

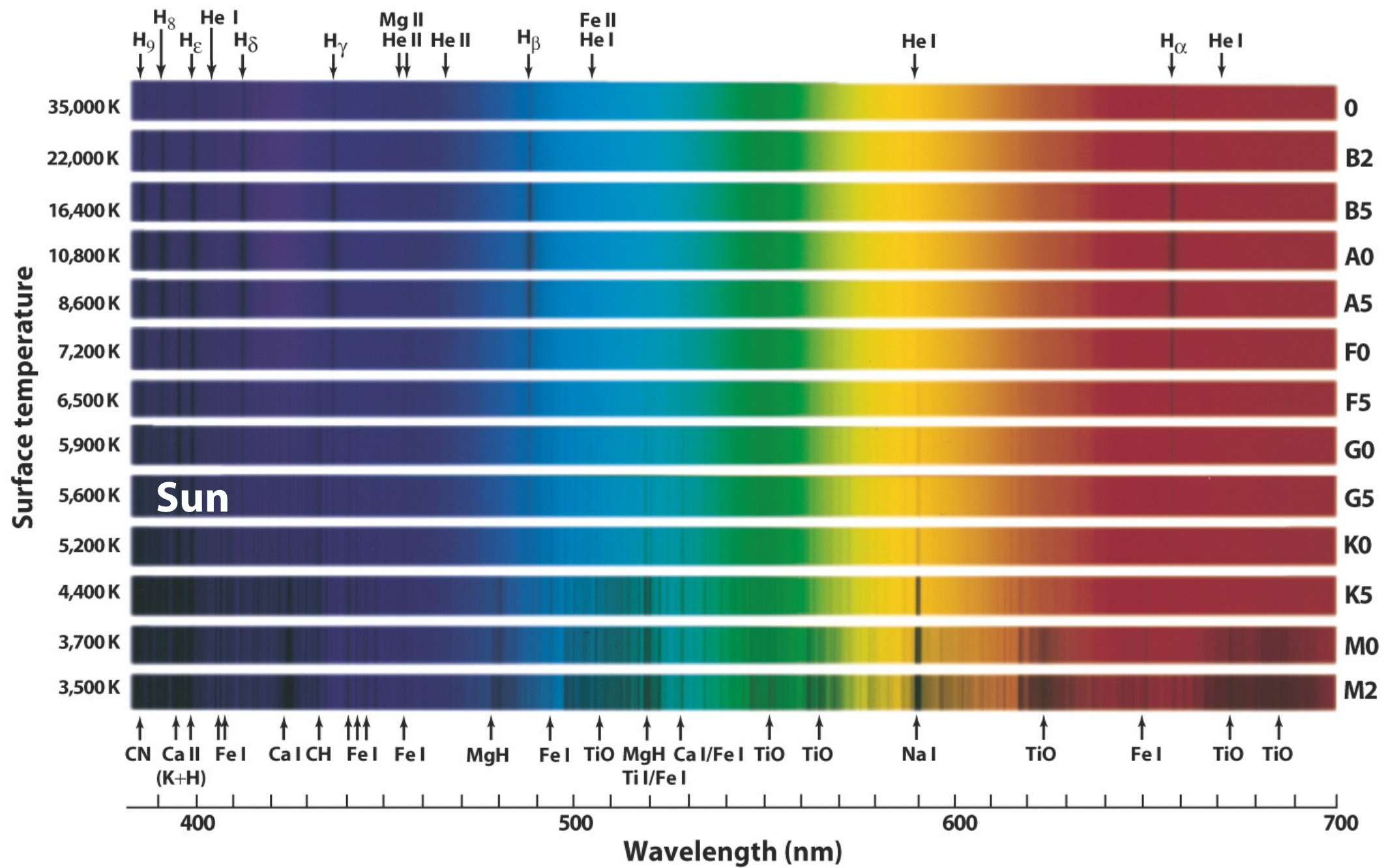
AST5770

Solar and stellar physics

Sven Wedemeyer, University of Oslo, 2025

Recap — 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 be **sorted into a sequence** as a function of temperature

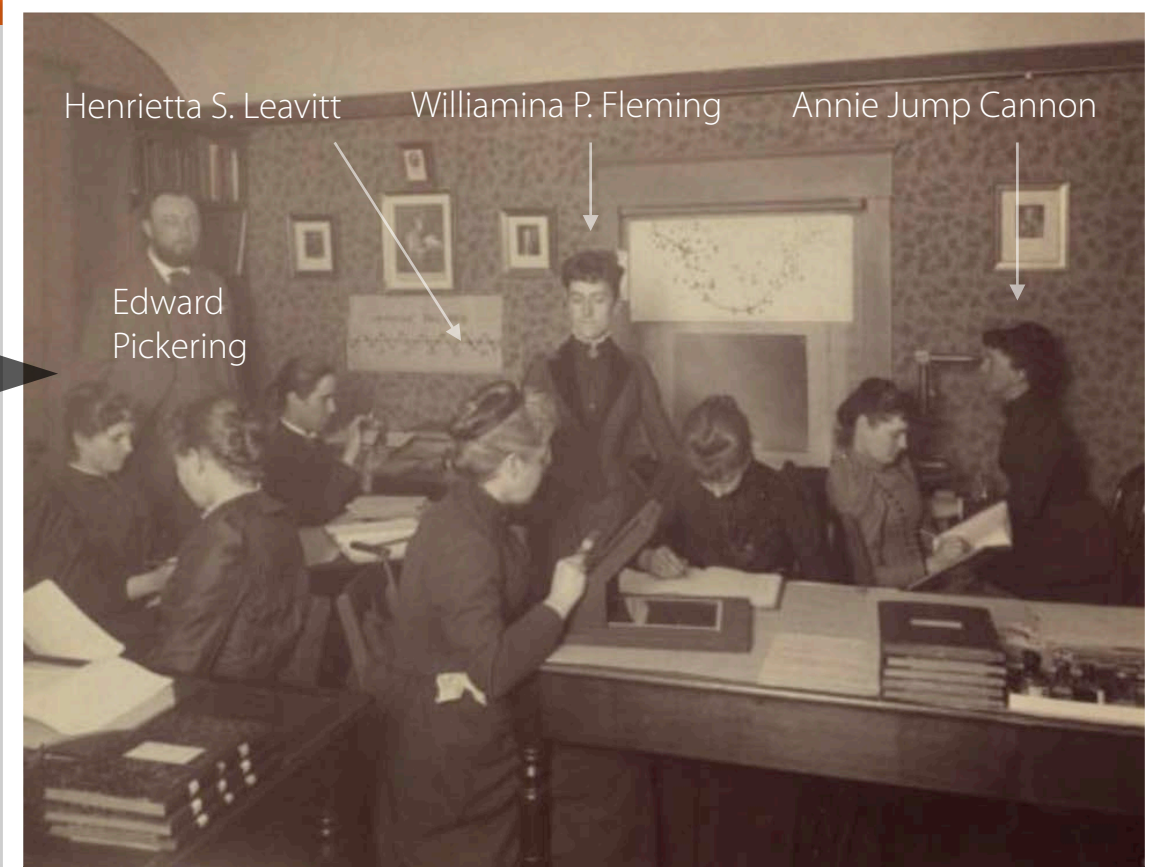


Spectral classification

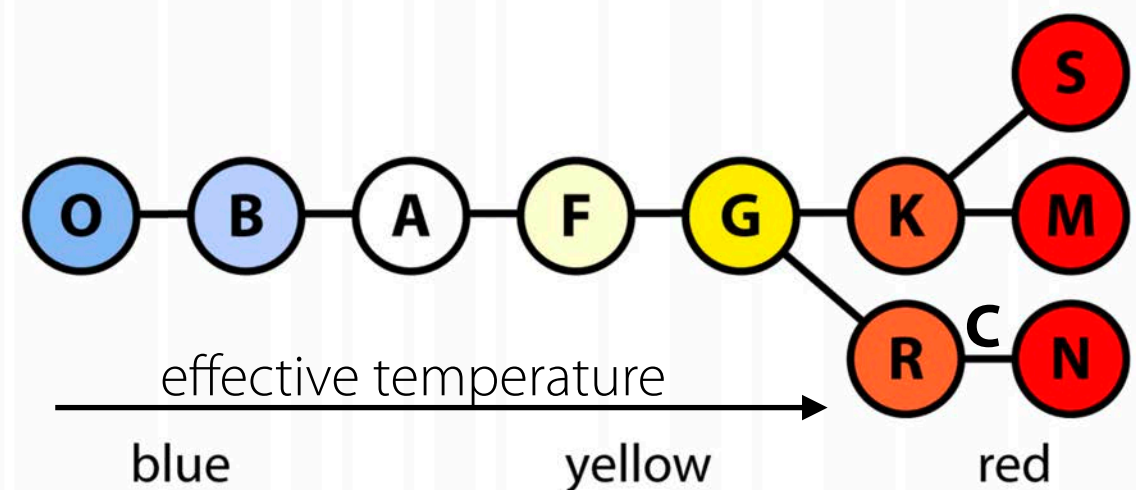
- Different classification schemes
- **Harvard spectral classification**
- Further developed and extended

➔ Morgan–Keenan system

- A star is classified by a
 - Spectral class
 - Decimal sub-division (0-9) with effective temperature decreasing with in increasing digit
 - Luminosity class



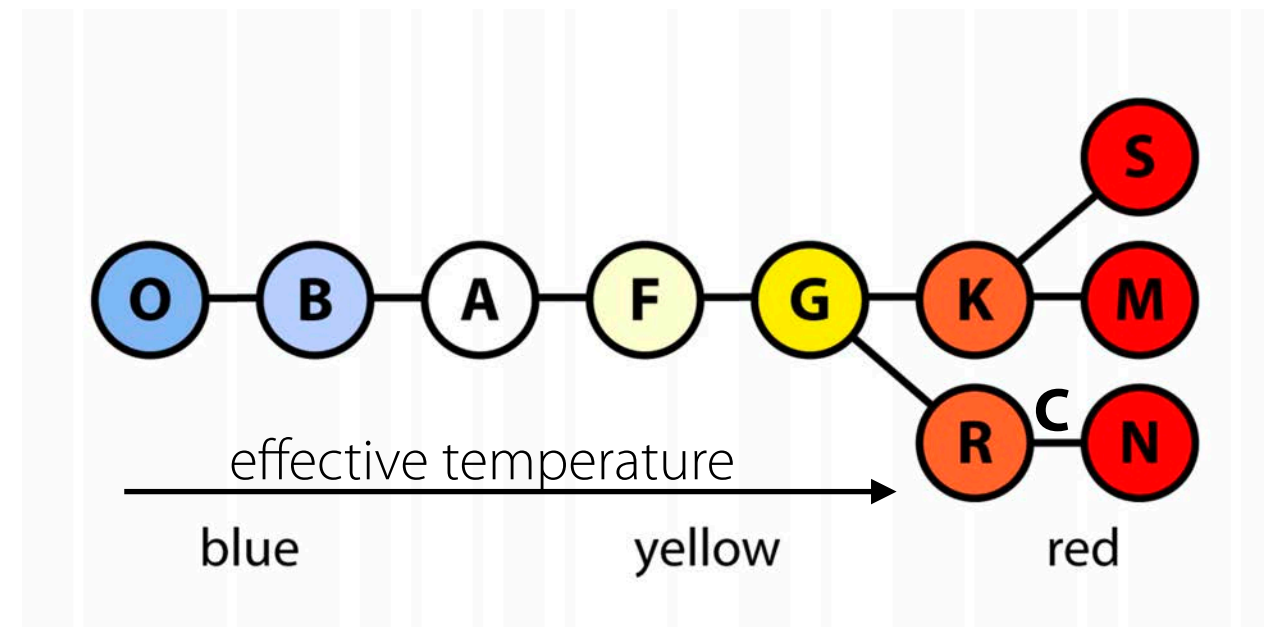
The women of Harvard College Observatory classifying stellar spectra.



Spectral classification

Main spectral classes

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



Spectral classification

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Supplementary classes of cool stars			
R (C)	red	$< 3\,000\text{ K}$	Carbon compounds, S-process elements
N (C)	red		Carbon compounds, S-process elements
S	red	$\sim 3\,000\text{ K}$	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)).

Spectral classification

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Very low mass /sub-stellar spectral classes (mostly brown dwarfs)

L	IR	$1\,500 - 2\,500\text{ K}$	lines of alkali metals (e.g. N) and metallic compounds (e.g. FeH)
Y	IR	$800 - 1\,500\text{ K}$	methane absorption lines
T	IR	$< 800\text{ K}$	water and ammonia lines

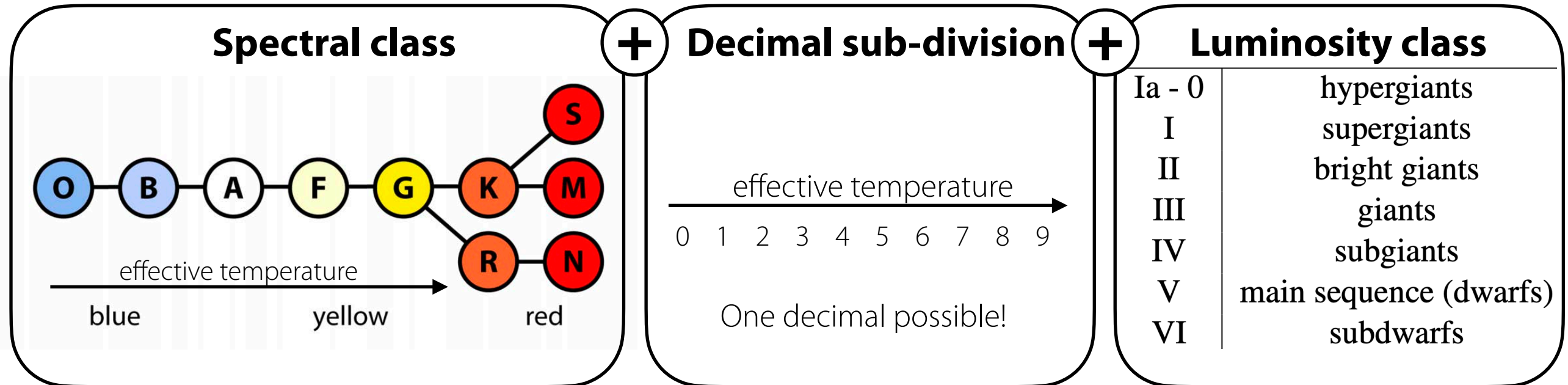
Spectral classification

Luminosity class

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

Spectral classification

- A star is classified by a



- 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

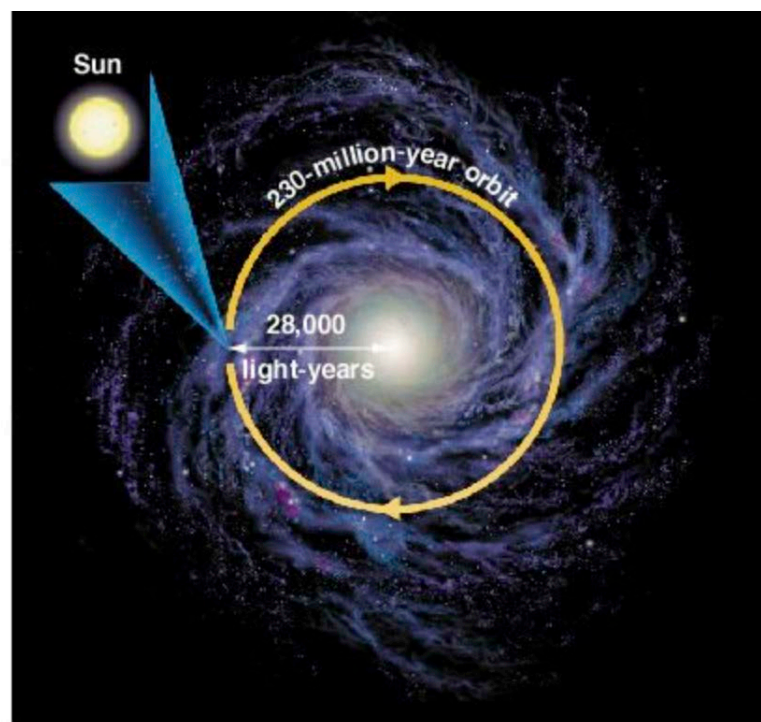
Additional classification

- Special spectral types
 - **W** for Wolf-Rayet stars with no hydrogen lines in their spectra
 - **D** for white dwarfs
 - ...
- **Extra information** can be added to the spectral type of a star if it differs from the other regular types / show **peculiarities**
 - e: presence of pronounced emission lines
 - v: variable spectral features.
 - ...
 - Example: M5.5Ve
- Please note that
 - the accuracy of a spectral classification depends on the quality of the available data
 - a spectral classification can change as a star changes

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



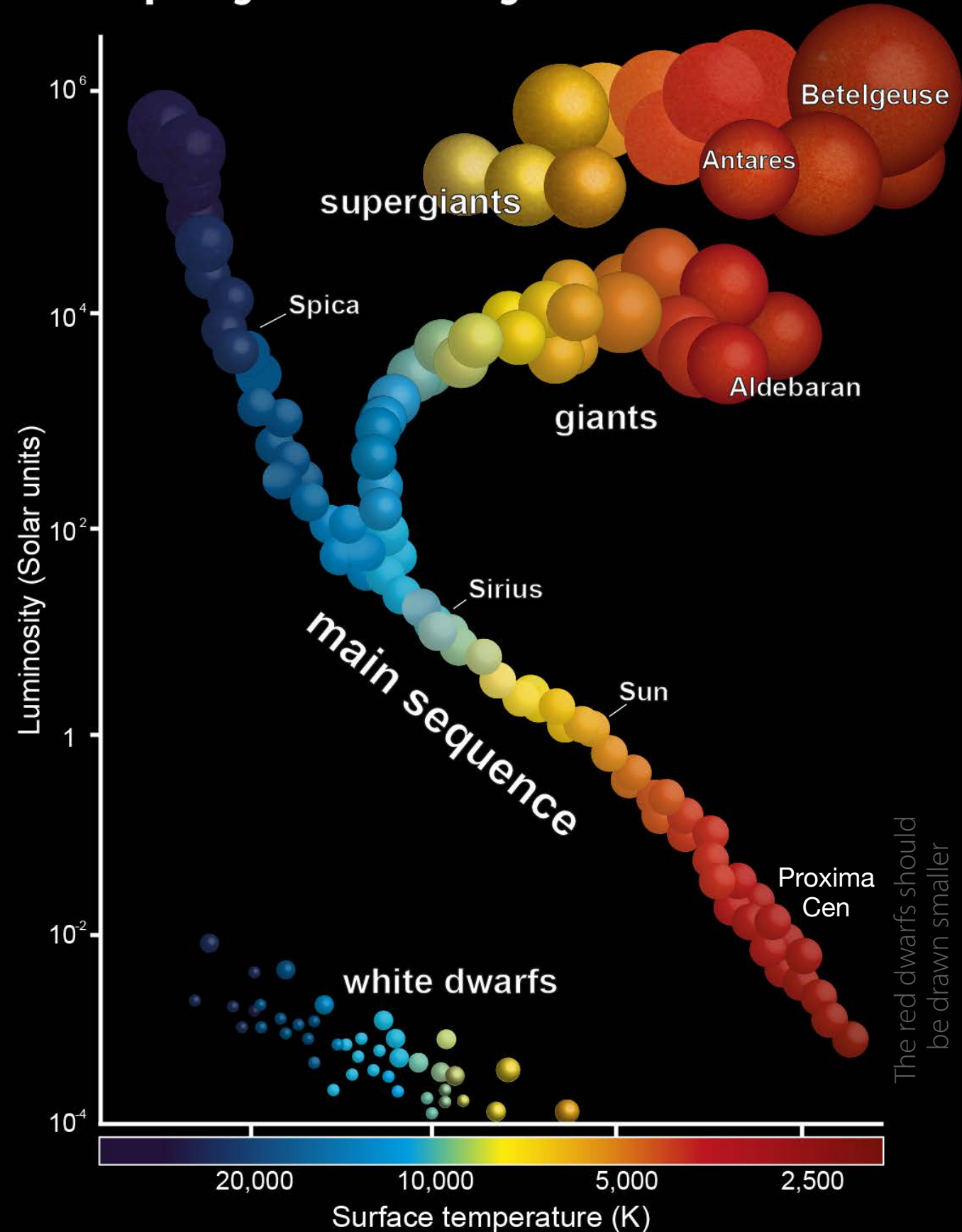
- Total number of stars in the Milky Way only known roughly:
100 - 400 billion stars

