Workshop on observational techniques

Research workshop on evolved stars

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06.09.2021-17.09.2021

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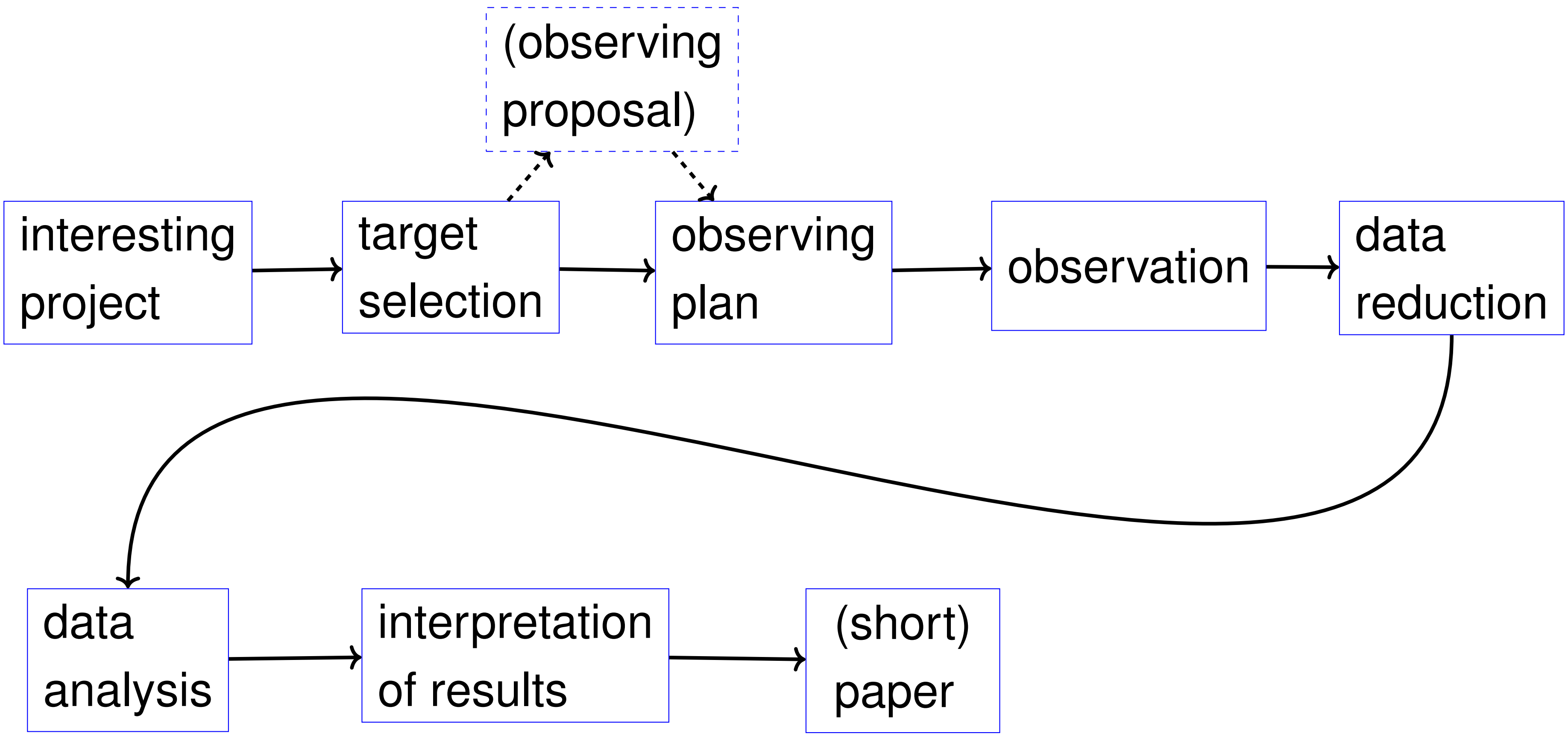
Universität Potsdam

Process of research in observational astrophysics



Organizational

- four observing groups a 3 or 2: we want to mix the students, so please can each student from Brno join another group
observing night	1	2	3	4	5	6	7	8
spectroscopy	A	C	B	D	A	B	C	D
photometry	B	D	A	C				

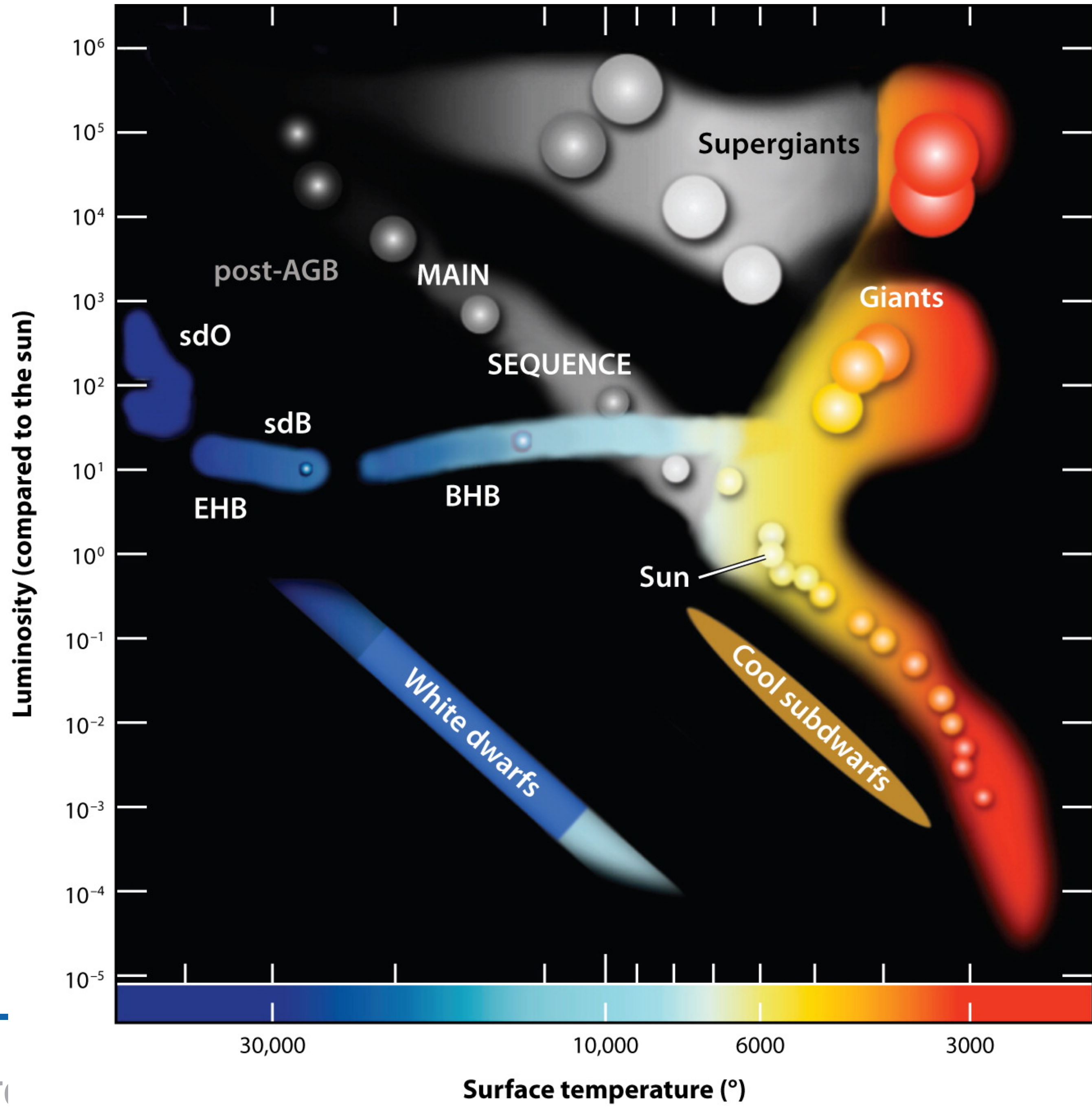
  observations start at $\sim 19:00$, so if you observe, please bring something for dinner
- Lecture plan: `https://stelweb.asu.cas.cz/en/seminars/workshops/workshop-2021/`
- Lectures start at 14:00, if there were no observations, and 16:00 if one or two groups did observe the last night
- one supervisor will be there during the day from 10:00 to help the students, who did not observe, with data reduction, analysis, results ....
- it is also possible to do some work during the observations

Organizational

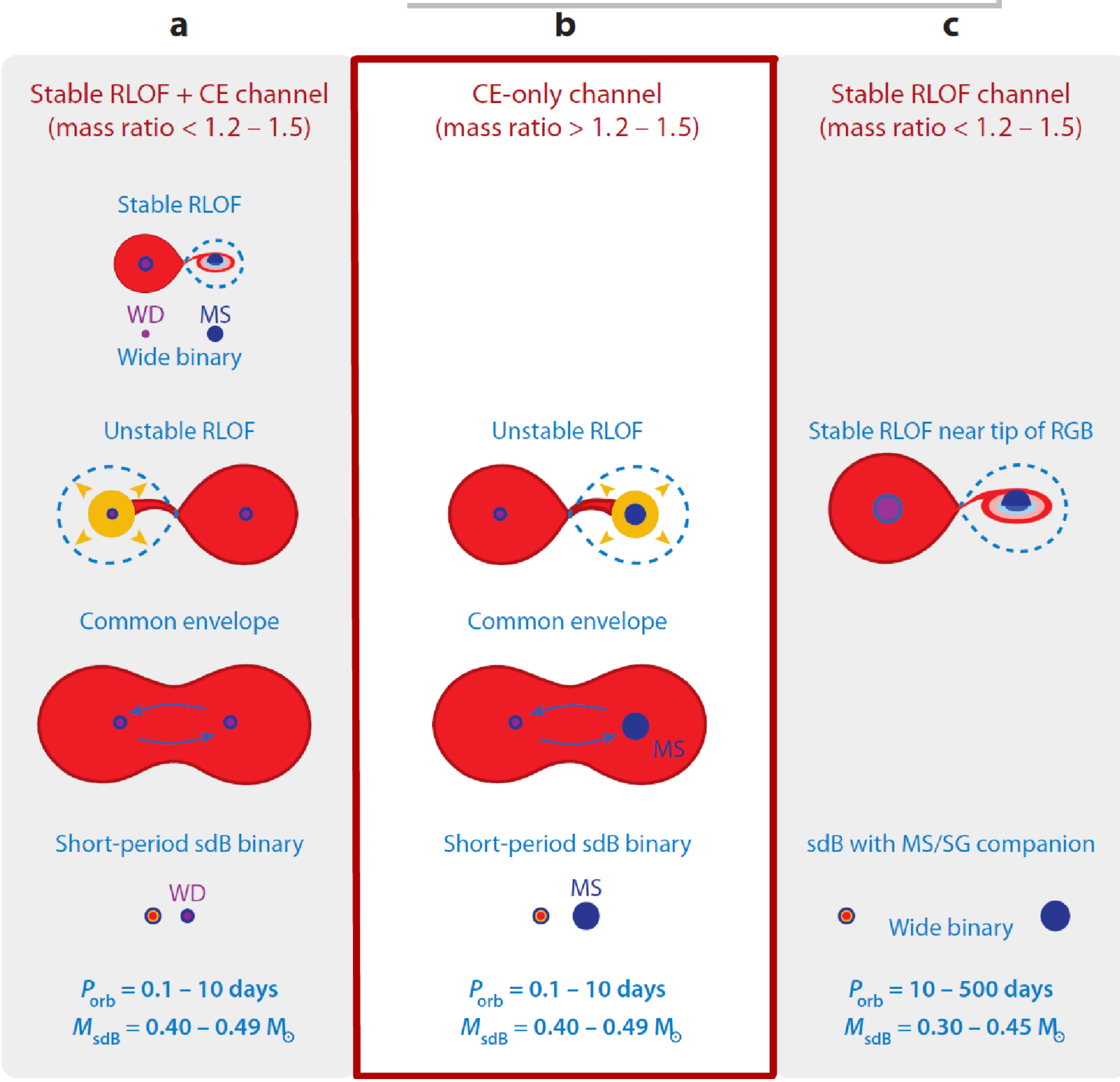
- second week: each group works on a different research project using data observed and reduced by different groups
- requirement for passing the course: every group reduces their own data, (short) paper about the research project with focus on the scientific goal, target selection, analysis methods, data analysis and discussion of results
- Deadline: 17.09.2021 (you should finish a draft the day before, so that you can work in feedback)

Photometric project

Hot subdwarf stars of spectral type B (sdB)



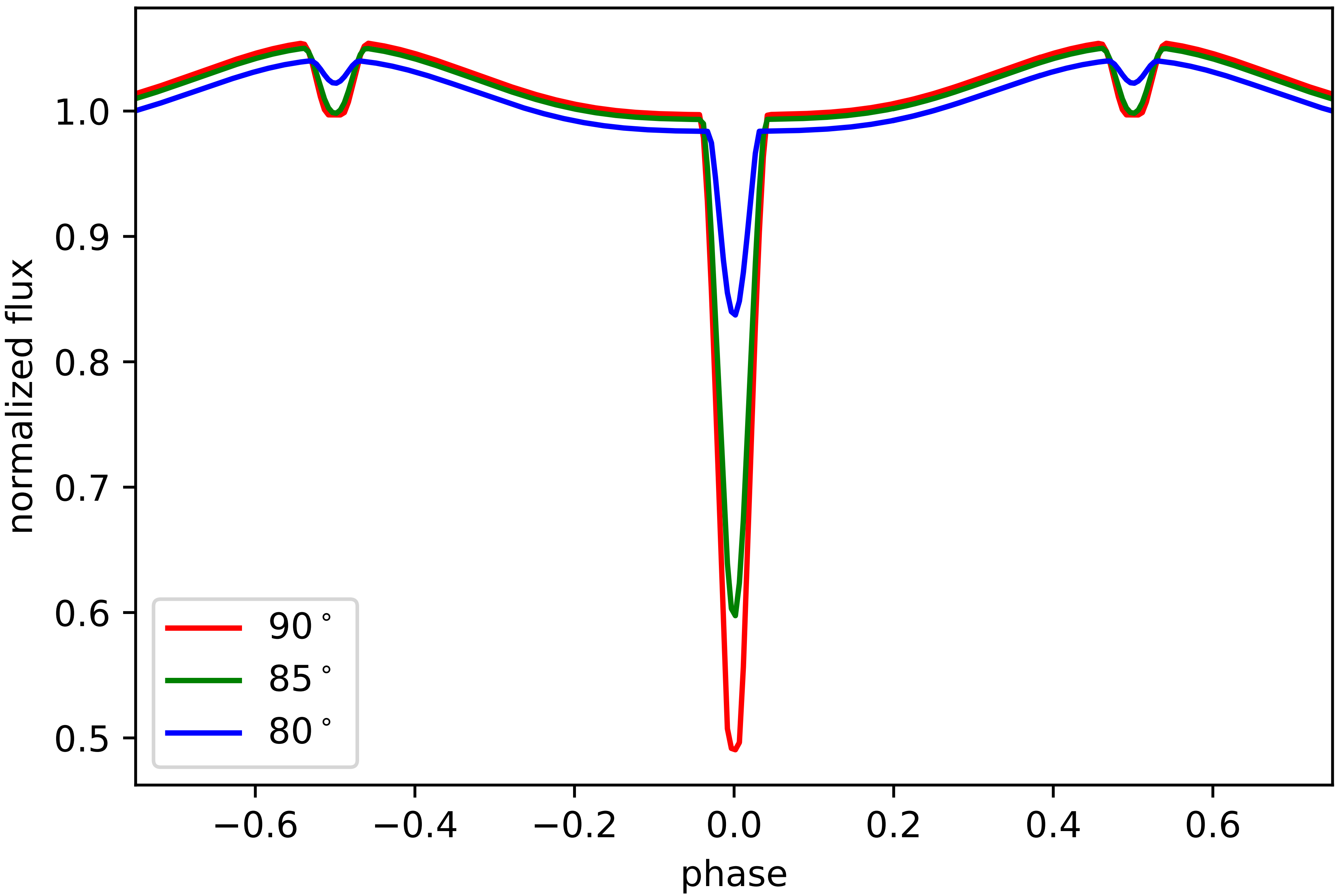
Formation of sdB binary



Han et al. (2002,2003)

Eclipsing Reflection effect systems

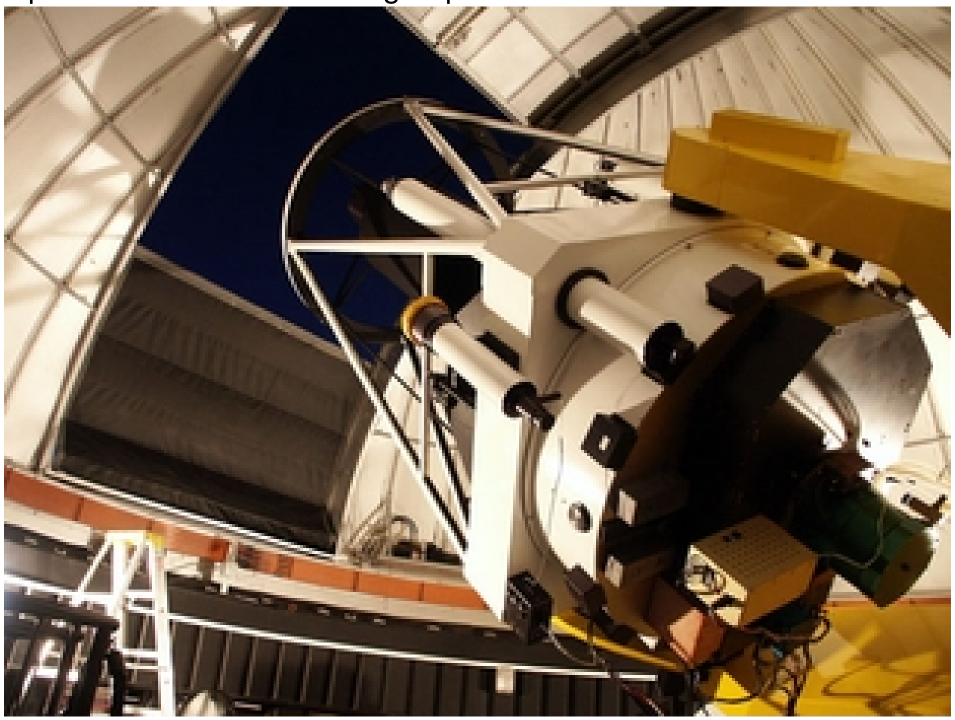
Eclipsing Reflection effect systems



Ground-based lightcurve surveys

OGLE

Optical Gravitational Lensing Experiment



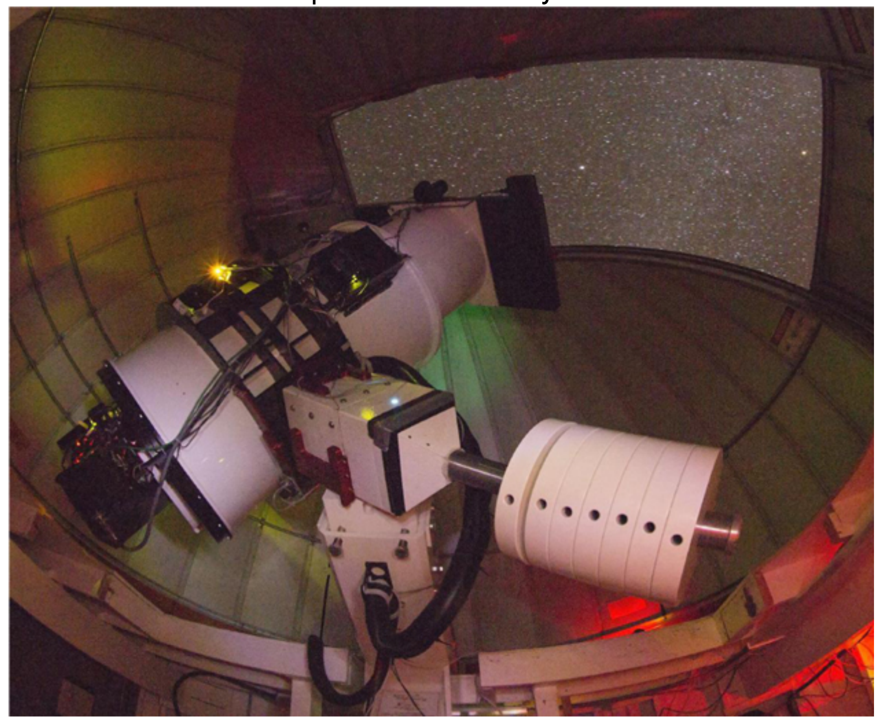
→ observation of the lightcurve of many stars in different fields

→ discovery of planetary transits, pulsators, eclipsing binaries

CRTS, PTF, ZTF, BlackGEM, ...

