ASTR21200

Observational Techniques in Astrophysics
Lecture 2

Bradford Benson

Course Schedule

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Schedule Spring 2024

bradfordbenson edited this page 18 minutes ago · 12 revisions

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Week	Date	Topic	Lecture	Homework / Lab	Tutorial
1	Mar-19	Intro to Astro Observing	Lect-1	HW-1, Due Mar-26	Python-1: Visibility
	Mar-21	Practical Observing	Lect-2		
2	Mar-26	CCDs and Astronomical Images	Lect-3	[HW-2, Due Apr-2]	Python-2: CCD Images
	Mar-28	Intro to Stone Edge	Lect-4		Python-3: Astropy Fits
3	Apr-2	Intro to Labs and Lab1	Lect-5	Lab-1, Due Apr-16	Python-4: RGB Images
	Apr-4	(Analysis and Help/Hack Session)			
4	Apr-9	Statistics	Lect-6		
	Apr-11	(Analysis and Help/Hack Session)		[HW-3, Due Apr23]	
5	Apr-16	Intro to Lab2	Lect-7	[Lab-2, Due May-2]	SEO Cheat Sheet
	Apr-18	(Analysis and Help/Hack Session)			
6	Apr-23	(Analysis and Help/Hack Session)			
	Apr-25	(Analysis and Help/Hack Session)			
7	Apr-30	Intro to Lab 3, Project Ideas	Lect-8	[Lab-3, Due May-16]	
	May-2	(Analysis and Help/Hack Session)			

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General Information

- Syllabus
- Schedule
- Stone Edge Observatory (SEO)
- SEO Observing Calendar
- SEO Data Archives

Labs and Observing

- Lab Report Guidelines
- Lab1
- Lab2
- Lab3
- Astro Data Archives

Computing Resources

- Astronomy Software
- Python
- GitHub
- ds9
- Source Extractor
- Jupyter
- LaTeX
- Topcat
- Astrometry.net
- Coadd or Stack Images
- Image Add, Sub, Arithmetic
- Awk and Sed

Clone this wiki locally

https://github.com/bradfordbenso

Lecture notes
Homework
Labs
Tutorials

Will be linked to "Schedule"

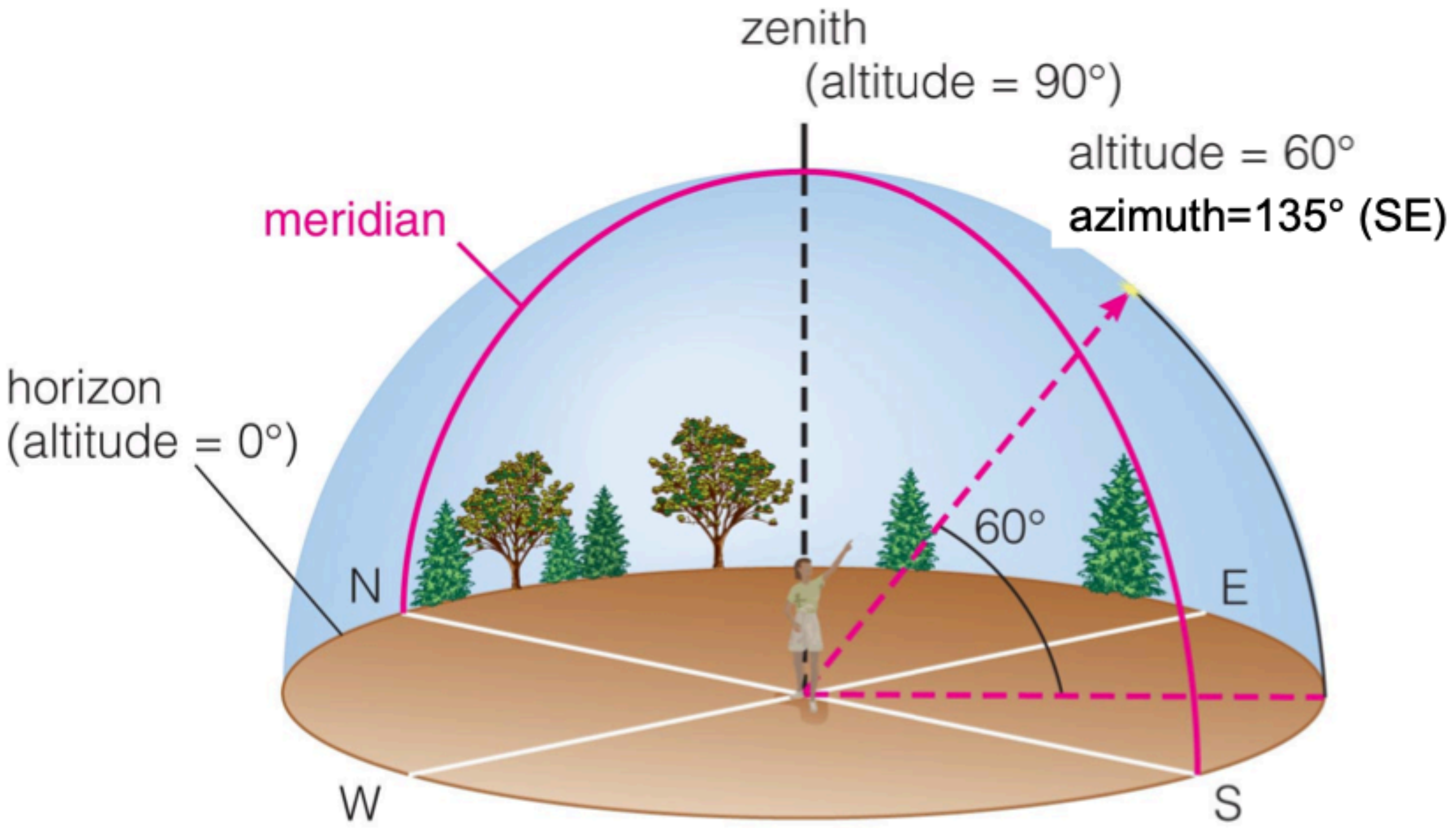
Office Hours

- During class:
    - feel free to ask questions before, during, after lecture!
- Slack:
    - feel free to ask questions via direct message or class ASTR21200 Slack channel!
- Office Hours:
    - **Brad: Thurs -12-1pm ERC 589**
    - Dillon: TBD
    - Rohan: TBD
    - Will be updated on class wiki homepage:
        - https://github.com/bradfordbenson/ASTR21200_2024/wiki

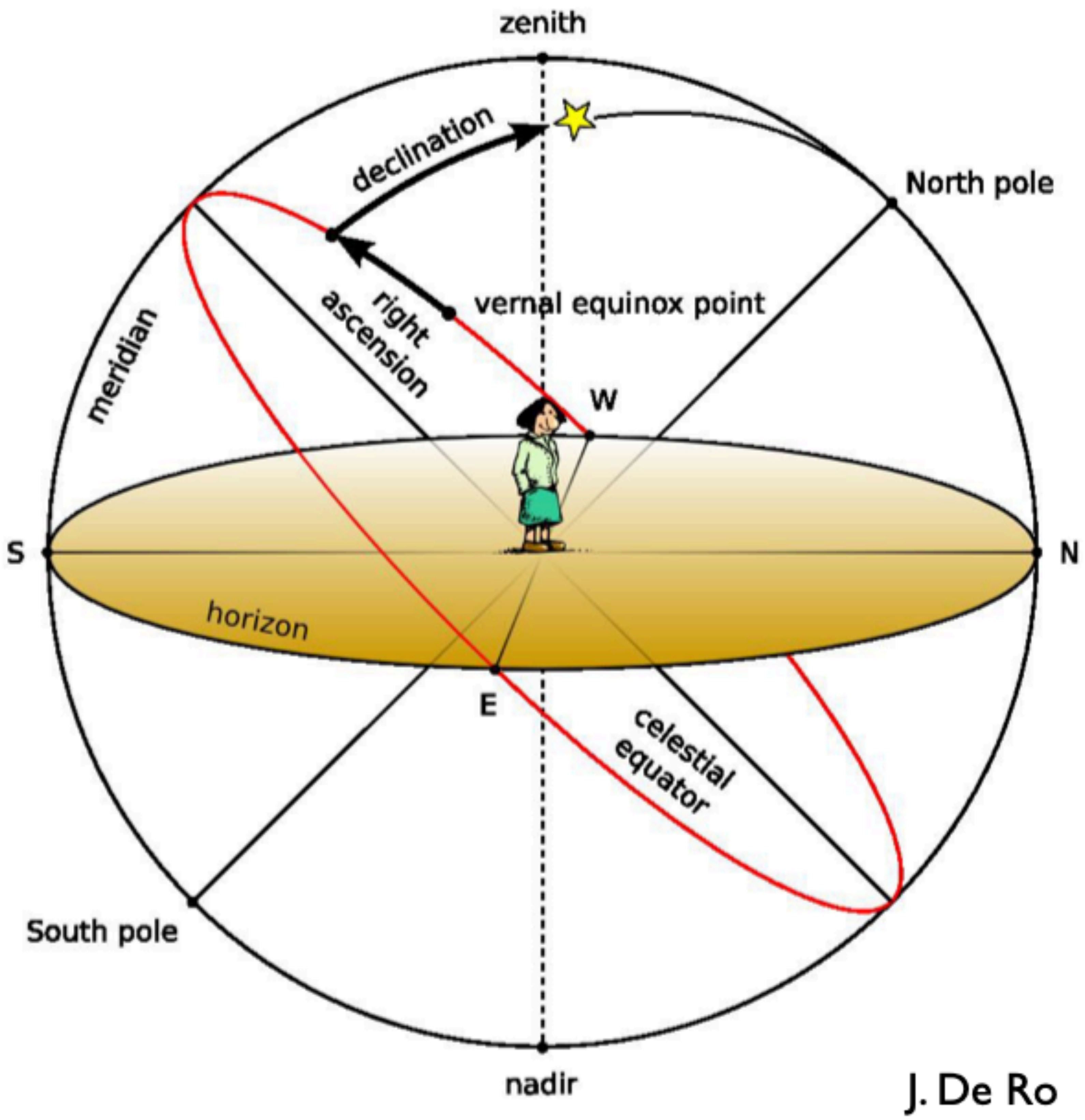
Last Lecture: Coordinate Systems

The sky above a specific location at a specific time is a half sphere which can be described by 2 angular coordinates:

- **On the Earth:** (Latitude, Longitude)
- **At the Telescope:** (Altitude, Azimuth)
- **Celestial Sphere:** (Right Ascension, Declination) - Equatorial Coordinate System

