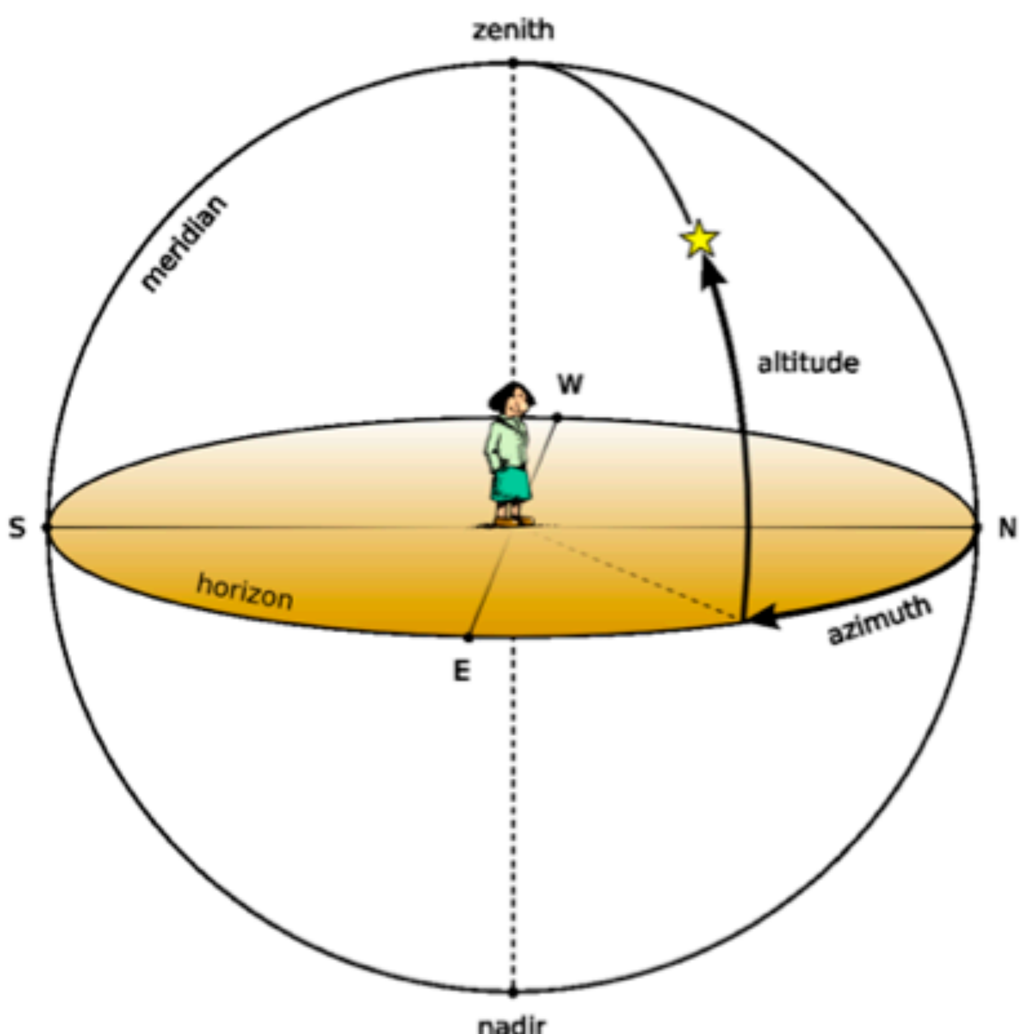
PHY 517 / AST 443: Observational Techniques in Astronomy

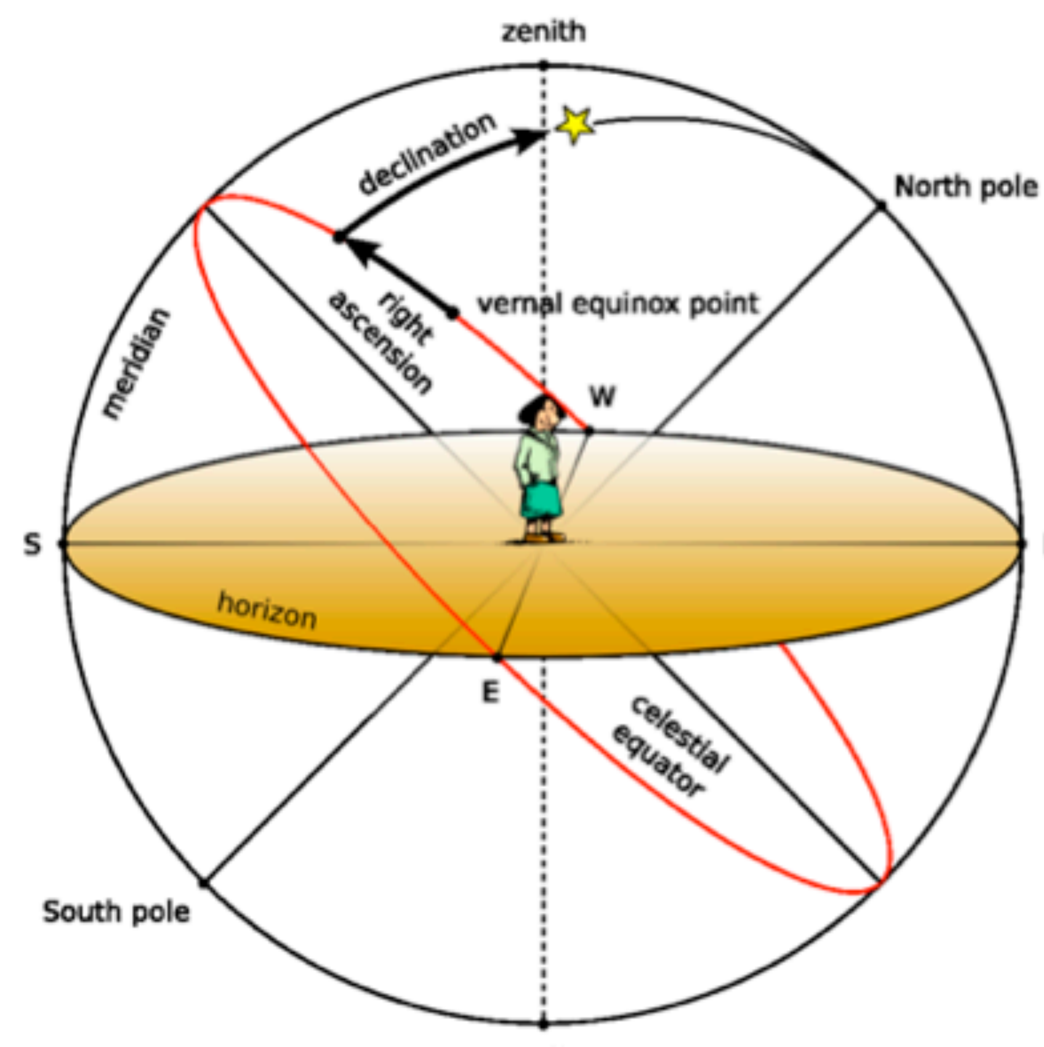
Lecture 2:
Time /
Flux and magnitudes /
Earth's atmosphere

Last time...

positions on a sphere can be described with 2 angular coordinates:

Position on Earth: latitude and longitude
View from observatory: altitude and azimuth
Position on sky: right ascension and declination





Last time...

the equatorial coordinate system (R.A. and Dec.) is fixed to the Sky, and rotates with the Sky

on sky maps, East is left when North is up (because you're looking up, not down)

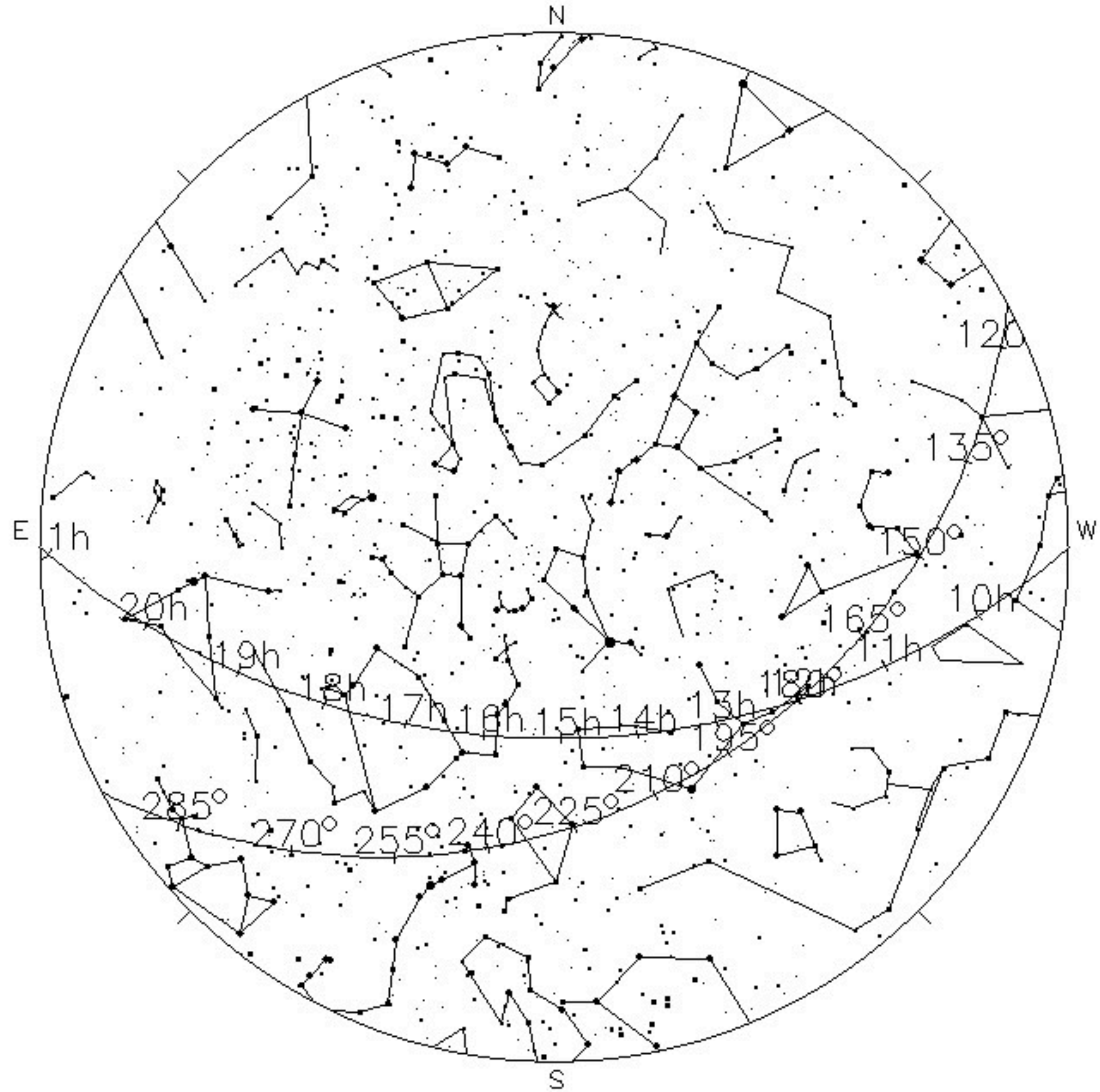
the sky "moves" East to West

R.A. is defined by time intervals between passing the meridian - it runs right to left on sky maps

Last time...

local sidereal time:
R.A. of the objects on the meridian

hour angle:
distance in R.A. to the meridian



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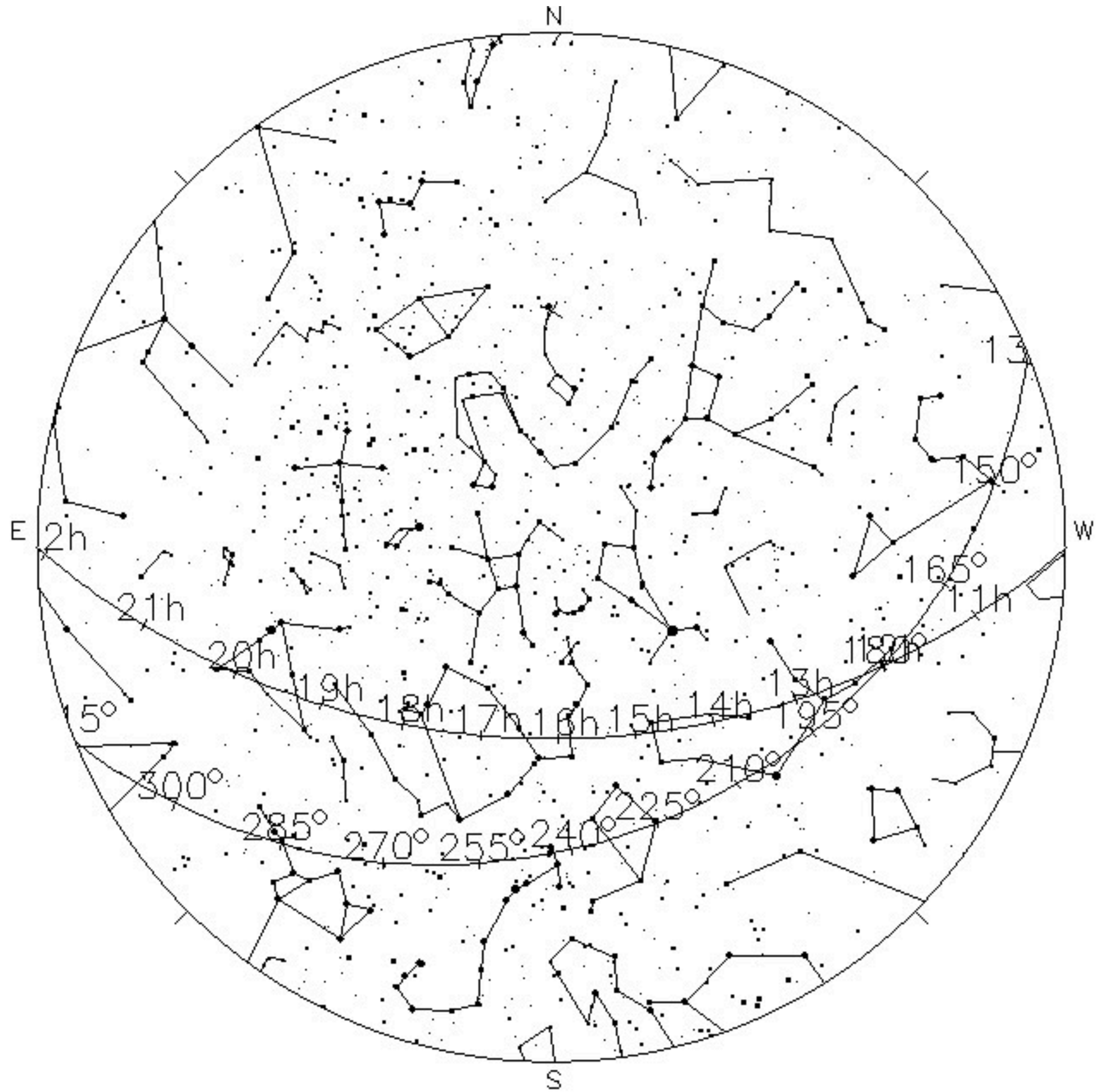


Time

Need to know the current time!

Your telescope needs it to convert (α, δ) to altitude+azimuth

You need to know when you took your observations

Much of the Sky is variable! E.g. supernovae, variable stars, gamma-ray burst, ...

Need a common, precise reference time

Sidereal time

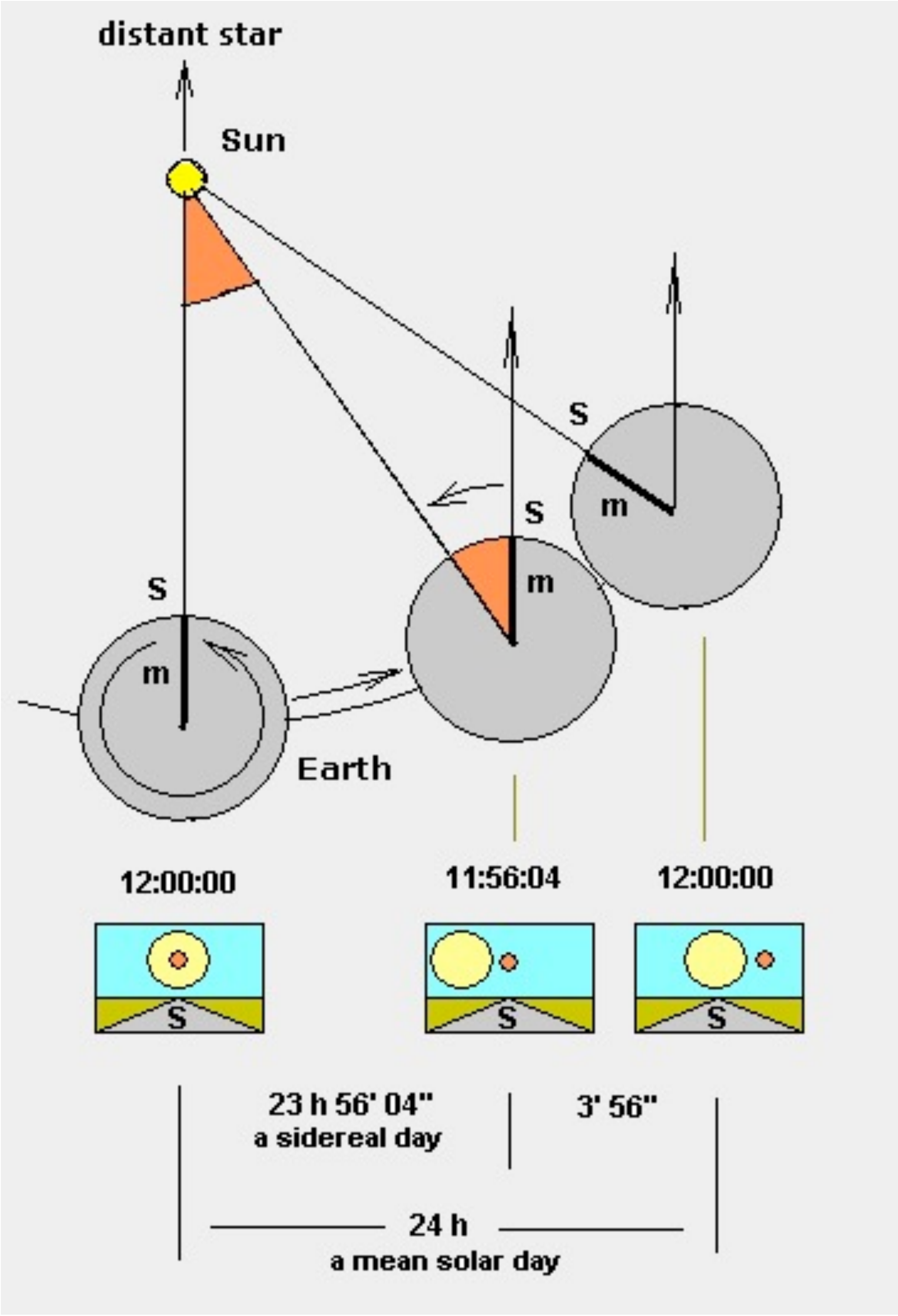
"sidereal" = "of the stars"

sidereal time: defined with respect to the stars

one rotation takes 23h 56min (a sidereal day)

same sky is overhead after 23h 56min

solar day: defined with respect to the Sun, takes 24h

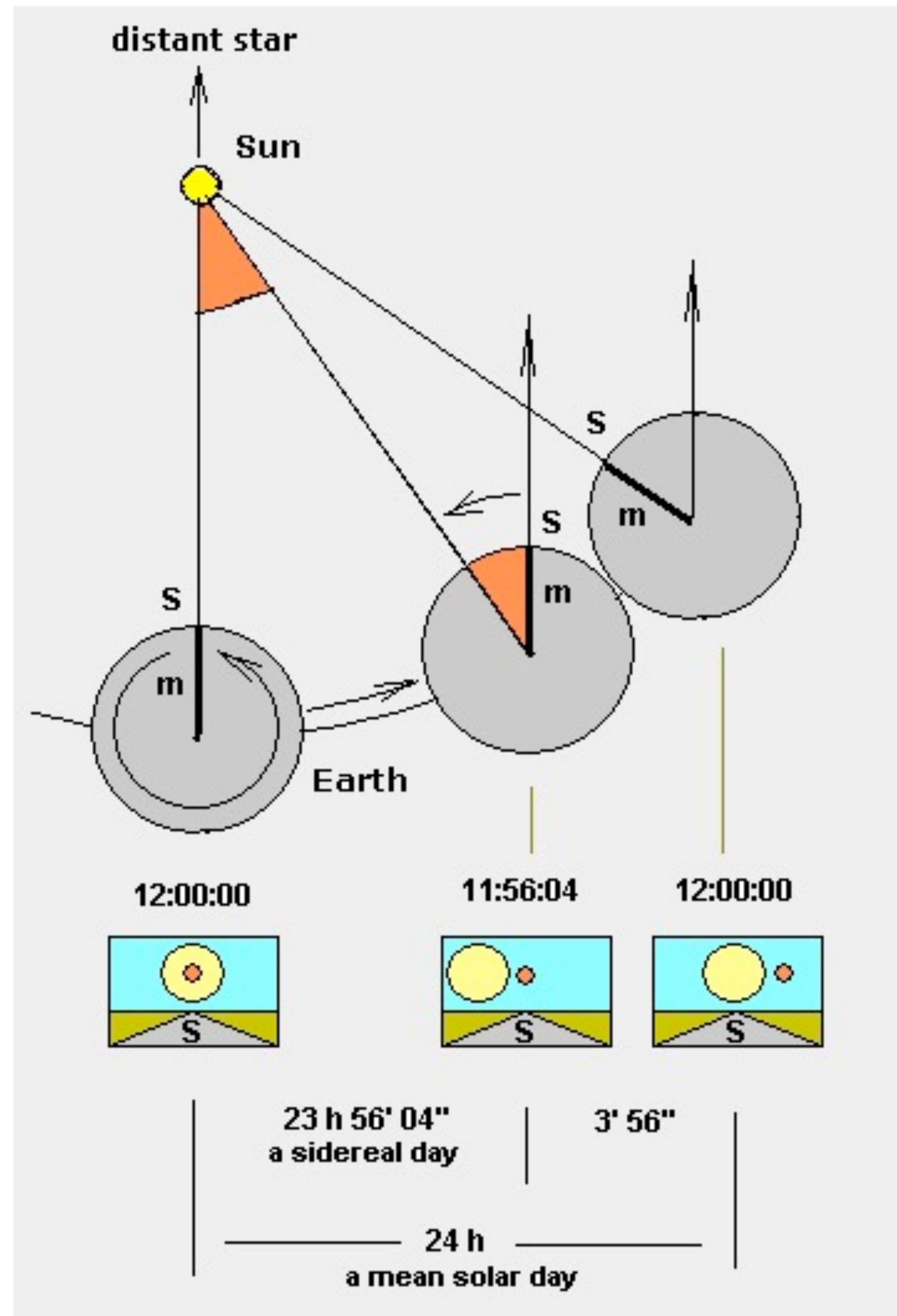


This means...

from one night to the next, stars rise 4 min earlier

one year has 365+1 sidereal days

HW question: Orion culminates at 1am in September; at what time does it rise 3 months later?



