



AST5770

Solar and stellar physics

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Recap

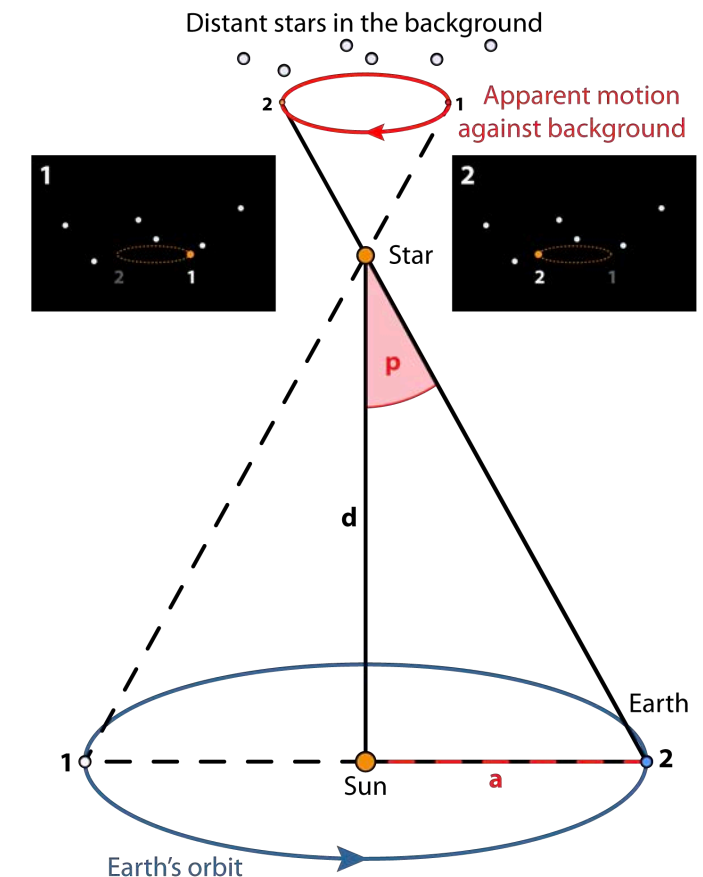
- **What is a star: gas + self-gravity + luminous + nuclear fusion**

- **Distances to the stars**

- Sun at 8 light-min = 1 AU $\approx 150 \times 10^6$ km
- Nearest star (after the Sun) at 4.3 ly

- **Measuring distances via parallactic angles (parallax)**

- Apparent motion of a star against (far away) background as seen over a year (Earth's orbit!)
- Distance d [pc] = $1/p$ ["] (p: parallax)
- Definition of parsec: 1 pc = 206265 AU = 3.26 ly
- Gaia mission mapped billions of stars in the Milky Way



- **Apparent size in the sky**

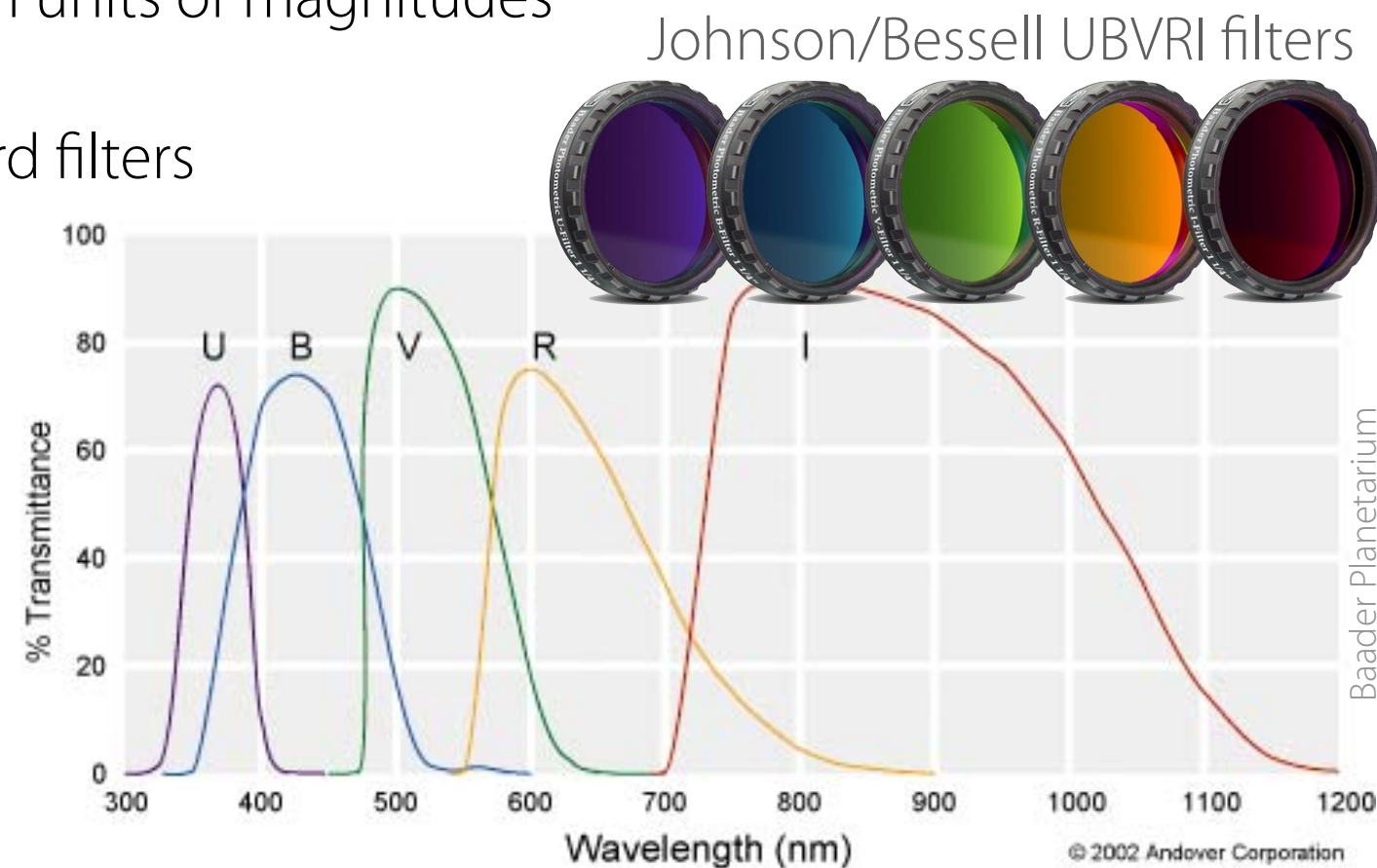
- Sun $\sim 1/2$ degree
- Interferometric imaging begins to slightly resolved huge nearby stars
- Most source remain point sources for now



