Introduction to photometry/spectroscopy

Research workshop on evolved stars

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29. 09. 2022

Institute for Physics and Astronomy
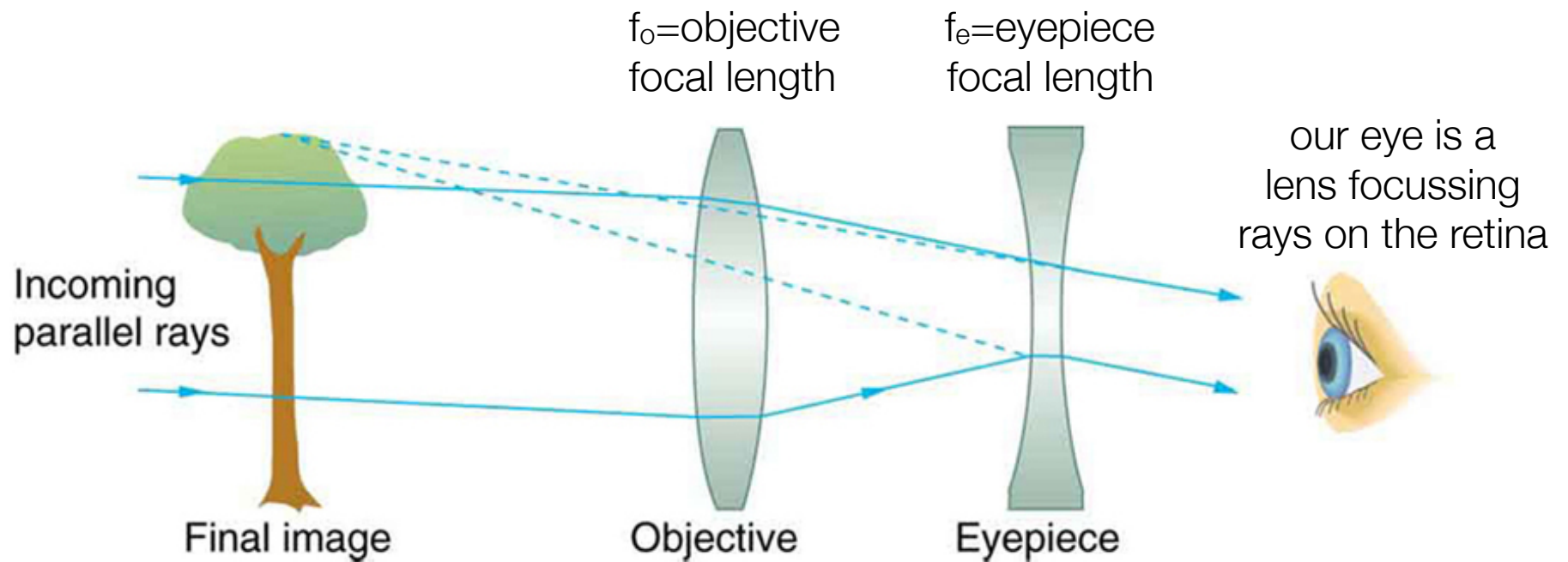
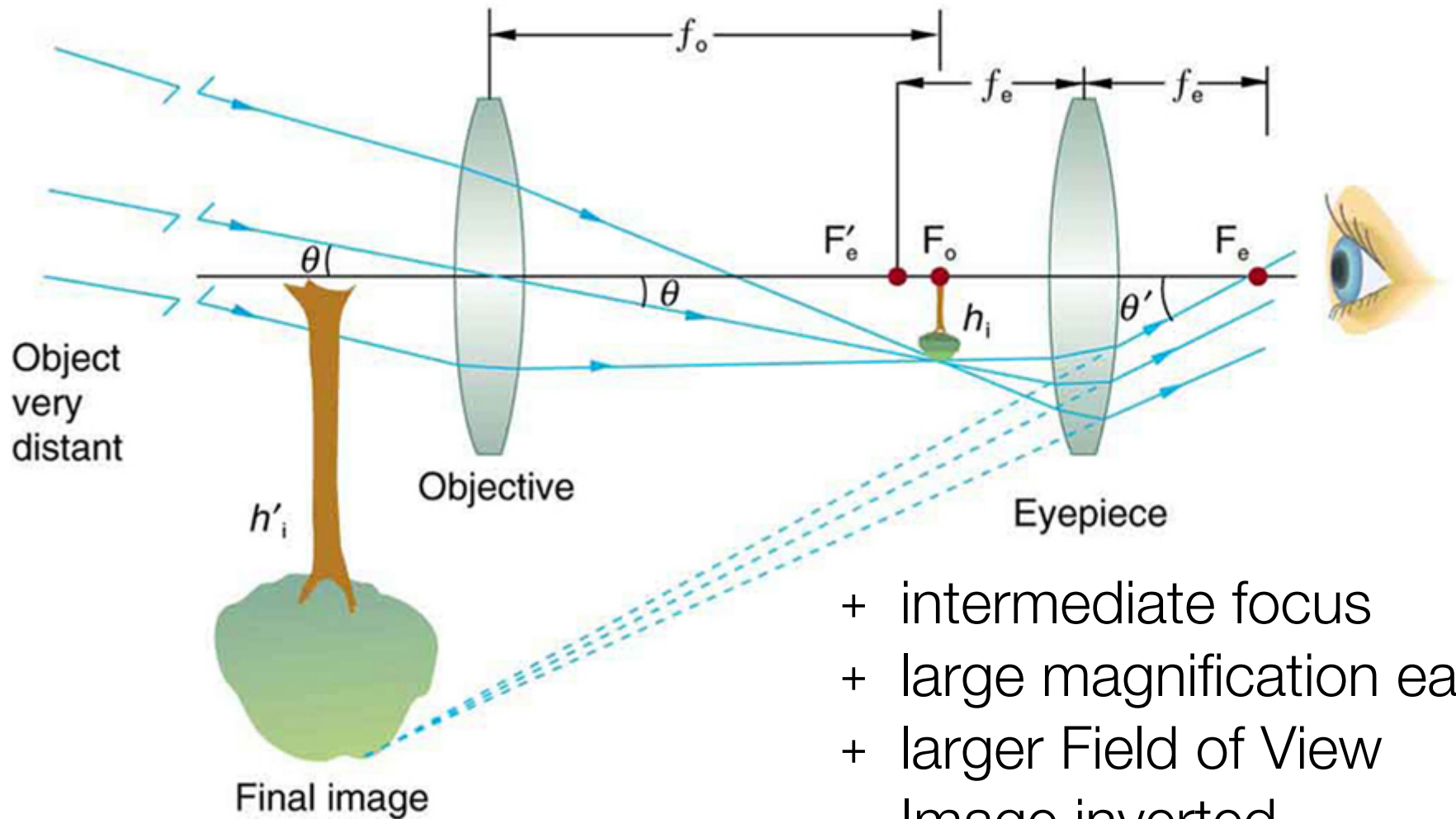Email: `matti.dorsch@fau.de`

Room: 2.118

Telescopes

The Galilean telescope

f_o=objective focal length

f_e=eyepiece focal length

our eye is a lens focussing rays on the retina

Incoming parallel rays

Final image

Objective

Eyepiece

+ upright image
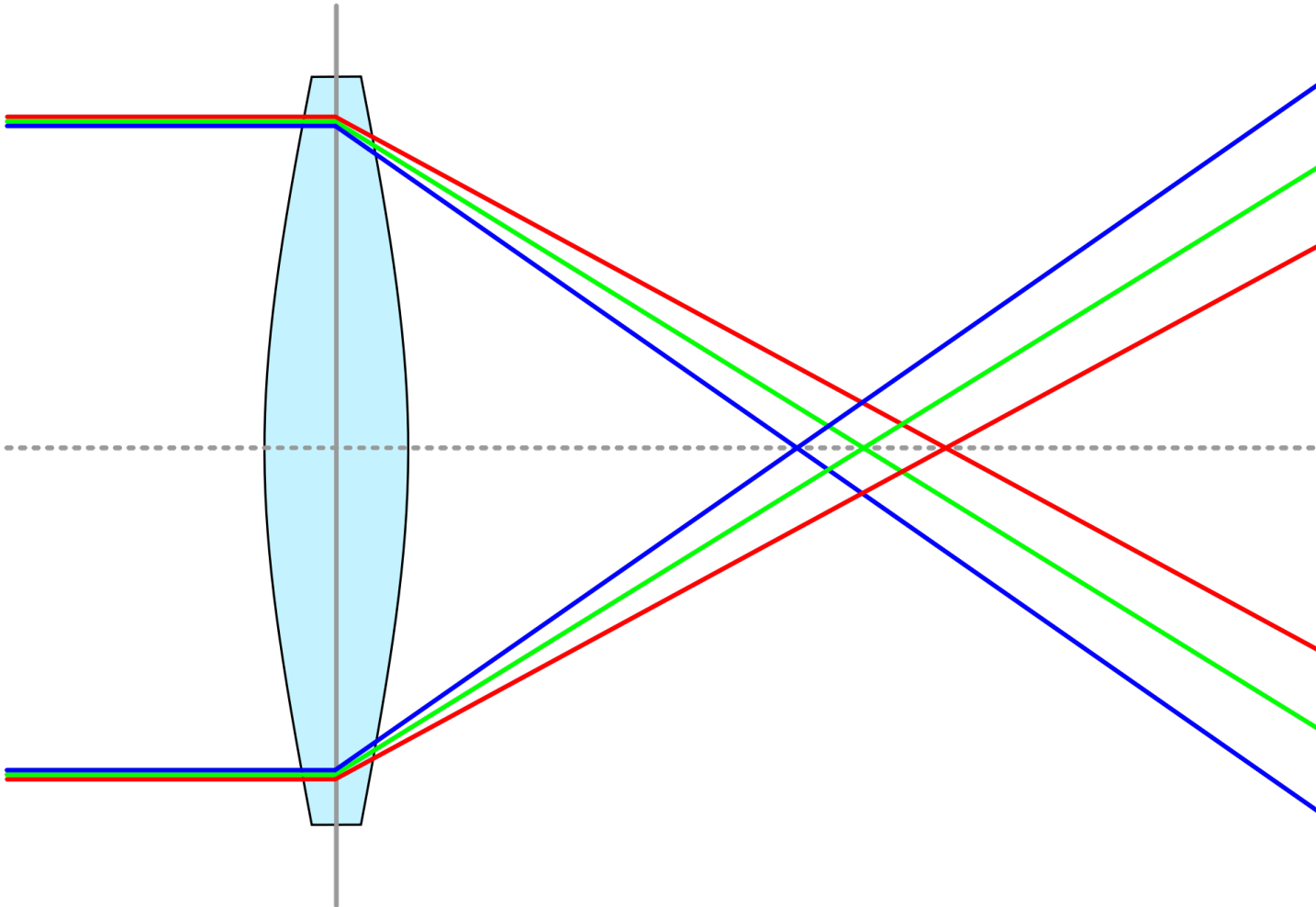+ Magnification = $|fo/fe|$
- small field of view

The Keplerian telescope

+ intermediate focus
+ large magnification easier
+ larger Field of View
- Image inverted
  (needs an erector)

Chromatic aberration

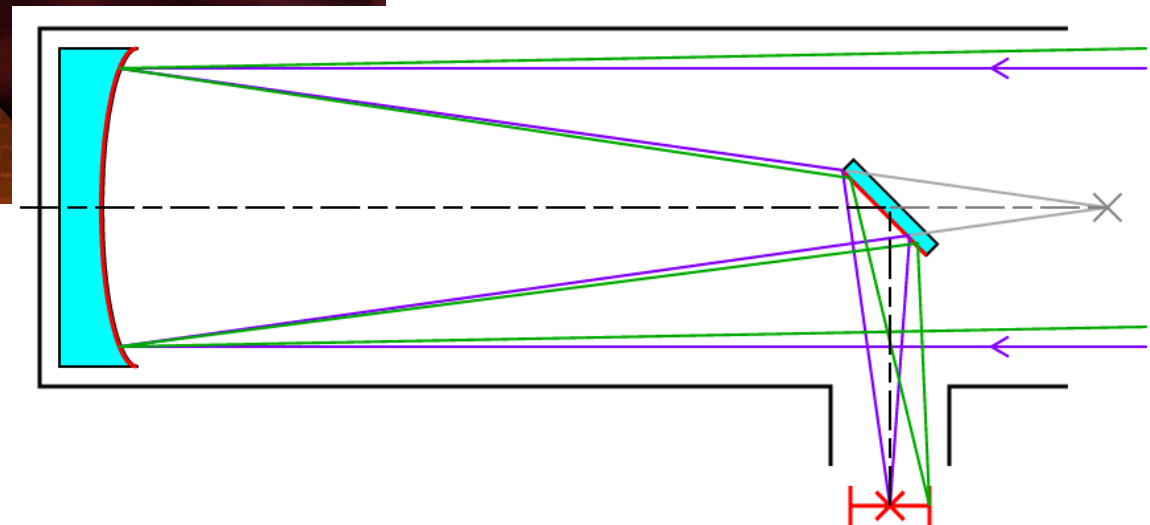Due to the wavelength dependence of the refractive index of glass $n(\lambda)$

Glass is also very heavy, big lenses are hard to manufacture and mount

Newton's reflector / telescope

Uses mirror to prevent chromatic aberrations present in refractors: $n_{glass}(\lambda)$

Reflection is achromatic!

Reflection at a Spherical Surface
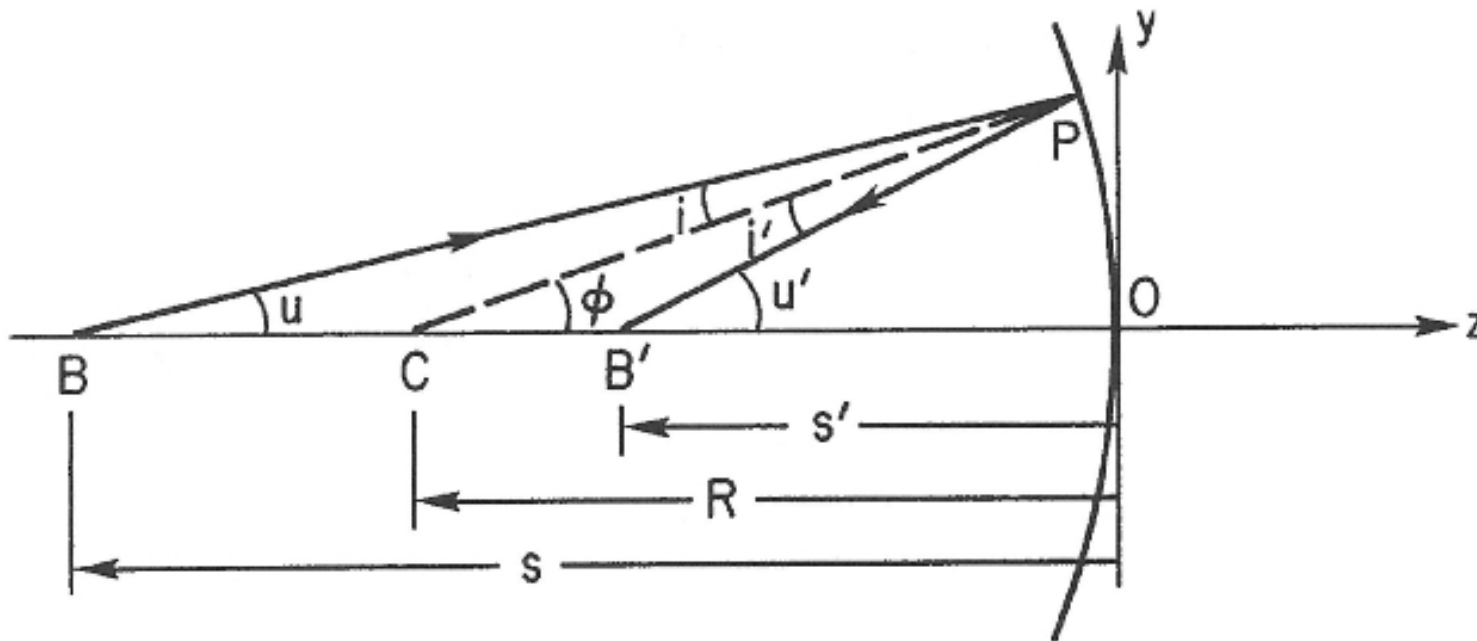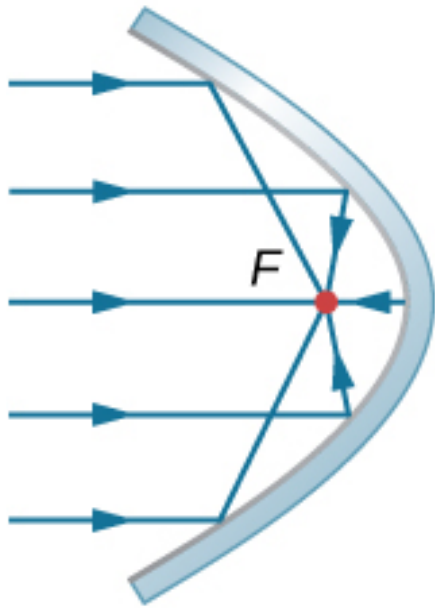
2.3. Paraxial Equation for Reflection

Fig. 2.4. Reflection at spherical surface. Here B and B' are conjugate axial points.

