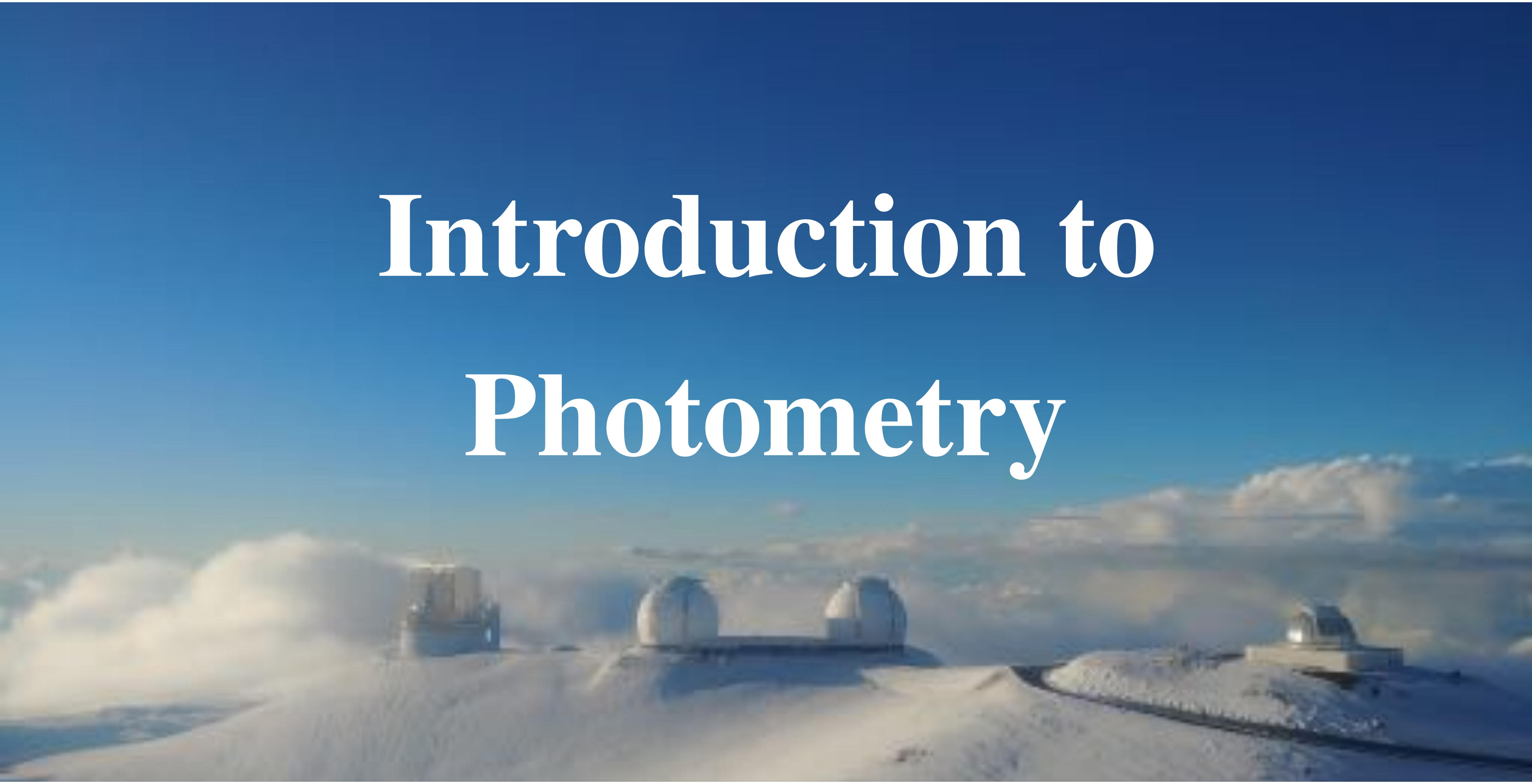
Introduction to Photometry



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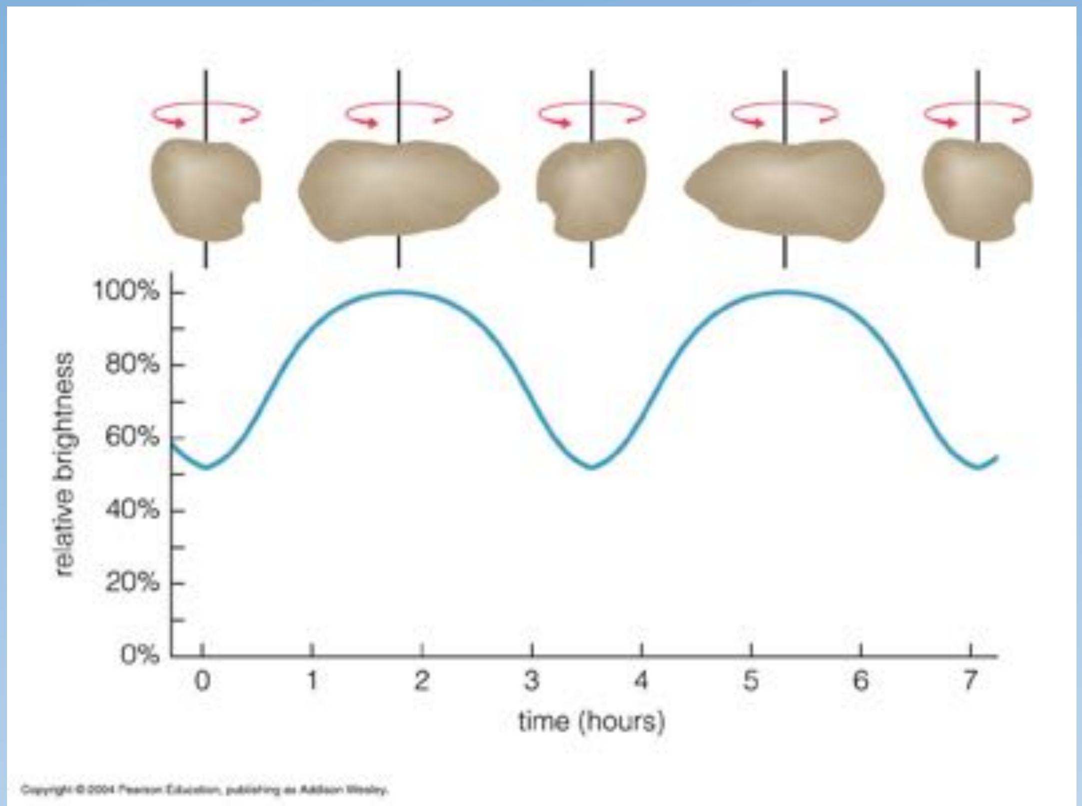
What is photometry?

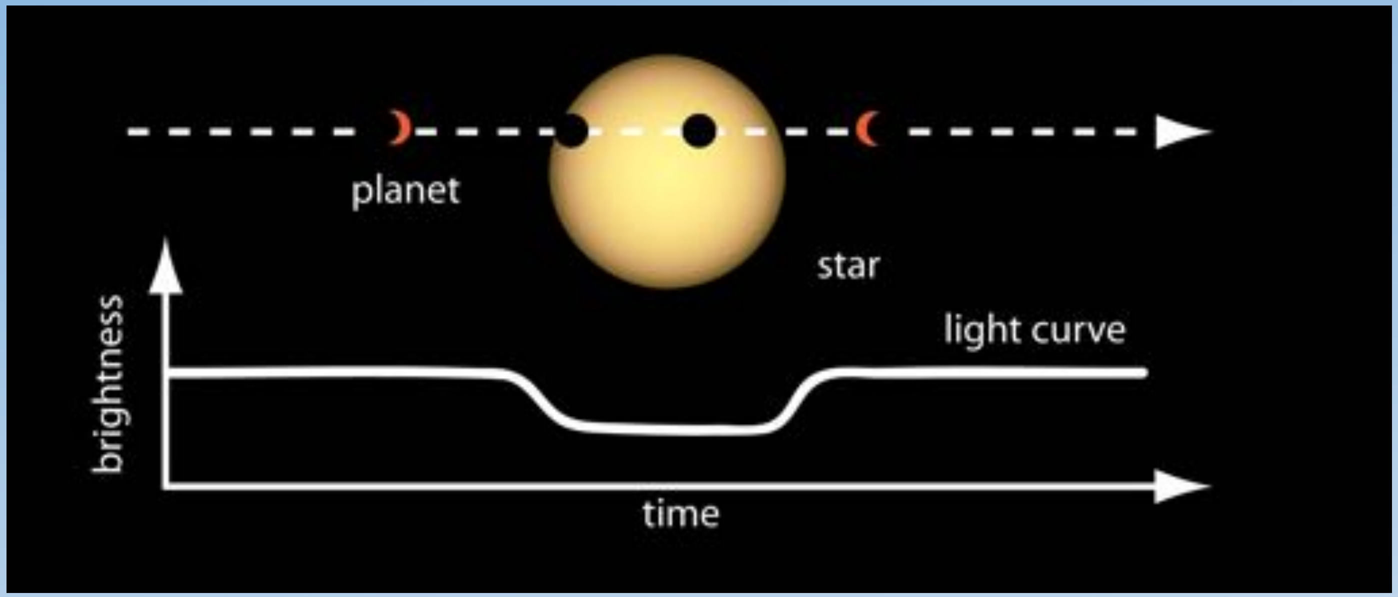
- Photometry is the measurement of the amount and temporal nature of the flux emitted by an object as a function of wavelength.