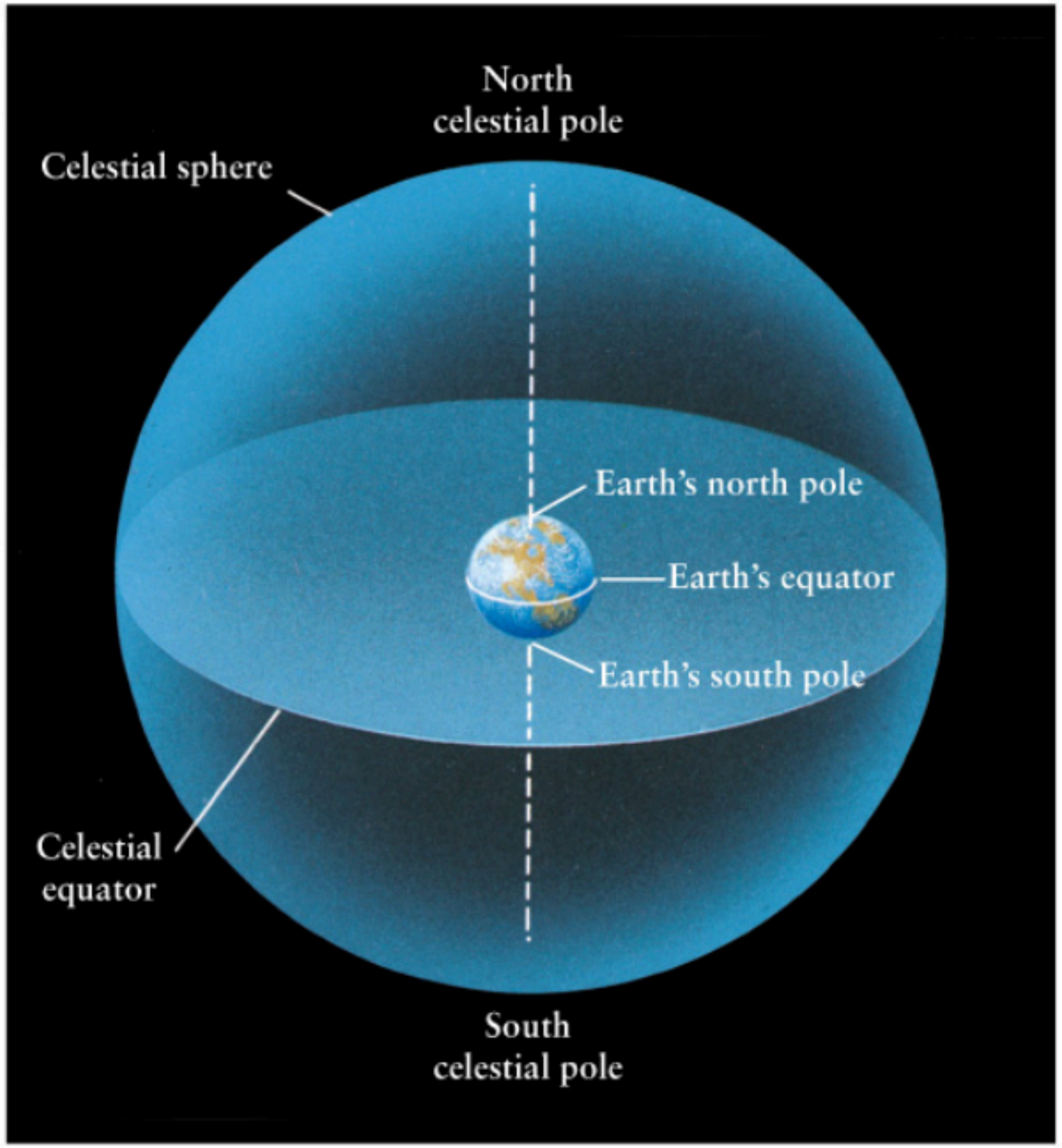


Pearson Education



Last Lecture: Coordinate Systems

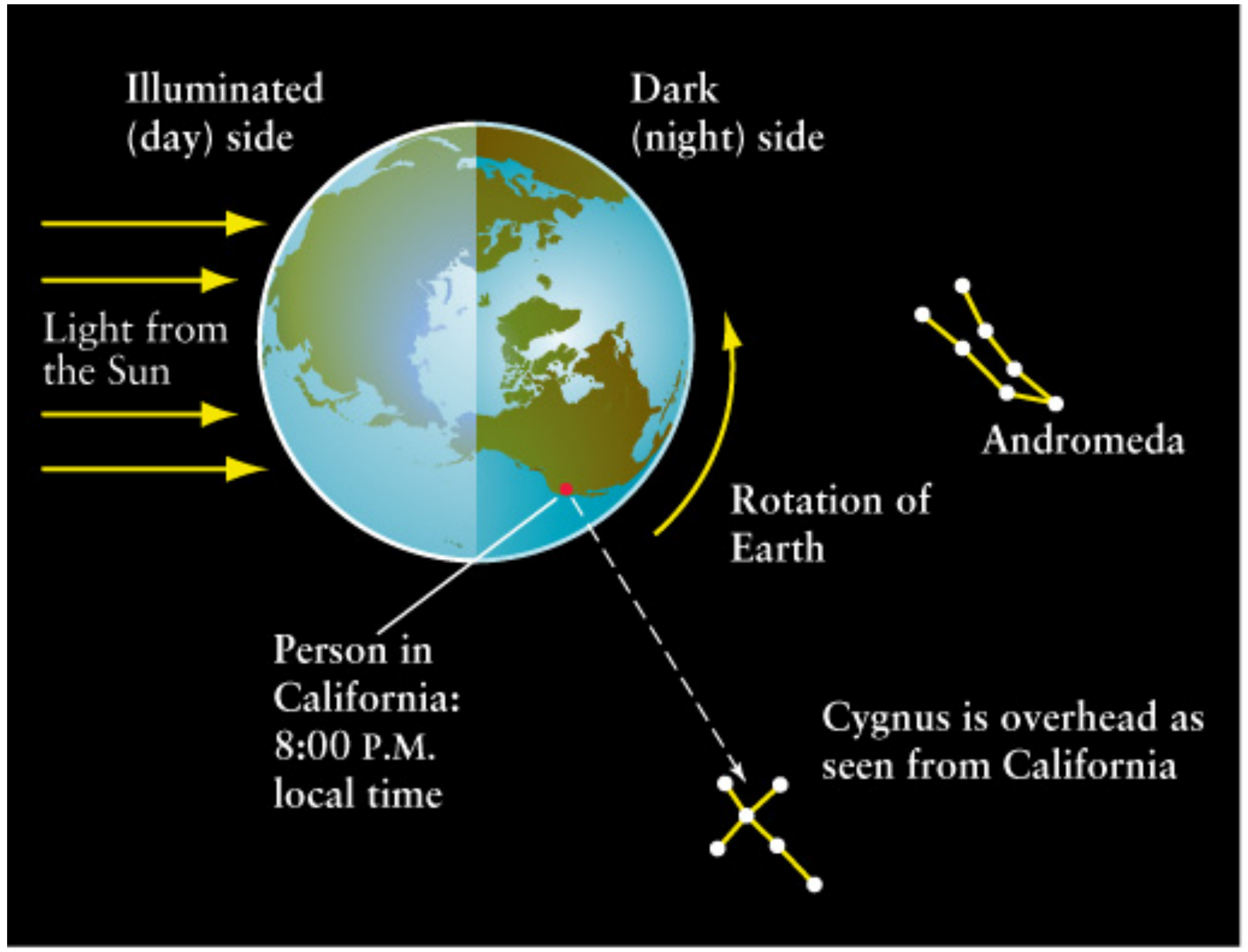
- Sky Maps - East is Left, North is Up
  - Because you are looking up at Sky (vs down at Earth), flipped relative to what you expect from Google Maps
- Equatorial Coordinates (R.A., Dec.) are fixed to the Sky, so rotates with the Sky as the Earth turns.



Bailey, Slater & Slater

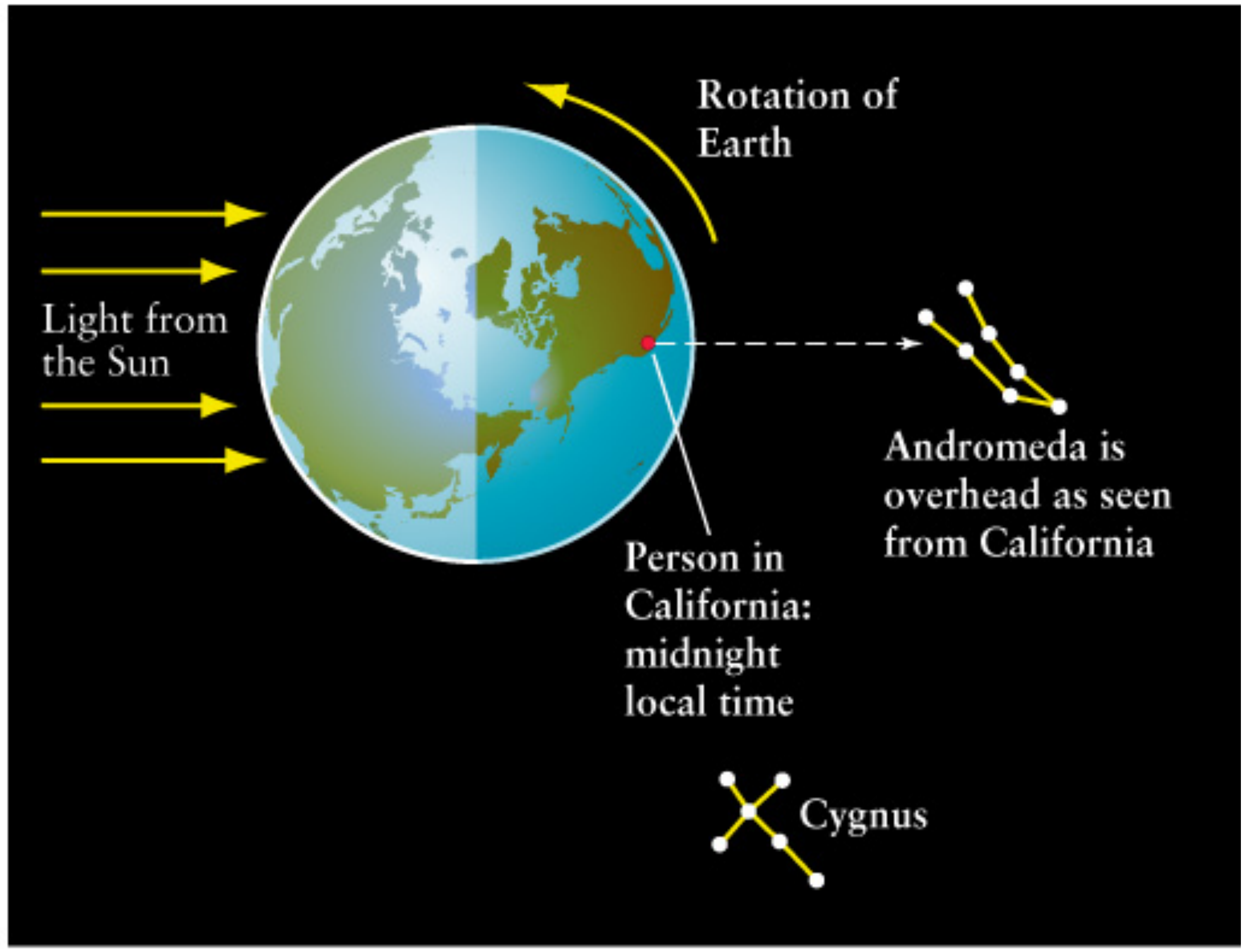
Last Lecture: Earth Rotation

- Sky “moves” East to West (Sun rises in East, sets in West)
- R.A. is defined by time intervals between passing the meridian
    - R.A. runs right to left on sky maps



(a) Earth as seen from above the north pole

Andromeda is to the East; Cygnus is overhead



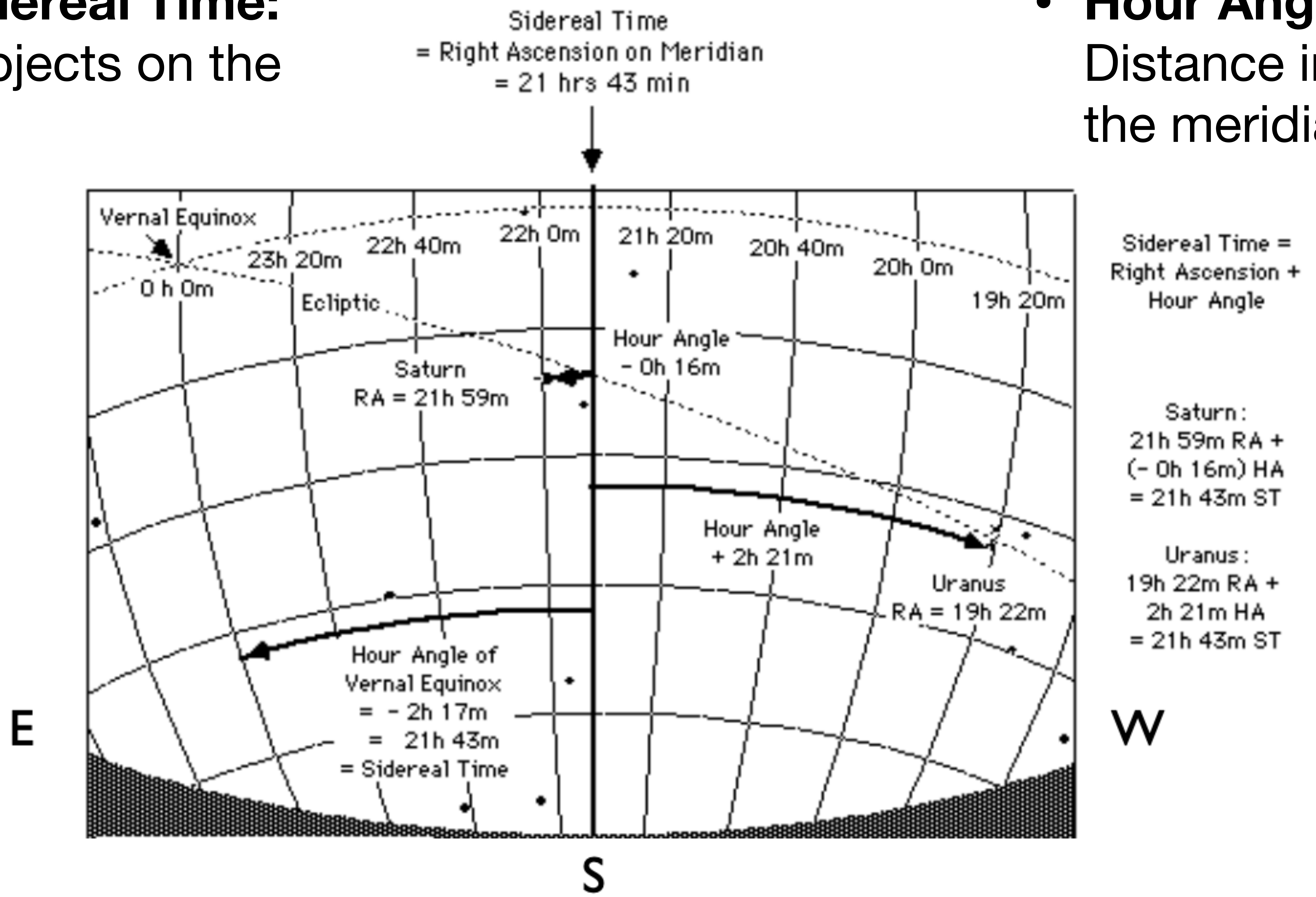
(b) 4 hours (one-sixth of a complete rotation) later

4 hrs later: Andromeda is overhead; Cygnus is to the West

Last Lecture: Local Sidereal Time (LST)

- **Local Sidereal Time:** R.A. of objects on the meridian

- **Hour Angle:** Distance in R.A. to the meridian



Need to know the current time when observing!

Obviously, but for what reasons exactly?

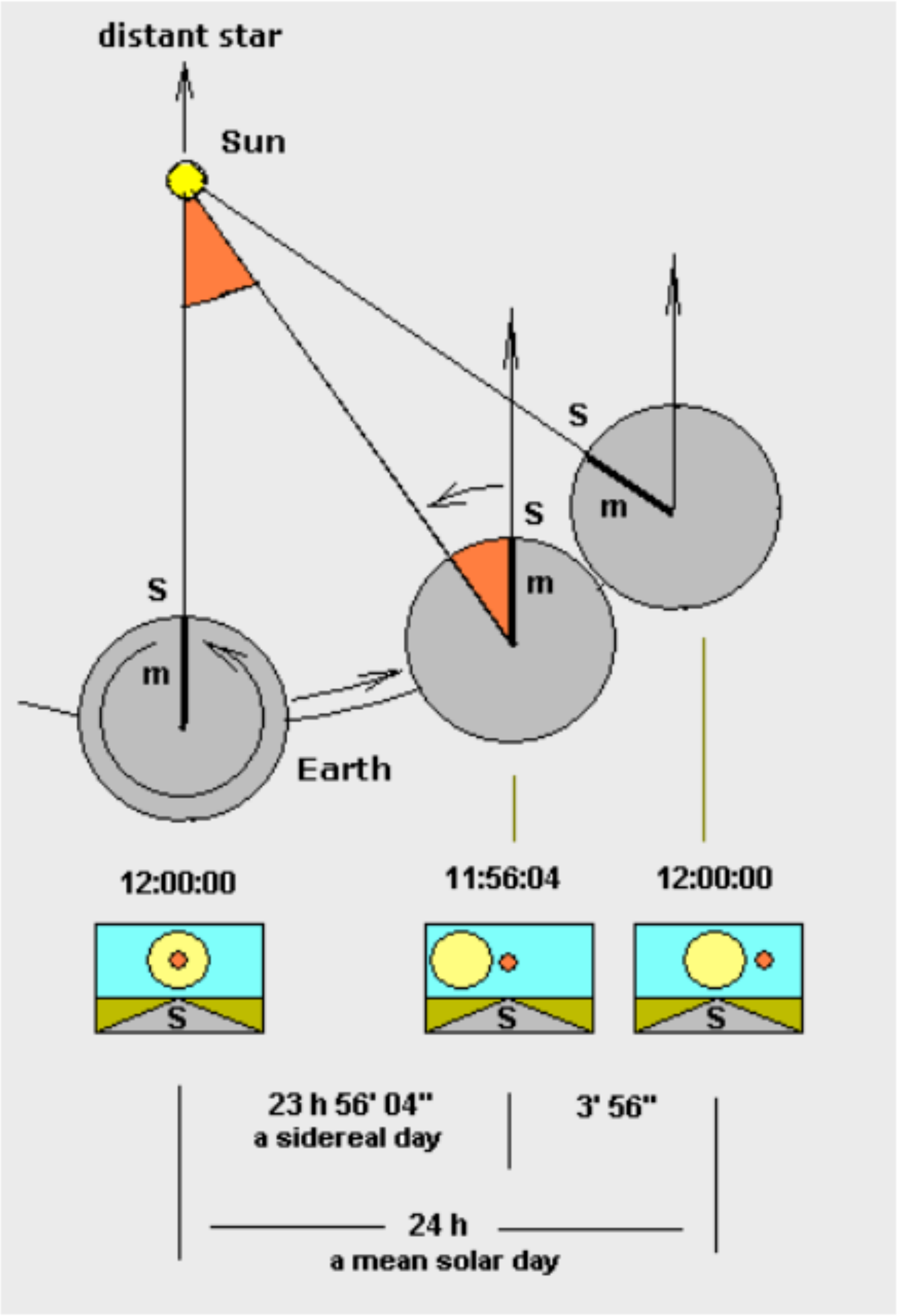
- Your telescope will need to know the LST to convert (R.A., Decl) to (Altitude, Azimuth)
- Will need to know in case you need to correlate with other information (e.g., weather, moon location, other telescope measurements, etc.)
- Much of the sky is variable, e.g., supernovae, variable stars, etc.