Betelgeuse ~ 50 milliarcsec

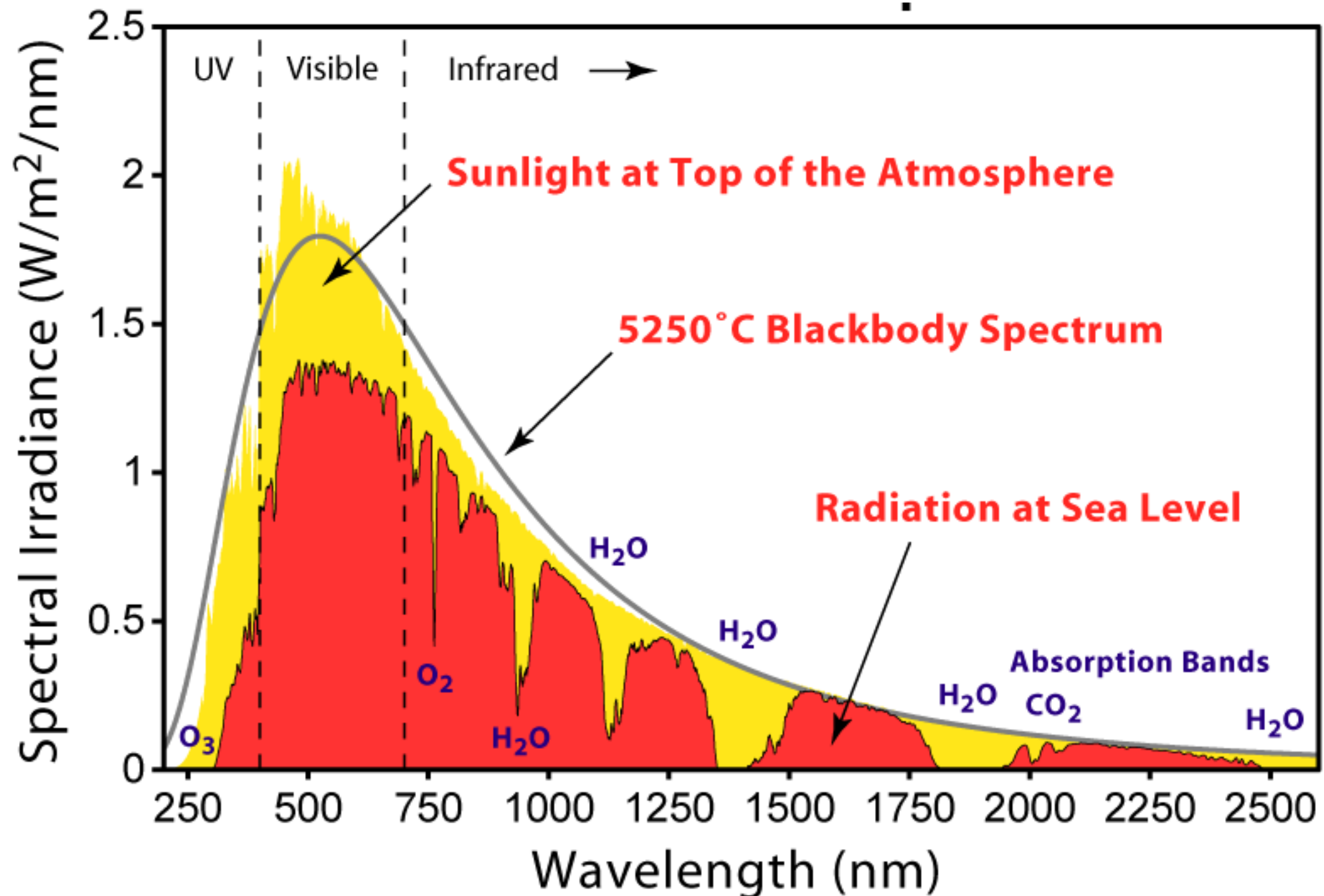
Recap

- **Radiative flux F** (*energy radiated per time unit through an area*)
- **Radiative flux density F_λ , F_ν** : F per wavelength or frequency unit
- **Bolometric = over all wavelengths**
- **Brightness** (related to the flux)
 - **Apparent brightness m** - as in the sky
 - **Absolute brightness M** - as if at a distance of 10 pc
 - Both measured on a logarithmic scale in units of magnitudes
- **Colour:** Brightness measured with standard filters
 - Brightness measured in a selected filter marked with corresponding index or as capital letter, e.g. $m_V = V$
- **Colour index:** difference of brightness measured in different bands, e.g. $m_B - m_V = B - V$



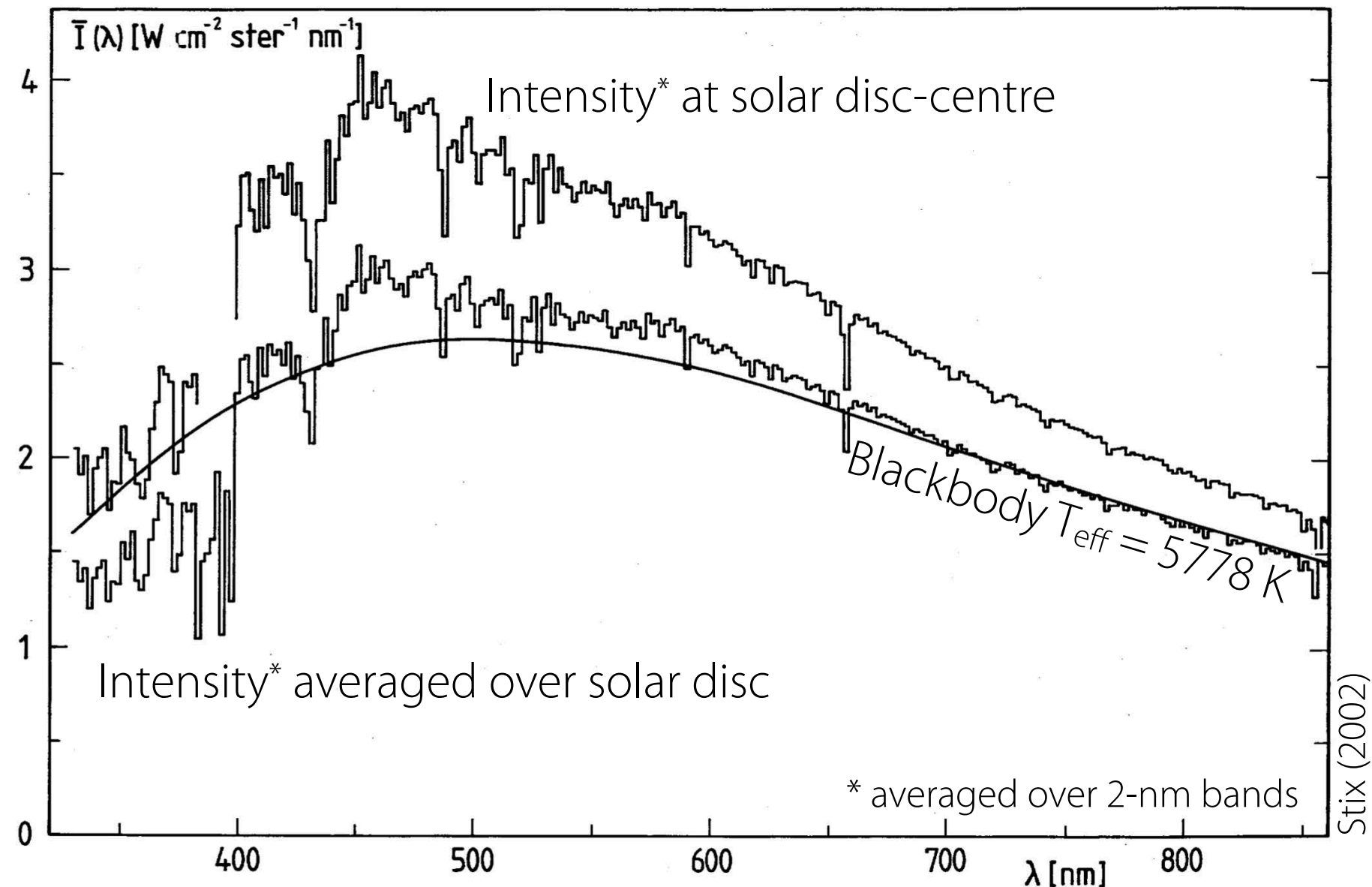
Observational stellar parameters

Solar spectrum



Observational stellar parameters

Solar spectrum



- Measured Sun's intensity as function of wavelength
- The black body spectrum for an effective temperature of $T_{\text{eff}} = 5778 \text{ K}$
- Data from Neckel and Labs (1984) - Also provided for your project assignment.

Observational stellar parameters

Stefan-Boltzmann law

- Radiation flux density (spectrum) resembles a **blackbody** spectrum, which is given by the Planck function $B_\nu(T)$.
- $B_\nu(T)$: spectral density of electromagnetic radiation emitted by a blackbody in thermal equilibrium at a given temperature T .

➡ The flux density F_ν of a blackbody:

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

➡ Bolometric flux by integration over all frequencies:

Stefan-Boltzmann law

$$F = \int_0^\infty F_\lambda d\lambda = \int_0^\infty F_\nu d\nu = \int_0^\infty \pi B_\nu(T) d\nu = \sigma T^4 \Rightarrow F = \sigma T_{\text{eff}}^4$$

- Stefan-Boltzmann constant:

$$\sigma = \frac{2\pi^5 k_B^4}{15h^3 c^2} = 5.67 \times 10^{-8} \text{W m}^{-2} \text{K}^{-4} = 5.67 \times 10^{-5} \text{erg s}^{-1} \text{cm}^{-2} \text{K}^{-4}$$