Stellar classification

Hertzsprung-Russell diagram

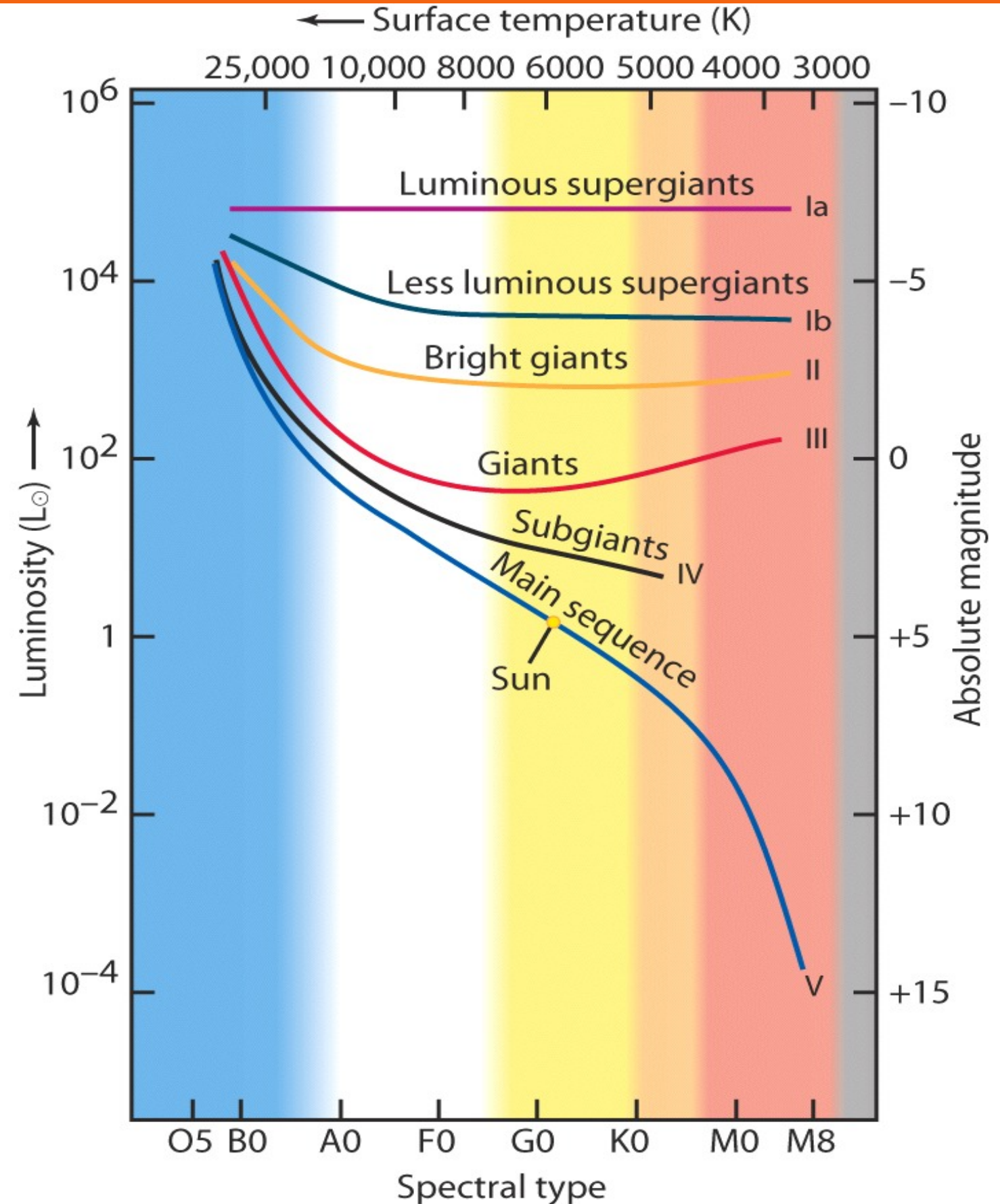
- Stars not randomly distributed
- Distribution yields important clues for stellar structure and evolution
- Different stellar types and evolution stages:
 - Main sequence
 - Giants and supergiants
 - Dwarf stars
 - ...

Hertzsprung–Russell Diagram



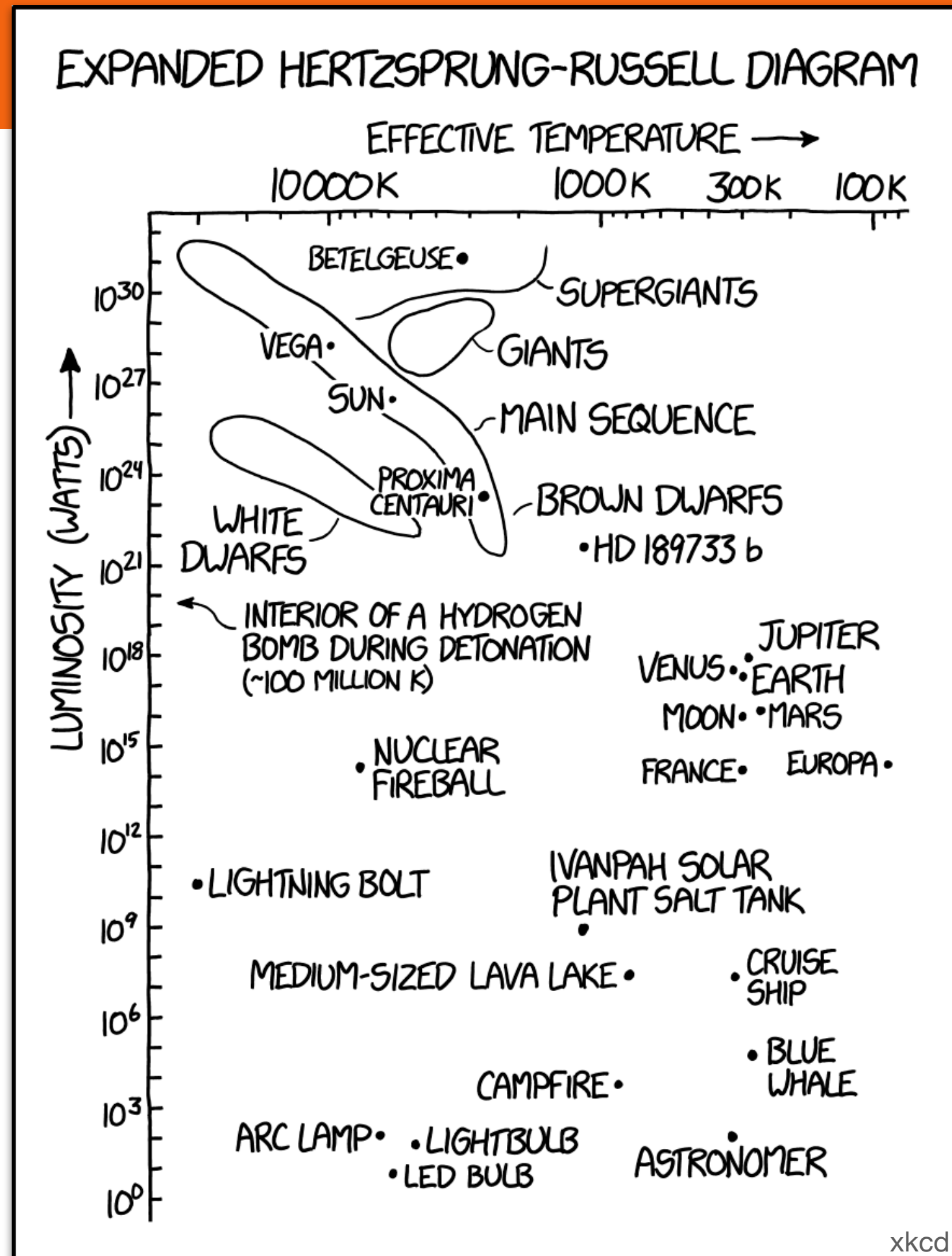
Stellar classification

Hertzsprung-Russell diagram



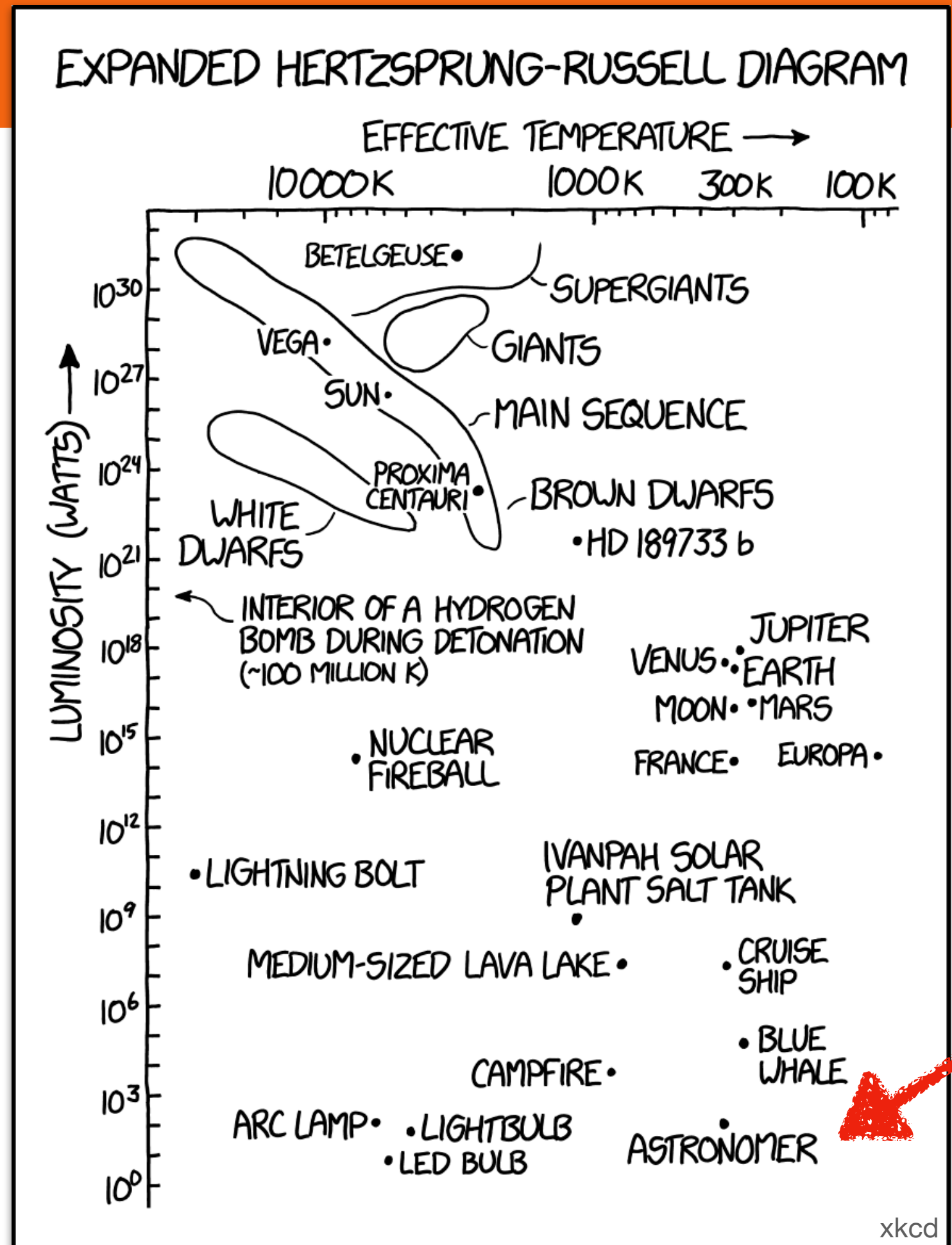
Stellar classification

Hertzsprung-Russell diagram



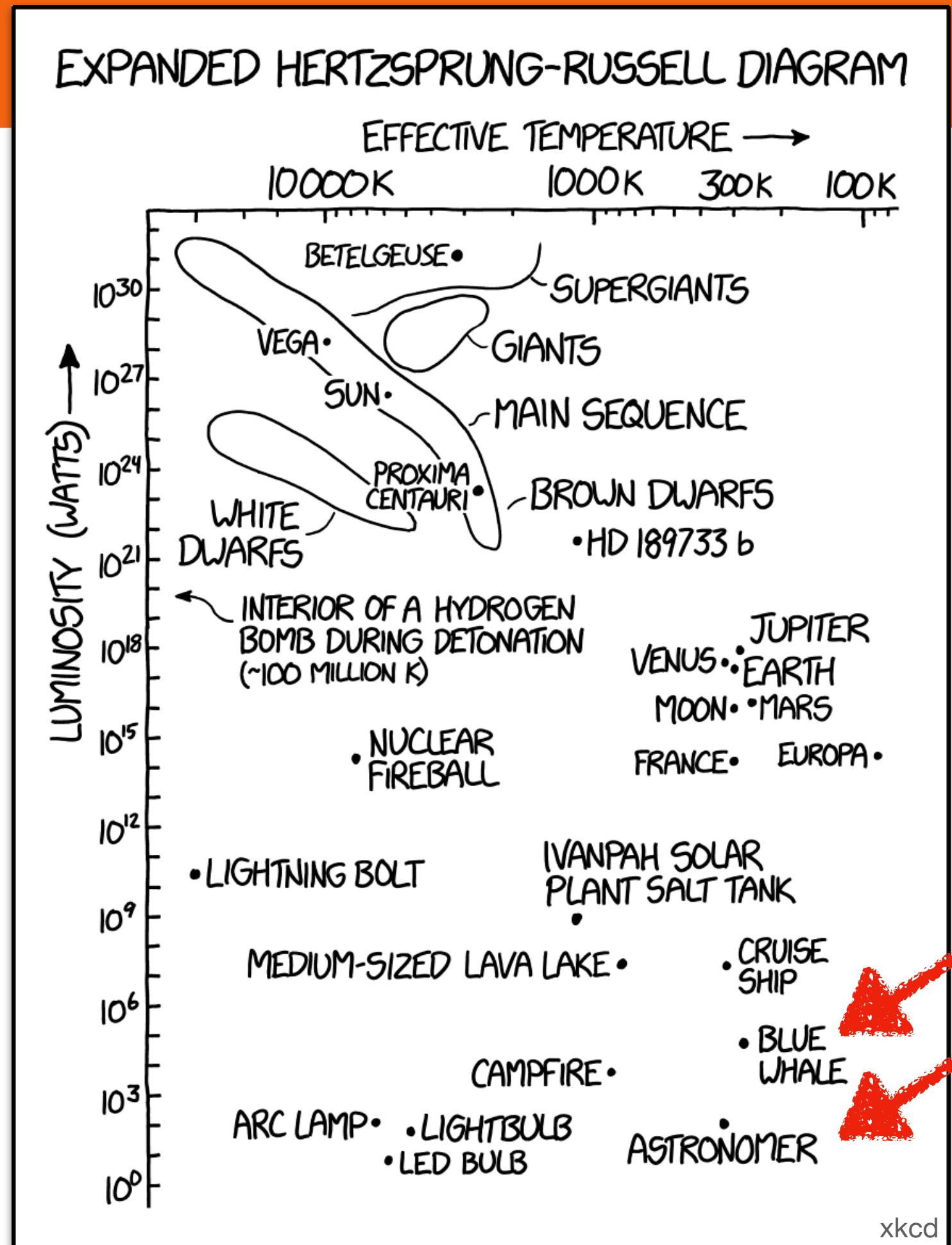
Stellar classification

Hertzsprung-Russell diagram



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 $M_{\min} \approx 0.08M_{\odot}$.
 - ➡ Objects with $M_{\min} < 0.08M_{\odot}$ (but more mass than planets): brown dwarfs ($M_{\text{bd}} < 0.08M_{\odot}$).
- Highest masses $M > 100M_{\odot}$
 - Known examples with up to $\sim 250M_{\odot}$
- 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

- **Main sequence stars**

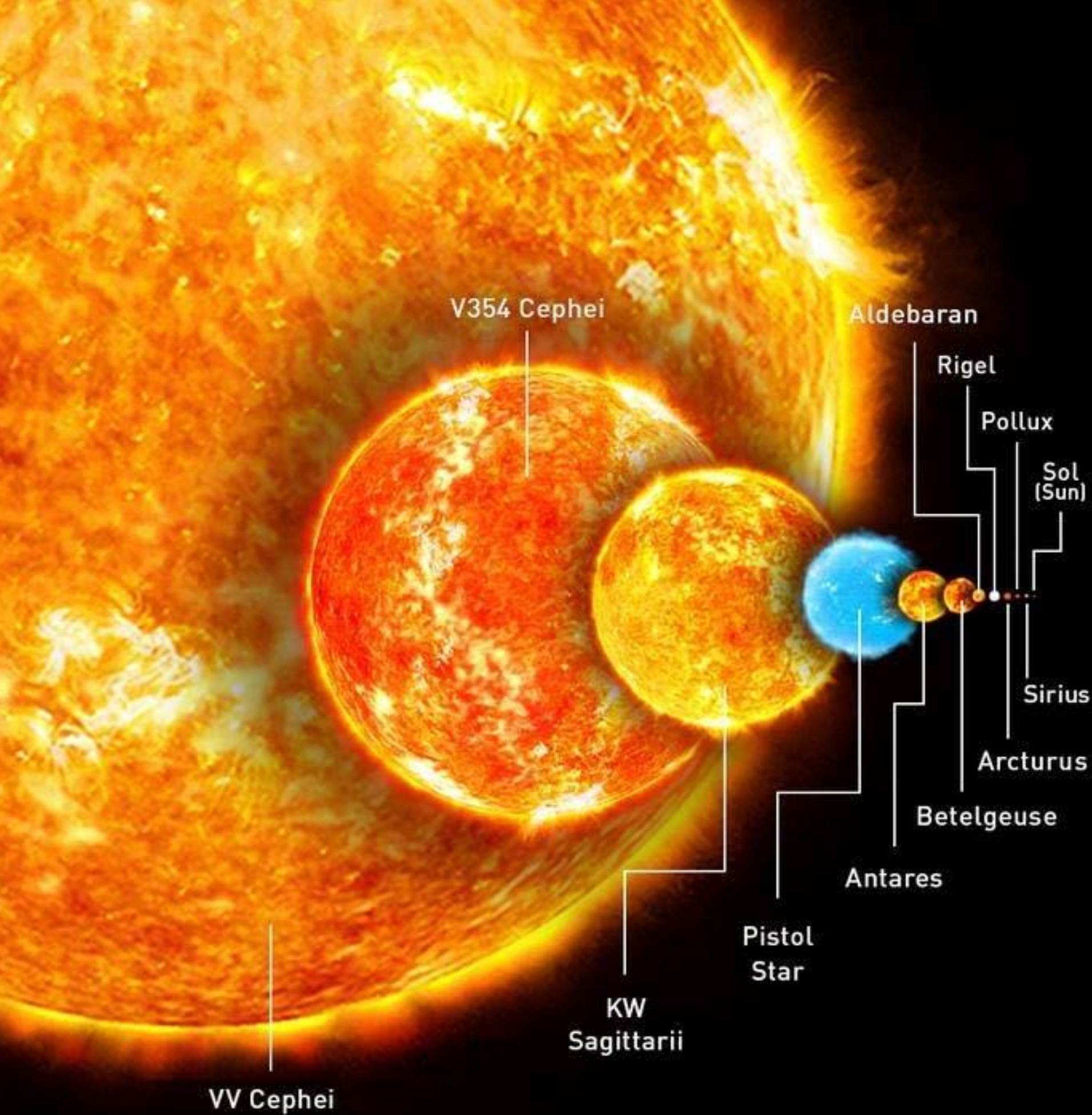
- Typical values: $0.1 R_{\odot}$ to $\sim 25 R_{\odot}$.
- Radii increase as function of effective temperature along the main sequence
- Red dwarfs at the cool end being much smaller than the Sun
- Hot main sequence stars being much larger than the Sun.