Solar time

apparent solar day: time between two passes of the meridian

problem: variable length (Earth's orbit is elliptical)

mean solar day: based on fictitious mean Sun that moves along the Sky at constant rate (measured on equator)

Universal Time (UT1): mean solar time at 0° longitude (Greenwich)

Coordinated Universal Time (UTC): based on atomic clocks, kept within 0.9s of UT1; international time standard

How to specify time

For common time format, quote UTC

```
OBSID    = 'ct4m20130615t234758' / Unique Observation ID
DATE-OBS= '2013-06-15T23:47:58.454694'   /  UTC epoch
TIME-OBS= '23:47:58.454694'     / Time of observation start (UTC)
MJD-OBS =        56458.99164878 / MJD of observation start
```

Purely numerical format: Julian Date

- days since noon on Jan 1, 4713 BC (JD=0)

- JD of Aug 30, 6pm in Stony Brook: 2457996.416667

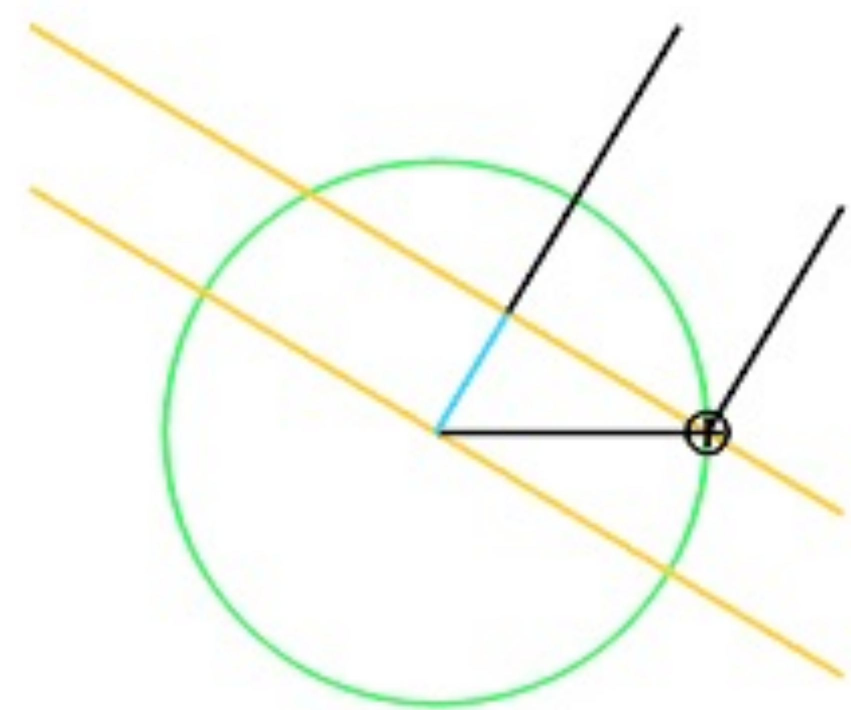
- Modified Julian Date (MJD):   MJD = JD - 2400000.5

http://aa.usno.navy.mil/data/docs/JulianDate.php

Heliocentric time

on short timescales, light travel path through Solar System becomes important

1 AU (astronomical unit; distance Earth-Sun) = 8.3 light-minutes



Heliocentric Julian Date: adjusted to the center of the Sun

Epochs

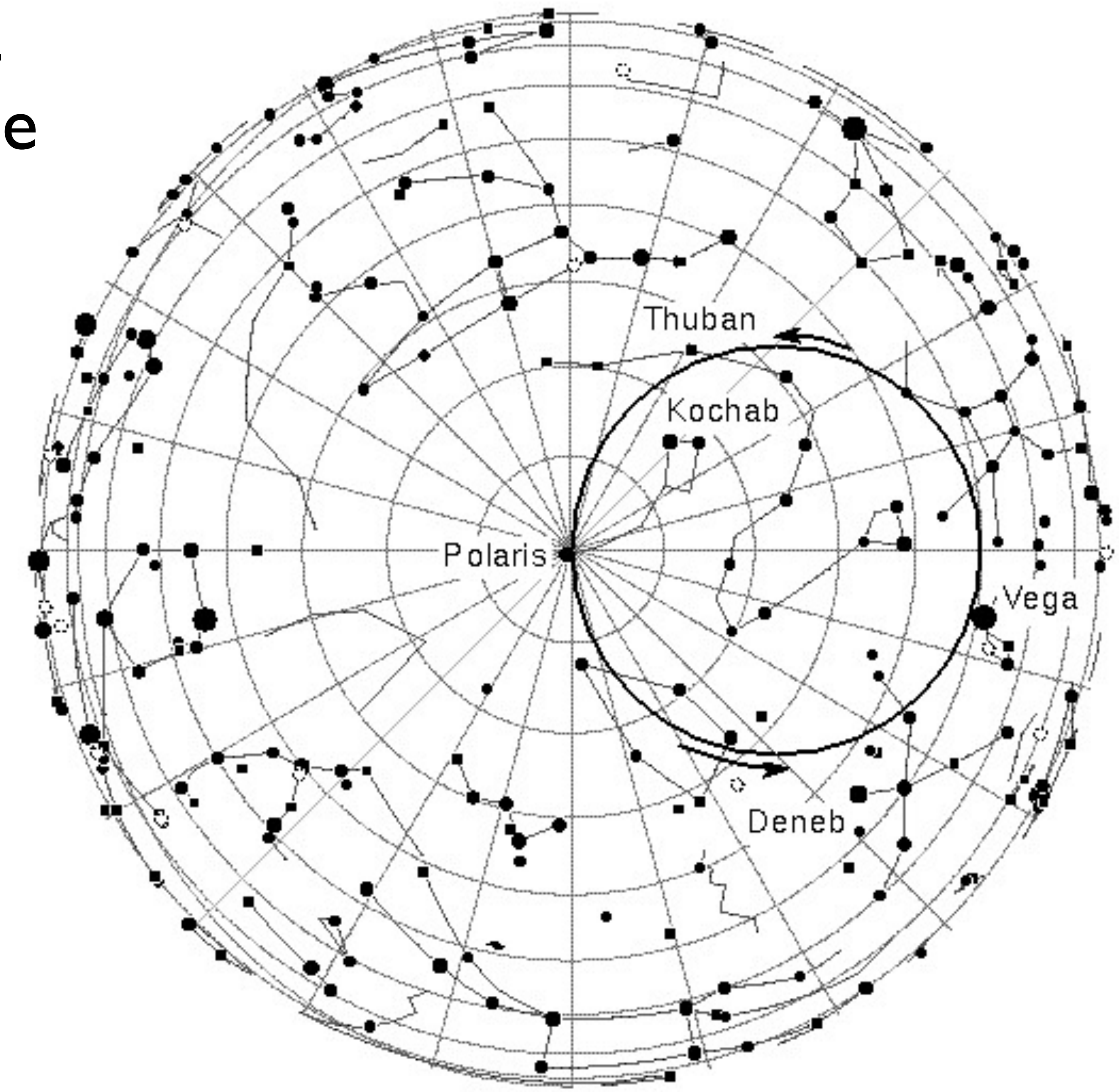
Earth's rotation axis is not constant in space with time

- precession, nutation
(Earth is a big gyroscope!)

- Earthquakes

All coordinates need to specified at a certain time (epoch), e.g.

J2000.0 :
- JD 2451545.0
- January 1, 2000, noon



The path of the precession of the Earth's rotation axis.
It takes 26,000 years to complete a full 360° wobble.

Flux and magnitude:
“How bright is it?”

Astronomical magnitudes

Ancient greeks categorized stars into 6 brightness classes:

- 0th magnitude: Vega
- 6th magnitude: faintest stars visible under dark sky

the eye responds ~logarithmically to flux

modern definition:

$$m_1 - m_2 \; = \; -2.5 \; \log\left(\frac{F_1}{F_2}\right)$$

the difference in magnitude describes the ratio in flux; magnitudes are always defined relative to a reference flux

the bigger the magnitude, the fainter the object!

Q: if $F_1/F_2 = 10$, how big is Δm?

Astronomical magnitudes

$$\boxed{m_1 - m_2 \;=\; -2.5\;\log\left(\frac{F_1}{F_2}\right)}$$

visual astronomy: keep old definition by making Vega the reference:

$$m \;=\; -2.5\;\log\left(\frac{F}{F_{\mathrm{Vega}}}\right)$$

examples:

Sun: -27 mag

Moon: -12.5 mag

Iridium flare: -8 mag

faintest galaxies in Hubble Ultra Deep Field: 30 mag

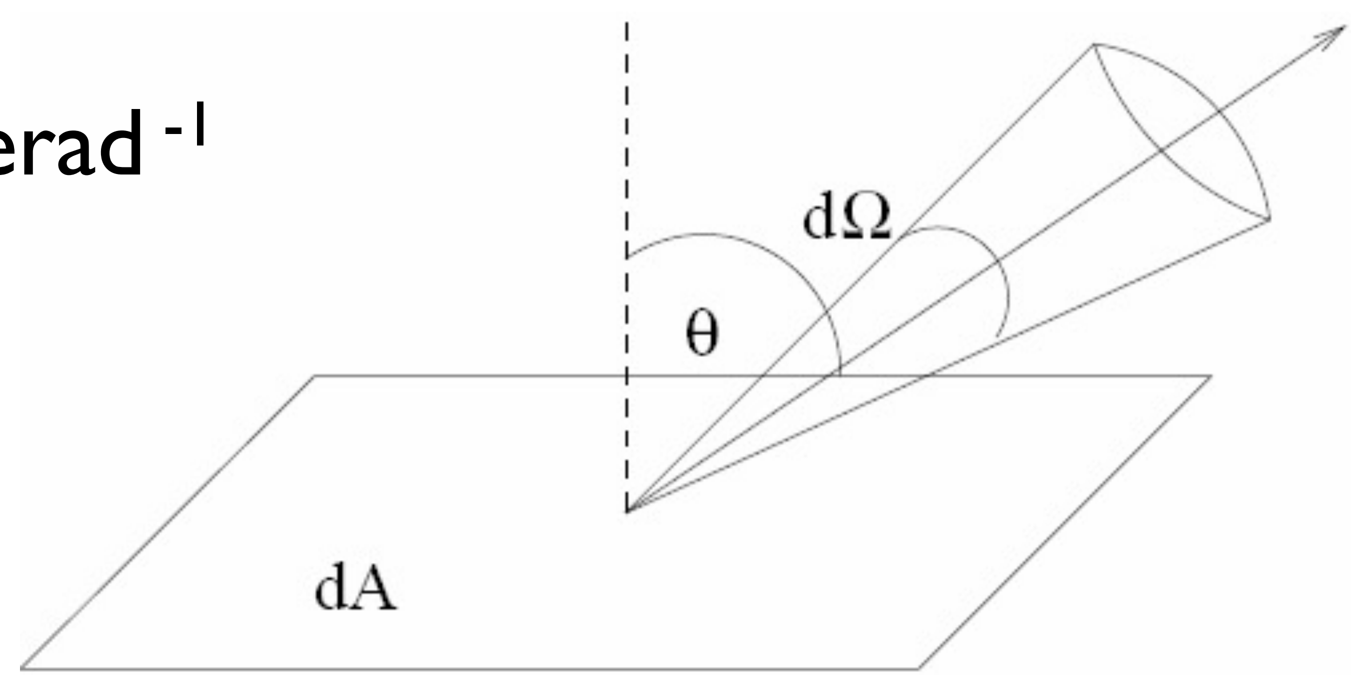
Physical descriptions

amount of energy passing through area *dA* , within *d*ω (at an angle θ from normal), in frequency range [ν,ν+*d*ν], during time *dt* is:

$$dE_\nu = I_\nu \cos\delta \, dA \, d\nu \, d\omega \, dt$$

specific intensity: I_ν

units: ergs s^{-1} cm^{-2} Hz^{-1} sterad^{-1}
or Jansky sterad^{-1}



intrinsic property of the object!

(e.g. *dA* on surface of star)

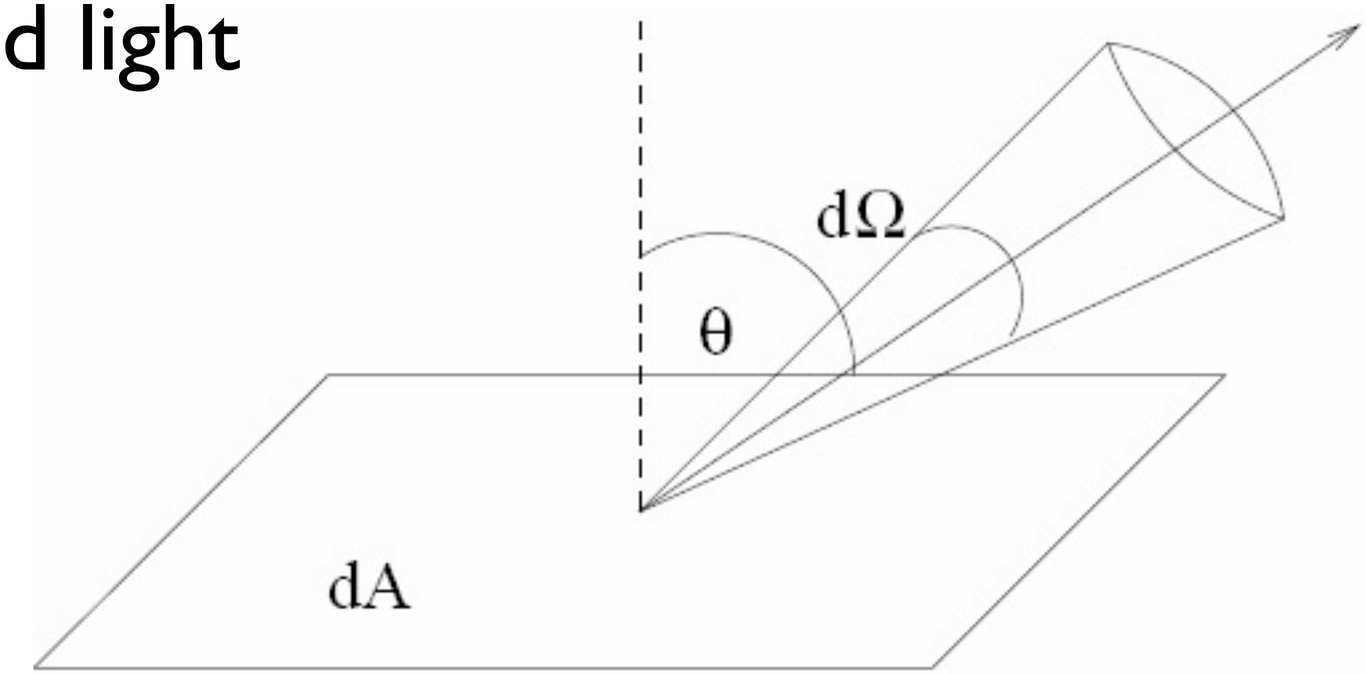
Physical descriptions

$$dE_\nu = I_\nu \cos\delta \; dA \; d\nu \; d\omega \; dt$$

spectral flux density: $$f_\nu = \int I_\nu \; \cos\delta \; d\omega$$

units: ergs s^{-1} cm $^{-1}$ Hz $^{-1}$ = Jansky

e.g. point sources, integrated light from extended sources



observable quantity

(e.g. $d\omega$ is solid angle of your eye, seen from star)

Physical descriptions

spectroscopy: can determine f_ν

otherwise: need to integrate f_ν over observed frequency (wavelength) interval

flux (density):

$$F = \int_{\mathrm{passband}} f_\nu \, d\nu$$
$$= \int_{-\infty}^{\infty} T_\nu \, f_\nu \, d\nu$$

T_ν: system response curve (e.g. filter transmission)

(note: usually specified as f_λ) $$f_\lambda = \frac{c}{\lambda^2} f_\nu$$

Physical descriptions

$$dE_\nu = I_\nu \cos\delta \, dA \, d\nu \, d\omega \, dt$$

luminosity:

$$L_\nu = \int f_\nu dA$$

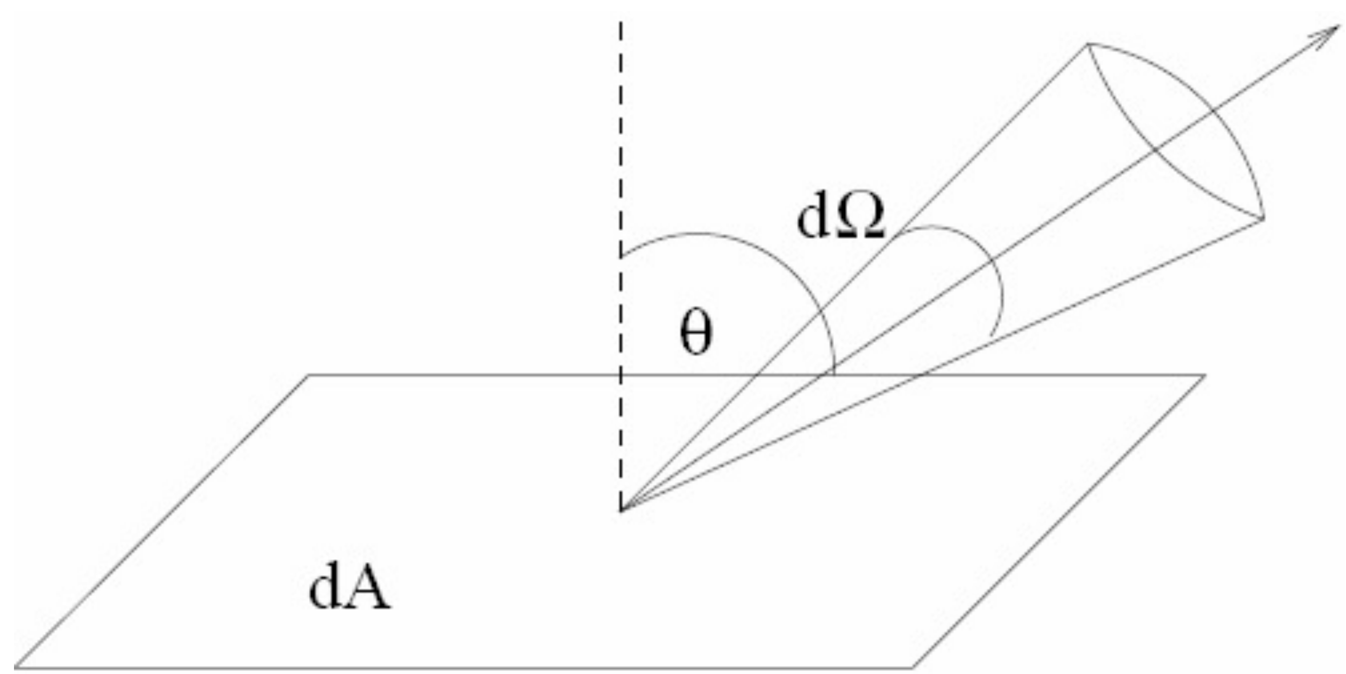
units: ergs s^{-1} Hz^{-1}

$$= f_\nu \int dA = f_\nu \, 4\pi d^2$$ (assuming isotropy)

intrinsic property of the object !

bolometric luminosity:

$$L_{\rm bol} = \int_{-\infty}^{\infty} L_\nu \, d\nu$$



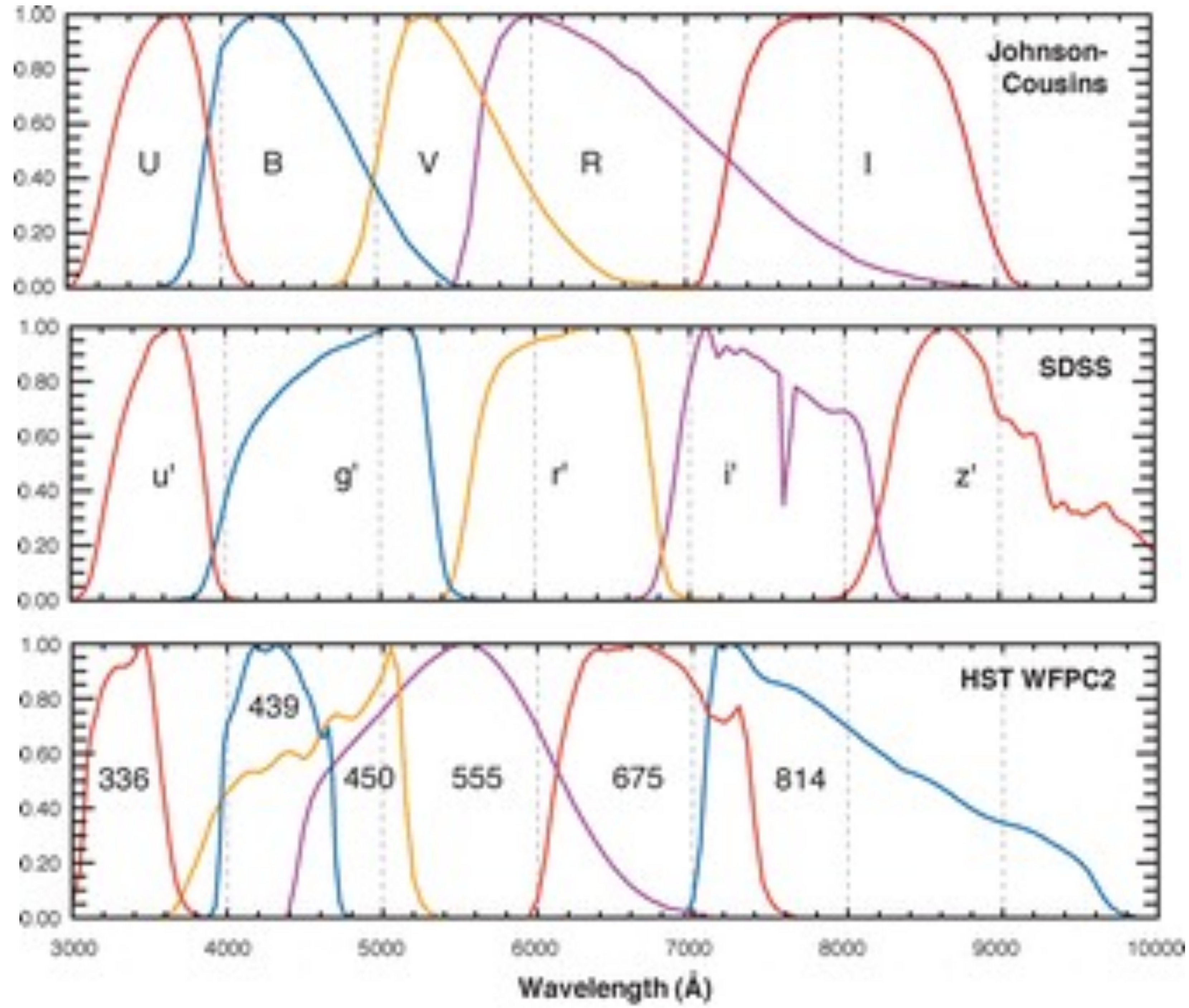
Filter systems

optical astronomy:

several standard photometric systems, "filter sets"

Johnson-Cousins: *UBVRI*

SDSS: *ugriz*



Color

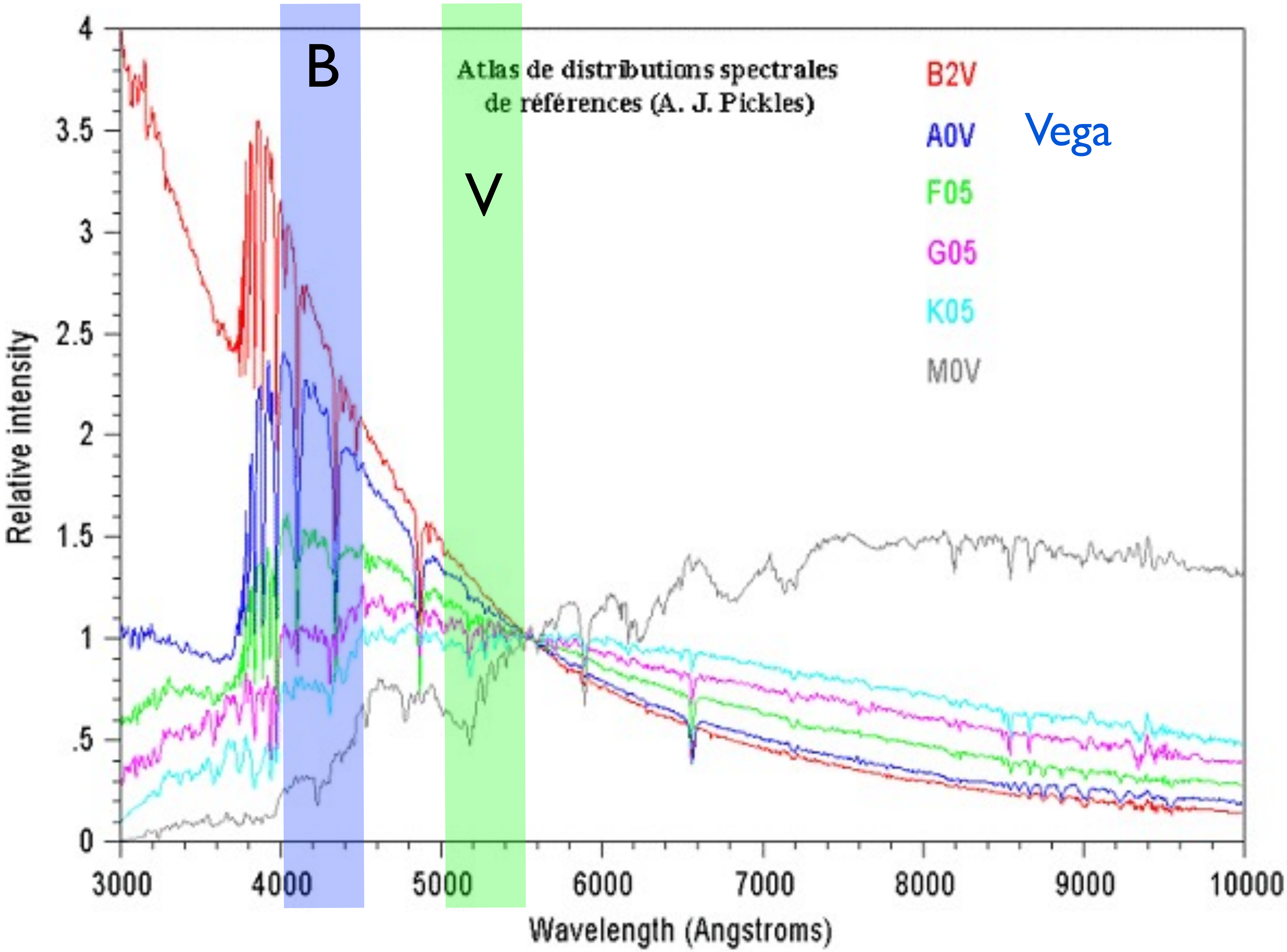
difference between magnitudes in two bands (e.g. B,V):

$$B - V = m_B - m_V = -2.5 \log \left(\frac{F_B}{F_V} \right)$$
$$= -2.5 \log \left(\frac{F_B}{F_{B,\mathrm{Vega}}} \right) + 2.5 \log \left(\frac{F_V}{F_{V,\mathrm{Vega}}} \right)$$