ATLAS

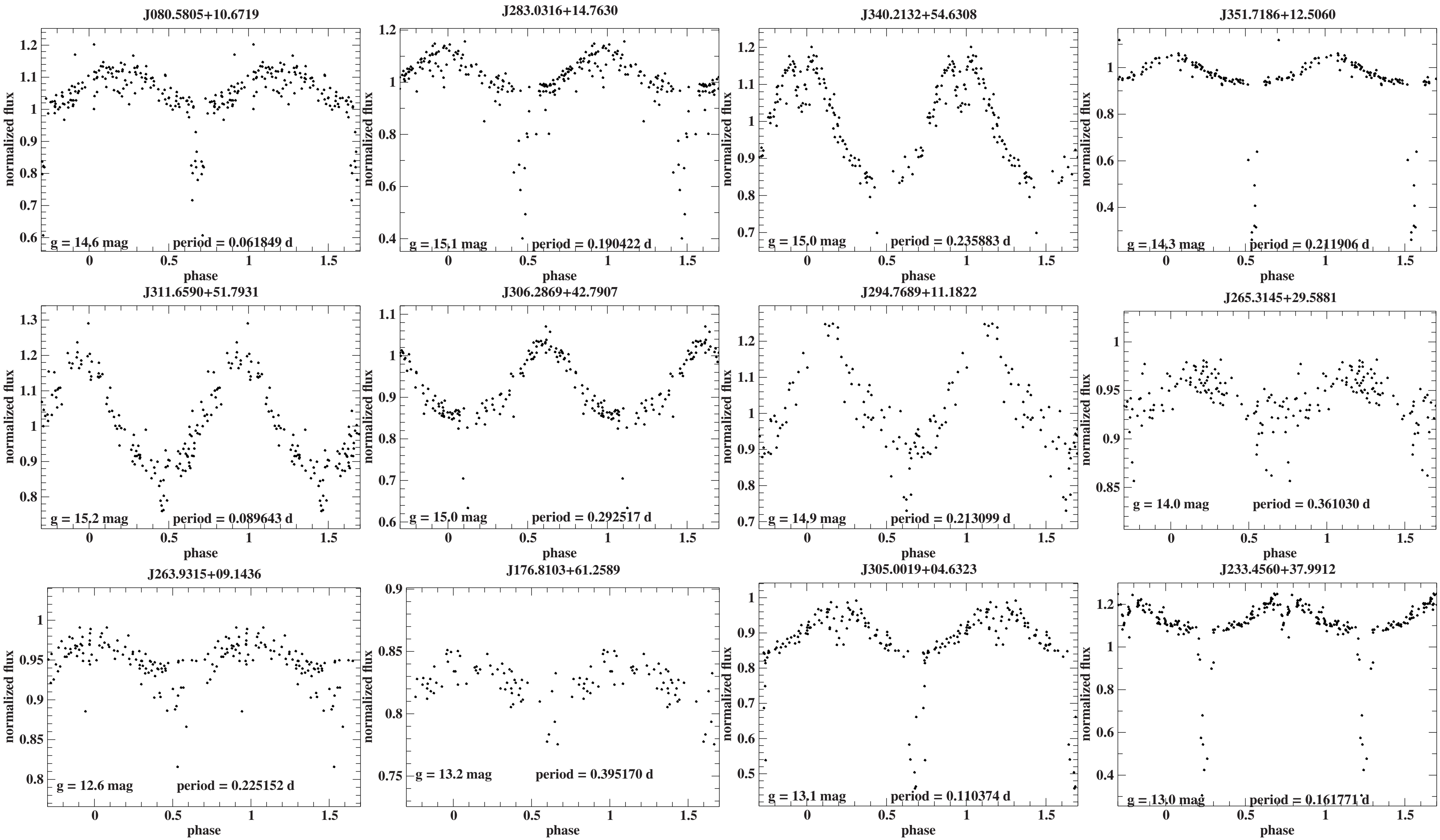
Asteroid Terrestrial-impact Last Alert System



→ a robotic astronomical survey looking for near-earth objects

→ located in Hawaii, planned in the southern hemisphere

150 HW Vir candidate systems: $P = 0.05 - 1.26$ d



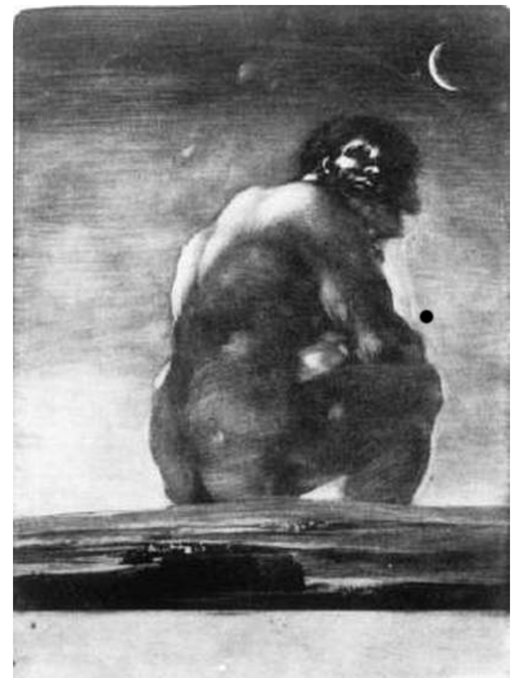
The EREBOS project

EREBOS (Eclipsing Reflection Effect Binaries from **Optical** Surveys)

- homogeneous data analysis of all newly discovered HW Vir systems
- photometric and spectroscopic follow-up of all targets to determine fundamental (*M*, *R*), atmospheric ($T_{\rm eff}$, $\log g$) and system parameters (*a*, *P*)
- spectroscopic and photometric follow-up

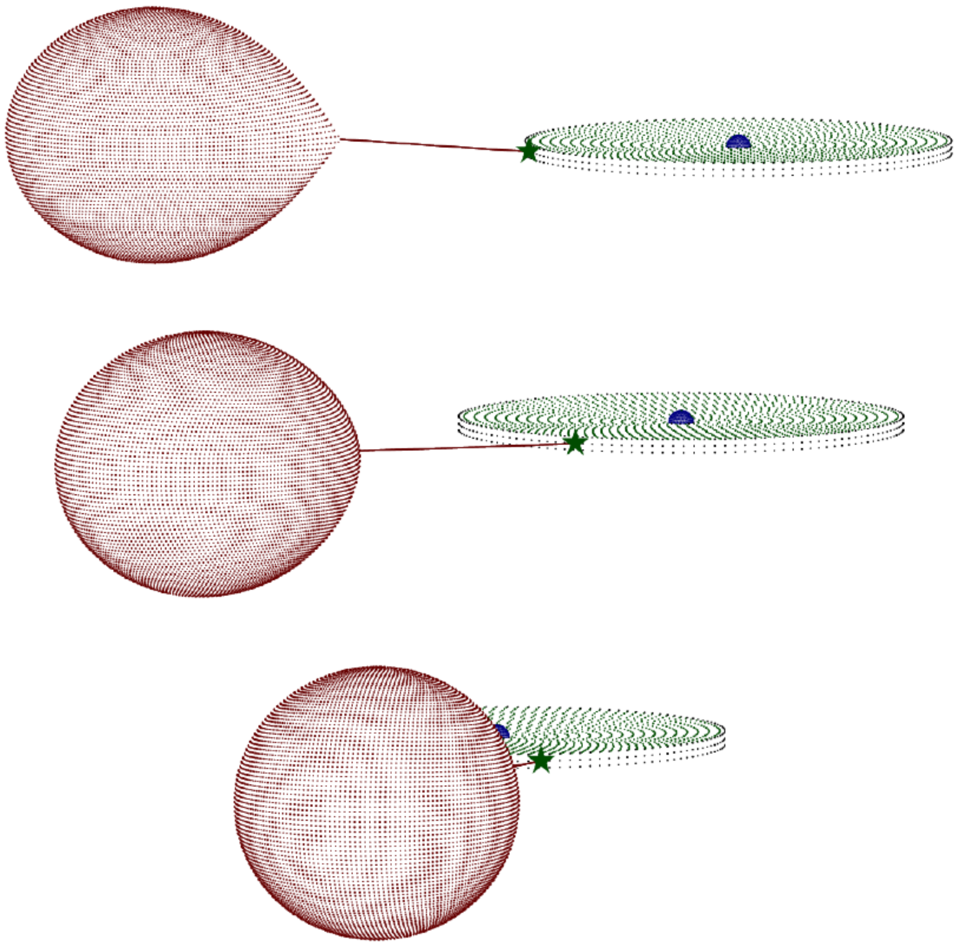
Key questions:

- minimum mass of the companion necessary to eject the common envelope?
- fraction of close substellar companions to sdB stars
- better understanding of the CE phase and the reflection effect



EREBOS
God of darkness

Lightcurve analysis with lcurve



A light curve can be generated as follows:

- Generate grids covering all objects (stars, disc, ...)
- set their surface brightness including all effects, e.g. limb darkening, gravity darkening, reflection effect, Doppler beaming, ...
- At every phase compute what can and cannot be seen, add up the fluxes.
- Deriving inclination, radii, masses by combing with spectroscopic data

Introduction to photometry/spectroscopy

Research workshop on evolved stars

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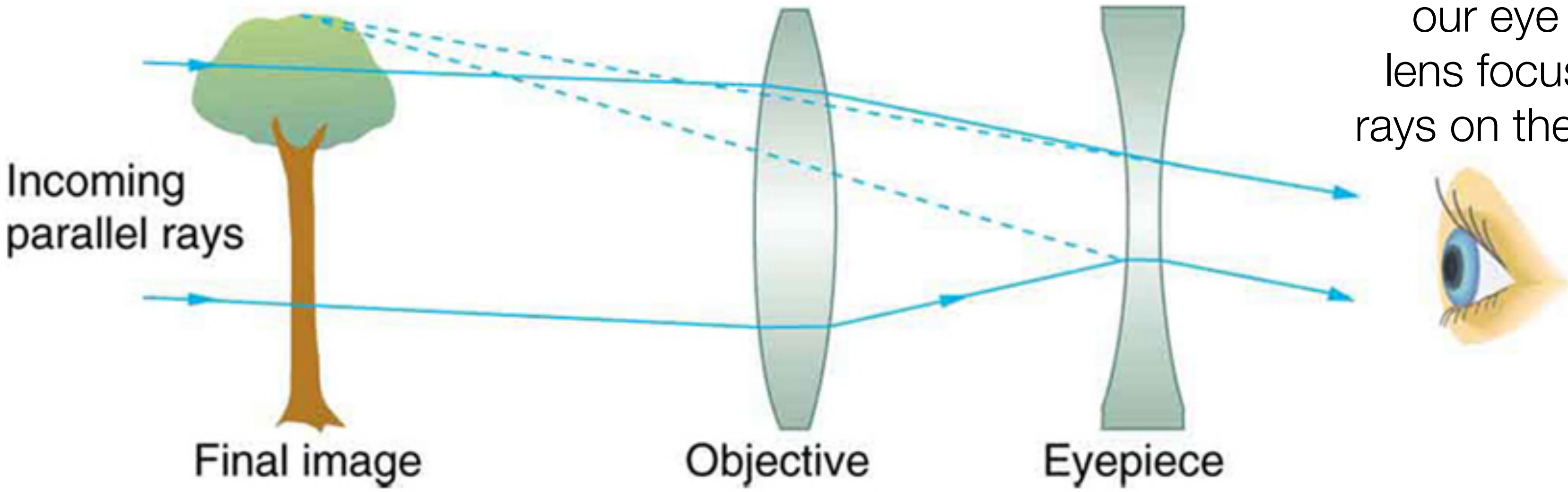
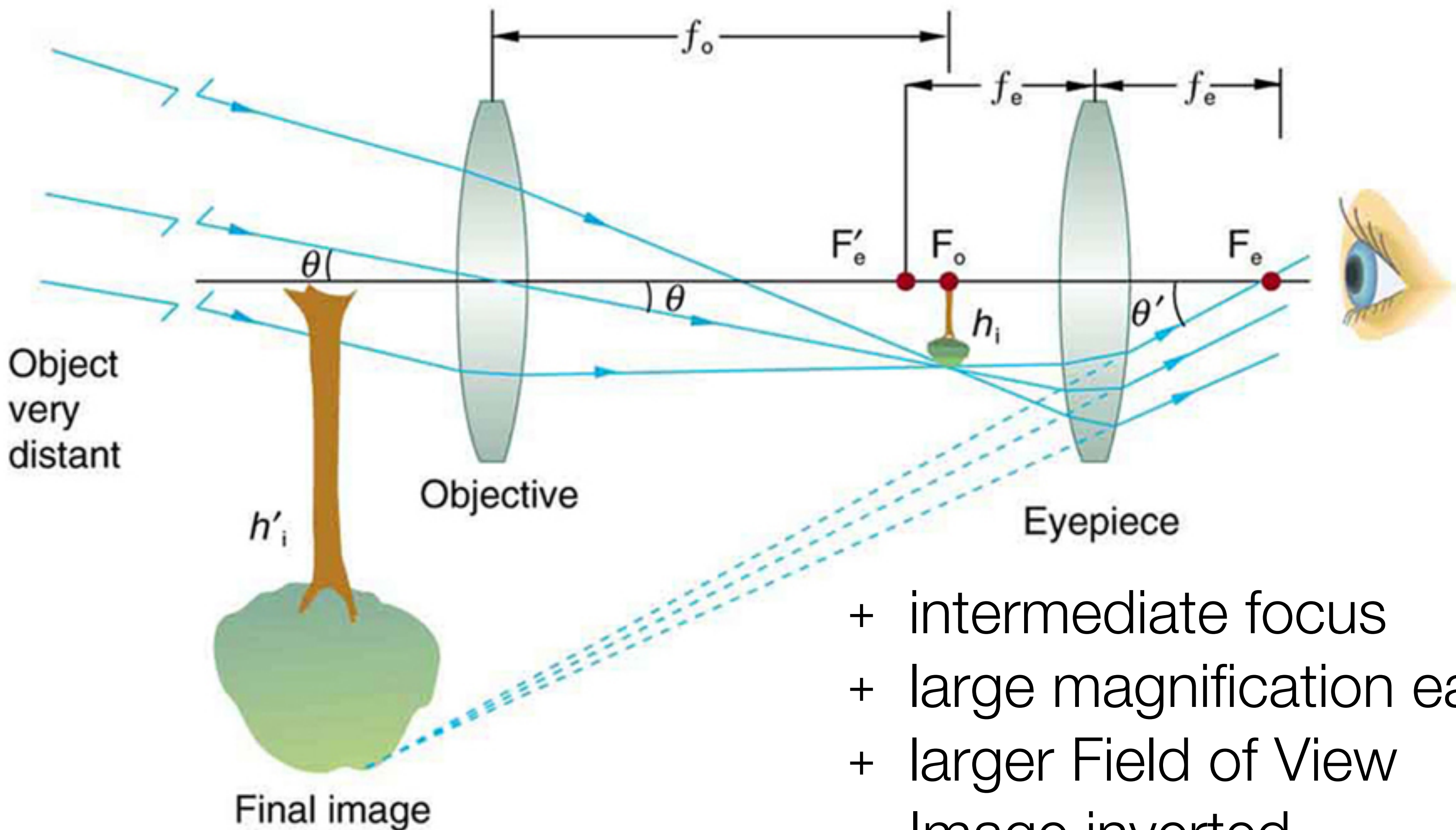
Telescopes

The Galilean telescope



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

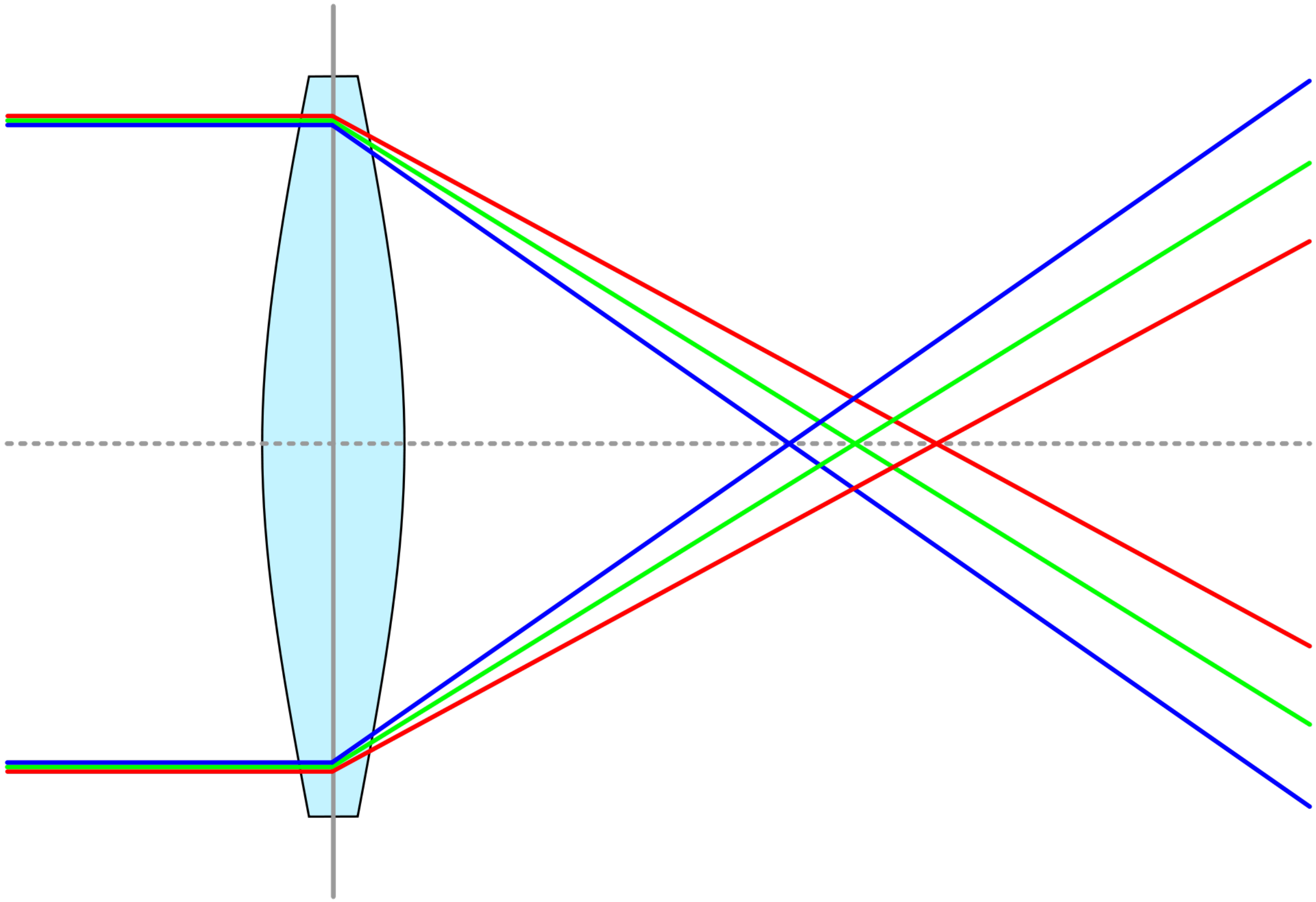
The Keplerian telescope



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

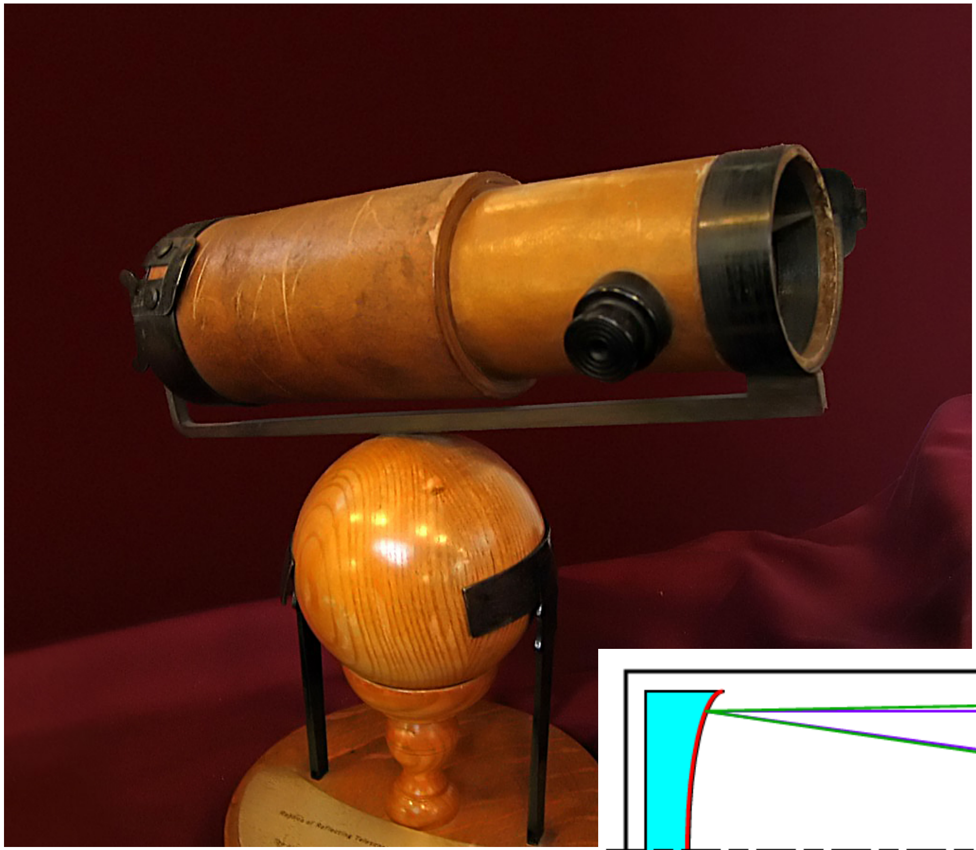
Chromatic aberration

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



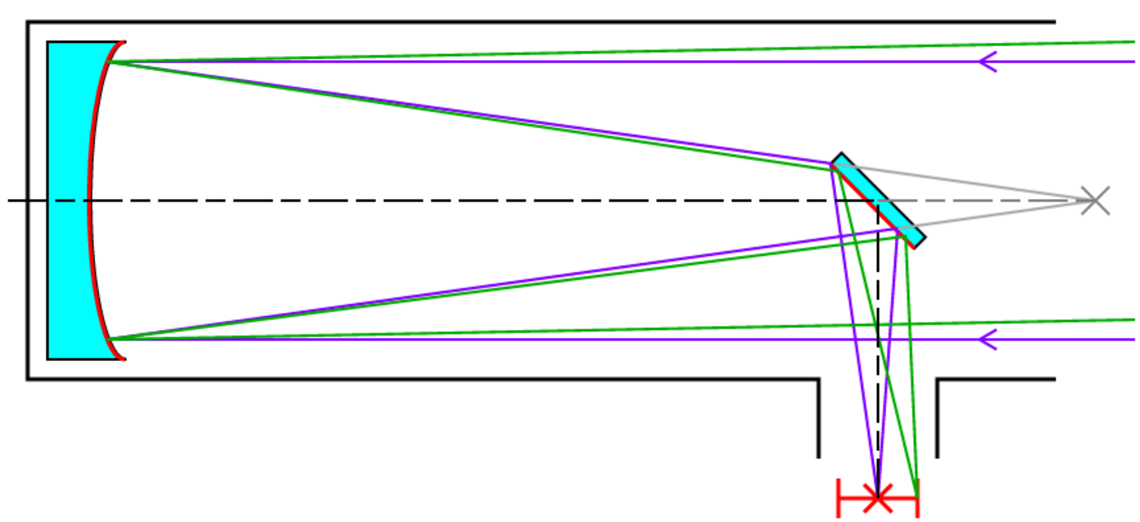
Glass is also very heavy, big lenses are hard to manufacture and mount

