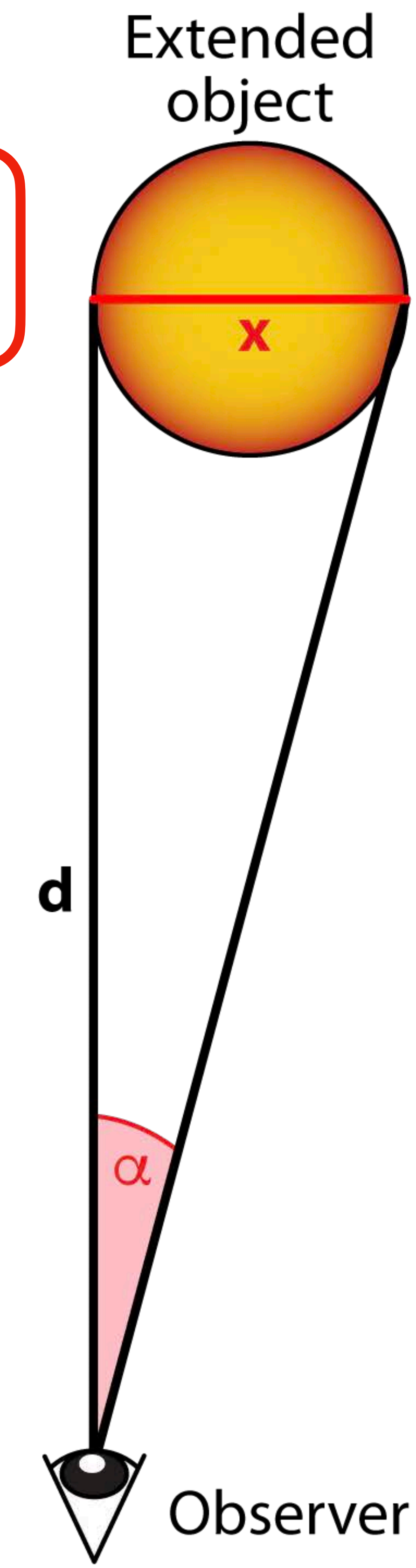
- Object on the sky with diameter x at distance d

➡ Apparent angular extent in the sky

$$\Delta\alpha = \arctan \frac{\Delta x}{d}$$

- **Examples:**

	Sun	Proxima Cen	Betelgeuse
$\Delta x = 2\,R$	$R_\odot = 696\,342$ km $\Delta x \approx 1.4\ 10^6$ km	$R = 1.07\ 10^5$ km $\Delta x = 2\,R$	$R = 900\,R_\odot$ $\Delta x = 2\,R$
d	$1\,AU = 1.6\ 10^{-5}$ ly	4.246 ly	548 ly
$\Delta\alpha$	1919″ ≈ 31′ ≈ 1/2 degree	0.0011″ 1.1 milliarcsec	0.05″ 50 milliarcsec
	Can be observed spatially resolved.	➡ Remains a point source for now.	At the limit for the largest interferometric arrays.



Stars in the sky – Distances and apparent sizes

Apparent sizes of stars

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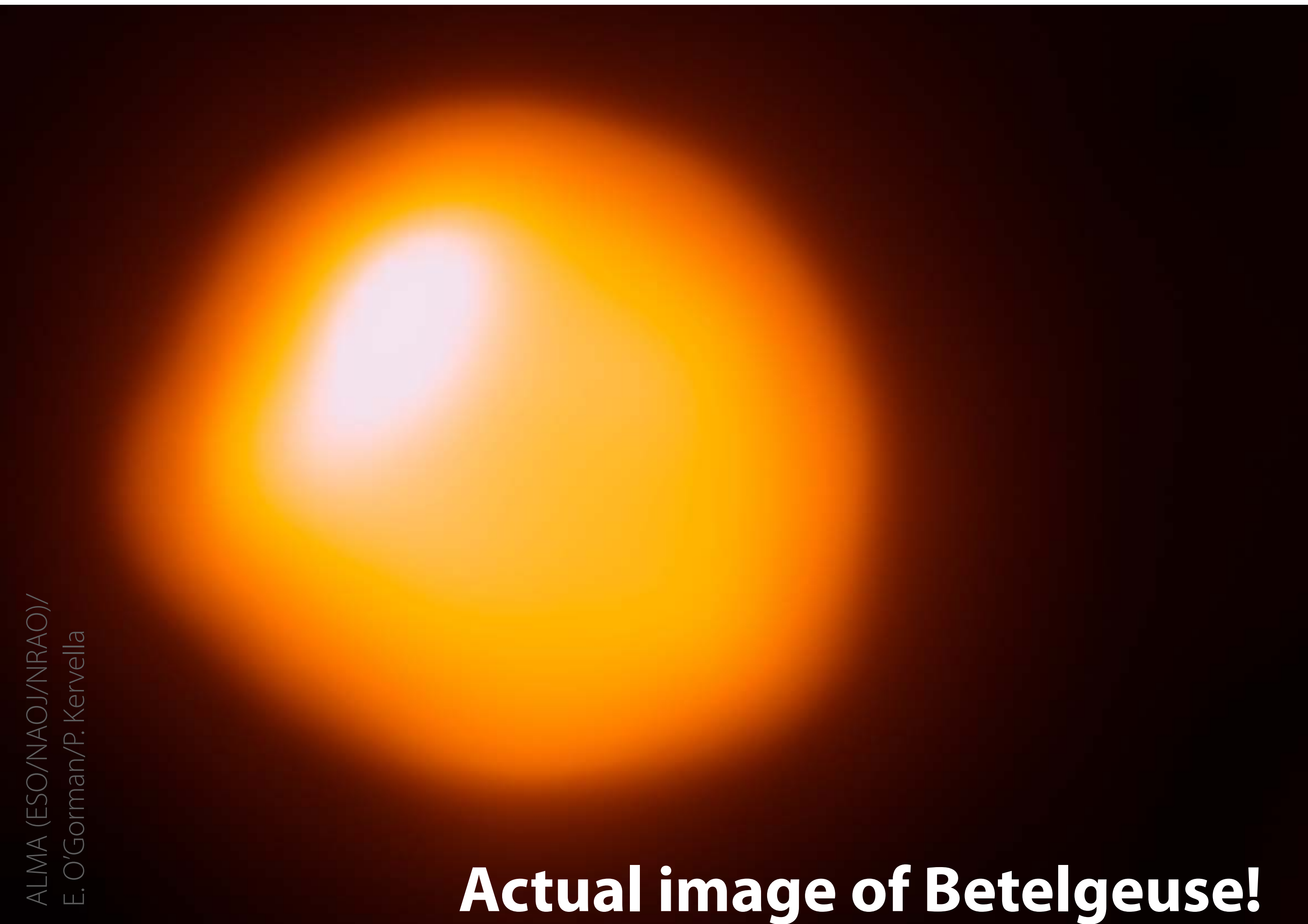

Betelgeuse
$R = 900\ R_\odot$ $\Delta x = 2\ R$
548 ly
0.05″ 50 milliarcsec
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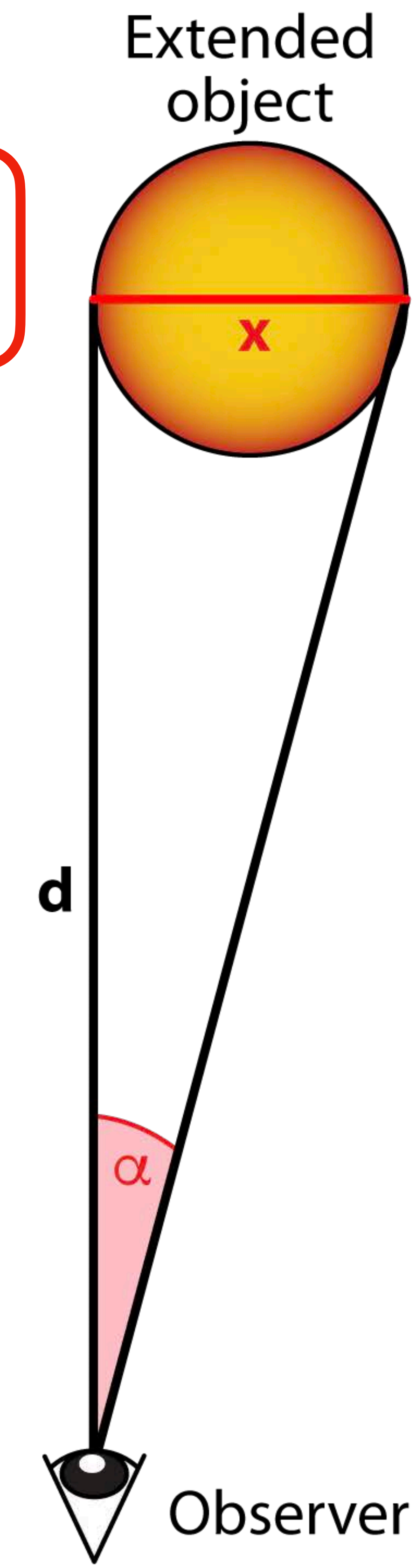


Observational stellar parameters

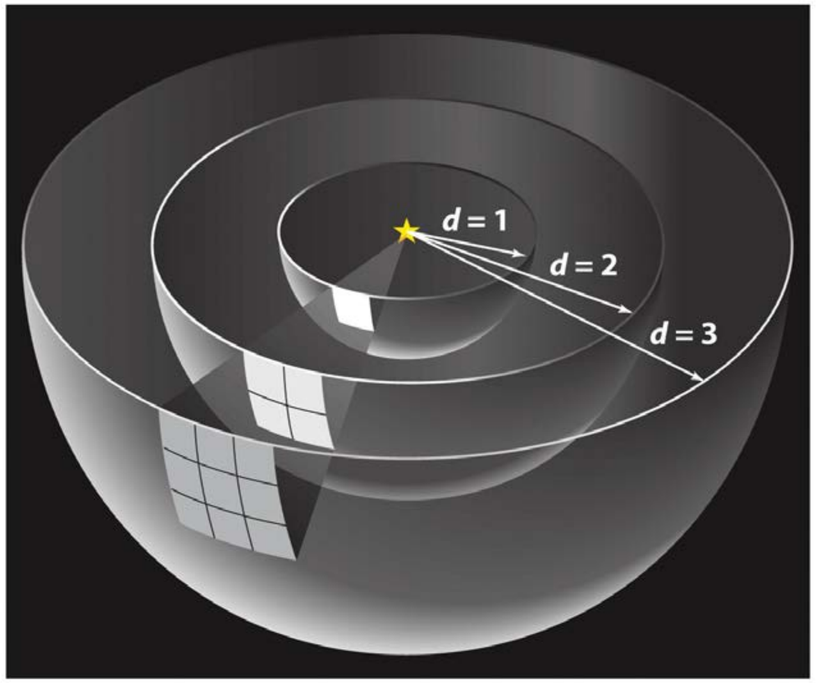
What differences do you see?

- **Apparent brightness**
- **Colours**

Cluster NGC 1783 (NASA/ESA Hubble Space Telescope)

Observational stellar parameters

Radiative flux and radiative flux density



- **Radiative flux** (also called radiation flux) **F**
  energy radiated per time unit through an area
  (over a given wavelength or frequency range)
  - Physical units: J s^{-1} m^{-2} = W m^{-2} (SI), erg s^{-1} cm^{-2} (cgs)

- **Radiative flux density** (also called spectrum)
  energy radiated per time unit through an area per wavelength or frequency unit (**F$_\lambda$** , **F$_\nu$**)

$$F_\lambda = \frac{d\nu}{d\lambda} F_\nu = \frac{c}{\lambda^2} F_\nu$$

  - In astrophysics, it is common to use F$_\nu$. The SI unit is W m^{-2} Hz^{-1}.
  - At millimetre and radio wavelengths, common to use the unit Jansky: 1 Jy = 10^{-26} W m^{-2} Hz^{-1}

- Radiative flux through integration over a given wavelength or frequency range

$$F = \int_{\nu_1}^{\nu_2} F_\nu \, d\nu \qquad F = \int_{\lambda_1}^{\lambda_2} F_\lambda \, d\lambda$$

Observational stellar parameters

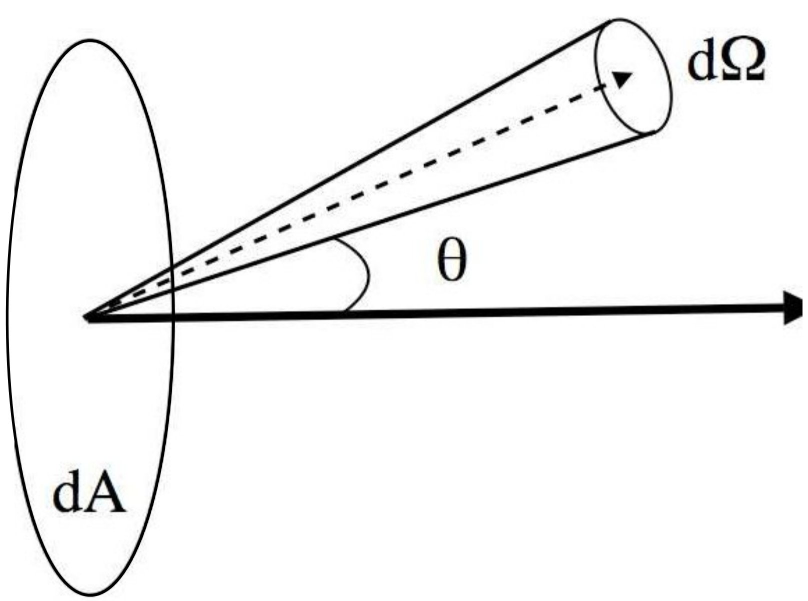
Irradiance and specific intensity

- **Irradiance** = radiative flux is received by an area (instead of emitted)

- **Total Solar Irradiance (TSI):**
  - measure of the radiation flux from the Sun that is received at the boundary of Earth's atmosphere.
  - Important in the context Sun's impact on Earth's climate.

- **Specific intensity:** I_ν = flux density F_ν emitted per solid angle Ω :

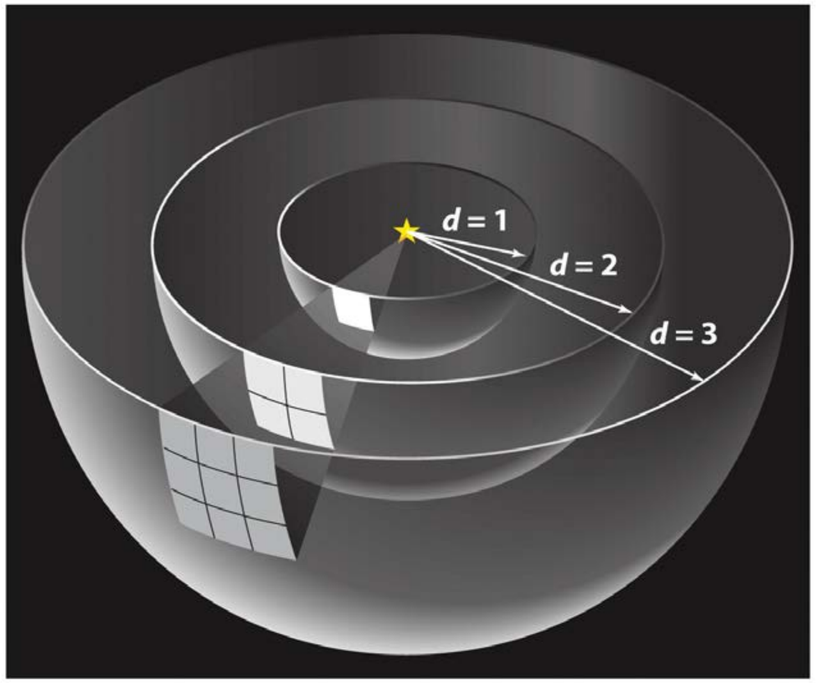
$$F_\nu = \int_\Omega I_\nu \cos\theta d\Omega$$



  - Physical units: $\mathrm{J\,s^{-1}\,m^{-2} = W\,m^{-2}\,Hz^{-1}\,sr^{-1}}$ (SI)

Observational stellar parameters

Apparent brightness scale



- **Radiative flux** (also called radiation flux) **F**
  energy radiated per time unit through an area
  (over a given wavelength or frequency range)

- **Apparent brightness m** measured on logarithmic scale
- Dimensionless unit magnitudo [mag]

  - star of first magnitude star = 100 times brighter than a 6th magnitude star.
  - Δm = 5 mag <-> brightness ratio of 100
  - Δm = 1 mag <-> $100^{1/5}$ = 2.512 (Pogson's Ratio)

$$\Delta m = m_1 - m_2 = -2.5 \log(F_1/F_2) \quad \text{[mag]}$$

  - **Flux ratio F_1/F_2** of the two stars.

- Origin of the scale defined by bright star α Lyrae, (m = 0 mag at all wavelengths)

Observational stellar parameters

Apparent brightness scale

bright	-26.7	Sun
	-12.6	Full moon
	-4.4	Venus (max.)
	-1.4	Sirius (brightest star in the sky)
	0.5	Betelgeuse (visual band, variable)
	6.5	Limit for naked eye
	10.0	Limit for binoculars
	11.1	Proxima Cen (visual band)
	15.1	Pluto
	31.5	Limit of Hubble Space Telescope
faint	~ 34	Limit of James Webb Space Telescope (infrared)

$\Delta m = 1$ mag = factor 2.512

- Individual stars
  - Different distances to us
  - Different "energy output"

Observational stellar parameters

Absolute brightness

- Apparent brightness depends on properties of the star but also on distance!

➡ Distance dependence to be removed for direct comparison of stellar properties

- **Absolute brightness** M
  - Also referred to as absolute magnitude
  - Definition: brightness that a star has at a (fictive) **standard distance of 10 parsec** from the observer

  ➡ (independent of the distance!)

Observational stellar parameters

Absolute brightness

➡ brightness at standard distance of 10 parsec

	Apparent brightness m_V*	Absolute brightness M_V*	Distance modulus $(m - M)_V$*	Distance
Sun	-26.74	4.83	-31.57	1 AU
α Cen A Solar-like star	0.01	4.38	-4.37	4.4 ly
Sirius A brightest star (after Sun)	-1.47	1.42	-2.89	8.7 ly
Proxima Cen closest star (after Sun)	11.13	15.6	-4.47	4.2 ly
Betelgeuse	0.5	-5.85	6.35	550 ly

* All brightness at visible wavelengths, astronomical extinction ignored (A=0)

- Sun would be among the fainter stars observable with the naked eye when observed from a distance of 10 pc.

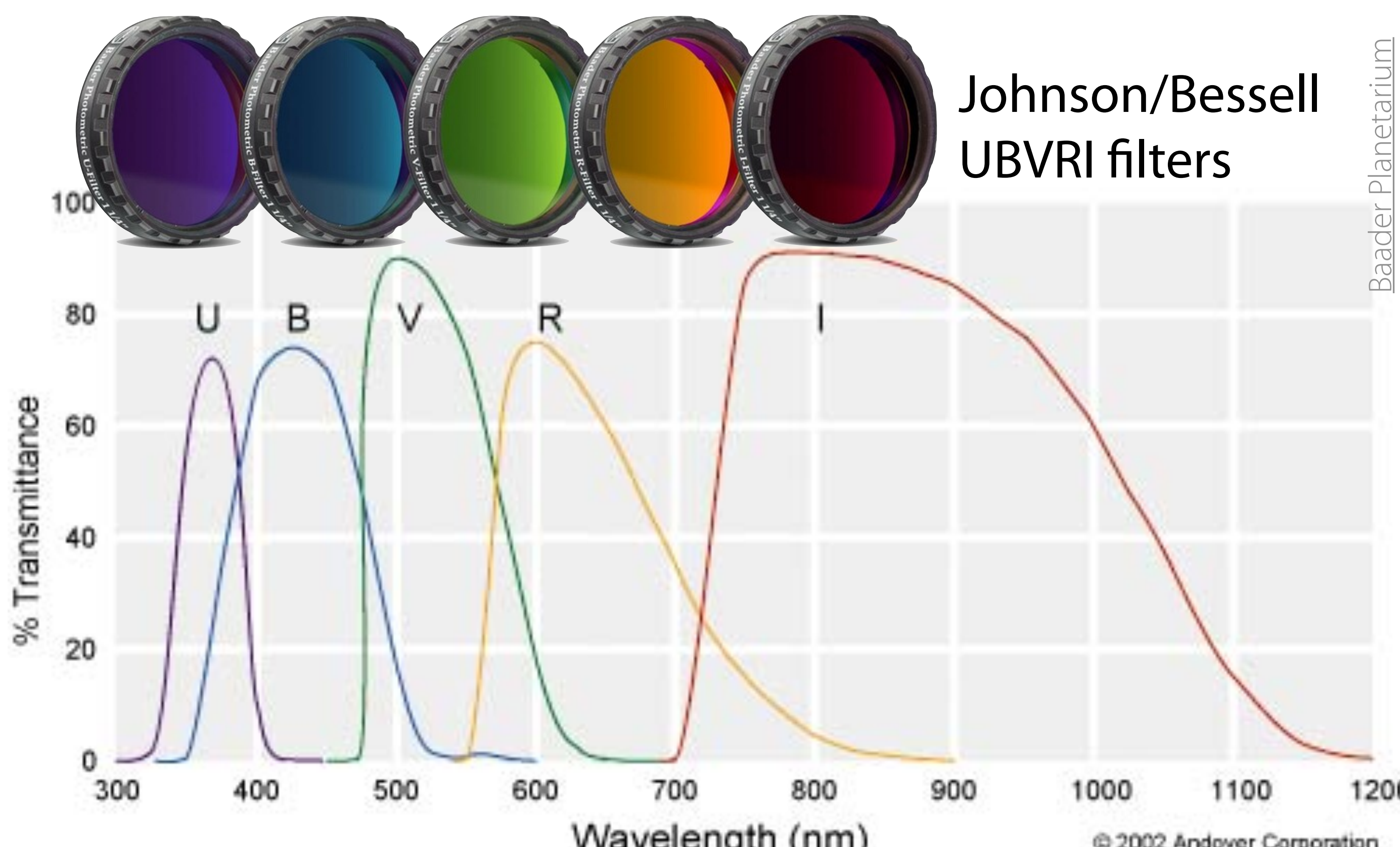
Observational stellar parameters

Photometry and colours

- Use of different filters in an observation
- Transmission of only limited wavelength ranges
- Standardised filter system(s)
  - Most common: UBVRI(+)
  - Originally **UBV** (ultraviolet — blue — visual)
  - Extended into the infrared (IR)

UBVRI filter system + extension

Filter	descript.	λ [nm]	FWHM [nm]
U	UV	365	66
B	blue	440	94
V	visual	548	88
R	red	658	138
I	IR	806	149
J	IR	1220	213
H	IR	1630	307
K	IR	2190	490
L	IR	3450	473
M	IR	4750	460



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- Brightness measured in a selected filter marked with corresponding index
- Example: Visual (**V**)
    - Apparent brightness: $m_V = V$ (Often only the filter ID is used!)
    - Absolute brightness: M_V

UBVRI filter system + extension

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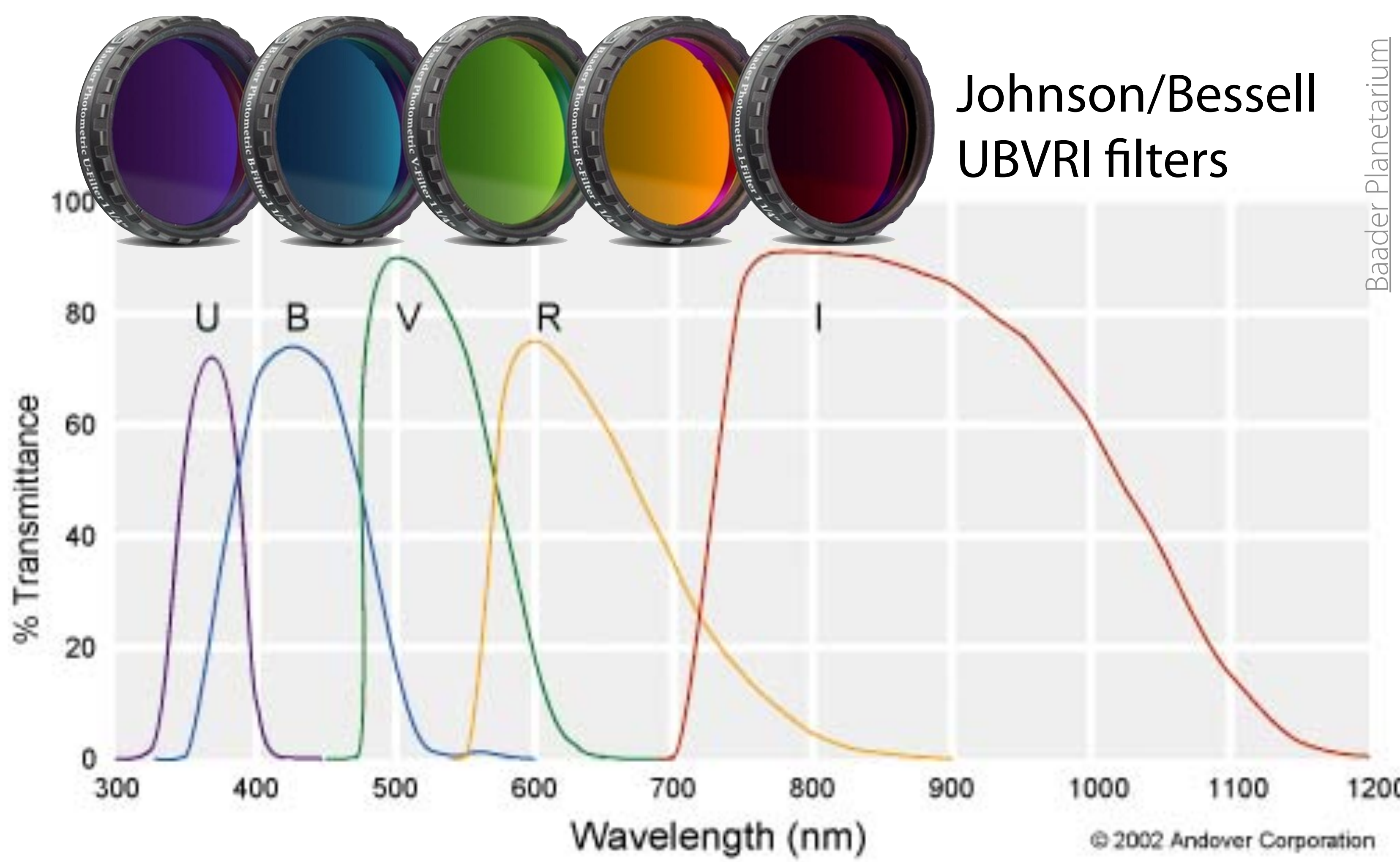


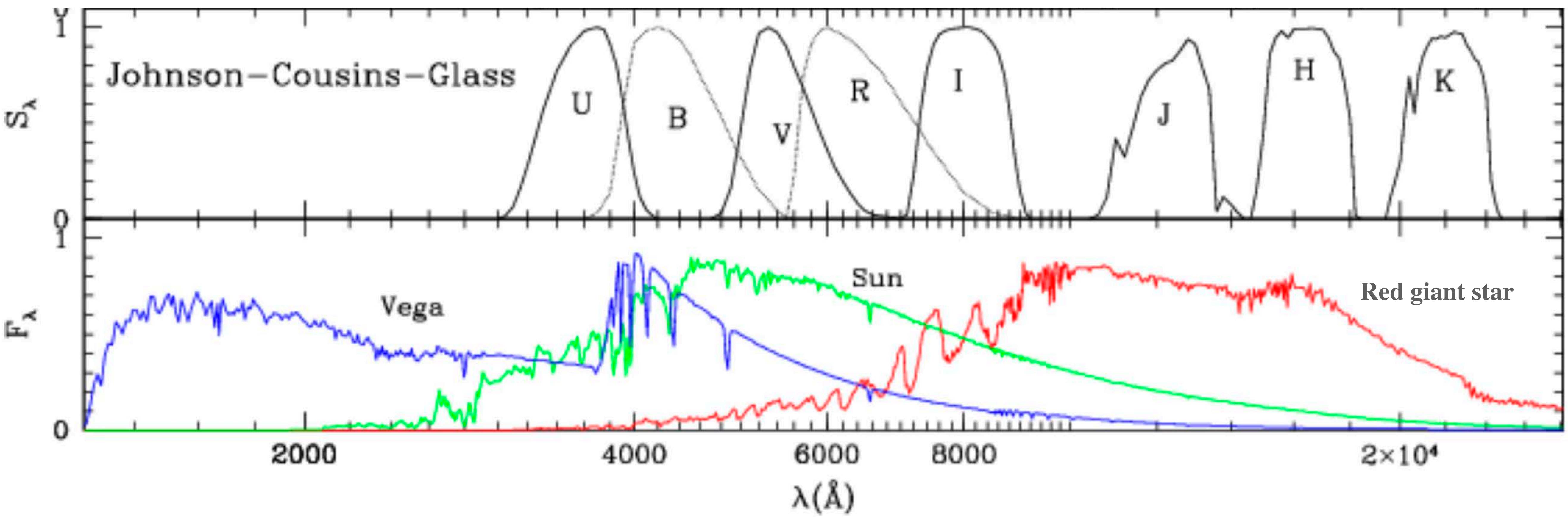
Observational stellar parameters

Photometry and colours, color index

- Measuring brightness with different filters captures **variation of flux density as function of wavelength** (spectrum)
  ➡ Reveals difference between stars

- **Colour index:**
  - **Examples**

Star	$U = m_U$	$B = m_B$	$V = m_V$	$(U-B)$	$(B-V)$
Sun	-25.85	-26.03	-26.70	0.18	0.67
Proxima Cen	14.21	12.95	11.13	1.26	1.82
Betelgeuse	~ 0.50	~ -1.6	~ -3.4	+2.06	+1.85



Observational stellar parameters

Blackbody spectrum and flux

- Radiation flux density (spectrum) resembles a **blackbody** spectrum, which is given by the Planck function **B_ν (T)** for a temperature T

➡ Flux density F_ν of a blackbody:

$$F_\nu = \pi B_\nu(T)$$

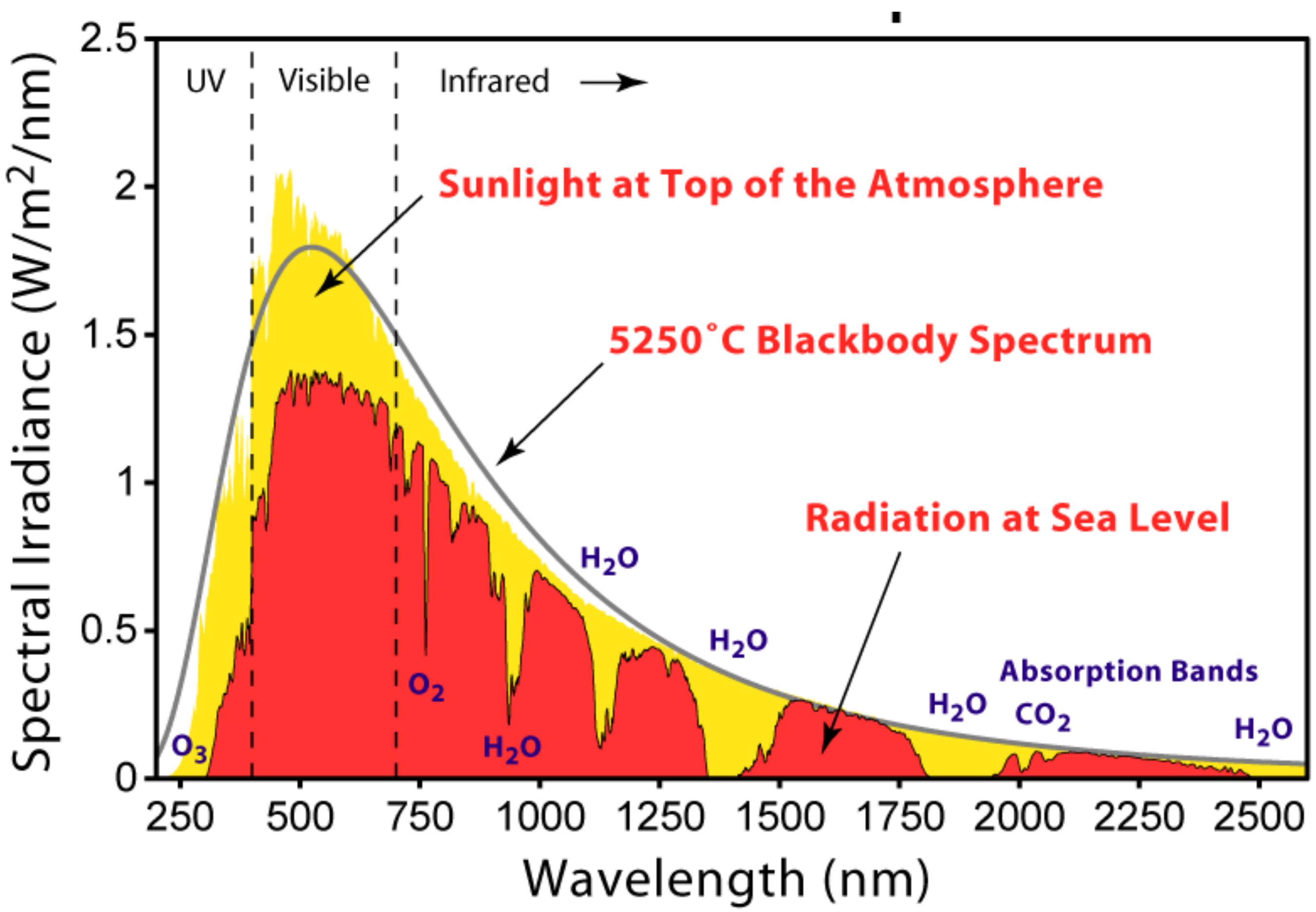
➡ Bolometric flux (over all frequencies/wavelengths)

$$F = \int_0^\infty F_\lambda d\lambda = \int_0^\infty F_\nu d\nu$$

$$F = \sigma T_{\text{eff}}^4$$

σ: Stefan-Boltzmann constant

Stefan-Boltzmann law



Observational stellar parameters

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$$F = \sigma T_{\mathrm{eff}}^4$$

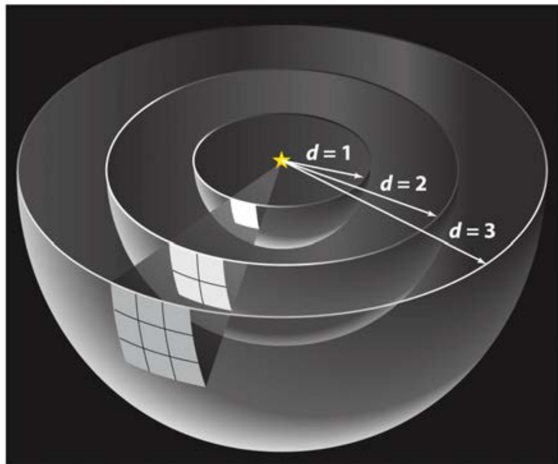
σ: Stefan-Boltzmann constant

Stefan-Boltzmann law

- **Example: Sun**
- Bolometric flux density of the Sun measured just outside Earth's atmosphere by a satellite:

➡ **solar constant** = 1.36 kW m^{-2}

- Radiation emitted from the Sun's "surface" at radius 1 $R_\odot$
- Diluted over a sphere with radius r=1 AU with surface area $A = 4\pi r^2$
- At Sun's surface ($1R_\odot$): **$F_\odot = 6.3 \cdot 10^7$ Wm^{-2}**
- **Effective temperature of the Sun: $T_{\mathrm{eff},\odot} \approx 5770$ K**



The solar "constant" varies slightly at 0.1% level ...

Observational stellar parameters

Luminosity

- **Total radiative energy output of a star** given by flux that emerges across the total surface of a star.
- Assumption: star is spherical with radius R

➡ Surface area $A = 4\pi R^2$

➡ **Luminosity** of a star L = A F

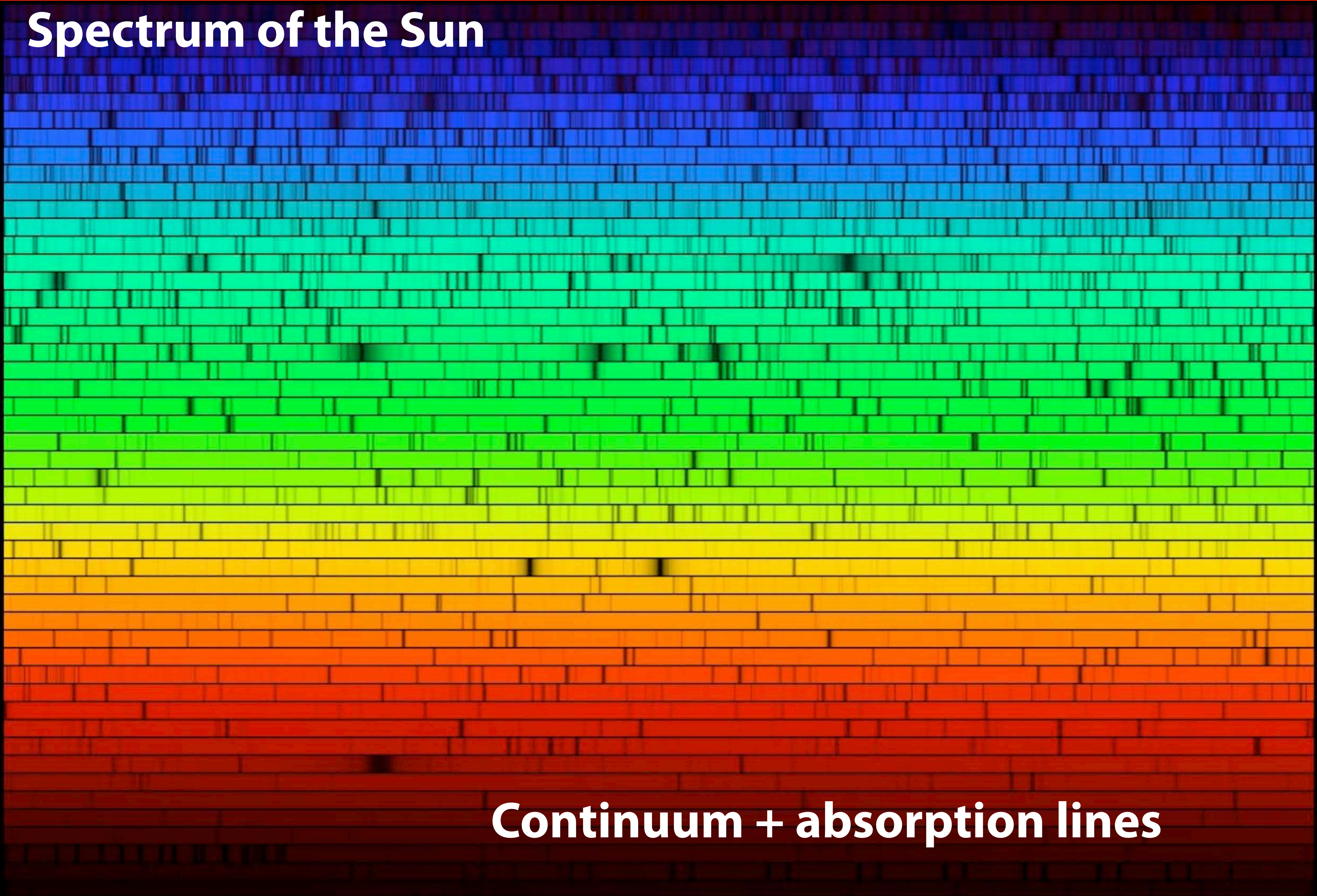
$F = \sigma T_{\rm eff}^4$

Stefan-Boltzmann law

$$L = 4\pi R^2 \sigma T_{\rm eff}^4$$

The luminosity is a fundamental property of a star!

Stellar spectra



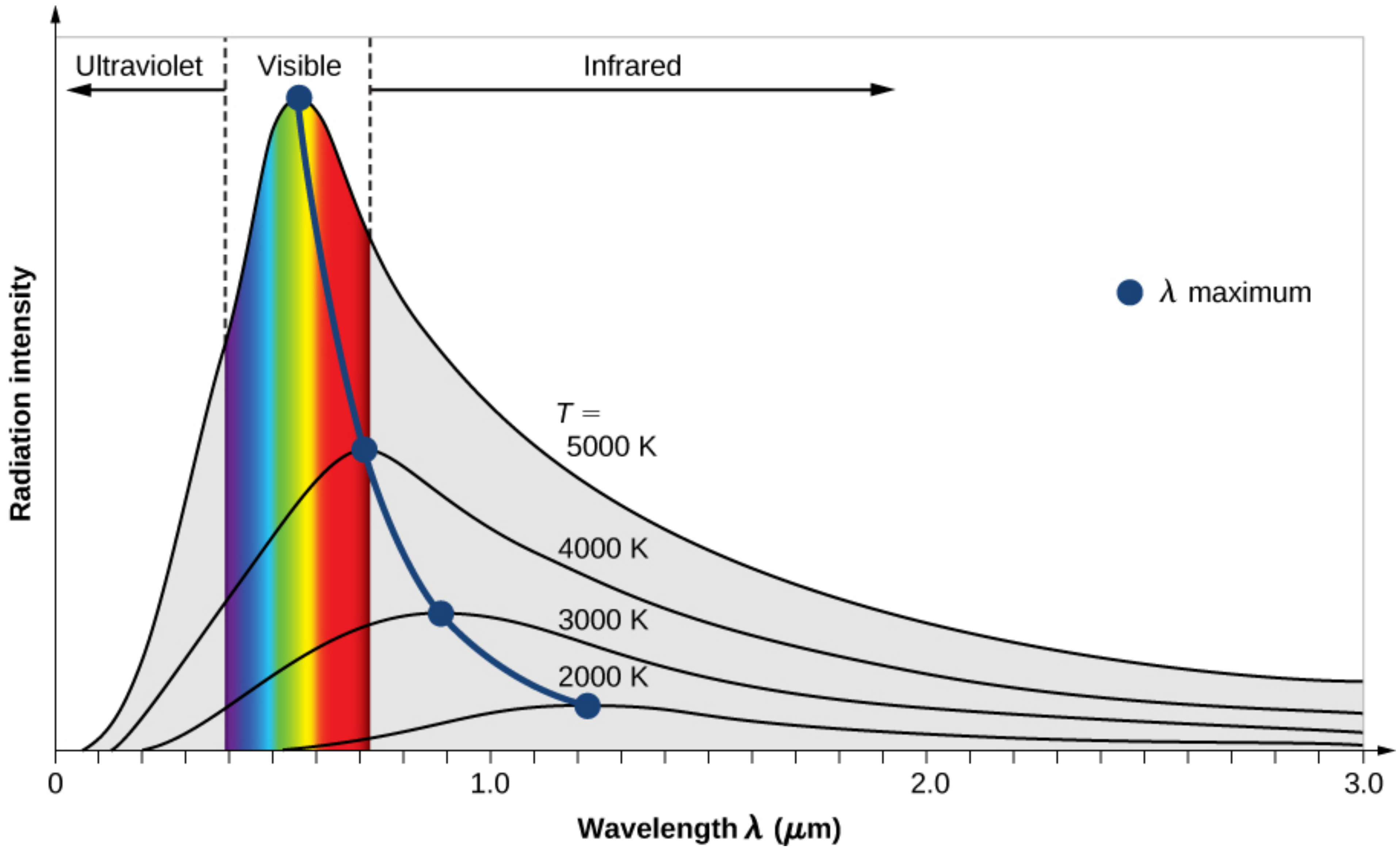
Stellar spectra

- Match observed continuum with blackbody for the right temperature

- Stefan-Boltzmann law: $F = \sigma T_{eff}^4$

➡ Effective temperature of the star

- Colour indices (derived with filters) can be used instead of full spectrum



- Increasing T_{eff}

➡ Bolometric flux F (integral under the curve) increases with T_{eff}^4

➡ Wavelength of peak becomes shorter: **Wien's displacement law** $\lambda_{max} = \frac{b}{T}$

Wien's displacement constant

$(b = 2.89777 \times 10^{-3}\, \mathrm{m \cdot K} \approx 2900\, \mu\mathrm{m \cdot K})$

Interactive app:
https://phet.colorado.edu/sims/html/blackbody-spectrum/latest/blackbody-spectrum_en.html

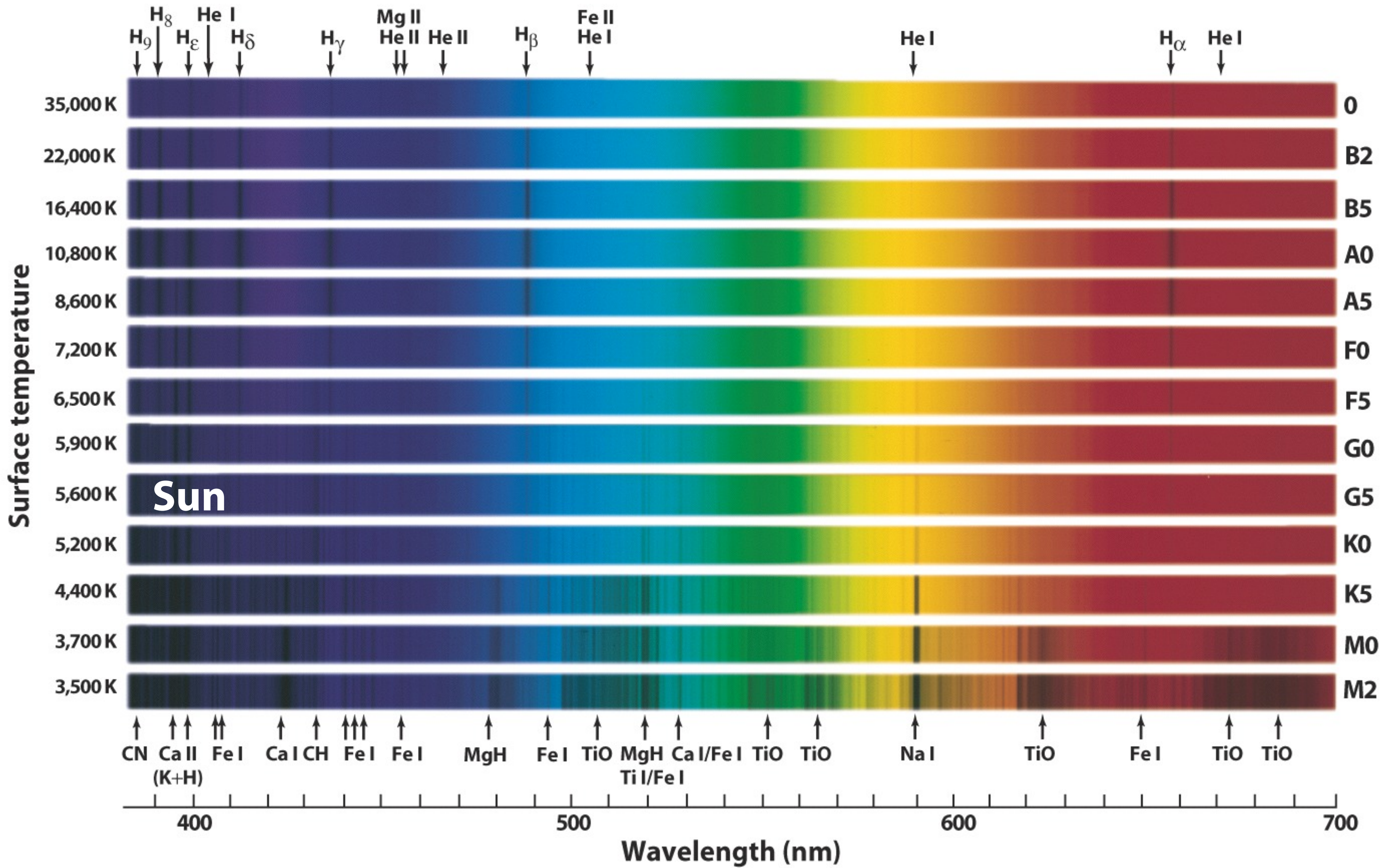
Stellar spectra

- Brightnesses, colour indices + **occurrence and strength of spectral lines for different ionisation stages**

➡ Information about temperature and chemical composition

➡ Sorting the different types into a sequence

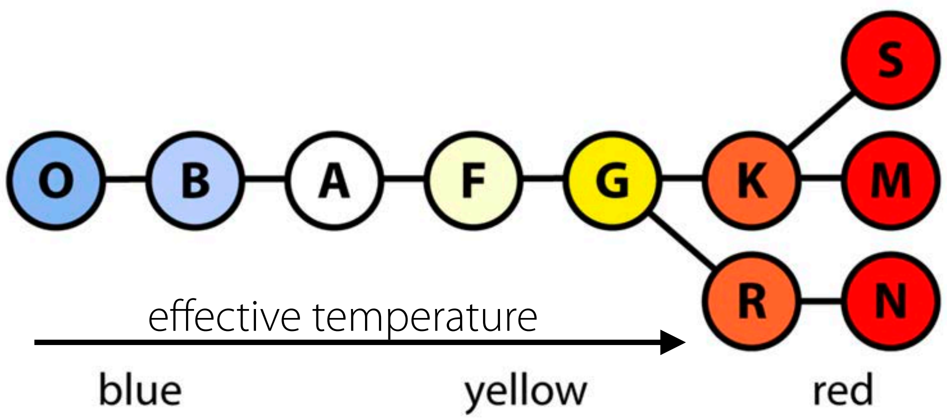
➡ Spectral types can sorted into a sequence as function of temperature



Spectral classification

- A star is classified by a

Spectral class + **Decimal sub-division** + **Luminosity class**



Decimal sub-division

effective temperature →

0 1 2 3 4 5 6 7 8 9

One decimal possible!

Luminosity class

Ia - 0	hypergiants
I	supergiants
II	bright giants
III	giants
IV	subgiants
V	main sequence (dwarfs)
VI	subdwarfs

- **Harvard spectral classification**
- Further developed and extended

➡ **Morgan–Keenan system**

- **Examples**

Sun	G2V
Sirius A	A0V
Proxima Cen	M5.5V
Betelgeuse	M1I
Aldebaran	K5III

Spectral classification

Main spectral classes			
O	violet	$> 28\,000$ K	less than few visible absorption lines, weak Balmer lines, ionised helium lines
B	blue	10 000 – 28 000K	neutral hydrogen lines, more prominent Balmer lines
A	blue	7 500 – 10 000K	strongest Balmer lines, other strong lines
F	blue-white	6 000 – 7 500K	weaker Balmer lines, many lines including neutral metals
G	white-yellow	5 000 – 6 000K	Balmer lines weaker still, dominant ionised calcium lines
K	orange-red	3 500 – 5 000K	neutral metal lines most prominent
M	red	$< 3\,500$ K	strong neutral metal lines and molecular bands

Supplementary classes of cool stars			
R (C)	red	$< 3\,000$ K	Carbon compounds, S-process elements
N (C)	red		Carbon compounds, S-process elements
S	red	$\sim 3\,000$ K	s-process elements, molecular bands (especially ZrO and TiO)

- **R,N or C-type: "carbon stars"** — red giant stars and Asymptotic Giant Branch (AGB) stars.
  - regular M-type giant stars have more oxygen and carbon -> referred to as "oxygen-rich" stars.
- **S-type stars:** carbon and oxygen are approximately equally abundant
  - prominently spectral features due to the s-process elements (e.g. zirconium monoxide (ZrO).

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Very low mass /sub-stellar spectral classes (mostly brown dwarfs)			
L	IR	1 500 – 2 500 K	lines of alkali metals (e.g. N) and metallic compounds (e.g. FeH)
Y	IR	800 – 1 500 K	methane absorption lines
T	IR	< 800 K	water and ammonia lines

Spectral classification

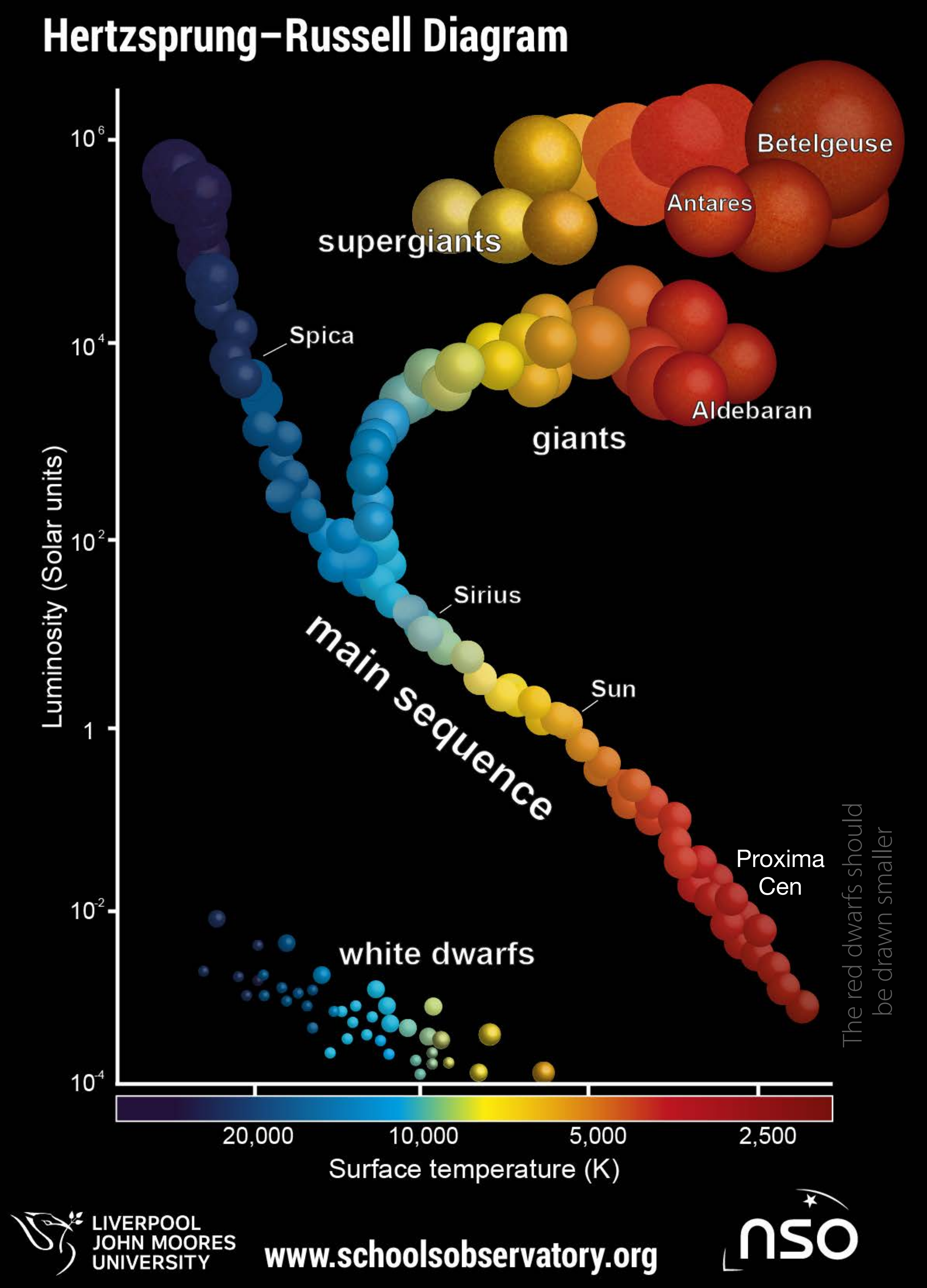
Stellar populations

- Observations show that decreasing **metal content** correlated with increasing age of stars.
- Stars (in our galaxy) can be further divided into populations according to their chemical composition or metallicity
  - **Population I:** "recent" stars, high metallicity
  - **Population II:** old stars, low metallicity
  - **Population III:** first stars in the universe (very low metal content)
- Originally, pop I+II, pop III added in 1978

Stellar classification

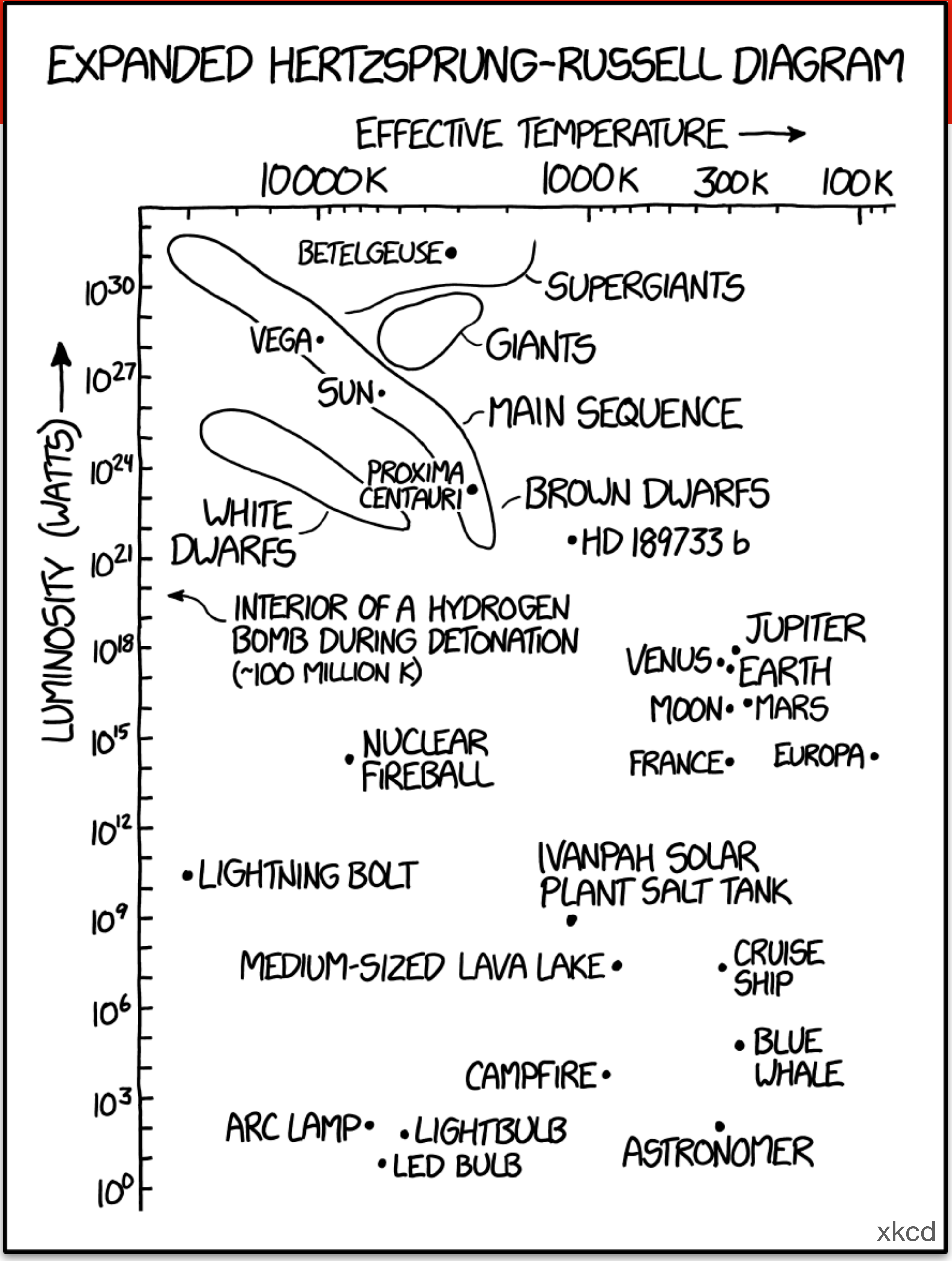
Hertzsprung-Russell diagram

- Stars not randomly distributed
- Distribution yields important clues for stellar structure and evolution
- Different stellar types and evolution stages:
  - Main sequence
  - Giants and supergiants
  - Dwarf stars
  - …



Stellar classification

Hertzsprung-Russell diagram



Physical stellar parameters

- The fundamental (global) parameters that describe a star are
  - **mass M,**
  - **radius R,**
  - **luminosity L.**
- They are commonly expressed in units of the solar values $M_\odot$, $R_\odot$, and $L_\odot$
- The parameters will change with time.
  - **Age** of a star also an important parameter!