Vega has 0 color, by definition

"blue" star: flux ratio (to Vega) in *B* filter greater than in *V*

Color



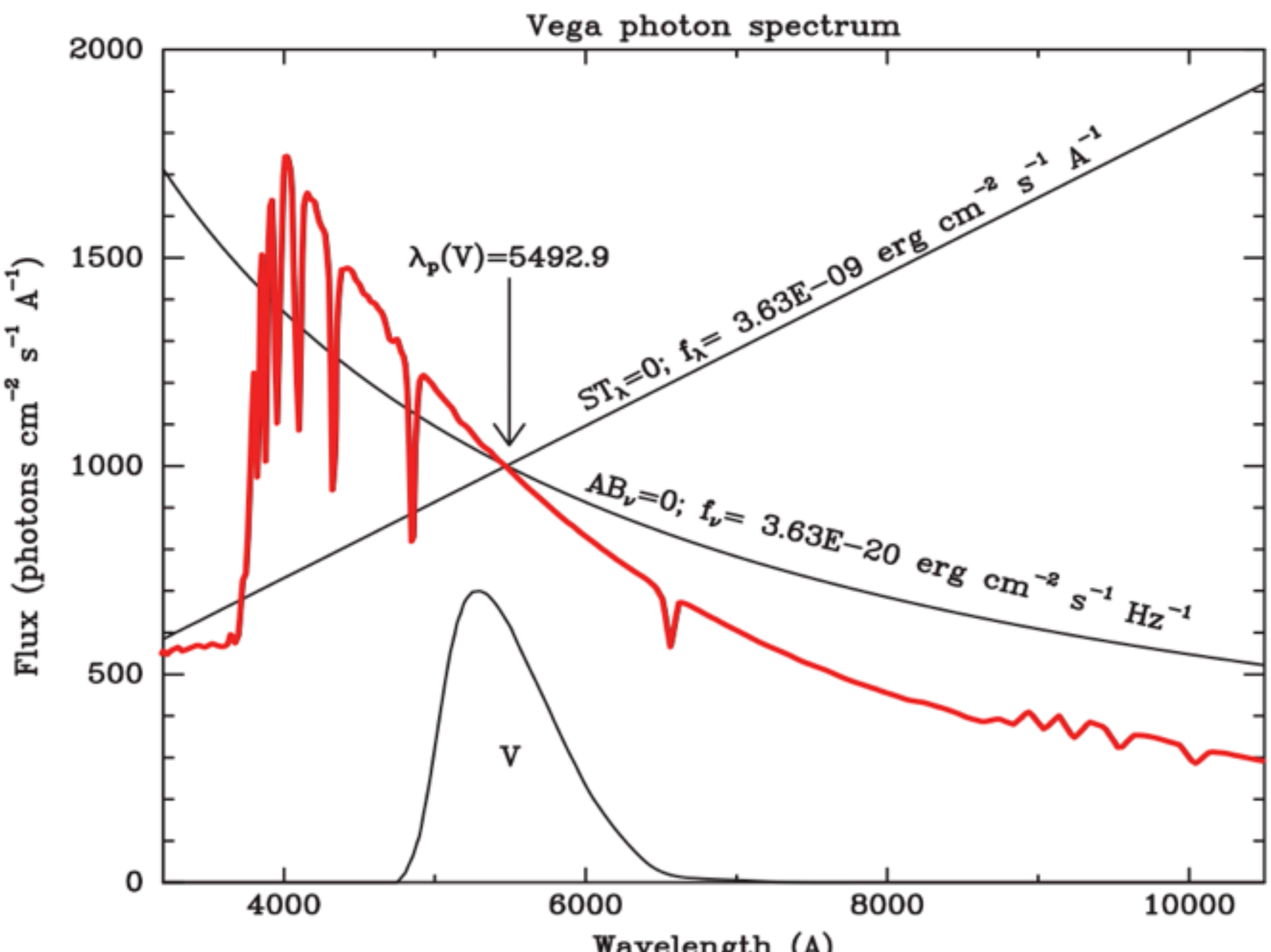
B
V
Atlas de distributions spectrales
de références (A. J. Pickles)
B2V
A0V
Vega
F05
G05
K05
M0V
Relative intensity
0
.5
1
1.5
2
2.5
3
3.5
4
3000
4000
5000
6000
7000
8000
9000
10000
Wavelength (Angstroms)

AB magnitudes

defined relative to *constant flux per unit frequency*

$$m_{\rm AB} \;=\; -2.5\ \log\left(\frac{f_\nu}{3631\ {\rm Jy}}\right)$$

normalized so that Vega is ~ 0 mag in *V* filter



Absolute magnitudes

so far: magnitudes (based on flux) are apparent, not intrinsic, properties of objects → depend on distance

absolute magnitude M: apparent magnitude if the object were at a distance of 10 parsec

distance modulus:
$$\begin{aligned} m - M &= -2.5\log\left(\frac{F(d)}{F(10\mathrm{pc})}\right) \\ &= -2.5\log\left(\frac{L/4\pi d^2}{L/4\pi(10\mathrm{pc})^2}\right) \\ &= 5\log\left(\frac{d}{10pc}\right) = 5\log(d[pc]) - 5 \end{aligned}$$

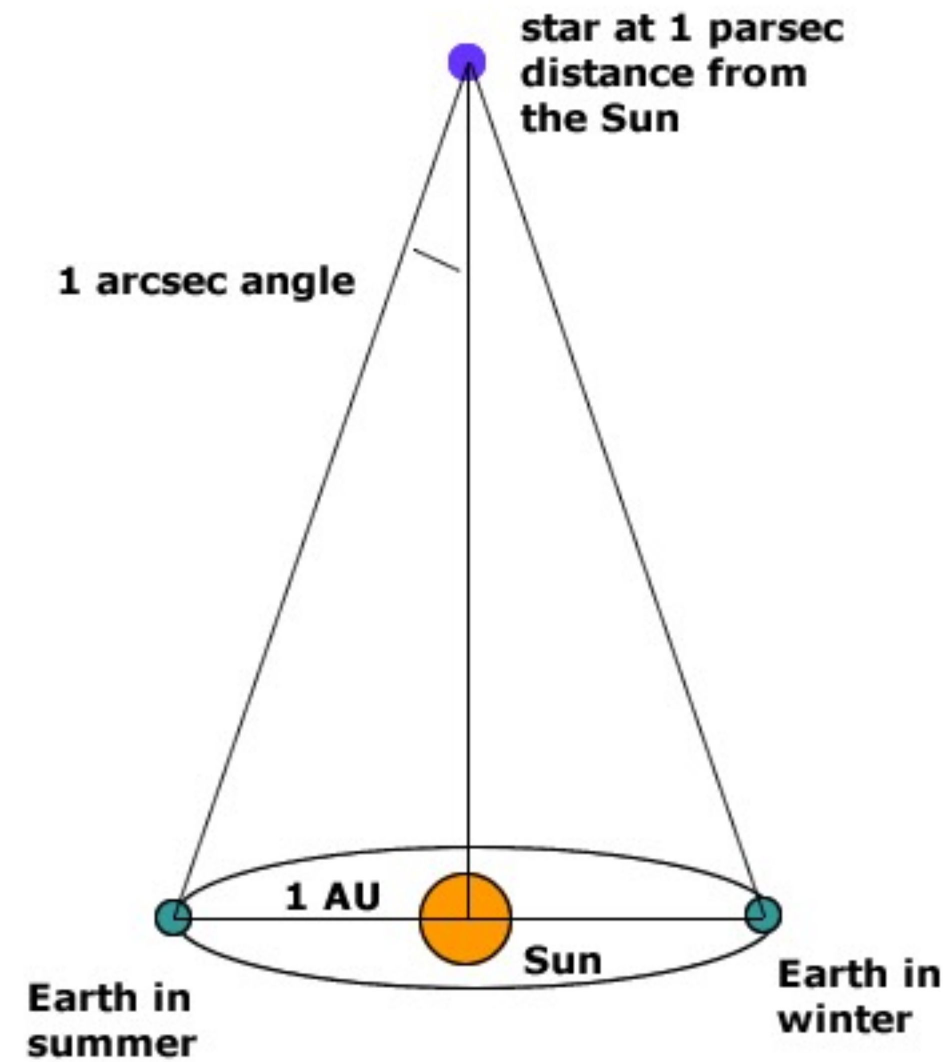
Parallax and parsecs

due to Earth's motion around the Sun, positions of (nearby) stars appears to shift

1 pc: distance to a star whose position shifts by 1" from 1 AU baseline

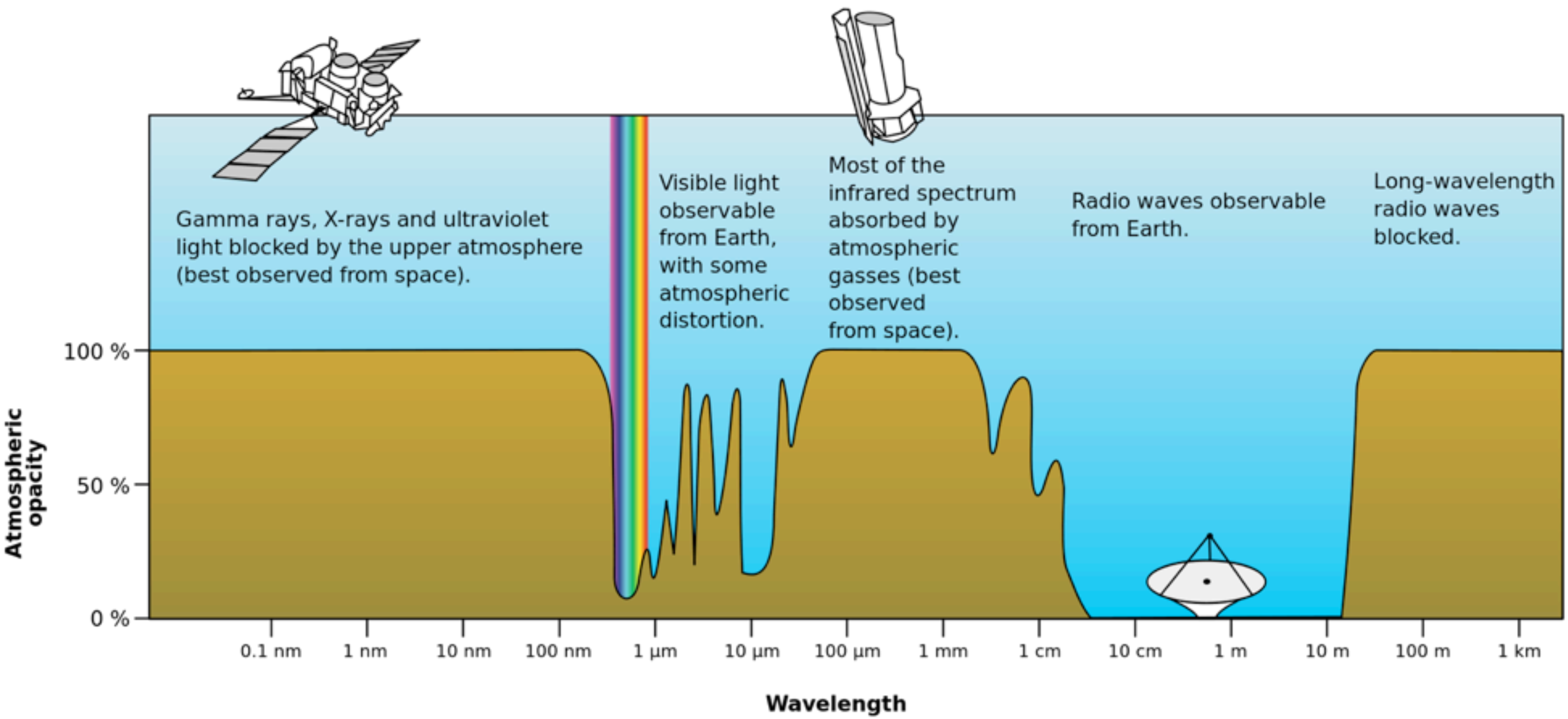
1 pc = 3.26 light-years = 3×10^{16}m

Proxima Centauri: ~1.3 pc



Earth's atmosphere

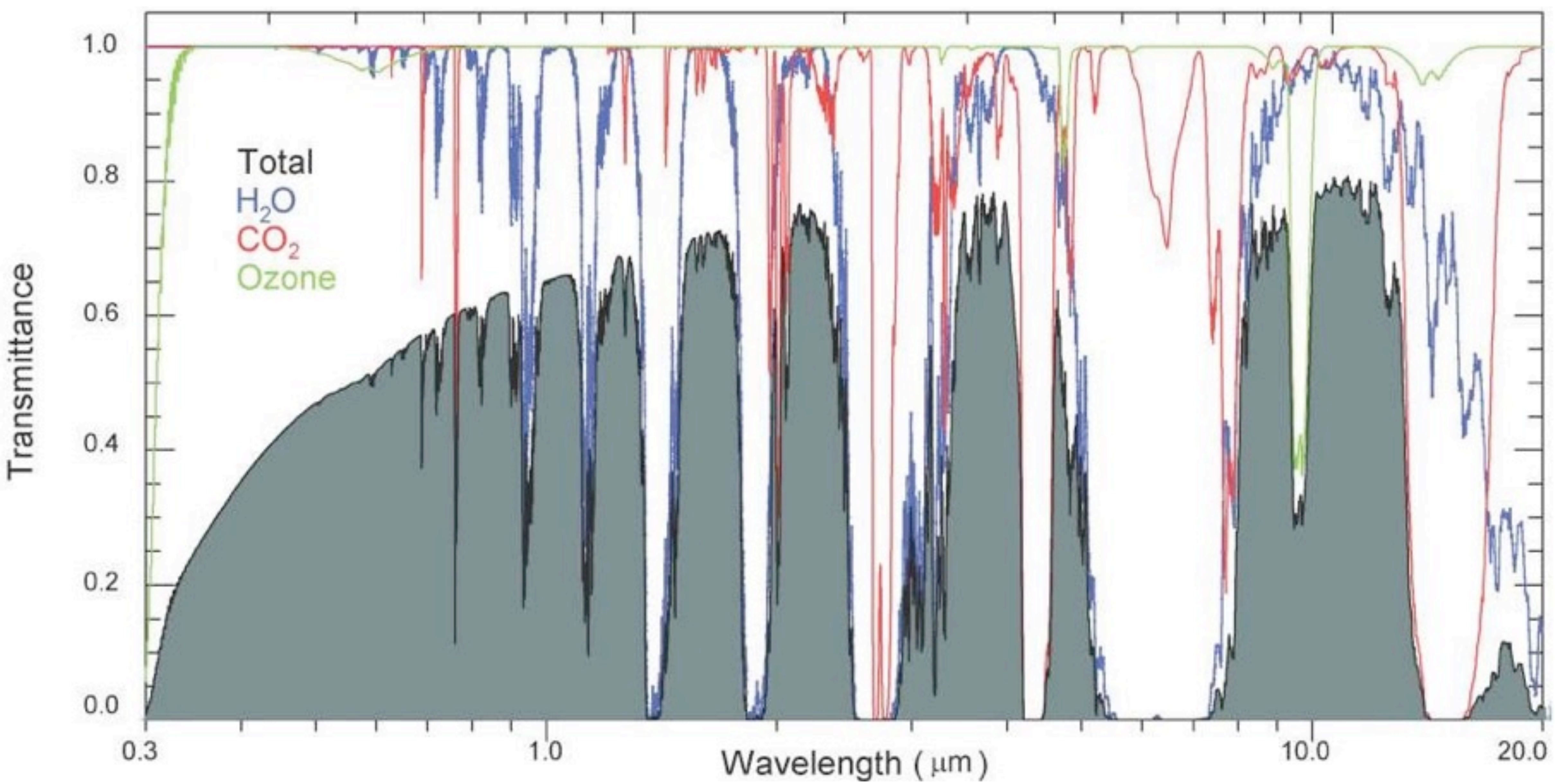
the atmosphere is opaque to most of the electromagnetic spectrum



Earth's atmosphere

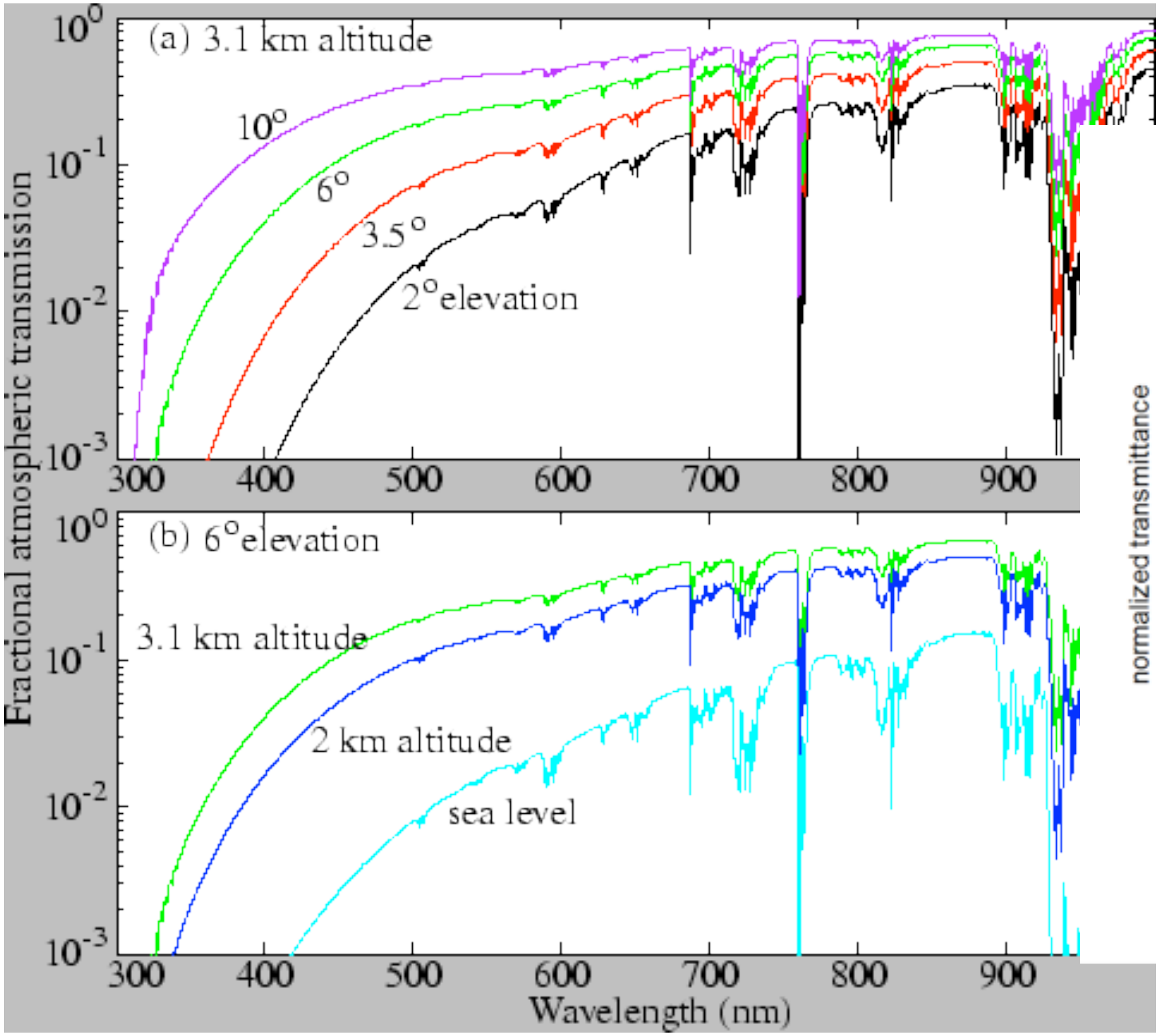
in the optical (~300nm - 1 μm) and near-infrared, extinction due to:

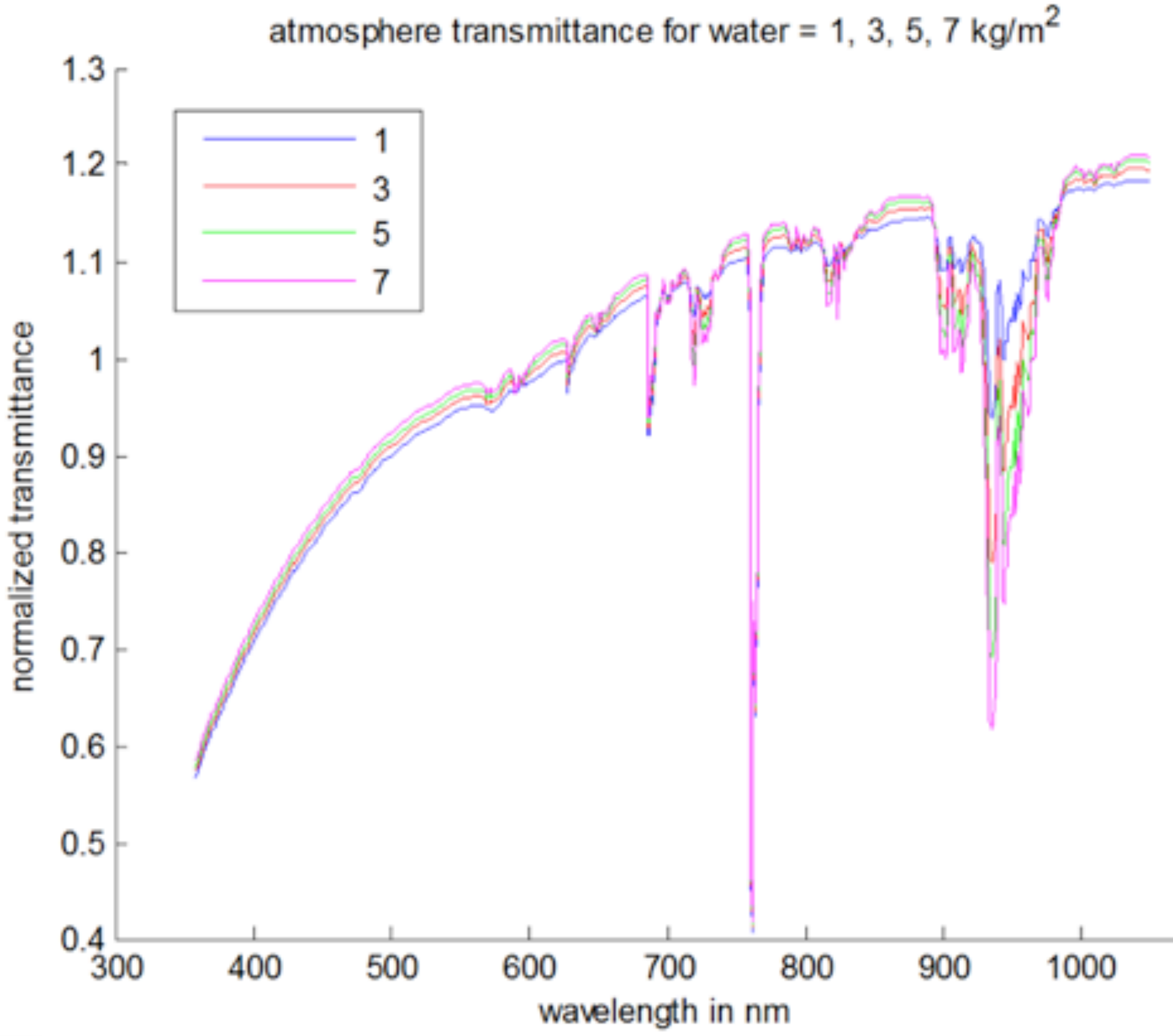
- scattering, e.g. Rayleigh $\propto \lambda^{-4}$
- absorption bands, mainly water