- **Red giants, supergiants, ...**

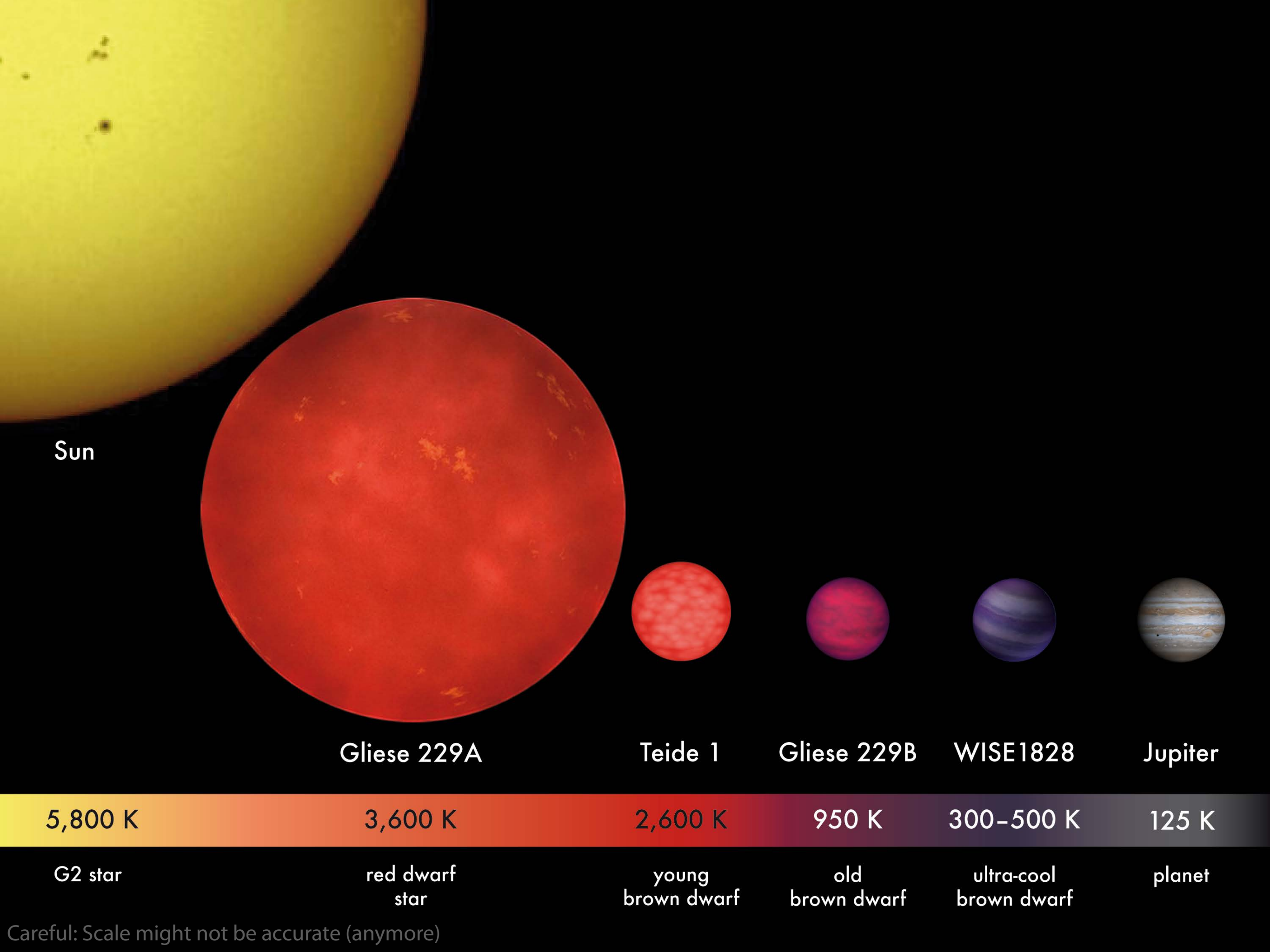
- Diameters larger than the orbit of Mars.
- Examples: Antares ($680 - 800 R_{\odot}$), Betelgeuse ($900 R_{\odot}$), and Mu Cephei ($972 - 1,260 R_{\odot}$).
- Largest stars: radii currently estimated to up $\sim 2000 R_{\odot}$.

- **White dwarfs**

- $R < 0.02 R_{\odot}$



Careful: Scale might not be accurate (anymore)



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

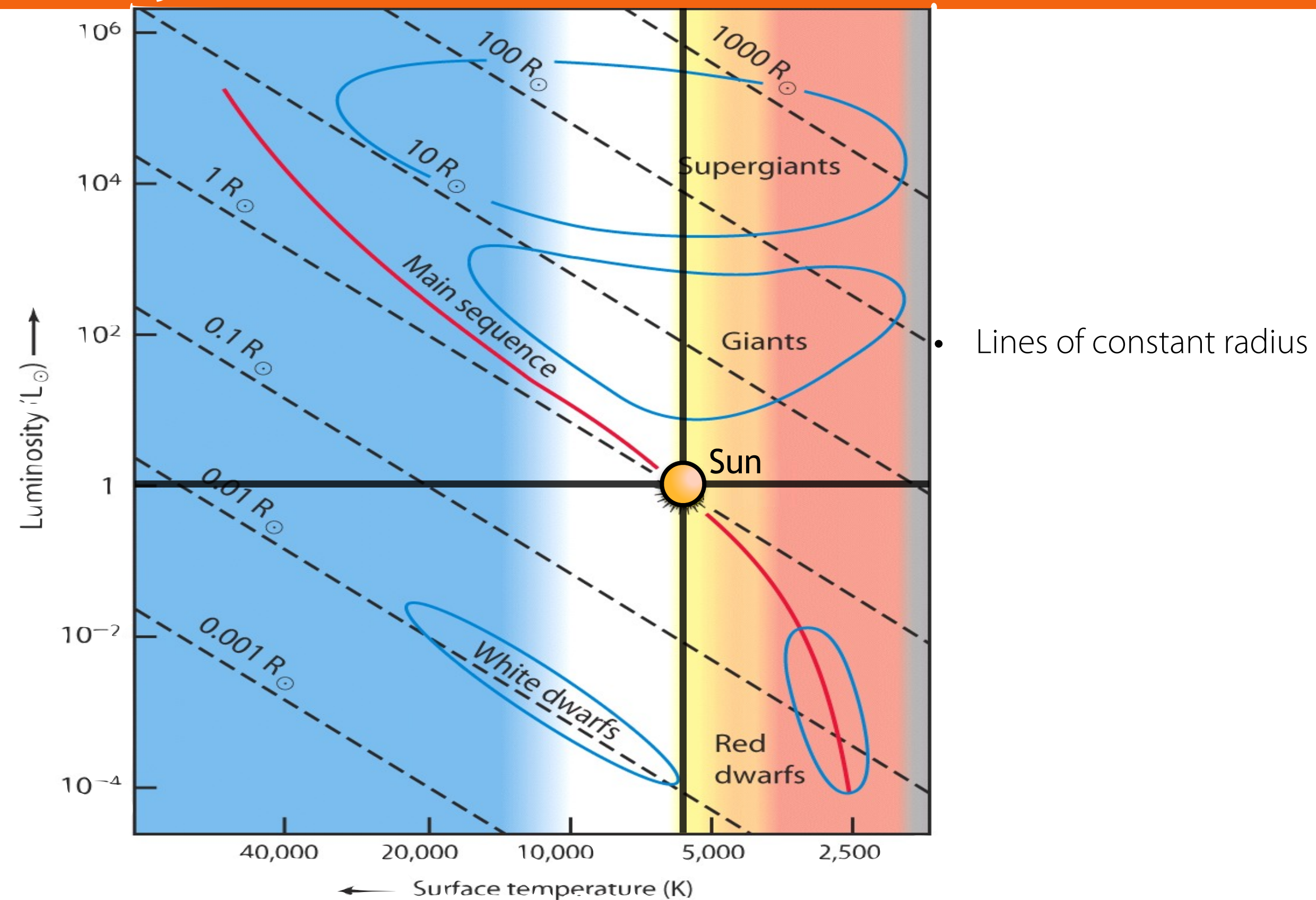
old
brown dwarf

ultra-cool
brown dwarf

planet

Careful: Scale might not be accurate (anymore)

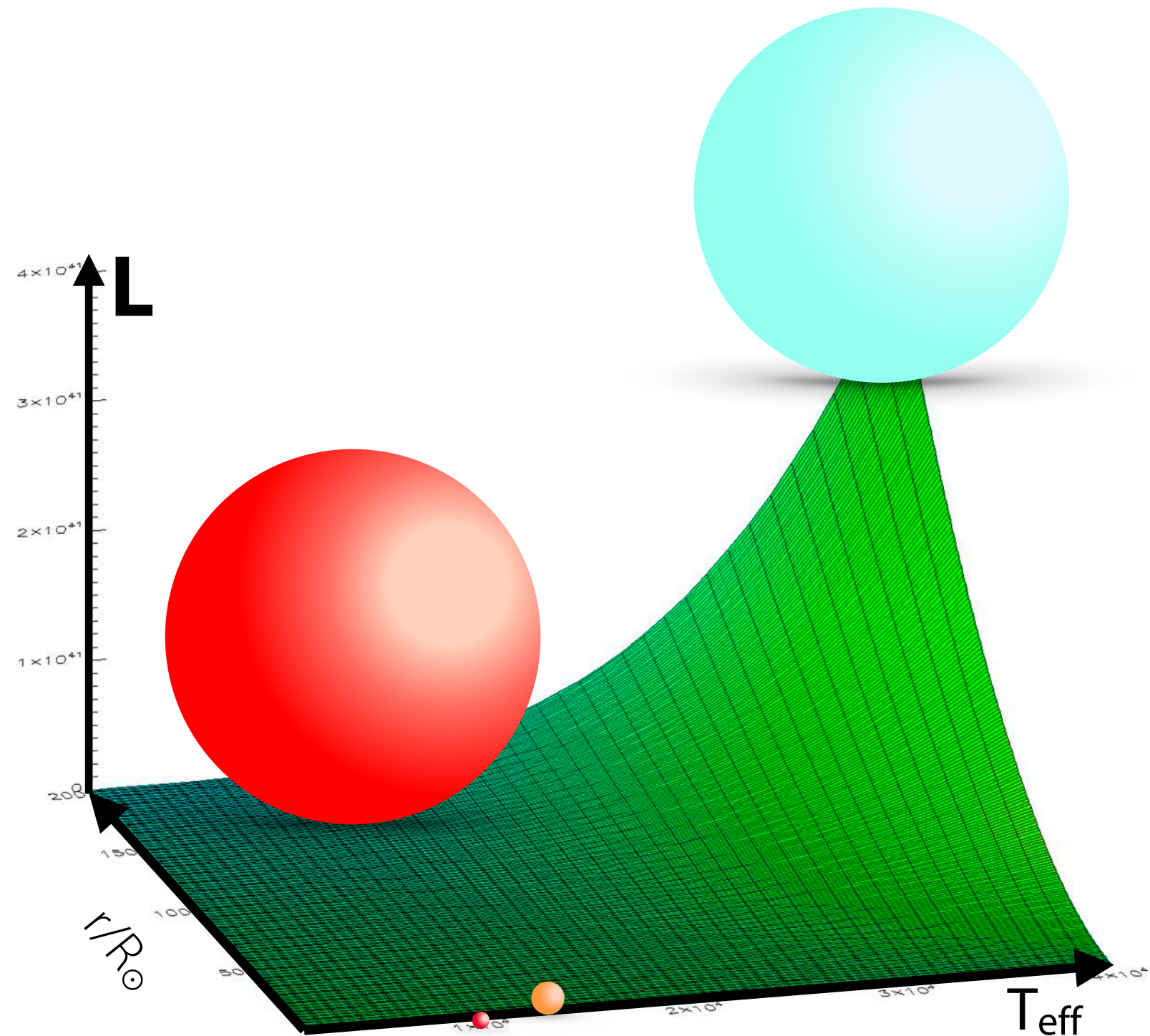
Physical stellar parameters



Physical stellar parameters

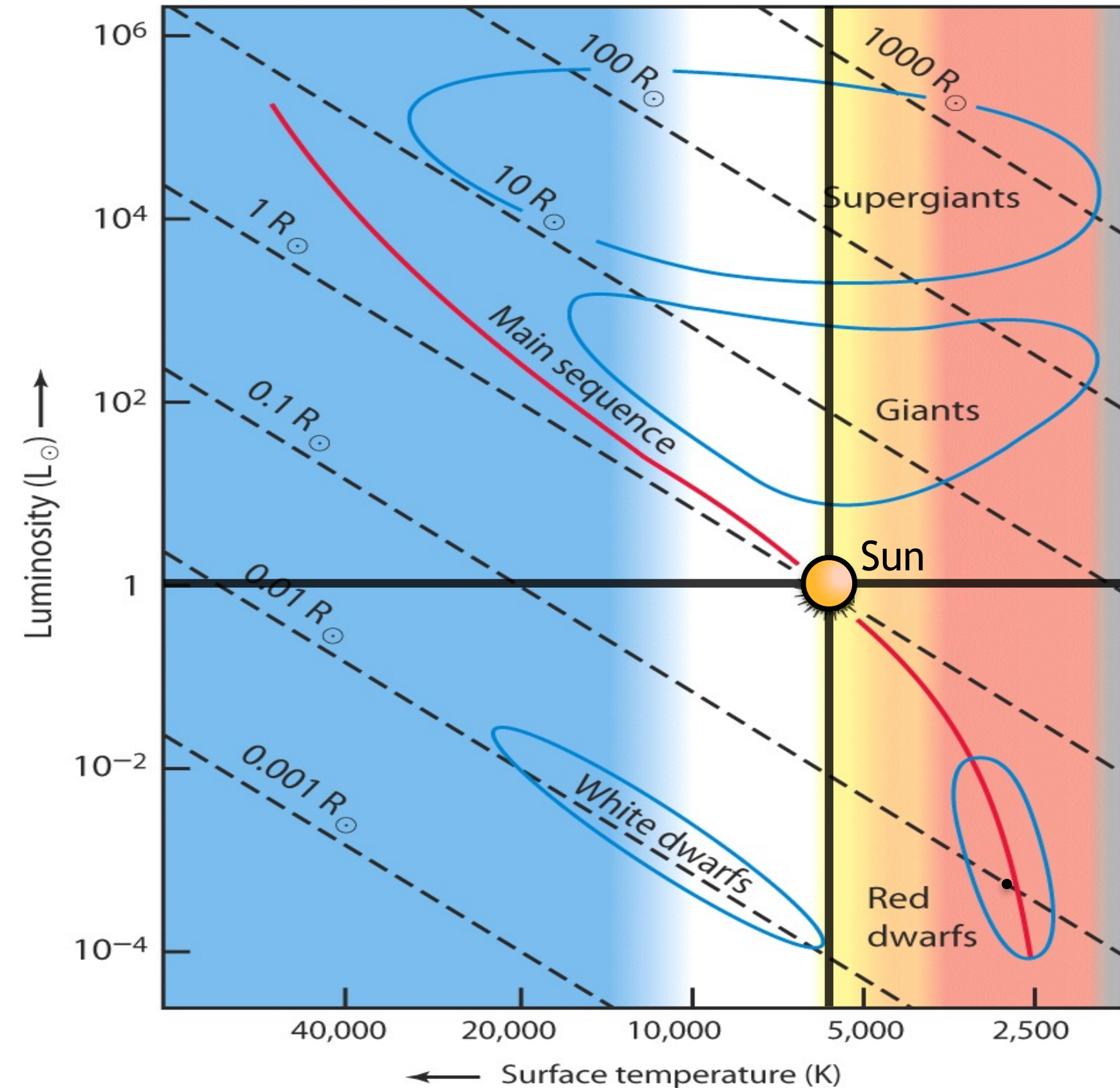
Luminosity $\Rightarrow L = 4\pi R^2 \sigma T_{\text{eff}}^4$

- The bolometric luminosity of stars spans many orders of magnitude: $10^{-4} L_{\odot} \text{ — } 10^6 L_{\odot}$
- Depends to **4th power** on T_{eff}
- $\Rightarrow$ 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:
 $L \sim 60\,000 \text{ — } 200\,000 L_{\odot}$.
 $\Rightarrow$ Large uncertainty is due to the poorly known distance!
- Example 2:** Red supergiant Betelgeuse $L \approx 100\,000 L_{\odot}$