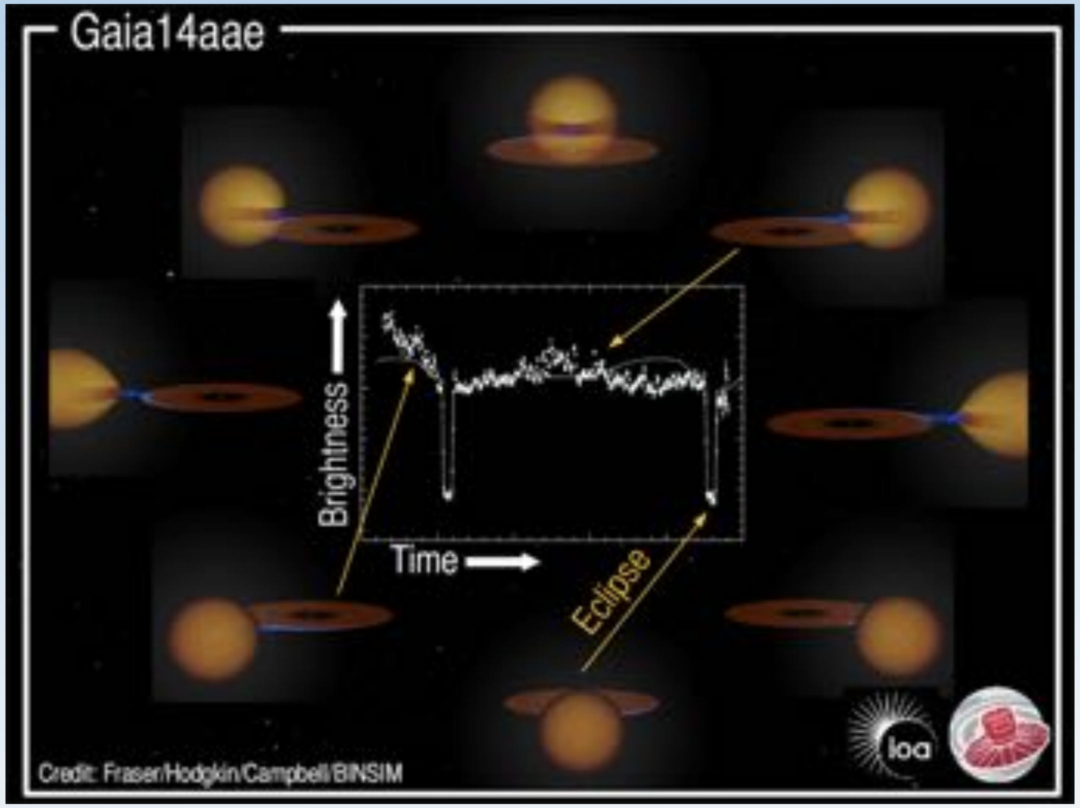
- The introduction of photography in the 19th century transformed astronomy from descriptive to an analytical science.

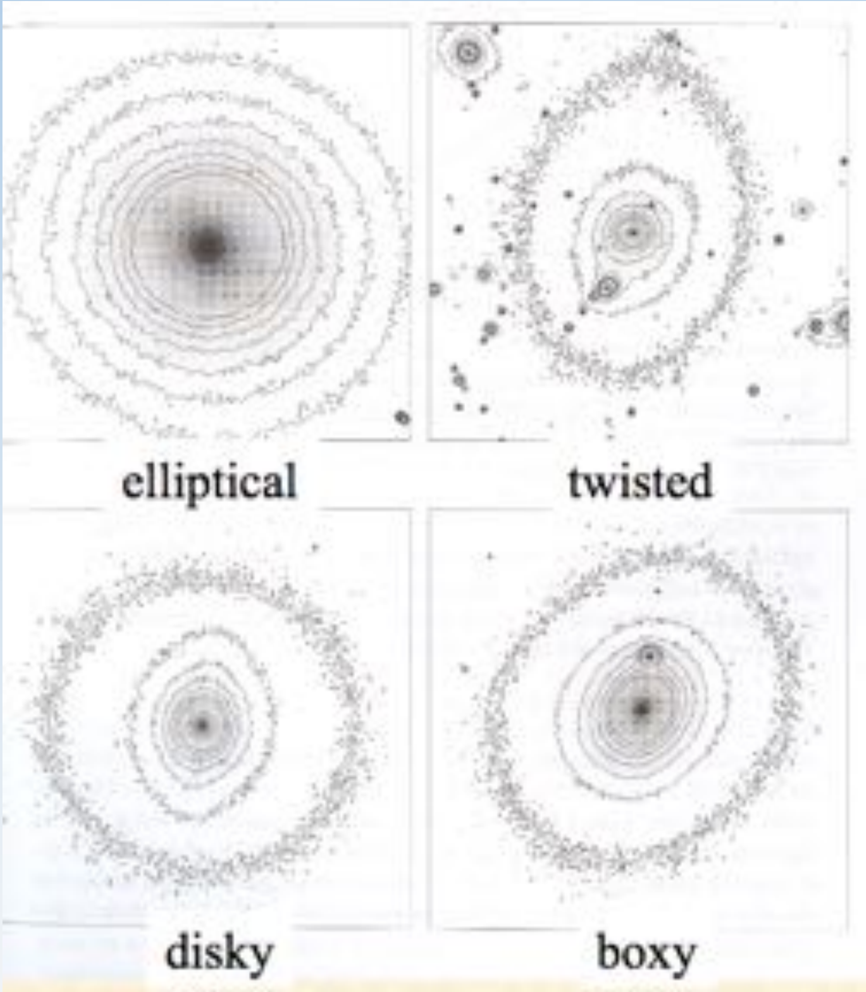
- The challenge is accurately converting instrumental measurements to physical quantities such as flux or flux density.

Examples of photometry









– prove the presence of a source
– the apparent brightness —> luminosity,
– the morphology of the sources —> type of object
– spectral energy distribution (SED)
– colour —> characterisation

Background

The Magnitude System

- The human eye has a logarithmic response to incident light.

- Earliest photometric observations were made by Hipparchus in ~130 BC, who divided stars into magnitudes: 5 magnitudes correspond to a factor of 100 difference in flux.

$$m_1 = C - 2.5\log_{10}(f_1)$$

$$m_1 - m_2 = 2.5\log_{10}\left(\frac{f_1}{f_2}\right)$$

Absolute vs. differential photometry

- **<u>Absolute photometry</u>**

- Photometric measurements reported in a standard system by means of a calibration process. This procedure permits to obtain the absolute flux of a given source => spectral type, gravity, reddening, age, distance.

- **<u>Differential photometry</u>**

- Photometric measurements of a given source with respect to one or more comparison sources which absolute flux is not necessarily known. Both the target and comparison objects are in the same image => *time series photometry*: relative flux variations, light curves.

- **Relative photometry**

- Comparing the instrument magnitude of the object to a known comparison object, and then correcting the measurements for spatial variations in the sensitivity of the instrument and the atmospheric extinction. Like differential photometry, but for when the two objects are in different areas of the sky.

- **Surface photometry**

- Measuring the spatial distribution of brightness within extended objects such as galaxies => surface brightness profile

Absolute Photometry

- Compare the signal of a target and a well known photometric standard object with exactly the same equipment. The comparison of the two signals yields photometric flux of the target. This process is known as **Photometric calibration.**

- This procedure requires the determination of

  – the instrument efficiency and wavelength dependence in the passband

  – the atmospheric transmission for ground-based observations

Vega Magnitudes

$$\text{Vega}: \; m_U = m_B = m_V = ... = m_N \equiv 0.0^m$$

1000 photons in V at the top of the atmosphere:

flux = f / hv = 1005 photons $cm^{-2}s^{-1}Å^{-1}$

Standard Stars

- For sensitive instruments Vega is far too bright -- so a network of secondary standards of fainter sources have been established: the Landolt system, based on A0 stars has become the standard magnitude system for many applications (Landold A.U., 1992, AJ Vol.104, p. 304).