Earth's atmosphere

details depend sensitively on observatory location, target altitude (elevation), water and aerosol content





Airmass

expresses the amount of air the light of an object passed through, relative to zenith

plane-parallel approximation:

$$\mathrm{AM} = \sec(z) = \frac{1}{\cos(z)}$$

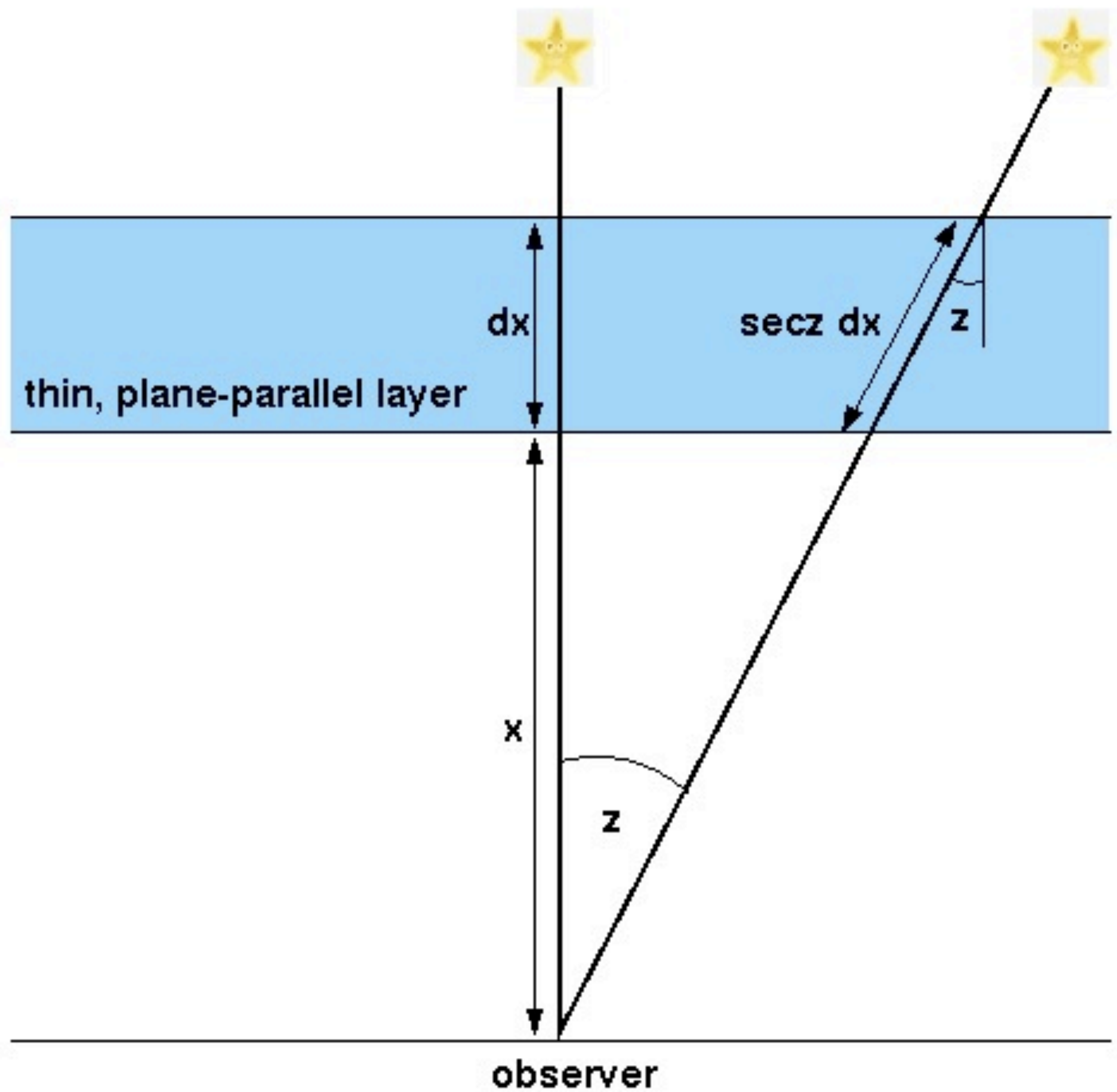
zenith distance:

z = 90° - altitude h

h=90°: AM=1

h=50°: AM=1.3

h=30°: AM=2



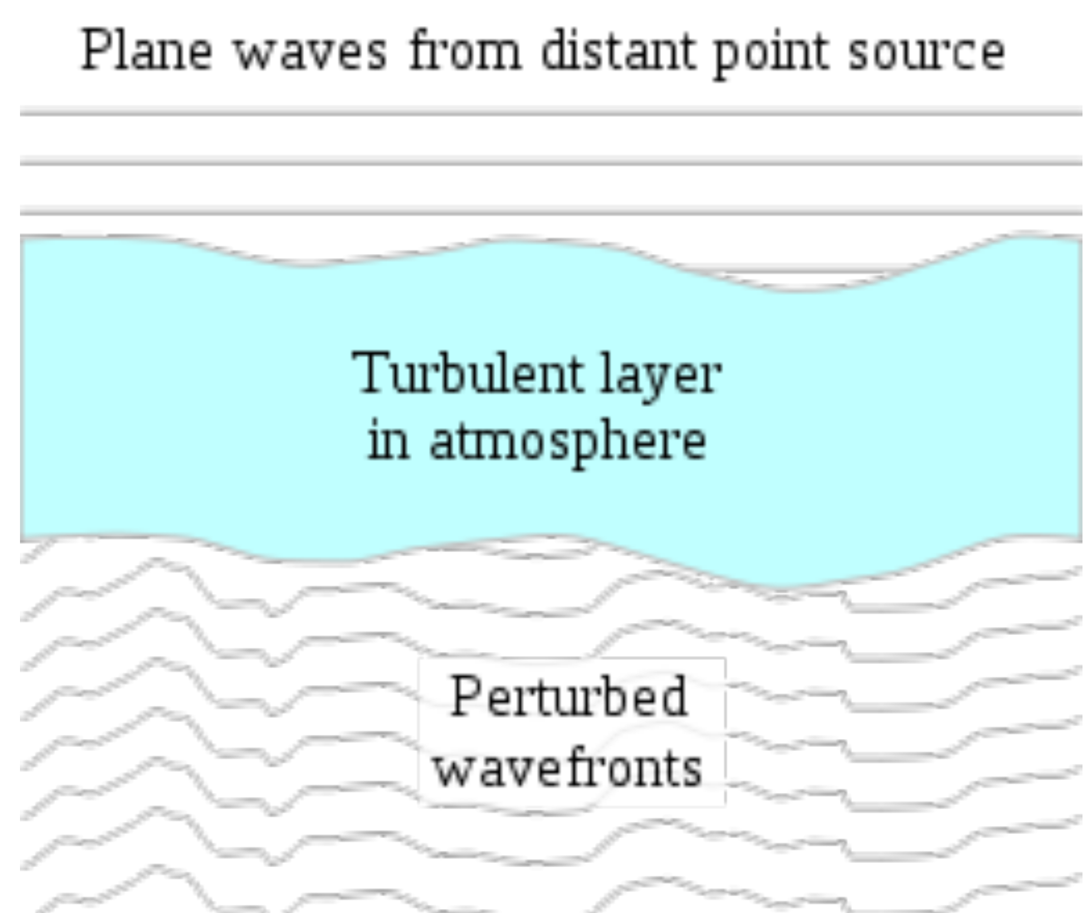
Seeing

diffraction-limited resolution of a telescope with entrance pupil *D*:

$$\theta_{\min} = 1.22\,\frac{\lambda}{D}$$

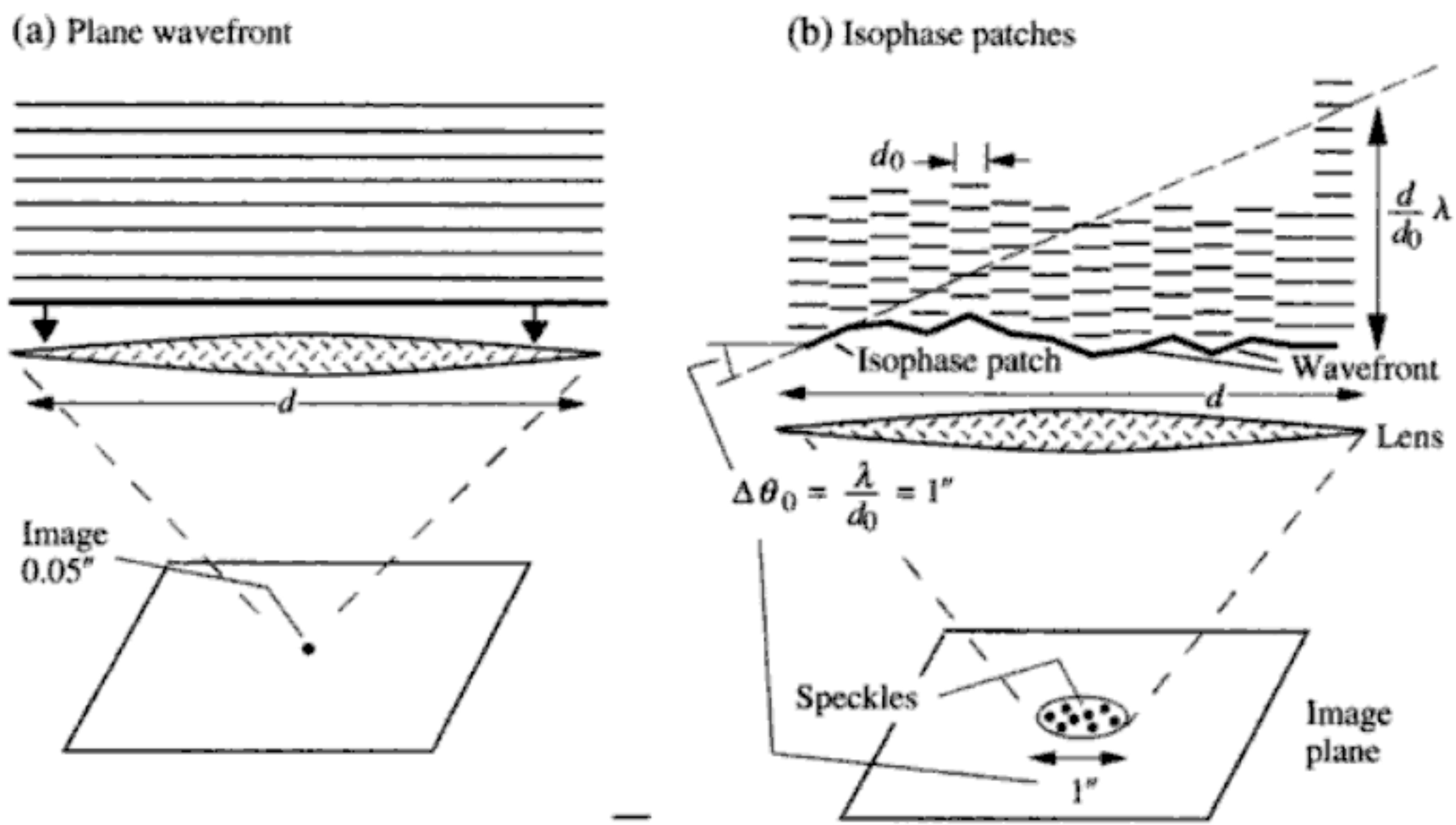
theoretical resolution of 14 inch telescope: ~0.3”

seeing: turbulence in the atmosphere, leads to “blurring” of images



Seeing

wavefront gets broken into isophase patches, each is a "mini-image" - interference leads to "speckles"



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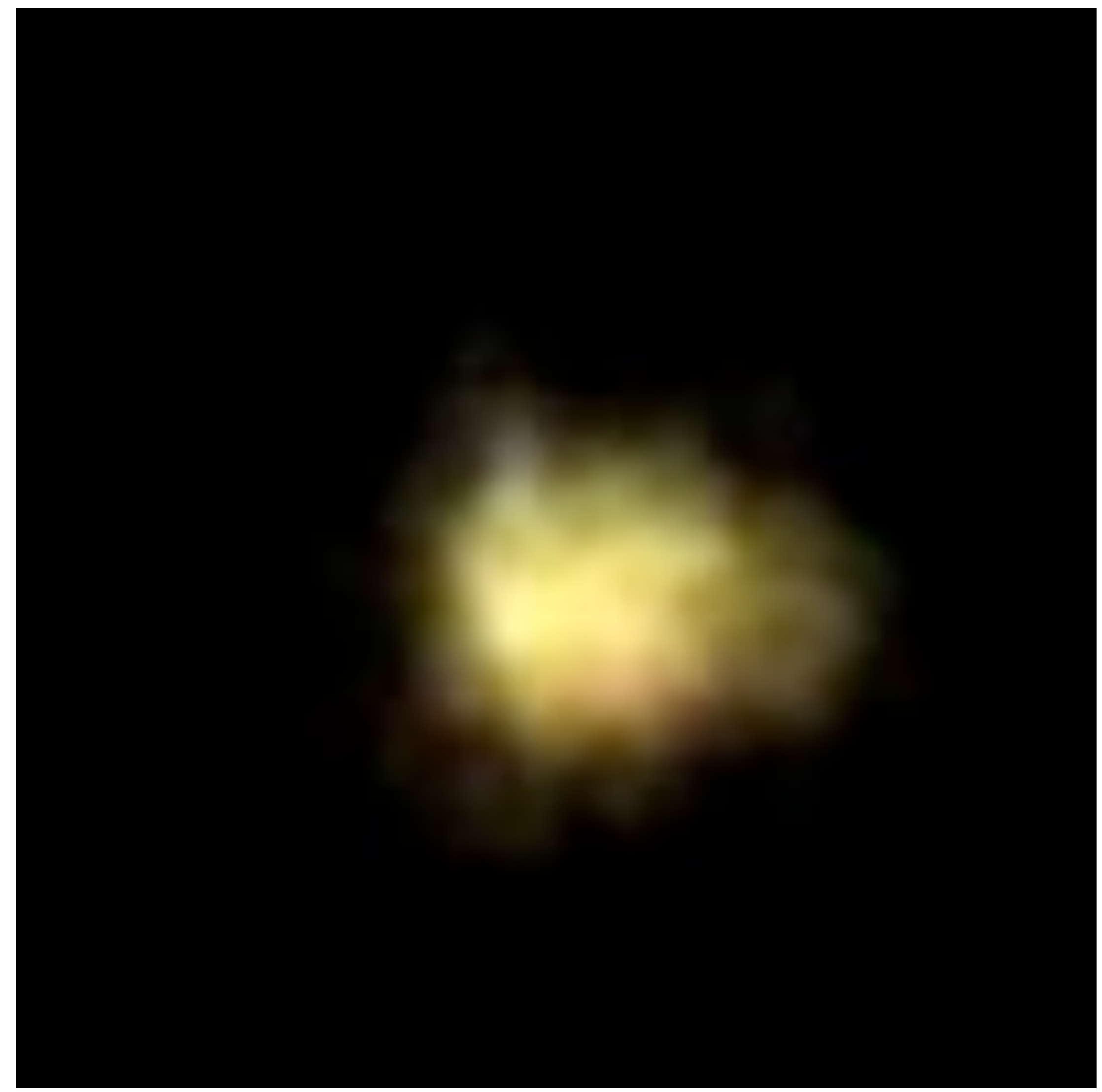


Seeing

depends on airmass: $\propto \mathrm{AM}^{0.6}$

and on wavelength: $\propto \lambda^{-1/5}$

Seeing

seeing gets better than 1” only at the world’s best observing sites (Mauna Kea, Chile)

highly dependent on local conditions

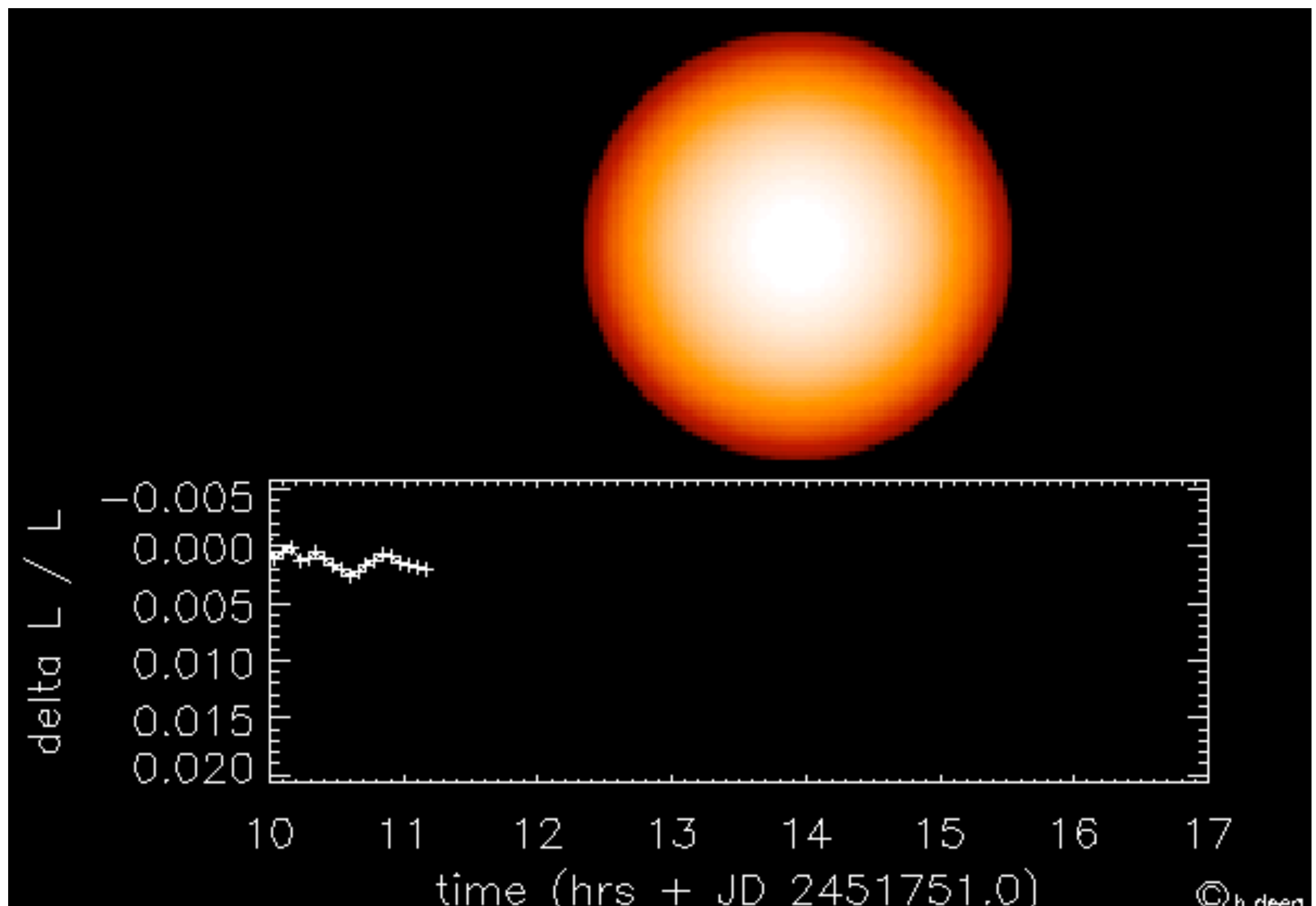
telescope dome can contribute significantly!

modern domes have lots of windows, day-time AC

Preparing for your observations

Homework

Start preparations for Lab 1:
- optical astronomical imaging
- time-series photometry
- detect an exoplanet transit!



Homework

database of all known exoplanets, pre-selected for transiting exoplanets:

http://exoplanet.eu/catalog/all_fields/?f=%22transit%22+IN+detection

pick suitable targets:

- which host stars are visible from Mt Stony Brook?
- ... at night-time in September / October?
- (... at a time you can get the TAs / instructor to be awake?)
- what is the dimming due to the planet? (need to calculate!) need at least 0.008 mag
- is the host star bright enough? ($V<12.5$)

Homework

triple-check your calculations!!!

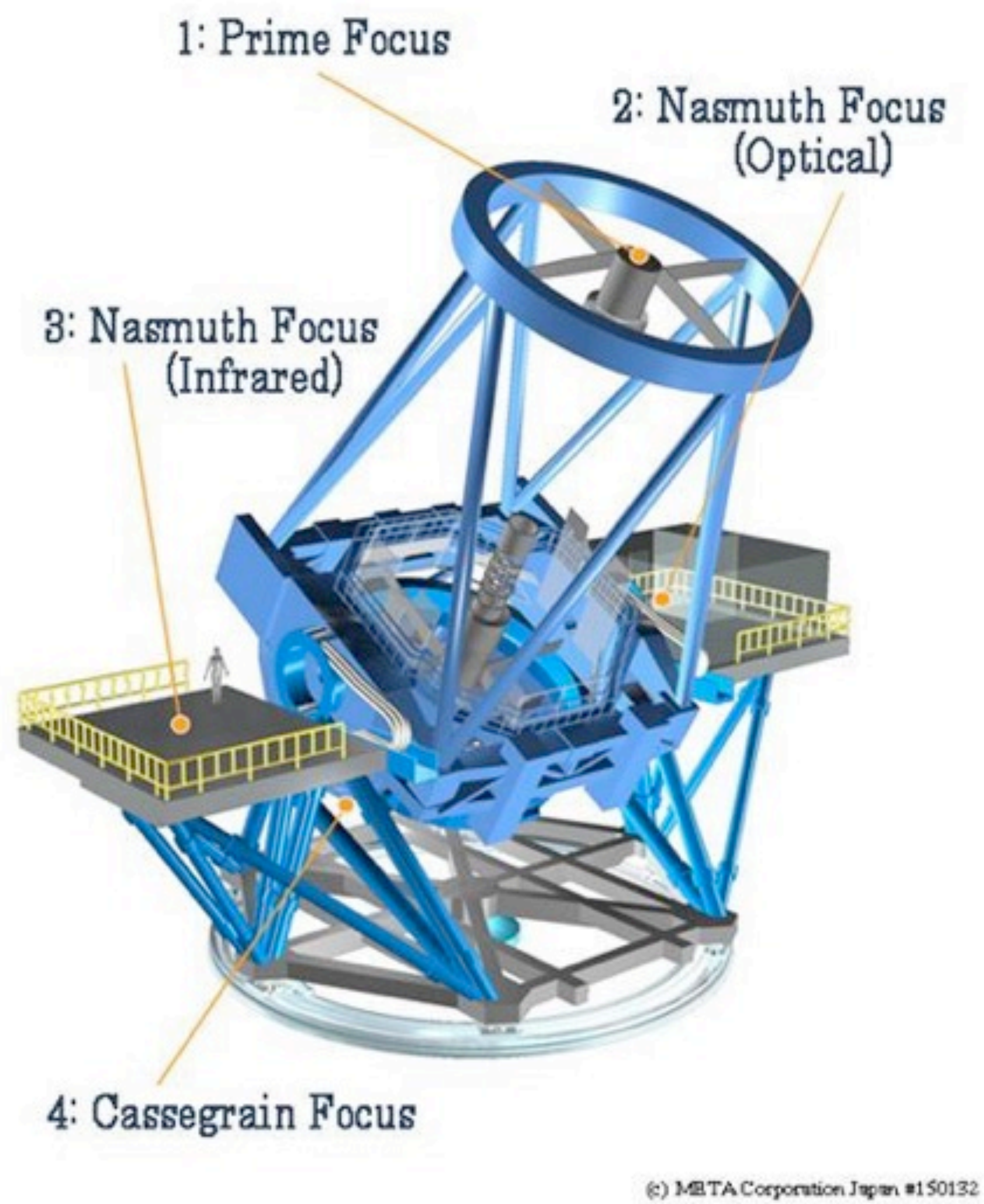
pick 3 transits / observing nights between September 6 and October 6 (spread out to accommodate the weather), e-mail your request to me (first-come, first-serve)

(A little bit about)

Telescopes

Big telescopes

- all big telescopes are reflectors (mirror telescopes)
- big lenses are too expensive / impossible to make
- many big telescopes have several instruments mounting points (at different foci)