- mirror equation: $1/s'_{image} + 1/s_{object} = 2/R$
- assuming $s = \infty \Rightarrow f = s' = R/2$
- two mirror system with distance $d \Rightarrow$ effective focal length $f = f_1 f_2 / (f_1 + f_2 - d)$
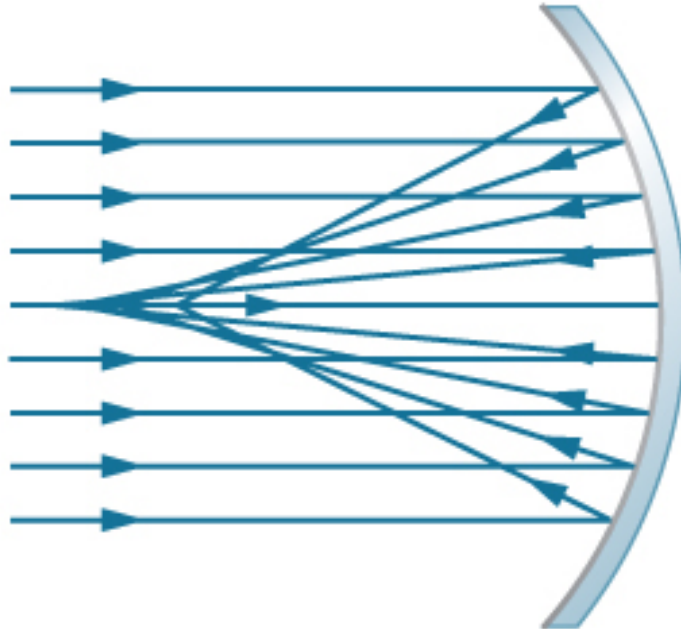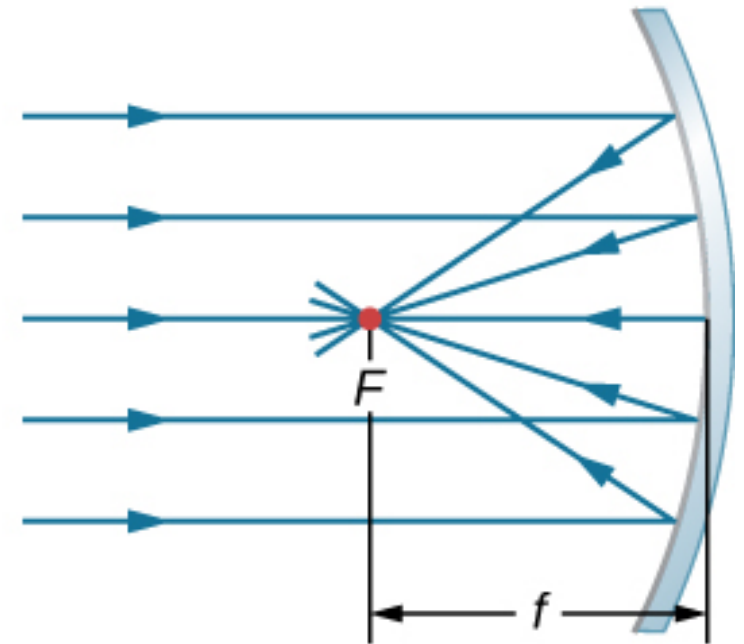
# Spherical aberration

Parabolic mirror

Large spherical mirror

Small spherical mirror

F

(a)

(b)

F

f

(c)

Telescope design considerations
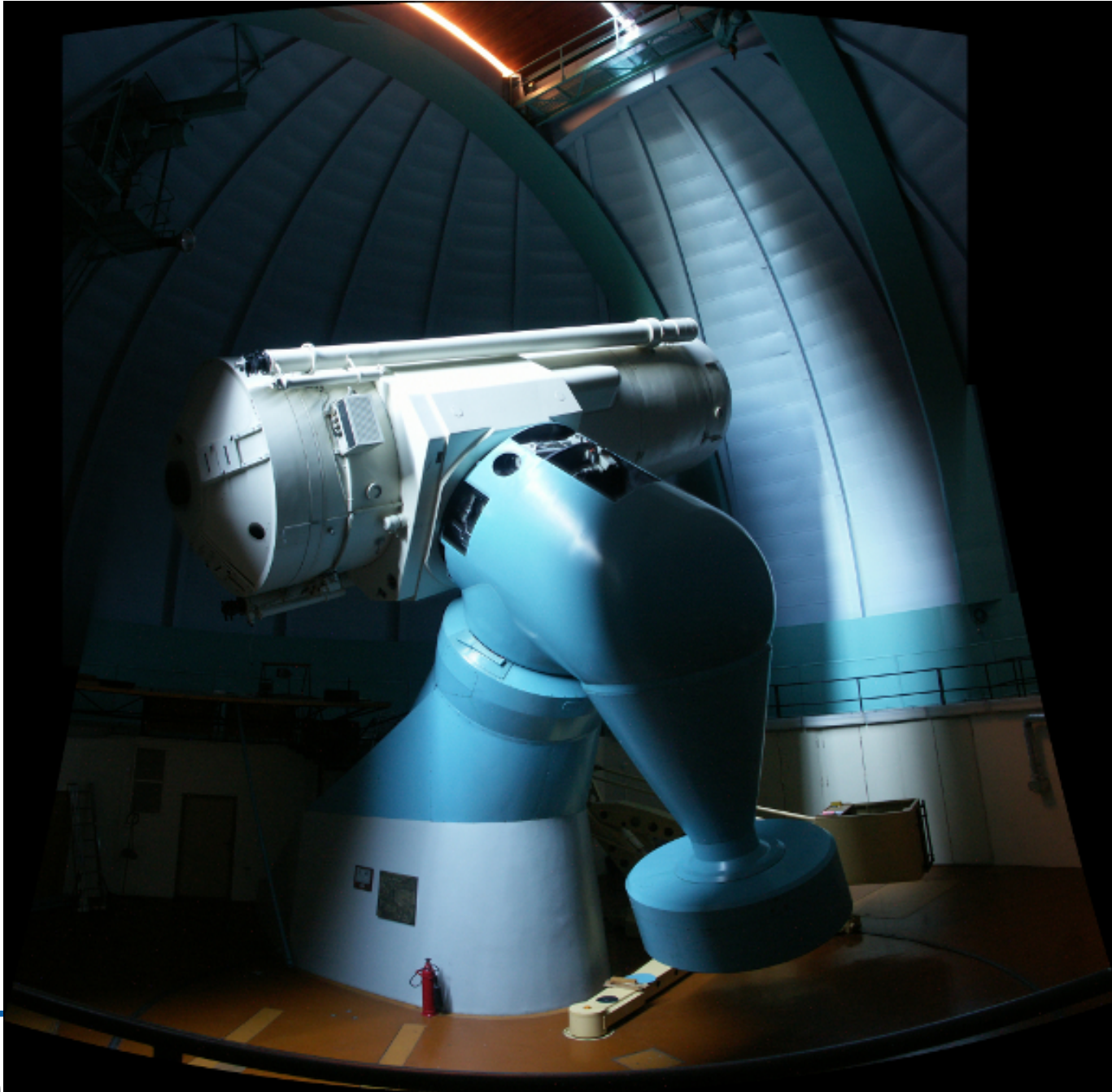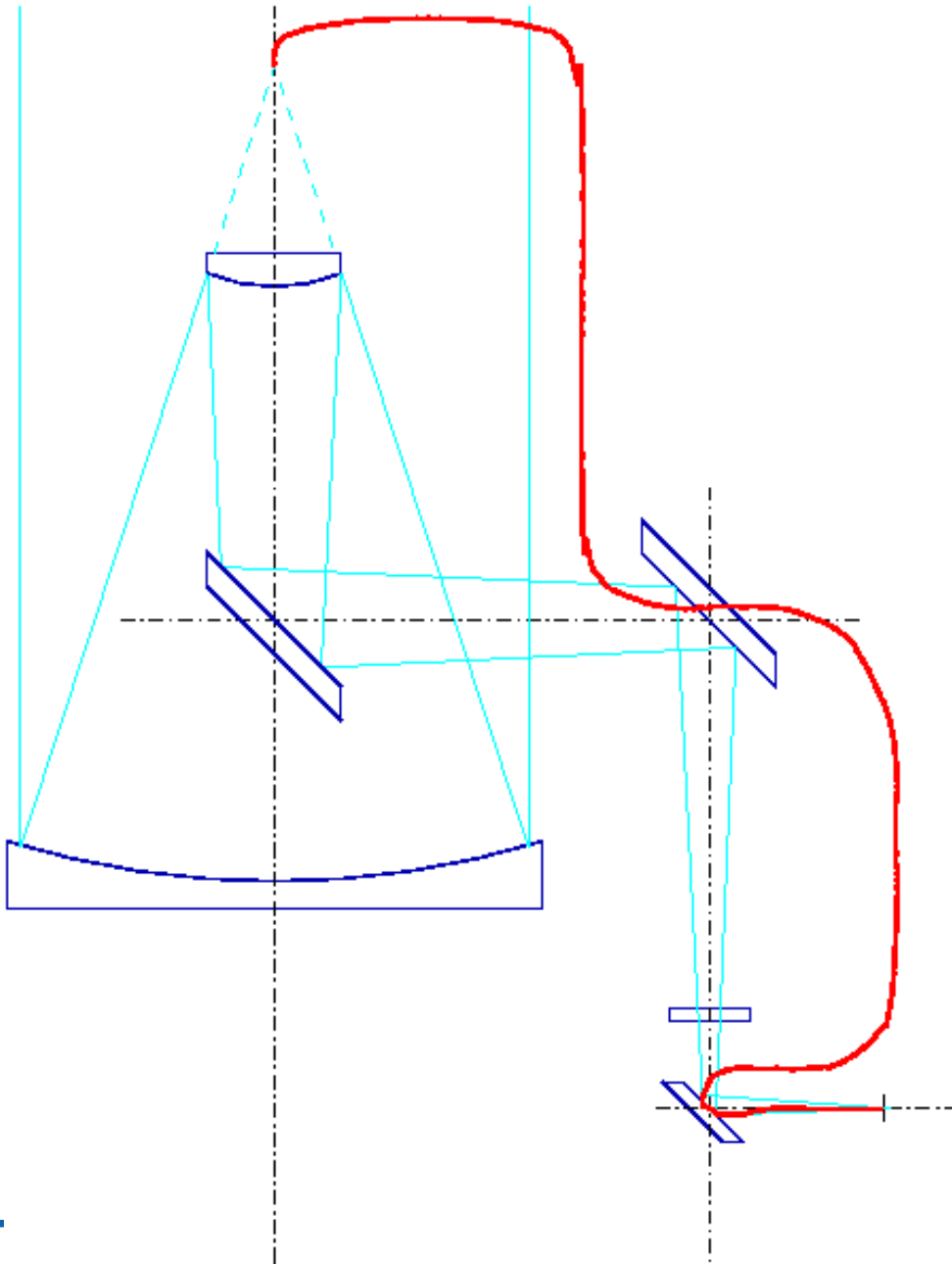
- Field of view (FoV): small focal ratio $F/D \rightarrow$ large FoV
  (limited by size of secondary mirror, vignetting)
- Collecting area: number of photons $\sim D^2$
- Angular resolution, Rayleigh criterion $1.22\lambda/D$
- Image quality: aberrations at large distance from optical axis, coma, astigmatism
- Mounts: equatorial, Altitude-Azimuth (altaz)
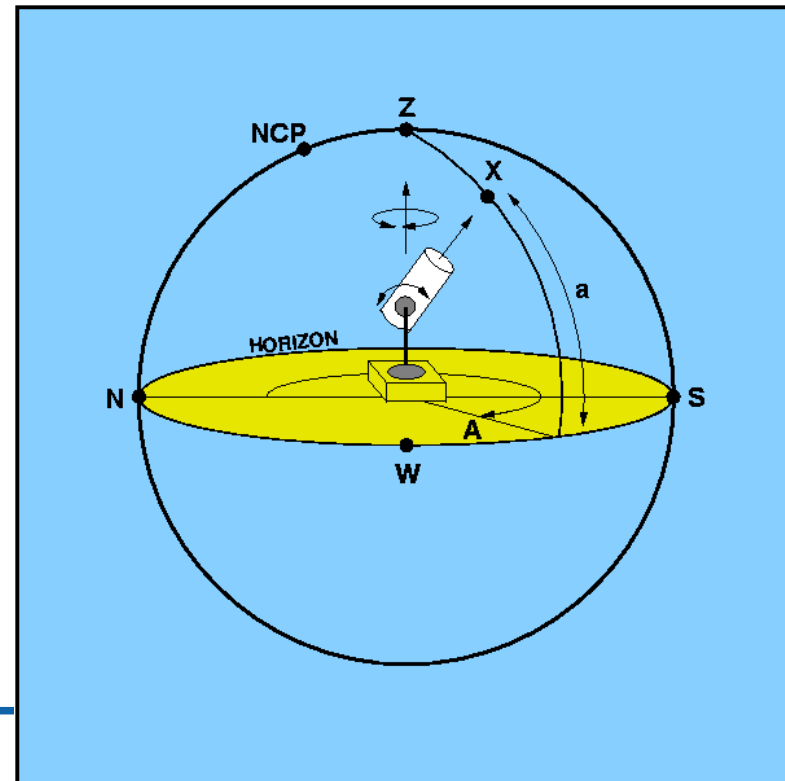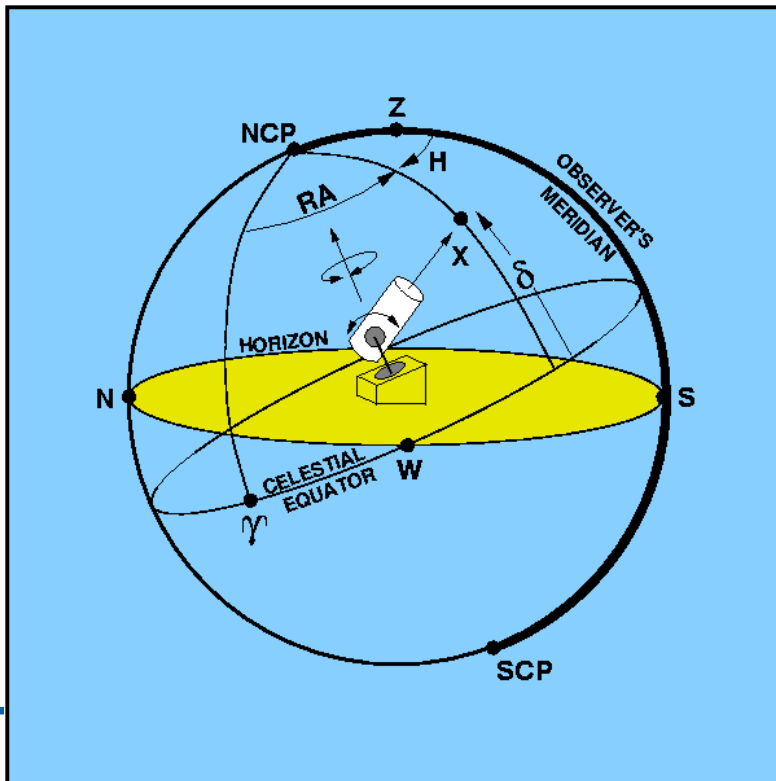
Perek 2-m telescope

Perek 2-m telescope

- Manufacturer: Carl Zeiss Jena
- Type of mount: Equatorial
- Primary parabolic mirror D=2 m, thickness 0.3 m, weight 2340 kg
- Original optical setting: primary, Cassegrain, coudé focus
- Current optical setting: optical fiber from primary to coudé focus
- Effective focal length: F=63.5 m
- Effective focal rati: f/4.5 in primary and f/32 in coudé.
- Instruments:
  - single order spectrograph
  - echelle spectrograph
  - photometric camera

Ondrejov 65cm-Telescope

- 65 cm primary paraboloidal mirror with 234 cm focal length
- Moravian G2-3200 CCD camera in primary focus
- BVRI filters
- effective focal ratio: f/3.6
  $\rightarrow$ quite noticeable coma: Paracorr coma corrector
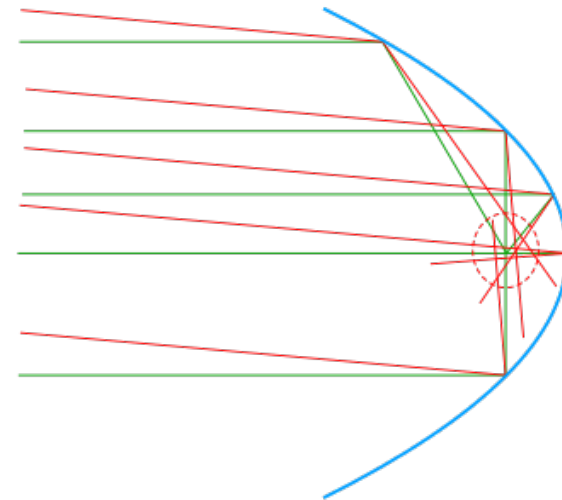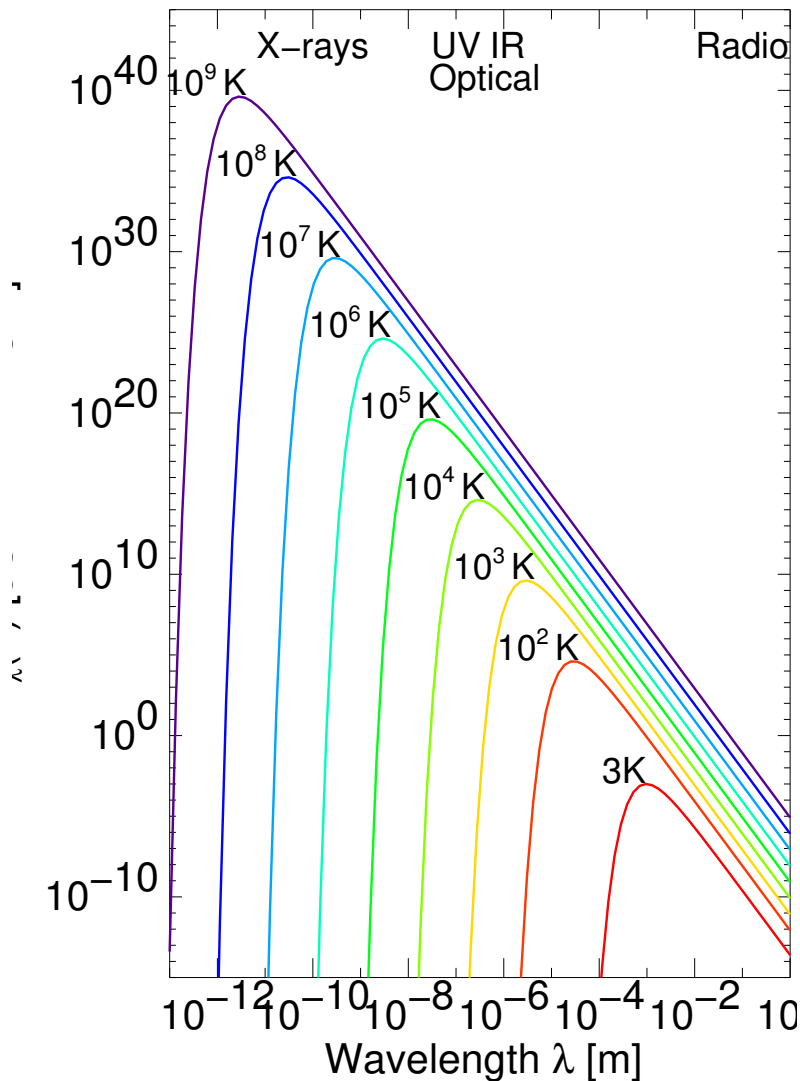
Photometry