Good photometric standard stars have the following properties:

– photometrically constant object at the 0.1 % to 1.0 % level as proven by long term monitoring,

– object with a normal continuum spectrum, in particular without narrow spectroscopic features like strong emission lines,

– single source without potentially disturbing other sources nearby

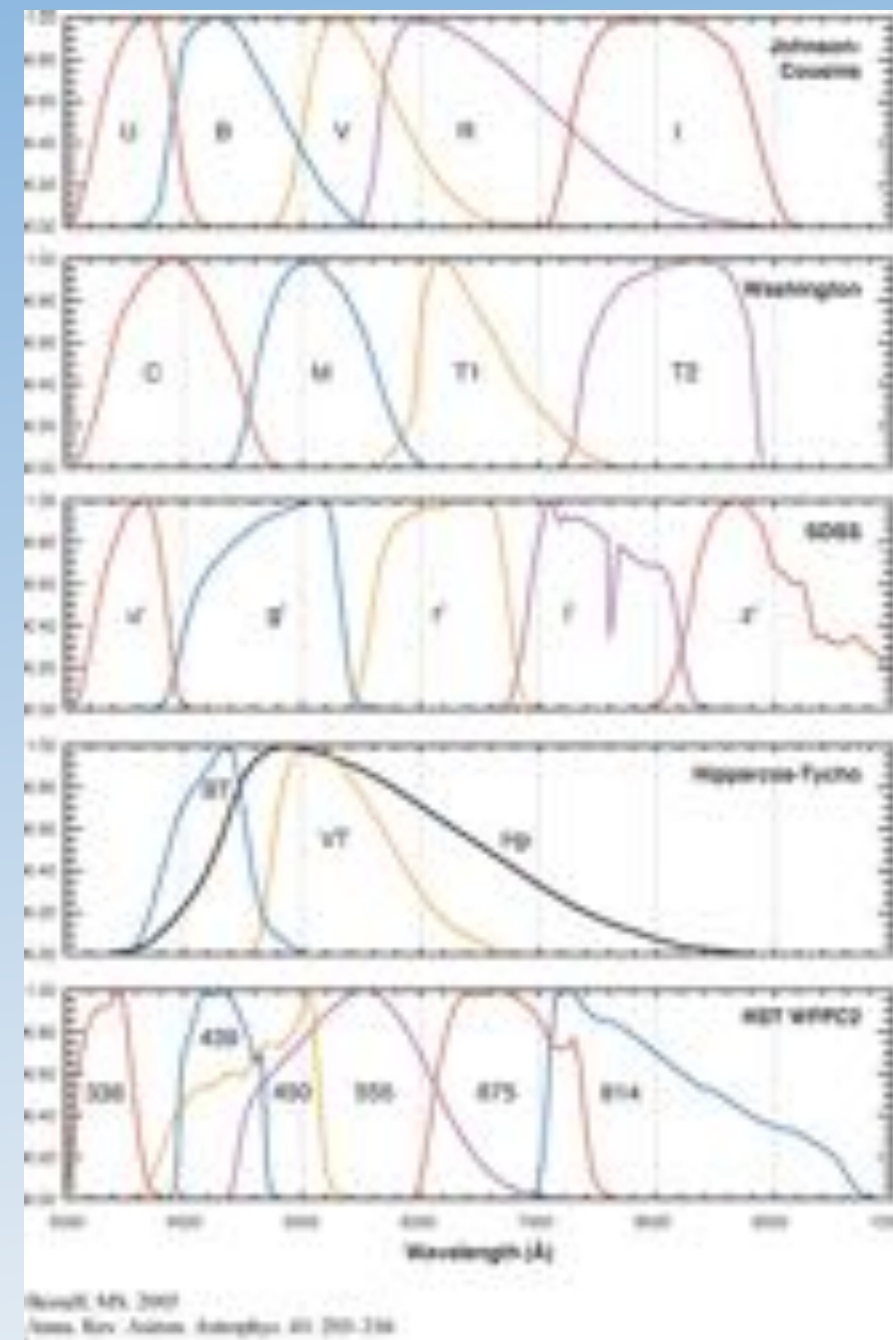
Passbands

- **Bolometric** magnitude: magnitude over all wavelengths. <— difficult to measure

- => magnitude system defined in a passband.

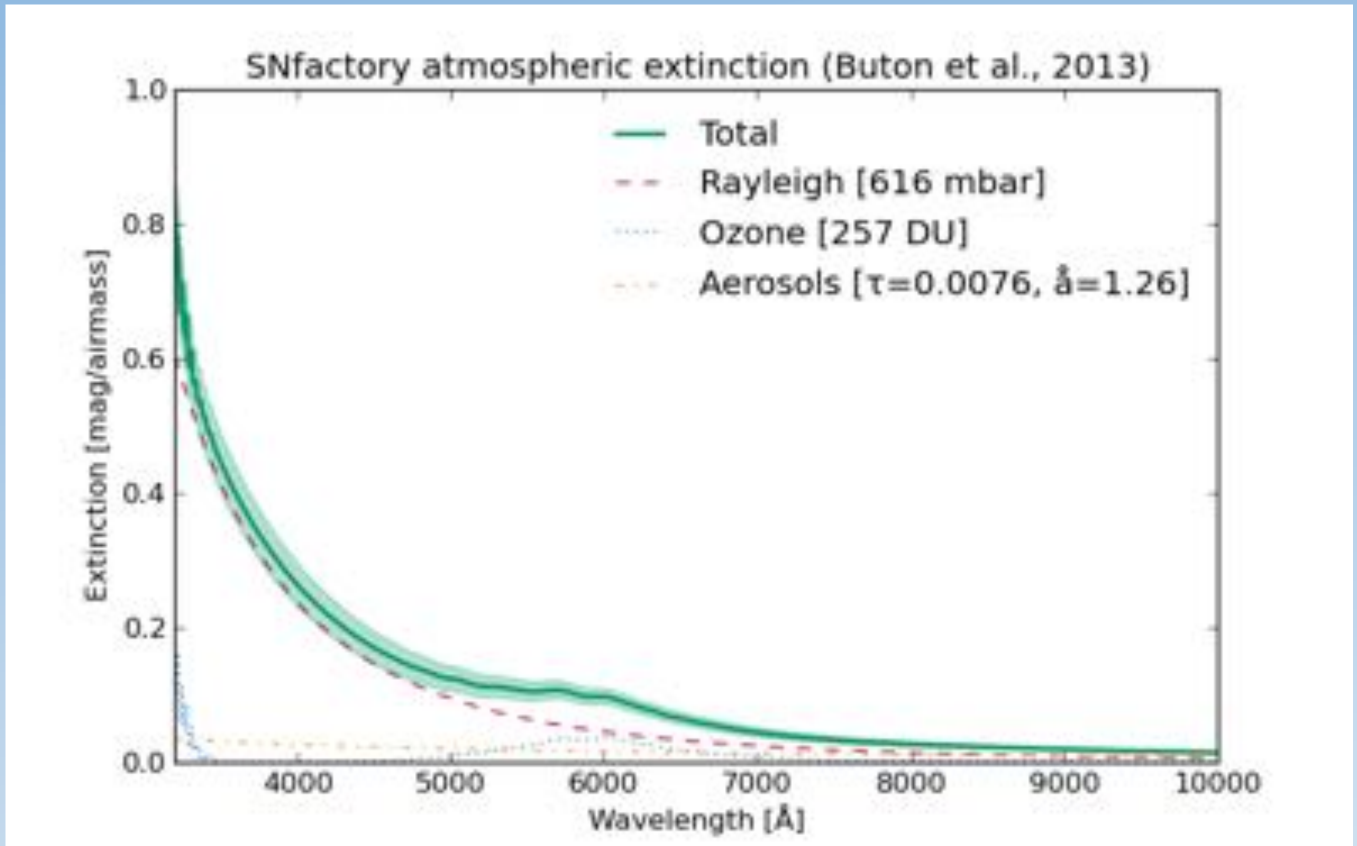
- Sensitivity depends on the optical system, detectors and filters used.