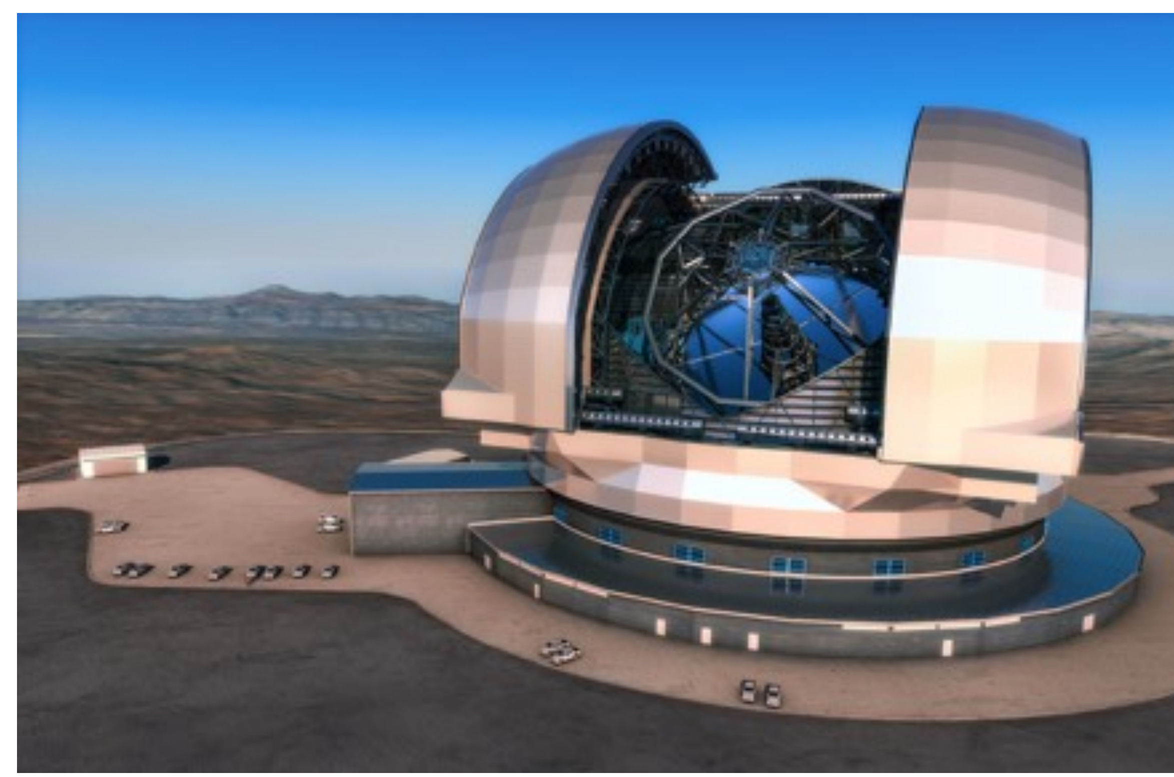


Aperture

- most (new) things in astronomy are faint (but not all!)
- need to gather as much light as possible
- the diameter of the mirror (aperture) is one of the main characteristics of a telescope

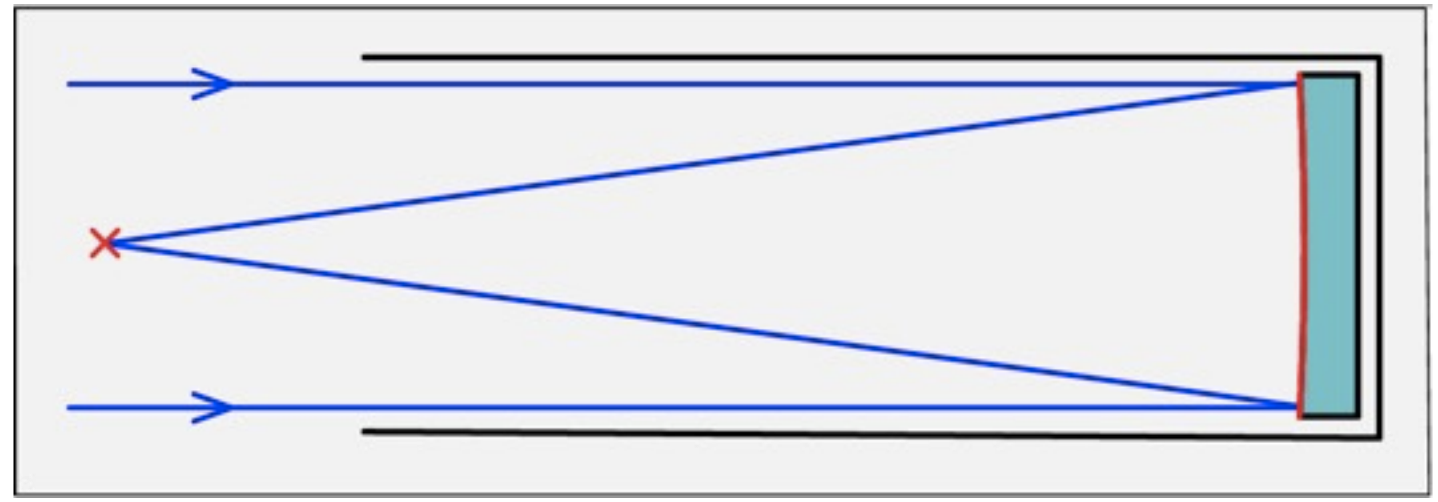
Keck Telescopes: 10m

next generation: 30m telescopes (~2025)

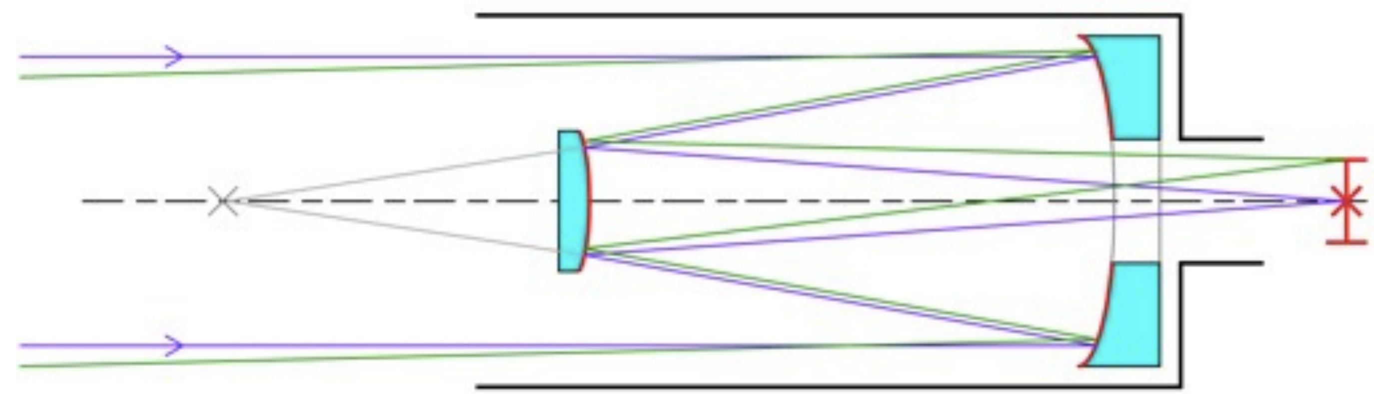


Telescope foci

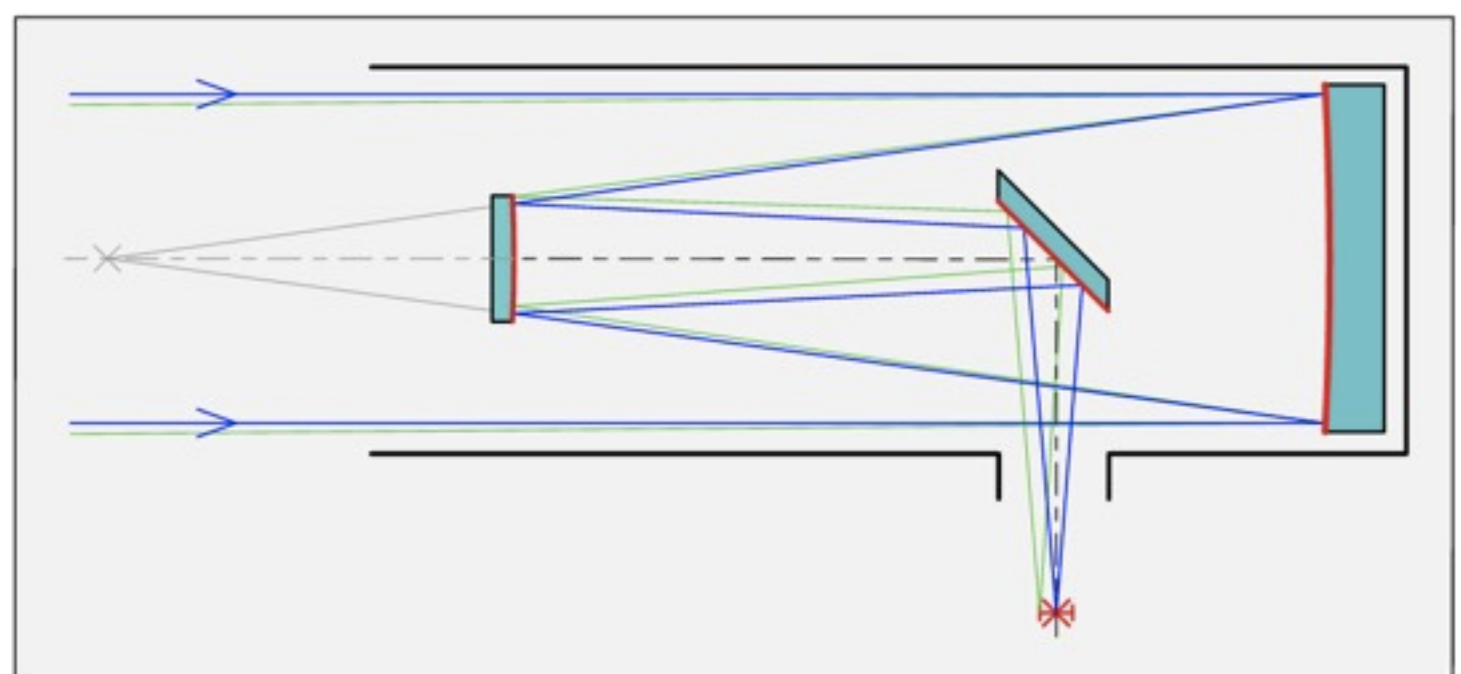
- prime focus: focus of primary mirror



- Cassegrain focus: secondary mirror in front of prime focus; secondary focus behind primary mirror

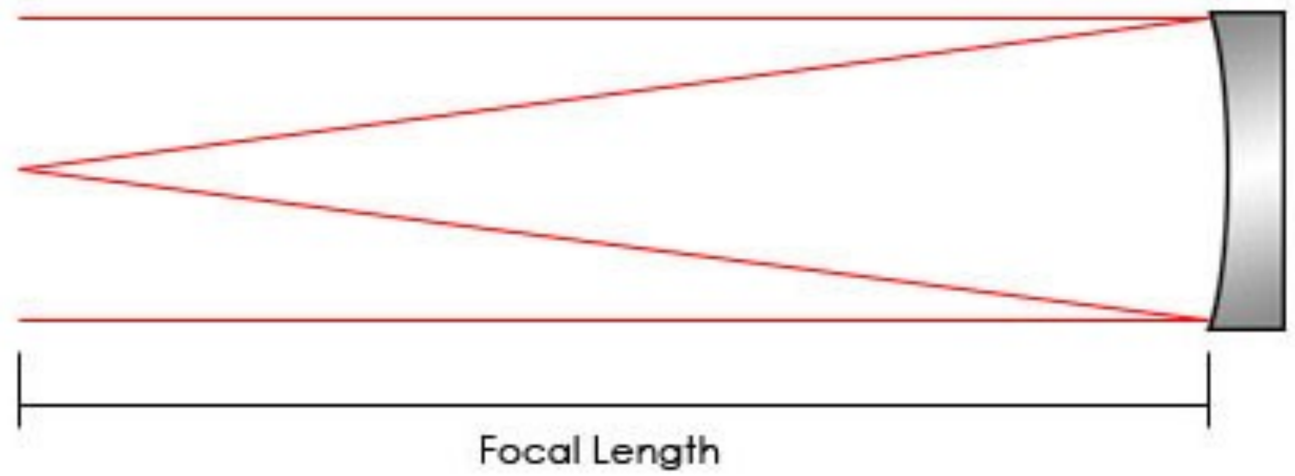


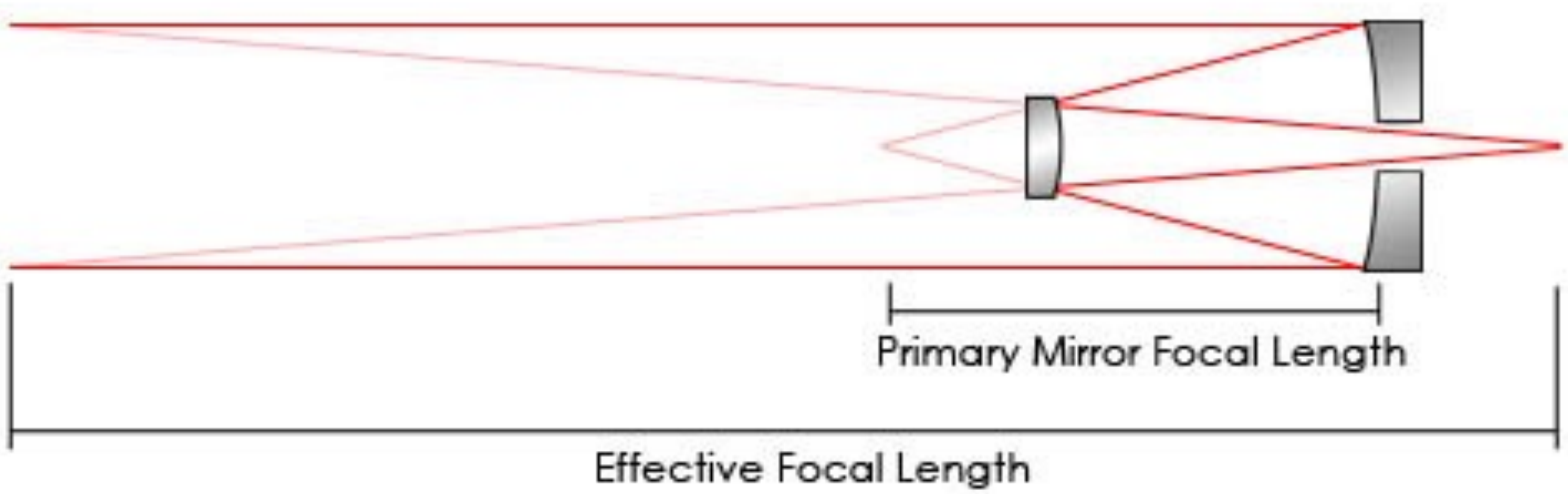
- Nasmyth focus: pick-up mirror, can be placed through mount axis



Focal length

distance from mirror / lens to the focus place





Focal ratio (“f number”)

distance from mirror / lens to the focus place

$$\text{focal ratio} = \frac{\text{focal length}}{\text{aperture}}$$

measure of how “fast” the lens / mirror is

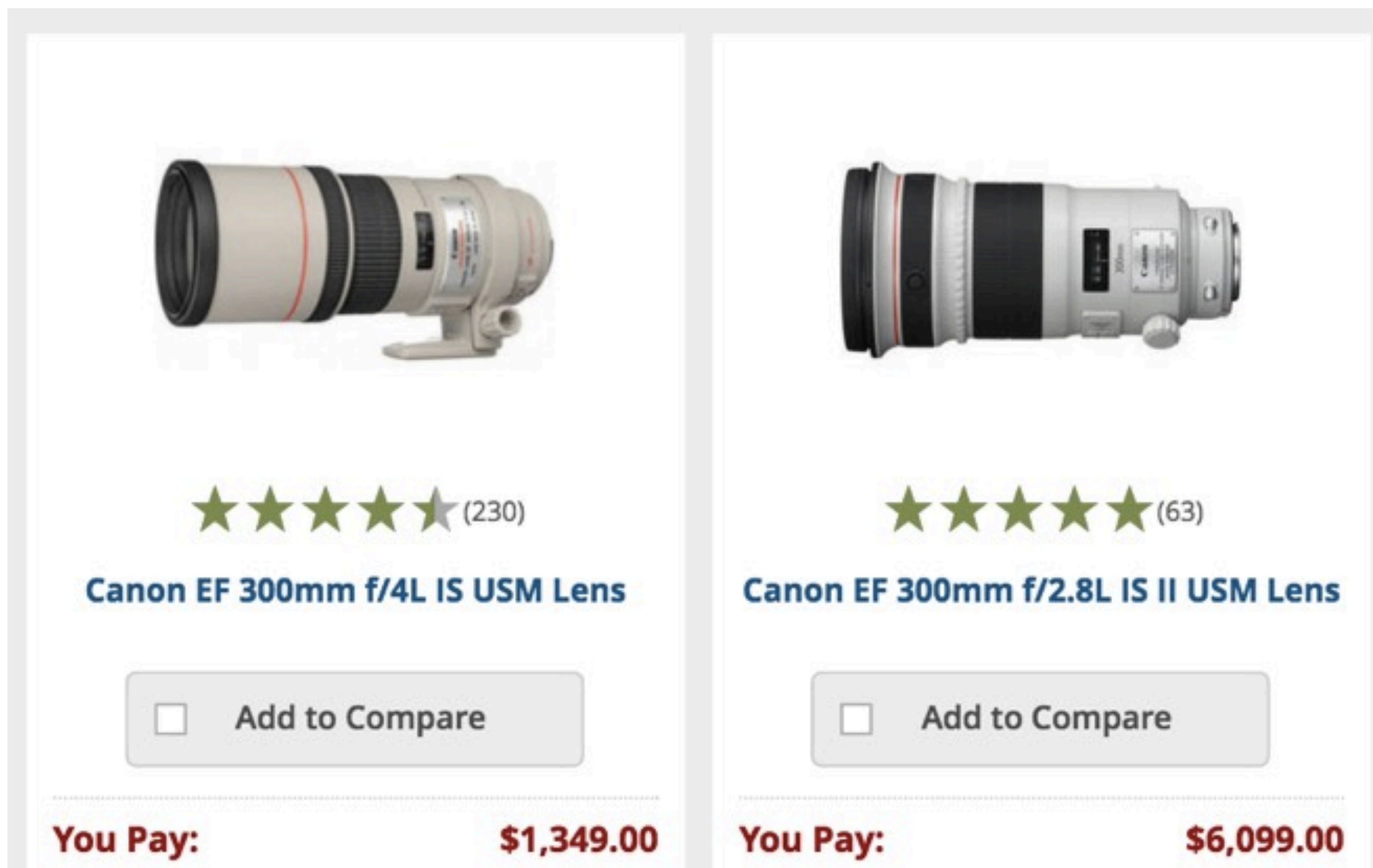


Plate Scale

how big is the image / how much sky does the detector see?

$$\theta \approx \tan\theta = \frac{y}{f}$$

$$\frac{d\theta}{dy} = \frac{1}{f}$$

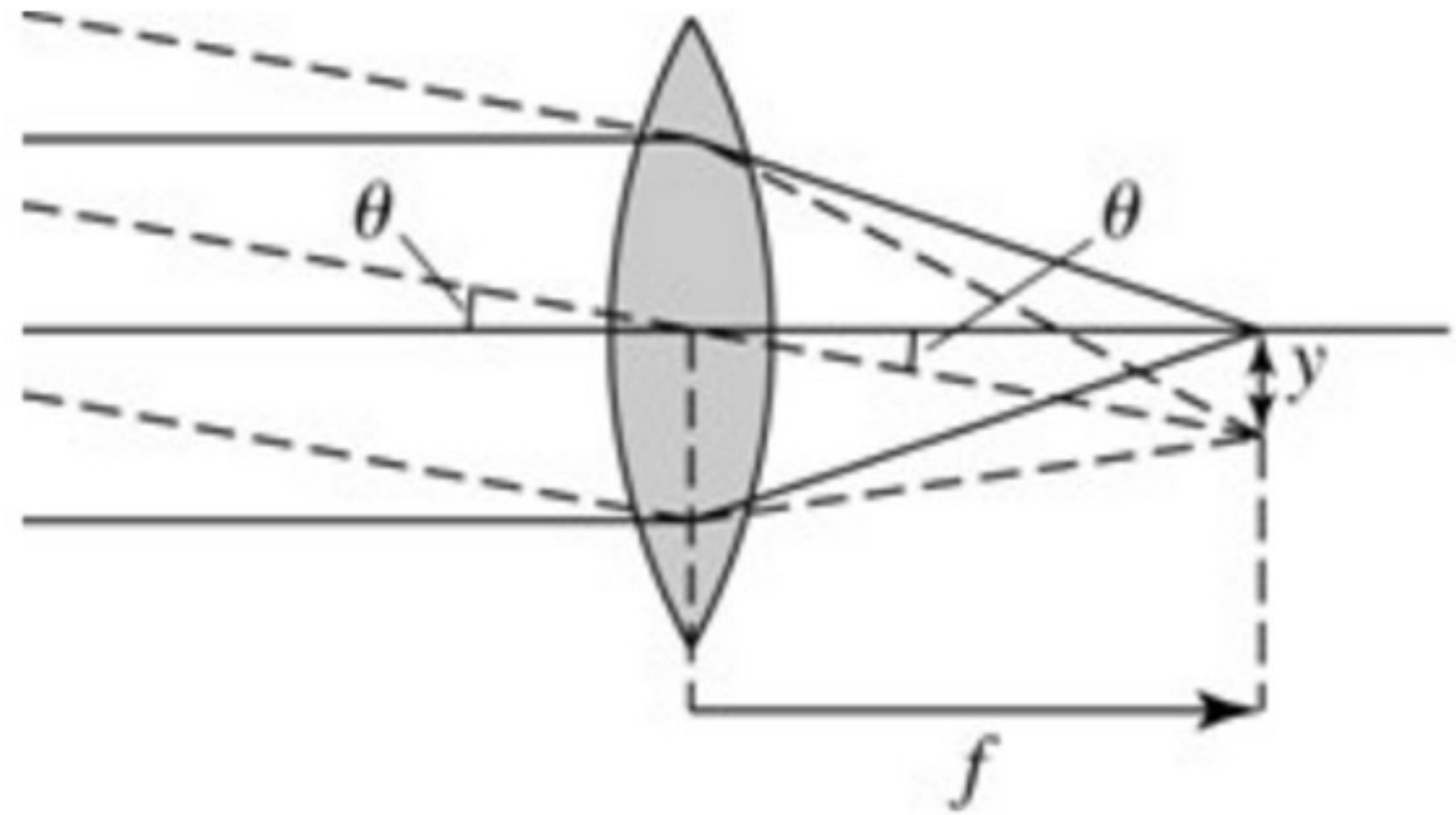


plate scale = (focal length)$^{-1}$

units: arcseconds / mm

CCDs

CCDs

- CCD: “charge-coupled device”
- CCDs are the detectors of choice over much of the electromagnetic spectrum (X-rays to infrared)
- replaced photographic plates
- similar to detectors found in digital cameras