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

X–rays   UV IR   Radio
Optical
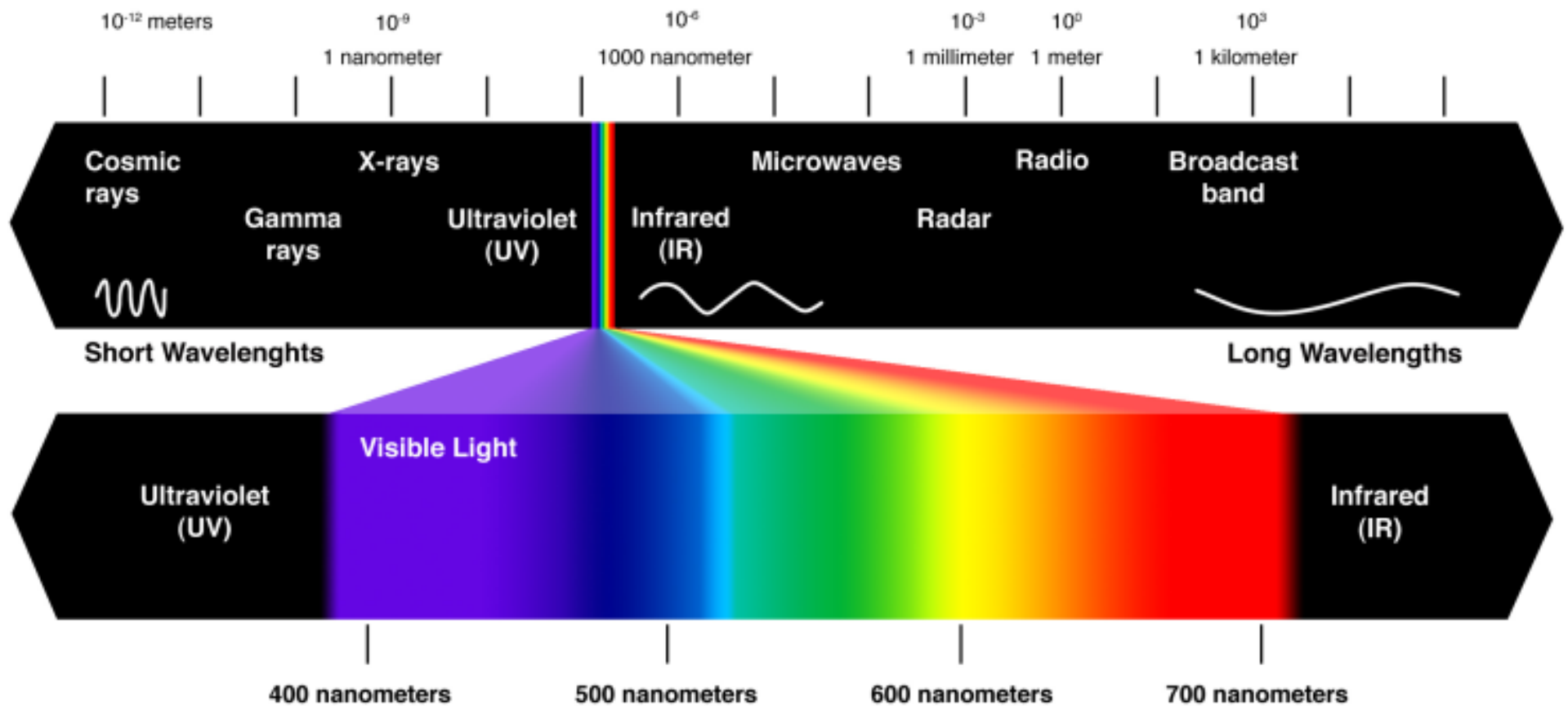
Stefan-Boltzmann law: Flux (power emitted per square-meter surface) of a blackbody:

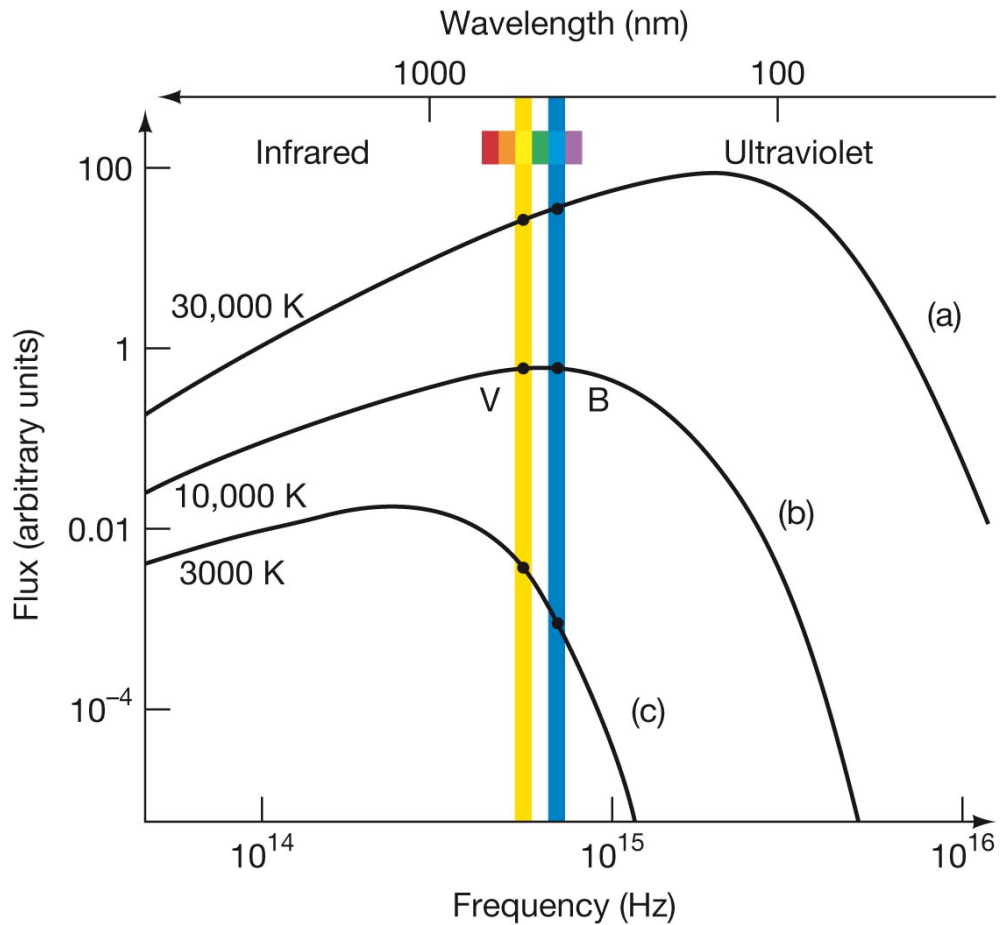$$F = B = \int_0^\infty B_\lambda(\lambda)\, d\lambda = \sigma T^4$$

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

"hotter bodies have a much higher luminosity"

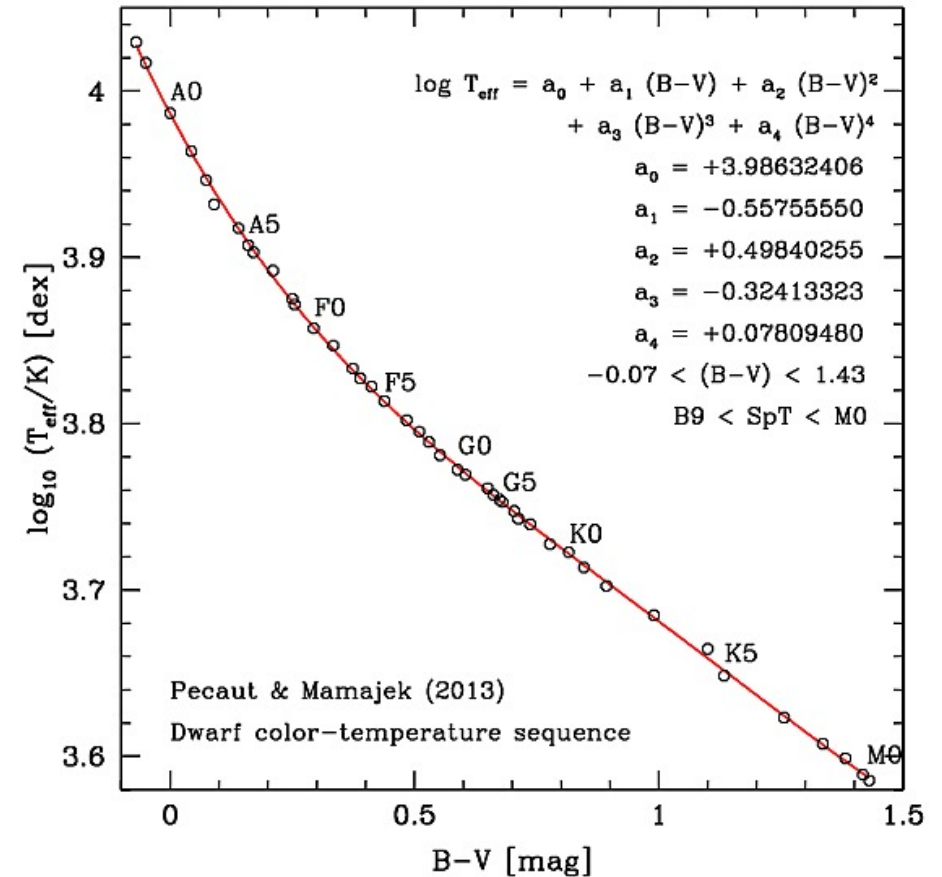**Wien's displacement law:** Wavelength of maximum blackbody emission:

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

"hotter bodies radiate at higher energies"

Color-temperature relation

Wavelength (nm)

Infrared   Ultraviolet

30,000 K

10,000 K

3000 K

Flux (arbitrary units)

V   B

(a)

(b)

(c)

Frequency (Hz)

© 2014 Pearson Education, Inc.

$$\log T_{eff} = a_0 + a_1 (B-V) + a_2 (B-V)^2 + a_3 (B-V)^3 + a_4 (B-V)^4$$

$a_0 = +3.98632406$

$a_1 = -0.55755550$

$a_2 = +0.49840255$

$a_3 = -0.32413323$

$a_4 = +0.07809480$

$-0.07 < (B-V) < 1.43$

$B9 < SpT < M0$

A0

A5

F0

F5

G0

G5

K0

K5

M0

$\log_{10} (T_{eff}/K)$ [dex]

B–V [mag]

Pecaut & Mamajek (2013)
Dwarf color-temperature sequence

Photometric filters
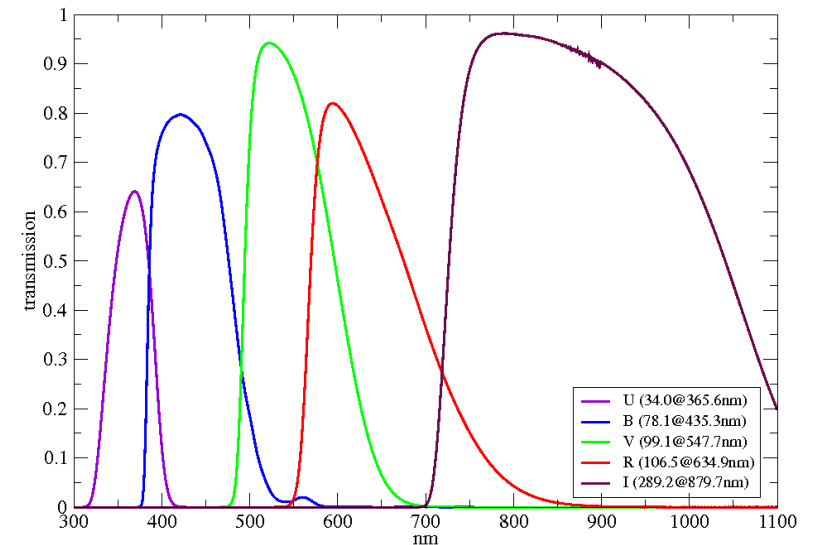
Johnson filters

Photometric system

- set of well-defined passbands (or filters)

- standard stars for each photometric system

- observations of lightcurves usually in one or several filters
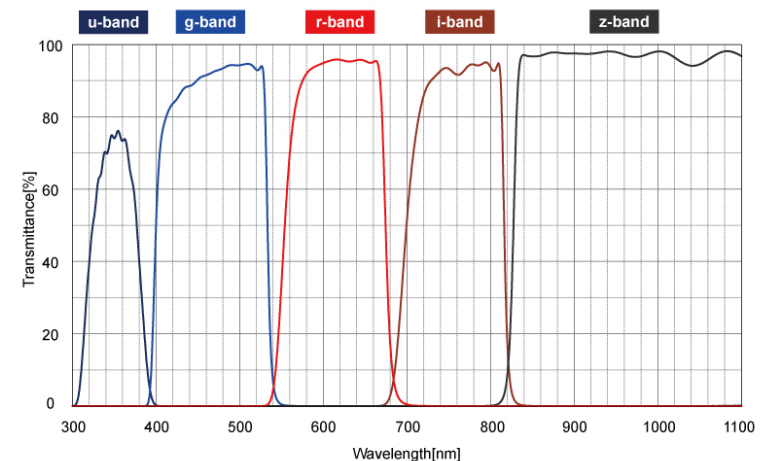
Bolometric correction

SDSS filters

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

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

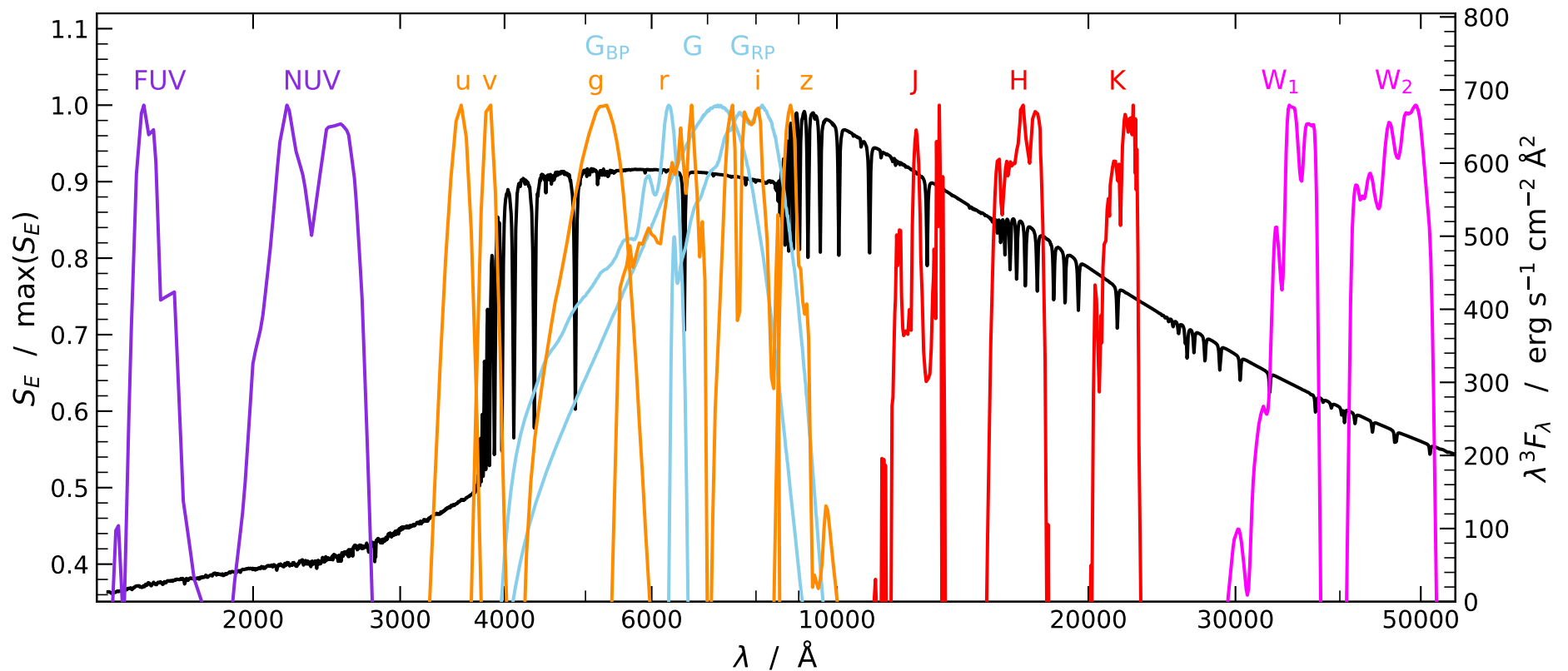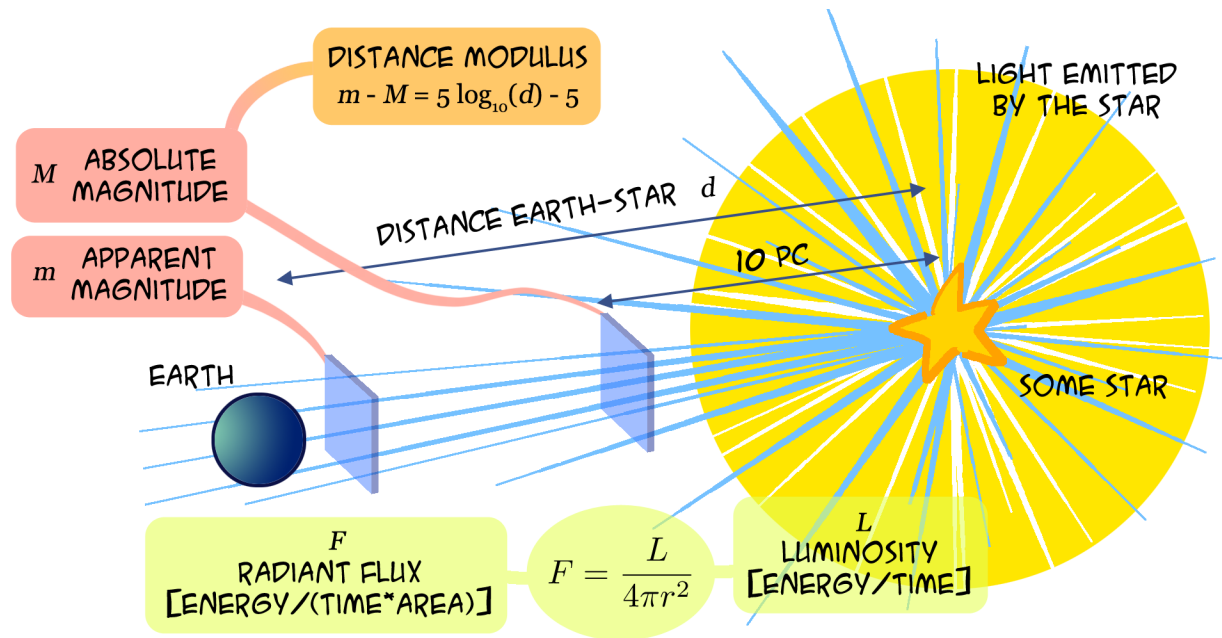# Photometric filters