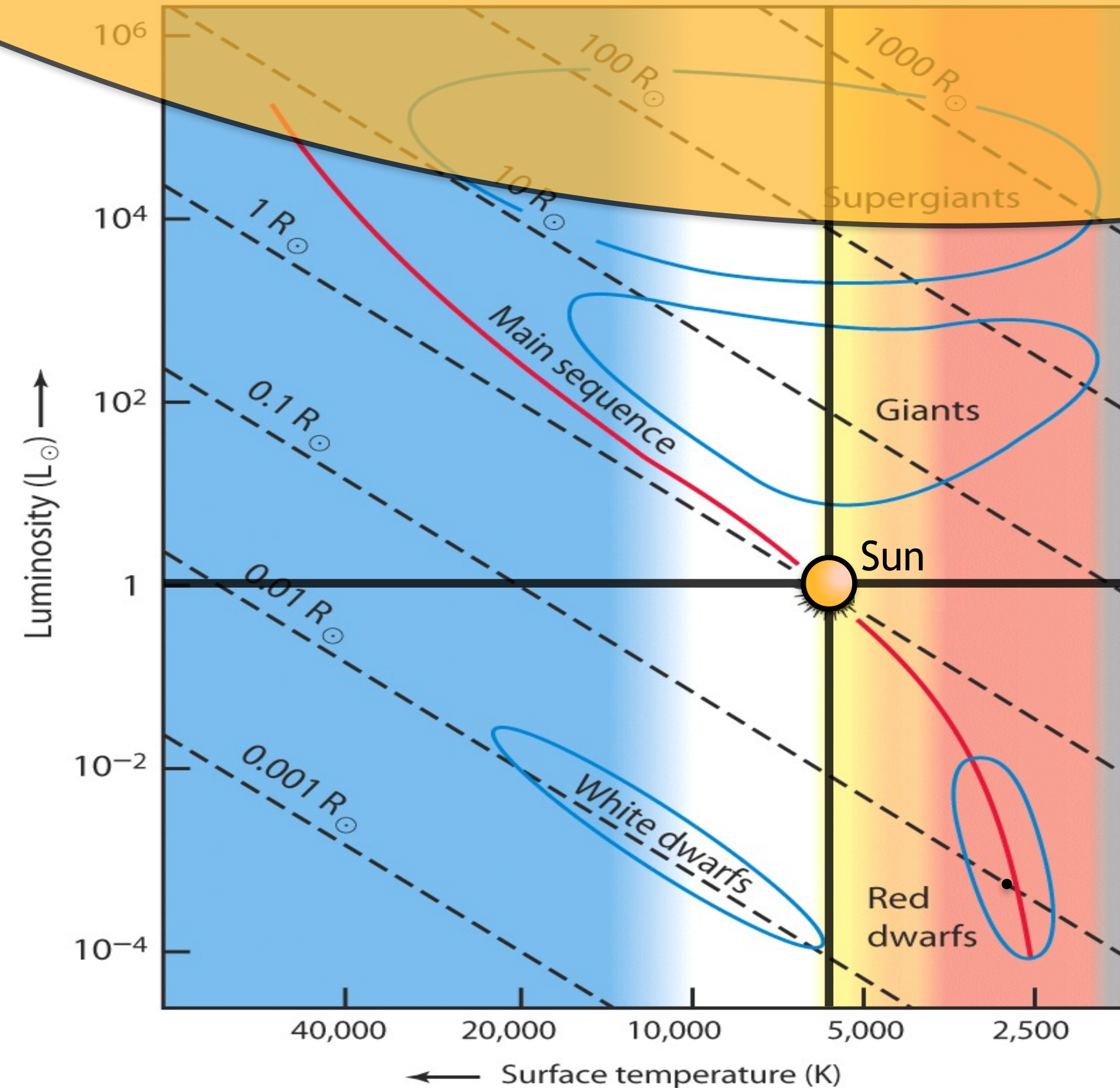
Physical stellar parameters

$$L \propto R^2 T_{\text{eff}}^4$$



Physical stellar parameters

$$L \propto R^2 T_{\text{eff}}^4$$



Super giant

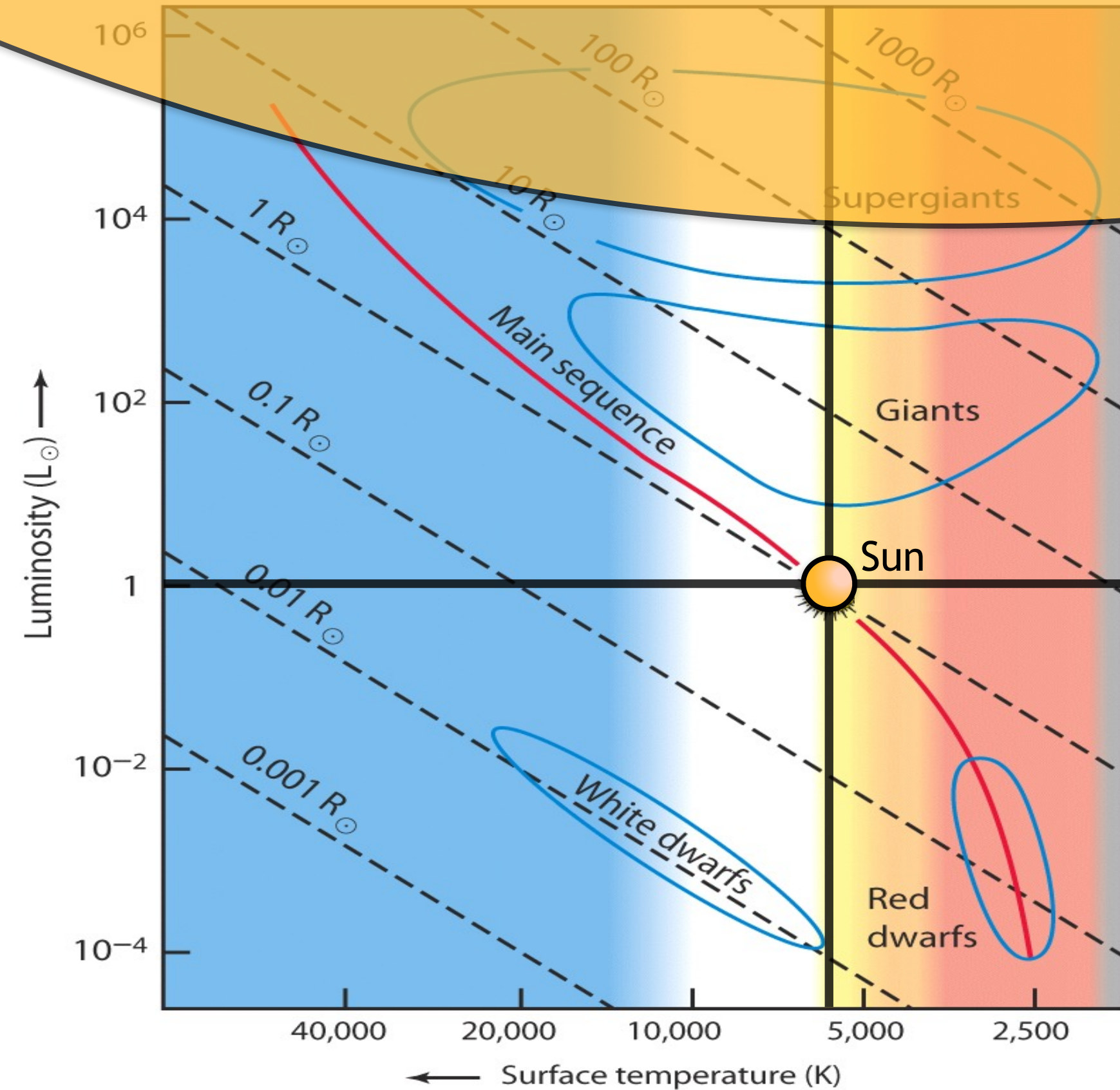
$$R = 100 R_{\odot}$$

$$T_{\text{eff}} = T_{\text{eff},\odot} = 5770 \text{ K}$$

$$\Rightarrow L = 100^2 L_{\odot} = 10\,000 L_{\odot}$$

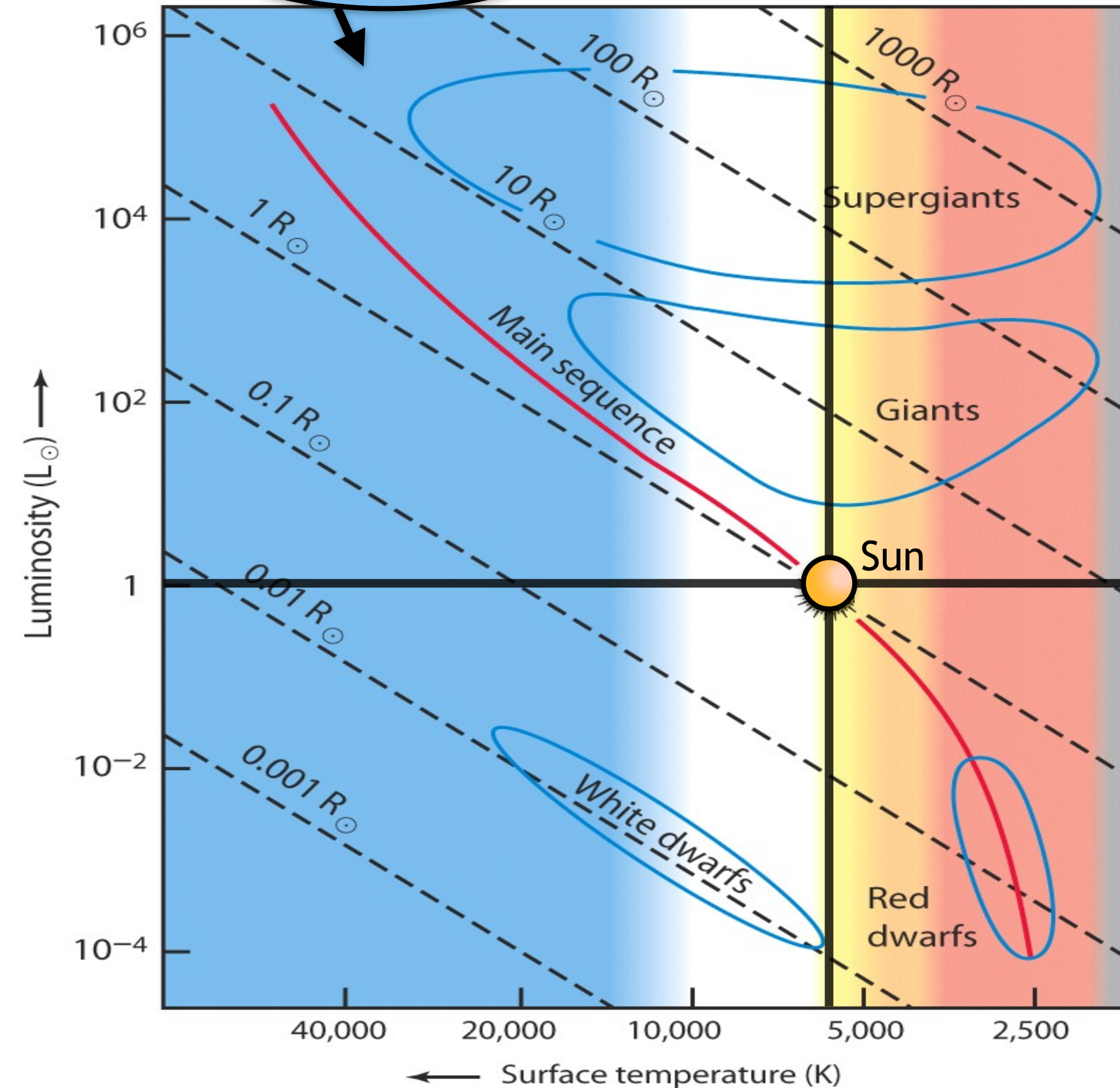
Physical stellar parameters

$$L \propto R^2 T_{\text{eff}}^4$$



Primary stellar parameters

$$L \propto R^2 T_{\text{eff}}^4$$



Spectral type O6

$$R = 18 R_{\odot}$$

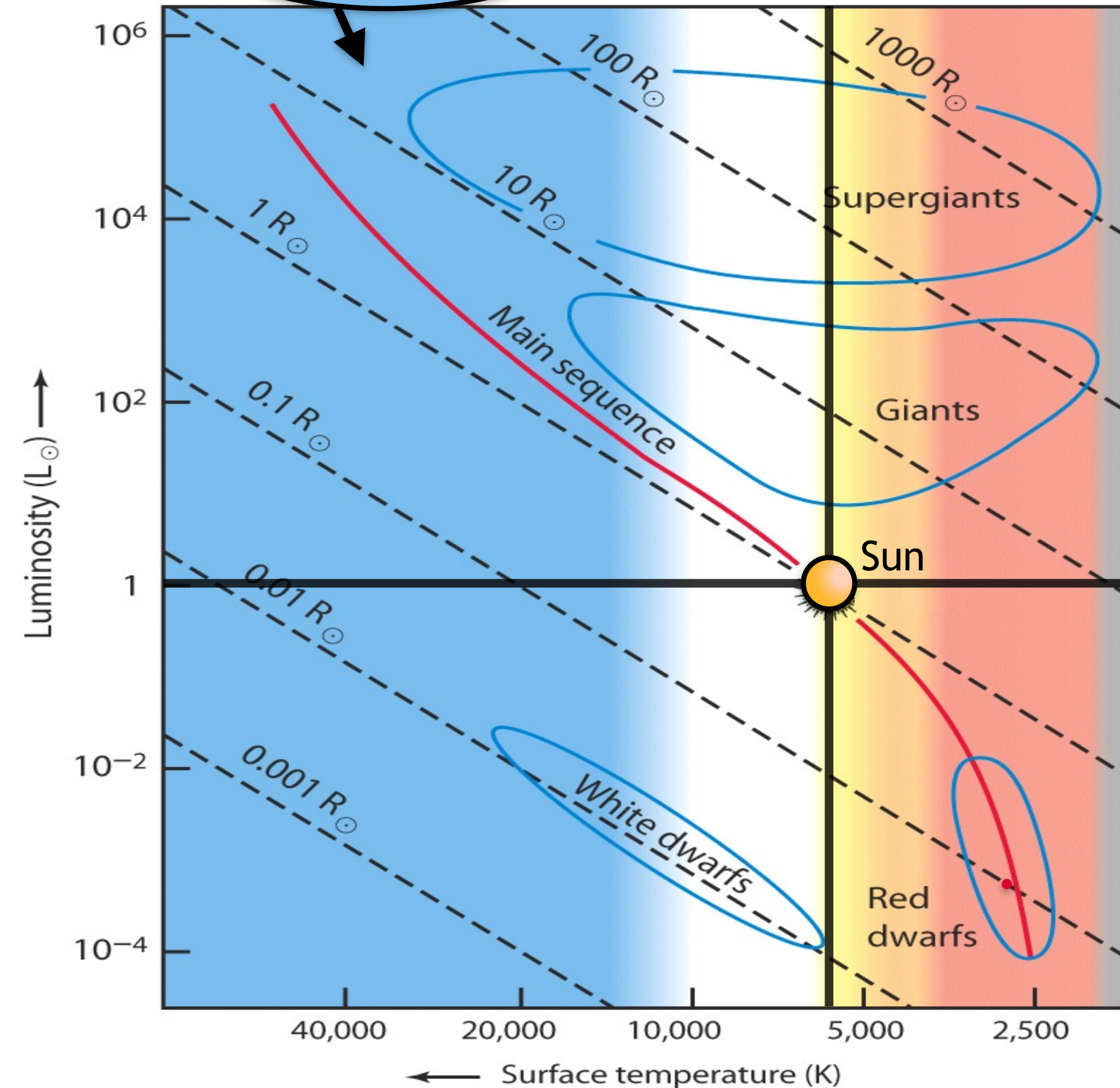
$$T_{\text{eff}} = 38\,000 \text{ K}$$

$$= 6.3 T_{\text{eff},\odot}$$

$$\Rightarrow L = 520\,000 L_{\odot}$$

Primary stellar parameters

$$L \propto R^2 T_{\text{eff}}^4$$



Spectral type O6

$$R = 18 R_{\odot}$$

$$T_{\text{eff}} = 38\,000 \text{ K}$$

$$= 6.3 T_{\text{eff},\odot}$$

$$\Rightarrow L = 520\,000 L_{\odot}$$

Red dwarf star

$$R = 0.1 R_{\odot}$$

$$T_{\text{eff}} = 0.5 T_{\text{eff},\odot} = 2885 \text{ K}$$

$$\Rightarrow L = 0.1^2 0.5^4 L_{\odot}$$

$$= 0.0006 L_{\odot}$$

$$= 0.06 \% L_{\odot}$$

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: $T_{\text{eff},\odot} \approx 5770 \text{ K}$.
- Typical values for other **main sequence stars** :
 - from $\sim 2\,200 \text{ K}$ for the coolest red dwarf stars
 - to up to $\sim 45\,000 \text{ K}$ for the hottest O-type stars.
- **White dwarfs** can exhibit much higher temperatures of up to $\sim 2 \times 10^5 \text{ K}$ (basically “exposed” stellar core remnants)

Physical stellar parameters

Gravity acceleration

$$g = \frac{GM}{R^2}$$

mass M ,
radius R ,
gravity constant G

- Commonly specified in logarithmic form as **log g** in cgs units.
 - Sun: $g_{\odot} = 274 \text{ ms}^{-2} = 2.74 \times 10^4 \text{ cm s}^{-2}$ — $(\log g)_{\odot} = 4.44$
 - Large range of stellar radii + dependence $g \propto R^{-2}$,
- ➡ g varies over 8 orders of magnitude from white dwarfs to supergiants

Giants and supergiants:	$g \leq 1 \times 10^{-2} \text{ m s}^{-2}$	$\log g \sim 0$
Main sequence:	$g \sim 2 \times 10^2 \text{ m s}^{-2}$	$\log g \sim 4.3 - 4.5$
White dwarfs:	$g \sim 1 \times 10^6 \text{ m s}^{-2}$	$\log g \sim 8$

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 $\log \epsilon$ relative to the Sun

- Hydrogen as origin of scale with $\log \epsilon (\text{H}) = 12$ and all other element relative to hydrogen:

$$A(\text{El}) = \log \epsilon = \log(n_{\text{El}}/n_{\text{H}}) + 12 \quad \text{n: number density of element}$$

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

$$\epsilon = \frac{(\text{M/H})_{\text{star}}}{(\text{M/H})_{\odot}} \quad \text{or} \quad \log \epsilon = [\text{M/H}]$$

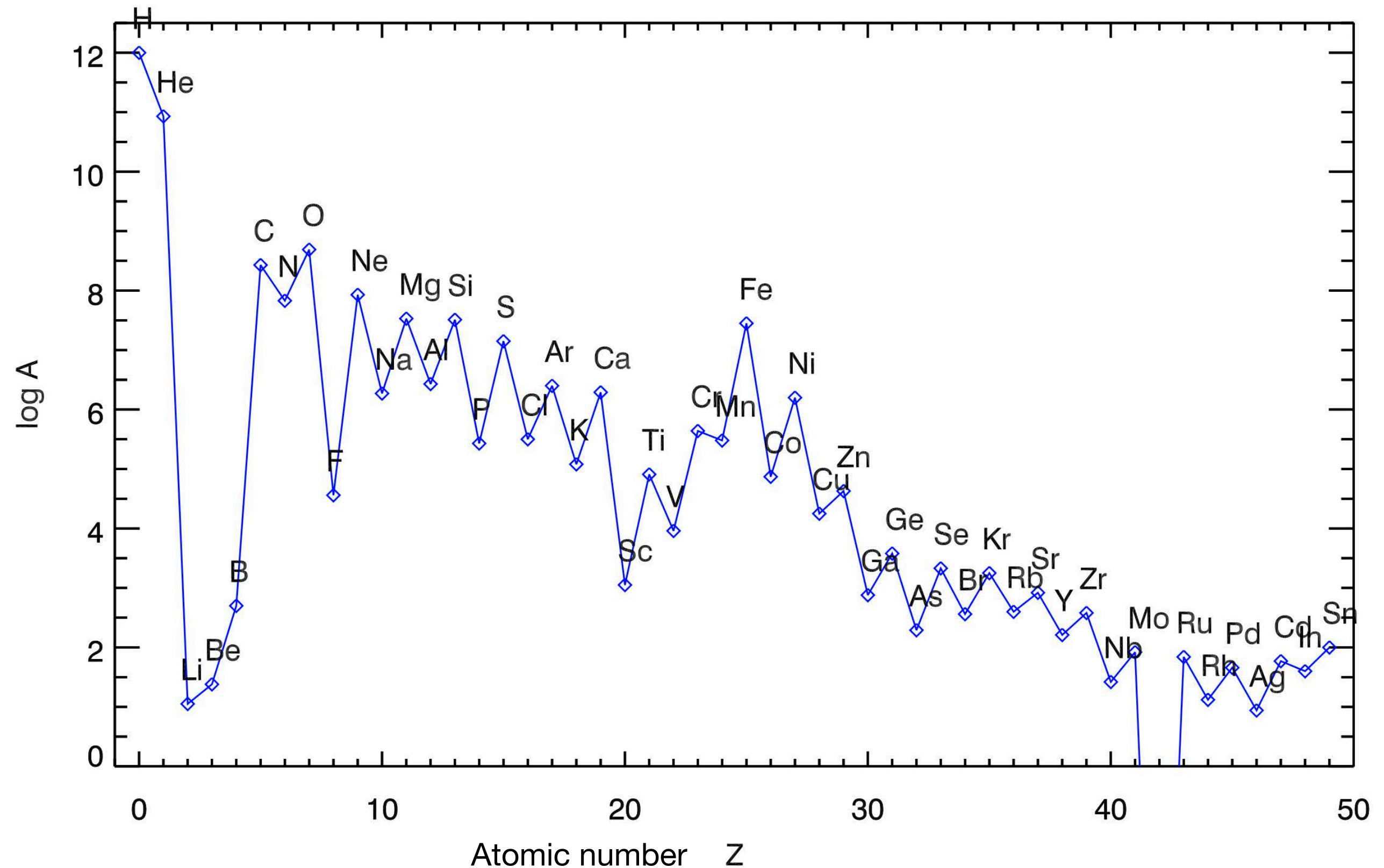
- Iron abundance relatively easy to measure due to large number of spectral lines (*and as an important nucleosynthesis product*) — often used as a *representative metal*