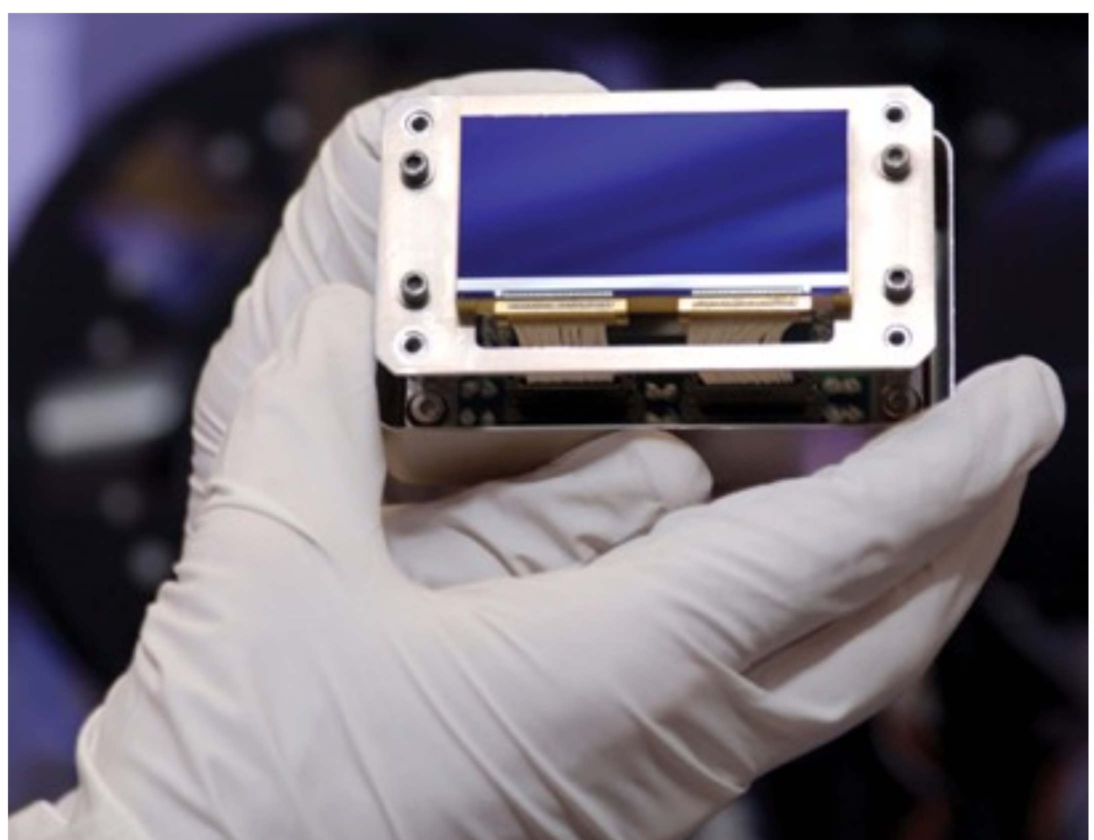
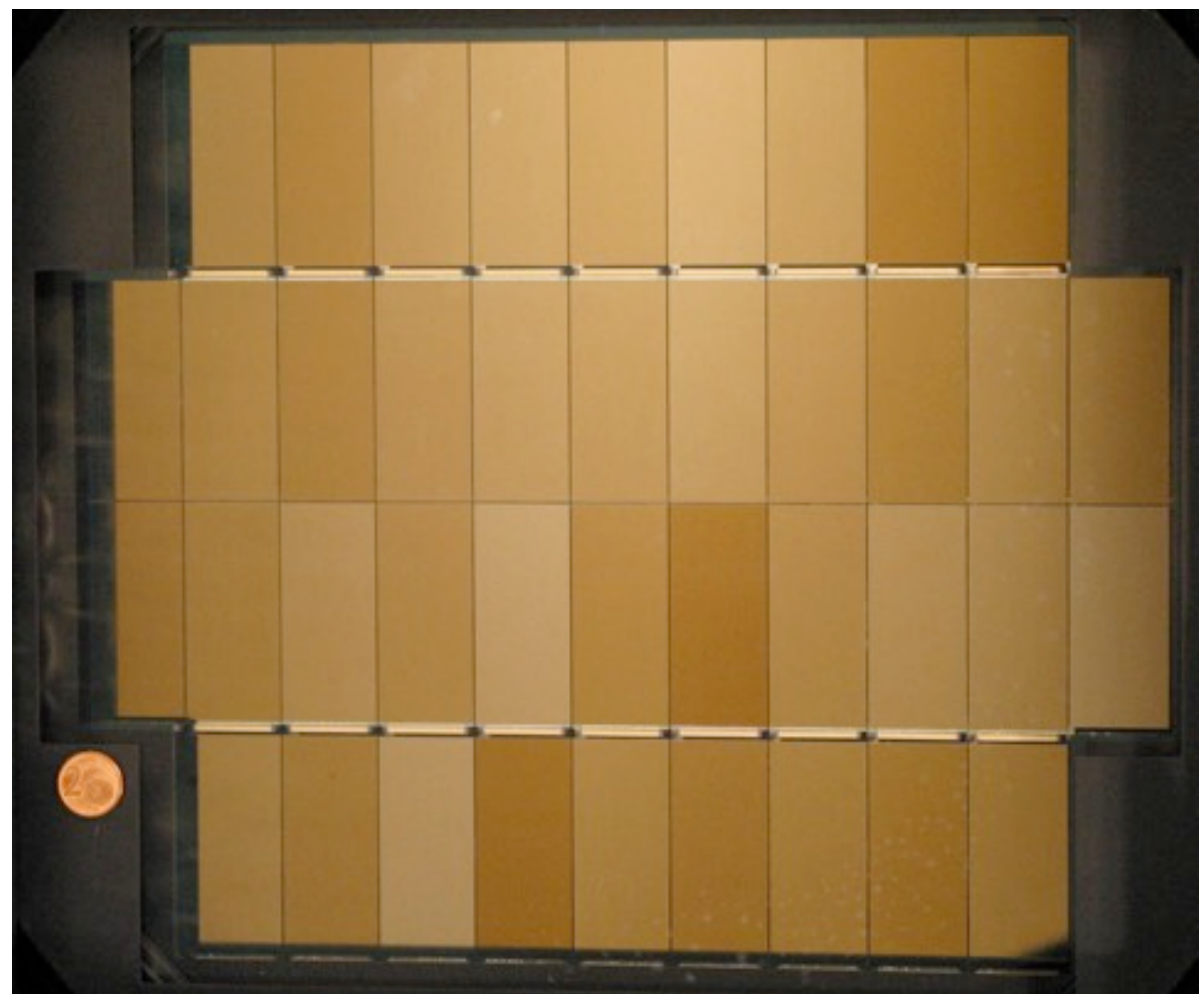


Figure 3. Kepler CCD in handling jig.

CCDs - Advantages

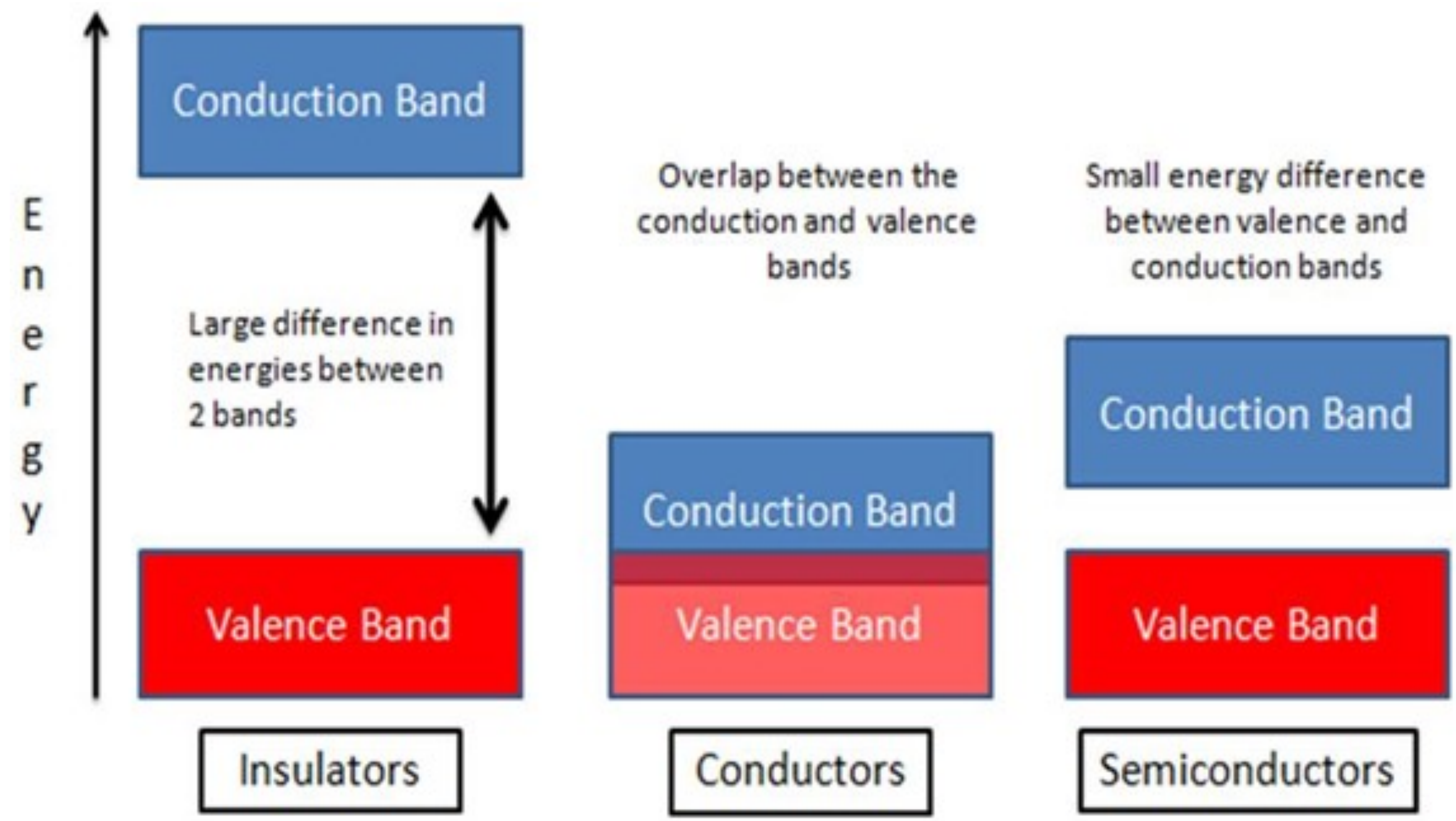
- (nearly) linear response $N_{\text{electrons}} \propto N_{\text{photons}}$
- high sensitivity
- low noise (especially when cooled)
- built-in digitization



CFHT MegaPrime

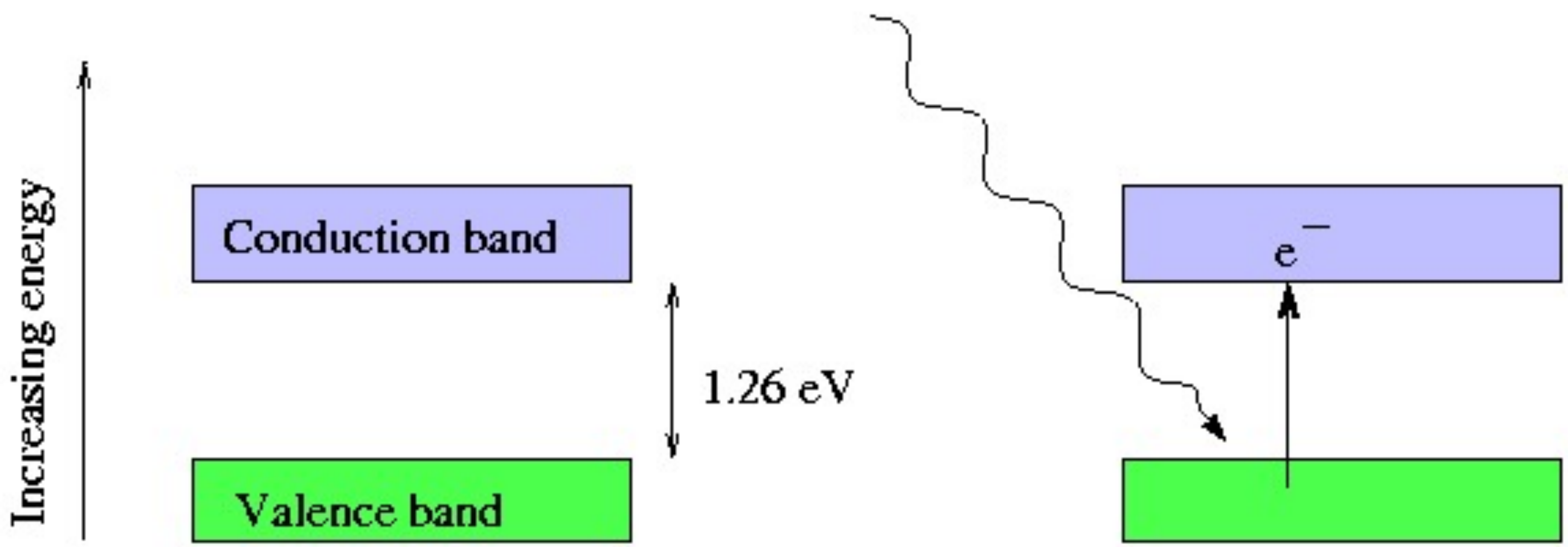
Semi-Conductors

- CCDs are made of semi-conducting silicon wafers
- key feature: small energy gap between "valence band" (energy levels of outermost bound electrons) and "conduction band" (energy levels of free electrons)



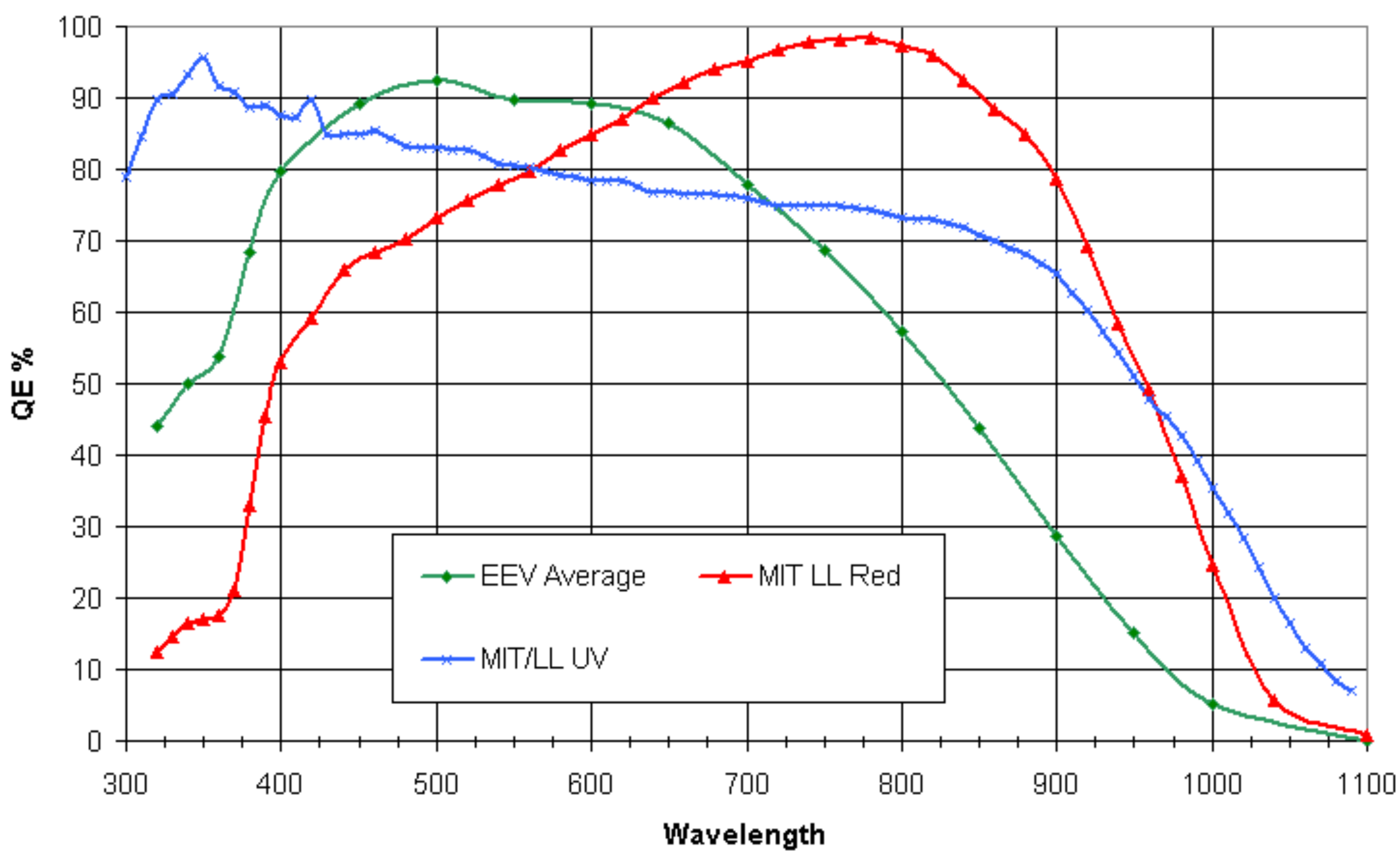
Photoelectric effect

- light is quantized, "photons" $E = h\nu$
- when a photon is absorbed, the energy is transferred to an electron → "jumps" into conduction band



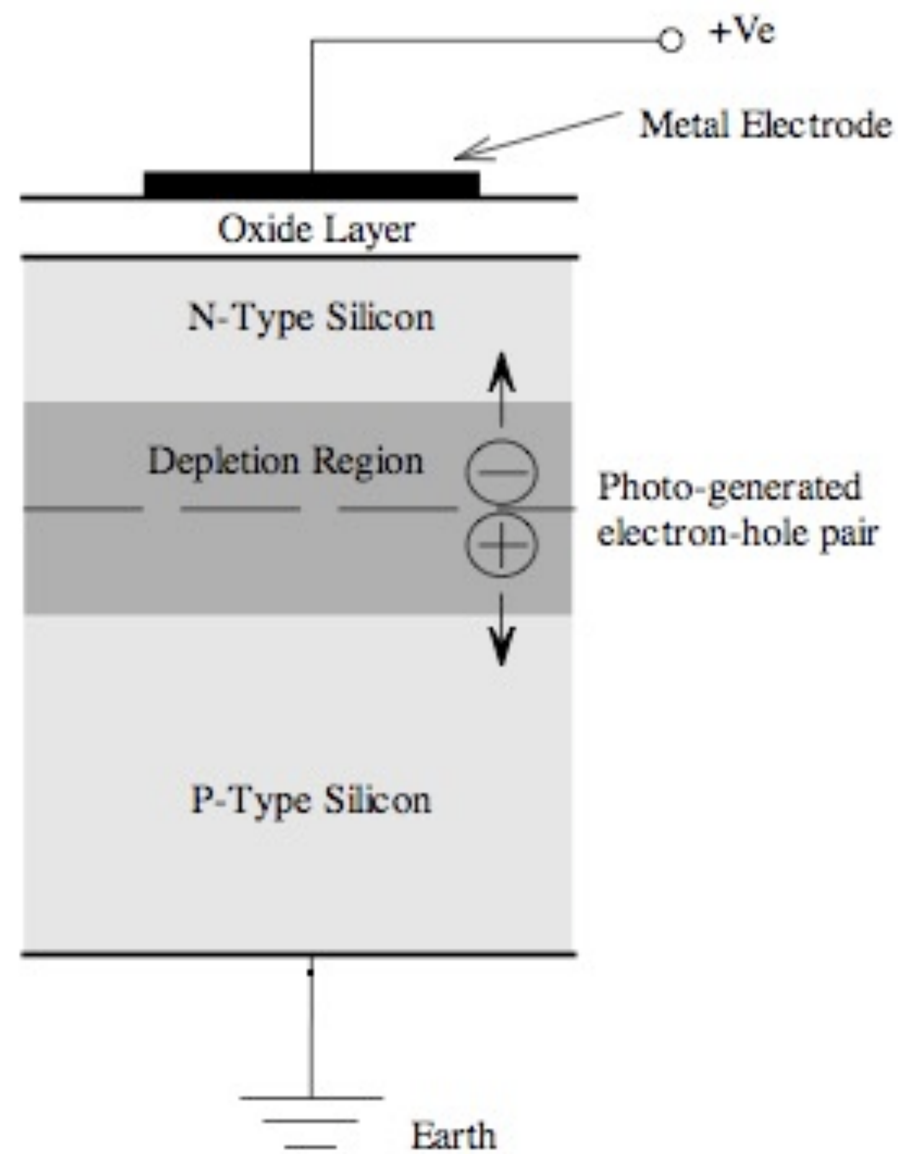
CCD Quantum Efficiency (QE)

- fraction of photons that are detected
- depends on wavelength
- different technologies lead to red vs. blue optimized CCDs