- **Stellar atmosphere** (layer from where we receive most of the observable information) is characterised by the following parameters:
  - **effective temperature T_{eff}**
  - **gravity acceleration g**
  - **chemical composition** (expressed as metallicity)
  - **magnetic field strength**
    (although the magnetic field is typically difficult to be expressed by just one parameter)

- Often stellar properties can only be derived with **significant uncertainties.**

Physical stellar parameters

Mass

- According to our definition of a star, nuclear fusion in its interior is required.

  ➡ Minimum mass of a star $M_{min} \approx 0.08 M_{\odot}$.

  ➡ Objects with $M_{min} < 0.08 M_{\odot}$ (but more mass than planets): brown dwarfs ($M_{bd} < 0.08 M_{\odot}$).

- Highest masses $M > 100 M_{\odot}$
  - Known examples with up to ~ $250 M_{\odot}$

- Number of stars with a certain mass decreases strongly with mass!

  ➡ only few very massive stars but very many low-mass stars.

  ➡ very massive stars are therefore typically far away

- Strong stellar winds and outflowing gas result in clouds surrounding these stars can make the determination of the stellar mass less reliable.

Physical stellar parameters

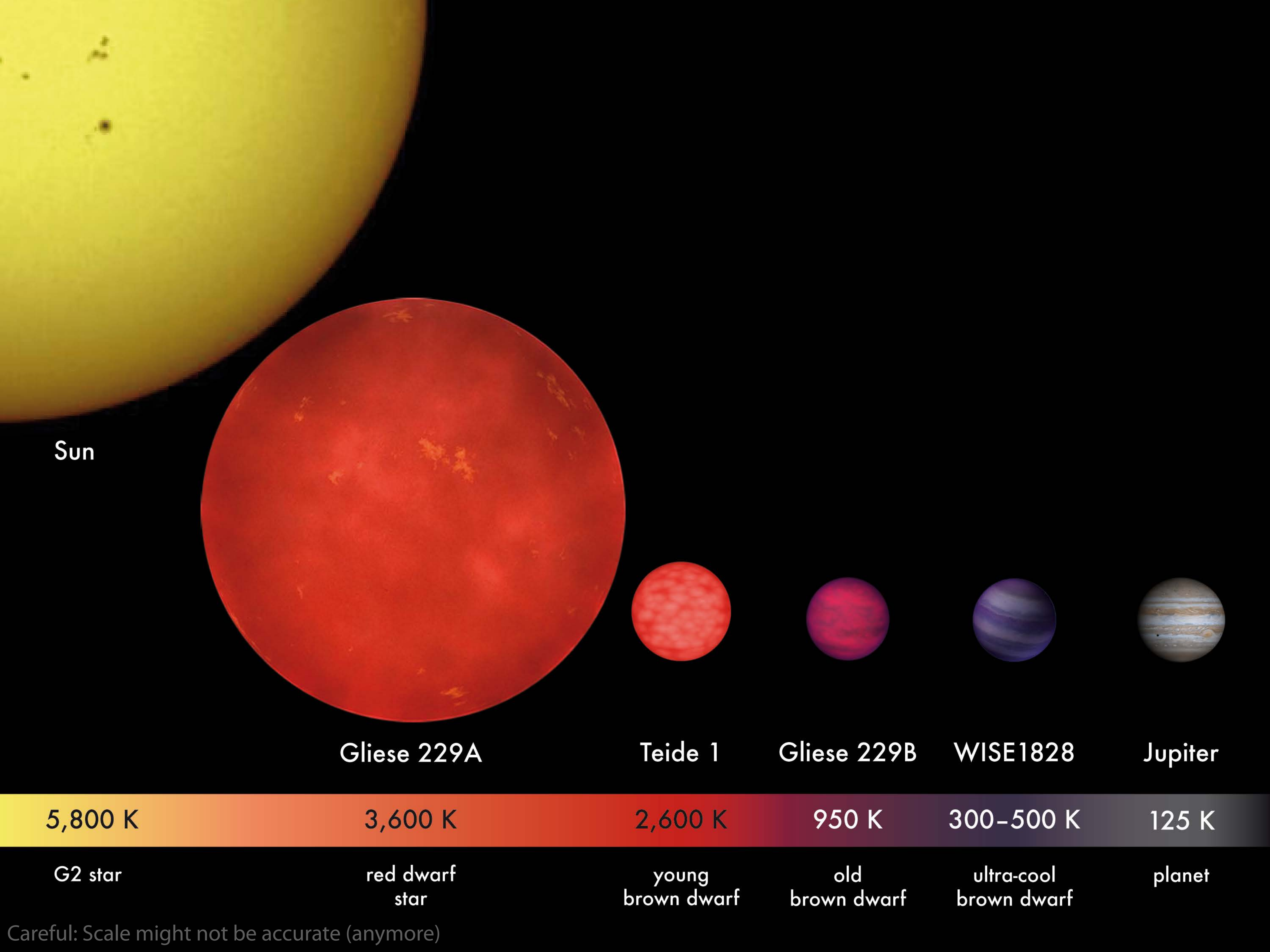
Radius

$R_\odot = 696\ 342$ km

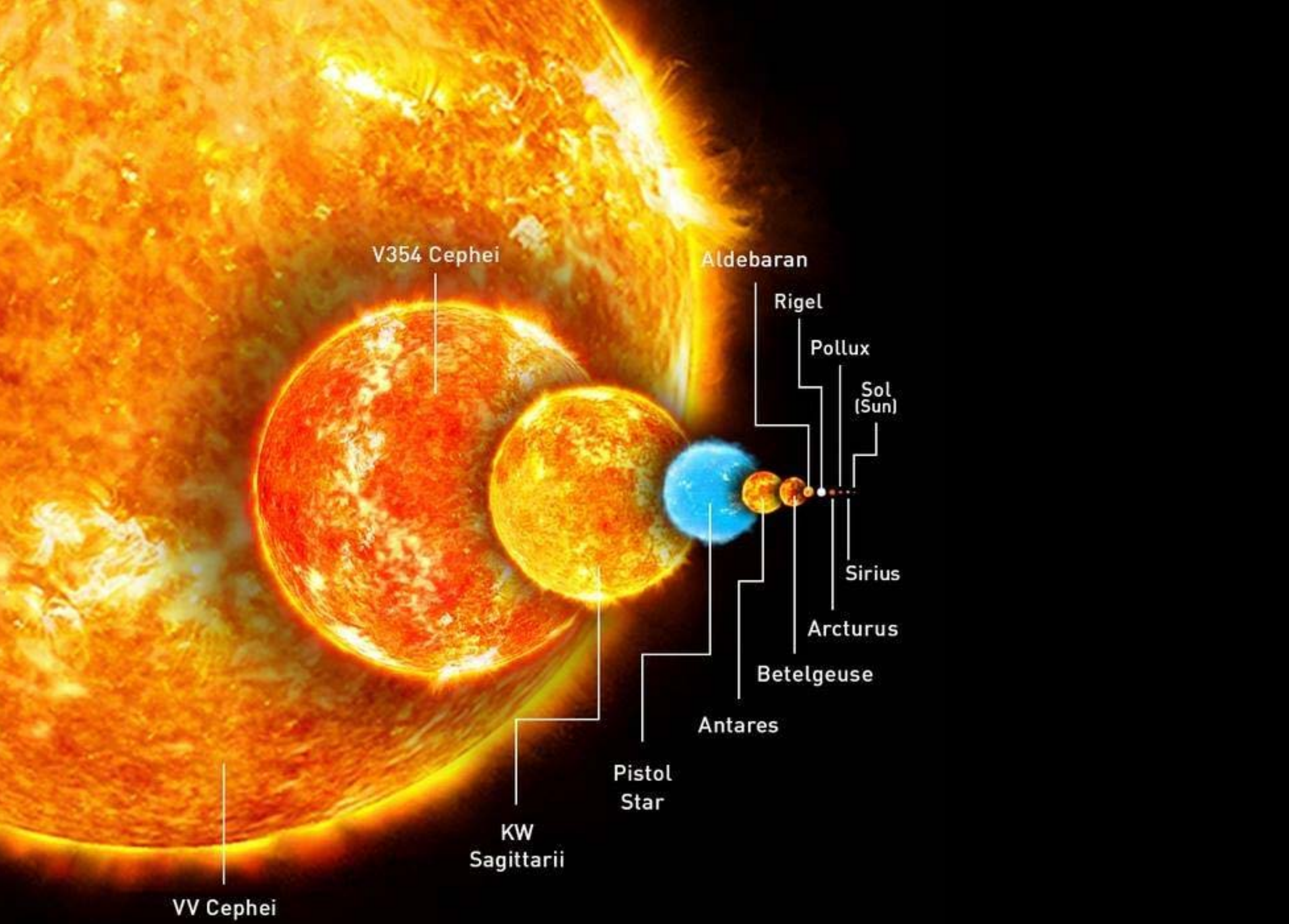
- **Main sequence stars**
  - Typical values: 0.1 $R_\odot$ to ~ 25 $R_\odot$.
  - Radii increase as function of effective temperature along the main sequence
  - Red dwarfs at the cool end being much smaller than the Sun
  - Hot main sequence stars being much larger than the Sun.

- **Red giants, supergiants, …**
  - Diameters larger than the orbit of Mars.
  - Examples: Antares (680 – 800 $R_\odot$), Betelgeuse (900 $R_\odot$), and Mu Cephei (972 – 1,260 $R_\odot$).
  - Largest stars: radii currently estimated to up ~ 2000 $R_\odot$.

- **White dwarfs**
  - $R < 0.02\ R_\odot$ https://nineplanets.org/wp-content/uploads/2020/09/Size-Comparision-of-Antares-Sun-and-Betelgeuse.jpg



Sun
Gliese 229A
Teide 1
Gliese 229B
WISE1828
Jupiter
5,800 K
3,600 K
2,600 K
950 K
300–500 K
125 K
G2 star
red dwarf star
young brown dwarf
old brown dwarf
ultra-cool brown dwarf
planet
Careful: Scale might not be accurate (anymore)



Careful: Scale might not be accurate (anymore)

Physical stellar parameters

Effective temperature

- Notes:
  - Spectrum of a star can – in first approximation – be described with a black body spectrum for an effective temperature T_{eff}
  - real stellar spectra deviate from blackbody curve
  - effective temperature of a star is defined over the integral
  - Sun: $T_{eff,\odot} \approx 5770$ K.
  - Typical values for other **main sequence stars** :
    - from ~ 2 200 K for the coolest red dwarf stars
    - up to ~ 45 000 K for the hottest O-type stars.
  - **White dwarfs** can exhibit much higher temperatures of up to ~ 2×10^5 K (basically "exposed" stellar core remnants)

Physical stellar parameters

Luminosity ➡ $L = 4\pi R^2 \sigma T_{eff}^4$

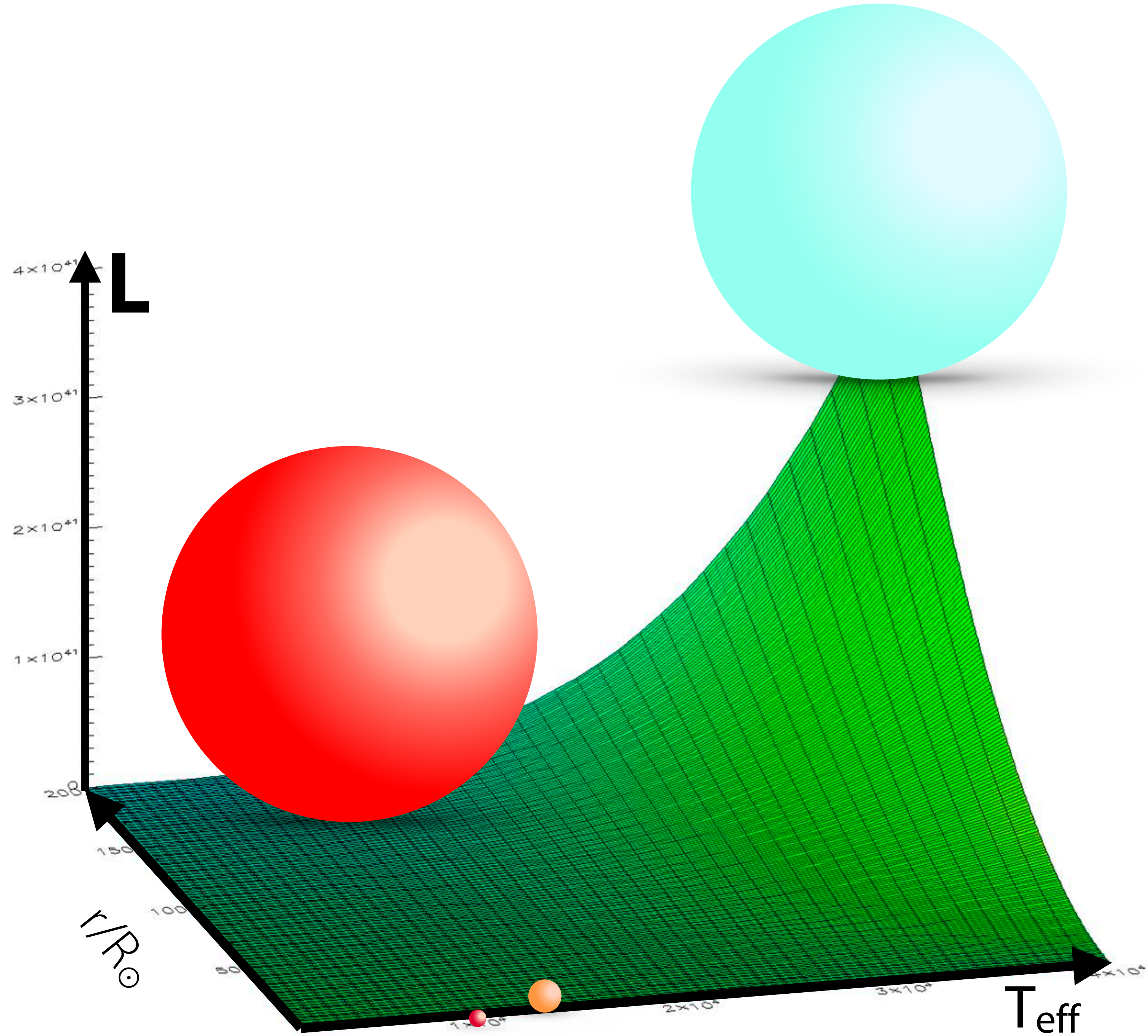
- The bolometric luminosity of stars spans r many orders of magnitude: **10^{-4} L⊙ — 10^{6} L⊙**

- Depends to **4th power** on T_{eff}

➡ Small difference in T_{eff} results in a large change in L!
(Same true for uncertainties)

- **Example 1**: blue-white supergiant Deneb (α Cyg) — one of the brightest stars in the sky:
  L ~ 60 000 — 200 000L⊙.
  ➡ Large uncertainty is due to the poorly known distance!

- **Example 2**: Red supergiant Betelgeuse L ≈ 100 000L⊙



Physical stellar parameters

Chemical composition

- Most stars (in particular main sequence stars) consist primarily of **hydrogen and helium**.
- The elements heavier than helium are commonly called **metals** in astrophysics, sometimes abbreviated as M.
- **Astronomical abundance scale**: logarithmic scale log ε relative to the Sun
  - Hydrogen as origin of scale with log ε (H) = 12 and all other element relative to hydrogen:

$$A(\mathrm{El}) = \log \varepsilon = log(n_{\mathrm{El}}/n_{\mathrm{H}}) + 12$$

n: number density of element

- The **metallicity** is the relative content of the metals, **M/H**, with respect to the Sun:

$$\varepsilon = \frac{(\mathrm{M/H})_{\mathrm{star}}}{(\mathrm{M/H})_{\odot}} \qquad \text{or} \qquad \log \varepsilon = [\mathrm{M/H}]$$

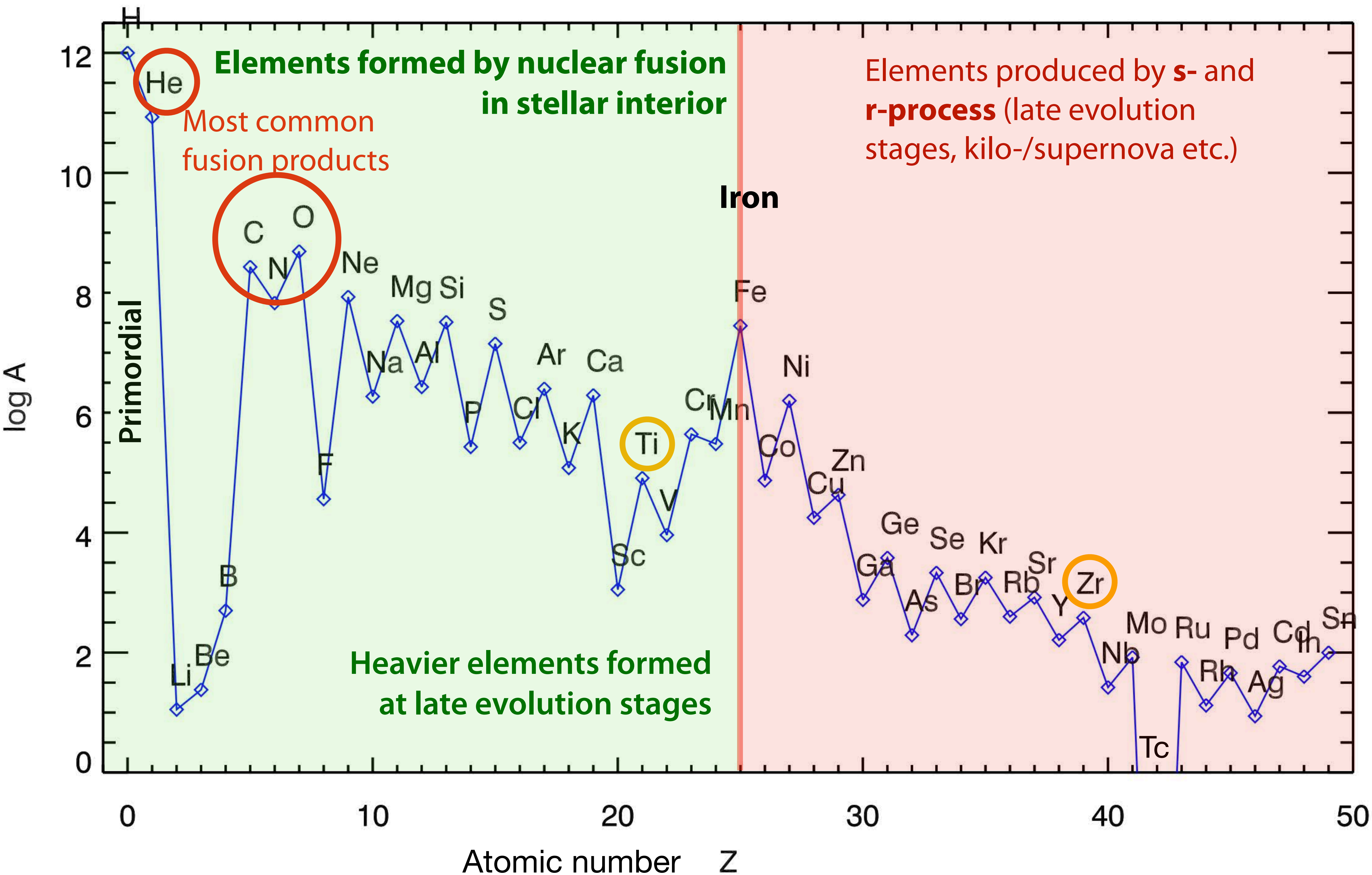
- Iron abundance relatively easy to measure due to large number of spectral lines (and as an important nucleosynthesis product) — often used as a representative metal

$$[\mathrm{Fe/H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{sun}}$$

- Also: Cosmo-chemical scale with silicon (Si) as reference but less common for stars

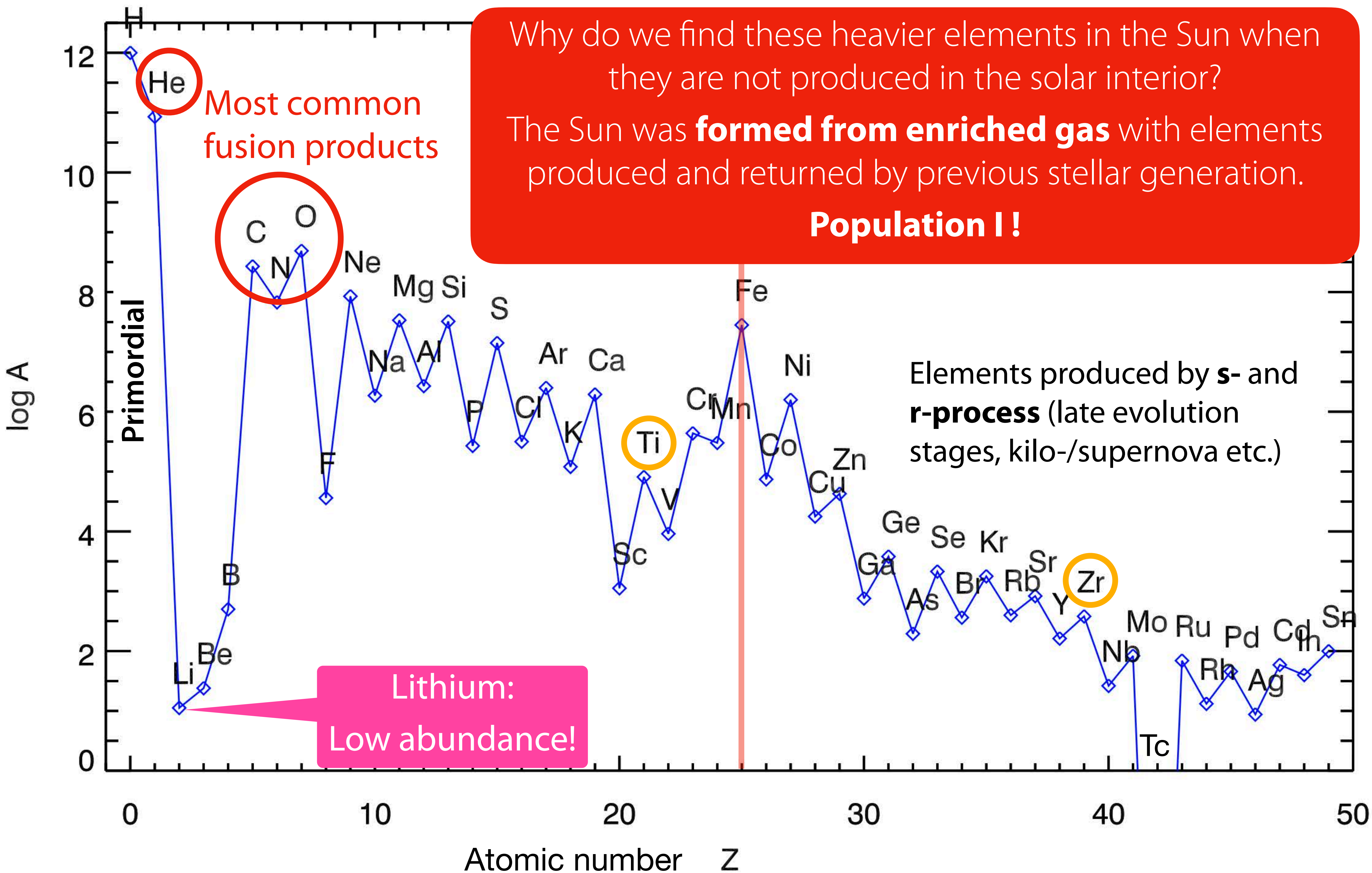
Physical stellar parameters

Chemical composition — Solar abundances



Physical stellar parameters

Chemical composition — Solar abundances



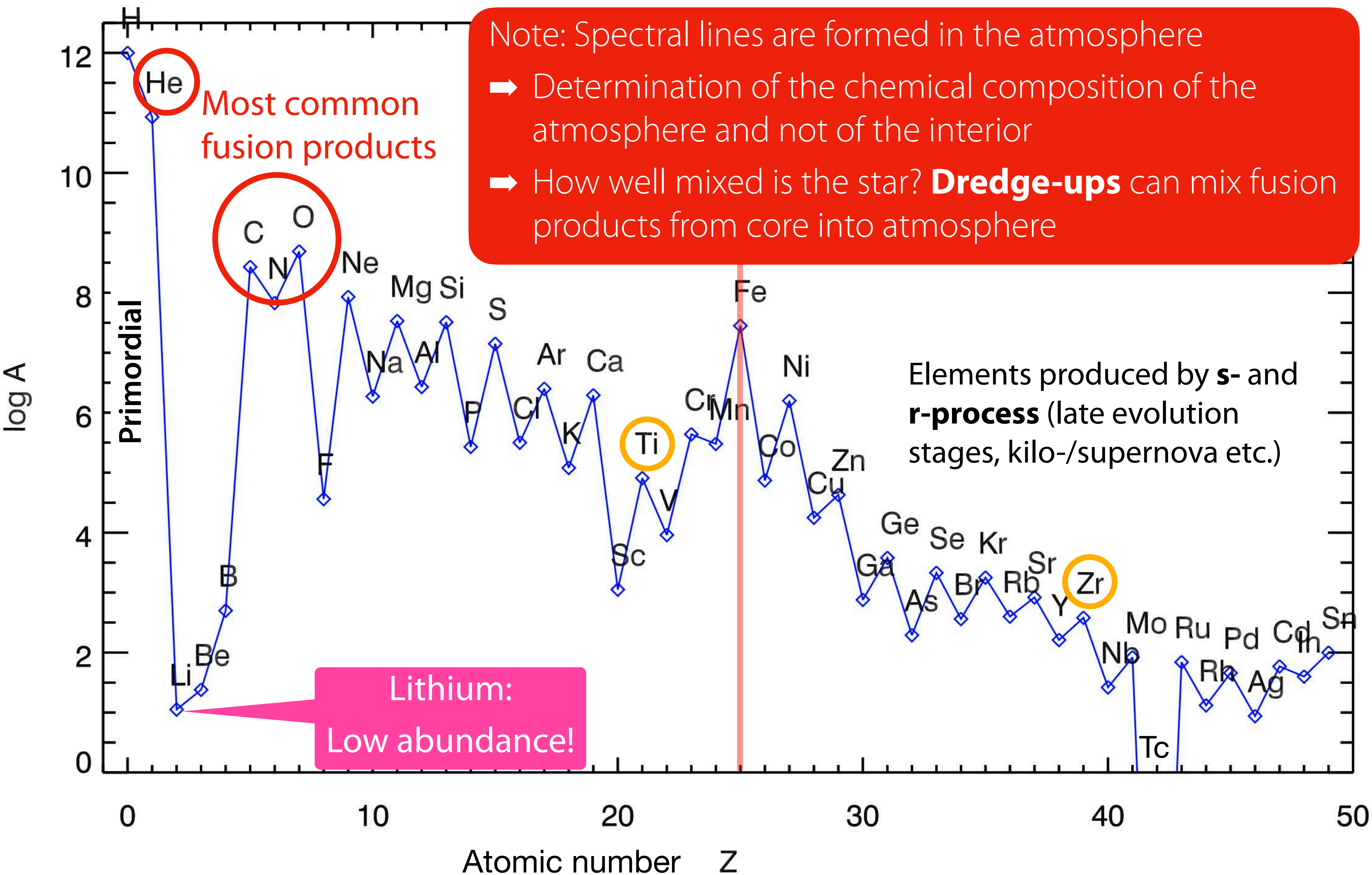
Physical stellar parameters

Chemical composition — Solar abundances

Note: Spectral lines are formed in the atmosphere

➡ Determination of the chemical composition of the atmosphere and not of the interior

➡ How well mixed is the star? **Dredge-ups** can mix fusion products from core into atmosphere

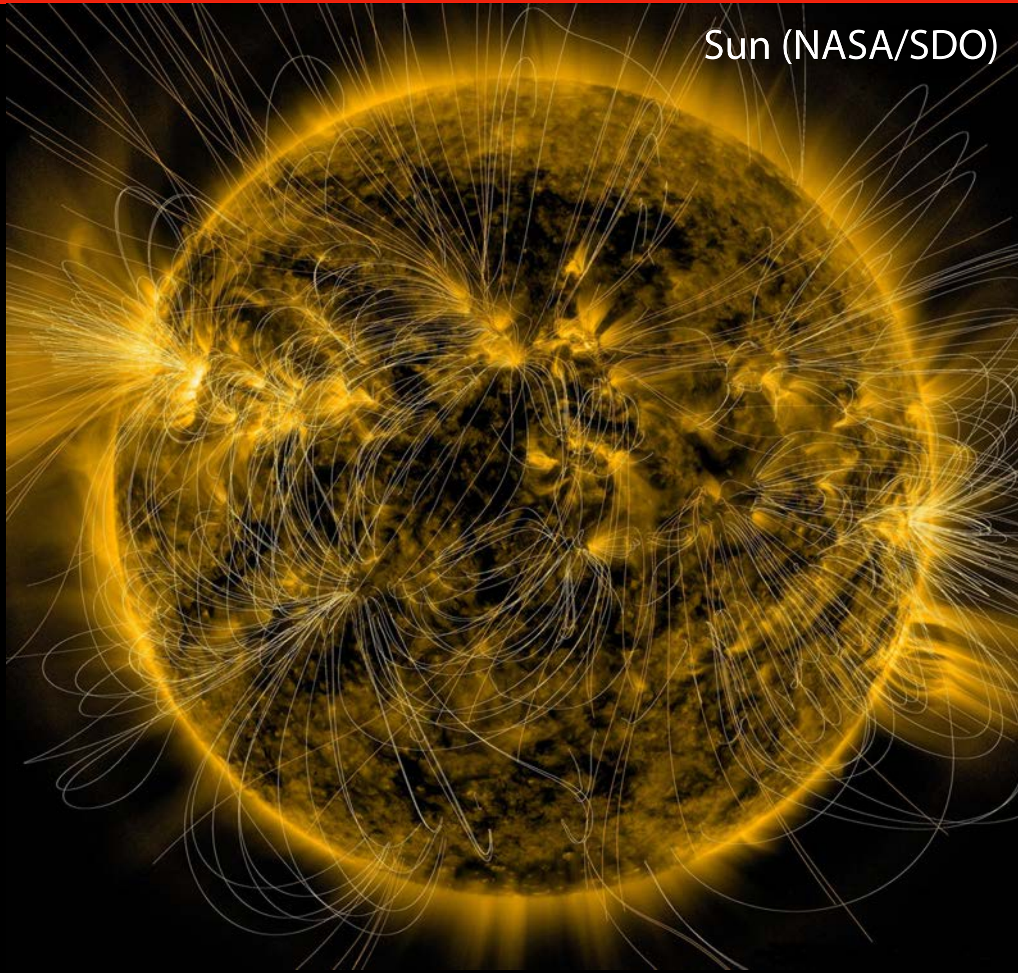


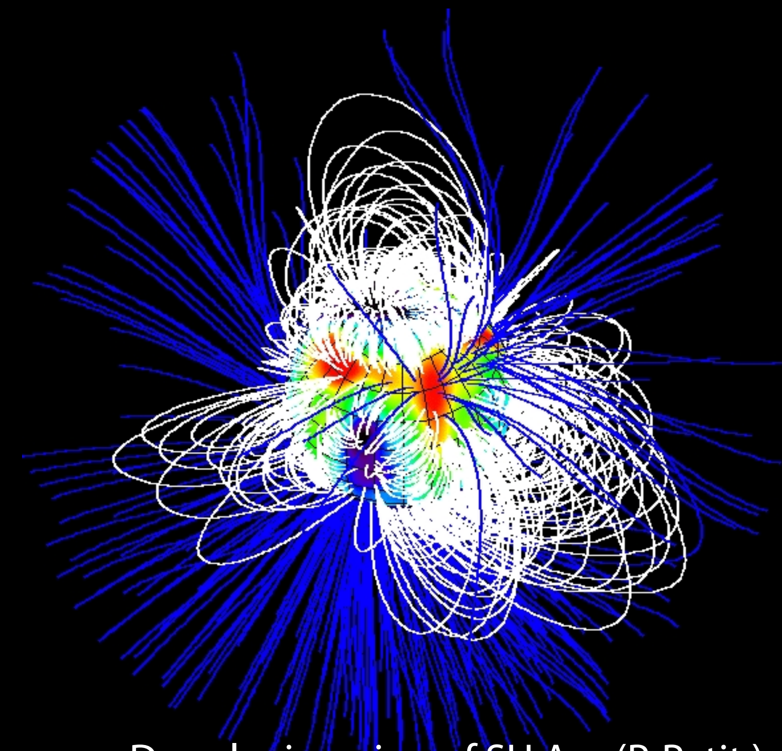
Physical stellar parameters

Magnetic field (B)

- Measurement via Zeeman effect in spectral lines
- **Sun**
  - Magnetic field very **inhomogeneous**/structured
  - In atmosphere, strongest: **Sunspots** B =2000–3000 G
  - Photosphere on average B ≈ 100–300 G
  - Min. in Quiet Sun and coronal holes: B < 1 G
  - Magn. field strength lower in upper atmosphere
- **Stars**
  - Only observed as point source but time series allow reconstruct of magnetic field as the star rotates

  ➡ Presence of starspots can be inferred
  - Average field strengths of several 1000 G are detected (up to 6000 G and higher in M-type dwarf stars, compare to White Dwarfs: 10^4 — 10^9 G)
- **Solar/stellar cycles:** Magnetic field changes


Sun (NASA/SDO)

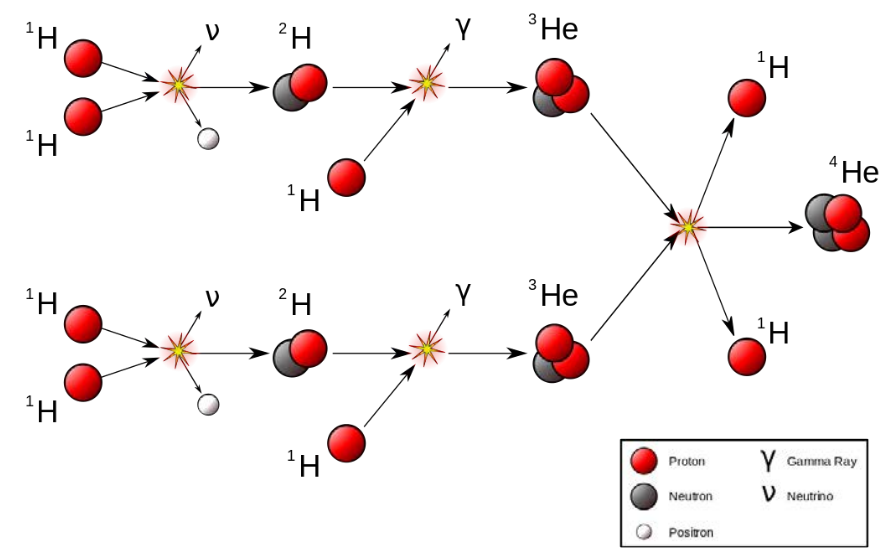

Zeeman Doppler imaging of SU Aur (P. Petit)

Physical stellar parameters

Lifetime of the Sun on the main sequence

- In solar interior: Thermonuclear fusion (here pp chain)
- 4 hydrogen nuclei (protons) → 1 helium nucleus (α particle)
- Mass difference $\Delta m = 4\ m_p - m_\alpha > 0$ corresponds then to released energy

$$\Delta E = \Delta m\ c^2$$



- **Energy released per fusion reaction:**

  $$E_{FUS} \sim 4.3 \times 10^{-12}\ \text{Ws}$$

Solar luminosity

$$L_\odot \sim 3.9 \times 10^{26}\ \text{W}$$

- Fusion reactions (pp) in the Sun per second: $N_{FUS} \sim L_\odot / E_{FUS} \sim \underline{10^{38}\ s^{-1}}$

- H-He fusion only in solar core, only ~10% of solar mass
- **Sun's lifetime ~ $\underline{10^{10}\ \text{yr}}$!**

Physical stellar parameters

Stellar lifetime on main sequence

- Longest time via hydrogen fusion ("hydrogen burning")

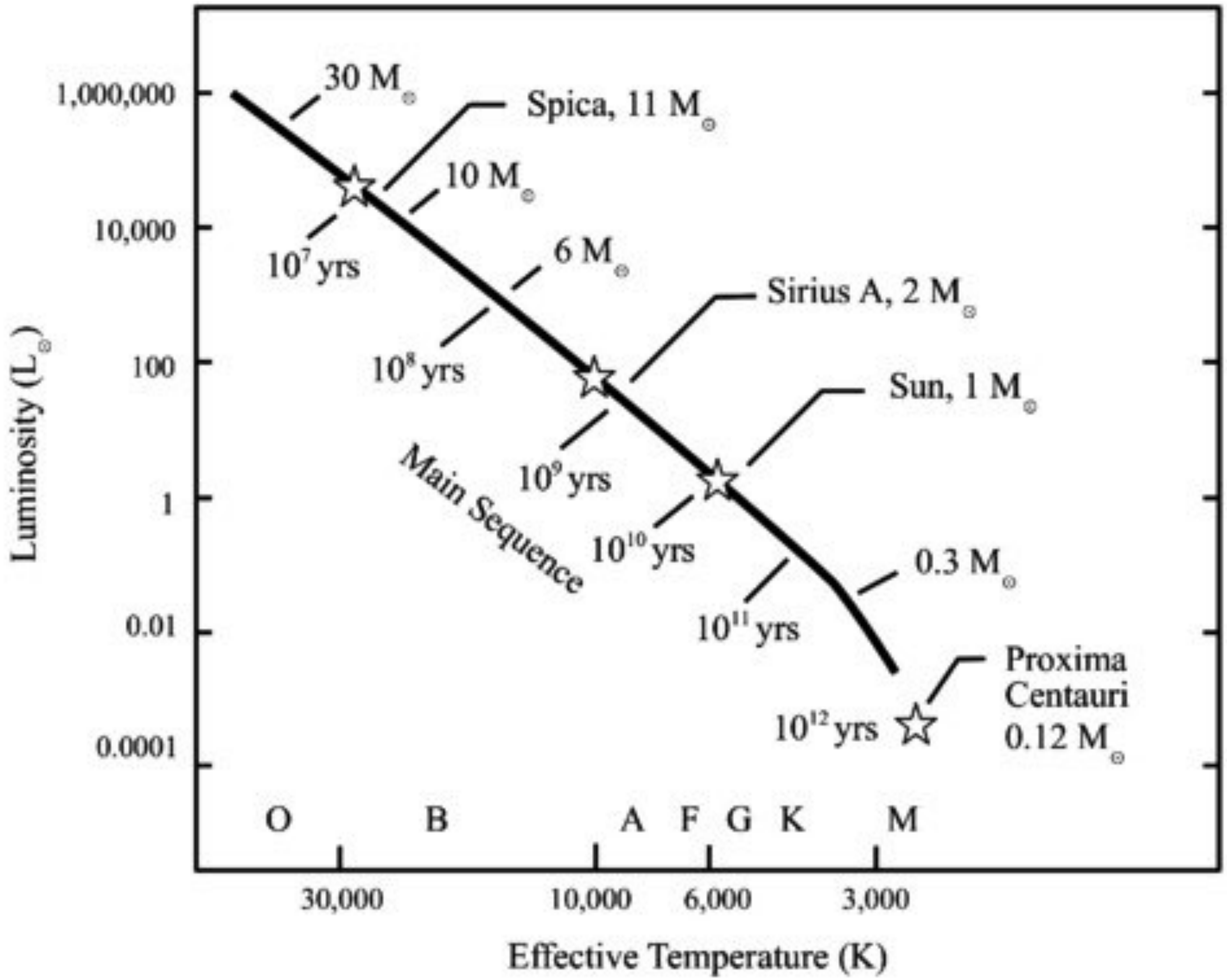
- Most stars therefore found there, forming the main sequence

- Higher luminosity

➡ Faster use fo nuclear "fuel"

➡ Shorter lifetime

➡ Massive stars life much shorter than low-mass stars



Physical stellar parameters

Overview

Type	Mass	Temp.	Luminosity	Life time [10^6yr]	Occurrence
O	50	40 000 K	100 000	10	0.00001 %
B	10	20 000 K	1000	100	0.1 %
A	2	8500 K	20	1 000	0.7 %
F	1.5	6500 K	4	3 000	2 %
G	1	5700 K	1	10 000	3.5 %
K	0.8	4500 K	0.2	50 000	8 %
M	0.3	3200 K	0.01	200 000	80 %

- **Main sequence stars** with same mass have typically similar radius, luminosity and temperature (only small slow changes during the time of the main seq. and chemical composition)

- **Low mass stars by far most abundant!**

Physical stellar parameters

Overview

Type	Mass	Temp.	Luminosity	Life time [10^6yr]	Occurrence
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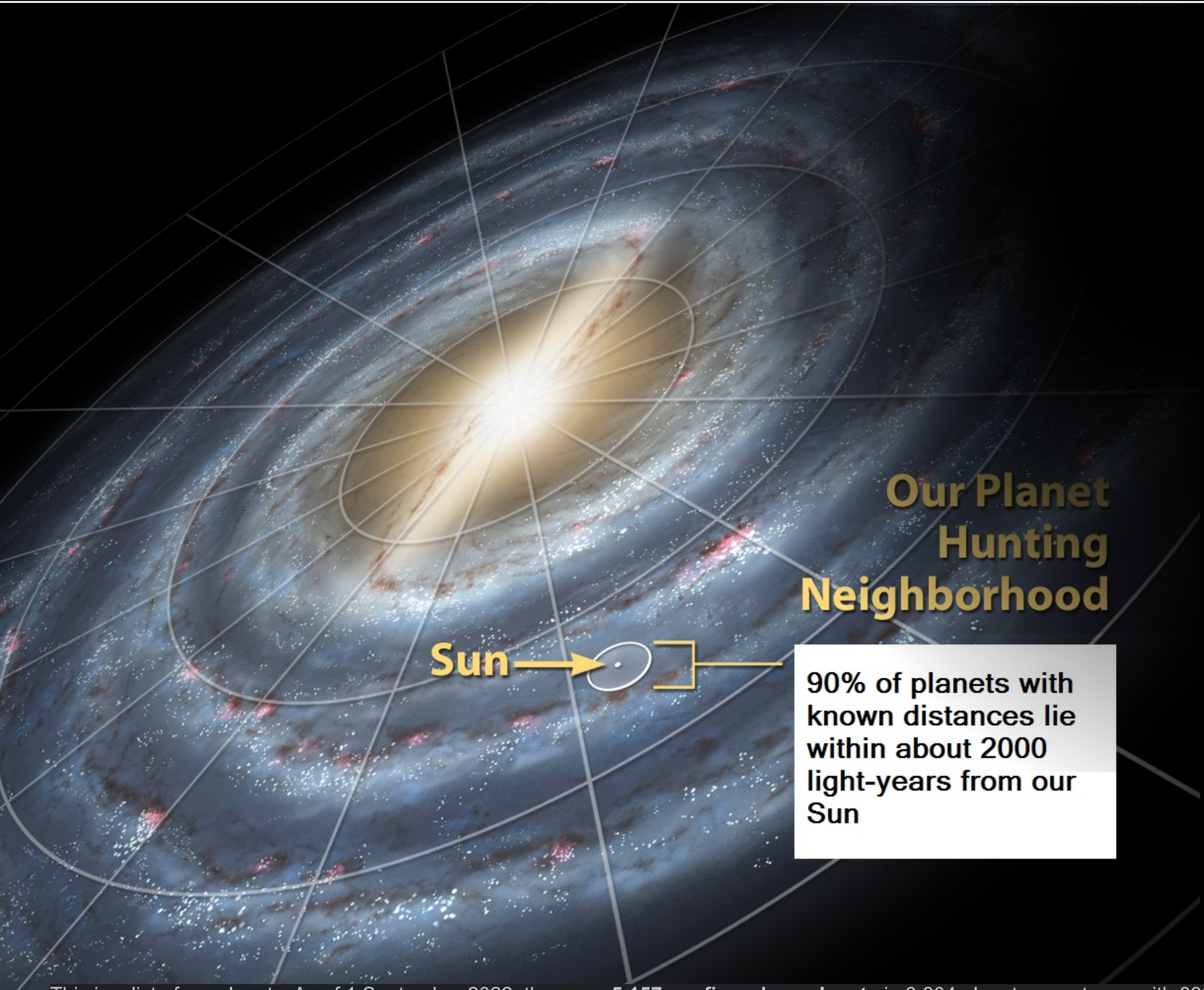
M	0.3	3200 K	0.01	200 000	80 %

- NOTE: This is the total expected lifetime on the main series (these stars are not older than the universe)
- No K or M-type dwarf has left the main sequence yet!
- Massive stars live only millions of years — Too short for the formation of life!?

How many are there?



- 100-400 billion stars in our galaxy (Milky Way)
- More stars in the universe than sand grains on the Earth …
- And likely at least as many exoplanets…

This is a list of exoplanets. As of 1 September 2022, there are **5,157 confirmed exoplanets** in 3,804 planetary systems, with 833 systems having more than one planet. Most of these were discovered by th Kepler space telescope.

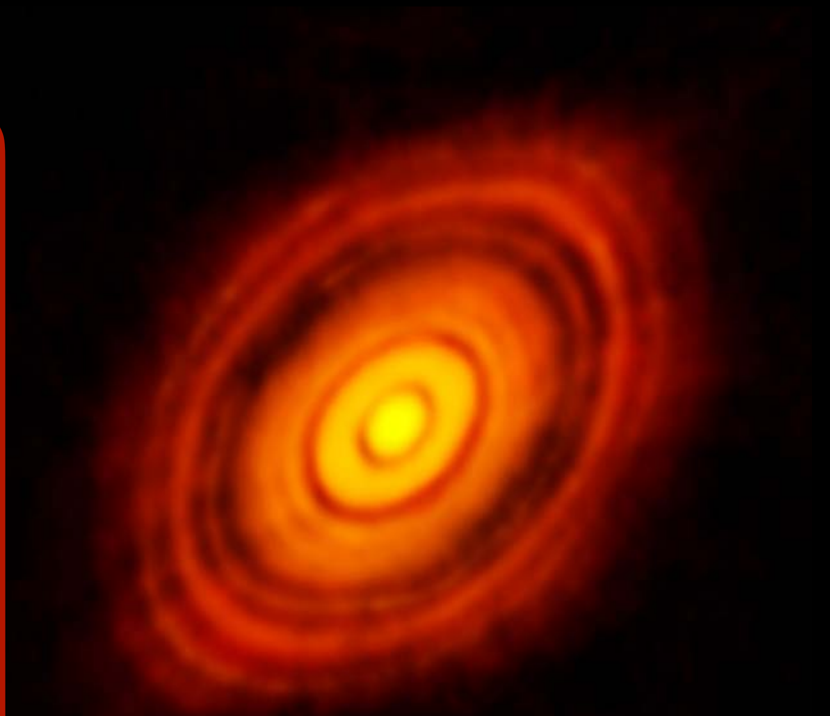
Stellar evolution

Stellar evolution

Star formation

- Star formation: Collapse of giant molecular cloud, fragmentation
  ➡ Stars typically form in groups (e.g., Pleiades)
- Formation of protostar once core becomes hot and dense enough to establish hydrostatic equilibrium
- Further contraction, approaching Zero Age Main Sequence (ZAMS) on Hayashi tracks (fully convective)

T Tauri stars:
pre-main sequence (age ~ 10^6 yr), accretion disk still optically thick, large IR excess observed



HL Tauri ALMA (ESO/NAOJ/NRAO)

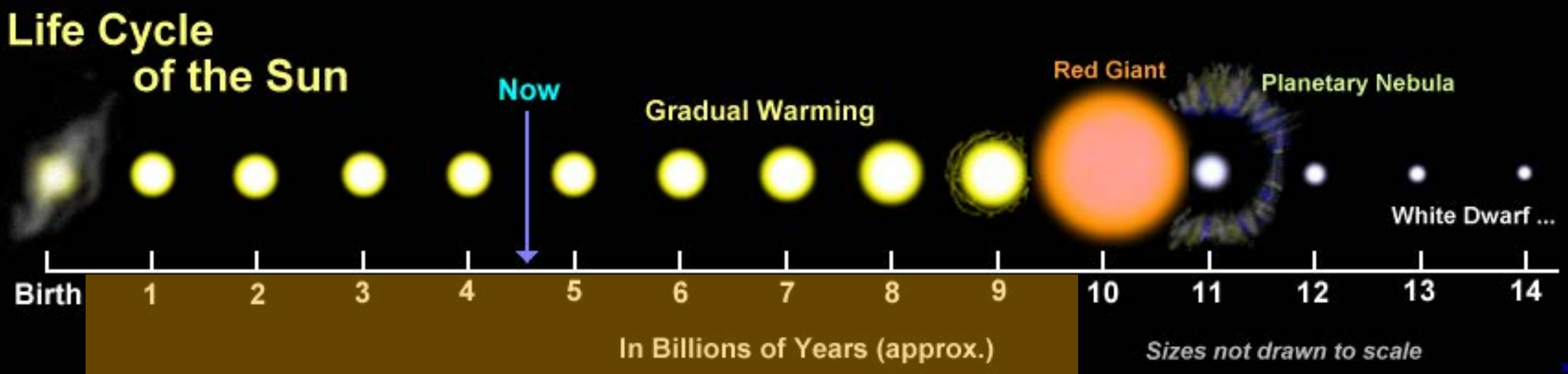
Pleiades (M45)

Stellar evolution

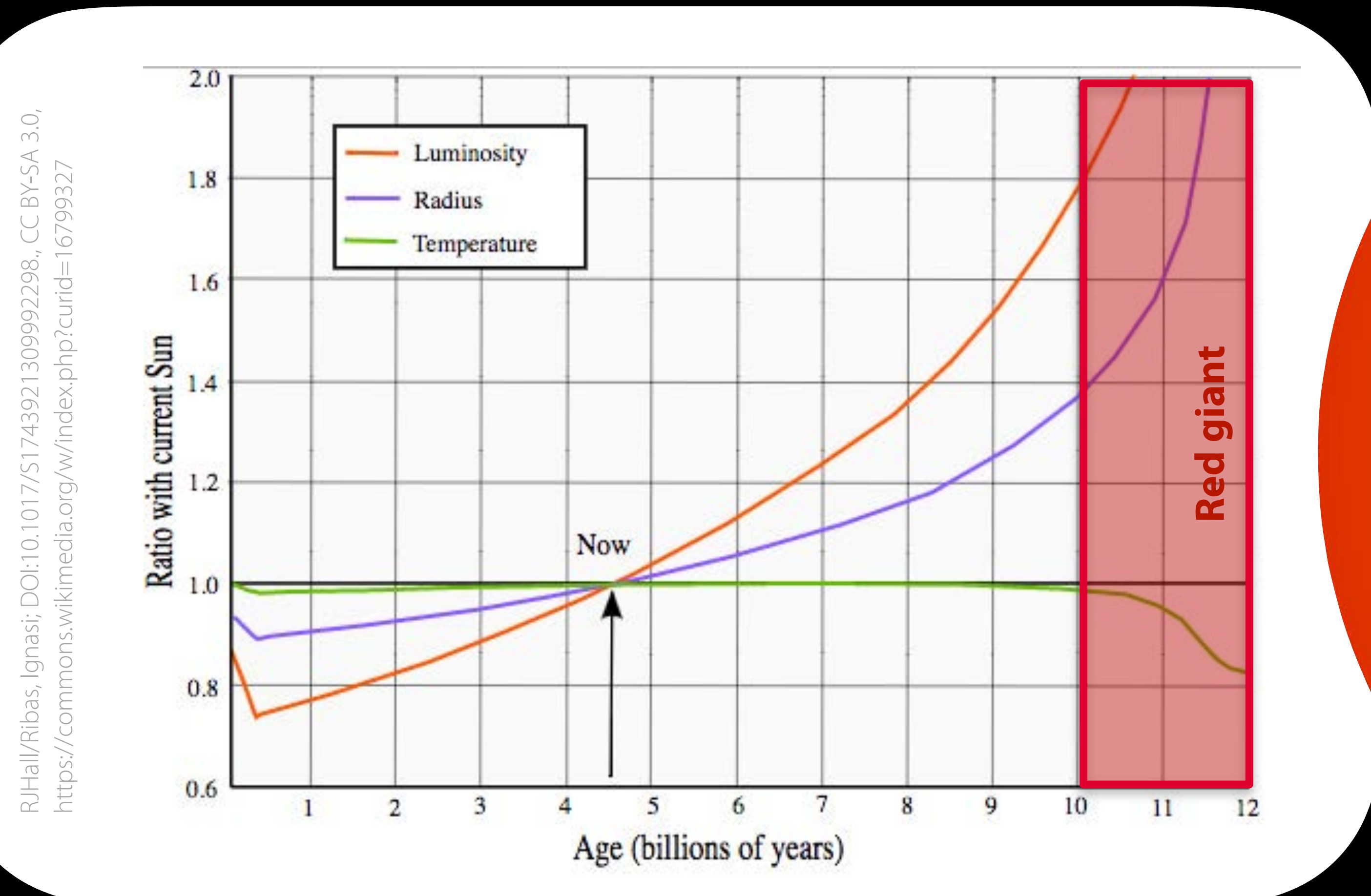
Overview

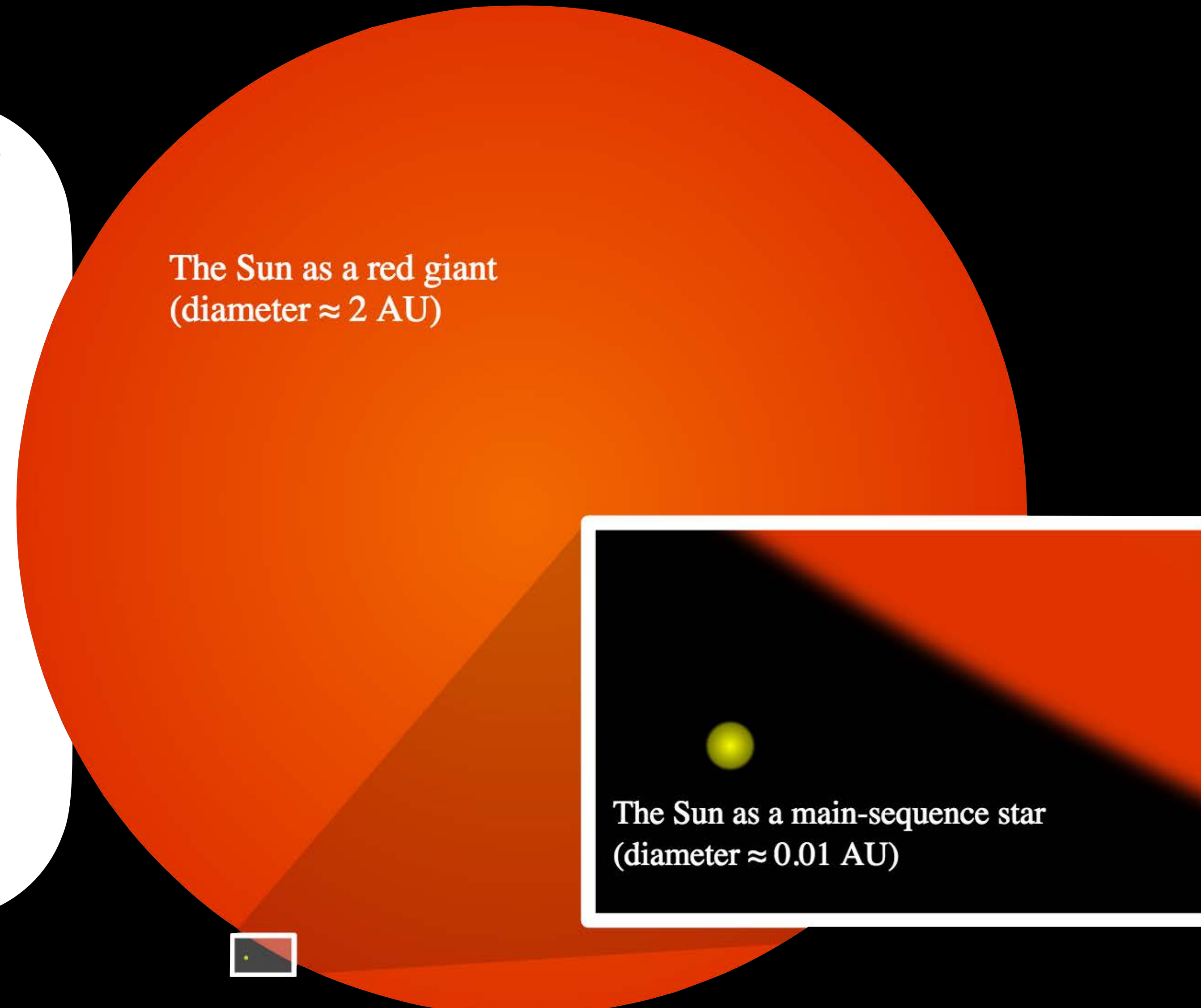
Sun's lifetime ~ 10^{10} yr!

