PHY 517 / AST 443:
Observational Techniques in Astronomy

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

Lab 1 (CCDs)

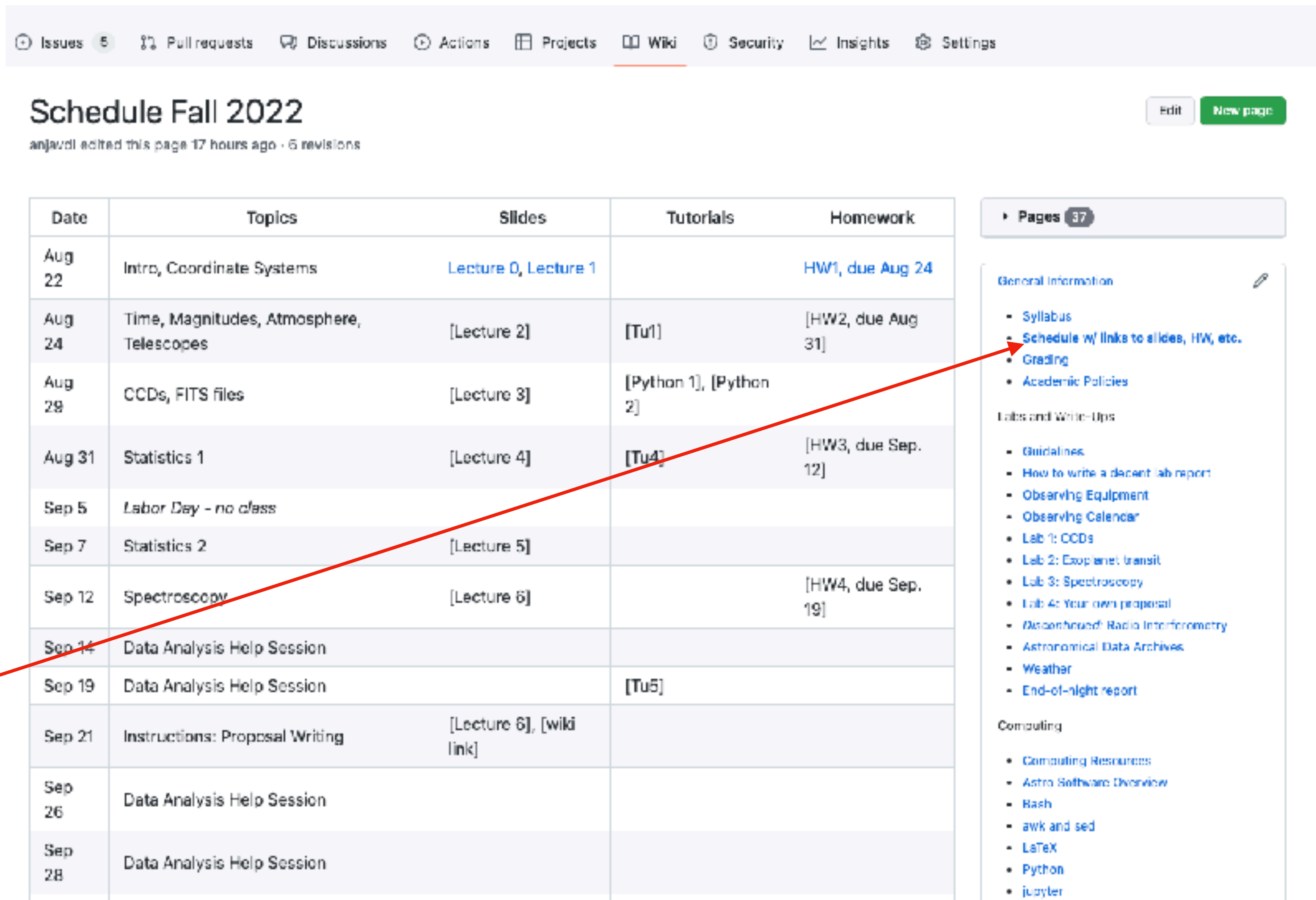
- Please schedule the day-time part of Lab 1 with the TAs ASAP
- If necessary, can split the day-time part over two sessions (imaging / spectroscopy)
- Come prepared! The TAs will quiz you before you can start.

Blind grading

- Lab reports, homeworks, etc. will be graded blindly - please submit your homeworks as SBUID_HW1.pdf

Class Material

slides, homeworks, tutorials, etc. *as used in this year's class* are linked from the schedule on the wiki



Date	Topics	Slides	Tutorials	Homework
Aug 22	Intro, Coordinate Systems	Lecture 0, Lecture 1		HW1, due Aug 24
Aug 24	Time, Magnitudes, Atmosphere, Telescopes	[Lecture 2]	[Tu1]	[HW2, due Aug 31]
Aug 29	CCDs, FITS files	[Lecture 3]	[Python 1], [Python 2]	
Aug 31	Statistics 1	[Lecture 4]	[Tu4]	[HW3, due Sep. 12]
Sep 5	*Labor Day - no class*			
Sep 7	Statistics 2	[Lecture 5]		
Sep 12	Spectroscopy	[Lecture 6]		[HW4, due Sep. 19]
Sep 14	Data Analysis Help Session			
Sep 19	Data Analysis Help Session		[Tu5]	
Sep 21	Instructions: Proposal Writing	[Lecture 6], [wiki link]		
Sep 26	Data Analysis Help Session			
Sep 28	Data Analysis Help Session			

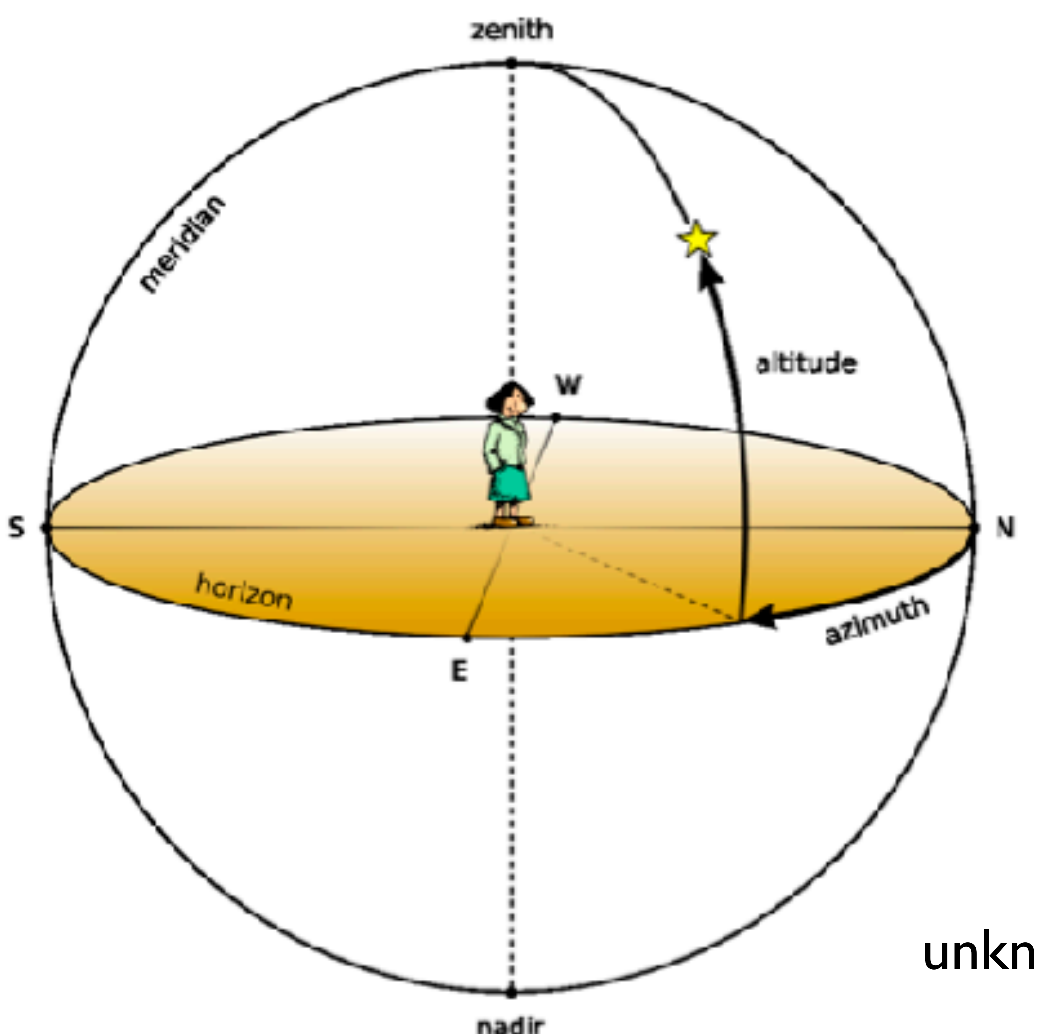
Office Hours

- during class (seriously!)
- easiest way to get in touch with me: slack
- office hours:
  - Prof.: Fr 2:30-3:30pm, ESS 453
  - Bela: Th, TBD - fill out slack poll!
  - Paras: Tu, TBD - fill out slack poll!
- by appointment

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



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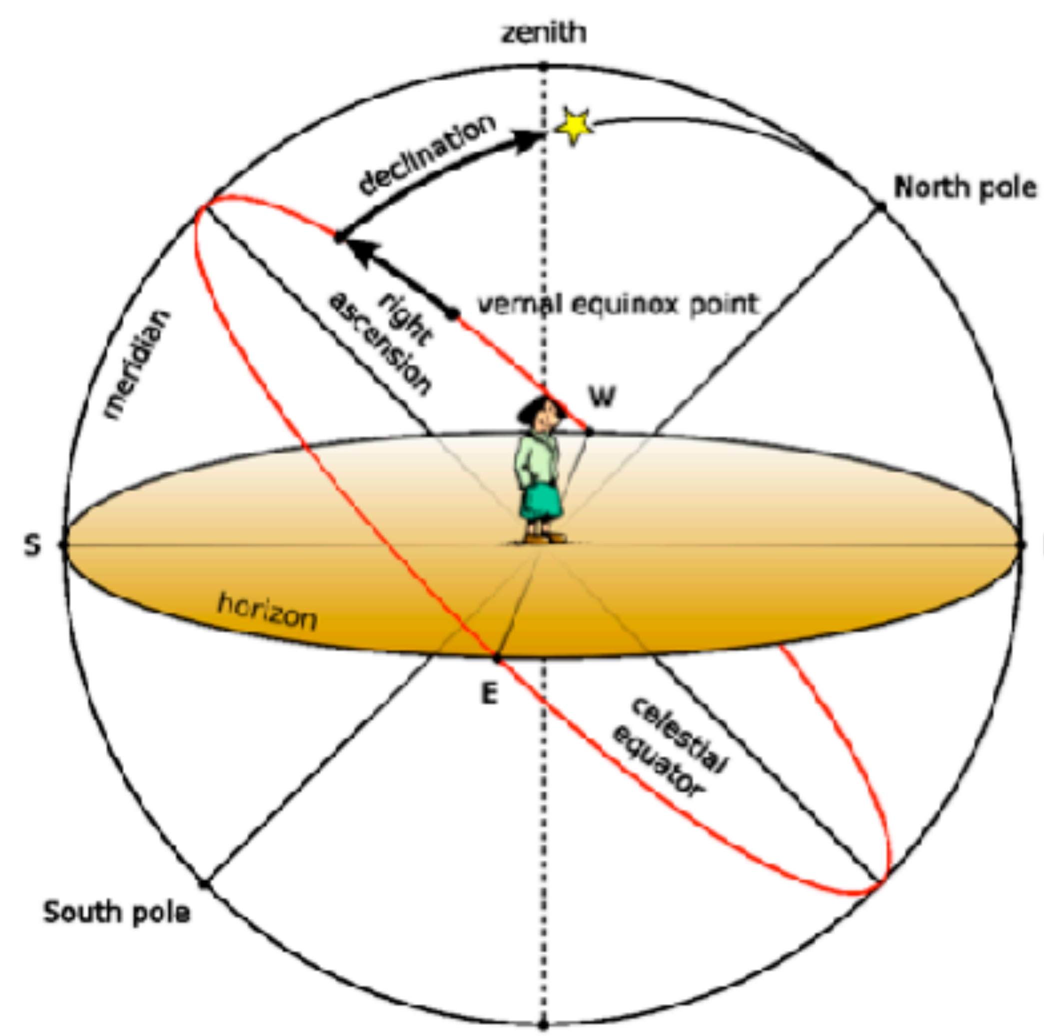
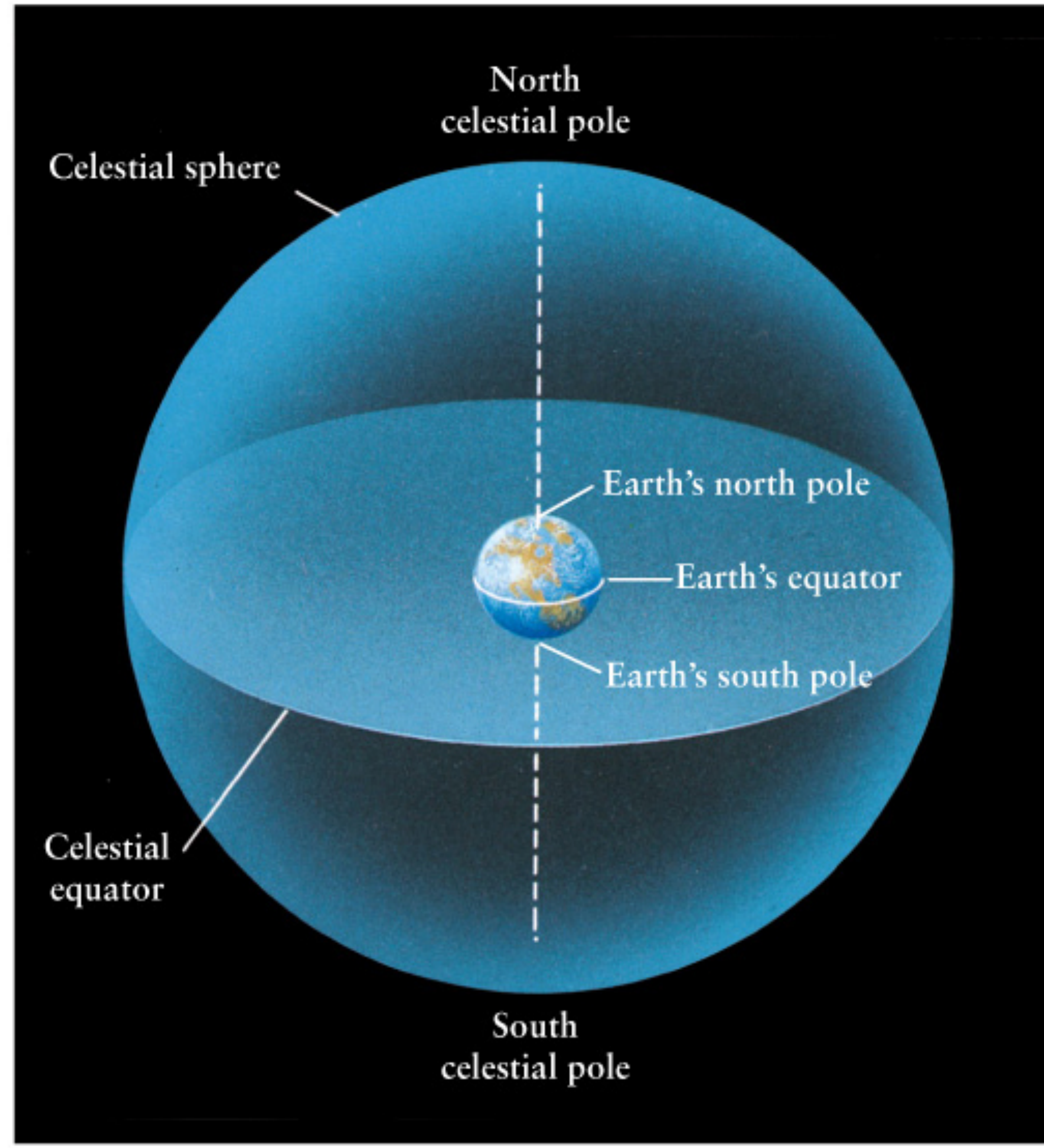


Last time...

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

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



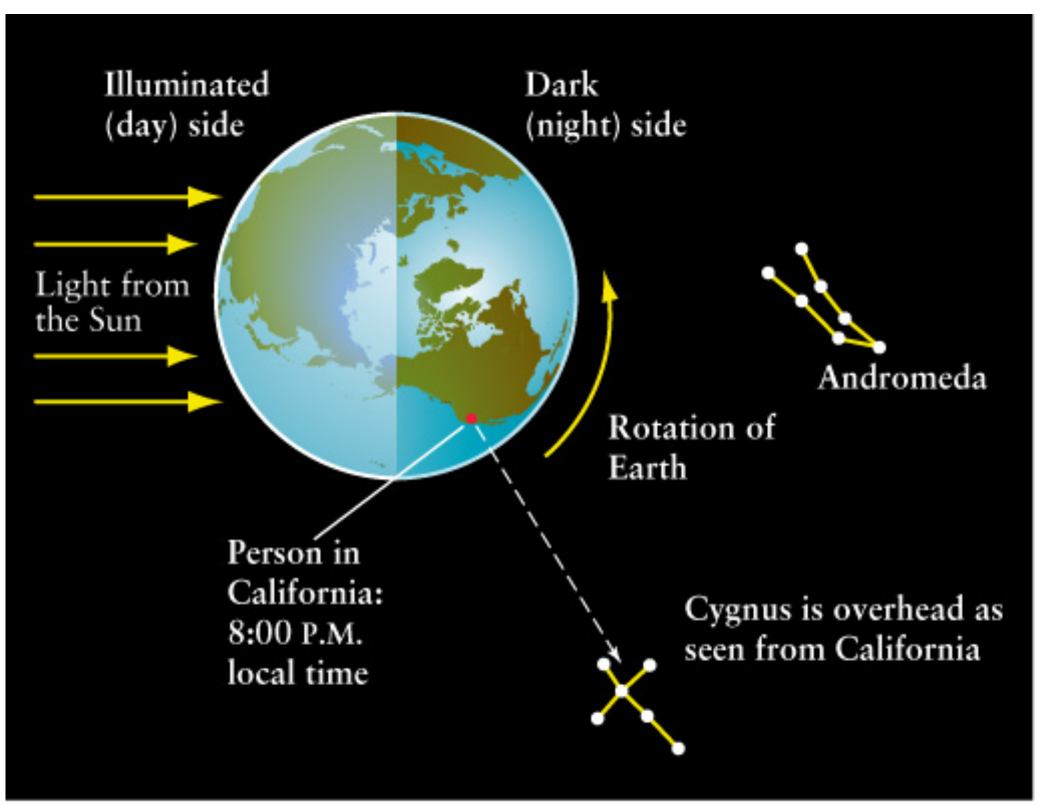
Bailey, Slater & Slater

Last time...

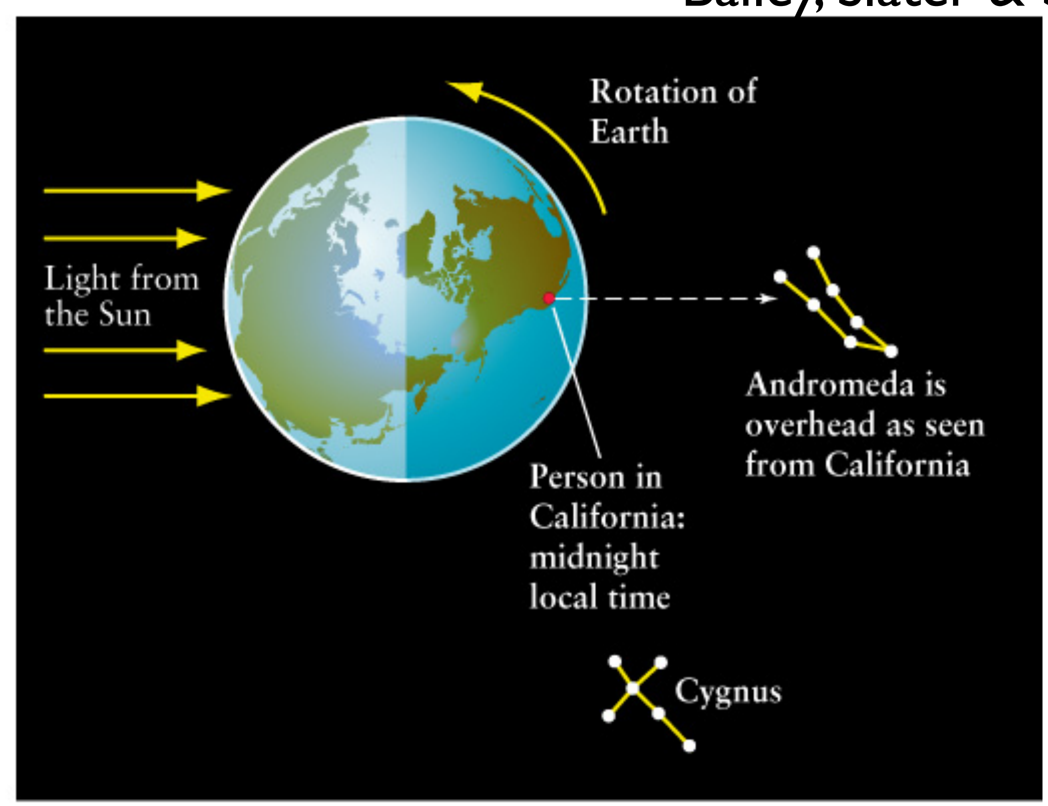
the sky "moves" East to West

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

Bailey, Slater & Slater



(a) Earth as seen from above the north pole

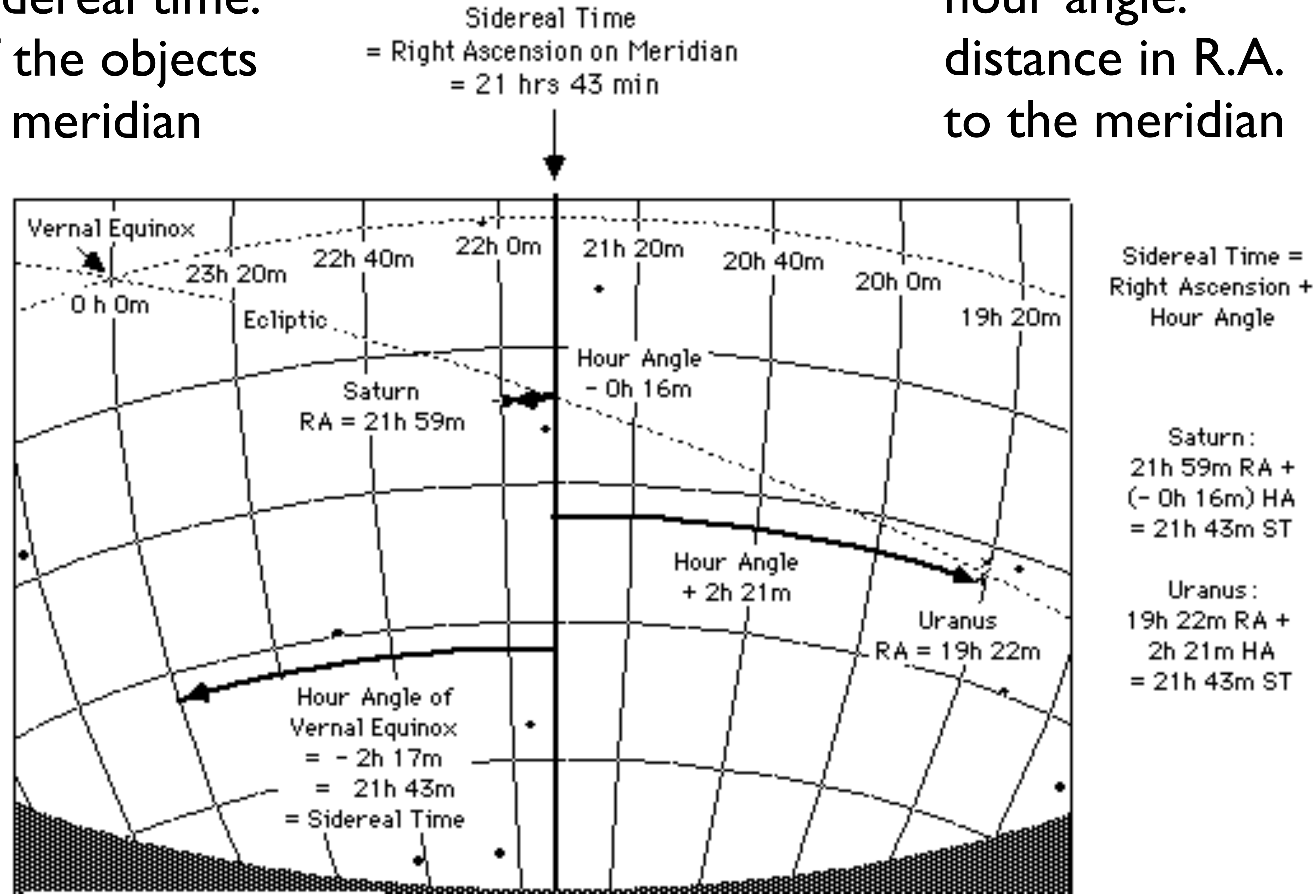


(b) 4 hours (one-sixth of a complete rotation) later

Last time...