- So Astronomers need a common, precise reference time

Sidereal Time

- “Sidereal” = “Of the stars”
- **Sidereal Time:** Defined with respect to the Stars
- One Earth rotation takes 23hr 56min
    - This is called "a sidereal day”
- Same sky is overhead after 23h 56min
- **Solar day:** Defined with respect to the Sun, takes 24-hrs

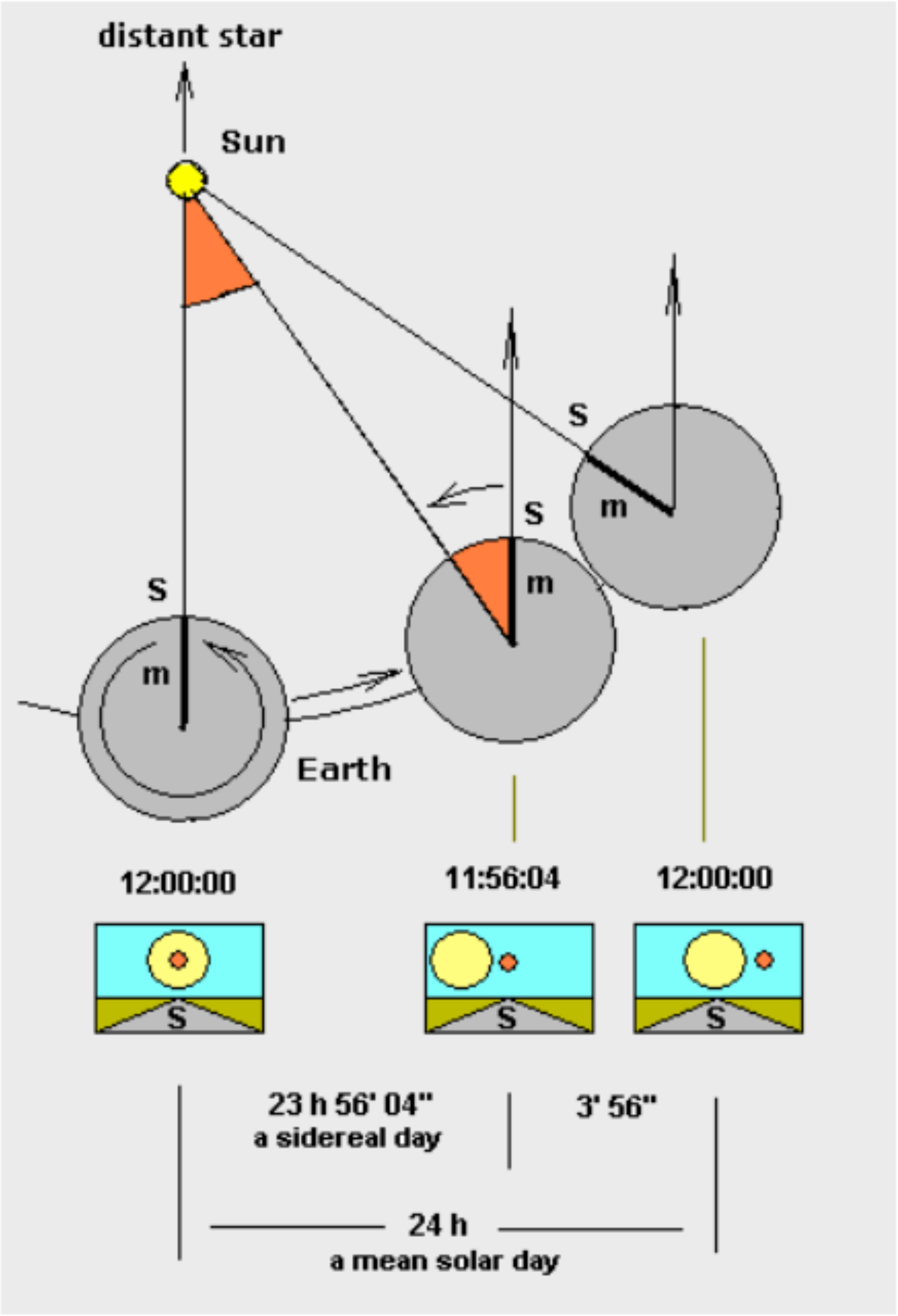
- **Wait, how can a “Solar” day and “Sidereal” day be different?**
    - *Because of the orbit of the Earth around the Sun!*



wikipedia

Sidereal Time

- ***From one night to the next, stars rise 4-min earlier!***
- Implies that 1-year (i.e., 1-orbit of the Earth around the Sun) has 365+1 Sidereal days



wikipedia

Solar Time

- **Apparent Solar Day:** Time between two passes of the meridian
    - Problem: Variable length (because Earth's Orbit is elliptical)
- **Mean Solar Day:** Based on fictitious mean Sun that moves along the Sky at a constant rate (measured on the equator)
- **Universal Time (UT1):** Mean Solar time at 0-deg longitude (Greenwich)
- **Coordinated Universal Time (UTC)**:
    - Based on atomic clocks, and kept within 0.9-sec of UT1
    - International Time Standard, and most typically used in Astronomy to reference observations
- UTC time is 3-hrs ahead of Chicago during daylight savings time, 4-hrs ahead during regular times

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 use “**Julian Date**” (JD)
  - Defined as the days since noon on January 1, 4713 BC (which is JD=0)
  - Since JDs are big numbers, people often define the **Modified Julian Date (MJD)**
    - MJD = JD - 2400000.5
  - The start of class today was:
    - March 21, 2024 at 10pm UTC -> JD = 2460391.416667
    - MJD = JD - 2400000.5 = 60390.916667

Heliocentric Time

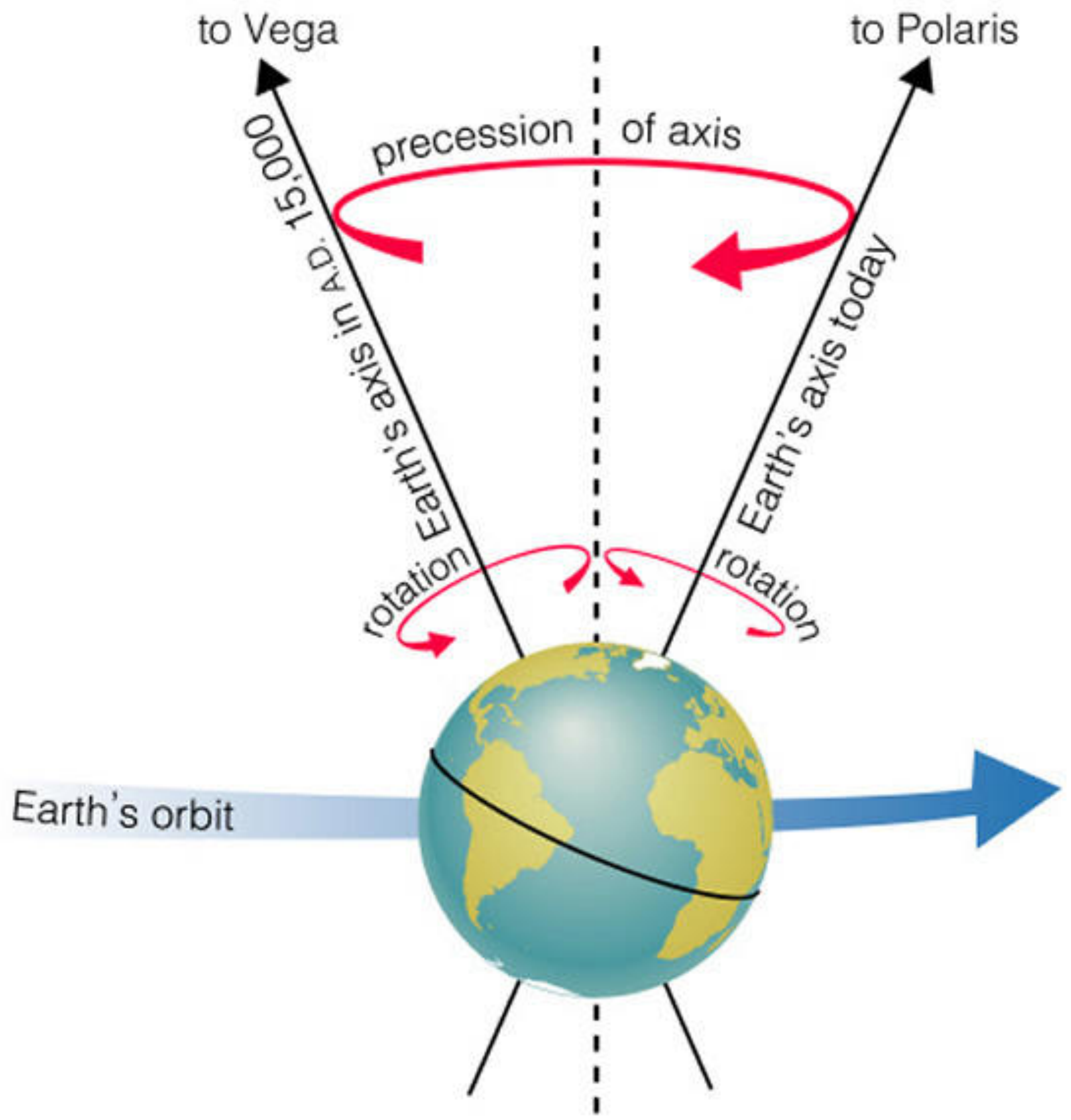
- On short timescales, light travel path through the Solar System becomes important

- 1 Astronomical Unit (or AU)
    - = Distance between Earth and 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
    - The Earth is effectively a big gyroscope that precesses over time
- Implies that the "Celestial Sphere" changes with time:
    - Polaris is only the "North Star" today, in 14,000 AD, Vega will be the new "North Star"
    - This precession is big, roughly 50-degrees
- All astronomical coordinates need to be specified at a certain time, or **Epoch**, e.g.:
    - **Standard Epoch currently used by most Astronomers is J2000.0**
        - January 1, 2000 noon = JD 2451545.0



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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 F1/F2 = 10, how big is Δm?

Astronomical Magnitudes

$$m_1 - m_2 = -2.5 \log\left(\frac{F_1}{F_2}\right) \longrightarrow m = -2.5 \log\left(\frac{F}{F_{\mathrm{Vega}}}\right)$$

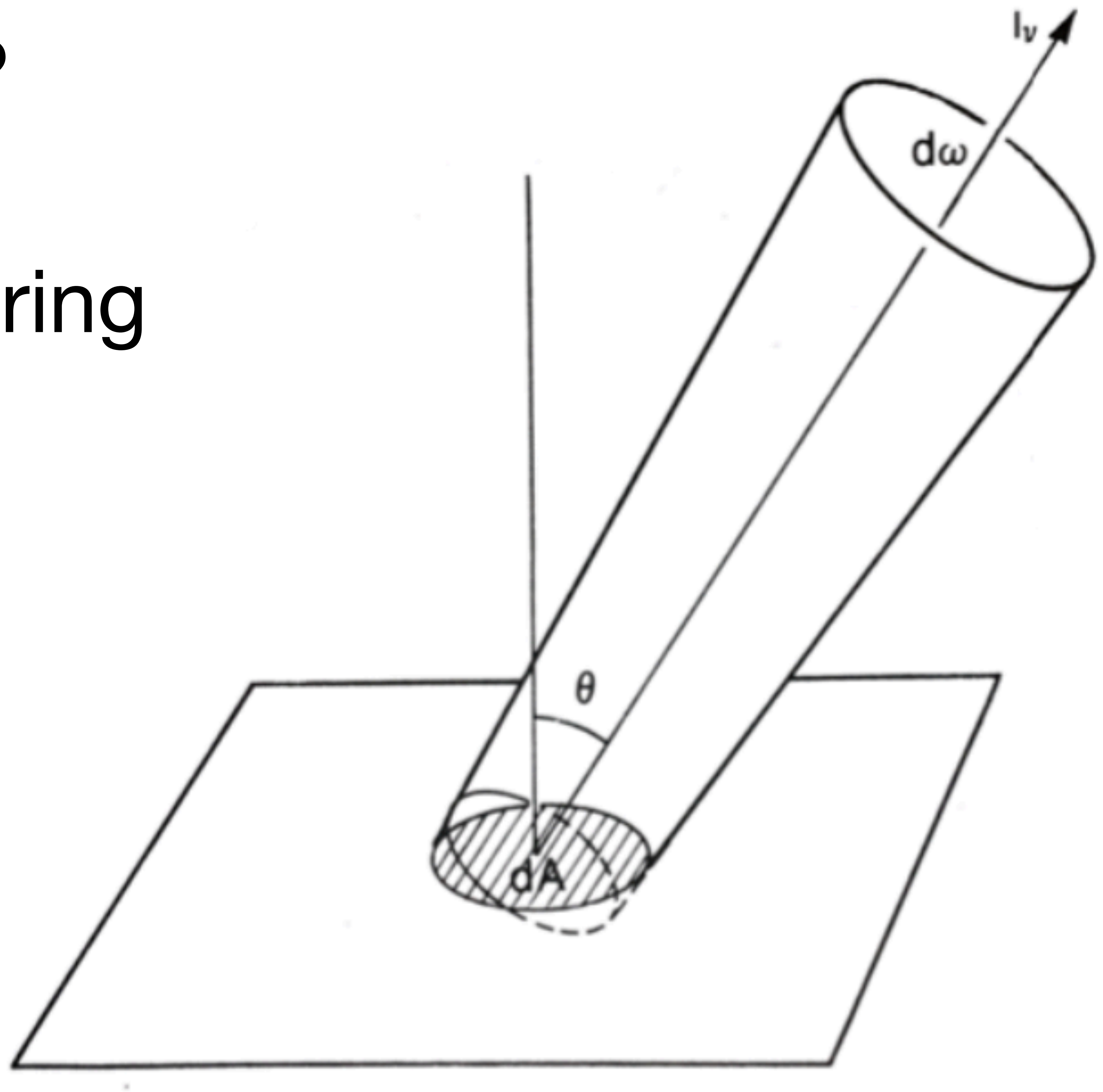
- Optical Astronomy:
  - Keep old definition by making Vega the reference defining “0th” magnitude
  - Examples:
    - Sun: -27 mag
    - Moon: -12.5 mag
    - Faintest galaxies in Dark Energy Survey (DES): 23 mag
    - Faintest galaxies in the Hubble Ultra Deep Field (UDF): 30 mag
      - Note: DES is 5000 deg^2 survey, and Hubble UDF is 0.003 deg^2 survey

Flux and Intensity

- In Astronomy, we often characterize the flux from, or intensity of, an object, but what do we mean by that?
- Amount of energy (dE_ν) passing through an area, *dA*, within solid angle $d\Omega$, in frequency range $[\nu,\nu+d\nu]$, during time *dt* is:

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

- Where:
  - $dAd\Omega$ could be something like the size (and effective) collecting area of your detector
  - **I_ν: Specific Intensity**
    - Units of J / [s m^2 Hz steradian]
    - An intrinsic property of the object (i.e., it should not depend on the observer or the measurement)