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

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

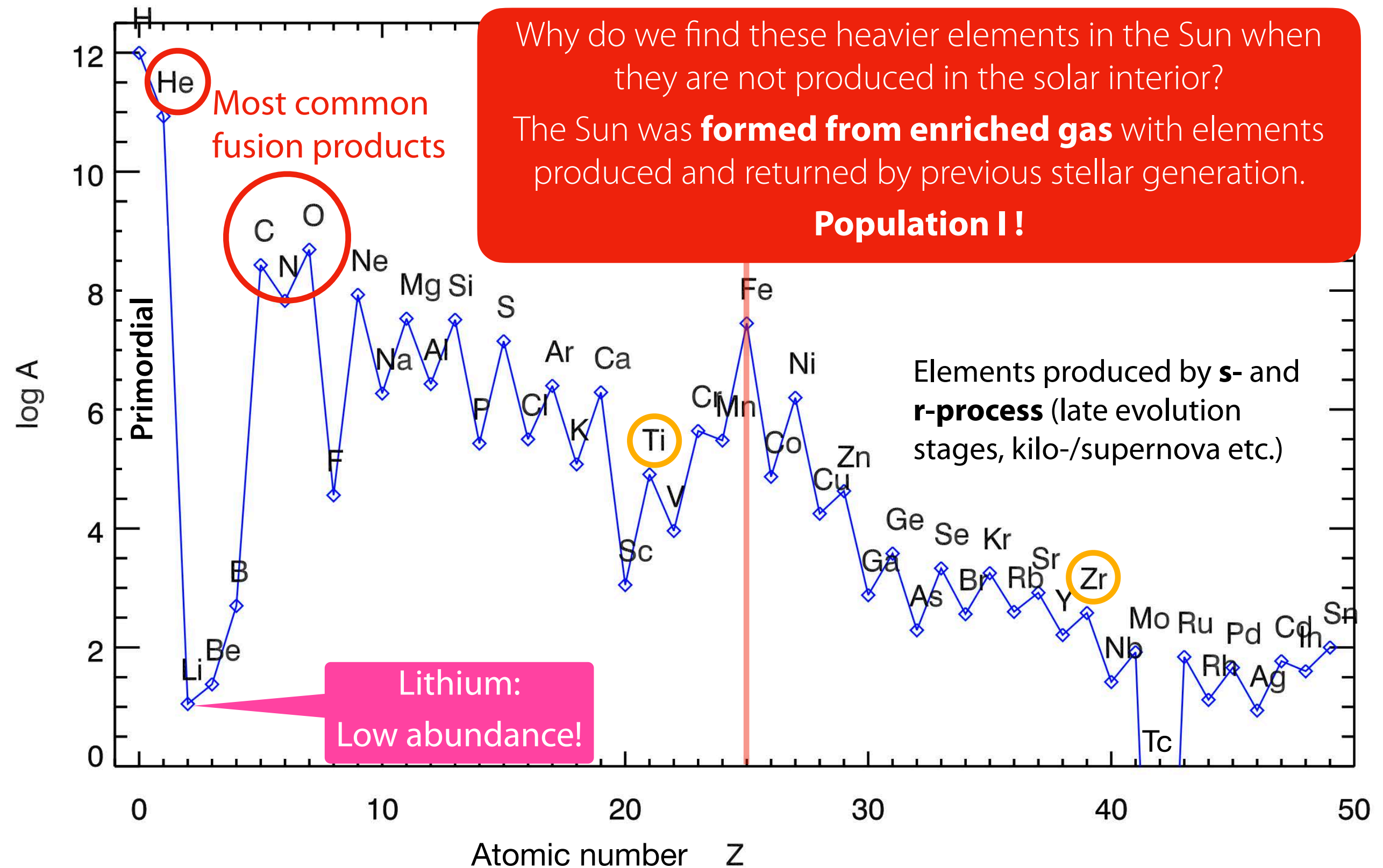
Physical stellar parameters

Chemical composition — Solar abundances



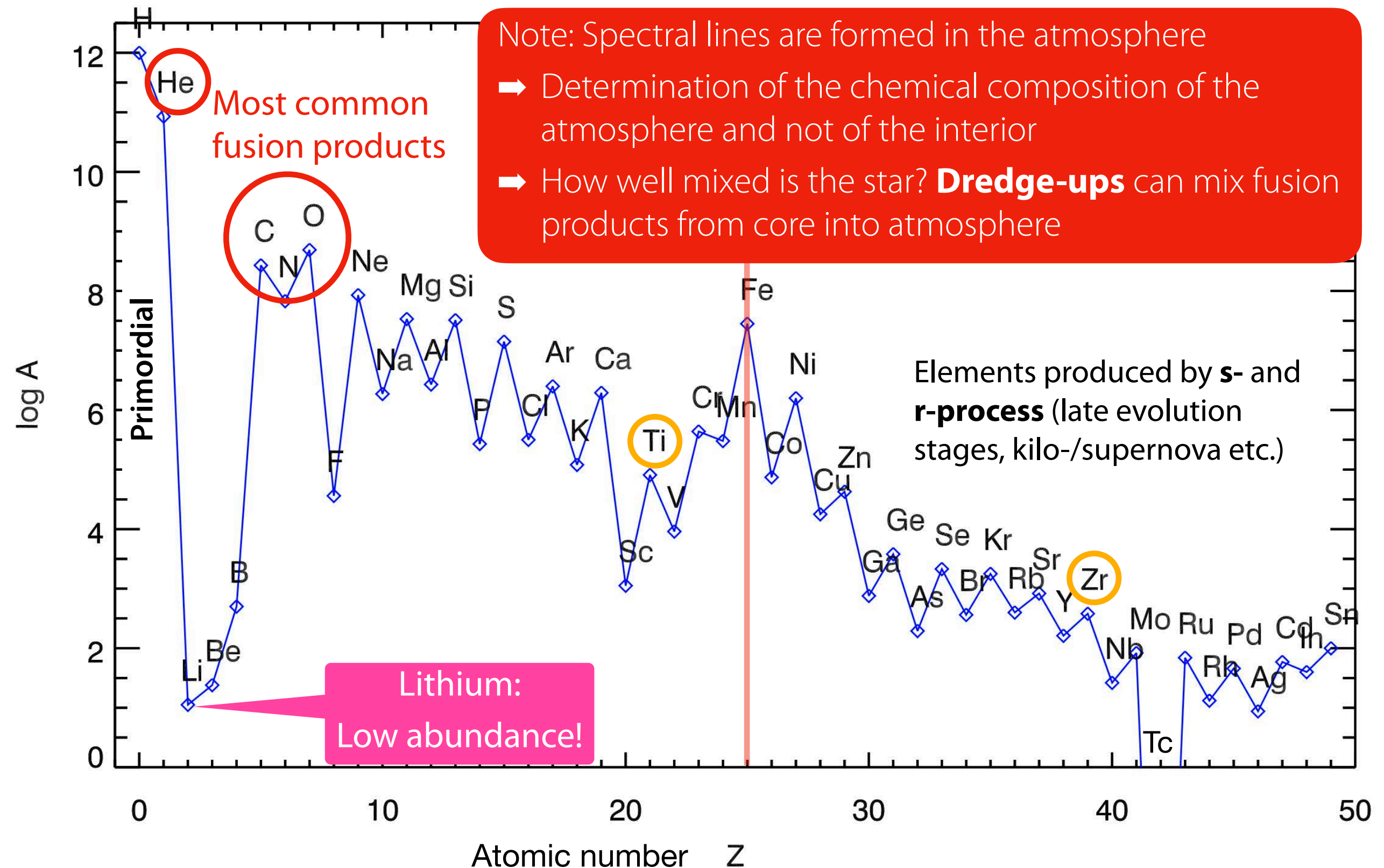
Physical stellar parameters

Chemical composition — Solar abundances



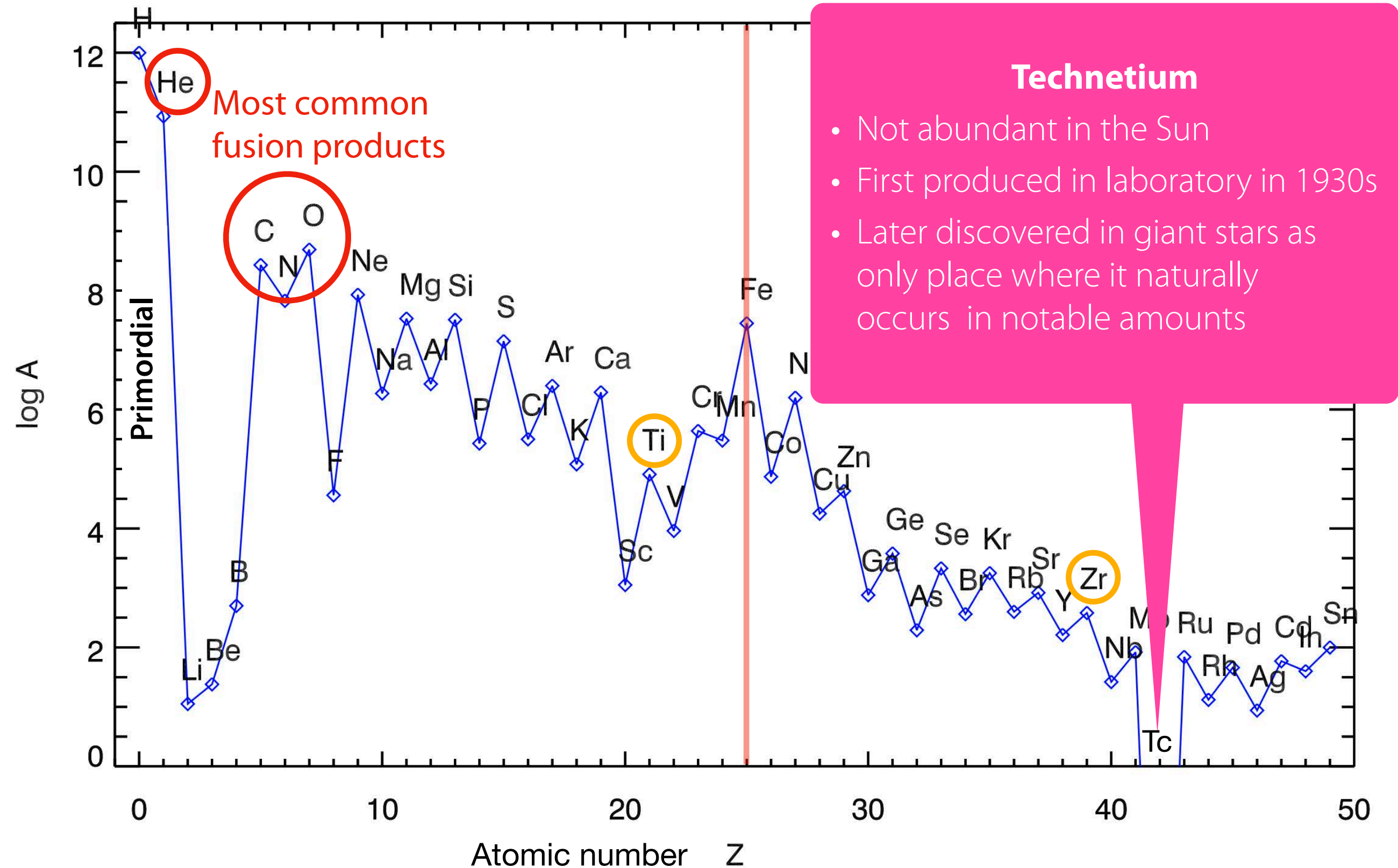
Physical stellar parameters

Chemical composition — Solar abundances



Physical stellar parameters

Chemical composition — Solar abundances



Periodic Table of the Elements

for Astronomers



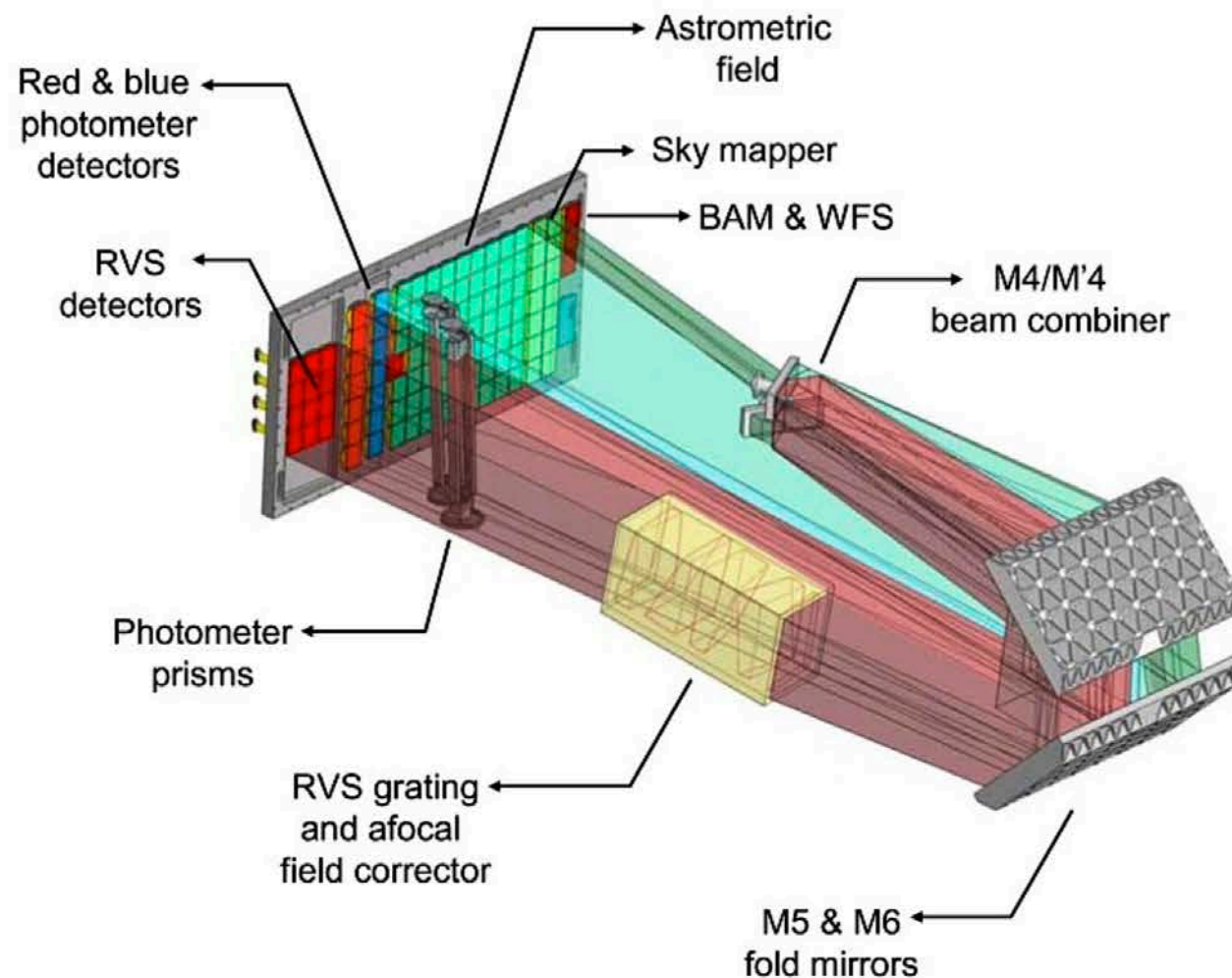
Heidi Weissman Kneale

This is really how astronomers see the periodic table according to astronomer and author Heidi Weissman Kneale (Supplied: Heidi Weissman Kneale (@heidikneale))

Physical stellar parameters

Addition: Broadband photometry with GAIA

Instrument



Passbands

Transmitted wavelength ranges

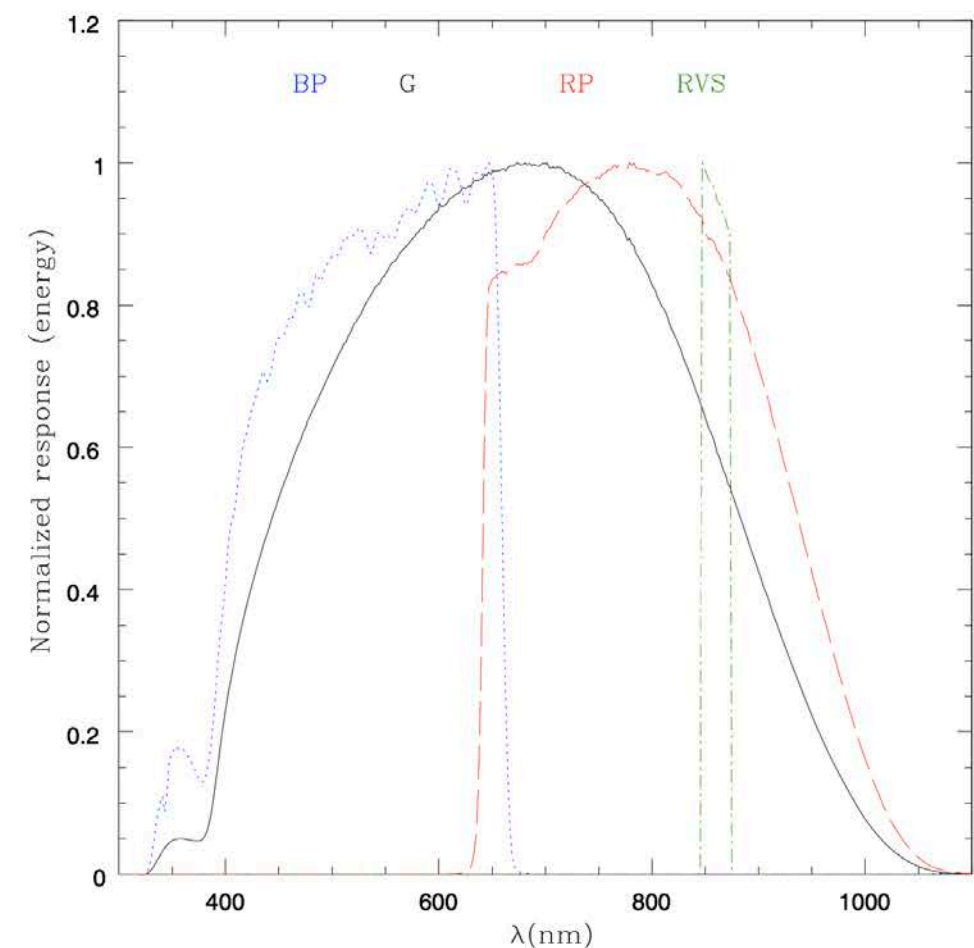


Fig. 2. On their way to the BP/RP and RVS sections of the focal plane, light from the two *Gaia* telescopes is dispersed in wavelength. Picture courtesy of EADS-Astrium.

Fig. 3. *Gaia* G (solid line), G_{BP} (dotted line), G_{RP} (dashed line) and G_{RVS} (dot-dashed line) normalised passbands.