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

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



Time

Need to know the current time!

Your telescope needs to know the LST in order 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

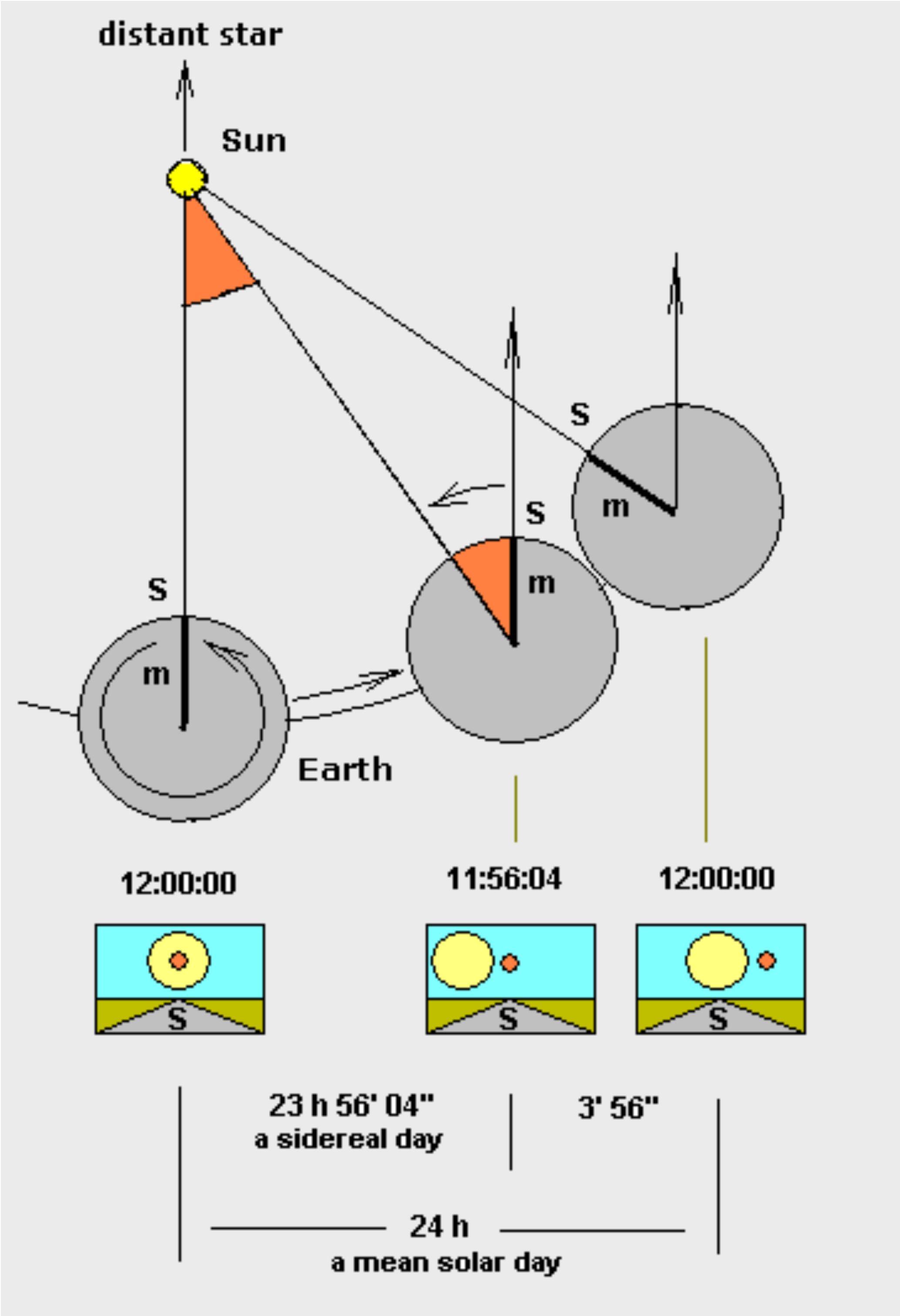
“sidereal” = “of the stars”

sidereal time: defined with respect to the stars

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

same sky is overhead after 23h 56min

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

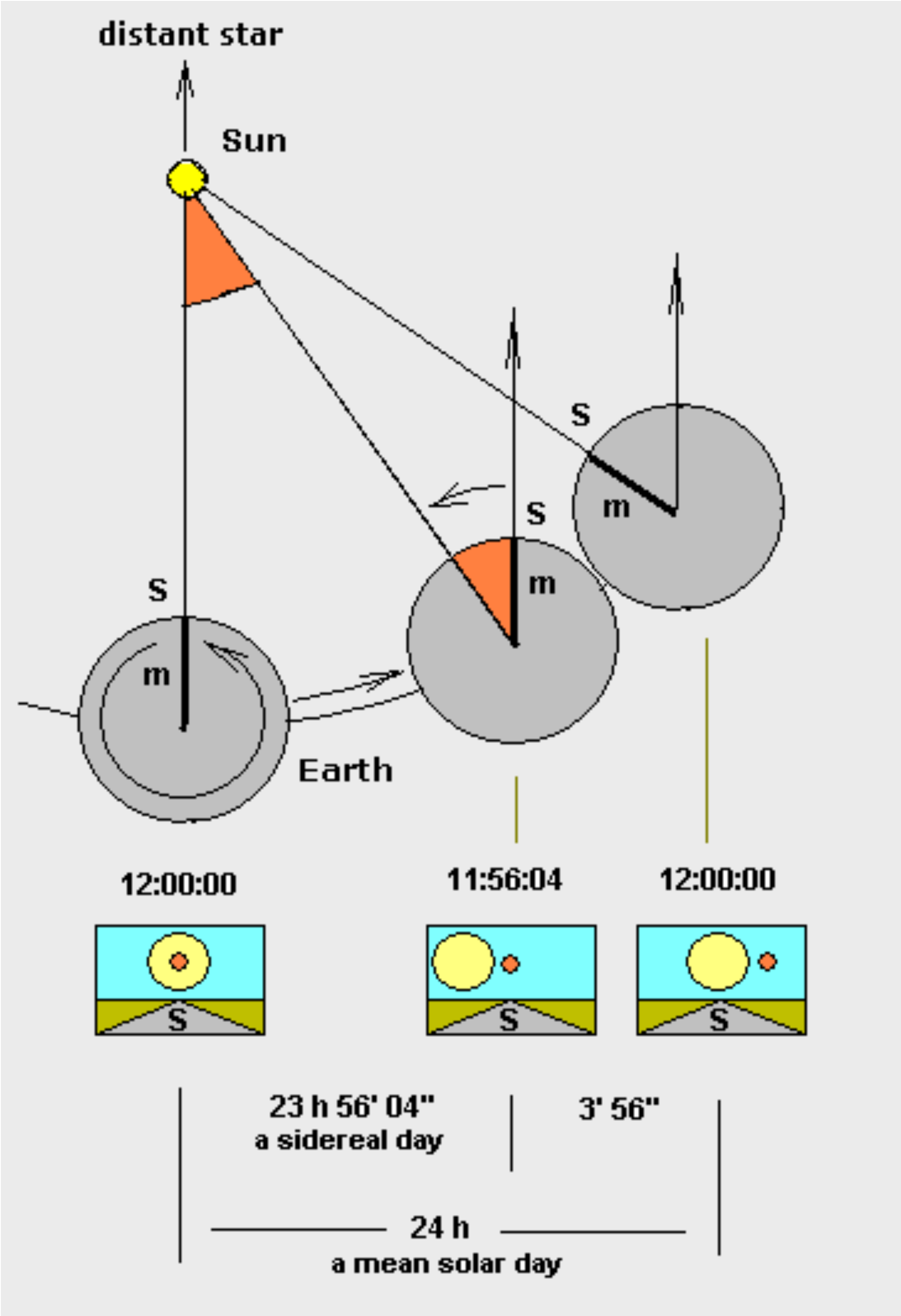


wikipedia

This means...

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

one year has 365+1 sidereal days



wikipedia

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

UTC time is 4h ahead of NY during daylight savings time, 5h during regular time

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 27, 2025, 3pm in Stony Brook: 2460915.291667

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

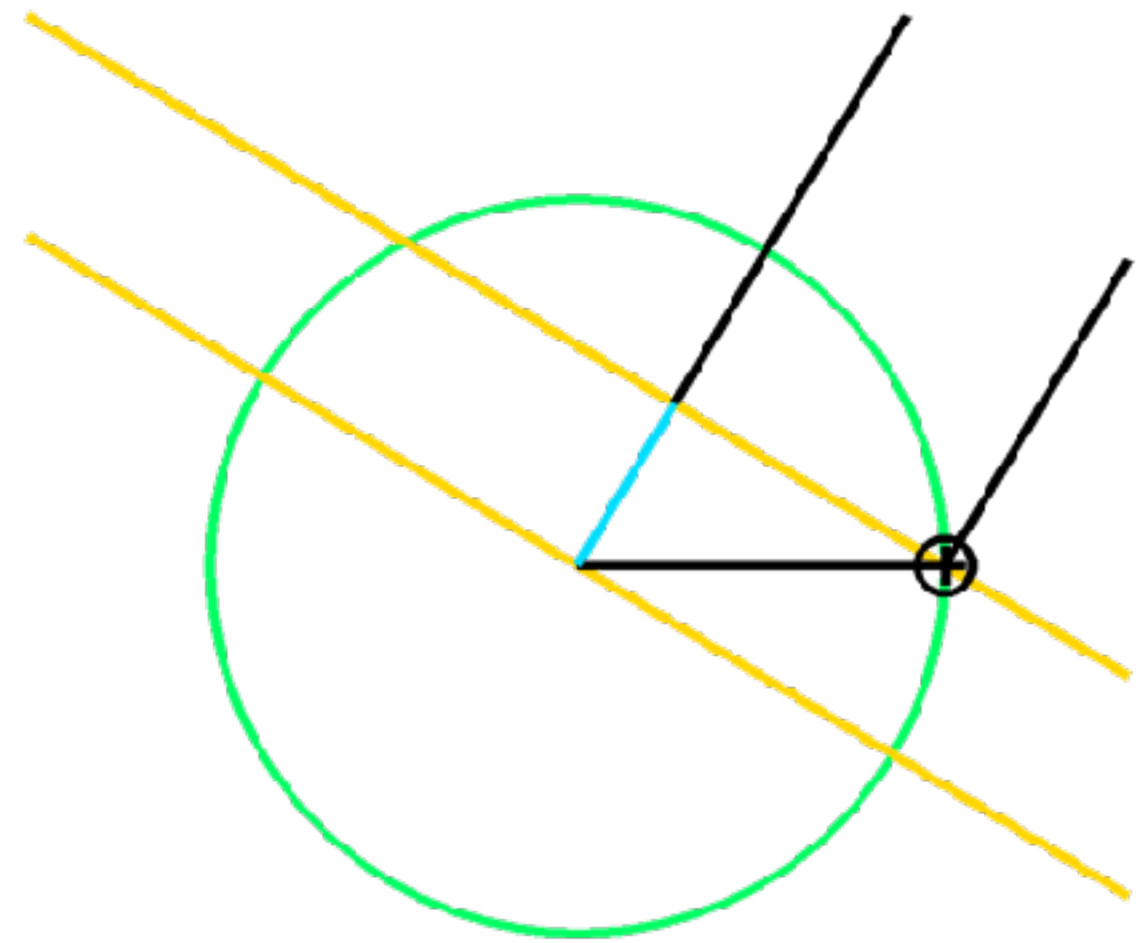
https://www.aavso.org/jd-calculator

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



J. Eastman

Epochs

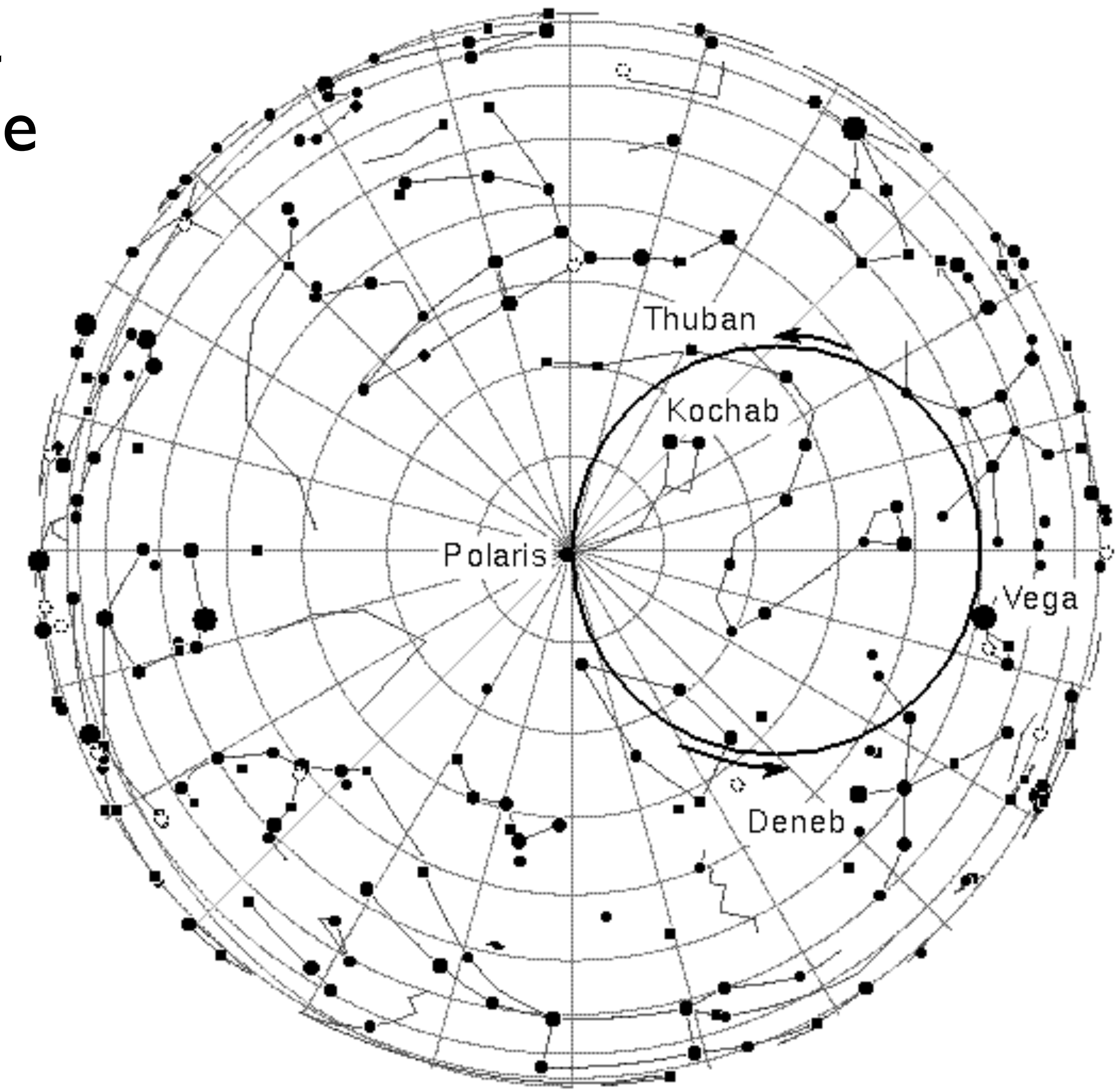
Earth's rotation axis is not constant in space with time

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

- Earthquakes

All coordinates need to be 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.

N. Strobel

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

faintest galaxies in Hubble Ultra Deep Field: 30 mag

Physical descriptions

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

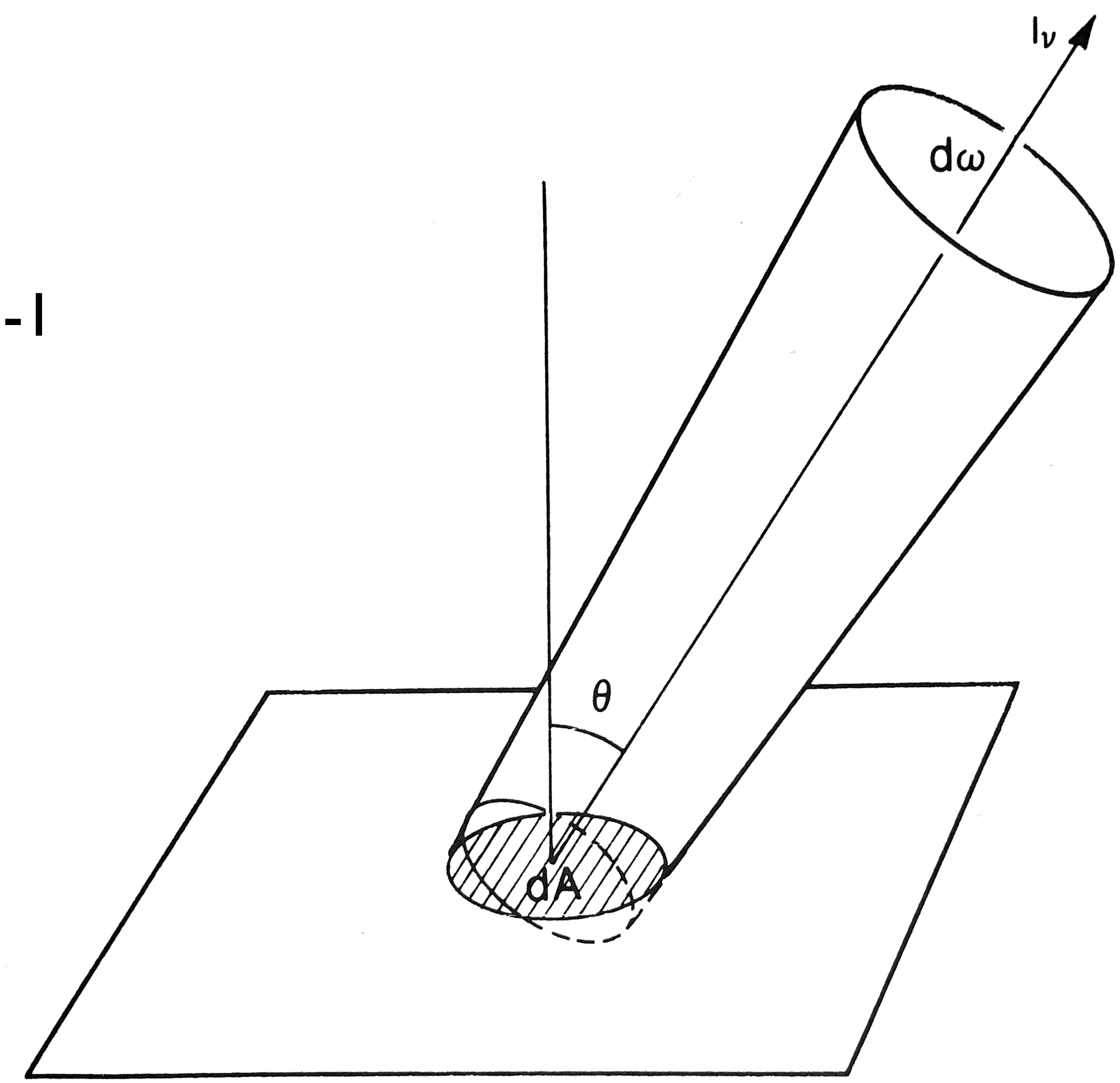
$$dE_\nu = I_\nu \, dA \cos\theta \, d\omega \, dt \, d\nu$$

specific intensity: I_ν

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

dA: any surface along light path; e.g. surface of star, or surface of detector

I_ν: intrinsic property of the object!



Karttunen et al.

Physical descriptions

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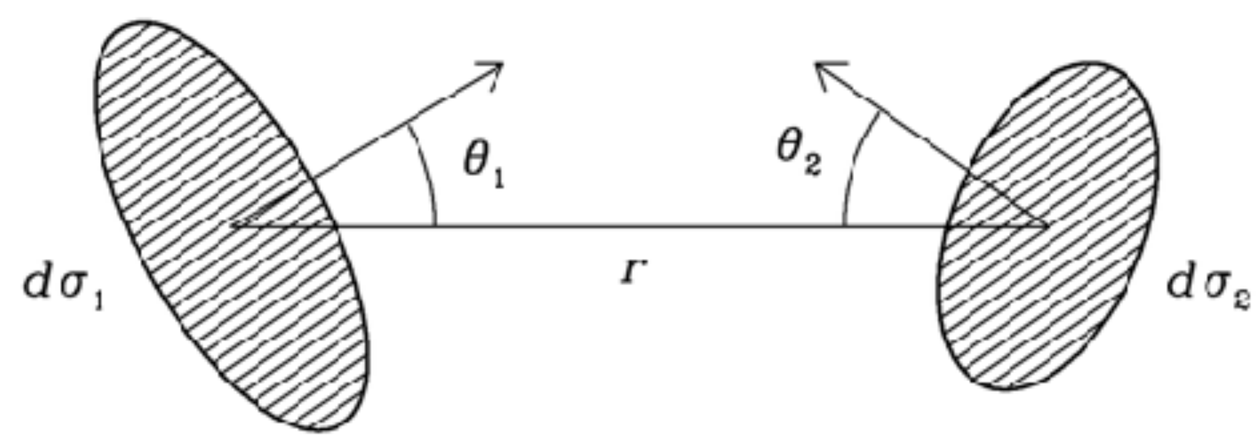
$$dE_\nu = I_\nu \, dA \cos\theta \, d\omega \, dt \, d\nu$$

specific intensity: I_ν

I_ν is constant along any ray in empty space

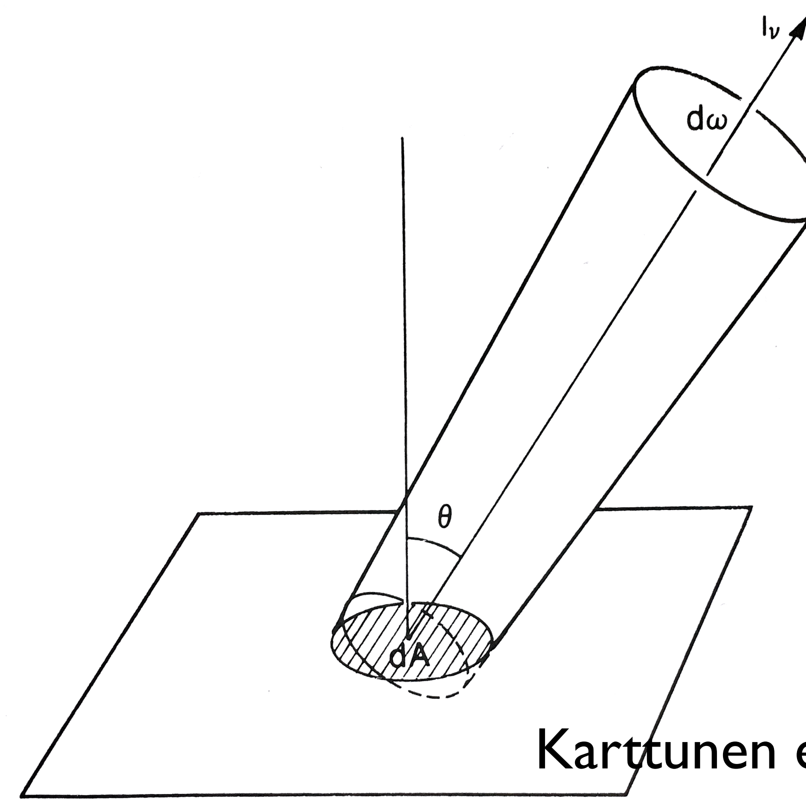
(Proof: $d\omega_1$ solid angle that $d\sigma_2$ subtends seen from $d\sigma_1$; $d\omega_2$ … $dE_1 = dE_2$)



Physical descriptions

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

integrate over solid angle: $$f_\nu = \int_\Omega d\omega \cos\theta \;\, I_\nu$$



Karttunen et al.