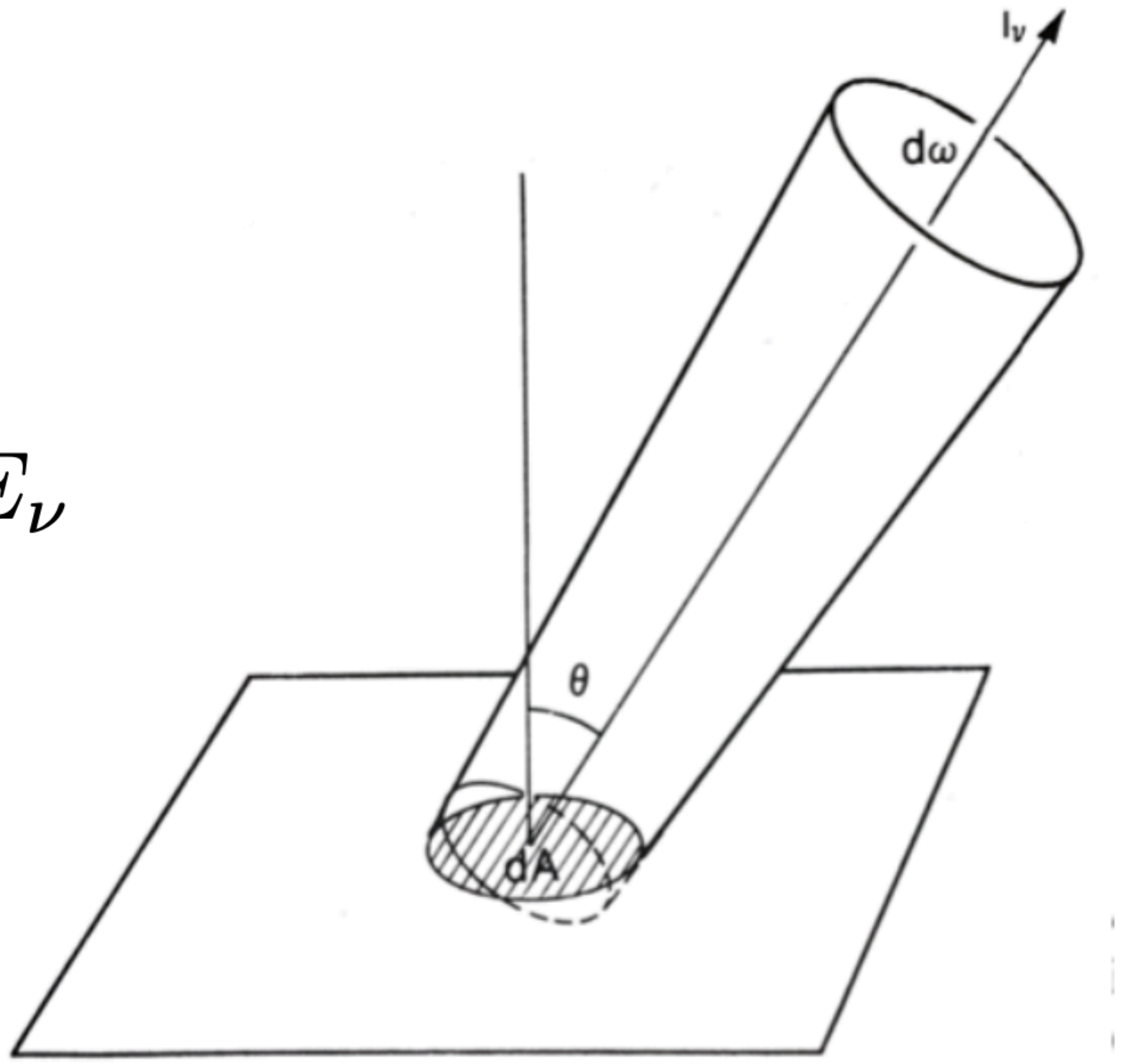
Karttunen et al.

Flux and Intensity

- We measure Flux by integrating the Specific Intensity over solid angle

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

$$f_\nu = \int_\Omega d\omega \cos\theta \; I_\nu$$
$$= \frac{1}{dA \; dt \; d\nu} \int_\Omega dE_\nu$$



Karttunen et al.

- **Spectral Flux Density, f_ν:**
  - Energy per area, per time, per frequency interval
  - We usually observe f_ν (or f_ν integrated over the frequency band of our detector)
  - Depends on the distance between the source and the observer.

Flux and Intensity

- Spectroscopy: Effectively measures f_ν in a narrow frequency band
- Otherwise, for most CCD images we will be making, we are really measuring an integral over the observed frequency to measure a **Flux, F**, where

$$F = \int_{\text{passband}} f_\nu \, d\nu$$

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

- Where T_ν: System response curve (e.g., filter transmission)
    - Note: We can define any of these quantities in terms of frequency (ν) or wavelength (λ), where:

$$f_\lambda = \frac{c}{\lambda^2} f_\nu$$

Luminosity

- **Luminosity, L_ν**
  - Units: J / [s Hz]
  - Integrate total flux from the object (i.e., this could be done either at surface of the star, or inferred from measurements at the detector, light-years away)
  - Luminosity is also an intrinsic property of the object (will not depend on observer)
- Bolometric Luminosity, L_{bol}
  - Integral of luminosity over all frequencies:

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

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

$$= f_\nu \int dA = f_\nu \, 4\pi d^2$$

Note: Assumes Isotropy, so if the source has a directionality, then cant assume constant flux over the surface area of the source.

Optical Filters

- Optical astronomy has several different standard “filter sets”
    - ***SDSS: ugriz -> Most common today***
    - Johnson-Cousins: *UBVRI*
- Why are people using different filters?!?
    - Technology evolves, so sometimes there are improvements that causes changes
    - Filters might depend on waveband or detector type, i.e., there could be some good reasons you want a different filter to match your detector
    - Space vs ground will want different filters

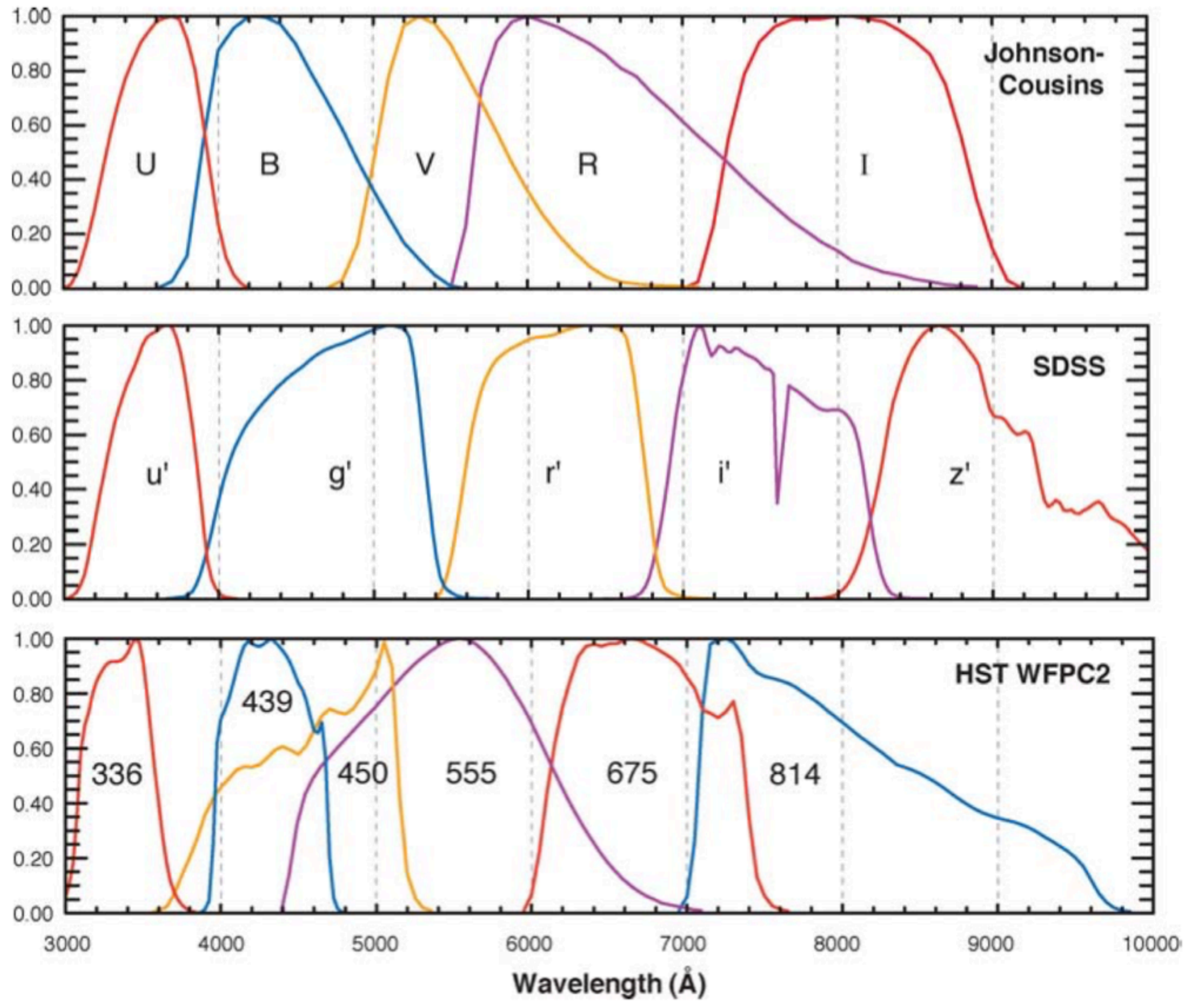


Figure 1 Schematic passbands of broad-band systems.

Note: 10 Angstroms = 1 nanometer

Bessel 2005

Color

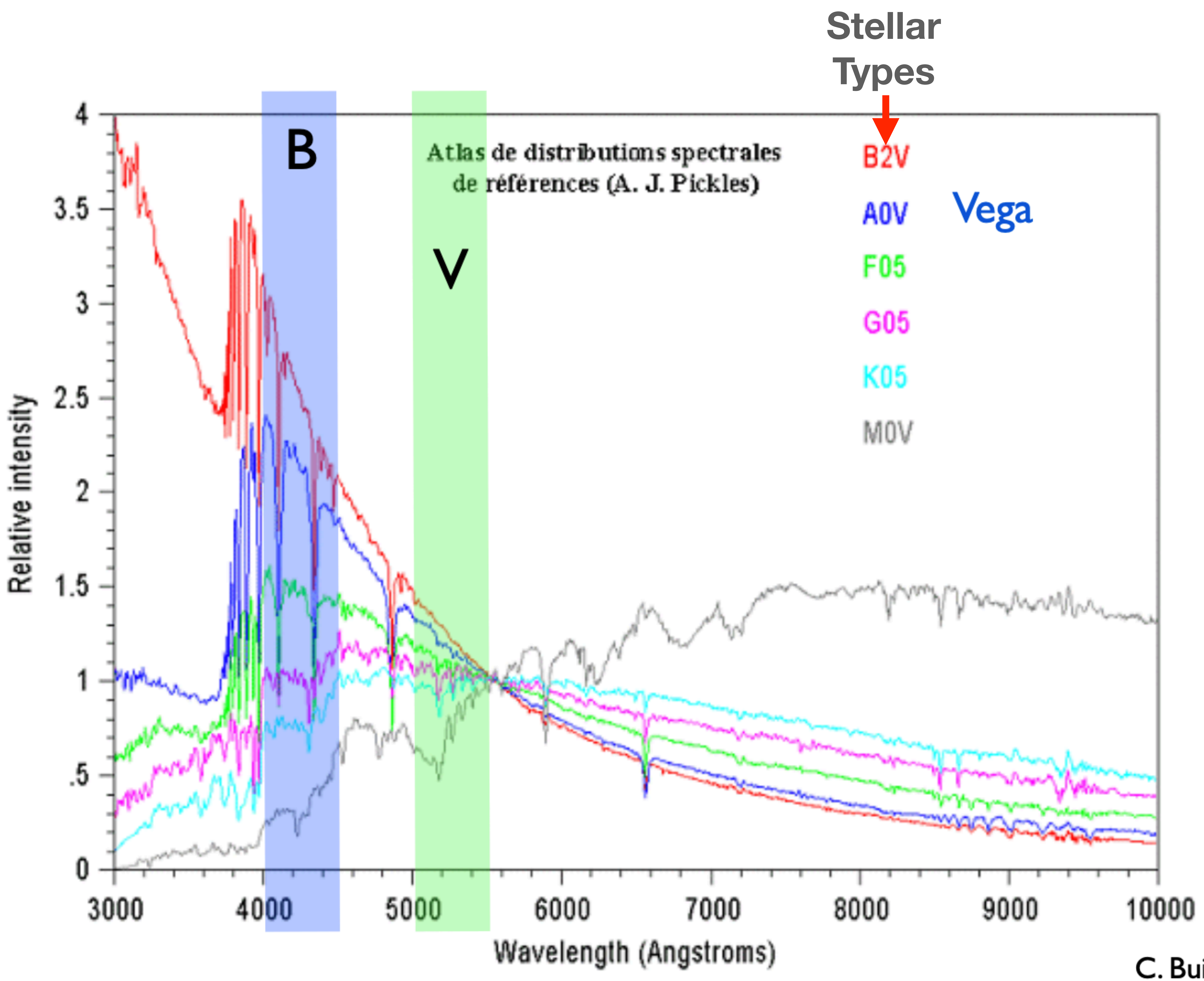
- Difference between magnitudes in two bands (e.g., B, V)

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

- Vega has 0 color, by definition
    - “Blue” star: Flux ratio (to Vega) in B filter greater than V
    - Q: Is (B-V) positive or negative for a blue star?