Physical stellar parameters

Addition: Broadband photometry with GAIA

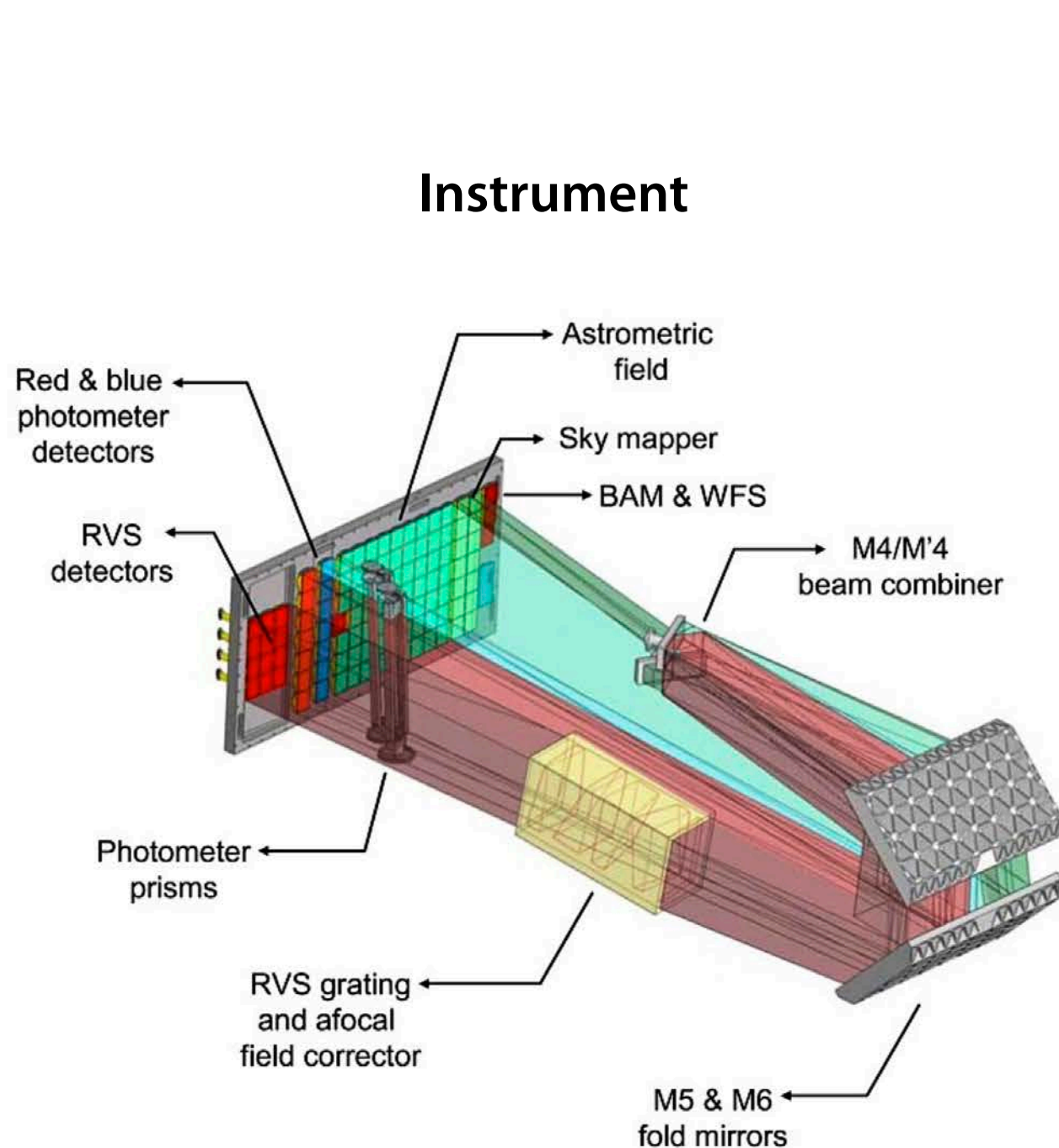


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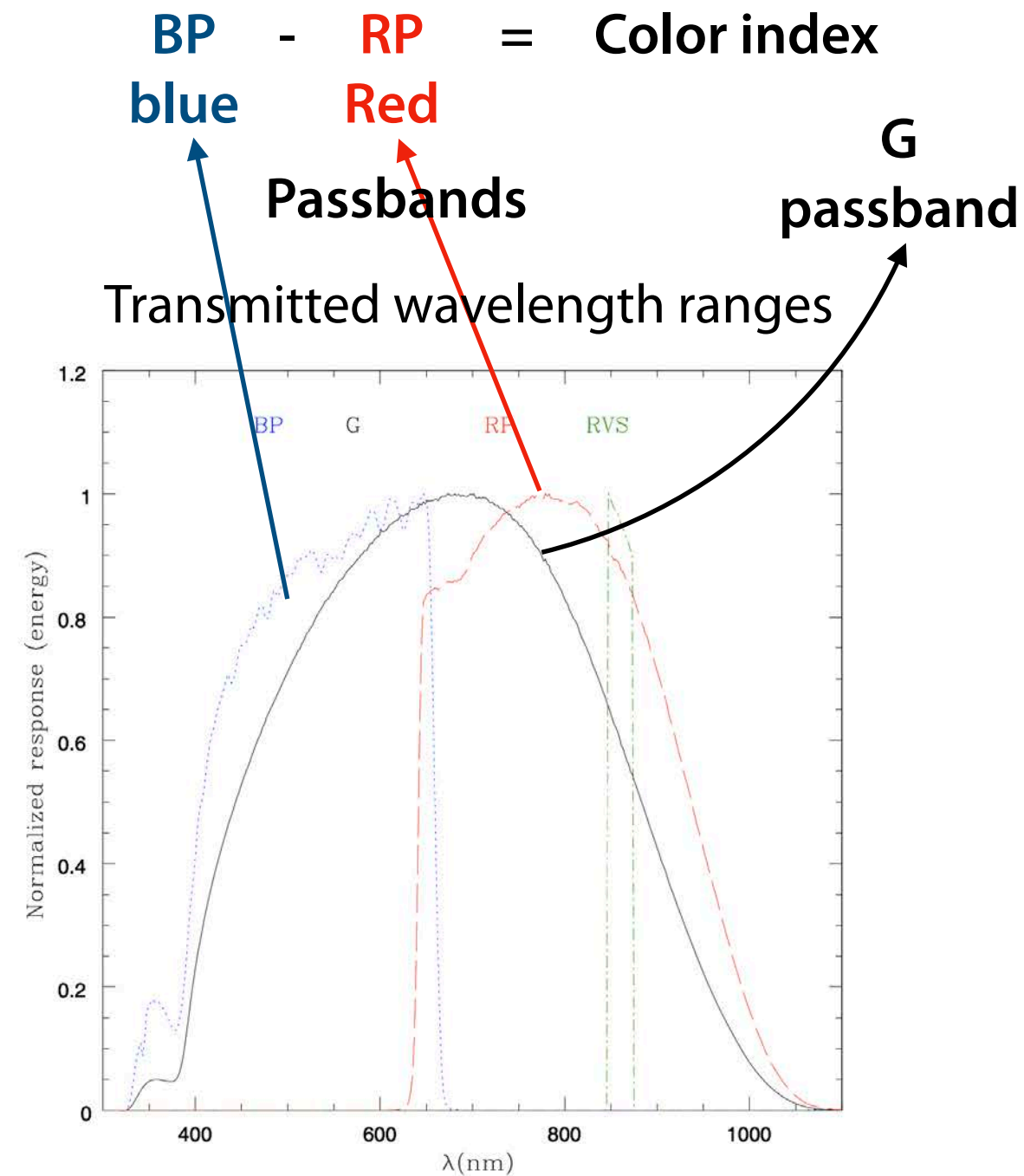
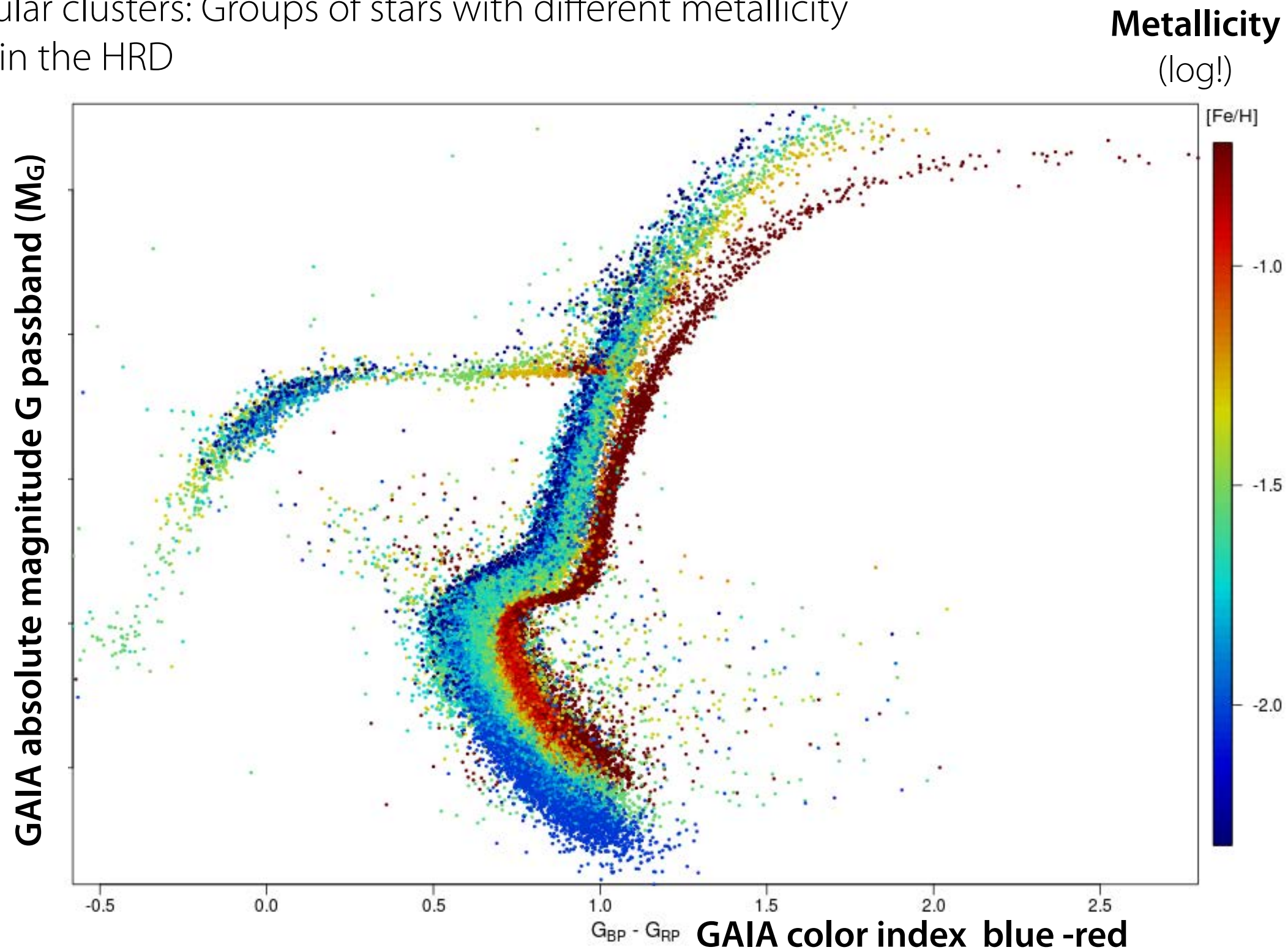


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Physical stellar parameters

Chemical composition

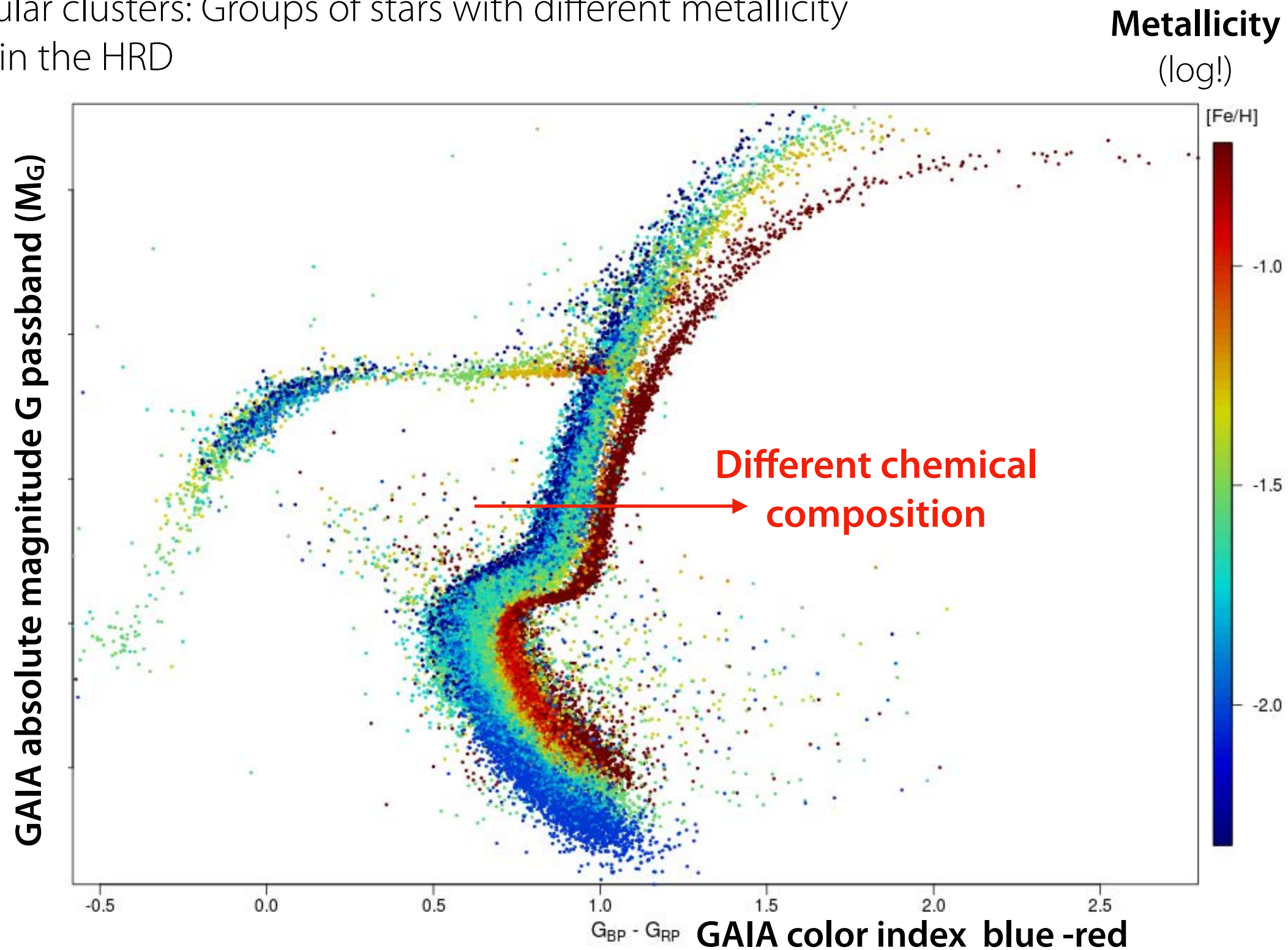
- HRD for 14 globular clusters: Groups of stars with different metallicity
- ➔ Distinct subsets in the HRD



Physical stellar parameters

Chemical composition

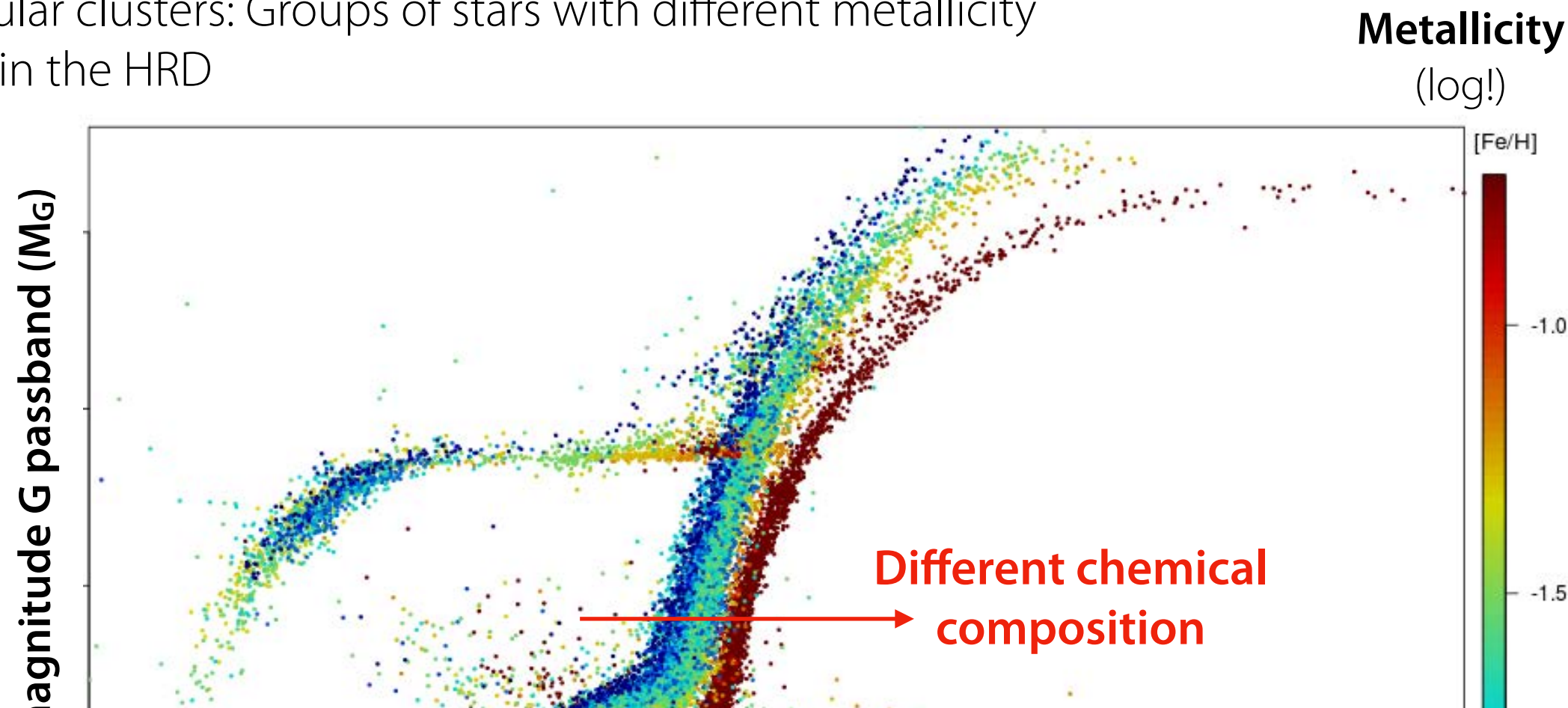
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Physical stellar parameters

Chemical composition

- HRD for 14 globular clusters: Groups of stars with different metallicity
- ➔ Distinct subsets in the HRD



- In general (all stars) range in metallicity: **$-4.5 < [Fe/H] < +1.0$**
- Note the logarithm
 - **$[Fe/H] = 0.0$: Solar metallicity**, relative abundance of metals (Fe) like in the Sun
 - $[Fe/H] = +1.0$: metals (Fe) 10 times more abundant in this star than in the Sun
 - $[Fe/H] = -2.0$: metals (Fe) 100 times less abundant in this star than in the Sun

Physical stellar parameters

Chemical composition

- Chemical composition of **stellar interior not directly observable**
- Specified only as mass fractions of hydrogen (X), helium (Y), and all heavier elements (Z):

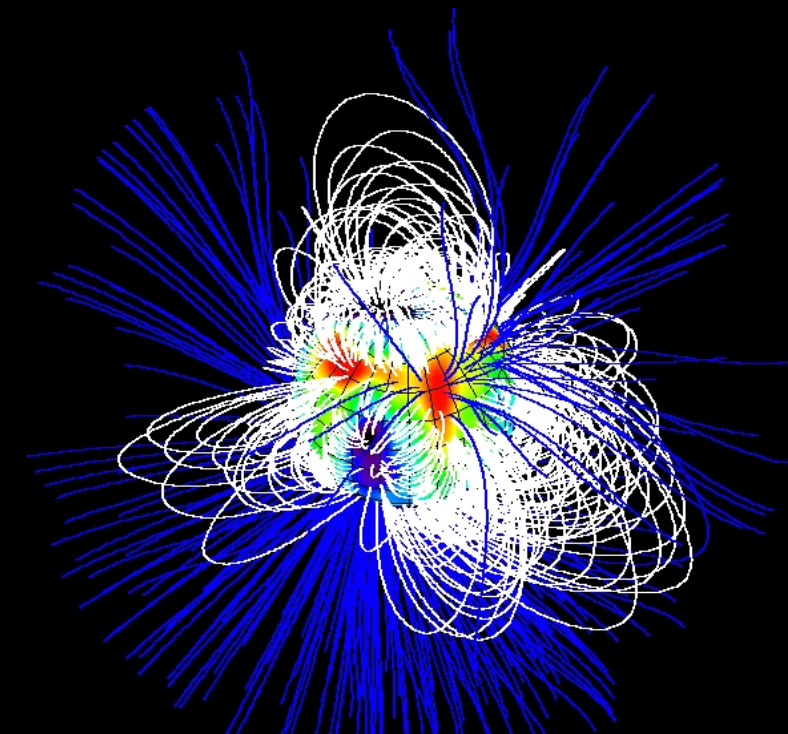
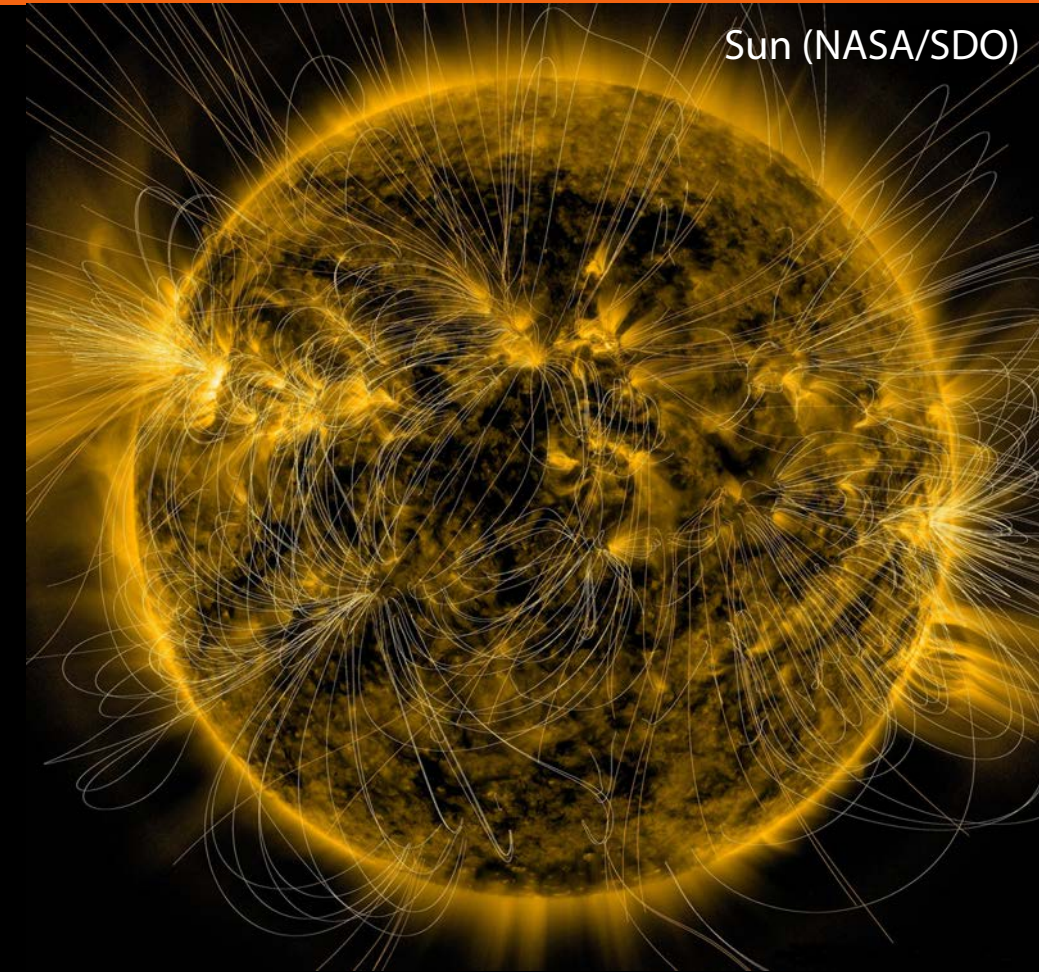
$$X+Y+Z=1$$

- Mass fractions vary with locations, in particular in radial direction from the core to the atmosphere (element segregation, fusion, etc.)
- Sun (based on models): $X = 0.73$, $Y = 0.25$, $Z = 0.02$.
- Numbers above refer to **number densities**, i.e. the number of particles per volume.
- Different atomic weight of elements/nuclei result in different values for the mass fraction!
- In terms of mass, the Sun consists of $\sim 90\%$ H, $\sim 10\%$ He, and only 0.1% for the remaining elements.
- Relative content (i.e. the **abundance**) of heavier elements in the Sun is roughly the same as for Earth (formed from the same material in the protostellar cloud)

Physical stellar parameters

Magnetic field (B)

- Measurement via Zeeman effect in spectral lines
- **Sun**
 - Magnetic field very **inhomogeneous**/structured
 - In atmosphere, strongest: **Sunspots** $B = 2000\text{--}3000\text{ G}$
 - Photosphere on average $B \approx 100\text{--}300\text{ G}$
 - Min. in Quiet Sun and *coronal holes*: $B < 1\text{ G}$
 - 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: $10^4\text{--}10^9\text{ G}$)
- **Solar/stellar cycles:** Magnetic field changes