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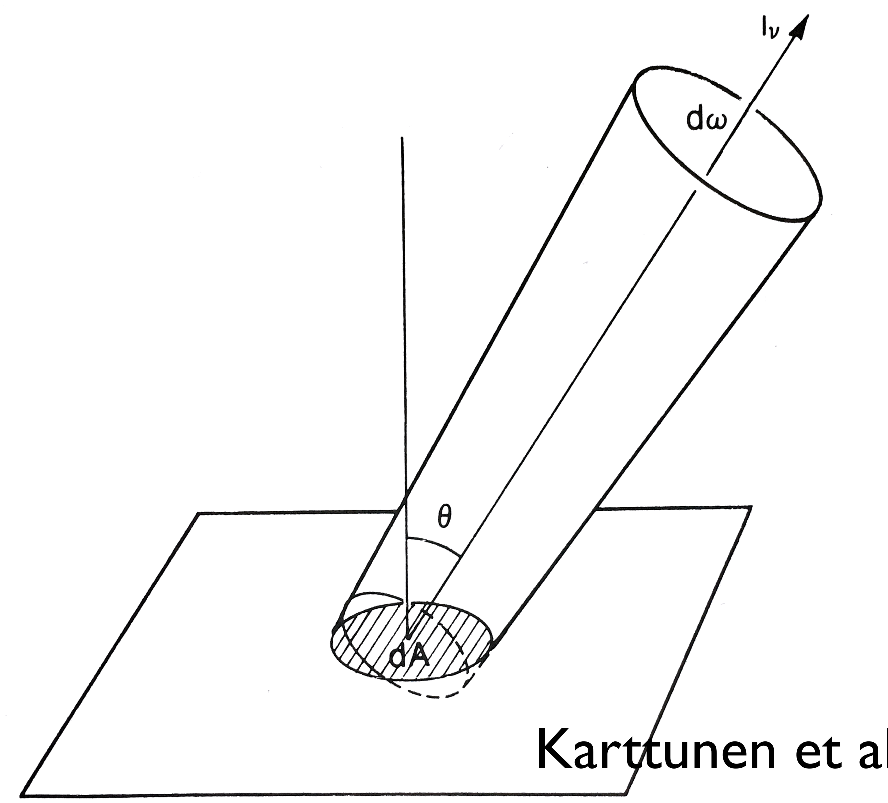
$$= \frac{1}{dA \;\, dt \;\, d\nu} \int_\Omega dE_\nu$$

spectral flux density f_ν: energy (leaving the surface of the star) per area, per time, per frequency interval

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



Karttunen et al.

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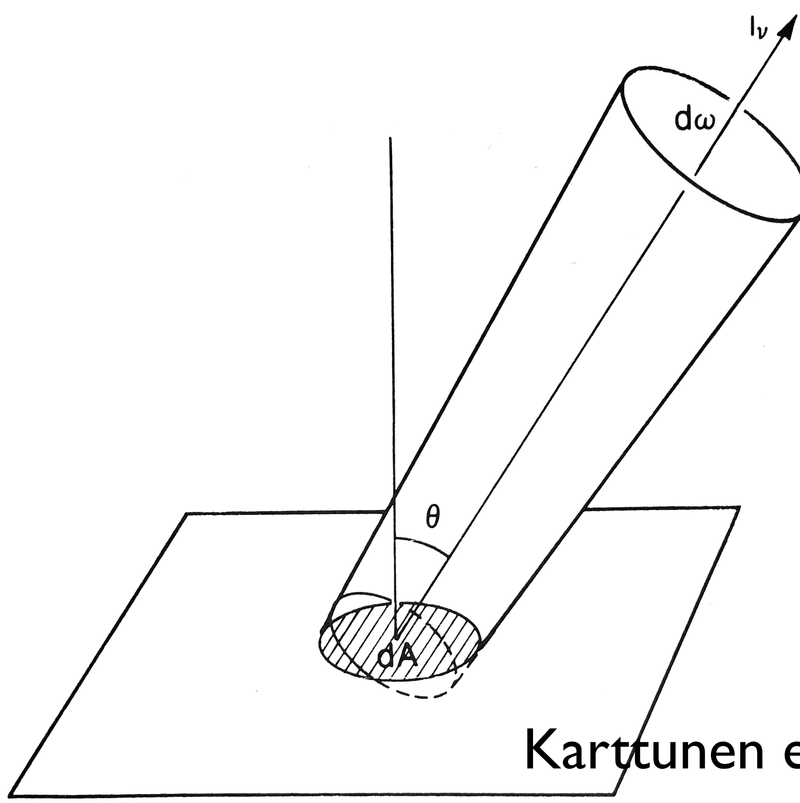
spectral flux density f_ν: energy (leaving the surface of the star) per area, per time, per frequency interval

for the observer: ($d\omega \cos\theta$) is the solid angle of the star seen from your eye

f_ν is usually what we observe

f_ν depends on distance source - observer



Karttunen et al.

Physical descriptions

spectroscopy: can determine f_ν

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

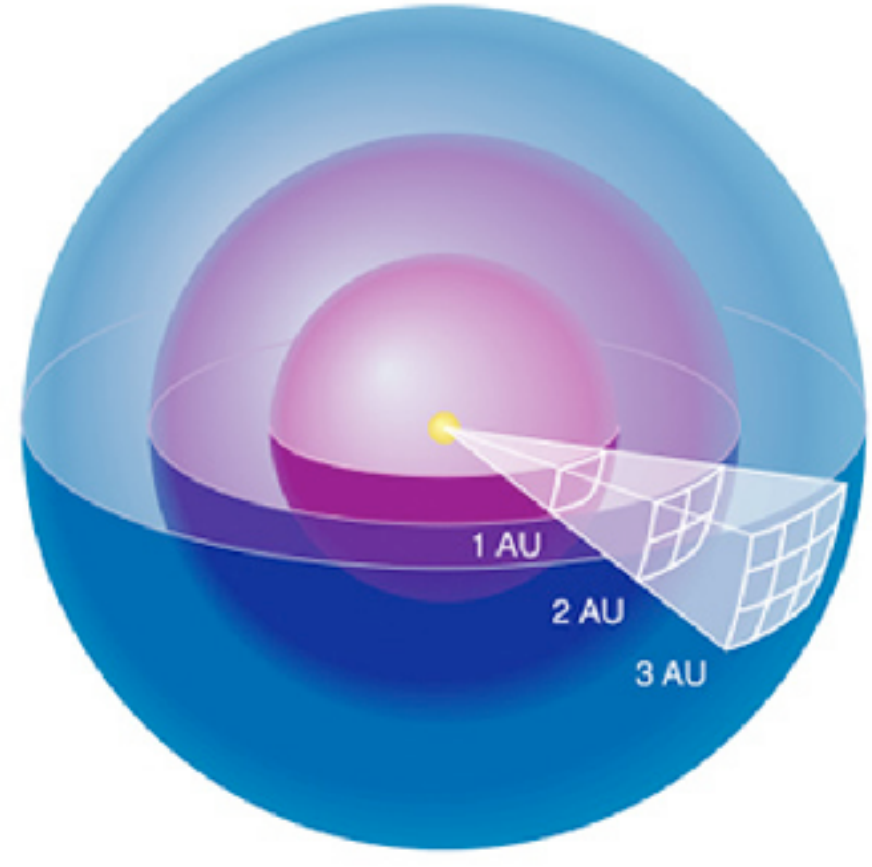
flux:

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

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

(note: usually specified for 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)

- integrate over surface area of star, flux through surface
- or: over sphere at distance d, flux drops as d^{-2}

➡ same result (because of conservation of photons)

intrinsic property of the object !

bolometric luminosity:

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

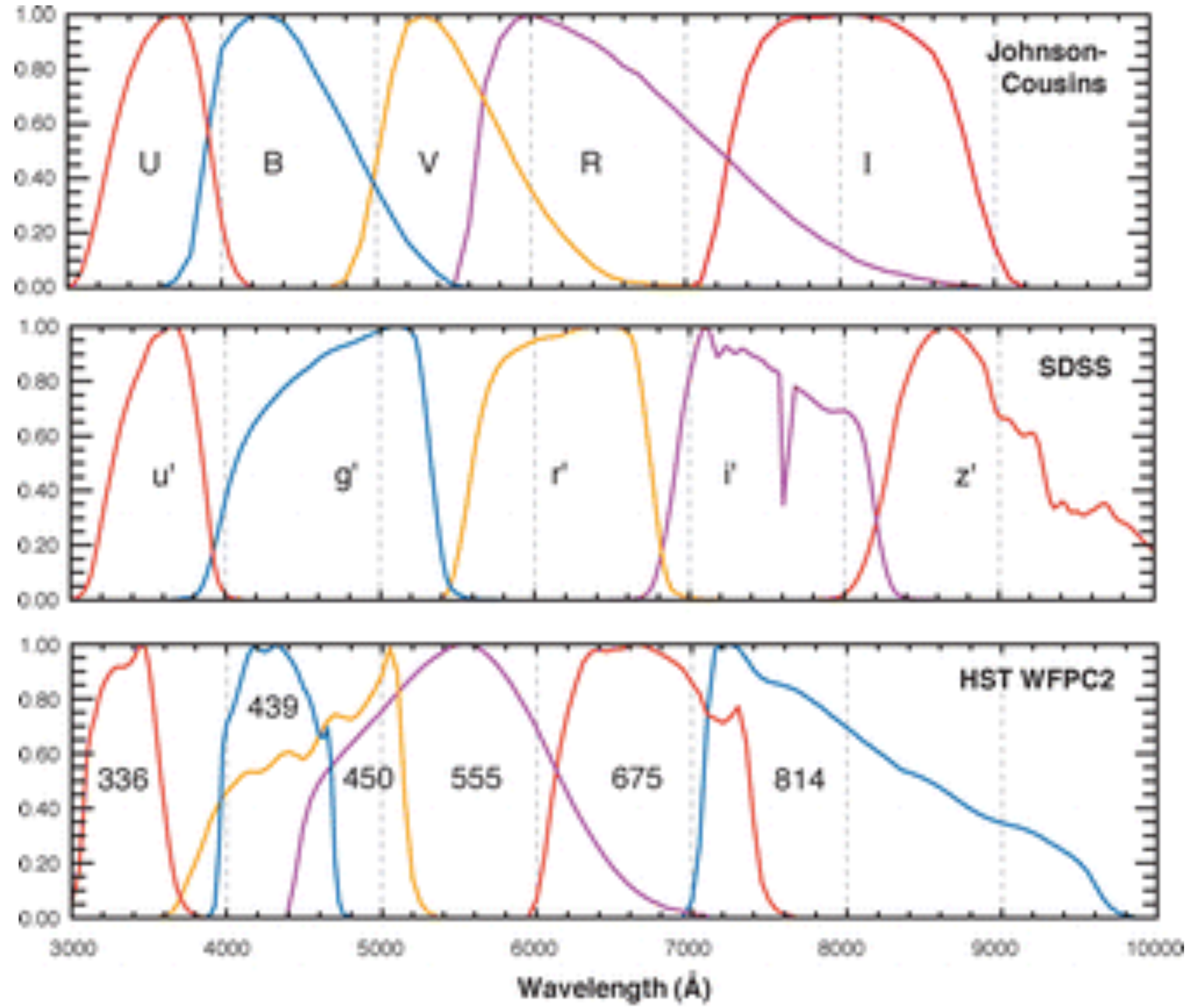
Filter systems

optical astronomy:

several standard photometric systems, "filter sets"

Johnson-Cousins: *UBVRI*

SDSS: *ugriz*



Bessel 2005

Color

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

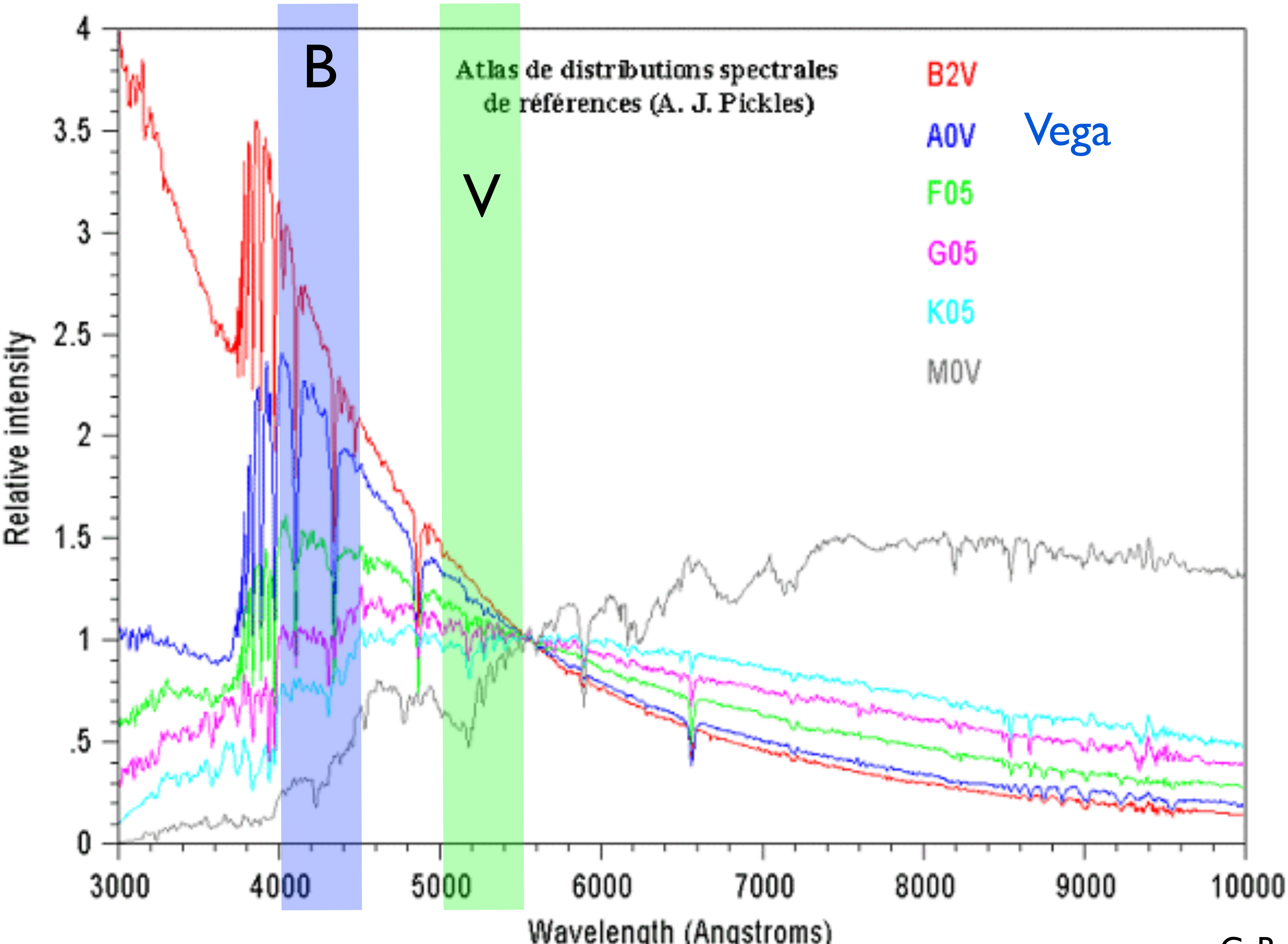
$$B - V = m_B - m_V = -2.5 \log \left(\frac{F_B}{F_V} \right)$$
$$= -2.5 \log \left(\frac{F_B}{F_{B,\mathrm{Vega}}} \right) + 2.5 \log \left(\frac{F_V}{F_{V,\mathrm{Vega}}} \right)$$

Vega has 0 color, by definition

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

Q: Is (B-V) positive or negative for a blue star?