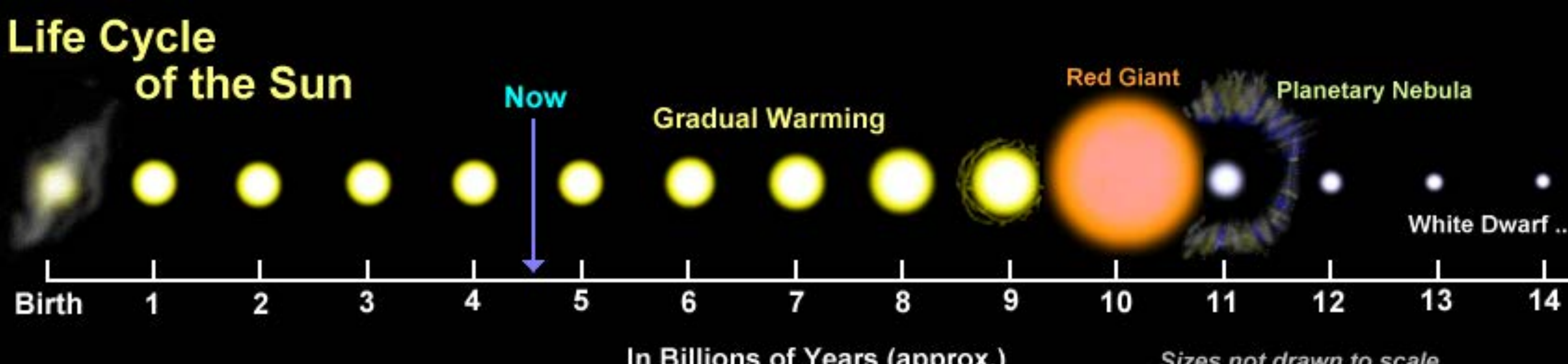
- **Main sequence**
  - Begins when reaching Zero Age Main Sequence (ZAMS)
  - Hydrogen fusion (H burning) in the core
  - Longest evolution stage
- **Post-main sequence evolution**
  - More complicated due to different fusion stages (elements) in the core and/or shells
  - Reached fusion stage highly mass-dependent
  - **Mirror principle** for stars with shell burning — expansion and contraction opposite of a shell (core — envelope)
  - **Equation of state** — beyond ideal gas



Solar evolution







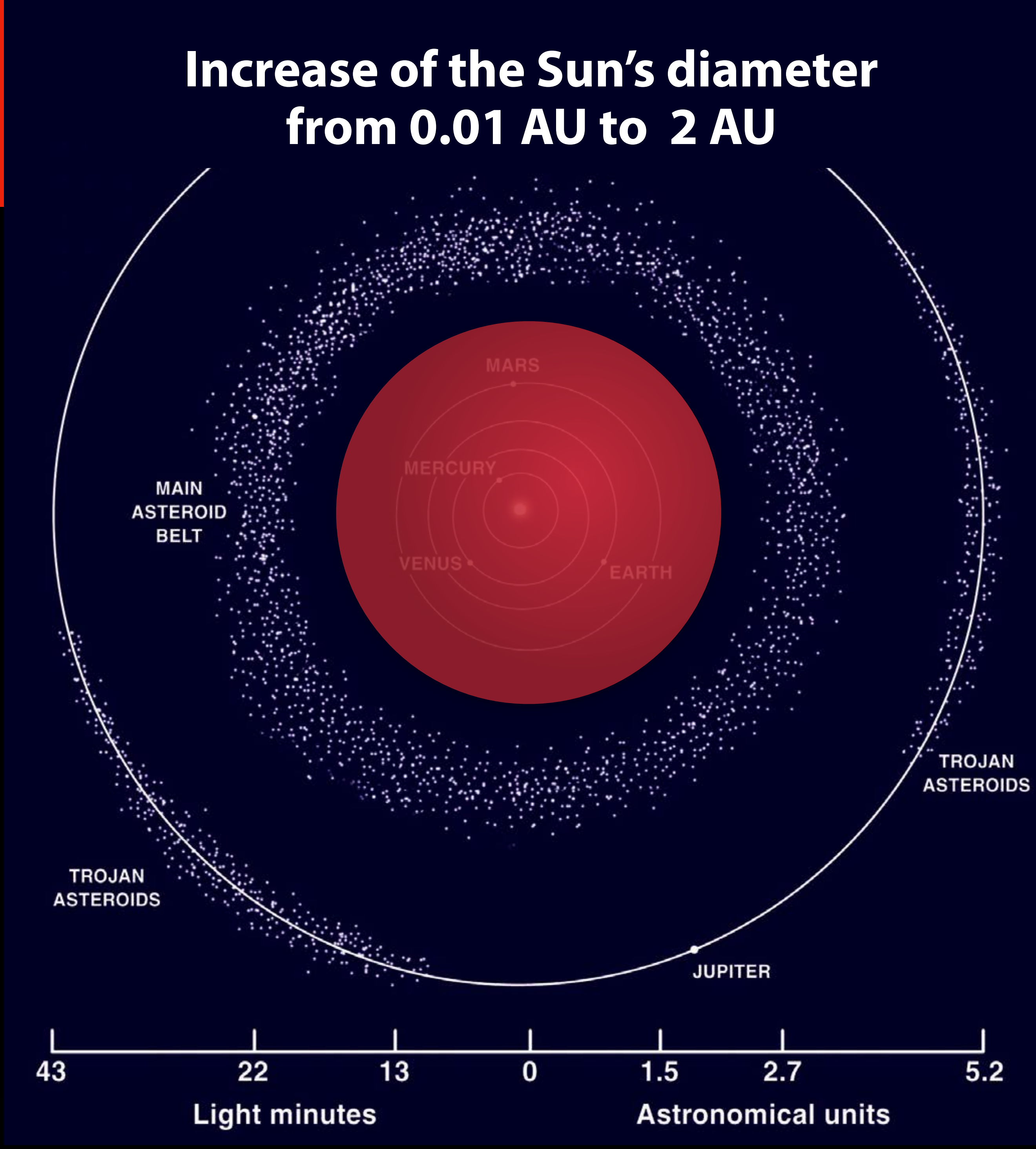
Solar evolution

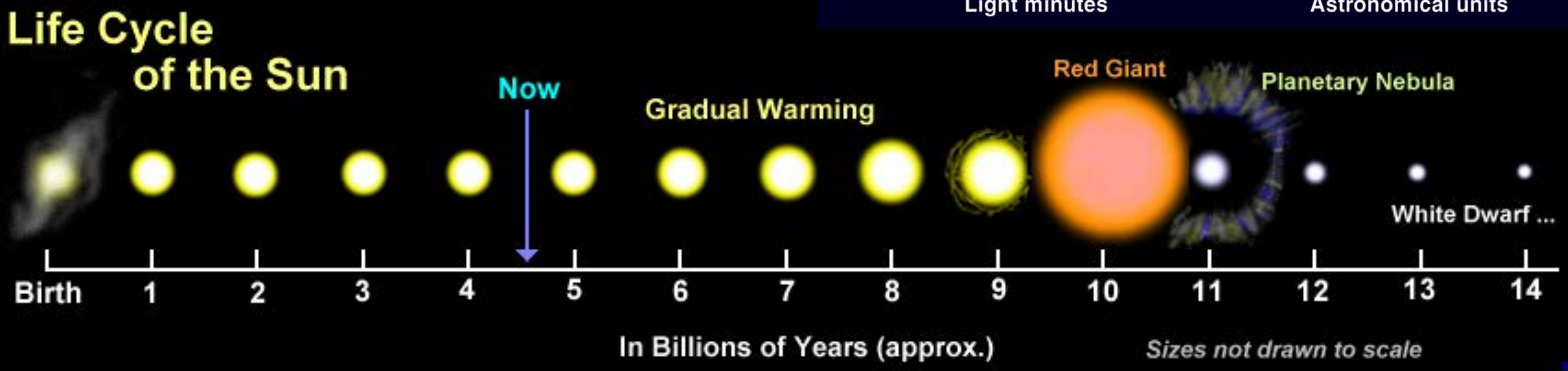
Late evolution stages

- **Red giant star**
- High radiation pressure in the star's interior makes the radius large
- The surface becomes large.
- Radiation is spread over a large area:

➡ Low surface temperature

➡ Low surface gravity





Solar evolution

Faint Young Sun paradox

- Models imply that Sun's brightness slowly increased (and will continue to increase)

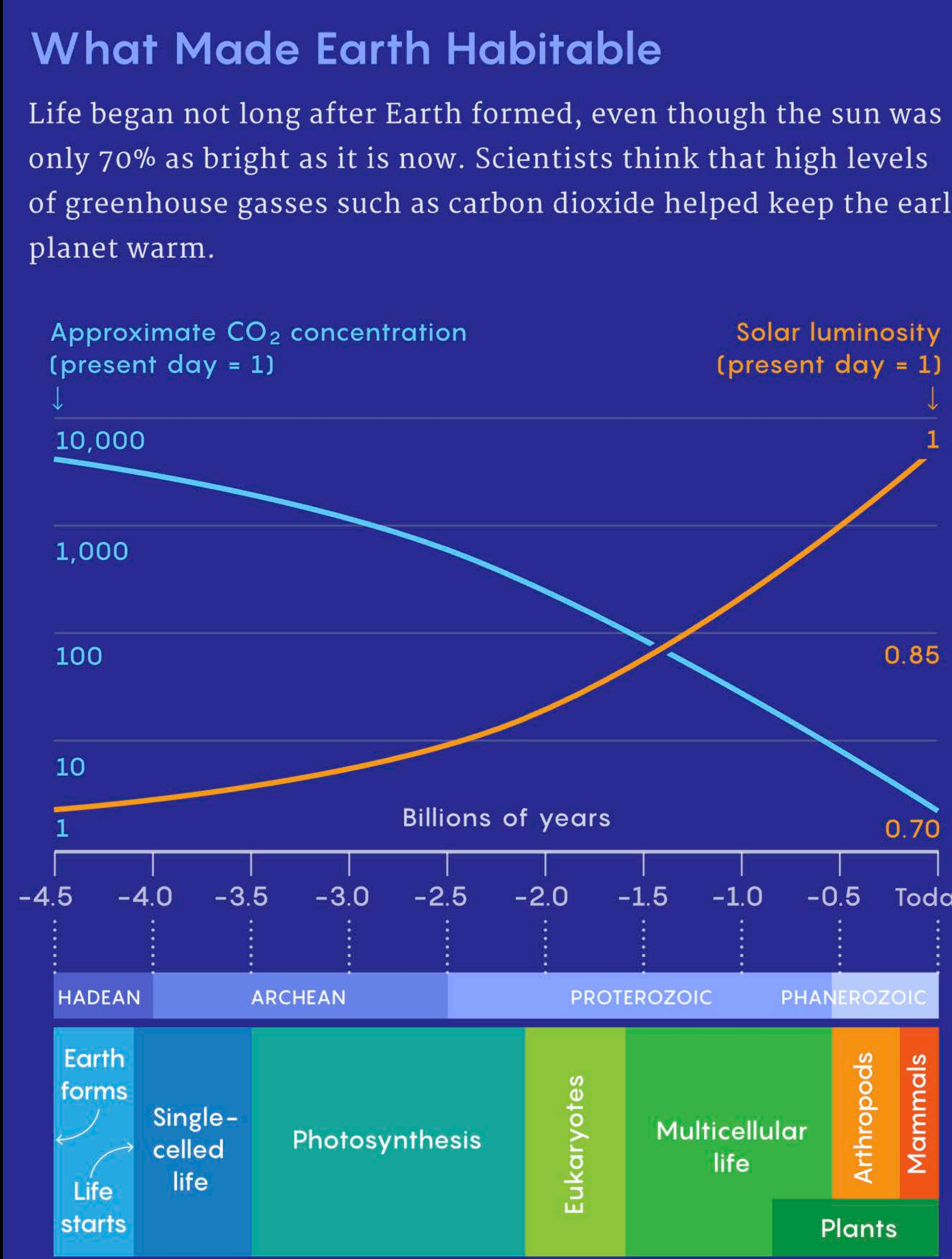
  ➡ 4.5 billion years ago: **~30% fainter than today!**

  ➡ But evidence for liquid water on Earth already 4 billion years ago!

  ➡ How was that possible at much lower solar irradiation levels?

  - Most likely compensated by other factors like green house effect (outgassing of CO_2), increased volcanism stimulated by gravitational influence of a much closer moon, …

  ➡ Implications for habitability of Earth and of exoplanets in general (formation of life!?)



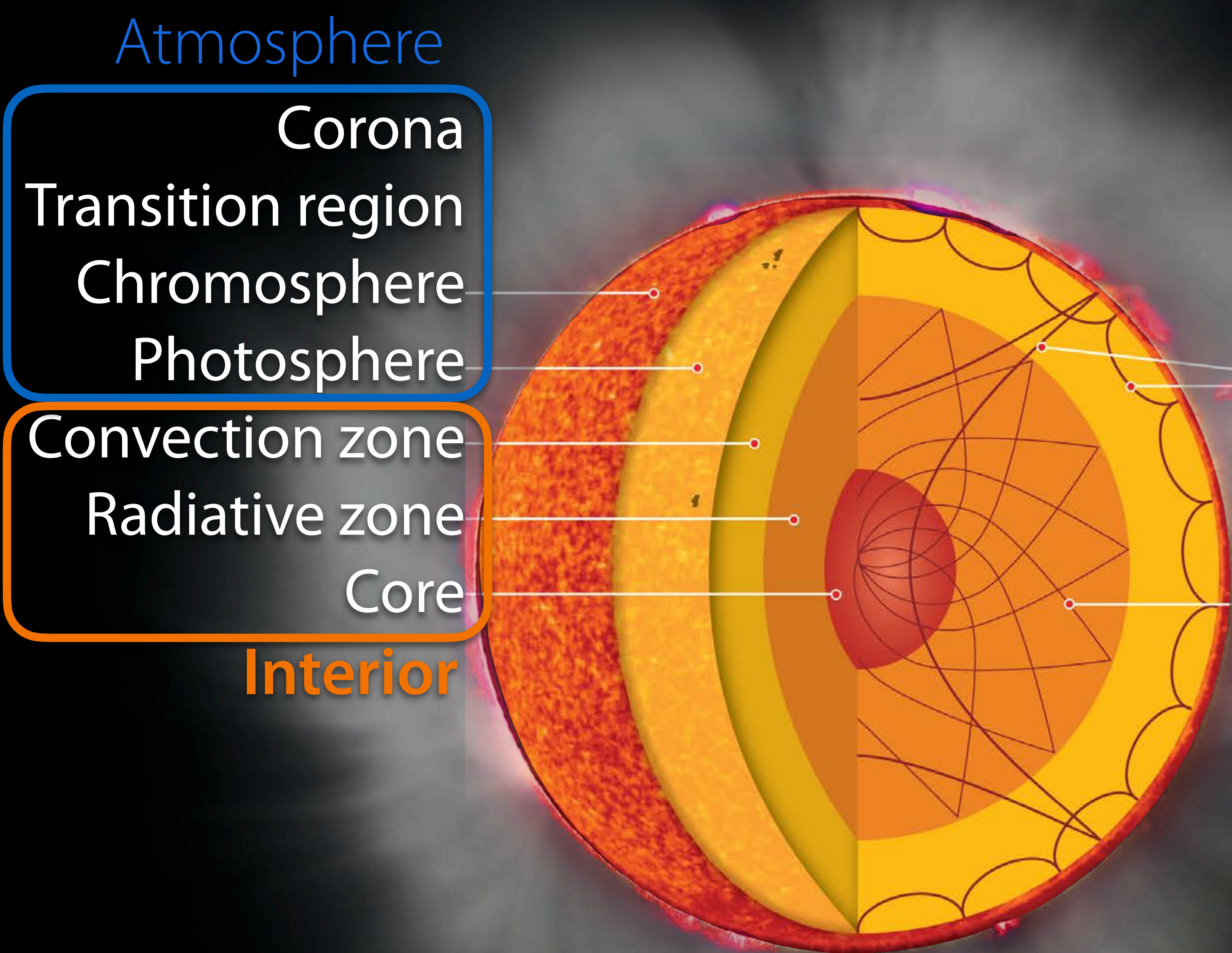
Samuel Velasco/Quanta Magazine; source: Catling and Kasting (2017)

Stellar interiors

—

Structure and energy transport

Stellar structure — The Sun

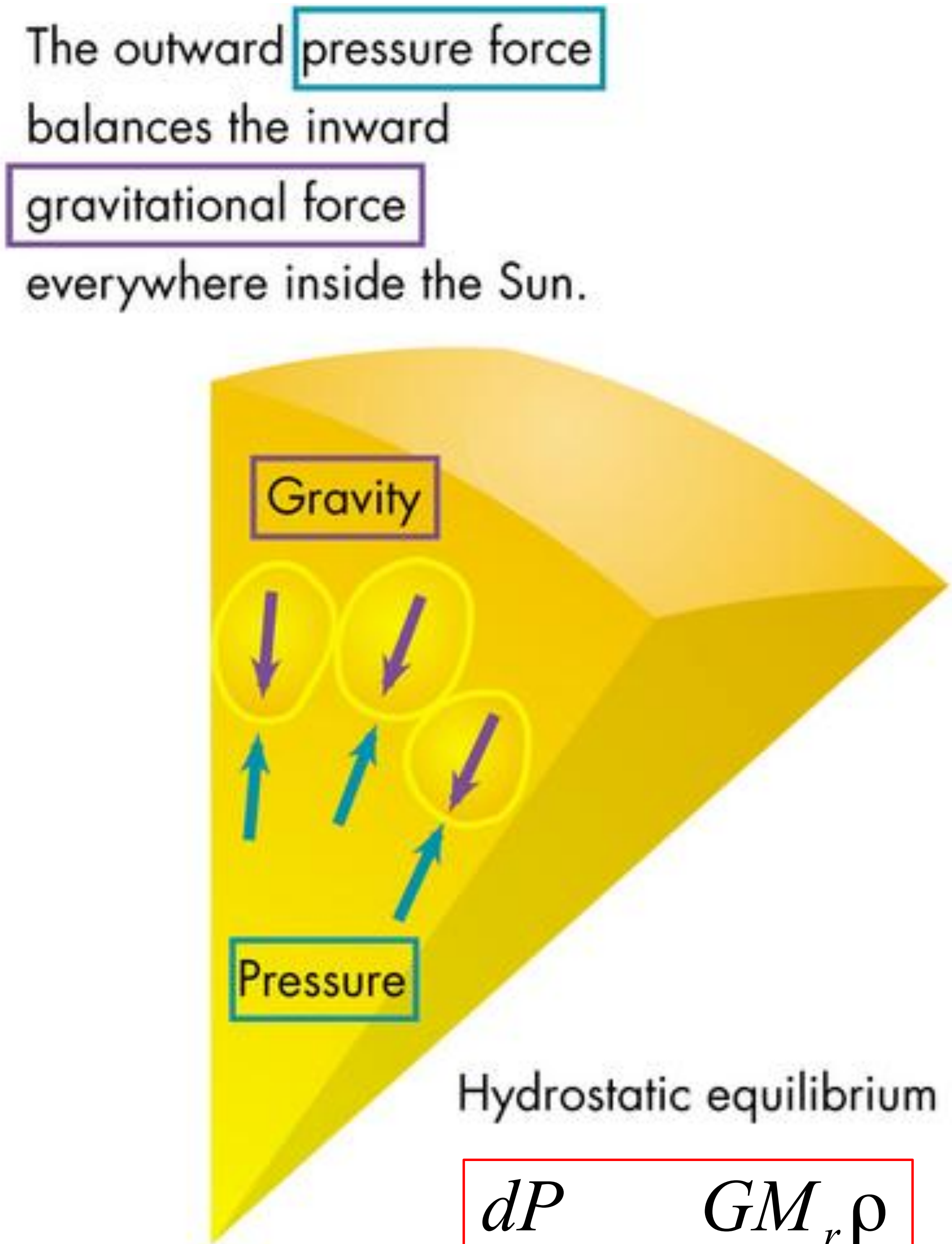


- **How do we know about the structure of the Sun below its "surface"?**
- Stellar models must explain the observations (mostly radiation emitted from the atmosphere)
- Solar neutrinos
- Oscillations of the surface — **helioseismology**

- **Asteroseismology** provides additional constraints on the determinations of stellar parameters (e.g., masses, radii, mean densities, ages)
- Synergies with exoplanet missions that look for small variations in the host star

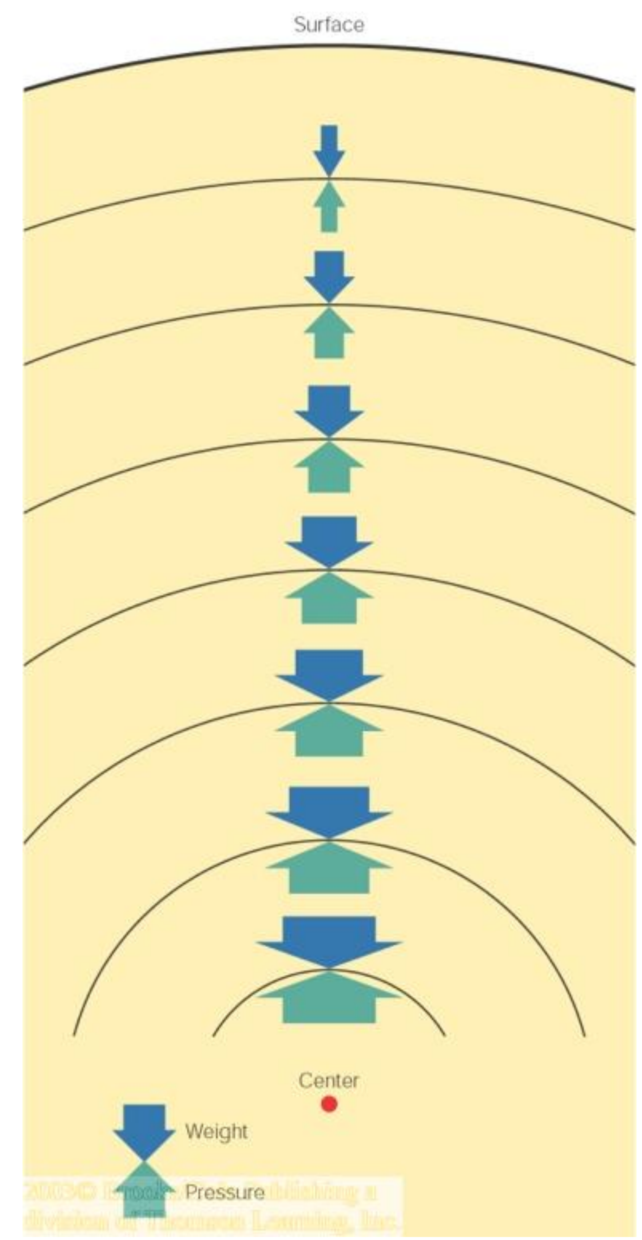
Stellar structure

Hydrostatic Equilibrium



$$\frac{dP}{dr} = -\frac{GM_r\rho}{r^2}$$

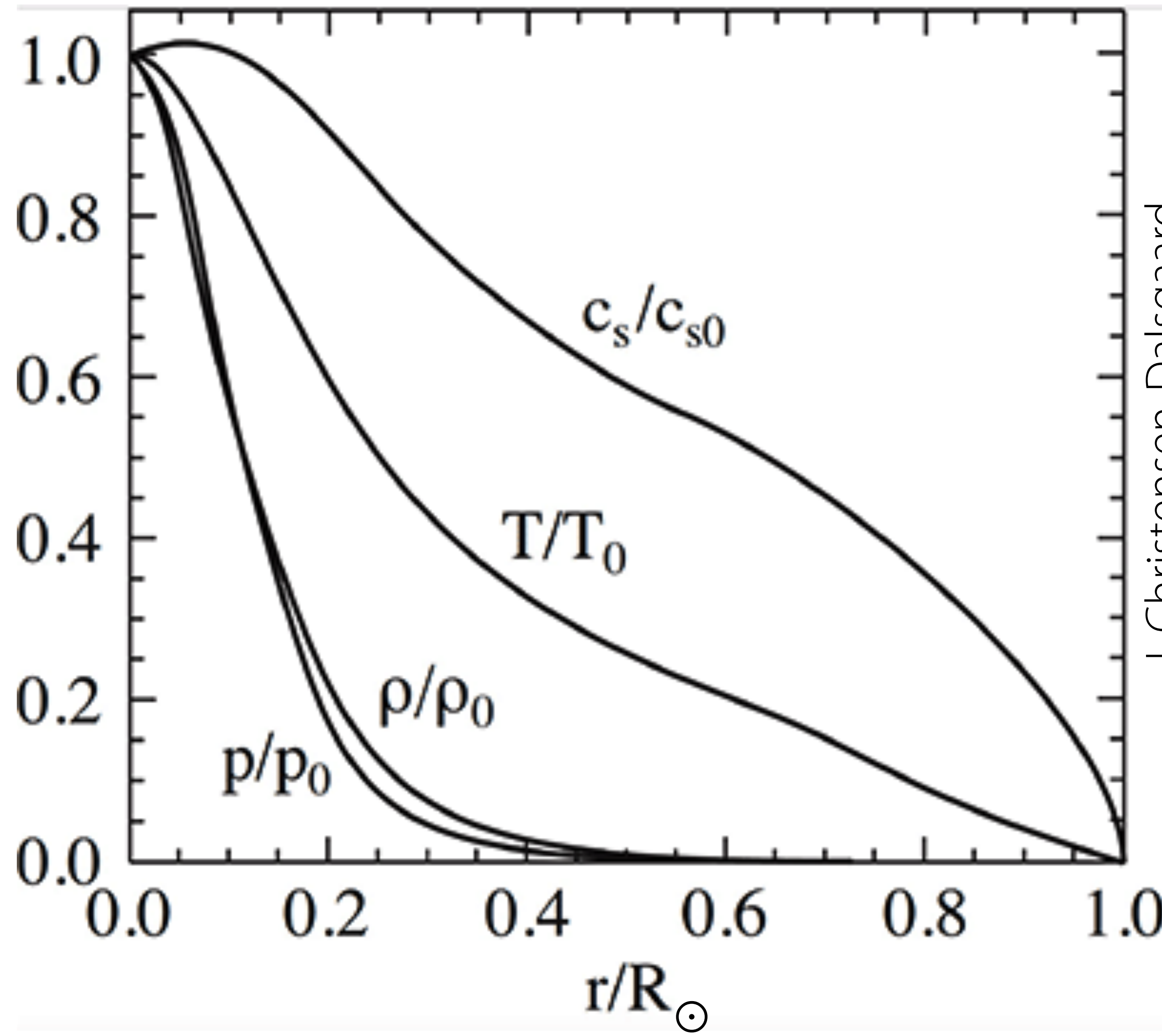
- Outward pressure of hot gas in the center balances the inward force due to gravity.
  - ➡ At any given radius balancing the weight of all layers above
  - ➡ Imbalance at some radius will result in corresponding adjustment of the stratification
  - ➡ Determines the interior structure (stratification)
- Main Sequence in the Hertzsprung-Russell diagram is a narrow strip as it requires stability over long enough time



Stellar interior

Standard model of the solar interior

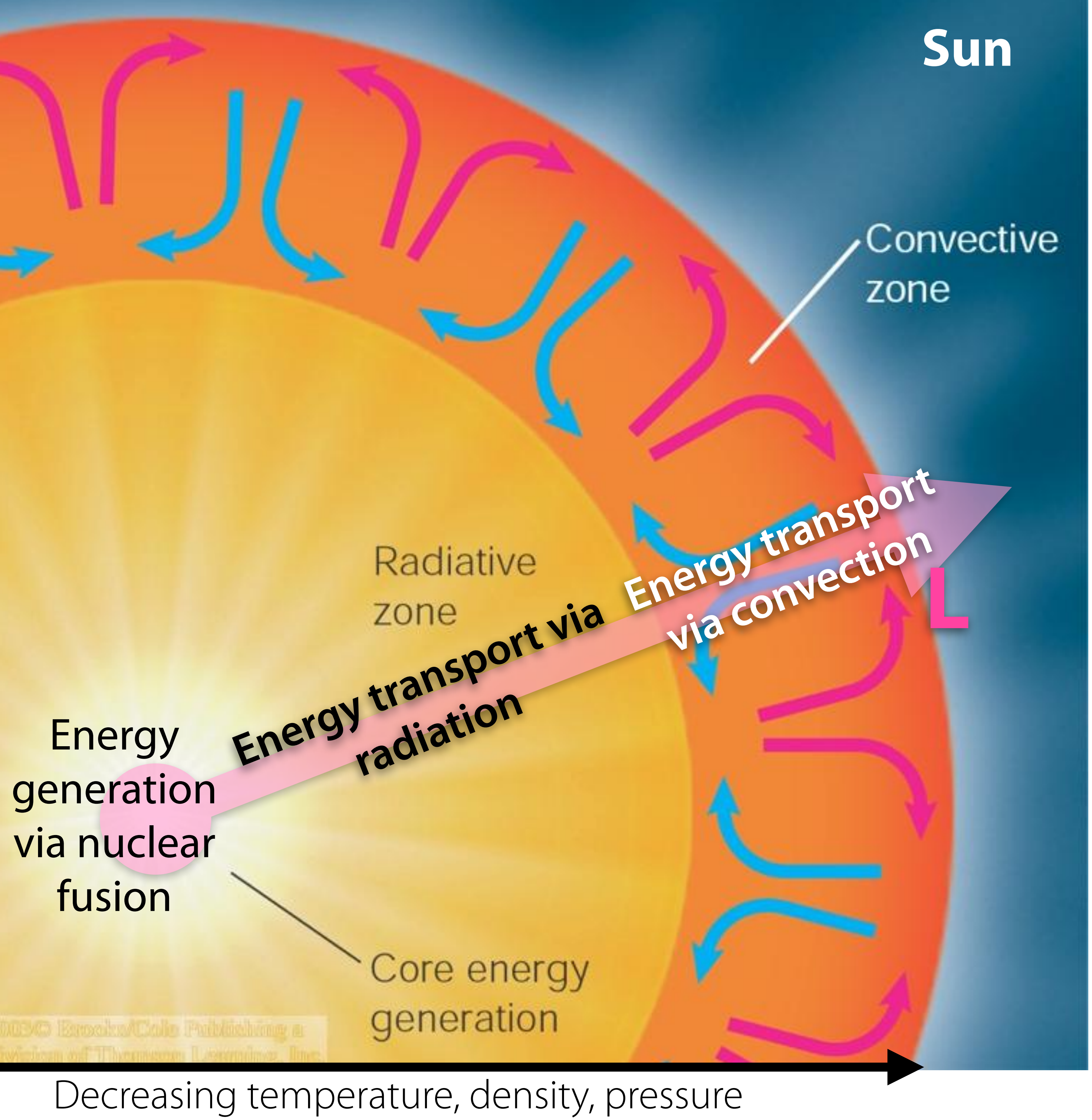
- Variation of (average) quantities as function of radius in the solar interior (r/R⊙)
- Scaled to value at solar centre
- Temperature T_0=1.57 10^7 K
- Mass density ρ_0=1.54 10^5 kg m^{-3}
- Pressure p_0=2.35 10^{16} Nm^{-2}
- Sound speed $c_{s,0}$=5.05 10^5 ms^{-1}



J. Christensen-Dalsgaard

Energy transport

In the Sun and solar-like stars



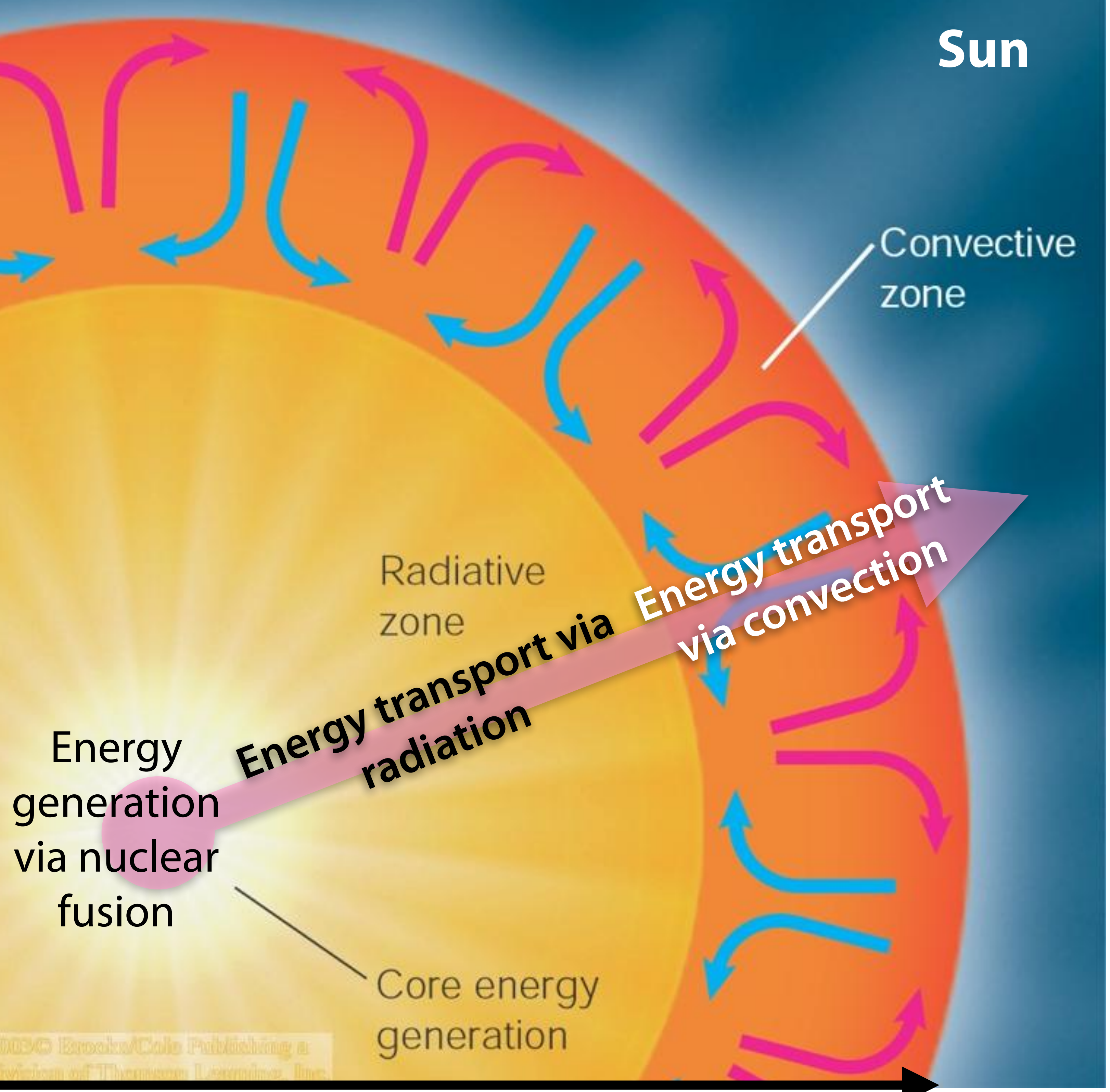
- At any depth in the Sun:
  - Energy flux **F** defined as the luminosity per unit area.
  - Energy transport by radiation (F_R) and by convection (F_C)
  - Conduction insignificant in solar interior

$$F = F_{\rm R} + F_{\rm C} = L/4\pi r^2$$

- Time for a photon to travel the distance centre-surface <u>without</u> interaction ~2s
- **In the dense solar interior: Mean free path of a photon only ~1 cm**
  - ➡ Time ~ thermal timescale of the Sun **~ 2 10⁷ yr**
  - ➡ Observed radiation due to fusion reactions (on average) tens of millions of years ago.

Energy transport

In the Sun and solar-like stars



Decreasing temperature, density, pressure

- Properties (e.g., temperature) change as function of distance from centre
- Gradients decisive for convective (in)stability criterion
- Convective energy transport very efficient

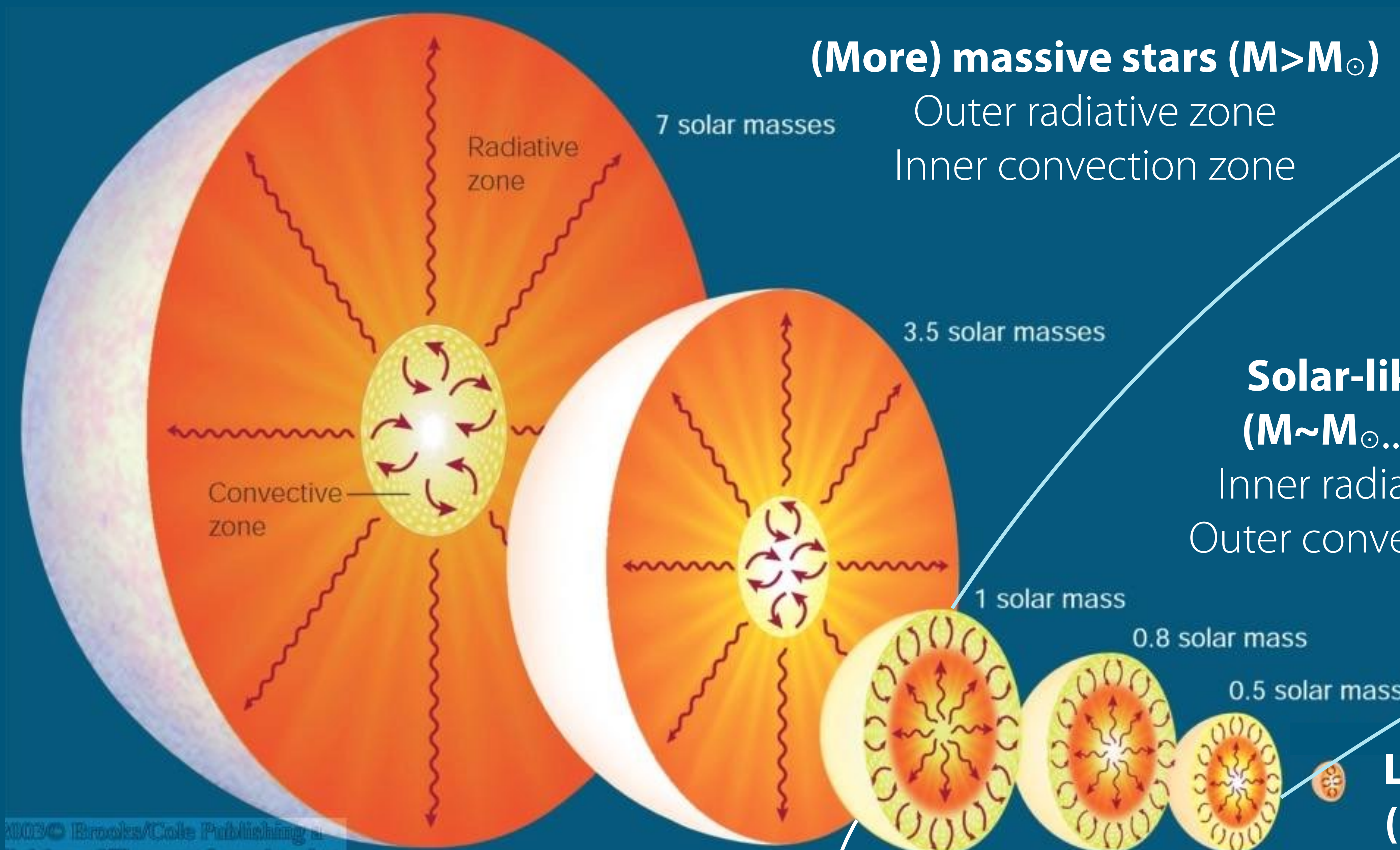
➡ Outer convection zone in the Sun and solar-like stars at $r > 0.7\ R_\odot$

- Convection cell diameter ~2 Mm near solar surface but much larger deeper in the convection zone
- Turnover time scale in the Sun between 200s at surface and 25 days at bottom of convection zone

Energy transport

Differences along the main sequence

- Significant structure changes at late evolution stages
- Multiple fusion shells and convection zones



(More) massive stars ($M>M_\odot$)
Outer radiative zone
Inner convection zone

Solar-like stars ($M \sim M_\odot ... 0.4M_\odot$)
Inner radiative zone
Outer convection zone

Low-mass stars ($M< 0.3\text{-}0.4M_\odot$)
Fully convective

Dominant fusion process	**CNO cycle**	**pp chain**

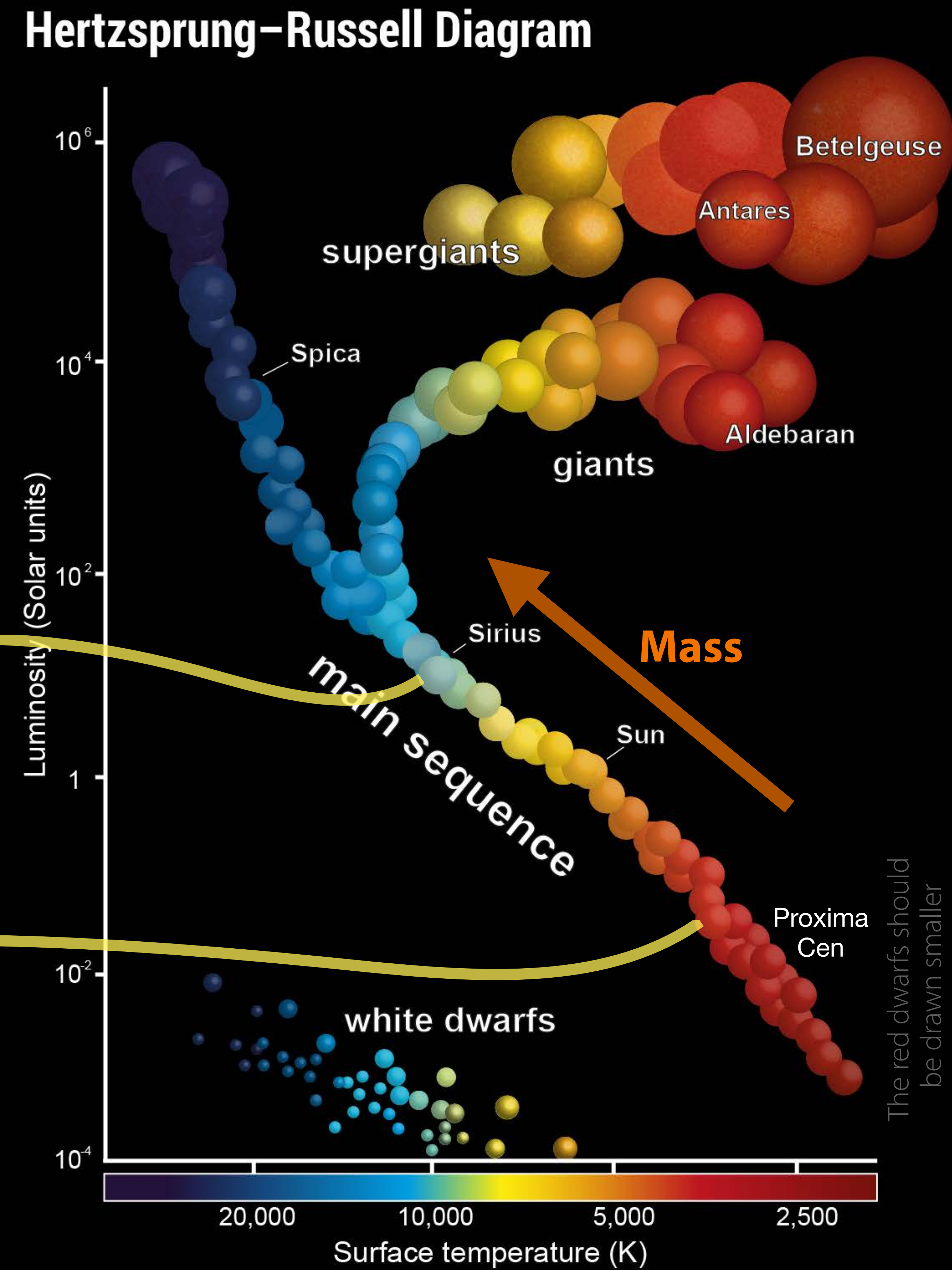
Energy transport

Differences along the main sequence

(More) massive stars ($M>M_\odot$)
Outer radiative zone
Inner convection zone

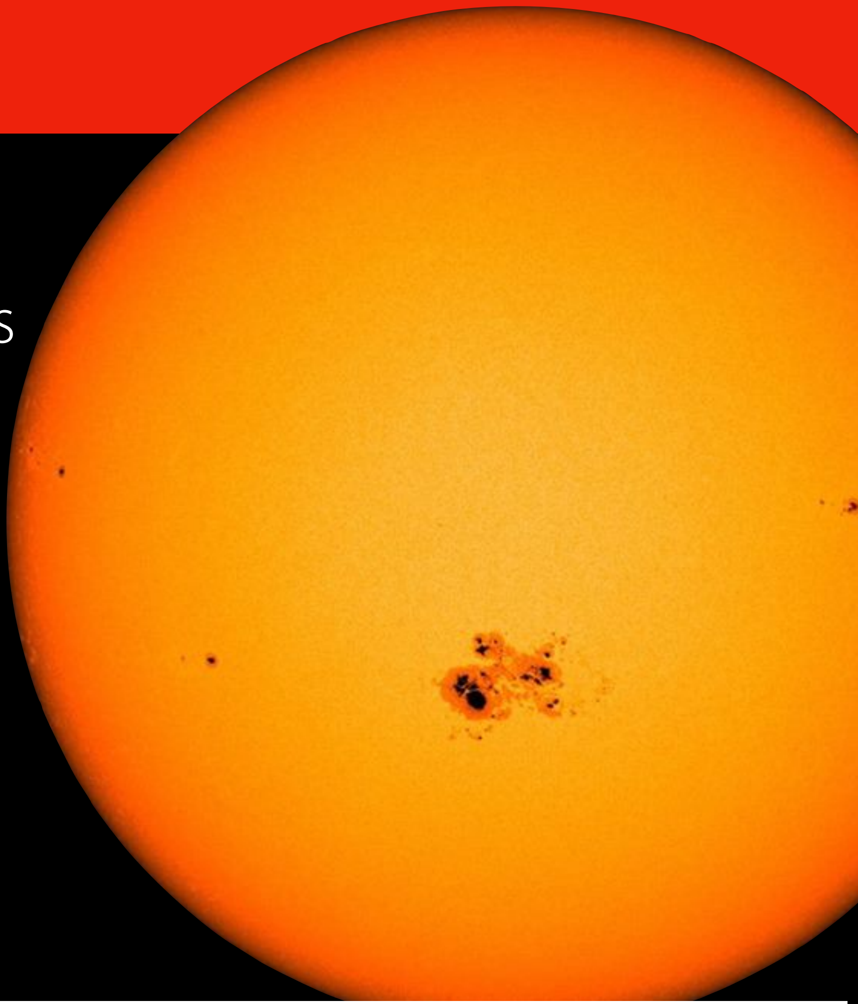
Solar-like stars ($M \sim M_\odot ... 0.4M_\odot$)
Inner radiative zone
Outer convection zone

Low-mass stars ($M< 0.3\text{-}0.4M_\odot$)
Fully convective



Rotation

Solar rotation

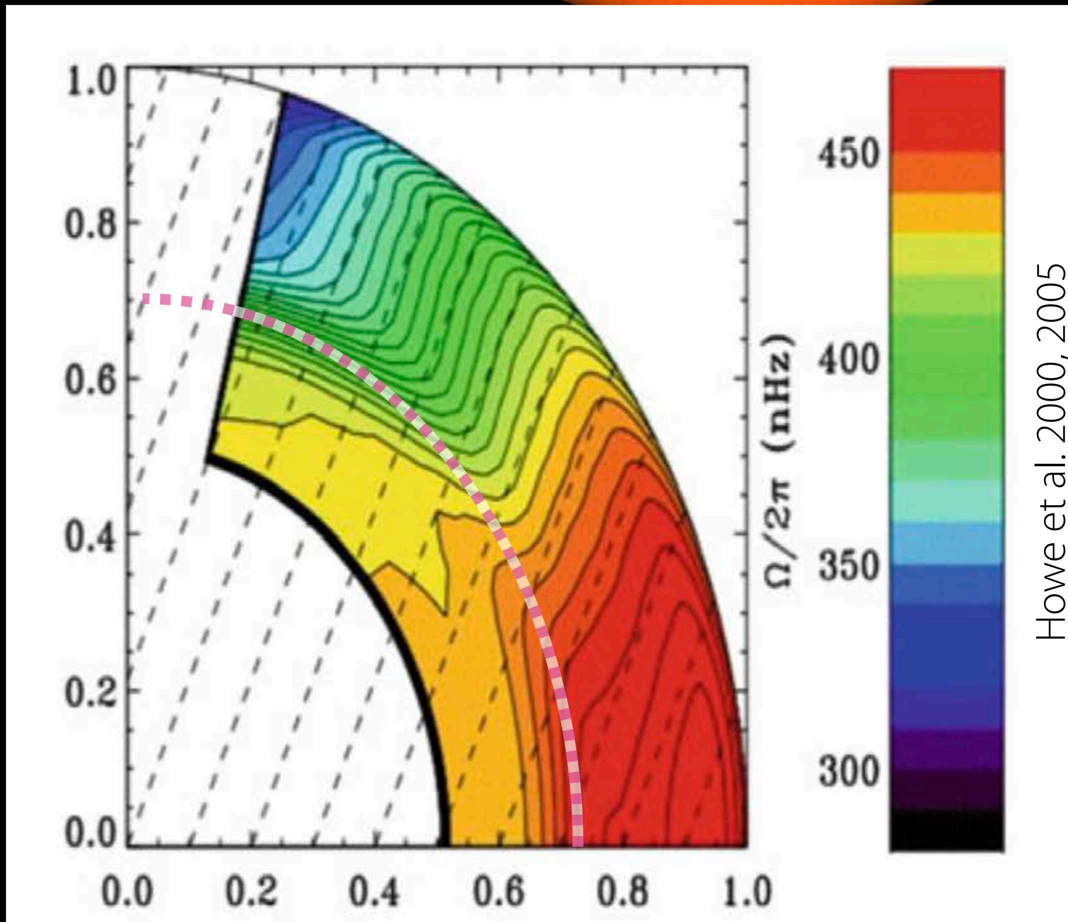


- Solar rotation becomes obvious from observing over several days as sunspots move across the solar disk
- Standard value: Carrington rotation period = **27.28 days**
- The Sun rotates faster at the equator than at poles — both depending on latitude and depth
  - **Differential rotation**

- Strong variation of rotation speed as function of radius, depending on latitude
- Strong change of rotation at the bottom of the convection zone

➡ "Tachocline": shear flows occur

- Internal rotation speeds and meridional flows derived with helioseismological methods!



Howe et al. 2000, 2005

Stellar rotation

Measuring rotation periods

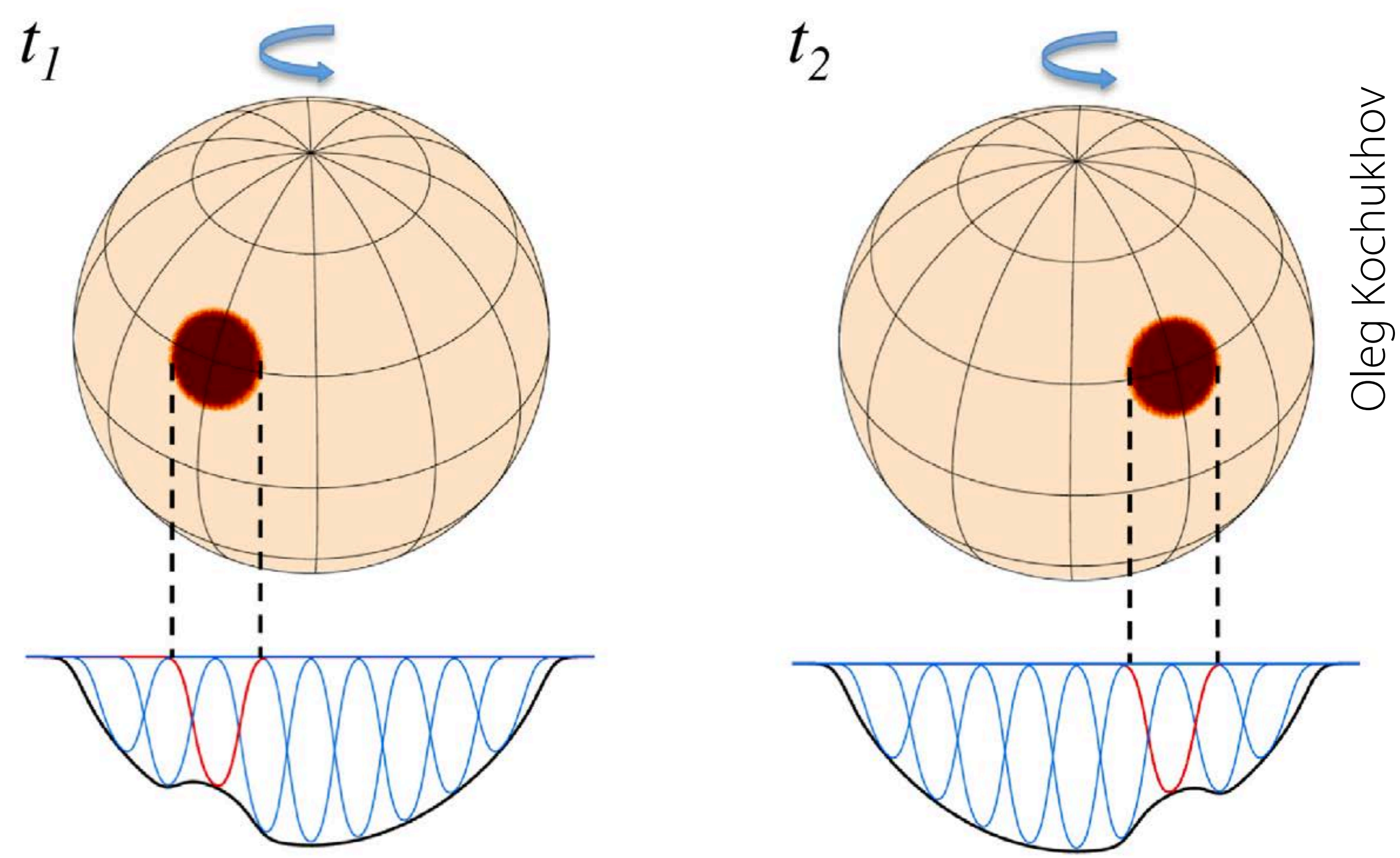
- **Spectroscopically**: rotational broadening of spectral lines.
- From **asteroseismic** measurements
- Detection of **rotational modulation** (over time) caused by a non-uniform surface on the star, .e.g. varying imprints of **starspots** in stellar spectra/light curves as they move across the unresolved stellar disk over time.

➡ Broadening of spectral lines allows to derive only the **projected** rotation rate / apparent rotational velocity:

$$v' = v \sin i$$

- i: angle between LOS and rotation axis of the star

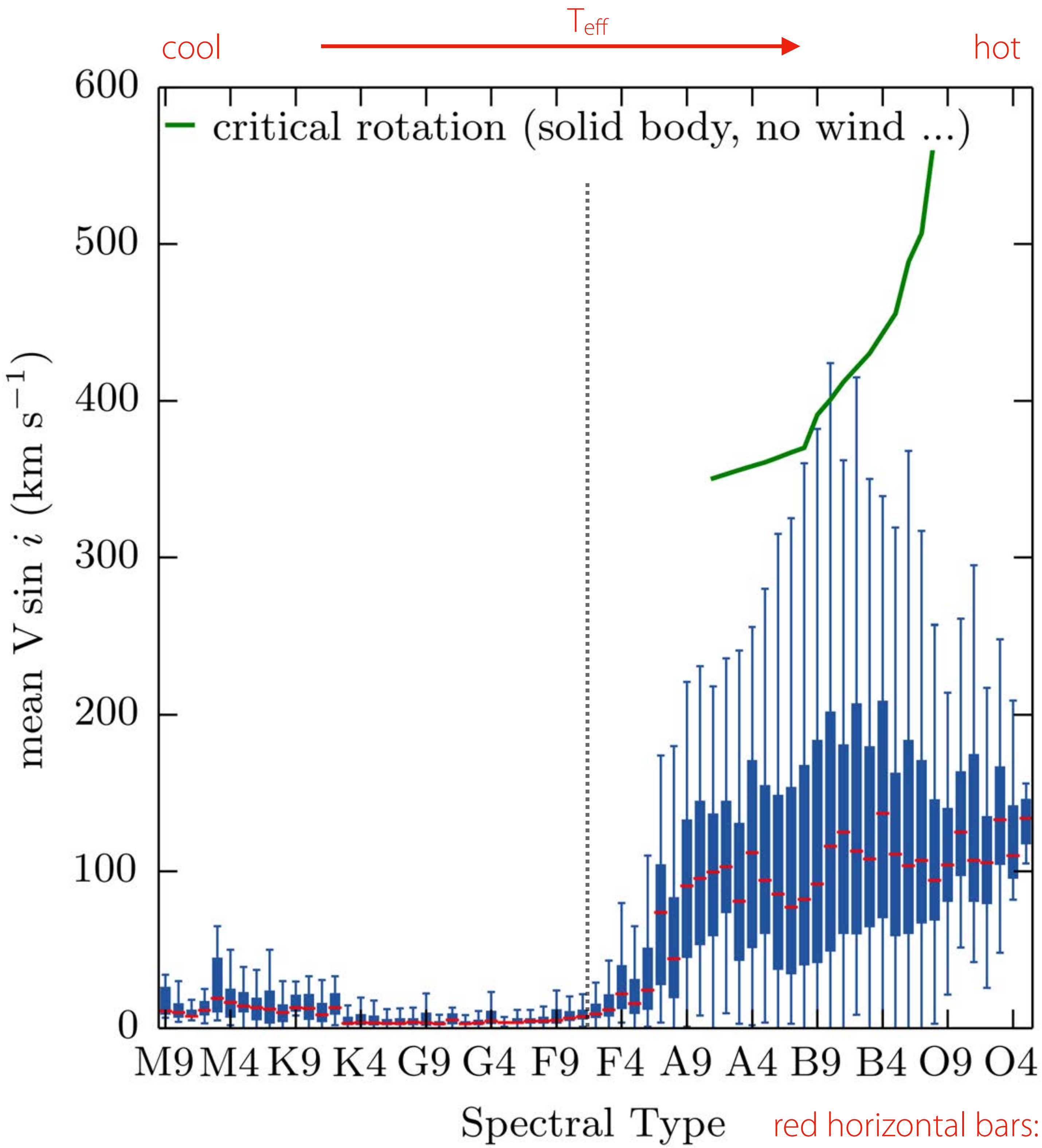
Rotational modulation of a spectral line caused by a large starspot



Stellar rotation

Measured v sin i

- Distribution of apparent rotational velocities (*v sin i*) as a function of spectral type.
- Some hot stars rotate as fast as 450 km/s
- Two stellar populations:
  - **Slow rotators** — stars cooler than F7: typically *v sin i* < 50 km/s; for many solar-like stars < 6 km/s.
  - **Fast rotators** — hotter stars: often *v sin i* > 100 km/s.
- The Sun rotates comparatively slowly at ~2 km/s
- Wide range at earlier spectral types (hot stars) due to
  - Large spread in actual rotation rates
  - Large spread in inclination angles

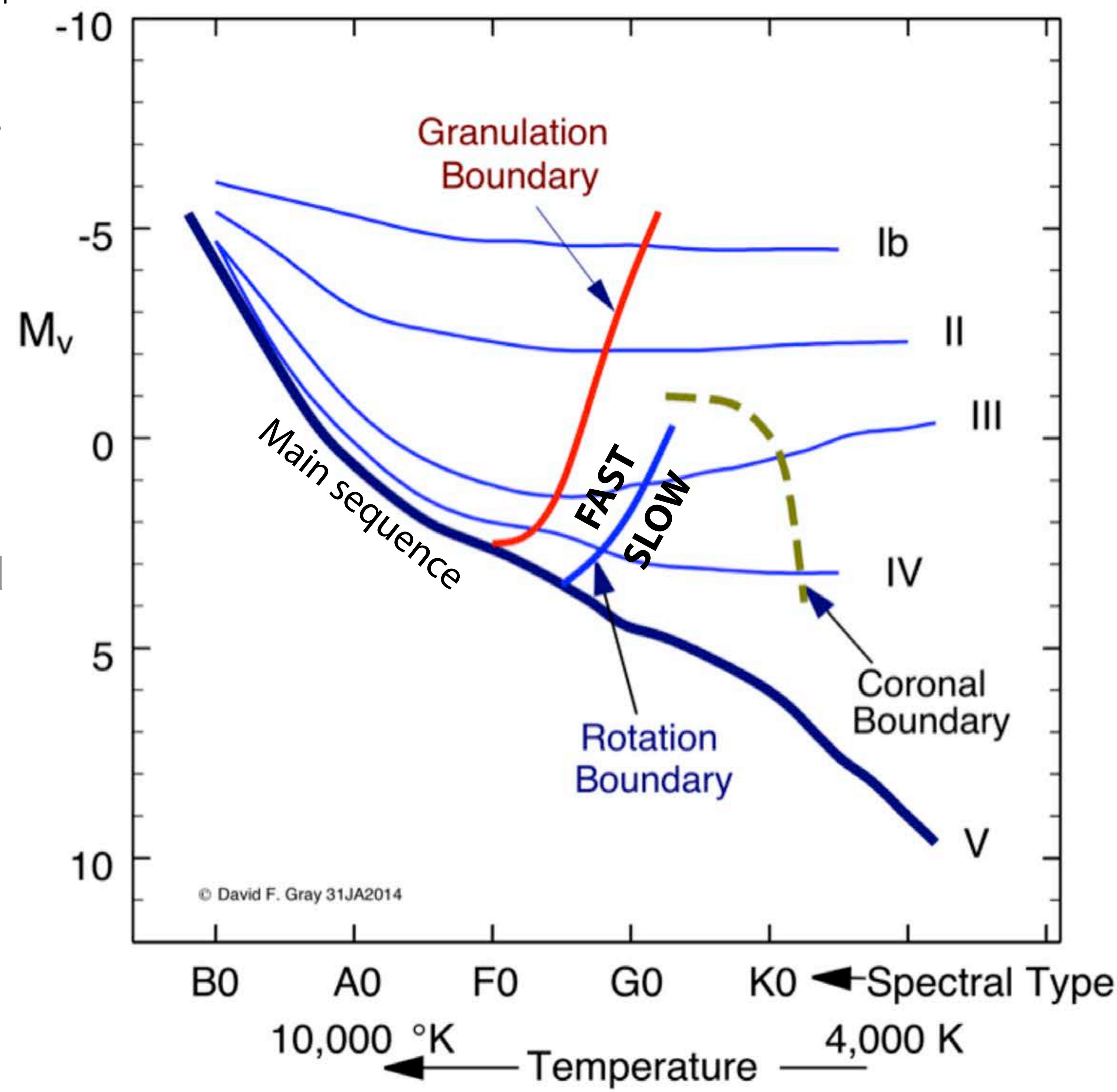


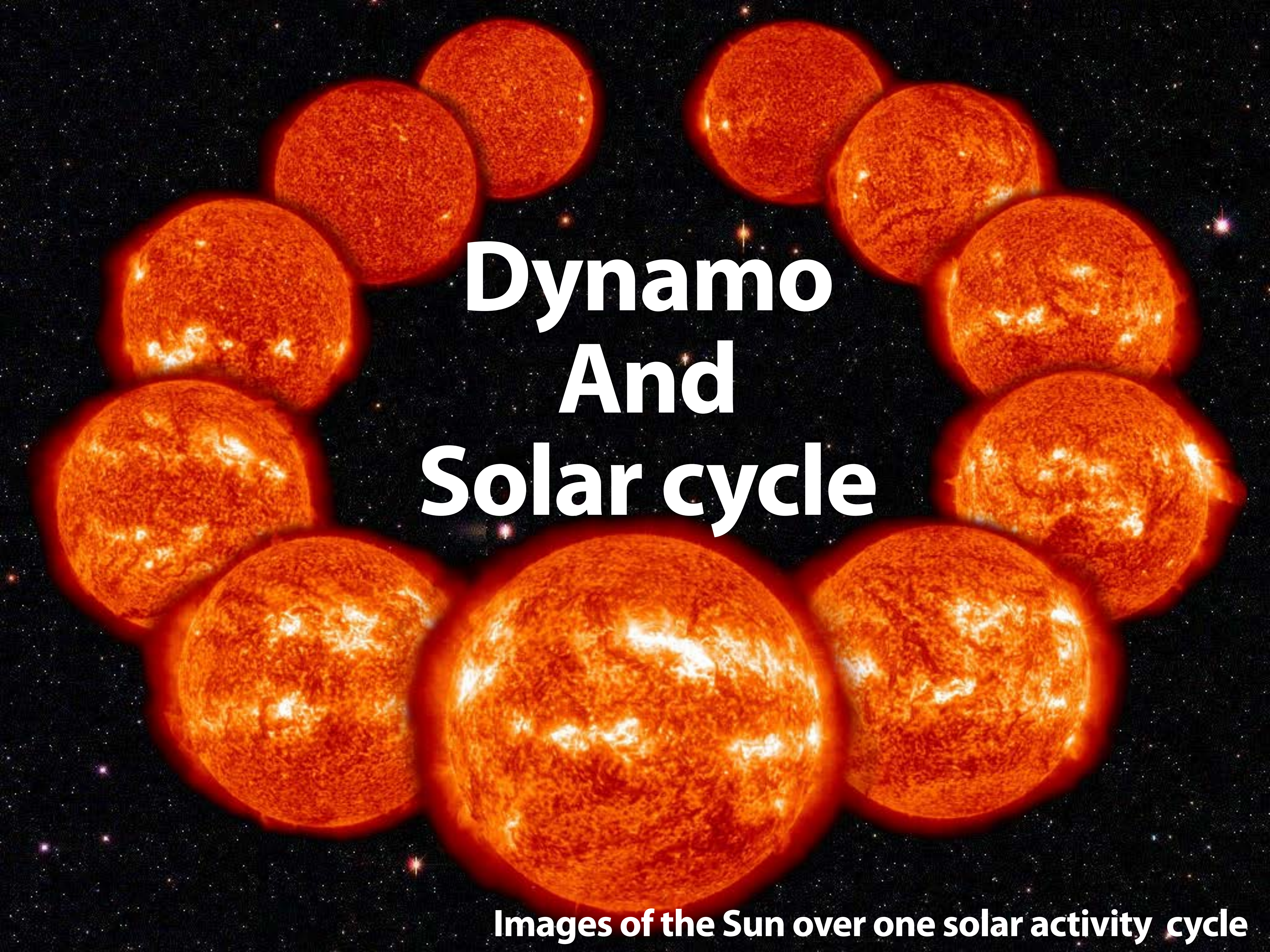
Y.Frémat
Values are taken from the catalog of Glebocki R. & Gnacinski P. 2005.