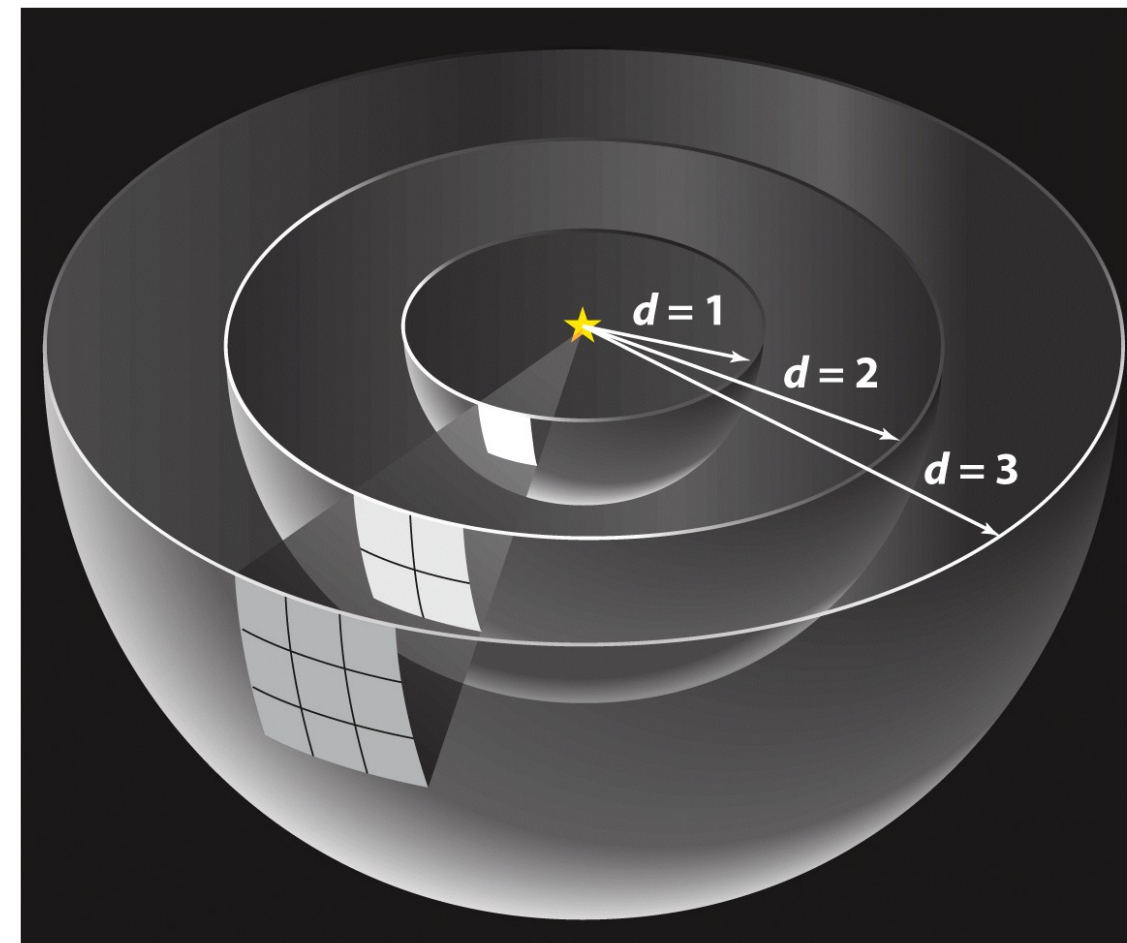
Observational stellar parameters

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}

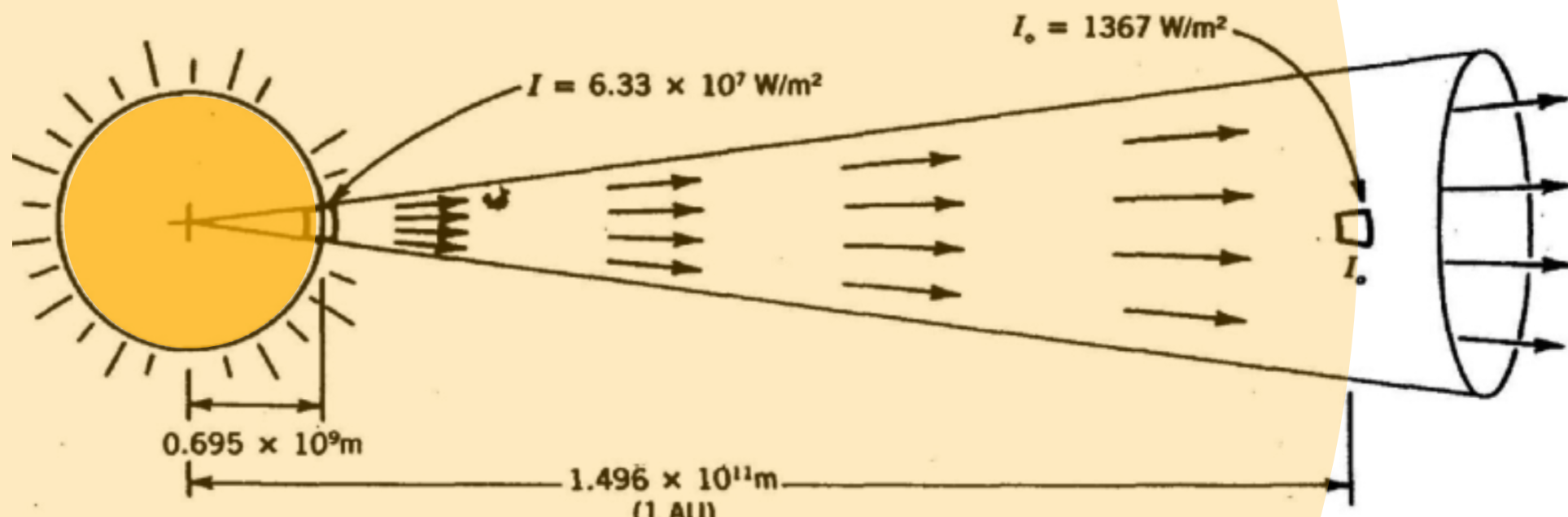
- Radiation emitted from the Sun's "surface" at radius $1 R_{\odot}$
- Diluted over a sphere with radius $d = 1 \text{ AU}$ with surface area $A = 4\pi d^2$



Observational stellar parameters

Stefan-Boltzmann law

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- Radiation emitted from the Sun's "surface" at radius $1 R_{\odot}$
- Diluted over a sphere with radius $d = 1 \text{ AU}$ with surface area $A = 4\pi d^2$
- Correction for "dilution" effect with the factor $d^2/R_{\odot}^2$ gives flux density at Sun's surface ($1 R_{\odot}$):
 $F_{\odot} = 6.3 \cdot 10^7 \text{ Wm}^{-2}$
- Stefan-Boltzmann law: $F_{\odot} = \sigma T_{\text{eff},\odot}^4 \rightarrow$ effective temperature of the Sun: **$T_{\text{eff},\odot} \approx 5770 \text{ K}$**



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

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

Stefan-Boltzmann law:

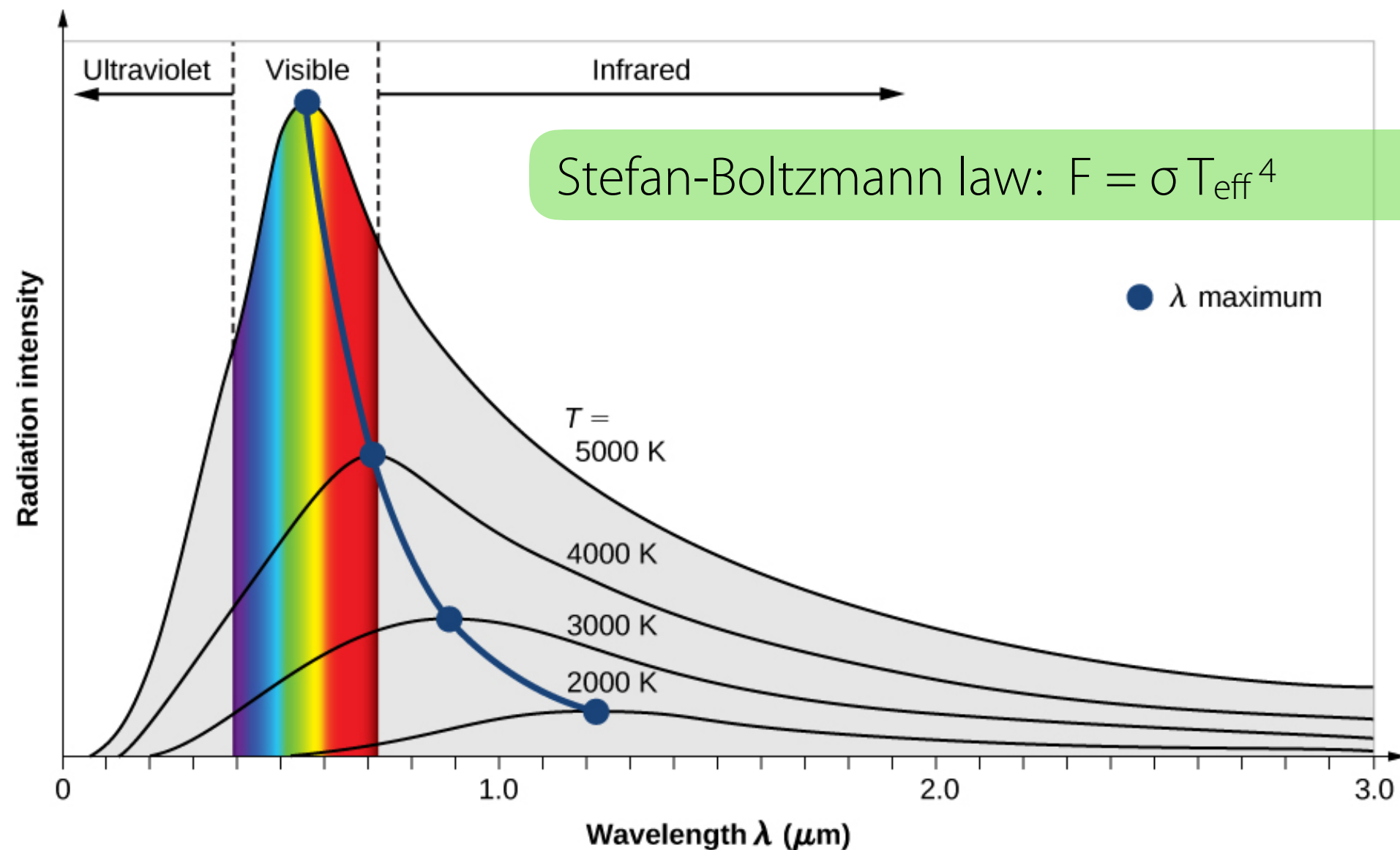
$$F = \sigma T_{\text{eff}}^4$$

- Units: W (SI) or erg s⁻¹ (cgs)
- Convenient to use the bolometric luminosity of the Sun as unit