Color



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

C. Buil

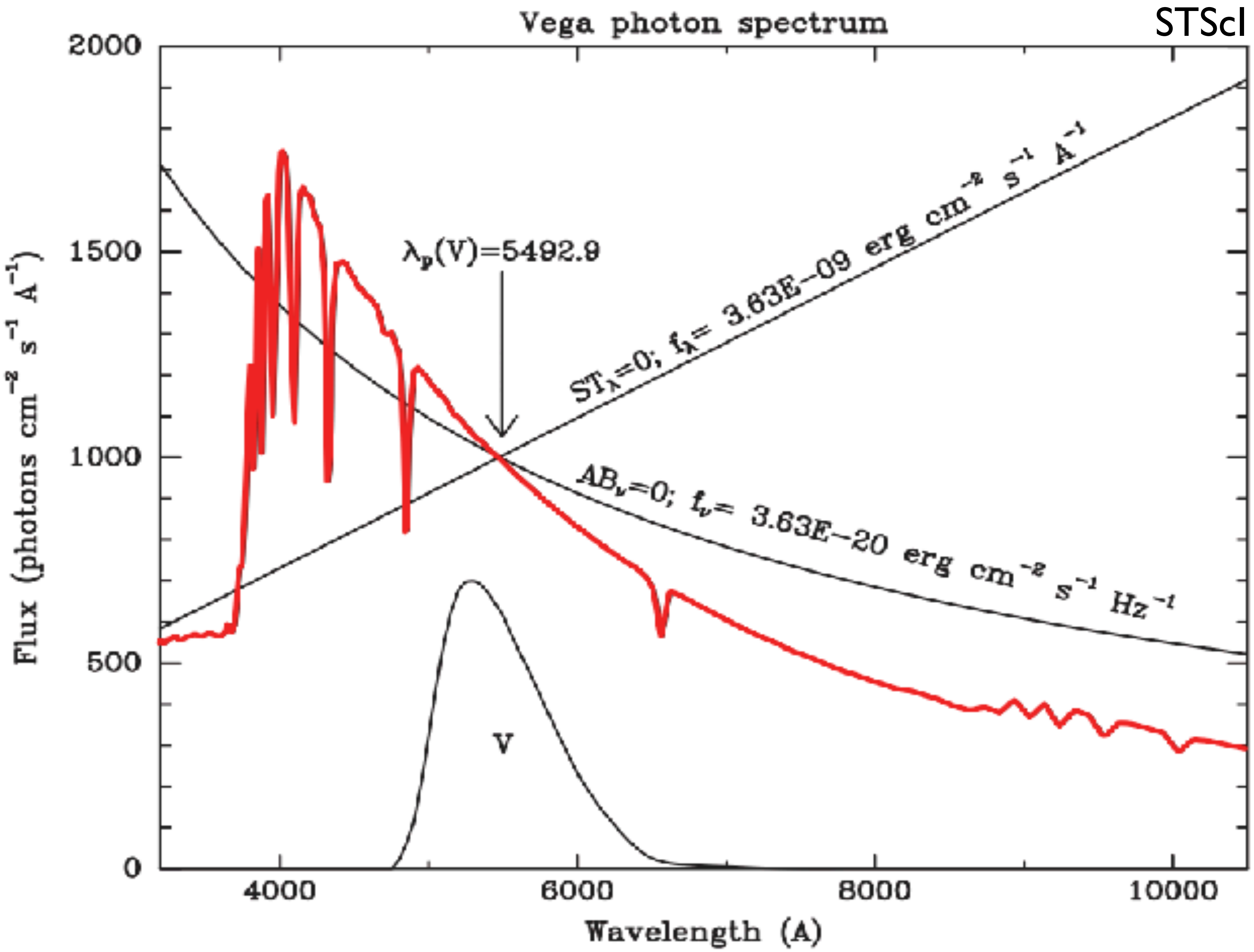
AB magnitudes

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

defined relative to *constant flux density*

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

STScI



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

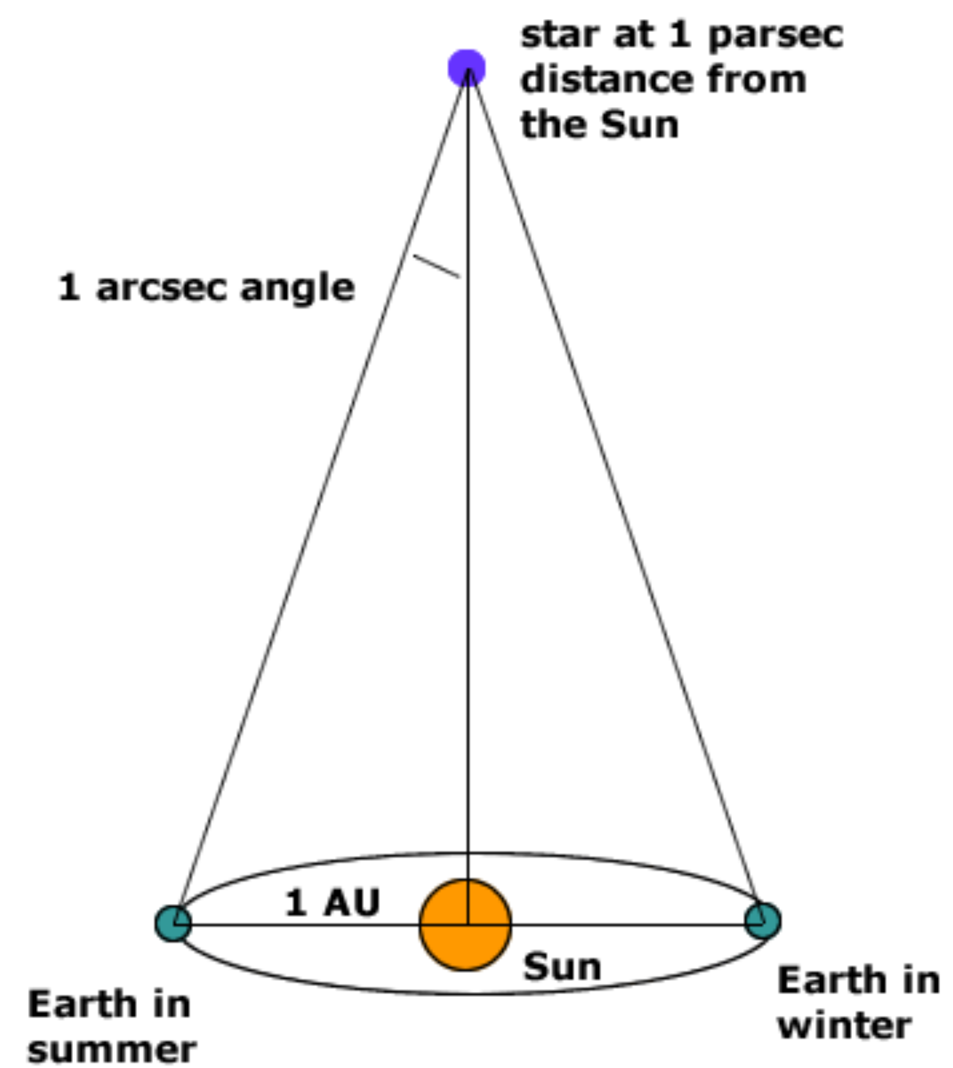
Parallax and parsecs

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

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

1 pc = 3.26 light-years = 3 x 10^{16}m

Proxima Centauri: ~1.3 pc

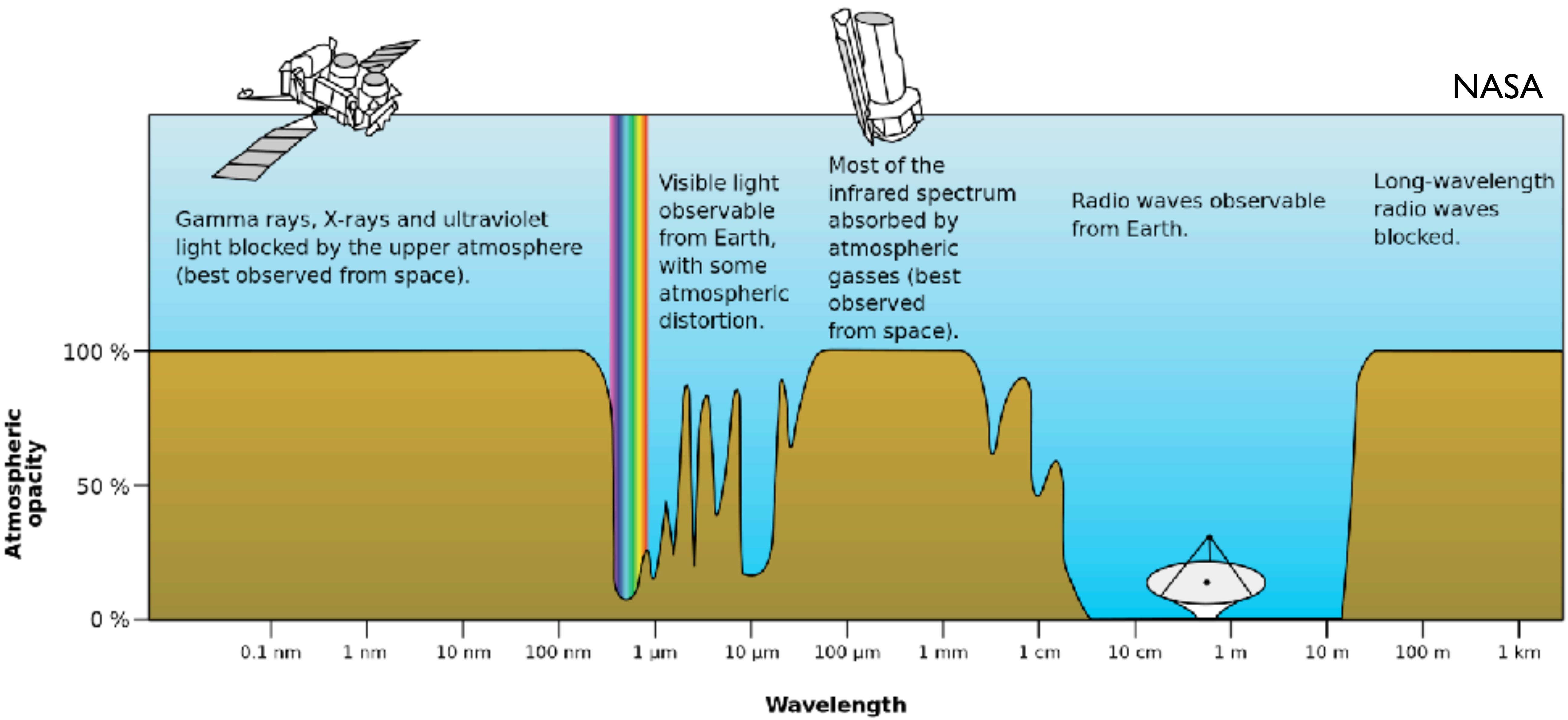


www.school-for-champions.com

Earth's atmosphere

the atmosphere is opaque to most of the electromagnetic spectrum

NASA

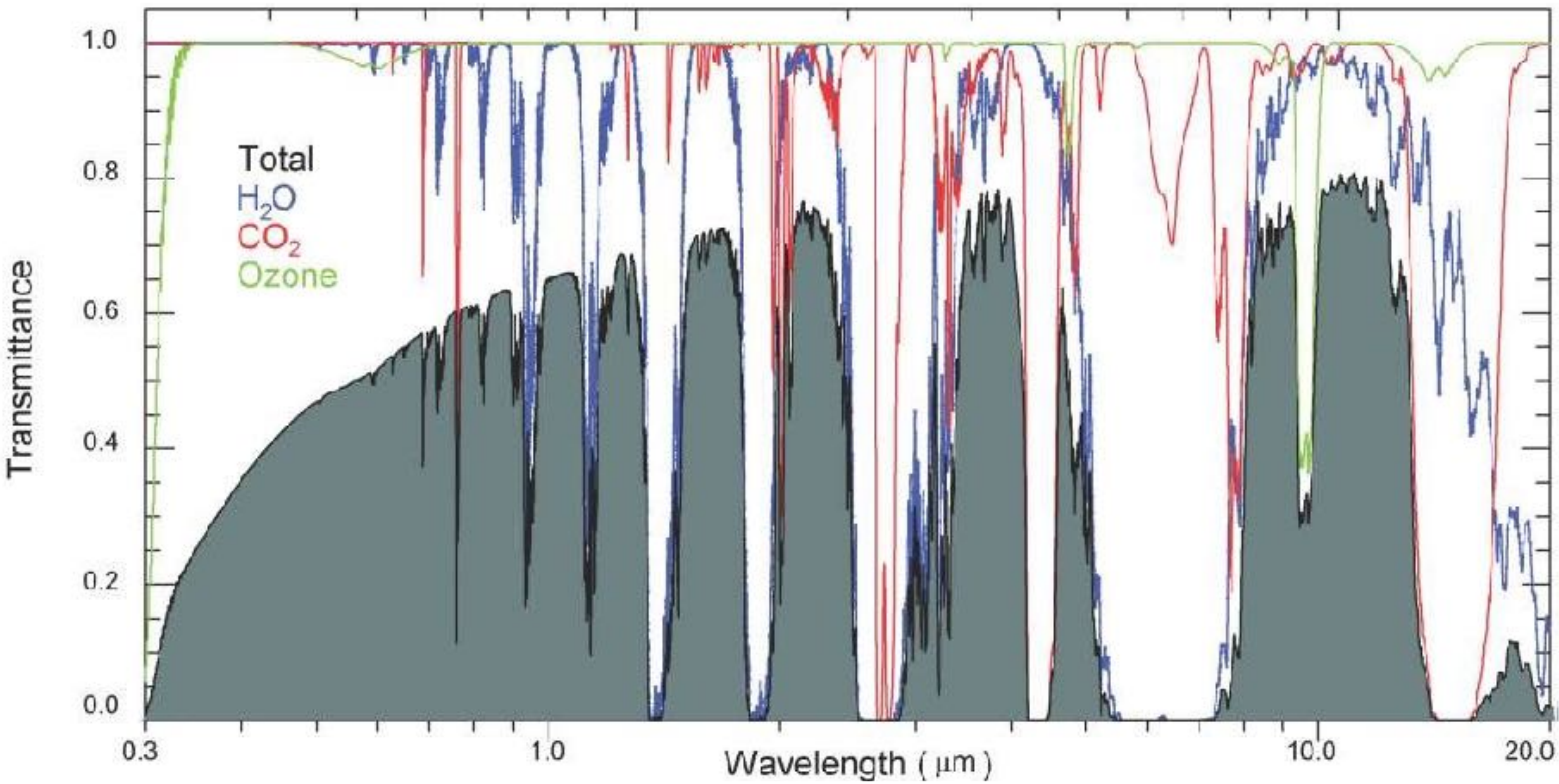


Earth's atmosphere

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

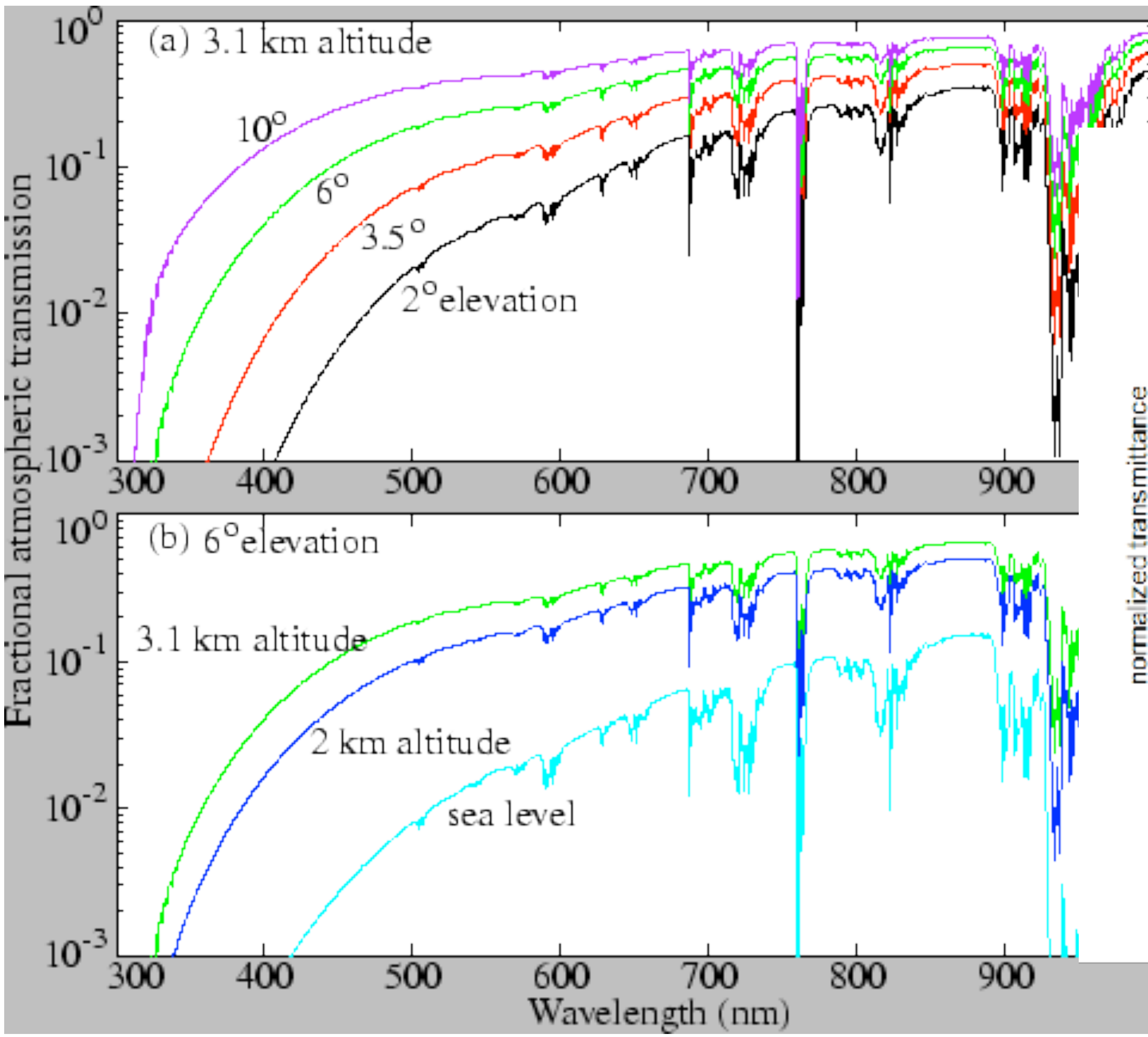
- scattering, e.g. Rayleigh $\propto \lambda^{-4}$
- absorption bands, mainly water

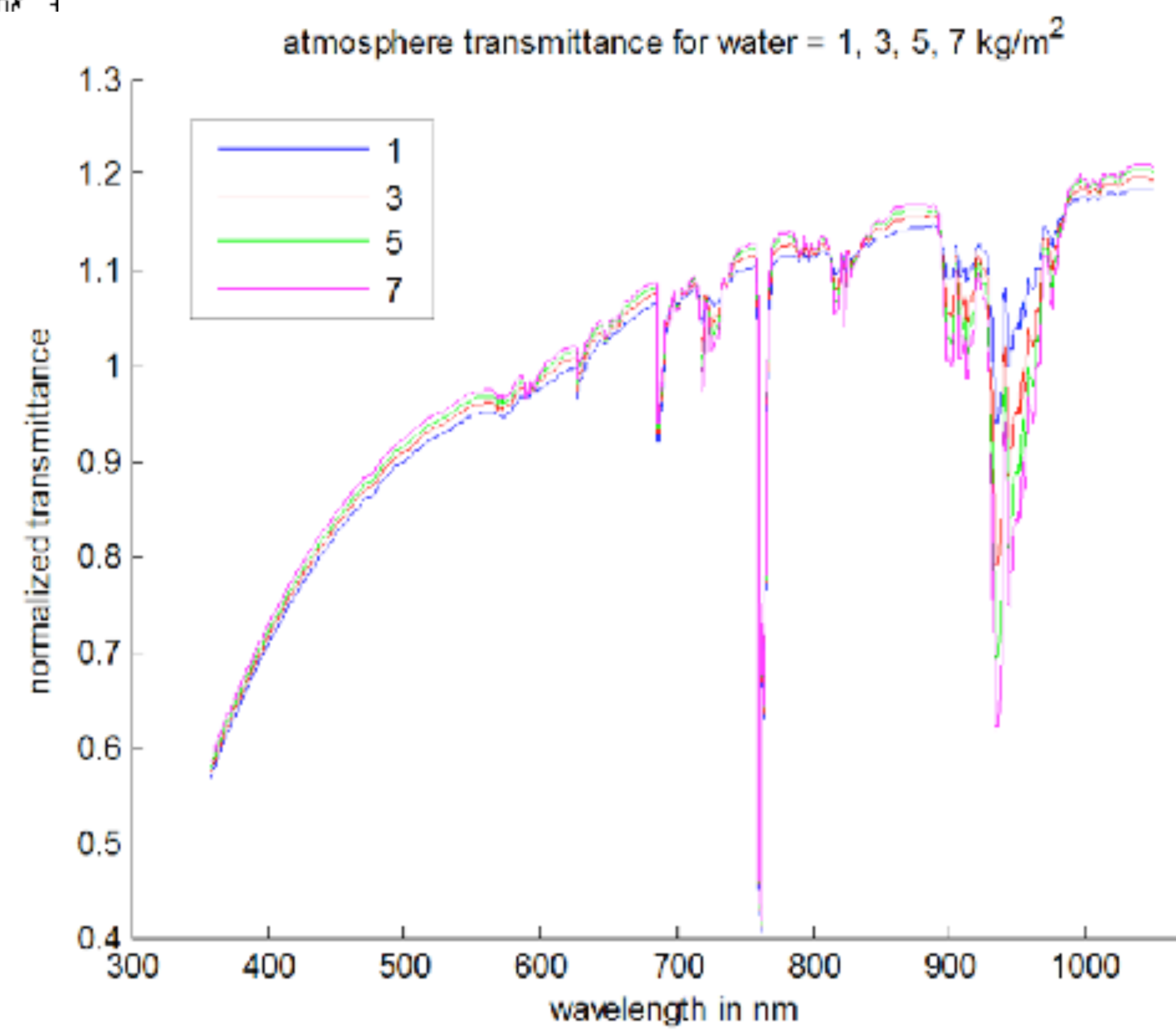
MODTRAN 4.0



Earth’s atmosphere

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





Ting Li

Airmass

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

plane-parallel approximation:

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

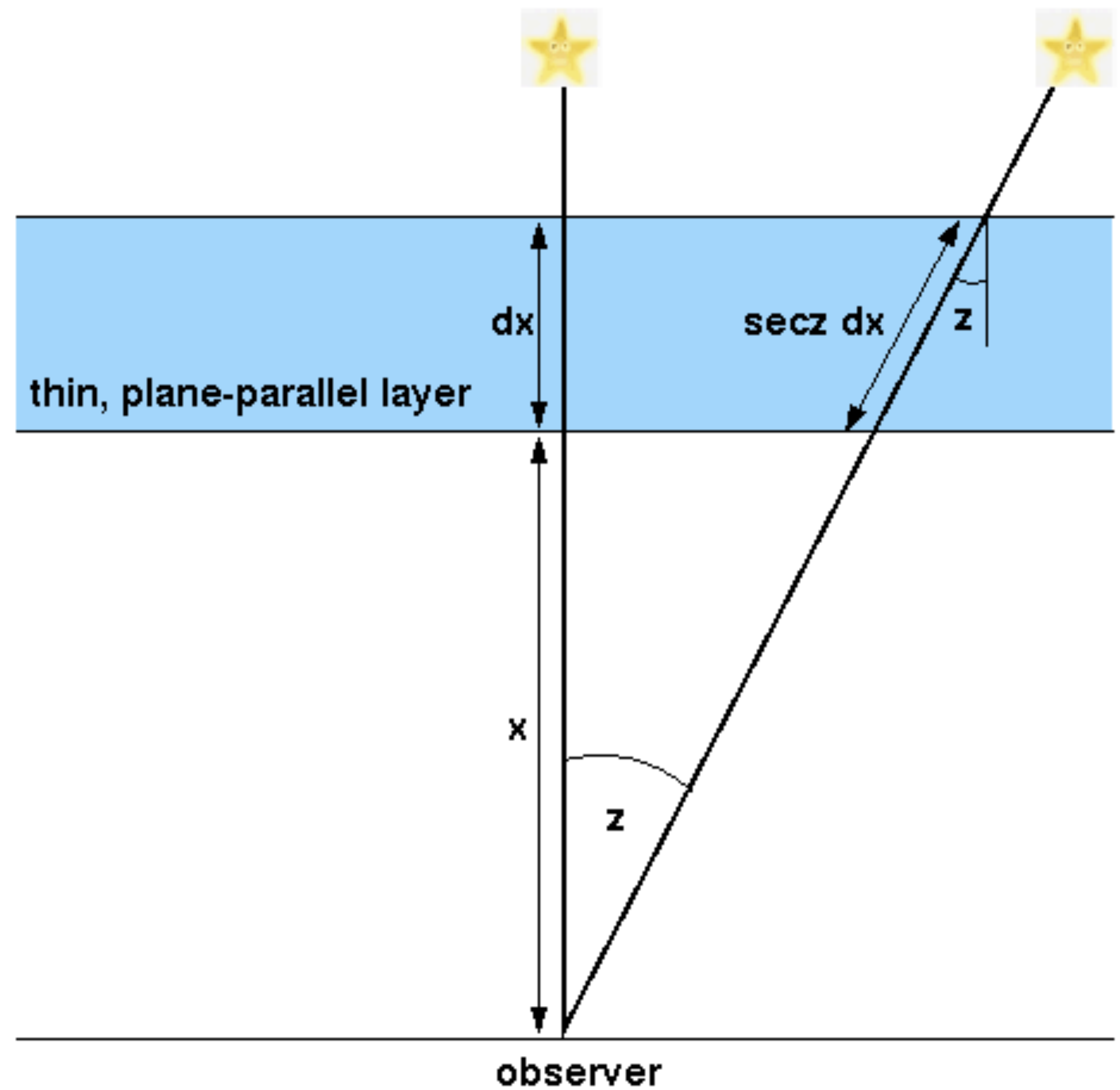
zenith distance:

z = 90° - altitude h

h=90°: AM=1

h=50°: AM=1.3

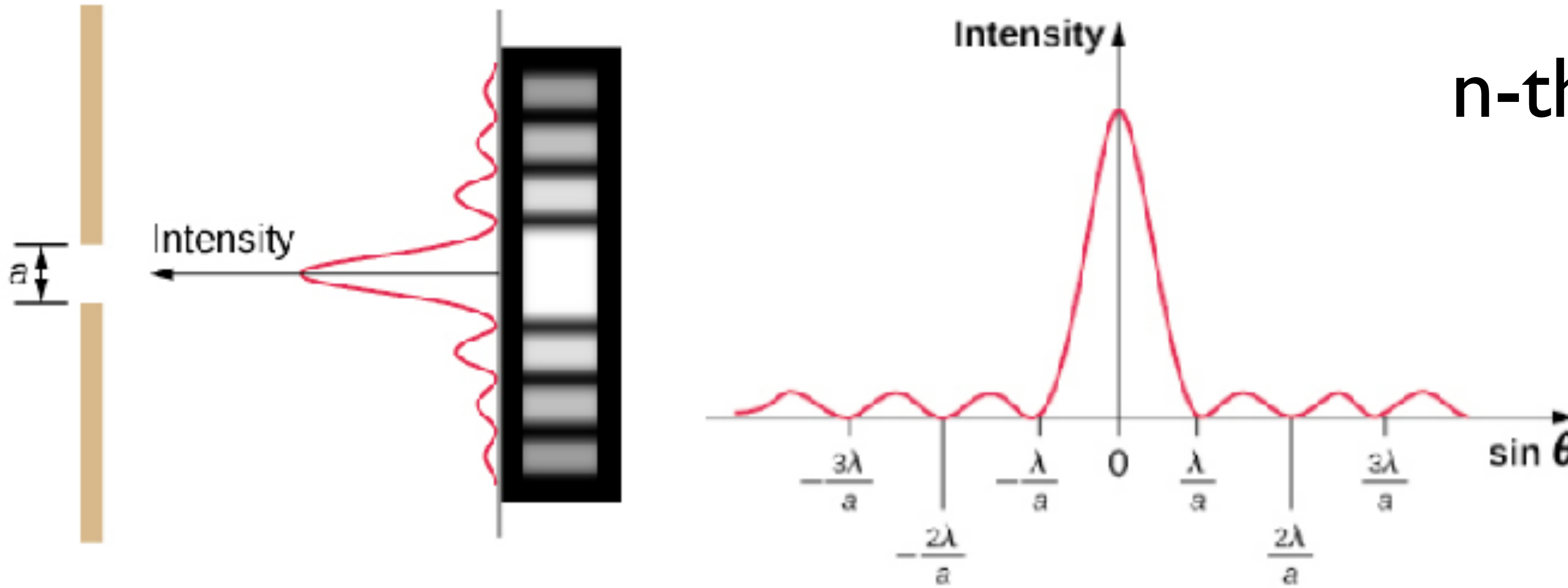
h=30°: AM=2



V. Dhillon

Telescope resolution

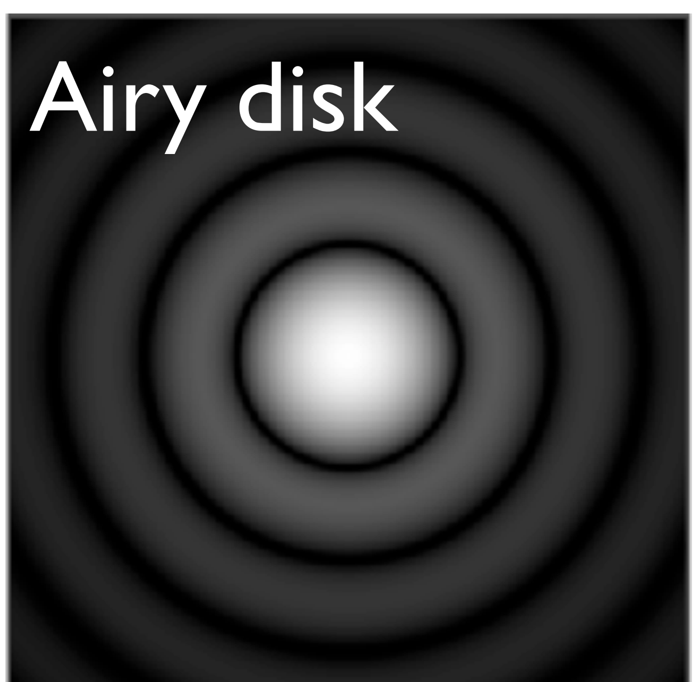
recall: single-slit diffraction

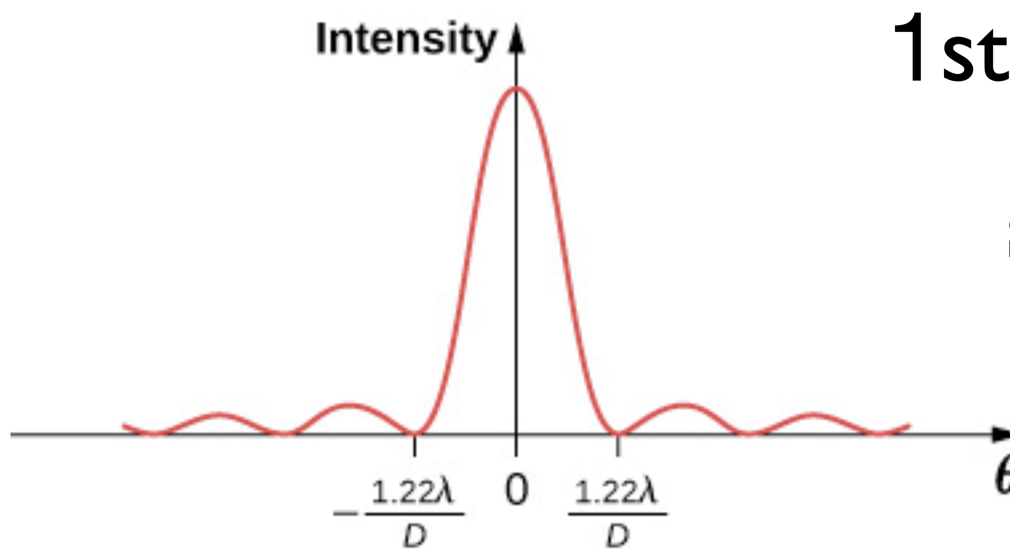


n-th minimum is at angle

$$\sin\theta = n\frac{\lambda}{a}$$

diffraction by a *circular aperture* with diameter D:





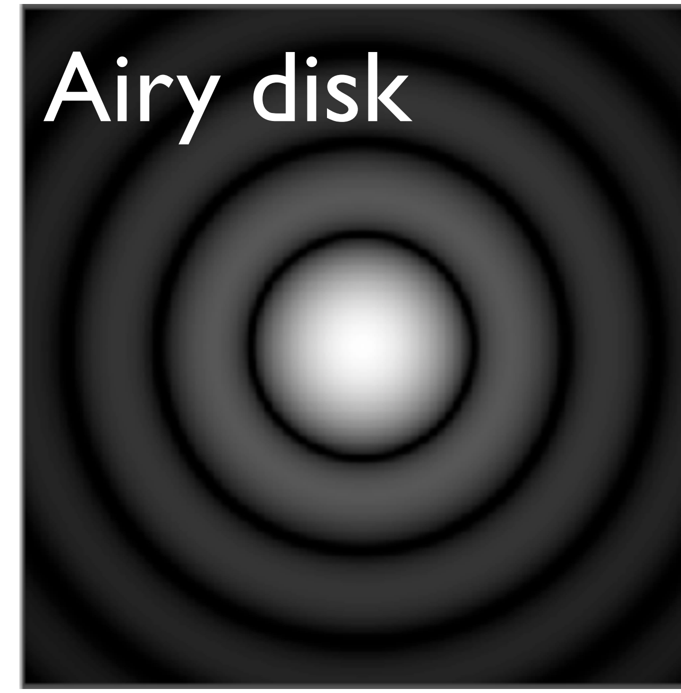
1st minimum is at angle:

$$\sin\theta \simeq \theta = 1.22\frac{\lambda}{D}$$

radius of the Airy disk

Telescope resolution

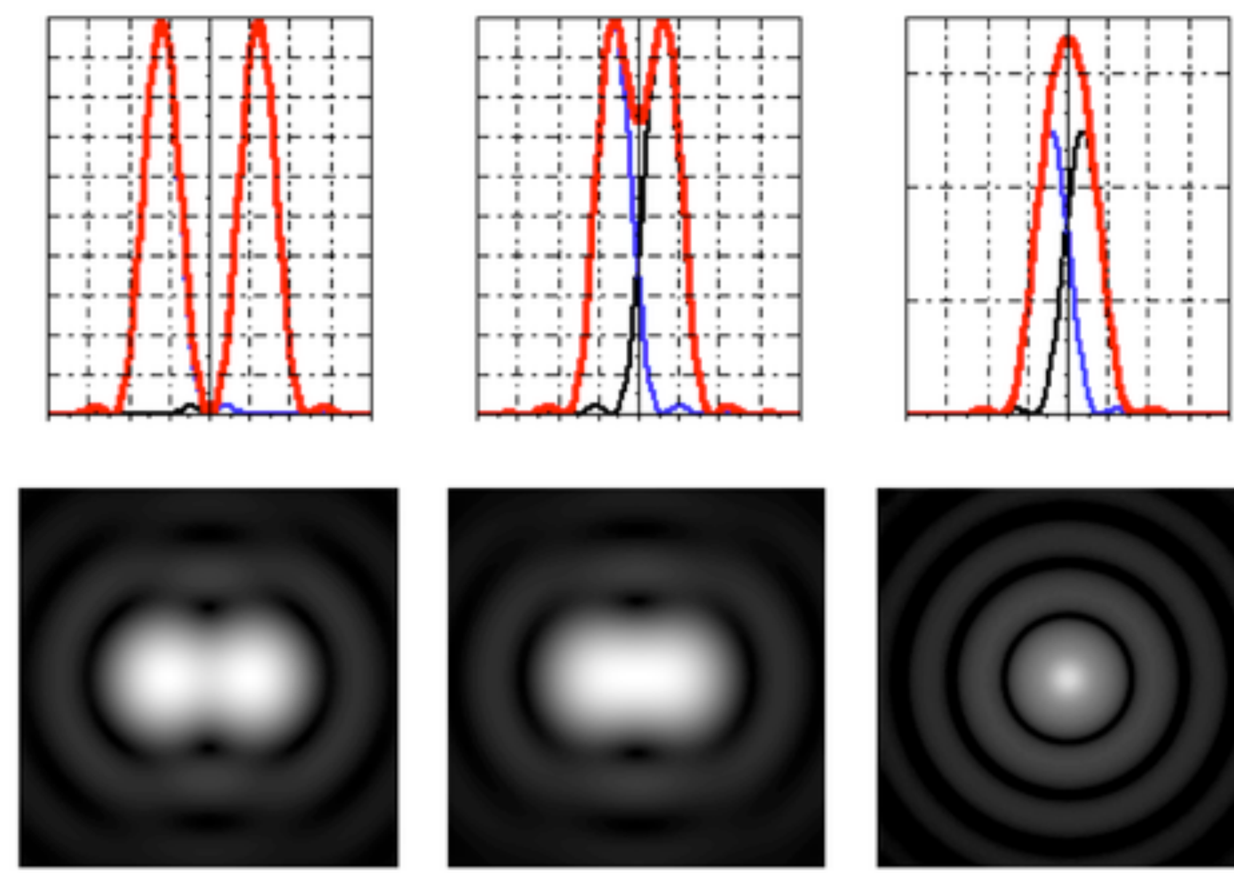
Light from a point source is imaged into an Airy disk of finite size → *fundamental resolution limit of a telescope*



Larger telescope: better resolution

Longer wavelengths: worse resolution

$$\theta = 1.22\frac{\lambda}{D}$$

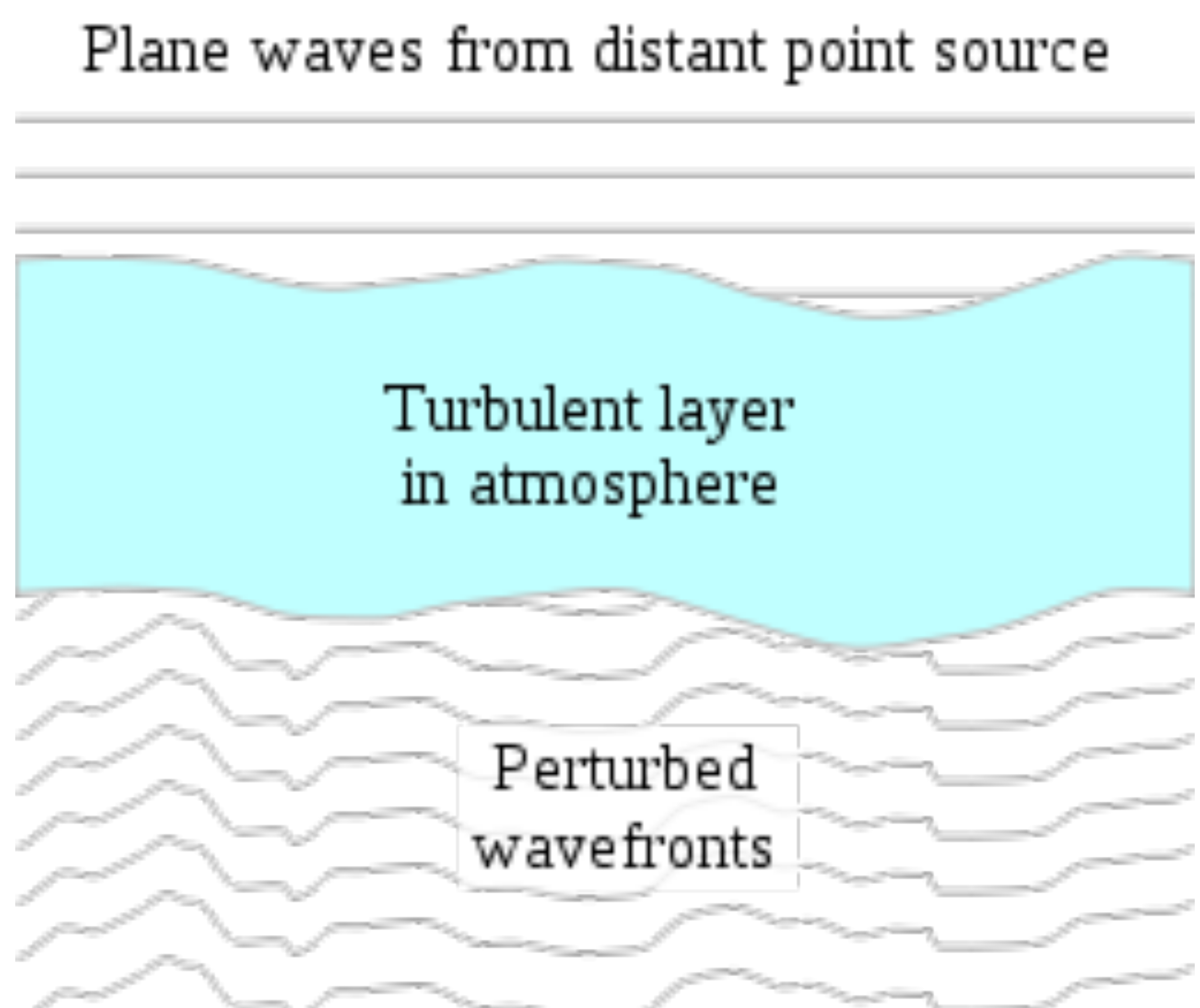


Rayleigh criterion: two point sources cannot be resolved if their separation is less than the radius of the Airy disk.

Seeing

theoretical resolution of 14 inch telescope: ~0.3”

in practice, the resolution of most telescope is limited by the atmosphere:

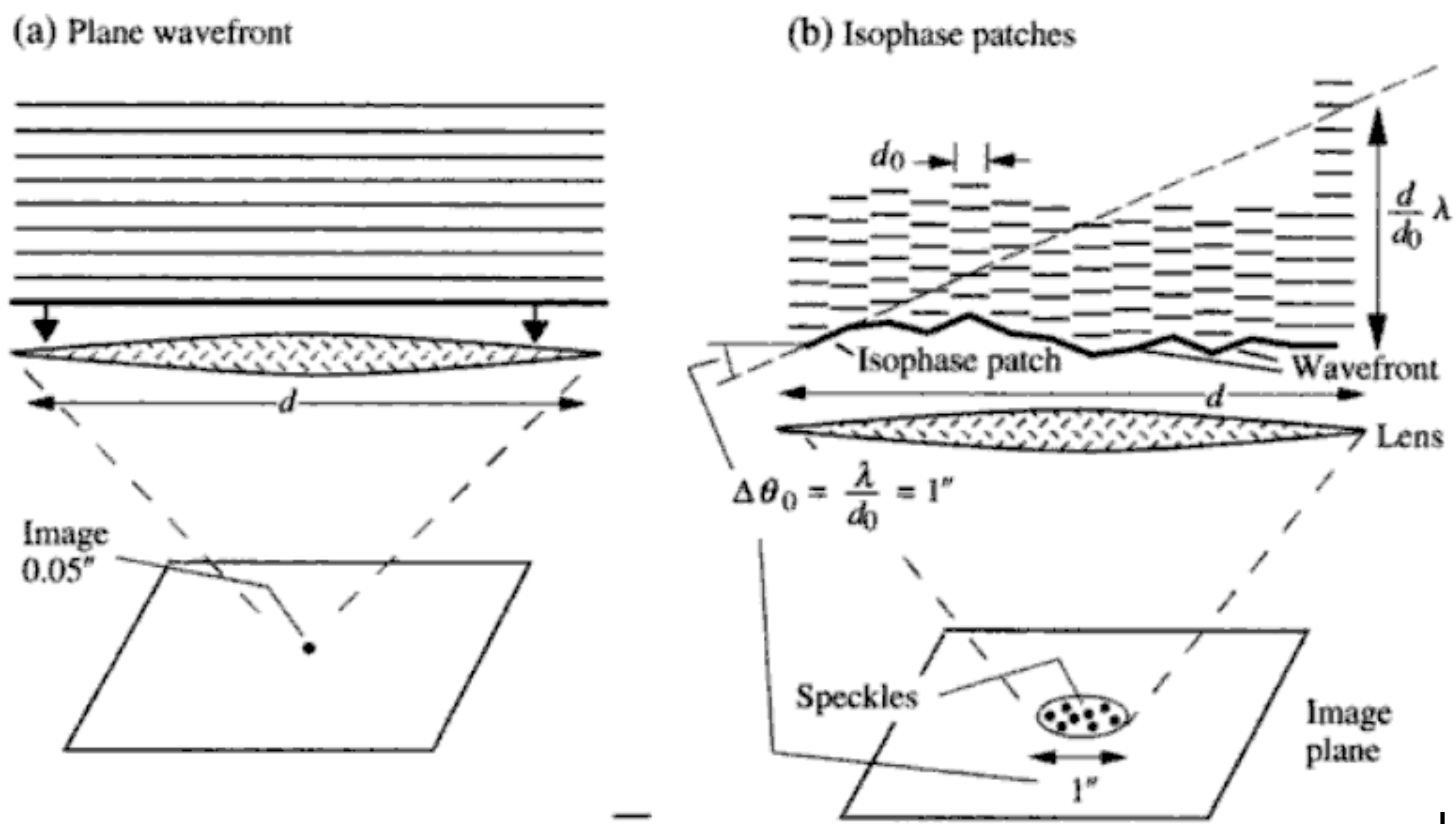


seeing: turbulence in the atmosphere, leads to “blurring” of images

D. Eccles

Seeing

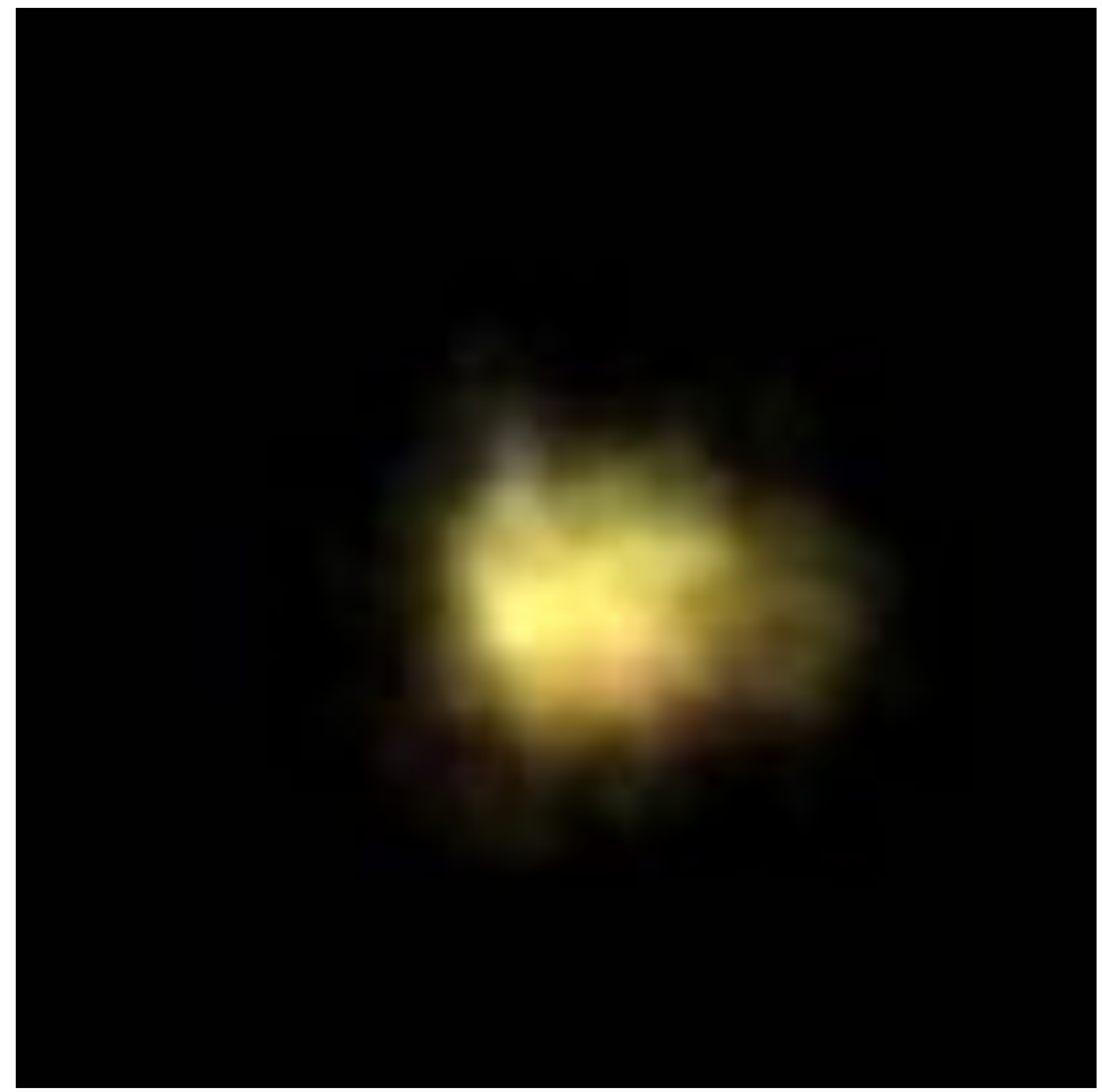
wavefront gets broken into isophase patches, each is a "mini-image" - interference leads to "speckles"



H. Bradt

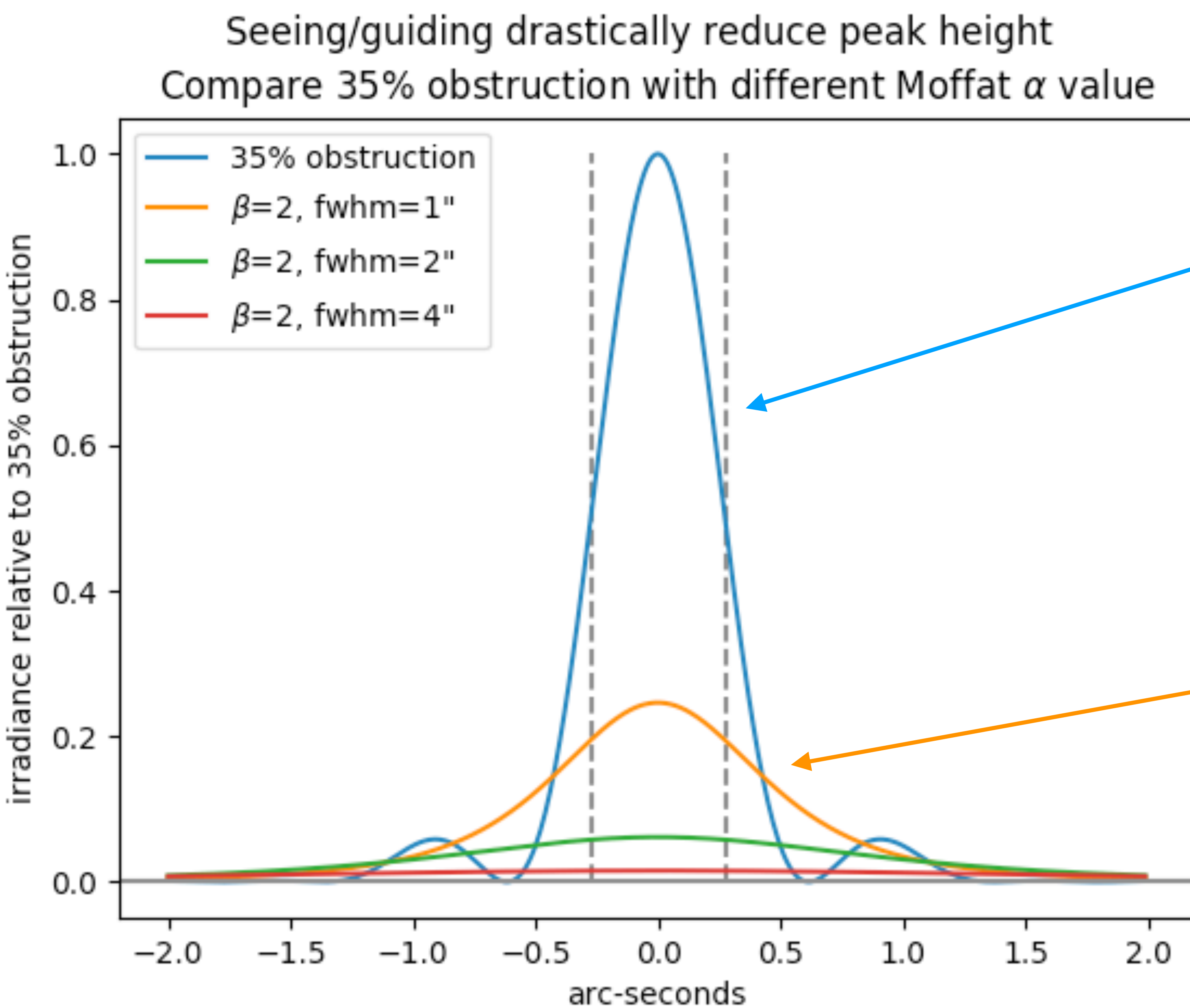
Seeing

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



MPIfR

Seeing



Airy disk for 8-inch telescope (with central obstruction), radius 0.58”