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

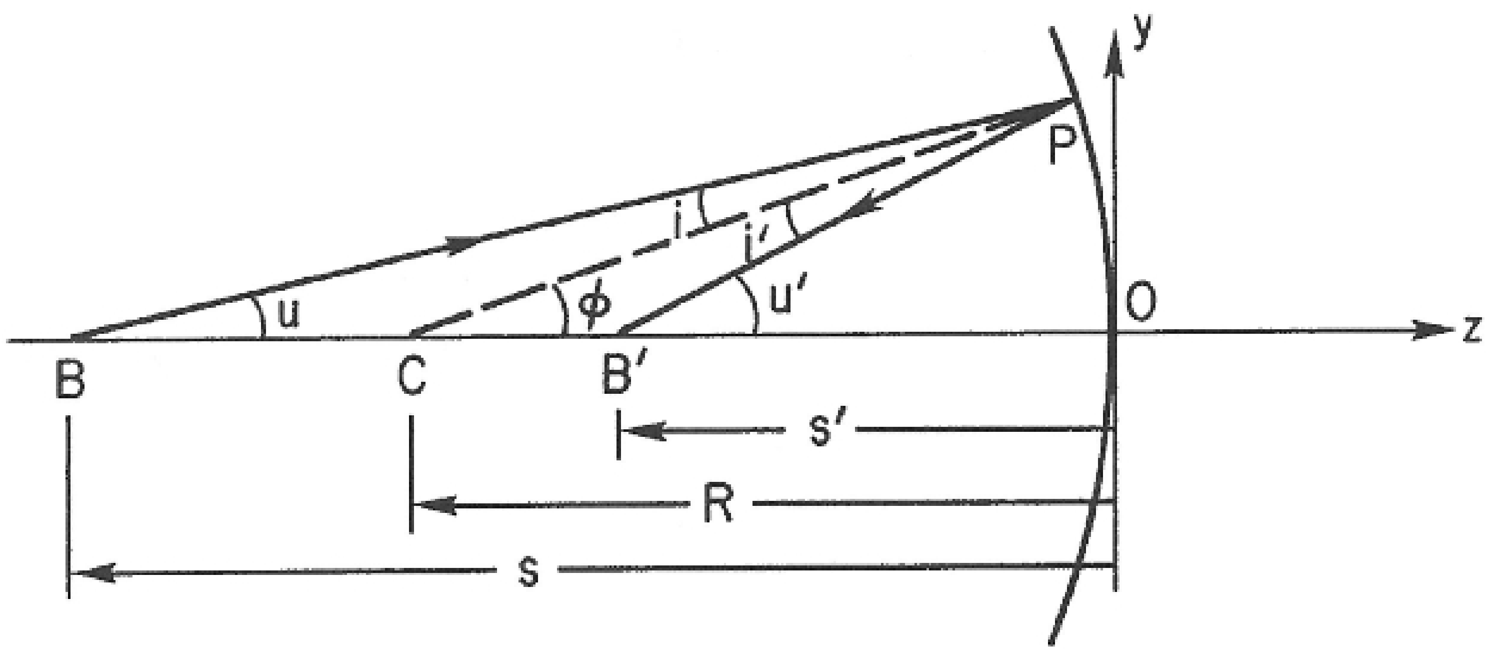
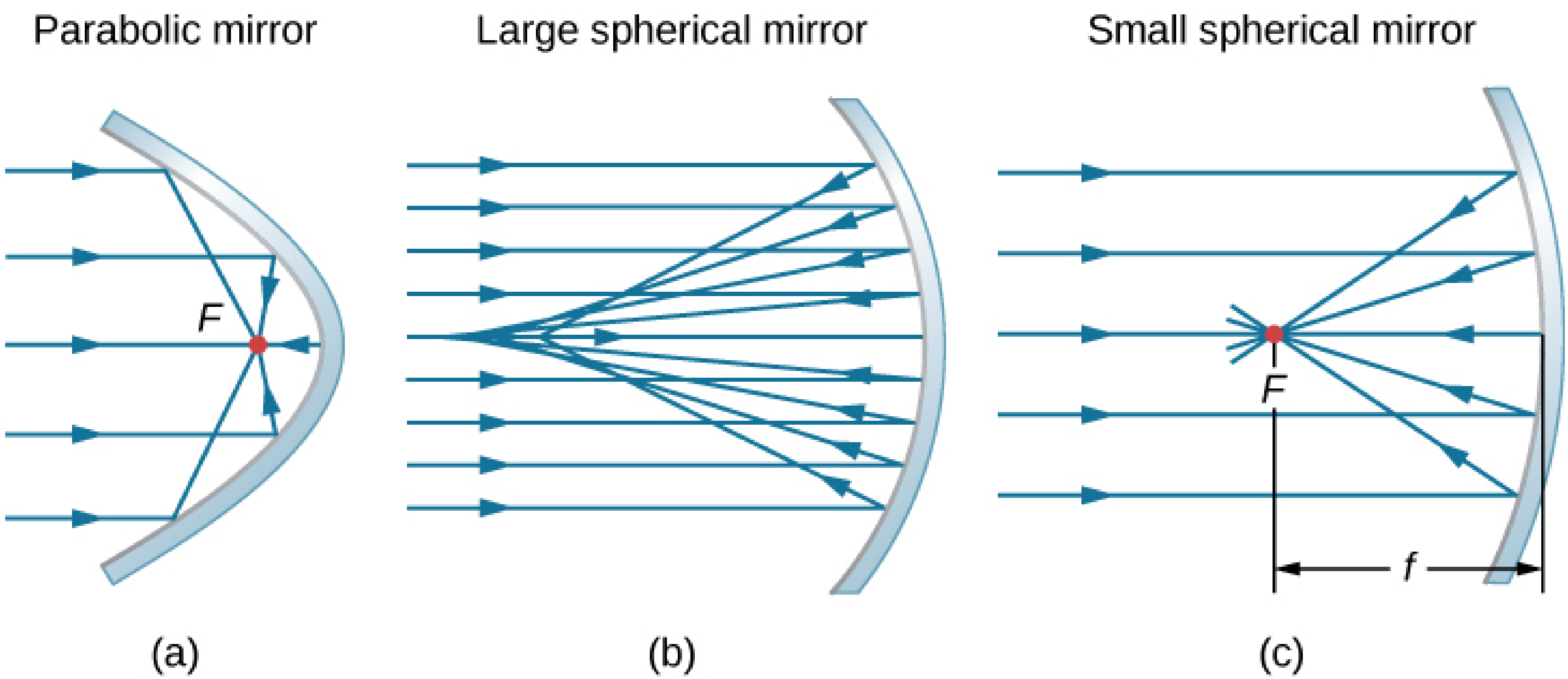


Fig. 2.4. Reflection at spherical surface. Here B and B' are conjugate axial points.

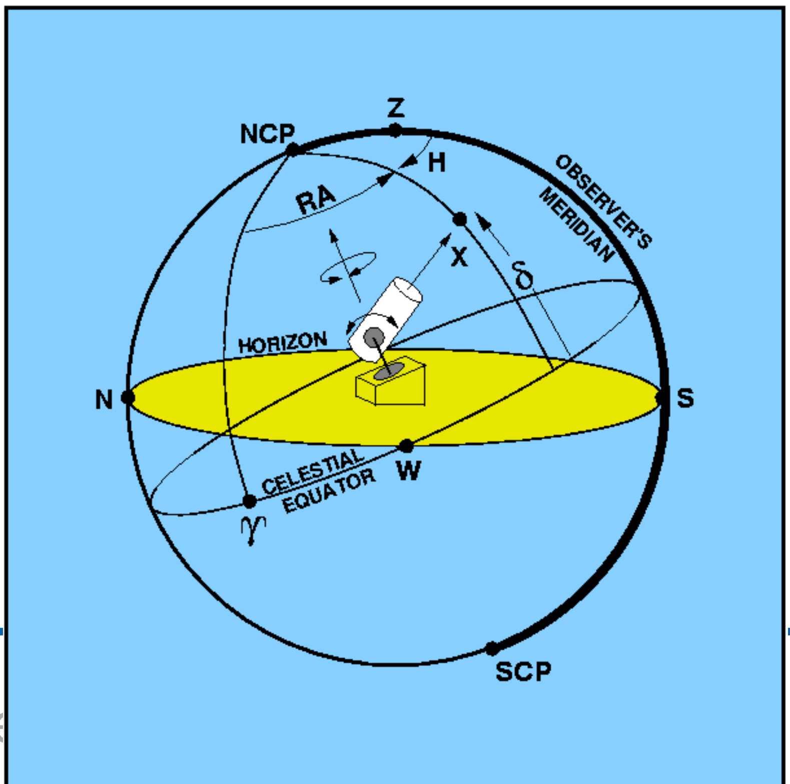
- Mirror equation $1/s' + 1/s = 2/R$
- assuming $s = \infty \Rightarrow f = s' = R/2$
- two mirror system $\Rightarrow$ effective focal length $f = f1f2/(f1 + f2 - d)$

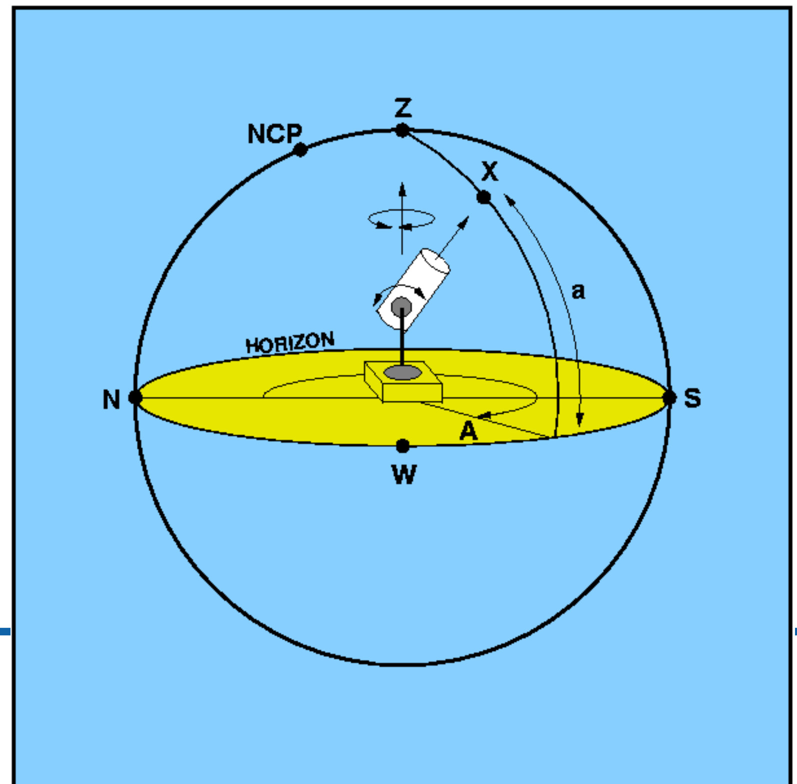
Spherical aberration



Telescope design considerations

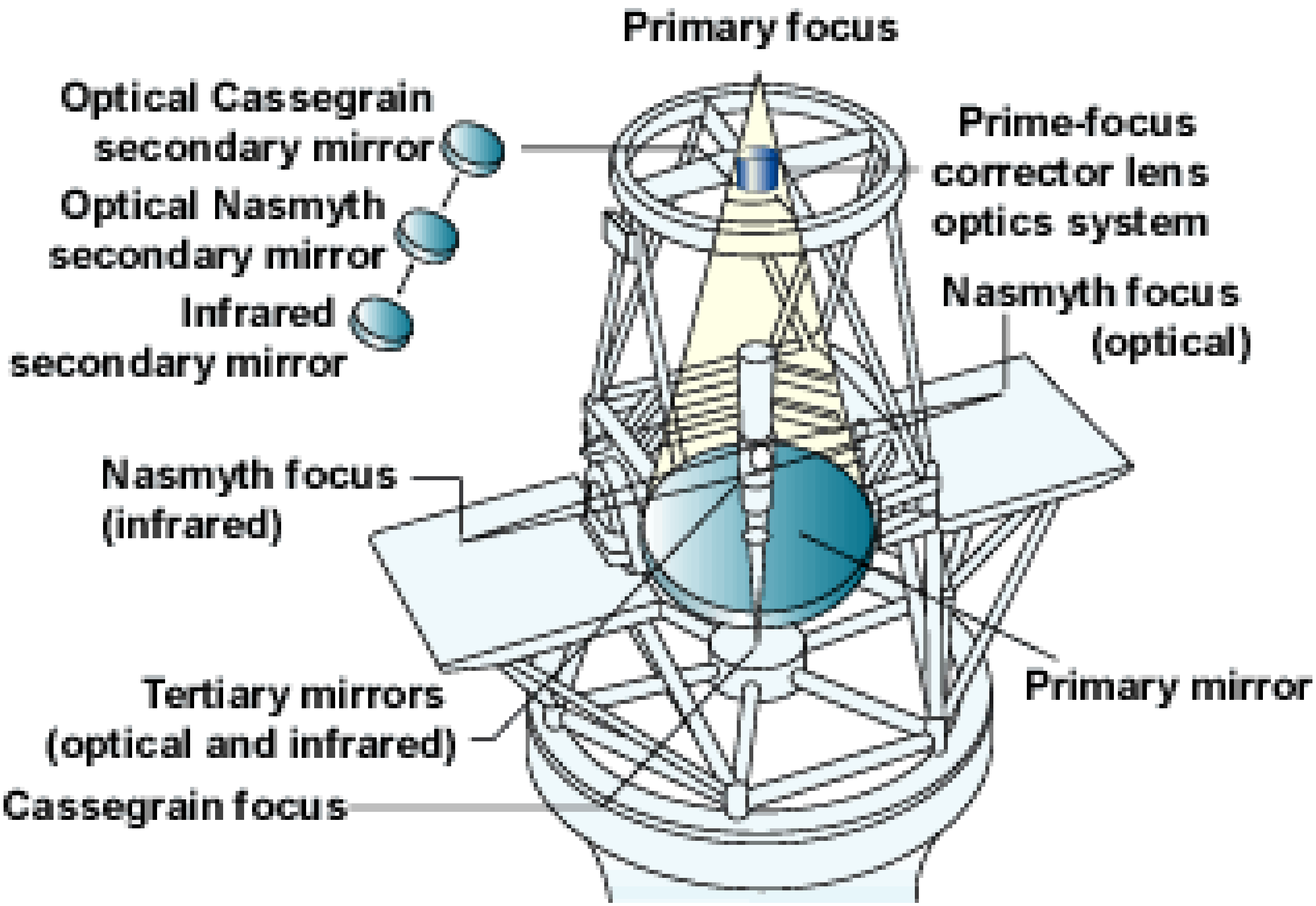
- Field of view: f number $f = F/D$, the smaller the larger is FoV (f/(F/D))
  $\rightarrow$ Limited by size of secondary mirror, vignetting
- Collecting area: number of photons $\sim D^2$
- thermal stability
- angular resolution, Rayleigh criterion $1.22\lambda/D$
- image quality: aberrations at large distance from optical axis, coma, astigmatism
- mounts: equatorial, Altitude-Azimuth (altaz)





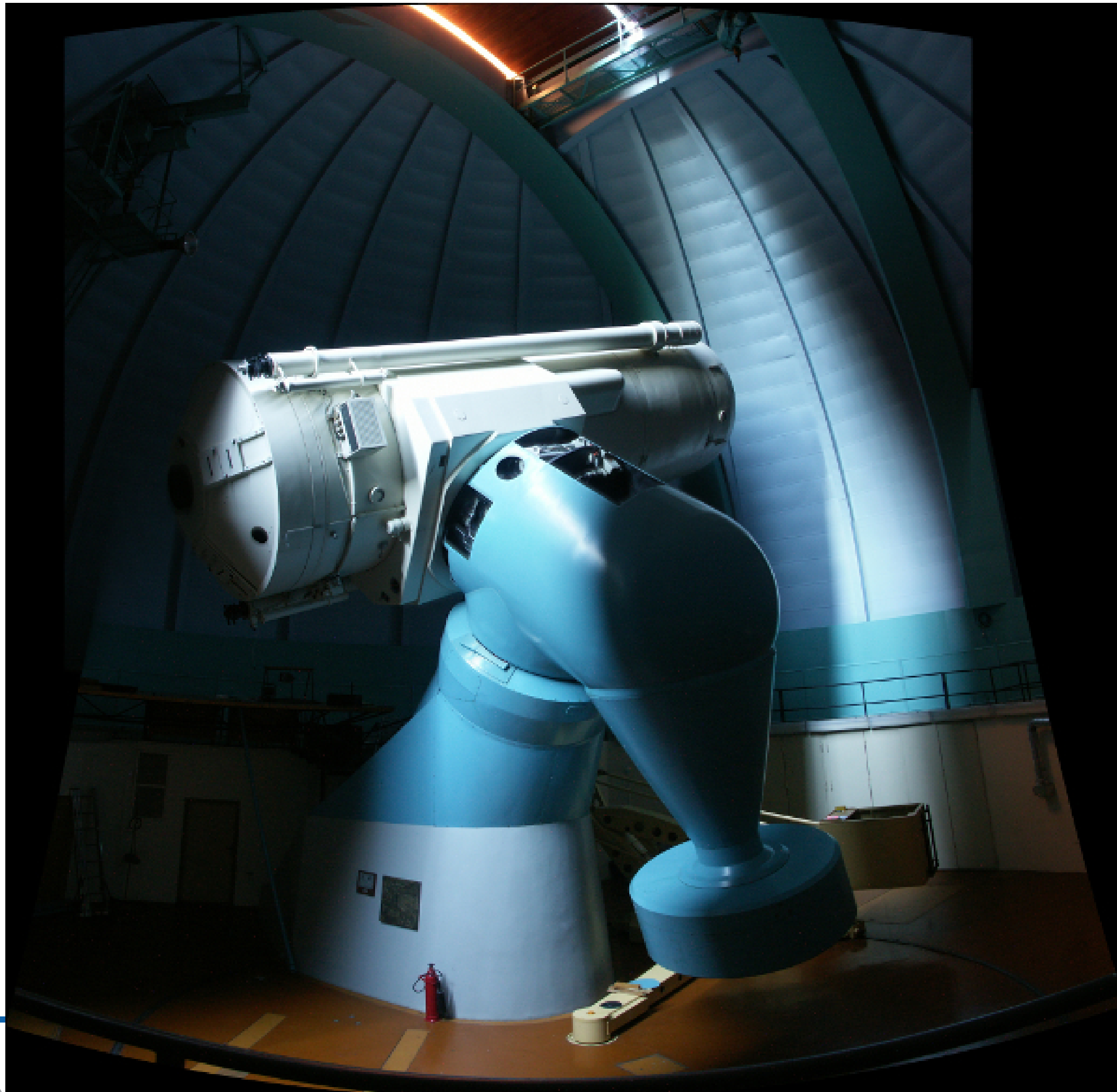
Telescope design considerations

- Focus:

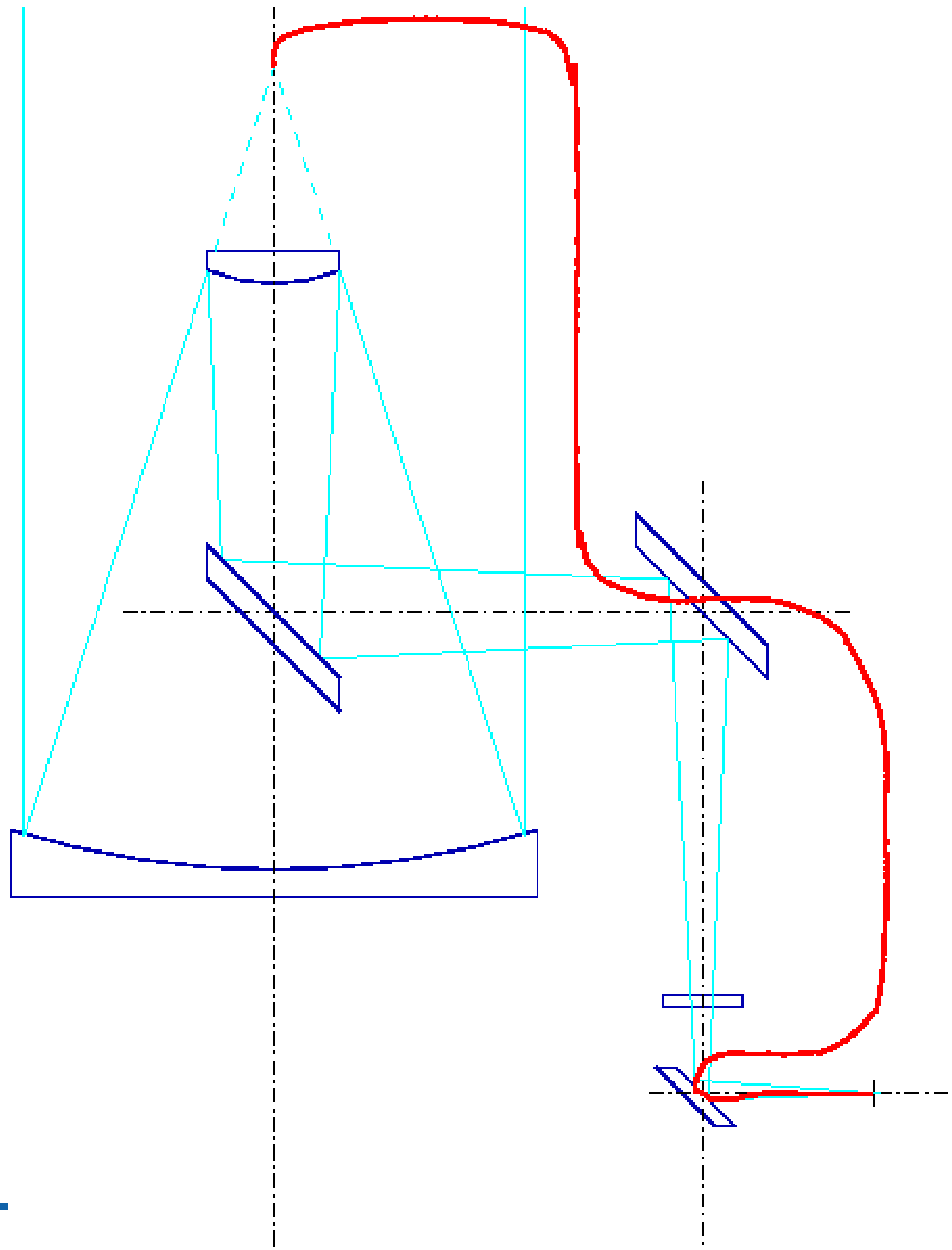


Subaru telescope

Perek 2-m telescope



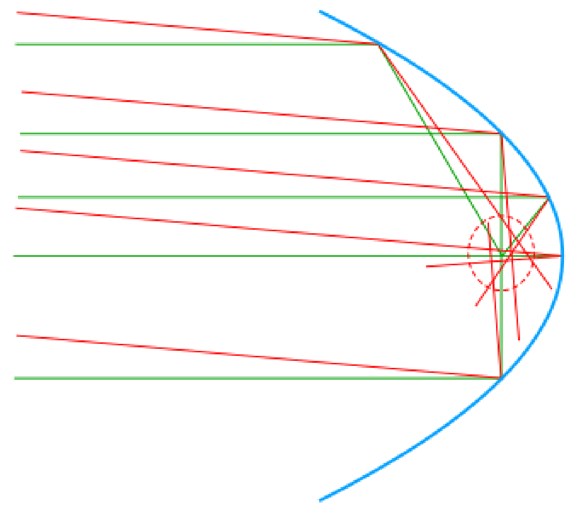
Perek 2-m telescope



- 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

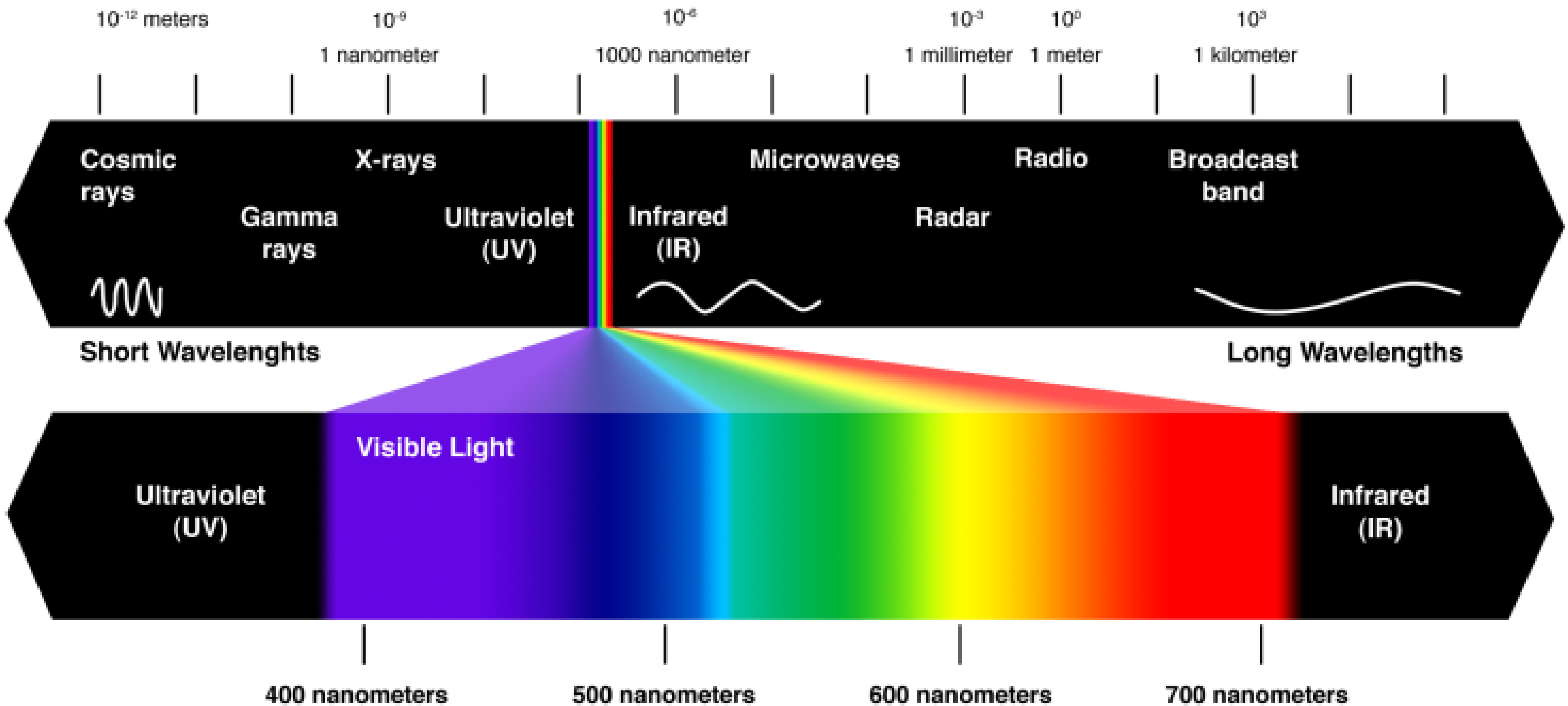
- 65 cm primary paraboloidal mirror with 234 cm focal length
- Moravian G2-3200 CCD camera in primary focus
- BVRI filters
- effecive focal ratio: f/3.6
  → quite noticeable coma: Paracorr coma corrector



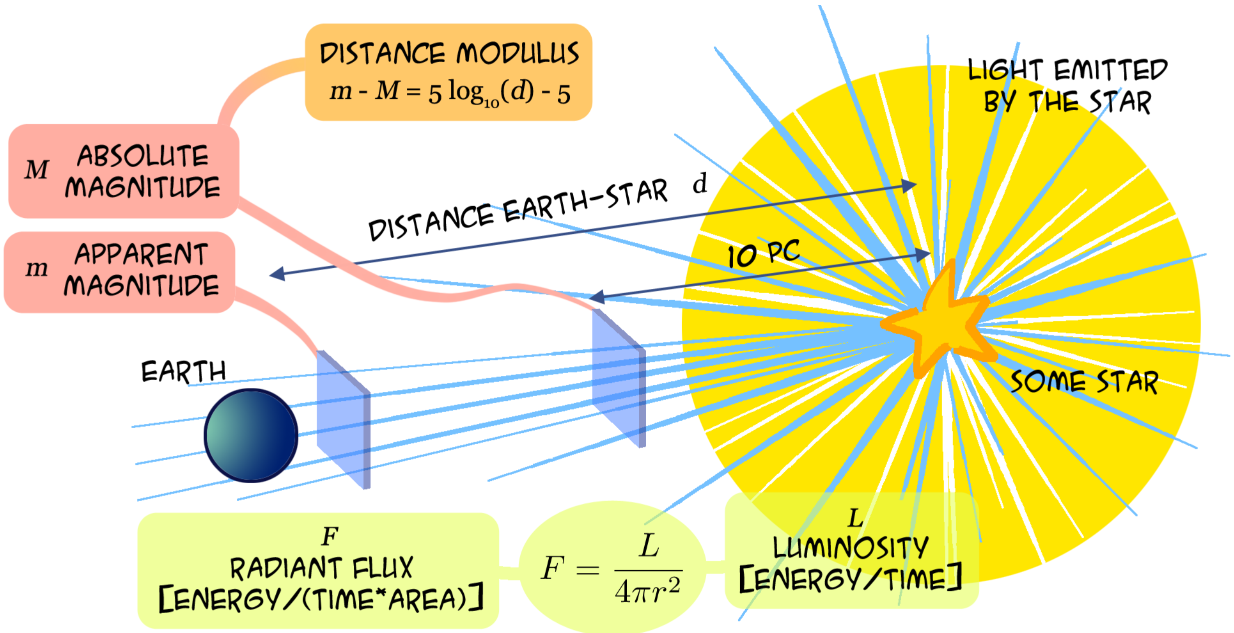
Photometry

What is Photometry?

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



Magnitudes



- apparent magnitude m

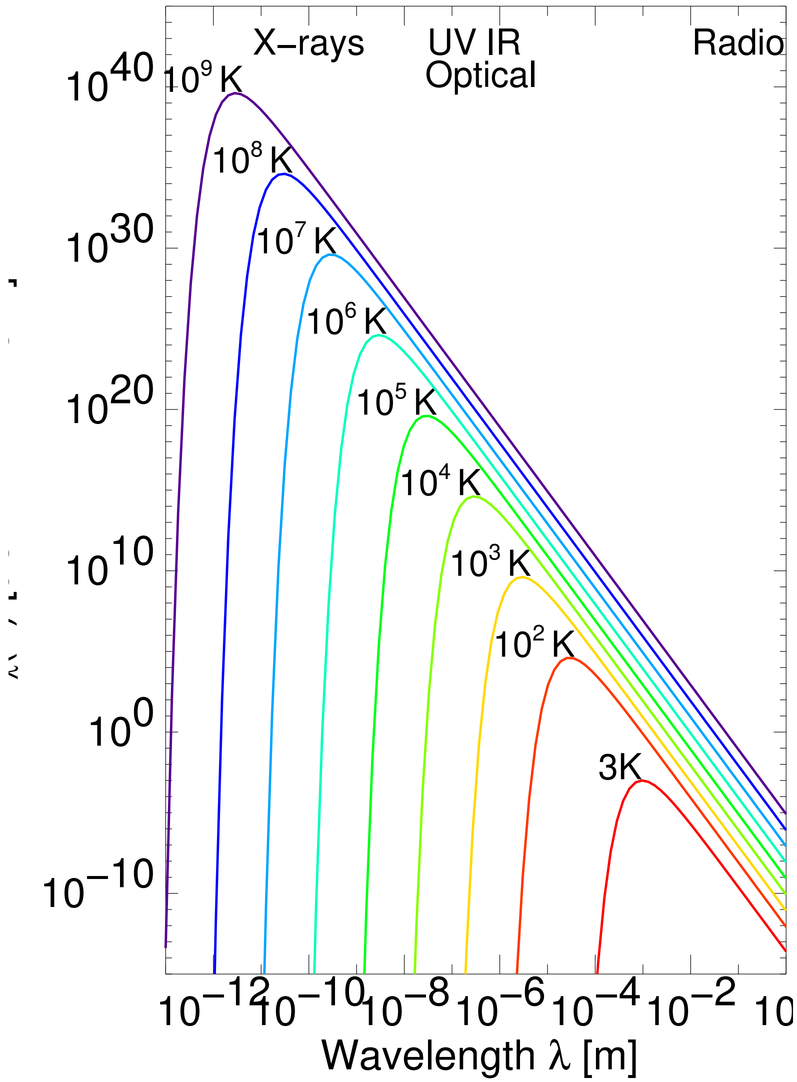
$$m_1 - m_2 = -2.5 \log(F_1/F_2) \quad (3.1)$$

- absolute magnitude M

$$m - M = 5 \log(d) - 5 \quad (3.2)$$

Bolometeric and extinction corrections may be necessary!

Planck's Radiation Law



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

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

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:

$$\lambda_{\max} T = 2.898 \times 10^{-3}\,\mathrm{m\,K}$$

"hotter bodies radiate higher energetic radiation"

Photometric filters

photometric system

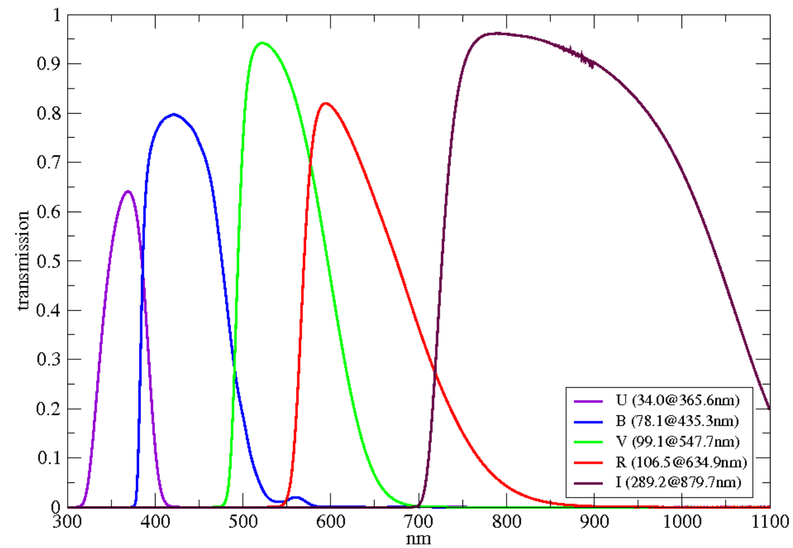
- set of well-defined passbands (or filters)
- standard stars for each photometric system
- observations of lightcurves usually in one or several filters

Bolometric correction

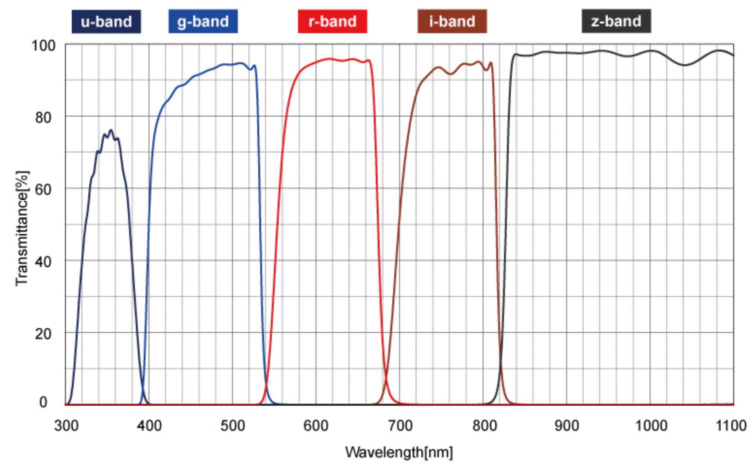
- converts observed magnitude in a certain filter to its bolometric magnitude (dependent on spectral type)