- Define colour magnitudes and colour index:

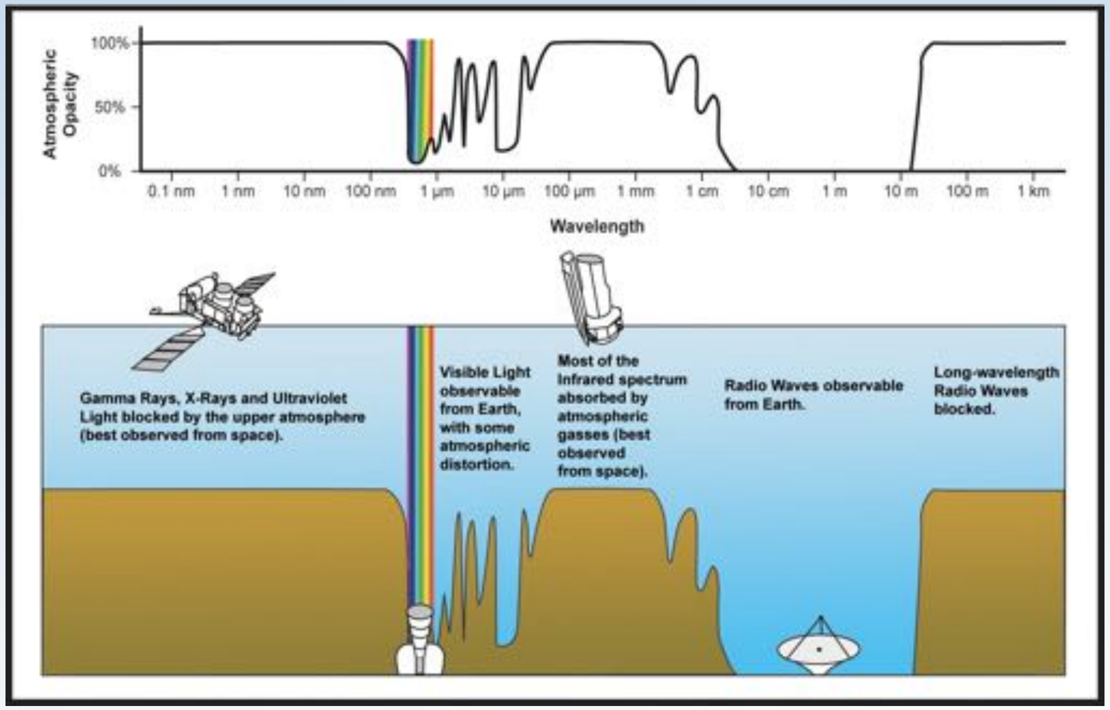


$$B - V = m_B - m_V = 2.5 \log(f_B / f_V) + C$$

Atmospheric Transmission and Extinction



- In ground-based observations the flux from a source is attenuated by the Earth atmosphere.Even for clear atmospheric “windows” the atmospheric extinction is about 10% and often significantly higher.



- Transmission of the “clear” atmosphere

extinction coefficient

$$T = \frac{I}{I_0} = e^{-X\cdot\tau(\lambda)}$$

$$X = \sec z$$

airmass

Zenith angle

Photometric Zero Point

- The zero point of an instrument, by definition, is the magnitude of an object that produces one count (or data number, DN) per second at an airmass of 1.

$$m = -2.5 \times \log_{10}(DN / t) + ZP$$

- The zero point determines the connection between observed counts and a standard photometric system. It depends on instrument and telescope transmittances as well as detector electronics.

- Zero point of telescopes can evolve due to dust build-up inside the telescope or mirror changes.

Photometric Calibration

- The complexity of photometric calibration depends on the quality of data: e.g. for milli-magnitude precision need to worry about second order effects, such as the colour-term dependence of airmass corrections.

- Typically require observations in multiple filters.

$$m_i = m_{Ii} + ZP_i + X \cdot \tau_i(\lambda) + A_{ij}(m_j - m_i)$$

instrumental magnitude of object in filter i

Zero Point in filter i

Airmass . extinction in filter i

magnitude of object in filters i and j

Colour term transformation coefficient. Obtained by observing standards of known m_i and mj

Point Spread Function

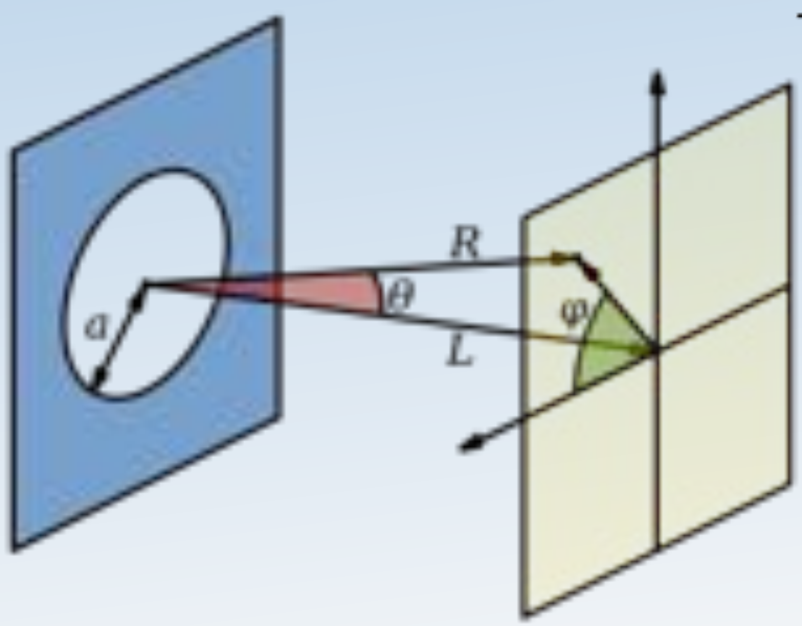
- Fraunhofer diffraction: Airy Pattern

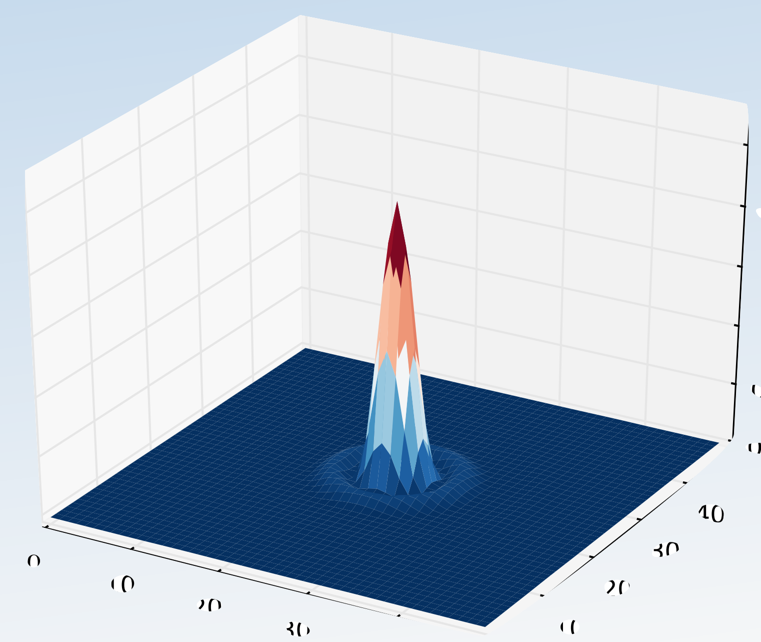
$$I(\theta) = I_0 \left(\frac{2J_1(ka\sin\theta)}{ka\sin\theta} \right)^2 = I_0 \left(\frac{2J_1(x)}{x} \right)^2$$

