Intro — me!

Matti

Career so far …

Study physics

↓

Study *hot subdwarfs (BSc)*

↓

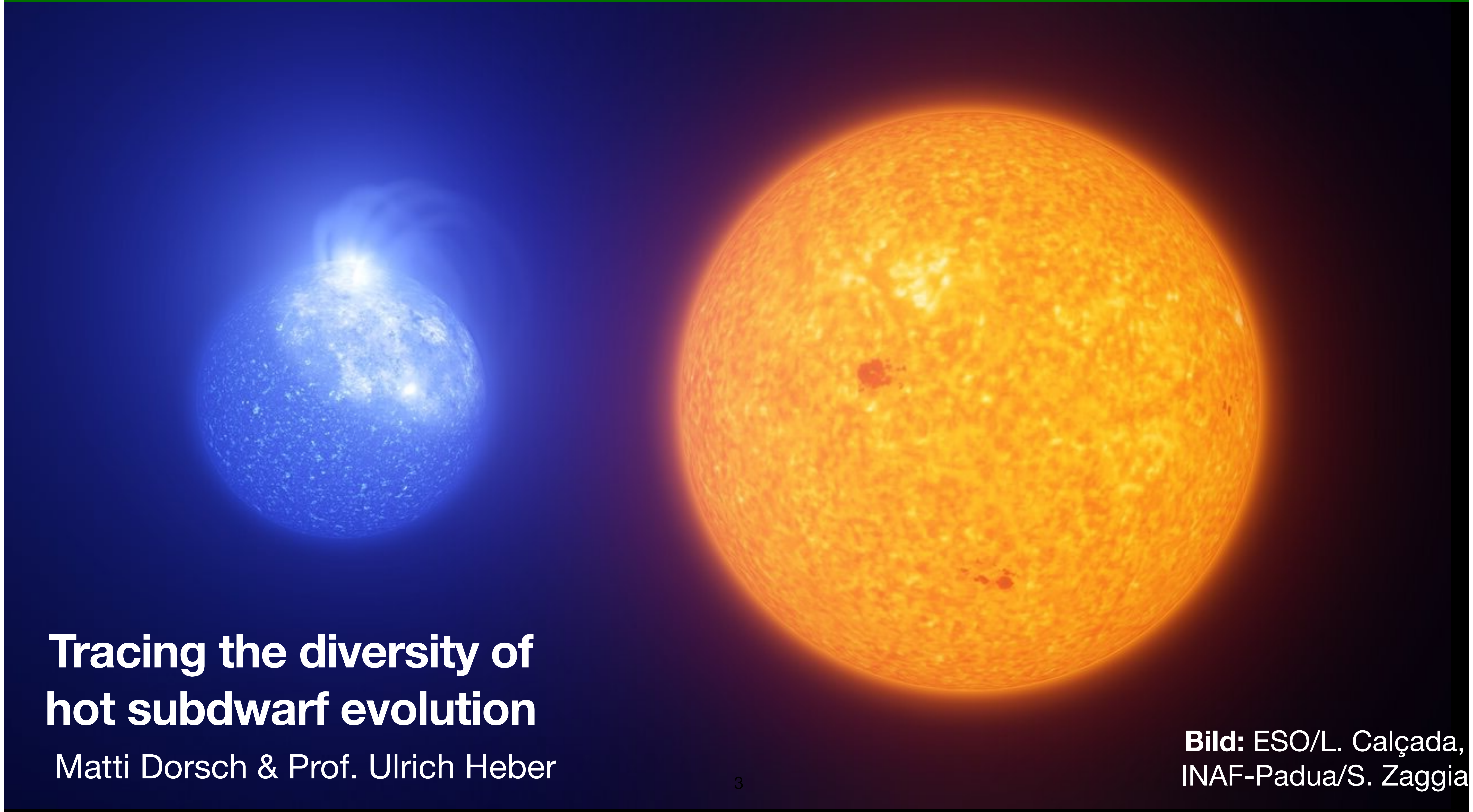
Study *hot subdwarfs (MSc)*

↓

Study *hot subdwarfs (PhD)*

Friedrich-Alexander-Universität
Naturwissenschaftliche Fakultät

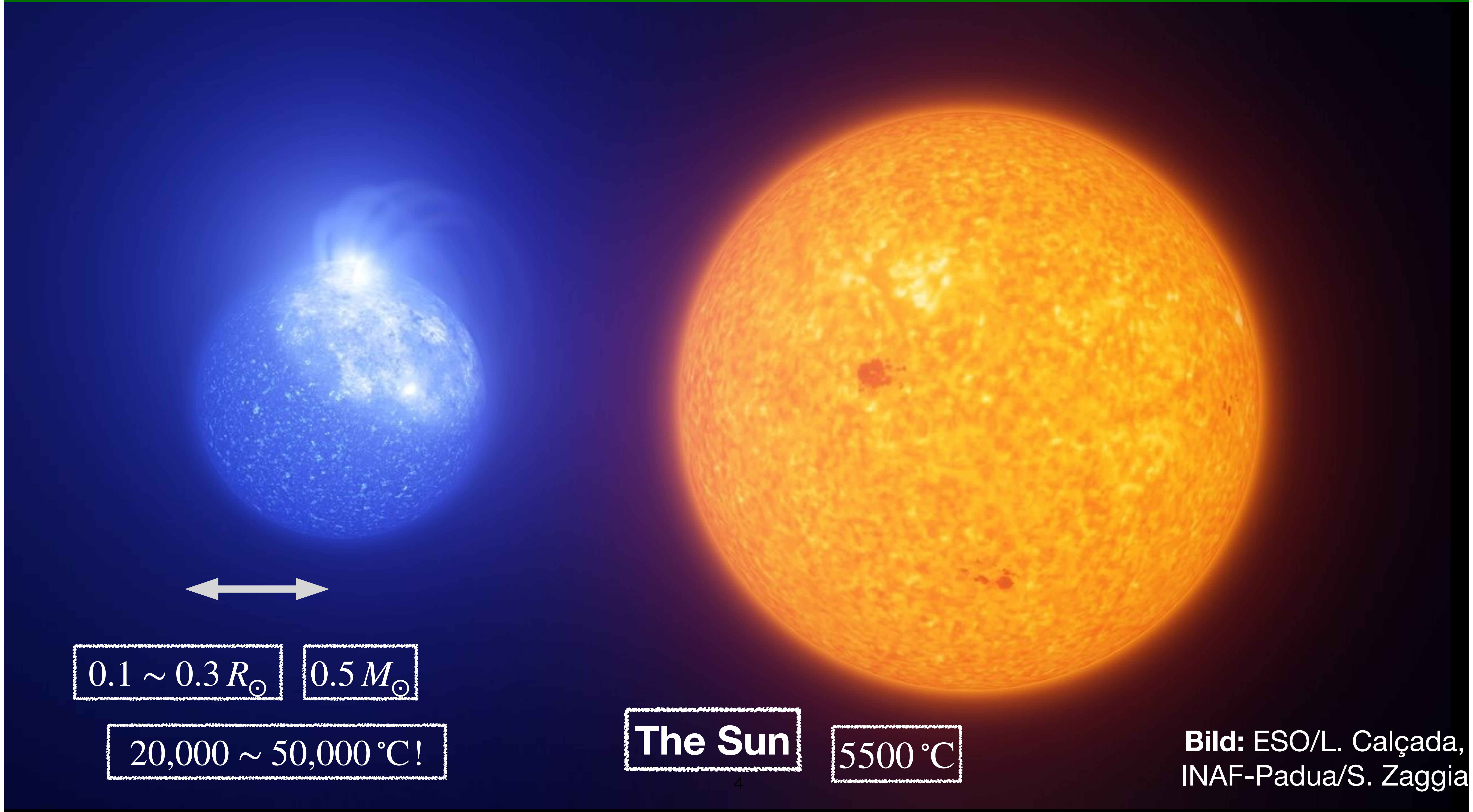
FAU

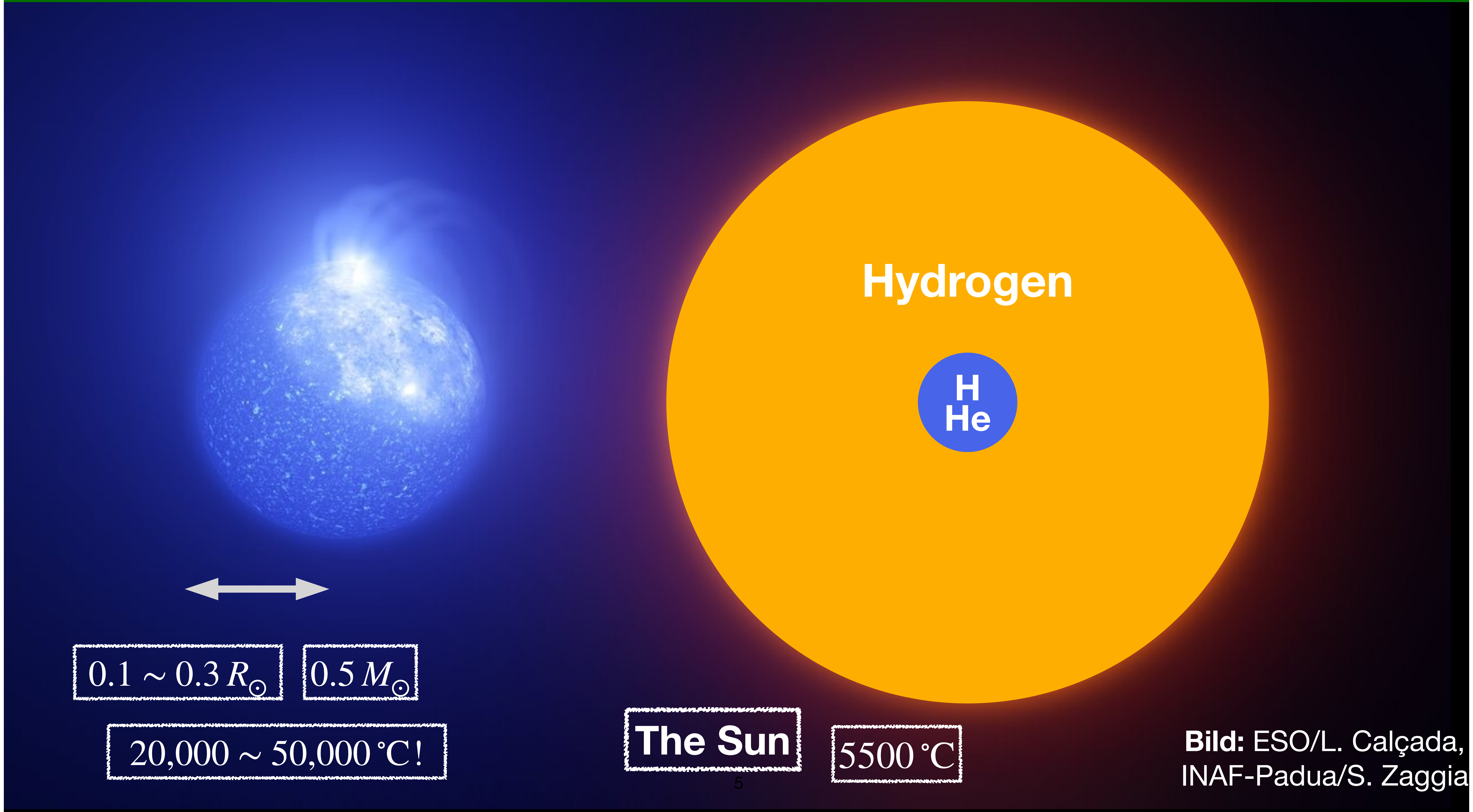


Tracing the diversity of hot subdwarf evolution

Matti Dorsch & Prof. Ulrich Heber

Bild: ESO/L. Calçada, INAF-Padua/S. Zaggia


$0.1 \sim 0.3\, R_\odot$
$0.5\, M_\odot$
$20{,}000 \sim 50{,}000\,^\circ\mathrm{C}!$
The Sun
$5500\,^\circ\mathrm{C}$
Bild: ESO/L. Calçada, INAF-Padua/S. Zaggia


Hydrogen
H
He
$0.1 \sim 0.3\, R_{\odot}$
$0.5\, M_{\odot}$
$20{,}000 \sim 50{,}000\,°C$!
The Sun
$5500\,°C$
Bild: ESO/L. Calçada, INAF-Padua/S. Zaggia

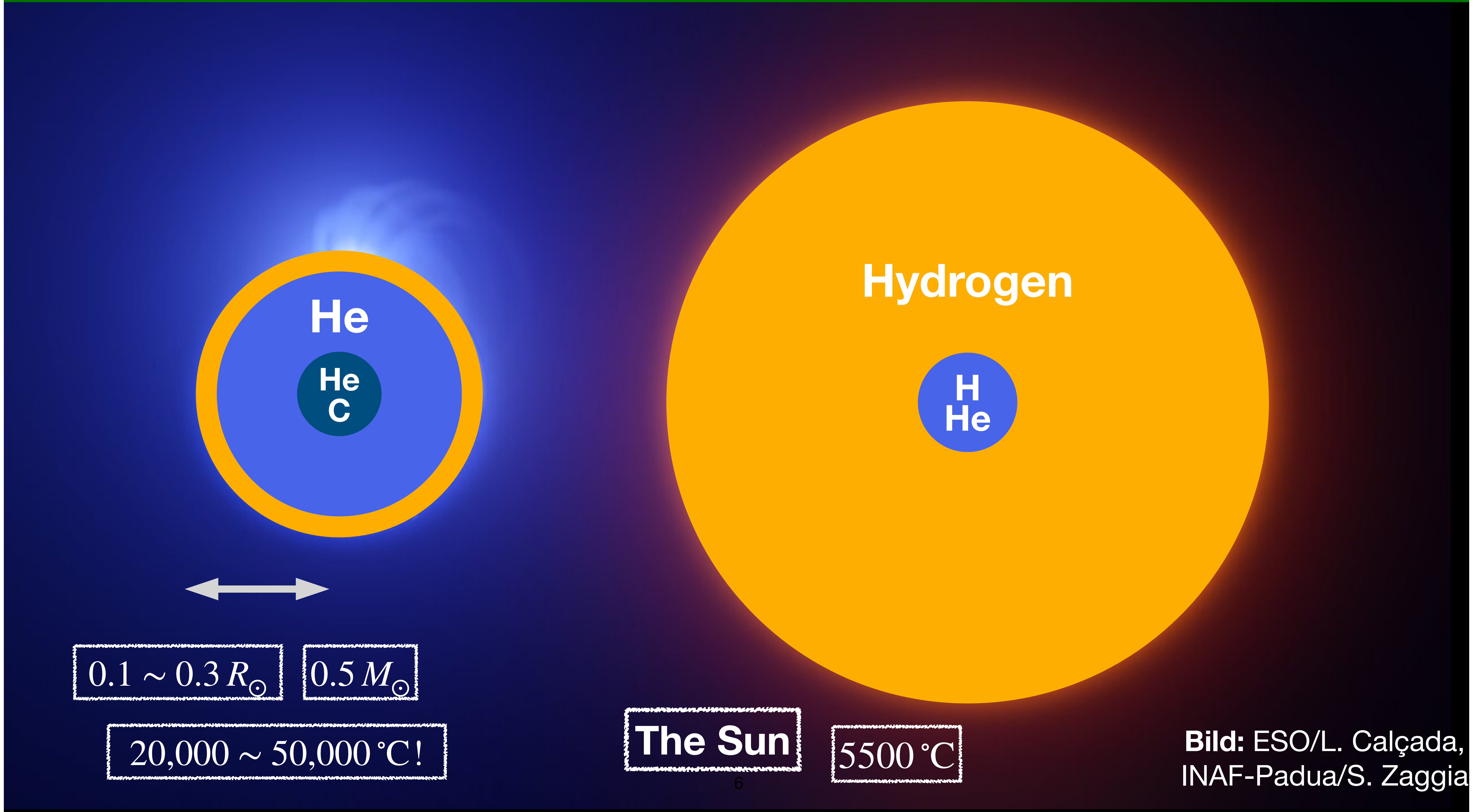
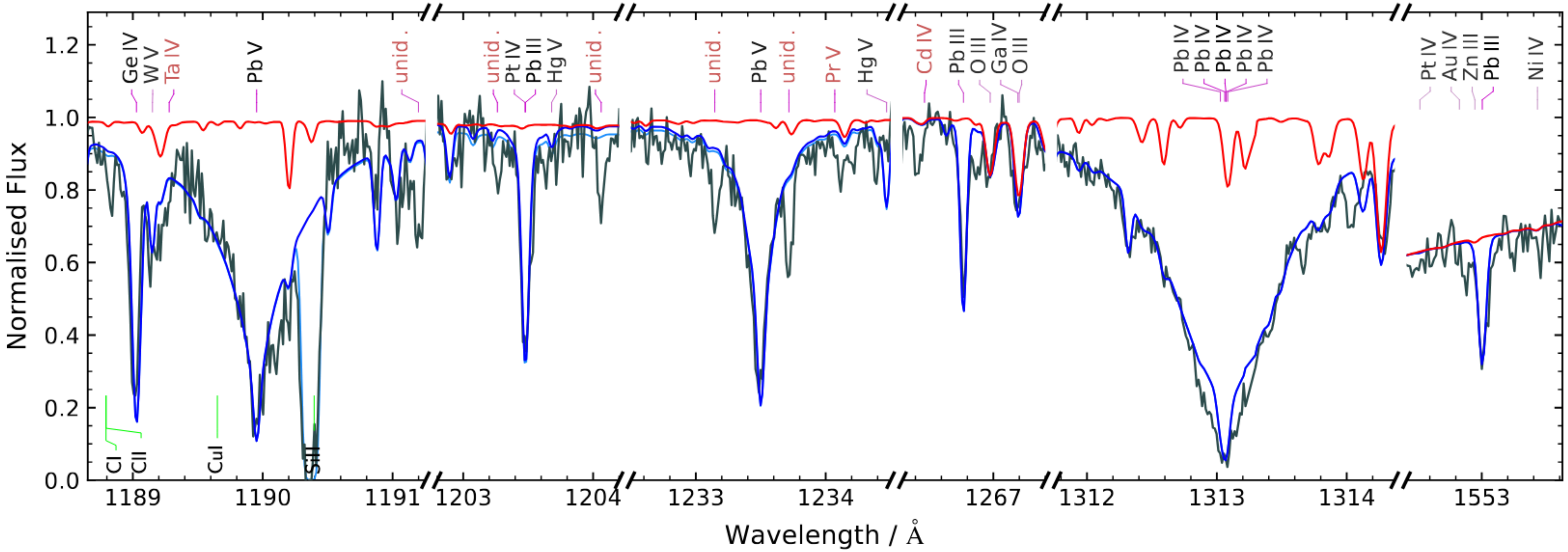


Bild: ESO/L. Calçada, INAF-Padua/S. Zaggia


Heavy metal stars!


Normalised Flux
Wavelength / Å
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1189
1190
1191
1203
1204
1233
1234
1267
1312
1313
1314
1553
Ge IV
W V
Ta IV
Pb V
unid.
unid.
Pt IV
Pb III
Hg V
unid.
unid.
Pb V
unid.
Pr V
Hg V
Cd IV
Pb III
O III
Ga IV
O III
Pb IV
Pb IV
Pb IV
Pb IV
Pb IV
Pt IV
Au IV
Zn III
Pb III
Ni IV
CI
CII
CuI
SiII

Introduction to photometry / spectroscopy

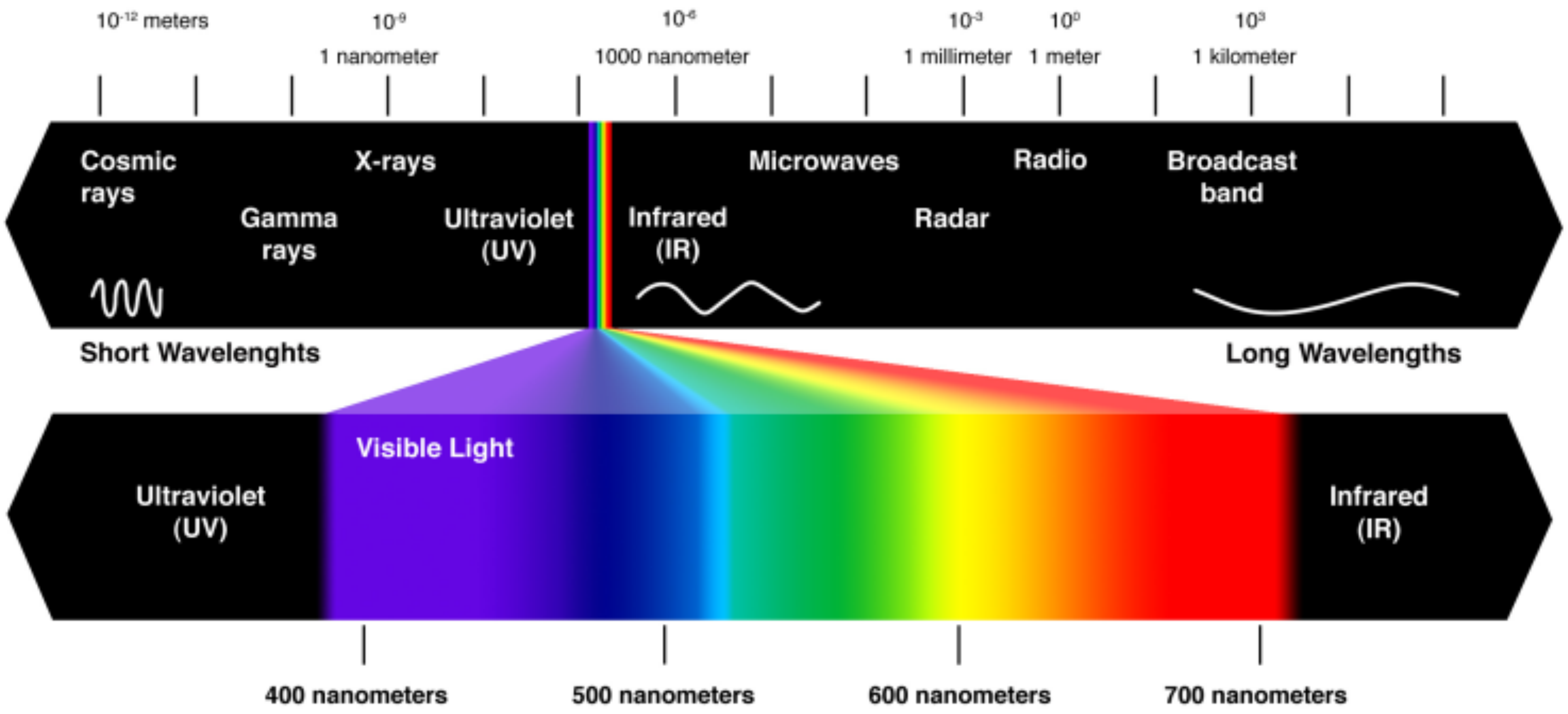
Research workshop on evolved stars

Matti Dorsch
24. August 2026

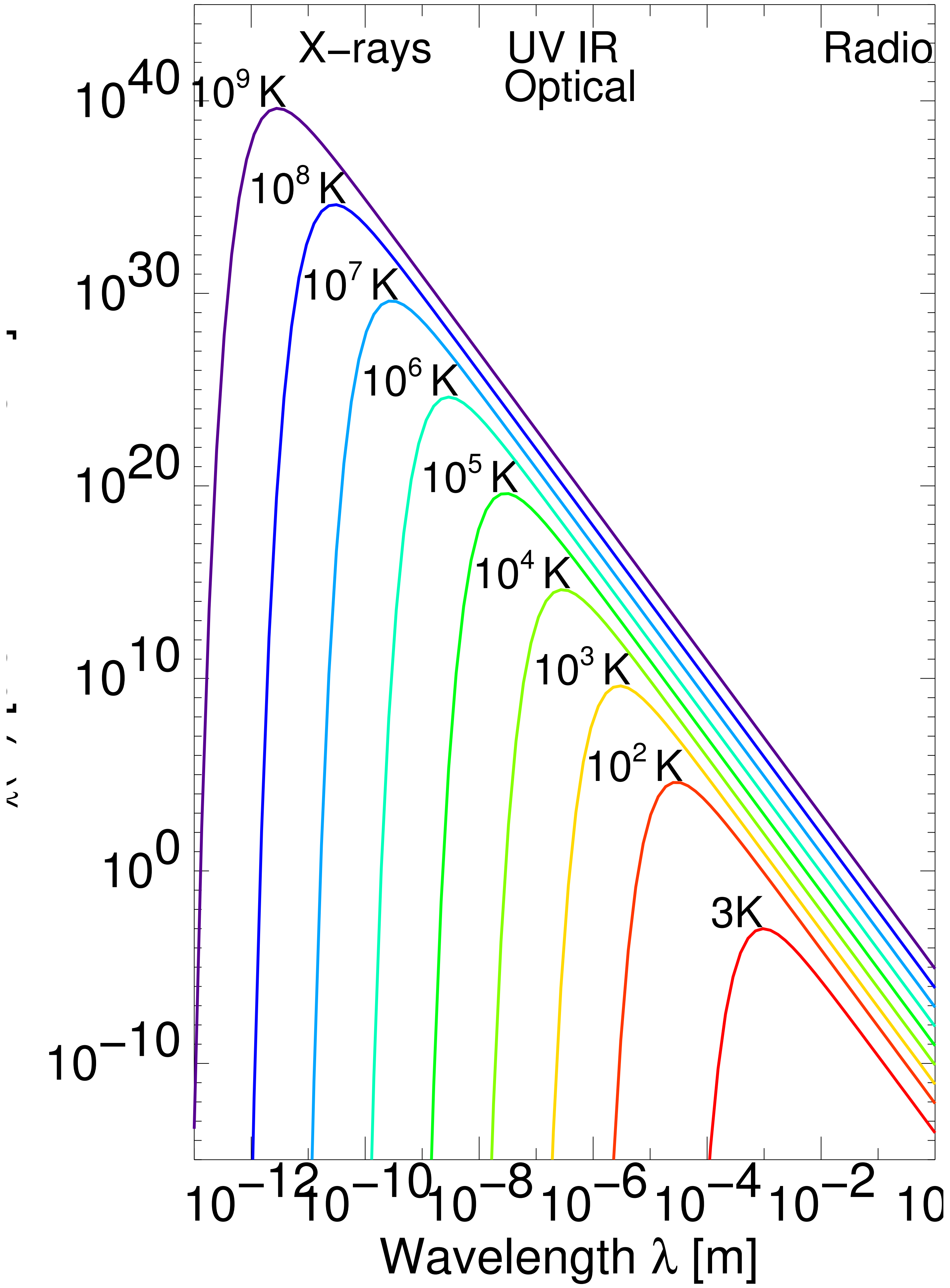
Photometry

What is Photometry?

from Greek photo- ("light") and -metry ("measure") aims at measuring the flux or intensity of electromagnetic radiation emitted by astronomical objects