A historic and current photometric reference: Vega!

Bolometric magnitudes

- apparent magnitude m_x in filter x

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

- 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
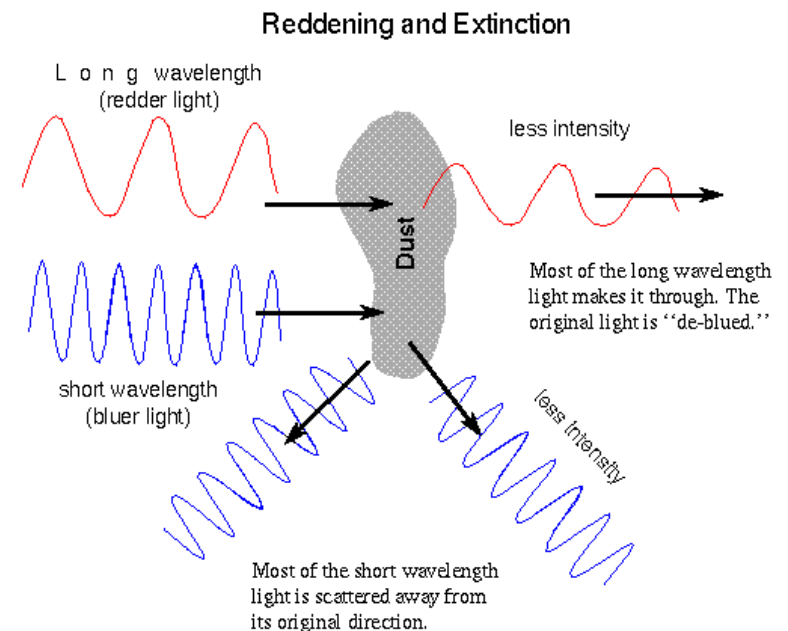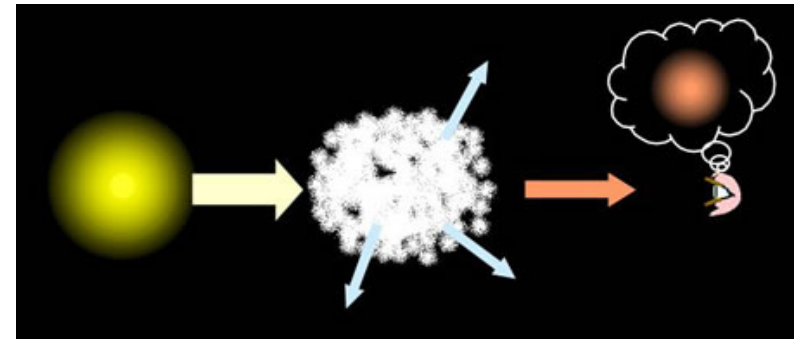
Interstellar reddening

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}

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

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

- true distance

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

Reddening and Extinction

Long wavelength (redder light)

less intensity

Most of the long wavelength light makes it through. The original light is "de-blued."

short wavelength (bluer light)

less intensity

Most of the short wavelength light is scattered away from its original direction.
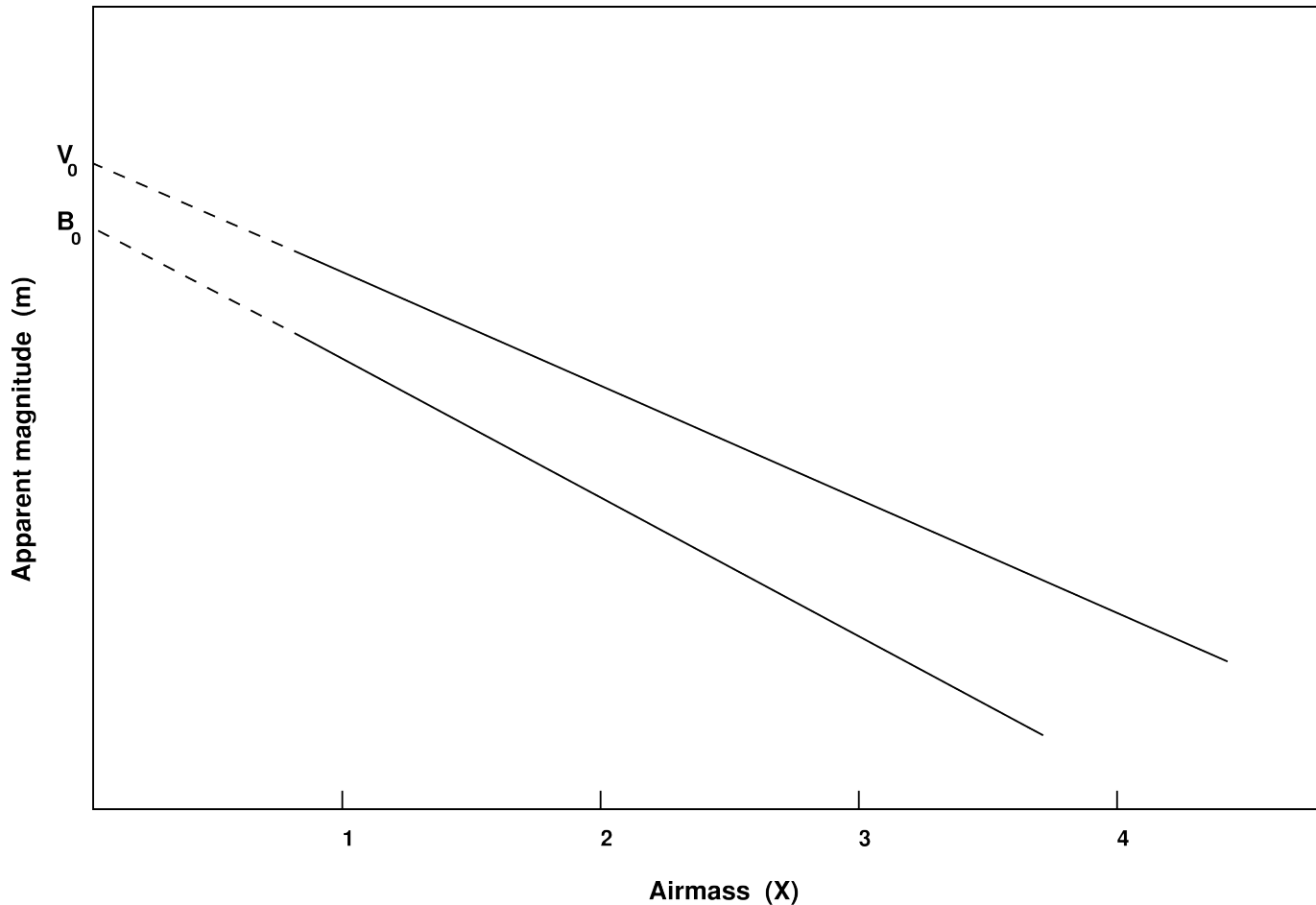
Interstellar reddening

$R(55) = 2.50$

$R(55) = 3.02$

$R(55) = 6.00$
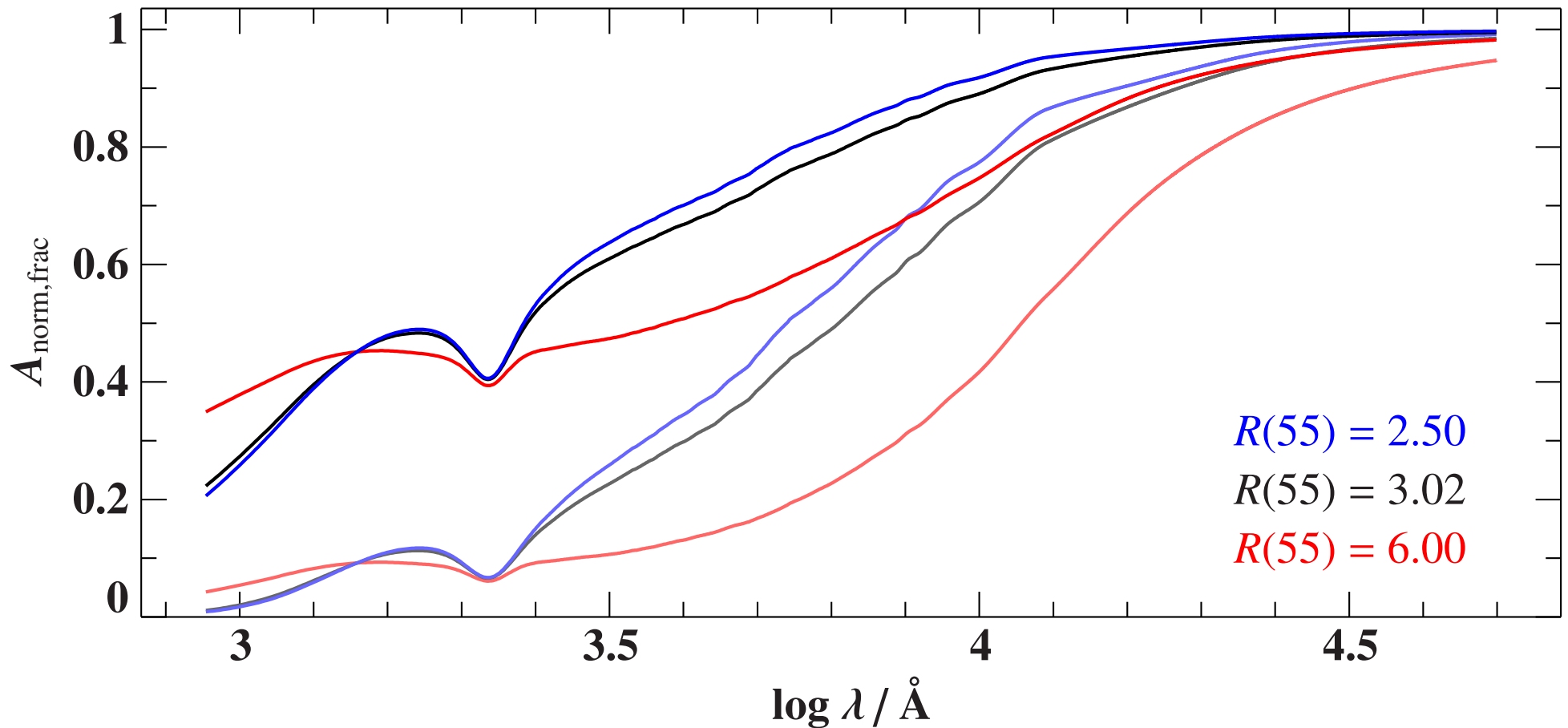
The darker curves are for a colour excess $E(44-55) = 0.1$ mag while the lighter curves are for 0.3 mag.
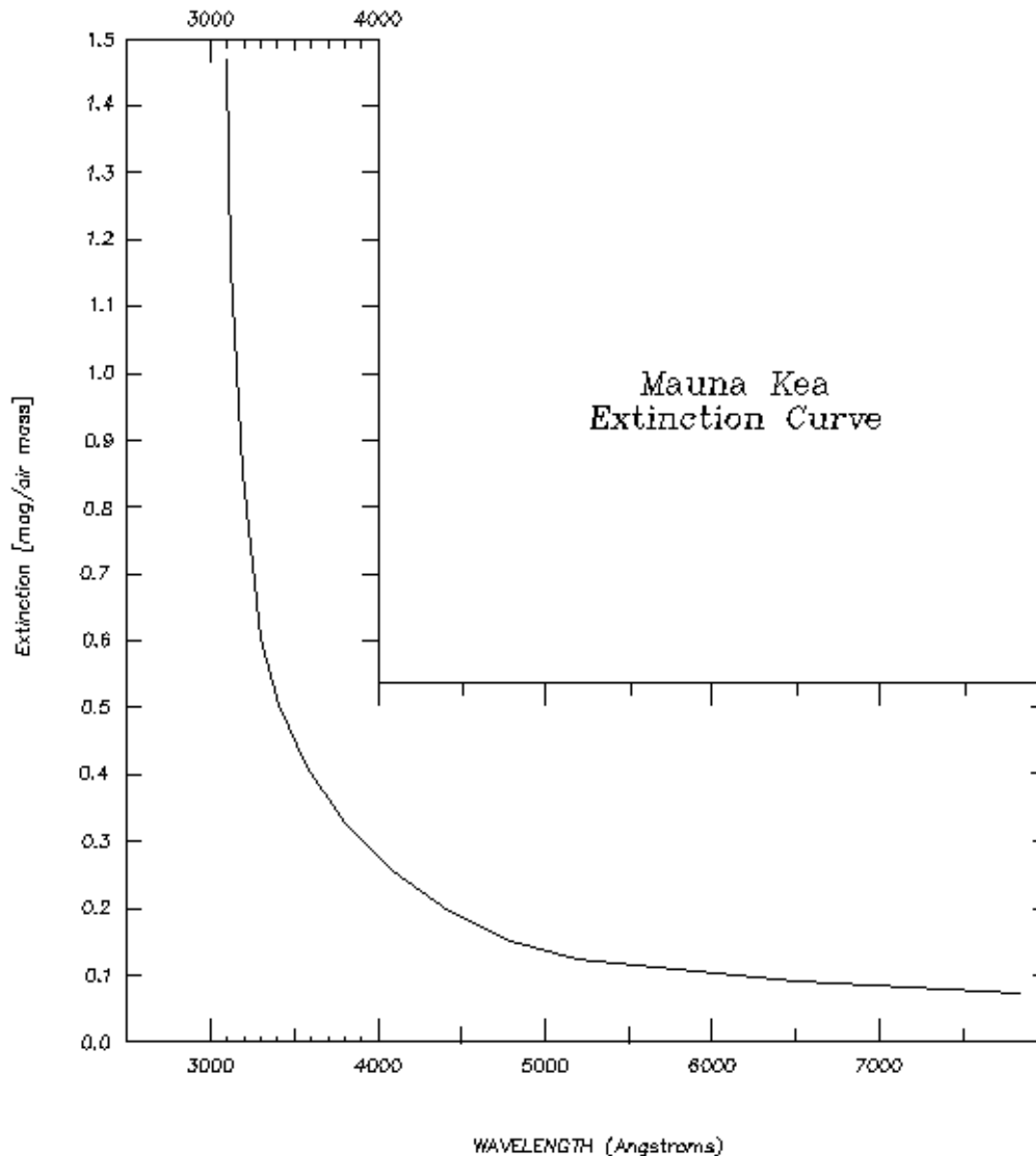
Atmospheric extinction

- $V = V_0 + \kappa(\lambda)X(z)$
  $\kappa(\lambda)$ 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