$$k = 2\pi/\lambda$$

J_1 is a Bessel function of the first order

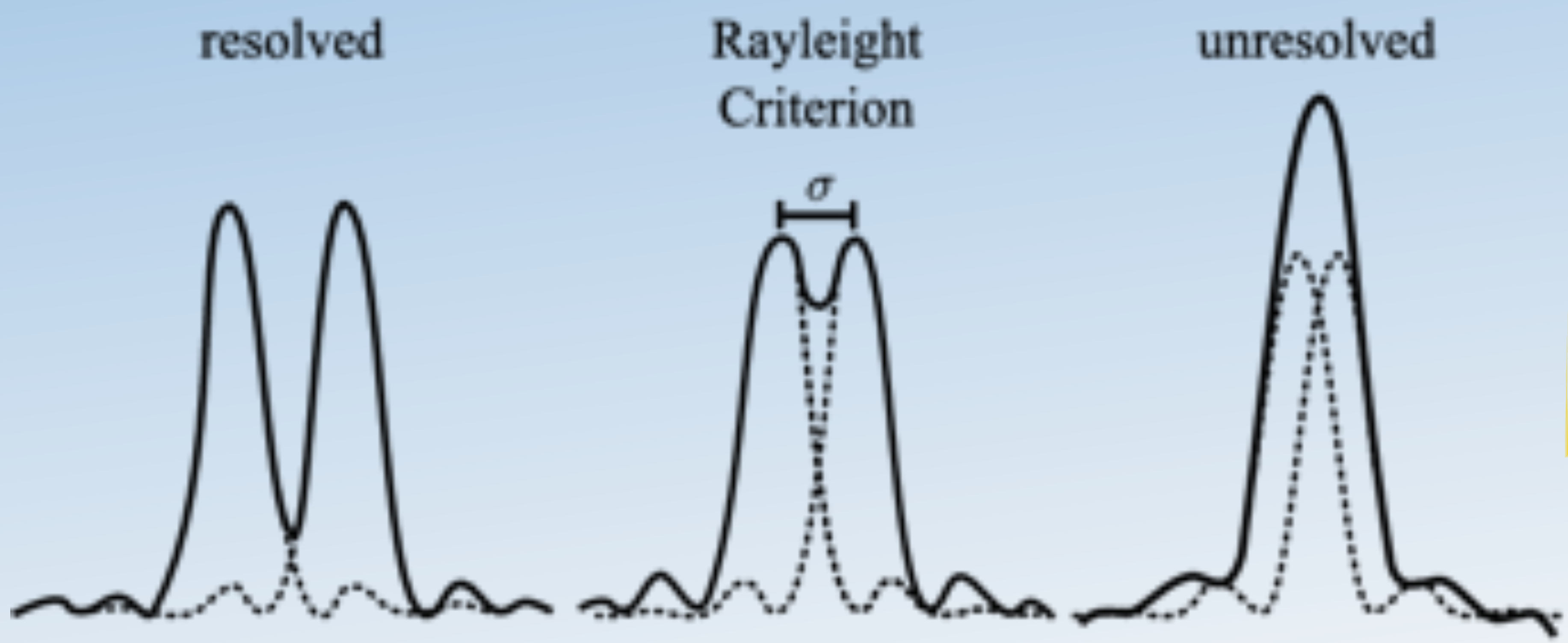
$$\varepsilon_{FWHM} = 1.028\frac{\lambda}{D}$$





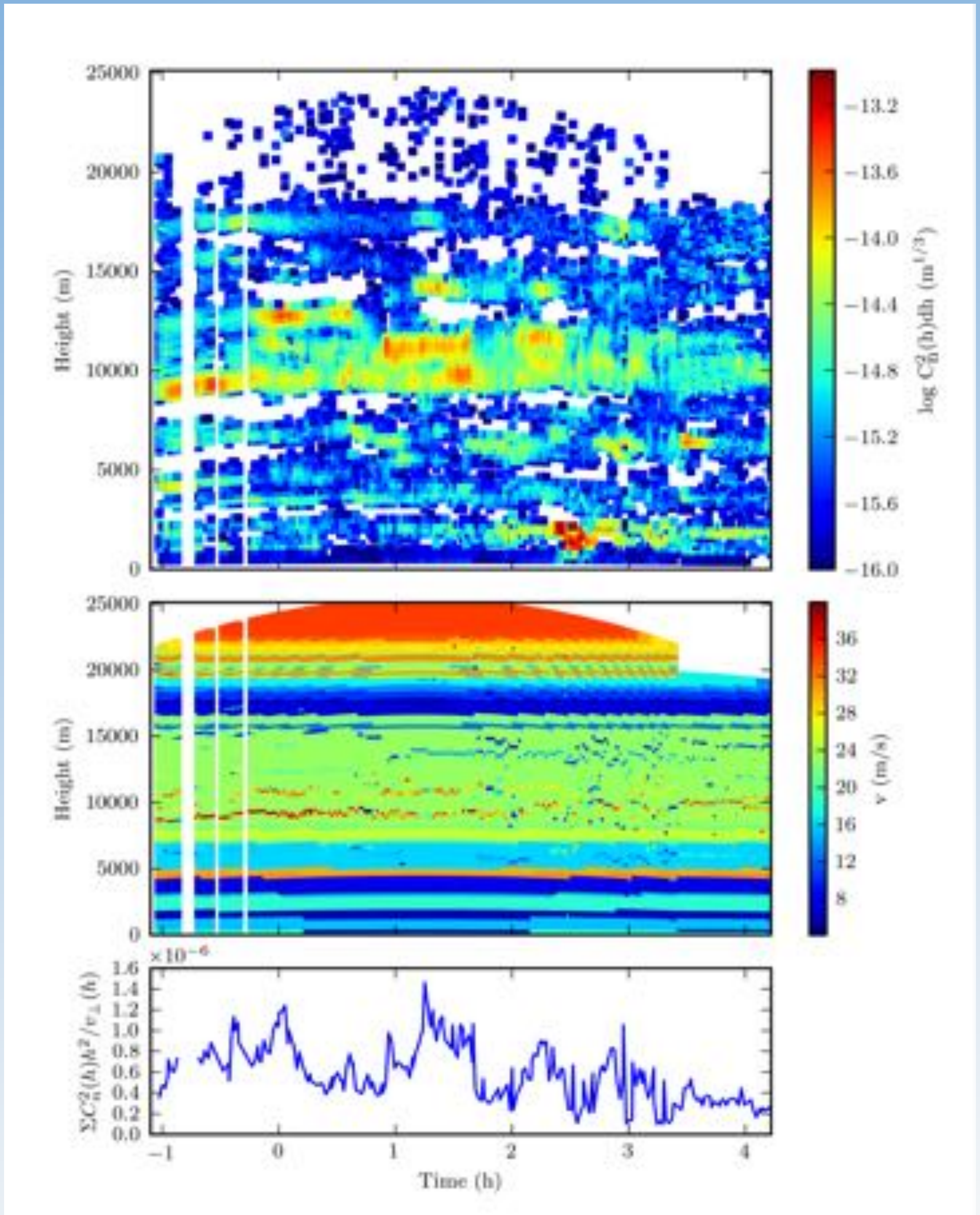
Rayleigh Criterion

- The Rayleigh criterion: two images are just resolved if the centre of the first Airy pattern is superimposed on the 1st dark ring of the 2nd pattern.



$$\boxed{\theta = 1.220\frac{\lambda}{D}}$$

The Atmosphere



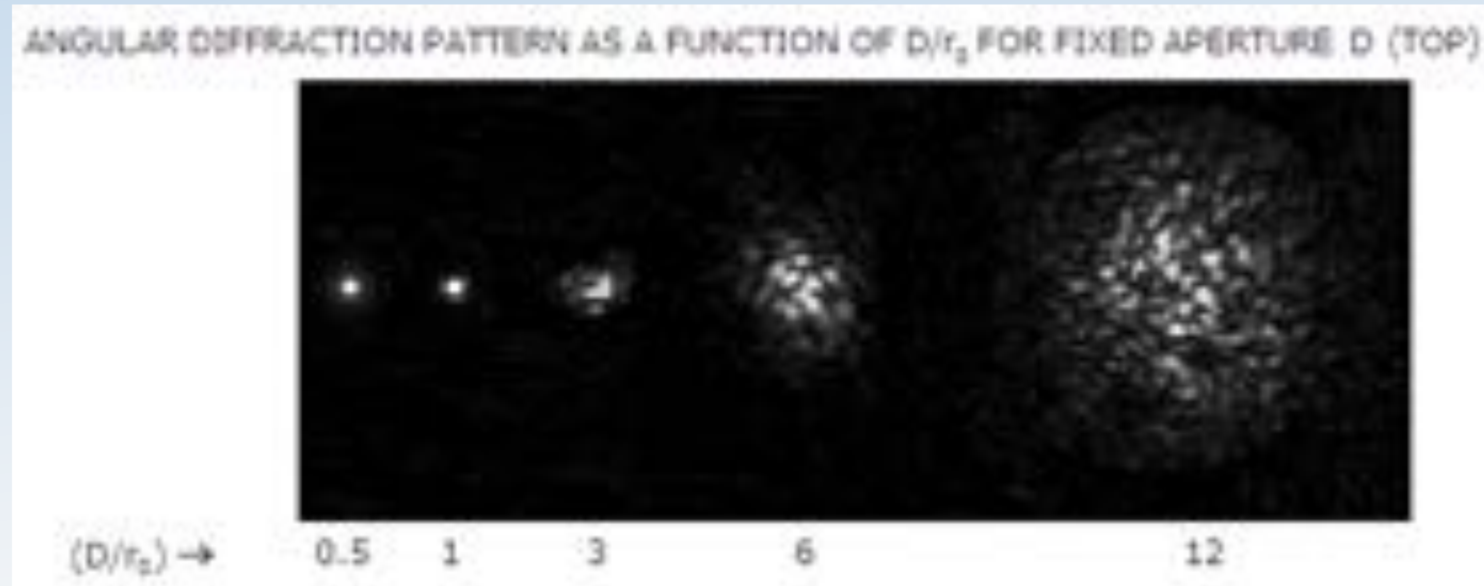
Atmospheric Effects: Seeing

- Atmospheric turbulence causes mixing of air from different altitudes, producing variations in temperature and humidity. This creates patches of air with different densities and hence varying refractive index.