Color

- Vega has a very particular spectrum gives its stellar type (i.e., a A0V type star)
- Other stars have very different spectral shapes

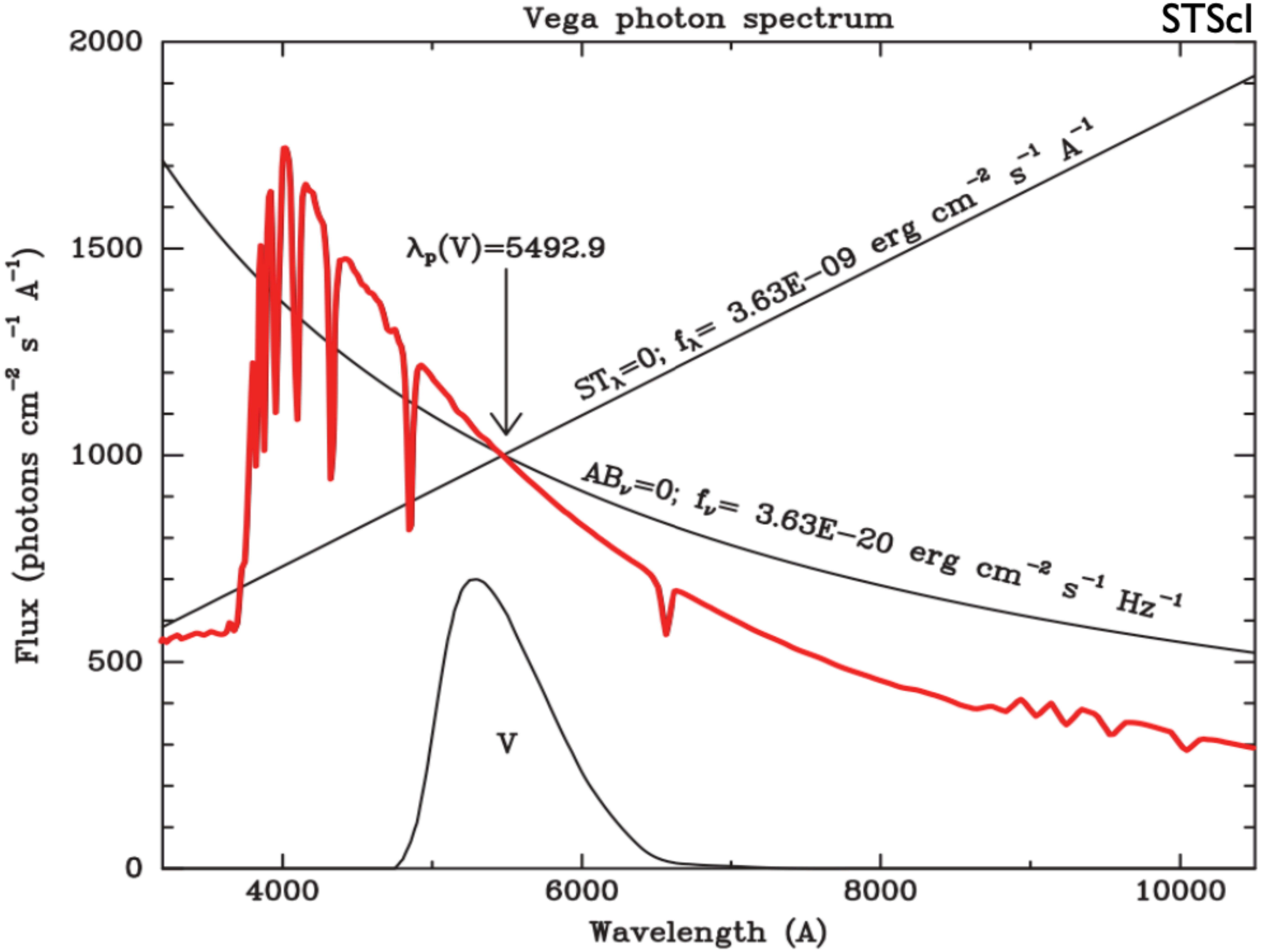


C. Buil

AB Magnitudes

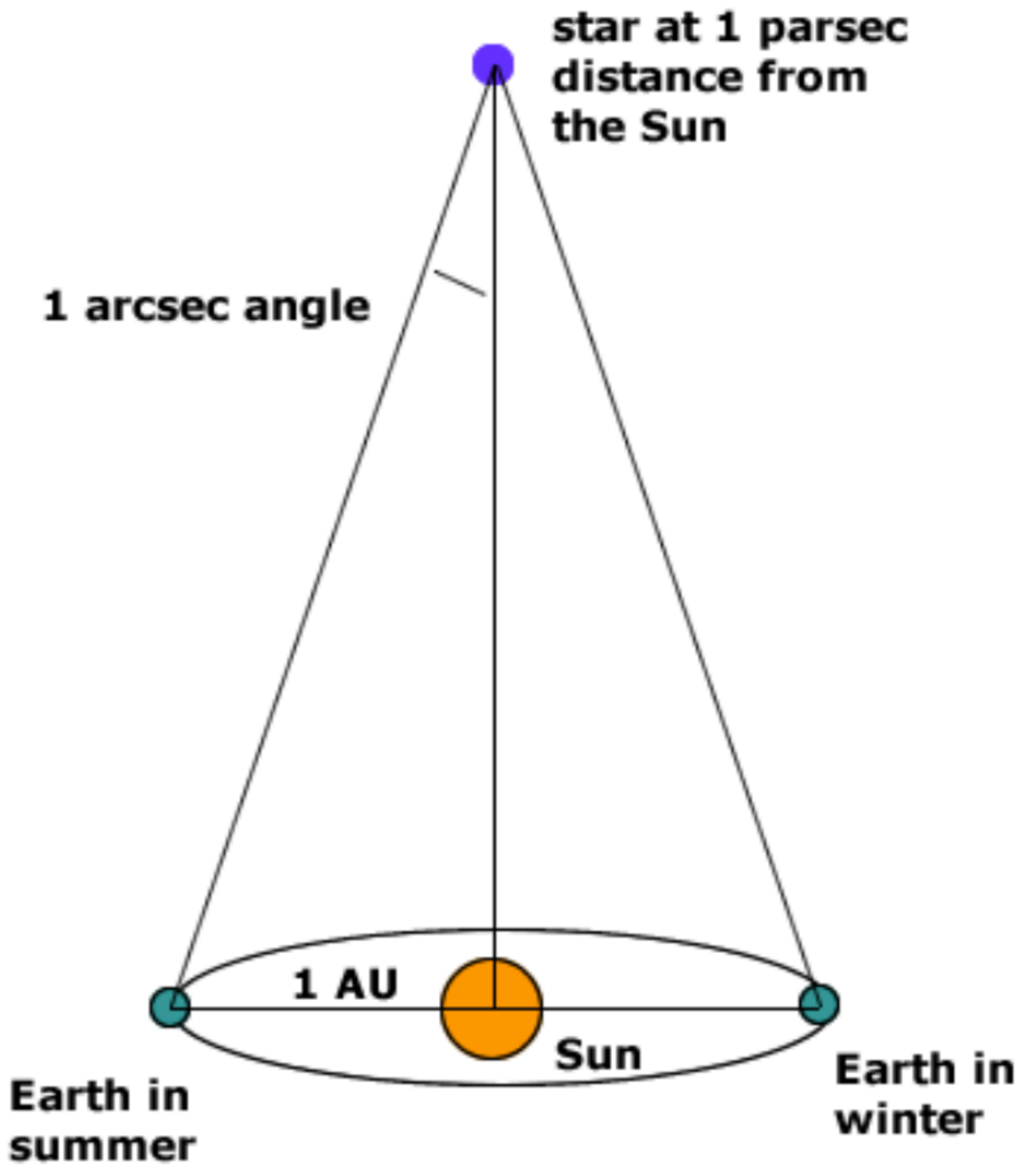
$$m_{\rm AB} = -2.5 \log\left(\frac{f_\nu}{3631\ \rm Jy}\right)$$

- Defined relative to constant flux density
- But normalized so that Vega is ~0-magnitudes in V filter
  - So stars with very different spectra and flux in other wavebands, might have same AB magnitude



Parallax and Parsecs

- Due to the Earth's motion around the Sun, positions of (especially nearby) stars appear to shift
- 1 parsec (pc) = Distance to a star whose position shifts by 1-arcsec (") from a 1 AU baseline
- 1 pc = 3.26 light-years = 3 x 10^{16} meters
    - Proxima Centauri: 1.3 pc
    - Milky Way is about 100,000 light years across (or 32, 000 parsecs)



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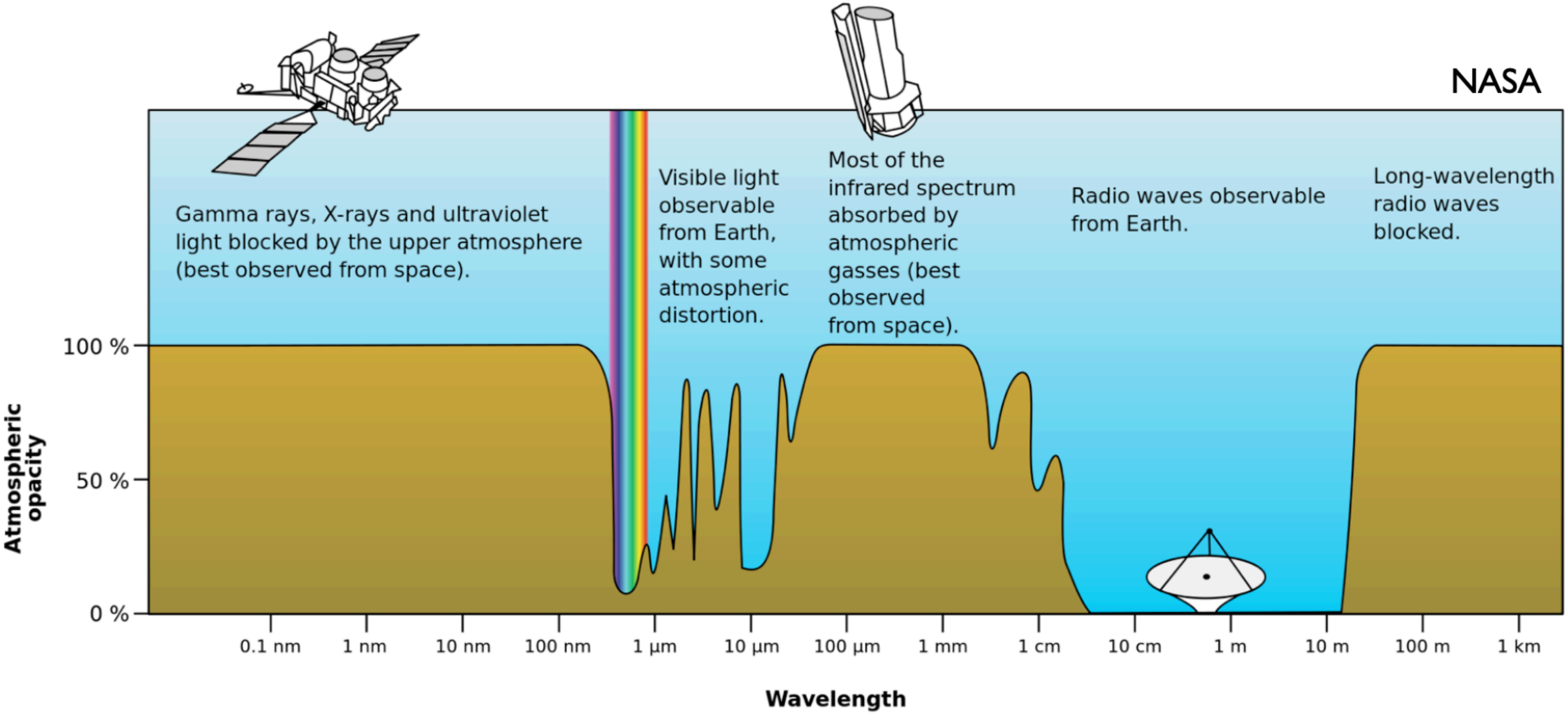
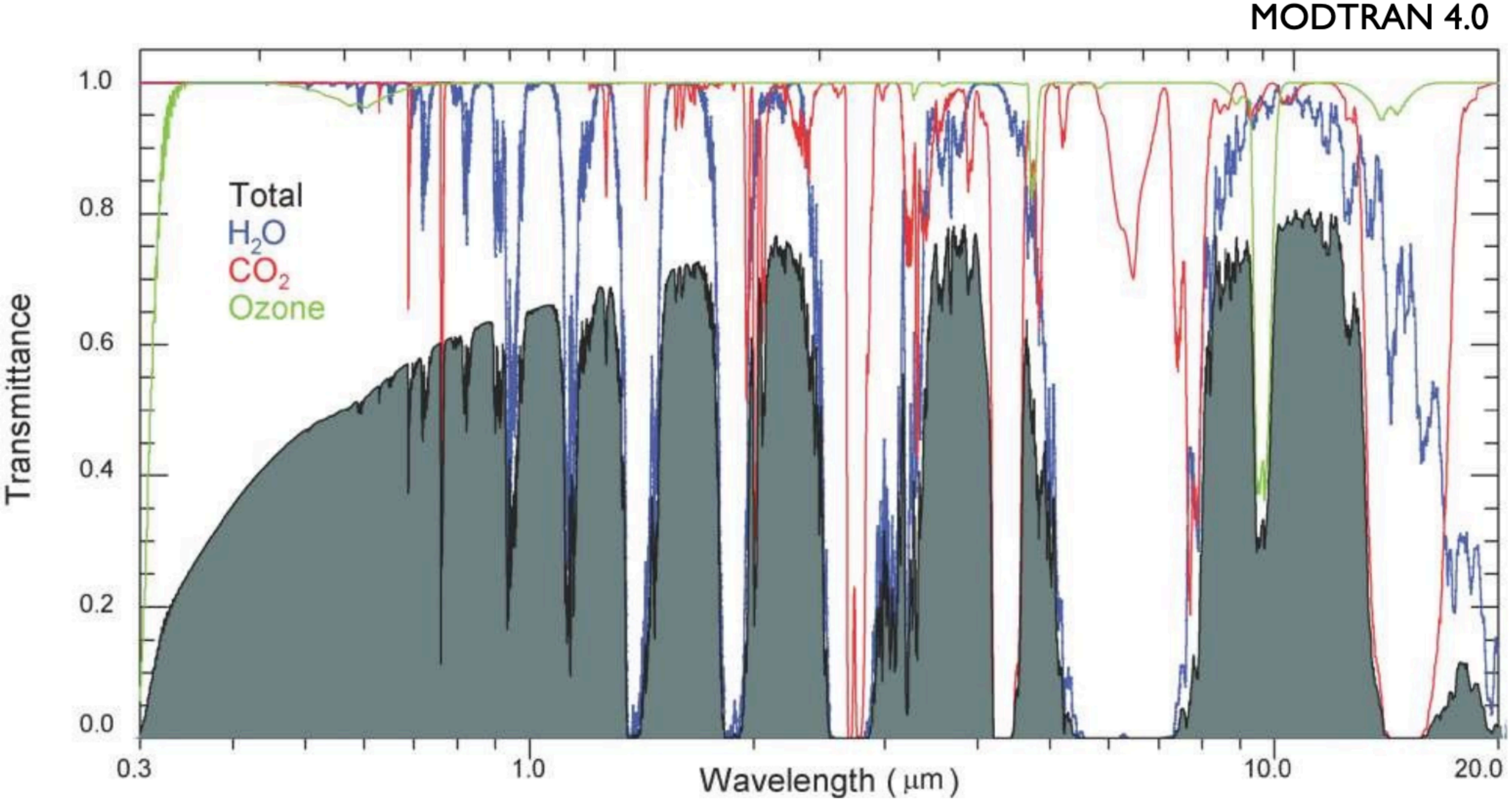
Earth’s Atmosphere

- The Earth’s atmosphere is opaque to most of the electromagnetic spectrum
- Astronomy at some wavelengths can only be done from space!