Stellar rotation

Across the HRD

- "**rotation boundary**" — sharp transition between fast and slow rotators
- Stars on the cool side basically one value for any given effective temperature and evolutionary status.
- Possible explanation: magnetic braking of the star due to the impact of **convection** on rotation properties (rotostat mechanism)
- Note that the rotation boundary is found not far from the granulation boundary beyond which there is no more surface convection
- Exceptions: Close binary stars can transfer orbital angular momentum to companion star through gravitational coupling, resulting in anomalous rotation

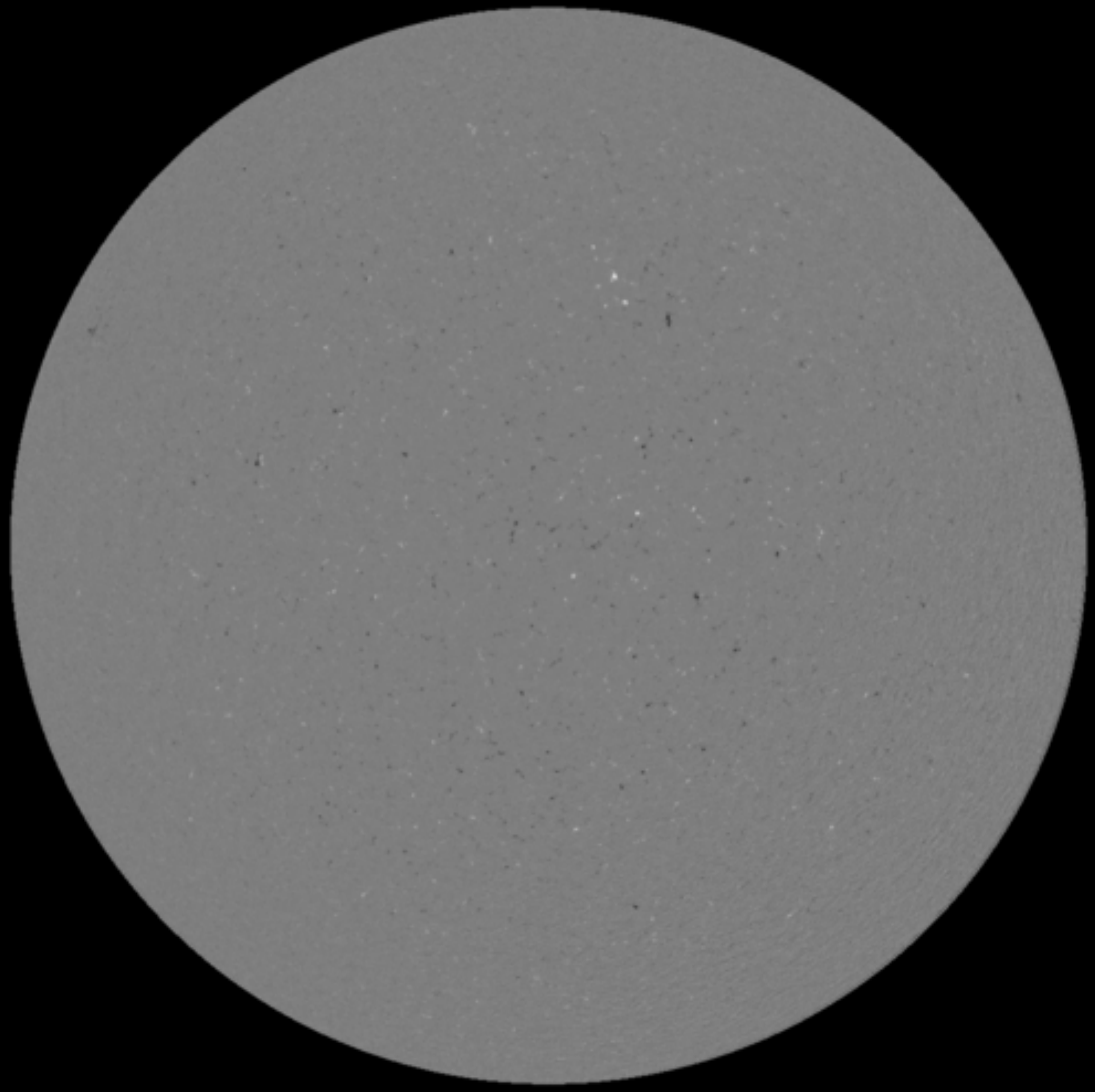



Dynamo
And
Solar cycle
Images of the Sun over one solar activity cycle

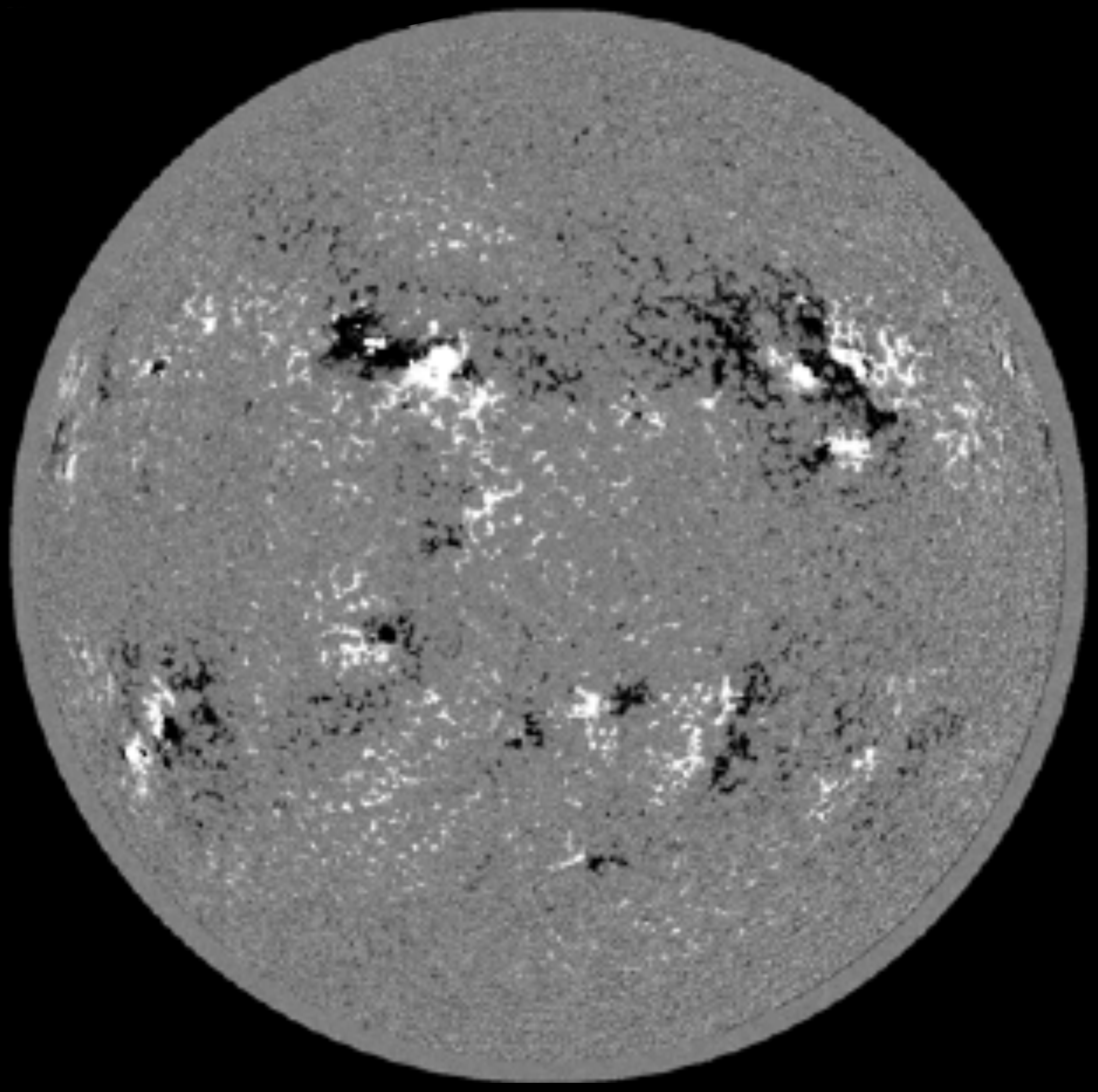
Dynamo — Solar cycle

Magnetograms

Minimum



Maximum



SOHO/MDI

Dynamo — Solar cycle

Corona

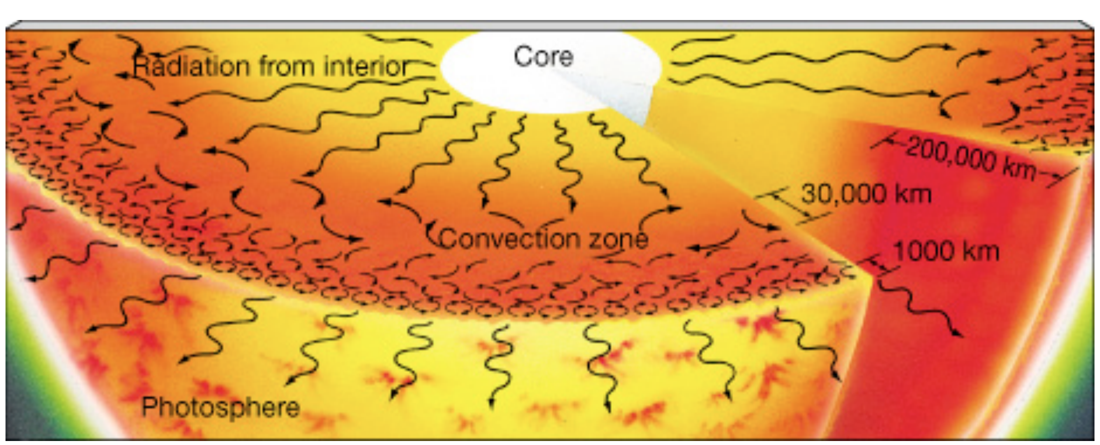
- Solar cycle clearly visible in the change of the coronal magnetic field

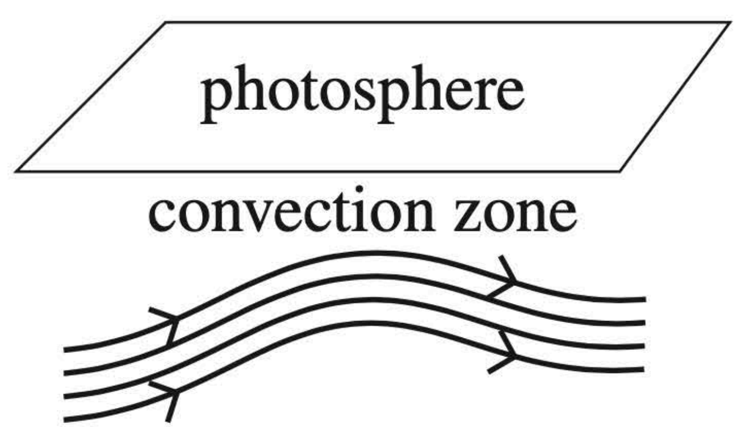
Corona visible — brighter solar disk is blocked out

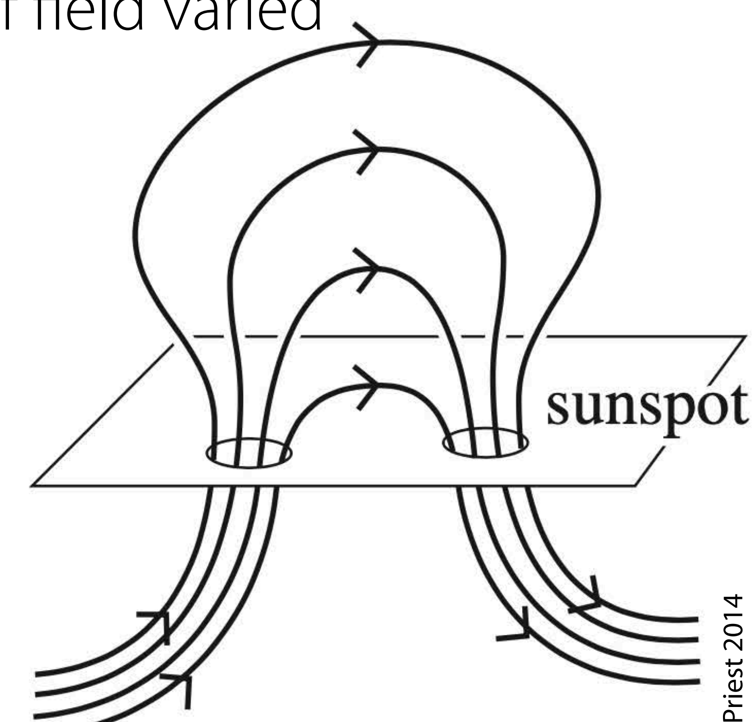
Dynamo

Overview

- Interior of the Sun: plasma (ionized gas) — **charged particles**
- Convection moves plasma around (**turbulence**)
  - ➡ Moving charged particles generate electric currents
  - ➡ Electric currents generate magnetic fields (via Ampere's law).
  - ➡ Changing magnetic fields change, induce electric currents (Faraday's law).
  - ➡ **Self-reinforcing dynamo process**
- Continuous generation of magnetic dipole fields
- Convection currents **stretch and twist** the magnetic field lines, increases magnetic tension (analogy for magnetic field lines: rubber bands)
- Magnetic field gets stronger in some locations and/or orientation of field varied
- Magnetic flux ropes form, rise to surface





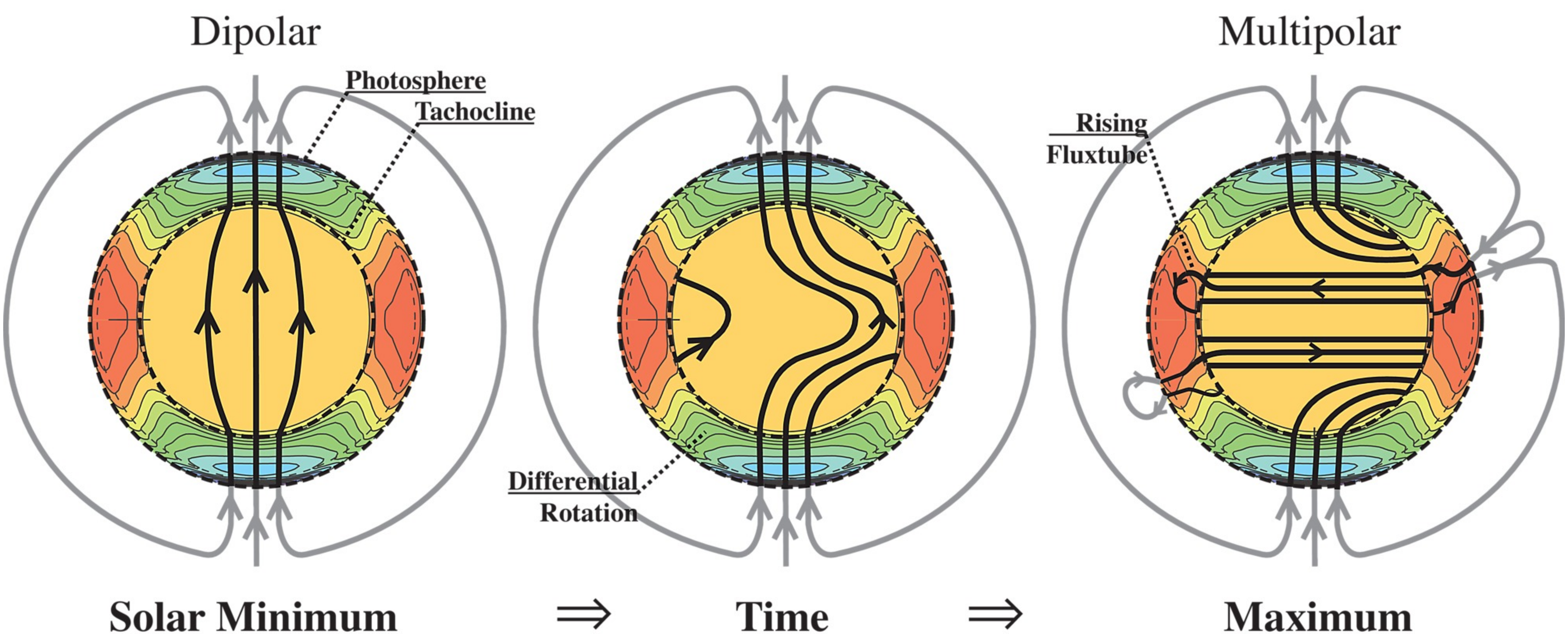


Priest 2014

Dynamo

Solar cycle — change of magnetic field configuration

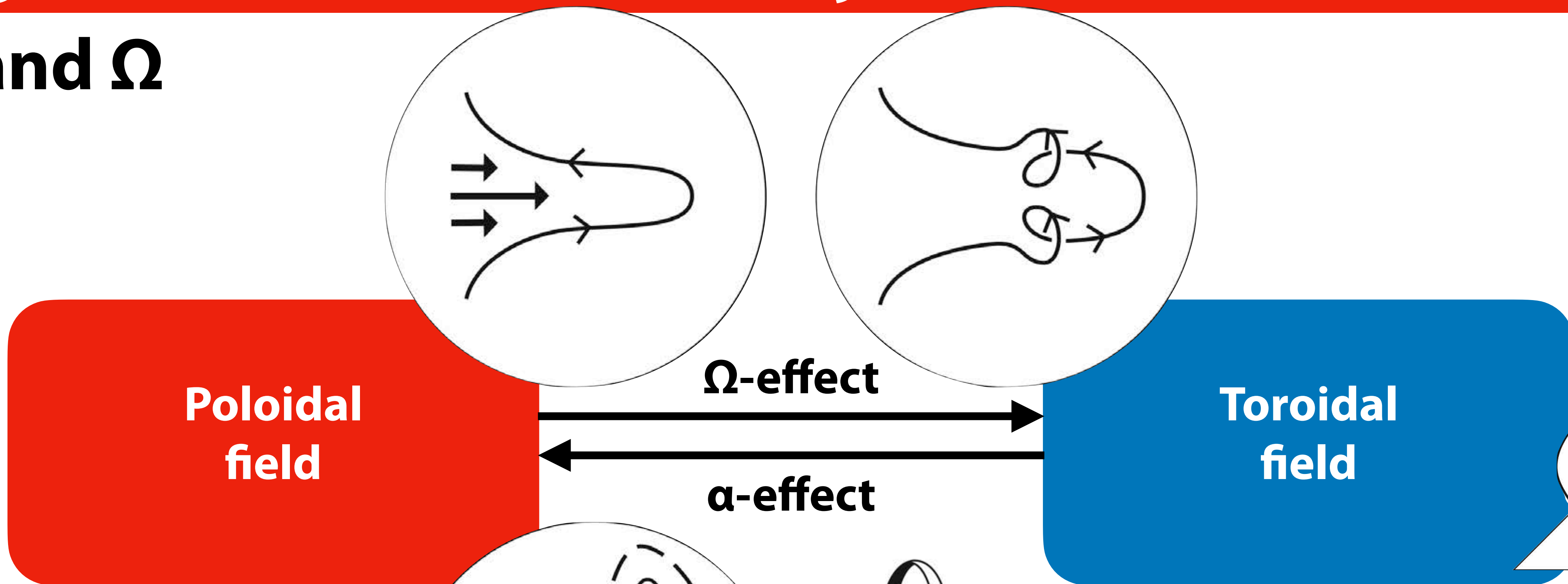
- Below **tachocline**: Rotation as solid body
- Above tachocline: **differential rotation** — faster rotation near equator, slower at poles
- Magnetic dipole field (poloidal) at solar minimum
- Over time: differential rotation shears magnetic field at the tachocline, drags it along the equator, **converts poloidal field into toroidal field**.

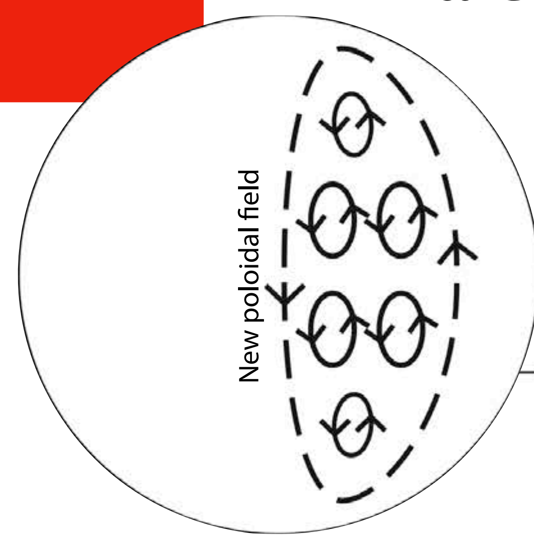


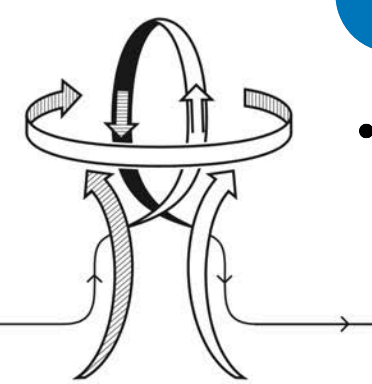
Higgins, Paul (2012): Schematic of the Solar Dynamo. figshare. Figure. https://doi.org/10.6084/m9.figshare.102094.v1

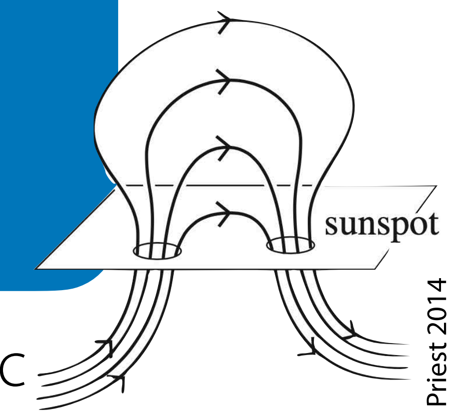
Dynamo — Solar cycle

α and Ω









- Predominates during **solar (activity) minima**

- generates magnetic activity (e.g., sunspots) during **solar (activity) maxima**

- **Solar cycle**: Changes back and forth between these extreme configurations, forming a solar activity cycle with ~11 year period
  - Global polarity of the Sun's magnetic field (N-S) swaps during that period
  - Complete cycle back to the same polarity = 2 x 11 yr = **22 yr = Hale cycle**

Dynamo

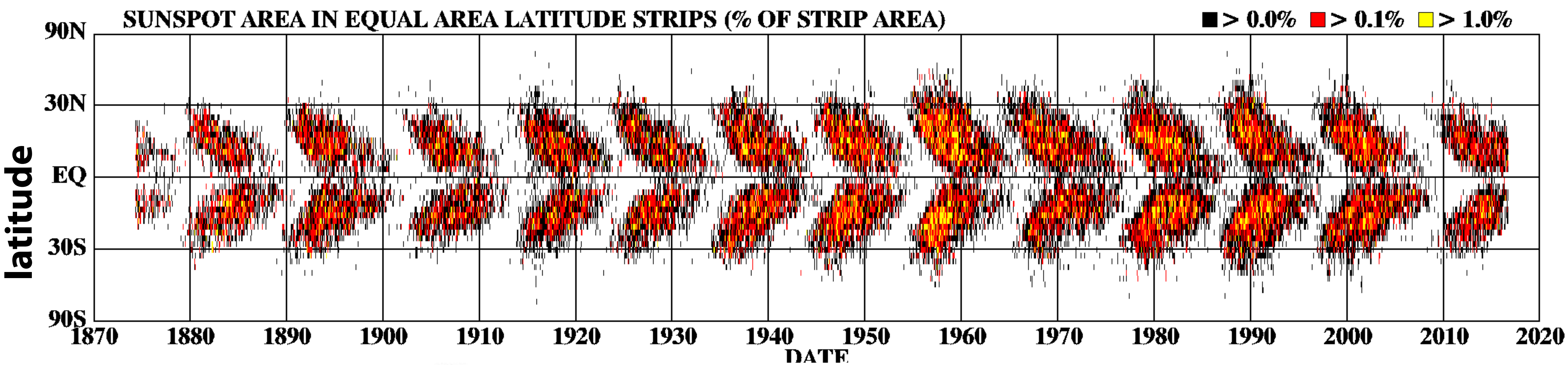
Magnetic fields at the surface — Active Regions

Solar cycle

Sunspots — latitude and time

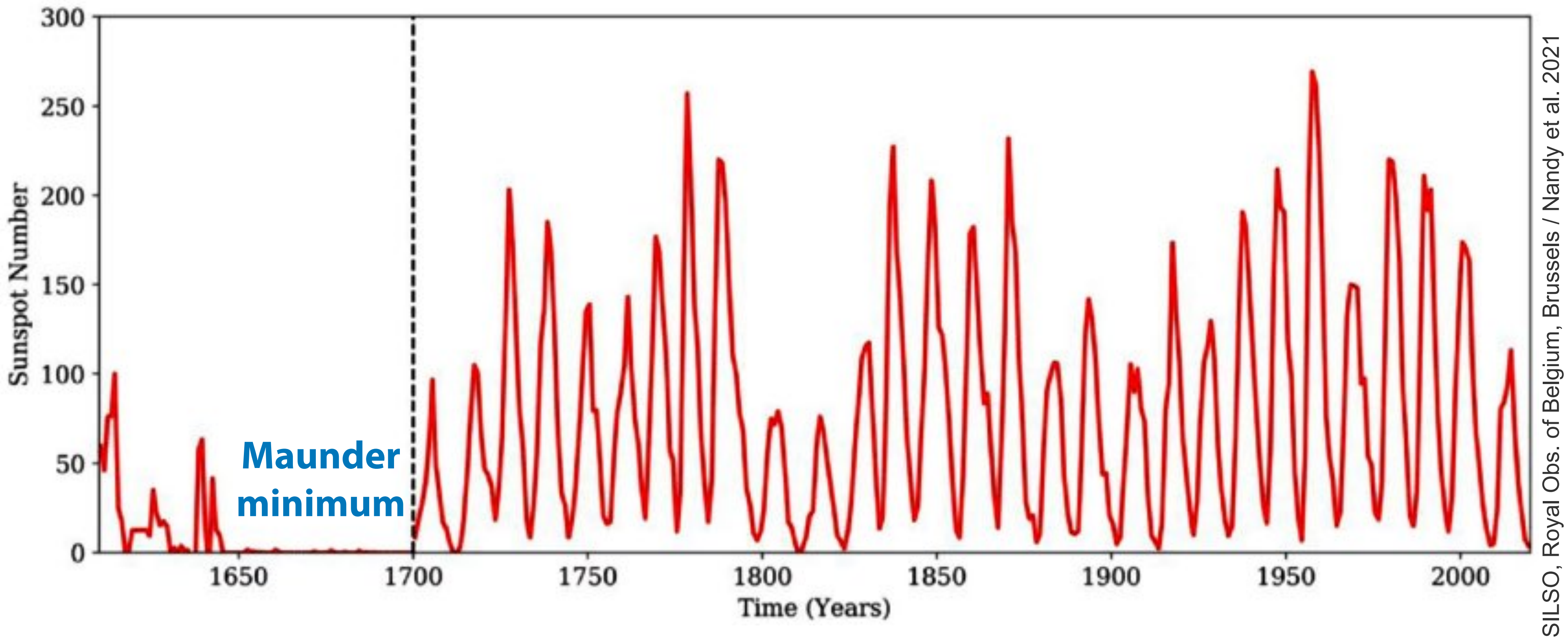
- Solar cycle — sunspots first at 30deg N/S, then gradually towards equator

Butterfly diagram: DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS



- Solar cycle: 11 yr
- N/S swap
- **Hale cycle** = 22 yr

- Sunspot number as measure for solar activity level



Solar cycle

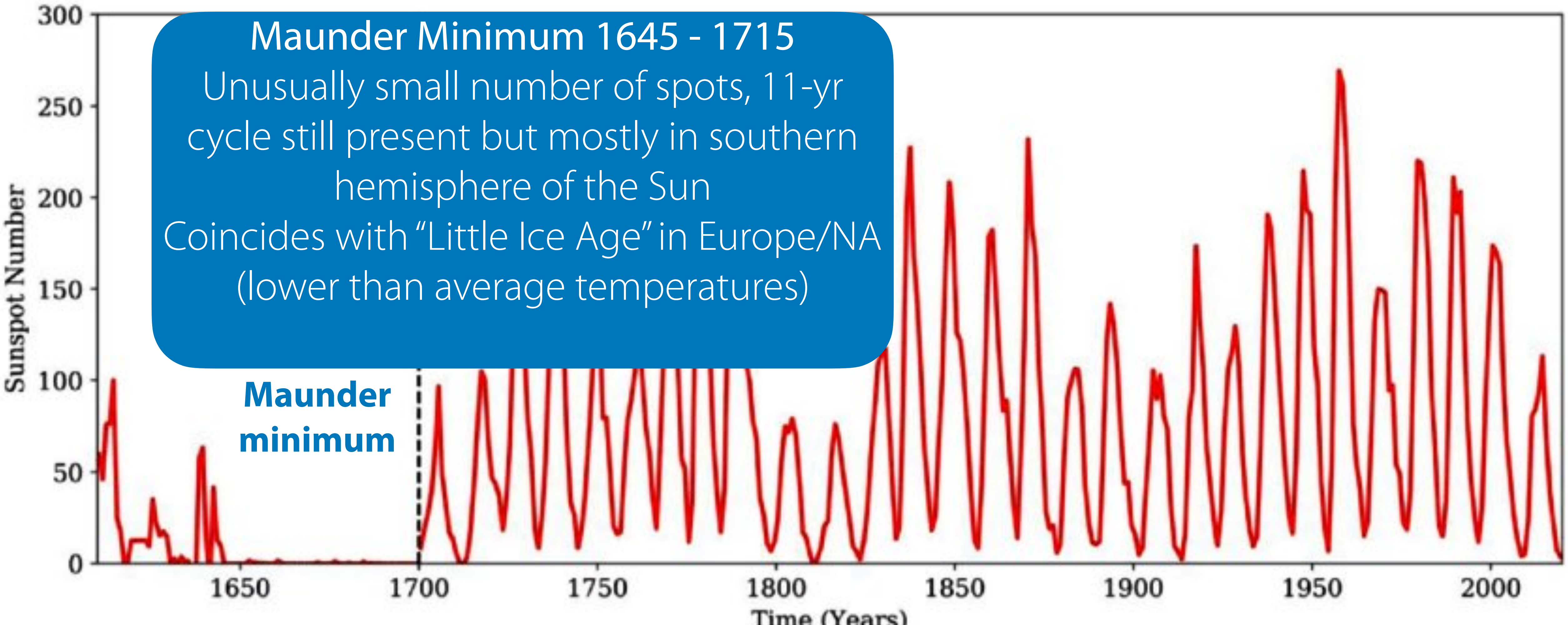
Sunspot number (Wolf number/Zürich sunspot number)

- Numerical measure for the "spottedness" of the Sun and thus its magnetic activity level

$$R = k \ (10\, g + s)$$

s: number of individual sunspots
g: number of sunspot groups
k: calibration factor (instrument, personal bias)

- Captures 11-yr cycle
- Correlates with indicators due to modulation of screening from cosmic rays (isotopes); tree rings, ice cores

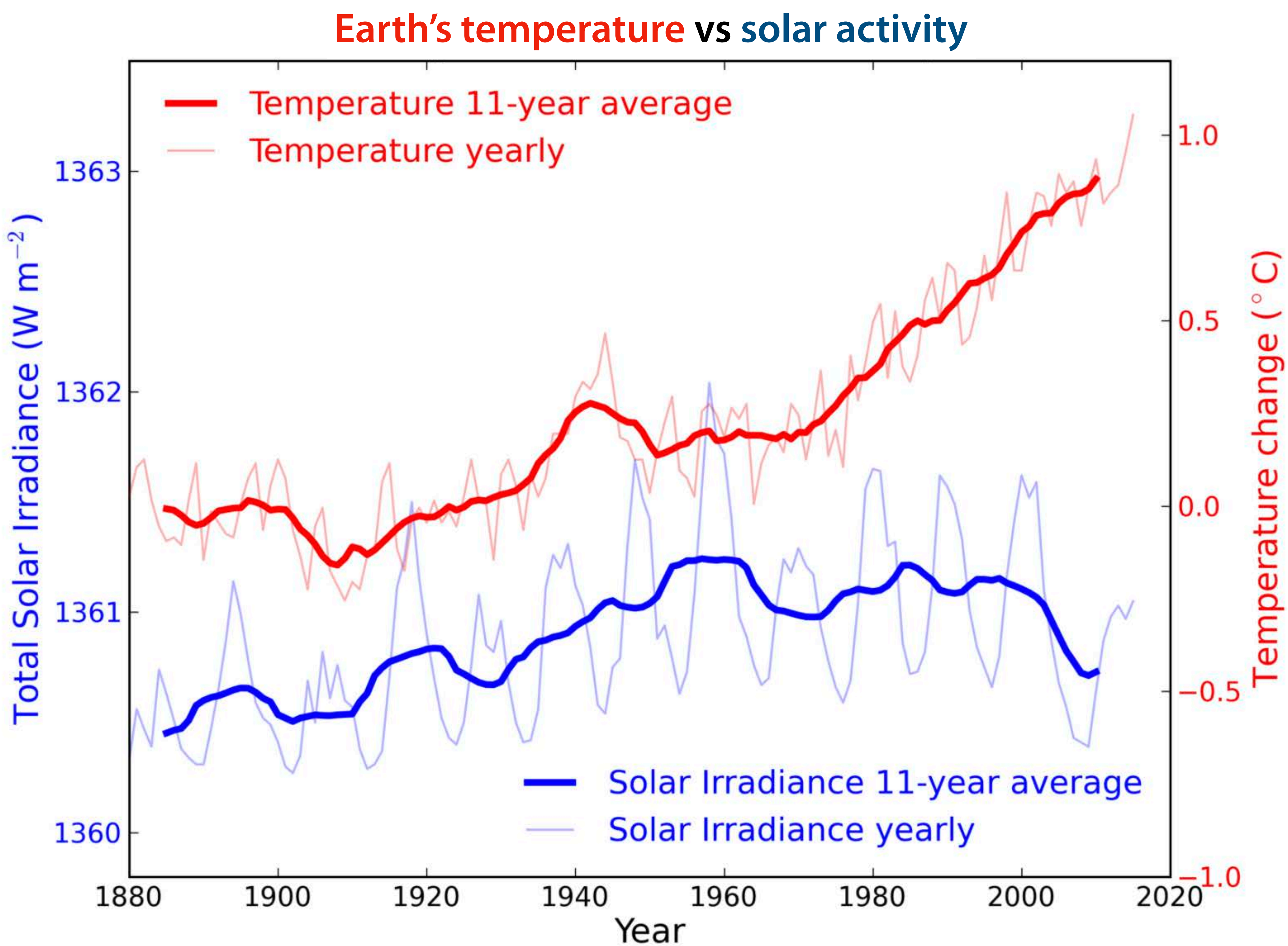


Maunder Minimum 1645 - 1715
Unusually small number of spots, 11-yr cycle still present but mostly in southern hemisphere of the Sun
Coincides with "Little Ice Age" in Europe/NA (lower than average temperatures)

SILSO, Royal Observatory of Belgium, Brussels / Nandy et al. 2021

Solar cycle

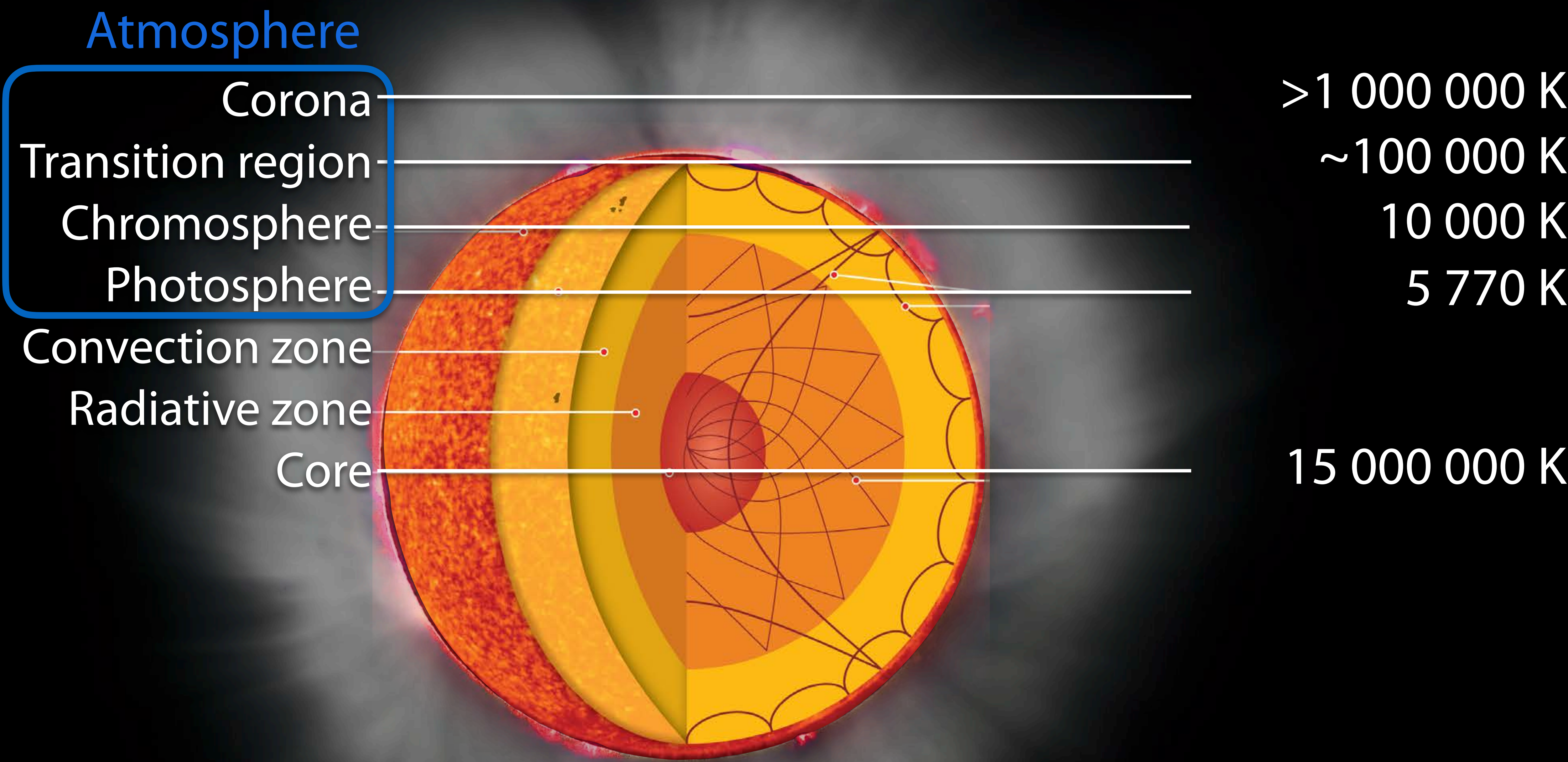
Variation of the Sun's total irradiance



NASA/ Krivova et al 2007/World Radiation Center/PMOD

The solar atmosphere

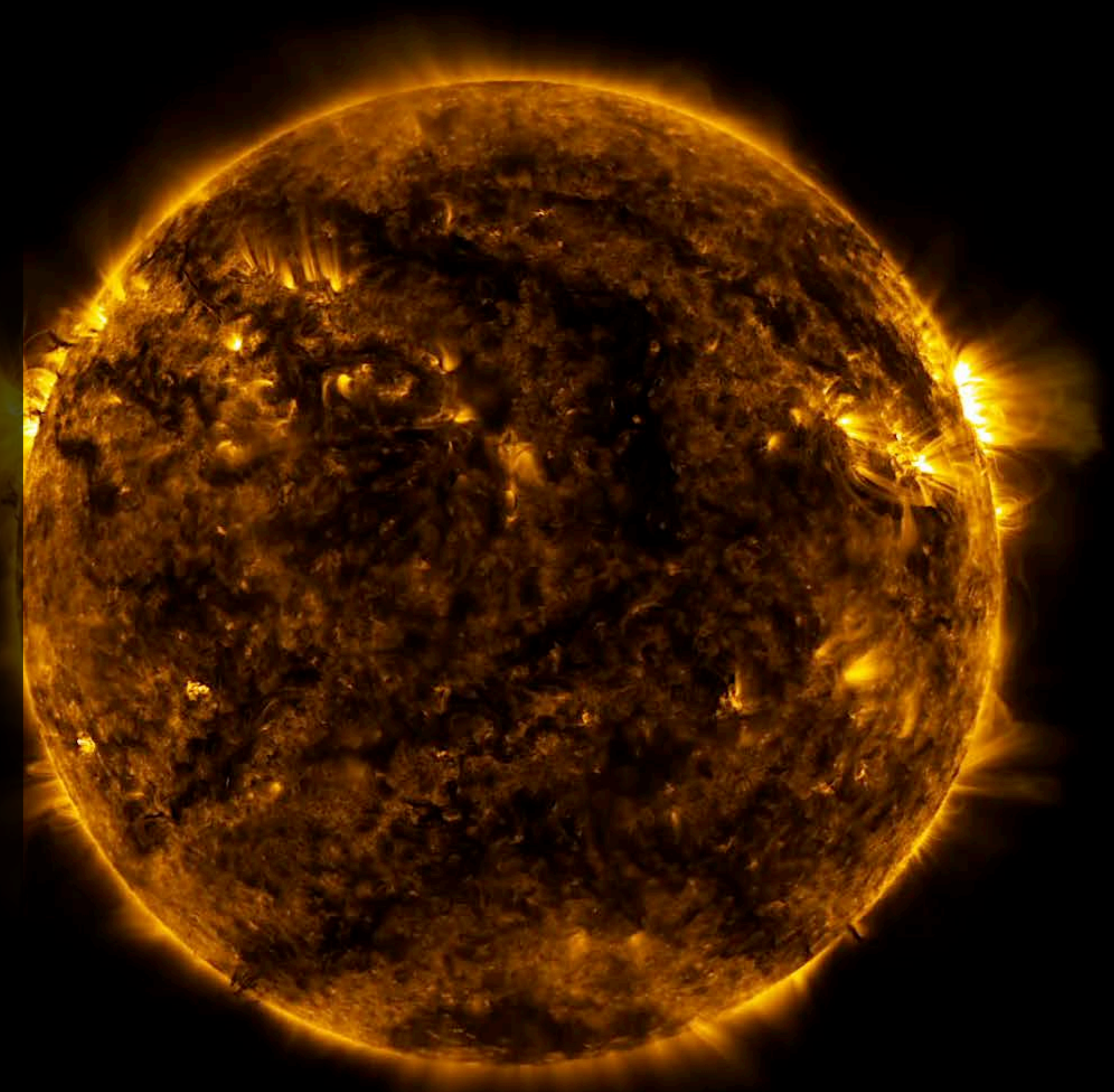
Stellar structure — The Sun



- **Why is the corona so hot??**
  - Known since 1940ies but one a big open questions about our Sun!
  - Candidates for heating mechanisms: Magnetohydronamic waves and magnetic reconnection
  - Acoustic waves probably less important
  - Working on it …

The solar atmosphere

Solar Dynamics Observatory SDO/NASA

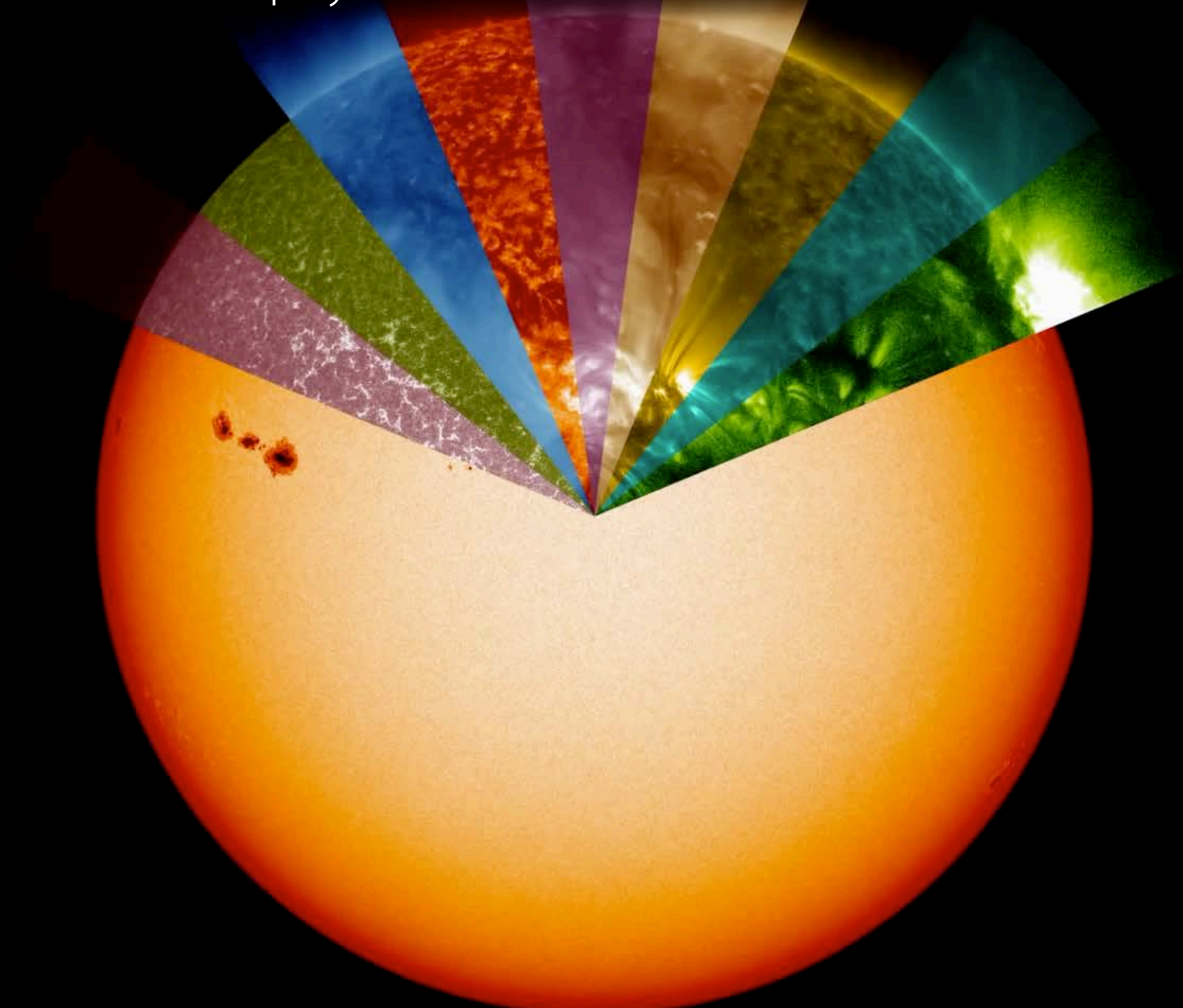


- Solar atmosphere
  highly dynamic
  intermittent
  dynamically coupled
- Structured on large range of spatial scales, down to (at least) 0.1 arcsec
- The Sun is dynamic on short timescales (down to seconds)
- Plethora of processes.
- Great plasma physics "laboratory"
- Explore yourself: https://www.jhelioviewer.org/

HOW TO OBSERVE THE SUN?