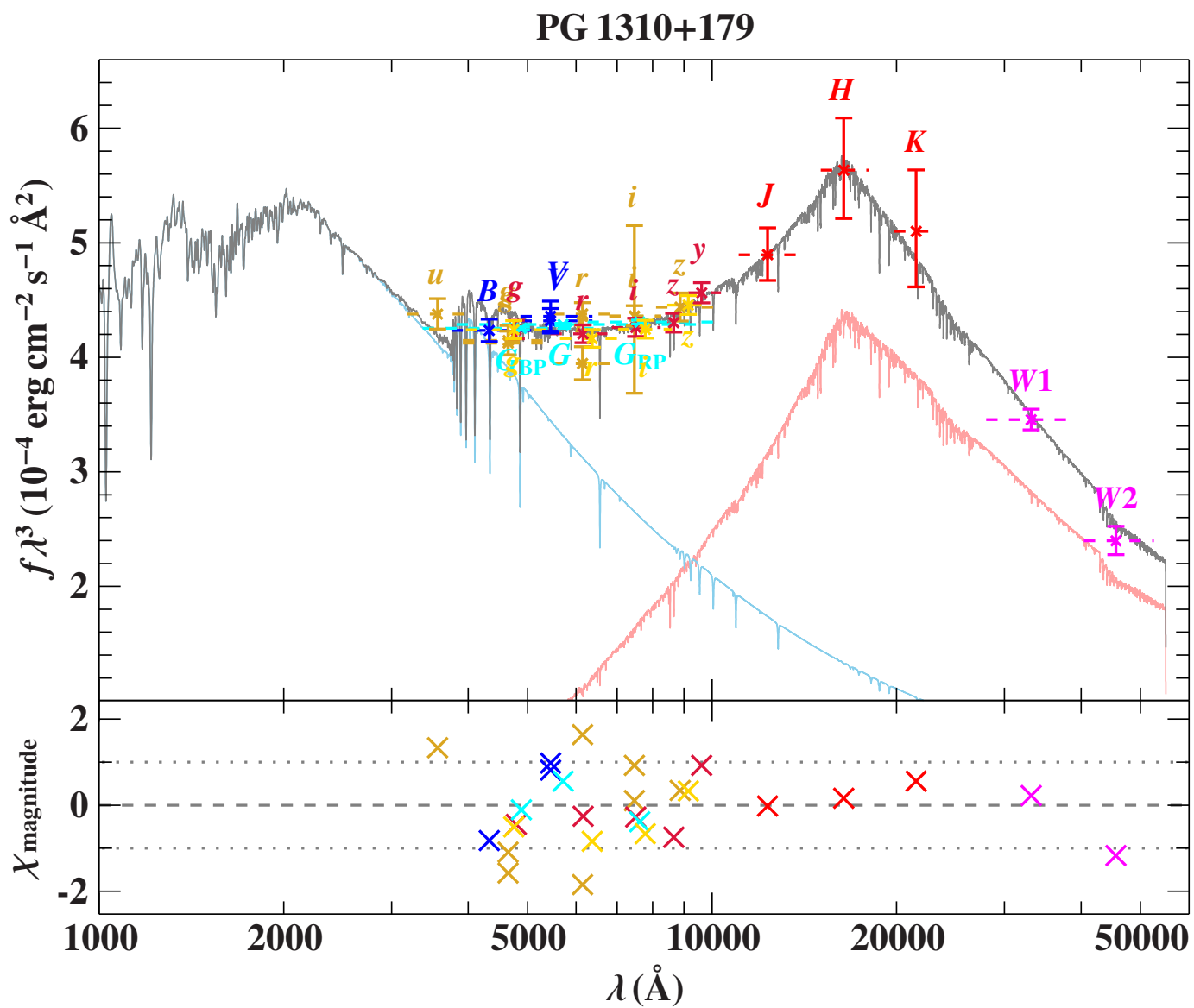Mauna Kea
Extinction Curve

- $V = V_0 + \kappa(\lambda)X(z)$ $\kappa(\lambda)$ 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

EC 21313-7301

Spectral energy distribution (SED) fitting

PG 1310+179
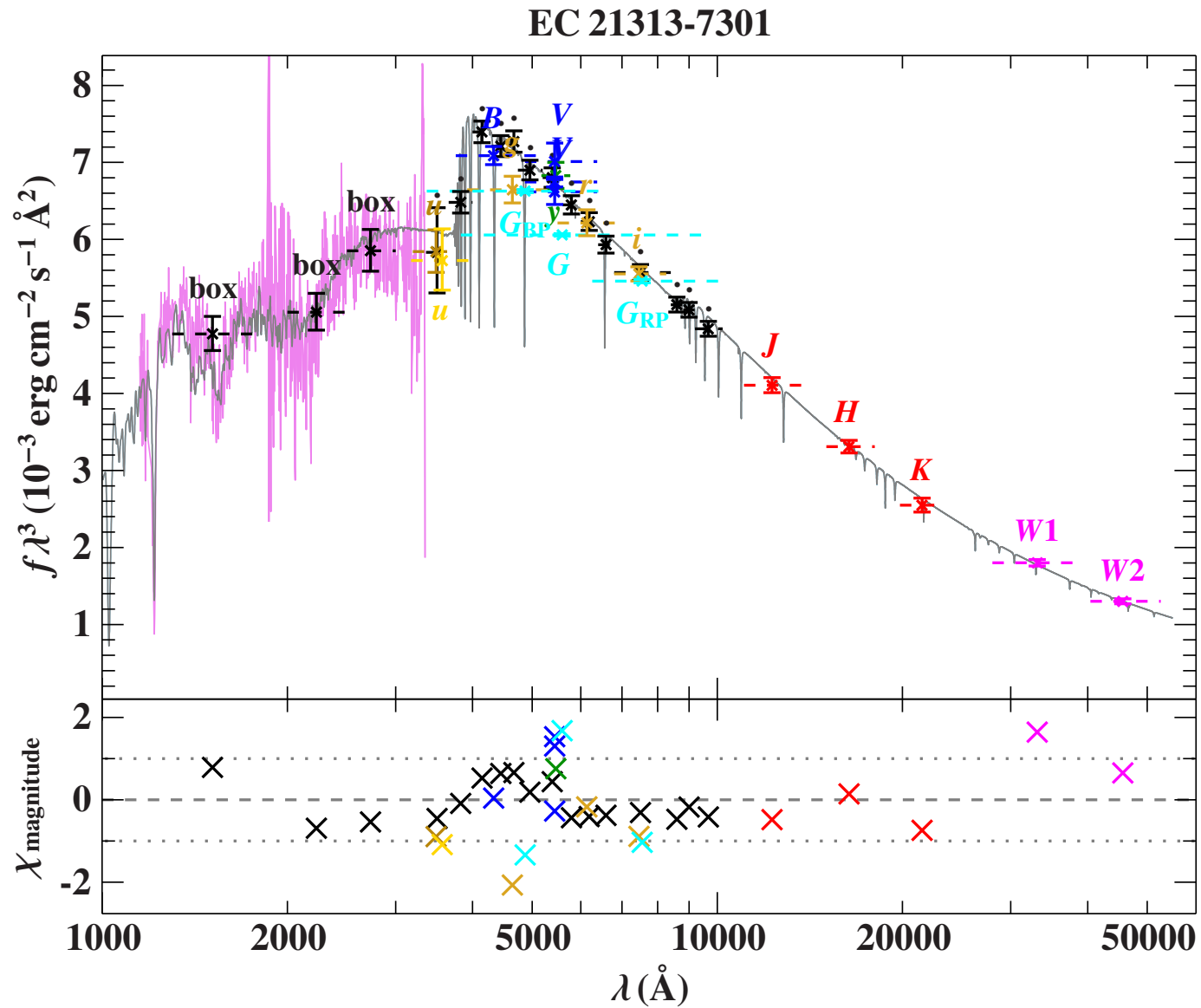
Absolute vs. differential photometry

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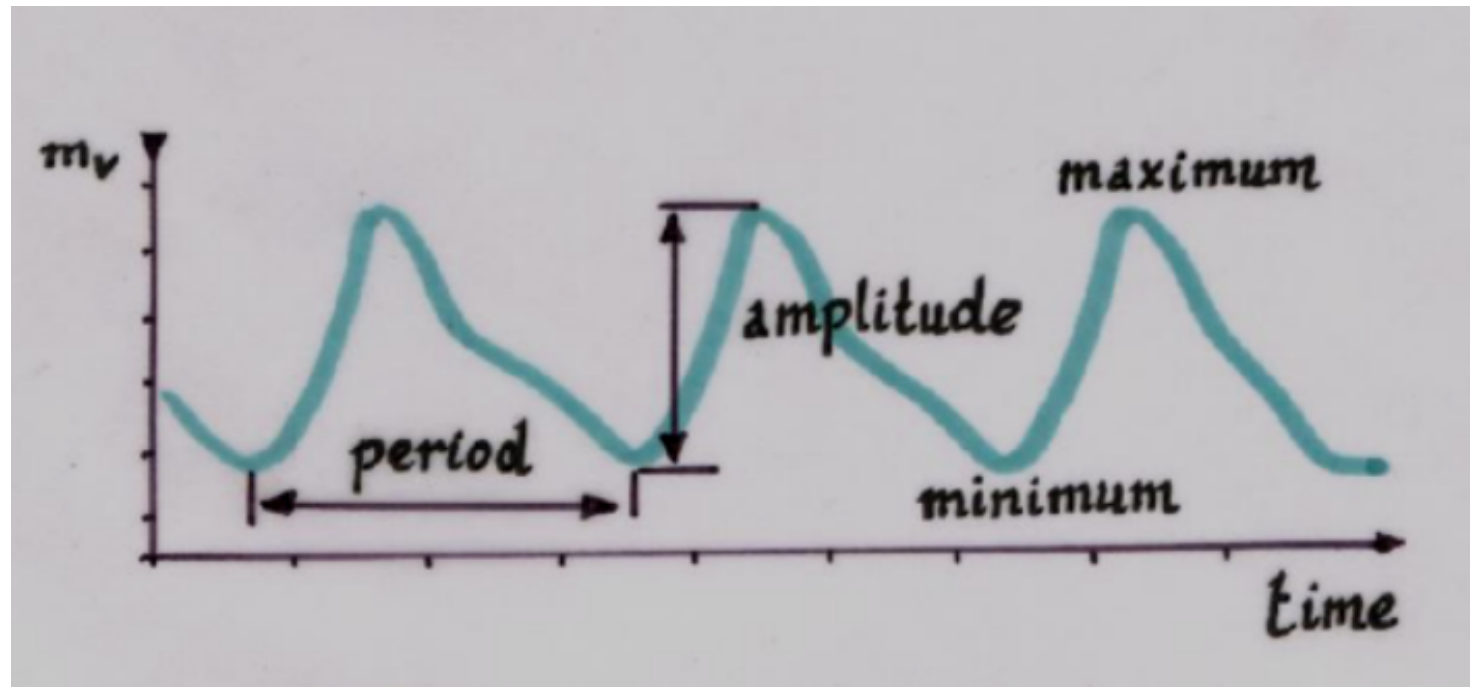
$\Rightarrow$ spectral type, gravity, reddening, age, distance

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.

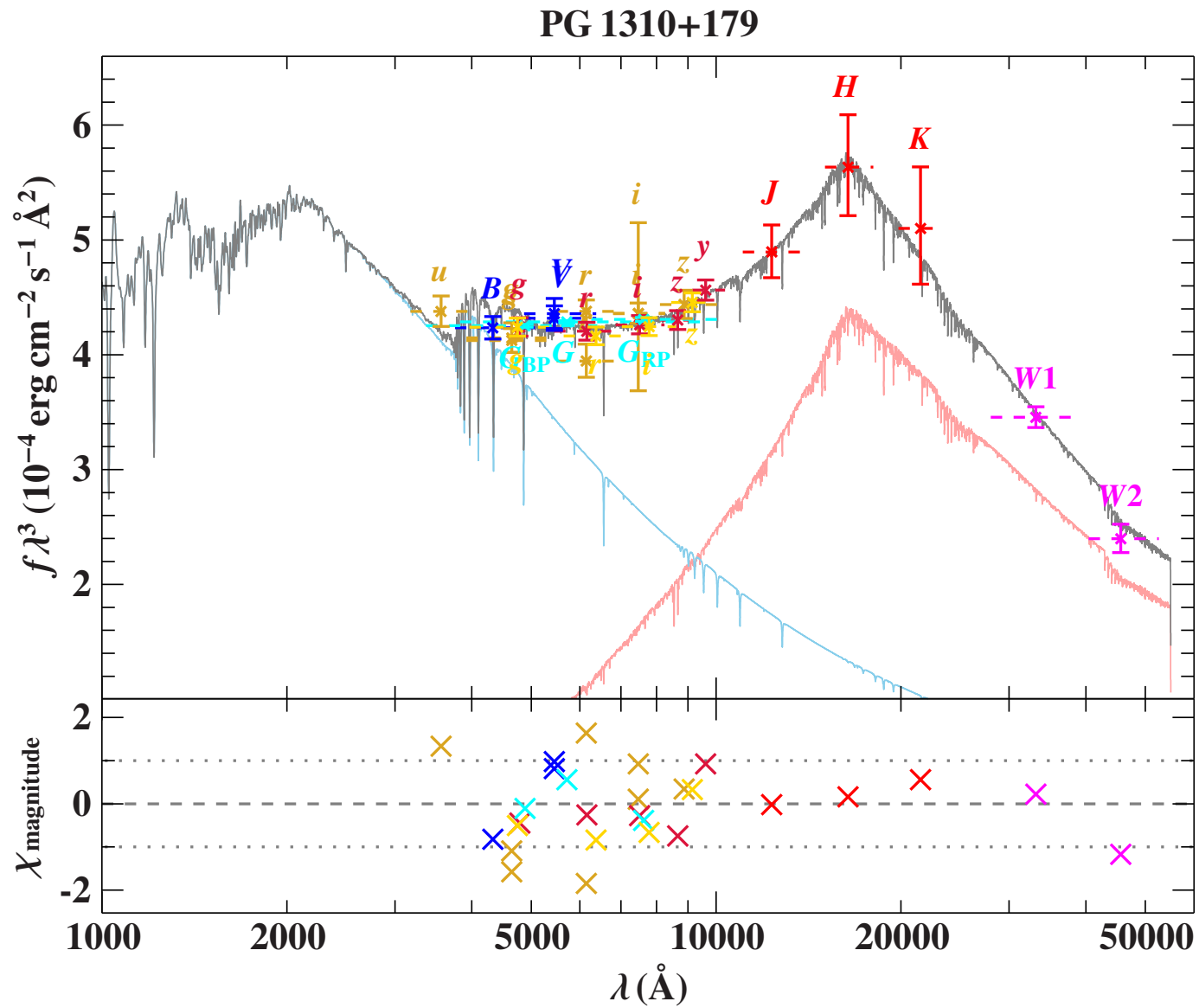$\Rightarrow$ relative flux variations, lightcurves

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

Lightcurves

PG 1310+179

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
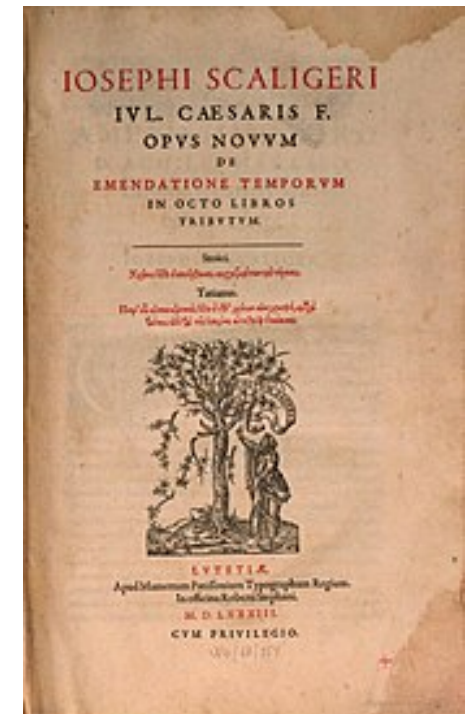
Modified Julian Date MJD