$$L_{\odot} = 3.84 \times 10^{26} \text{ W.}$$

Stellar spectra

- **Blackbody spectra**
for different
temperatures



- Increasing T_{eff}
 - ➡ Bolometric flux F (integral under the curve) increases with T_{eff}^4
 - ➡ Wavelength of peak becomes shorter: Wien's displacement law

$$\lambda_{\text{max}} = \frac{b}{T}$$

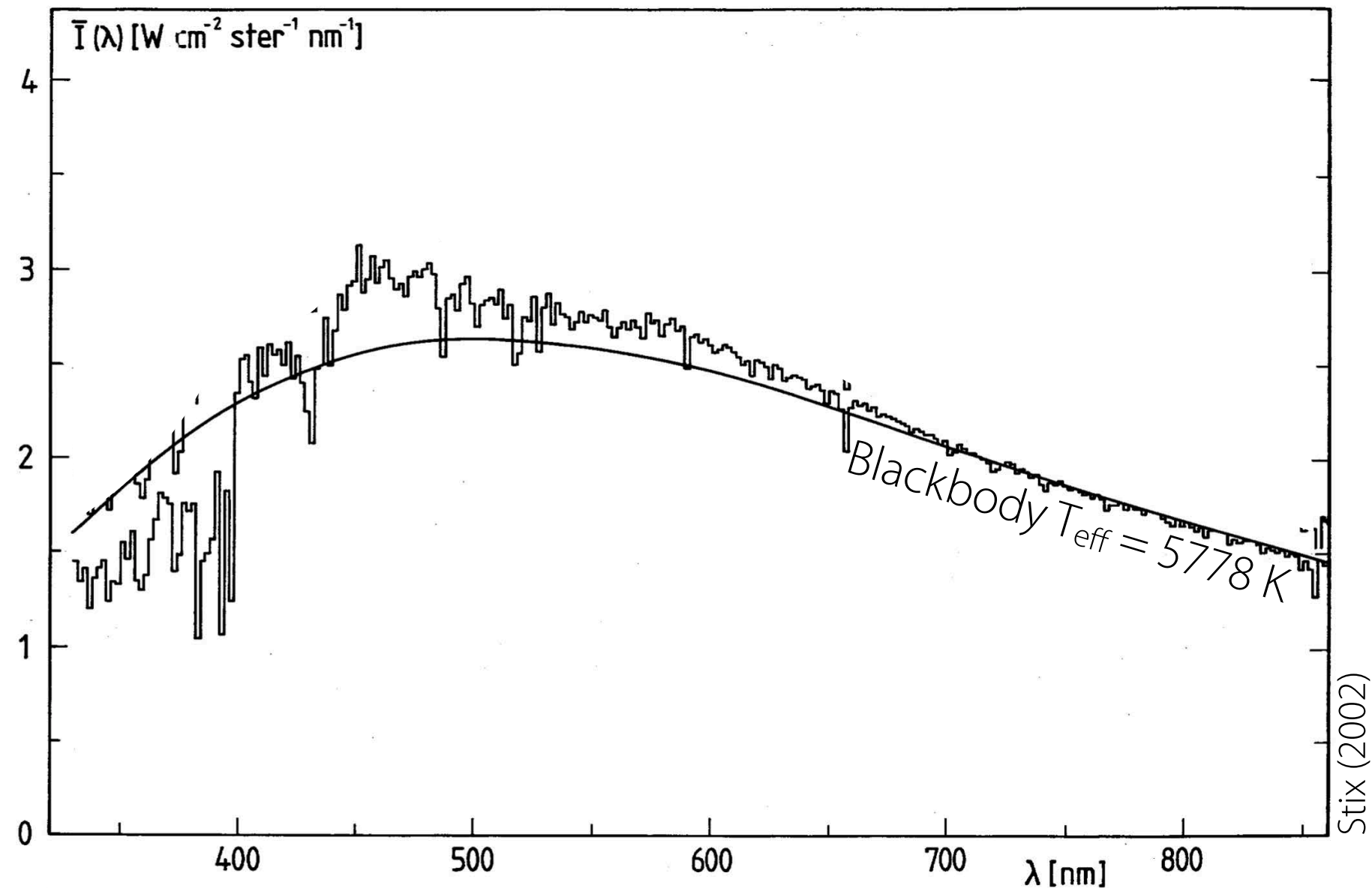
Wien's displacement constant

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

Interactive app:

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

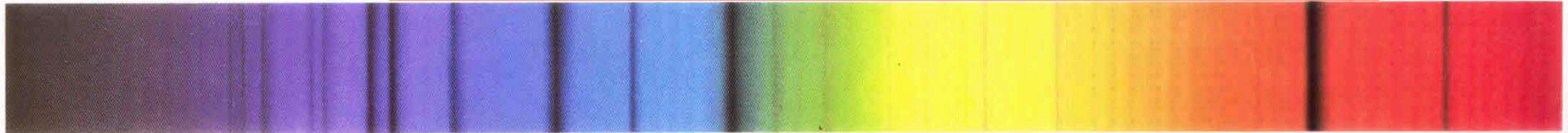
Stellar spectra



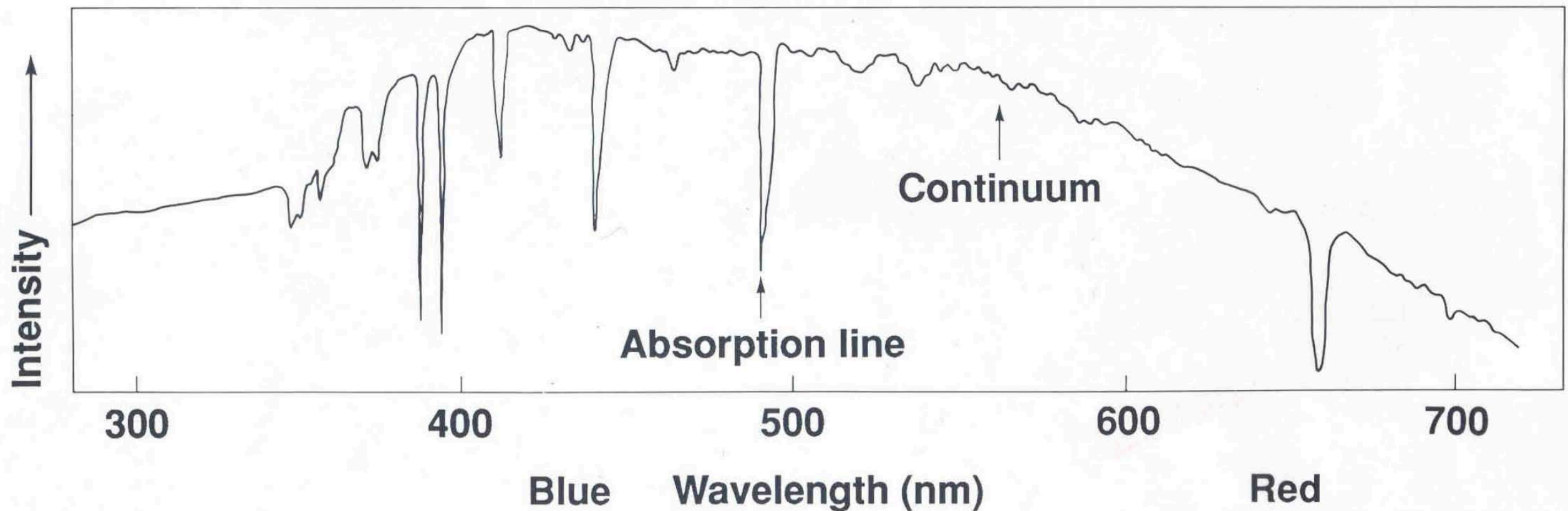
- A real stellar spectrum ...
 - ... is reasonably well described at longer wavelengths
 - ... **deviates** in particular at shorter wavelengths and/or in wavelength regions with many (absorption) lines!