$$BC_V = M_{\mathrm{bol}} - M_V \qquad (3.3)$$

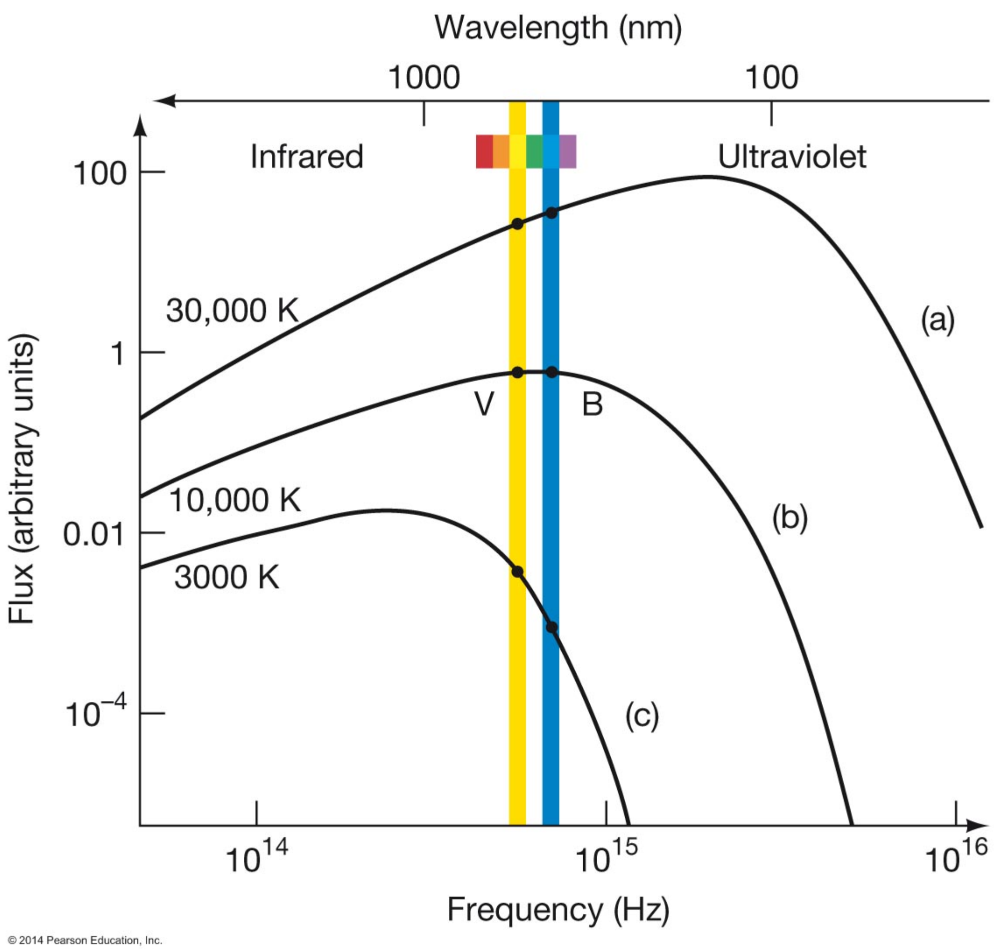
Johnson filters

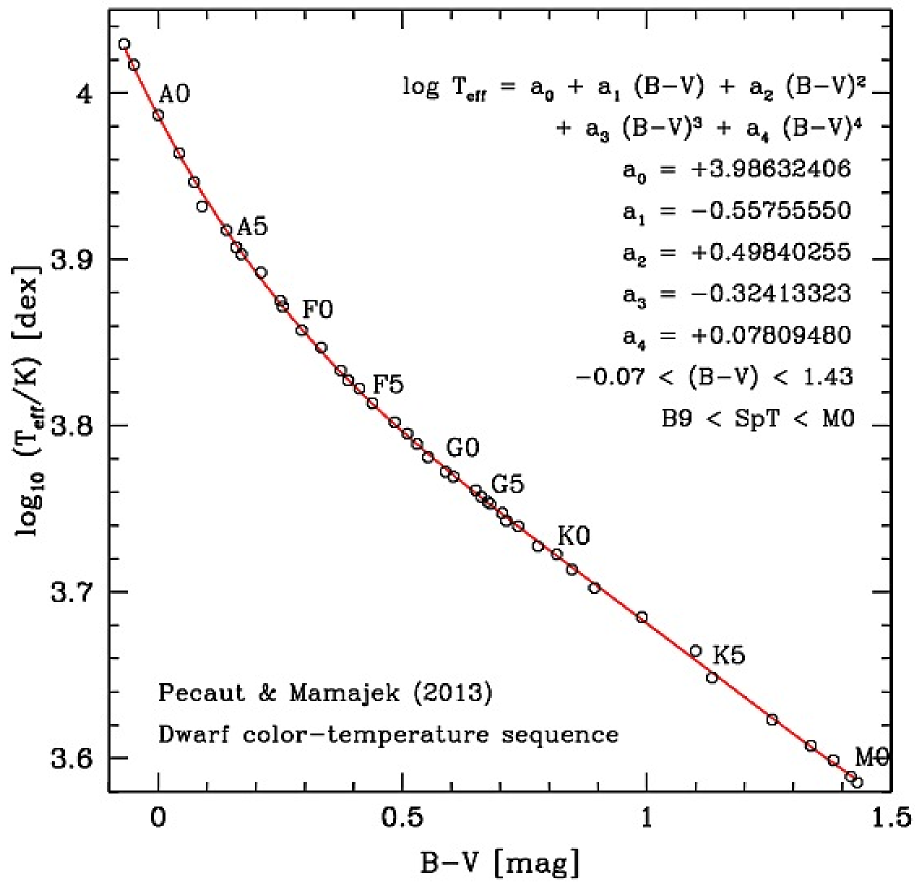


SDSS filters



Color-temperature relation





Interstellar Reddening

Extinction A_V

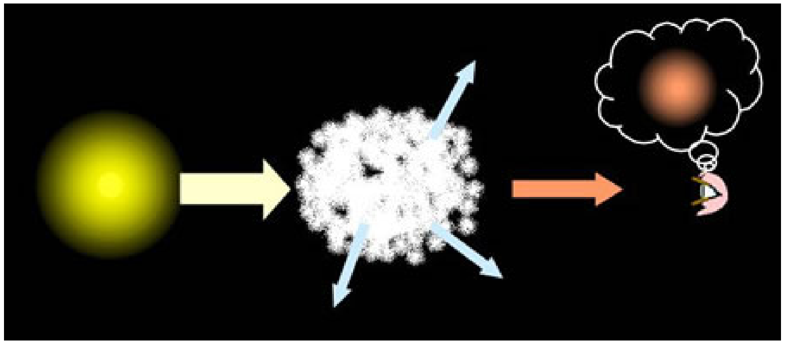
- absorption and scattering of electromagnetic radiation by dust and gas between an emitting astronomical object and the observer
- shorter wavelengths (blue) are more heavily reddened than longer (red) wavelengths
- colour index $B - V$, colour excess E_{B-V}

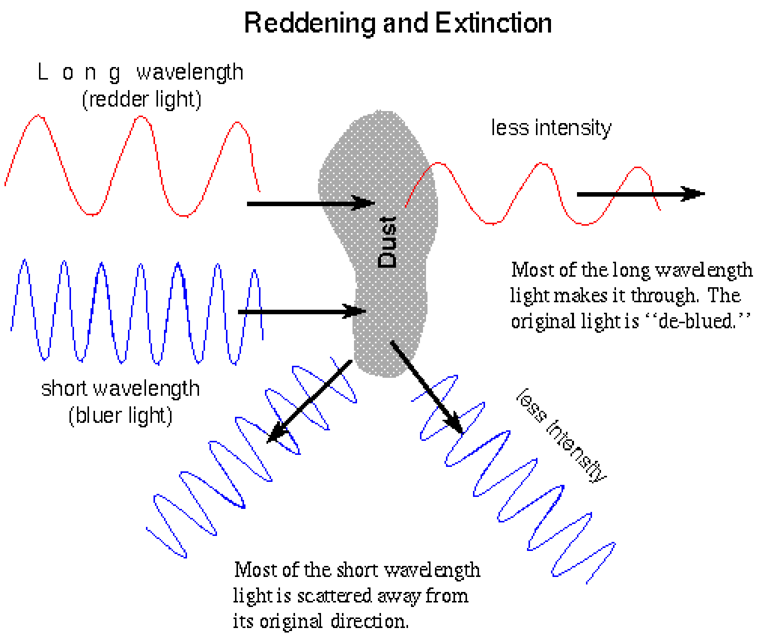
$$E_{B-V} = (B - V) - (B - V)_0 \tag{3.4}$$

$$A_V = R_V E_{B-V}, \; R_V \approx 3.1 \text{ (Milky Way)} \tag{3.5}$$

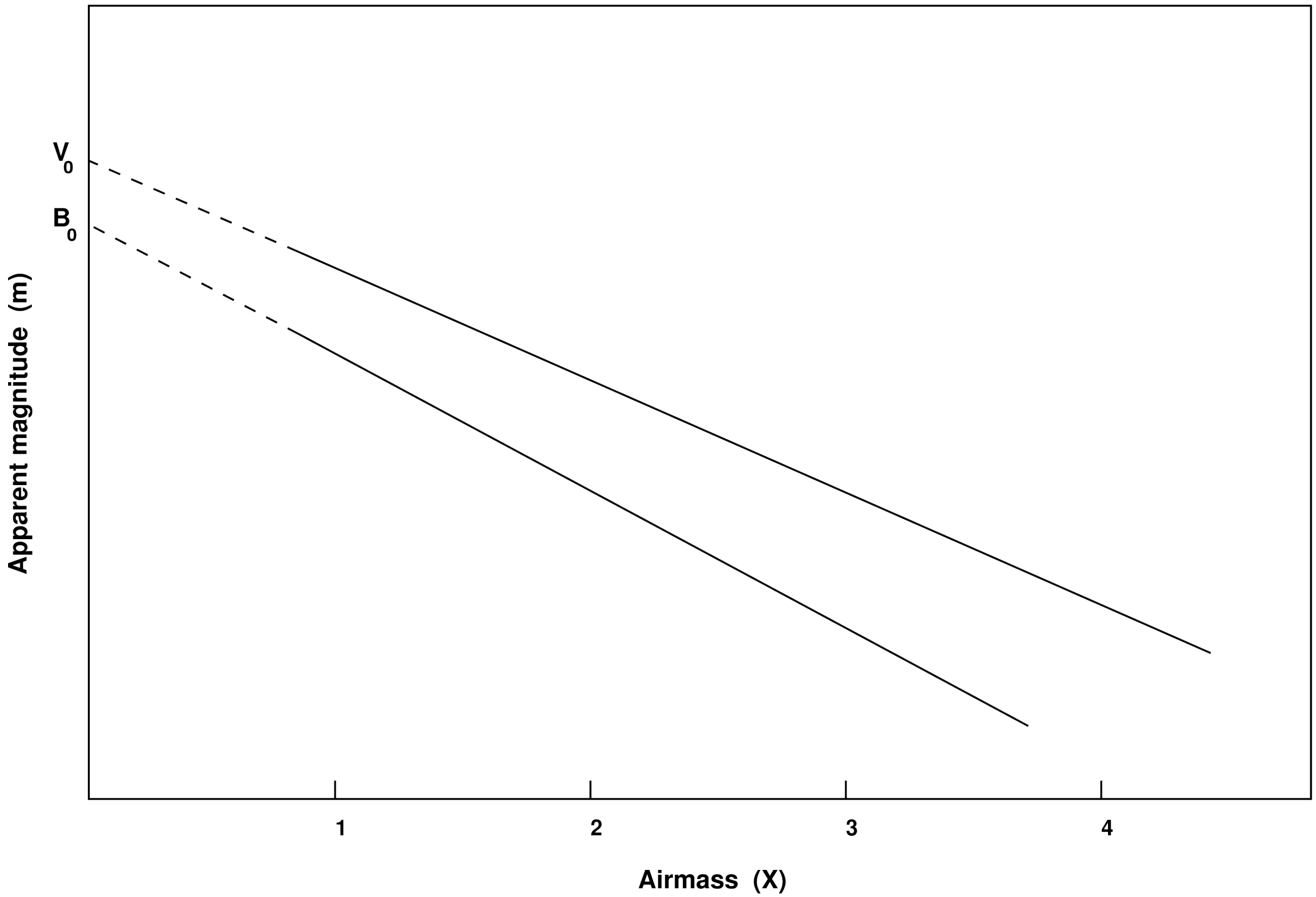
- true distance

$$d = 10^{0.2(m - M + 5 - A_V)} \tag{3.6}$$





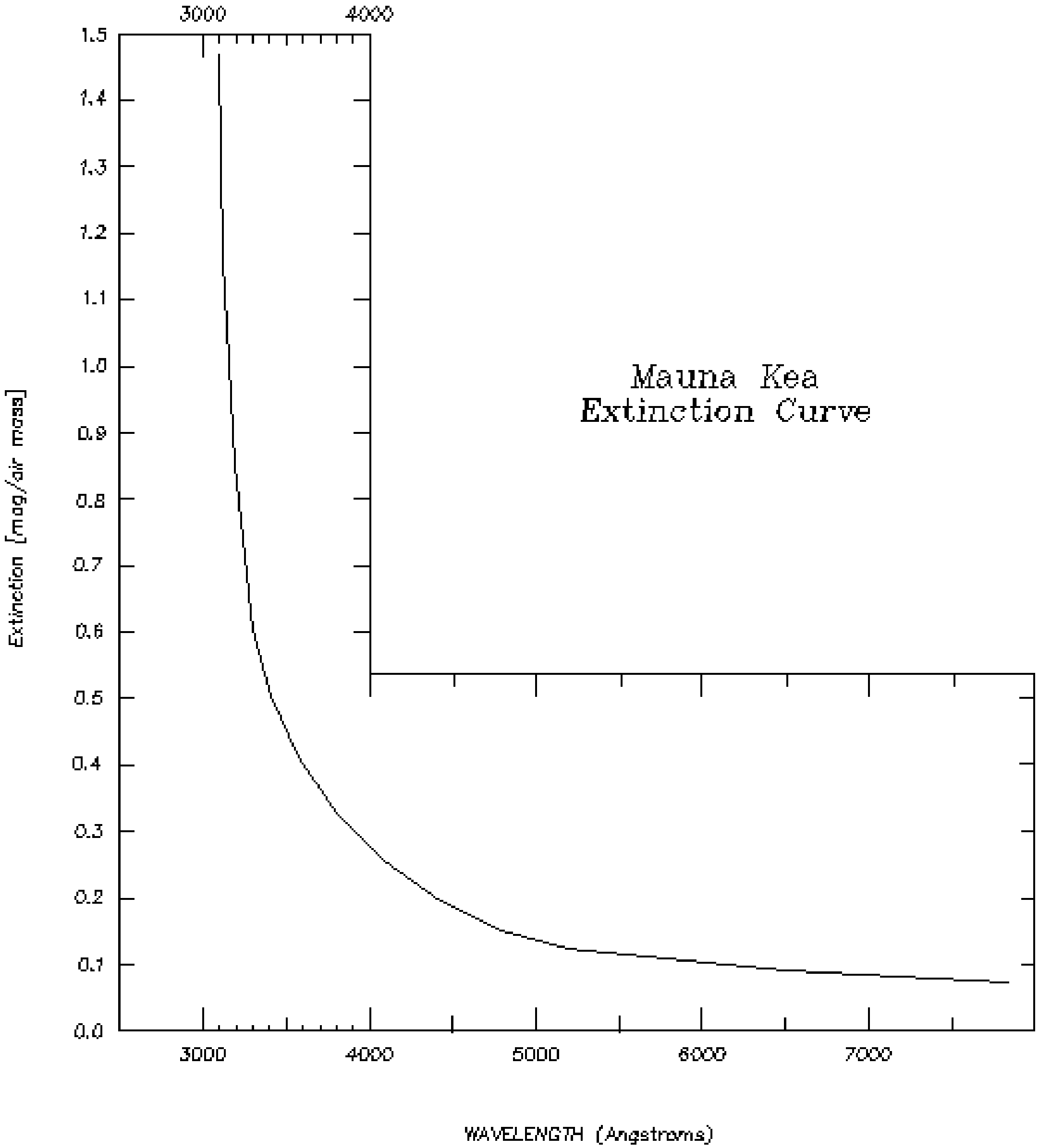
Atmospheric extinction



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

Absolute vs. differential photometry

Absolute photometry

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

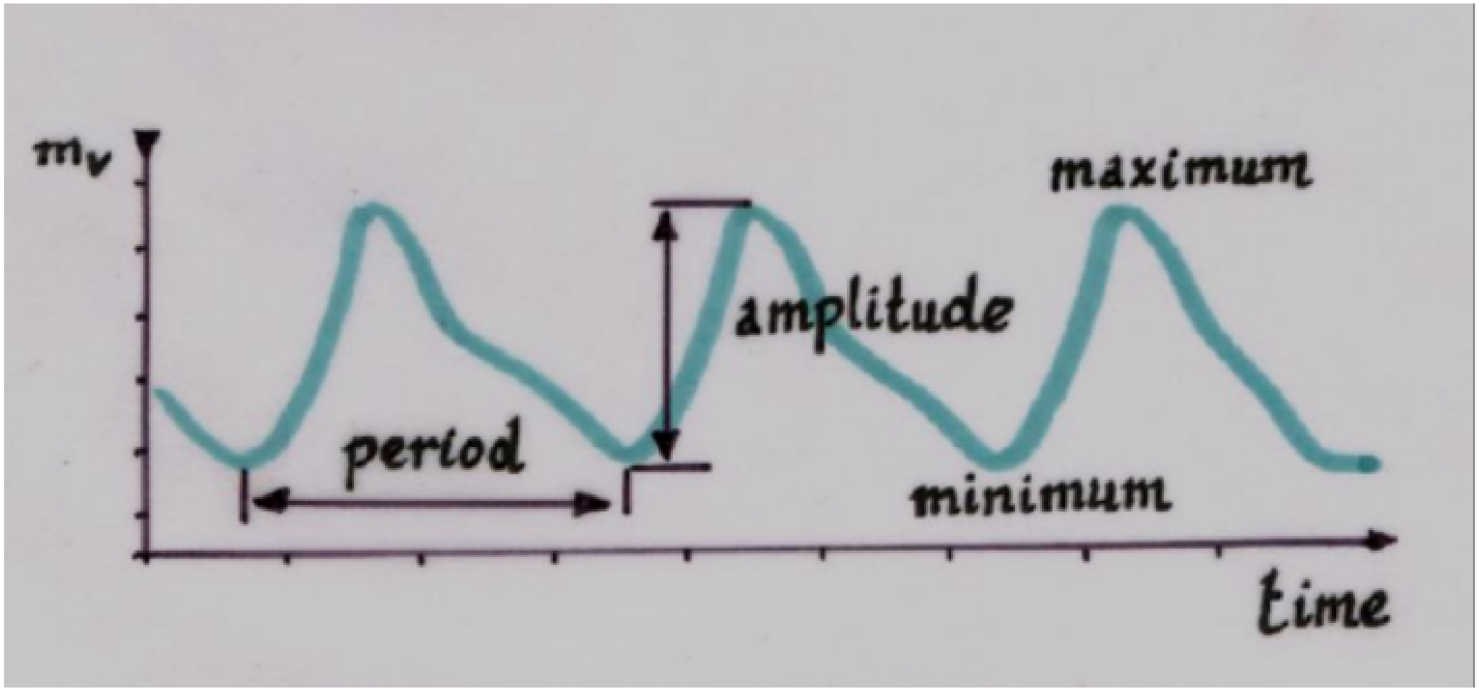
Differential photometry refers to photometric measurements of a given source with respect to one or more comparison sources which absolute flux is not necessarily known.

$\Rightarrow$ relative flux variations, lightcurves

"Vega" magnitudes

- definition of an absolute magnitude system?
- system bases on the flux of Vega, $m_{\text{Vega}} \equiv 0$ **at all wavelengths**
- $\boxed{m \equiv -2.d \log f_\lambda + 2.5 \log f_{\lambda,\text{Vega}}}$
- zero-point depends on the flux of Vega and is different in different bands
- **Landolt system** based on A0 stars standard magnitude system
- **SDSS ugriz sytem:** based on measurement of 140 standard stars measured relative to Vega
- work on a new photometric system not reliant on Vega