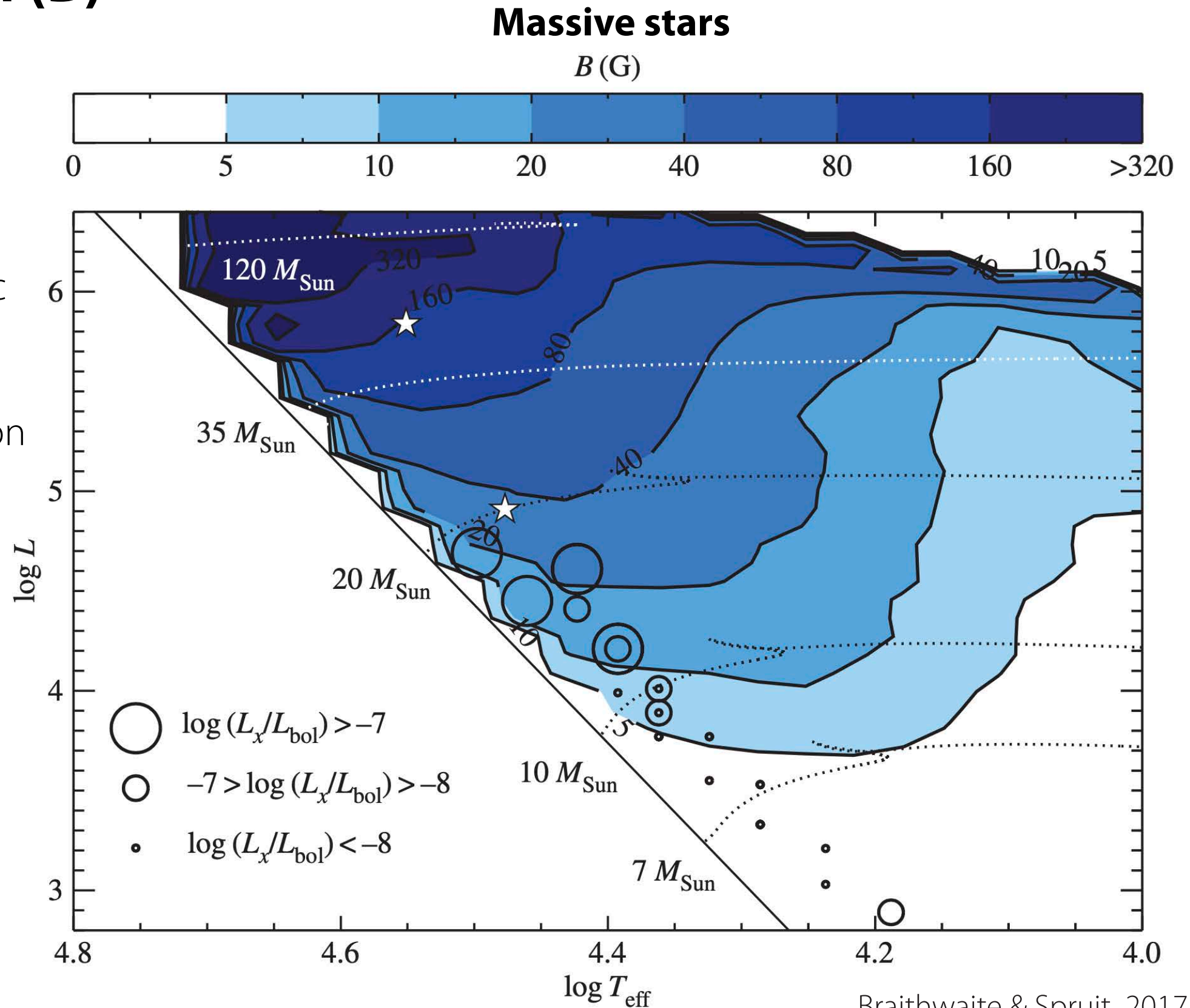
Zeeman Doppler imaging of SU Aur (P. Petit)

Physical stellar parameters

Magnetic field (B)

- Magnetic field generation via dynamo

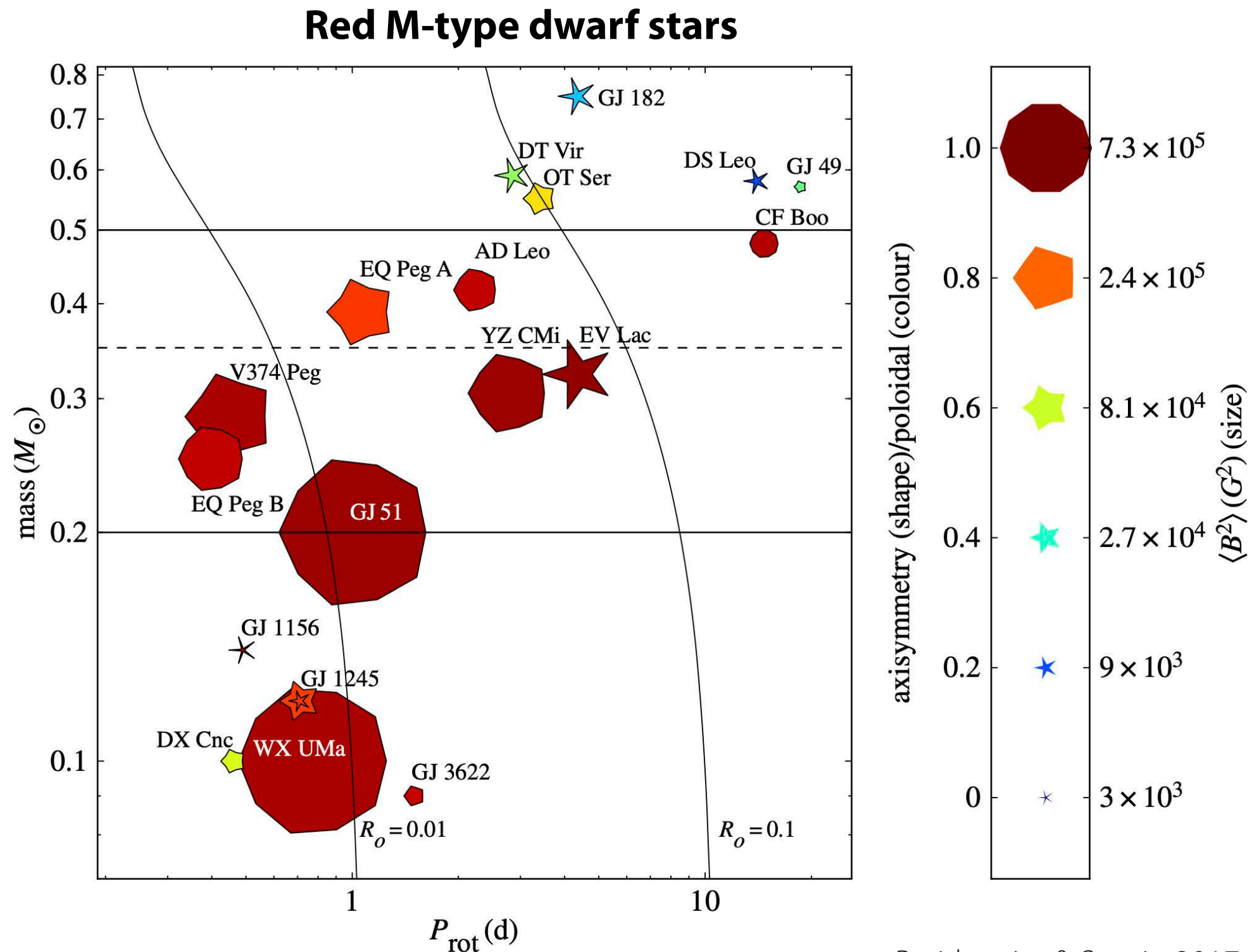
➔ We expect magnetic field strengths to depend on stellar structure and rotation



Physical stellar parameters

Magnetic field (B)

- Rotation rate of a star important for magnetic field generation via dynamo



Relations between fundamental parameters

Mass-luminosity relation

- Observations of main-sequence stars imply a relation of L and mass M of a star is related as n

$$L / L_{\odot} = a (M / M_{\odot})^n$$

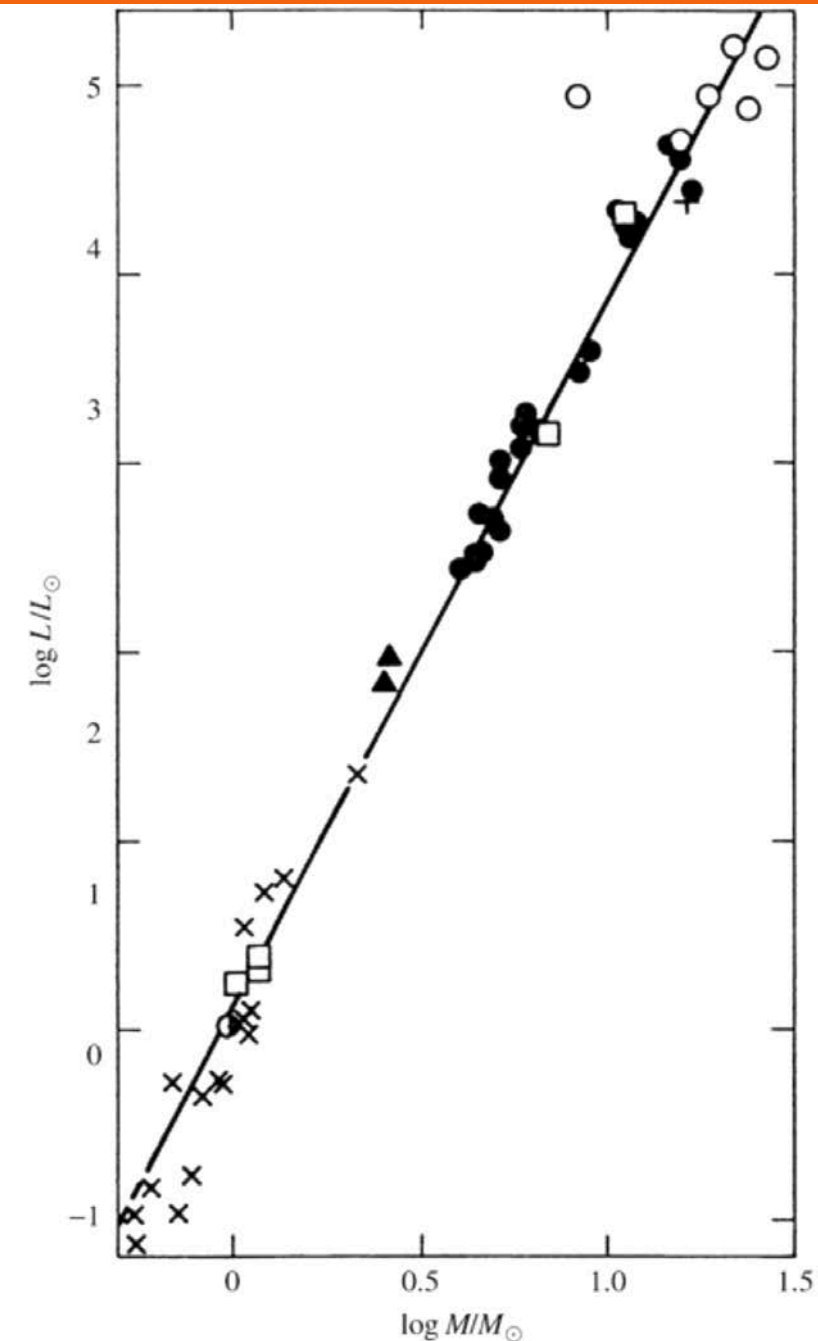
- Exponent n (and factor a)
 - same for subsets of stars with similar internal structure / nuclear power source; varies for different stellar types accordingly.

$M/M_{\odot}$	< 0.43	$0.43 - 2$	$2 - 55$	> 55
a	0,23	1	1,4	$3.2 \cdot 10^4$
n	2,3	4	3.5	1

- The mass-luminosity relation can be derived by using aforementioned equations for g and L :

$$g = \frac{GM}{R^2} \Rightarrow M = \frac{gR^2}{G} \quad \text{and} \quad L = 4\pi R^2 \sigma T_{\text{eff}}^4 \Rightarrow \frac{M}{L} = \frac{1}{4\pi G \sigma} \frac{g}{T_{\text{eff}}^4}$$

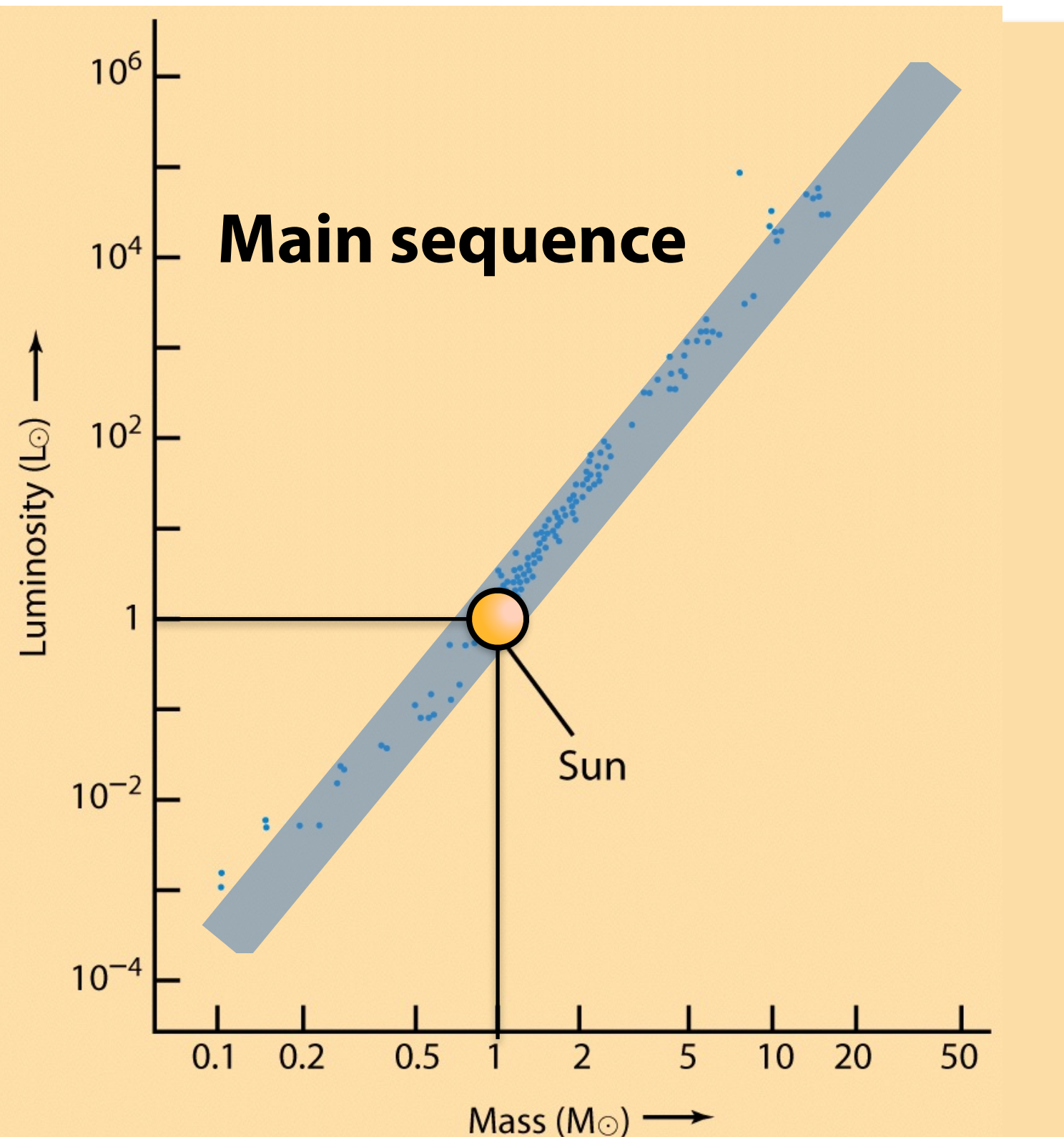
- ➔ The ratio M/L can thus be derived from the parameters T_{eff} and g , which can be determined from stellar spectra.



Relations between fundamental parameters

Mass-luminosity relation

$$\frac{L}{L_{\odot}} = \left(\frac{M}{M_{\odot}} \right)^n$$



Spectral class O6

$$R = 18 R_{\odot}$$

$$T_{\text{eff}} = 38\,000 \text{ K}$$

$$= 6.3 T_{\text{eff},\odot}$$

$$\Rightarrow L = 520\,000 L_{\odot}$$

Red dwarf star

$$R = 0.1 R_{\odot}$$

$$T_{\text{eff}} = 0.5 T_{\text{eff},\odot} = 2885 \text{ K}$$

$$\Rightarrow L = 6 \cdot 10^{-4} L_{\odot}$$

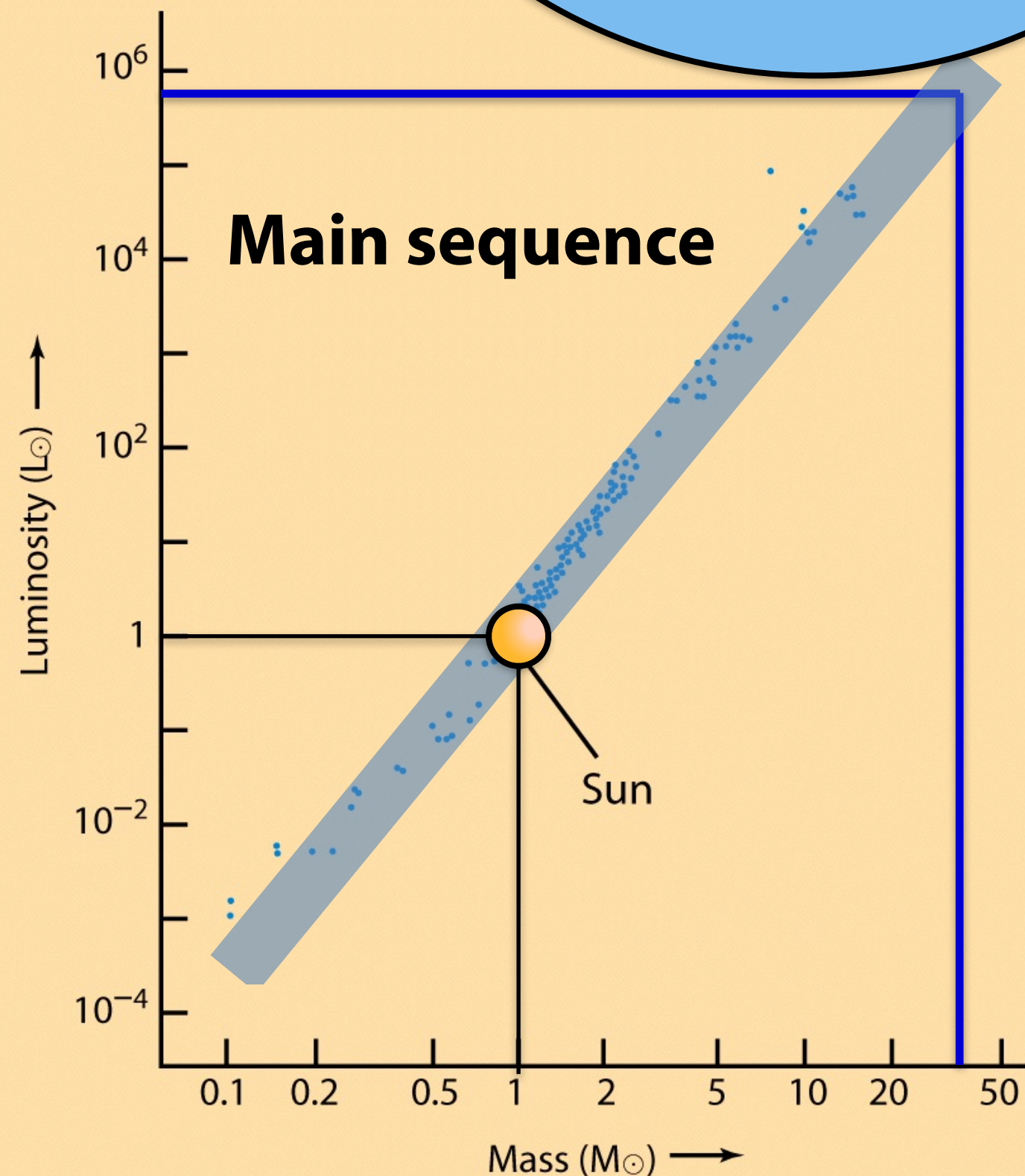
$$\Rightarrow L = 0.06 \% L_{\odot}$$

Relative

Mass-luminosity

ntal parameters

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Spectral class O6

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$$\Rightarrow M = 40 M_{\odot}$$