Planck's Radiation Law



Stefan-Boltzmann law: Flux (power emitted per square-meter surface) of a blackbody:

$$F = B = \int_0^\infty B_\lambda(\lambda)\,d\lambda = \sigma T^4$$

where $\sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$

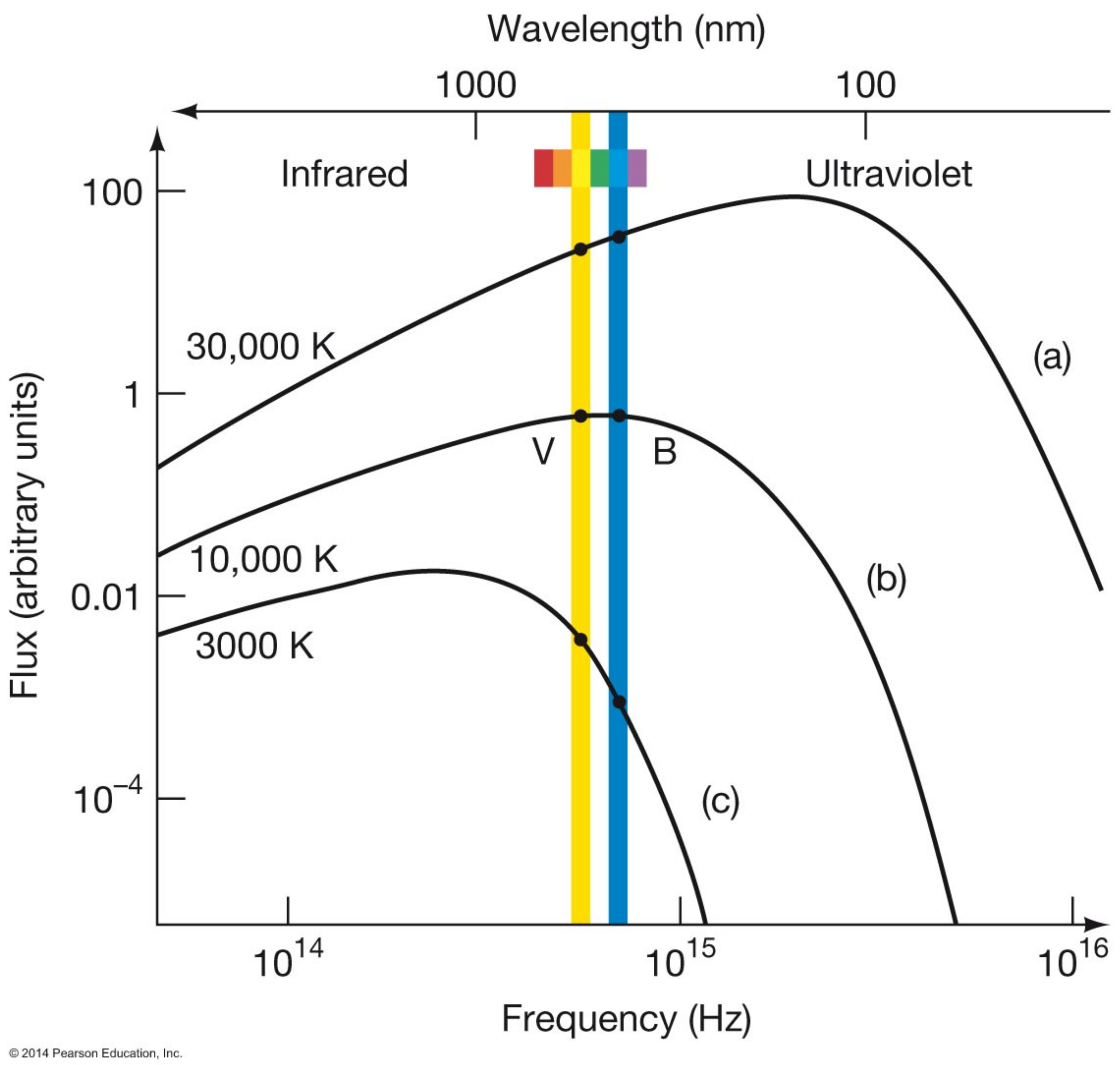
"hotter bodies have a much higher luminosity"

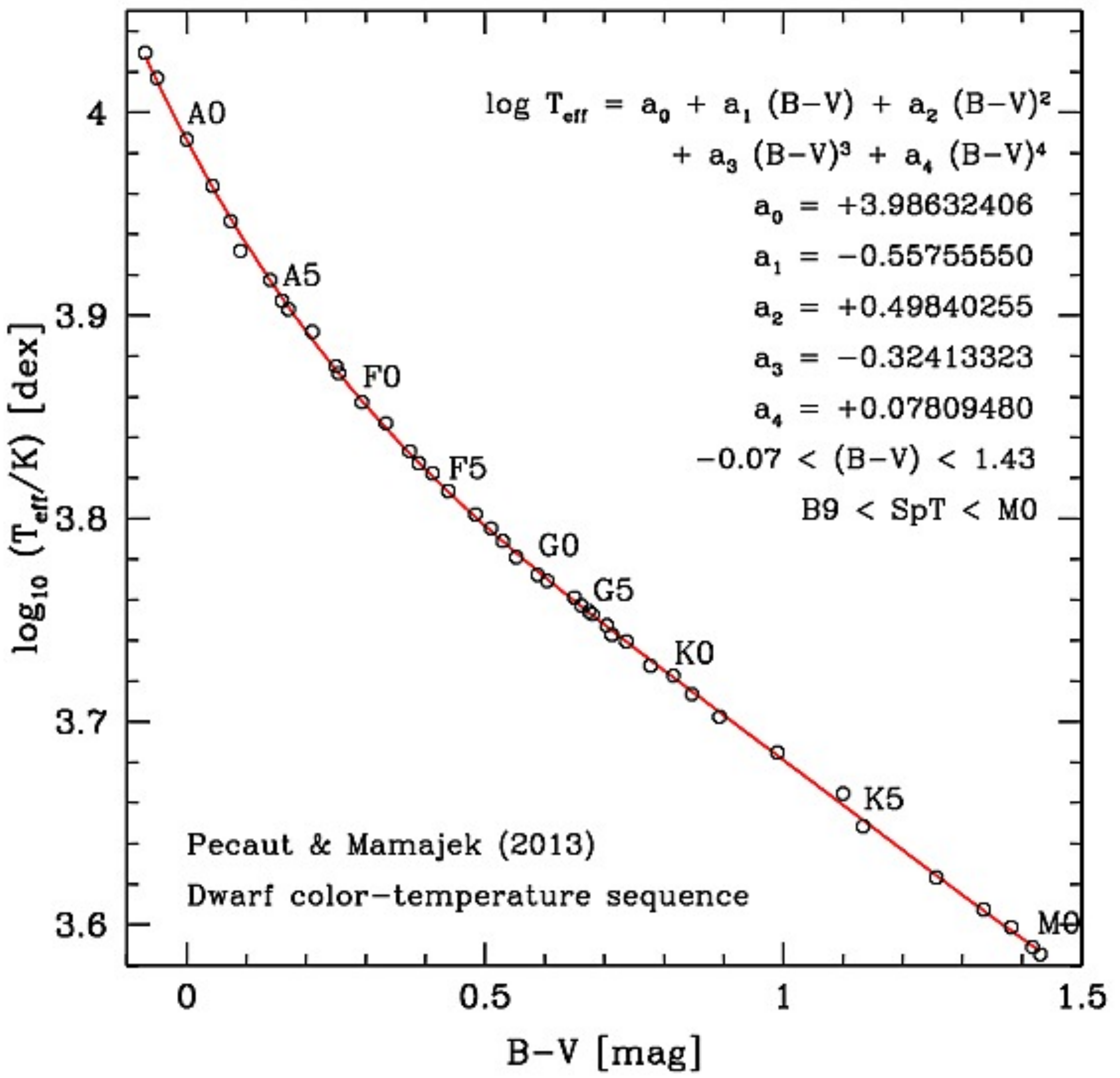
Wien's displacement law: Wavelength of maximum blackbody emission:

$$\lambda_{max} = 2898/T\ \mu\mathrm{m}$$

"hotter bodies radiate at higher energies"

Color-temperature relation





Photometric filters

Photometric system

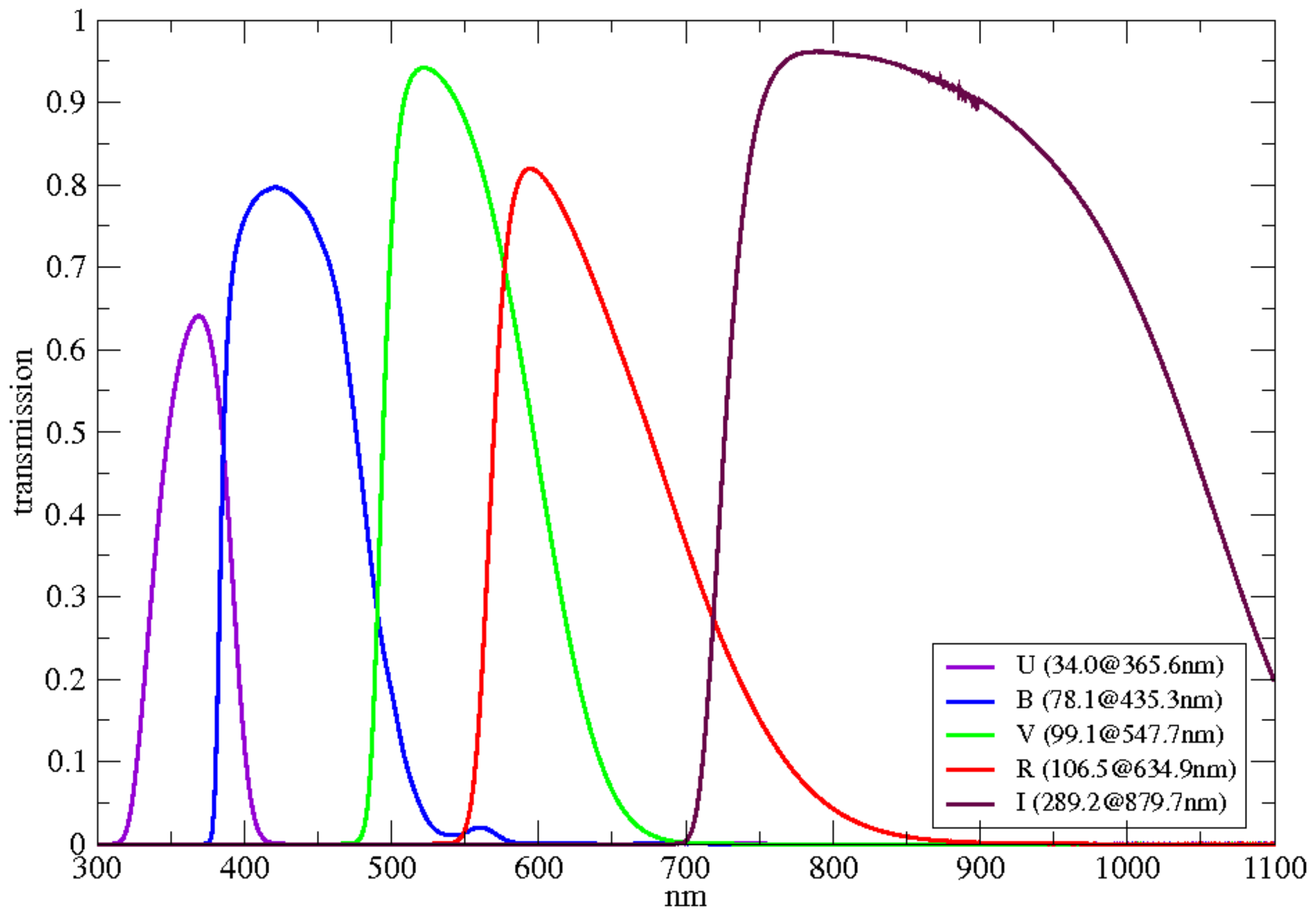
- set of well-defined passbands (or filters)
- standard stars for each photometric system
- observations of lightcurves usually in one or several filters

Bolometric correction

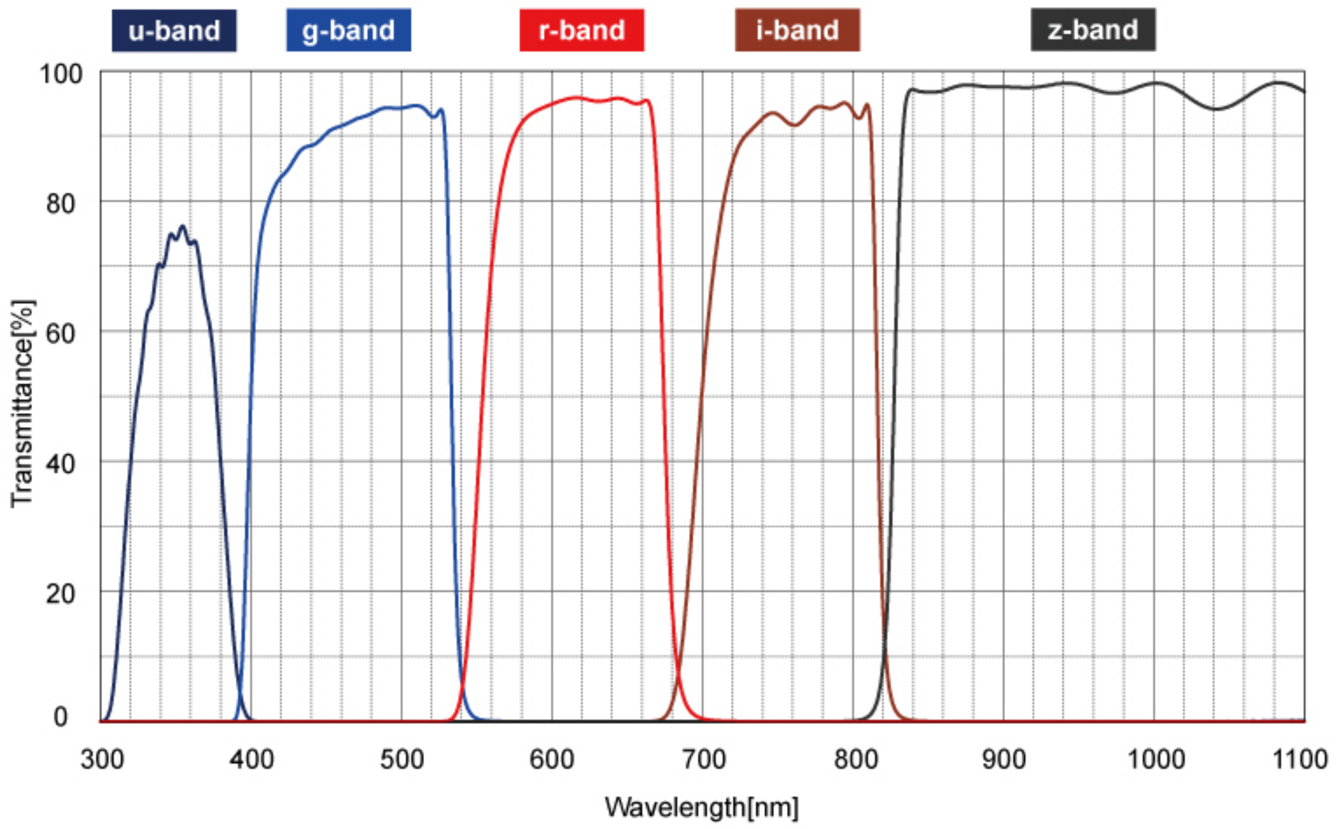
- converts observed magnitude in a certain filter to its bolometric magnitude (dependent on spectral type)

$$BC_V = M_{bol} - M_V \qquad (2.1)$$

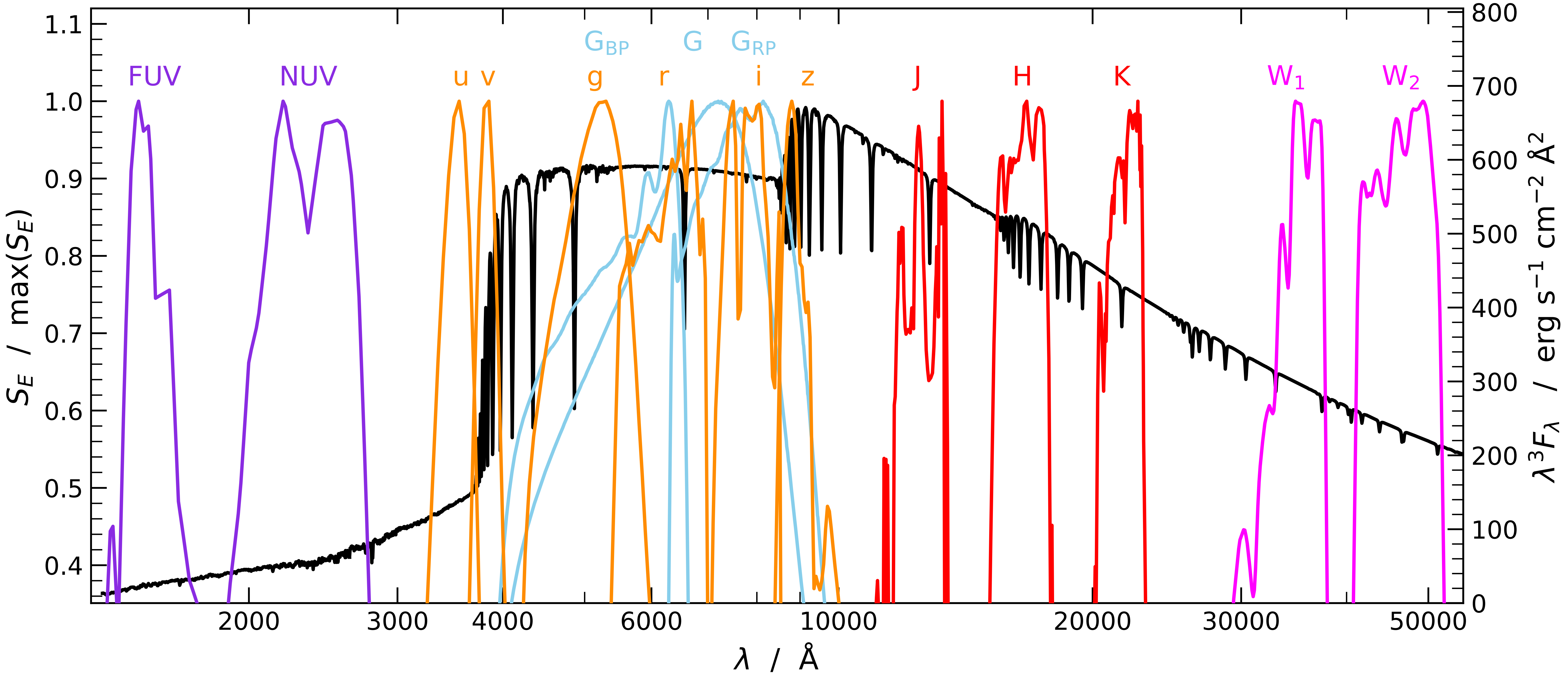
Johnson filters



SDSS filters

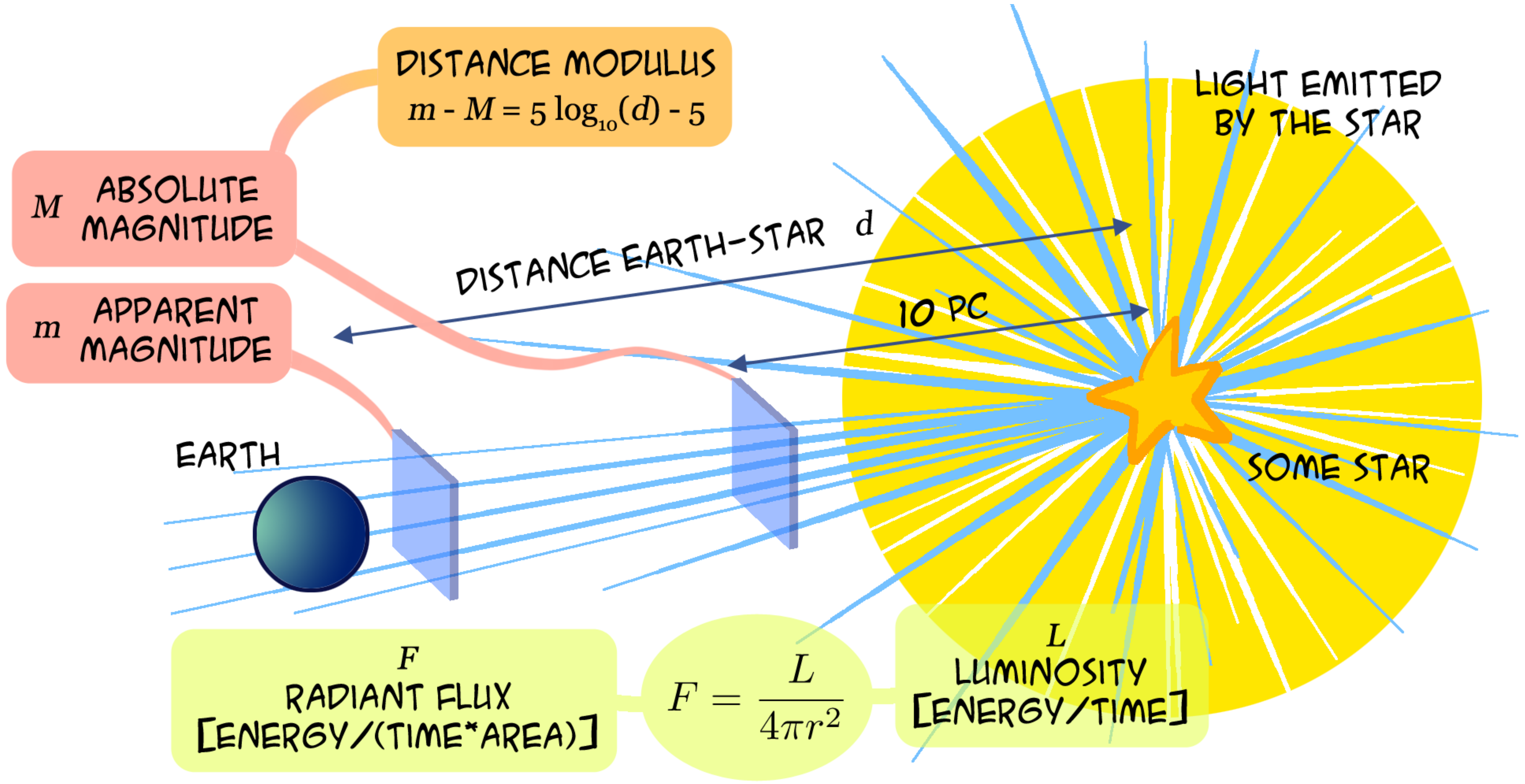


Photometric filters



A historic and current photometric reference: Vega!

Bolometric magnitudes



- apparent magnitude m_x in filter x

$$m_x - m_{x,\mathrm{ref}} = -2.5 \log(F_x / F_{x,\mathrm{ref}}) \qquad (2.2)$$

- absolute magnitude M_x in filter x

$$m_x - M_x = 5 \log(d) - 5 \qquad (2.3)$$

Extinction correction and BC $\rightarrow$ bolometric absolute magnitude

Interstellar reddening

Extinction A_V

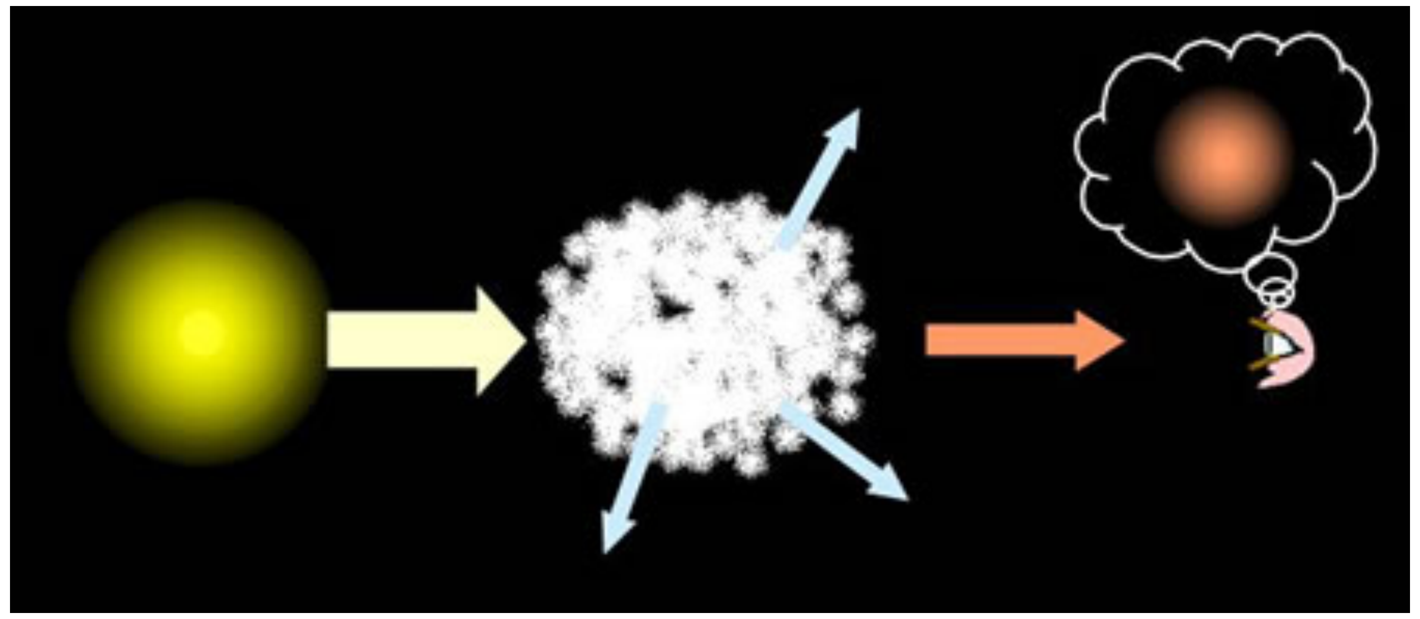
- absorption and scattering of electromagnetic radiation by dust and gas between an emitting astronomical object and the observer
- shorter wavelengths (blue) are more heavily reddened than longer (red) wavelengths
- colour index $B-V$, colour excess E_{B-V}