- 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)
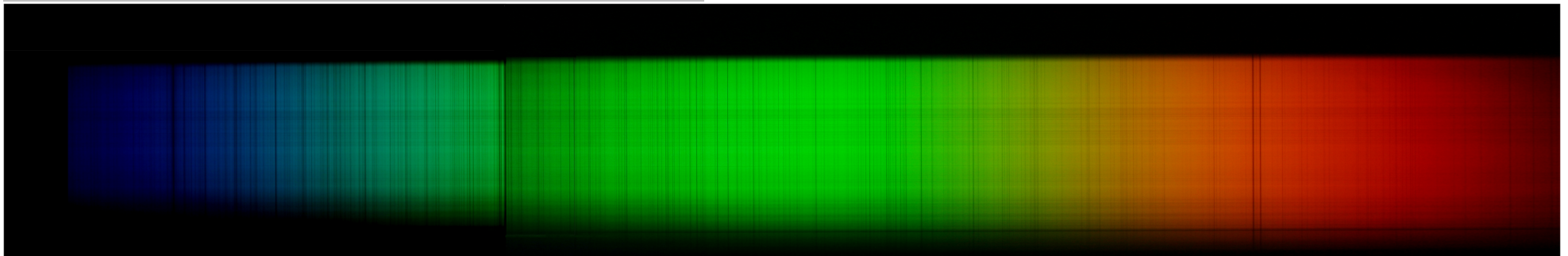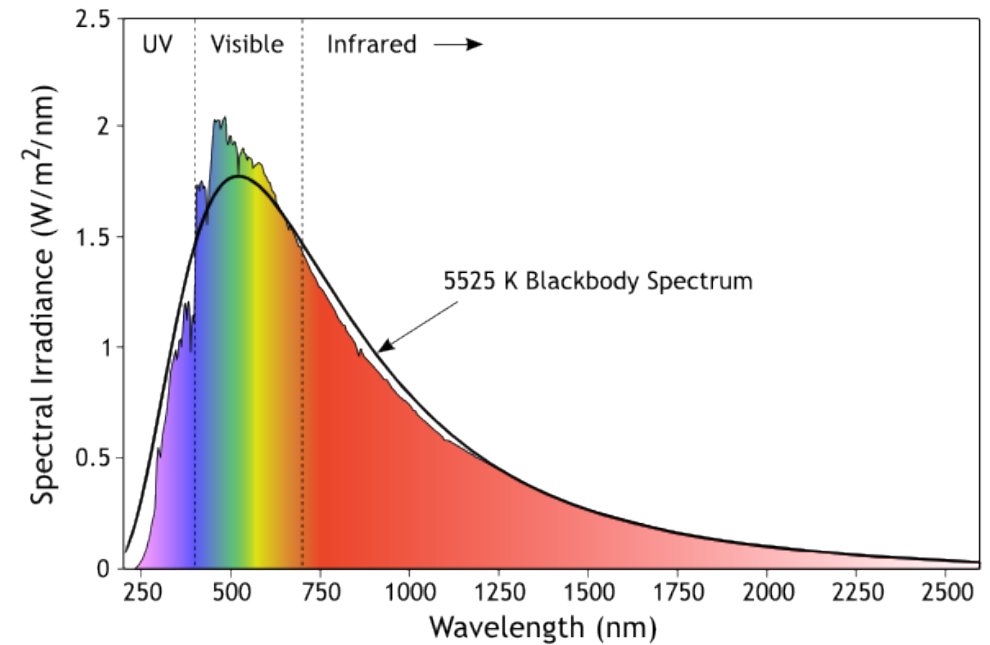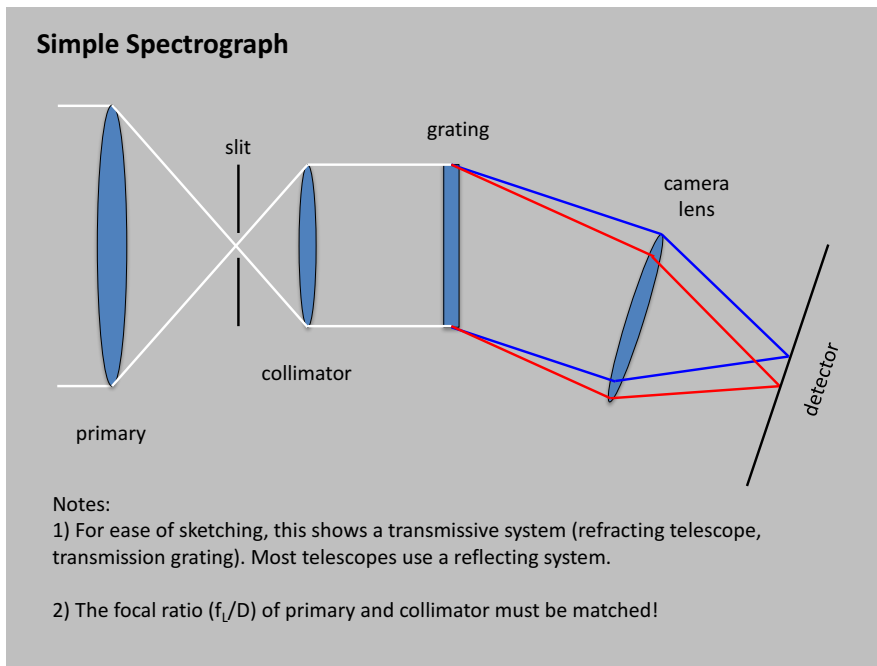
Barycentric Julian Date BJD

- 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)

Simple Spectrograph

slit
grating
camera lens
collimator
detector
primary

Notes:
1) For ease of sketching, this shows a transmissive system (refracting telescope, transmission grating). Most telescopes use a reflecting system.

2) The focal ratio (f_L/D) of primary and collimator must be matched!
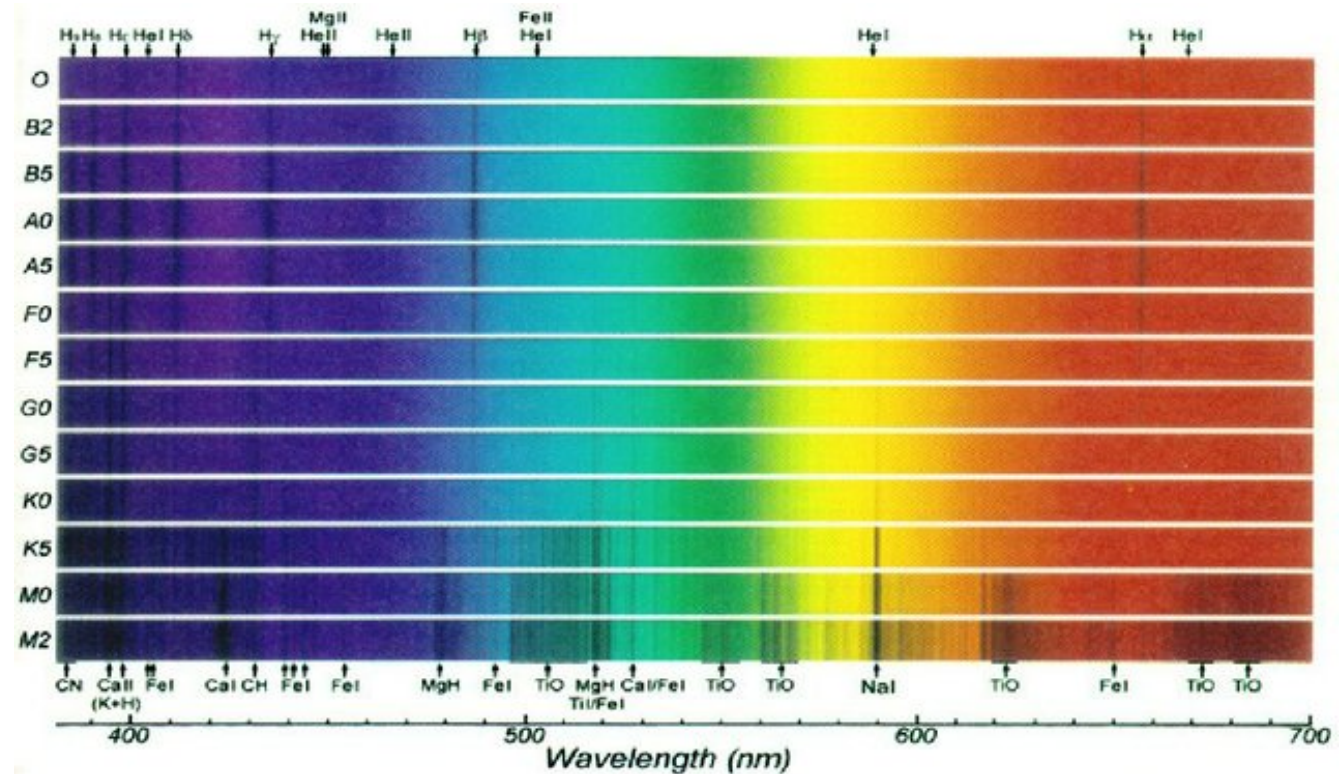

5525 K Blackbody Spectrum

Joseph von Fraunhofer saw 1814 almost 600 lines in the spectrum of the sun
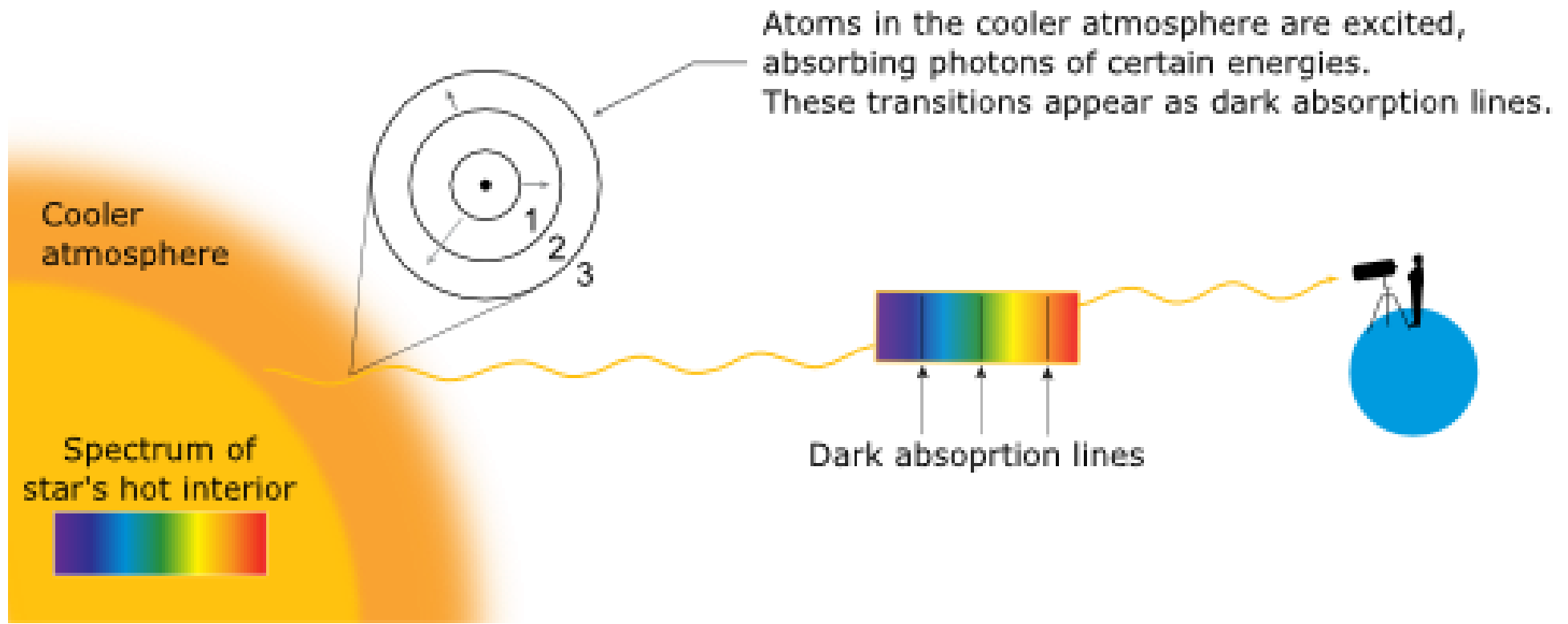
What can we learn from stellar spectra?

Spectra provide a lot of information about an astronomical object:

- temperature
- surface gravity
- chemical composition
- stellar winds
- magnetic fields
- projected rotation
- radial velocity:

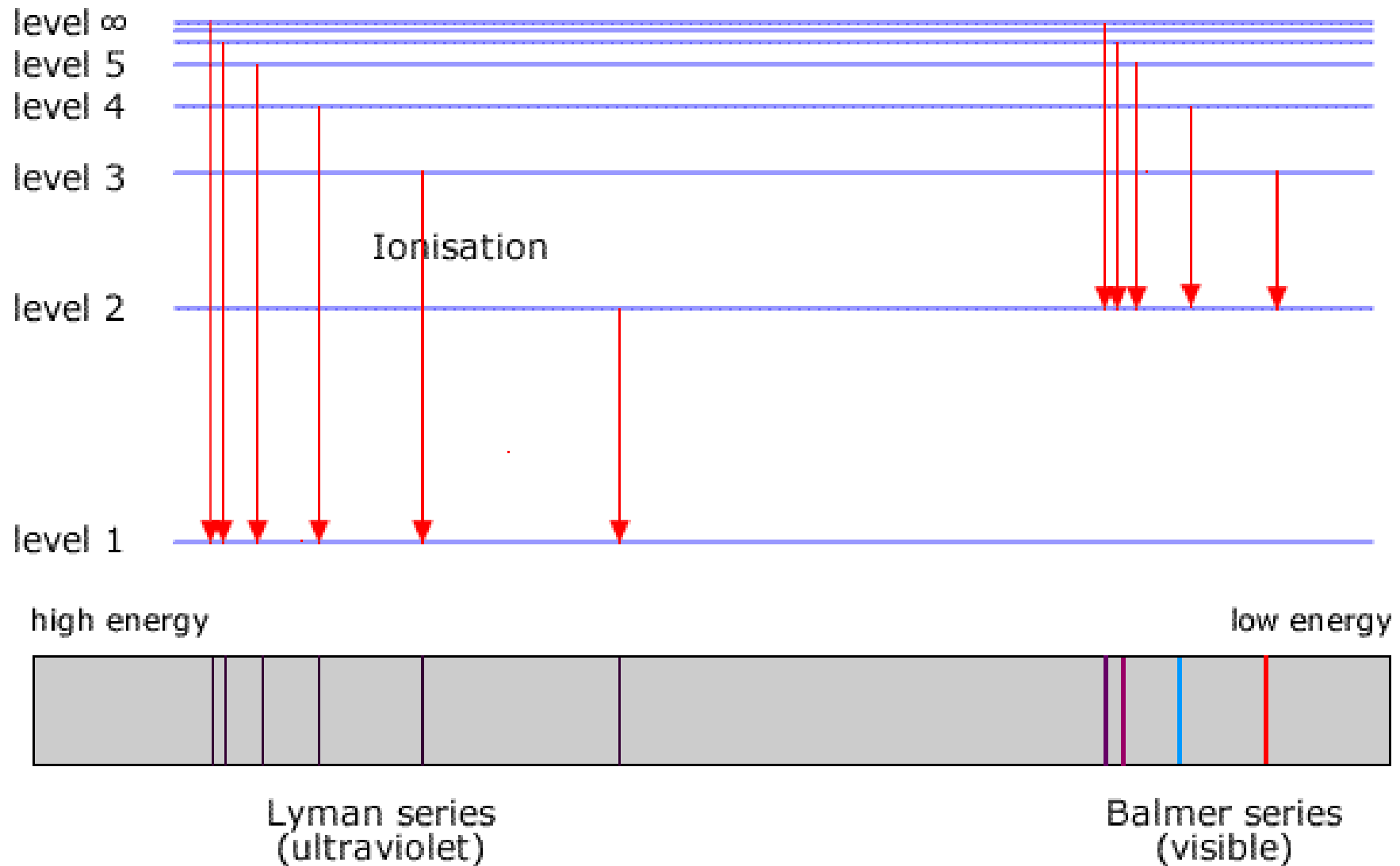 Doppler effect $\frac{v}{c} = \frac{\Delta\lambda}{\lambda}$

Formation of stellar spectra

Atoms in the cooler atmosphere are excited, absorbing photons of certain energies. These transitions appear as dark absorption lines.

Cooler atmosphere

Spectrum of star's hot interior

Dark absoprtion lines

Hydrogen spectrum

Transitions responsible for the first two series in the hydrogen spectrum

Energy level population and ionization stage

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

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

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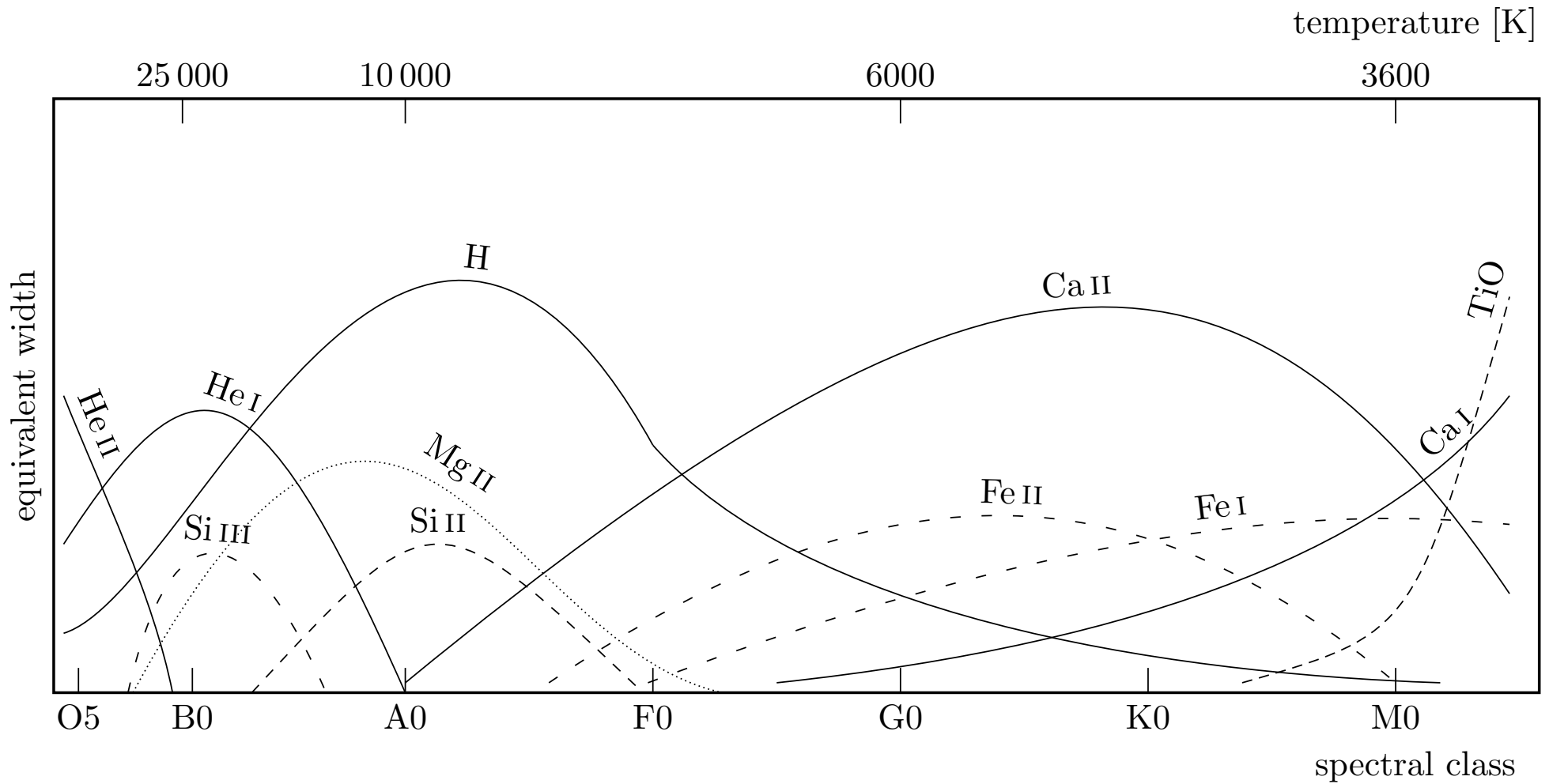
$$\frac{N_j}{N_i} = \frac{g_j}{g_i} e^{-\frac{E_j - E_i}{kT}} \qquad (3.2)$$

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

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

Line strength vs temperature

Fundamental Astronomy: Karttunen et al.