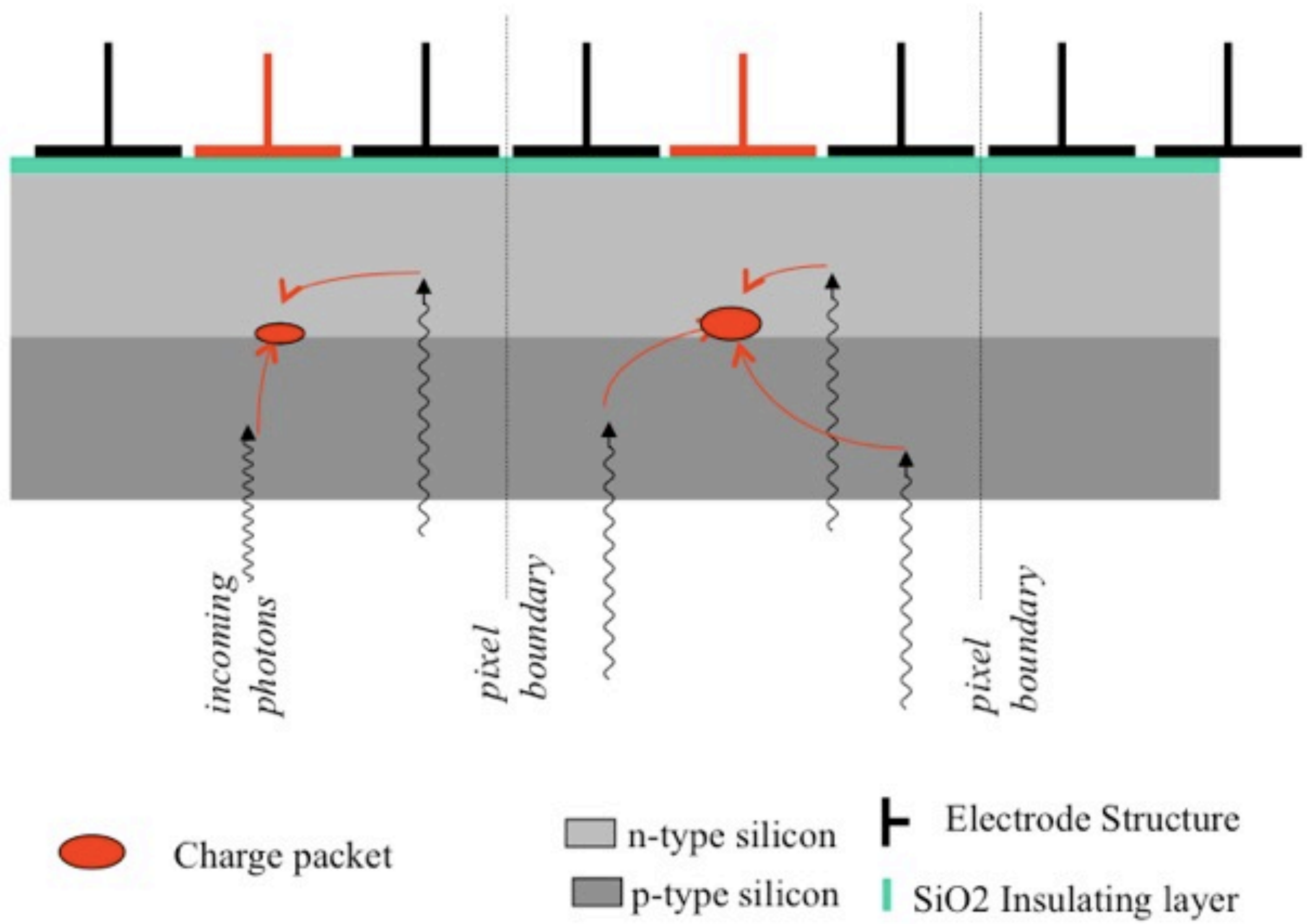
One pixel

- apply an electric field to keep electrons / holes separated



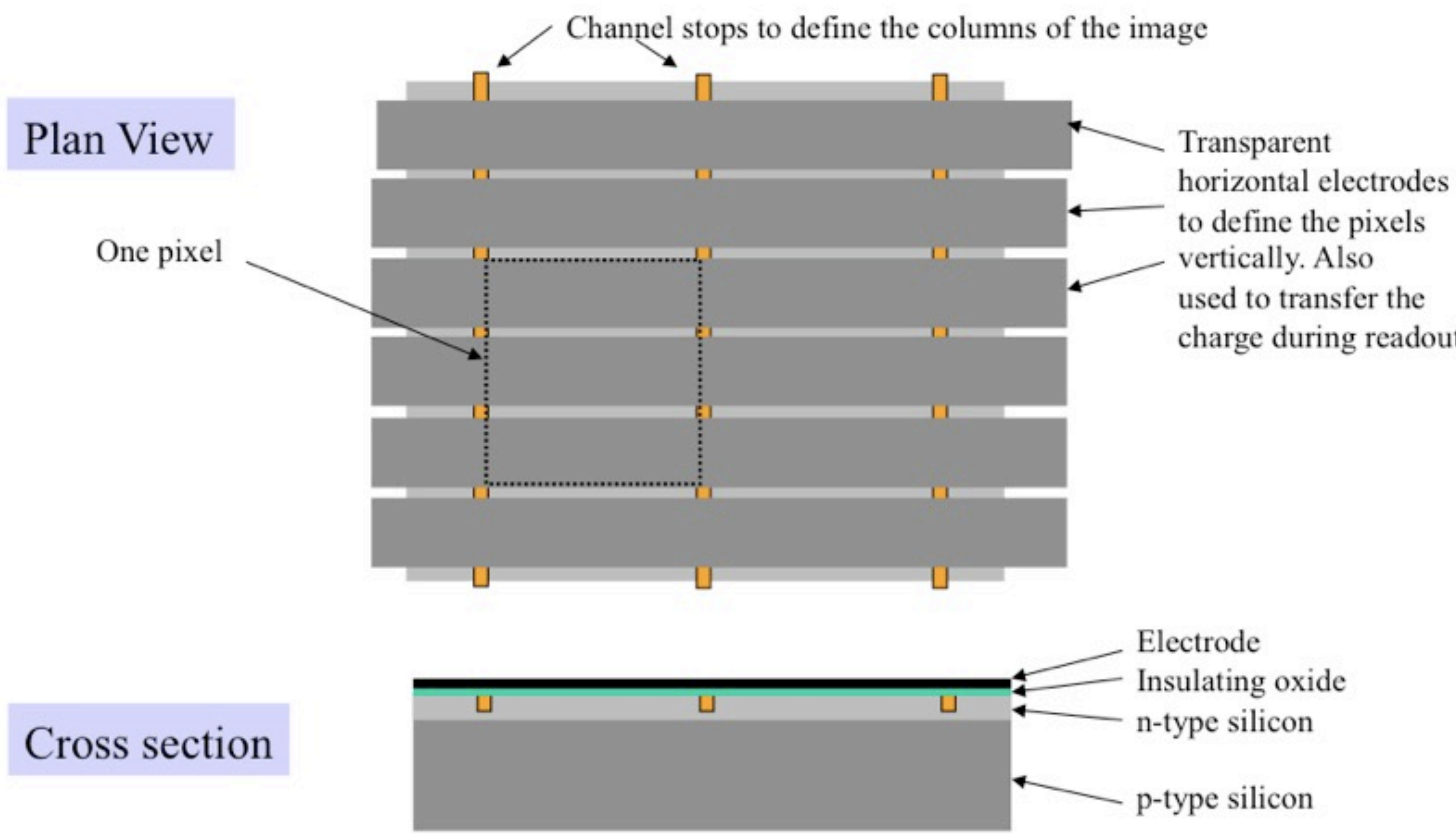
Many pixels

- pixels are defined by the electric field generated by the applied electrodes



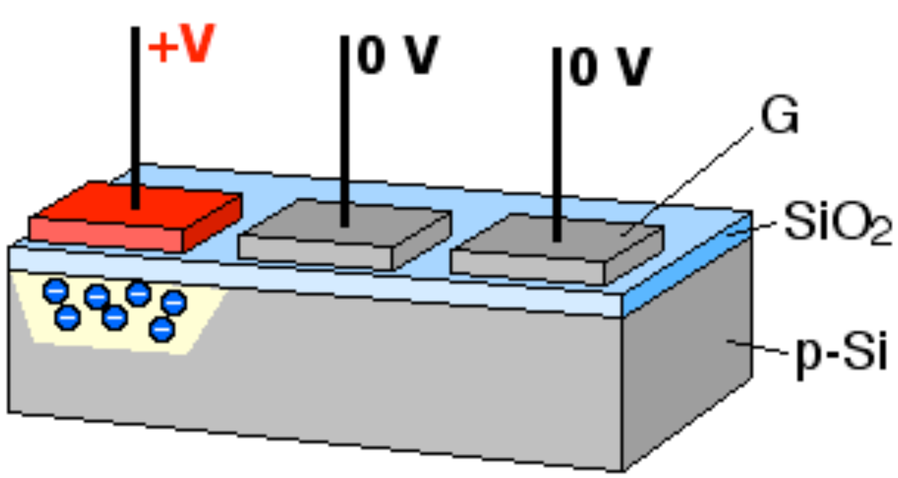
Many pixels

- ... and by insulator strips between columns



Reading out CCDs

- "rainbuckets on conveyor belts" analogy
- 1 conveyor belt = 1 CCD column
- in practice: modulate the electric fields to move pixel charges



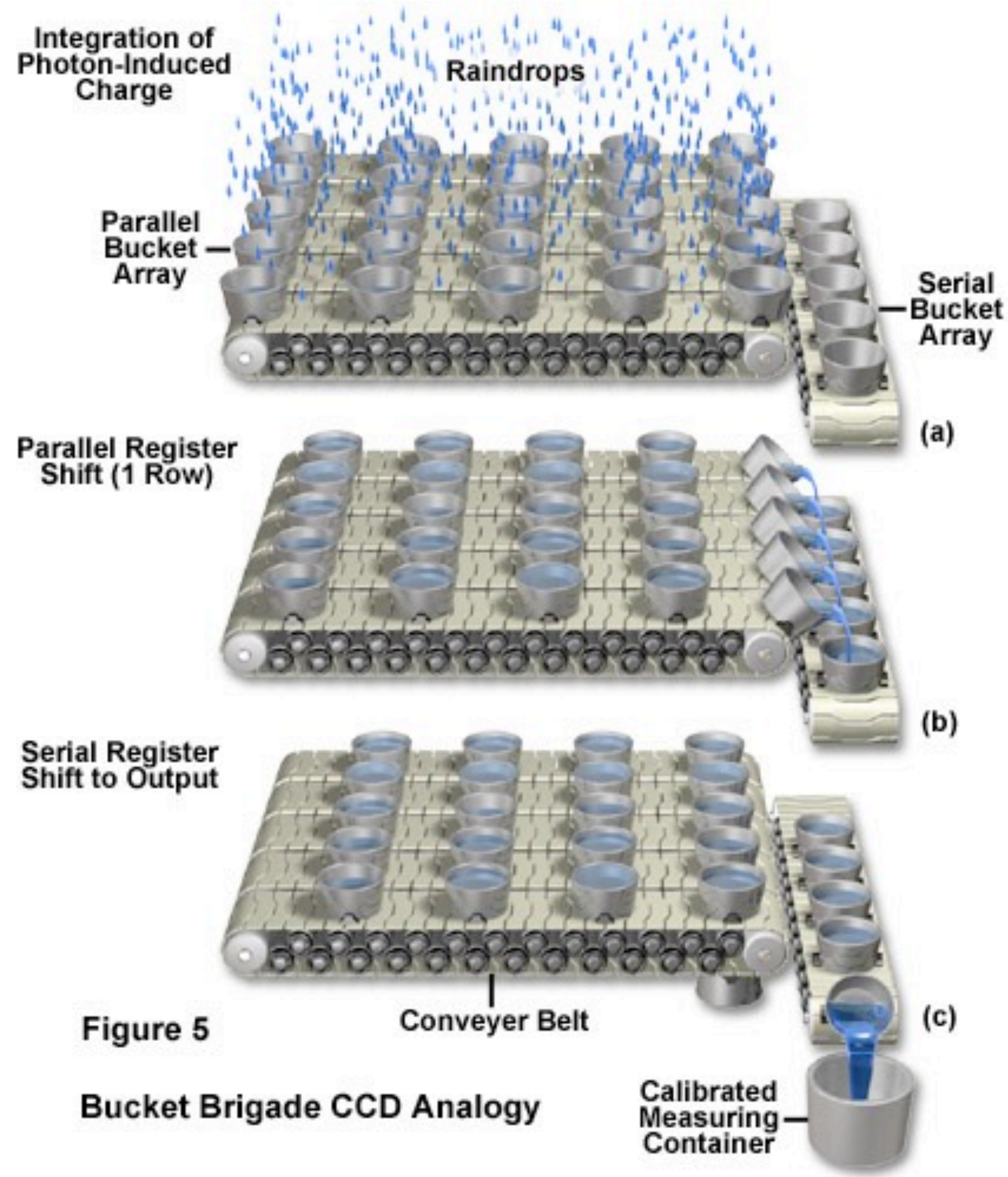


Figure 5

Bucket Brigade CCD Analogy

Assembling the Image

- each charge collection is passed to an amplifier and analog-to-digital converter (ADC)
- final output: "counts" or ADUs (analog-to-digital units) → *integer value*
- can apply rescaling: "gain"

$$\text{gain G} = \frac{N_{\text{electrons}}}{N_{\text{counts}}}$$

Full Well Capacity

- each pixel can only hold a limited charge → *full well capacity*, of the order of 100 000 e^-
- ADCs have a maximum output value, e.g. 16-bit = 2^{16} = 65536 counts
- gain should be chosen roughly so that ADC maximum ~ full well
- typically, gain ~ 2-4

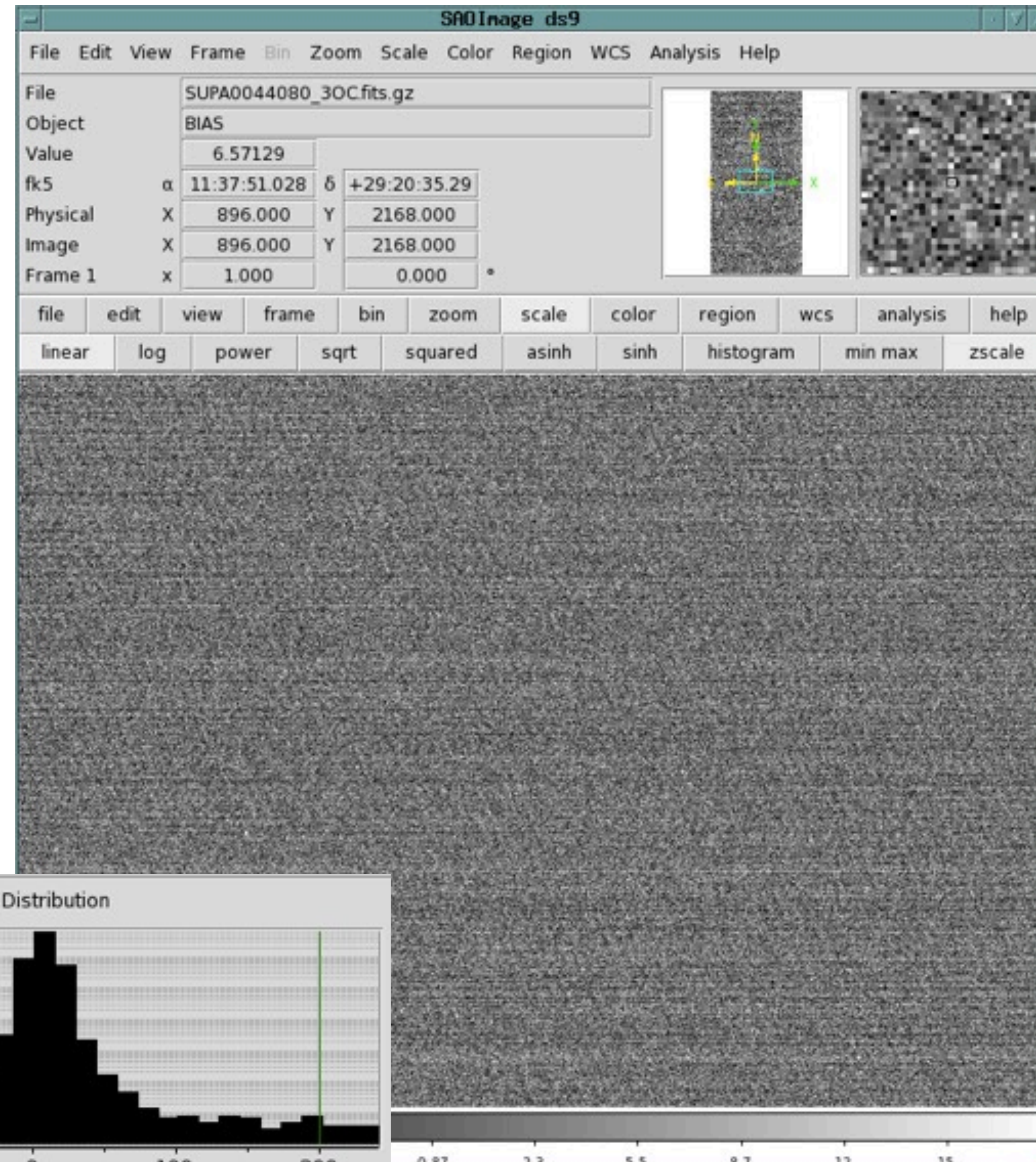
Read-out noise and bias level

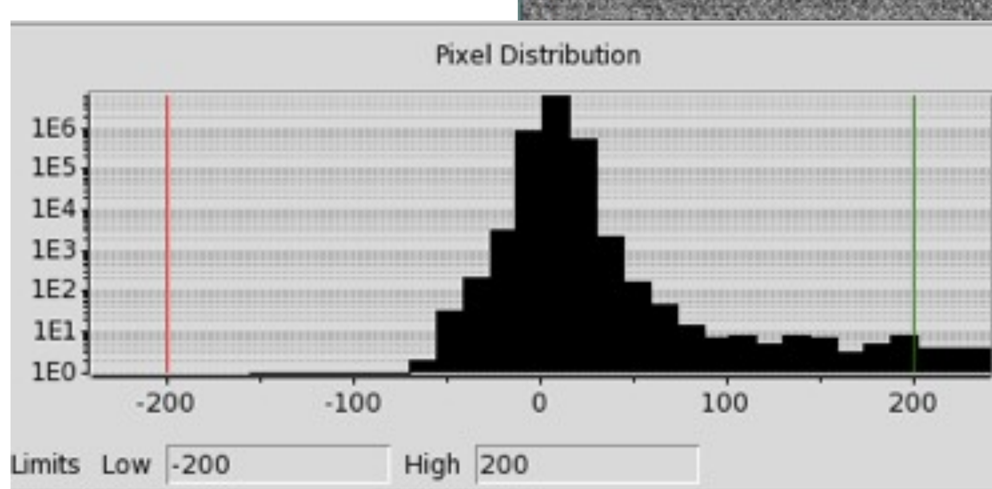
- various electronics can introduce noise into the signal before it reaches the ADC, e.g. the amplifiers
- the slower the read-out, the lower the noise

- bias level: an electronically induced offset which ensures that the ADC always gets a positive input
- the bias needs to be subtracted so that the counts are proportional to the signal

Bias images

- images with 0s exposure time
- single bias frame: pixel values scatter around the bias level, width of this distribution is the read-noise
- master bias frame (median or average of many bias frames): read-noise is averaged out, remaining structure is due to electronics





$$\sigma \sim 5e^-$$

Overscan region

- problem: the bias level may not be stable
- images on large astronomical cameras come with an overscan region
- each row is clocked out more often than there are physical pixels
- can be used as an in-situ estimate of the bias level
- use the extra pixels to estimate the bias level of each row; subtract it from entire row
- the overscan is subtracted from all images (including bias frames)

Dark current

- the energy gap in the semi-conductor is small → thermal noise leads to extra charge accumulation
- proportional to the exposure time
- cooling the CCDs significantly mitigates dark current
- professional astronomical CCDs cooled to -100˚C → almost no dark current

- dark frame: images taken with closed shutter, same exposure time, same temperature as science frames
- similar to bias frames; need to be subtracted

Flat-field

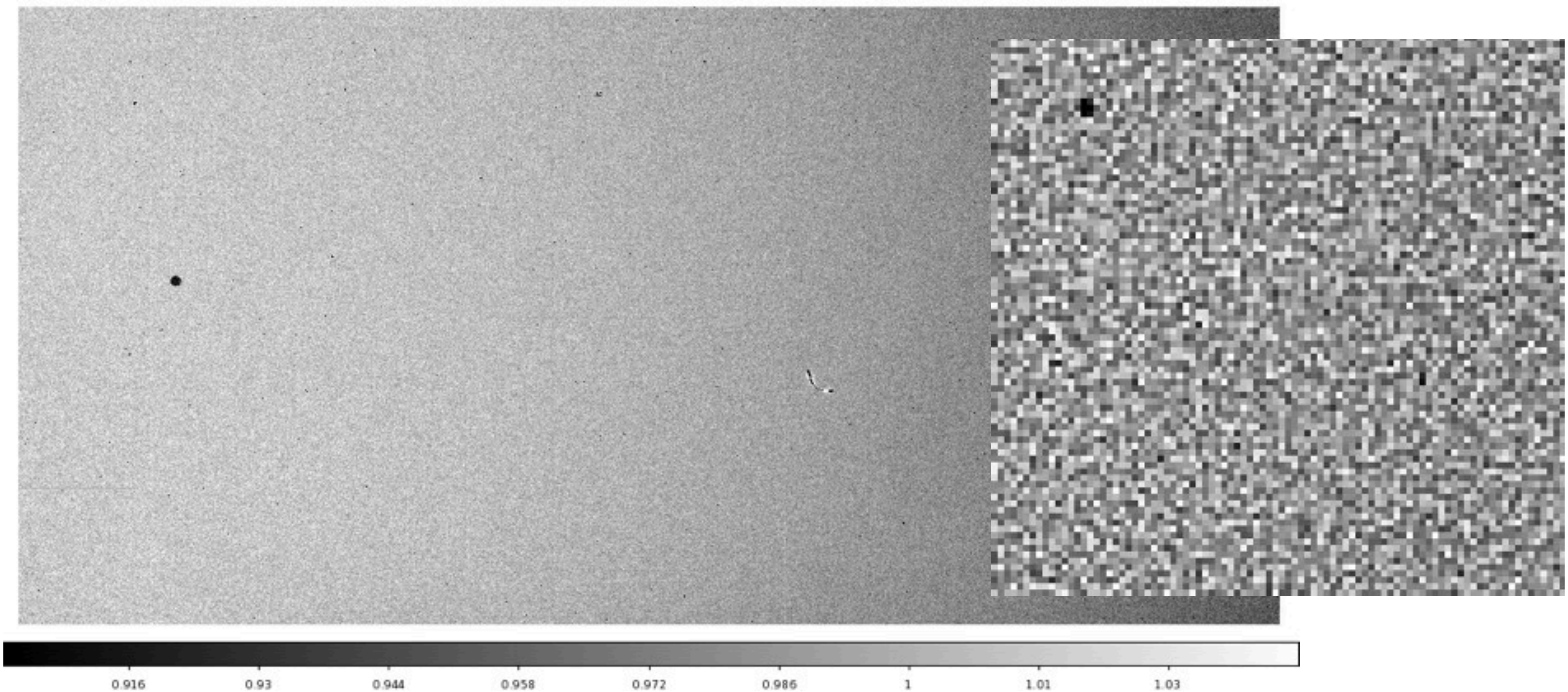
- the pixels in a CCD do *not* have uniform sensitivity
- due to variations in silicon crystal, electric field, pixel size, illumination (vignetting)

$$N_{\text{electrons}} \;=\; A_{ij}\; N_{\text{photons}}$$

- A_{ij} different for each pixel
- need to correct for differences for meaningful measurements

Flat-field

- flat-field: take an image of a spatially uniform source of light (e.g. the twilight sky, or a screen in the dome)
- input signal ($N_{photons}$) is the same for each pixel; variations in N_{counts} are due to different sensitivies



Flat-field

- flat-field is a *multiplicative* correction (unlike bias / dark)

- in practice: take a series of flat-field images
- correct each flat image by the bias image (overscan if available)
- average the flat-field images (reduces counting noise) → master flat-field

- each science image needs to be corrected by the master bias (or dark) and the master flat-field:

$$\frac{\text{science image} - \text{master bias}}{\text{master flat}}$$

Types of flat fields

dome flats:

✓ easy

✓ constant conditions

– not entirely uniform

– different spectrum than astronomical objects

Types of flat fields

twilight flats:

✓ same "source"

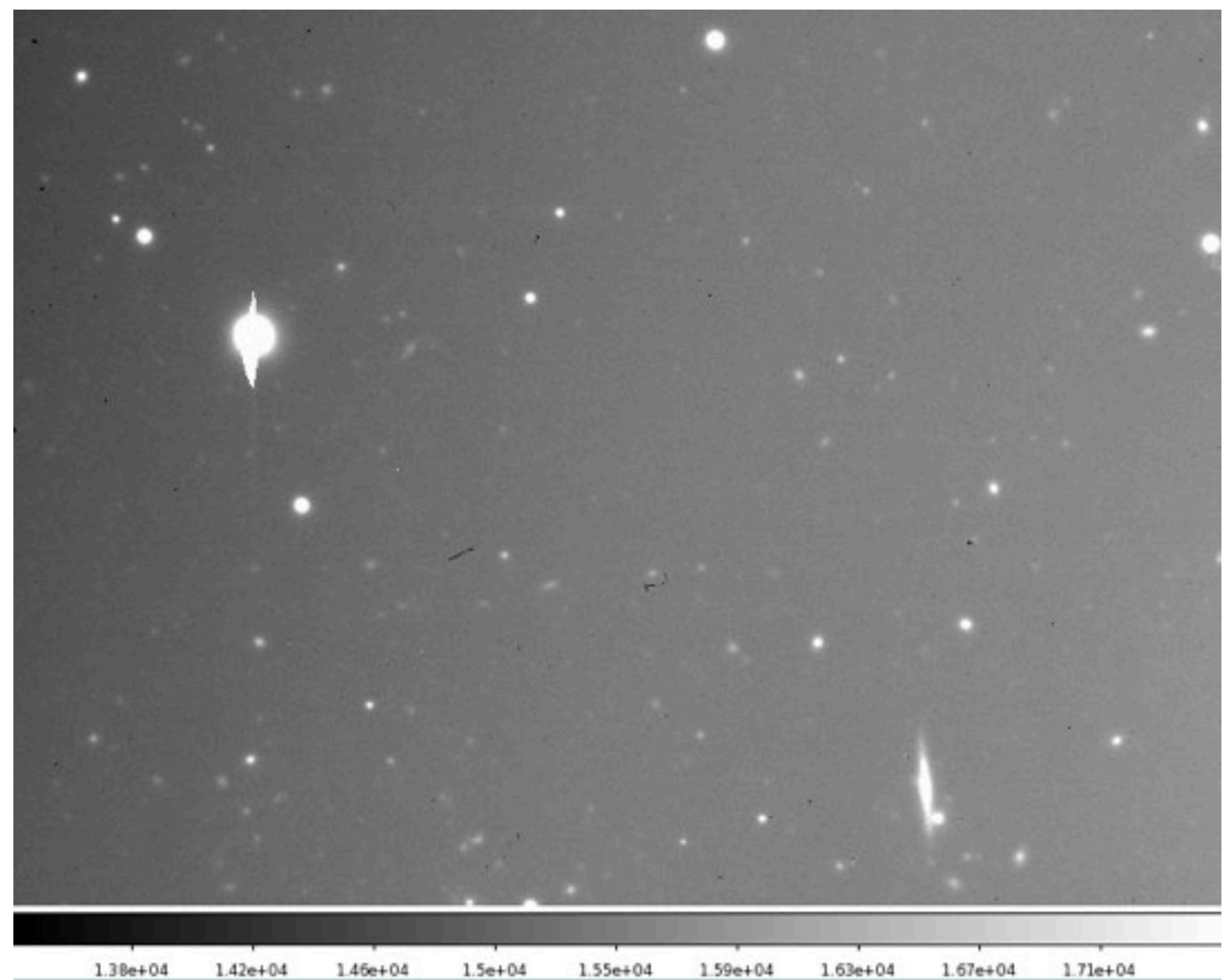
✓ almost uniform

– variable

– difficult

Types of flat fields

night-sky flats: if observations of several different targets are taken in one night, can average these images into flat-fields assembled from the sky background (best to mask out detected objects)