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

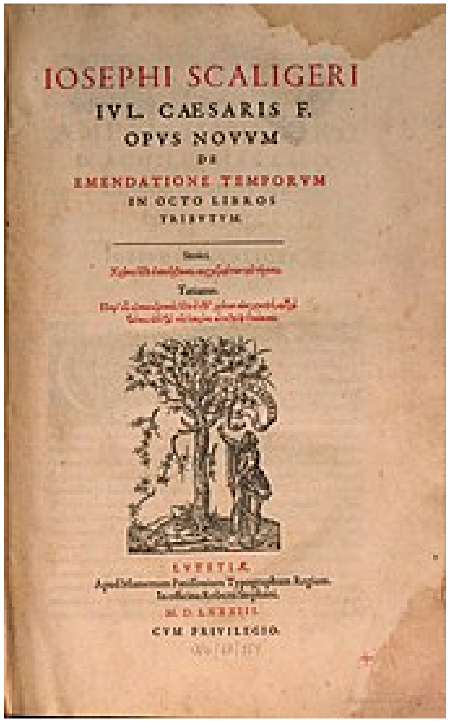
Julian Date

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

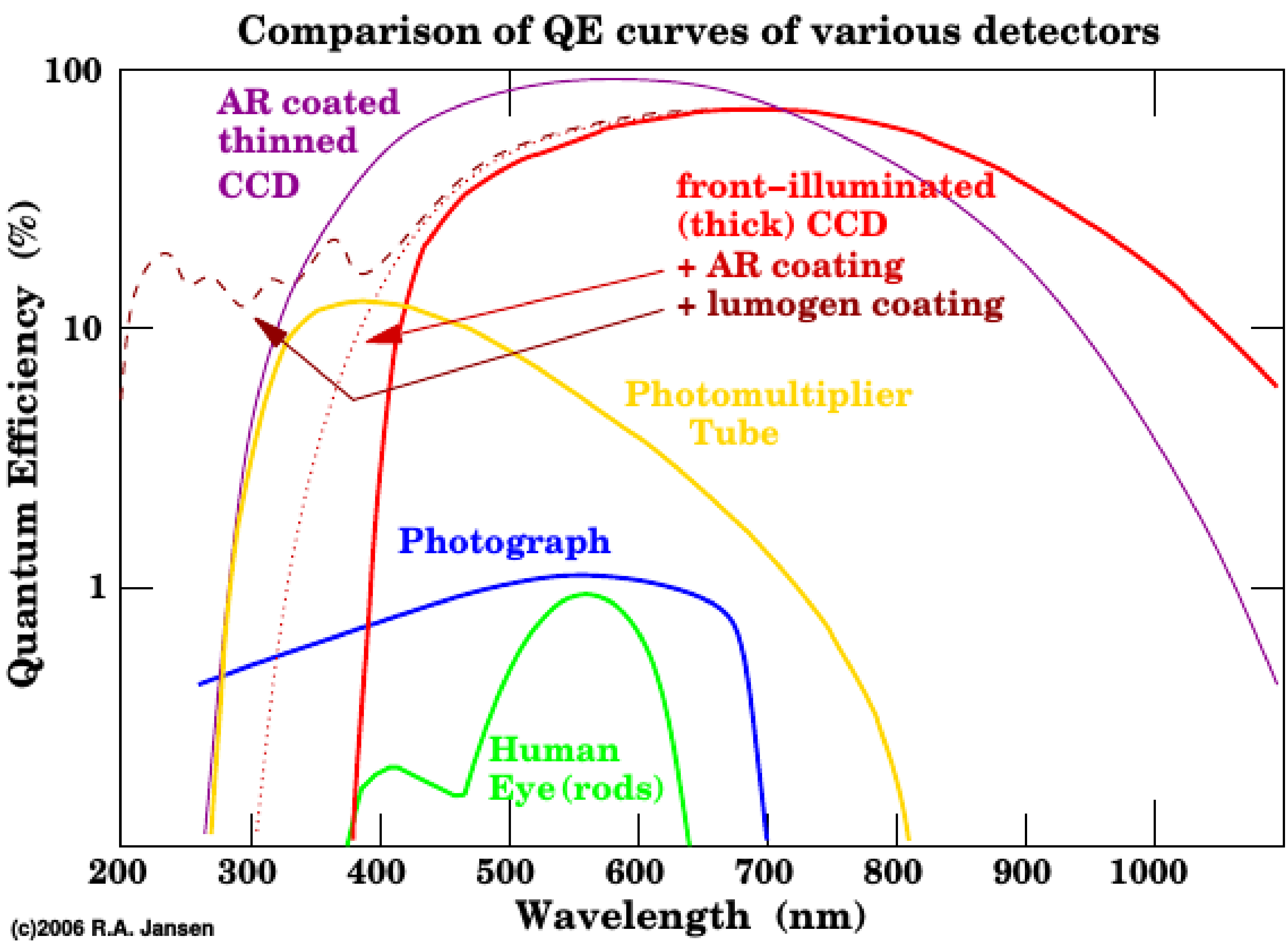
Heliocentric Julian Date HJD

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

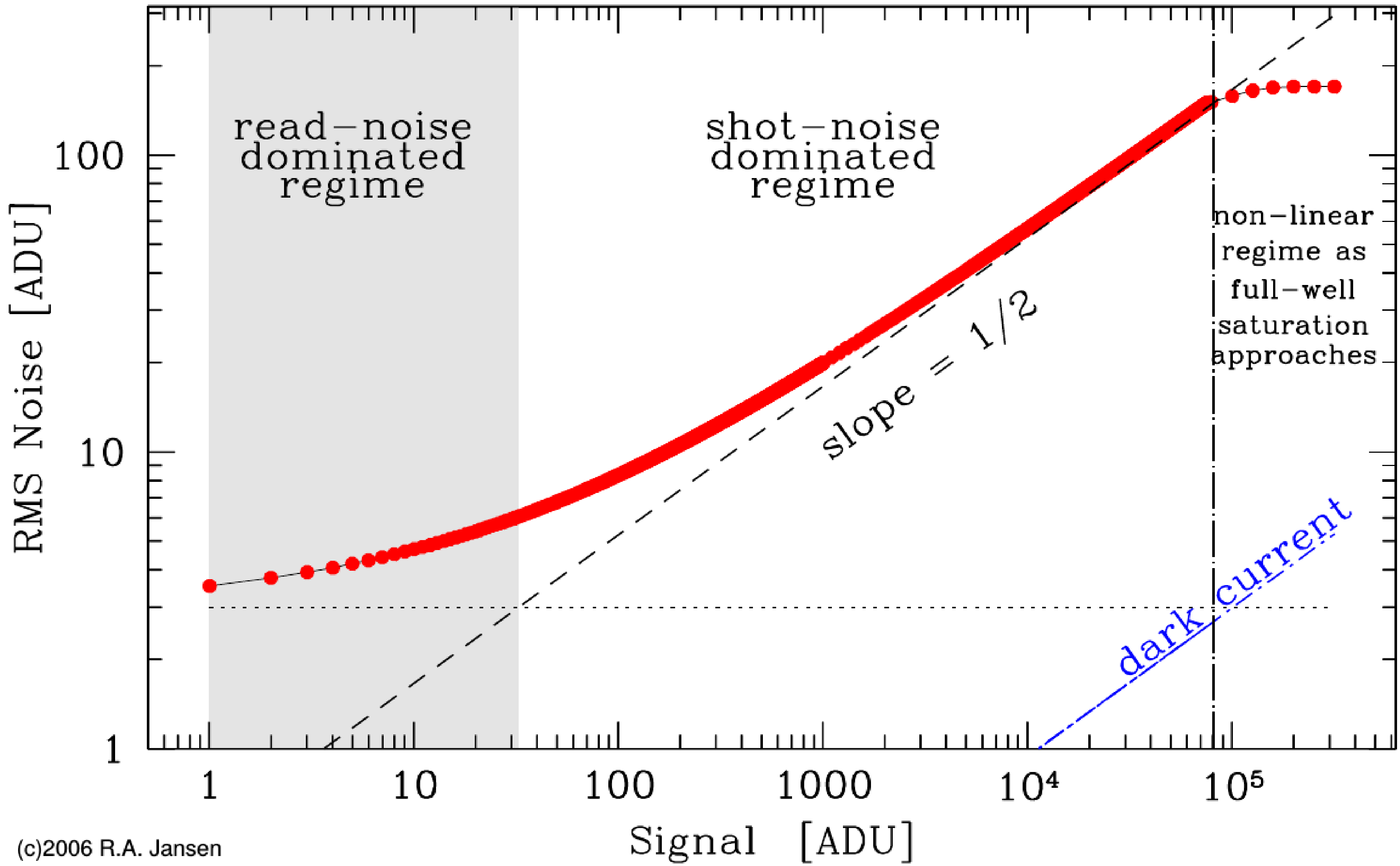
Barycentric Julian Date BJD

- 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

Quantum efficiency of various detectors



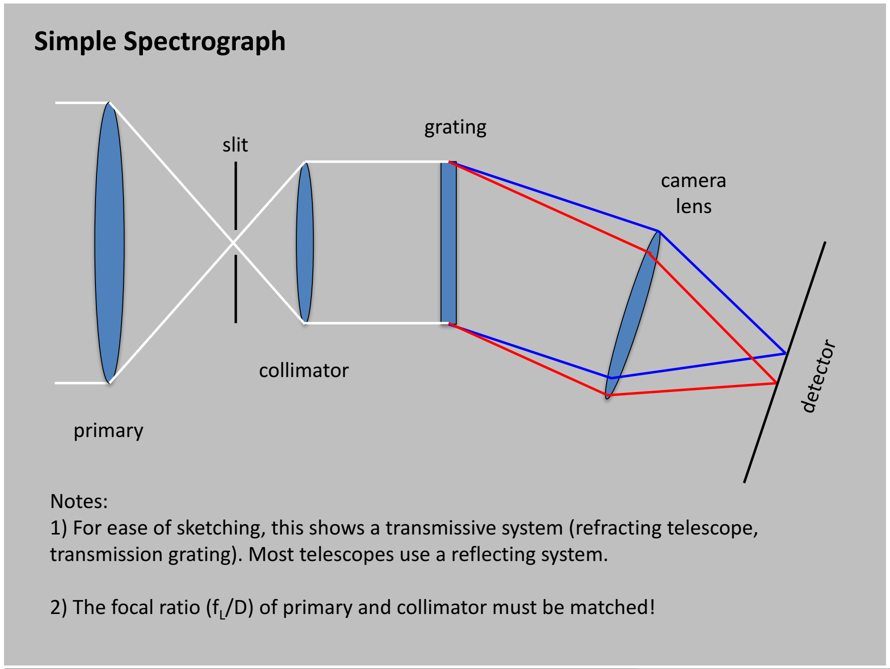
Noise in CCDs

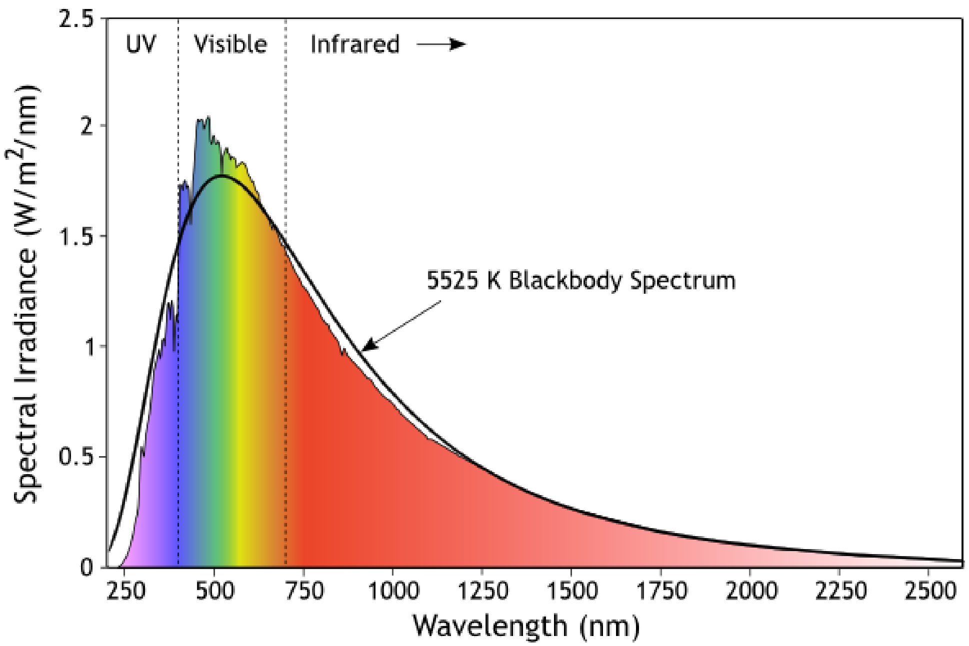


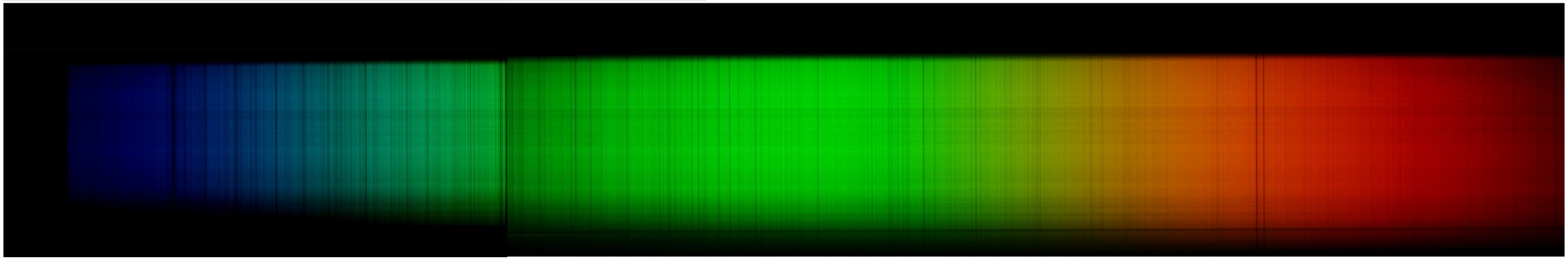
Spectroscopy

What is spectroscopy?

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





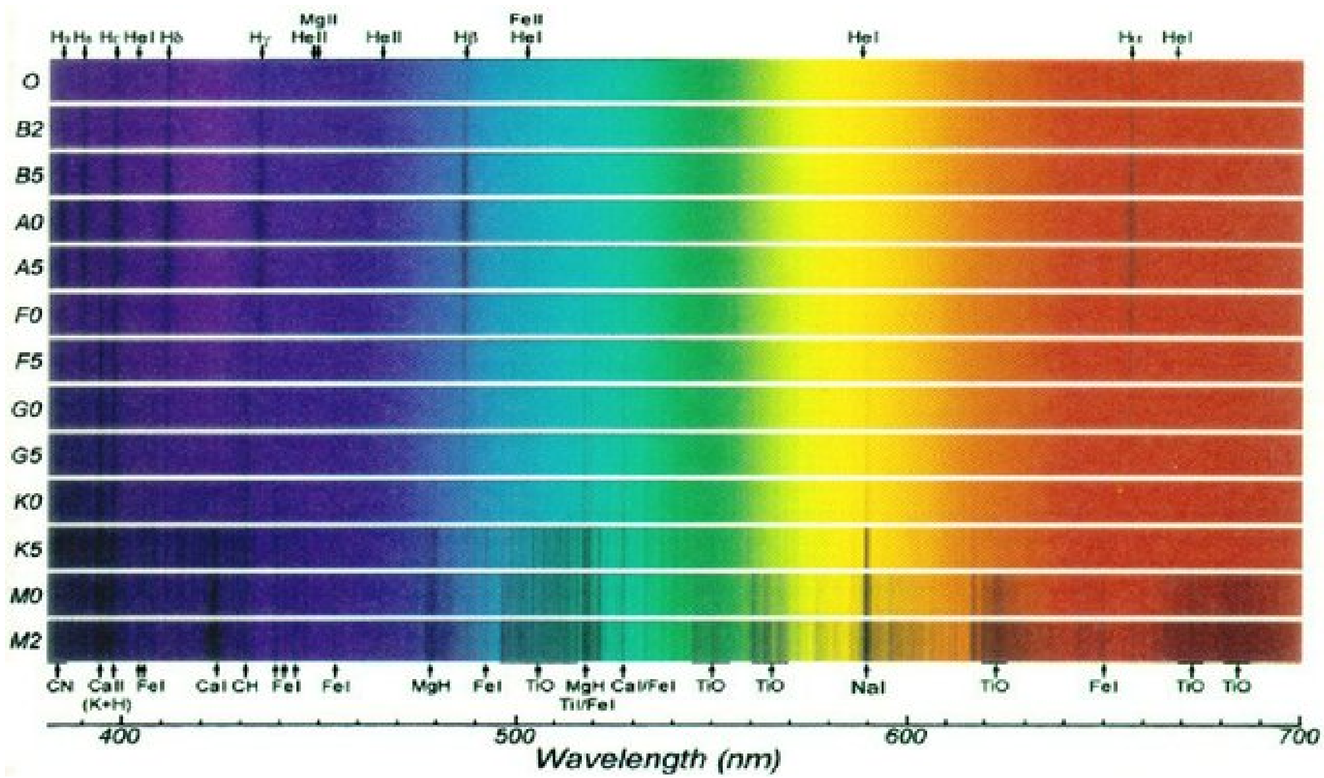


Joseph von Fraunhofer saw 1814 almost 600 lines in the spectrum of the sun

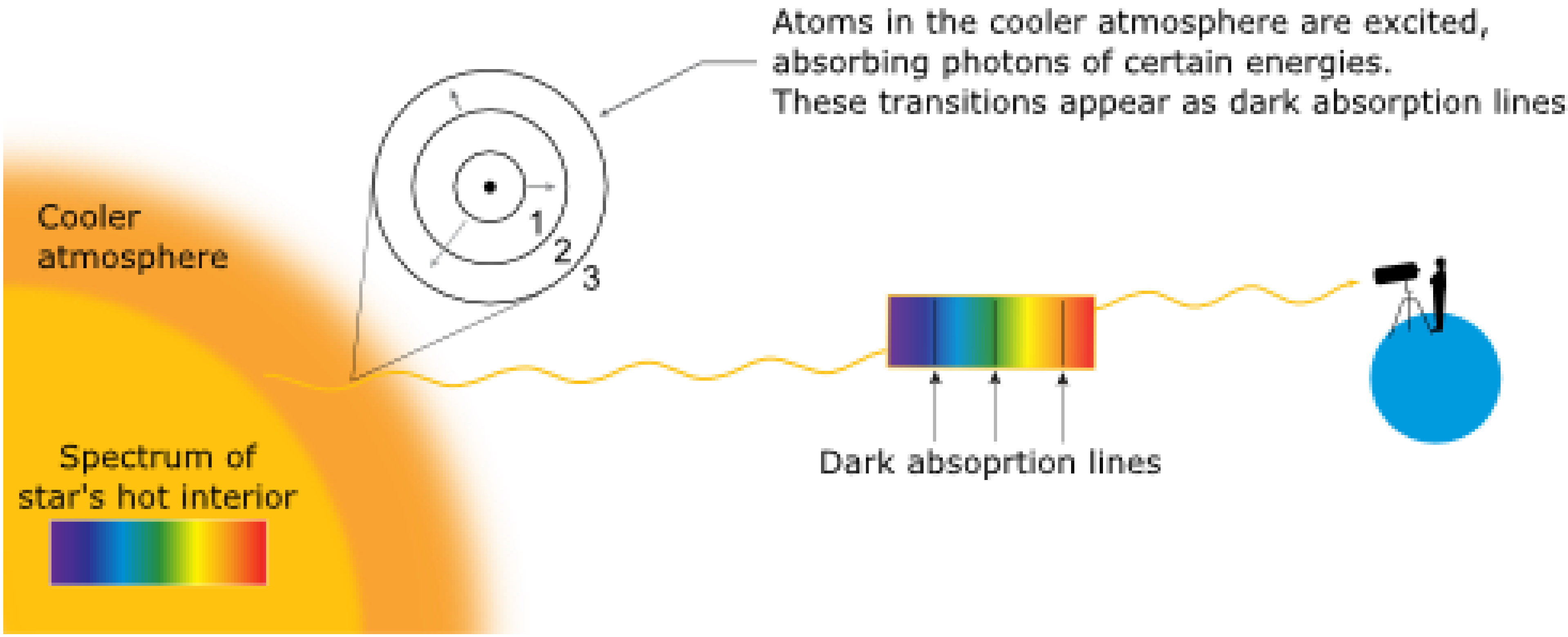
What can we learn from stellar spectra?