$$D_\phi(\mathbf{r}) \;=\; 2.914\, k^2 \sec(Z)\, r^{5/3} \int_0^\infty C_n^2(h)\, dh = \; 6.88 \left(\frac{|\mathbf{r}|}{r_0}\right)^{5/3}$$

$$r_0 = \left(0.423\, k^2 \sec(Z) \int_0^\infty C_n^2(h)\, dh\right)^{-3/5}$$

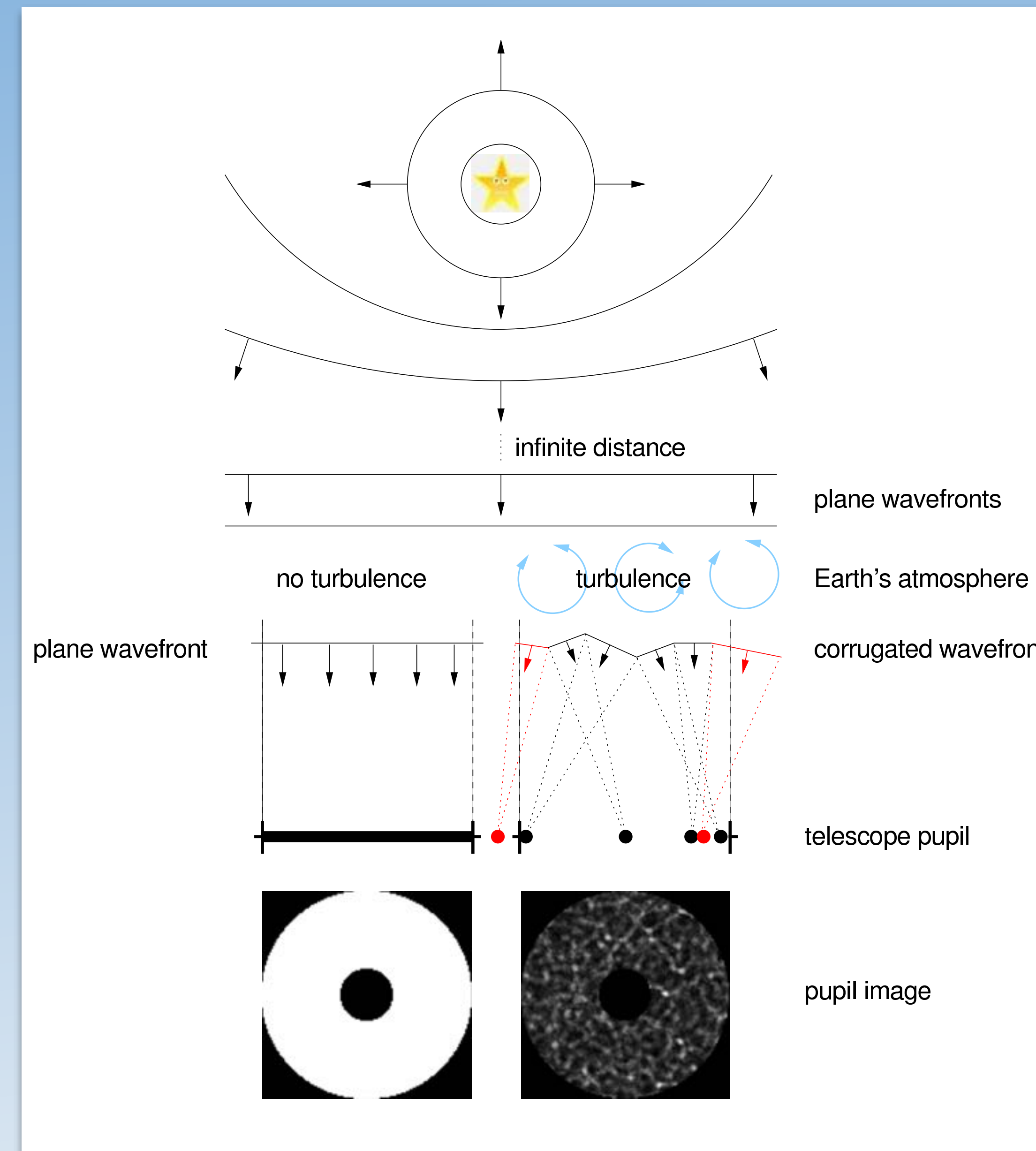
$$\varepsilon_{FWHM} = 0.976 \frac{\lambda}{r_0}$$



Atmospheric Effects: Scintillation

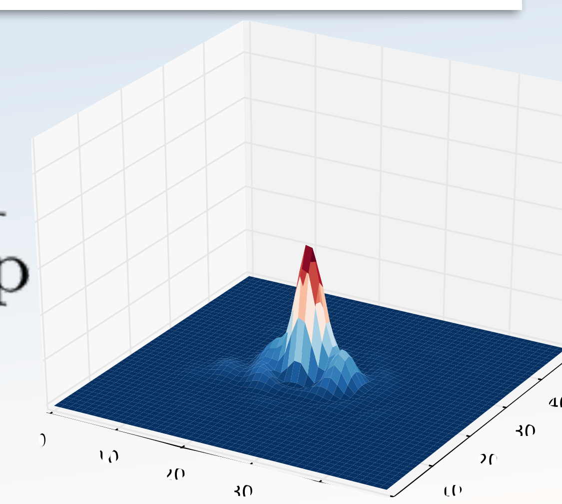
Intensity variations caused by interference of the light wave with itself creating ``flying shadows'' pattern seen in the pupil moved along by the wind.

There is no correlation between scintillation and angular seeing, as scintillation is strongly dependent on the height of the turbulence. In contrast, seeing has no height dependence.



$$\sigma_I^2 = \sum \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}$$

$$\sigma_I^2 = 10.7 \cos(Z)^{-3} \int_0^\infty \frac{C_n^2(h) h^2}{V_\perp(h)} \mathrm{d}h D^{-4/3} t_{\mathrm{exp}}^{-1}$$



Basic photometry procedure

Summary of Photometric Procedure

For the photometric measurement one needs the following steps:

- a flux measurement for the target,
- flux measurement for photometric standard stars with the same instrument,
- correction for the atmospheric extinction for the target star and photometric standard star,
- flux ratio conversion into a magnitude difference,
- calculation of the magnitude of the target, using the magnitude of the standard star and the derived magnitude difference,
- consideration of possible colour effects due to deviations of the instrument efficiency from the standard filter pass band.

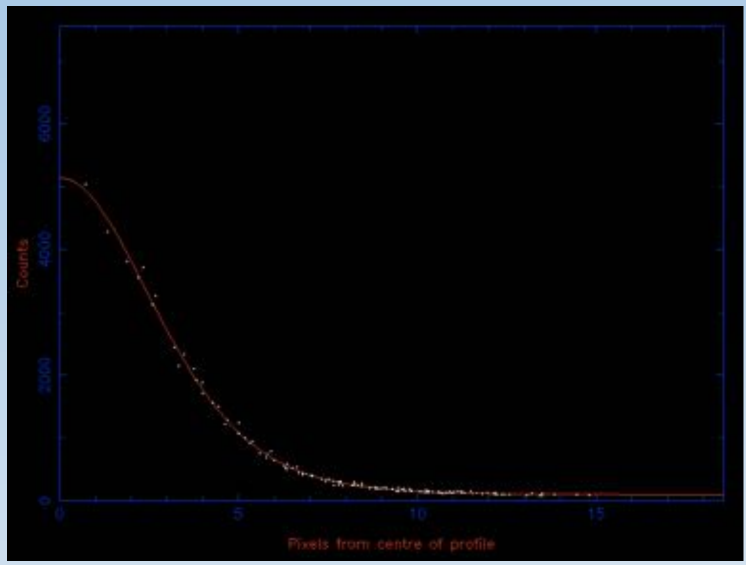
The atmospheric extinction correction is not necessary if the target is measured in the same image with the calibration source.