Line broadening

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

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

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

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

$$(3.5)$$

Line broadening

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 $R = \lambda/\Delta\lambda$

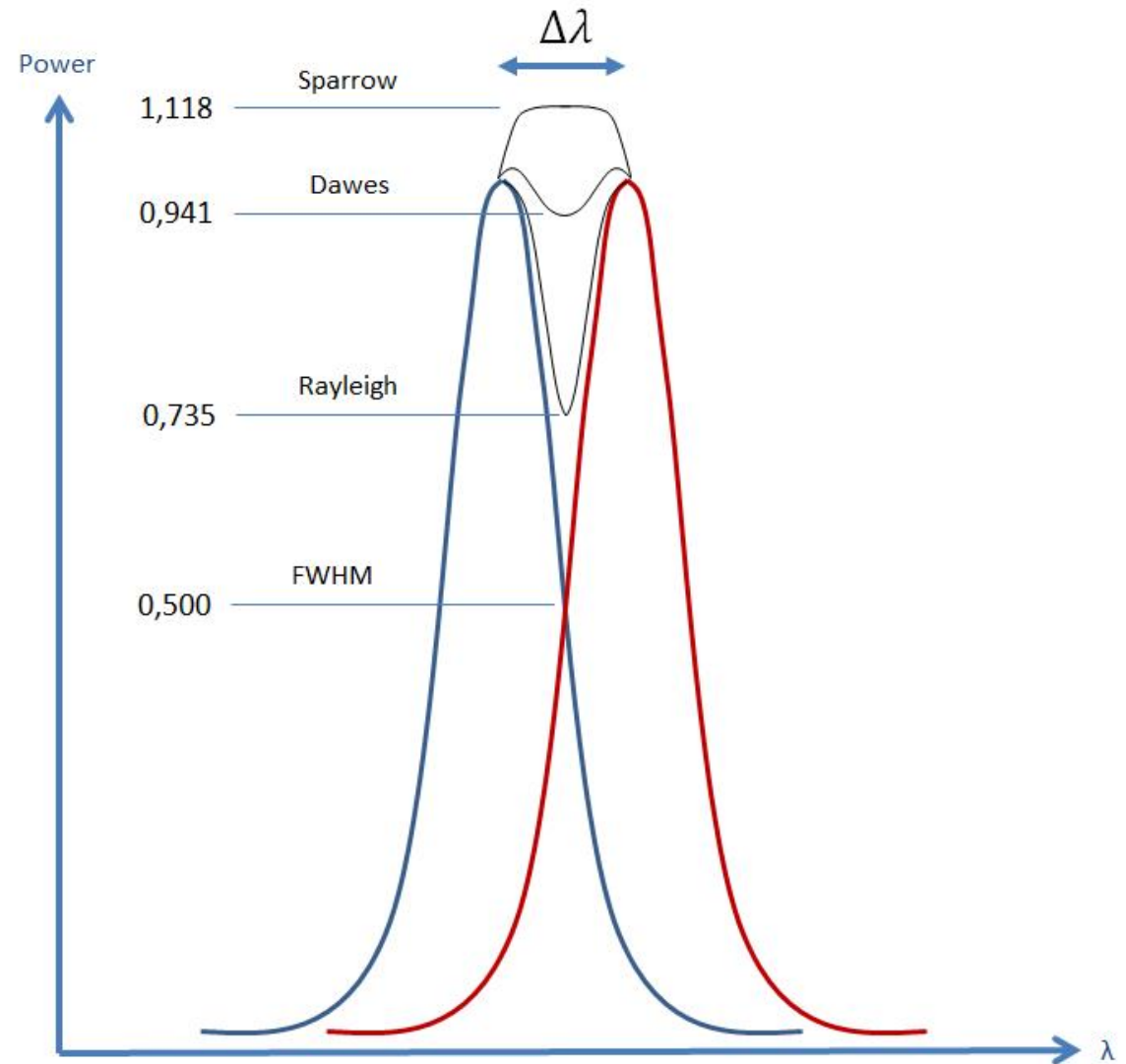$$\text{FWHM} = c/2\sqrt{\ln 2}R \qquad \text{(Gaussian)} \qquad (3.6)$$

Total line Profile

$$\Phi_\nu = \Phi_\nu^{\text{Gaussian}} \star \Phi_\nu^{\text{Lorentz}} \equiv \Phi_\nu^{\text{Voigt}} \qquad (3.7)$$

Other effects: Zeeman Splitting, stellar winds

Properties of Spectrographs

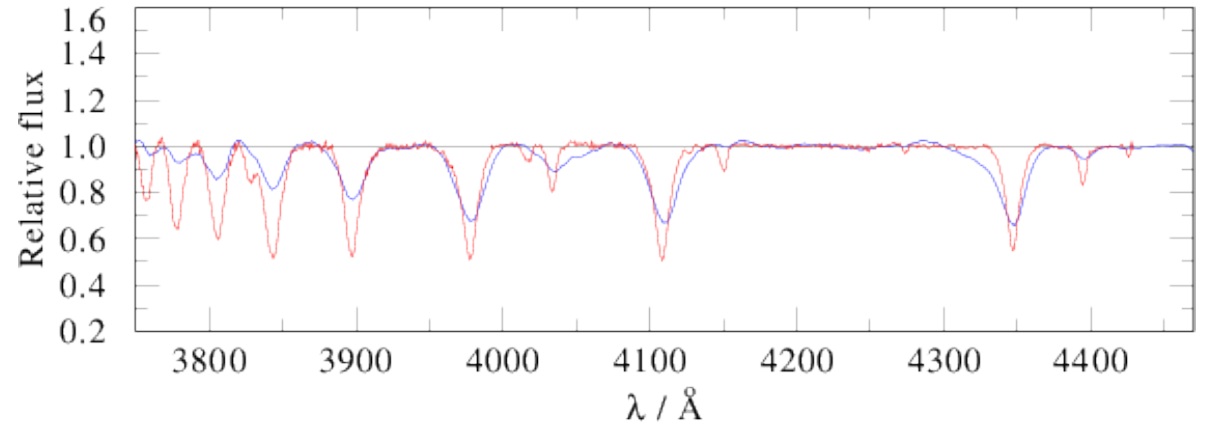• Spectral resolution

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

Properties of Spectrographs

Alkaid

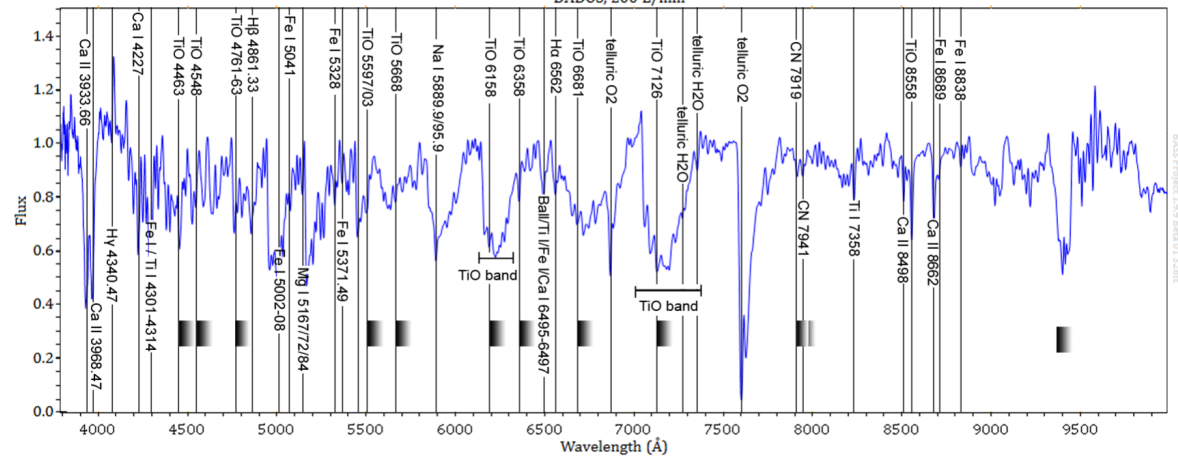Beteigeuze M2 Iab - Normiertes Spektrum
DADOS, 200 L/mm

- Spectral resolution

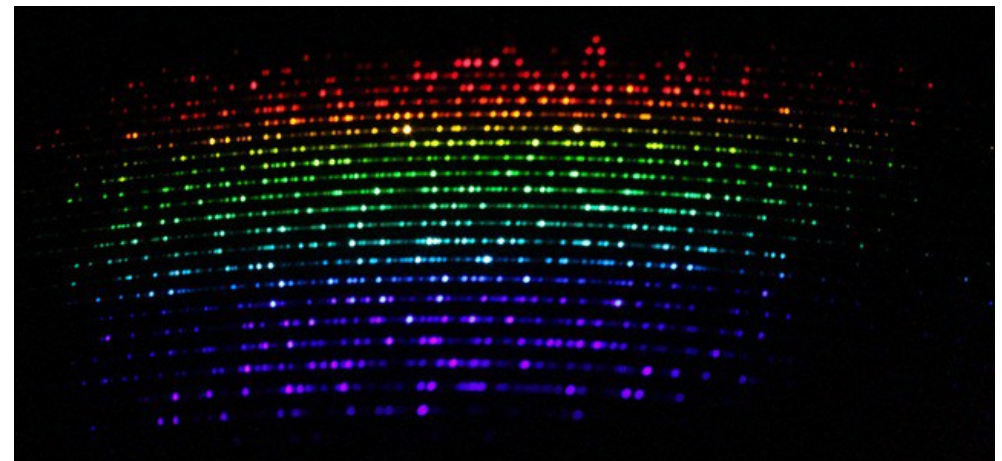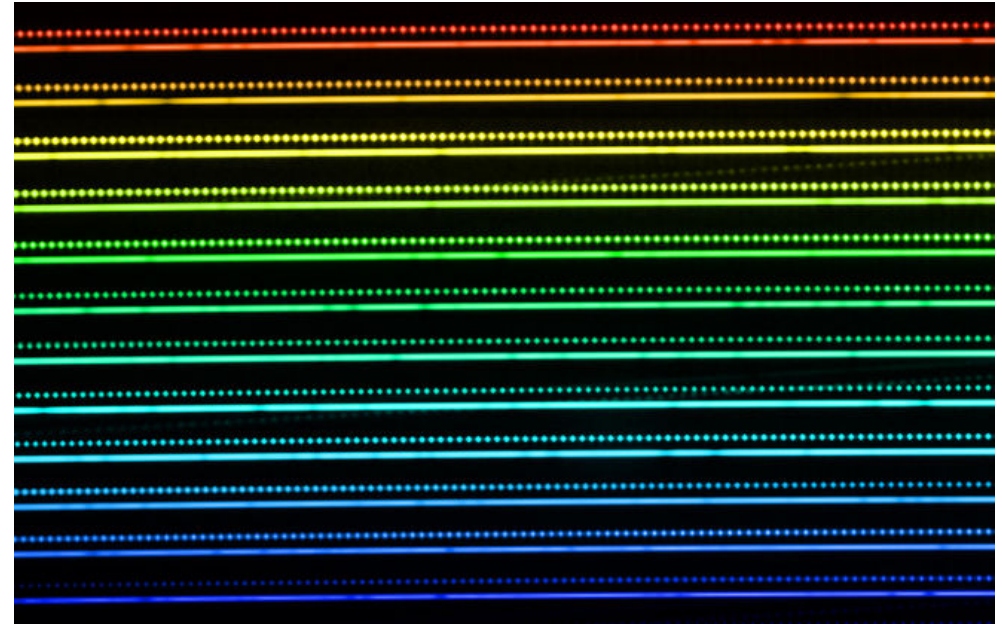$$R = \frac{\lambda}{\Delta\lambda}$$

- wavelength range

Properties of Spectrographs

- Spectral resolution

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

- wavelength range
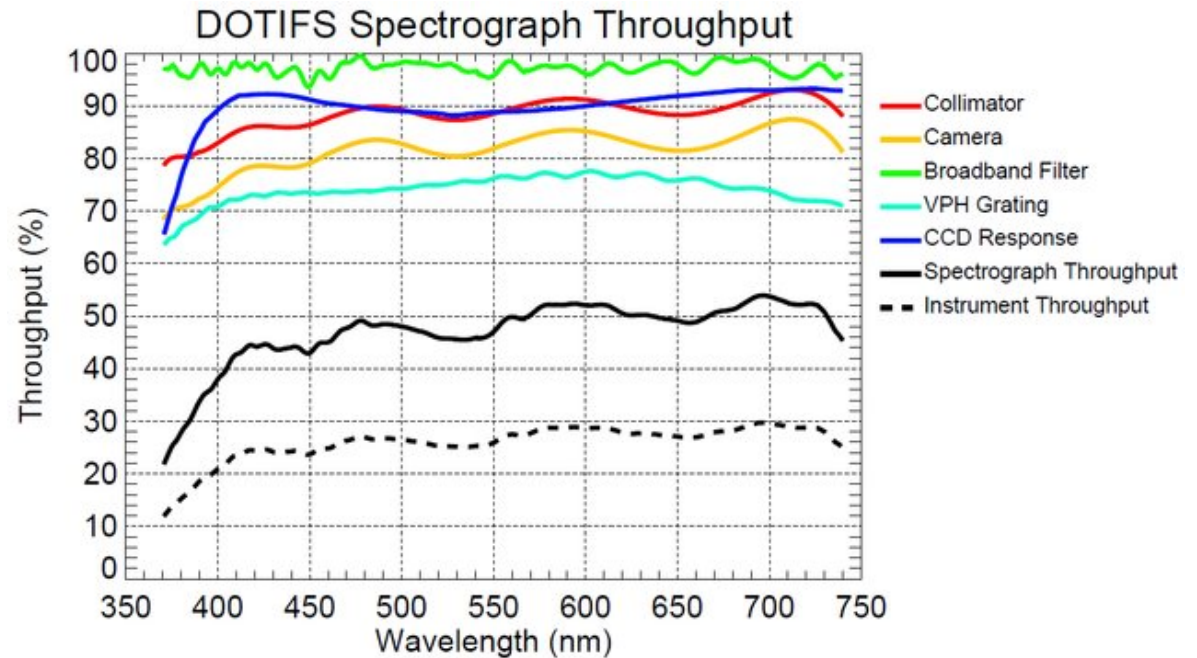
- wavelength calibration and stability
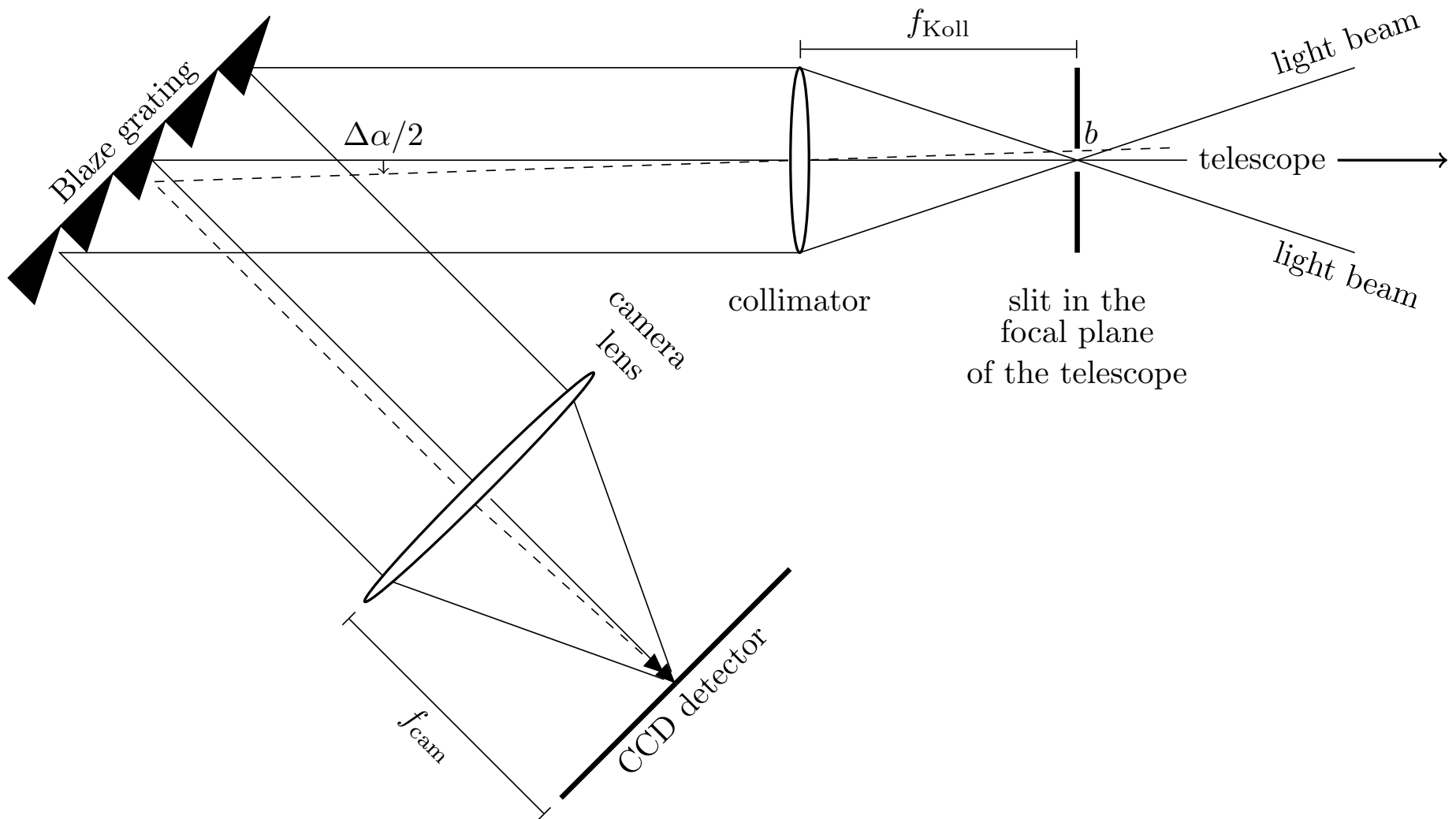
Properties of Spectrographs