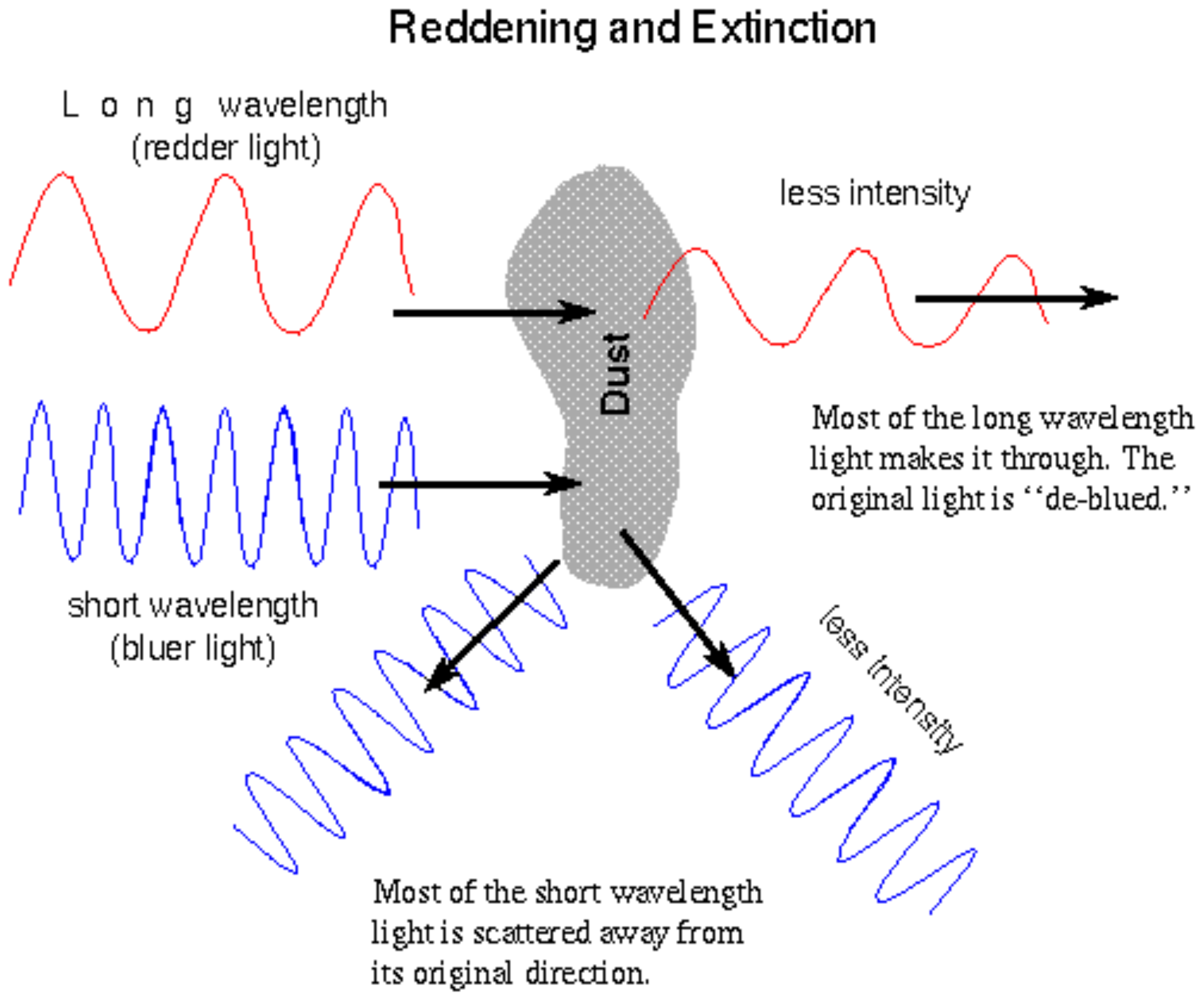
$$E_{B-V} = (B-V) - (B-V)_0 \tag{2.4}$$

$$A_V = R_V E_{B-V}, \ R_V \approx 3.1 \text{ (Milky Way)} \tag{2.5}$$

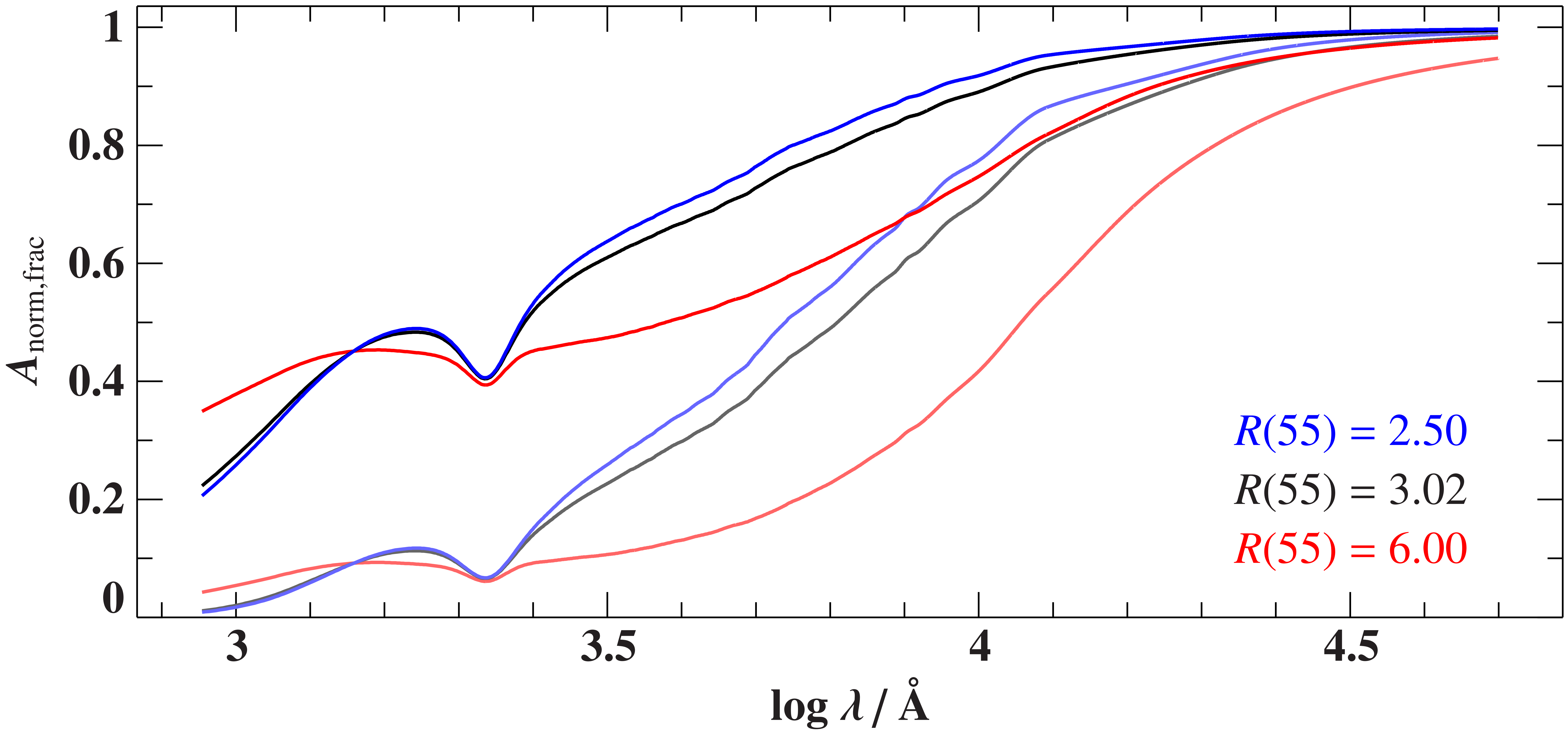
- true distance

$$d = 10^{0.2(m-M+5-A_V)} \tag{2.6}$$



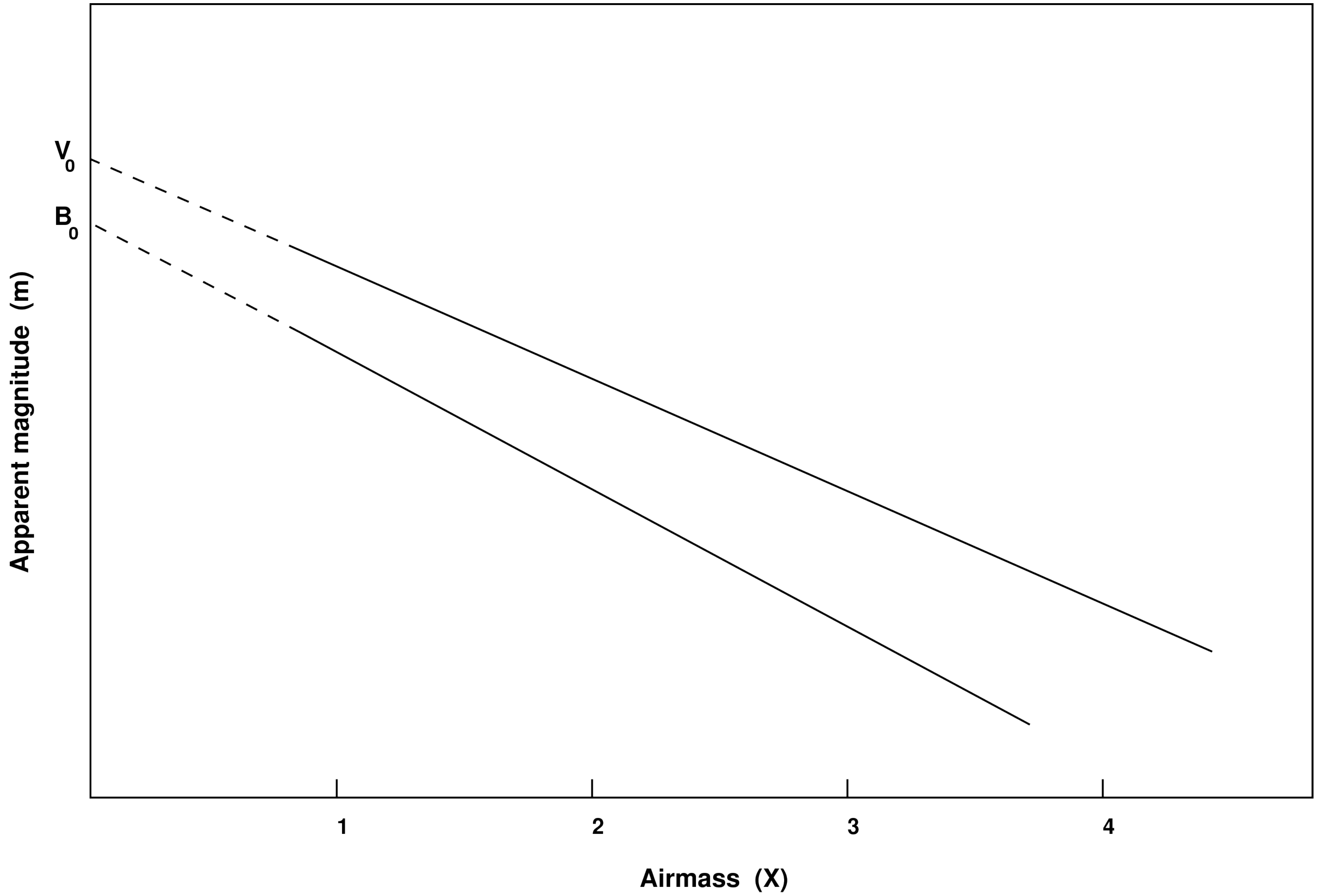


Interstellar reddening



The darker curves are for a colour excess $E(44-55) = 0.1$ mag while the lighter curves are for 0.3 mag.

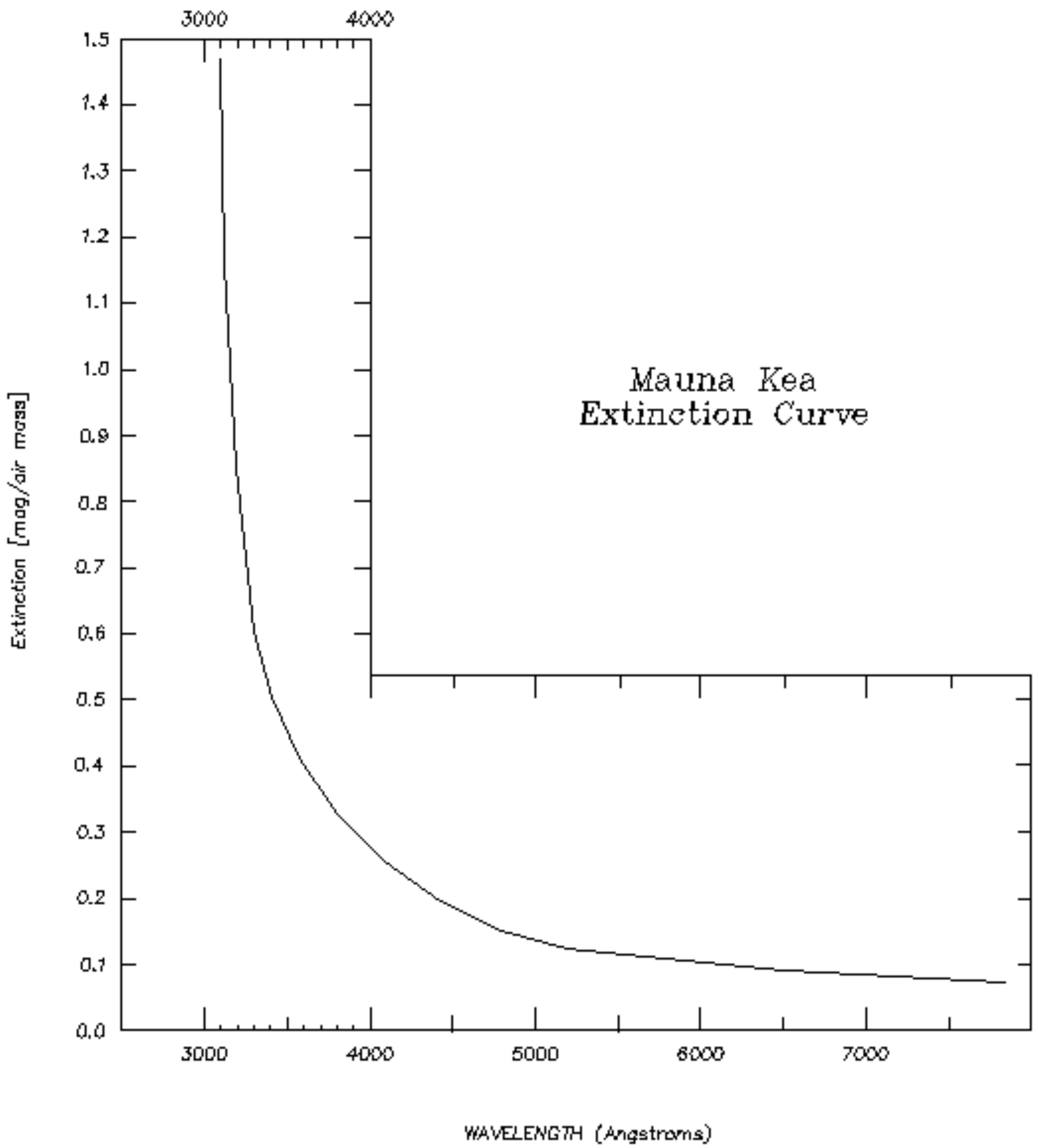
Atmospheric extinction



- $V = V_0 + \kappa(\lambda)X(z)$
  $\kappa(\lambda)$ is the extinction coefficient
  z is the zenith distance
  X is the air mass
  $X(z) \approx \cos^{-1} z$
- extinction greater for blue than for red

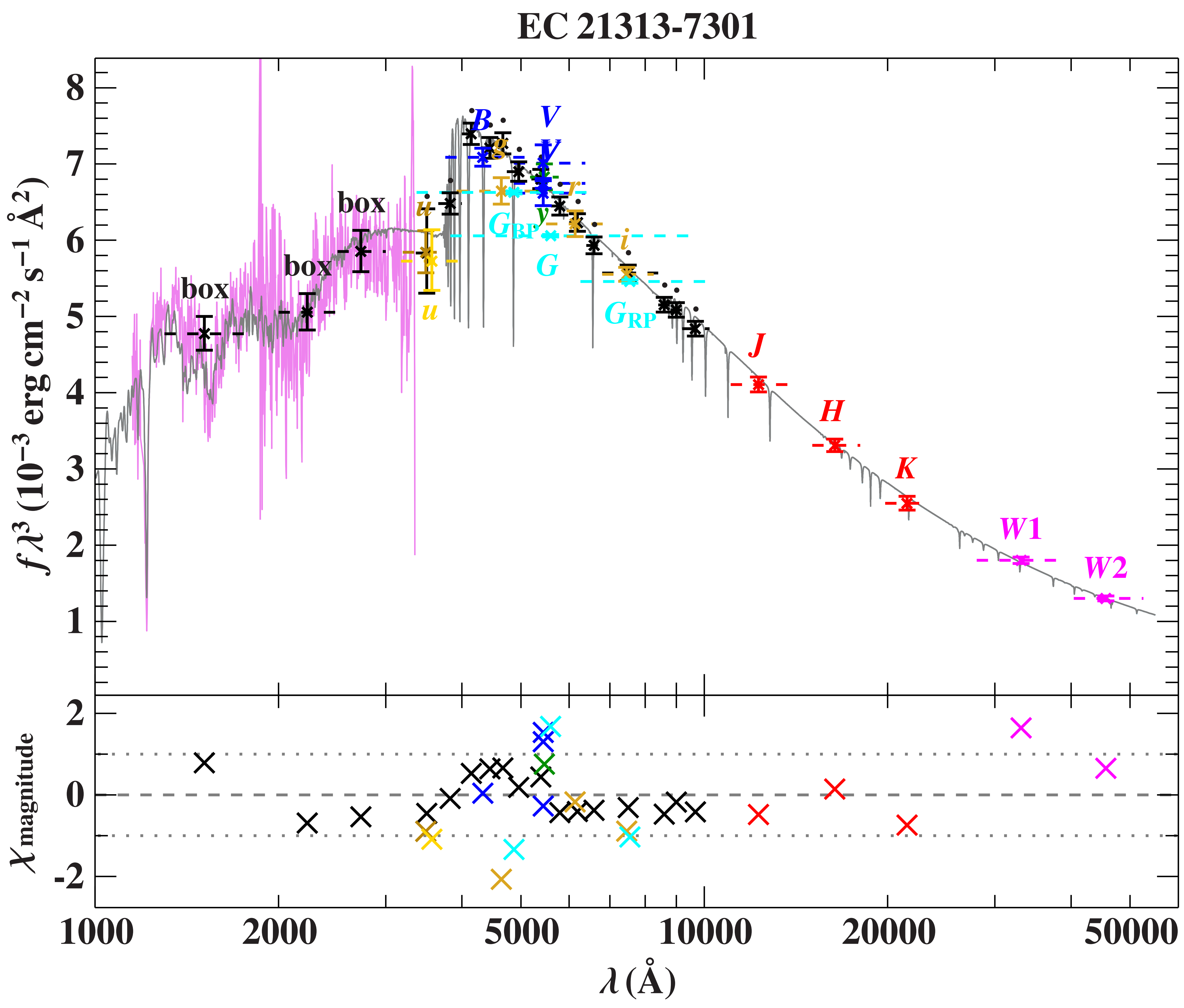
Standard stars to correct for atmospheric extinction and calibrate the sensitivity of the instrument

Atmospheric extinction

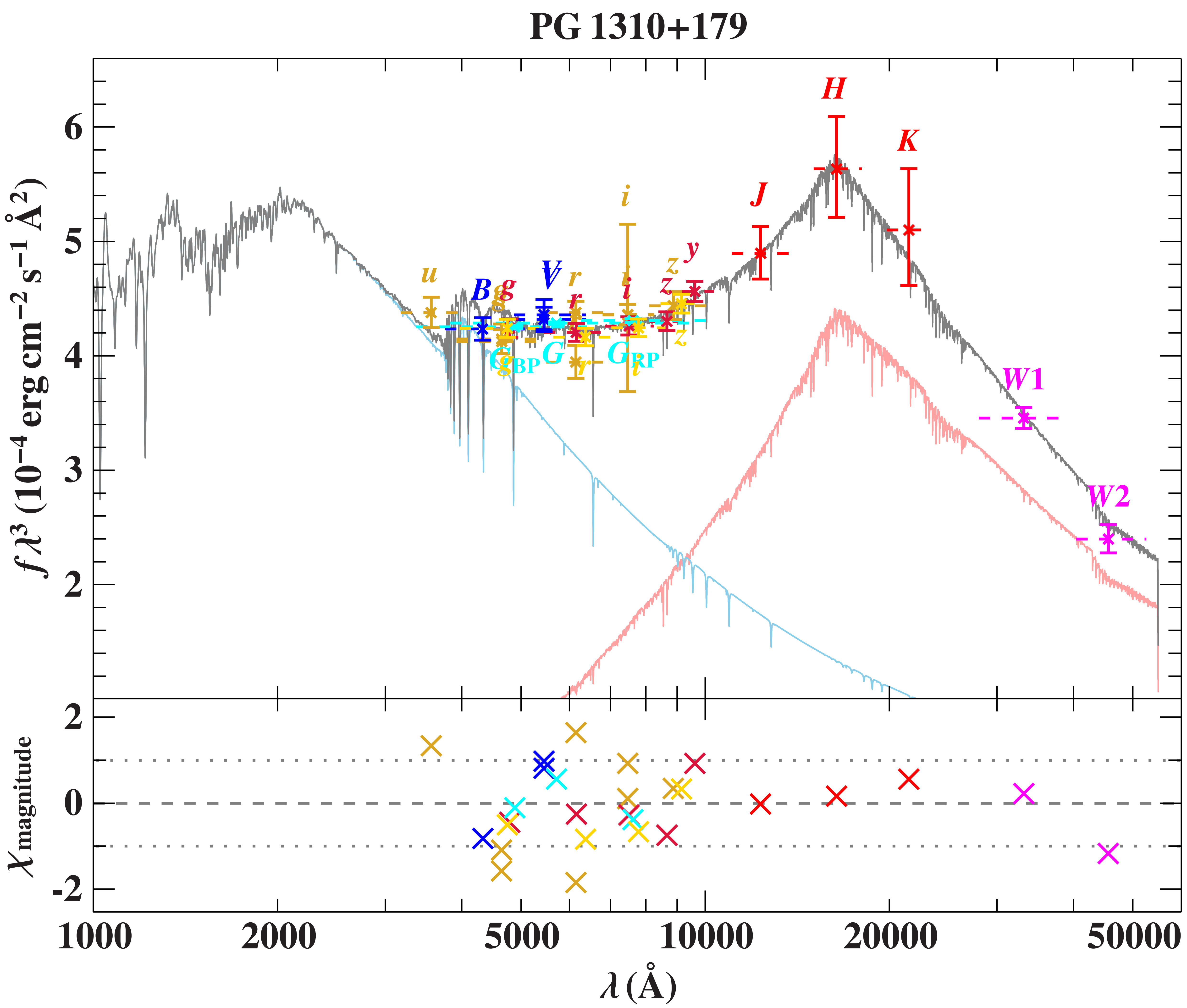


- $V = V_0 + \kappa(\lambda)X(z)$ $\kappa(\lambda)$ is the extinction coefficient
  z is the zenith distance
  X is the air mass
  $X(z) \approx \cos^{-1} z$
- extinction wavelength-dependent
- blue stars are getting weaker compared to red stars

Spectral energy distribution (SED) fitting



Spectral energy distribution (SED) fitting



Absolute vs. differential photometry

Absolute photometry – SEDs

Absolute photometry refers to photometric measurements reported in a standard photometric system by means of a calibration process. This procedure permits to obtain the absolute flux of a given source.

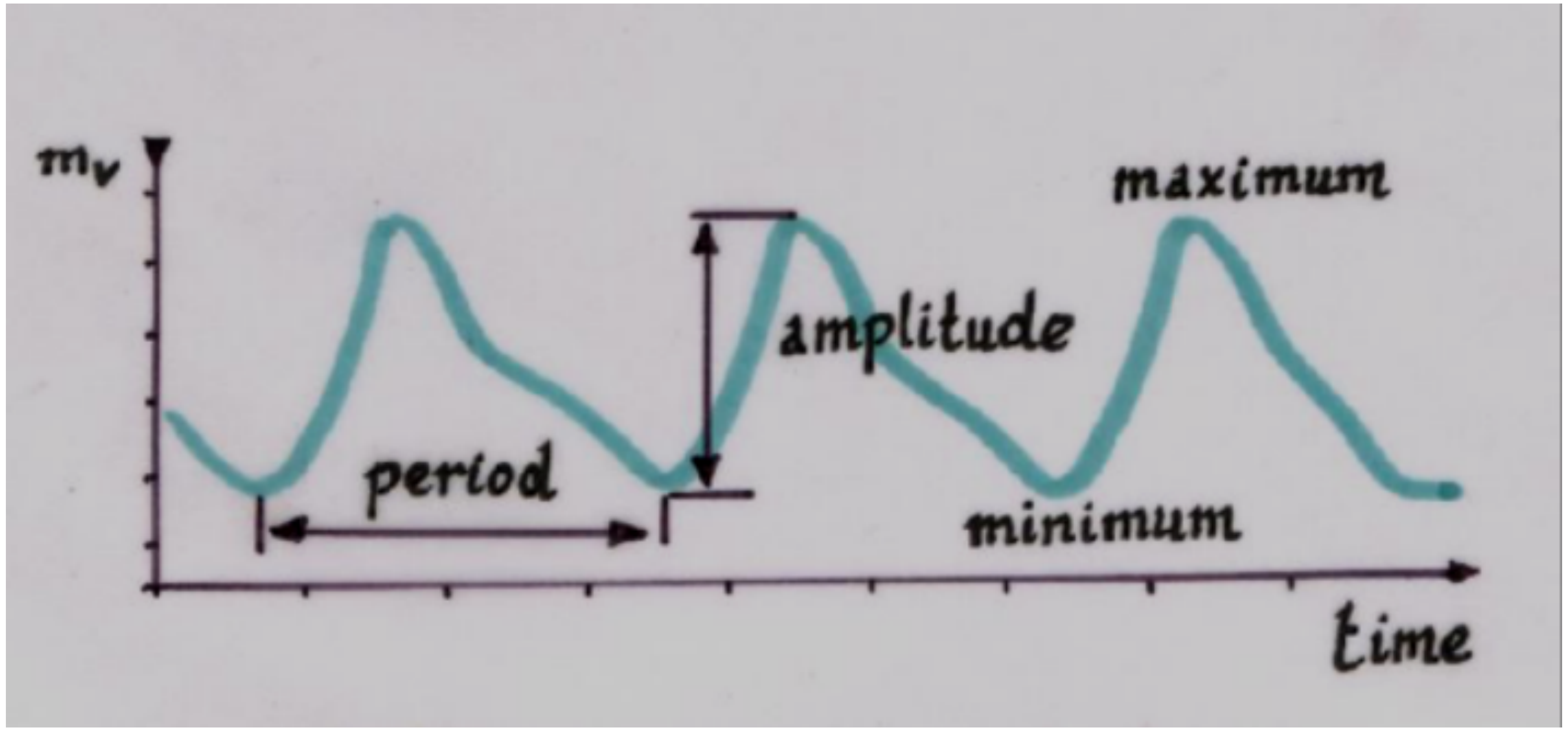
$\Rightarrow$ spectral type, gravity, reddening, age, distance

Differential photometry – lightcurves

Differential photometry refers to photometric measurements of a given source with respect to one or more comparison sources which absolute flux is not necessarily known.