Moffat profiles with FWHM seeing 1”, 2”, 4”

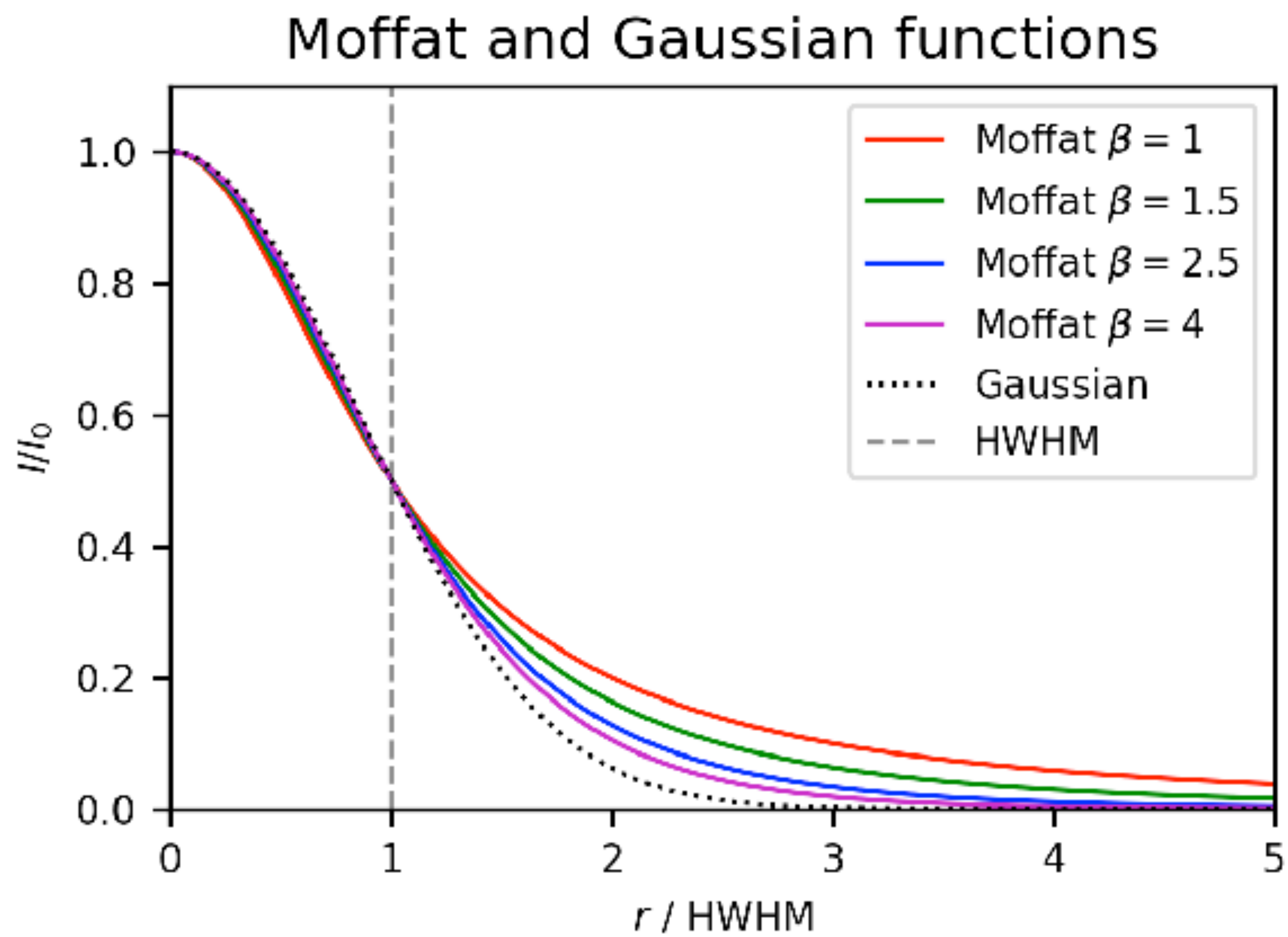
cloudynights forum, user: MetaGuide

Point Spread Function

Point Spread Function (PSF): the observed light distribution of stars in the image

determined by atmosphere and instrumentation

approximately Gaussian, but 2-parameter profiles (e.g. Moffat) are a better description



quoted as Full Width at Half Maximum (FWHM), FWHM ~ 2.35 σ

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

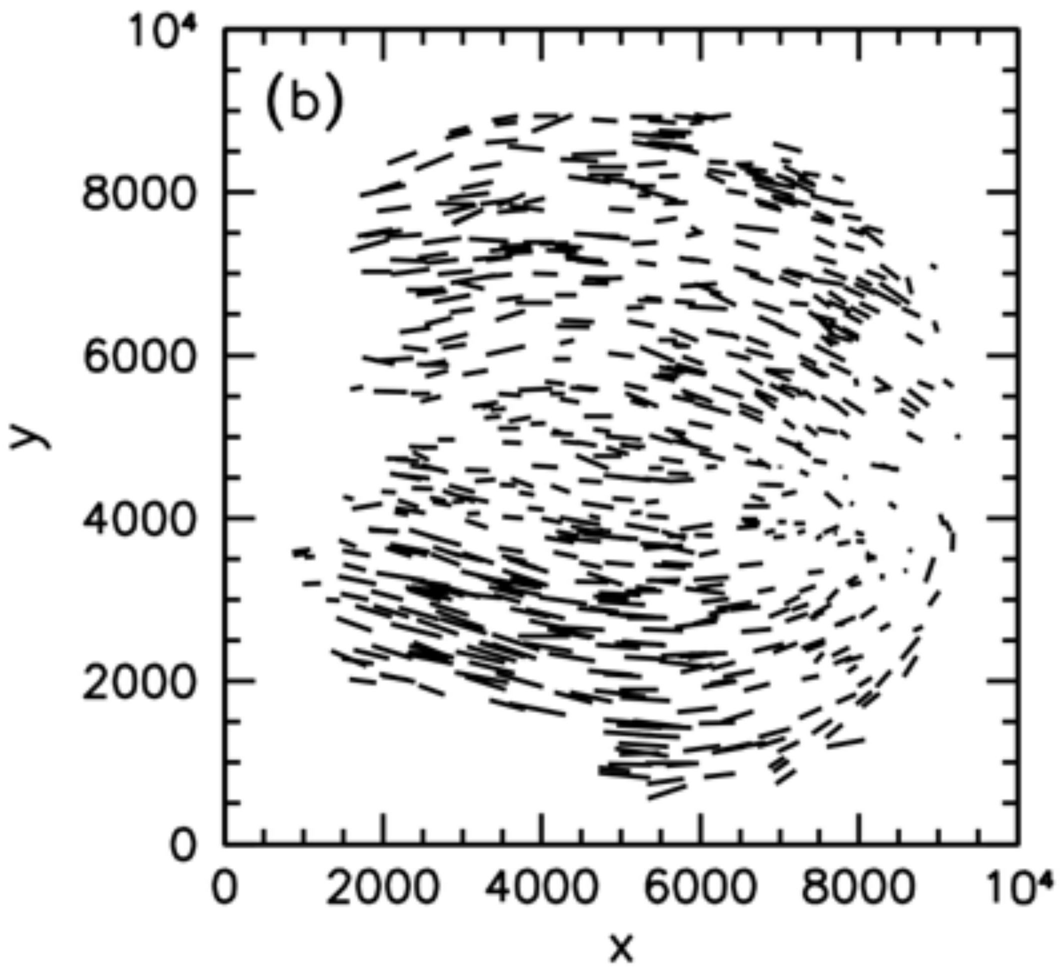
telescope dome can contribute significantly!

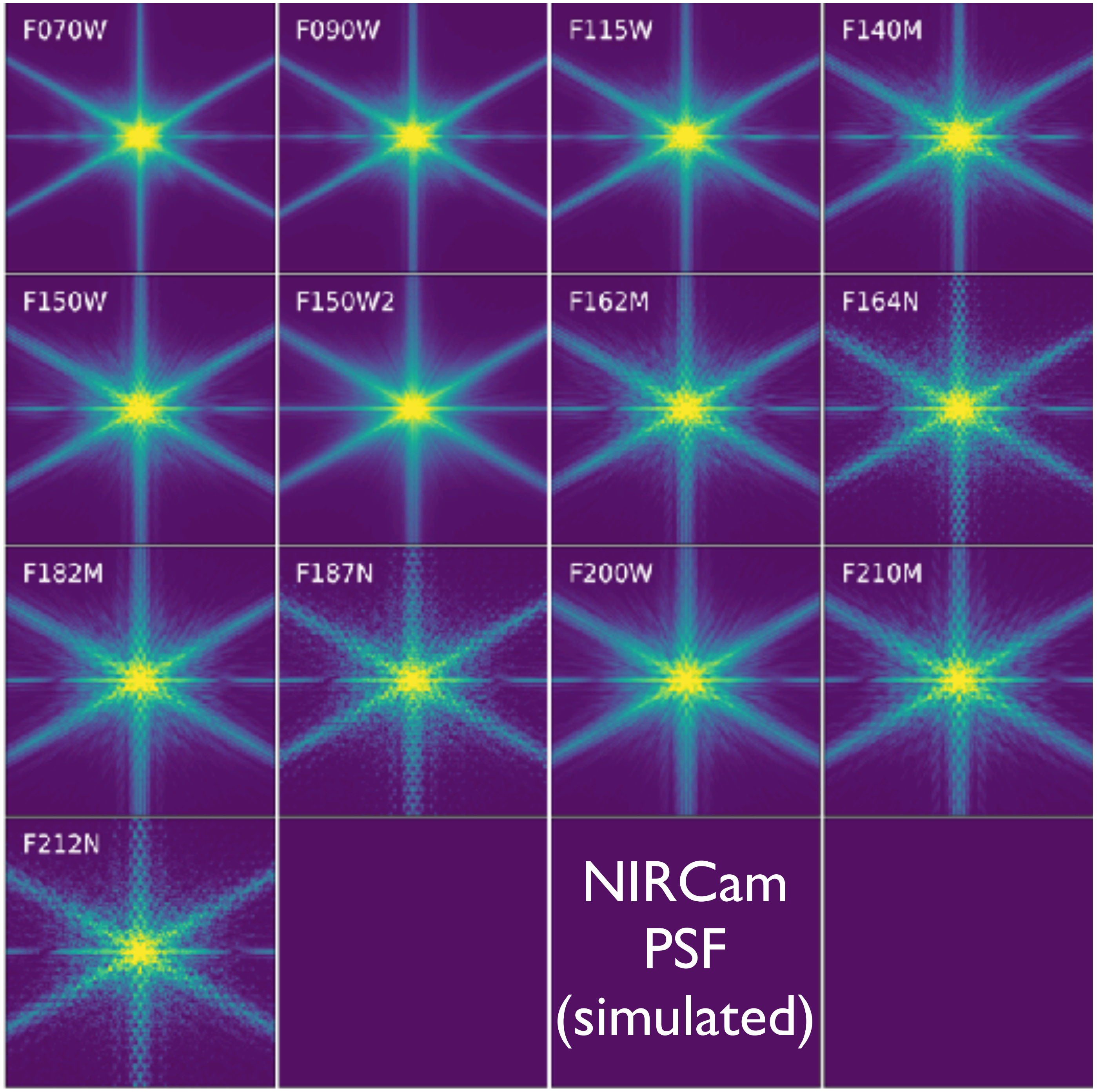
modern domes have lots of windows, day-time AC

Point Spread Function

Instrumentation limitations:

- PSF is not necessarily circularly symmetric
- PSF usually varies over the field of view





(A little bit about)

Telescopes

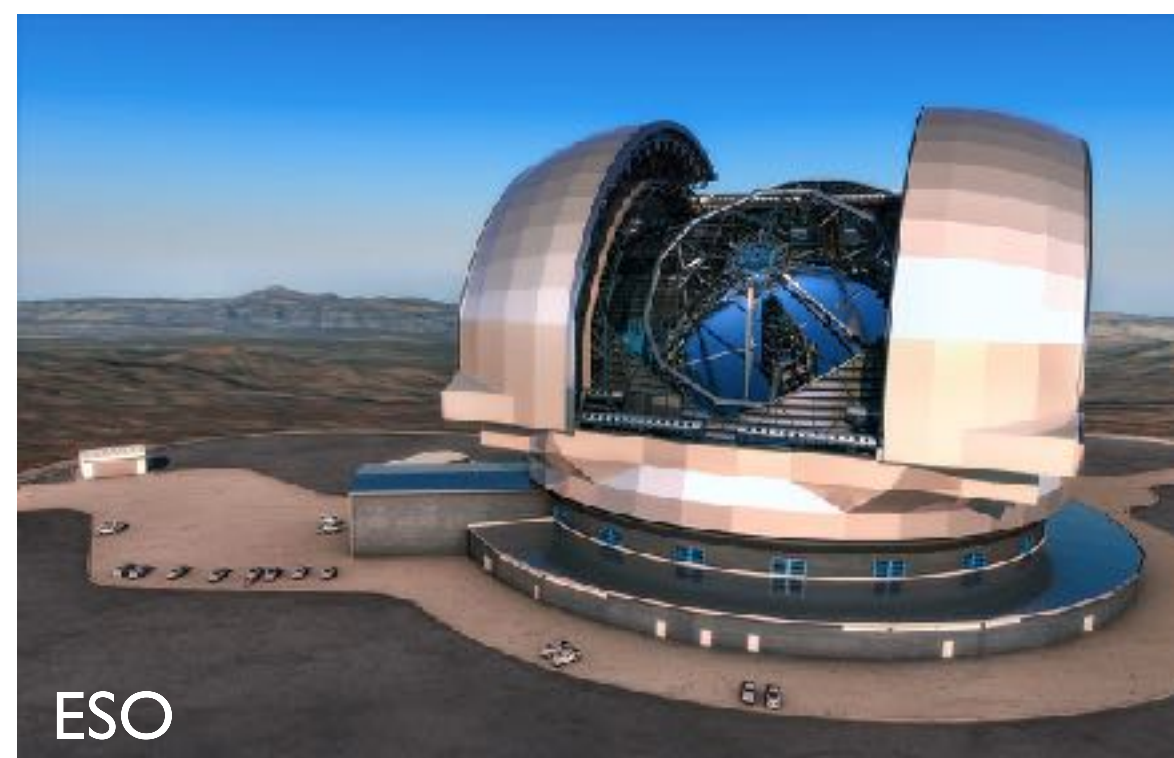
Aperture

- most (new) things in astronomy are faint (but not all!)
- need to gather as much light as possible
- larger aperture → better resolution, if using adaptive optics to counteract atmospheric seeing
- the diameter of the mirror (aperture) is one of the main characteristics of a telescope

Keck Telescopes: 10m

L. Hatch

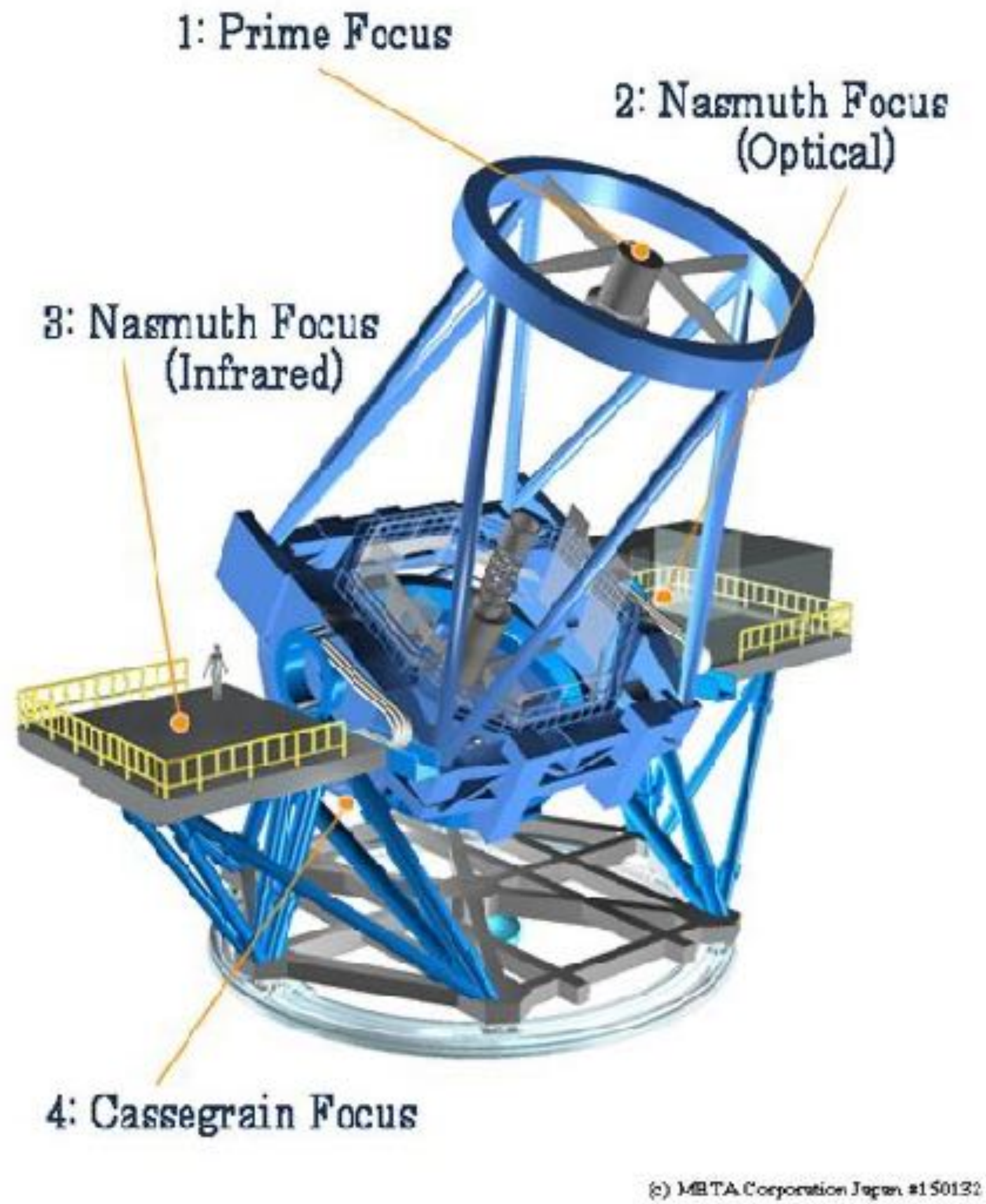
next generation: 30m telescopes (~2028)



ESO

Big telescopes

- all big telescopes are reflectors (mirror telescopes)
- big lenses are too expensive / impossible to make