✓ most similar to data

✓ uniform

– need “empty” fields

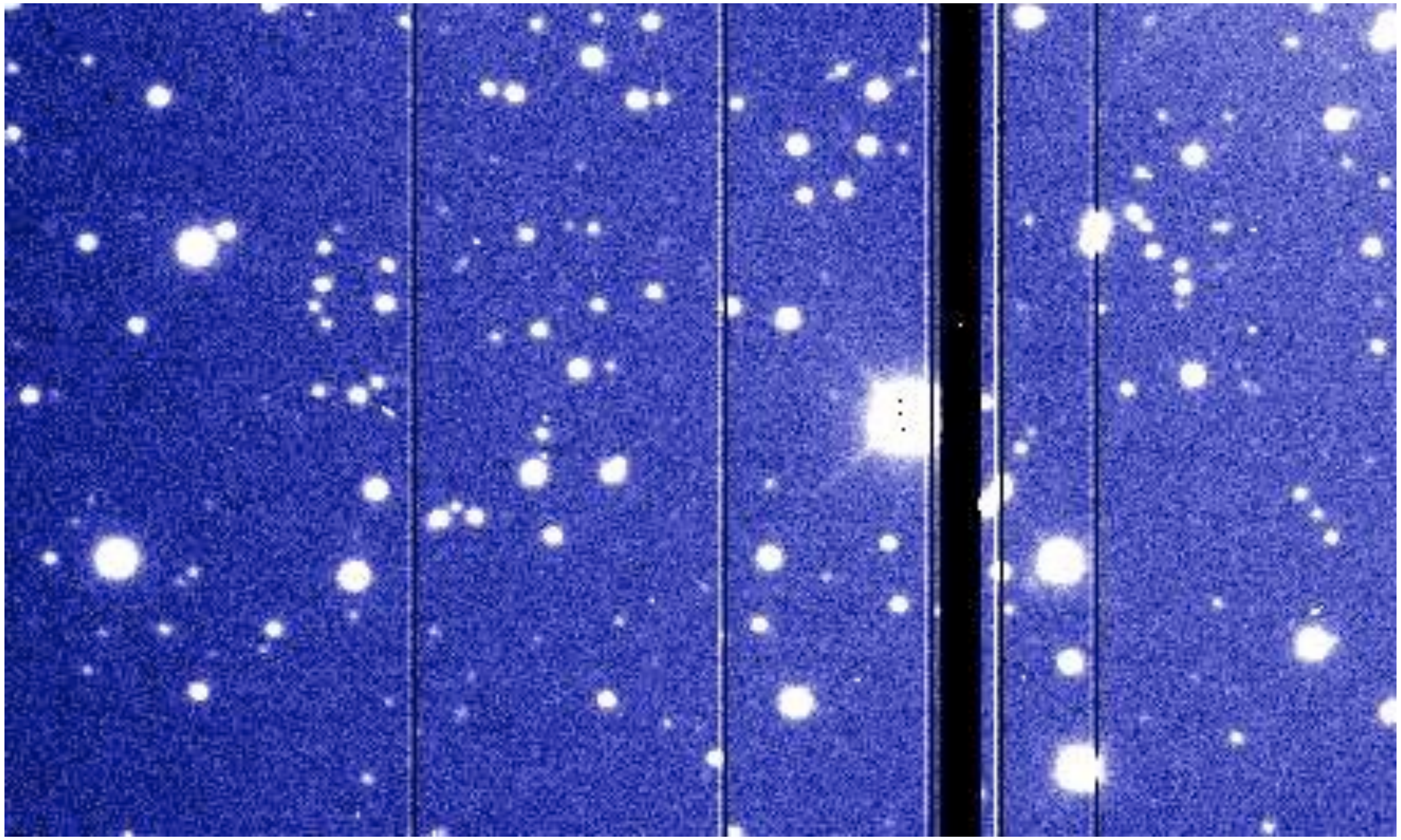
– need a lot of images

Artefacts

dead pixels / columns / rows: no (or little) response

hot pixels / columns / rows: very high noise

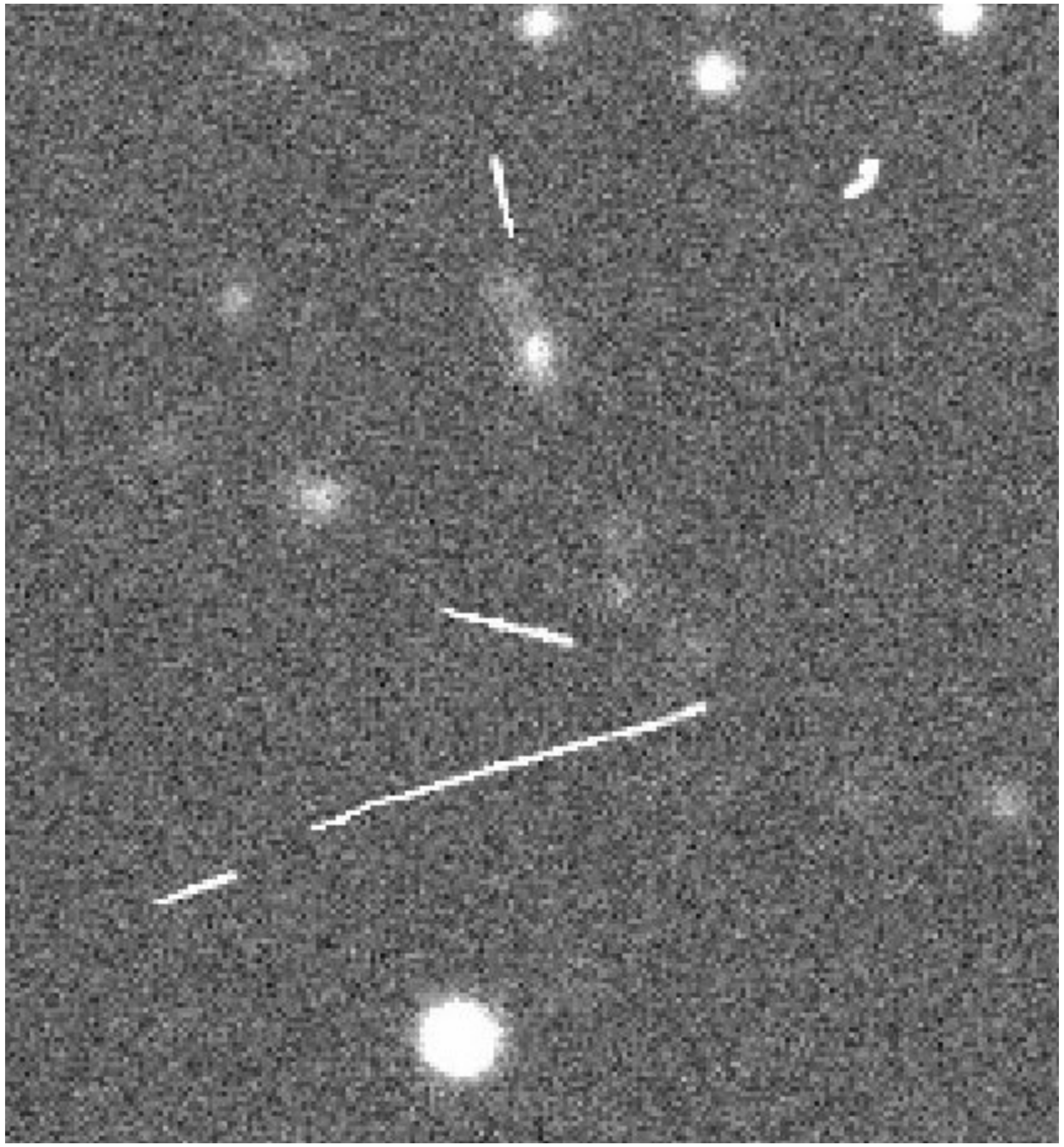
signal is not recoverable; pixels need to be masked in all exposures



Artefacts

cosmic rays: charged particles hit the CCD

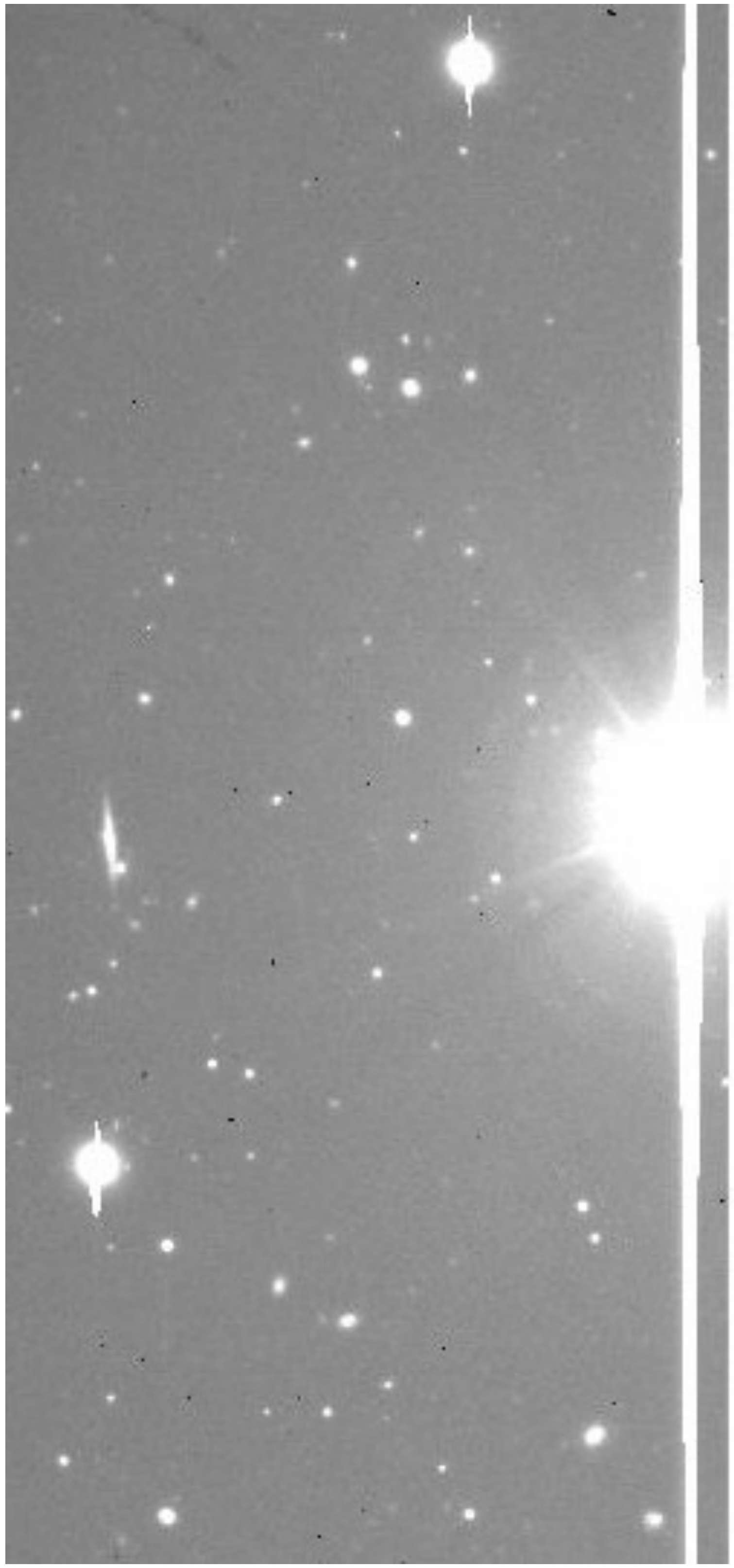
need to be masked - single exposure



Artefacts

saturation spikes: when full well capacity is reached, electrons spill over into neighboring pixels

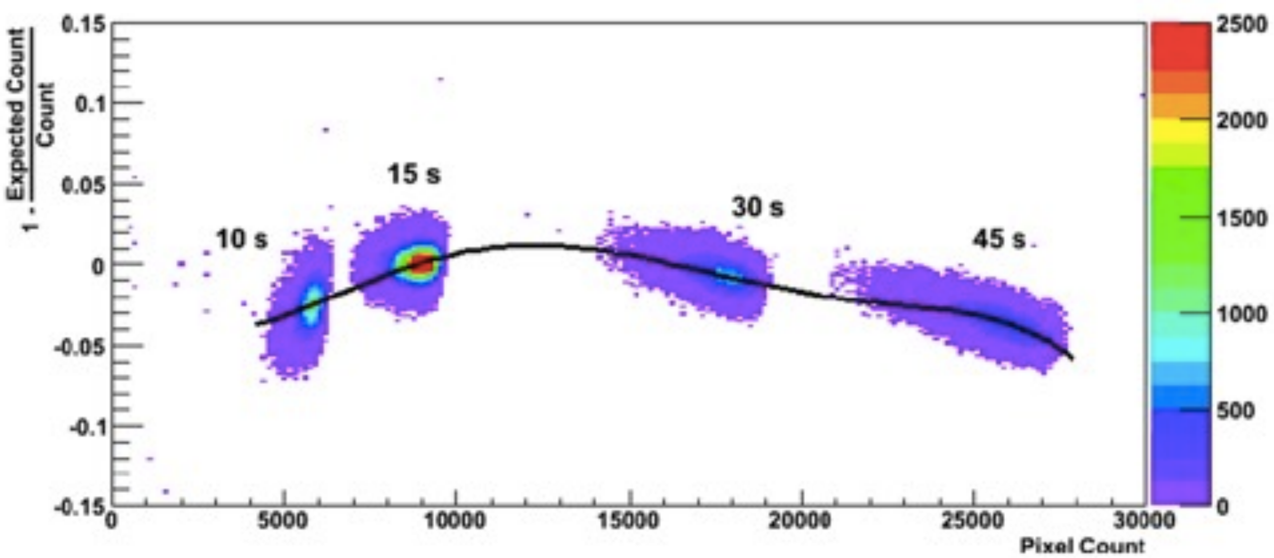
need to be masked - single exposure

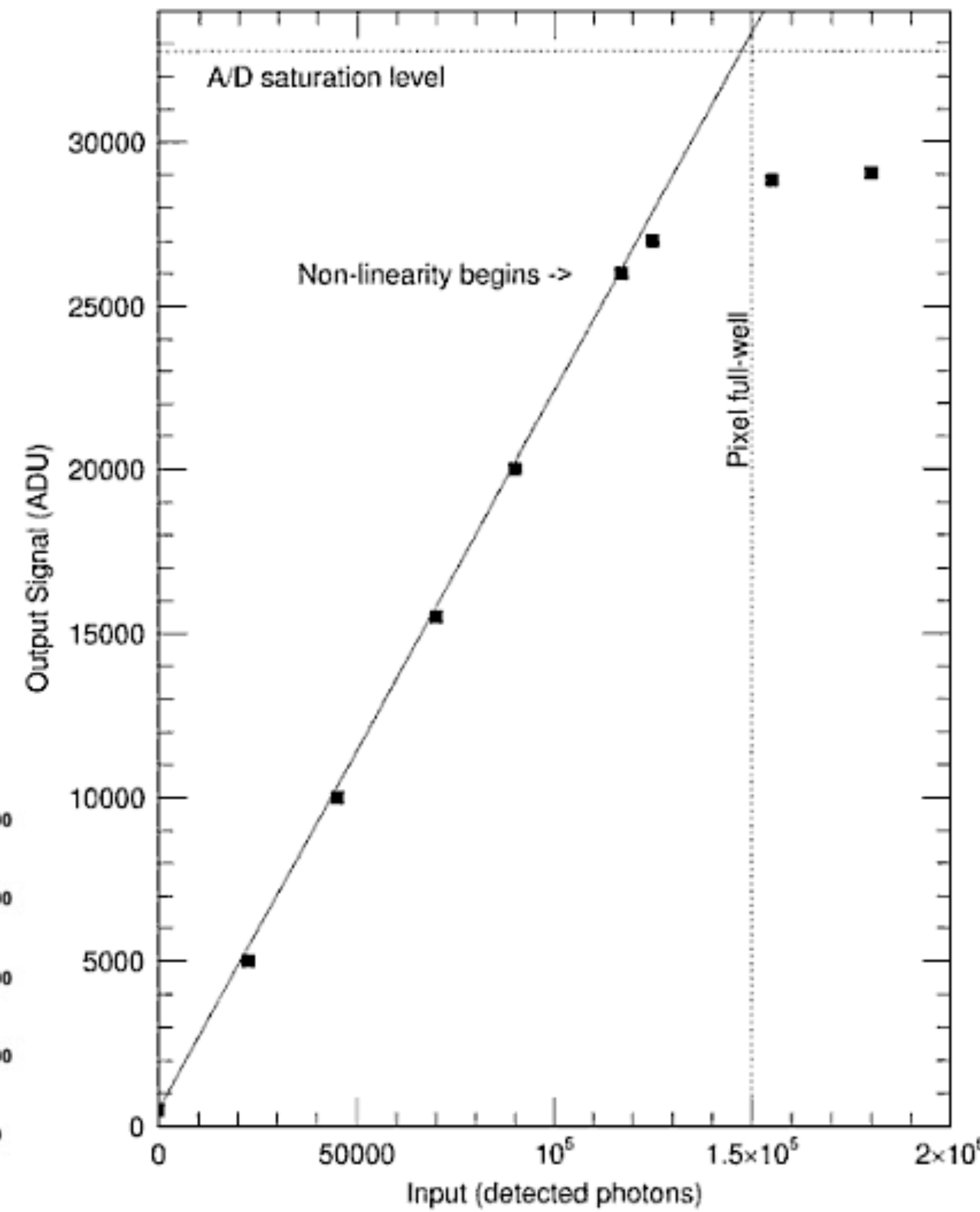


Artefacts

non-linearity: even before saturation level is reached, response becomes non-linear

can be measured from dome-flats





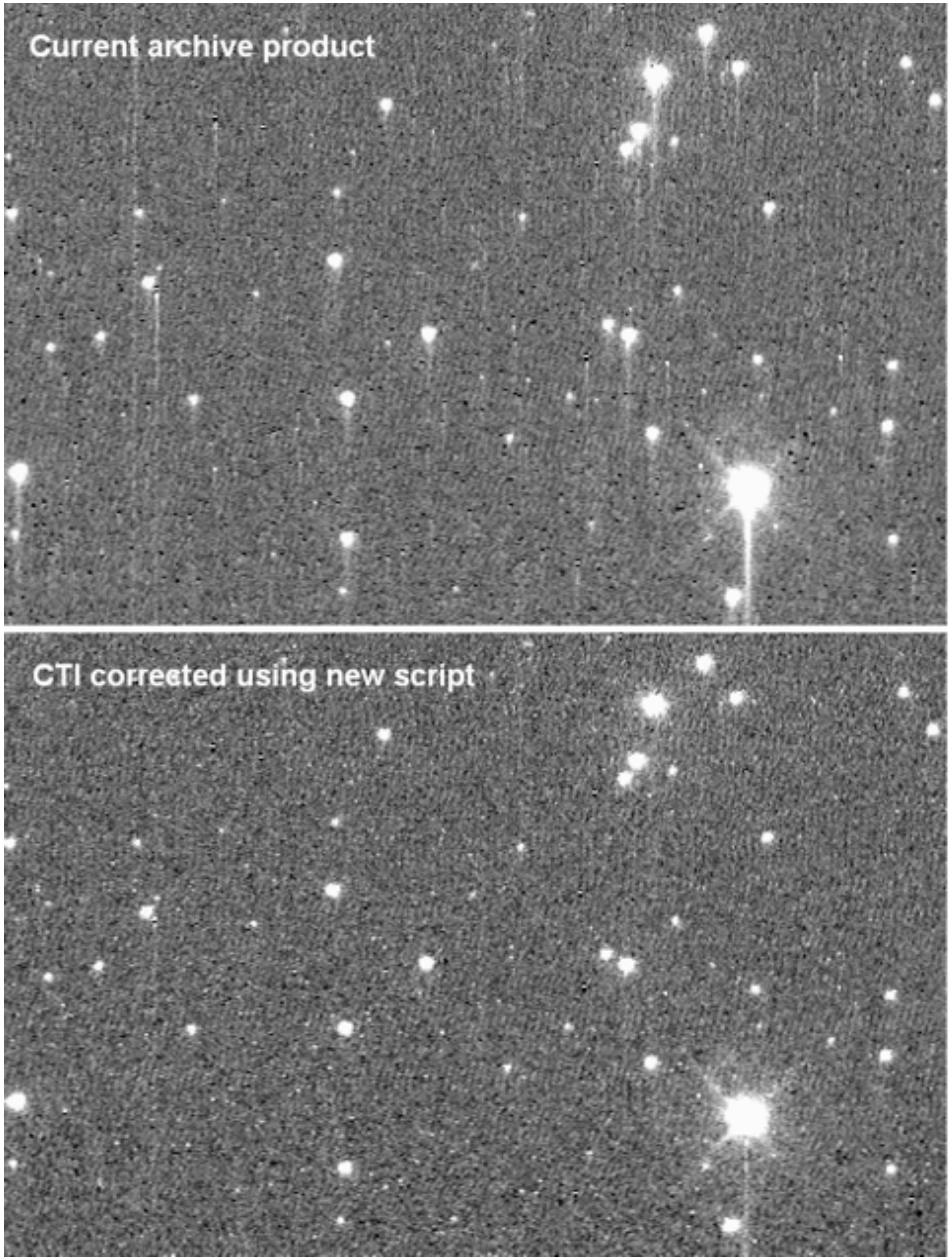
Artefacts

Charge Transfer Inefficiency (CTI): not all electrons are transferred from one pixel to the next during read-out

Charge Transfer Efficiency (CTE): fraction of photons that is transferred

CTI is a significant problem for Hubble's cameras because of radiation damage

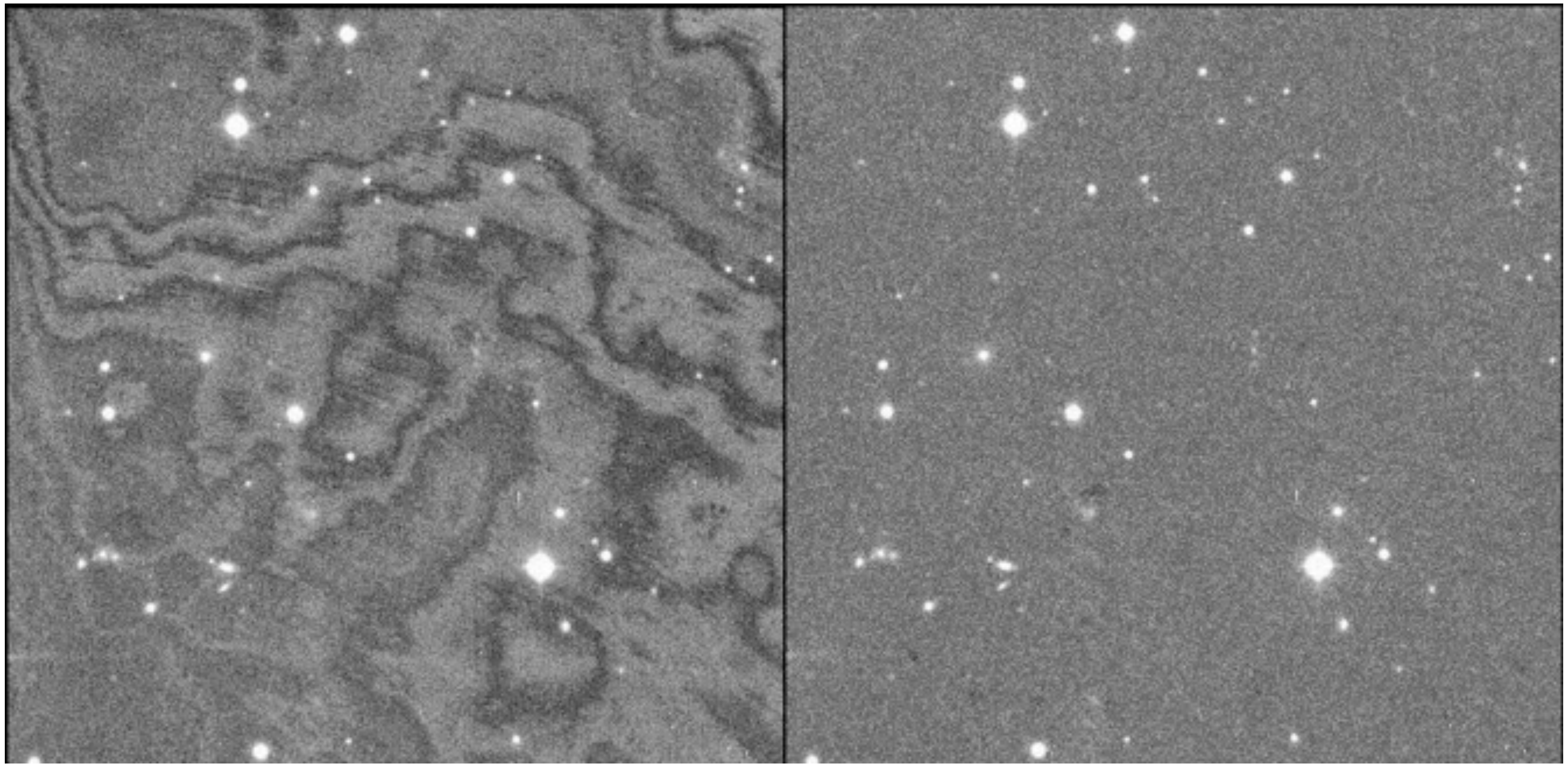
correction based on re-distributing charge



Artefacts

fringing: some light is reflected within the CCDs → leads to interference with incident light

fringing increases with wavelength, and decreases with thickness of CCDs



needs to be modeled; e.g. by subtracting a heavily smoothed image