$\Rightarrow$ relative flux variations, lightcurves

Lightcurves



Lightcurve = brightness versus time

- time-series observations
- period P: time between successive minima / maxima, for binaries equal orbital period
- Amplitude A: difference between magnitude at minimum and maximum

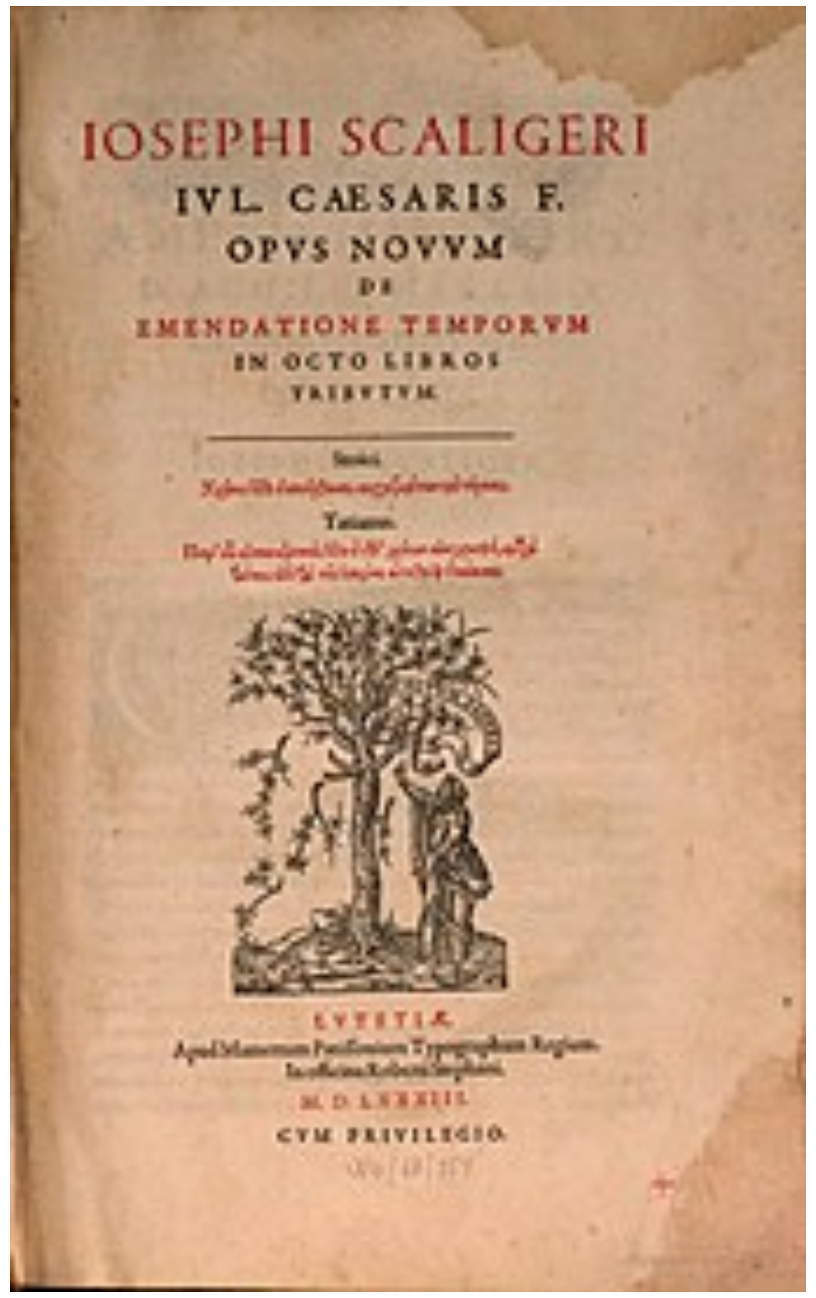
Julian Date

Julian Date JD

- time in days and fractions of a day since:

  1. January -4712 BC, 12:00 UT

  21. May 2019, 04:47:30.62 UT $\equiv$ 2458624.69966



Modified Julian Date MJD

- MJD = JD - 2400000.5

Heliocentric Julian Date HJD

- corrected for differences in the Earth's position with respect to the Sun (maximum correction ± 8.3 min)

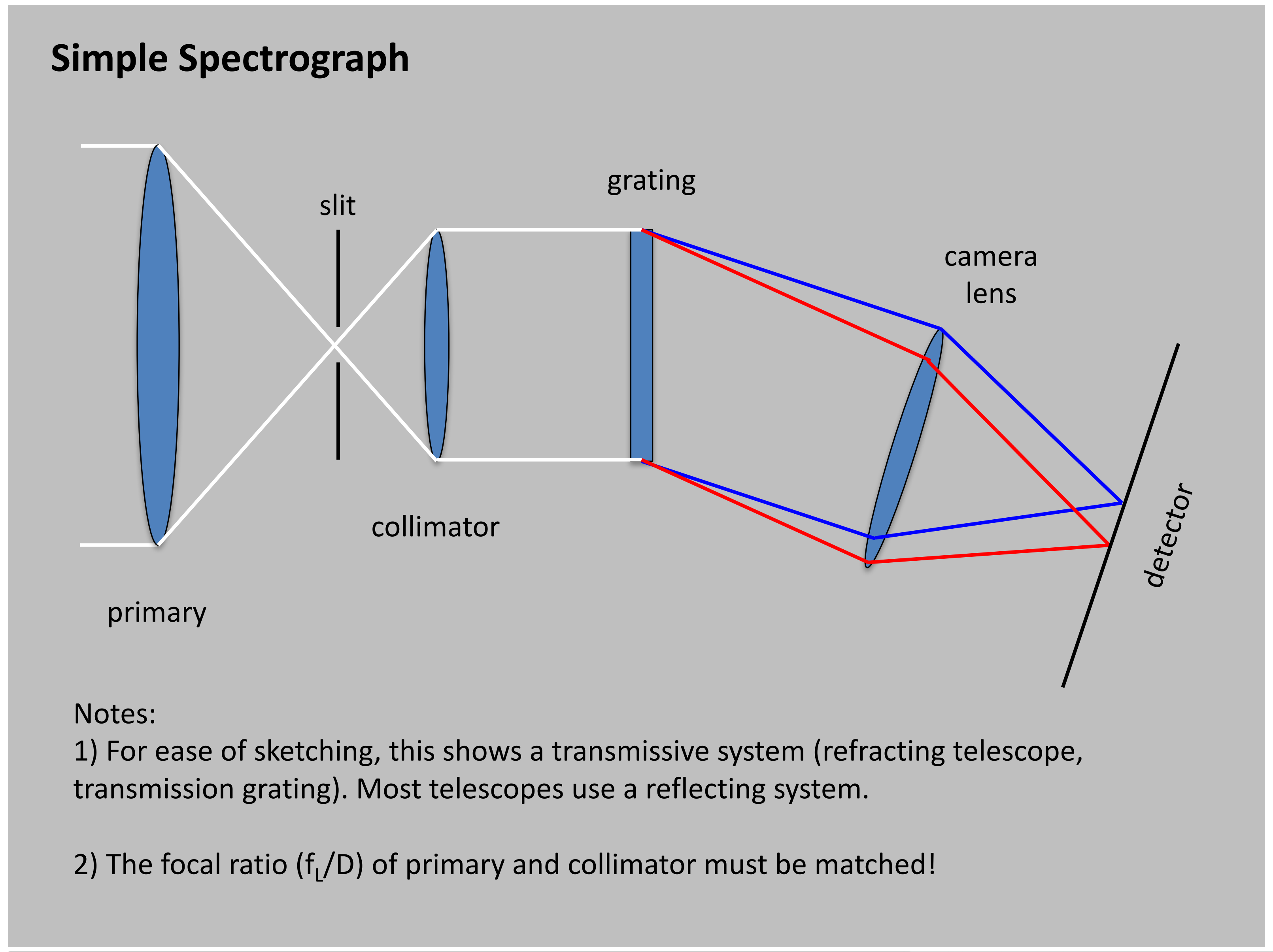
Barycentric Julian Date BJD

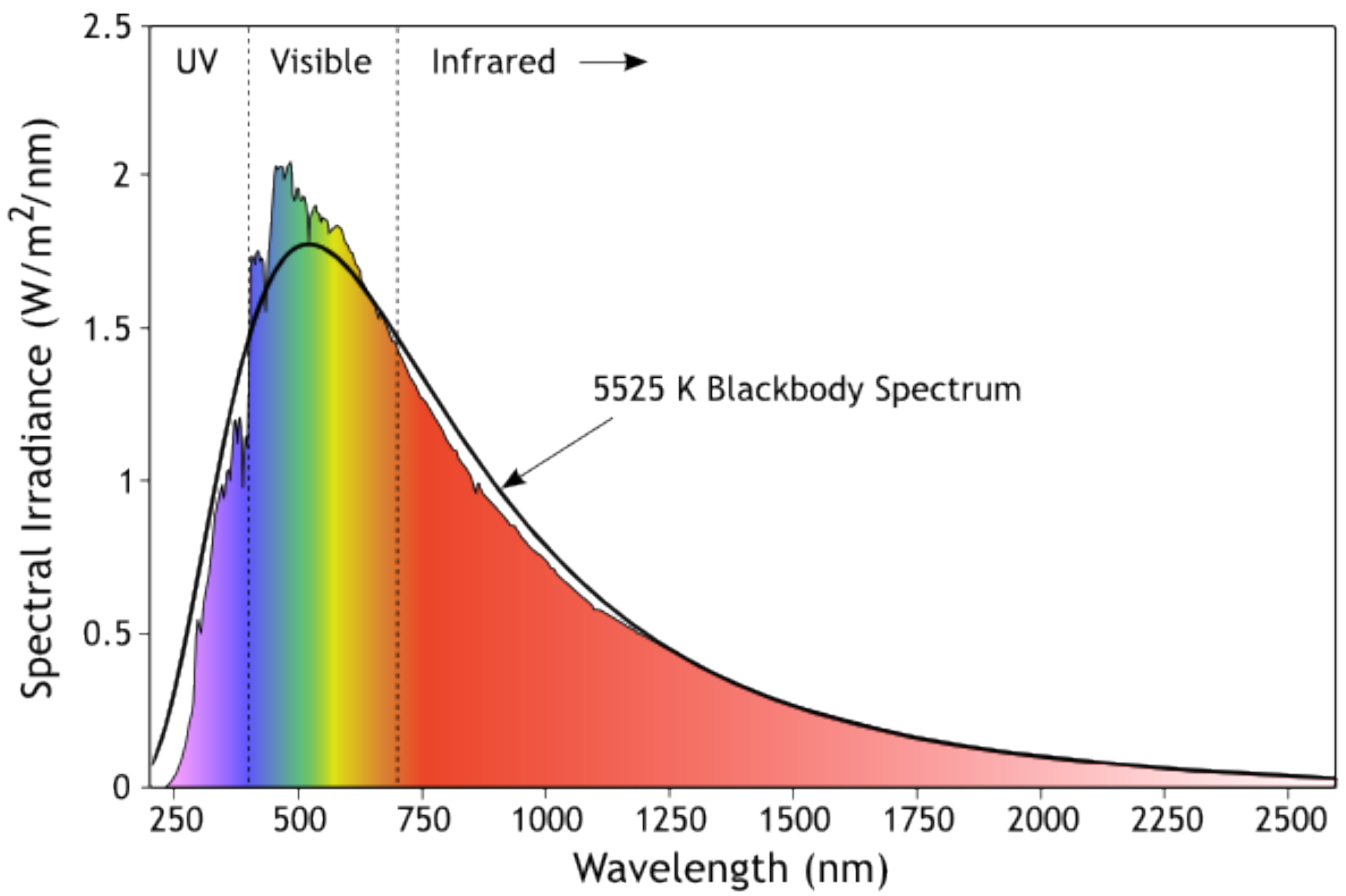
- corrected for differences in the Earth's position with respect to the barycentre of the Solar System
- difference between HJD and BJD is up to ± 4 s

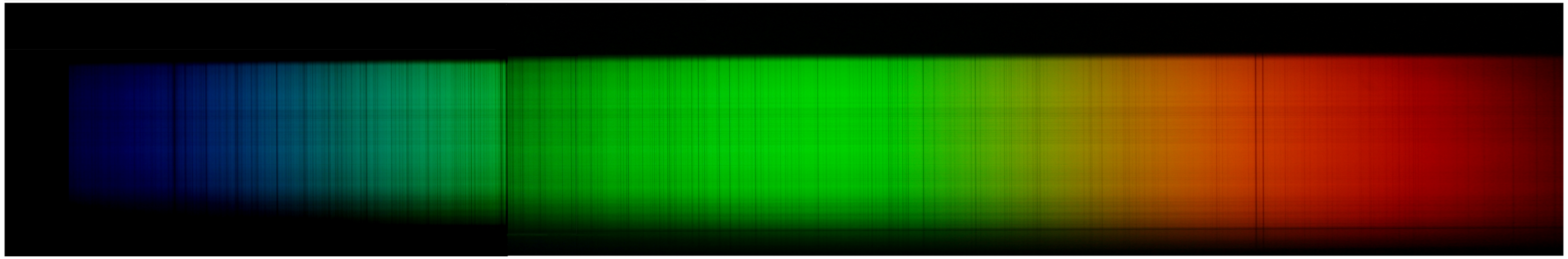
Spectroscopy

What is spectroscopy?

technique of splitting light (or more precisely electromagnetic radiation) into its constituent wavelengths (a spectrum)





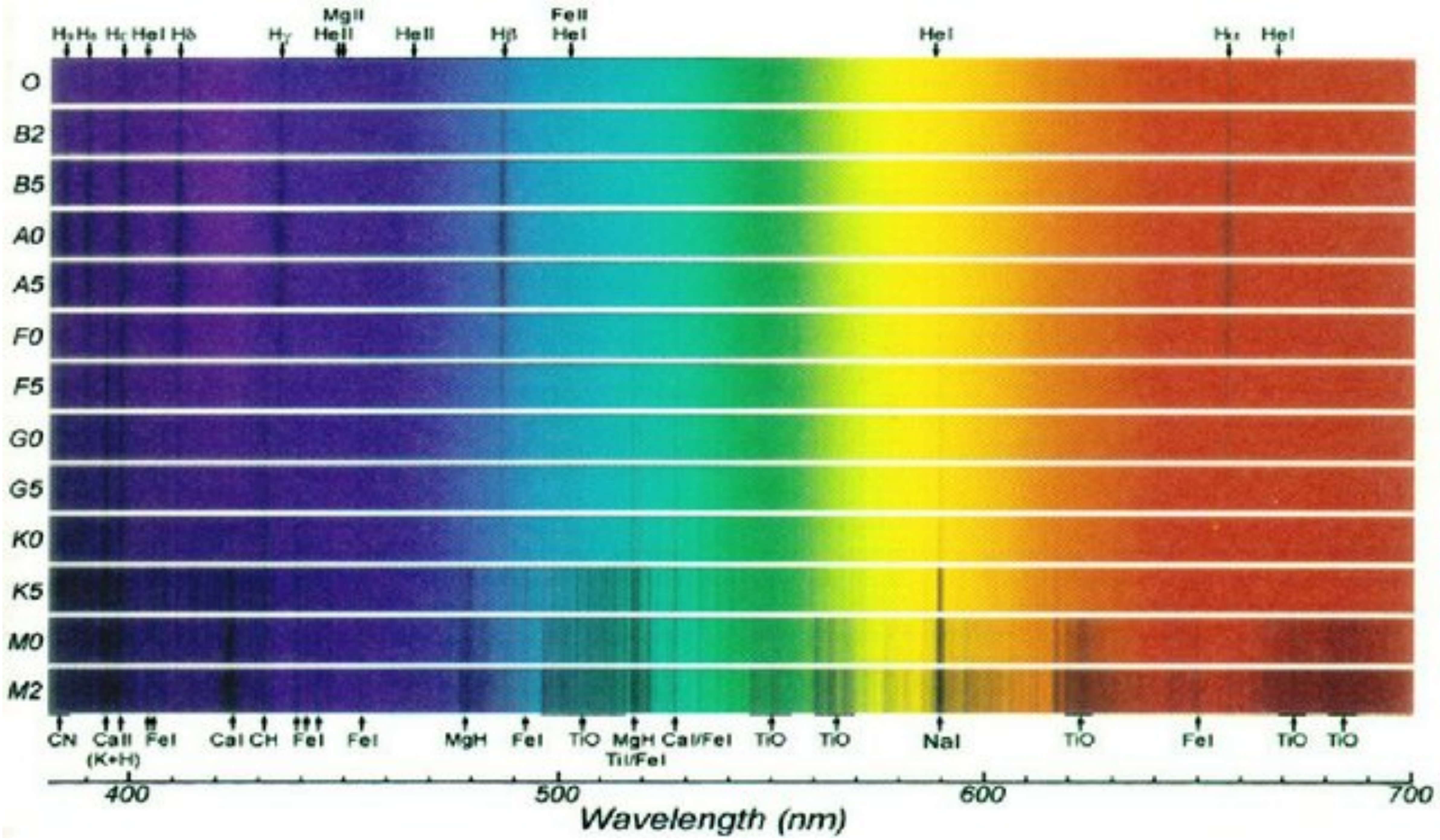


Joseph von Fraunhofer saw 1814 almost 600 lines in the spectrum of the sun

What can we learn from stellar spectra?

Spectra provide a lot of information about an astronomical object:

- temperature
- surface gravity
- chemical composition
- stellar winds
- magnetic fields
- projected rotation
- radial velocity:
  Doppler effect $\frac{v}{c} = \frac{\Delta\lambda}{\lambda}$



What is a stellar atmosphere?

- Stellar interiors are in-transparent to photons

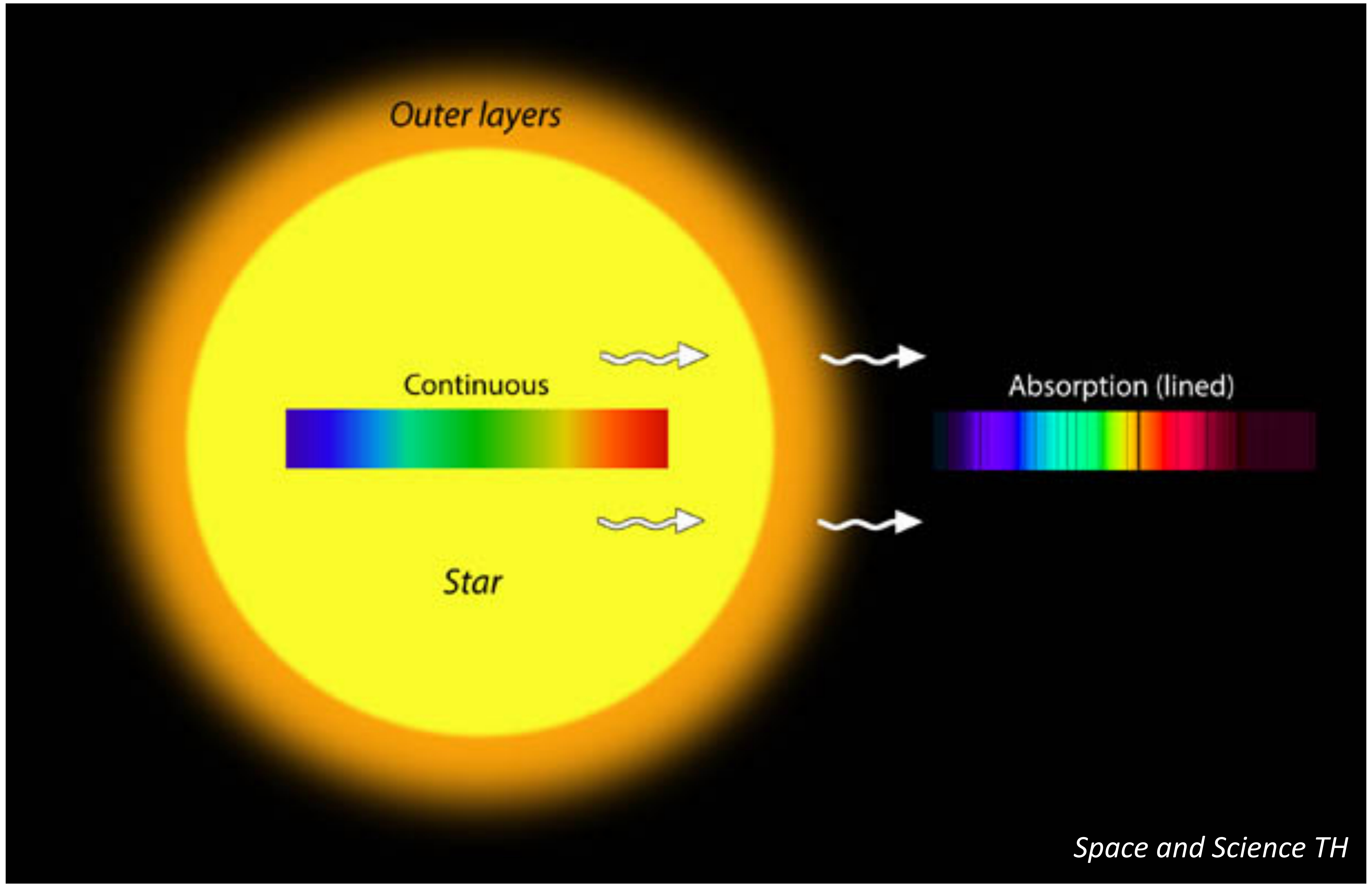
↓

The stellar interior is an almost perfect black body.

- The stellar atmosphere is the region from which photons can escape into space

↓

These are the photons we can observe.



We need to model the atmospheric structure and how photons are transferred from the bottom to the surface

What is a stellar atmosphere?

- Stellar interiors are in-transparent to photons

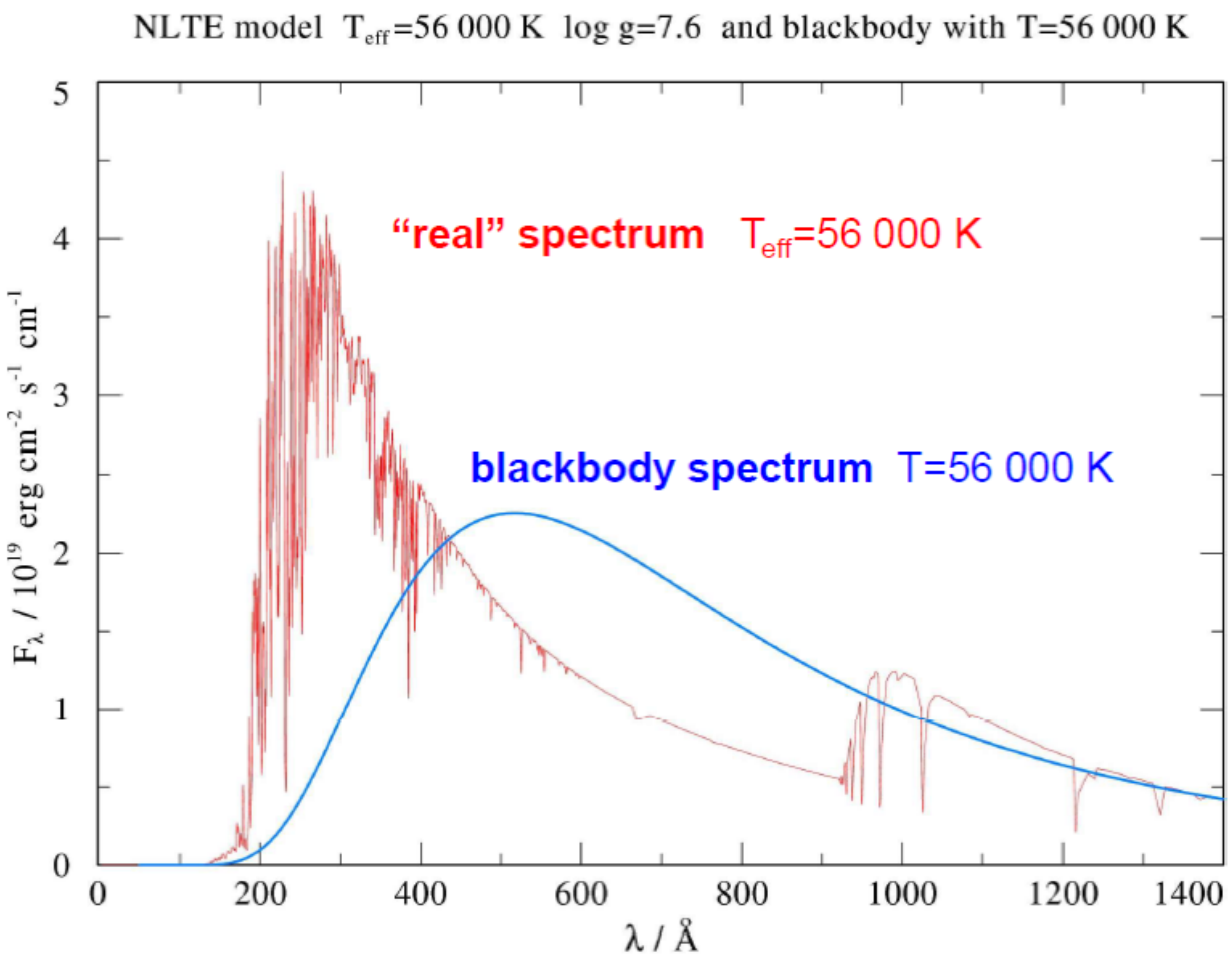
↓

The stellar interior is an almost perfect black body.

- The stellar atmosphere is the region from which photons can escape into space

↓

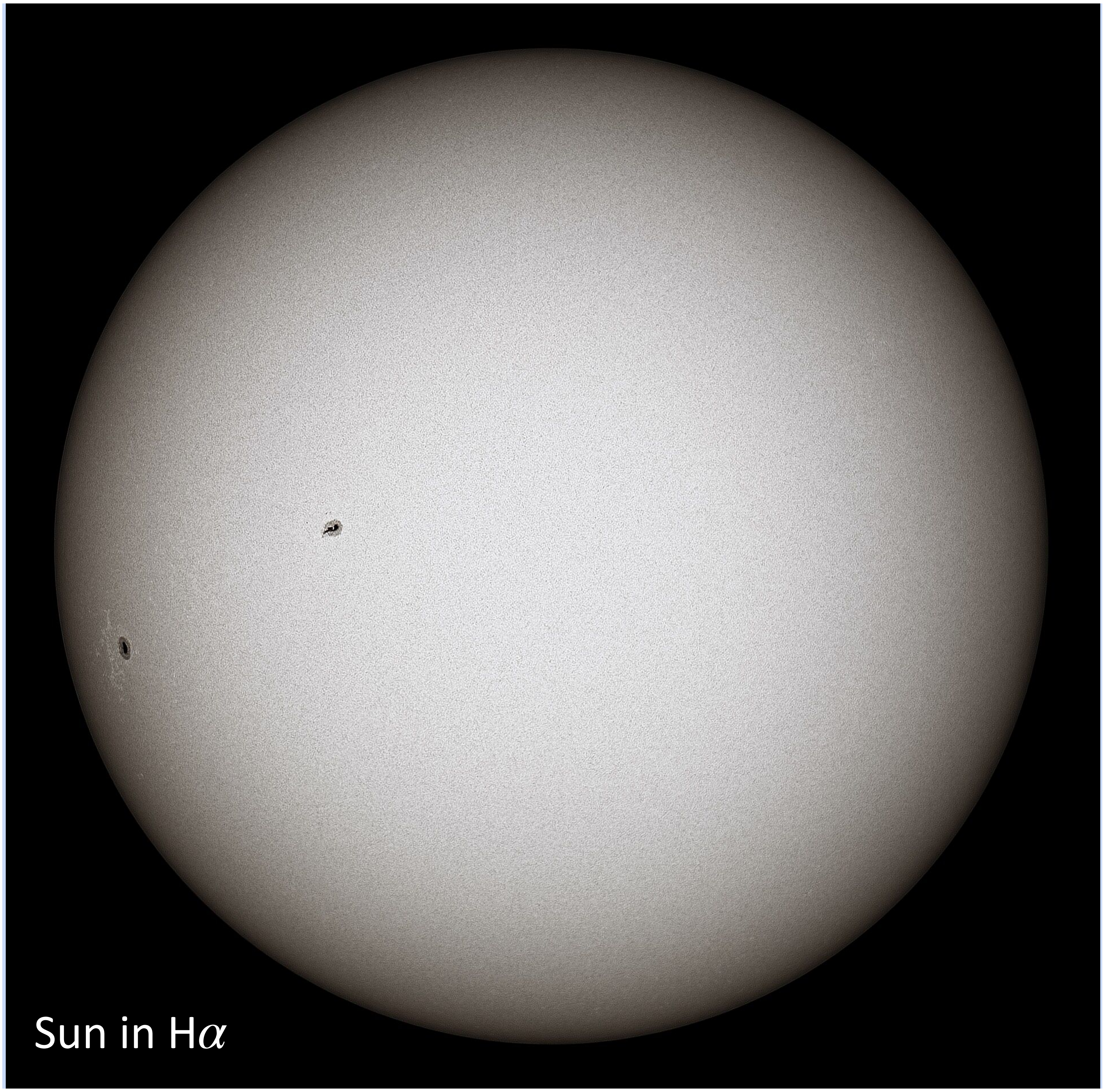
These are the photons we can observe.