Image centering

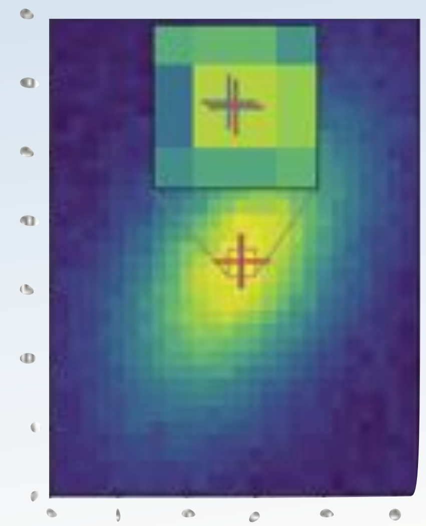
- **Centre of mass**

$$\bar{x} = \frac{\sum_{i=-L}^{i=L} (A_i - \bar{A}) x_i}{\sum_{i=-L}^{i=L} (A_i - \bar{A})}$$

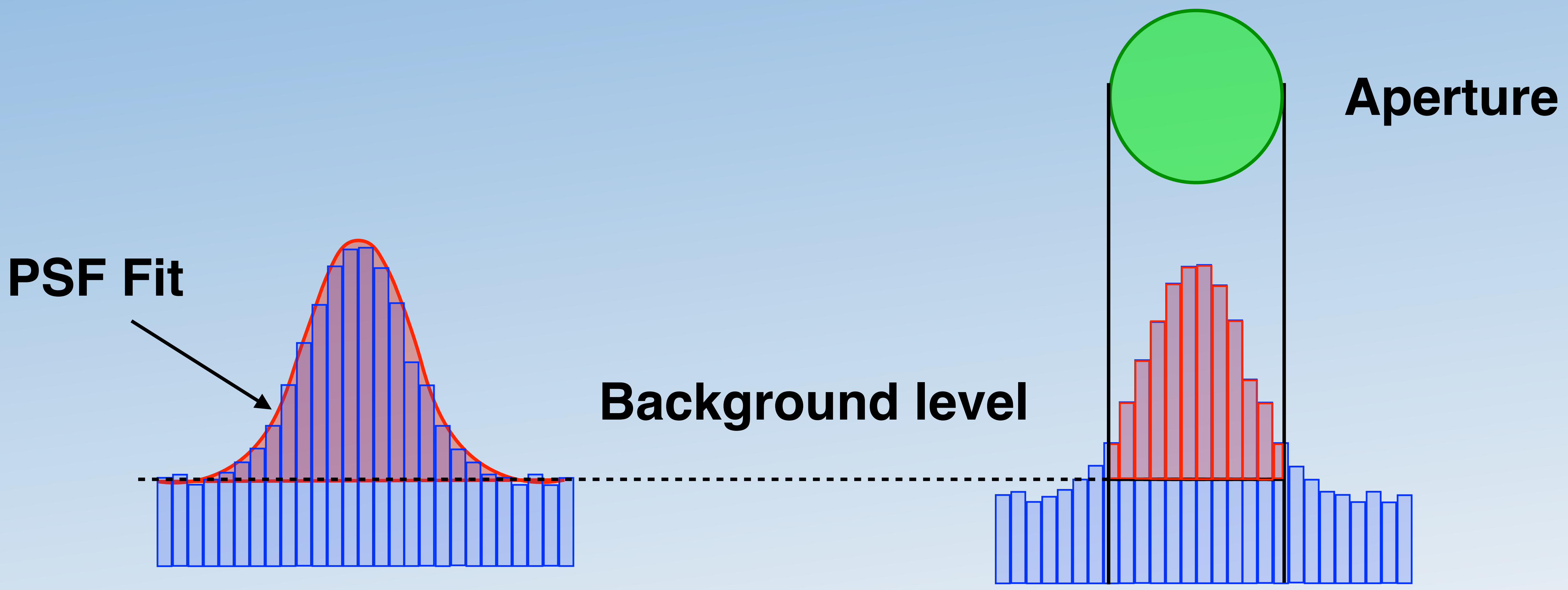
- **1-D Gaussian Fitting:** add up the light from the star along the rows and then the columns of the CCD —> a one-dimensional stellar profile in the x direction and another in the y direction. The resulting profiles are fit with a one-dimensional Gaussian (or similar) function.



- **2-D Gaussian Fitting:** fit a 2D Gaussian to the 2D distribution of the data



Estimating point source intensity: PSF fitting vs. Aperture photometry



Aperture photometry

- Makes no assumption about the shape of the PSF
- Sum all counts within an area $A=\pi r^2$
- Remove estimated sky background

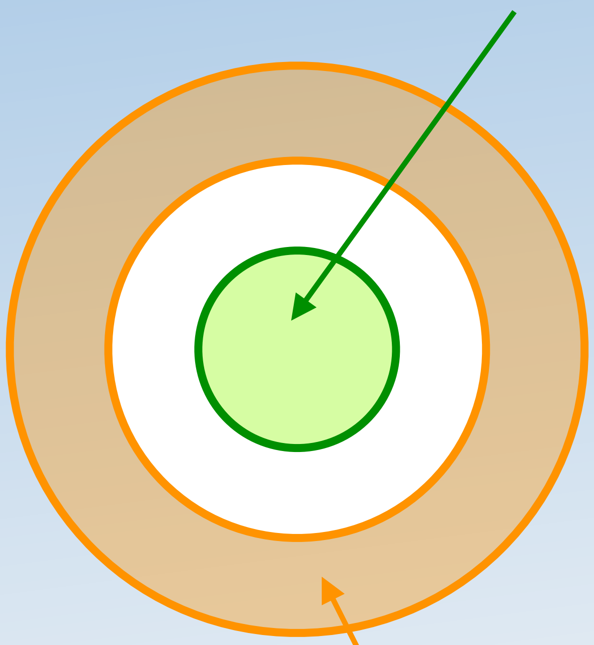
Partial pixels - Options:

a) Not using partial pixels

b) Using every pixel within aperture

c) Weighting counts within partial pixel

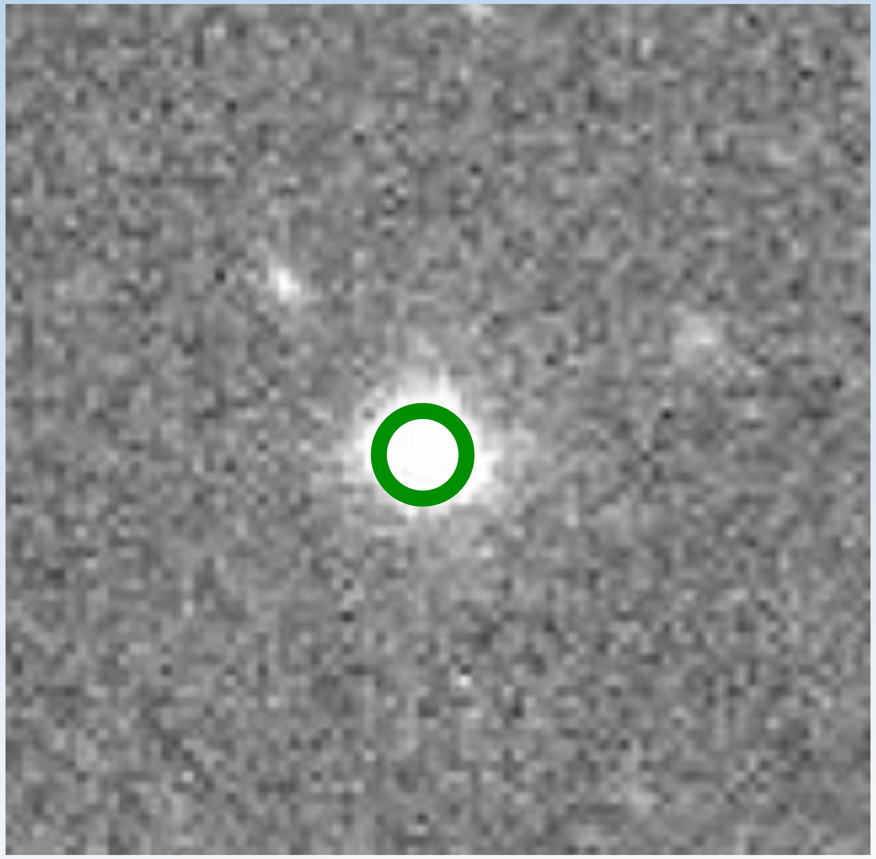
Measure light from star + sky



Measure sky value

Best aperture size?