- Different continua and spectral lines probing different plasma properties in different domains/layers

➡ Multi-wavelength co-ordinated space-borne/ground-based campaigns as standard in modern solar physics



- Explore yourself: https://www.jhelioviewer.org/

Solar Dynamics Observatory SDO/NASA

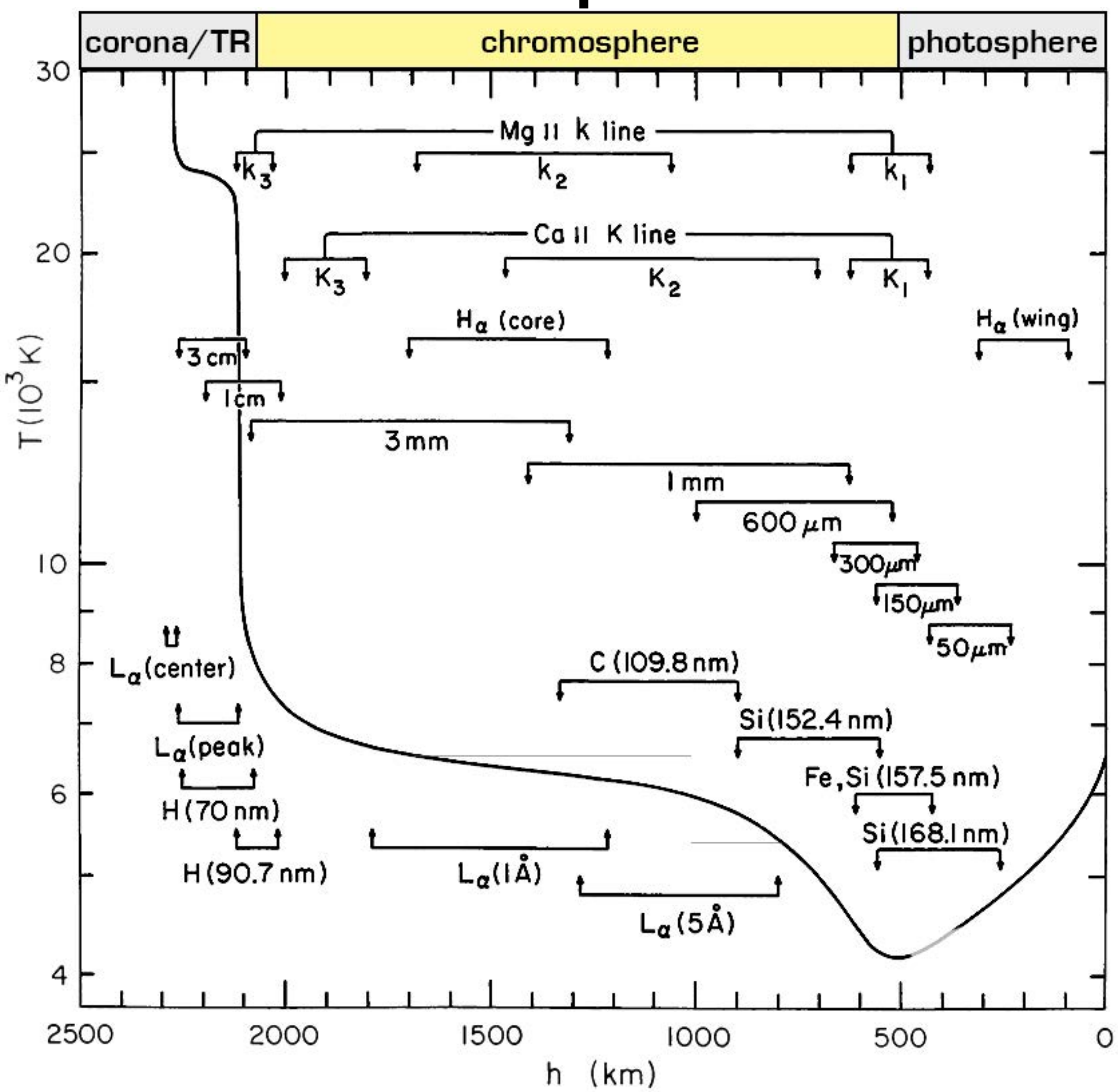
The solar atmosphere

Semi-empirical model atmosphere

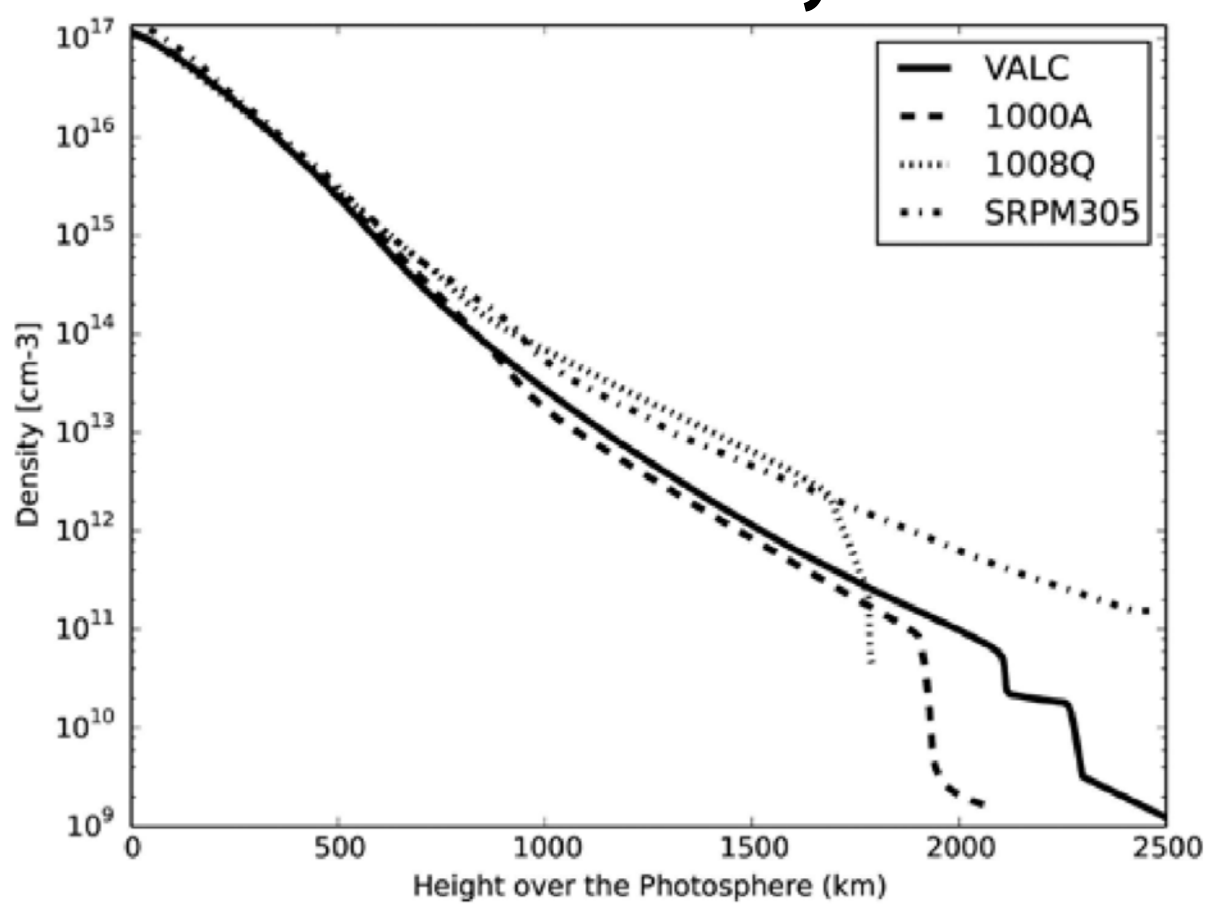
VAL: Vernazza, Avrett, Loeser (1981)

- Average stratification of the solar atmosphere (temperature, density etc…)
- Still used as a reference but solar atmosphere much more complicated and dynamic

Gas temperature



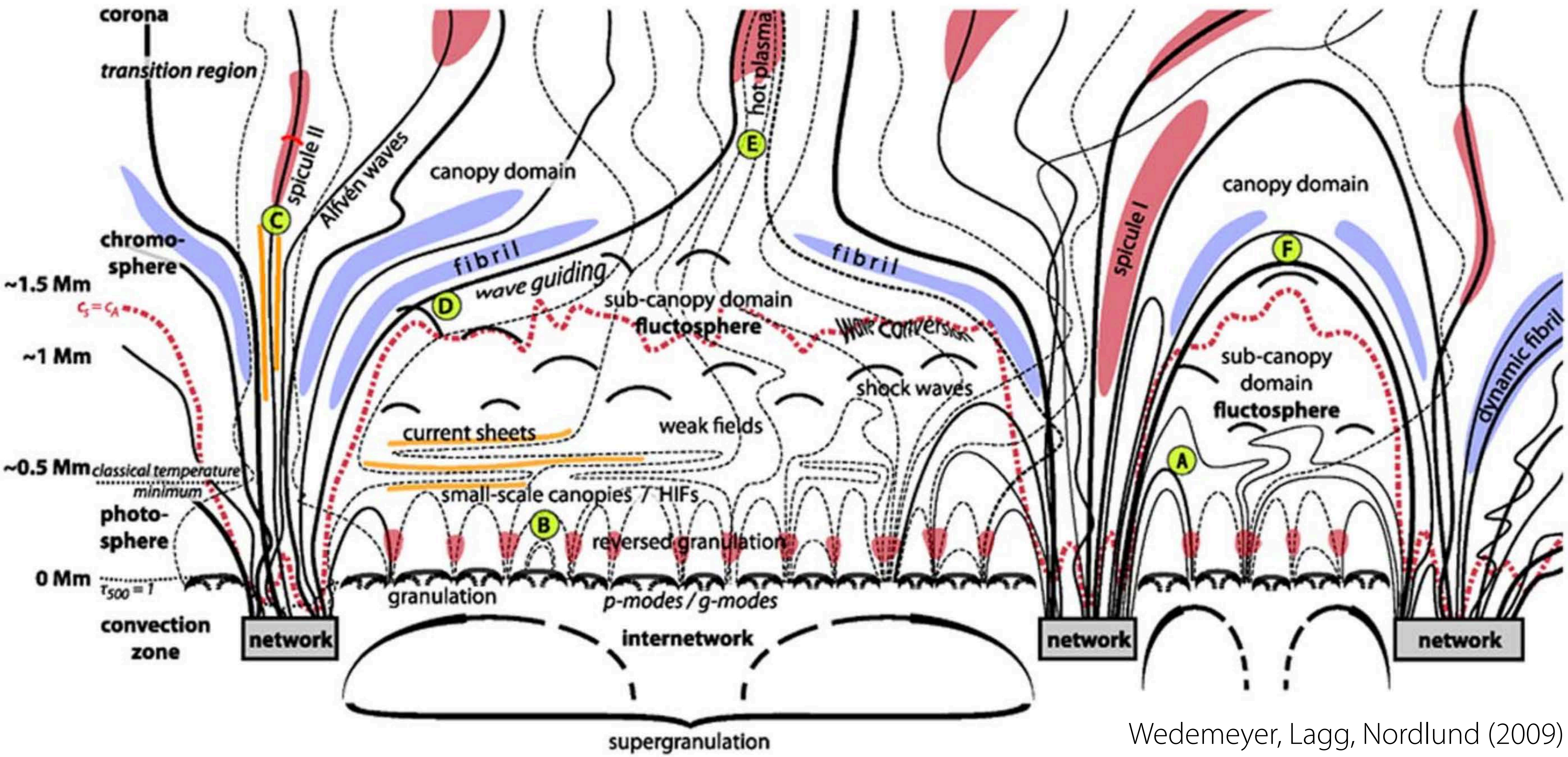
Gas density



The solar atmosphere

Structure of "Quiet Sun" regions

- Modern telescopes with high spatial + temporal + spectral show a new picture of the "Quiet" Sun
- Dynamic intermittent structure across many scales, plethora of physical processes



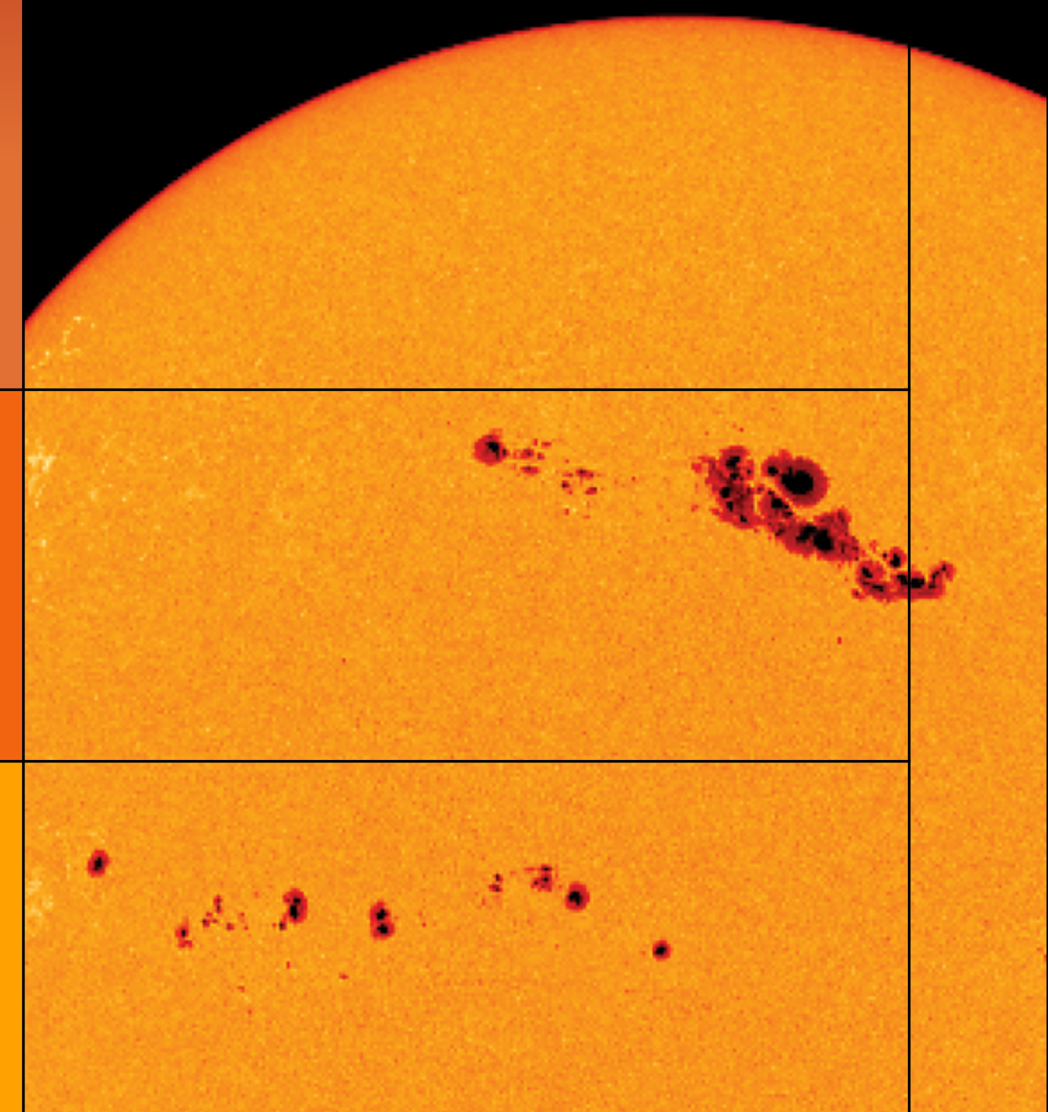
Wedemeyer, Lagg, Nordlund (2009)

The solar atmosphere

Different regions — photosphere

(Average) magnetic field strength ↓

Region	Feature	Component
Active Region (Large) area with strong magnetic field	**Sunspot** Areas of concentrated very strong field, appear dark	**Umbra** Central compact part, dark **Penumbra** Surrounding, filamentary
	Faculae bright (filamentary) areas	
Quiet Sun Outside Active Regions, weaker magnetic field	**Network** Concentrations of strong magnetic field, filamentary/ mesh-like	
	Inter-network Areas with weak magnetic field inside network cells	

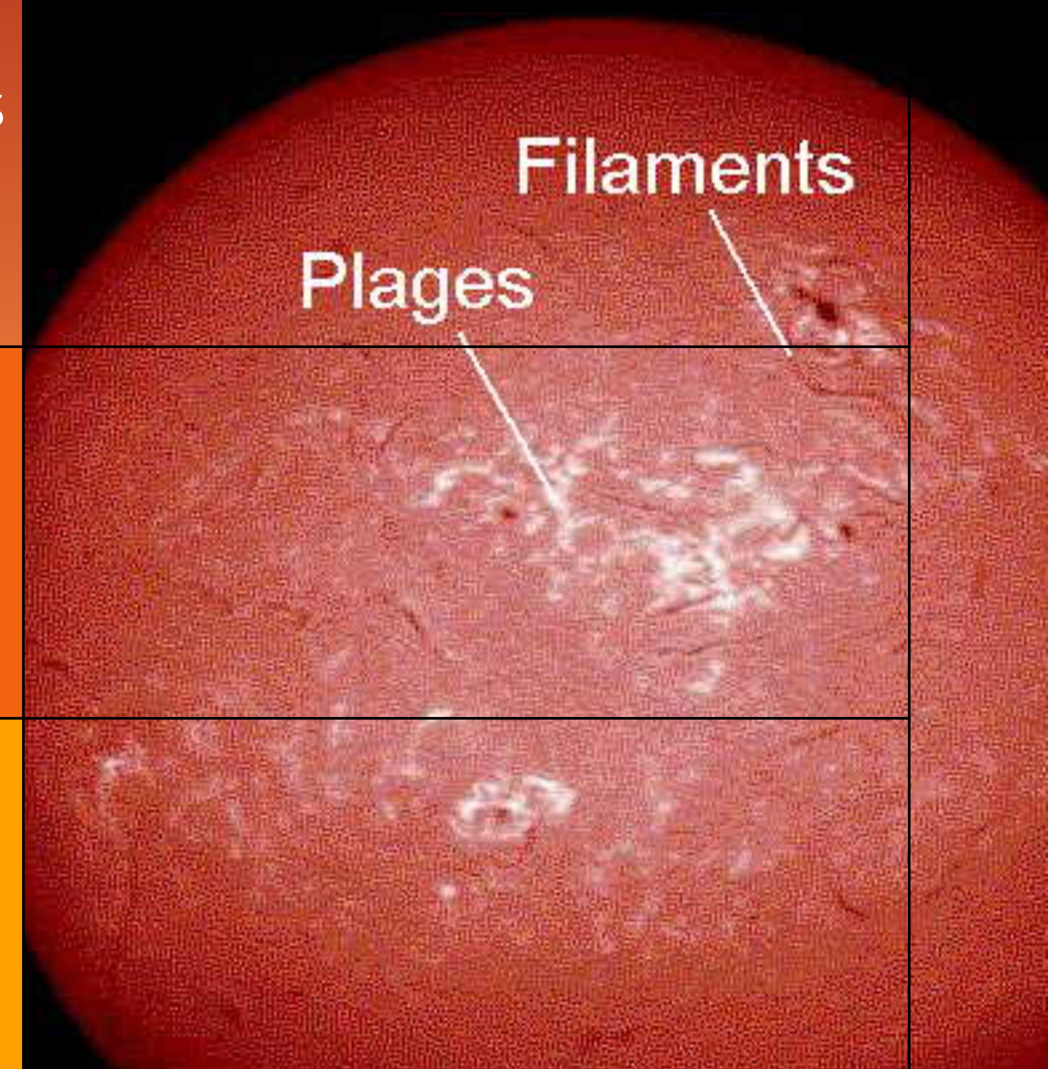


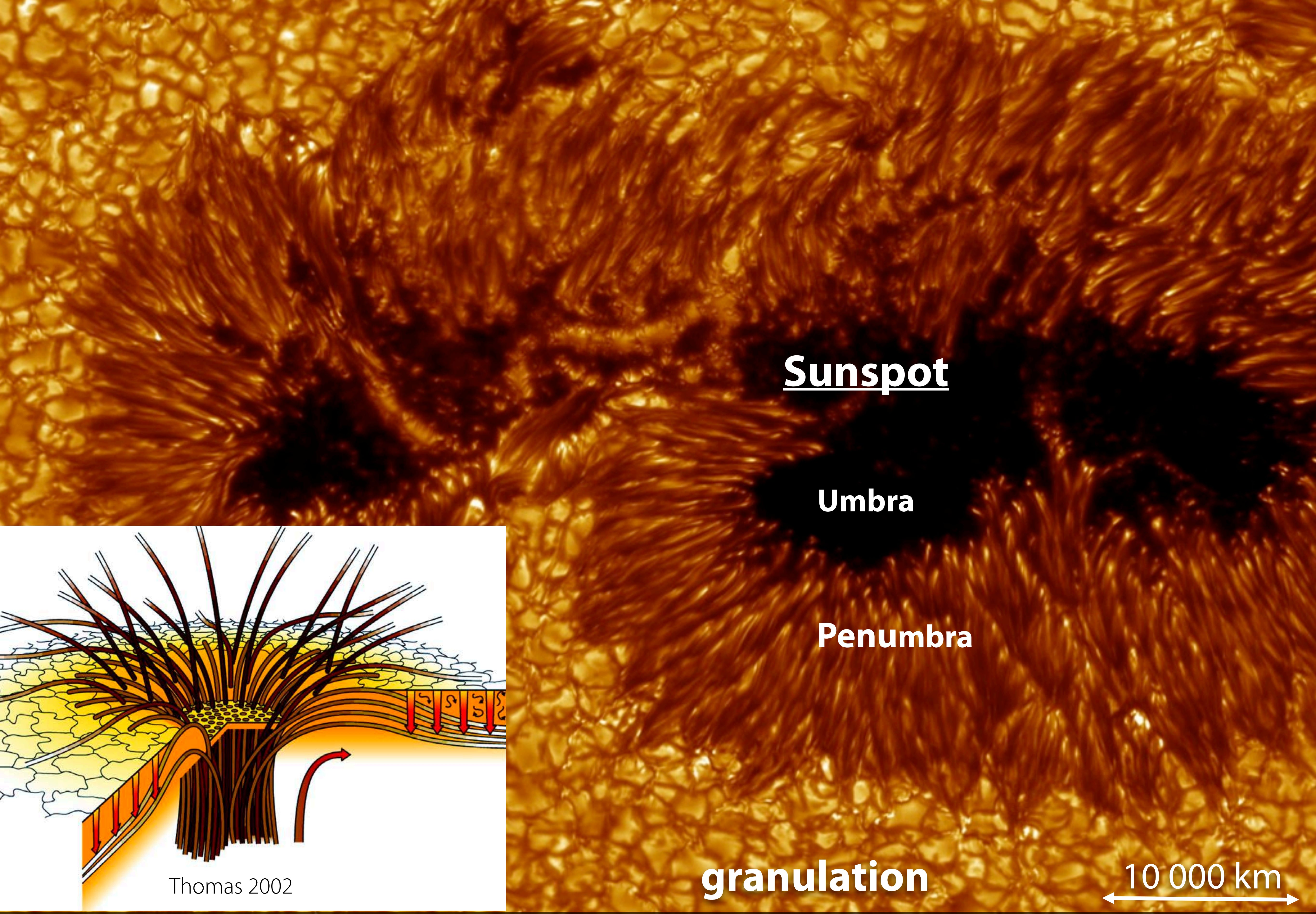
The solar atmosphere

Different regions — chromosphere

(Average) magnetic field strength ↓

Region	Feature	Component
Active Region (Large) area with strong magnetic field	**Sunspot** Areas of concentrated very strong field, appear dark	**Umbra** Central compact part, dark **Penumbra** Surrounding, filamentary
	Plage bright area, higher temperature, often proceeds formation of sunspots	
Quiet Sun Outside Active Regions, weaker magnetic field	**Network** Concentrations of strong magnetic field, filamentary/ mesh-like	
	Inter-network Areas with weak magnetic field inside network cells	





Thomas 2002

Photosphere of the Sun = $\tau(\lambda=500nm) = 1$
narrow layer where visible continua become optically thick

G-band (430nm)

Magnetism

Plasma-Beta

- Plasma-β describes the ratio of thermal to magnetic pressure

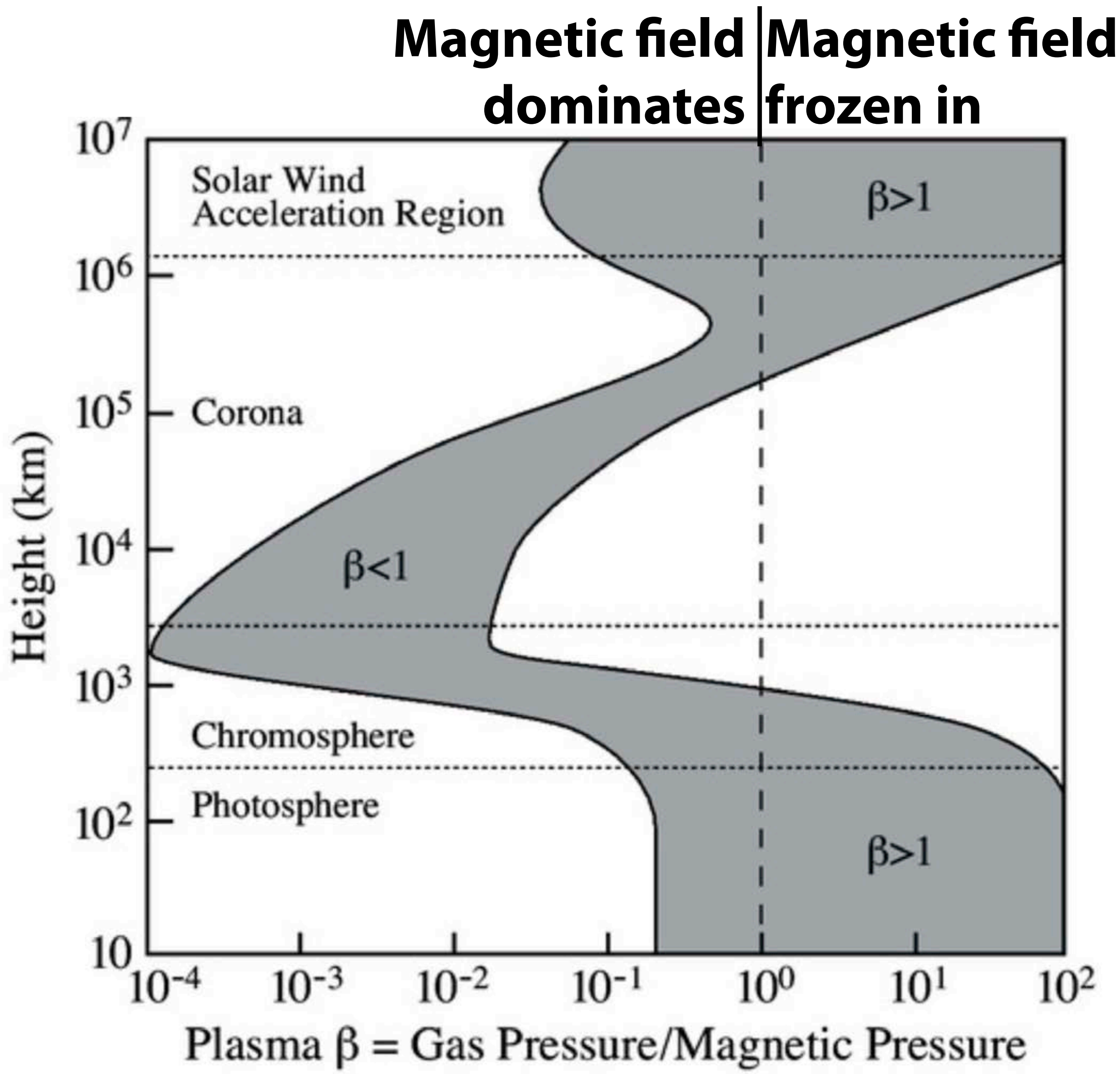
$$\beta = \frac{P_g}{P_m} = \frac{8\pi P_g}{B^2}$$

Magnetic pressure

$P_m = B^2 / 8\pi$

- **β < 1: Magnetic field dominates** and dictates the dynamics of the gas
- **β >1: Thermal gas dynamics dominate** and forces the field to follow — The magnetic field is **frozen-in.**

- β is a local quantity but the typical range of values changes with radius:
    - Convection zone: β >1
    - Lower atmosphere (outside strong magnetic field concentrations): β >1
    - Chromosphere: transition to β < 1
    - Corona: β <<1



K.R. Lang, Tufts University; Adapted from G. Allen Gary, Solar Physics 203, 71-86 (2001).

Stellar activity

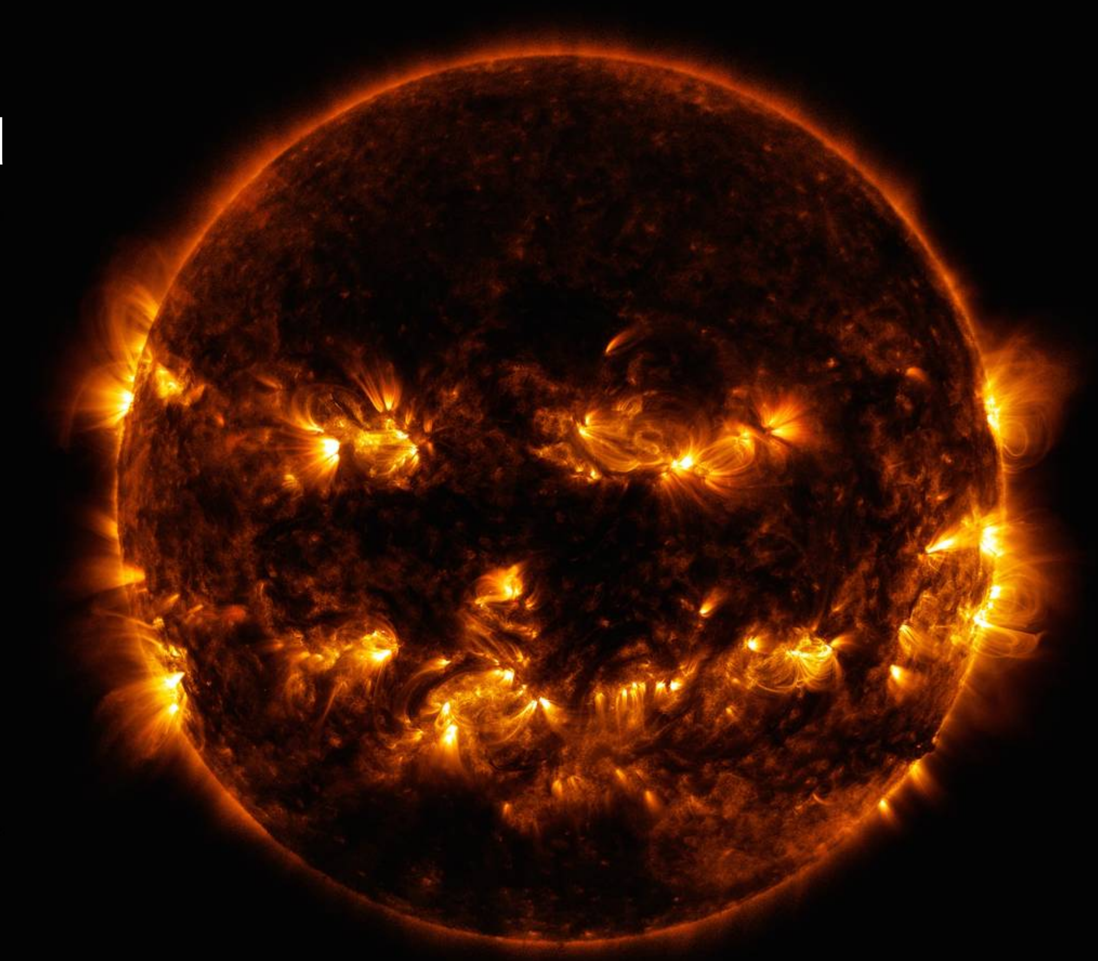
Stellar activity

What is stellar activity?

- **Stellar activity** refers to all phenomena in a stellar atmosphere that result in
  - **Variability** of the emitted radiation
    (on different timescales, except for pulsations, or influences of accompanying objects/disks)
  - **Heating** of the outer atmosphere
    (existence of a chromosphere, temperatures above radiative equilibrium)

- Mostly found for **cool stars** due to the presence of surface convection and the resulting highly structured magnetic fields in their atmospheres
  - Initially activity thought to be produced by the dissipation of acoustic waves in the atmosphere (acoustic heating; Biermann 1948; Schwarzschild 1948).
  - Today understood that dissipation of magnetic energy is essential.

➡ **Magnetic activity** is synonym of stellar activity.



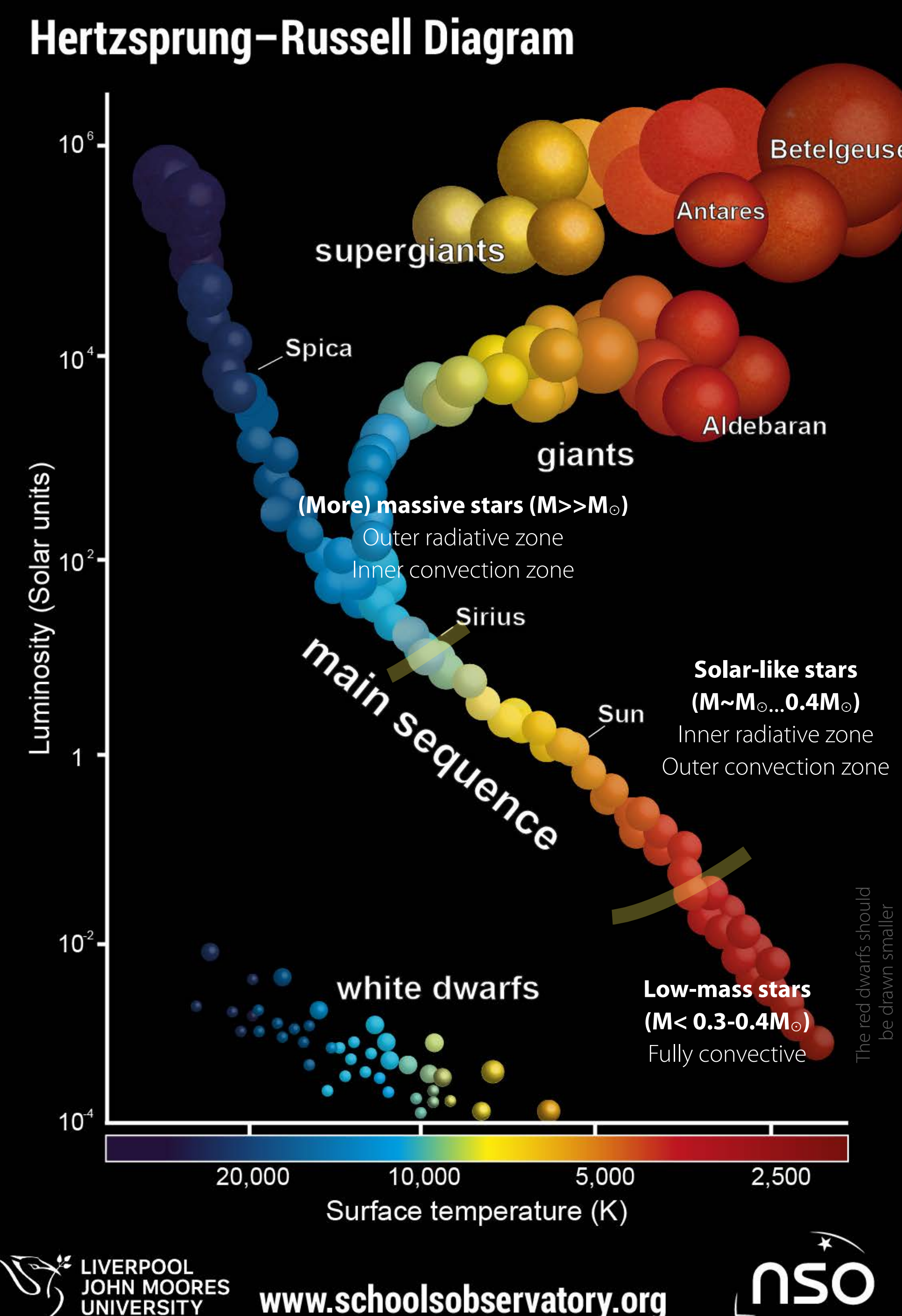
Further reading: Hall, Living Rev. Solar Phys., 5, (2008), 2

Stellar activity

What is stellar activity?

- **We have learned so far about…**
  - **… main-sequence stars:**
    - Differences of global properties (mass, radius, T_{eff},…)
    - Differences in their inner structure incl. extent and location of convection zones
  - **… the Sun:**
    - generation of magnetic via a dynamo
    - resulting solar activity cycle

- **What do we now expect to see in terms of activity cycles for other main sequence stars?**



Stellar activity

Activity indicators

- Activity indicators use impact of magnetic field on the cores of spectral lines such as the Ca II H and K spectral lines (integrated across the (unresolved) stellar disk))

➡ Measures of the overall magnetic activity level of the star, for instance:

R_{HK}-index

$$R'_{HK} = \frac{F_{HK} - F_{HK,phot}}{\sigma T_{eff}^4}$$

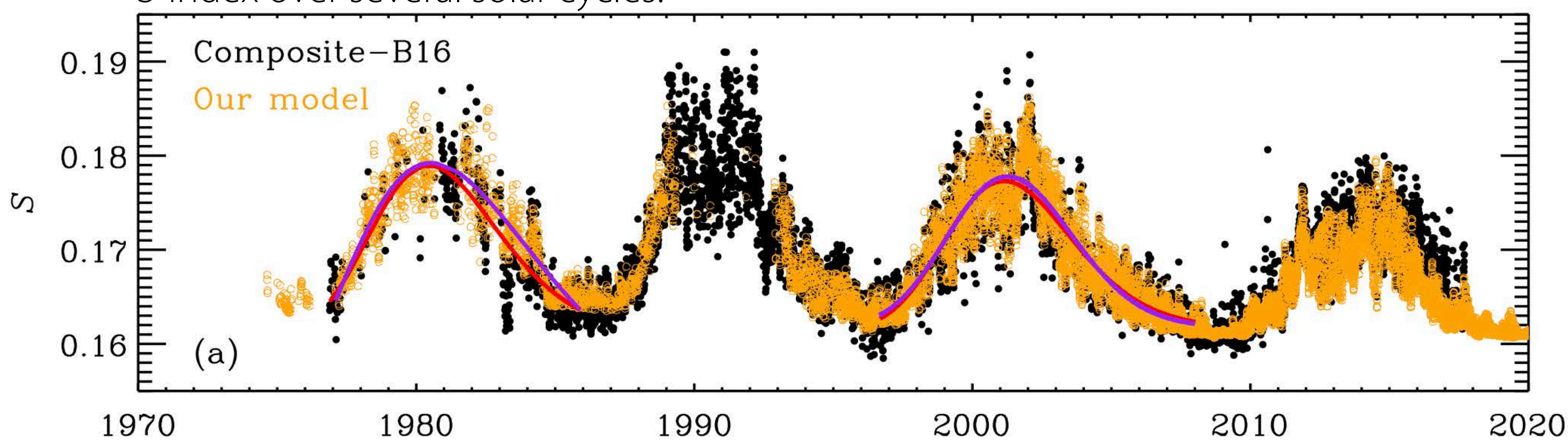
F_{HK}: flux, $F_{HK,\,phot}$: flux, photospheric contributions

S-index

$$S(t) \propto \frac{N_H(t) + N_K(t)}{N_R(t) + N_V(t)}$$

N: Counts (flux) in the passbands

S-index over several solar cycles:

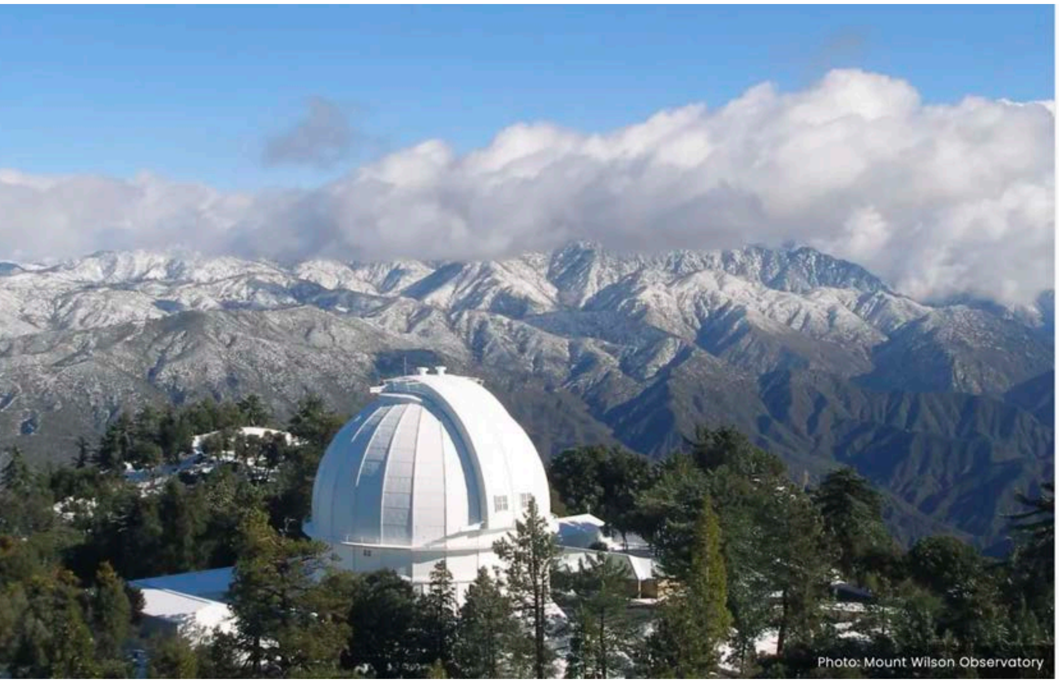


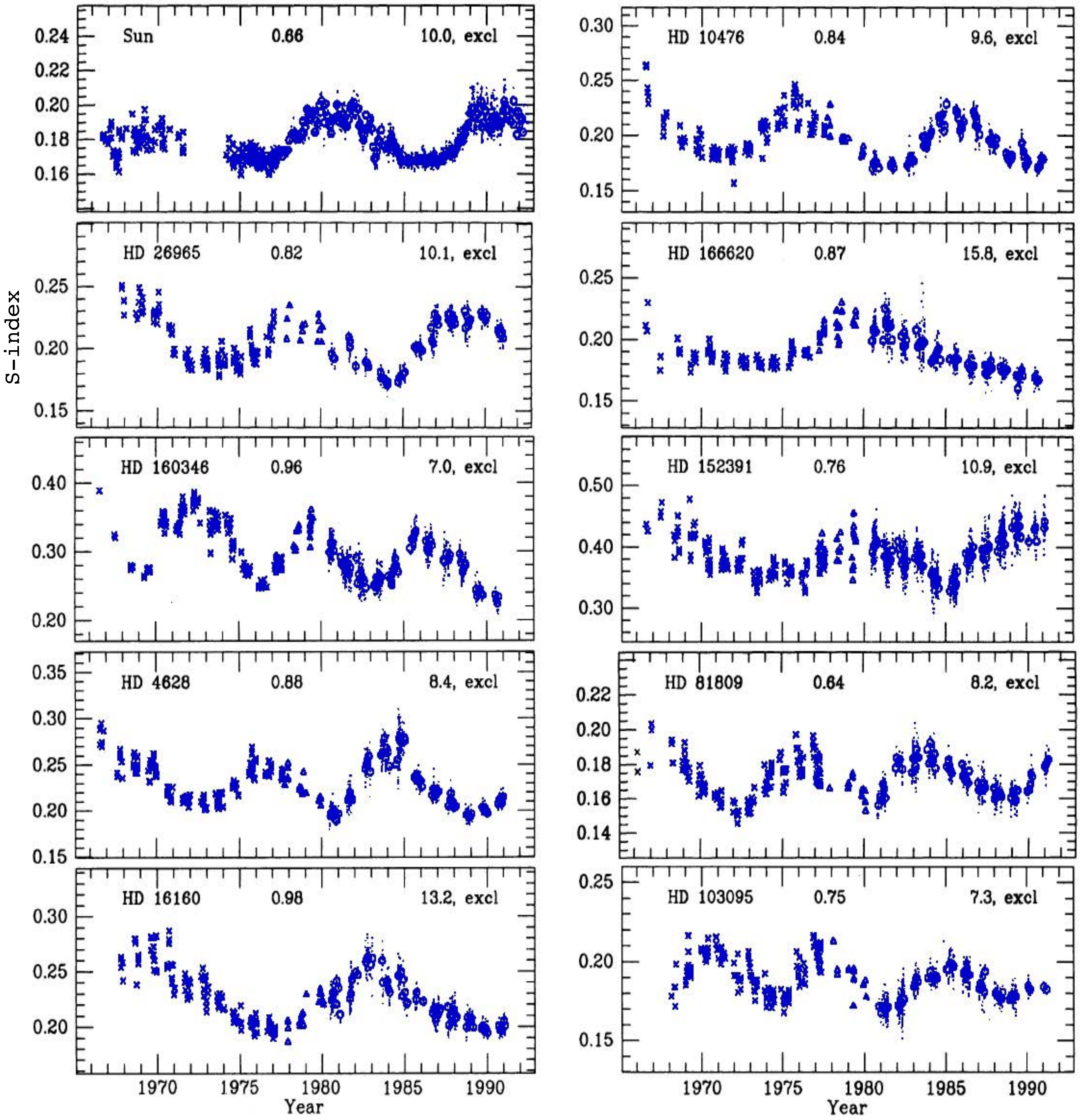
Sowmya et al 2021

Stellar activity cycles

Ca II observations

- Magnetic activity cycles found for many stars (survey at **Mount Wilson Observatory**)
- Survey ended in 2000's after more than 30 years of Ca II HK observations

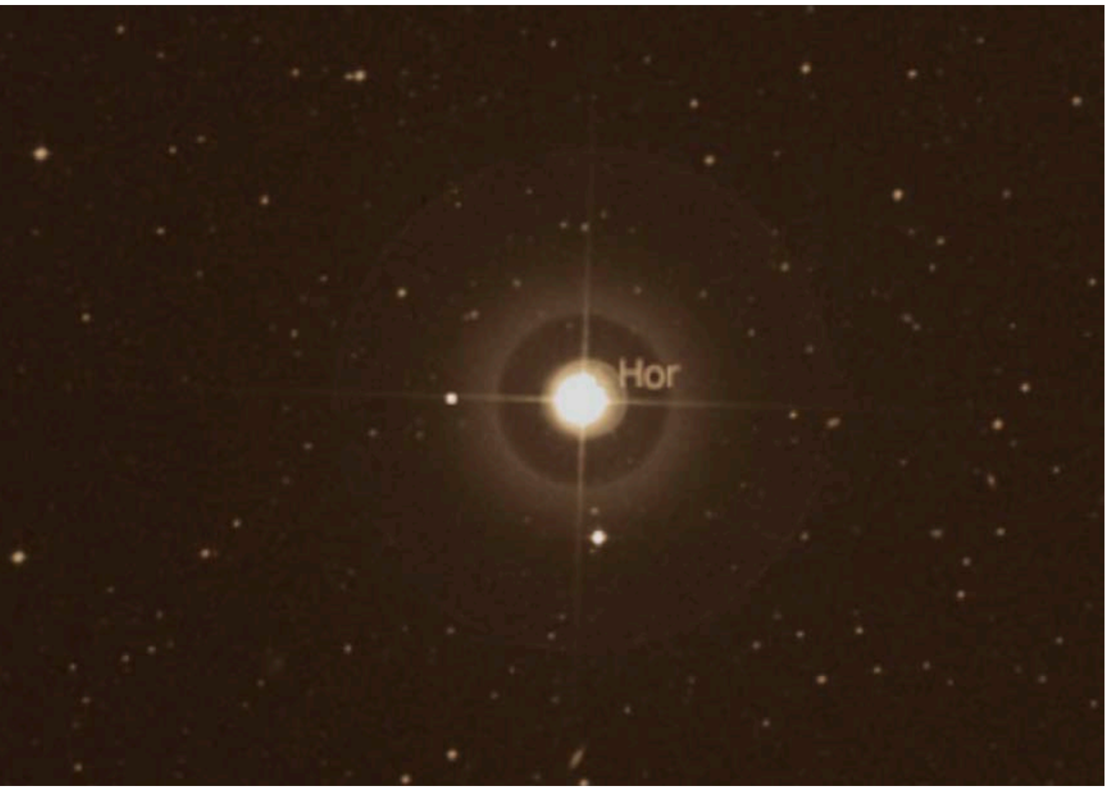


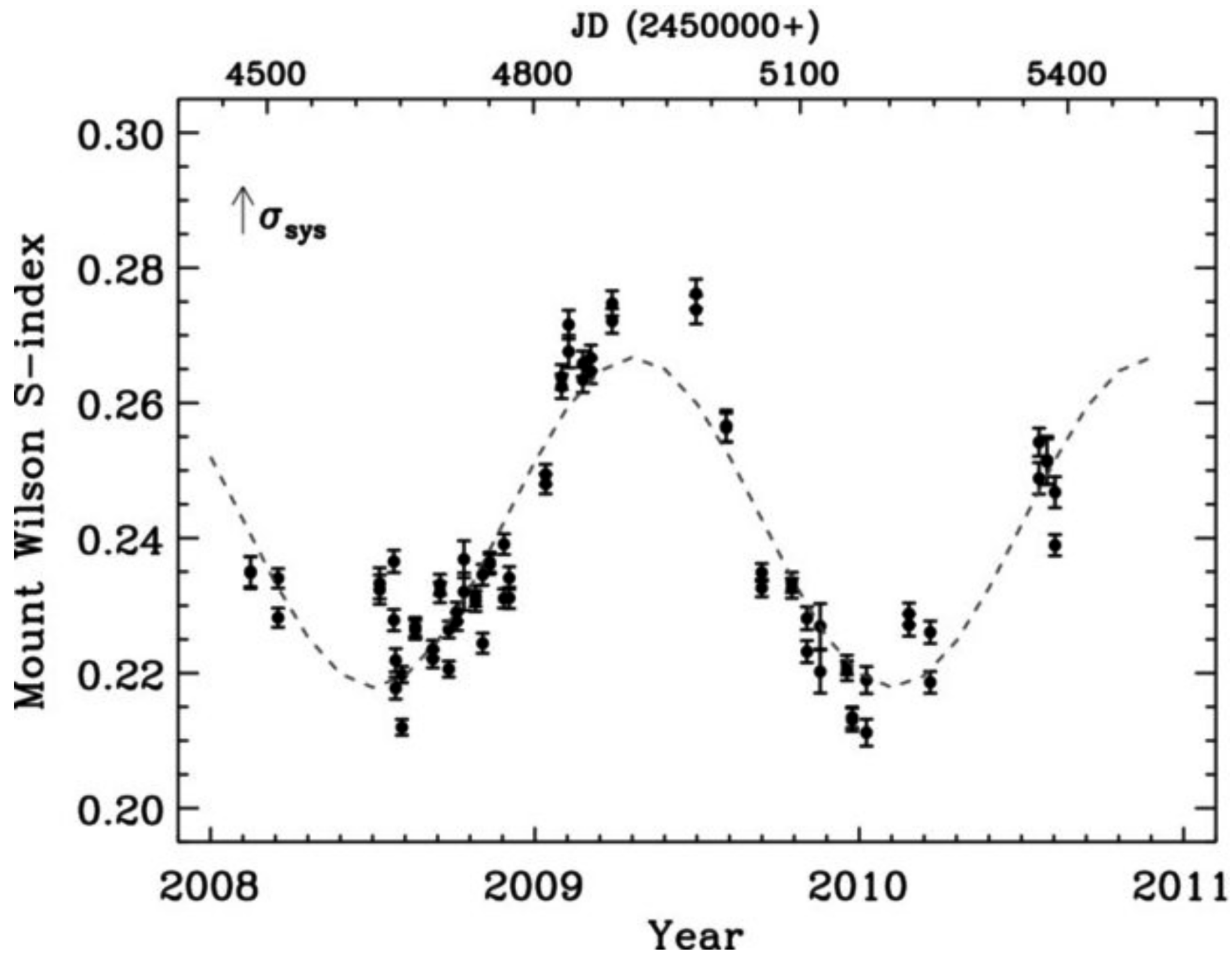


Baliunas et al. (1995)

Stellar activity cycles

Shortest measured stellar activity cycle in a solar-like star





Metcalfe et al 2010

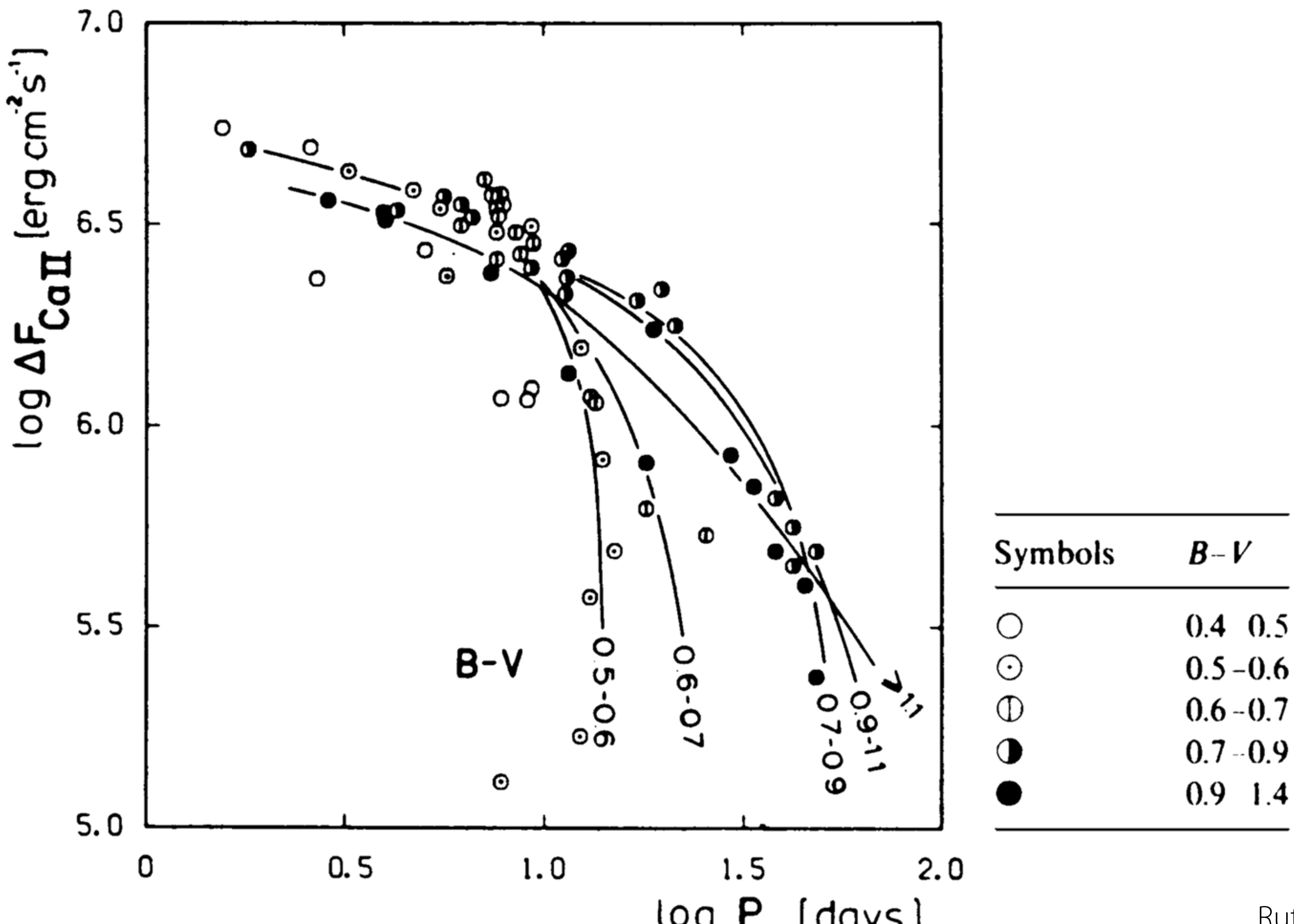
- G0V star ι Horologii (iota)
- **Magnetic activity cycle of 1.6 yr**
- $M=1.25\ M_\odot$
- $R = 1.18\ R_\odot$
- Rotation period 8.5 d
- Rotation speed $v \sin i \sim 7$ km s^{-1}
  ➡ 3 times faster than the Sun, among the faster rotating stars of that spectral type
- Consistent with coronal activity cycle found from XMM x-ray measurements

Stellar activity cycles

Ca II observations

- Statistical analysis of many (cool) stars: Ca II flux vs. rotation period
- Increase of Ca II flux with decreasing rotation period

➡ **Faster rotators have higher activity — generation of stronger magnetic field via a dynamo**

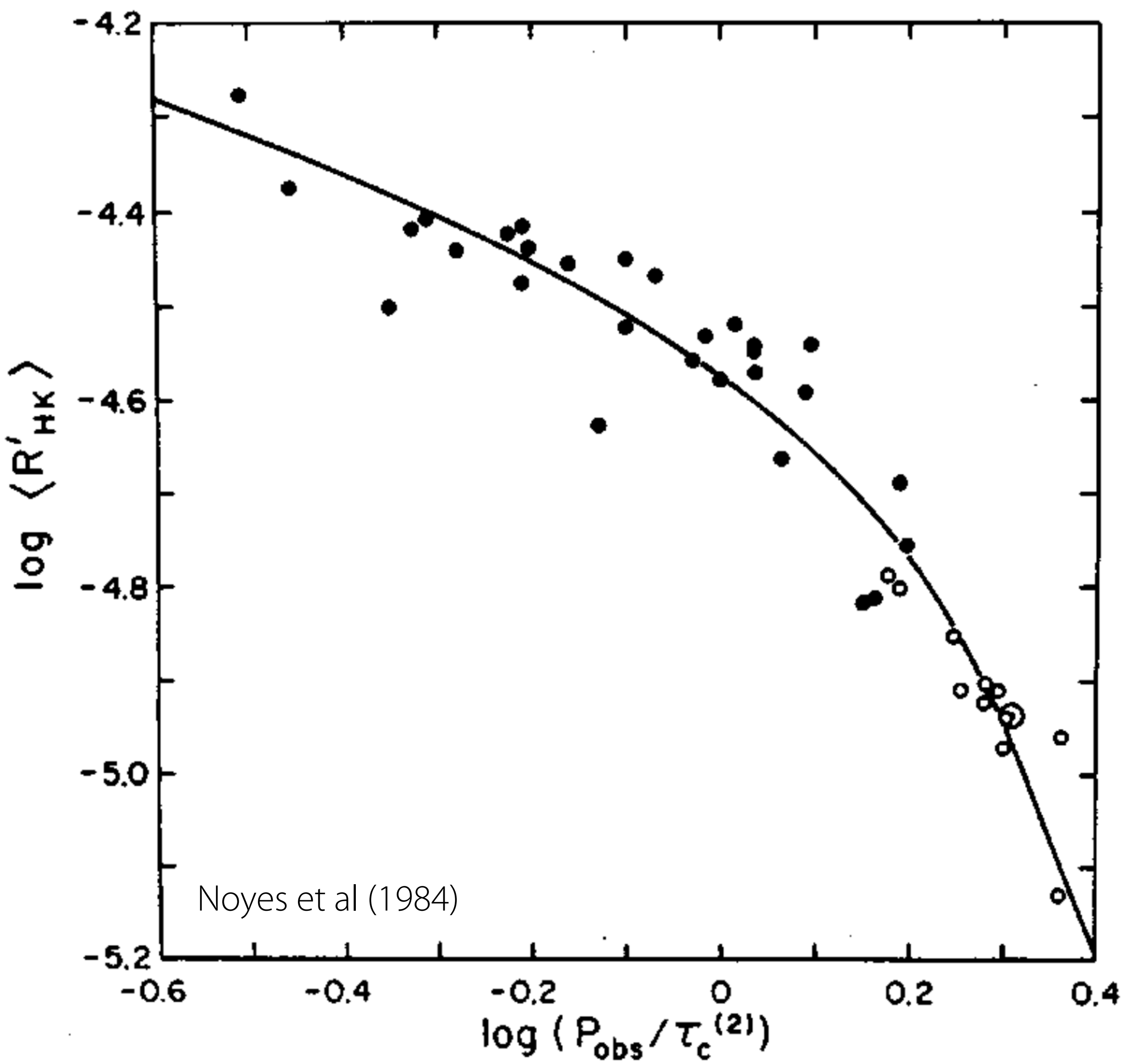


Rutten & Schrijver (1987)

Stellar activity cycles

Ca II observations

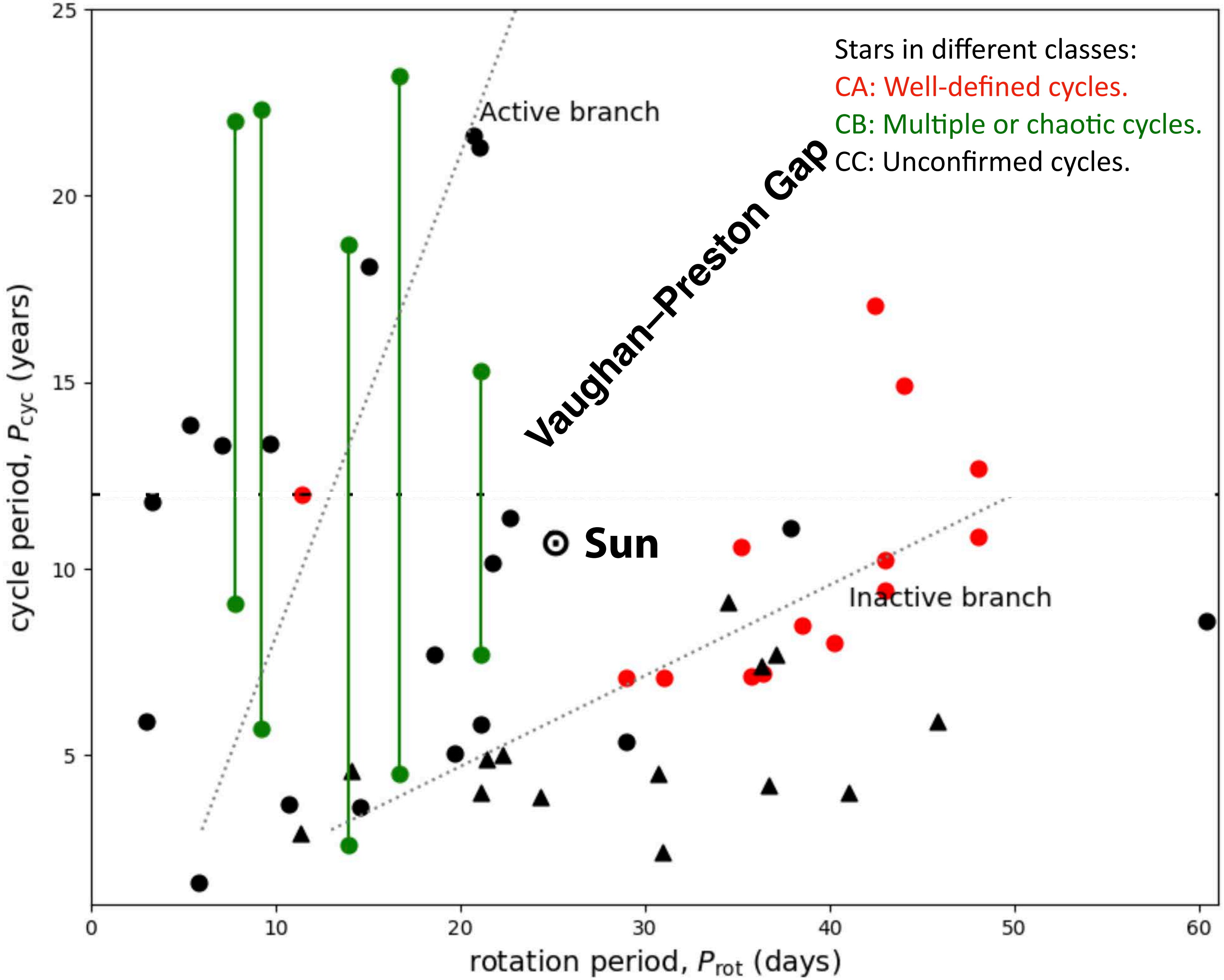
- Similar: Ca II activity indicator (R'_{HK}) vs. Rossby number
  (Rossby number: ratio of observed rotation period to convective turnover time)
- Clear indication of the **importance of stellar rotation and convection** for the efficiency of stellar dynamos and the resulting (magnetic) activity level



Stellar activity cycles

Activity cycle vs. rotation

- Statistics for many stars shows trend:
- Longer activity cycles for longer rotation periods
- Range between **active branch** (stars with strong activity) and **inactive branch** (stars with weak chromospheric activity)
- Branches divided by Vaughan–Preston Gap
  - Due to properties of stellar dynamos?
  - Or a statistical artefact?