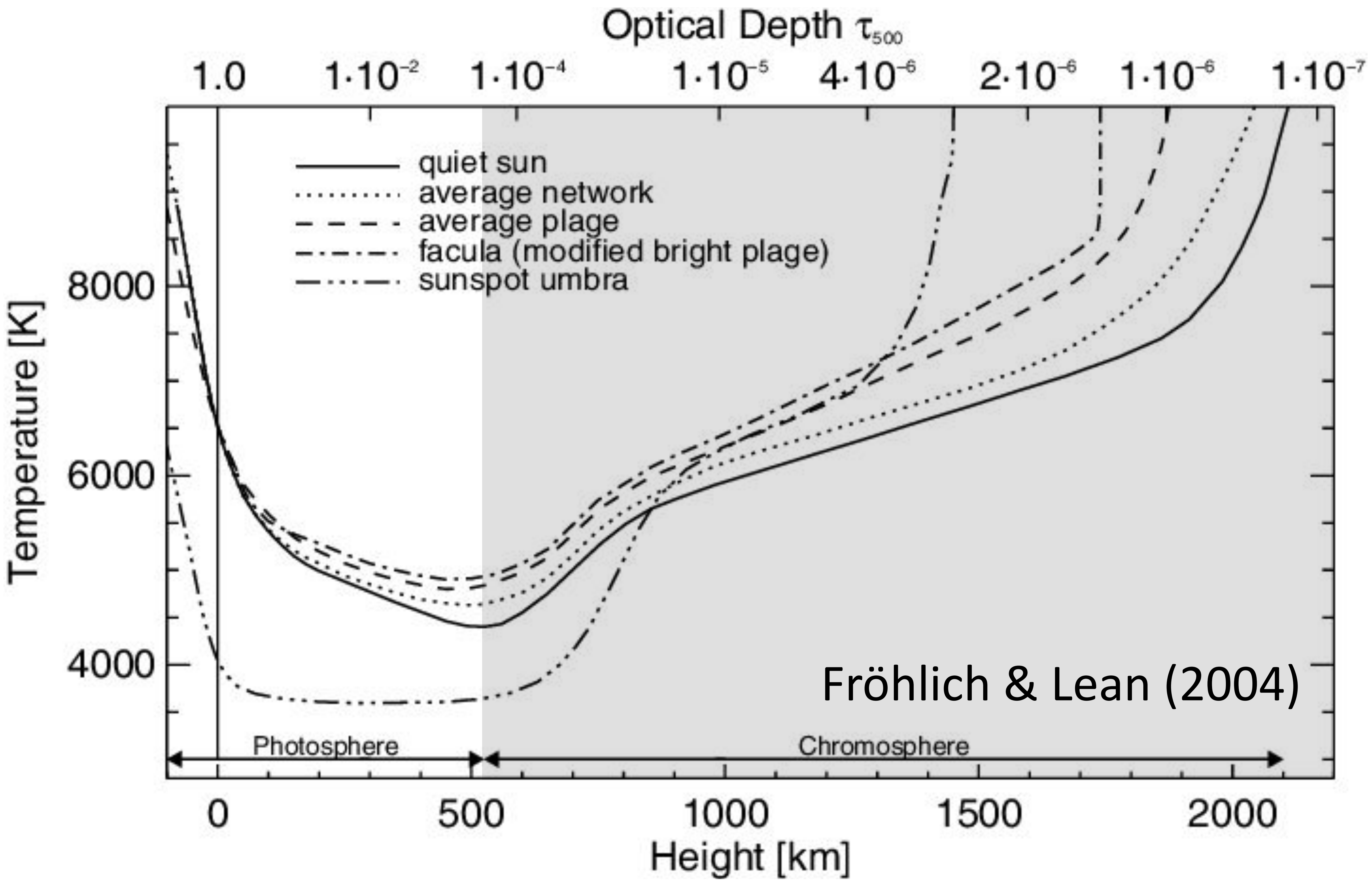
$$\int_0^\infty F_\nu \, d\nu = \sigma_{SB} T_{eff}^4$$

T_{eff} = temperature of a blackbody with same total energy flux as that of the star („equal areas" under spectral energy distributions)

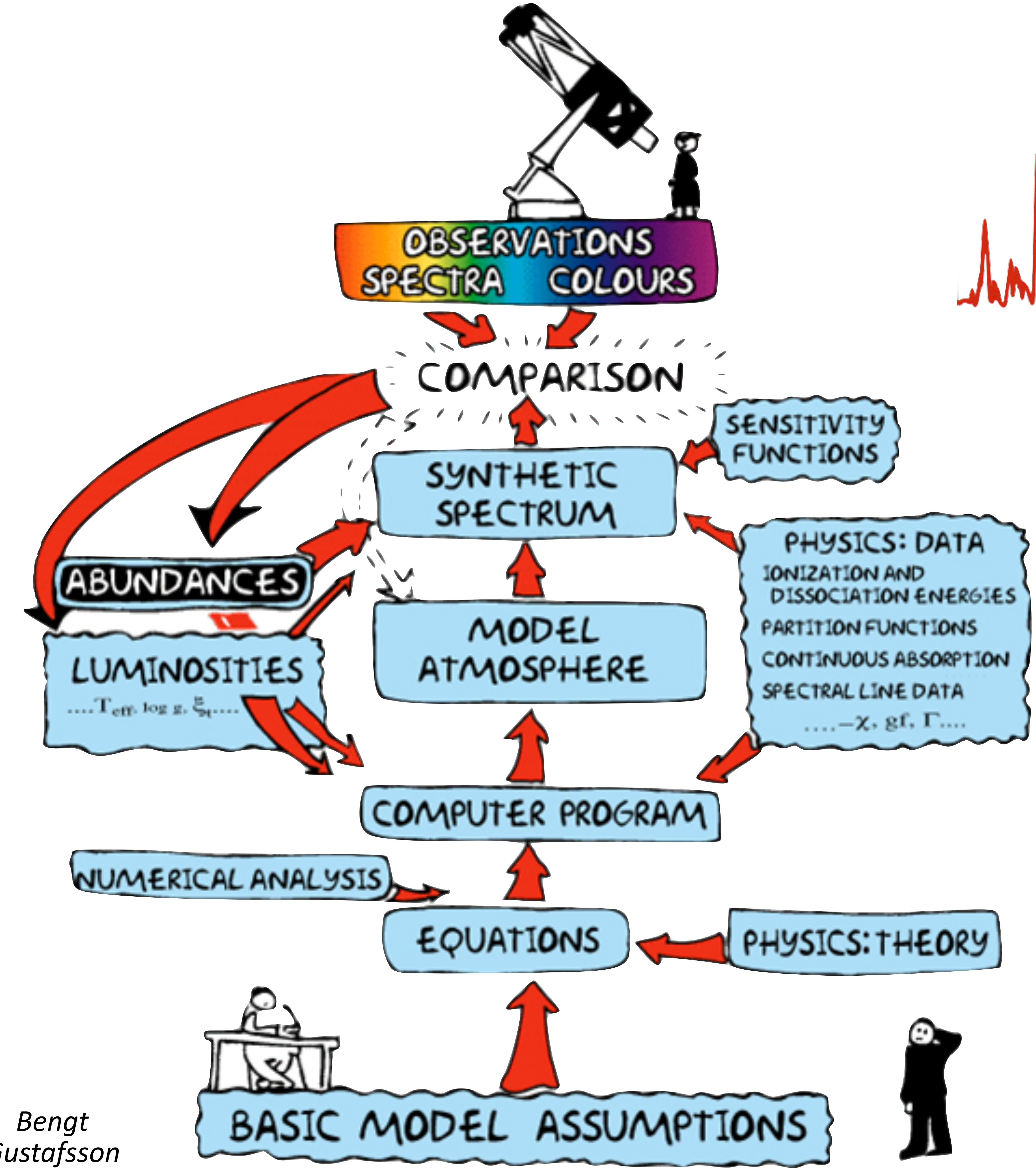
What is a stellar atmosphere?



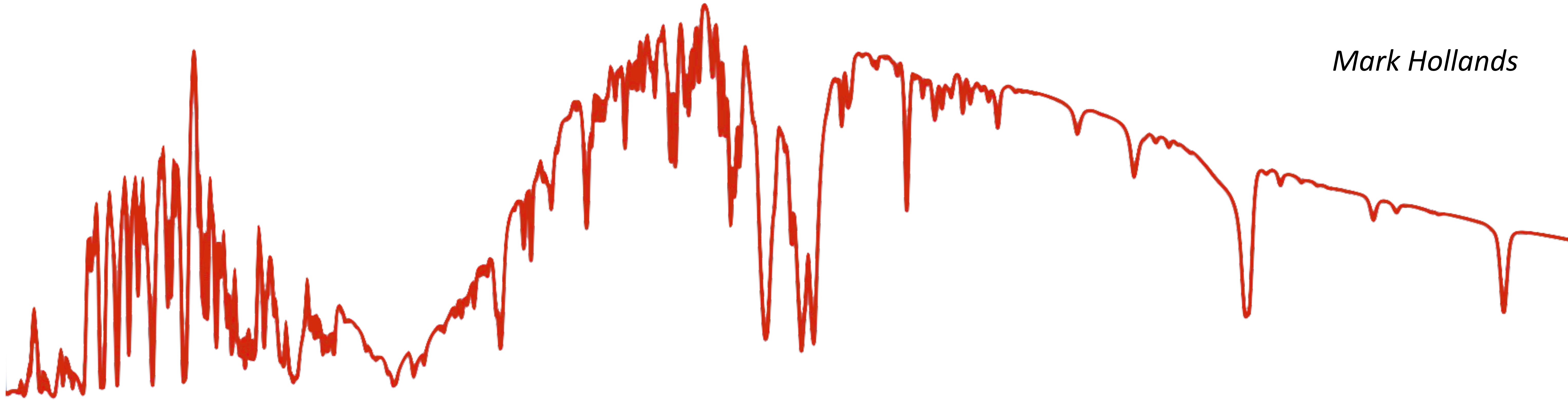
Solar atmospheric structure



The inversion problem



Bengt Gustafsson



Mark Hollands

<u>Inversion problem</u>

Given a set observations
derive the physics that produced them

Start with the outcome, calculate the causes

Radiative opacities

Opacity: Bound-bound absorption

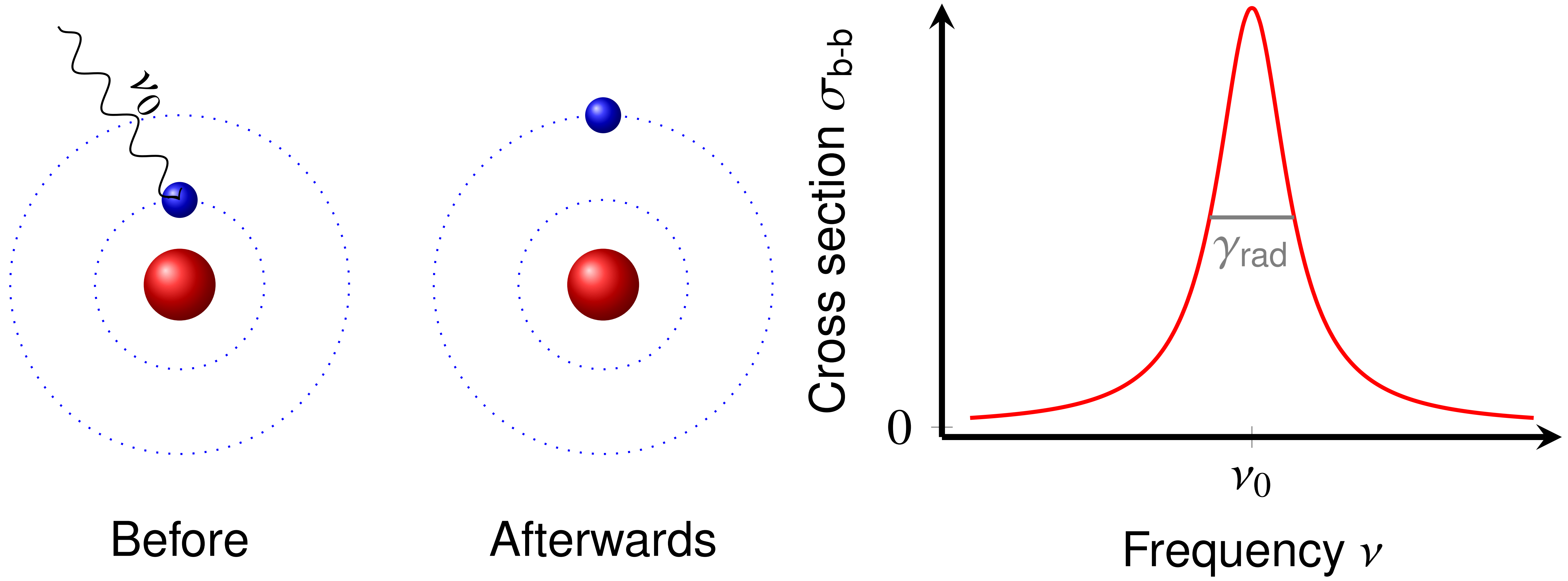


Figure 40: Bound-bound absorption is the absorption of a photon with energy $h\nu_0$ by an atom during which a bound electron makes a transition to a bound state of higher energy. The laboratory cross section is given in Eq. (101). The central frequency ν_0, oscillator strength f (dimensionless), and damping constant γ_{rad} (units: s^{-1}) are atomic properties (e is the electron charge, m_e the electron mass, and c the speed of light).

$$\sigma_{\text{b-b}}(\nu) = \frac{\pi e^2}{m_\text{e} c} \frac{f\gamma_{\text{rad}}/4\pi^2}{(\nu-\nu_0)^2 + (\gamma_{\text{rad}}/4\pi)^2} = 0.02654 \frac{f\gamma_{\text{rad}}/4\pi^2}{(\nu-\nu_0)^2 + (\gamma_{\text{rad}}/4\pi)^2}\,\text{cm}^2\,. \quad (101)$$

courtesy Andreas Irrgang

Emergent specific intensity

$$I_{\mu\nu}(\tau_\nu = 0) = \int_{\tau_1=0}^{\tau_2=\infty} S_\nu(t_\nu)\, e^{-t_\nu/\mu}\, \mathrm{d}t_\nu/\mu$$

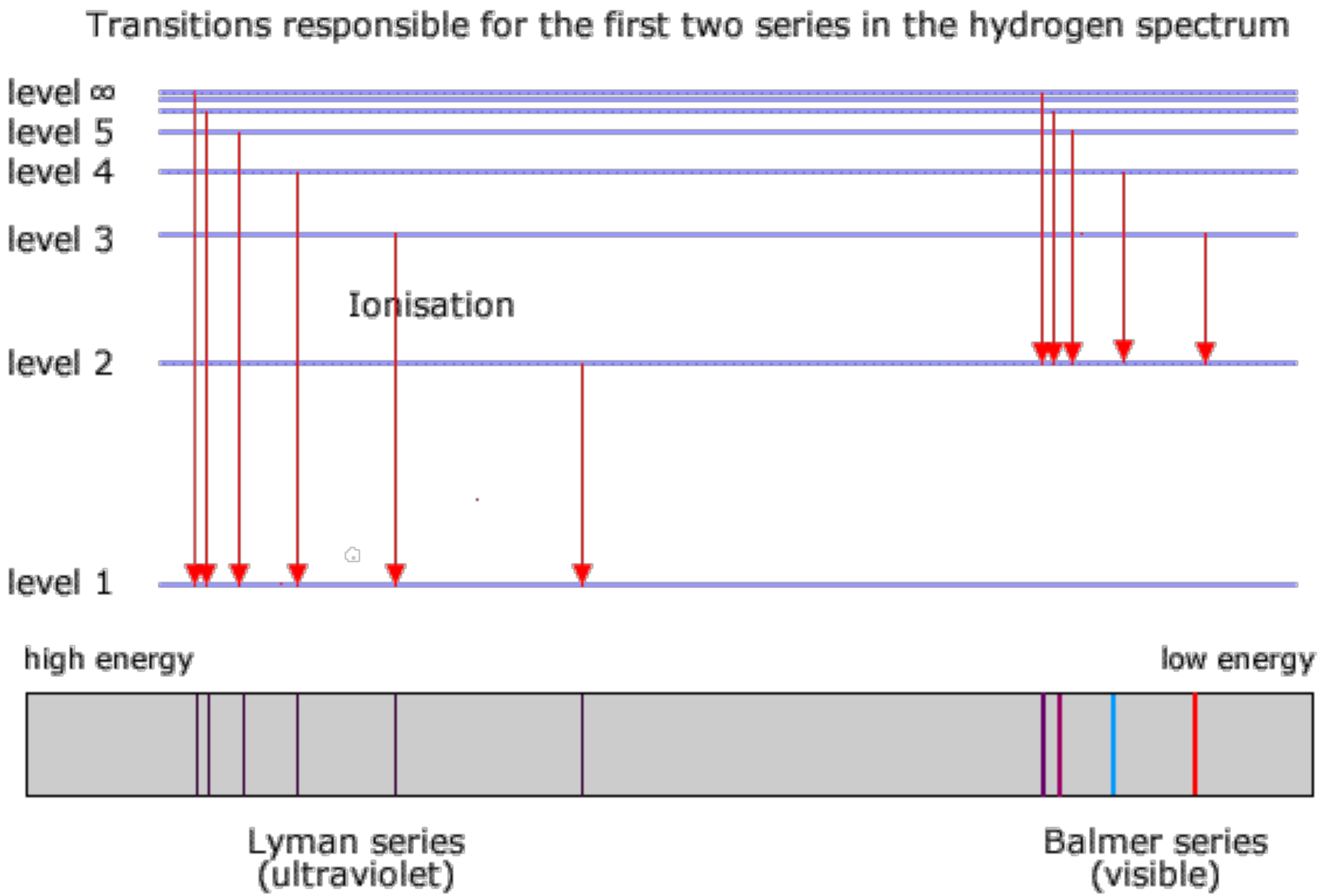
- χ_ν total absorption coefficient = „opacity“
- η_ν^{tot} total emission coefficient
- μ $\cos\Theta$, where Θ is the polar angle
- $S_\nu(\tau_\nu) = \chi_\nu/\eta_\nu^{\text{tot}}$ „source function“

bound-bound | bound-free | free-free

$$\chi_\nu = \kappa_\nu^{\text{scatter}} + \underbrace{\sum_i \sum_{j>i} \kappa_{ij}^{\text{bb}} + \sum_i \kappa_{ij}^{\text{bf}} + \sum_k \kappa_k^{\text{ff}}}_{\equiv \kappa_\nu^{\text{thermal}}},$$

similar for η_ν^{tot}

Hydrogen spectrum



Radiative opacities

Opacity: Bound-free absorption

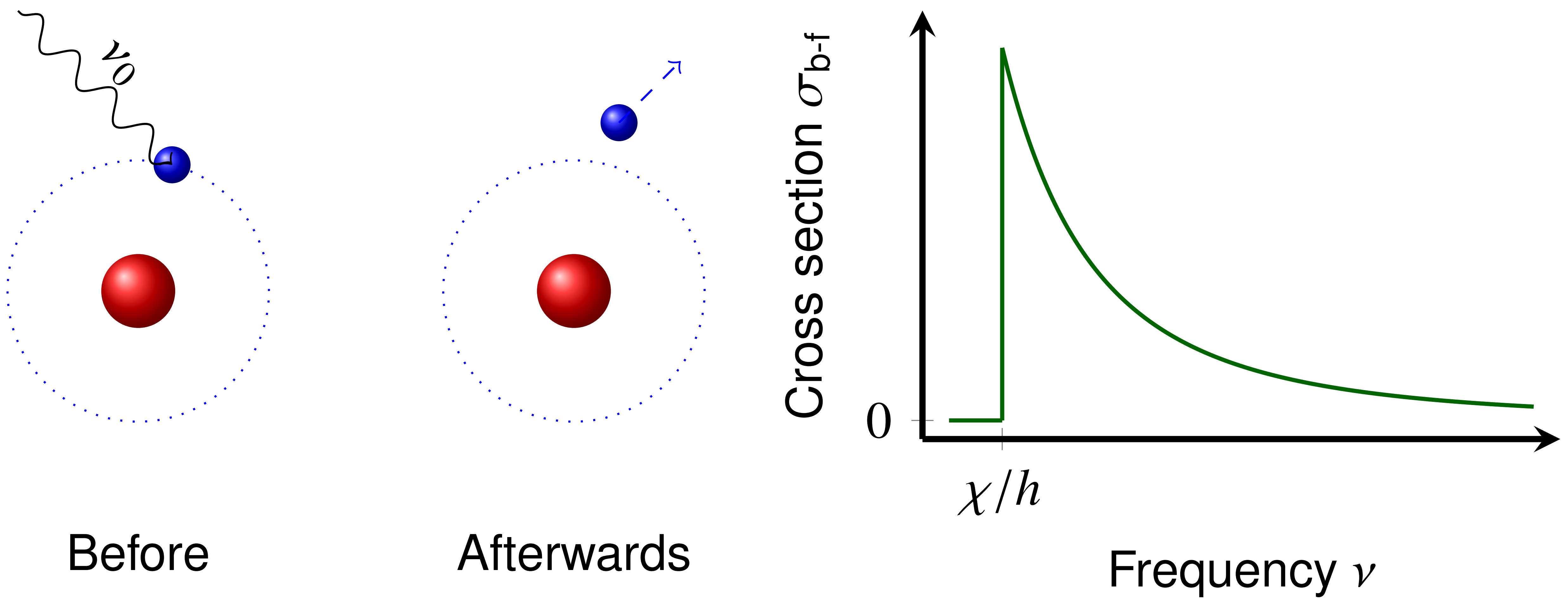


Figure 41: Bound-free absorption is the absorption of a photon by an atom during which a bound electron is released from the atom if the photon energy $h\nu_0$ exceeds the ionization energy χ. The laboratory cross section for a hydrogenic atom with charge $\mathcal{Z}$ and principal quantum number n is given in Eq. (102). The dimensionless Gaunt factor g depends also on the angular momentum quantum number l and is at the order of unity.

$$\sigma_{\text{b-f}}(\nu) = \frac{64\pi^4 m_e e^{10}}{3\sqrt{3}ch^6} \frac{\mathcal{Z}^4}{n^5} \frac{g(\nu,n,l,\mathcal{Z})}{\nu^3} = 2.8154\times10^{29} \frac{\mathcal{Z}^4}{n^5} \frac{g(\nu,n,l,\mathcal{Z})}{\nu^3}\ \text{cm}^2\,. \quad (102)$$

courtesy Andreas Irrgang

Emergent specific intensity

$$I_{\mu\nu}(\tau_\nu = 0) = \int_{\tau_1=0}^{\tau_2=\infty} S_\nu(t_\nu)\, e^{-t_\nu/\mu}\, \mathrm{d}t_\nu/\mu$$

χ_ν total absorption coefficient = „opacity“

η_ν^{tot} total emission coefficient

μ $\cos\Theta$, where Θ is the polar angle

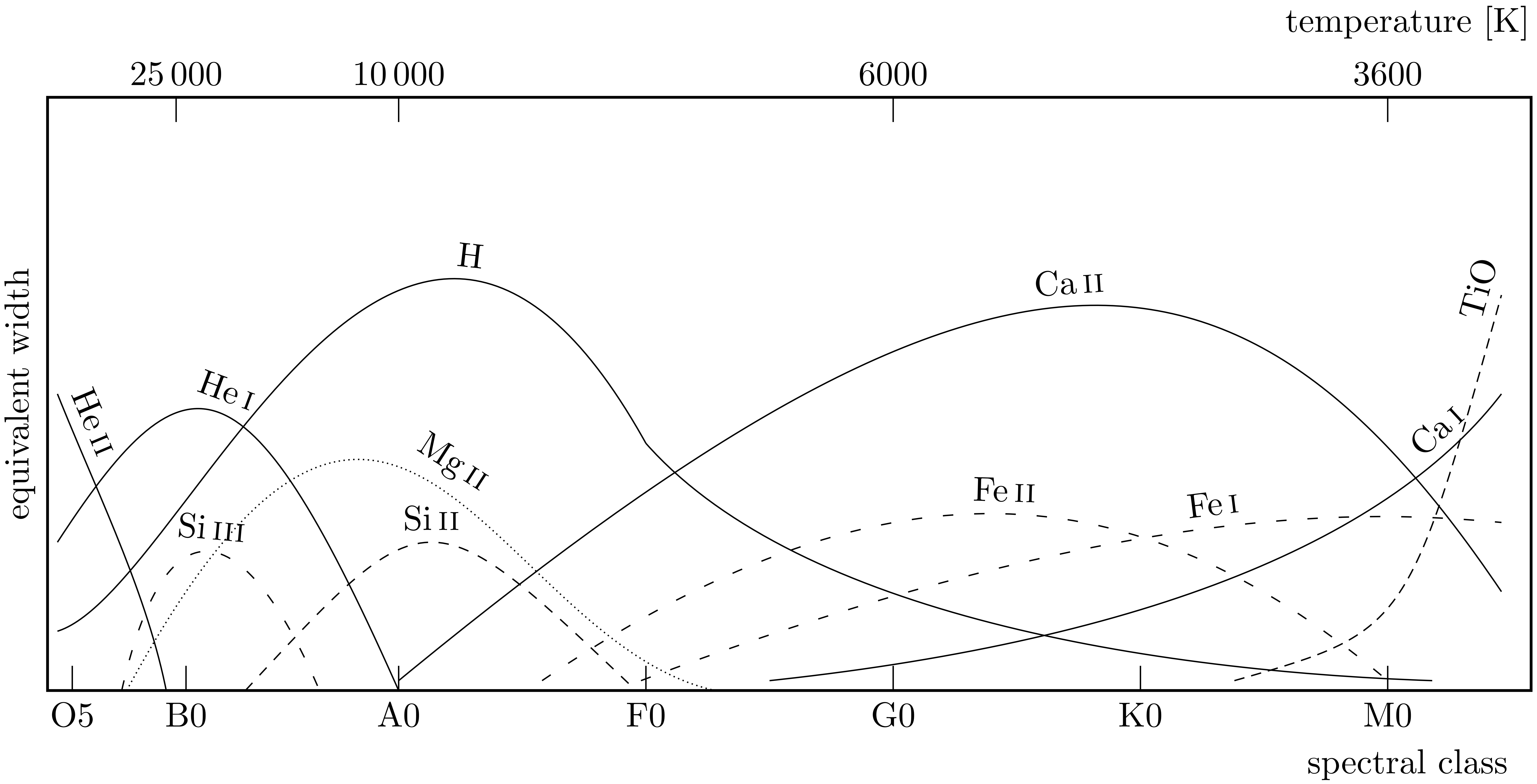
$S_\nu(\tau_\nu) = \chi_\nu/\eta_\nu^{\text{tot}}$ „source function“

bound-bound, bound-free, free-free

$$\chi_\nu = \kappa_\nu^{\text{scatter}} + \underbrace{\sum_i \sum_{j>i} \kappa_{ij}^{\text{bb}} + \sum_i \kappa_{ij}^{\text{bf}} + \sum_k \kappa_k^{\text{ff}}}_{\equiv \kappa_\nu^{\text{thermal}}},$$

similar for η_ν^{tot}

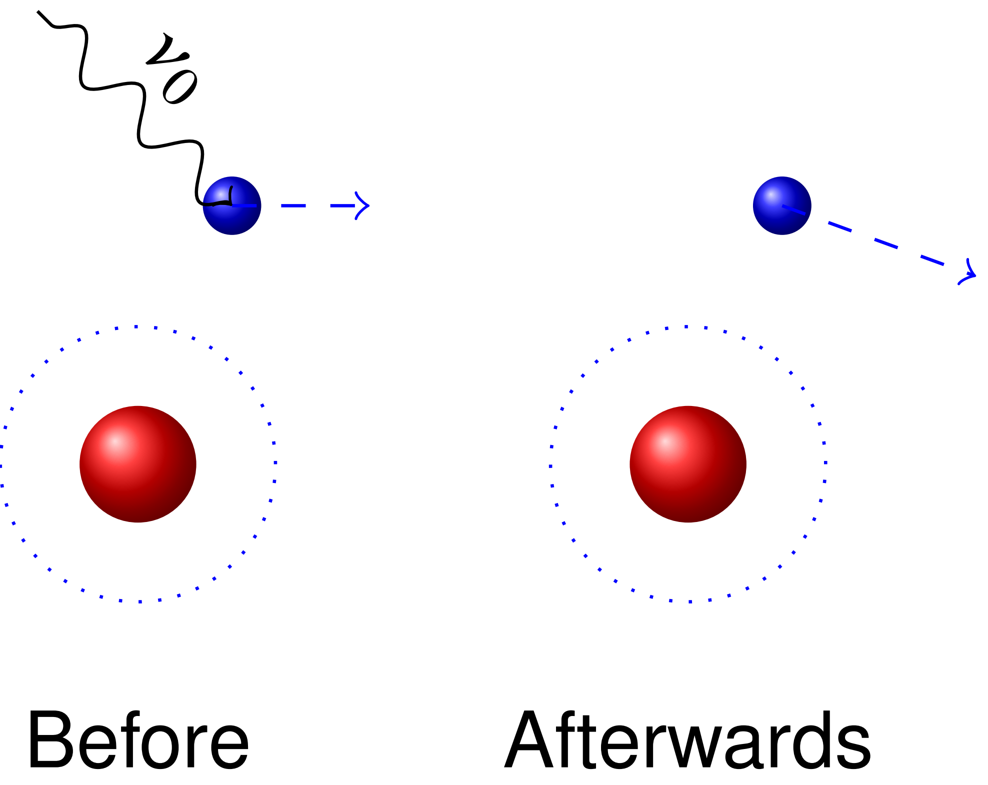
Line strength vs temperature



Fundamental Astronomy: Karttunen et al.