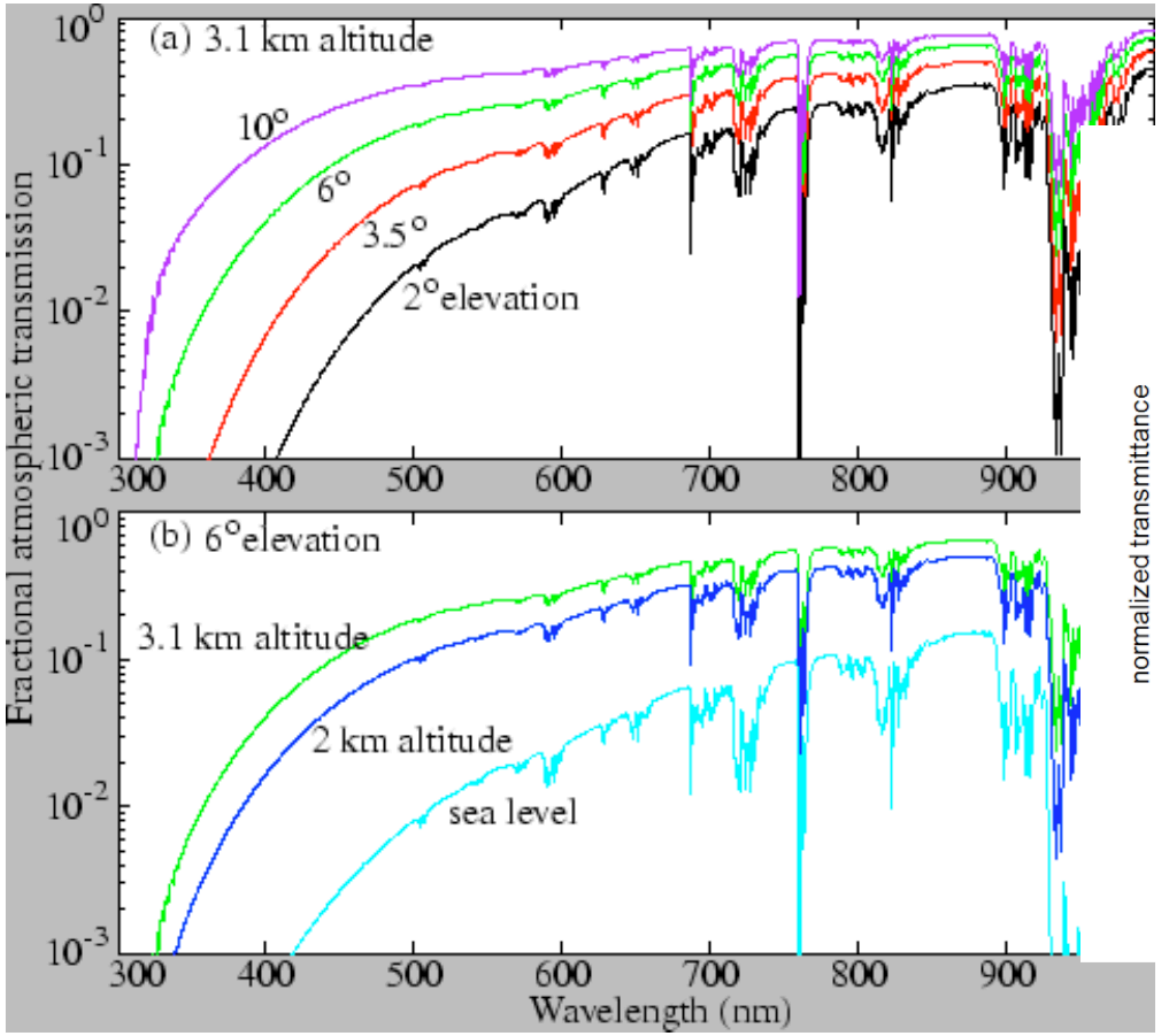
Earth's Atmosphere

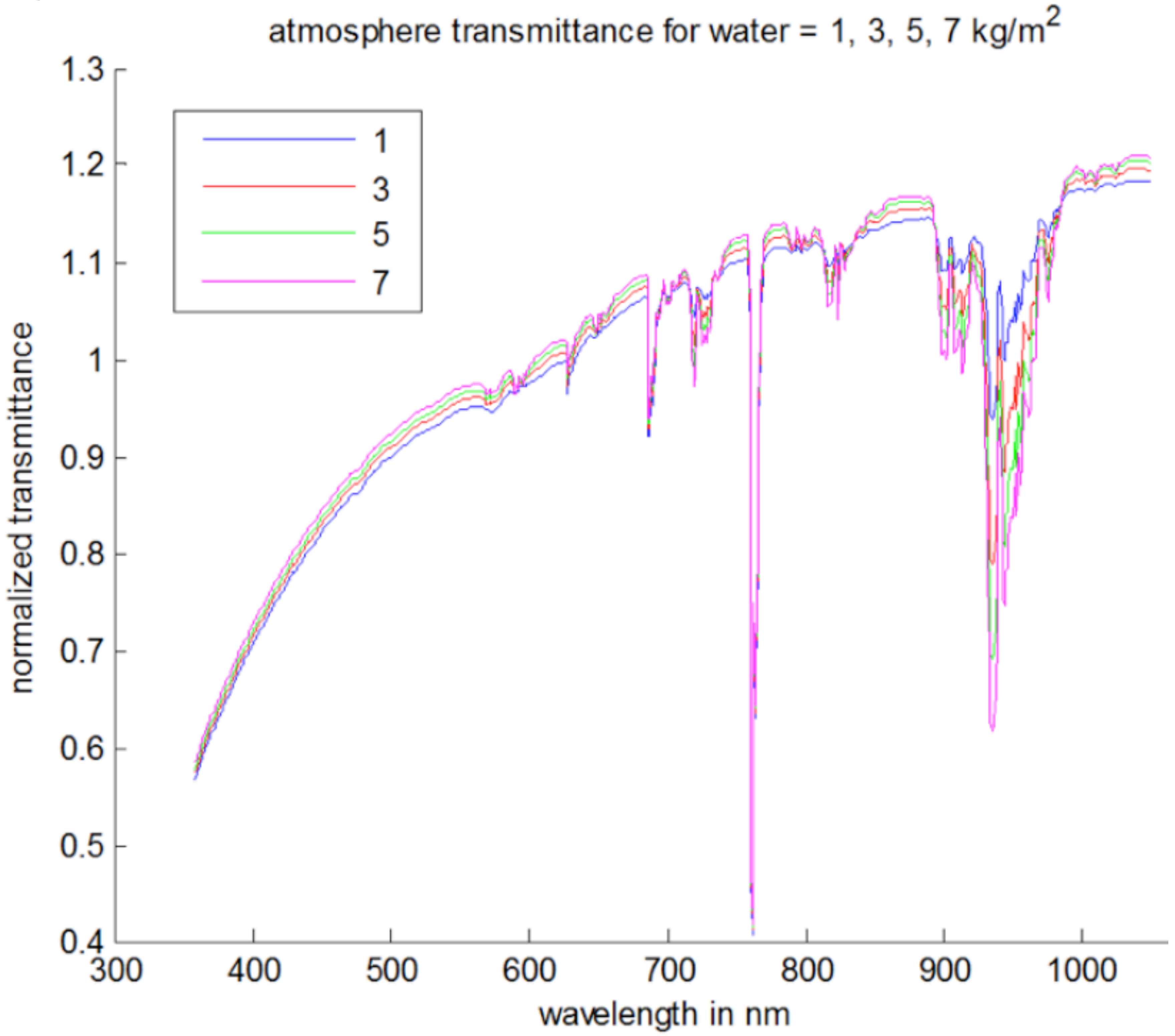
- In the optical (~300-nm to ~1 μm) and near-infrared, extinction mainly due to:
  - Scattering, e.g., Rayleigh ~ λ^4
  - Absorption, mainly water vapor and some other molecules (CO2, O2, etc.)



Earth's Atmosphere

- Details depend significantly on the observatory location, target altitude / elevation, and water or aerosol content.



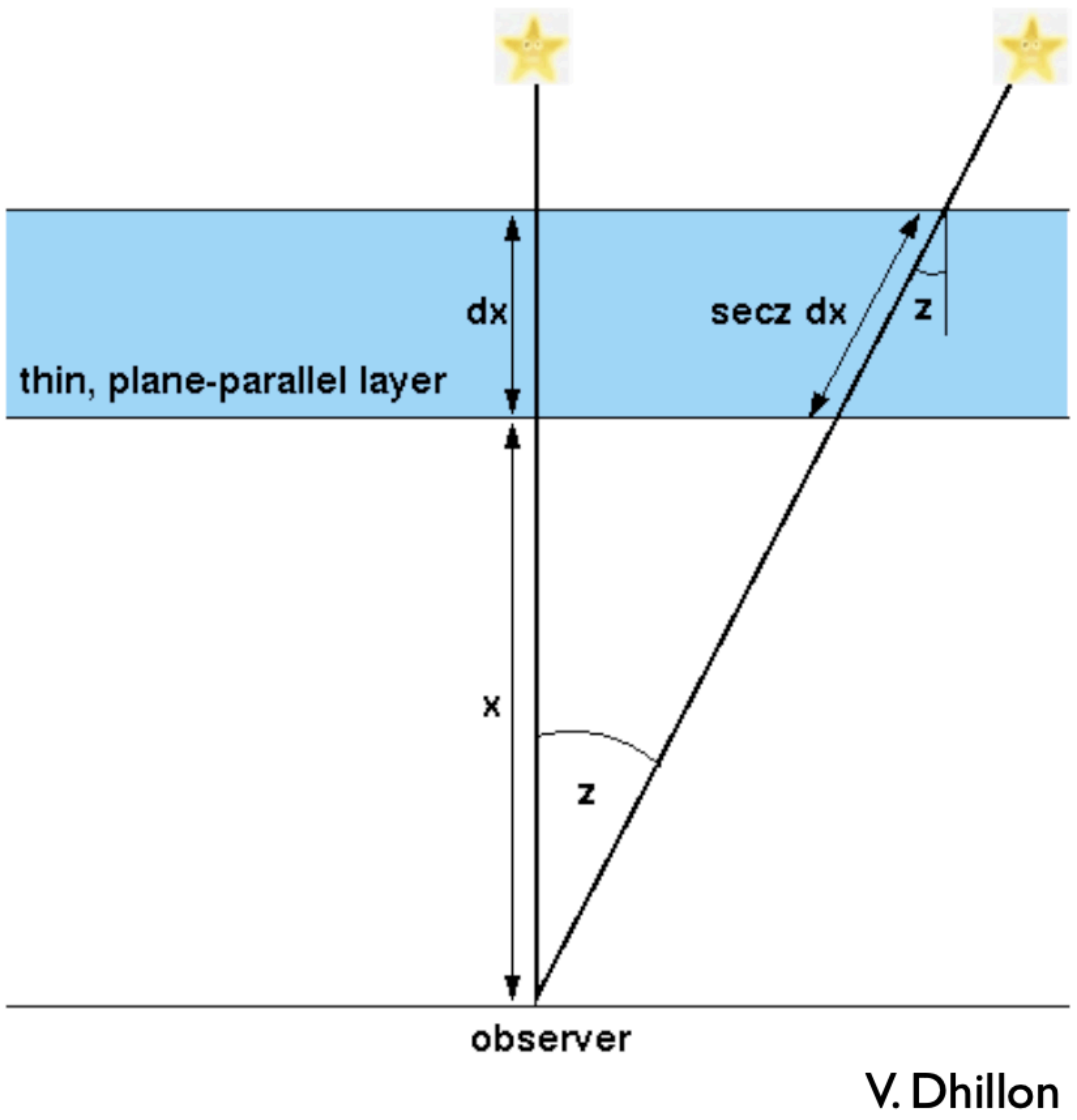


Ting Li

Airmass

- Useful to define an "Airmass" or AM
  - Expresses the amount of air that light has to pass through, relative to zenith
- Plane-parallel approximation:
  - AM = 1 / cos(90^o-El) = sec(90^o-El)

- El=90^o: AM=1
- El=50^o: AM=1.3
- El=30^o: AM = 2
- El=20^o: AM = 2.9

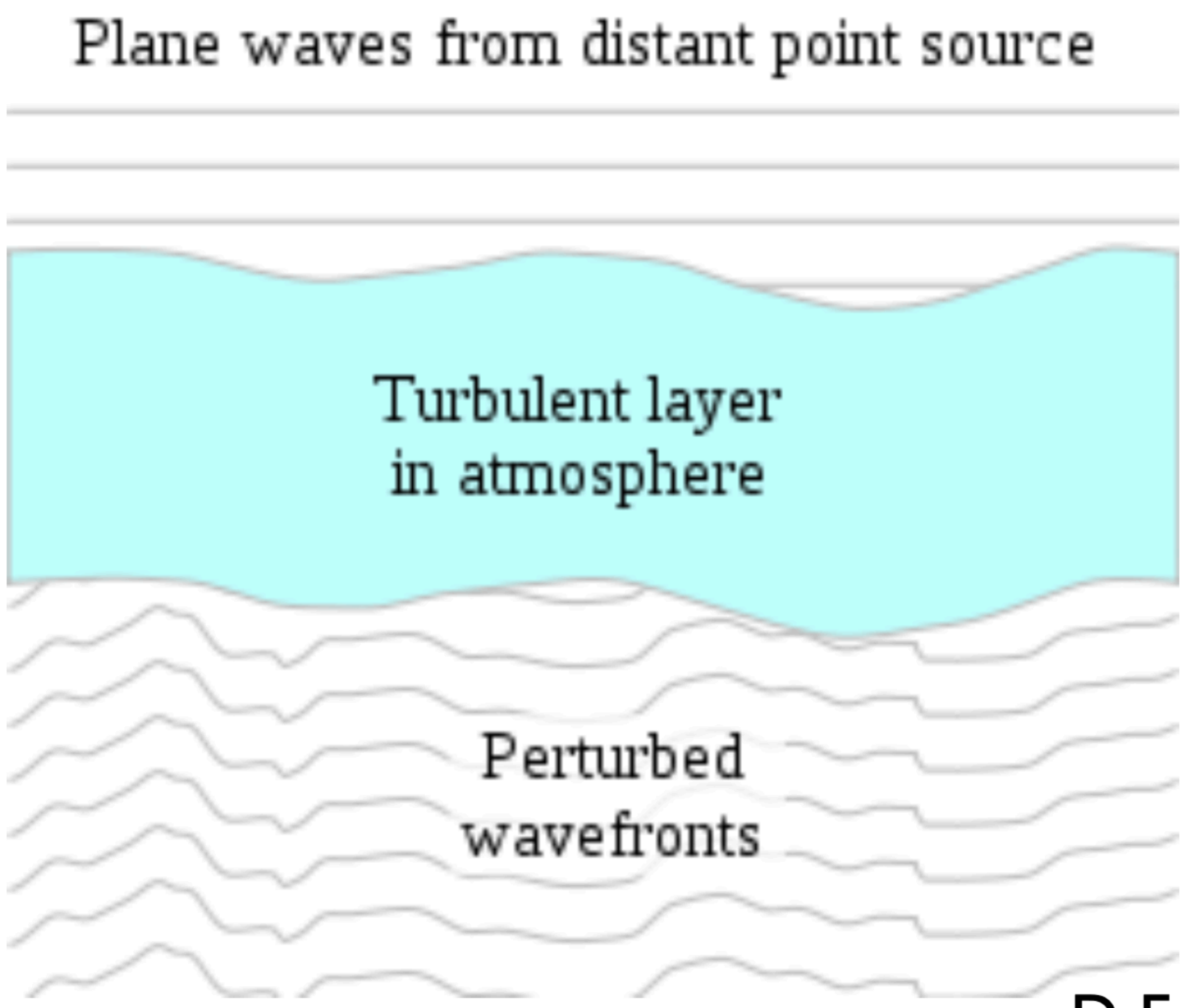


Atmospheric Seeing

- Diffraction-limited resolution of a telescope with aperture, D:

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

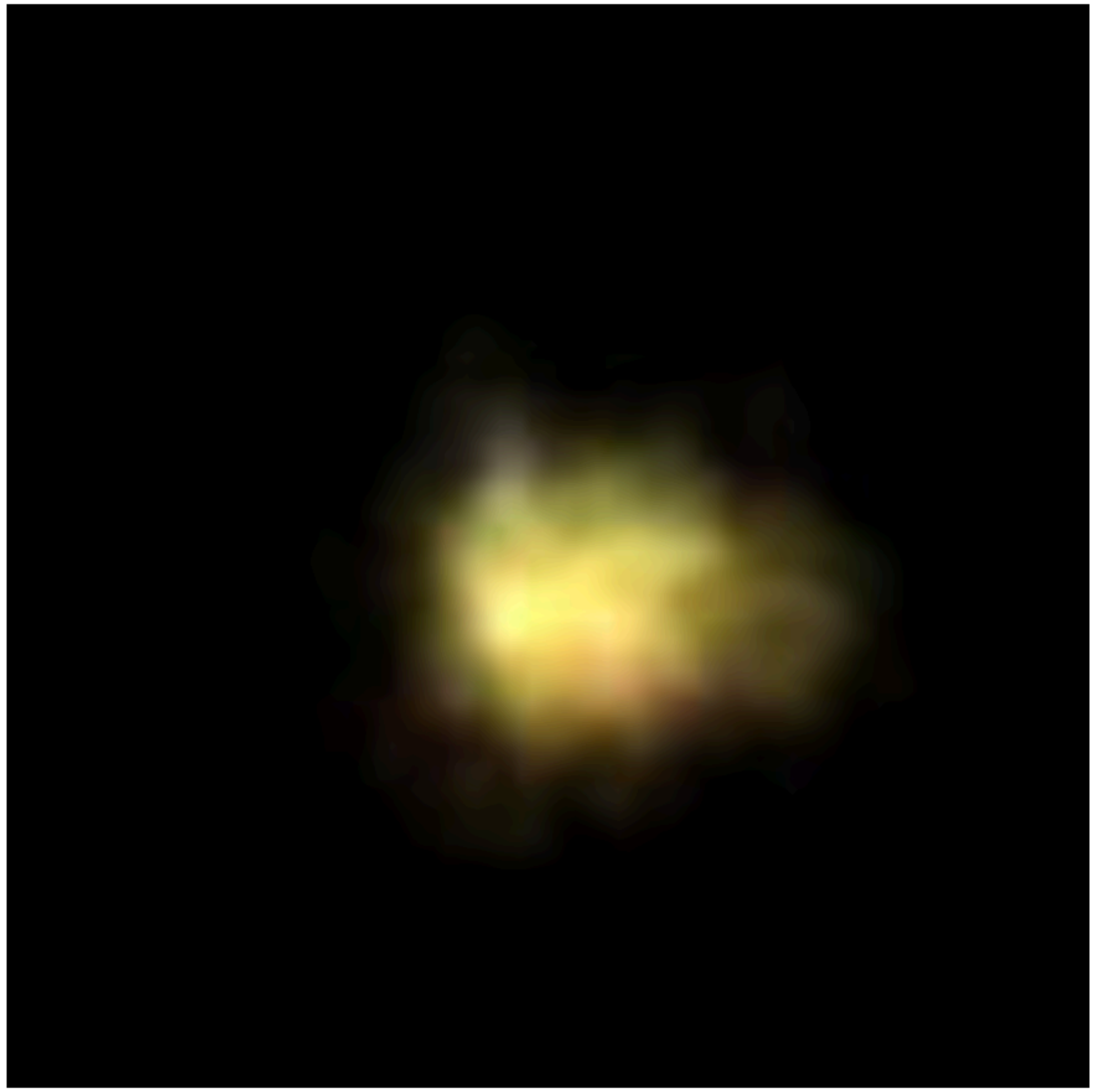
- Theoretical resolution of a 10-meter telescope in the optical is ~0.01”.
- In practice, **seeing** from the turbulent atmosphere “blurs” images, so even 10-meter class optical telescopes often are limited to ~1” resolution



D. Eccles

Atmospheric Seeing

- Effect causes the wavefront to be effectively broken up, and create “mini-images”, where seeing creates “speckles” and effectively blurs the image



MPIfR

Atmospheric Seeing

- In the optical, seeing depends on both Airmass/AM and wavelength proportional to

Blurring (From seeing) $\propto \mathrm{AM}^{0.6}$

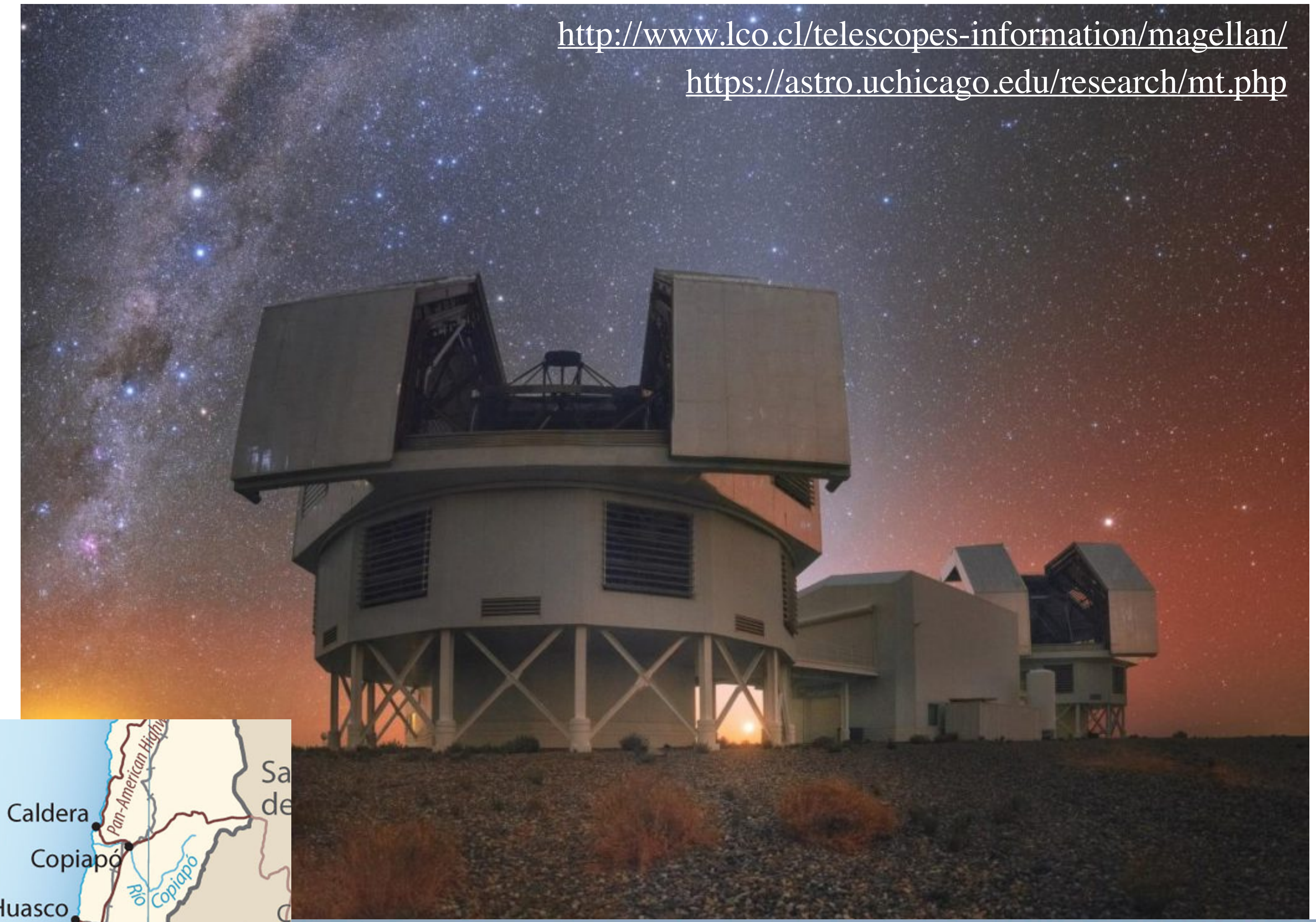
Blurring (From seeing) $\propto \lambda^{-1/5}$

- So looking through more atmosphere (higher AM) is worse.
- And looking through less transmissive atmosphere is worse (i.e., why its better towards 1 um, compared to 300-nm)

A bit about telescopes

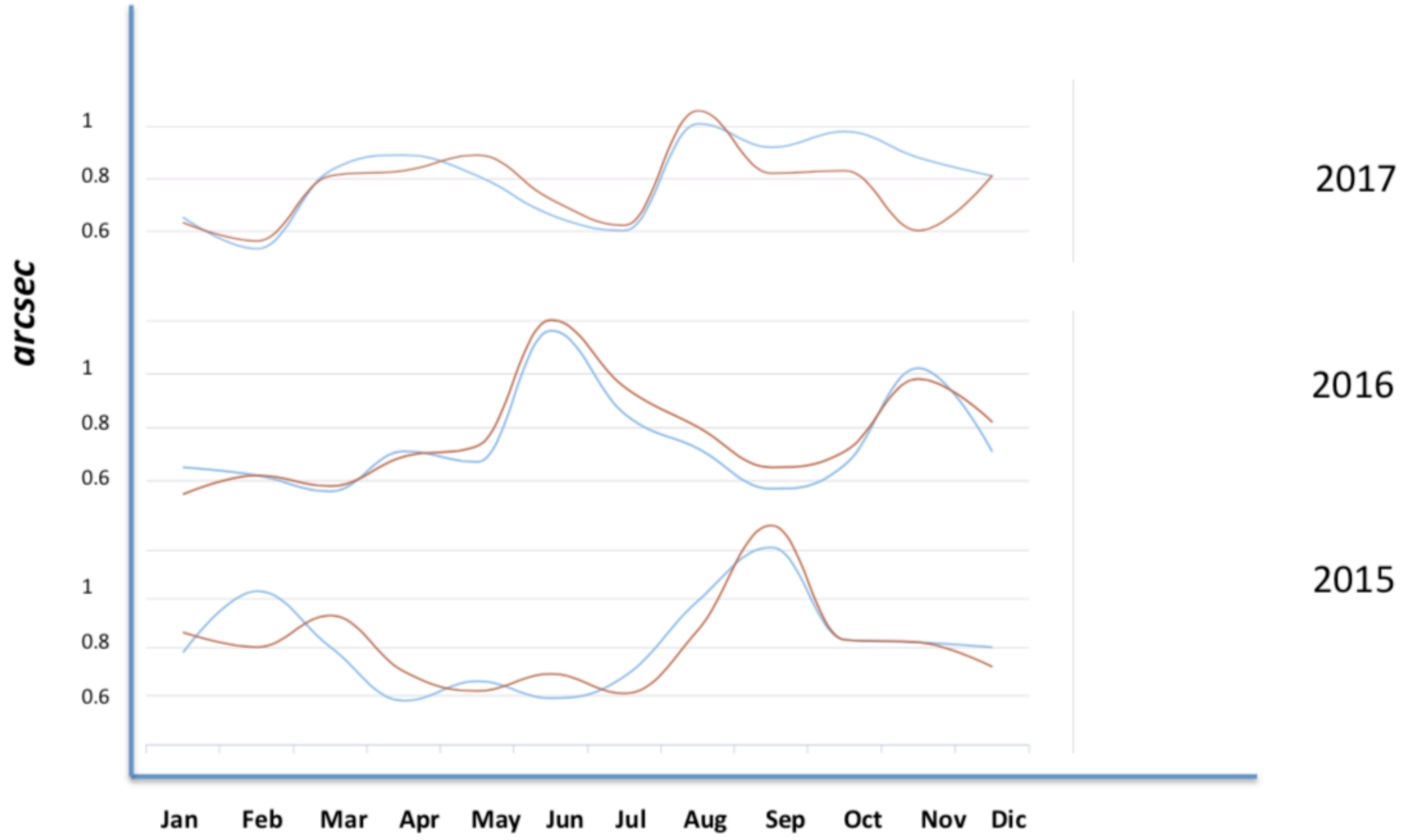
Telescopes: The Magellan Telescopes

- Magellan: Two 6.5-m telescopes (Baade, Clay)
- At Las Campanas Observatory (LCO) in Chile
  - 2500-m / 8500-ft
- U. Chicago has ~28-nights / year total on both telescope
  - Observing Semesters; UC proposals due in April and October each year
- LCO also future site of Giant Magellan Telescope (GMT)



Magellan Seeing

- Daily seeing varies ~0.5-1.5 arcsec
  - Remember, diffraction is ~0.01-arcsec, 100x less
- Some year-to-year variation between seasons, no obviously “good” or “bad” season



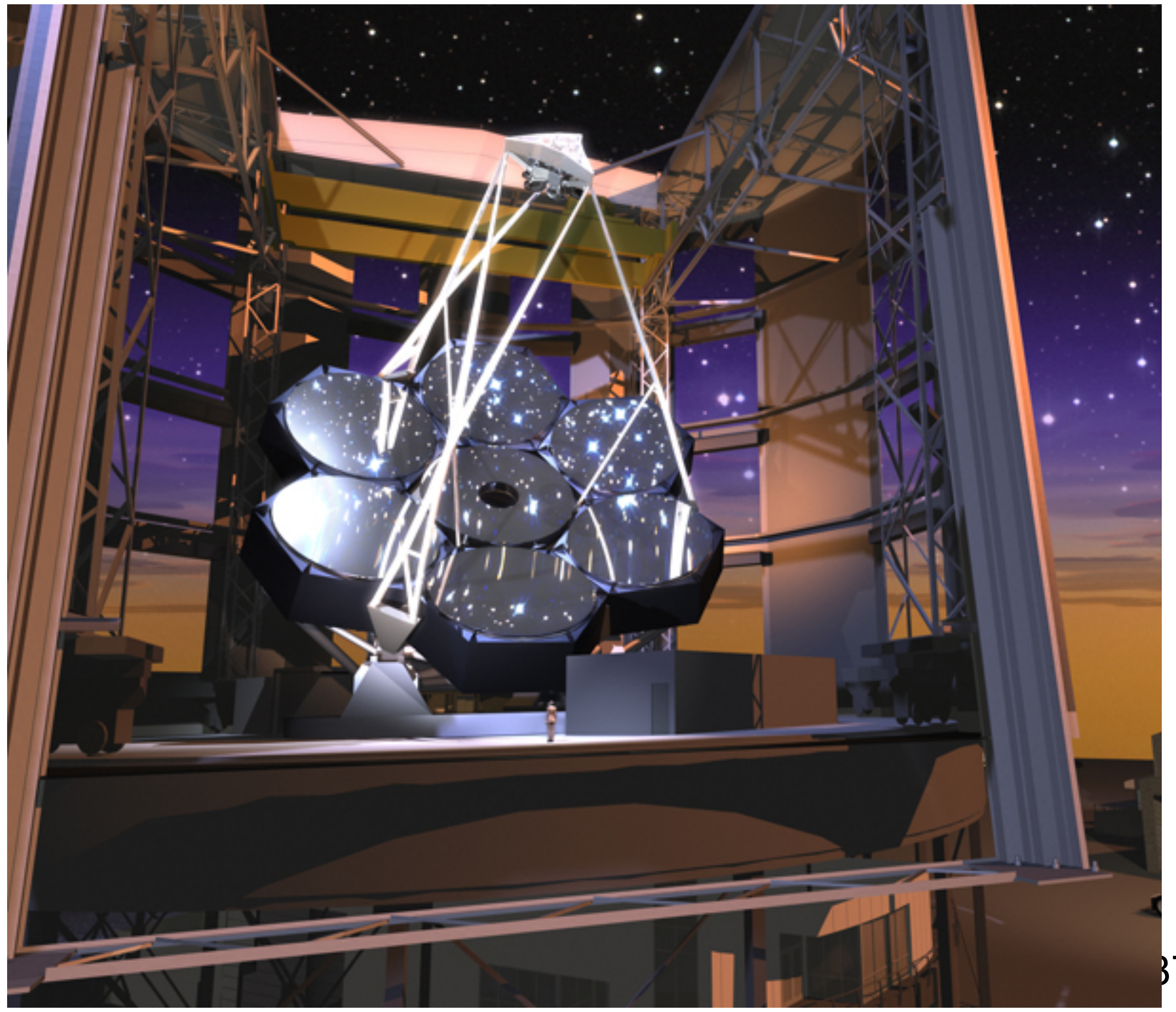
Telescope Apertures (or Diameters)