Spectra provide a lot of information about an astronomical object:

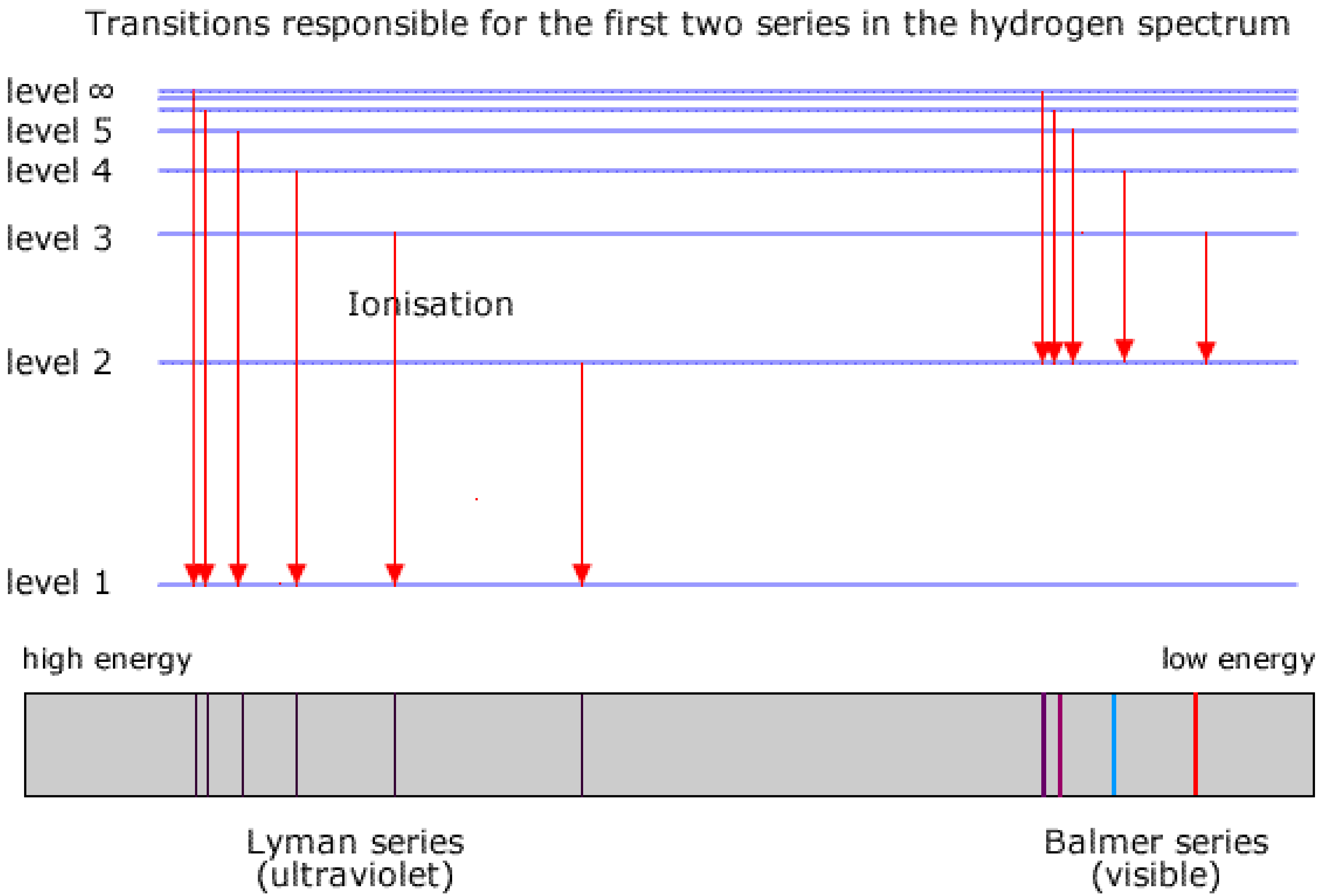
- temperature
- density
- pressure
- magnetic fields
- stellar winds
- chemical composition
- abundances
- distance
- motion:
  Doppler effect $\frac{v}{c} = \frac{\Delta\lambda}{\lambda}$



Formation of stellar spectra



Hydrogen spectrum



Energy level population and ionization stage

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

$$\sigma_{ij} = \frac{\pi e^2}{mc} f_{ij} \Phi_\nu \tag{4.1}$$

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

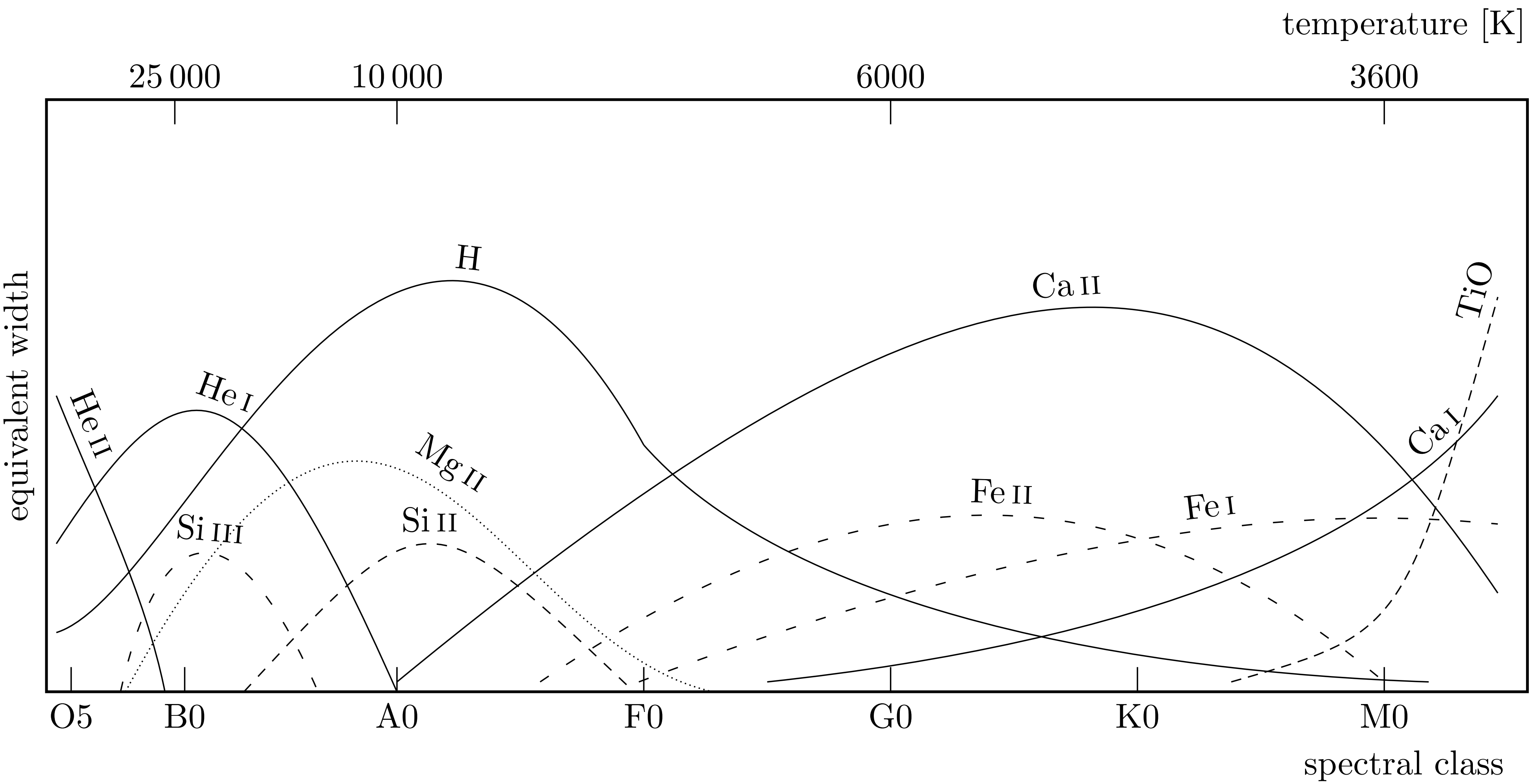
$$\frac{N_j}{N_i} = \frac{g_j}{g_i} e^{-\frac{E_j - E_i}{kT}} \tag{4.2}$$

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

$$\frac{N(X_{r+1})}{N(X_r)} = \frac{2kTg_{r+1}}{P_e g_r} \left(\frac{2\pi m_e kT}{h^2} \right)^{3/2} e^{-\chi_i/kT} \tag{4.3}$$

Line strength vs temperature



Fundamental Astronomy: Karttunen et al.

Line broadening

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

$$\Phi_\nu^{\text{rad}} = \frac{\gamma_{\text{rad}}/4\pi^2}{(\nu - \nu_{ij})^2 + (\gamma_{\text{rad}}/4\pi)^2},\ \gamma_{\text{rad}} = \frac{1}{\tau_{\text{low}}} + \frac{1}{\tau_{\text{up}}} \qquad \text{(Lorentzian)} \qquad (4.4)$$

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

$$\Phi_\nu^{\text{Doppler}} = \frac{1}{\sqrt{\pi}\Delta\nu_{\text{D}}} \exp(-(\nu - \nu_0)/\Delta\nu_D)^2,\ \Delta\nu_D = \frac{\nu_0}{c}\sqrt{\frac{2kT}{m}} \qquad \text{(Gaussian)} \qquad (4.5)$$

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 $R = \lambda/\Delta\lambda$

$$\mathrm{FWHM} = c/2\sqrt{\ln 2}R \qquad \text{(Gaussian)} \tag{4.6}$$

Total line Profile

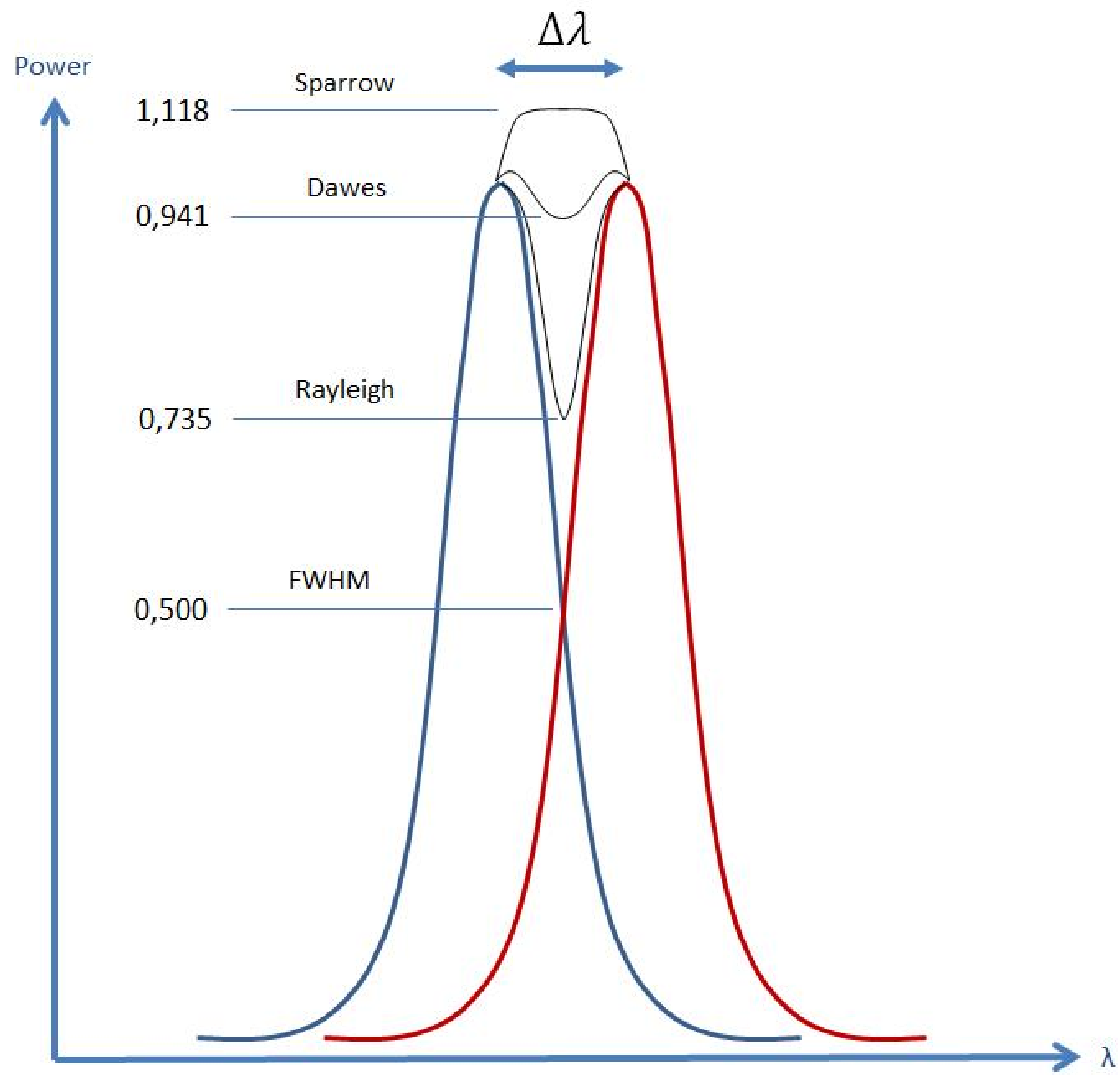
$$\Phi_\nu = \Phi_\nu^{\mathrm{Gaussian}} \star \Phi_\nu^{\mathrm{Lorentz}} \equiv \Phi_\nu^{\mathrm{Voigt}} \tag{4.7}$$