Radiative opacities

Opacity: free-free absorption



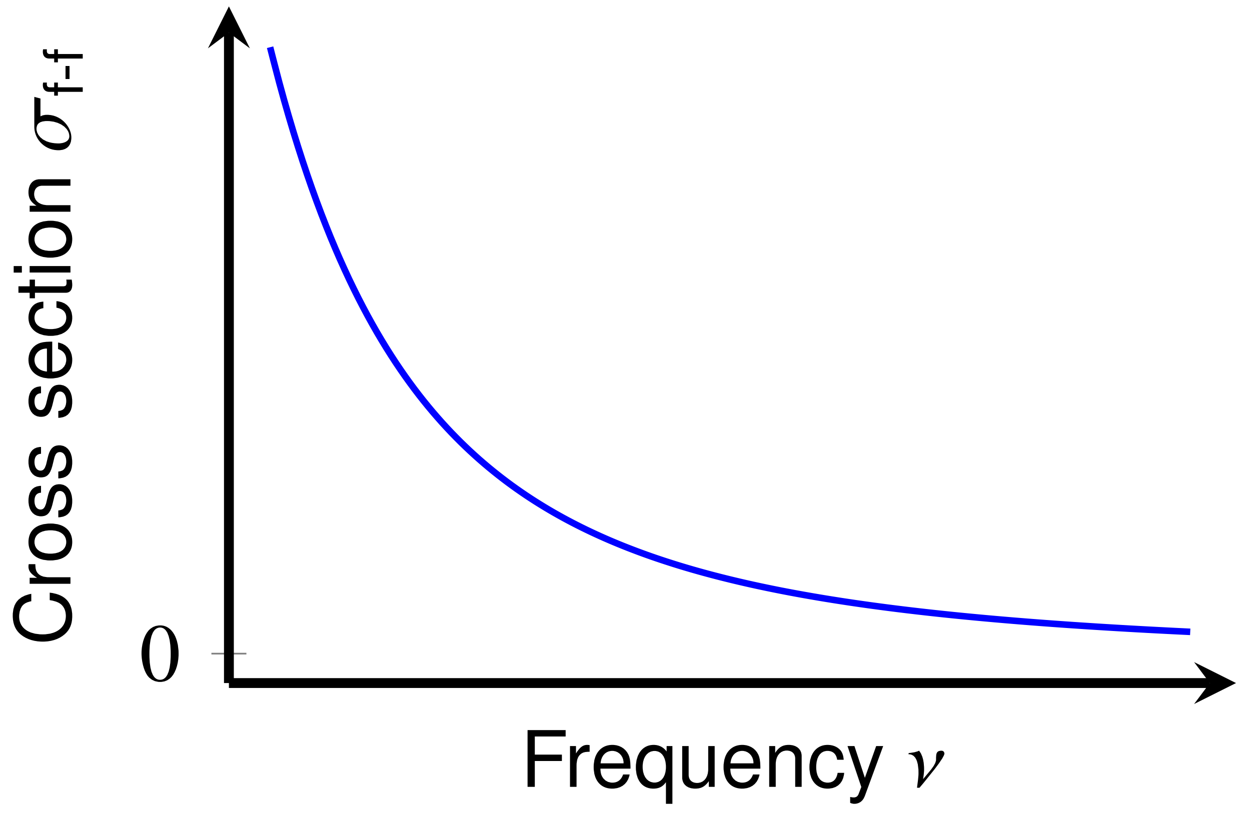


Figure 42: Free-free absorption is the absorption of a photon by a free electron as it passes an ion and makes a transition to another free state of higher energy. Its inverse process is bremsstrahlung. The cross section for electrons following a Maxwellian velocity distribution is given in Eq. (103). The dimensionless temperature-averaged Gaunt factor $\bar{g}_{\text{f-f}}$ is near unity for almost all astrophysical circumstances.

$$\sigma_{\text{f-f}}(\nu) = \frac{16\pi^2 e^6}{(6\pi m_e)^{3/2} hc} \frac{\mathcal{Z}^2 n_e \bar{g}_{\text{f-f}}(\nu, \mathcal{Z}, T)}{(kT)^{1/2}\nu^3} = 3.6923 \times 10^8 \frac{\mathcal{Z}^2 n_e \bar{g}_{\text{f-f}}(\nu, \mathcal{Z}, T)}{T^{1/2}\nu^3} \text{ cm}^2 . \tag{103}$$

courtesy Andreas Irrgang

Emergent specific intensity

$$I_{\mu\nu}(\tau_\nu = 0) = \int_{\tau_1=0}^{\tau_2=\infty} S_\nu(t_\nu)\, e^{-t_\nu/\mu}\, \mathrm{d}t_\nu/\mu$$

χ_ν total absorption coefficient = „opacity"

η_ν^{tot} total emission coefficient

μ $\cos\Theta$, where Θ is the polar angle

$S_\nu(\tau_\nu) = \chi_\nu/\eta_\nu^{\text{tot}}$ „source function"

bound-bound, bound-free, free-free

$$\chi_\nu = \kappa_\nu^{\text{scatter}} + \underbrace{\sum_i \sum_{j>i} \kappa_{ij}^{\text{bb}} + \sum_i \kappa_{ij}^{\text{bf}} + \sum_k \kappa_k^{\text{ff}}}_{\equiv \kappa_\nu^{\text{thermal}}},$$

similar for η_ν^{tot}

Radiative opacities

Opacity: Electron scattering

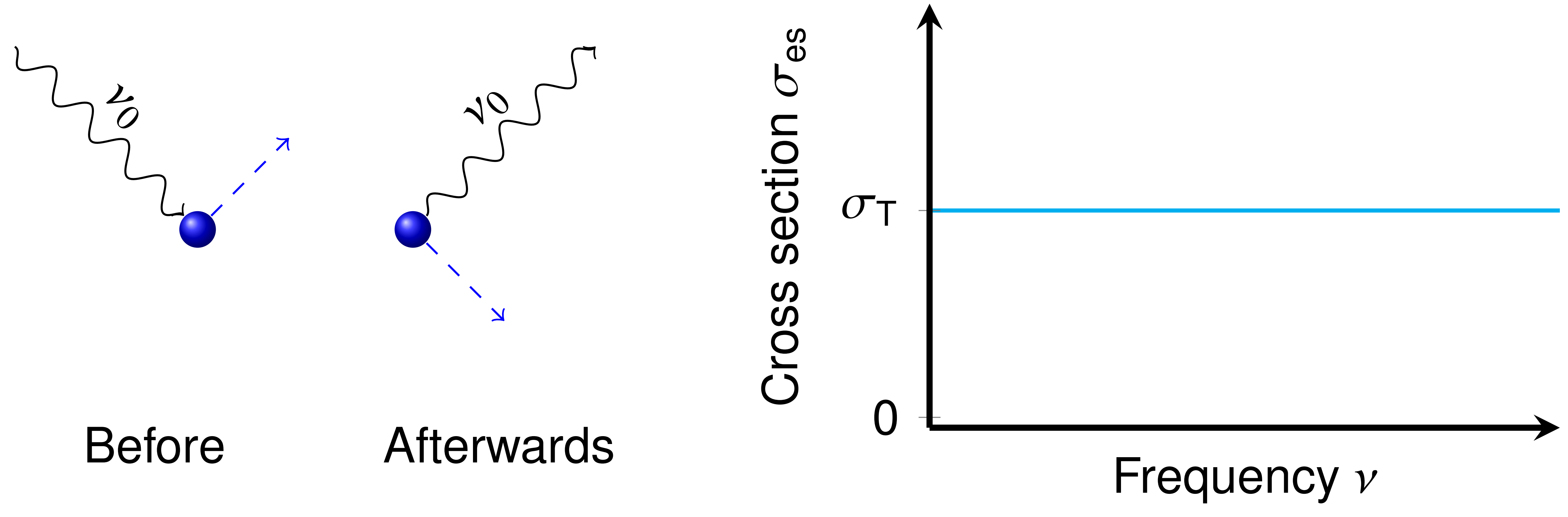


Figure 43: The scattering of photons by individual free electrons in the gas is commonly called *Compton scattering*, or in the non-relativistic approximation usually applicable in stars, *Thomson scattering*. The cross section for Thomson scattering is a constant which is given in Eq. (104). The scattering from ions or molecules via bound electrons is called *Rayleigh scattering* and becomes only important in those regions where ionization is incomplete, i.e., in the stellar envelope.

$$\sigma_{\mathrm{es}} = \sigma_{\mathrm{T}} \equiv \frac{8\pi}{3}\left(\frac{e^2}{m_{\mathrm{e}}c^2}\right)^2 = 6.6525 \times 10^{-25}\,\mathrm{cm}^2\,. \qquad (104)$$

courtesy Andreas Irrgang

Emergent specific intensity

$$I_{\mu\nu}(\tau_\nu = 0) = \int_{\tau_1=0}^{\tau_2=\infty} S_\nu(t_\nu)\, e^{-t_\nu/\mu}\, \mathrm{d}t_\nu/\mu$$

χ_ν total absorption coefficient = „opacity“

η_ν^{tot} total emission coefficient

μ $\cos\Theta$, where Θ is the polar angle

$S_\nu(\tau_\nu) = \chi_\nu/\eta_\nu^{\mathrm{tot}}$ „source function“

bound-bound, bound-free, free-free

$$\chi_\nu = \kappa_\nu^{\mathrm{scatter}} + \underbrace{\sum_i \sum_{j>i} \kappa_{ij}^{\mathrm{bb}} + \sum_i \kappa_{ij}^{\mathrm{bf}} + \sum_k \kappa_k^{\mathrm{ff}}}_{\equiv \kappa_\nu^{\mathrm{thermal}}},$$

similar for η_ν^{tot}

Radiative opacities

The total opacity

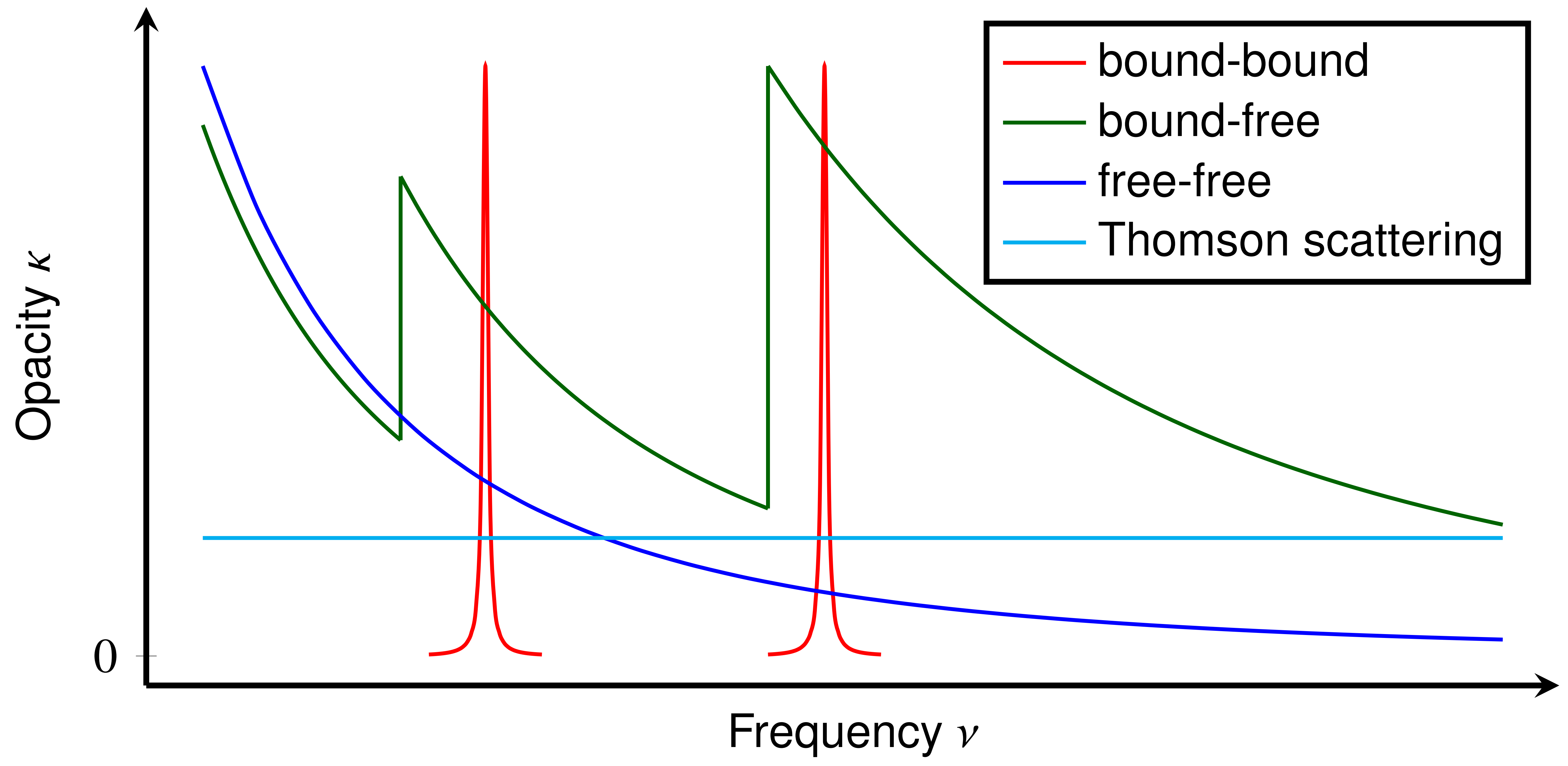


Figure 45: The total opacity is a superposition of the four individual processes. Moreover, the contributions from all the available chemical species have to be considered. The total opacity is hence a (complex) function of the chemical composition as well as of the thermodynamic state of the stellar matter: $\kappa = \kappa(T, \rho, \{X_i\})$.

courtesy Andreas Irrgang

Emergent specific intensity

$$I_{\mu\nu}(\tau_\nu = 0) = \int_{\tau_1=0}^{\tau_2=\infty} S_\nu(t_\nu)\, e^{-t_\nu/\mu}\, \mathrm{d}t_\nu/\mu$$

χ_ν total absorption coefficient = „opacity"

η_ν^{tot} total emission coefficient

μ $\cos\Theta$, where Θ is the polar angle

$S_\nu(\tau_\nu) = \chi_\nu/\eta_\nu^{\mathrm{tot}}$ „source function"

bound-bound, bound-free, free-free

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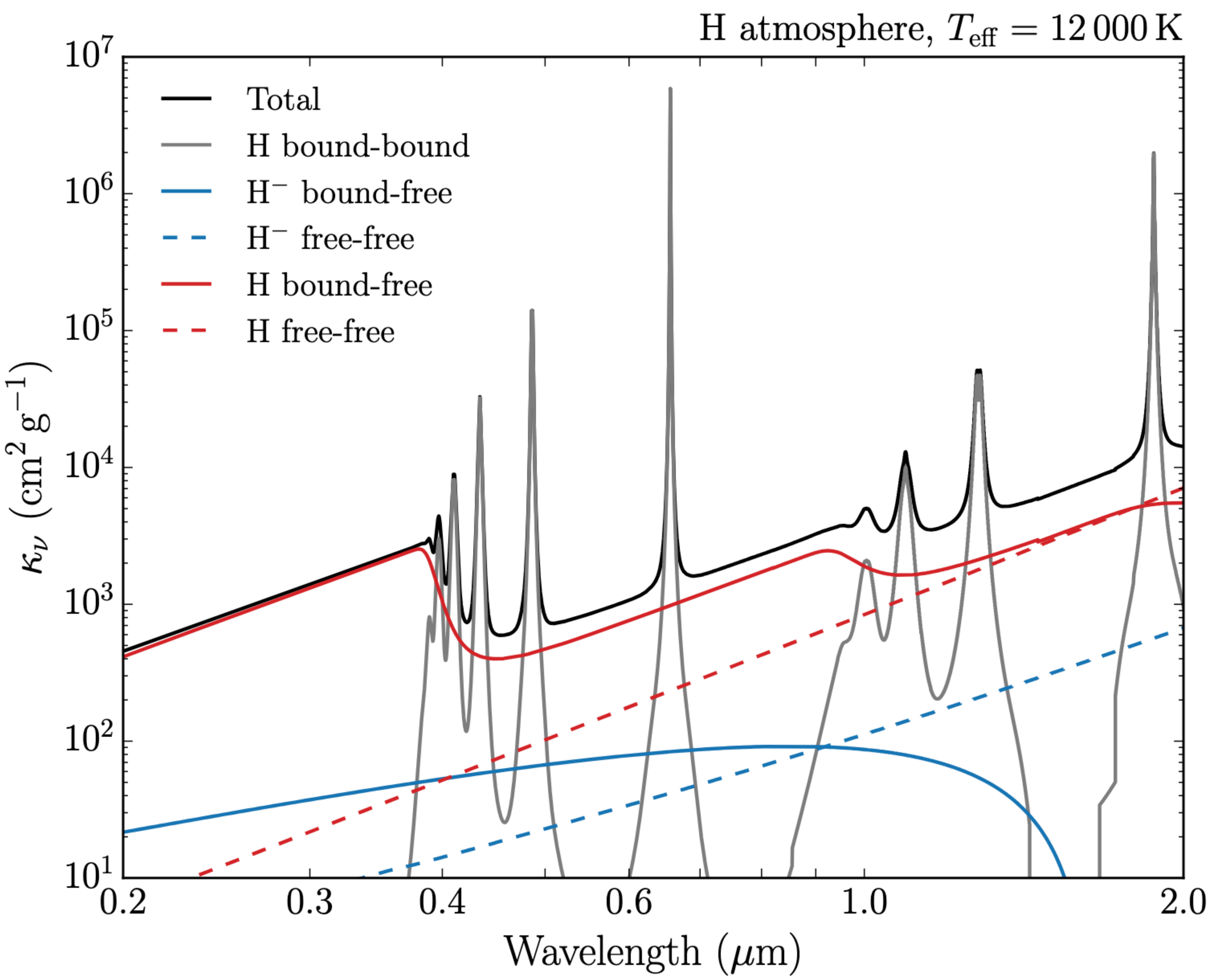
Radiative opacities



Radiative opacity in a DA WD, by Saumon et al. (2022)

Emergent specific intensity

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$$\chi_\nu = \kappa_\nu^{\rm scatter} + \underbrace{\sum_i \sum_{j>i} \kappa_{ij}^{\rm bb} + \sum_i \kappa_{ij}^{\rm bf} + \sum_k \kappa_k^{\rm ff}}_{\equiv \kappa_\nu^{\rm thermal}},$$

similar for $\eta_\nu^{\rm tot}$

Energy level population and ionization stage

Line strength: # of absorbers x line absorption cross-section σ_{ij}

$$\sigma_{ij} = \frac{\pi e^2}{mc} f_{ij} \Phi_\nu \tag{3.1}$$

f_{ij} is the oscillator strength, which is related to the transition probability, Φ_ν the absorption profile

Boltzmann-equation: population of the energy levels within an atom depends in a detailed way upon the mechanisms for populating and de-populating them: radiative, collisional & spontaneous

$$\frac{N_j}{N_i} = \frac{g_j}{g_i} e^{-\frac{E_j - E_i}{kT}} \tag{3.2}$$

g_i/g_j are statistical weights that take into account degeneracy of energy states

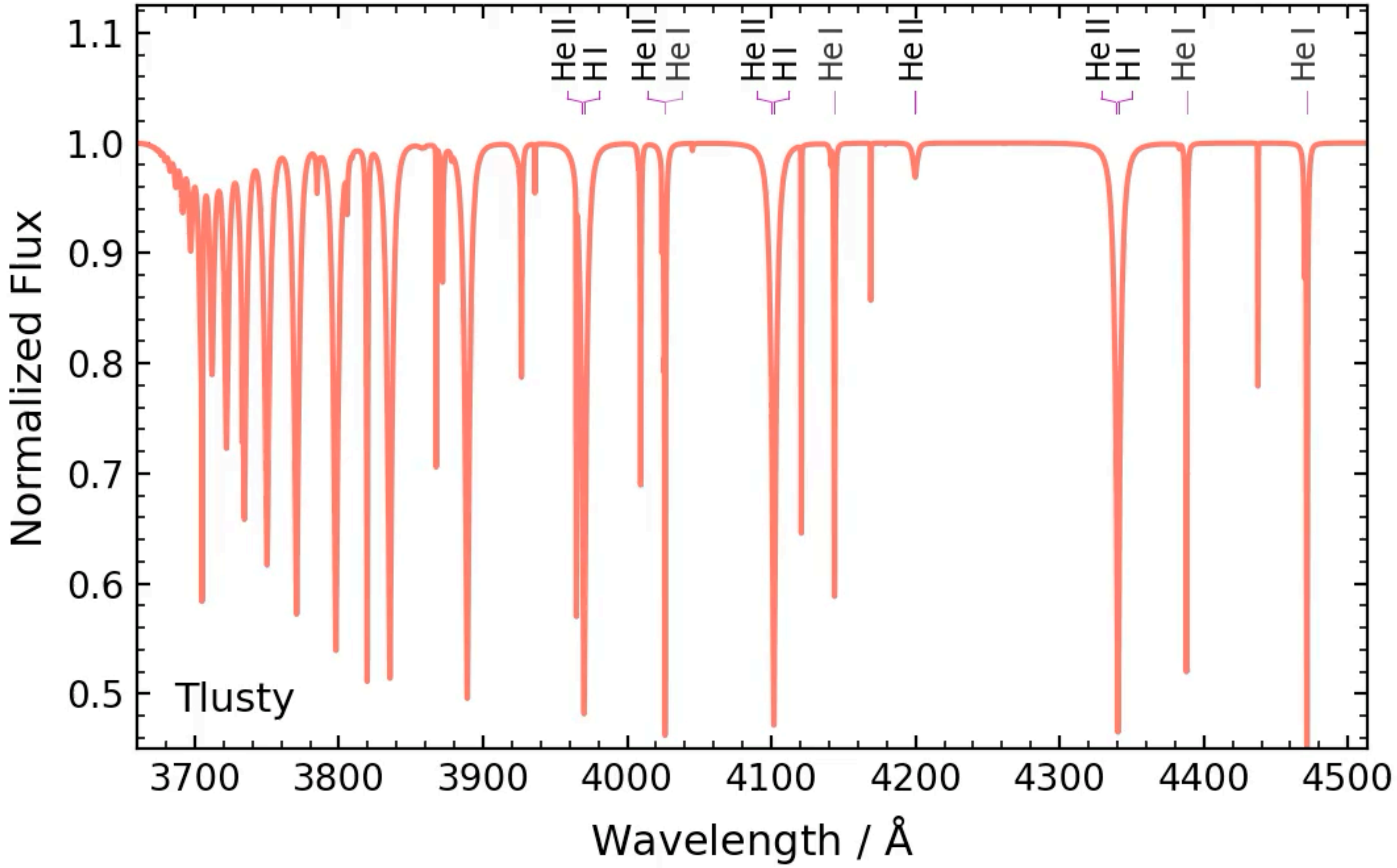
Saha equation: number of atoms in a given ionization stage