Observational stellar parameters

$H\delta$ 410	$H\gamma$ 434	$H\beta$ 486	Balmer lines	$H\alpha$ 656
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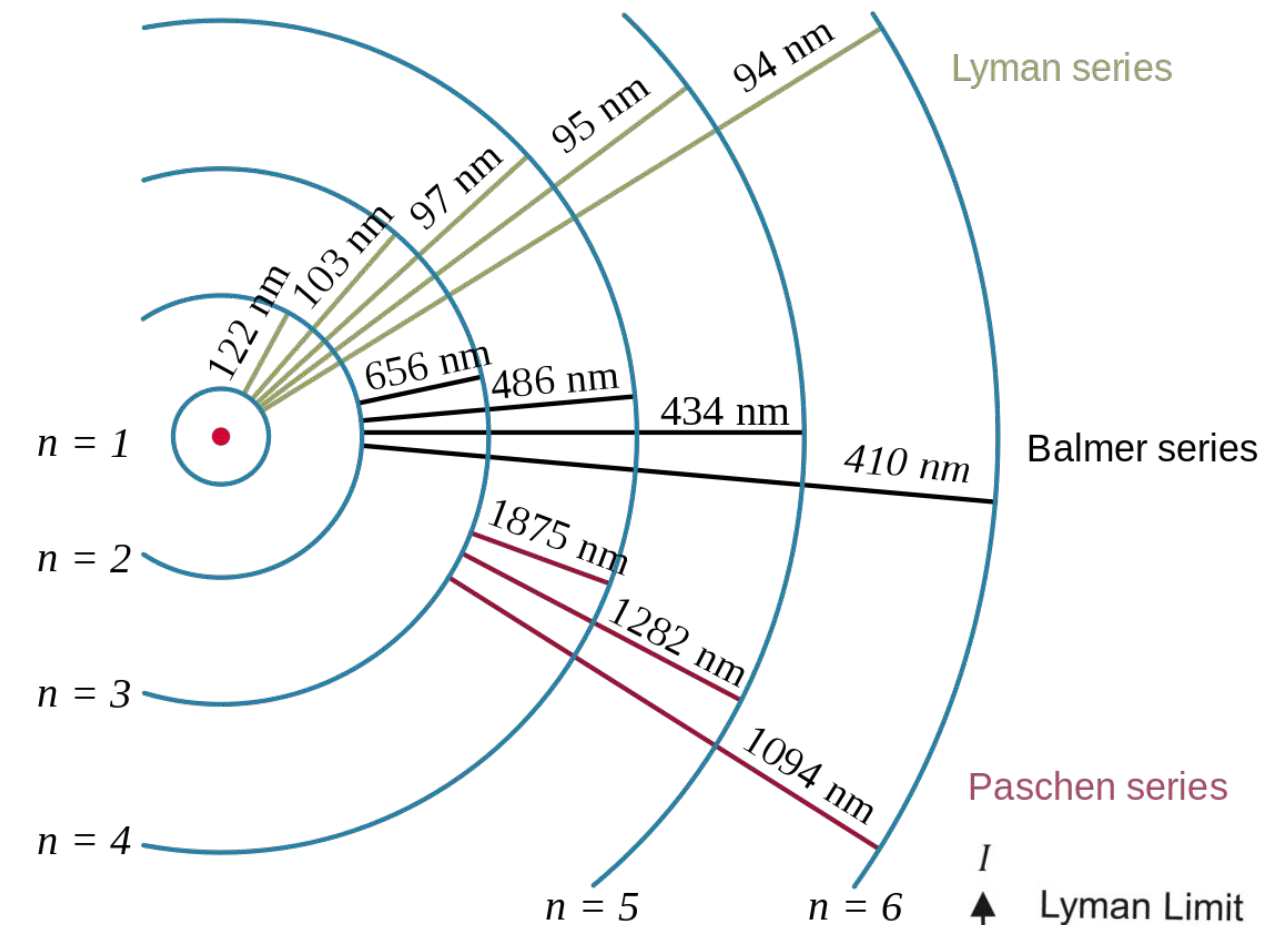


Ca II

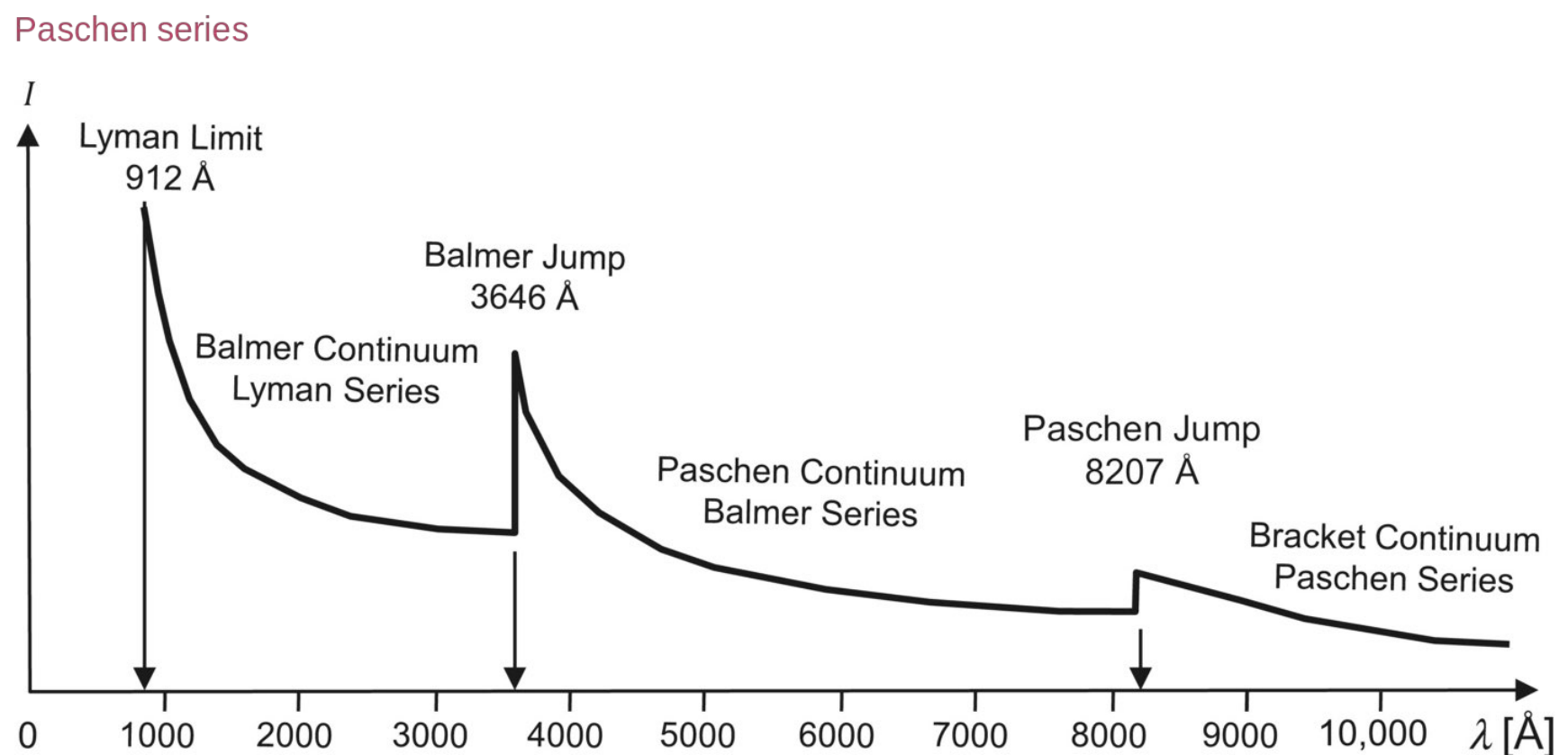


Stellar spectra

Hydrogen lines and continua



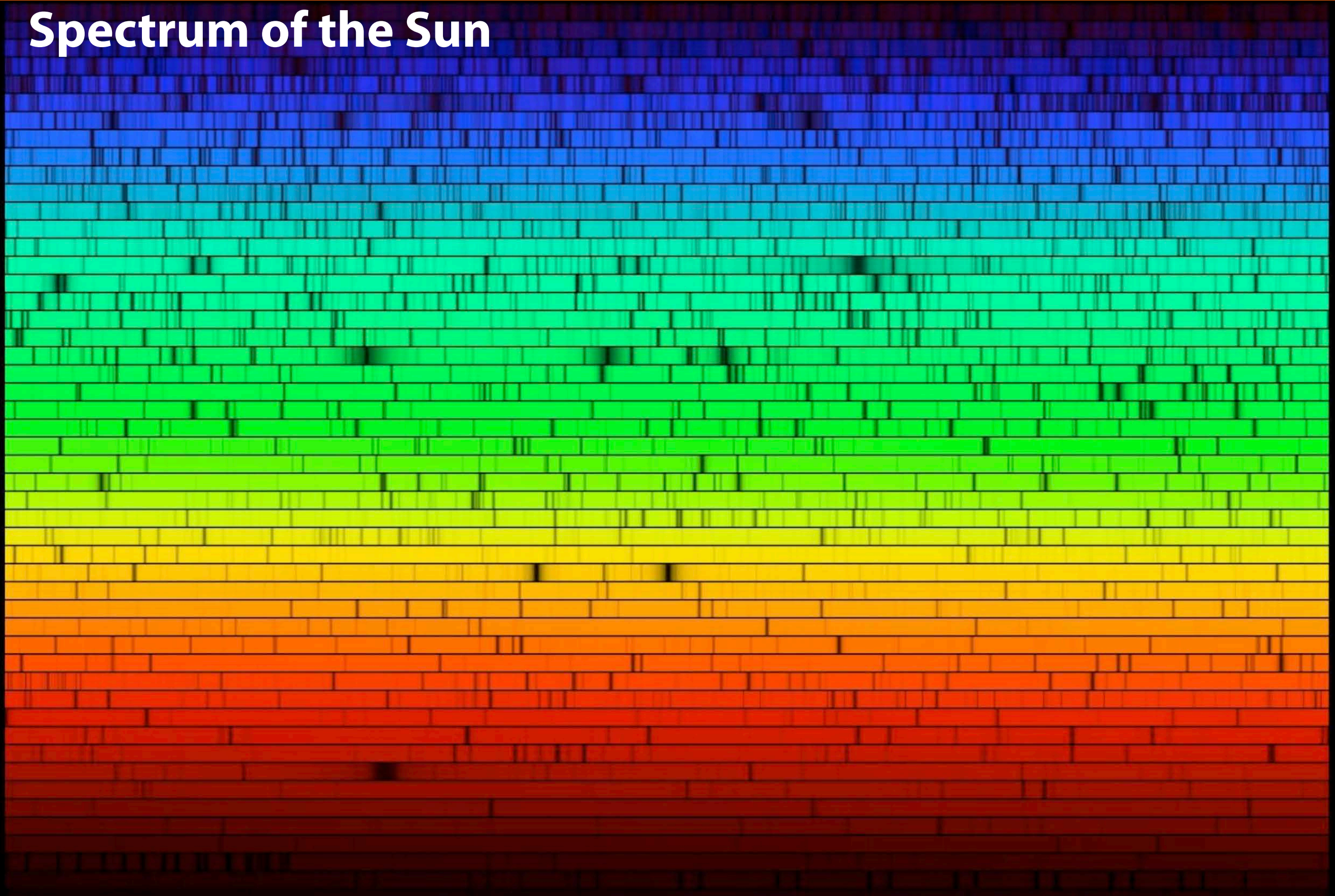
- Energy of photon $E = h \nu$
- Photon absorbed at matching energy differences in the atom
- Hydrogen energy levels: $E_n \propto n^{-2}$
- Rydberg formula $\lambda^{-1} \propto (n_1^{-2} - n_2^{-2})$