Other effects: Zeeman Splitting, stellar winds

Properties of Spectrographs

- Spectral resolution

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

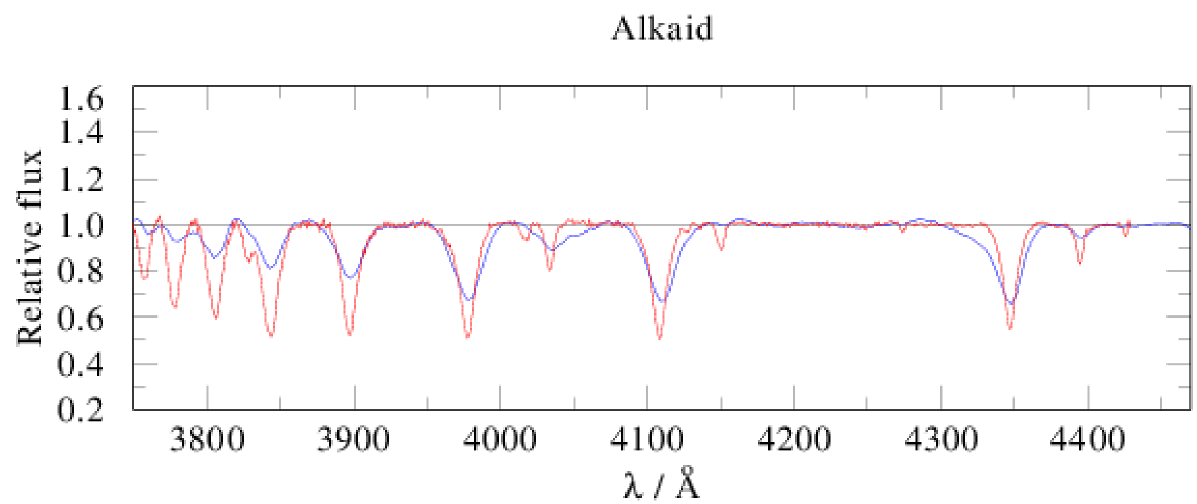


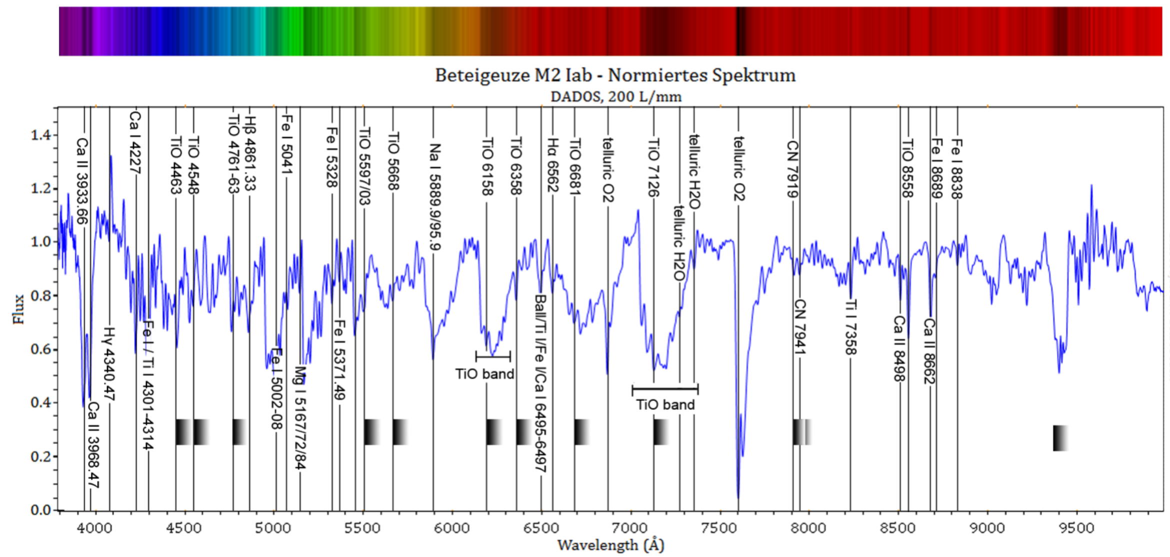
Properties of Spectrographs

- Spectral resolution

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

- wavelength range



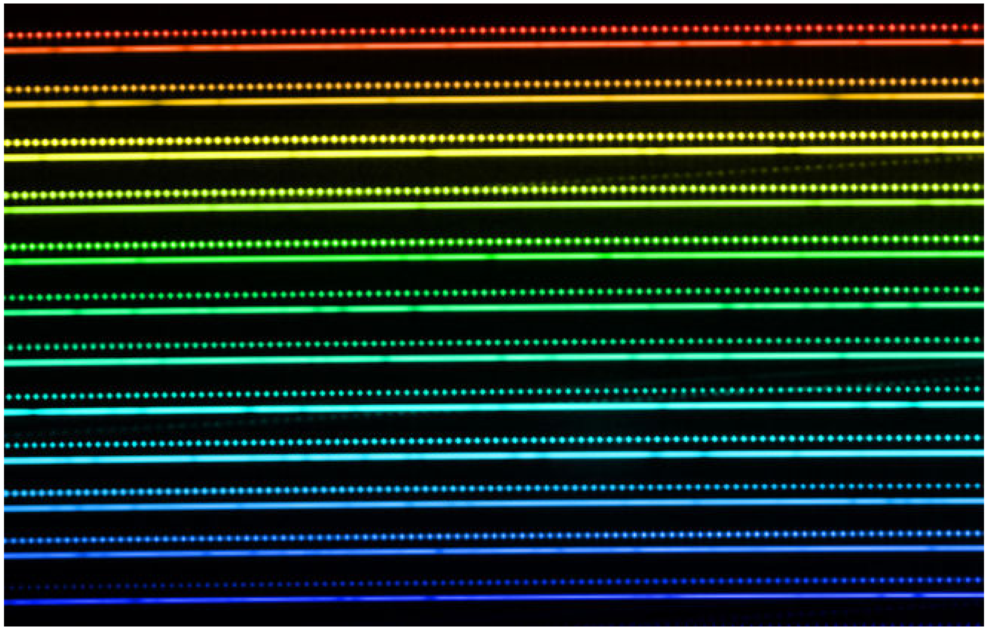


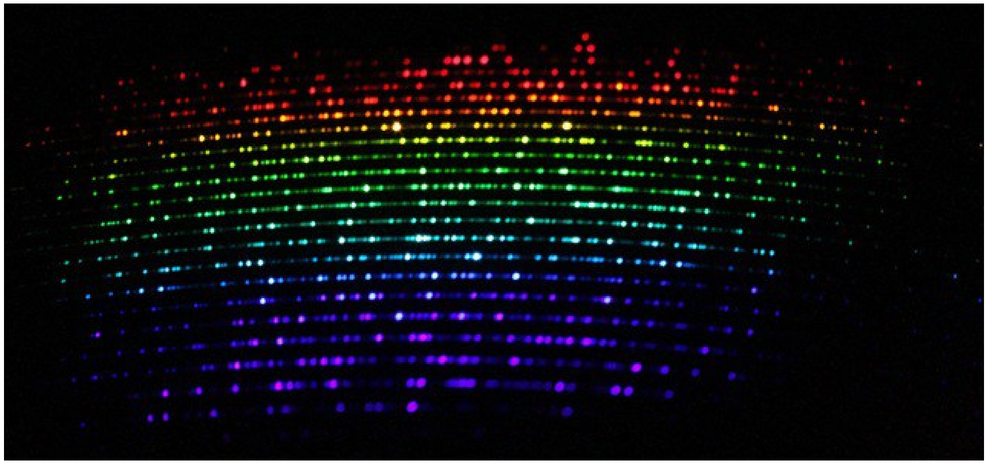
Properties of Spectrographs

- Spectral resolution

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

- wavelength range
- wavelength calibration and stability



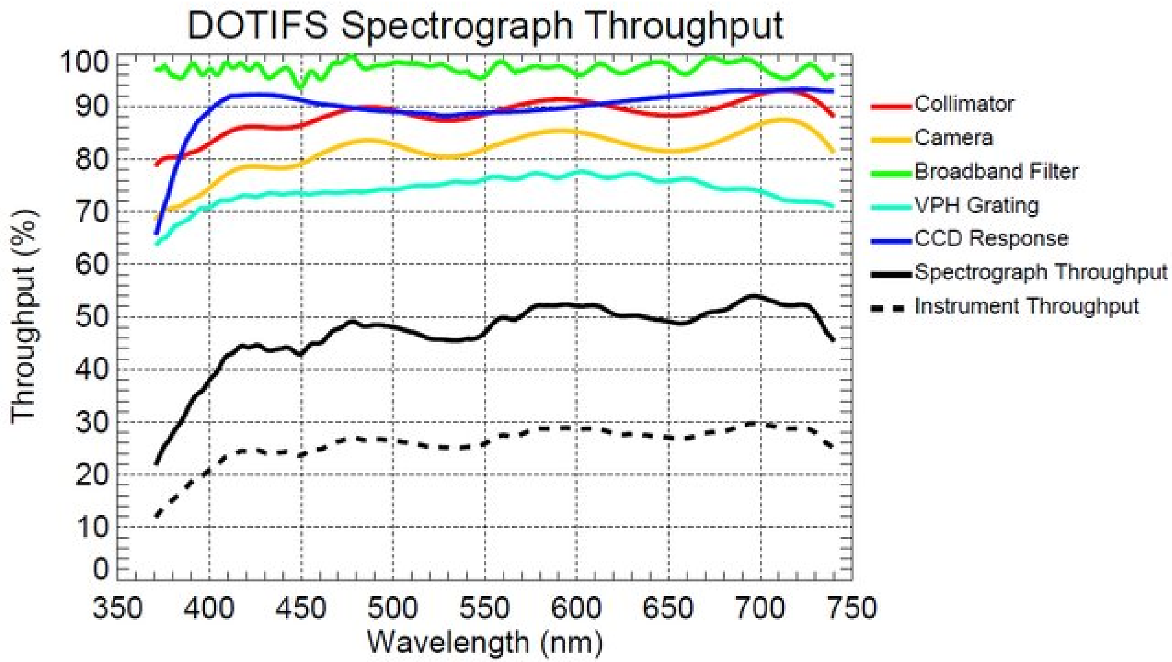


Properties of Spectrographs

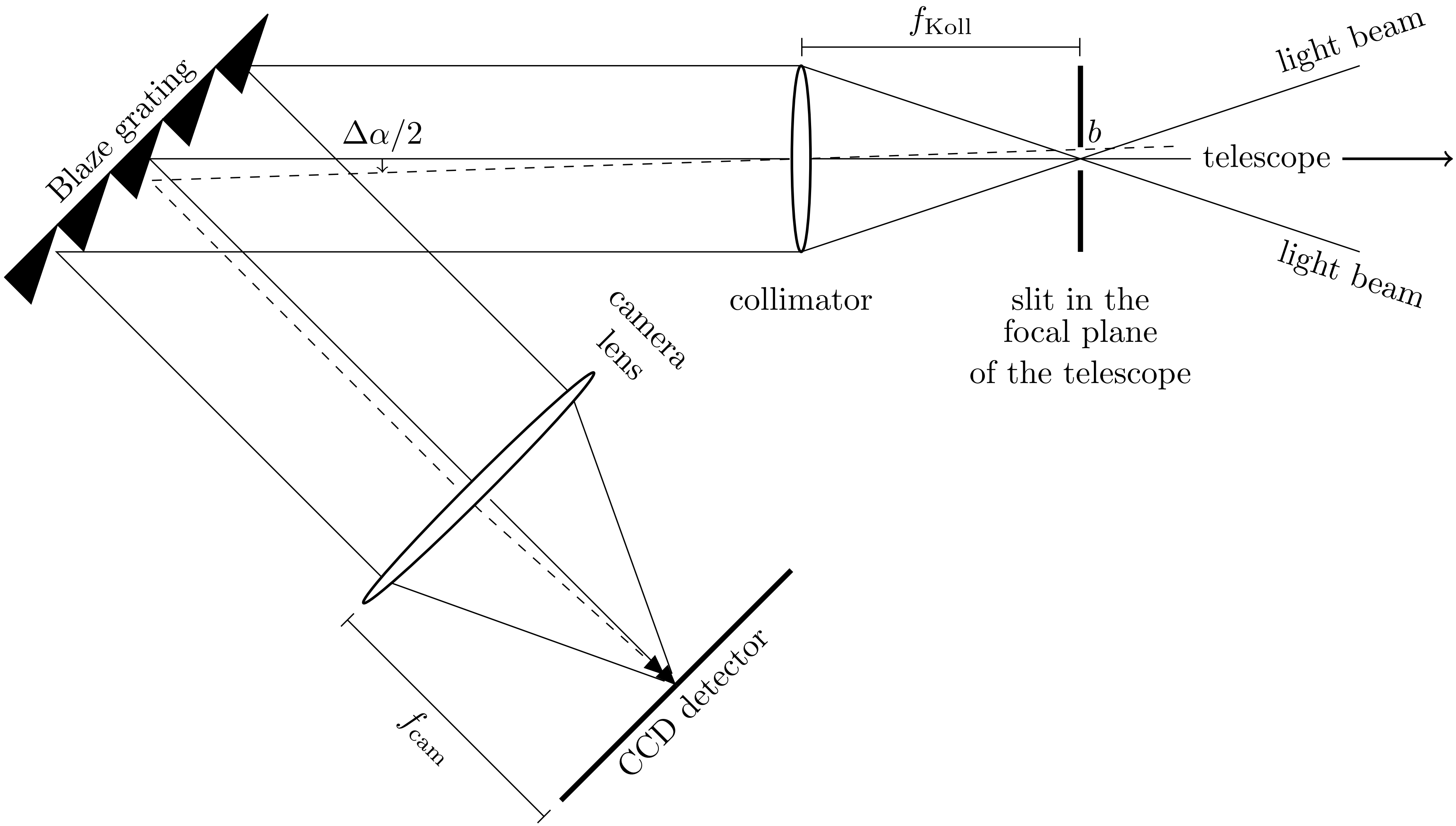
- Spectral resolution

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

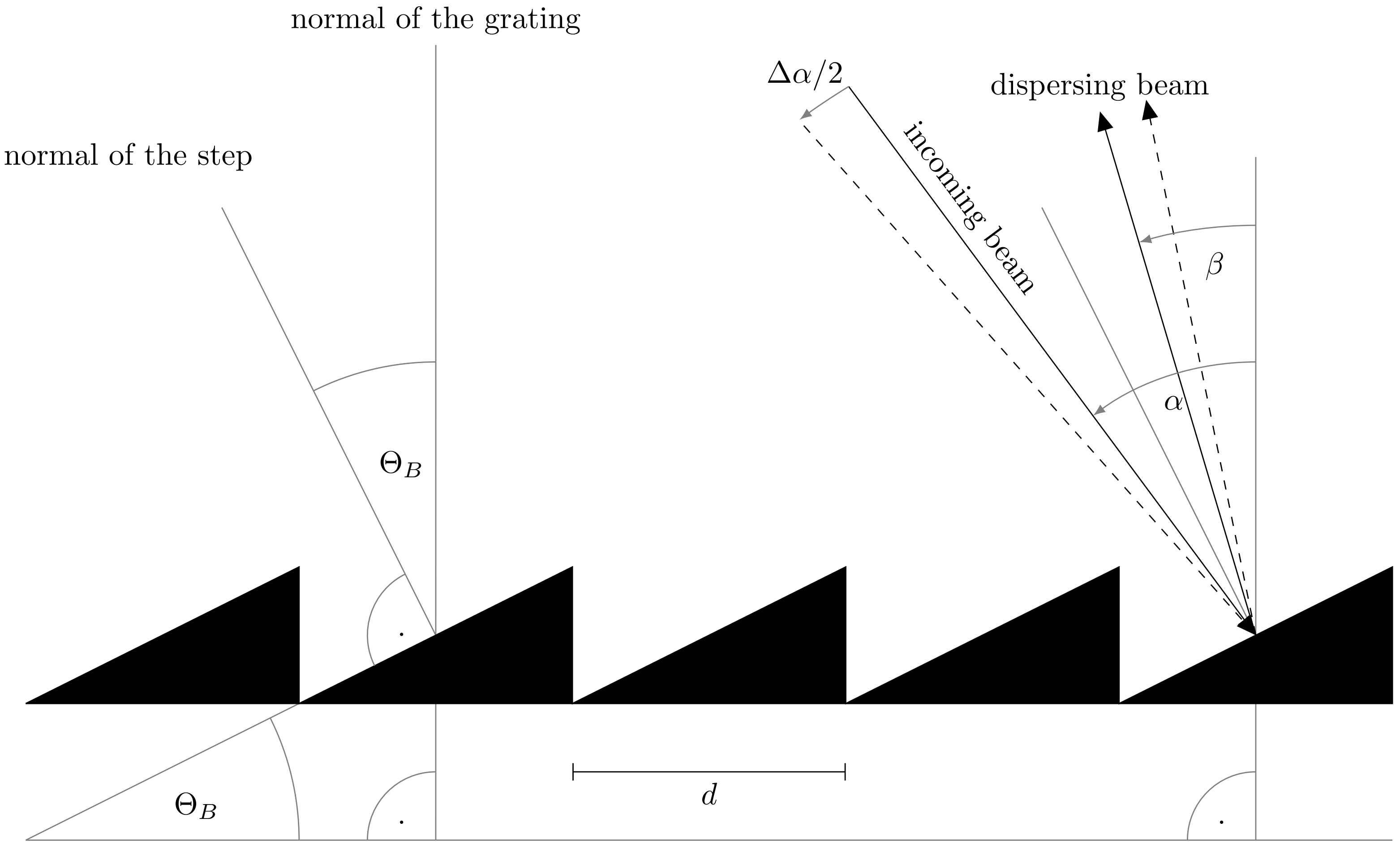
- wavelength range
- wavelength calibration and stability
- throughput for best efficiency
- efficiency in the blue/red
- limiting magnitude



Long-slit spectrograph

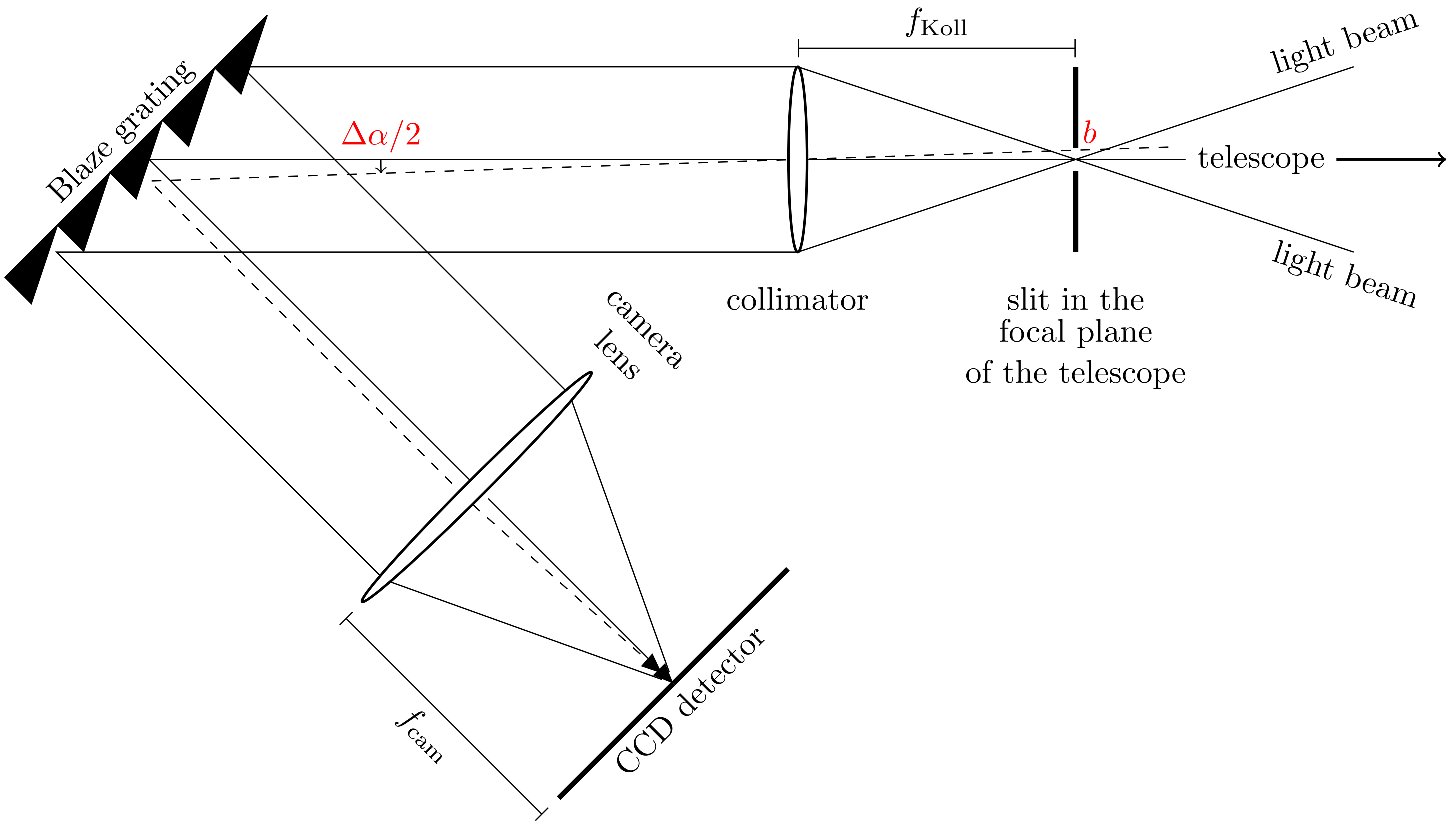


Grating equation



$$\boxed{n\lambda = d\sin\alpha + d\sin\beta}, \qquad \alpha + \beta = 2\Theta_B \tag{4.8}$$

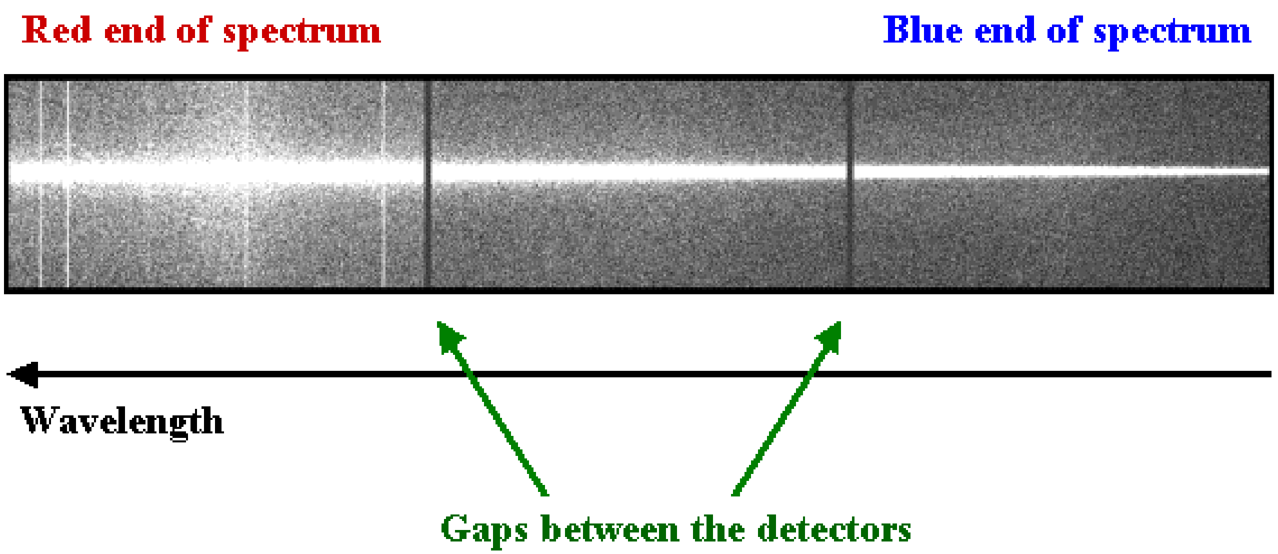
The role of the slit

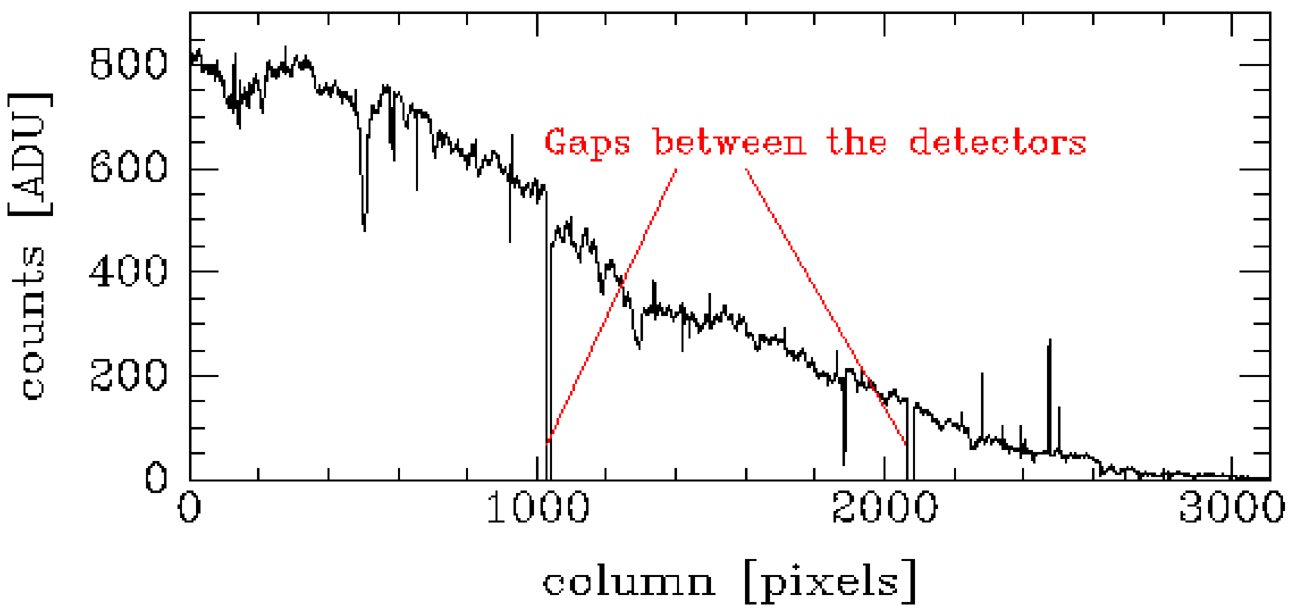


$$b = f_{\rm Koll}\Delta\alpha, \qquad \Delta\lambda = \frac{d\lambda}{d\alpha}\Delta\alpha = \frac{d}{n}\cos\alpha\Delta\alpha = \text{const}$$

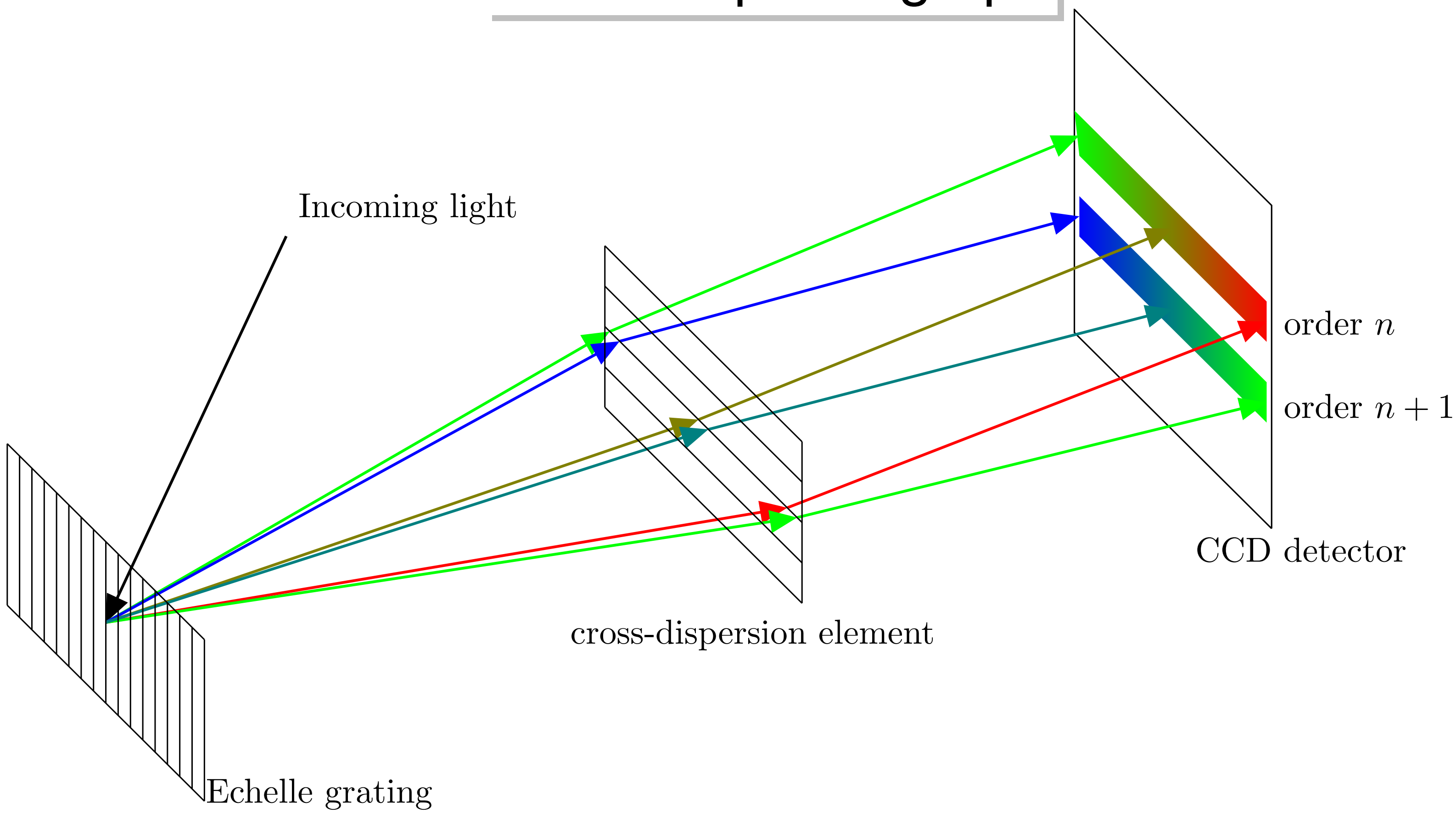
$$\boxed{R_{\rm slit} = \frac{nf_{\rm Koll}}{db\cos\alpha}\lambda} \tag{4.9}$$

A long-slit spectrum





Echelle spectrograph



- optimized for high incidence angles $\Theta_B > 45^\circ$ 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