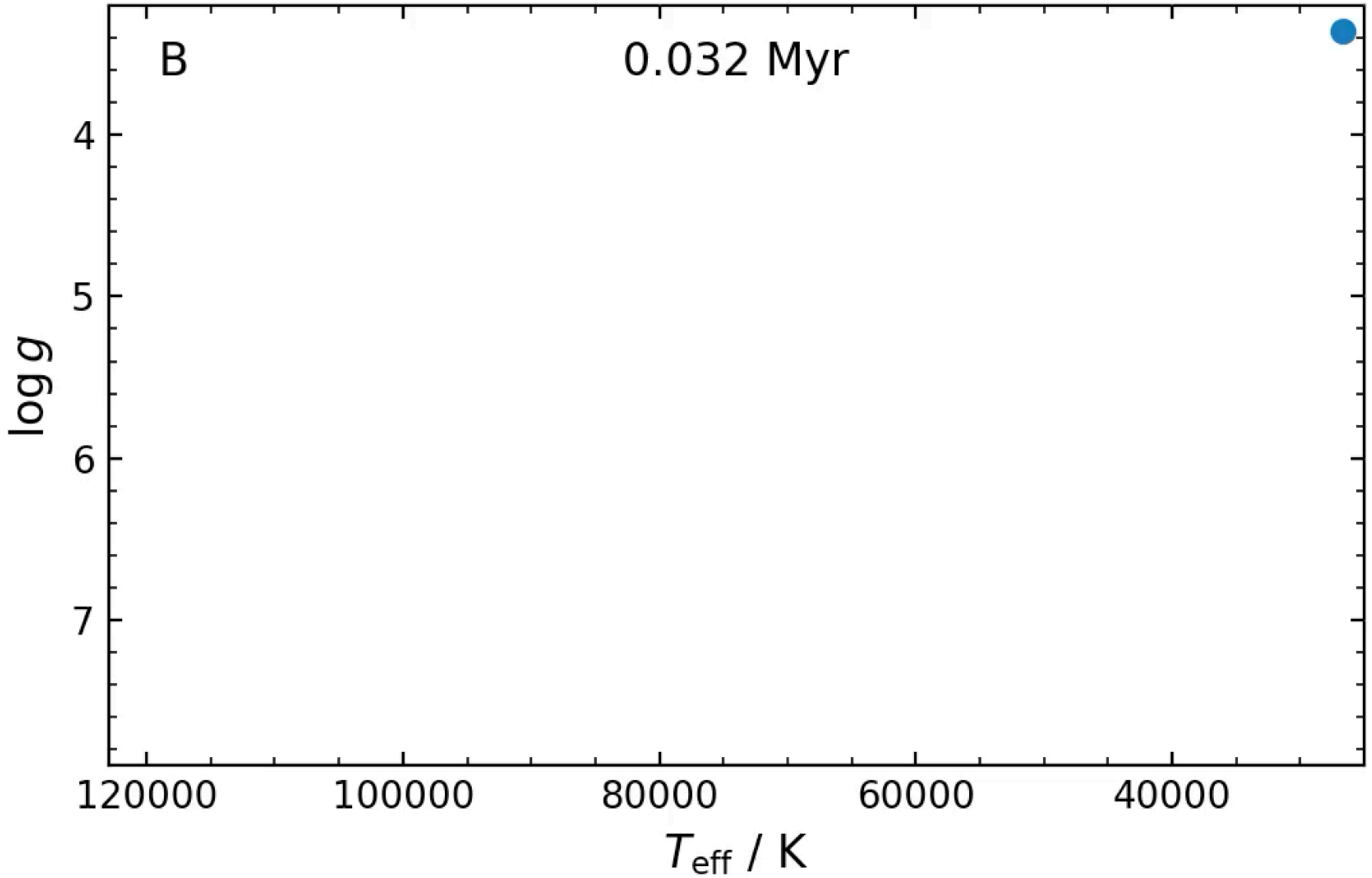
$$\frac{N(X_{r+1})}{N(X_r)} = \frac{2kTg_{r+1}}{P_e g_r} \left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-\chi_i/kT} \tag{3.3}$$

Why we need model spectra

$T_{\rm eff}$ $\log g$ Helium Metals Radiative acceleration Wind strength Field strength

$0.53\,M_\odot$ *(Miller-Bertolami+ 2016)*





Why we need model spectra

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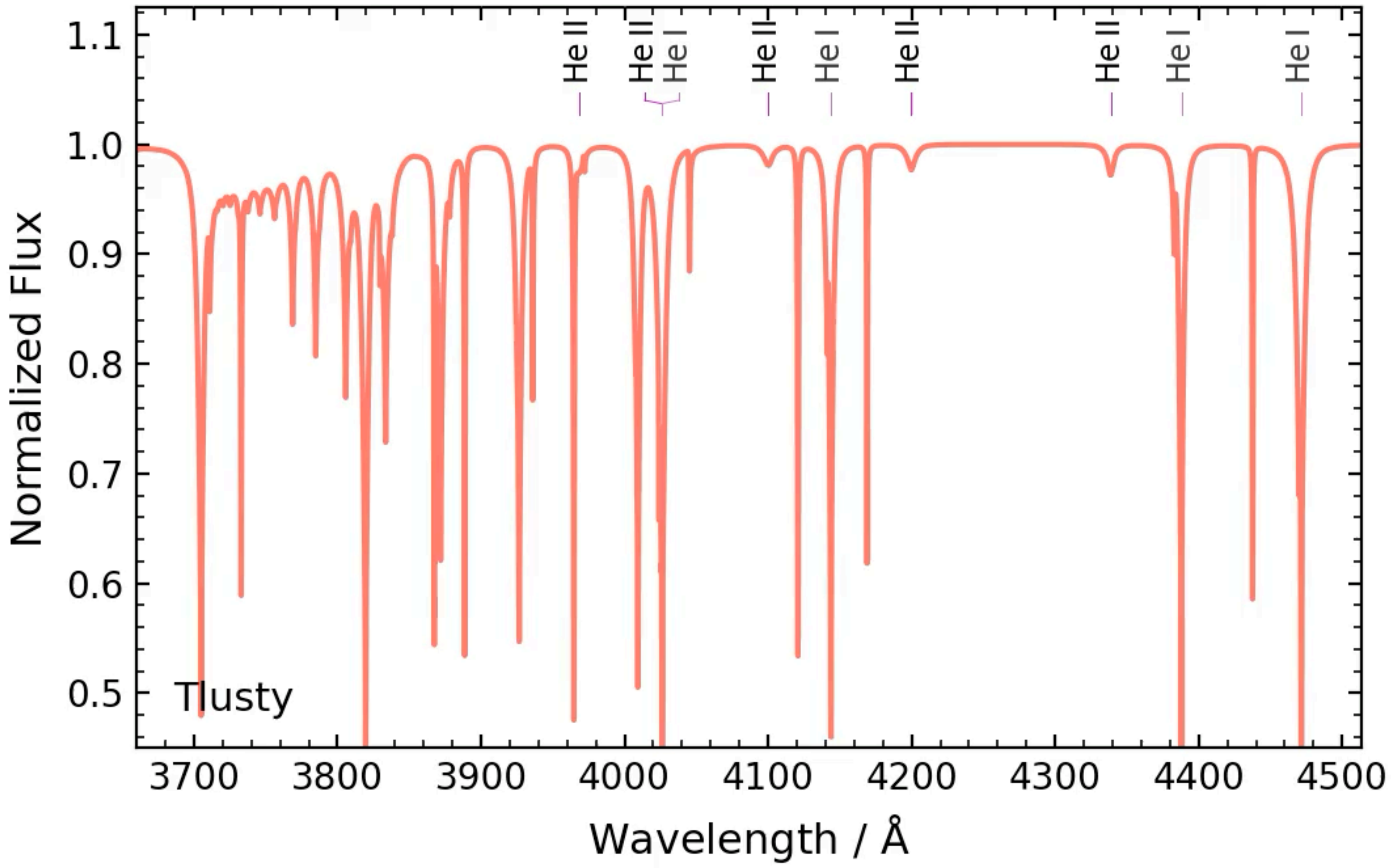
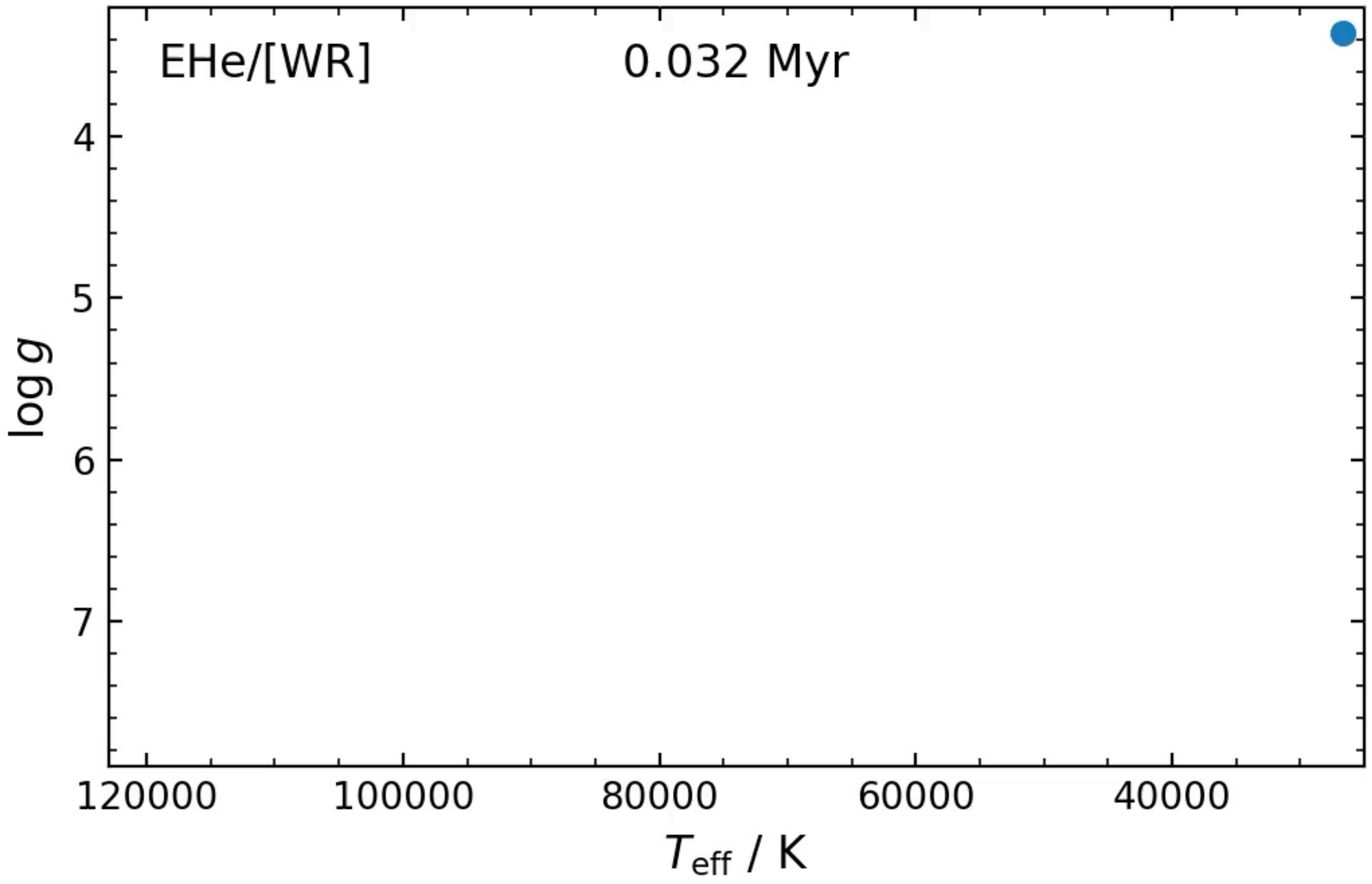
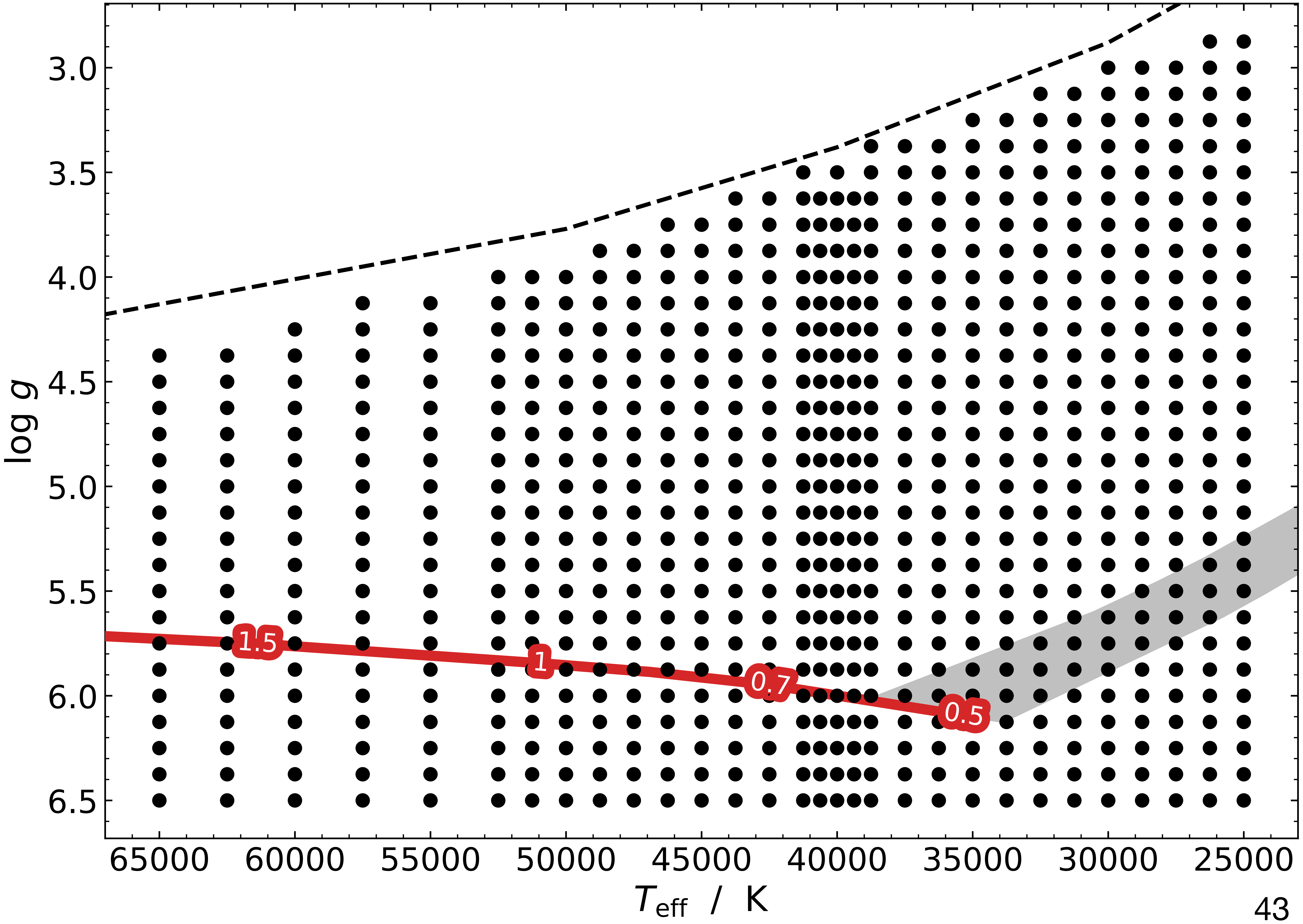




A large grid of model spectra

A slice of the grid for $\log n(\mathrm{He})/n(\mathrm{H}) = +1$

- First step — re-determine atmospheric parameters: T_{eff}, $\log g$, helium abundance
- Over 17,000 models covering the sdO/B parameter space
  - Opacity from H, He, C, N, O, Ne, Si, P, S, Fe, Ni
  - non-LTE („LTE“ = Local Thermal Equilibrium)



A large grid of model sp

- First step — re-determine atmospheric parameters: T_{eff}, $\log g$, helium abundance
- Over 17,000 models covering the sdO/B parameter space
  - Opacity from H, He, C, N, O, Ne, Si, P, S, Fe, Ni
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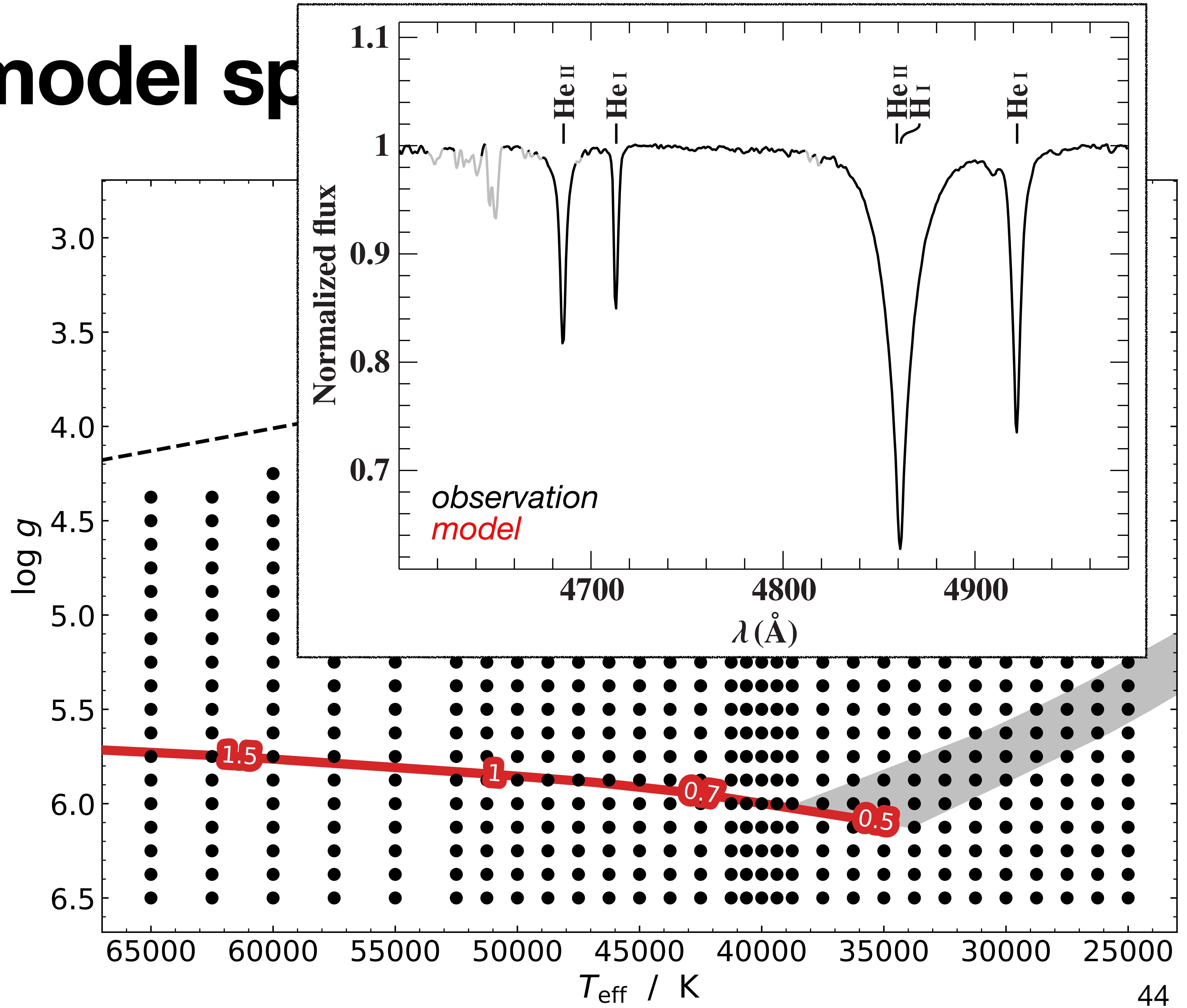


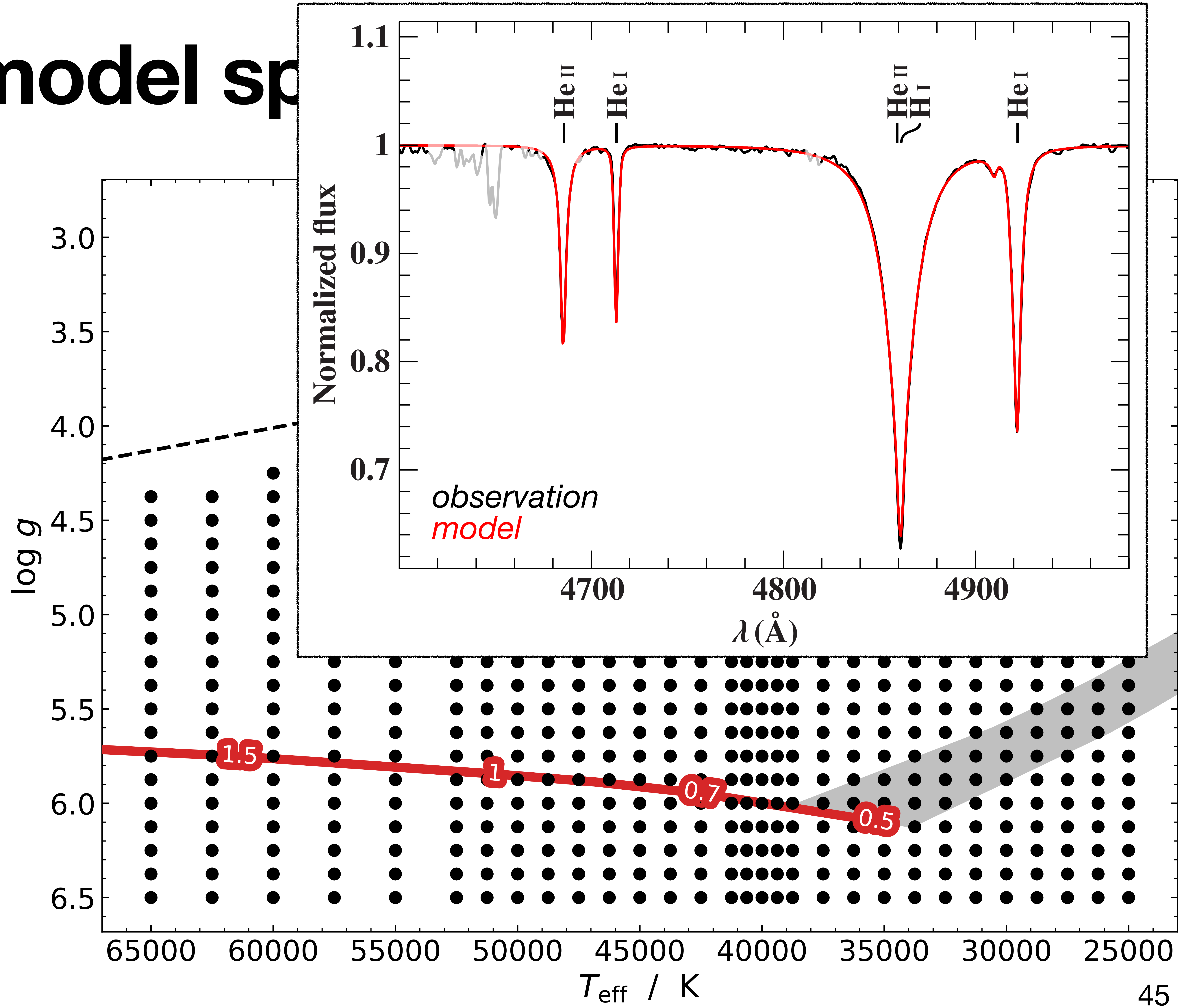
A large grid of model sp

- First step — re-determine atmospheric parameters: T_eff, $\log g$, helium abundance

Best χ^2 fit

↓

$T_\mathrm{eff} = 35000 \pm 700\,\mathrm{K}$
$\log g = 5.9 \pm 0.1$
$\log n_\mathrm{H}/n_\mathrm{He} = -0.6 \pm 0.1$



Line broadening

Natural line broadening: from the uncertainty principle due to finite life time

$$\Phi_\nu^{\mathrm{rad}} = \frac{\gamma_{\mathrm{rad}}/4\pi^2}{(\nu-\nu_{ij})^2 + (\gamma_{\mathrm{rad}}/4\pi)^2},\ \gamma_{\mathrm{rad}} = \frac{1}{\tau_{\mathrm{low}}} + \frac{1}{\tau_{\mathrm{up}}} \qquad \text{(Lorentzian)} \qquad (3.4)$$

Pressure broadening: due to collisions with other atoms, or charged particles in the plasma; linear Stark effect for Hydrogen lines, quadratic Stark effect for non-hydrogenic atoms and ions, Van der Waals broadening: non-hydrogenic atoms with neutral hydrogen

Thermal broadening: Doppler shift due to thermal movement of the atoms

$$\Phi_\nu^{\mathrm{Doppler}} = \frac{1}{\sqrt{\pi}\Delta\nu_{\mathrm{D}}} \exp(-(\nu-\nu_0)/\Delta\nu_D)^2,\ \Delta\nu_D = \frac{\nu_0}{c}\sqrt{\frac{2kT}{m}} \qquad \text{(Gaussian)} \qquad (3.5)$$

Line broadening

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v_{rad}}{c}$$

Rotational broadening: Doppler shift due to stellar rotation, we can observe the projection of the rotational velocity in line-of-sight

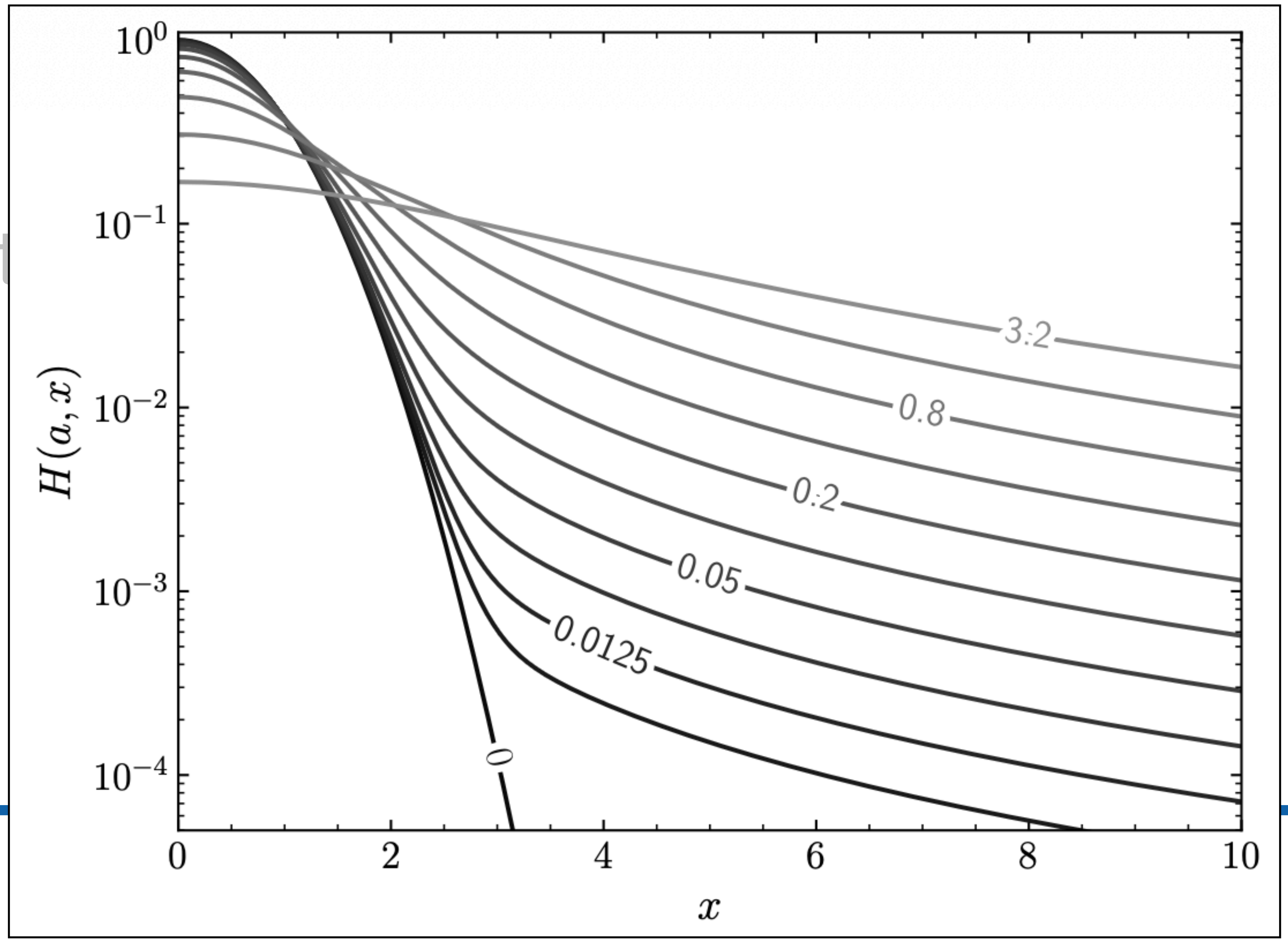
Instrumental profile: additional broadening depending from the spectral resolving power $R = \lambda/\Delta\lambda$