Boro Saikia et al. (2018) A&A 616, A108 (2018)

Stellar activity cycles

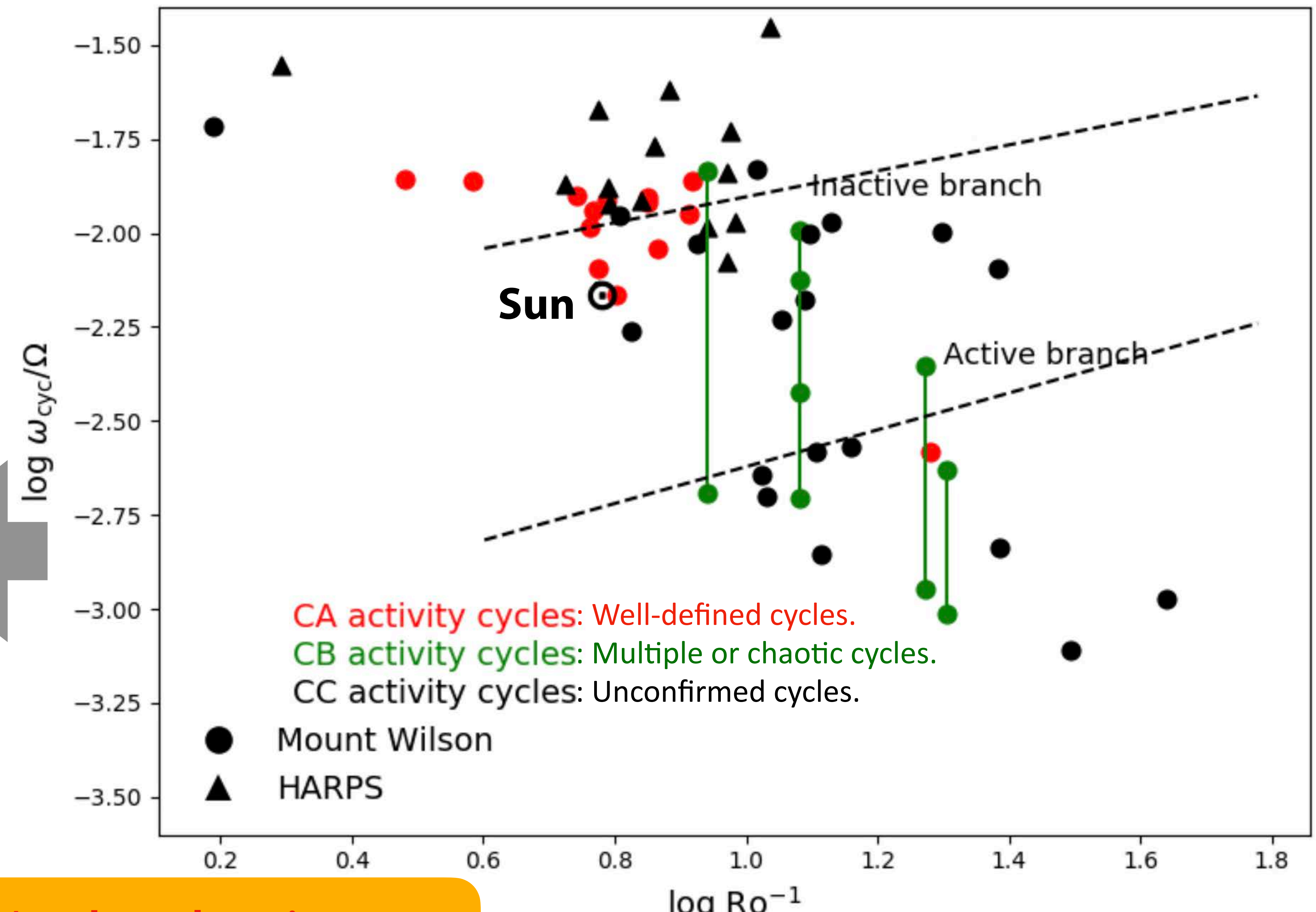
Activity cycle vs. rotation

- For same stars: ratio of cycle frequency ω_{cyc} and rotation rate Ω vs. Rossby number Ro

- Remember:
  Rossby number = ratio of inertial to Coriolis forces
  (Ratio of rotation period to convective turnover time)

- Dependence of activity cycle and Rossby number

➡ Properties of the global dynamo of stars and thus their activity cycles depend on Rossby number and rotation rate



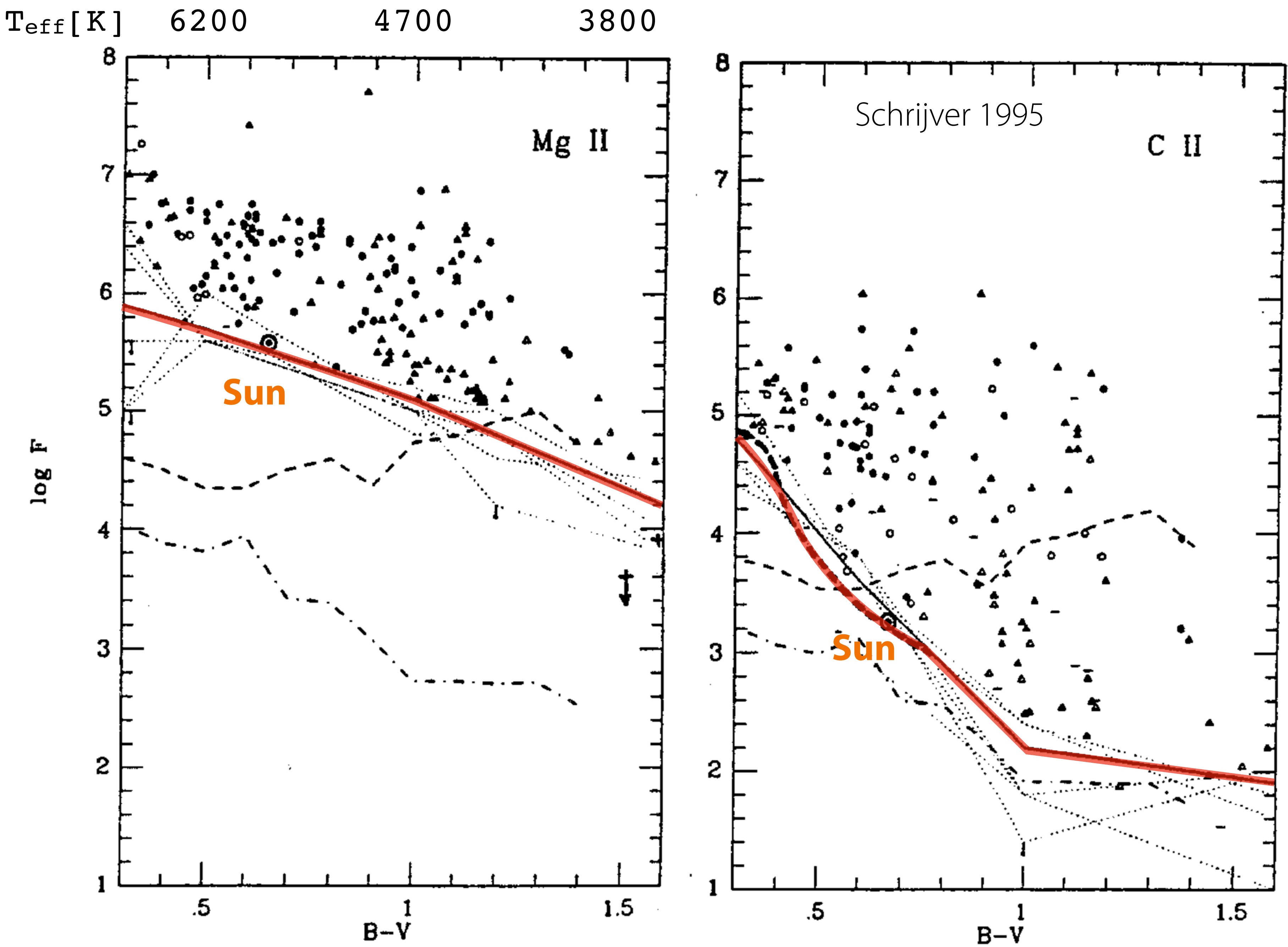
Boro Saikia et al. (2018) A&A 616, A108 (2018)

➡ **The Sun is only a weakly/moderately active star.**

Stellar activity

Basal flux limit

- Next to Ca II, spectral lines of other species used as activity indicators (here Mg II and C II)
- Large spread in values for the flux in these lines
- Lower limit:
  Basal flux limit
- (Was) thought of being produced by acoustic waves that would be present even for a star without magnetic field
  (Biermann 1948; Schwarzschild 1948)



- **Wilson-Bappu Effect (1957):** Linear relation between the absolute magnitude and log of Ca II K line widths for G-type and later stars (dwarfs and giants)

$$M_v = 27.59 - 14.94 \log W_o$$

Stellar activity

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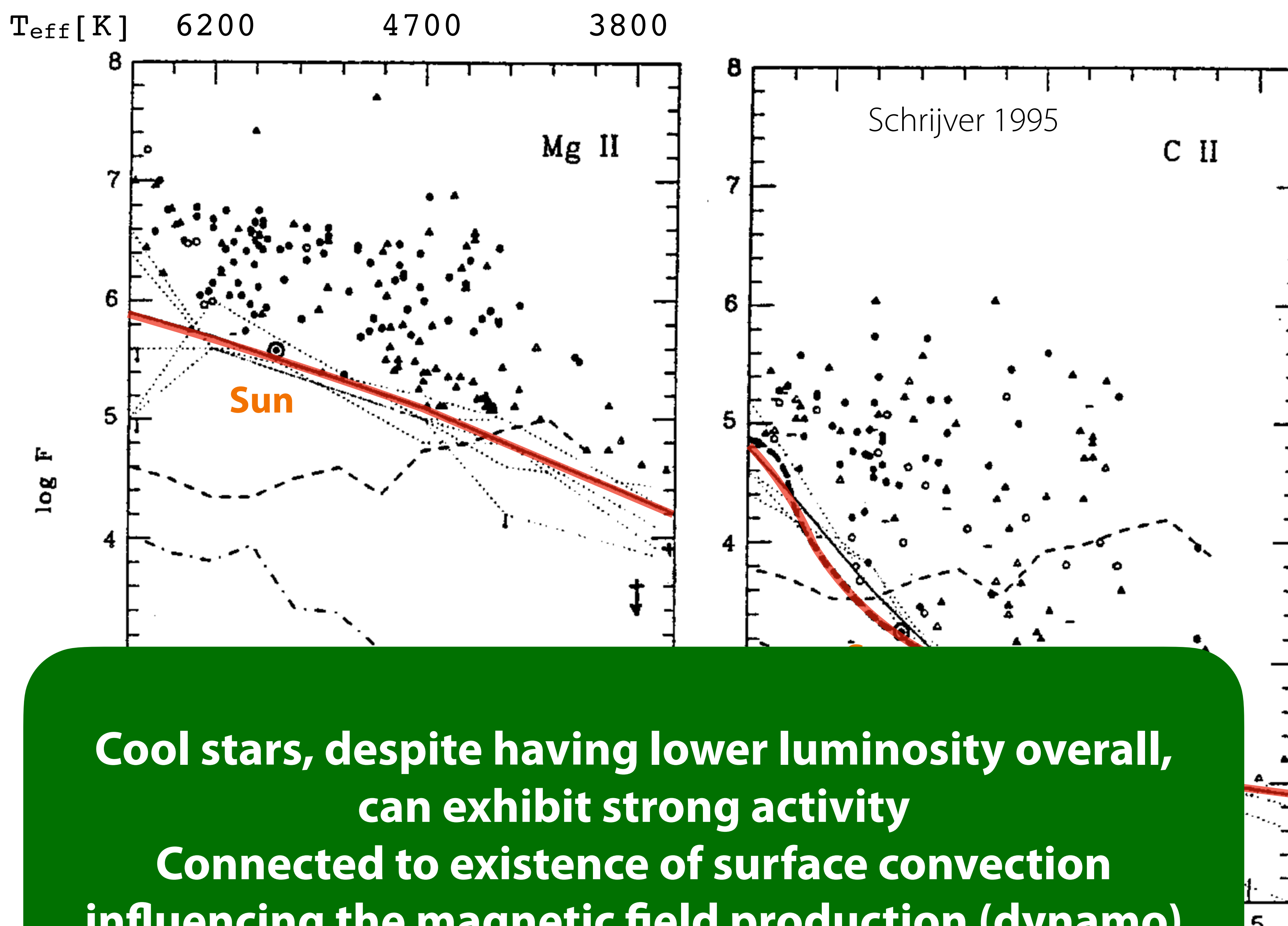


- **Wilson-Bappu Effect (1957):** Linear relation between the absolute magnitude and log of Ca II K line widths for G-type and later stars (dwarfs and giants)
  $M_v = 27.59 - 14.94 \log W_o$

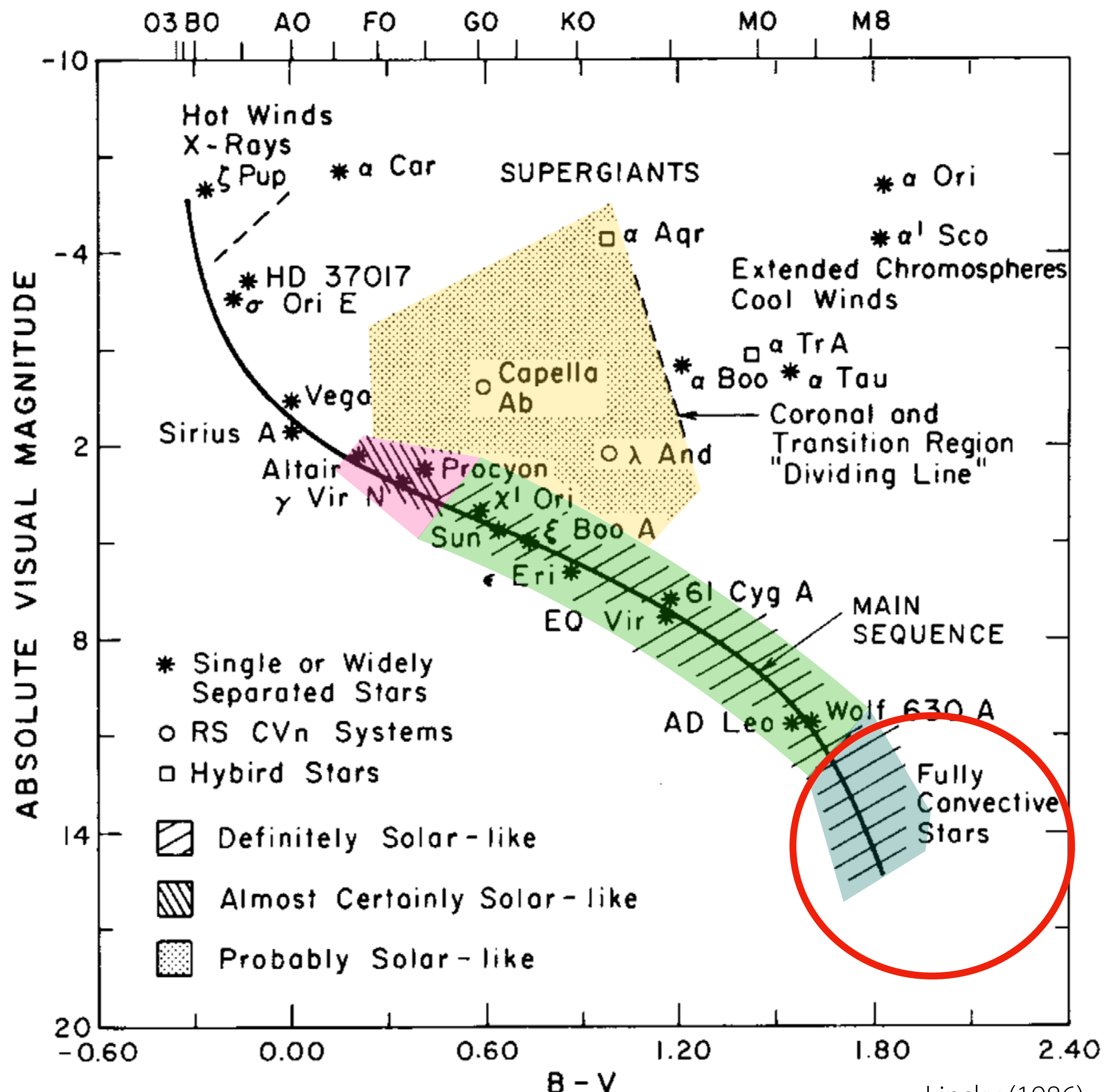
Cool stars, despite having lower luminosity overall, can exhibit strong activity
Connected to existence of surface convection influencing the magnetic field production (dynamo)

Stellar activity

Across the HRD

- Activity across the HRD as indicated by the existence of chromospheres (and coronae), resulting emission (e.g. Ca II), and (measurable) magnetic fields
- Clearly connected to presence of surface convection

◉ **The Sun is only a weakly/ moderately active star.**



Linsky (1986)

Stellar dynamos

Fully convective stars

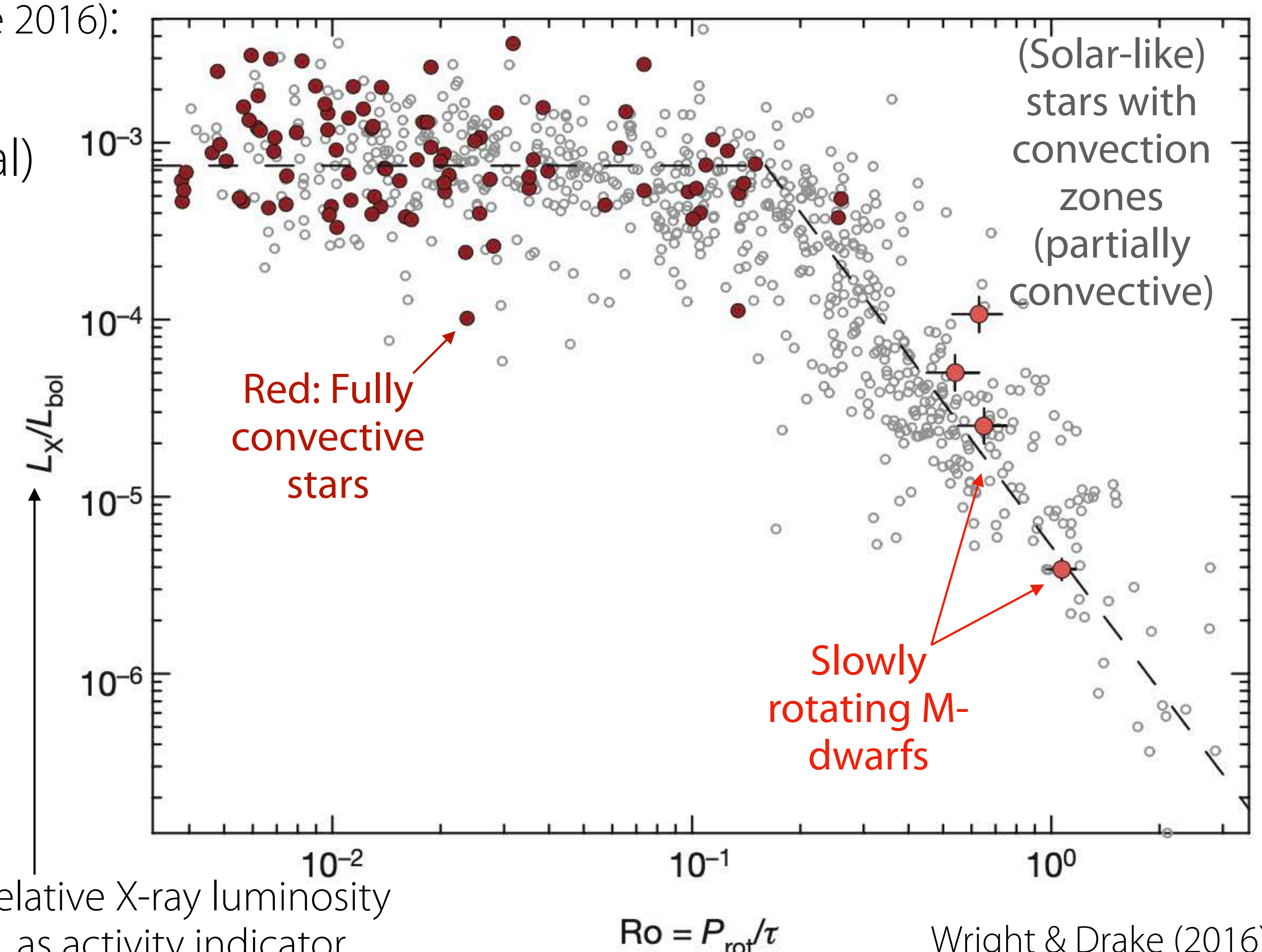
- Stars with low mass M< 0.3-0.4$M_{\odot}$ are fully convective
  - No inner radiative zone and no tachocline
  - ➡ How do they generate the strong magnetic fields / activity that are/is observed?
- Observational challenging: stars at and beyond transition (sp. type > M5) are very faint objects, reliable magnetic field measurements etc. difficult
  - BUT: coolest stars seem to be active (detected H α in emission with no obvious discontinuity, flares observed for very cool M-dwarfs)
  - Relationship rotation rate — activity level poorly known for M-type dwarf stars
  - Many M-dwarfs relatively rapid rotators
- Theoretical models succeed in explaining dynamos for fast rotating low-mass stars but still difficult for slower rotators

Stellar dynamos and activity

Rotation-activity relation

- Despite lack of a tachocline: Fully convective M-dwarfs fit the same rotation–activity sequence as solar-type stars with outer convection zones!
    - Activity and magnetism of late-type stars increase with decreasing Rossby number, then saturate

- Most likely explanation (Wright & Drake 2016):
    - Both rotation and turbulence (convection) important for (global) dynamos in <u>all</u> late-type stars (Lehtinen et al 2020)
    - Fully and partially convective stars have rotation-dependent dynamos that share important properties
    - Tachocline not a vital ingredient.
      — **Differential rotation**
      + Coriolis force is sufficient!
    - **Still many open questions, active field of research!**

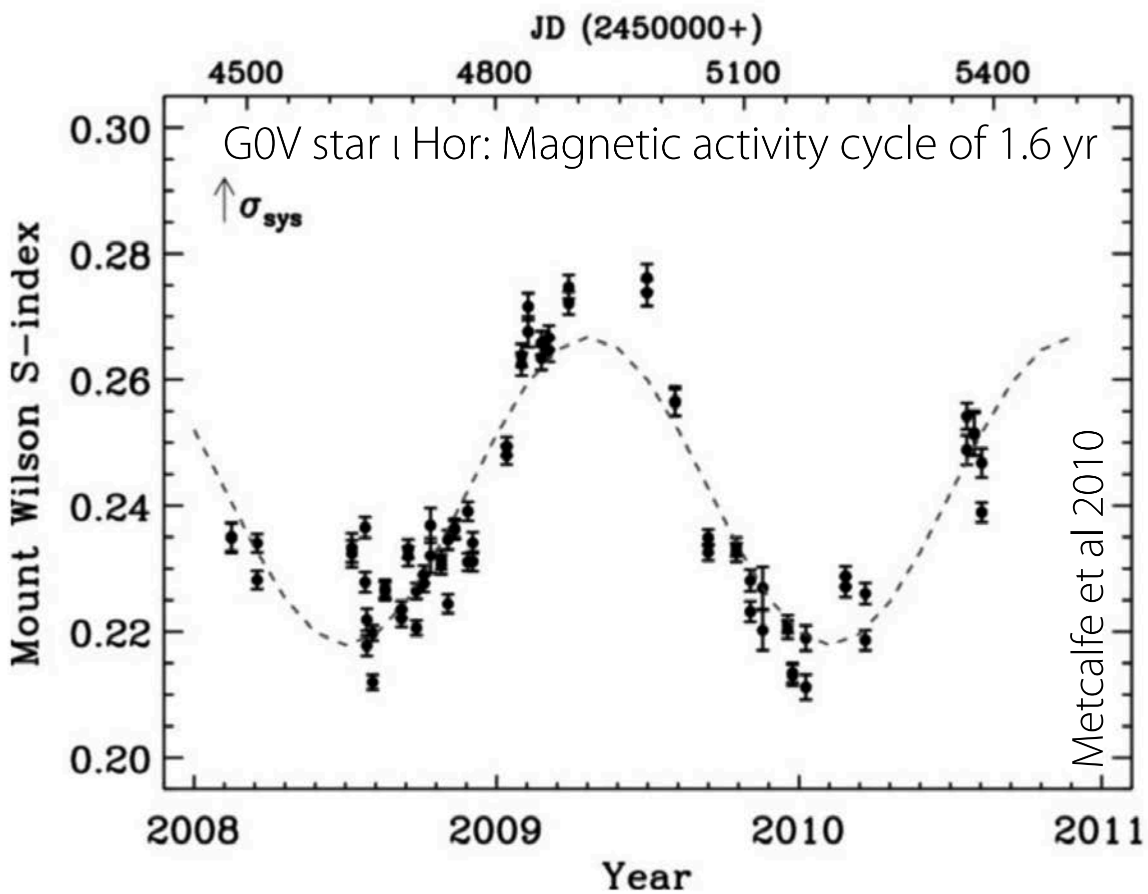


Wright & Drake (2016)

Stellar activity

Summary

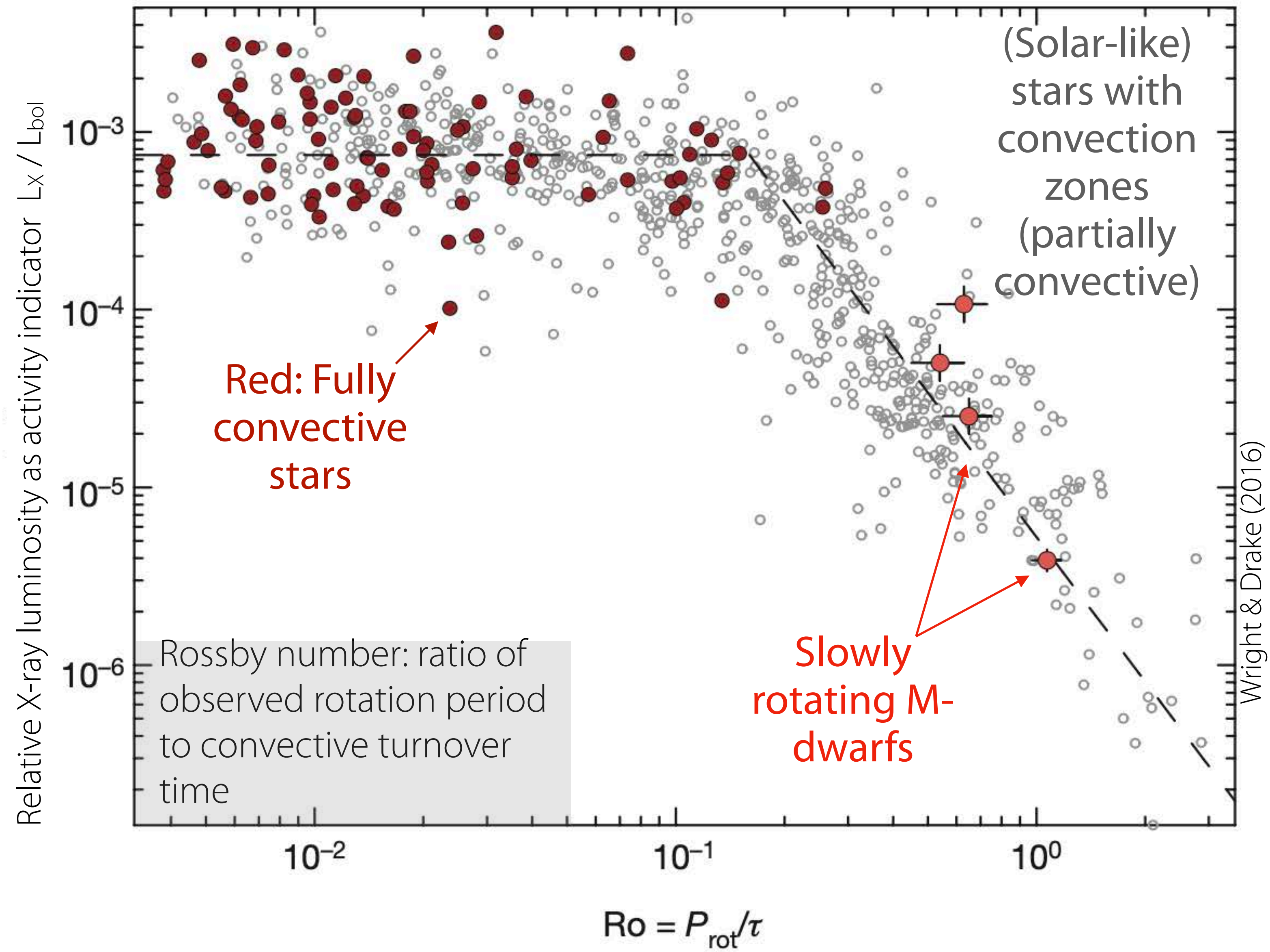
- **Stellar activity** refers to all phenomena in a stellar atmosphere that result in **variability** of the emitted radiation and **heating** of the outer atmosphere (existence of a chromosphere, temperatures above radiative equilibrium)
- Found for **cool late-type stars** due to the presence of surface convection, dynamo and the resulting highly structured **magnetic fields** in their atmospheres
- Activity indicators based on spectral features from in the upper atmosphere (chromosphere/corona), e.g.: S-index based on Ca II H & K
  - Large spread in activity with a basal flux limit — between active and inactive branch
- The Sun is only a weakly/moderately active star.
- Activity related to magnetic field strength of a star!
- **Rotation and convection important for dynamos.**
- Activity cycles periods vary (as short as 1.6 yr) →



Stellar dynamos and activity

Summary

- Clear **rotation-activity relation**: Activity and magnetism of late-type stars at a saturated level for small Rossby number, decline for larger Ro values
- **Fully convective** M-dwarfs fit the same relation as solar-type stars with outer convection zones despite lack of a tachocline!



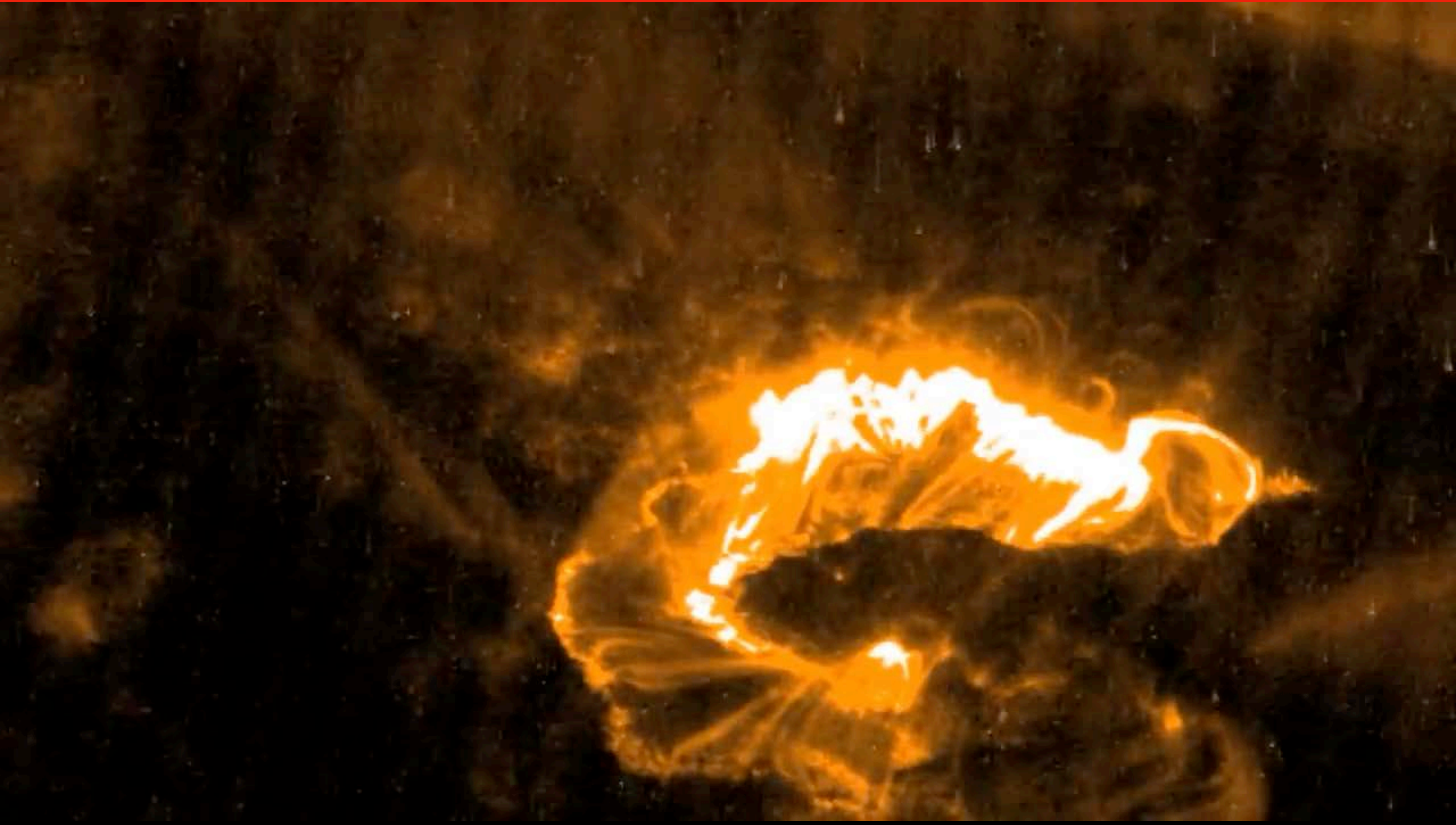
- Most likely: Fully and partially convective stars have rotation-dependent dynamos that share important properties
- Tachocline not a vital ingredient.

➡ **Differential rotation + Coriolis force sufficient!**

- **Still many open questions, active field of research!**

Flares

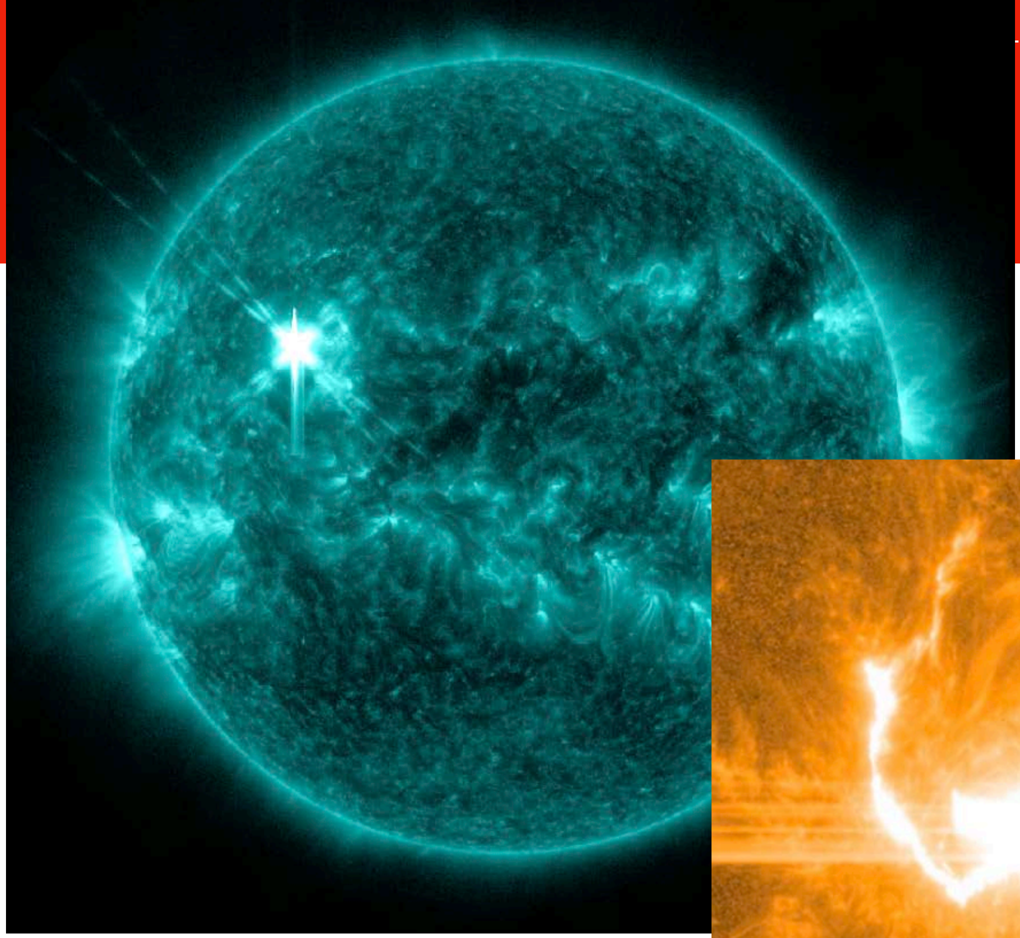
Flares



- Flares = Intense eruptions on the Sun with emission of radiation across the whole spectrum (γ- and X-rays, UV, visible / white light … radio) and energetic particles

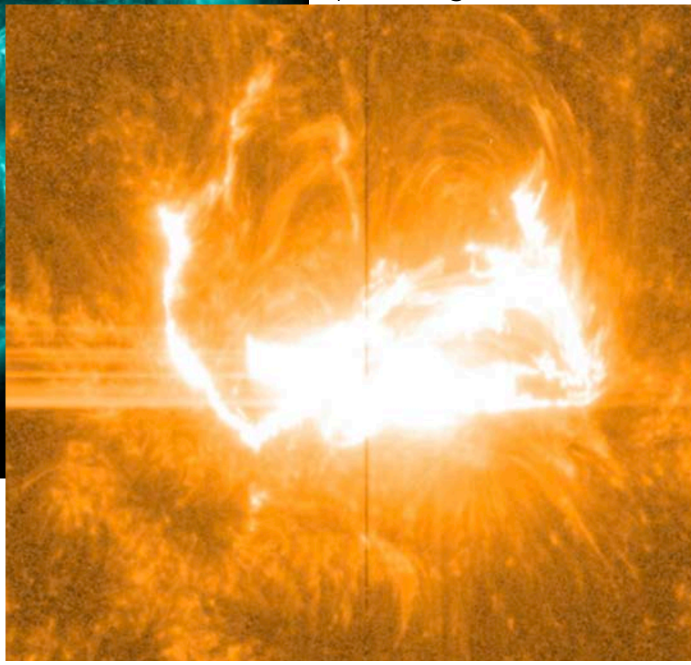
Flares

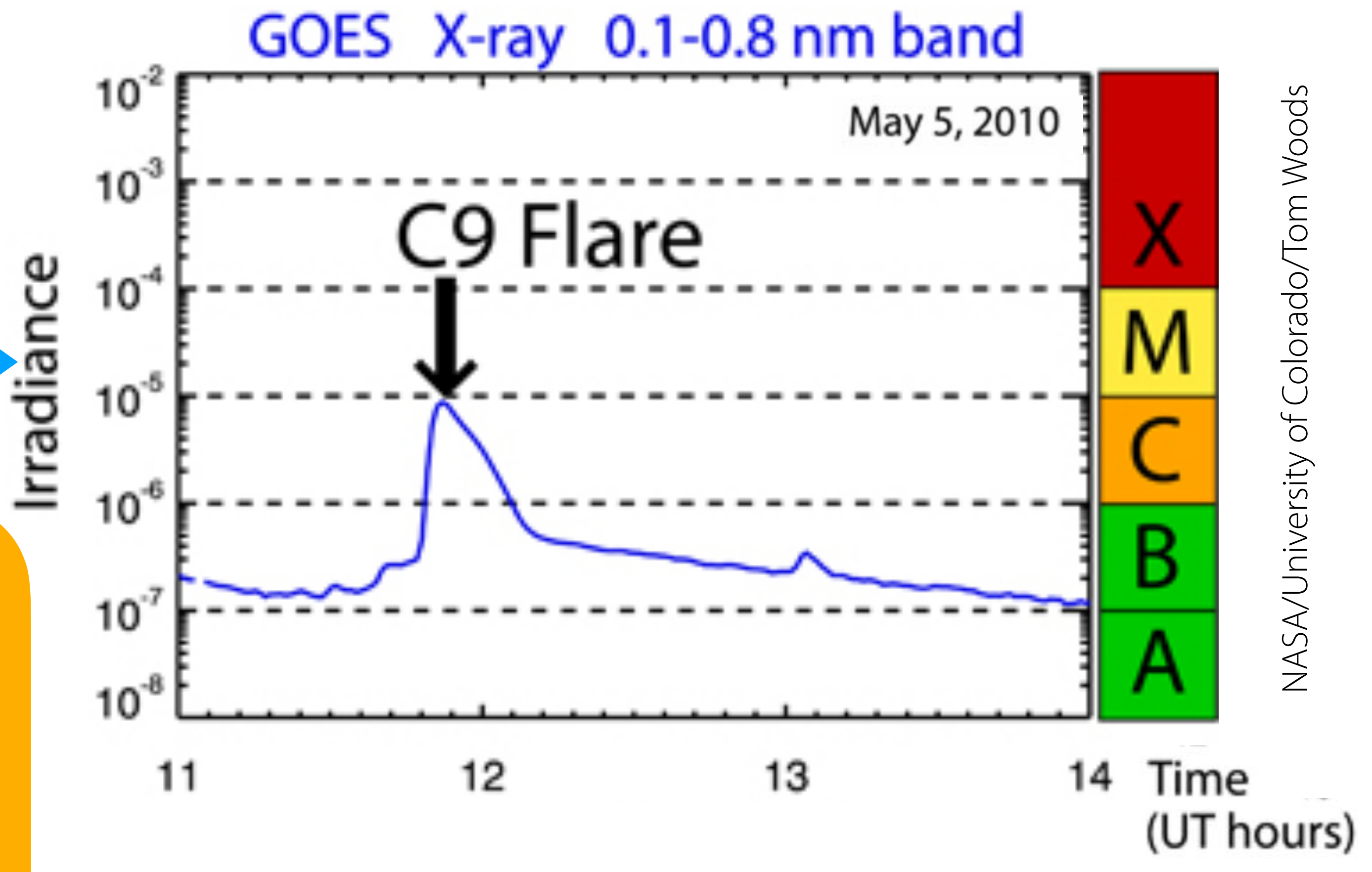
- **Sudden brightening with emission across the whole electromagnetic spectrum**
- **Huge amount of energy released** (10^{27} - 10^{32} ergs), most of it emitted within a few min/10min
- Three major phases:
  - Pre-flare phase
  - Impulsive phase (incl. peak, main)
  - Gradual phase (post-flare)
- **Classification** according to peak flux in soft X-ray band (GOES)
  - X (strongest)
- **Event size**: height of a flaring loop from < 10Mm to 100 Mm
- Size correlates with flare duration (10^3-10^4 s) and amount of released energy



NASA/SDO/AIA

NASA/IRIS/Goddard Space Flight Center

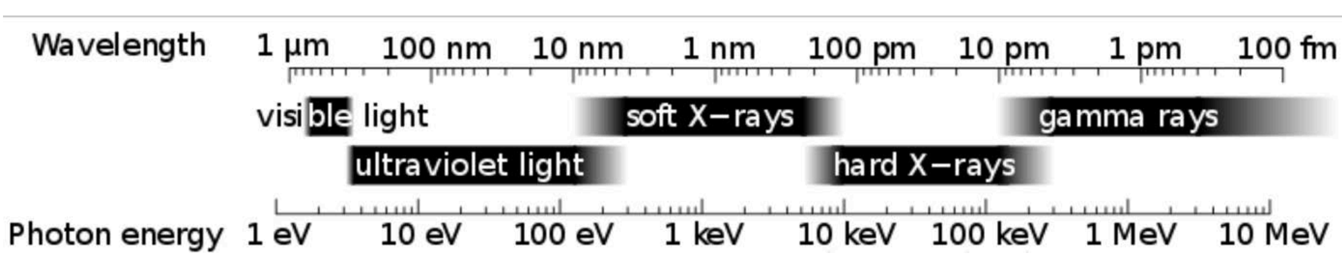


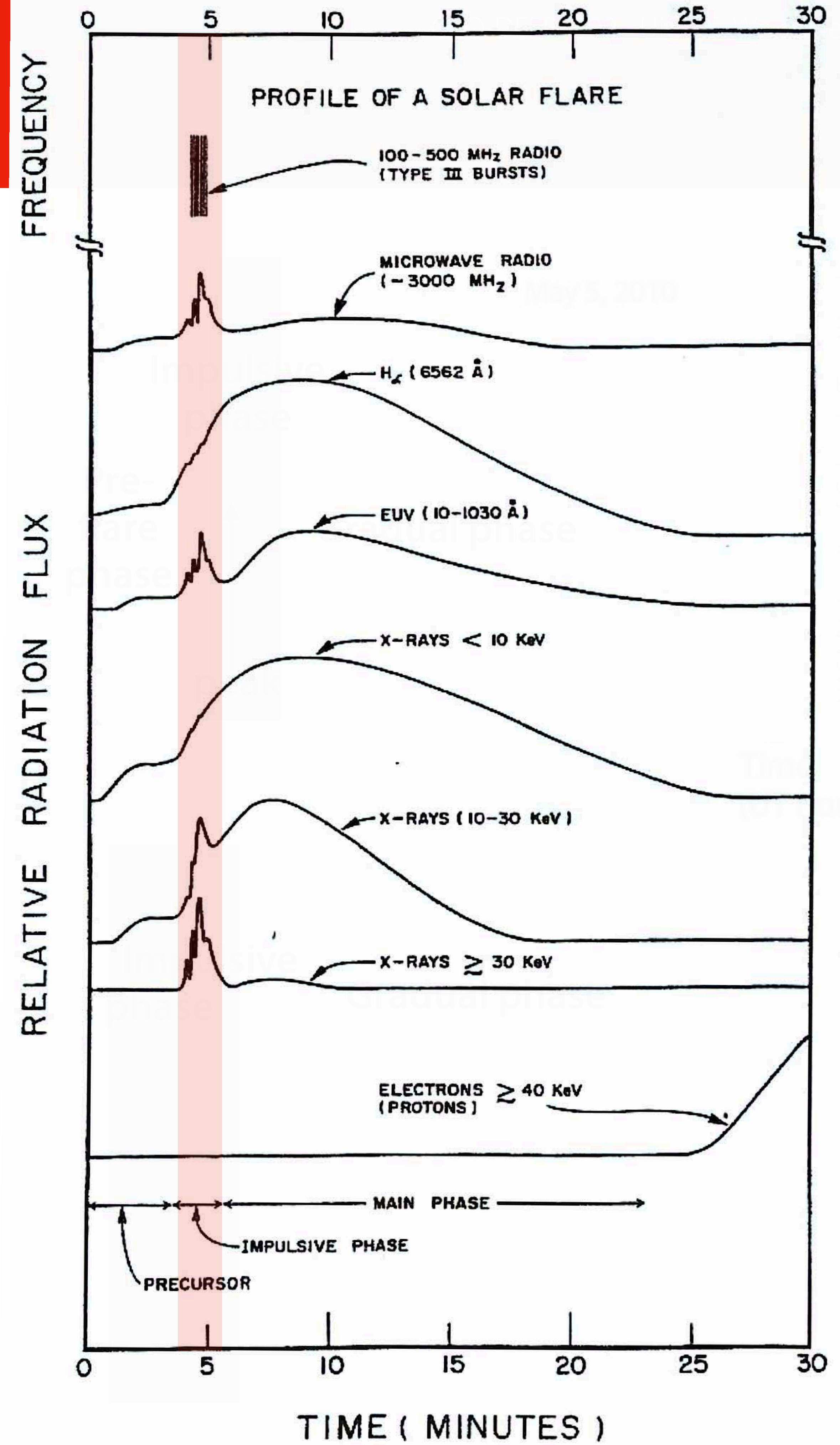


Flares

Temporal evolution

- **Sudden brightening that involves all layers of the solar atmosphere**
- **Emission across the whole electromagnetic spectrum** but different temporal variation (incl. rapid increase) depends on wavelength region
- Total energy released in flares varies from event to event
  - Range: 10^{27} - 10^{32} ergs, most of it emitted within a few 10min
  - For comparison: One H-bomb = 10 million TNT = 5 10^{23} ergs

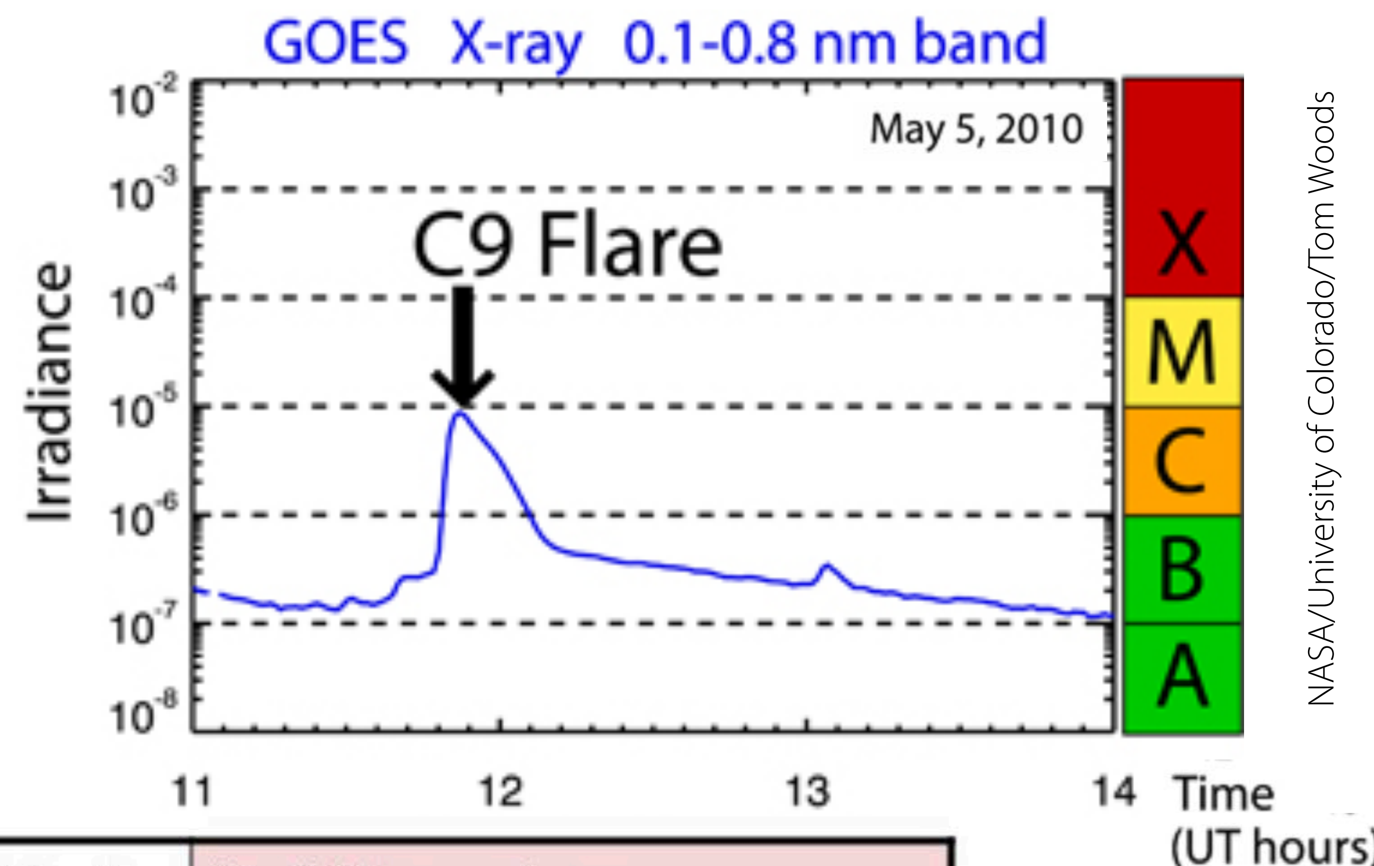




Flares

Classification

- Alternative classifications schemes based on other measurable indicators, e.g.:
  - Radio flux at 5G Hz
  - Area with enhanced emission in Hα



Hα classification			Radio flux at 5000 MHz in s.f.u.	Soft X-ray class	
Importance Class	Area (Sq. Deg.)	Area 10^{-6} solar disk		Importance class	Peak flux in 1-8 Å w/m^2
S	2.0	200	5	A	10^{-8} to 10^{-7}
1	2.0–5.1	200–500	30	B	10^{-7} to 10^{-6}
2	5.2–12.4	500–1200	300	C	10^{-6} to 10^{-5}
3	12.5–24.7	1200–2400	3000	M	10^{-5} to 10^{-4}
4	>24.7	>2400	3000	X	$>10^{-4}$

Hα sub-classification by brightness:
F – faint, N – normal, B – bright

1 s.f.u. = 10^4 jansky = 10^{-2} W m^{-2} Hz^{-1}

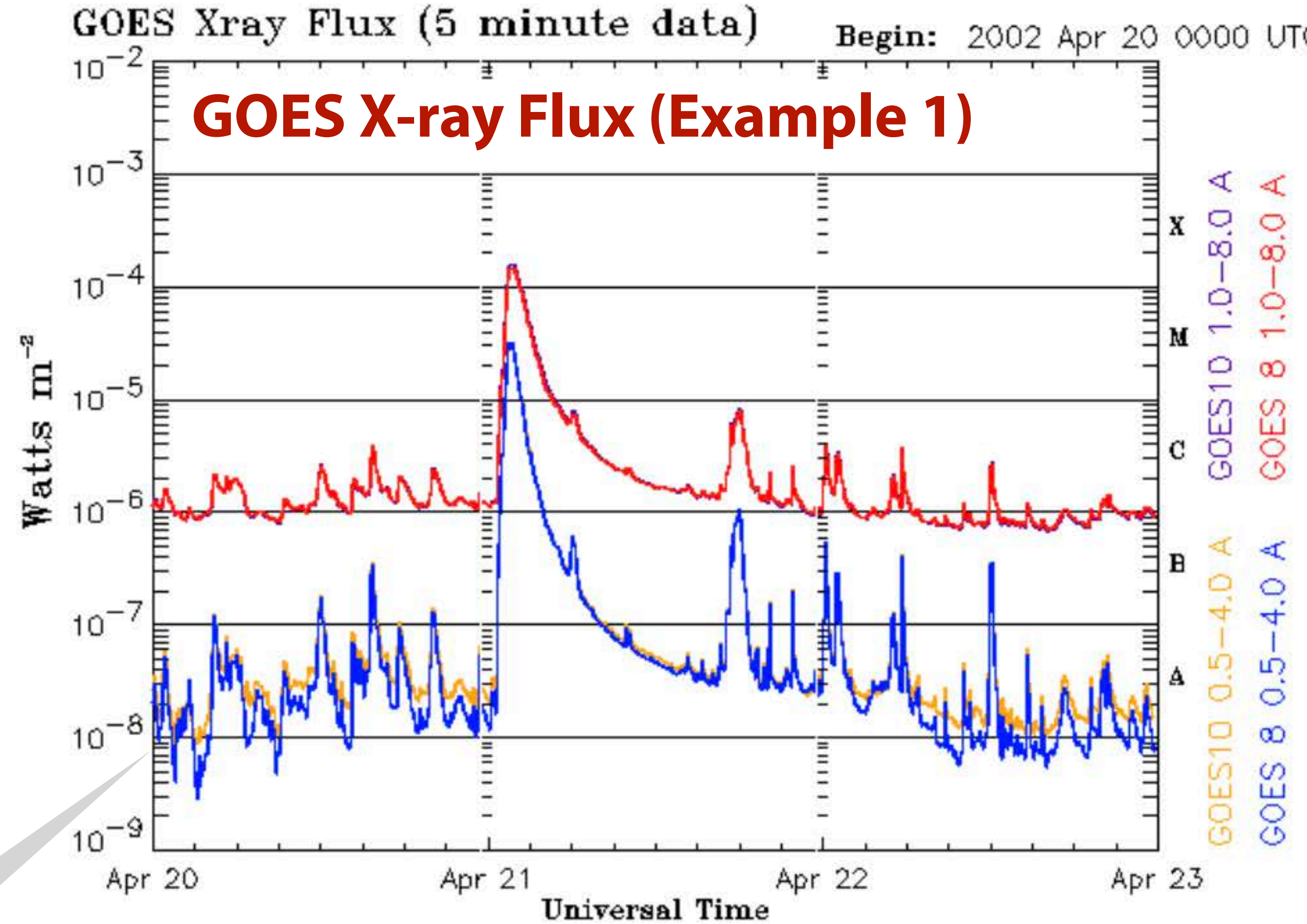
Flares

GOES observations

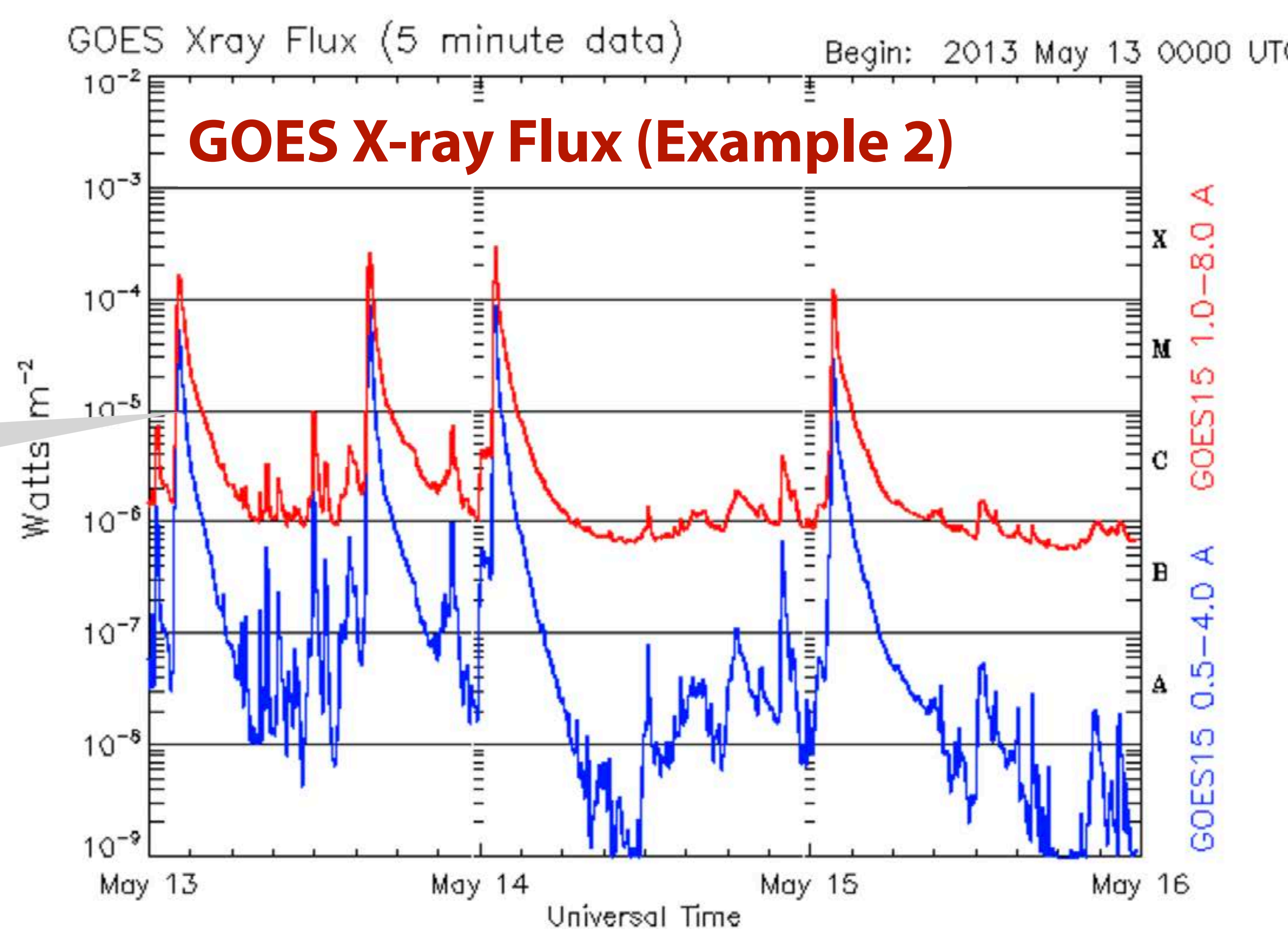
- GOES detects the X-ray irradiance of the whole Sun
- A single flare significantly varies the detected X-ray irradiance despite affecting only small region on the Sun!