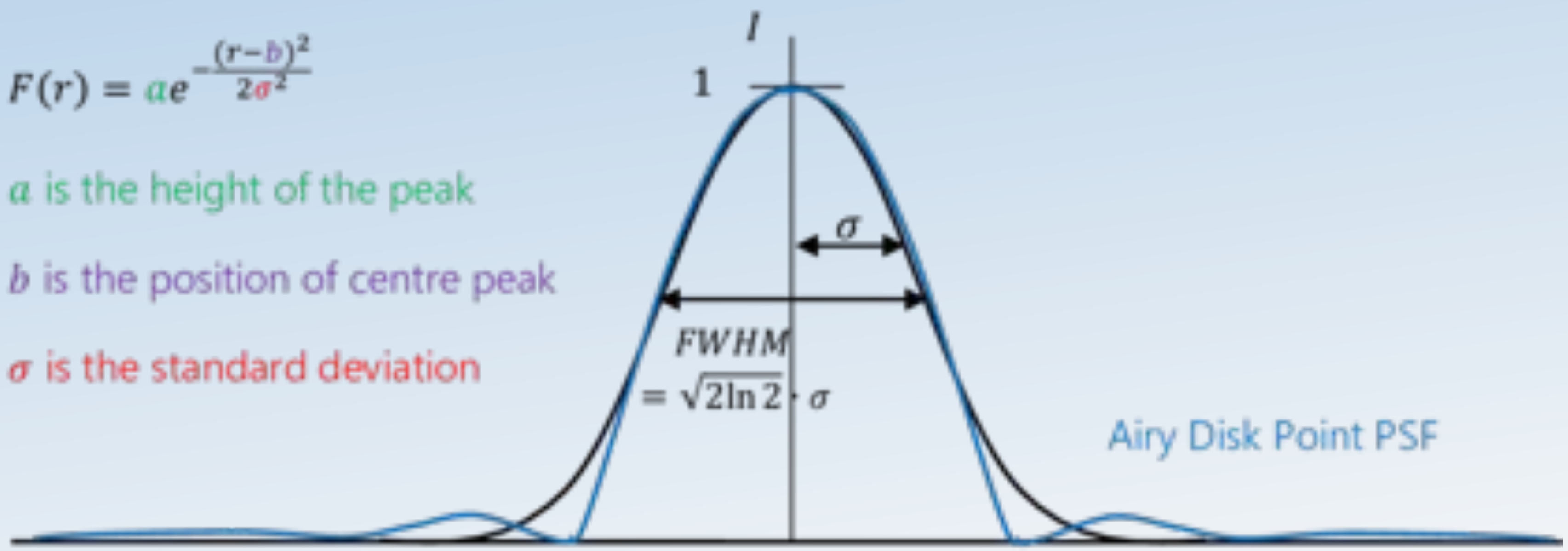
- Optimum aperture radius provides the highest S/N.
  - Large aperture:
  - include more light -> more signal
  - more contamination
  - more noise from sky
  - -> lower S/N
  - Small aperture:
  - less contamination
  - lose signal from source
  - -> lower S/N



Profile fitting

- Involves modelling the PSF by a function. Most common is Gaussian

$$G(r) \propto \exp(r^2/2a^2)$$



Other functions to Describe PSF:

- Modified Lorentzian

$$L(r) \propto \frac{1}{1 + (r^2/a^2)^b}$$

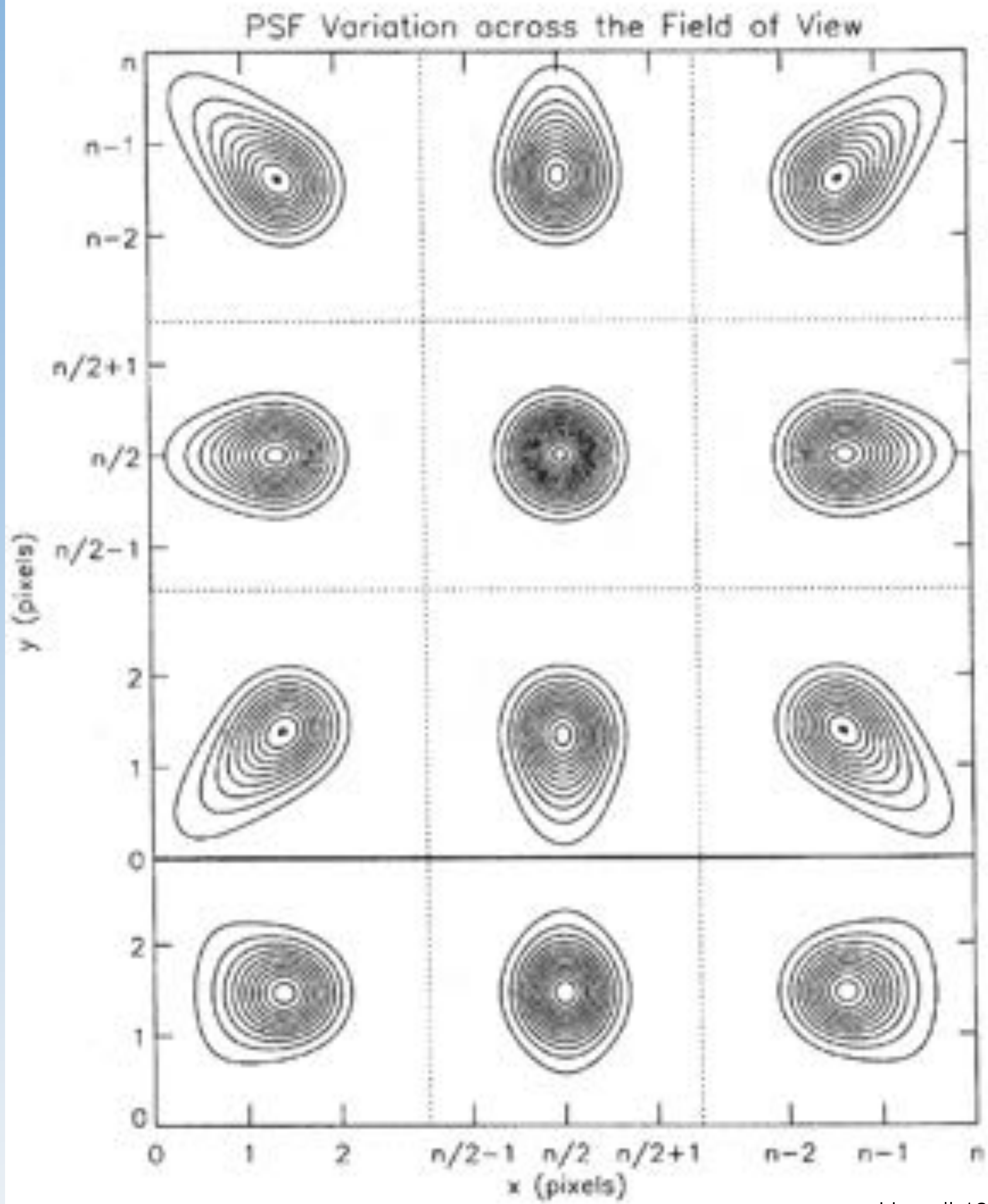
- Moffat

$$M(r) \propto \frac{1}{(1 + r^2/a^2)^b}$$

- Encircled Energy

$$EE(R) = \int_R^0 2\pi I(r) r dr \Big/ \int_0^\infty 2\pi I(r) r dr$$

Empirical PSFs



Howell 1996

Measurement

Signal-to-Noise Ratio

$$S/N = \frac{S_* t}{\sqrt{S_* t + n_{\mathrm{pix}}(S_{\mathrm{sky}} t + S_{\mathrm{dark}} t + S_{\mathrm{read}}^2)}}$$

Total number of photons from the object per second	Number of sky photons per second per pixel	Dark current; electrons per second per pixel	Time-independent readout noise, electrons per pixel

- Poisson $\sigma = \sqrt{n}$

Uncertainties

$$m \pm \sigma(m) = C - 2.5\log(S \pm N)$$

$$= C - 2.5\log(S) - 2.5\log(1 + N/S)$$

$$\sigma(m) = 2.5\log(1 + N/S)$$

$$\sigma(m) = \pm 2.5/2.3[N/S - 1/2(N/S)^2 + 1/3(N/S)^3 \ldots]$$

$$\sigma(m) \approx \pm 1.0875(N/S) \approx (S/N)^{-1}$$

- Systematic errors: e.g. non-linearity when approaching full well, shutter vignetting, cosmic rays and hot pixels, changing airmass, atmospheric conditions, telescope tracking and rotation, flat field errors etc.

Limiting Magnitude

- **Detection limit**: the faintest apparent magnitude of a celestial body that is detectable
- The magnitude uncertainty increases rapidly as one approaches the detection limit
- Can solve S/N equation for magnitude that gives required S/N (typically 5).