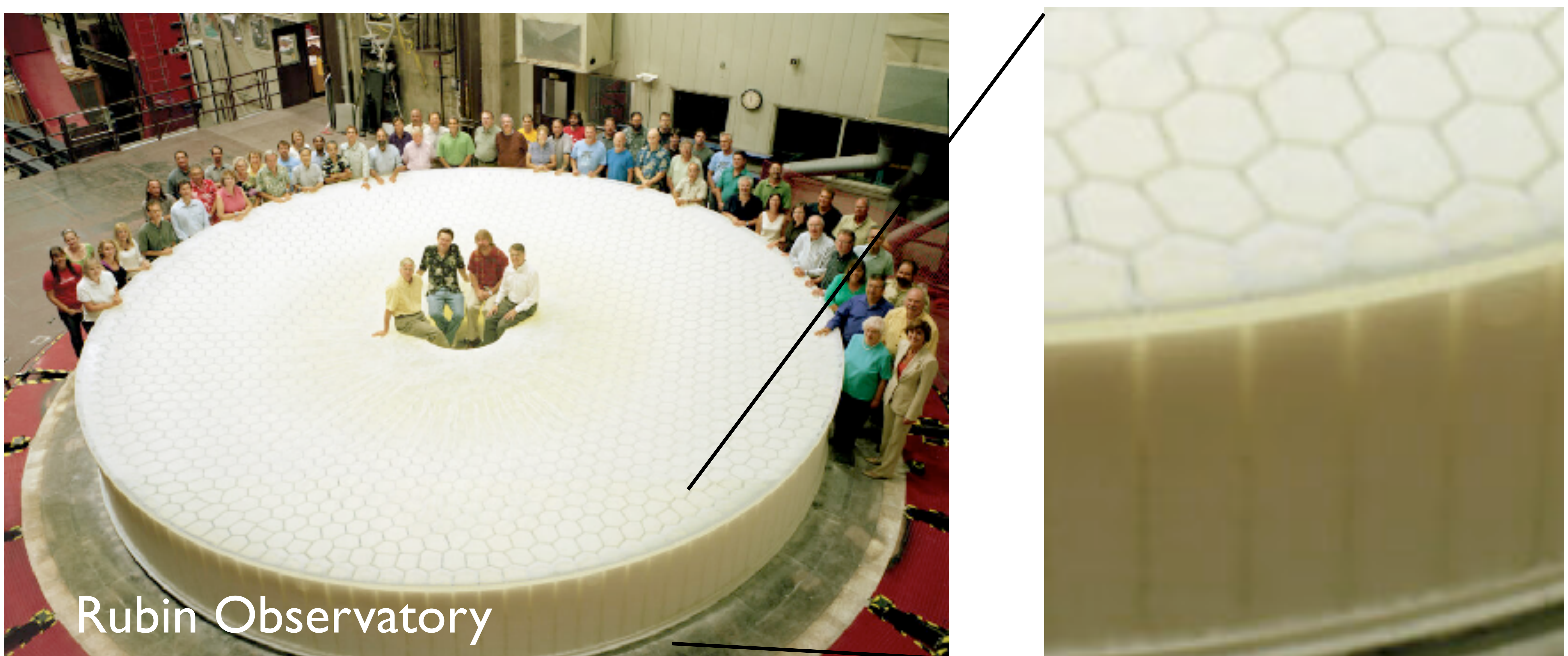
Subaru Telescope

Active optics

Problem: large glass mirrors deform under gravity

Solution: thin mirrors, supported by actuators, control shape through actuators

- Corrects full field of view (FOV)
- “Slow” correction

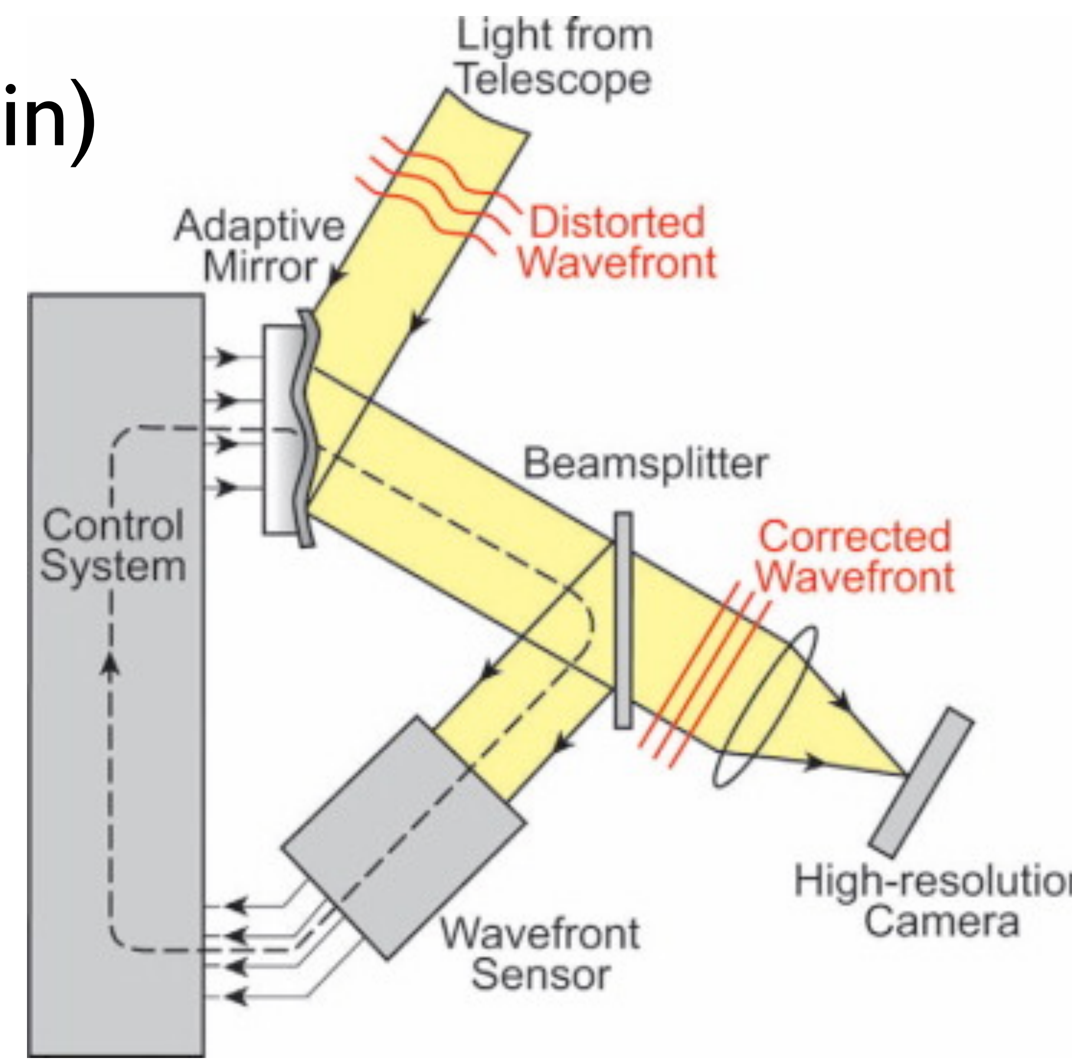


Adaptive optics

Problem: Earth's atmosphere blurs optical images

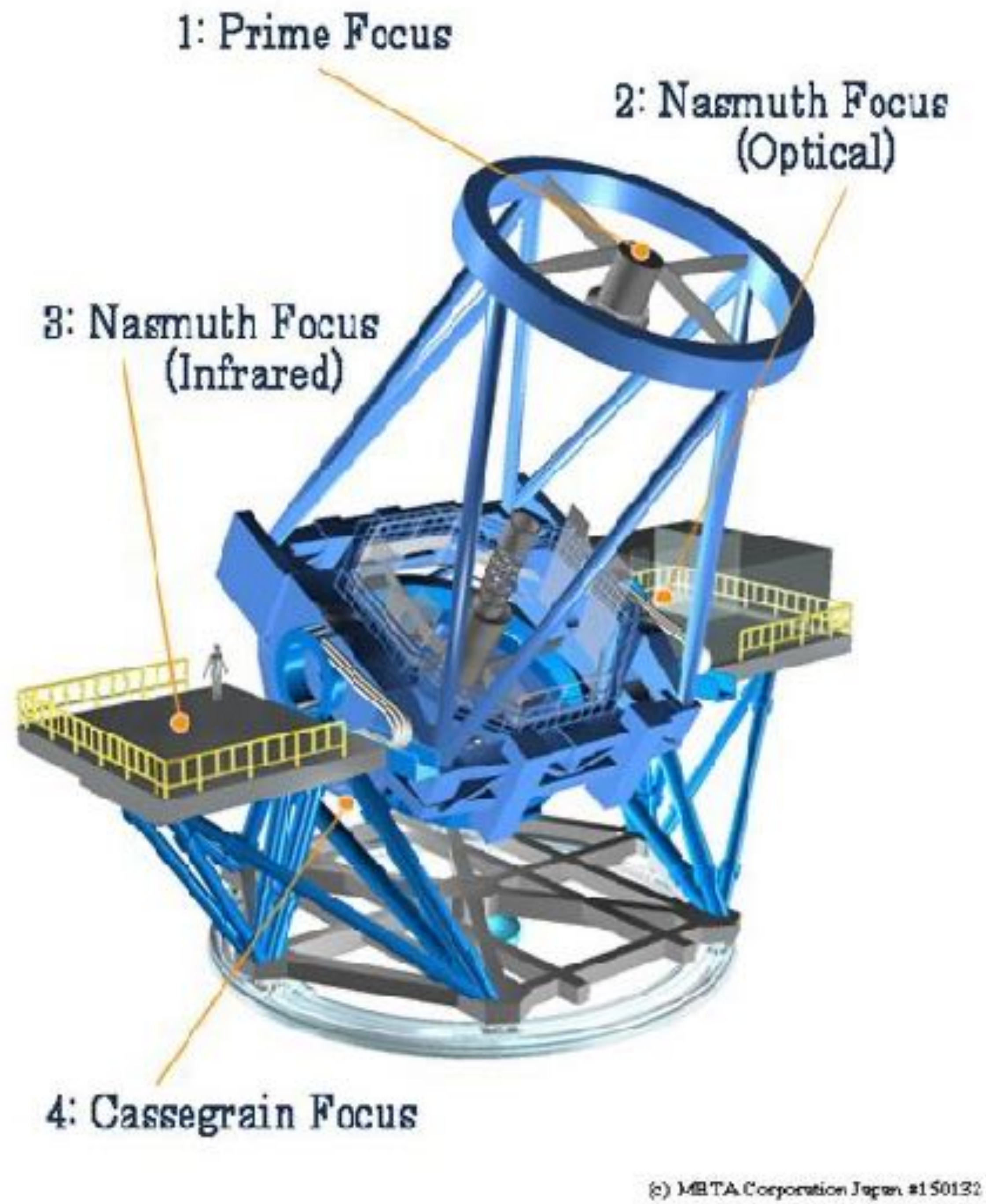
Solution: use a wavefront sensor and deformable secondary mirror to "iron out" wavefront distortions

- FOV limited by coherence length of atmospheric turbulence (a few arcmin)
- "Fast" correction (1000 Hz)



Big telescopes

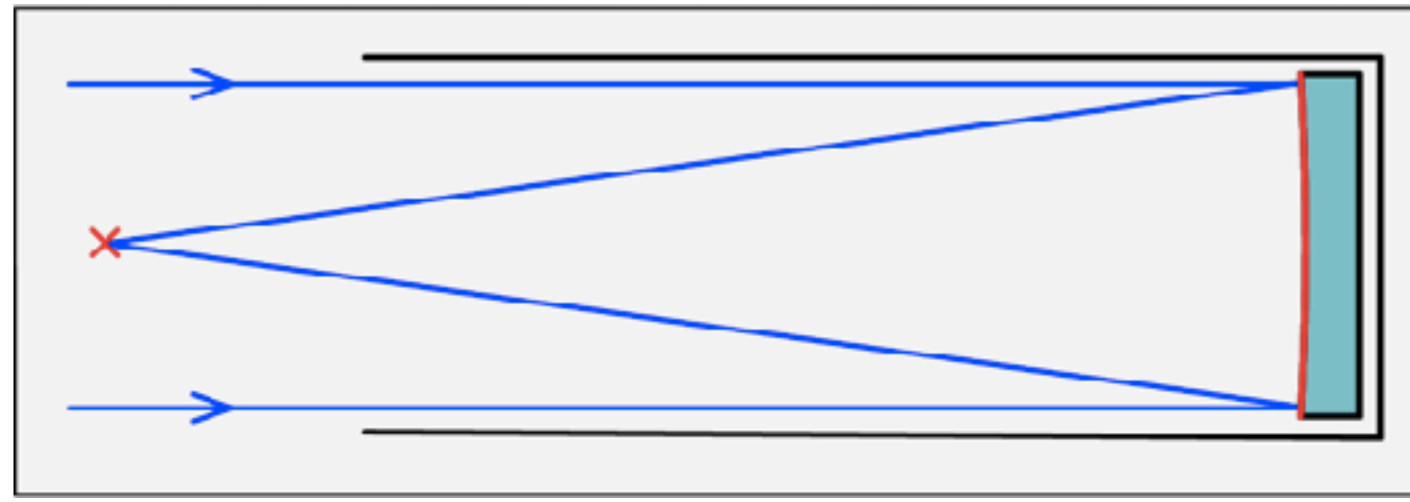
- most big telescopes have several instrument mounting points (at different foci)



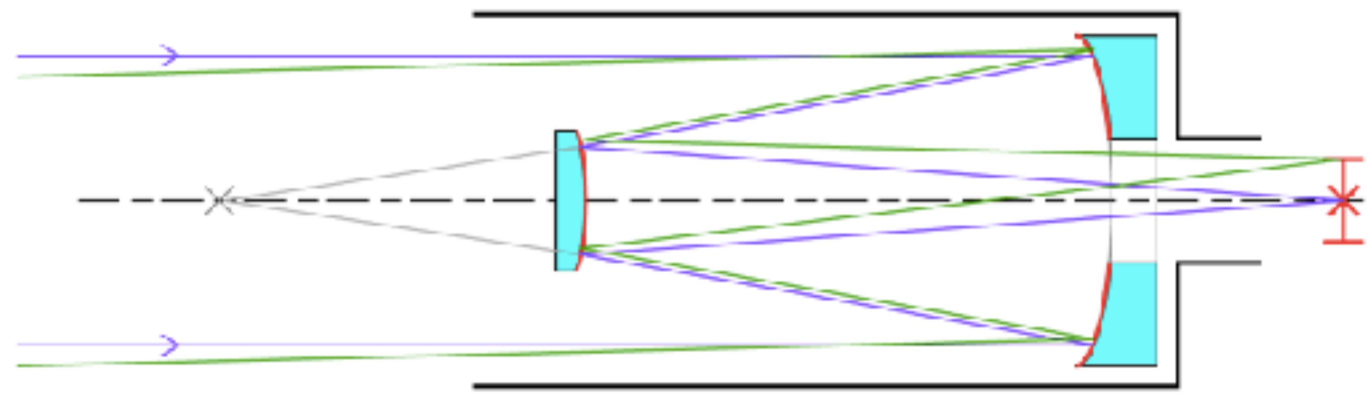
Subaru Telescope

Telescope foci

- prime focus: focus of primary mirror

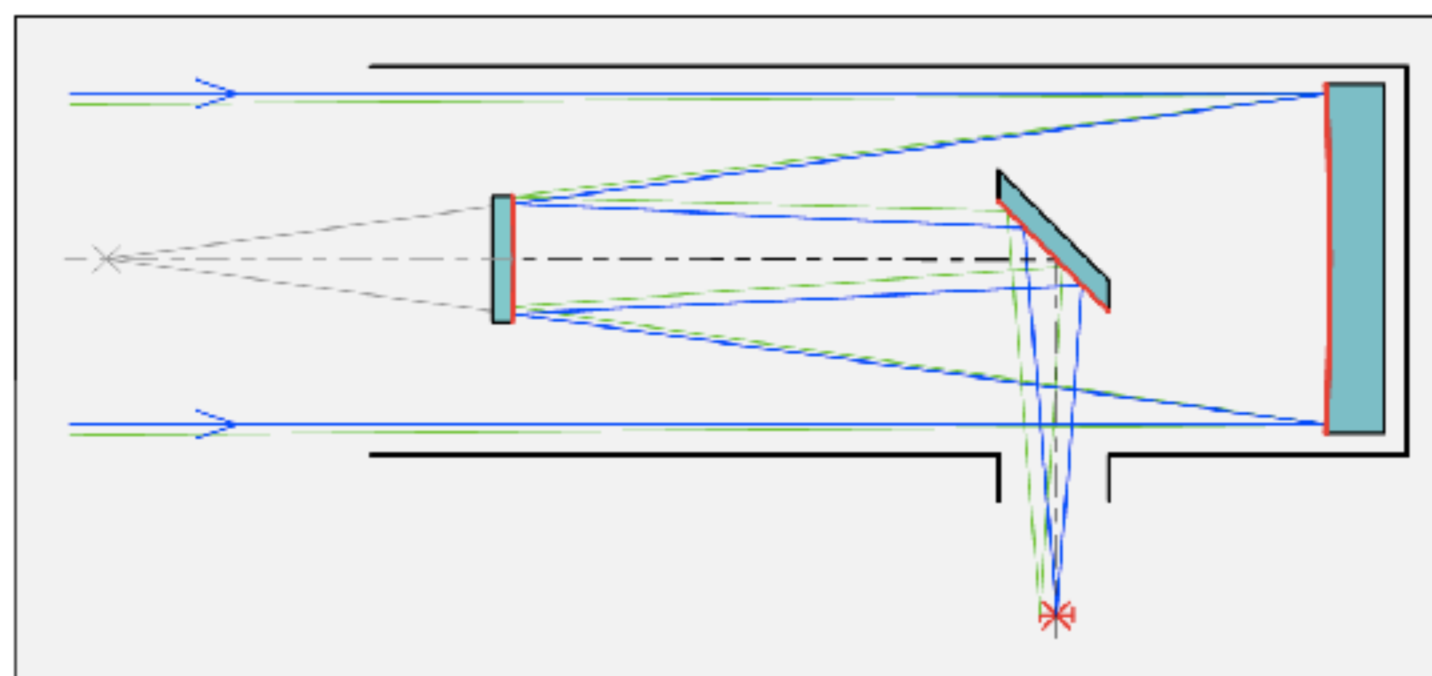


- Cassegrain focus: secondary mirror in front of prime focus; secondary focus behind primary mirror



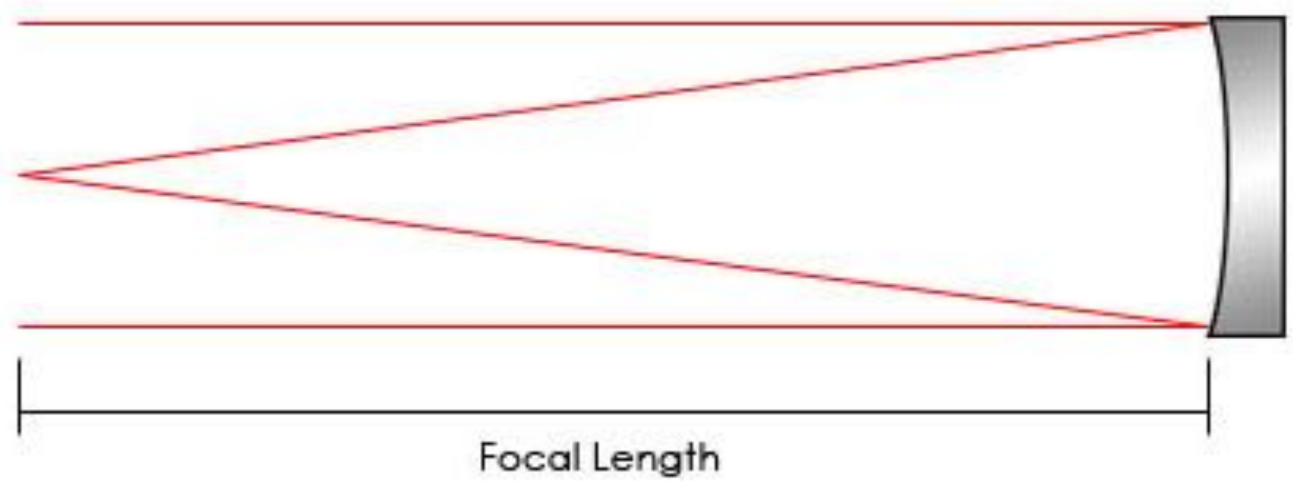
K.Vedala

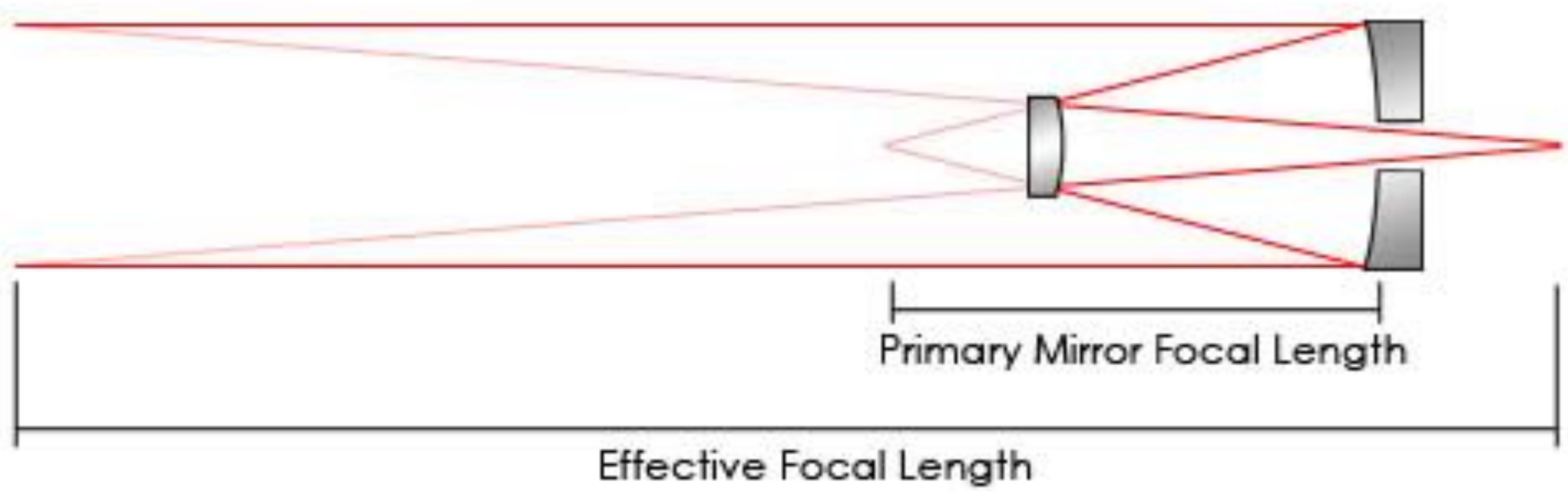
- Nasmyth focus: pick-up mirror, can be placed through mount axis



Focal length

distance from mirror / lens to the focal plane

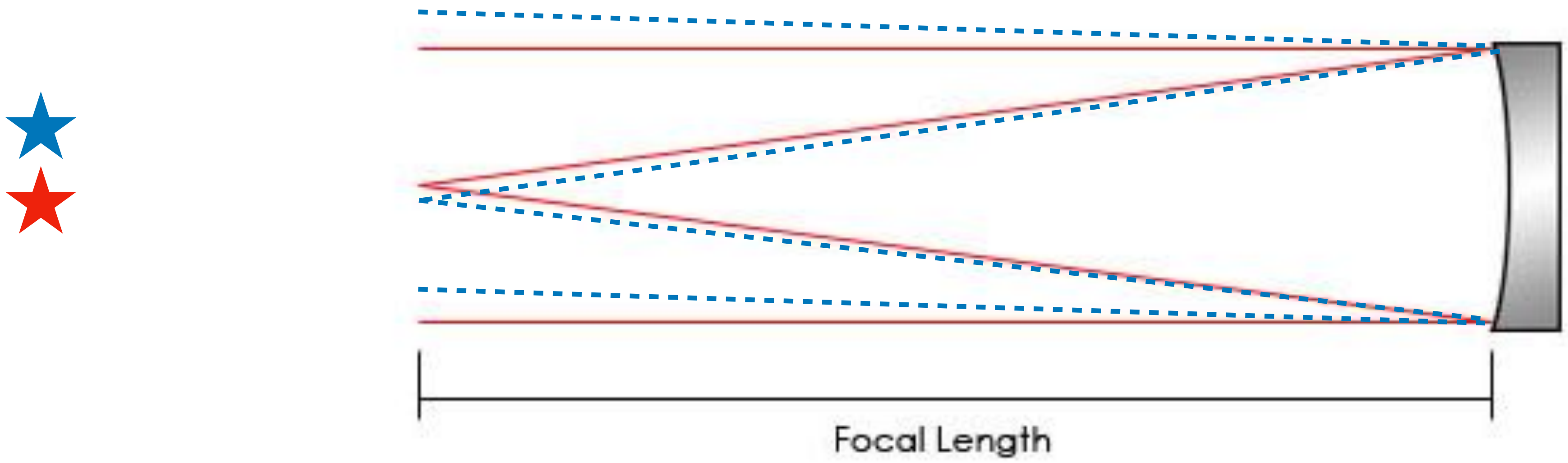




Starizona

Focal length

distance from mirror / lens to the focal plane



short focal length → large area of sky → low magnification

long focal length → small area of sky → high magnification

Plate Scale

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

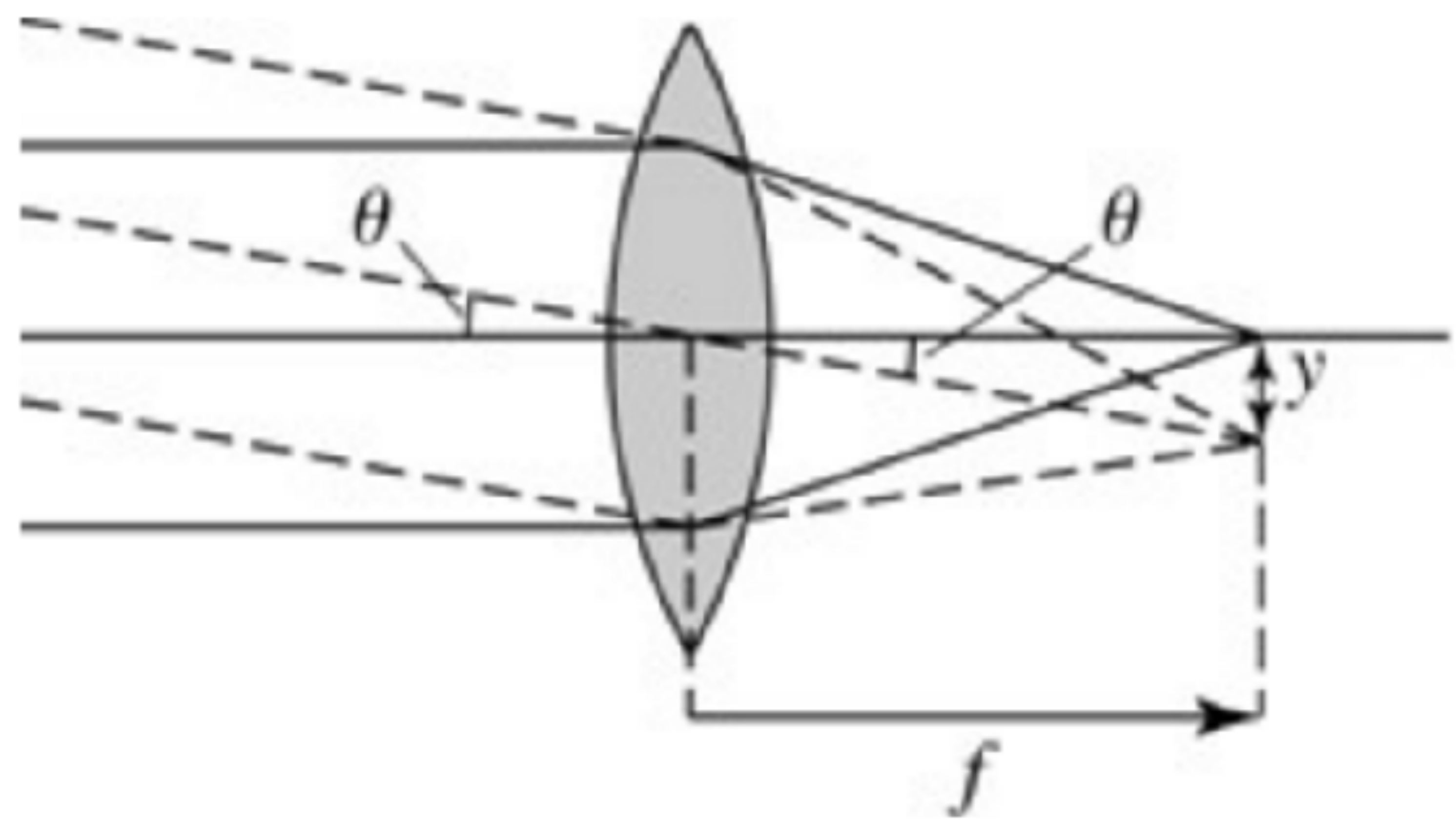
$$\theta \approx \tan\theta = \frac{y}{f}$$