➡ Notable deviations from blackbody!

Stellar spectra

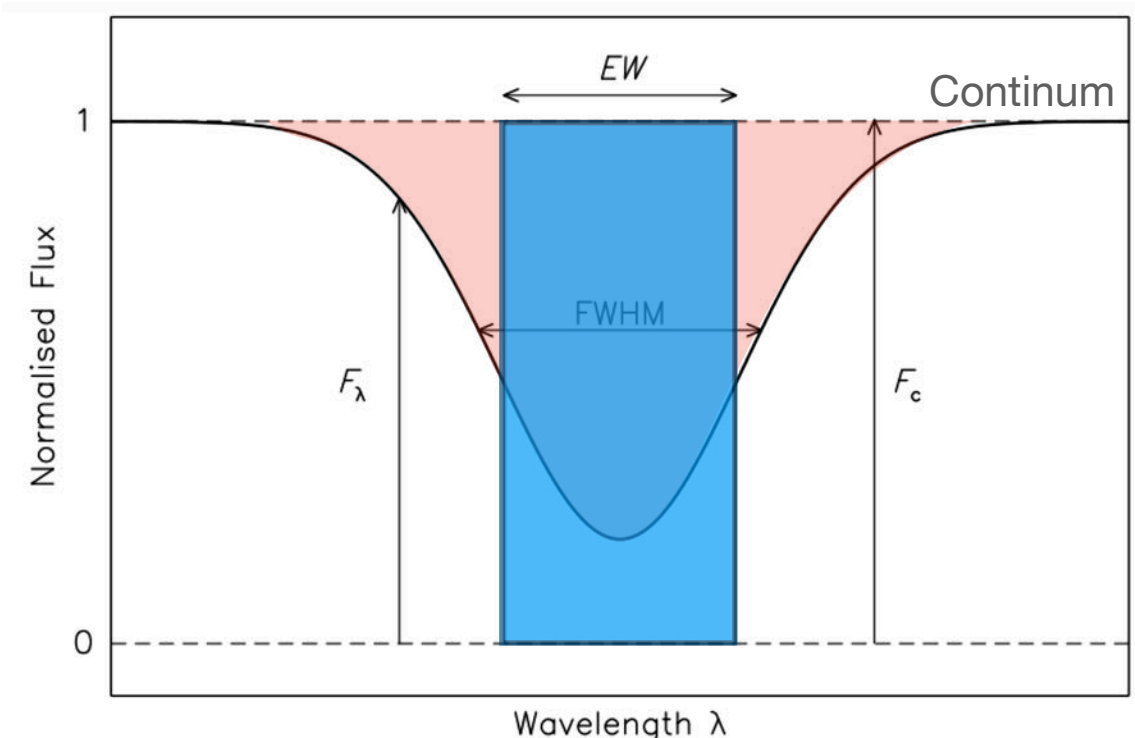
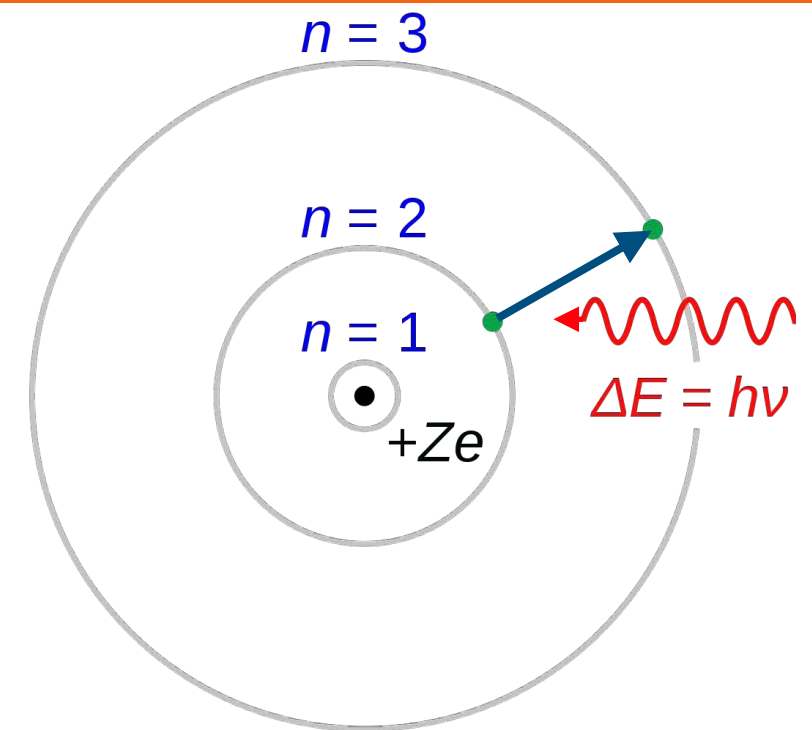
Spectrum of the Sun



Spectral classification

Line strength

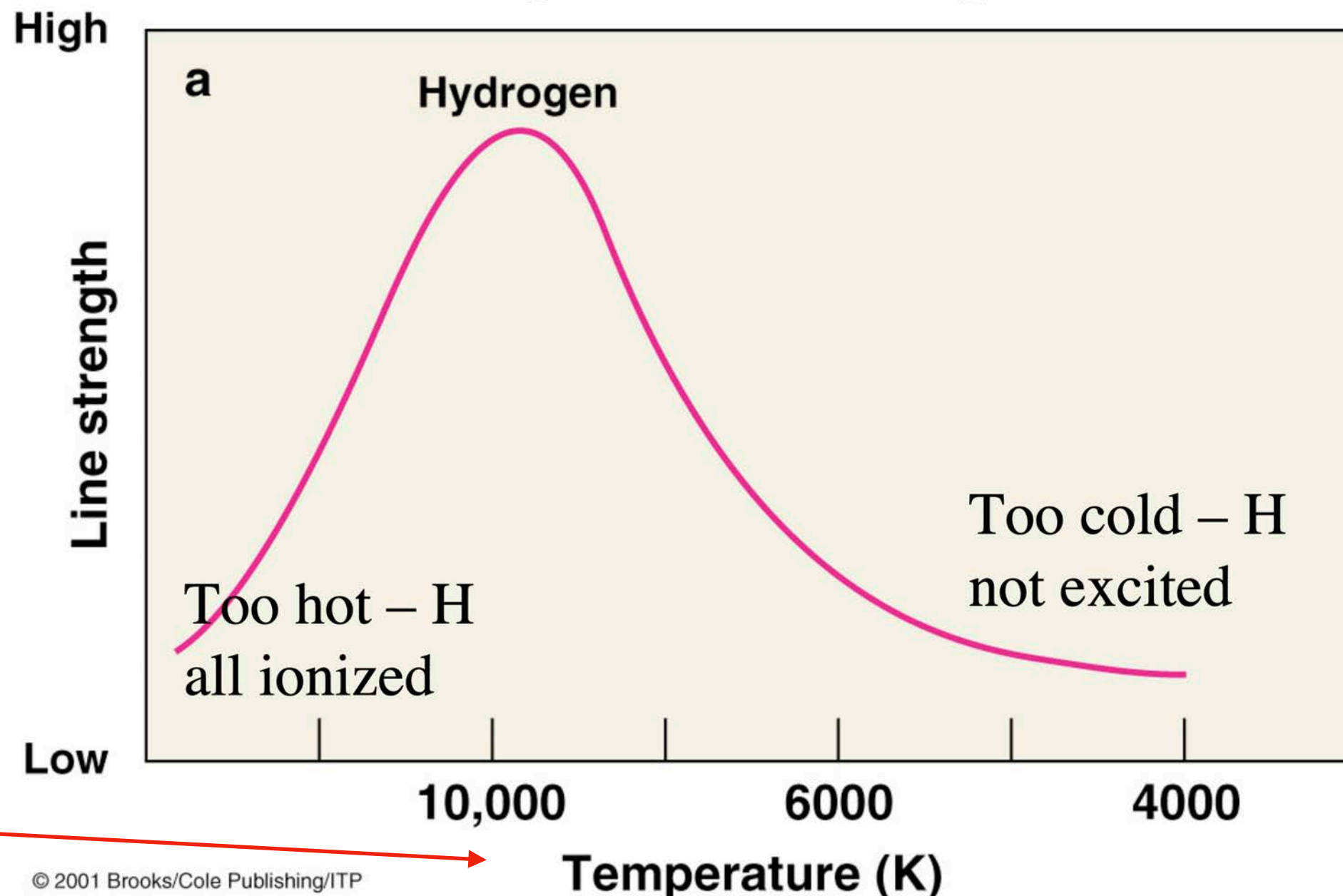
- **Strength of a spectral line** depends on the number of atoms/molecules with electrons in the starting orbit for the spectral line under consideration
- **Example: H- α** line at 656.3nm in absorption, $n=2 \rightarrow n=3$
 - ➡ H atoms needed that have electrons in level $n=2$,
 - ➡ Must already have absorbed a photon to raise $n=1 \rightarrow n=2$
 - ➡ Requires high enough temperature
- Level populations and thus strength of a spectral line depends thermodynamic properties of the gas (and chemical abundance)
- Line strength measured as **equivalent width**
 - Area between spectral line and continuum and reshape into rectangle that extends from 1 to 0
 - Width of covered area