- Spectral resolution
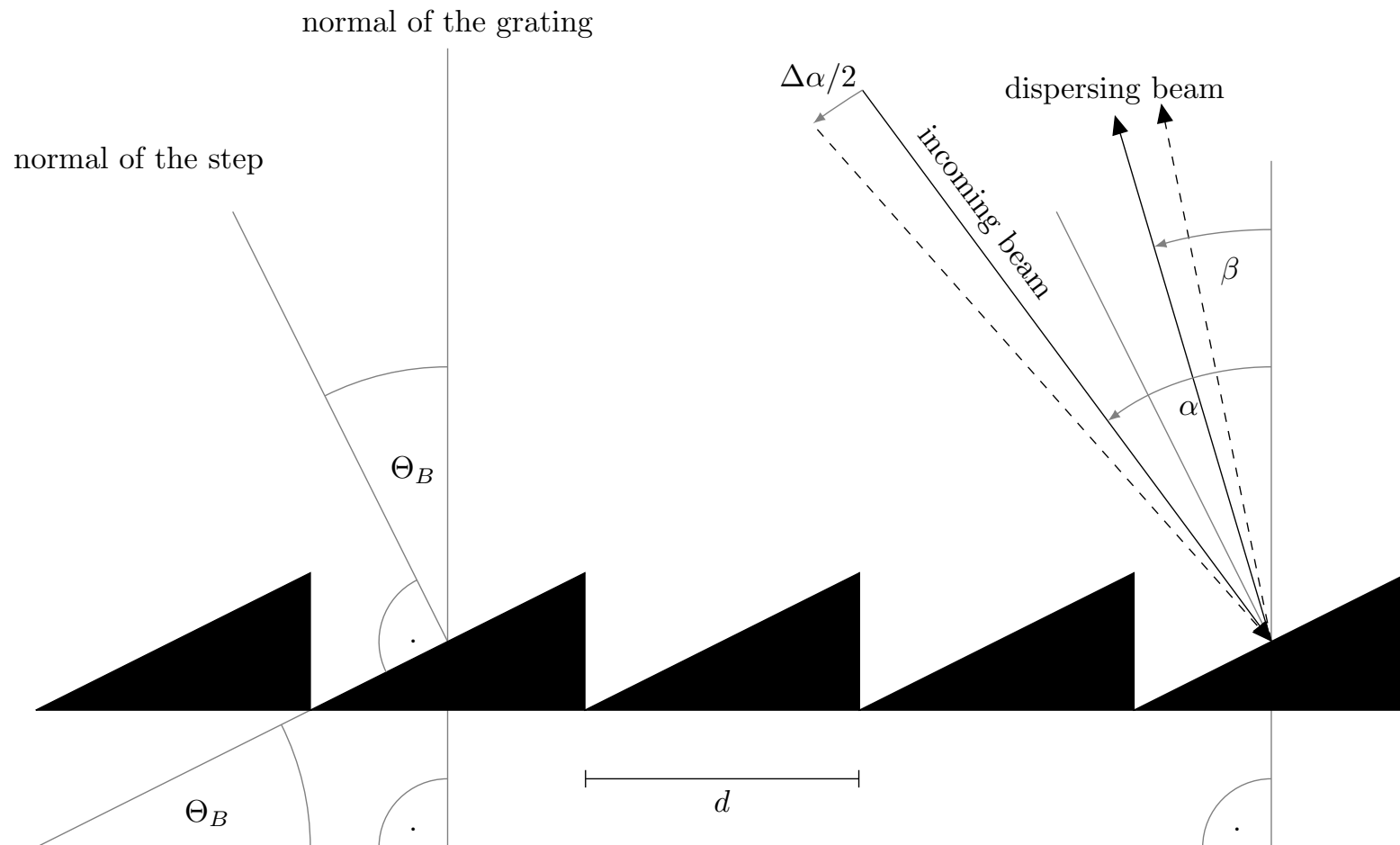
$$R = \frac{\lambda}{\Delta\lambda}$$

- wavelength range

- wavelength calibration and stability

- throughput for best efficiency

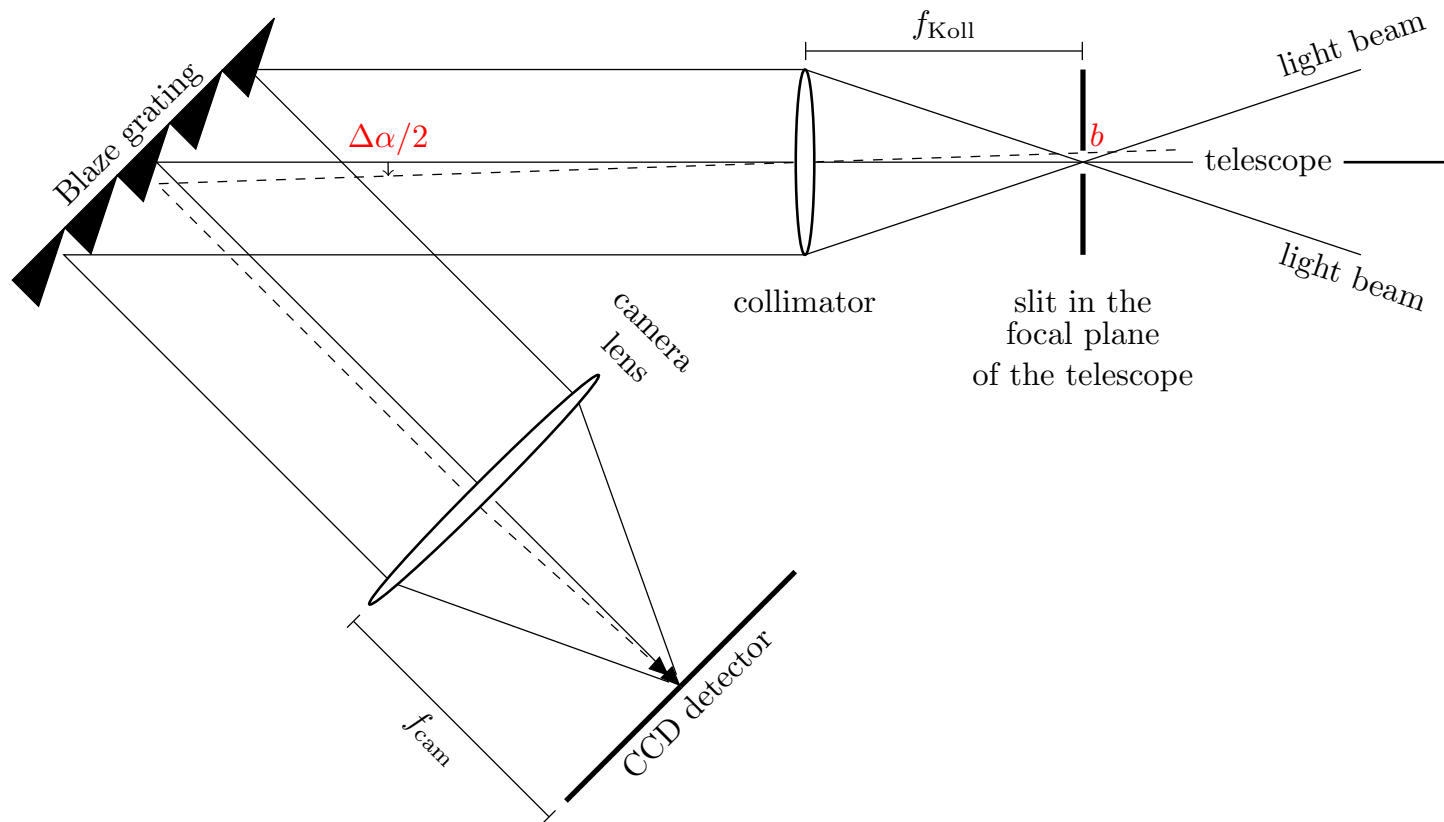- efficiency in the blue/red

- limiting magnitude

DOTIFS Spectrograph Throughput

Long-slit spectrograph

Grating equation

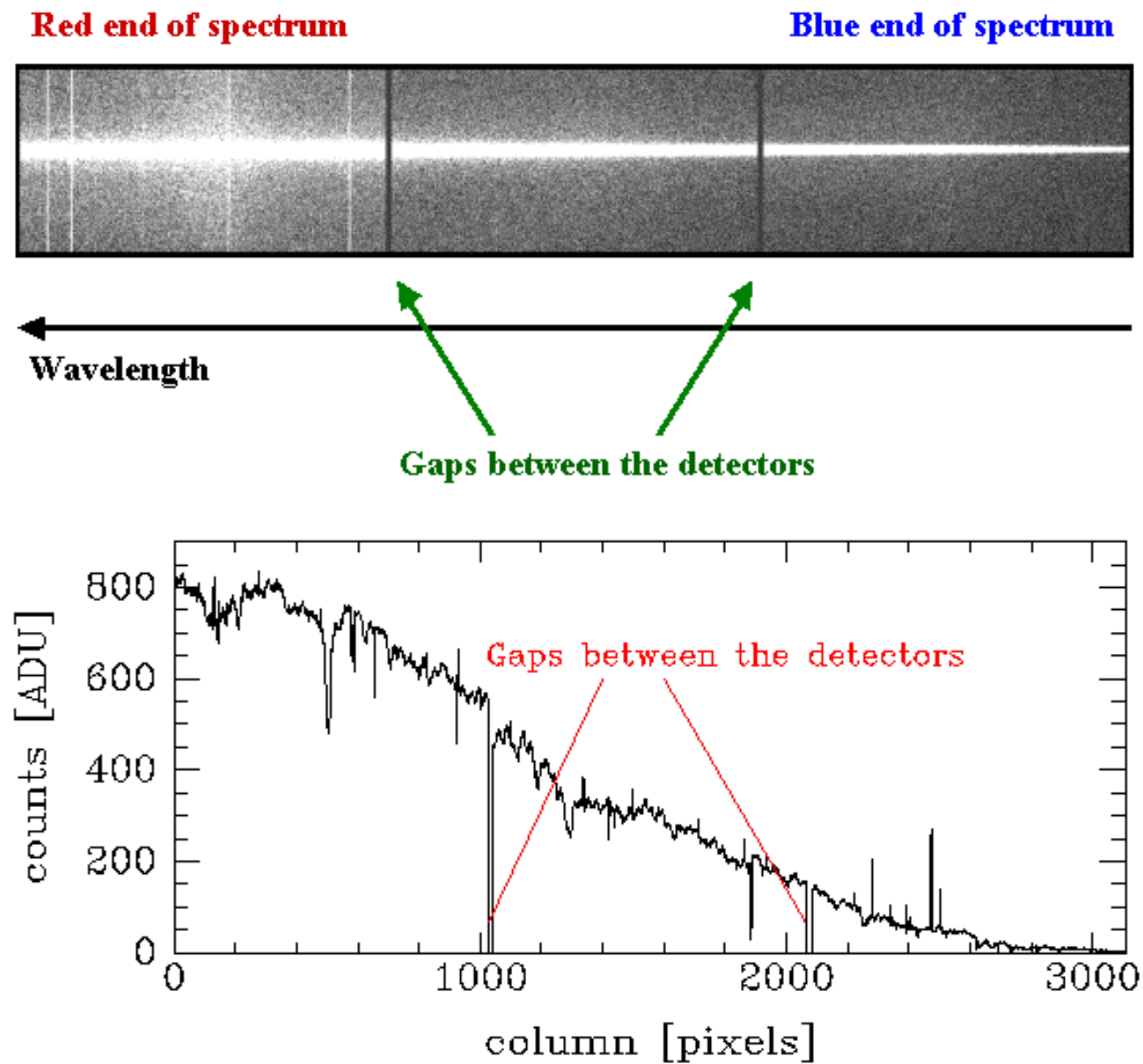$$\boxed{n\lambda = d\sin\alpha + d\sin\beta}, \qquad \alpha + \beta = 2\Theta_B \qquad\qquad (3.8)$$
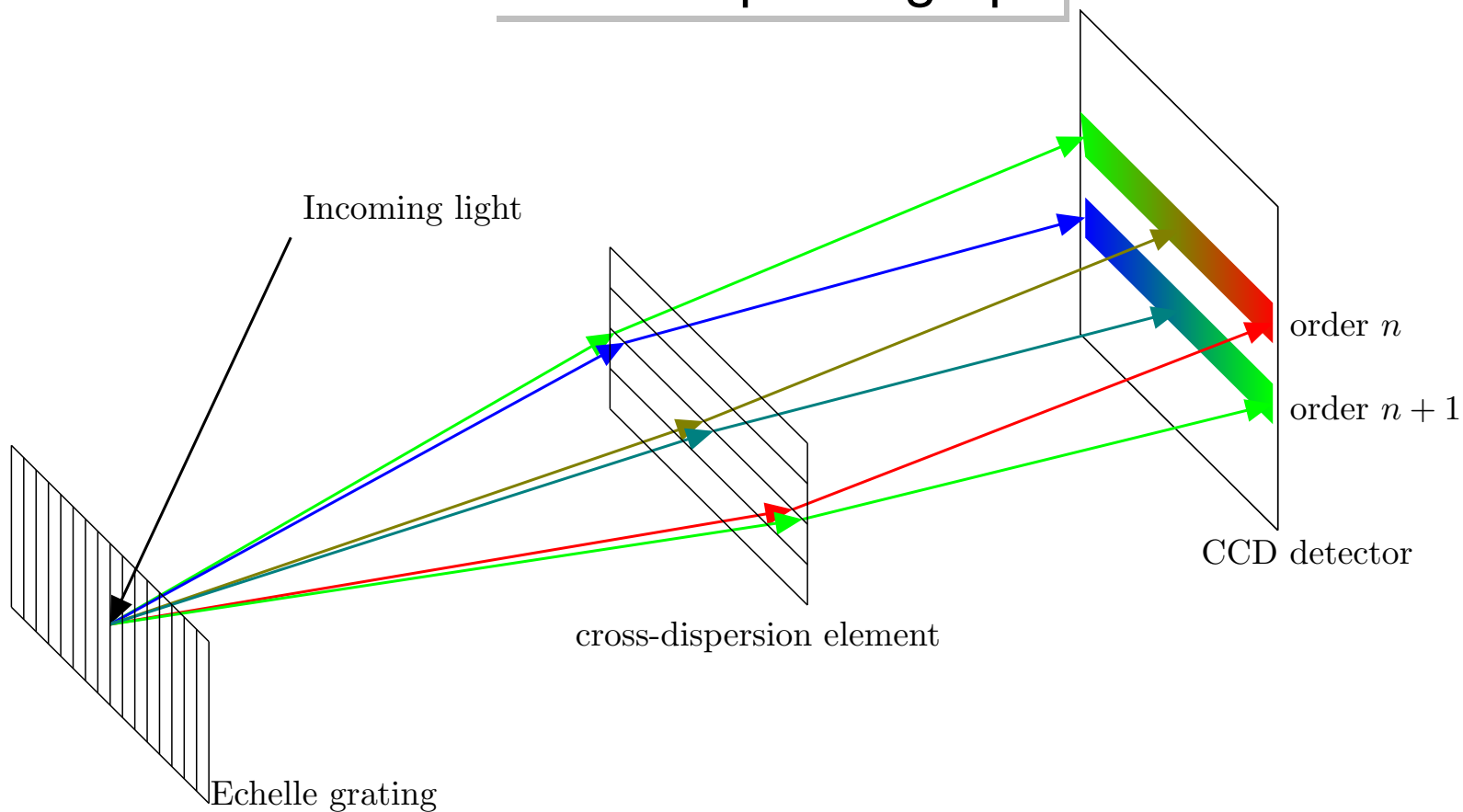
The role of the slit

$$b = f_{\text{Koll}}\Delta\alpha, \qquad \Delta\lambda = \frac{d\lambda}{d\alpha}\Delta\alpha = \frac{d}{n}\cos\alpha\,\Delta\alpha = \text{const}$$

$$\boxed{R_{\text{slit}} = \frac{nf_{\text{Koll}}}{db\cos\alpha}\lambda} \tag{3.9}$$

A long-slit spectrum

Echelle spectrograph

Incoming light

cross-dispersion element

Echelle grating

order n

order $n+1$

CCD detector

- optimized for high incidence angles $\Theta_B > 45°$ and high orders

- separate overlapping orders by cross-dispersion element
- Blaze wavelength $n\lambda_n^0 = d[\sin\alpha + \sin(2\Theta_B - \alpha)]$

$$R_{\text{Echelle}} = \frac{f_{\text{Koll}}}{b\cos\alpha}[\sin\alpha + \sin(2\Theta_B - \alpha)] = \text{const}$$

Echelle spectrum