Different colors = different bands

GOES class according to **0.1-0.8nm band (red)**



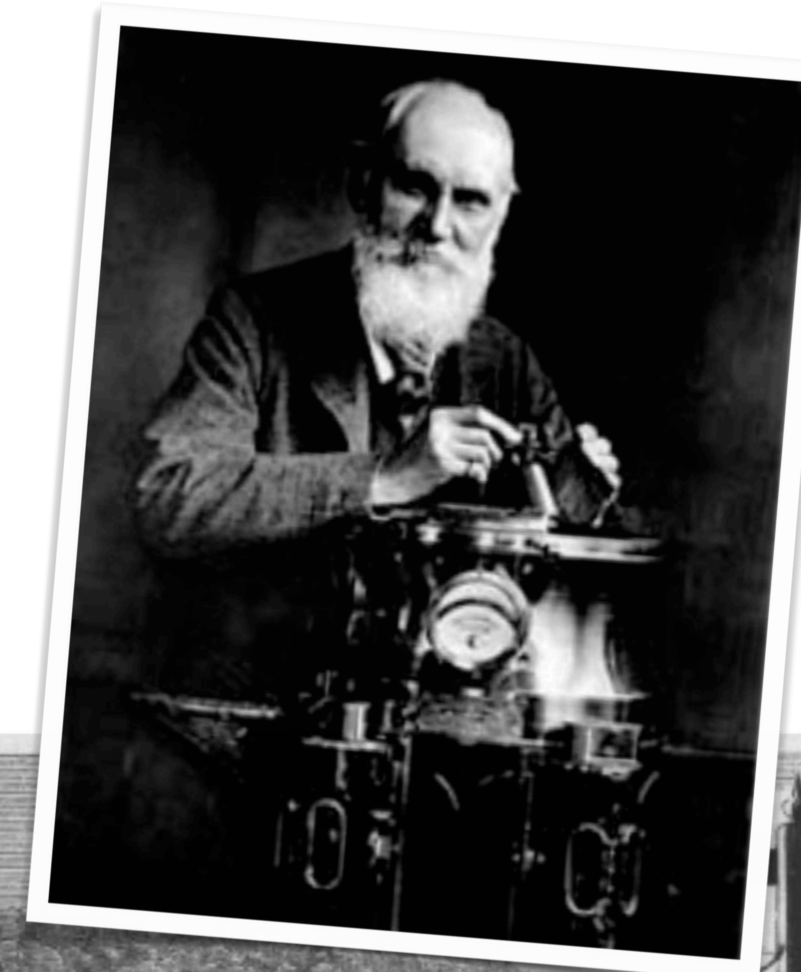
Sequence of several flares including 4 X-class flares within 3 days



Flares

Carrington

- Richard Carrington (1826-1875)   English astronomer
- Particularly famous for the first continuous detailed observation of sunspots.
- Established that the sun rotates differentially (so must be a fluid not a solid body!)
- Began the series of solar rotations now known as Carrington Rotations.



Richard Carrington built this manor house with an adjoining observatory Redhill, Surrey. It was from here that he witnessed the solar flare. (Imag Royal Astronomical Society)

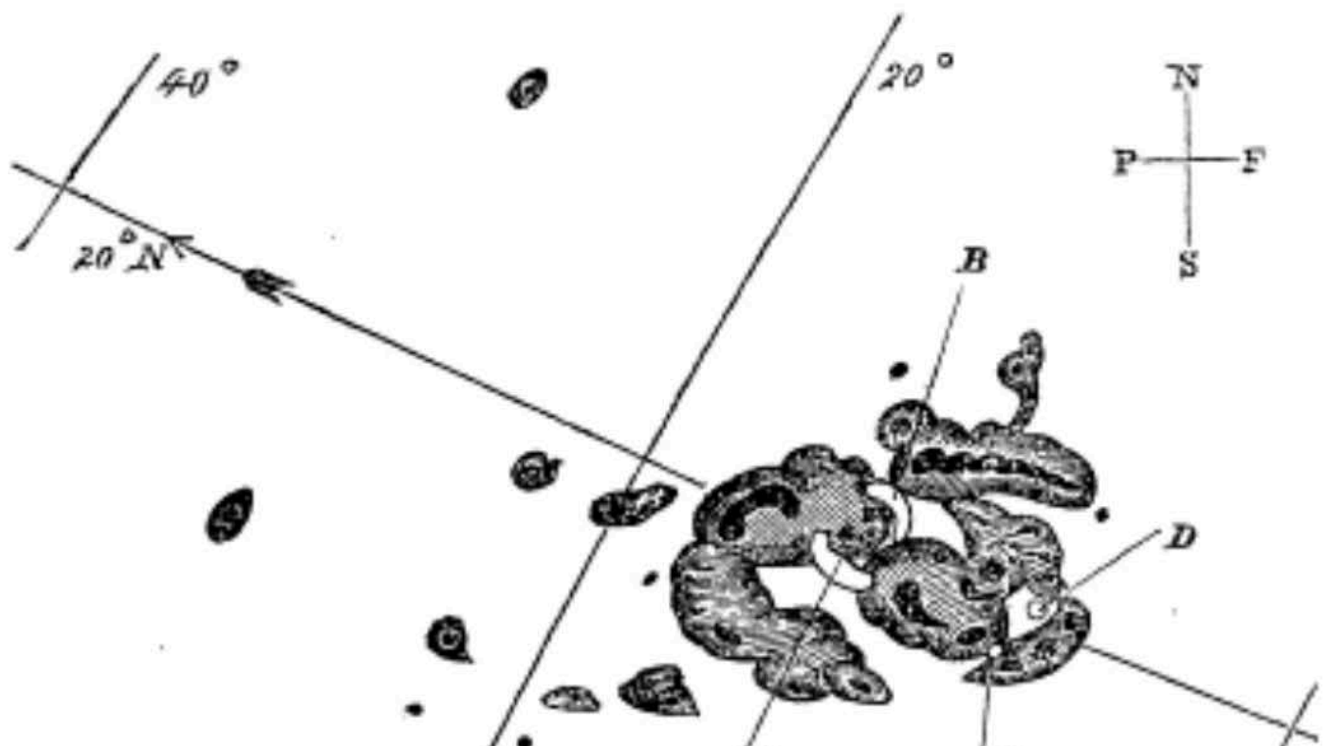
Flares

Carrington event — 1859

- The Great Flare of 1859 — observed by Richard Carrington
- First solar flare ever reported!
- White Light Flare – only the strongest flares notable in white light.
- No flare approaching this intensity has been observed since.
- Caused geomagnetic storm (Aug. 27-Sep.7)
- Aurora seen as far south as Cuba/ Colombia!
- Telegraph systems / wires in Europe and the US affected / failed, sparks caused fires at telegraph stations
- Night sky lit brighter than full moon

Description of a Singular Appearance seen in the Sun on September 1, 1859. By R. C. Carrington, Esq.

While engaged in the forenoon of Thursday, Sept. 1, in taking my customary observation of the forms and positions of the solar spots, an appearance was witnessed which I believe to be exceedingly rare. The image of the sun's disk was, as usual with me, projected on to a plate of glass coated with distemper of a pale straw colour, and at a distance and under a power which presented a picture of about 11 inches diameter. I had secured diagrams of all the groups and detached spots, and was engaged at the time in counting from a chronometer and recording the contacts of the spots with the cross-wires used in the observation, when within the area of the great north group (the size of which had previously excited general remark), two patches of intensely bright and white light broke out, in the positions indicated in the appended diagram by the letters A and B, and of the forms of the spaces left white. My



Historic geomagnetic data at:
http://www.geomag.bgs.ac.uk/education/carrington.html

Monthly Notices of the Royal Astronomical Society, Volume 20, November 11, 1859

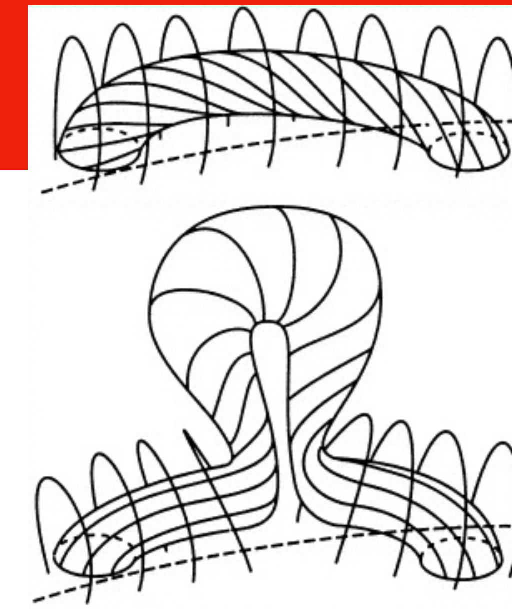
A one-time event?

➡ Arctic/Antarctic ice cores indicate that ***flares of similar strength on avg. occur once in a century.***

Flares

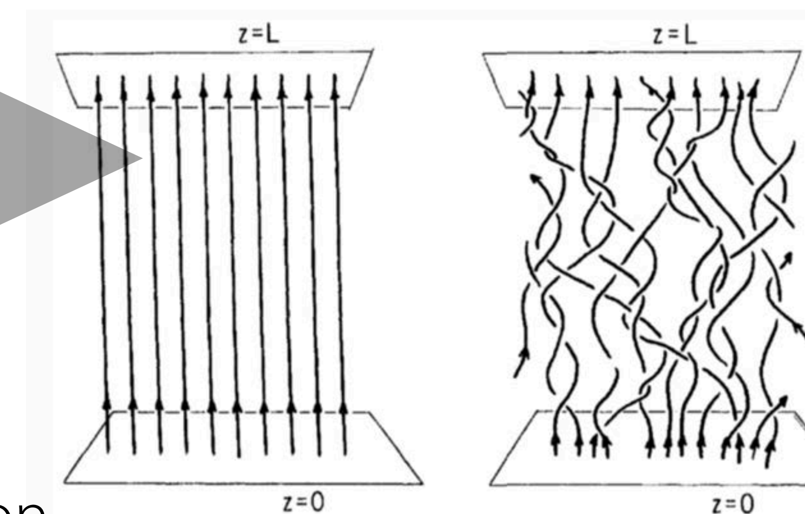
Towards a physical model

- **Key physical processes for producing a flare**
  - Emergence of magnetic field from interior into atmosphere (flux emergence)



  - Twisting and stressing of magnetic field due to convective motions at/near surface

➡ Energy stored in the entangled magnetic field (magnetic tension!)



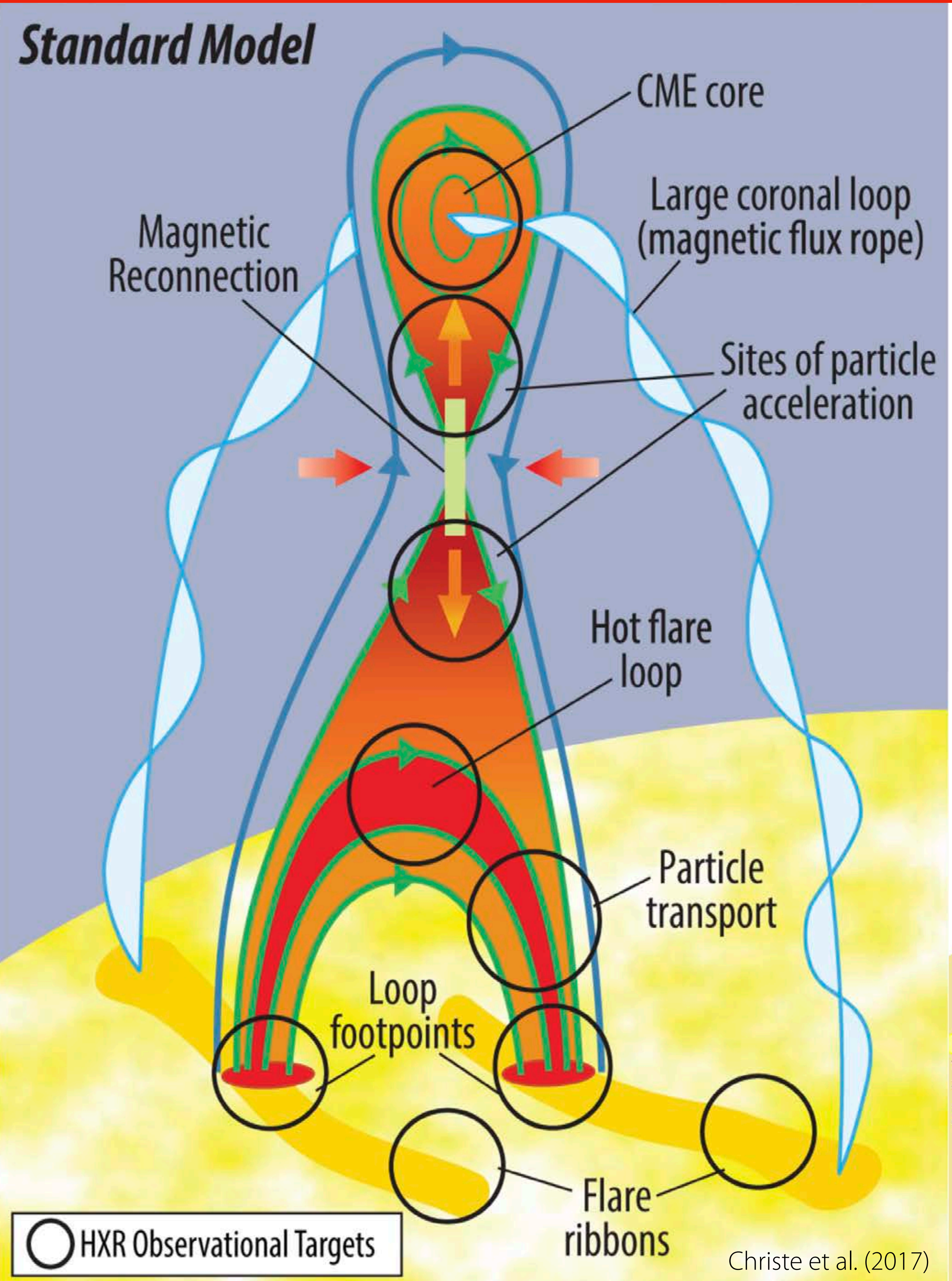
Parker (1994)

  - Local enhancement of electric current in the corona (formation of a current sheet)
  - Rapid dissipation of electric current (**magnetic reconnection**)

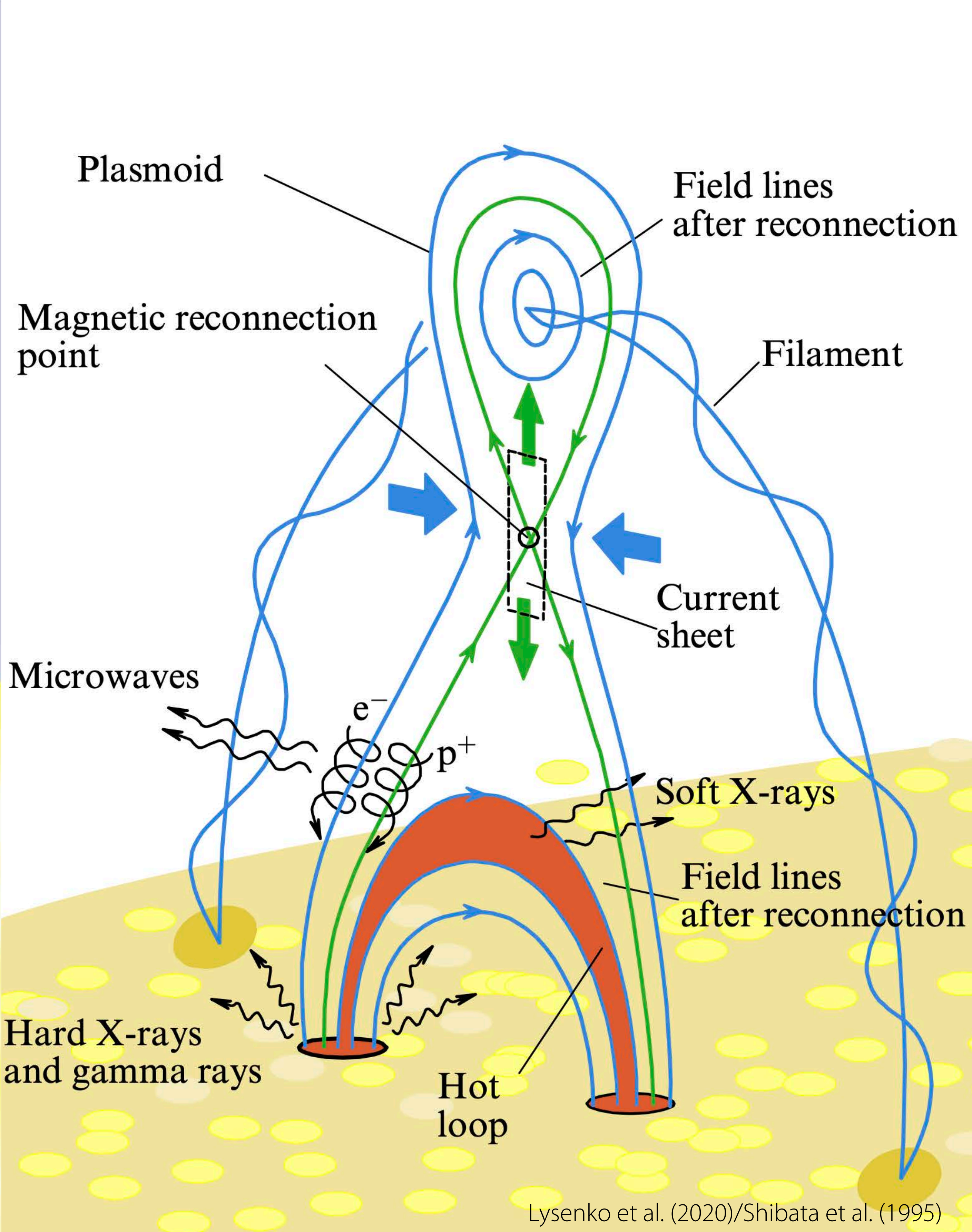
NASA Goddard

  - Sudden release of stored energy causes shock heating, mass ejection, and particle acceleration.

Flares



Christe et al. (2017)



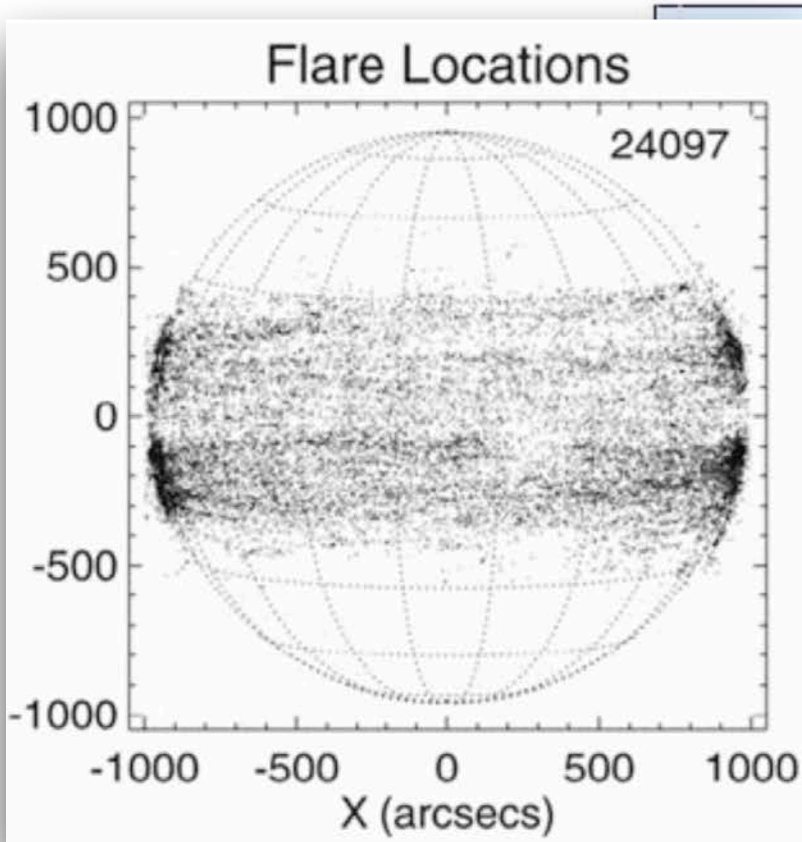
Lysenko et al. (2020)/Shibata et al. (1995)

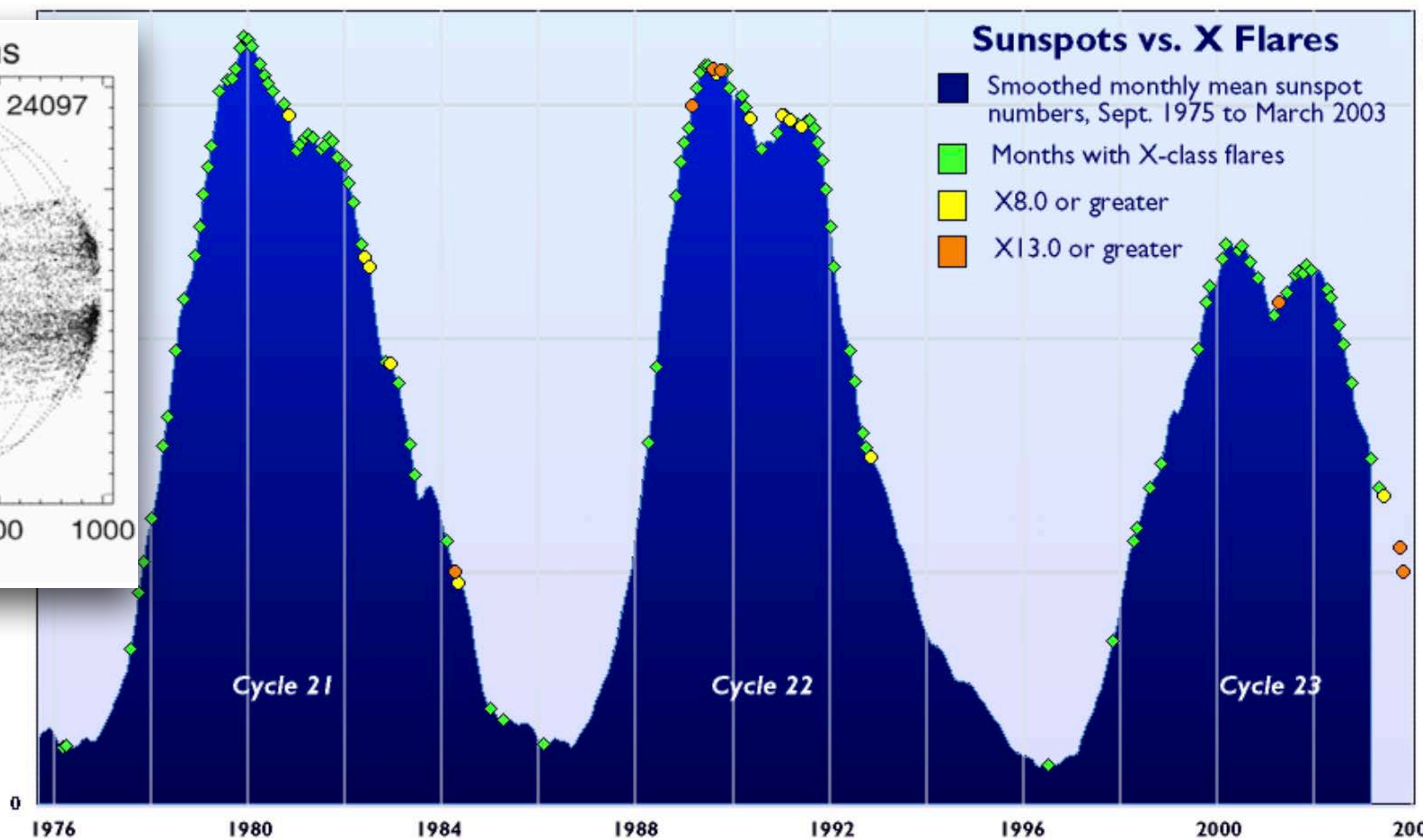
Flares

Occurrence of major (X-class) flares over the solar cycle

- Flares occur in Active Regions

➡ Number of flares (and X-class flares) thus varies with the number of present sunspots and thus with the solar cycle

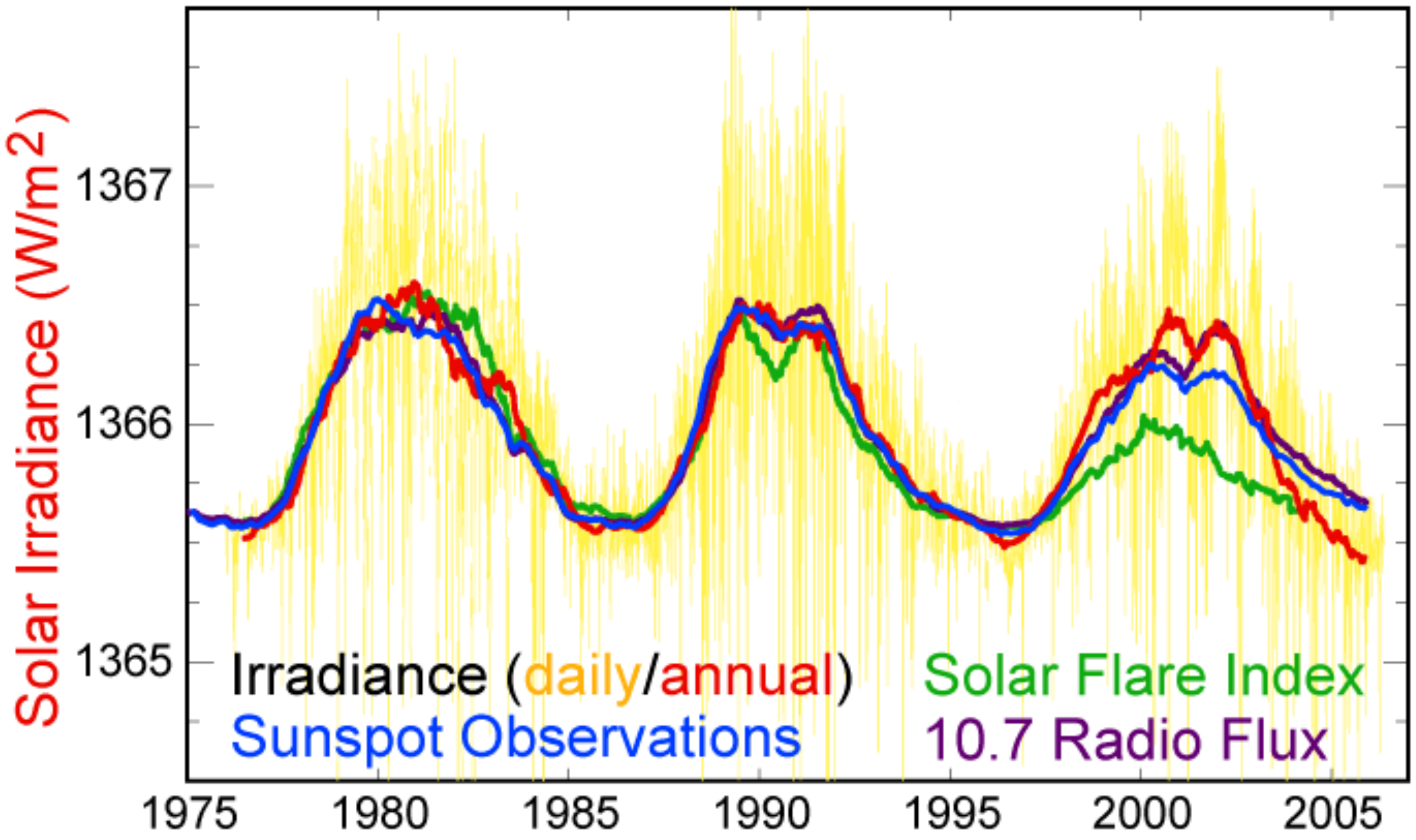




Flares

Occurrence

- Total number per day depends on flare intensity!
- Solar minimum: on average one per day
- Solar maximum: on average as high as 20 per day
- Flare rate is very **irregular**!
  - There can be long periods of time at solar minimum with no detectable flare!
  - A large active region can produce many flares in just a few days.



Solar flare index:
based on flare's brightness and importance.

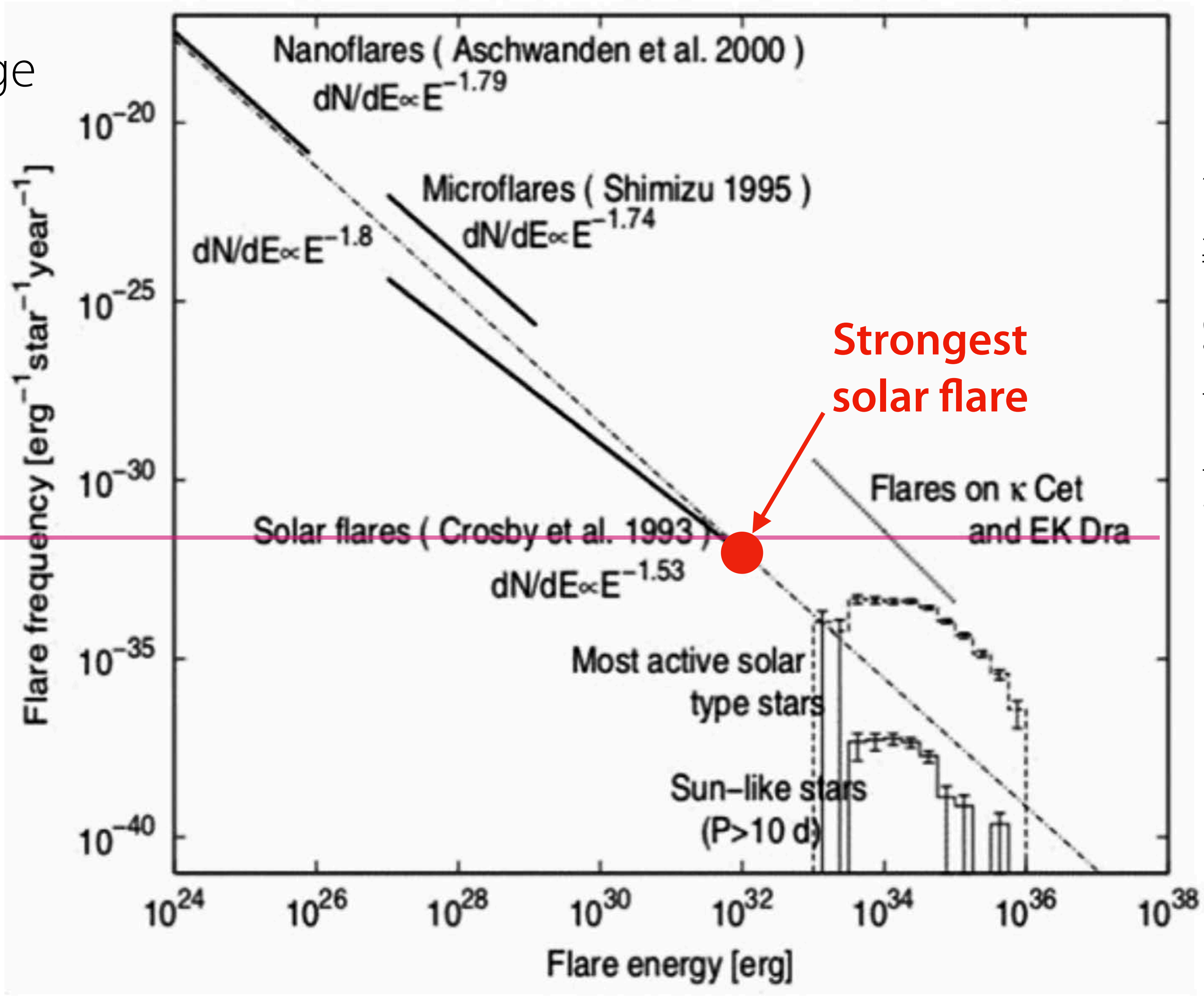
Flares

Flares as a scalable phenomenon

- Magnetic field on the Sun is structured on a larger range of scales
- “Stored” magnetic energy in stressed magnetic field scales correspondingly
- Magnetic reconnection can trigger energy release in structure over a large range of spatial scales.
- From small to large:
  - Nanoflares
  - Microflares
  - (normal) flares

Observed on the Sun

  - **Superflares**
  - **Megaflares**
    - Observed on other stars
    - M-dwarfs know for strong flares (e.g., AD Leo, Proxima Cen)
    - Can outshine whole star for minutes



Aschwanden & Parnell (2002)

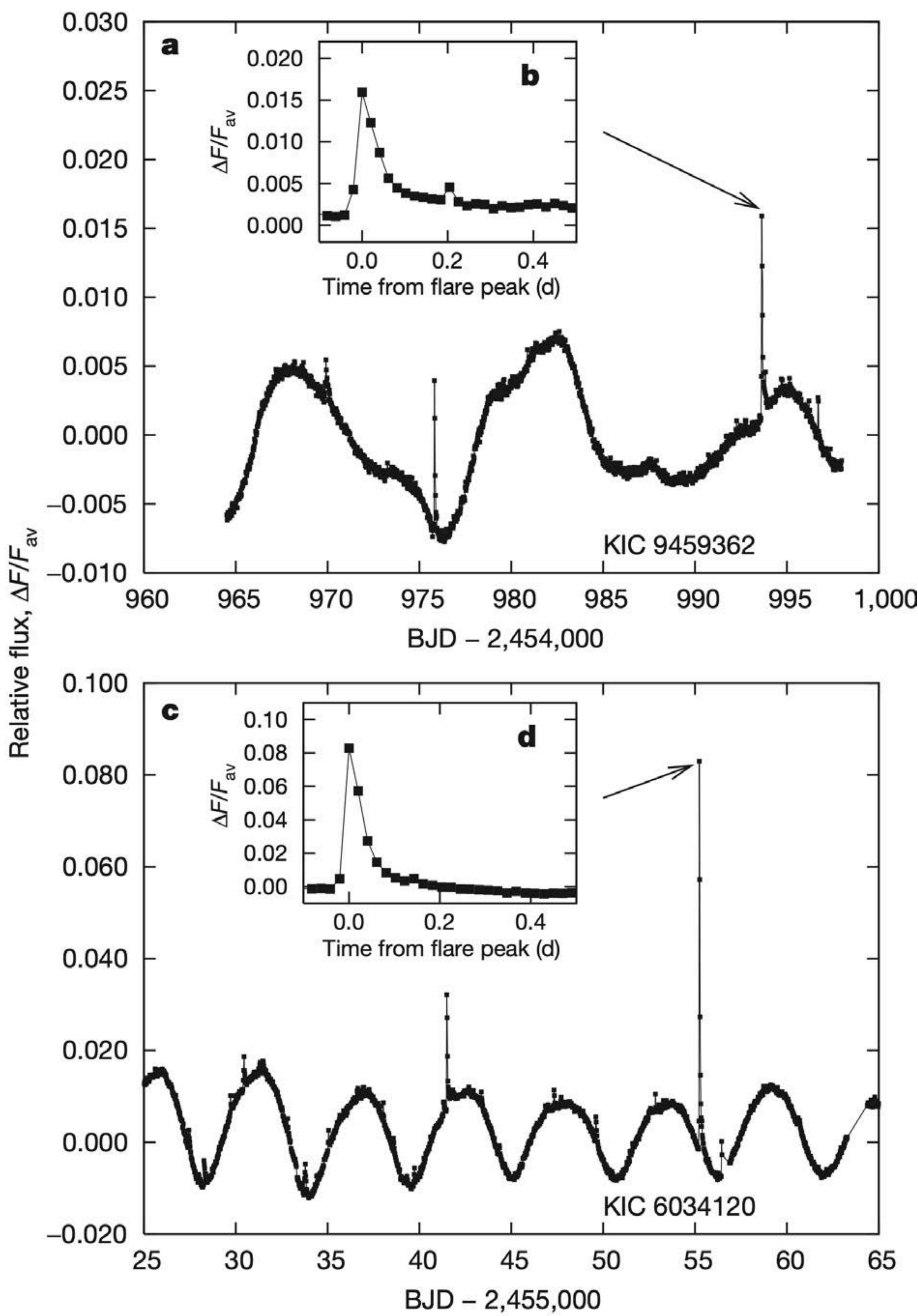
Stellar flares

Superflares   Maehara et al (2012)

- Kepler observations
- G-type main-sequence star KIC 9459362
  - Relative flux variation ($\Delta F/F_{av}$): 1.4%
  - Flare duration: 3.9 h
  - Total released energy: 5.6 10^{34} erg
- G-type main-sequence star KIC 6034120
  - Relative flux variation ($\Delta F/F_{av}$): 8.4%
  - Flare duration: 5.4 h
  - Total released energy: 3.0 10^{35} erg

- In total: 365 superflares from ~83000 stars observed over 120 days.

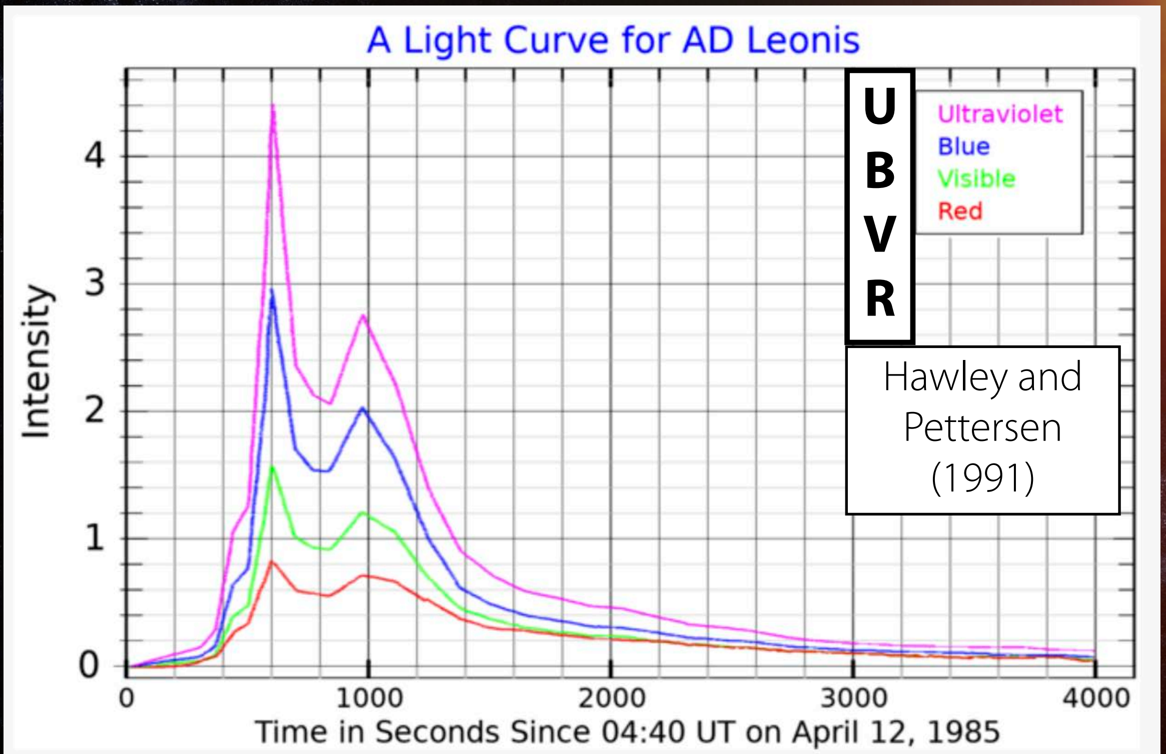
➡ Superflare occurring on a star once every ~350 yr.

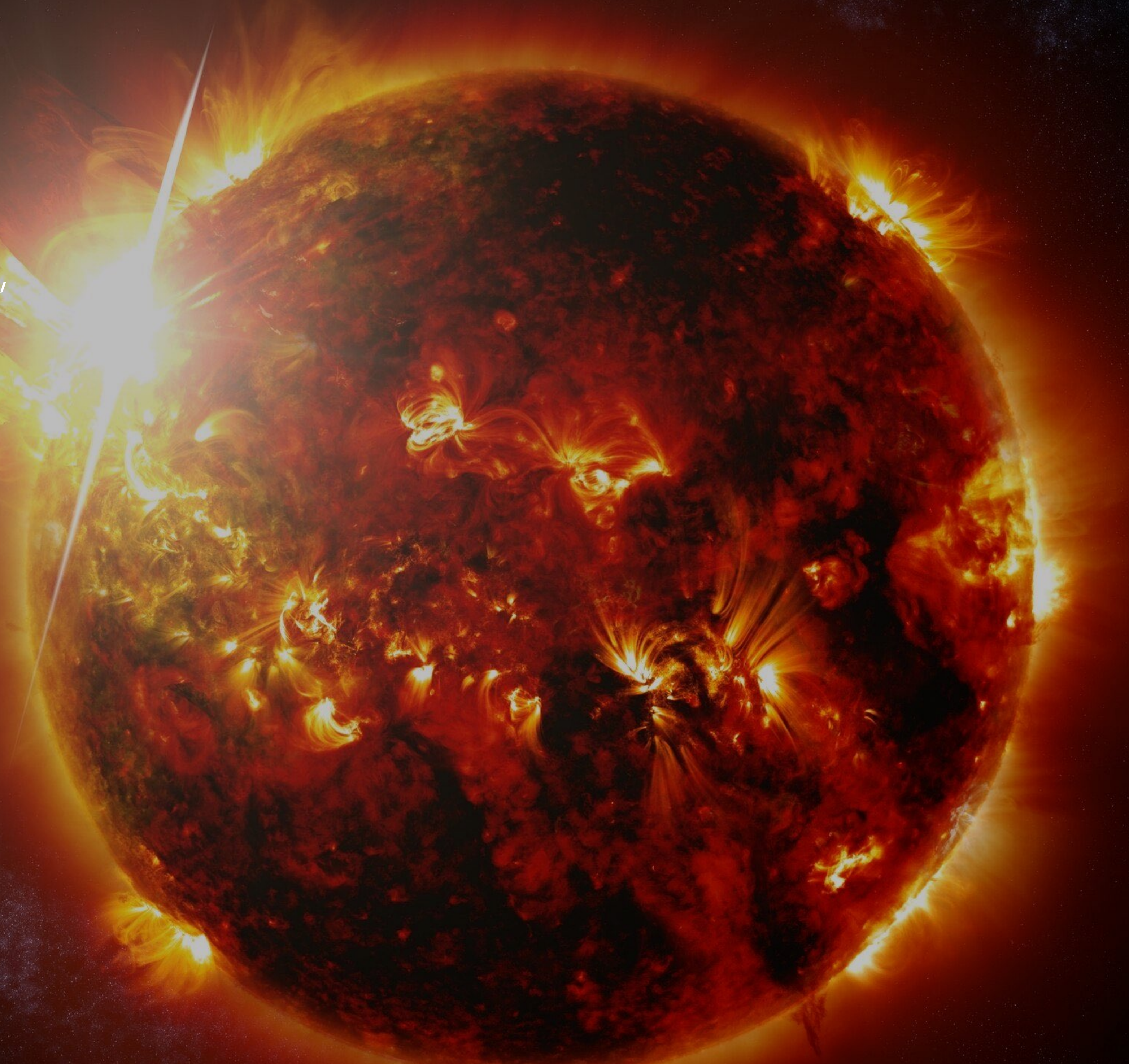


Stellar flares

Megaflares

- Megaflares on M-dwarf stars:
  The flare can outshine the whole stars for minutes
- Prominent examples:
  - Proxima Cen: Flare on May 1, 2019, lasted just 7 seconds, brightest ever detected flare in millimeter and far-UV wavelengths.
  - AD Leo: Well-studied flare star.

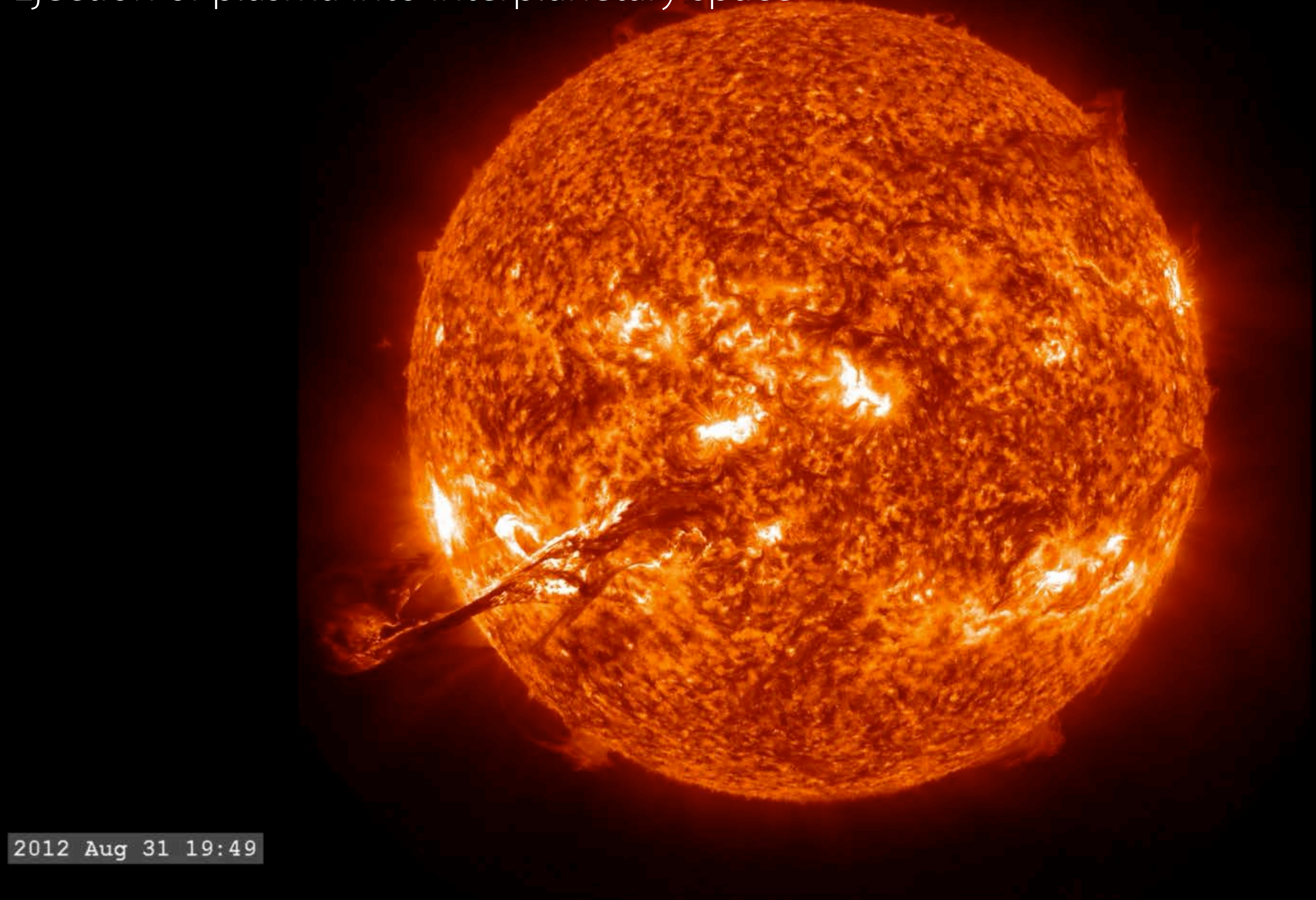




Credits: NASA's Goddard Space Flight Center/S. Wiessinger

Coronal Mass Ejection

- Sometimes in connection with flare (but can occur separately)
- Ejection of plasma into interplanetary space

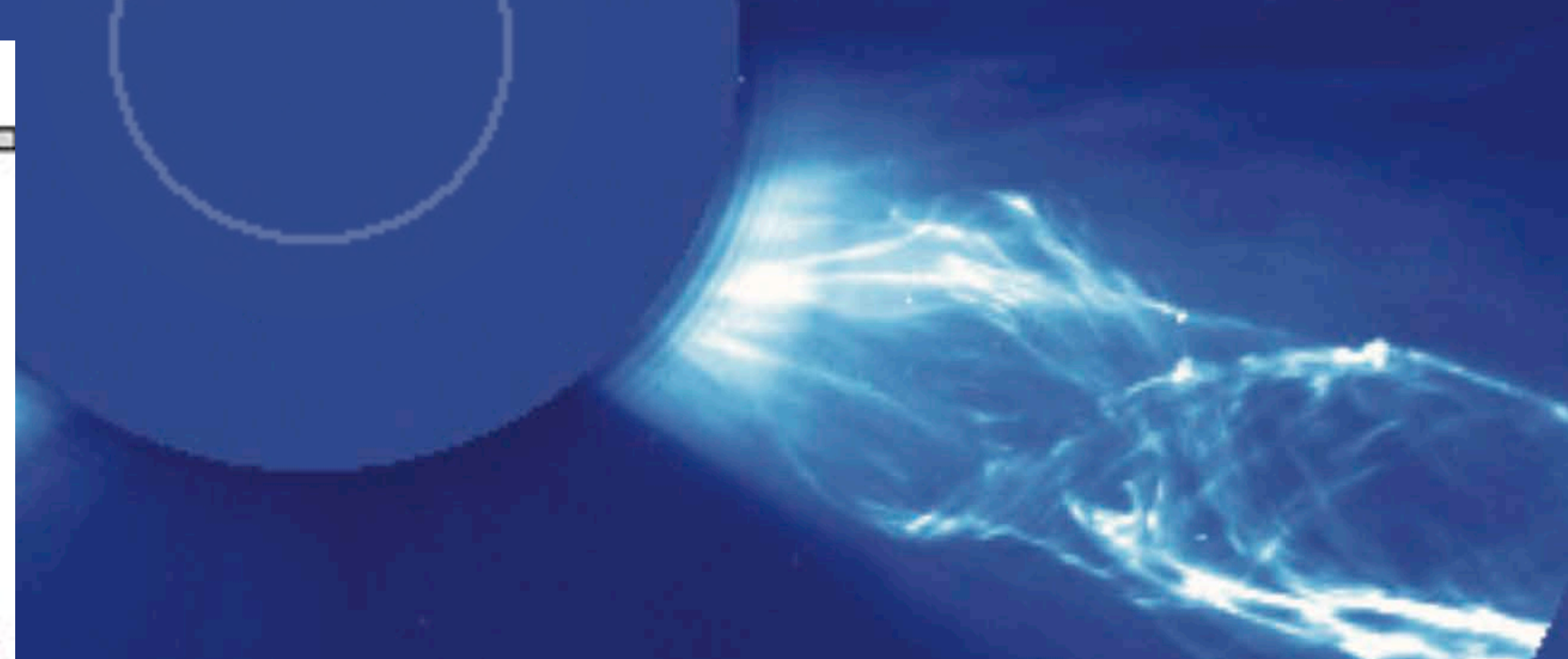


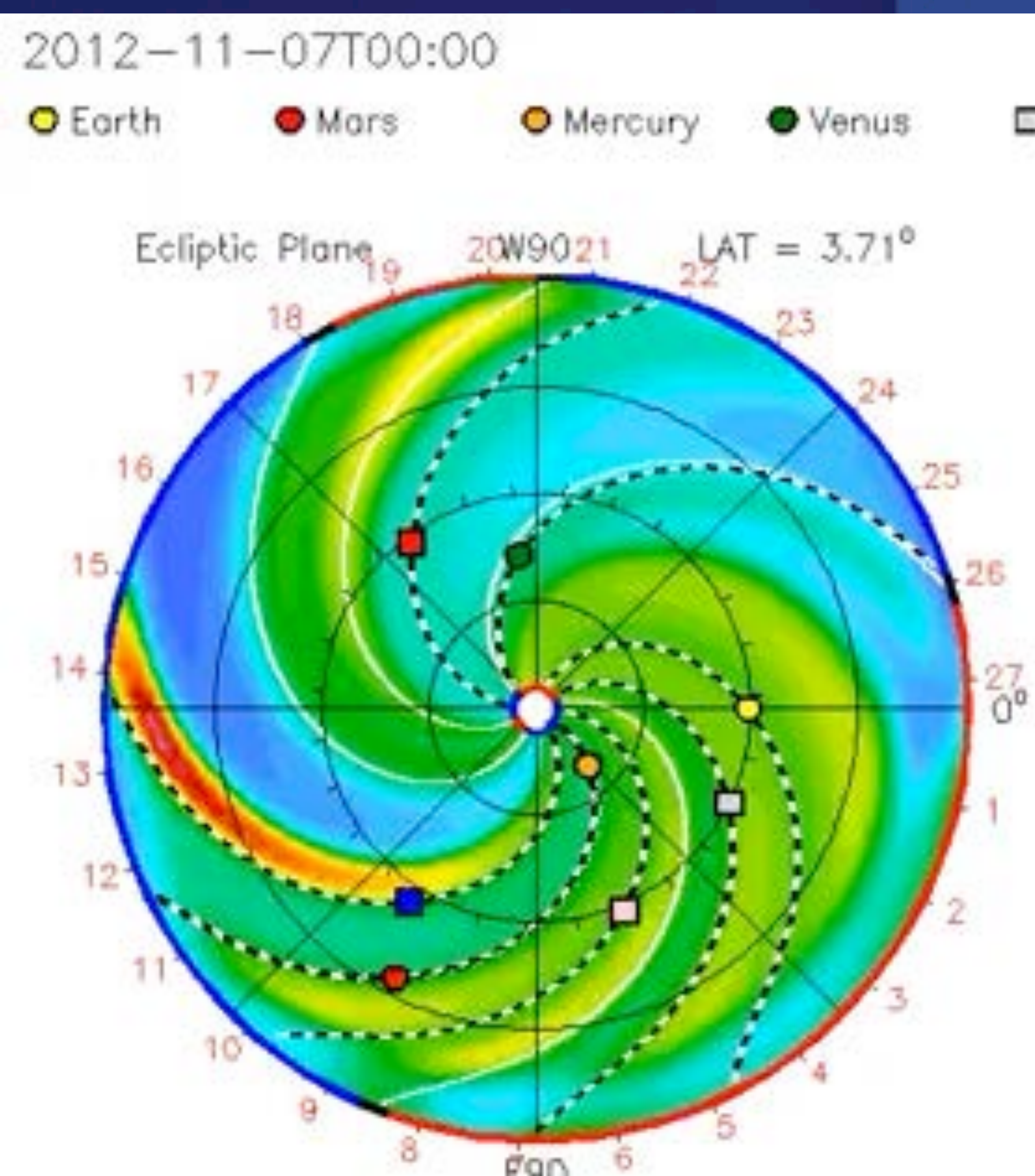
- August 31, 2012 — Eruption of a long filament, producing a CME
- CME speed > 5 10^6 km/s, not directed to Earth (but disturbed magnetosphere, caused aurora)
- Ejection from different viewpoints: SDO, STEREO, SOHO

Coronal Mass Ejection

- Central bright helical structure = erupting filament
  ➡ Unwinding of filament
- In most cases CMEs associated with an eruptive prominence or/and a flare BUT CME and flare not always seen together!
- CMEs may contribute as much as 10% to the whole mass loss by the solar wind.

SOHO/Lasco C2 image

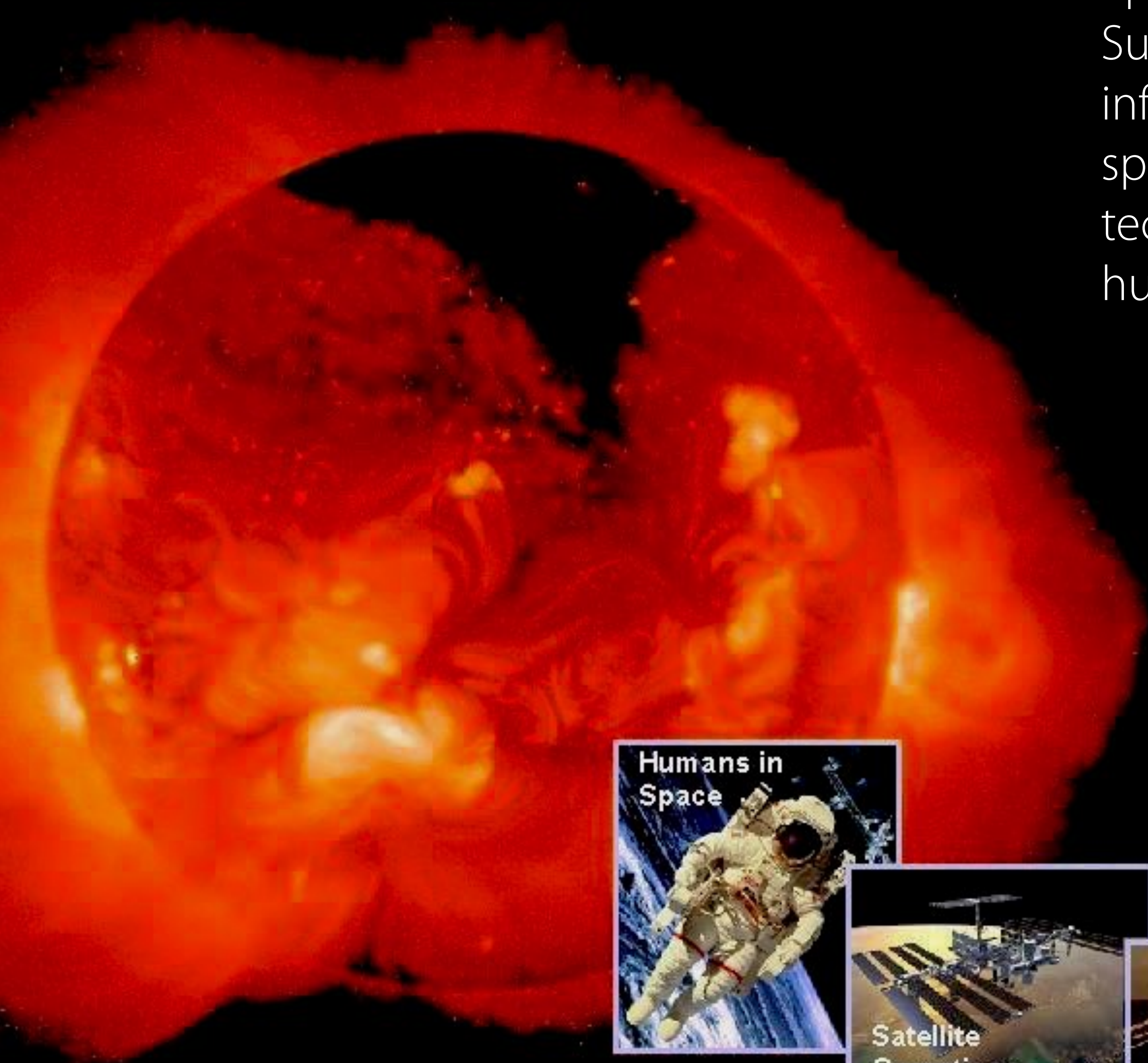


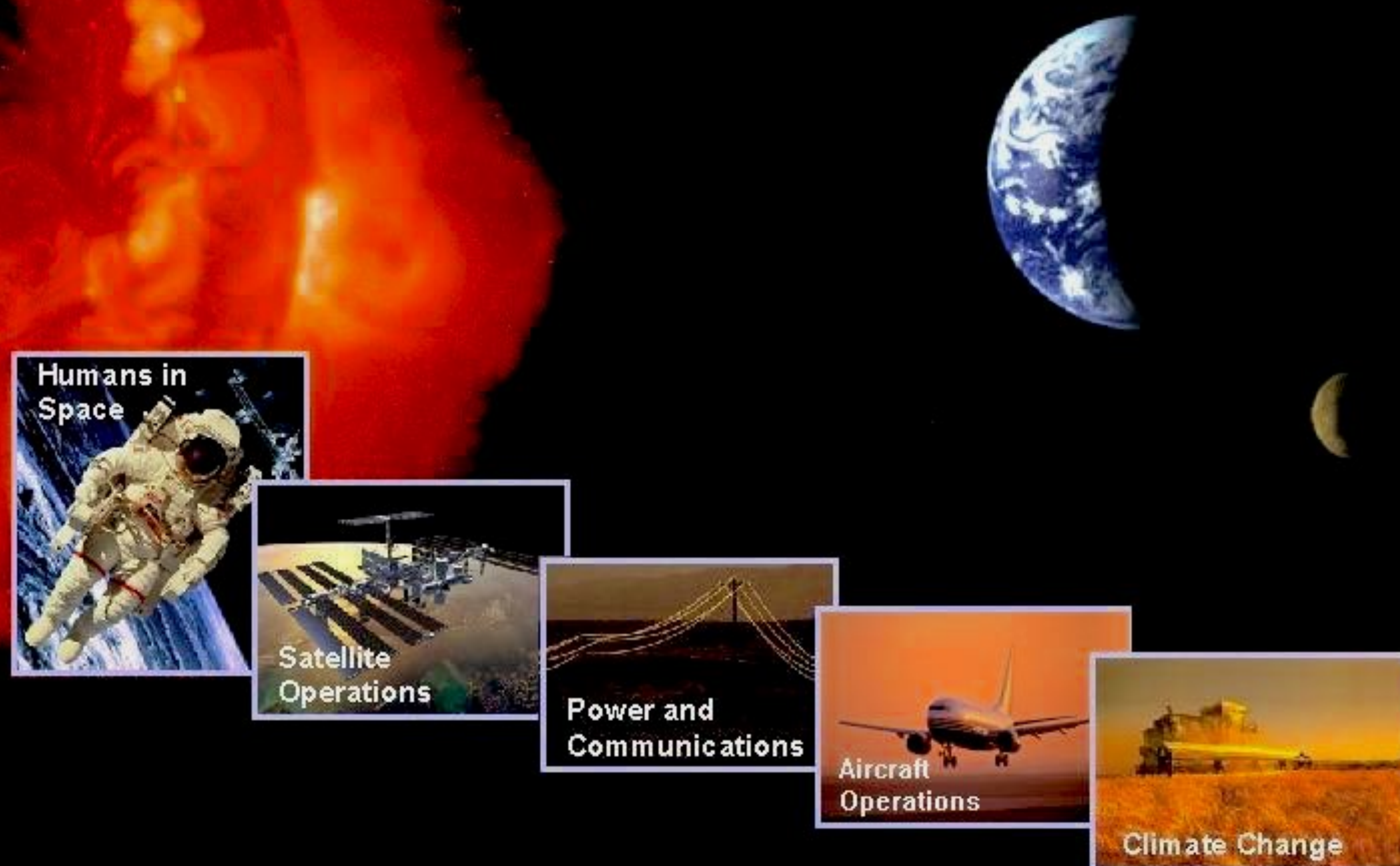


- CME propagates away from Sun, reaches Earth orbit within a few days
- Can cause geomagnetic storms (space weather)
- Space weather forecast needed!
  — Currently under development.