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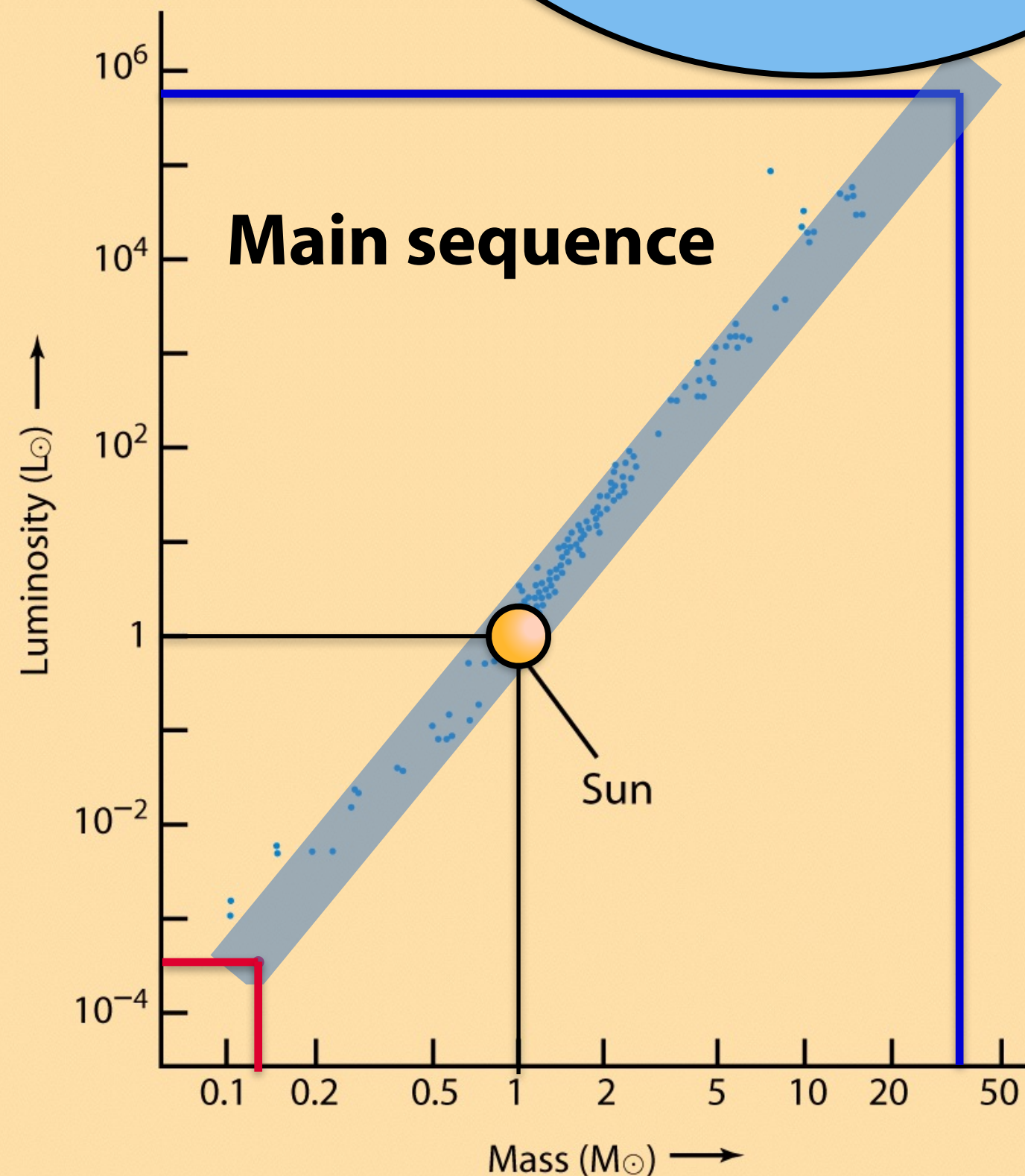
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$$\Rightarrow L = 0.06 \% L_{\odot}$$

$$\Rightarrow M = 0.12 M_{\odot}$$

Relations between fundamental parameters

Mass-radius relation

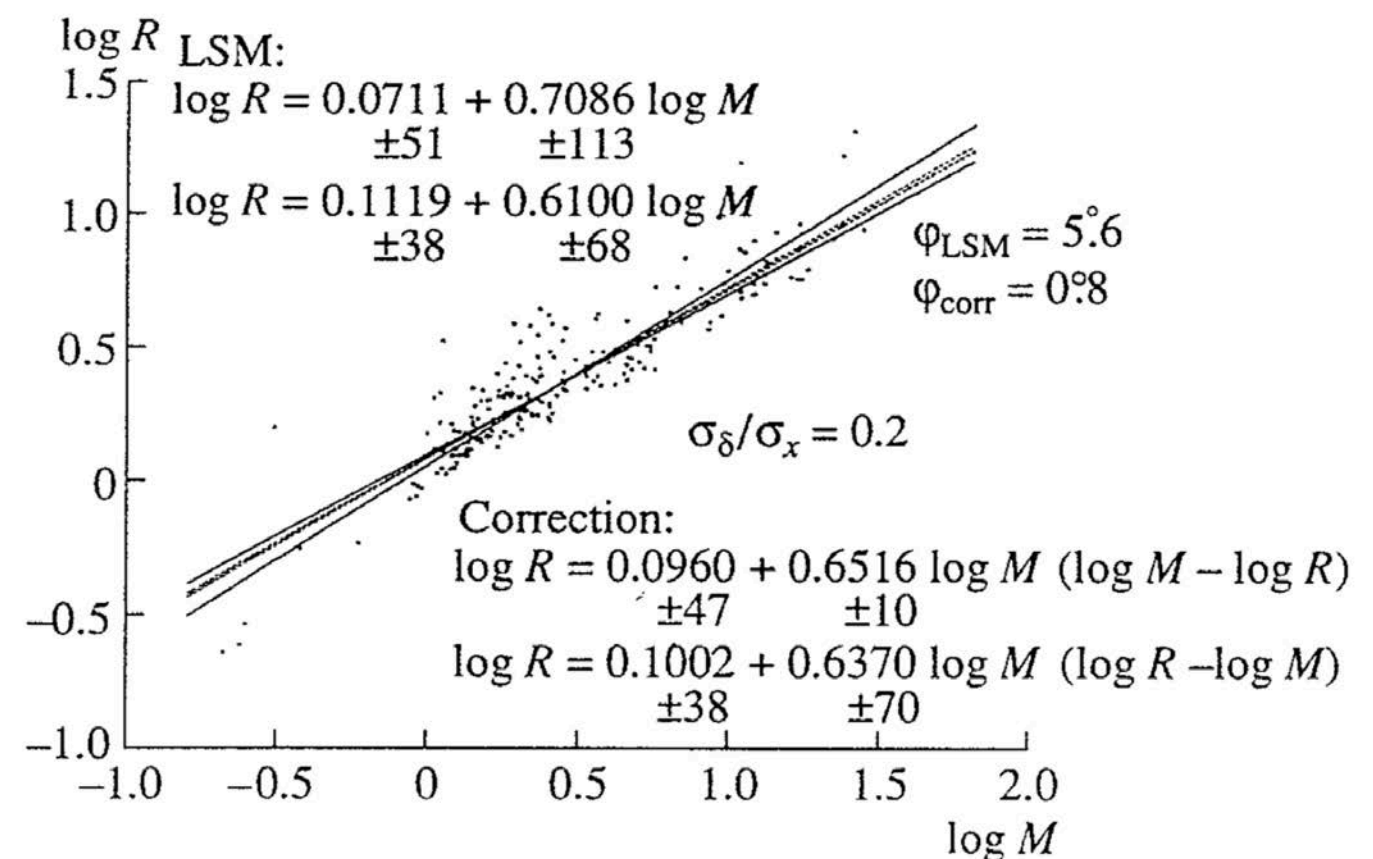
- Mass and radius related via the gravitational acceleration at the surface (which can be estimated from spectral lines)

$$g = \frac{GM}{R^2}$$

- Empirically for main sequence stars with $M \geq M_{\odot}$

$$R/R_{\odot} = (M/M_{\odot})^{0.6}$$

- More precise relations can be found when considering internal structure of stars in detail



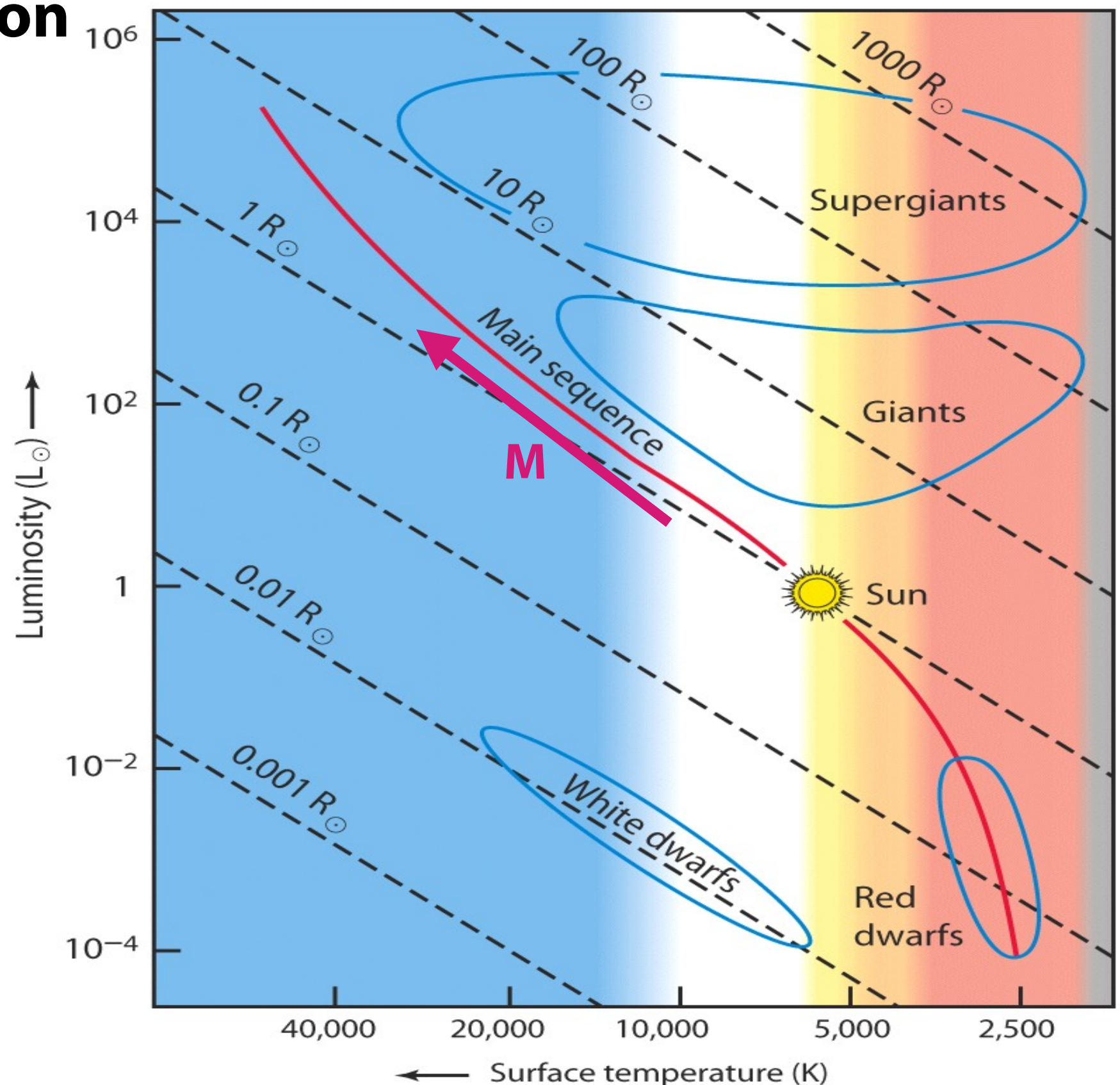
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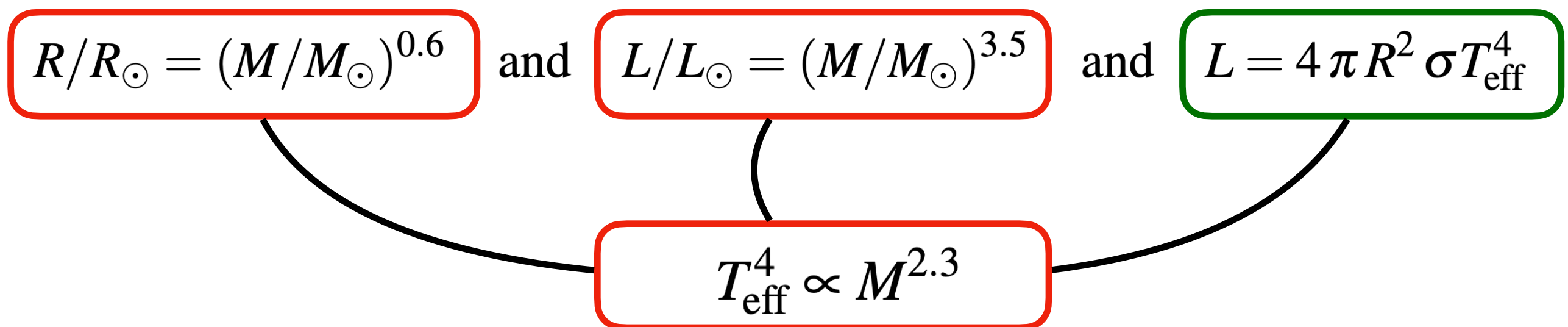
$$M \geq M_{\odot}$$

- Careful: Masses are not typically given in HRD as relations dependent on stellar structure in more complicated way than for main sequences



Relations between fundamental parameters

Mass-temperature relation

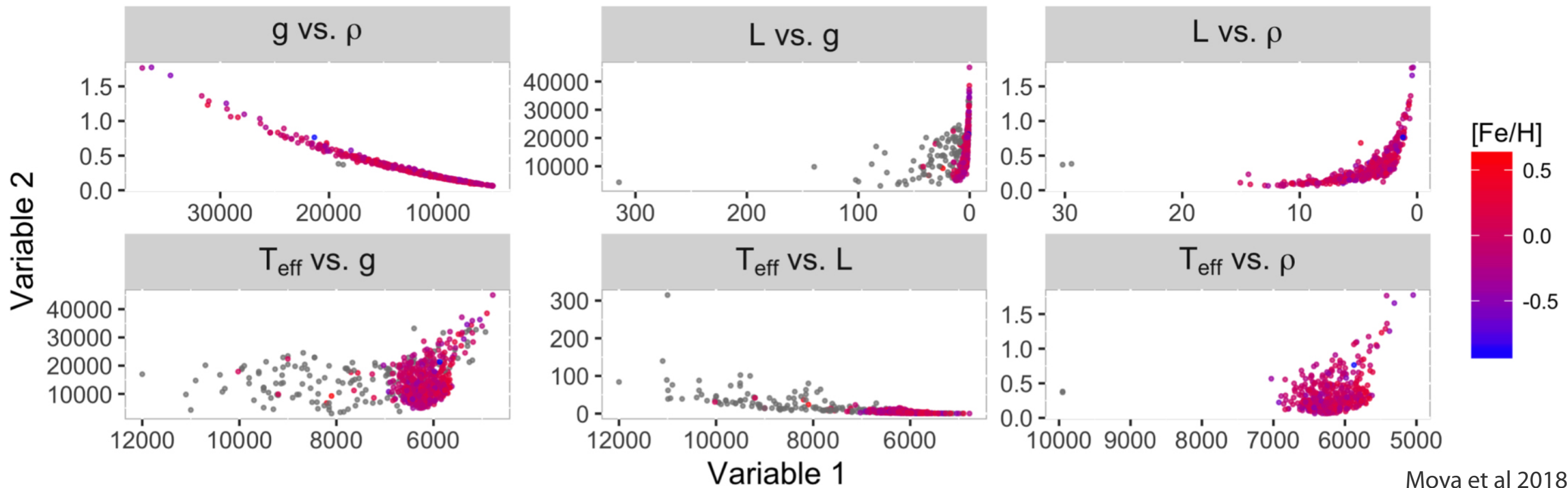


- ➡ Along main sequence: **Effective temperature(roughly) proportional to the stellar mass**
- Please note: Empirical relations based on subgroups of stars
 - ➡ To be applied and interpreted within limits
 - ➡ Detailed physical consideration of stellar structure superior.

Relations between fundamental parameters

Empirical relations

Correlations between independent variables



- Please note: Empirical relations based on subgroups of stars
 - ➡ To be applied and interpreted within limits
 - ➡ Detailed physical consideration of stellar structure superior.
 - ➡ Often it is more than just two parameters that are related!

Physical stellar parameters

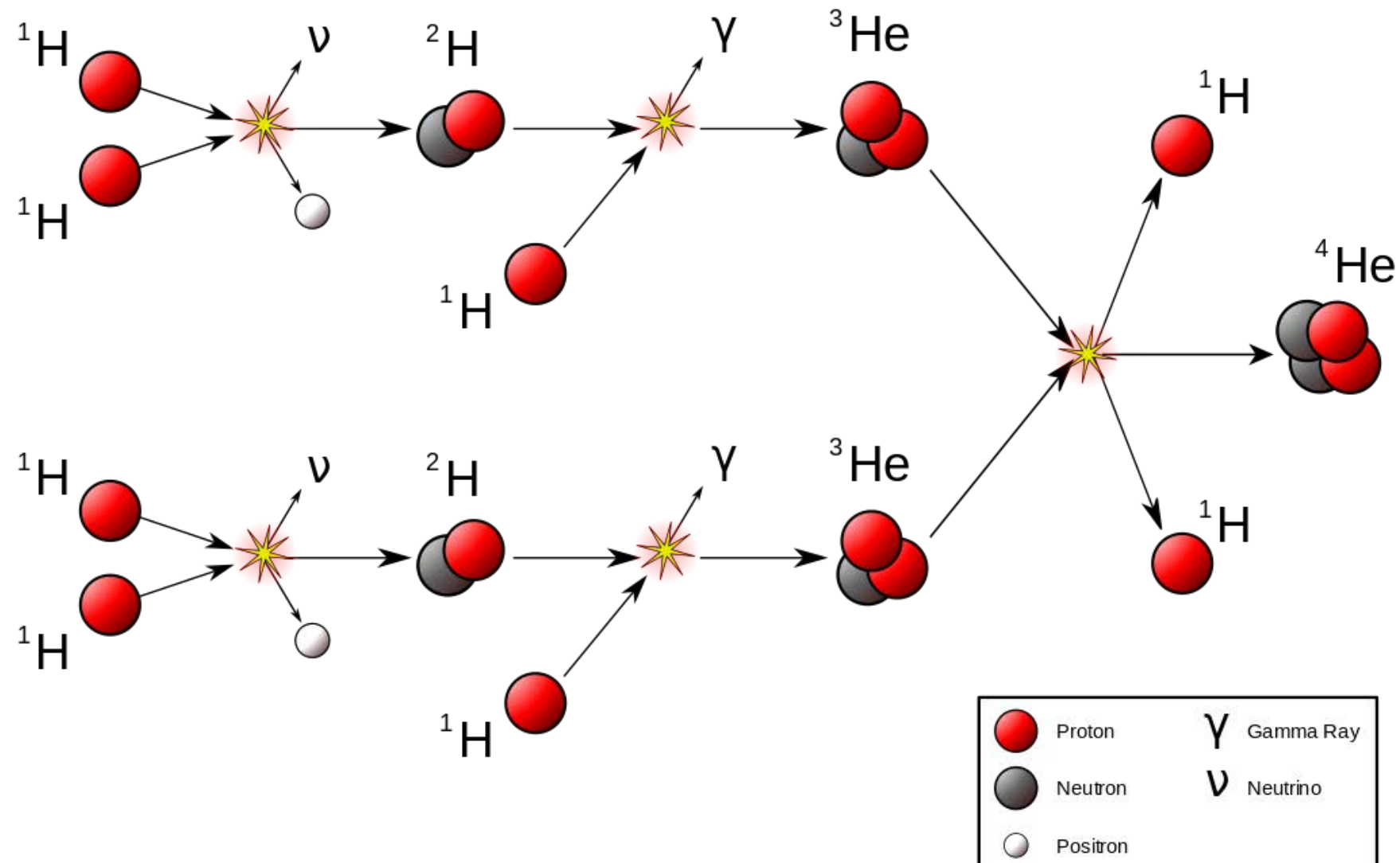
Lifetime of the Sun on the main sequence

- In solar interior: Thermonuclear fusion (here pp chain)
- 4 hydrogen nuclei (protons) $\rightarrow$ 1 helium nucleus (alpha 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:**

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



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But we know: **Sun's lifetime ~ 10¹⁰ yr!**

- ➡ Corresponds to 10% of solar mass.
- ➡ Explanation: H-He fusion only in solar core (and also not constant rate)
- ➡ More detailed evolution models needed.