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

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

units: angle / length

e.g. arcseconds / mm



unknown

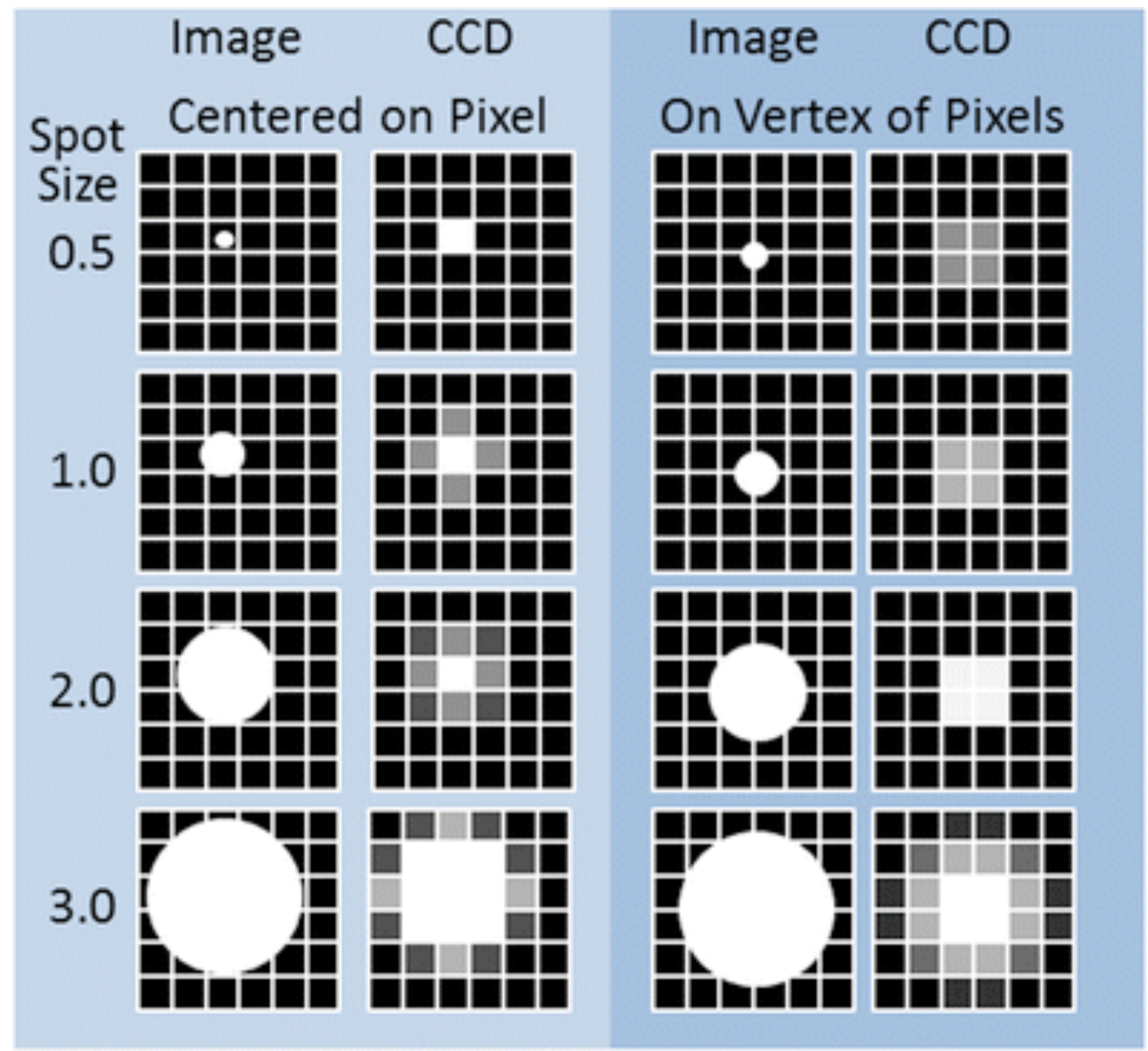
Detector resolution

- larger pixels: more photons, higher signal-to-noise, lower resolution
- smaller pixels to *resolve* the PSF, i.e. several pixels per resolution element (a few arcseconds)

Reu et al. 2014

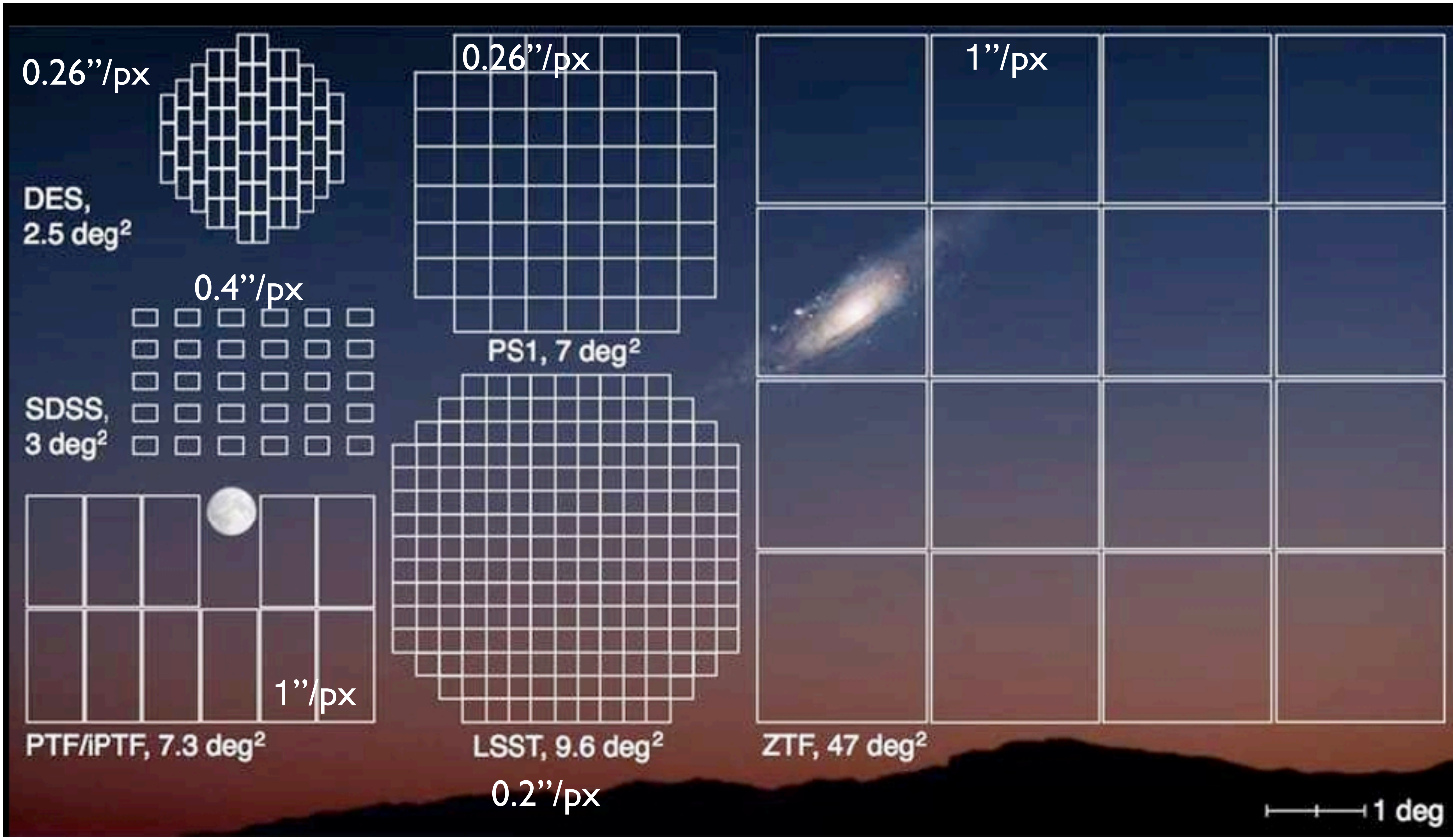
Nyquist sampling: 2 pixels per PSF width

In practice: 2.5 pixels per PSF FWHM



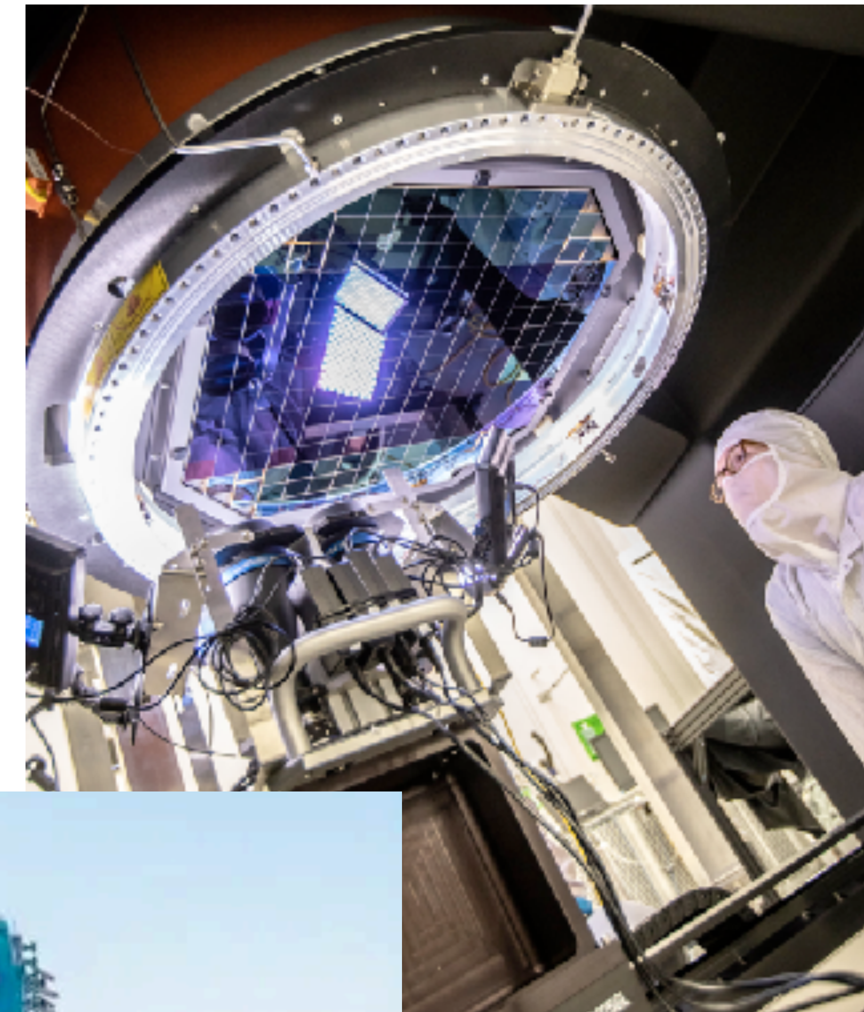
Field of View

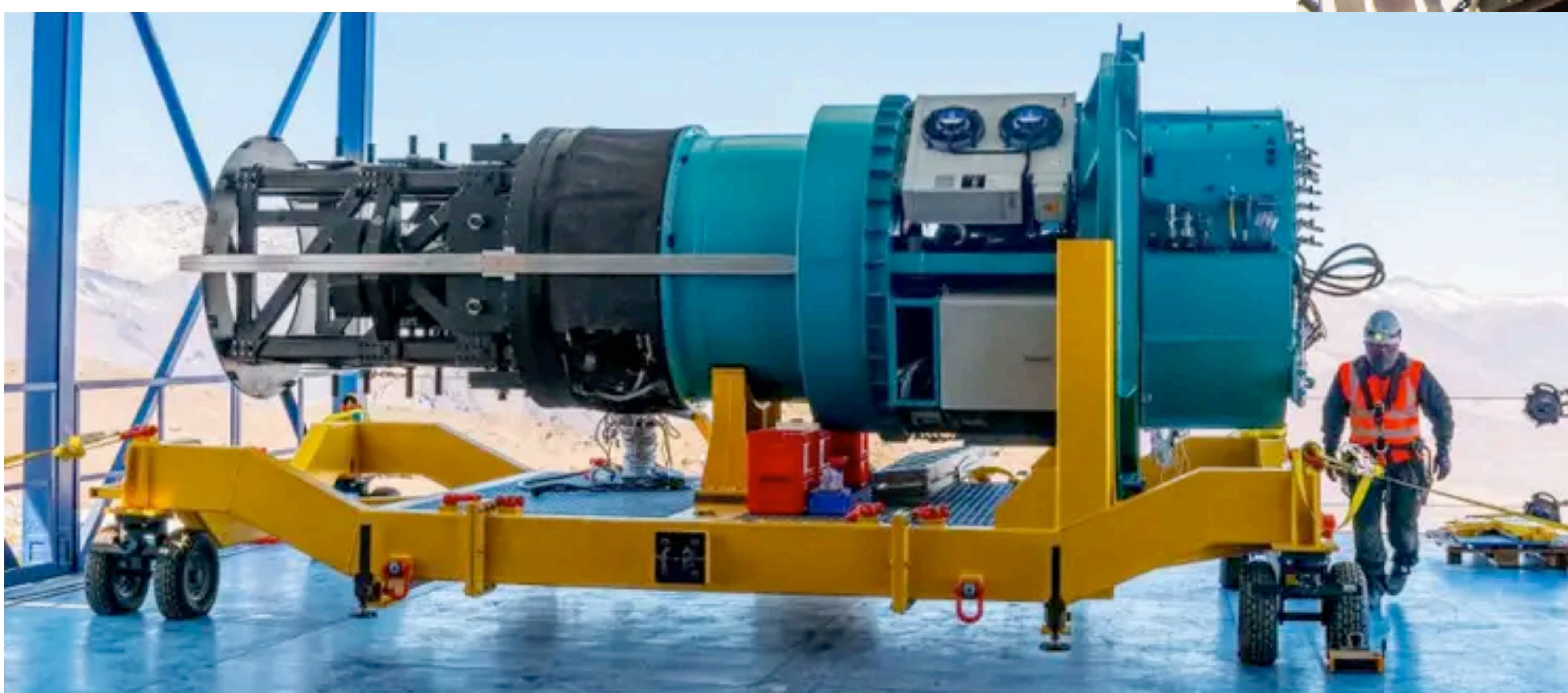
Larger FOV - more discovery space! Trade-off with resolution.



LSSTCam

- Largest Camera ever built!
- 189 4K x 4K CCDs = 3.2 Gigapixels
- Large FOV, fully sampled



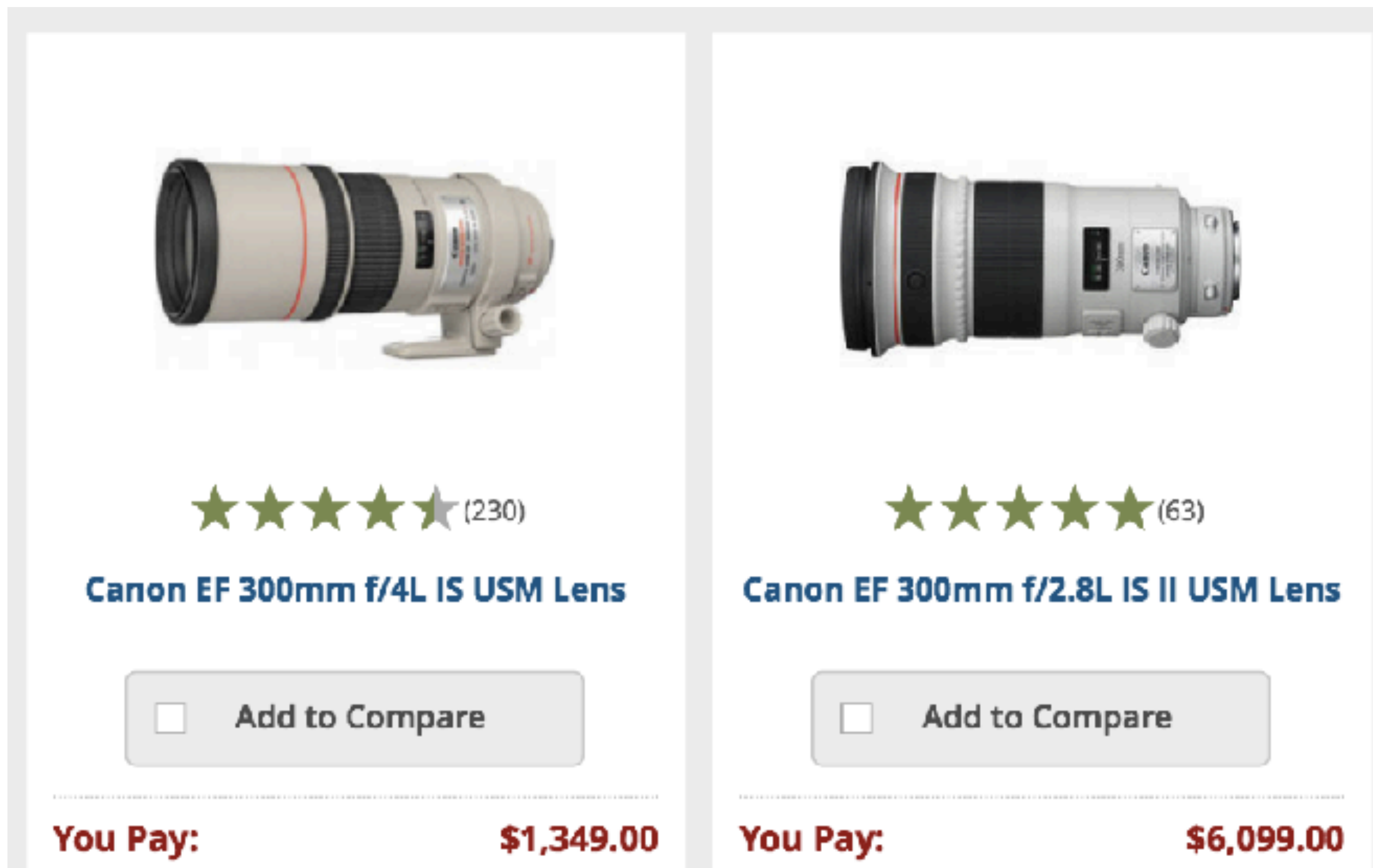


Rubin Observatory

Focal ratio ("f number")

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

measure of how "fast" the lens / mirror is



B&H

Vera C. Rubin Observatory

- 8.4m mirror
- f/1.2 focal ratio !
- will conduct *Legacy Survey of Space and Time* (LSST)

Can follow construction at

https://www.lsst.org/news/see-whats-happening-cerro-pachon

Homework 2 (due next Wed)

Request observing time for the Lab 1 "pretty picture"

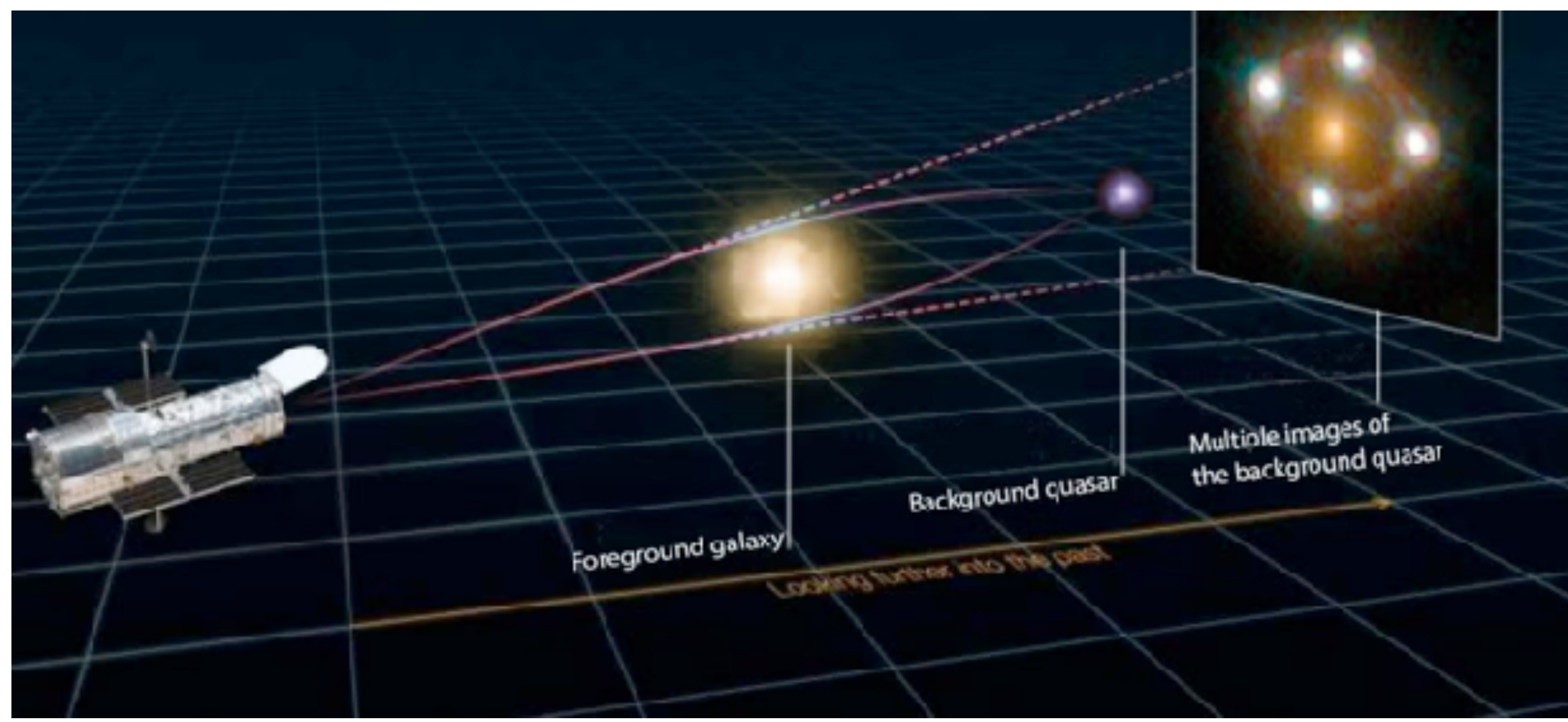
- think of some objects you would like to image
- look up their coordinates (e.g. Simbad, wikipedia)
- look up their size and magnitude
- make a StarAlt plot to verify that the object is well observable

- check the Observing Calendar for available dates
- message / e-mail the TAs + instructor; include a justification of your request (StarAlt plot, size, brightness, choice of filters [BVRI, Ha])

SBU Astro Club

Next Wednesday

- lecture will (probably) be given by Prof. Simon Birrer
- teaching evaluation as part of his path to tenure



Tutorials

- remaining lectures will be followed by tutorials (bash, python, some astronomy software)
- bring your laptop (if you have one)

- tutorials will take place in the computing lab
- each group "gets" (at least) one machine - note its name; this is the machine that you will log into for analyzing data

- today: bash / Linux