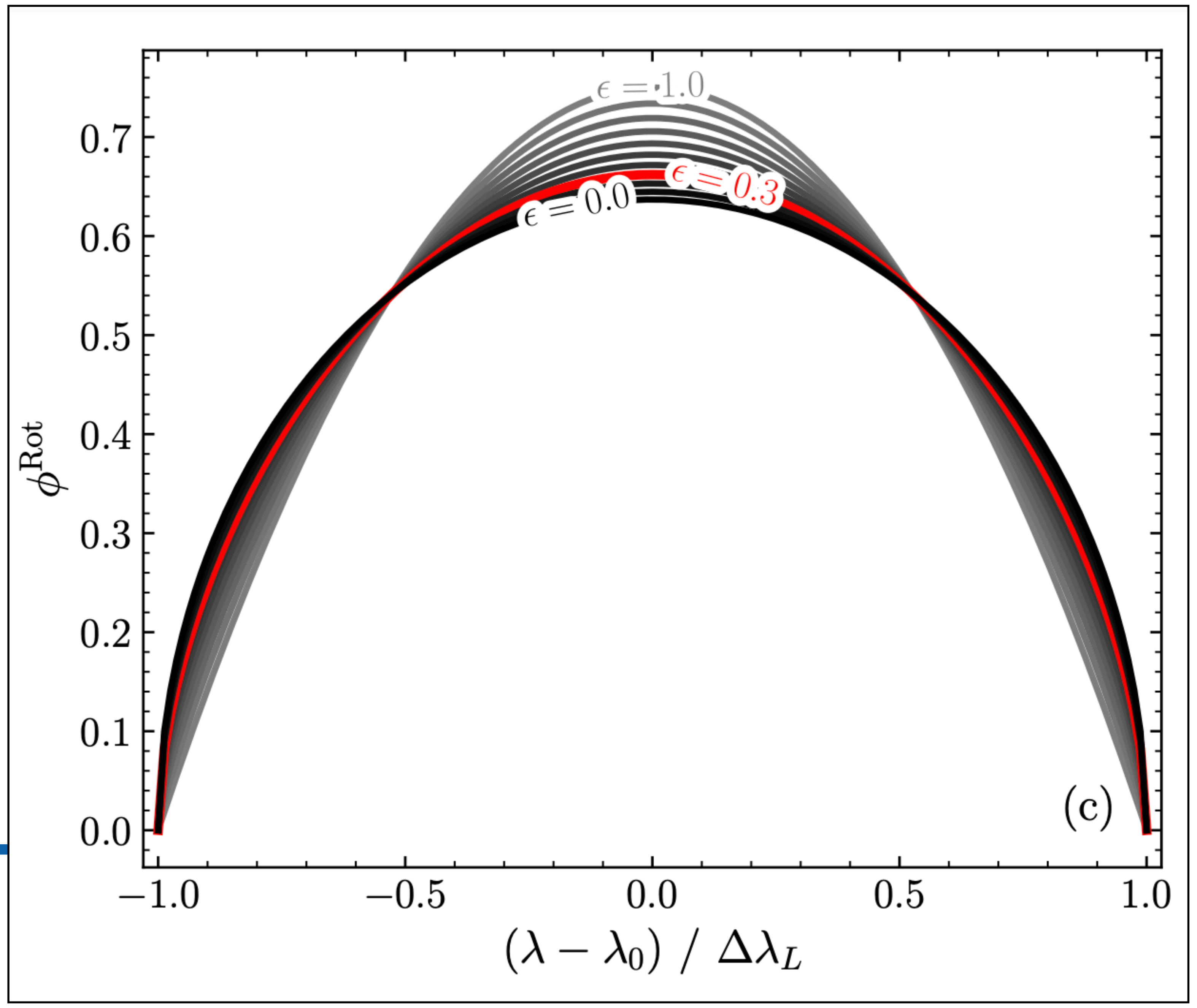
$$\mathrm{FWHM} = c/2\sqrt{\ln 2}R \qquad \text{(Gaussian)} \tag{3.6}$$

Total line Profile

$$\Phi_\nu = \Phi_\nu^{\mathrm{Gaussian}} \star \Phi_\nu^{\mathrm{Lorentz}} \equiv \Phi_\nu^{\mathrm{Voigt}} \tag{3.7}$$

Other effect

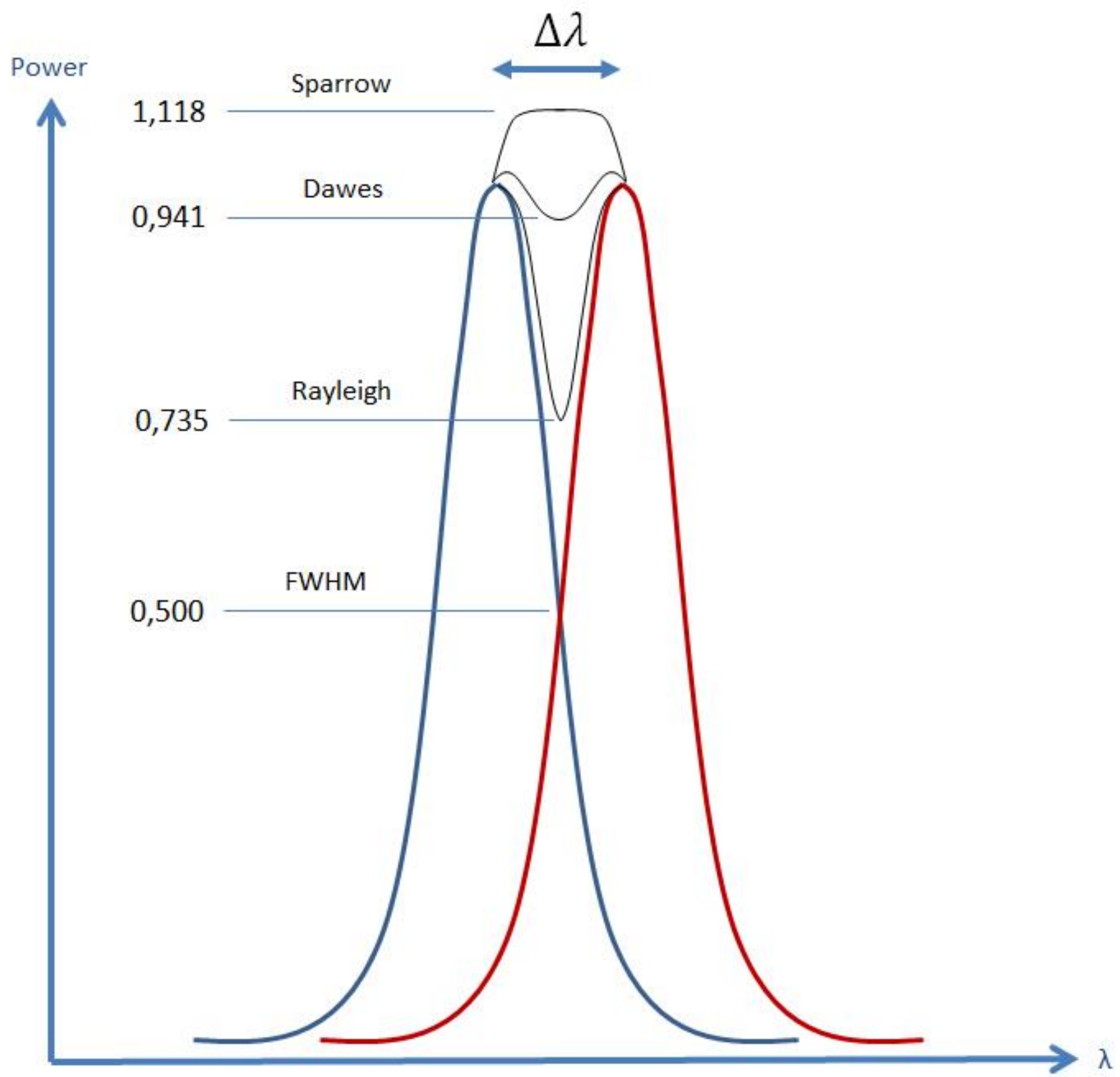




Properties of Spectrographs

- Spectral resolution

$$R = \frac{\lambda}{\Delta\lambda}$$

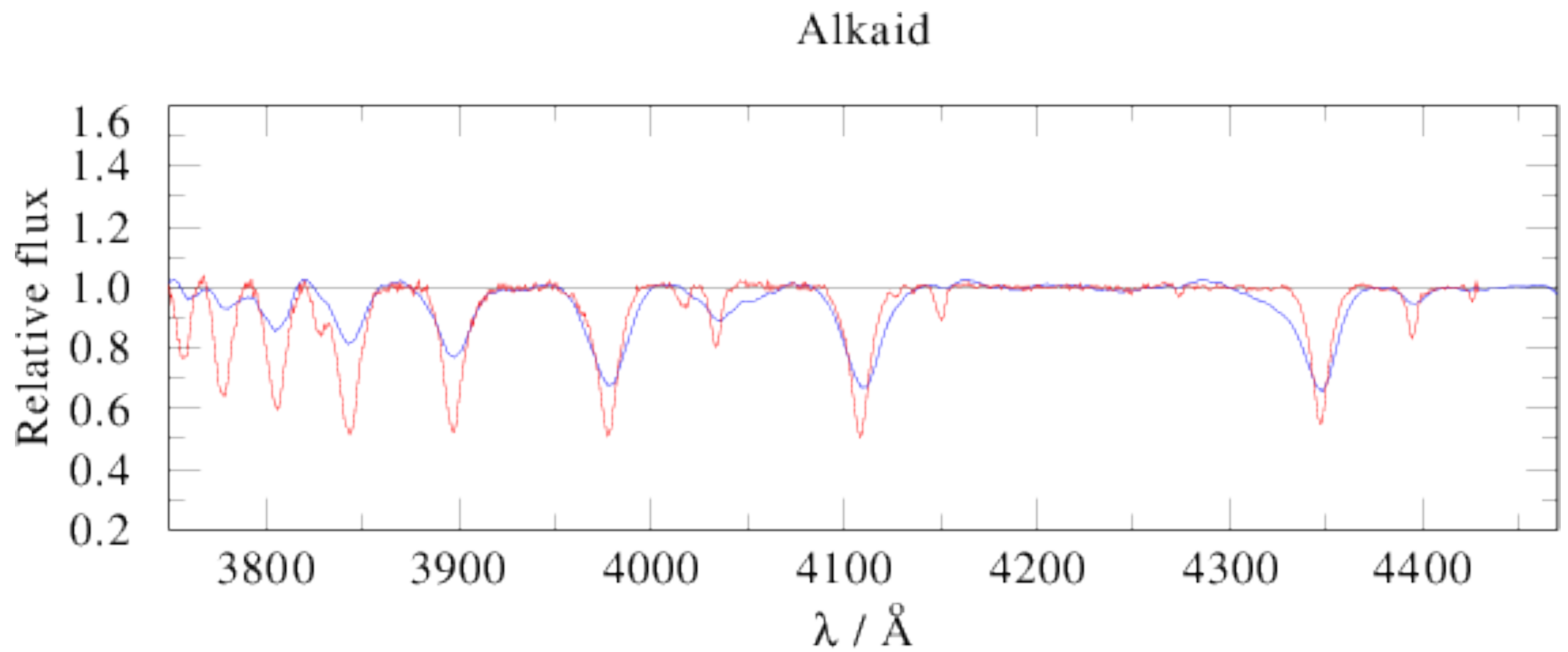


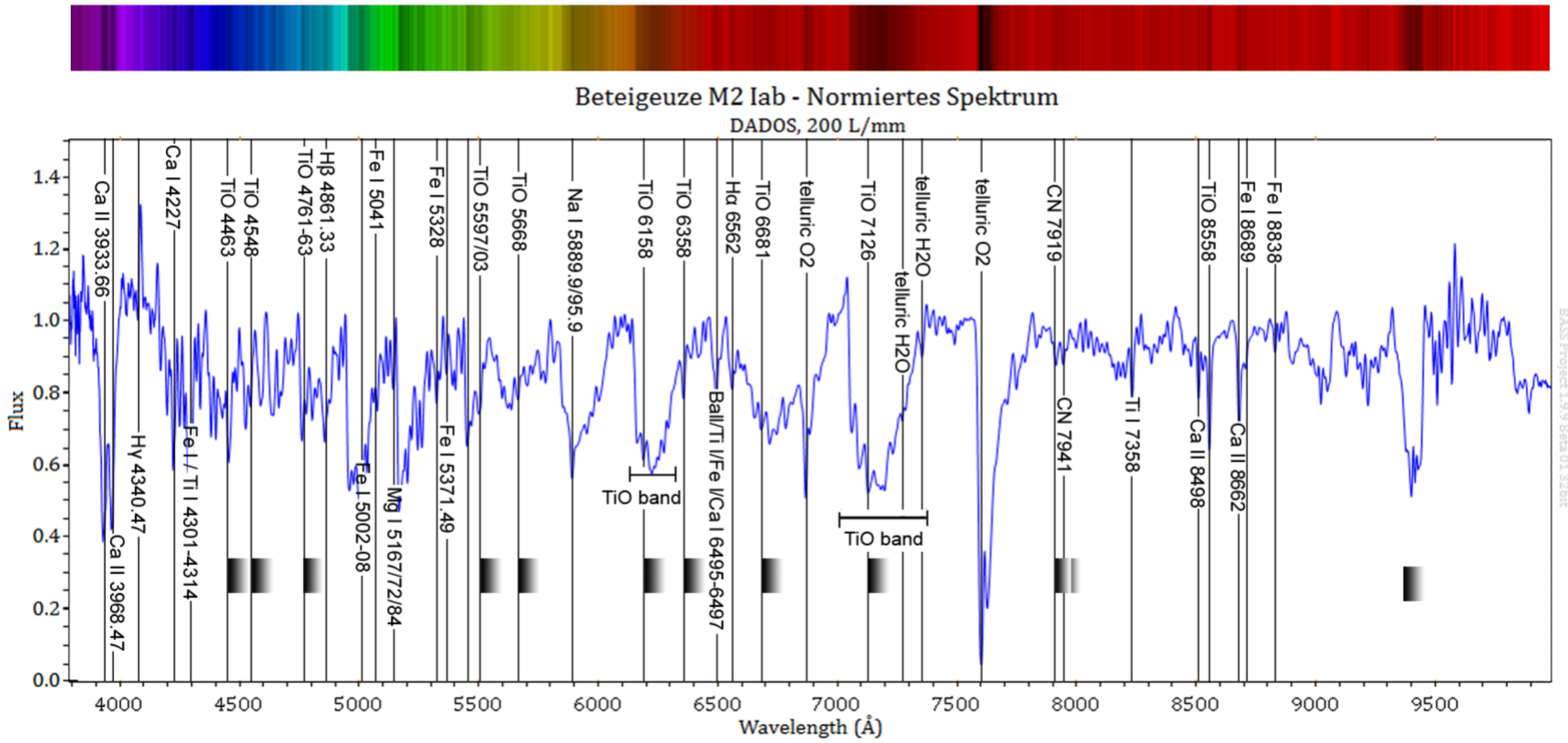
Properties of Spectrographs

- Spectral resolution

$$R = \frac{\lambda}{\Delta\lambda}$$

- wavelength range



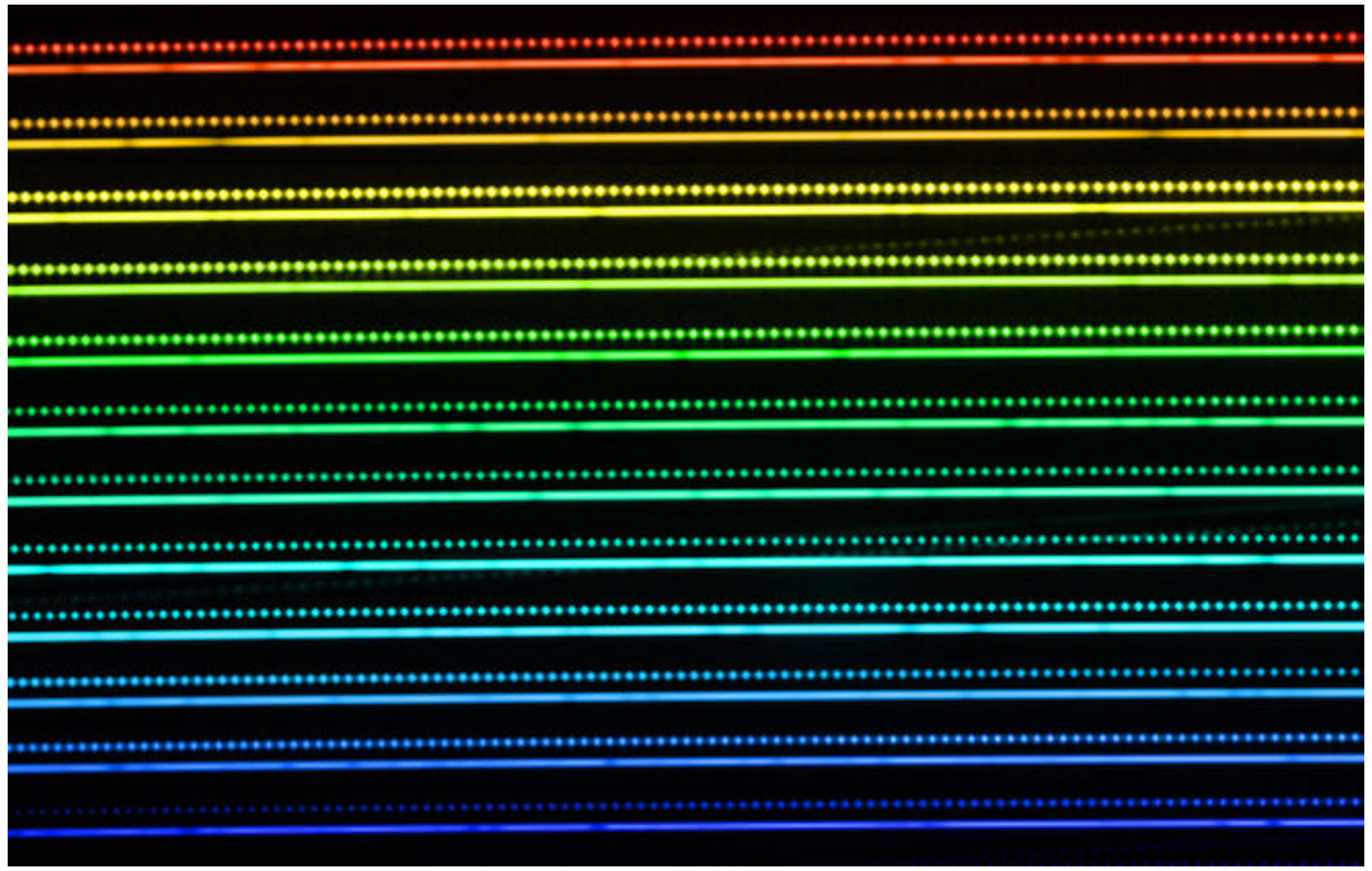


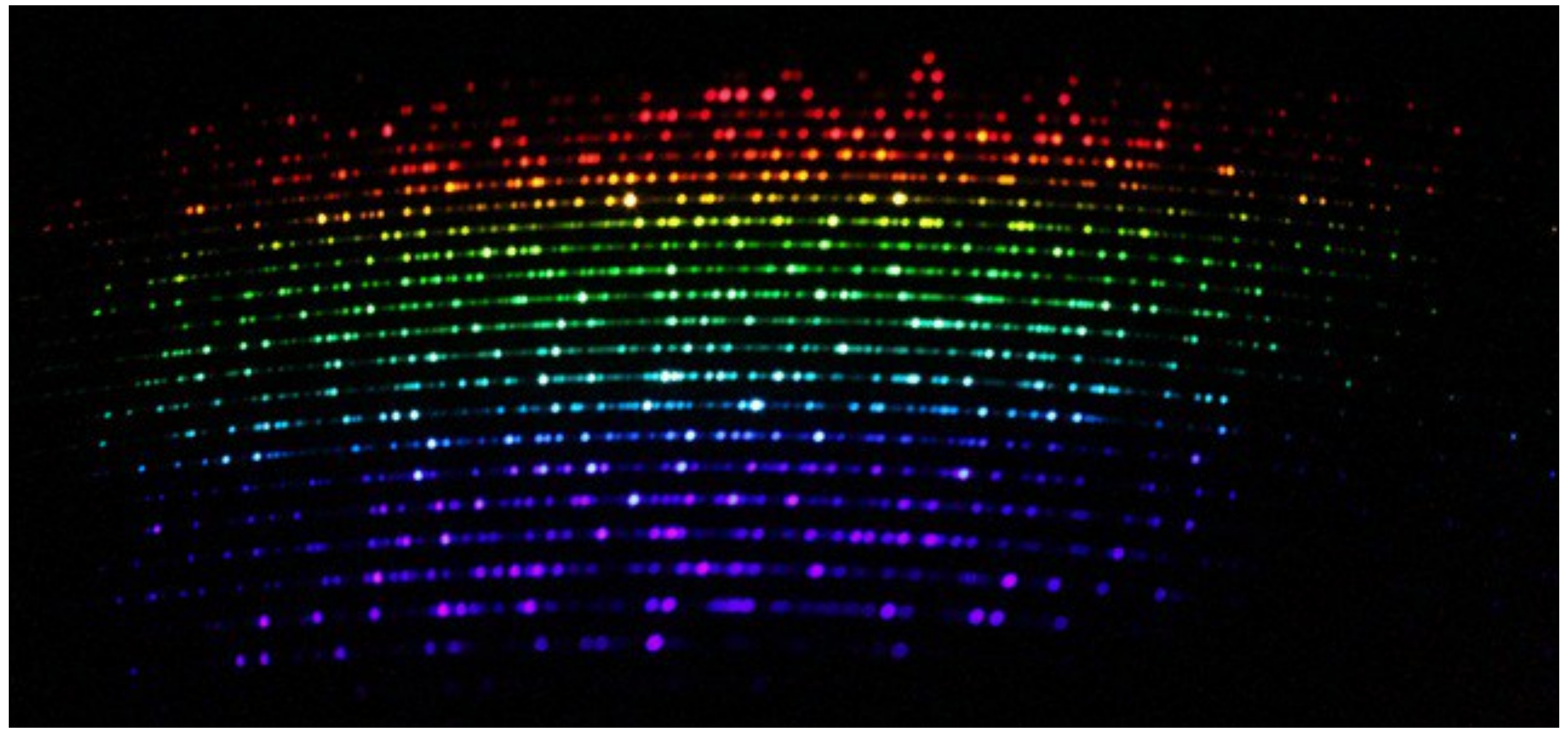
Properties of Spectrographs

- Spectral resolution

$$R = \frac{\lambda}{\Delta\lambda}$$

- wavelength range
- wavelength calibration and stability



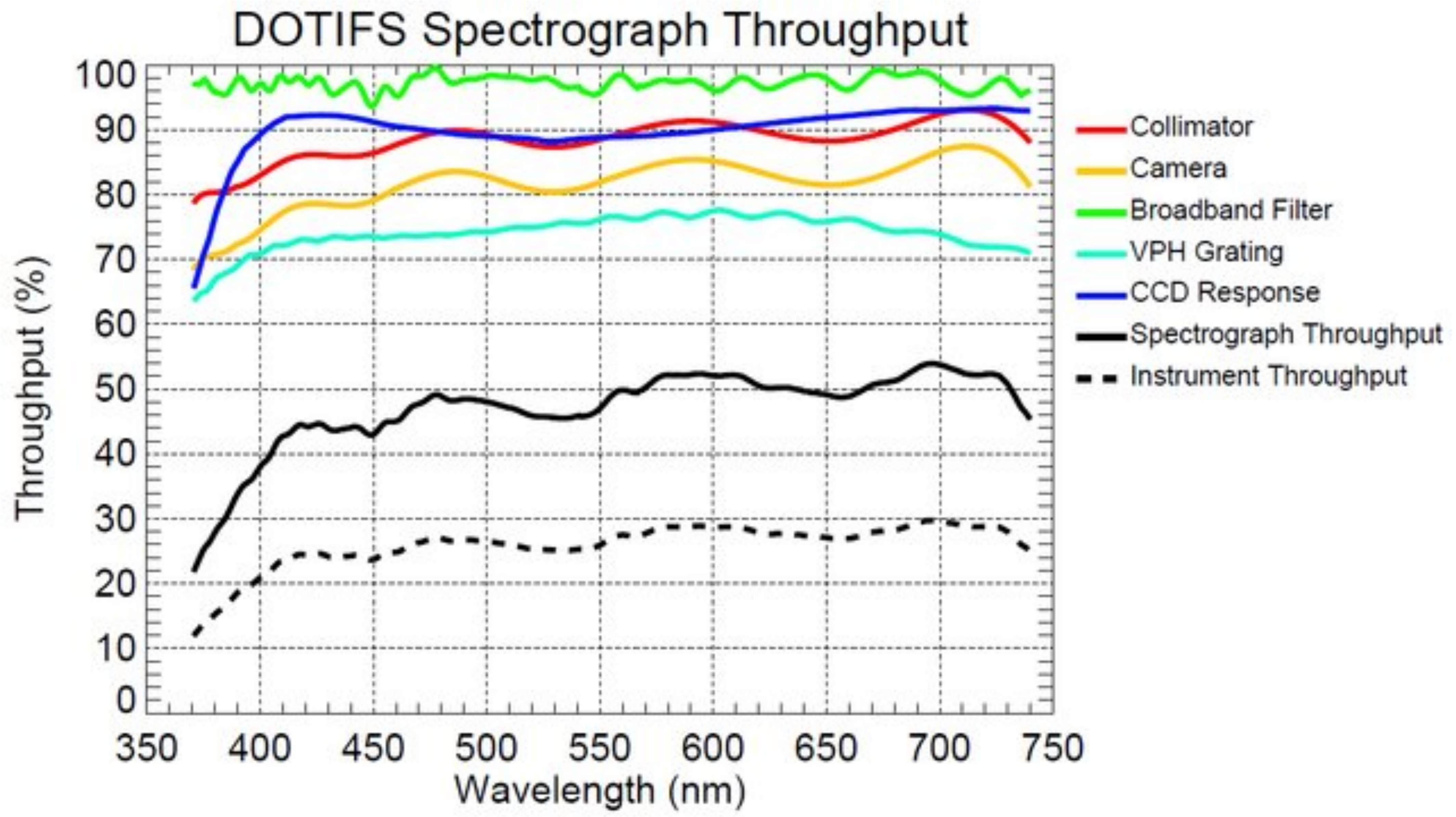


Properties of Spectrographs

- Spectral resolution

$$R = \frac{\lambda}{\Delta\lambda}$$

- wavelength range
- wavelength calibration and stability
- throughput for best efficiency
- efficiency in the blue/red
- limiting magnitude



Summary

Photometry = brightness of stars as seen on earth, in filters

Spectroscopy = detailed picture of the stellar surface

Combining both allows us to study stars in detail