Space Weather

Space weather refers to conditions on the Sun and in the space environment that can influence the performance and reliability of space-borne and ground-based technological systems, and can endanger human life or health.





Space Weather

Solar flare classification	Associated X-ray flux - I (W/m^2)	Possible effects on Earth
B	$I < 1E\text{-}06$	none
C	$1E\text{-}06 \leq I < 1E\text{-}05$	Possible effects on space missions.
M	$1E\text{-}05 \leq I < 1E\text{-}04$	Blackout in radio transmissions and possible damages in astronauts outside spacecraft.
X	$I \geq 1E\text{-}04$	Damage to satellites, communication systems, power distribution stations and electronic equipment

Table 1.1: Description of solar flare classes (TANDBERG-HANSSEN; EMSLIE, 2009)

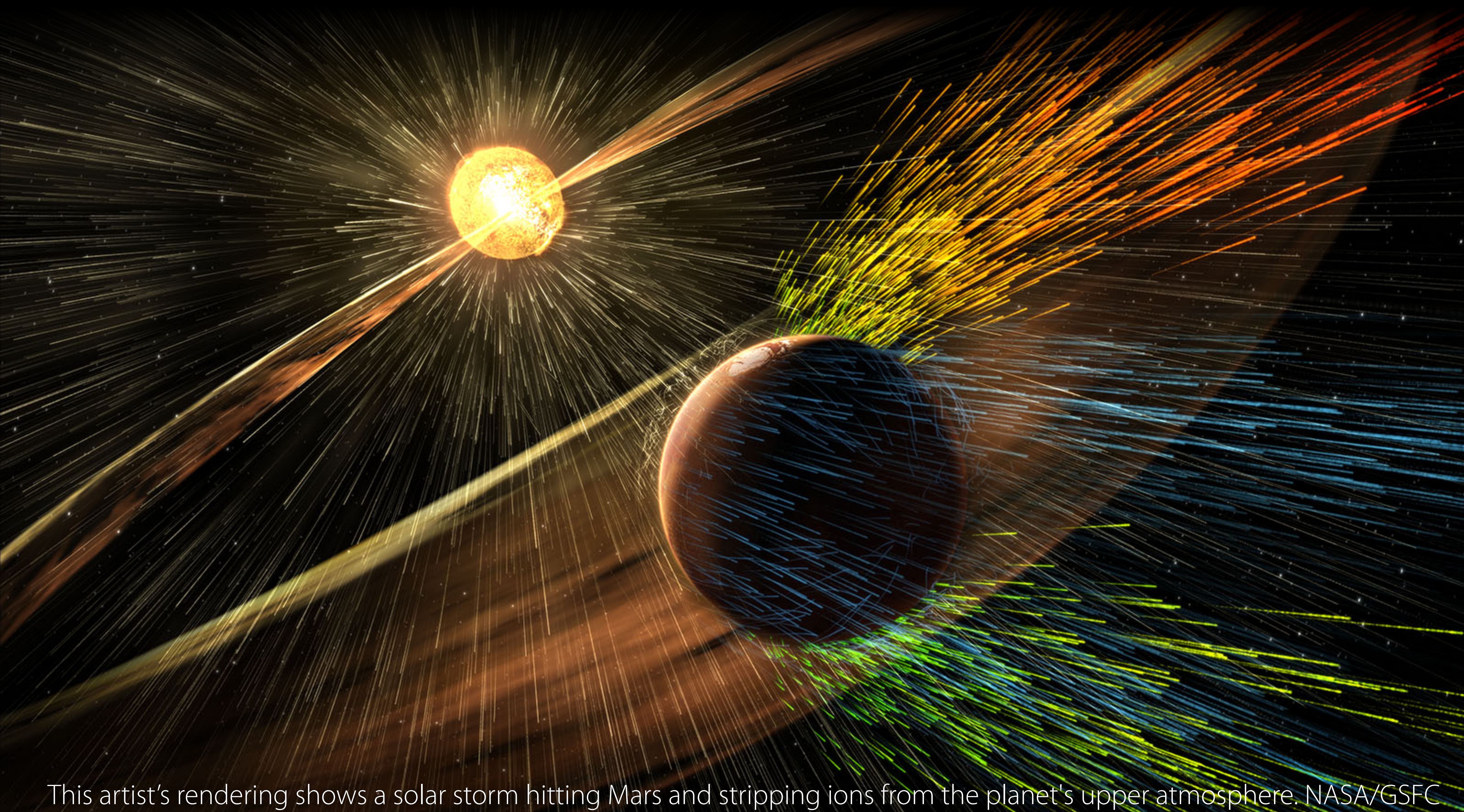
- **Example: March 1989** - X15 flare + 2 CMEs leading to a geomagnetic storm
  - Some satellites lost control for several hours.
  - GOES satellite communications interrupted, weather images lost.
  - Sensor malfunction on Space Shuttle Discovery
  - Currents induced in power lines in **Quebec**, Canada, leading to **power outage** for 9 hrs.

Solar Wind and Heliosphere

Stellar rotation

Solar/stellar winds

- Stream of charged particles released from the upper atmospheric layers of a star



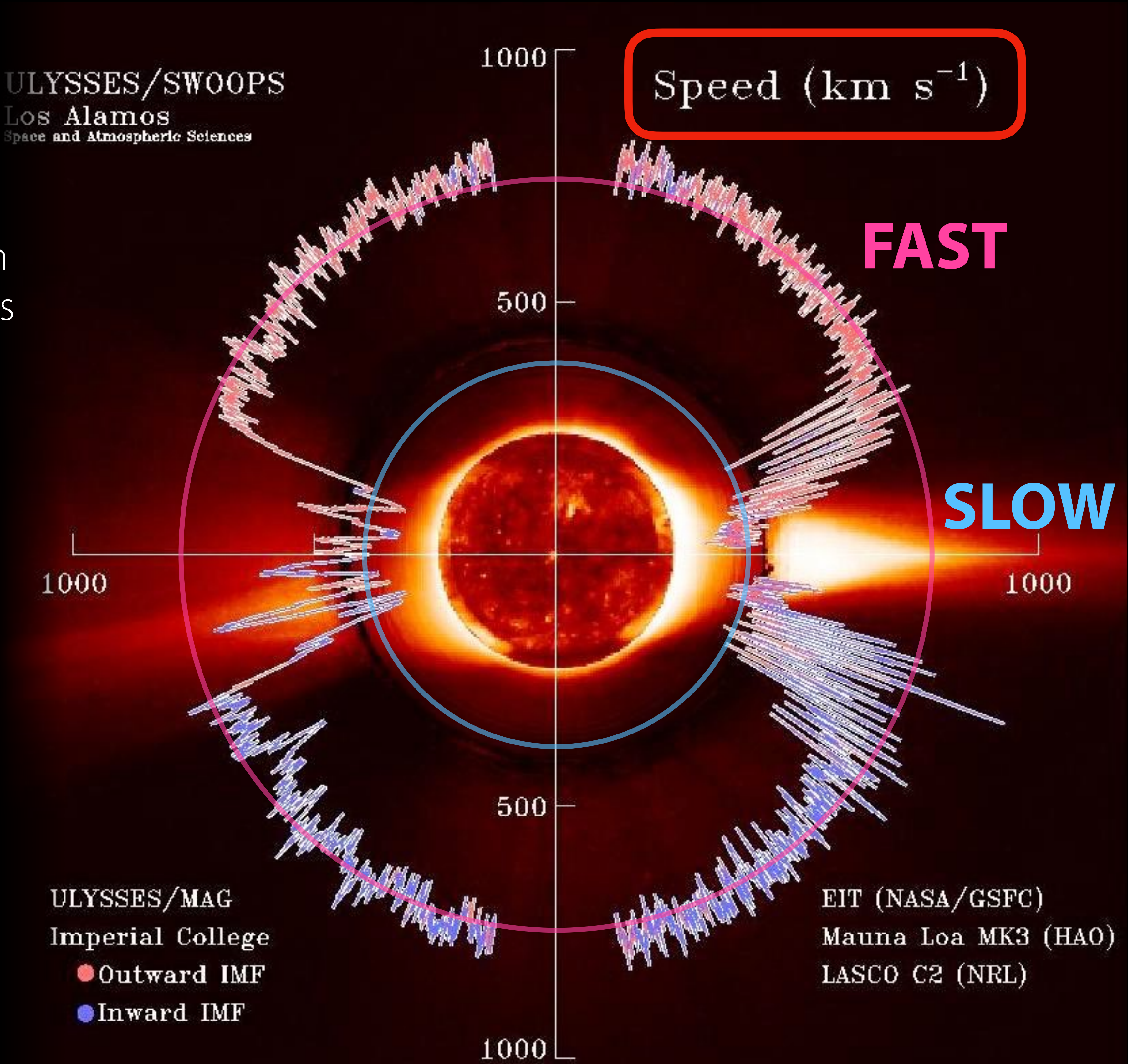
This artist's rendering shows a solar storm hitting Mars and stripping ions from the planet's upper atmosphere. NASA/GSFC

Solar Wind and Heliosphere

Components

- Ulysses 1990-2009 (ESA/NASA)
- Left the ecliptic to study Sun from other inclination angles
  - Such an orbit challenging (gravity assist at Jupiter)

- 3D measurements of solar wind, ions + electrons
- Measured variation of solar wind as function of latitude
- **Different components of solar wind (fast, slow)**
- **Solar wind varies over solar cycle**

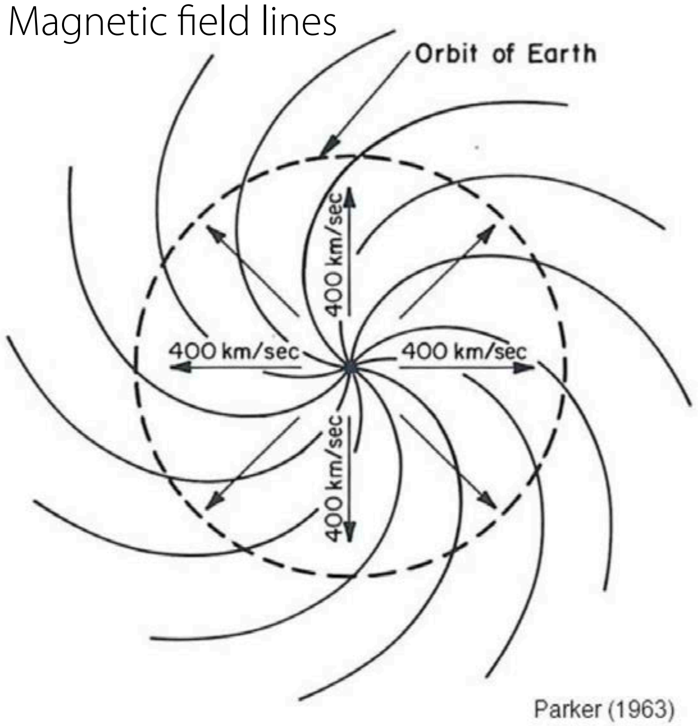


Solar Wind and Heliosphere

Parker spirals

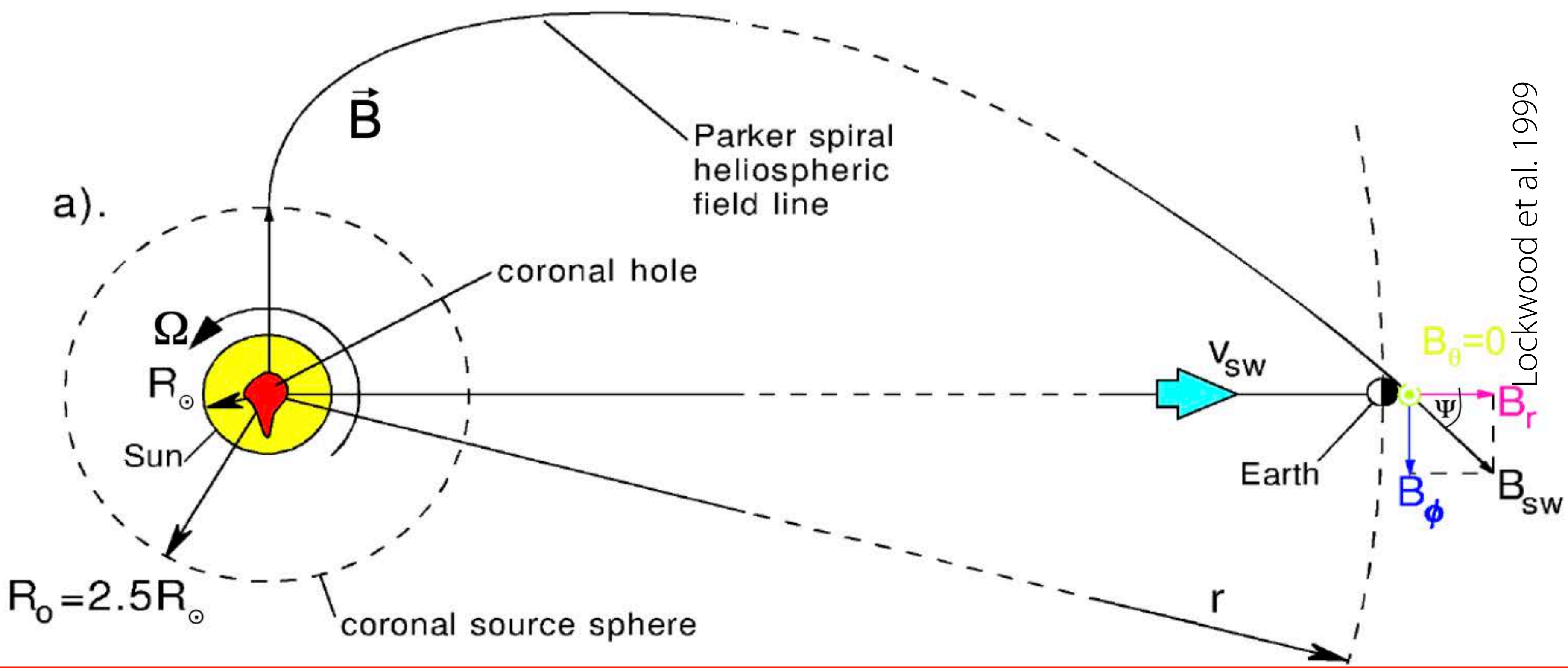
- Magnetic field of the Sun extends into interplanetary space (throughout solar system)
- Field tethered to Sun while Sun rotates, magnetic tension

➡ **Parker spirals**



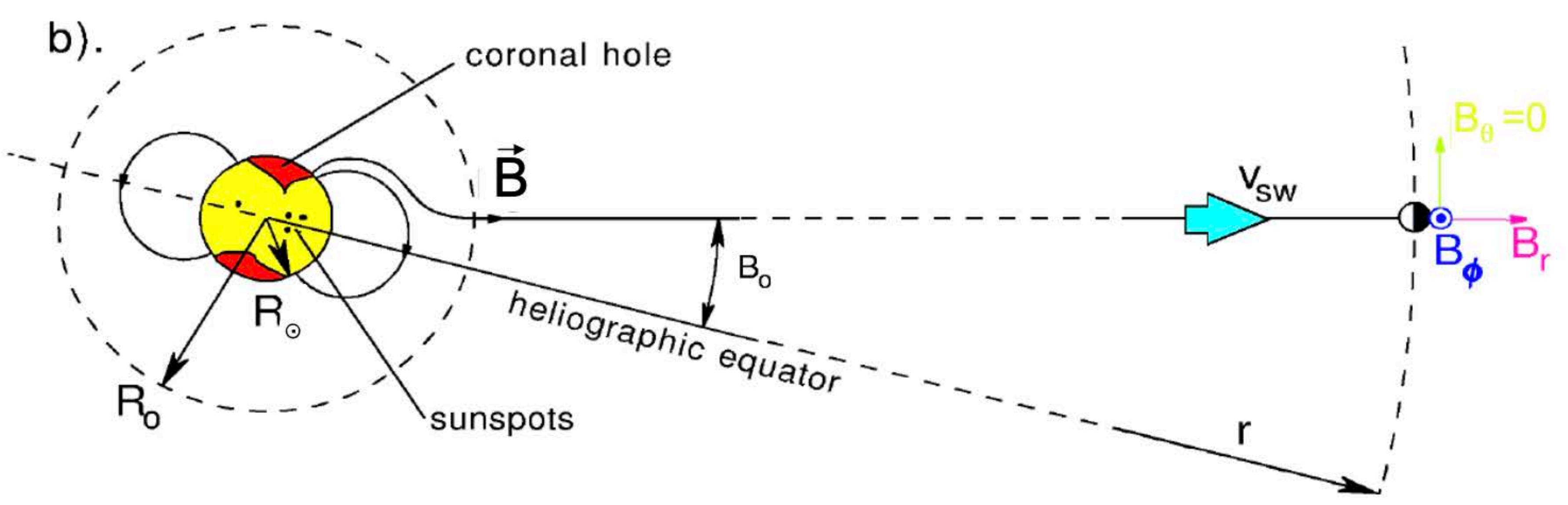
Parker (1963)

Poleward view



Lockwood et al. 1999

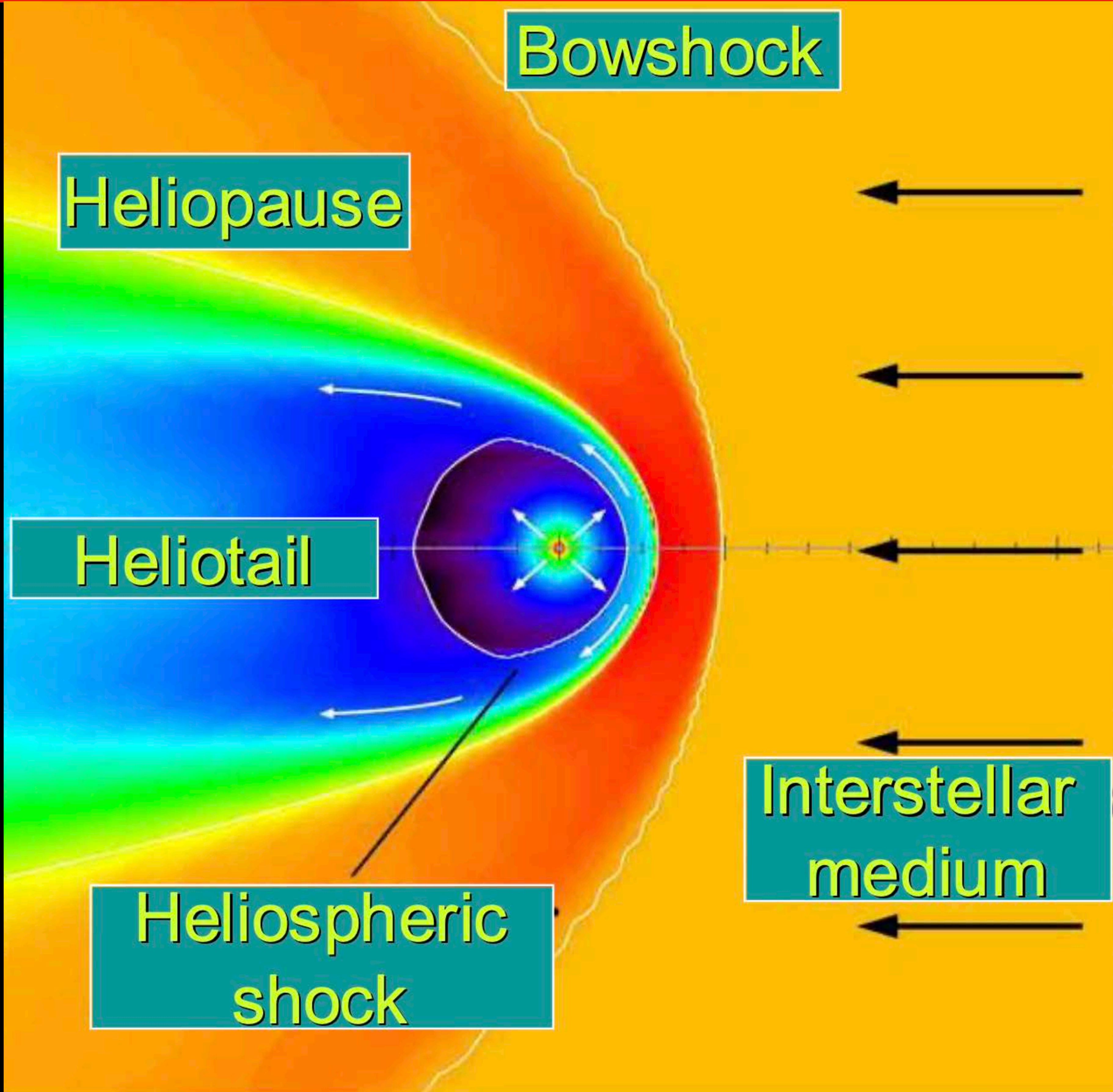
View from ecliptic



Solar Wind and Heliosphere

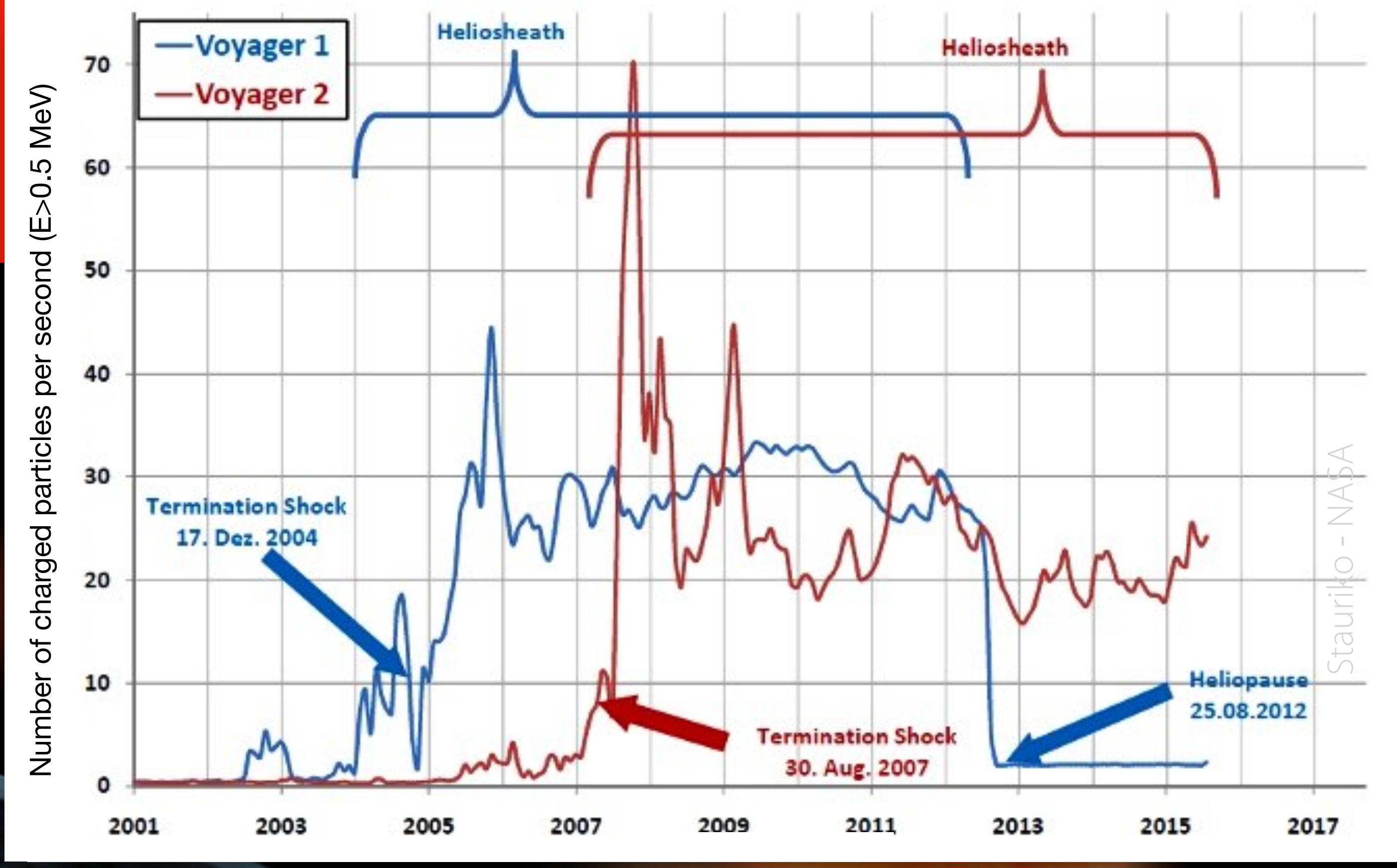
Heliosphere

- Definition: Region where solar wind and solar magnetic field dominate over interstellar medium and galactic magnetic field
- "Bubble" embedded in interstellar medium, produced by outflowing solar wind
- **Heliopause:** boundary of the heliosphere
- **Bow shock:** interstellar medium is slowed relative to the Sun.
- **Heliospheric shock:** solar wind is decelerated relative to Sun

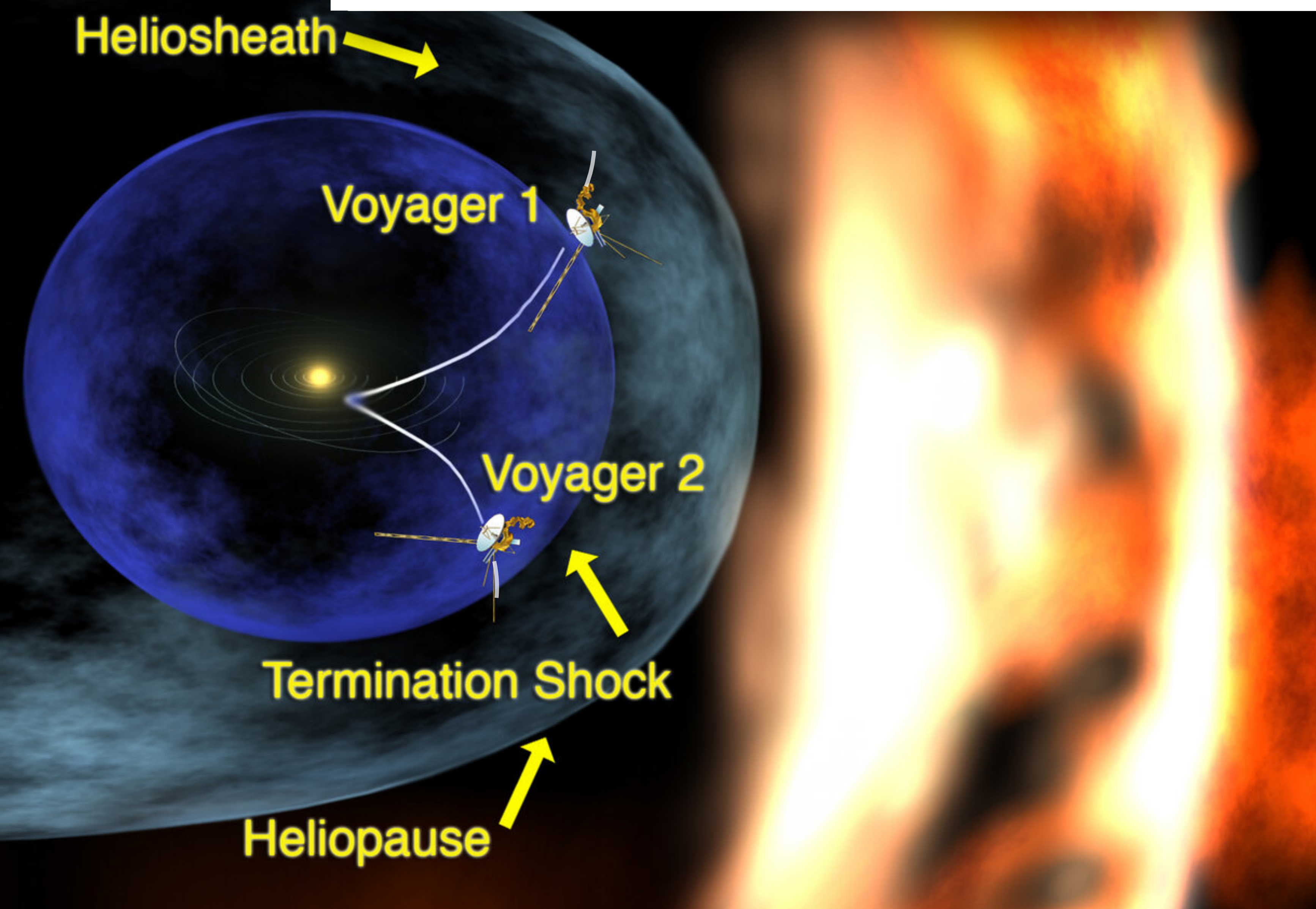


Solar Wind and Heliosphere

Heliosphere



- Voyager 1 and 2 launched in 1977, in different directions
- Reached heliopause:
  - Voyager 1: 2012
  - Voyager 2: 2018
  - Measured changes in number density of charged particles



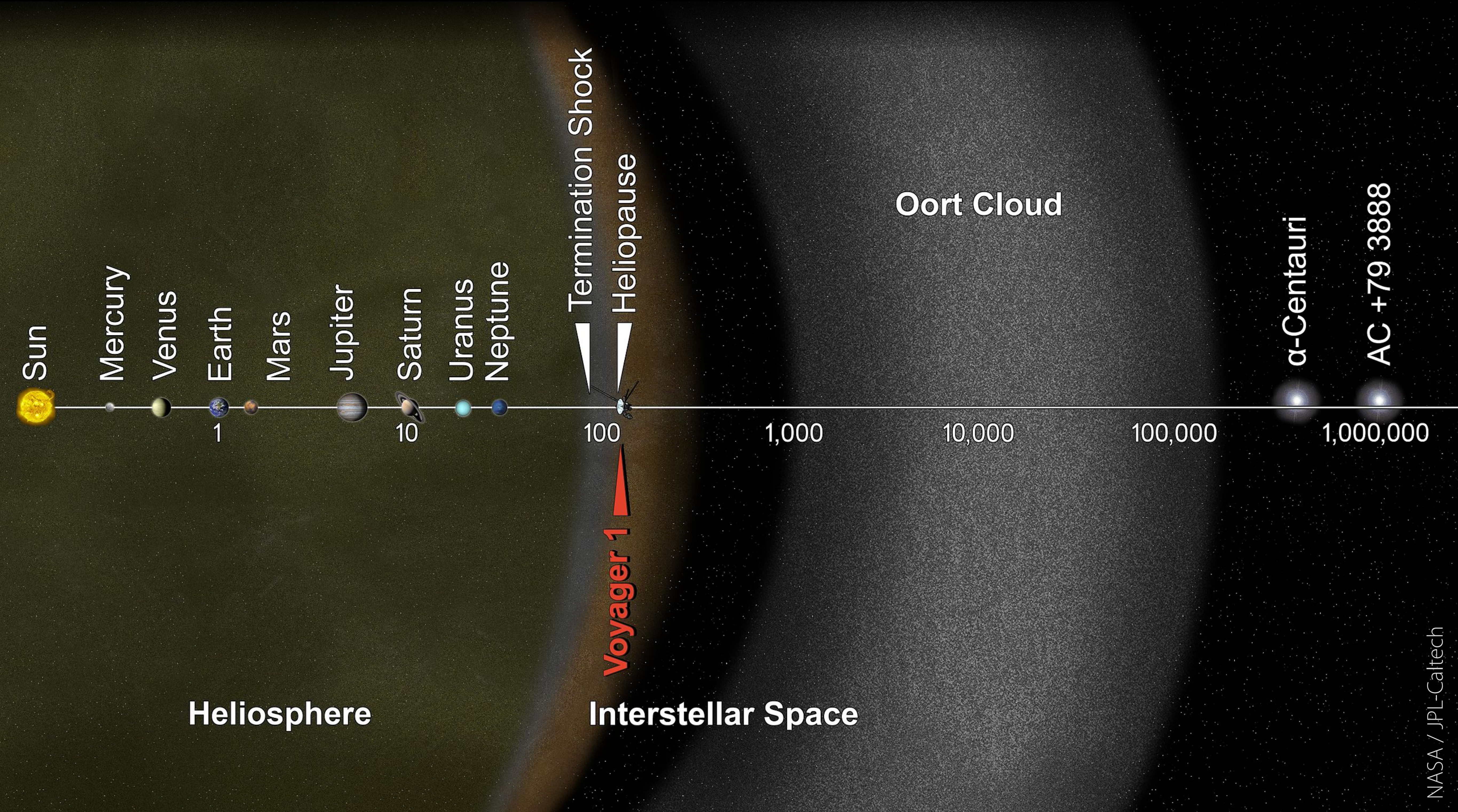
Rough positions in ~2008. Illustration only.

ESA

Solar Wind and Heliosphere

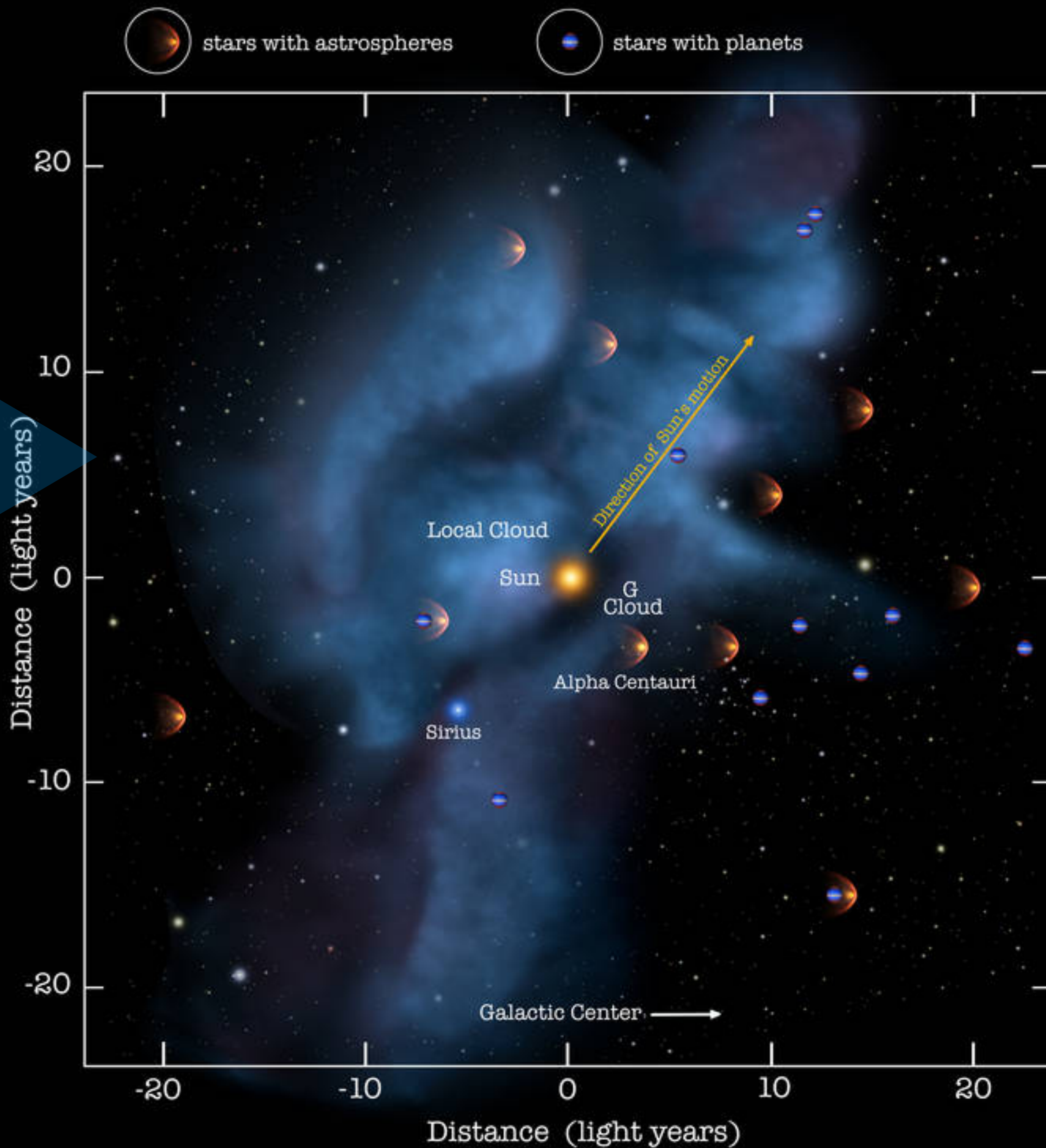
Heliosphere

- **Heliosphere:** protective shielding against Galactic Cosmic Rays (hazardous for life)



Beyond the heliosphere

- Astrosphere = like heliosphere but around other stars
- Detected around some other (nearby) stars
- Astrosphere around α Centauri (nearest star)!
- More candidates
- Many systems likely analogous to our solar system with astrospheres shielding a planetary system.



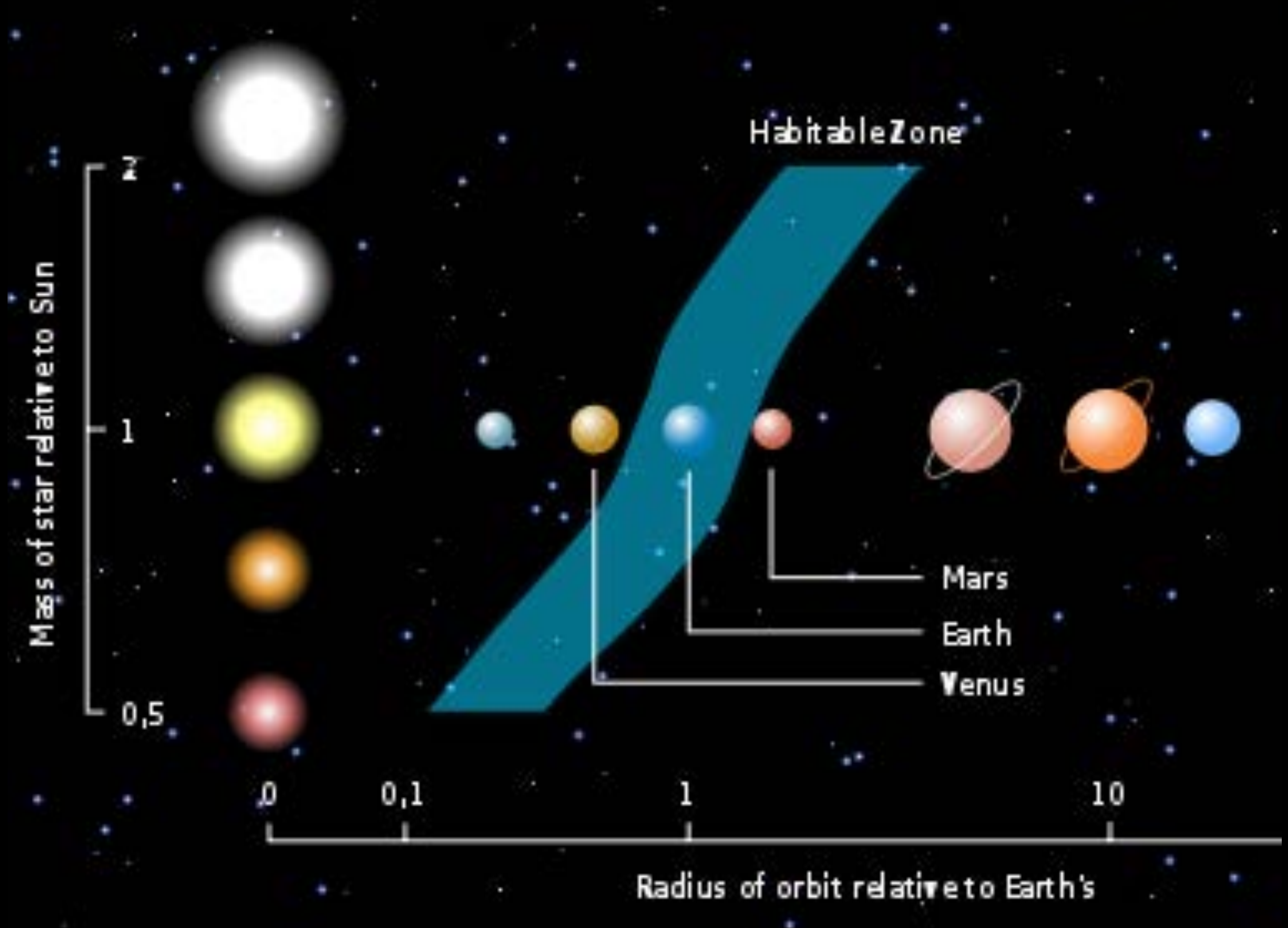
NASA/Goddard/Adler/U. Chicago/Wesleyan

Stars as hosts of extrasolar planets

Stars as hosts of extrasolar planets

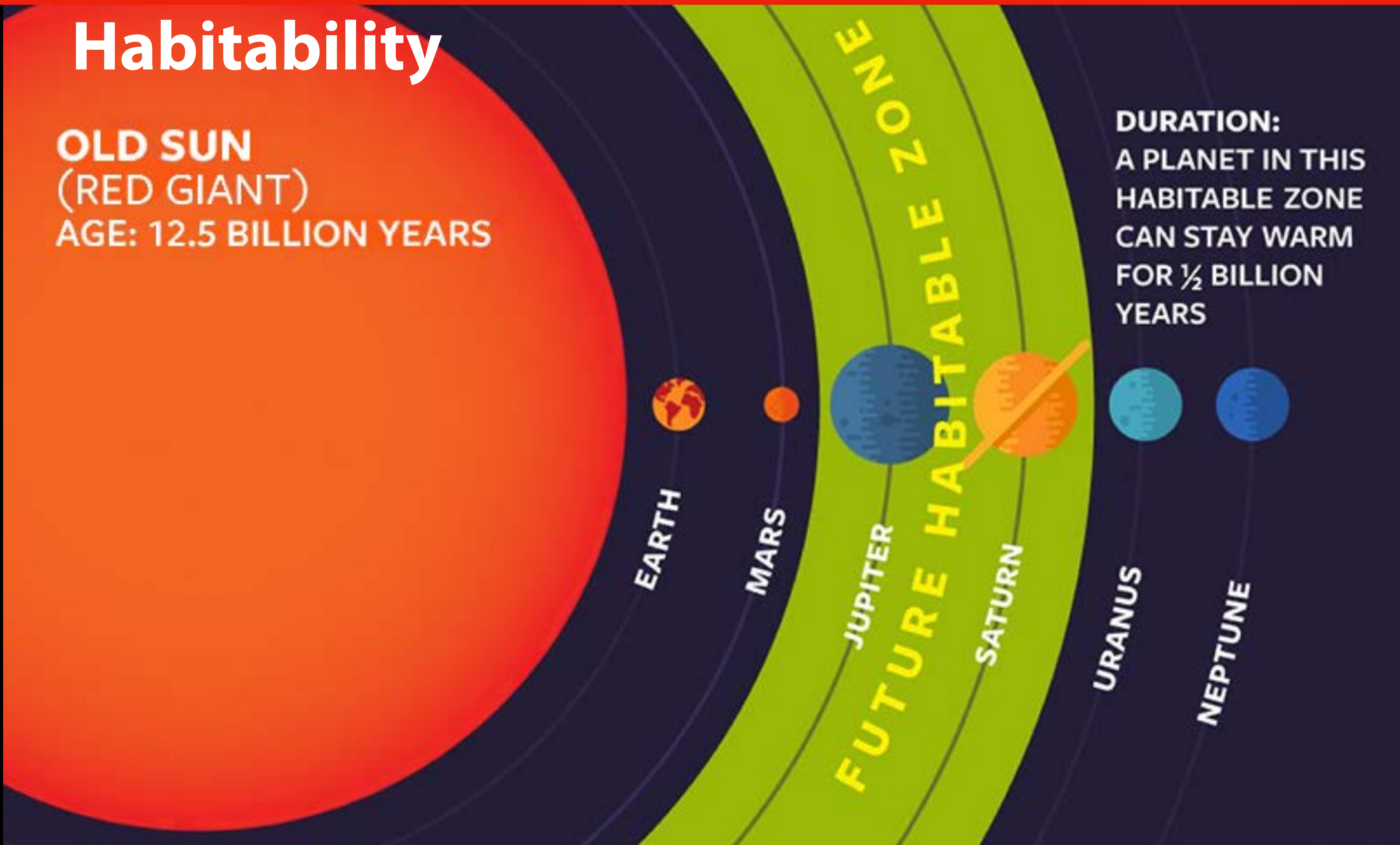
Habitability

- **Habitable zone** = distance from star where water can (in principle) exist in liquid form
  - Does not mean that there has to be water on a planet within the HZ!
- Defined by the irradiation of a planet and thus by the **luminosity** of the host star and the distance to it!
- Habitable zone closer to the host star for the red dwarf stars with low luminosity

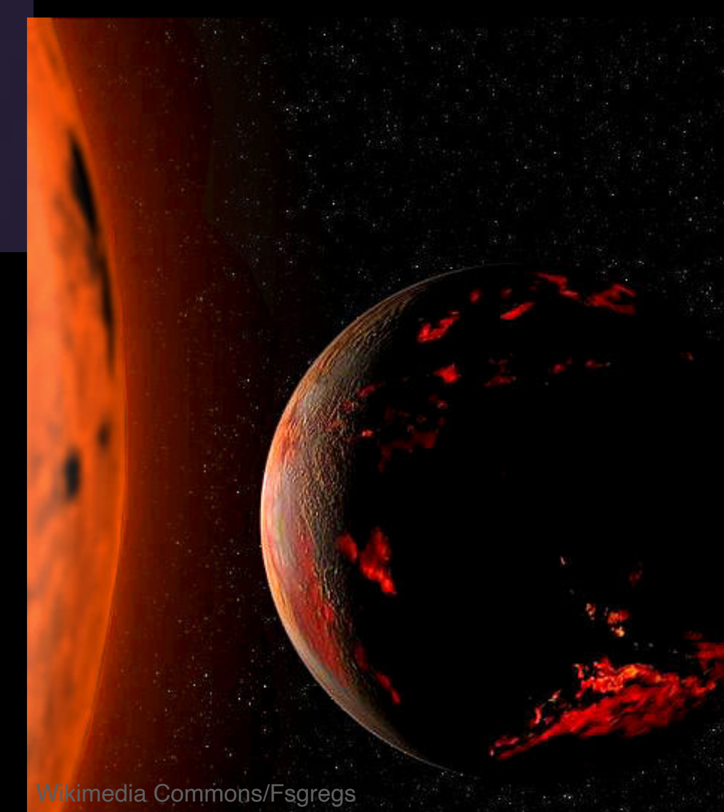


Stars as hosts of extrasolar planets

Habitability



- Habitable zone changes with luminosity as stars evolve
- Further out when the Sun turns into a red giant
- Planets move further out due to Sun's mass loss
- Will Earth "survive"?


Wikimedia Commons/Fsgregs

Stars as hosts of extrasolar planets

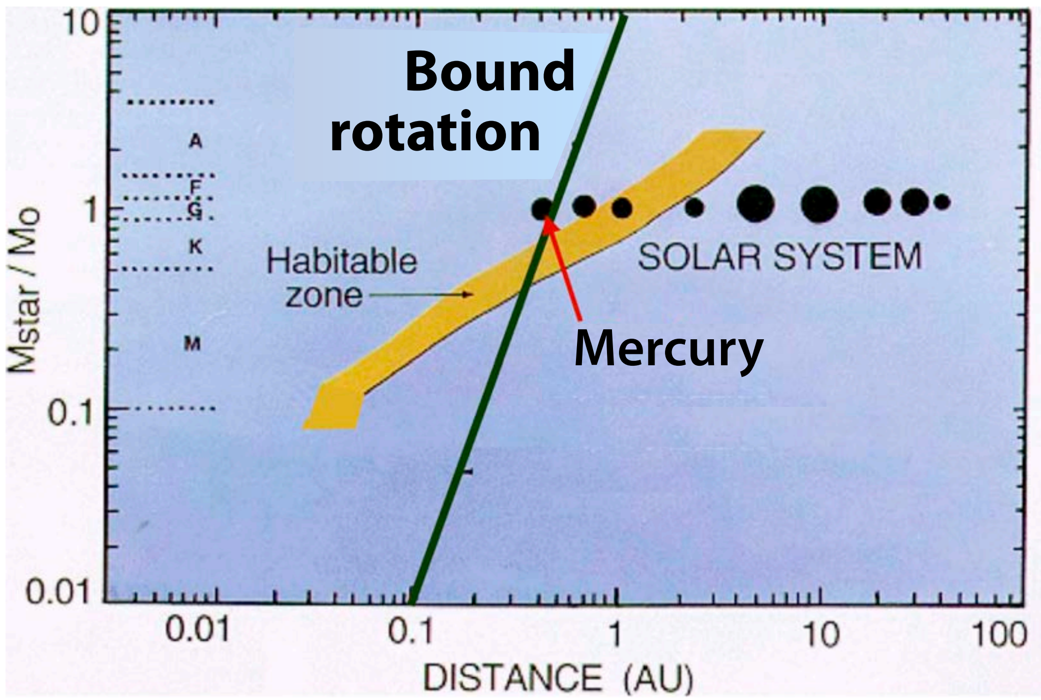
Low-mass stars (M-dwarfs)

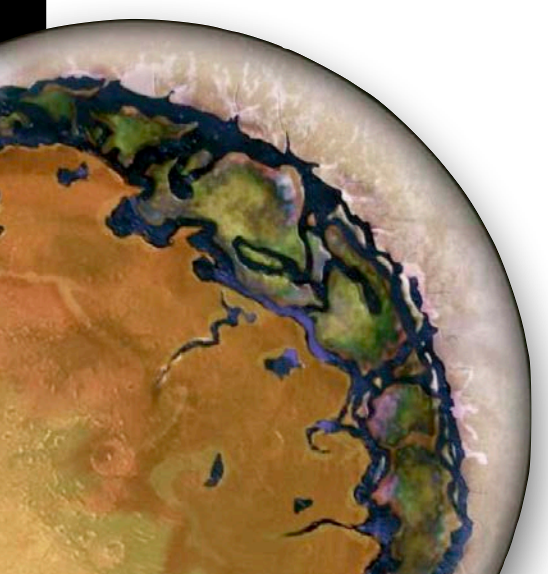
High-mass stars (O/B-type)

Faint — **Luminosity** — Very bright

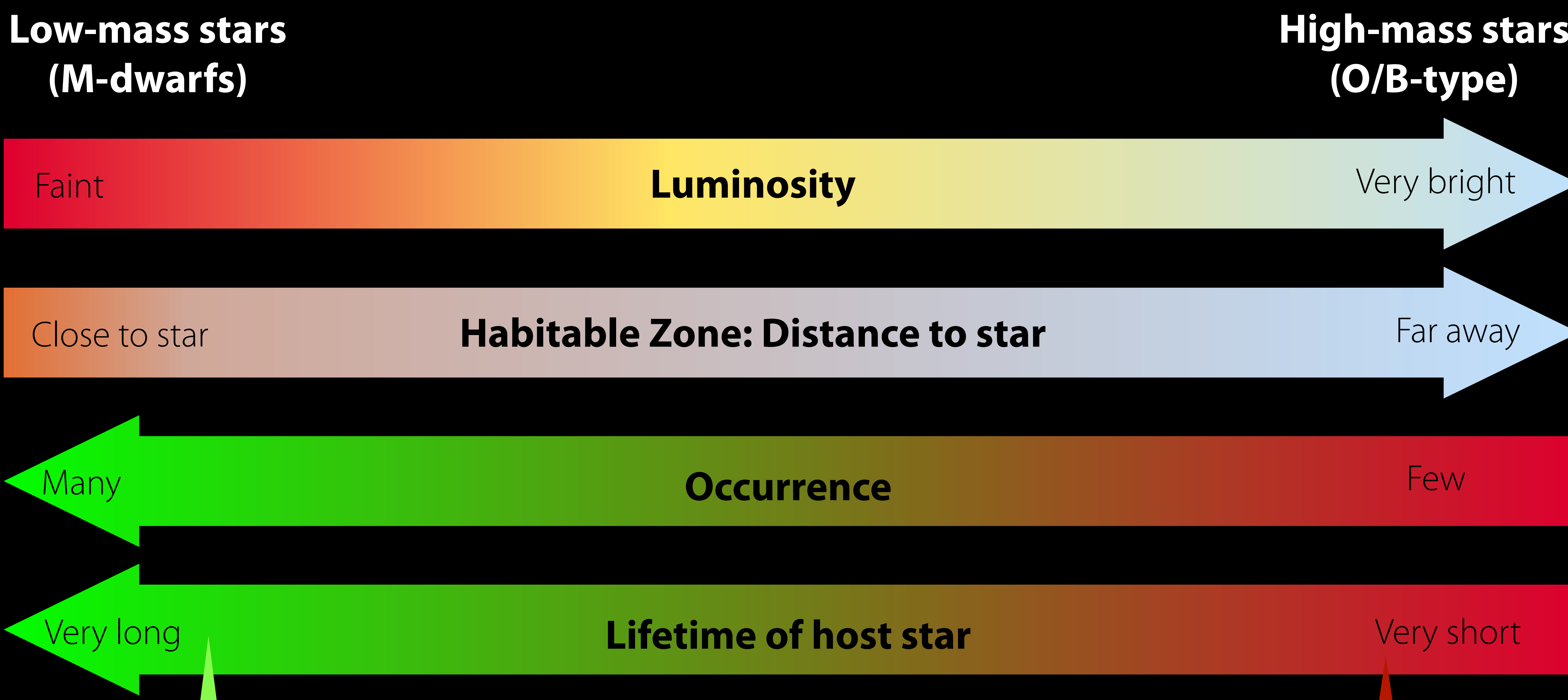
Close to star — **Habitable Zone: Distance to star** — Far away

- **Tidal locking** of planets if too close to the host star: bound rotation, showing always same side to star (like Earth-Moon)
  - Permanent day and permanent night side with large temperature differences
  - May trigger strong winds
  - Implications for habitability?





Stars as hosts of extrasolar planets



- More time for geological changes of planets and formation of adequate atmosphere
- More time for the (potential) development of life

- Too short lifetime!

Stars as hosts of extrasolar planets

Low-mass stars (M-dwarfs)		High-mass stars (O/B-type)
Faint	**Luminosity** →	Very bright
Close to star	**Habitable Zone: Distance to star** →	Far away
Many	← **Occurrence**	Few
Very long	← **Lifetime of host star**	Very short
Not much	← **Harmful (high-energy) radiation (UV, X-rays)**	Intense

- Depends also on distance to host star!

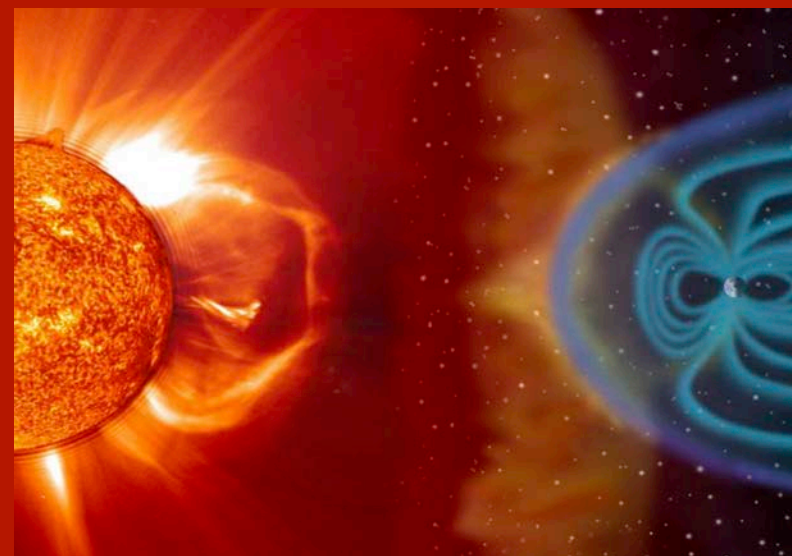
$$H_2O \xrightarrow{\nu} OH^- + H^+$$

- Harmful for organic material
- Dissociates water, can lead to (partial) loss of planetary atmosphere

Stars as hosts of extrasolar planets

Low-mass stars (M-dwarfs)

High-mass stars (O/B-type)



Faint — Very bright

Close to star — **nce to star** — Far away

Many — **Occurrence** — Few

st star — Very short

iation (UV, X

- Habitable zone close to star
- M-dwarfs known for **megaflares**
- Tidal locking may inhibit planetary magnetic field - no protection!

➡ Large doses of harmful radiation and particles!

- Planets would be affected by strong mass loss of the host star (strong stellar winds)

Activity — **Activity and winds** — Winds

Essential take-aways

- **Evolution and final final state strongly mass- dependent!**
- Adjustment of structure: core and shell burning of increasingly higher stages (stops depending on mass), change in radiative / convective zones
- Extreme mass loss (in late stages) influences evolution

High mass
Few, short-lived
Luminous, large
No surface convection
No activity (no dynamo)
High mass loss / winds

Low mass
Many, long-lived
Faint, small
Surface convection
(or even fully convective)
Strong magnetic fields
High activity (mega flares)