Spectral classification

Line strength

- Strength of a spectral line depends on chemical abundance of the element and thermodynamic properties such as the gas **temperature**

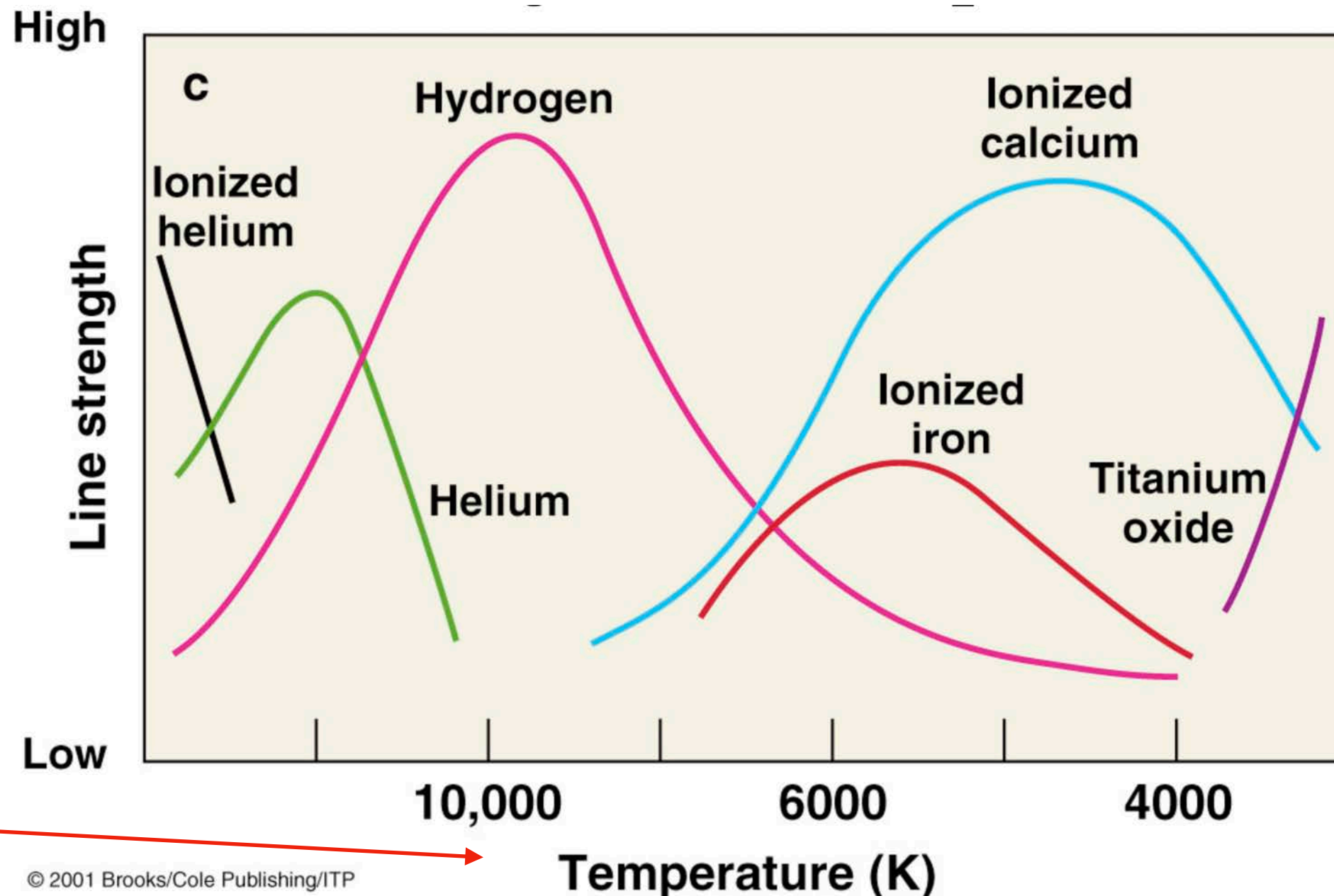


Reversed
axis!

Spectral classification

Line strength

- Analysis of many spectral lines of different elements (and ionisation stages) allows to determine the gas temperature



Reversed
axis!

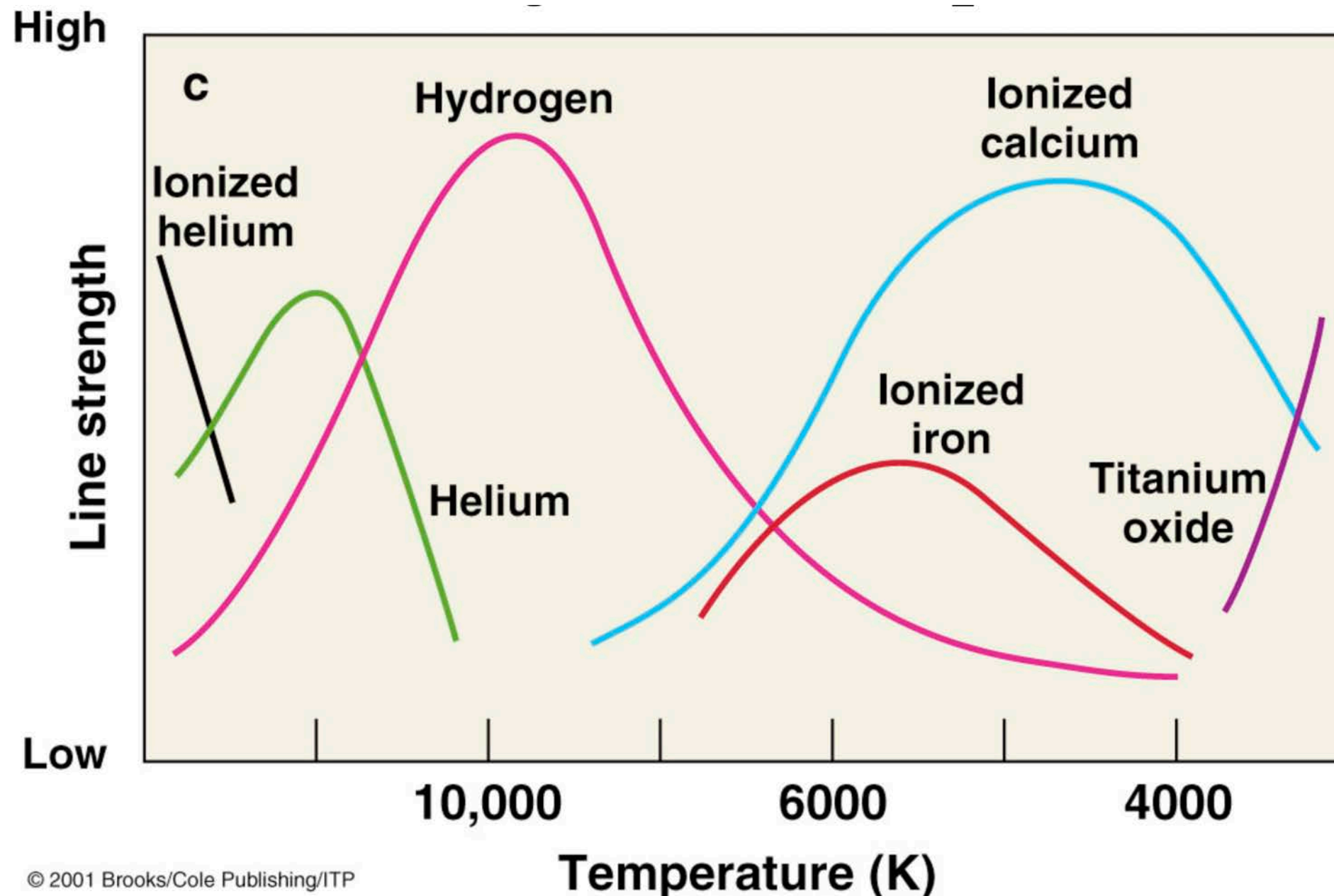
Spectral classification

Line strength

- Saha equation: Ionization degree for any gas in thermal equilibrium

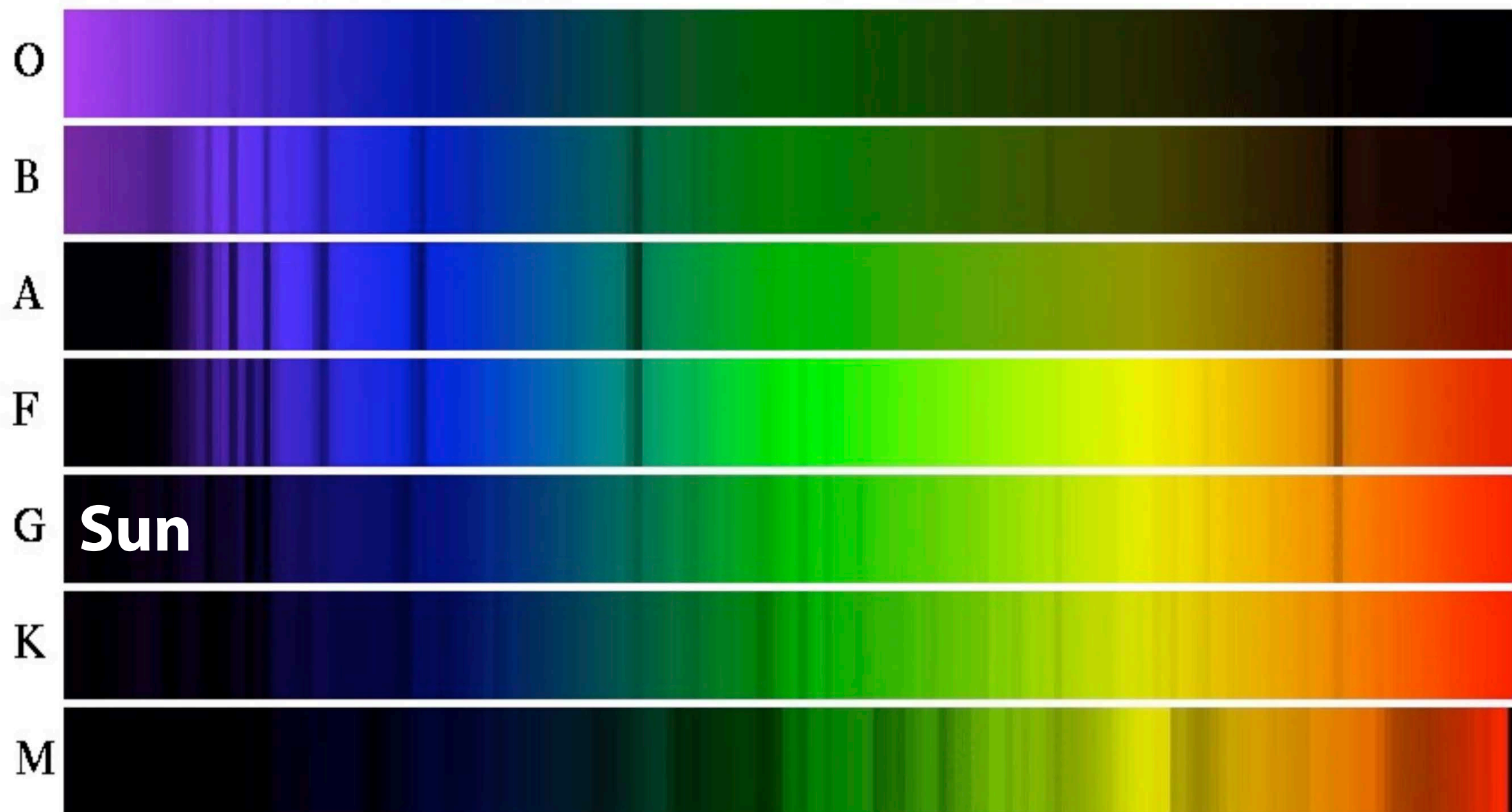
$$\frac{n_{i+1} n_e}{n_i} \propto \exp \left[-\frac{(\epsilon_{i+1} - \epsilon_i)}{k_B T} \right]$$

n: Number density of atoms in the i-th ion state (i electrons removed)
 ϵ : ionisation energy



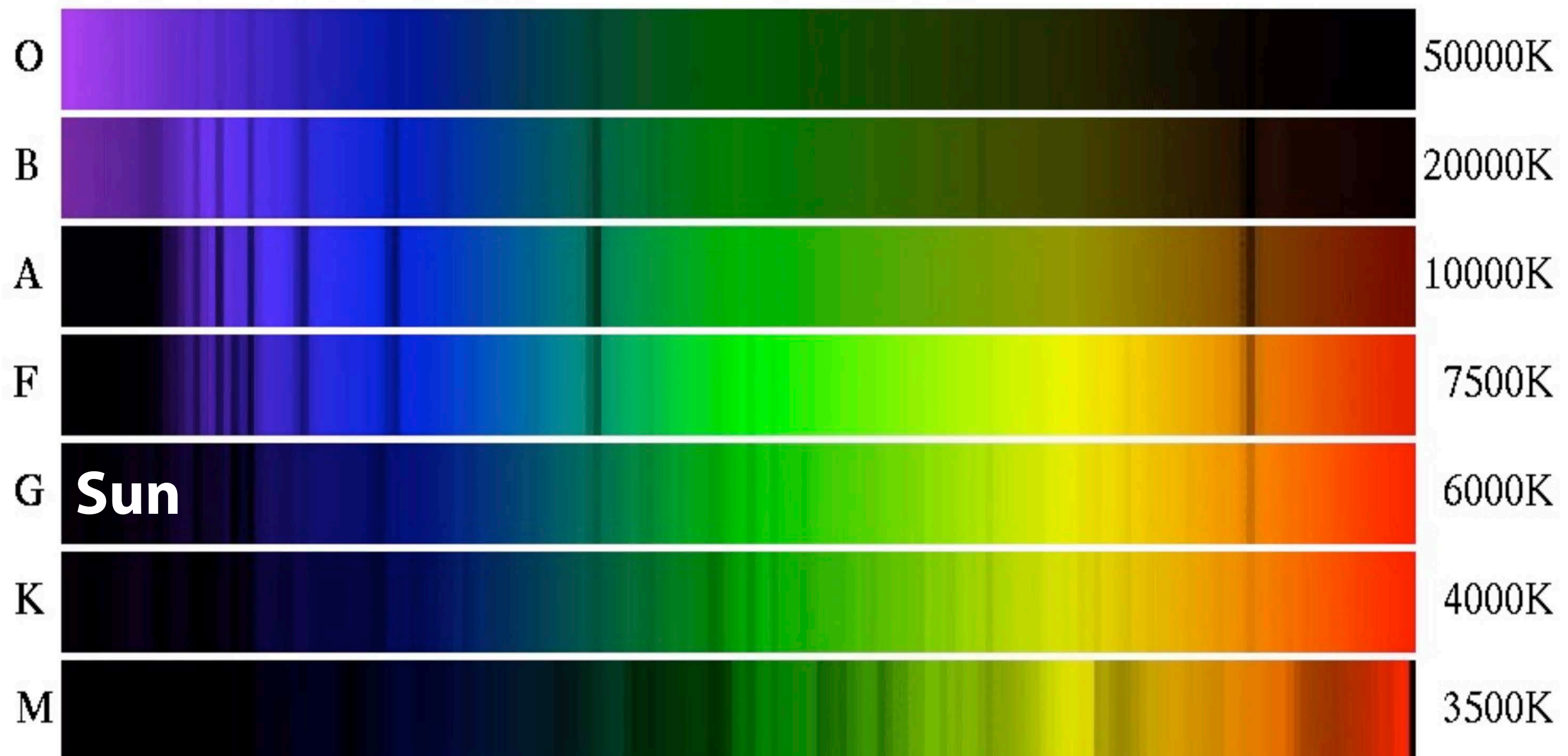
Spectral classification

- Spectral types defined according to occurrence and strength of spectral lines
- ➡ Sorting the different types into a sequence



Spectral classification

- Measuring brightnesses, colour indices, spectral lines (+Stefan-Boltzmann law)
- ➔ Spectral types can be sorted into a sequence as function of temperature



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 function of temperature