- Astronomy is always trying to detect fainter objects
- So need to gather as much light as possible
- The diameter (aperture) of the mirror is one of the main characteristics of a telescope that determines its sensitivity (remember: Flux ~ dA)

Magellan Telescopes: 6.5-meter

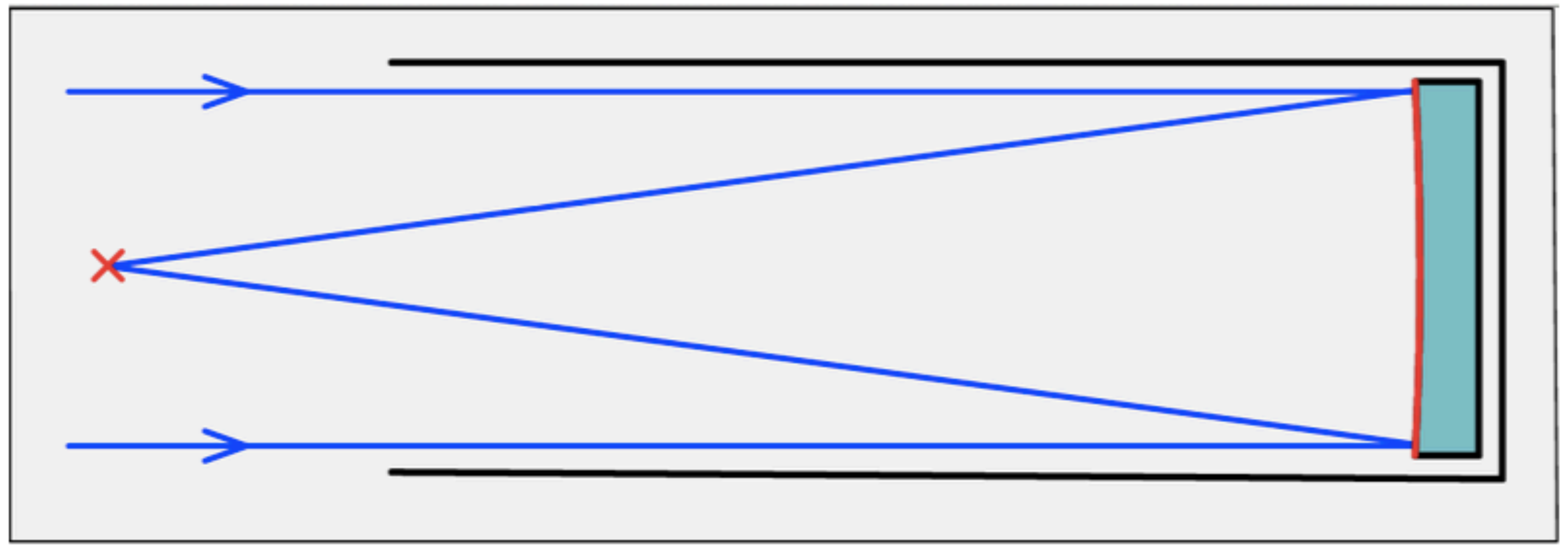
Keck Telescopes: 10-meter

Next-Generation 30-m telescopes (~2030s)
(Including the “Giant Magellan Telescope)

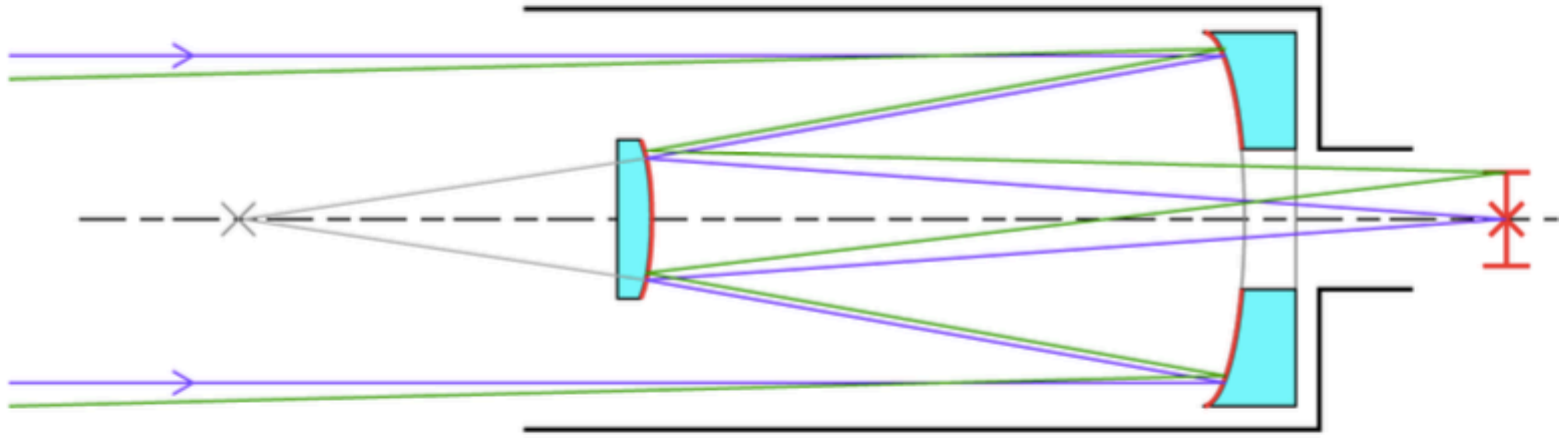


Telescope Foci

- prime focus: focus of primary mirror

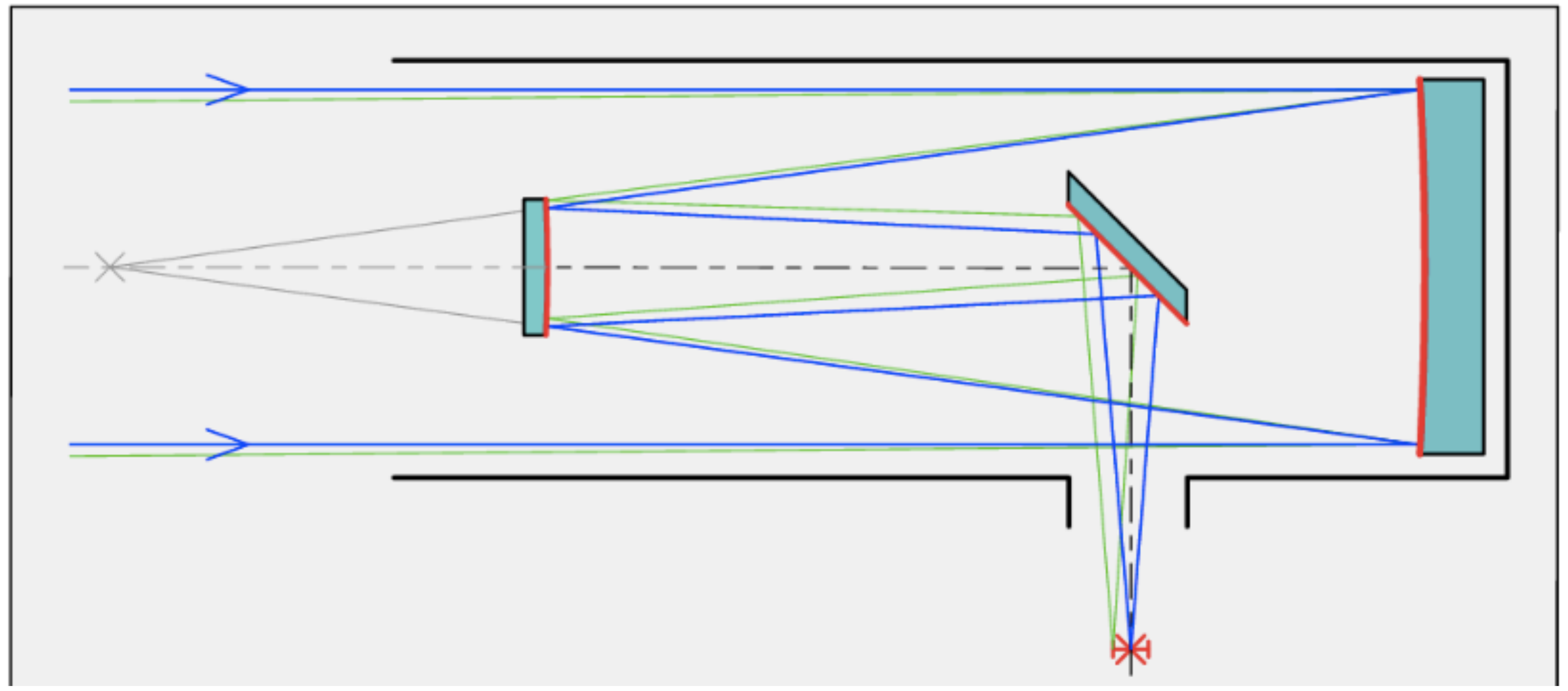


- Cassegrain focus: secondary mirror in front of prime focus; secondary focus behind primary mirror



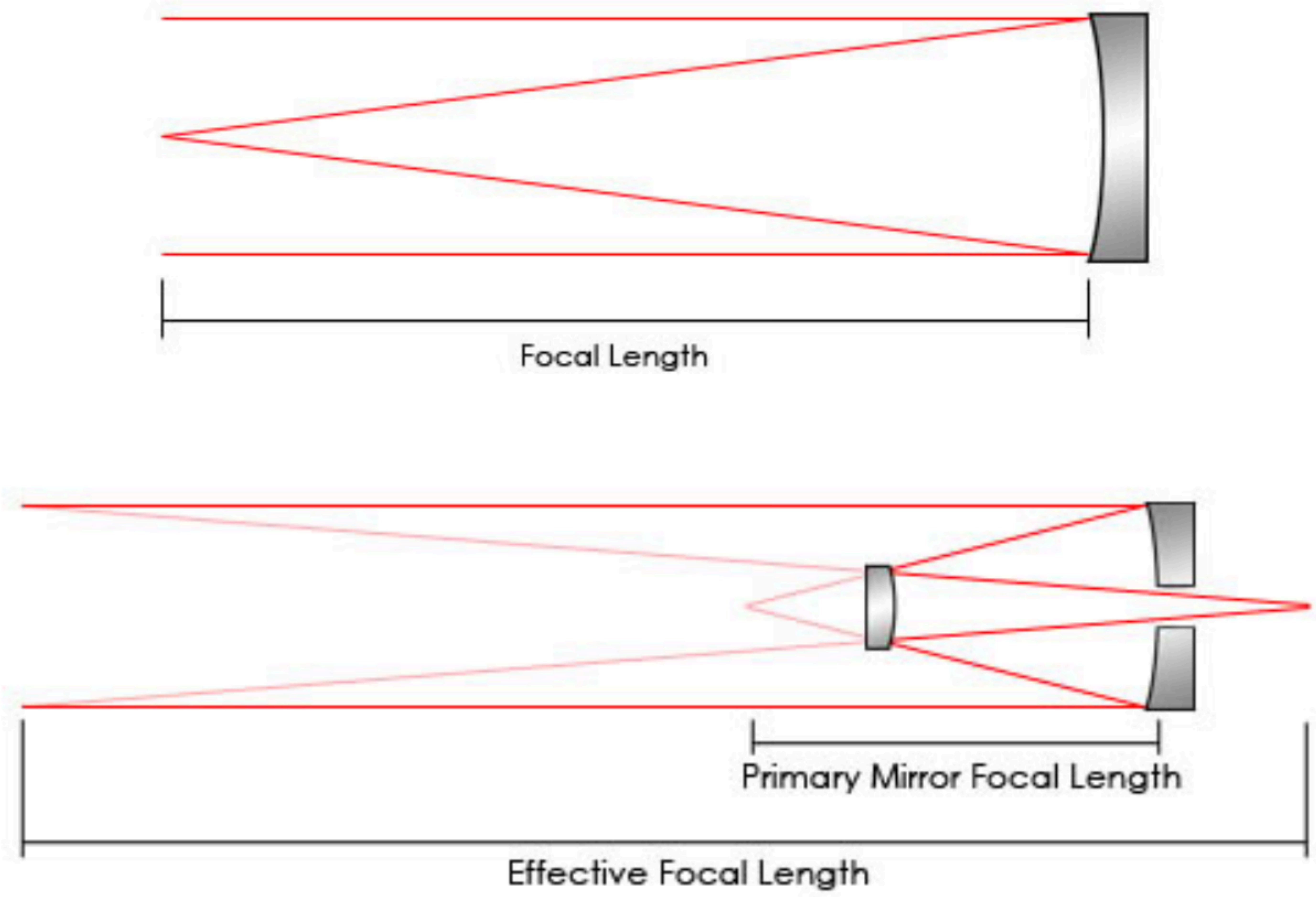
K. Vedala

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

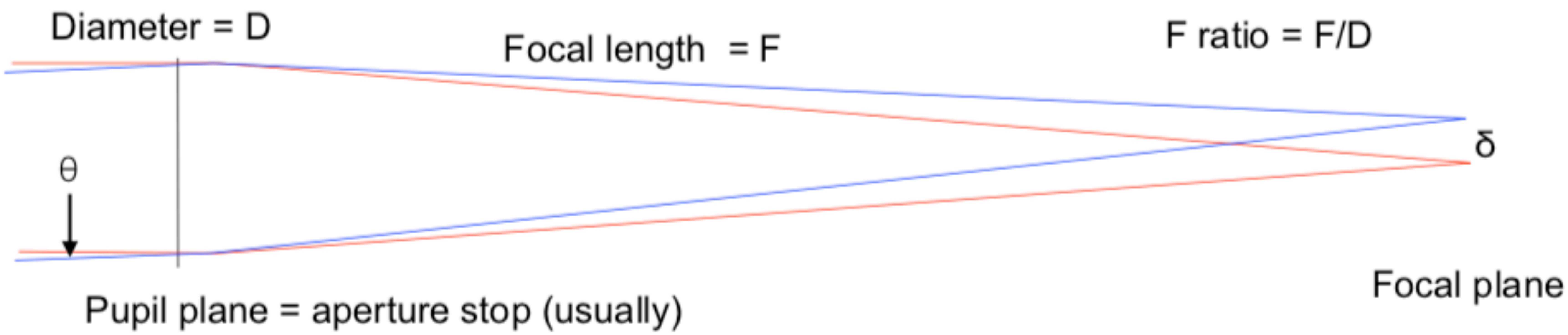


Focal Length

- Distance from the mirror (or lens) to the focal plane

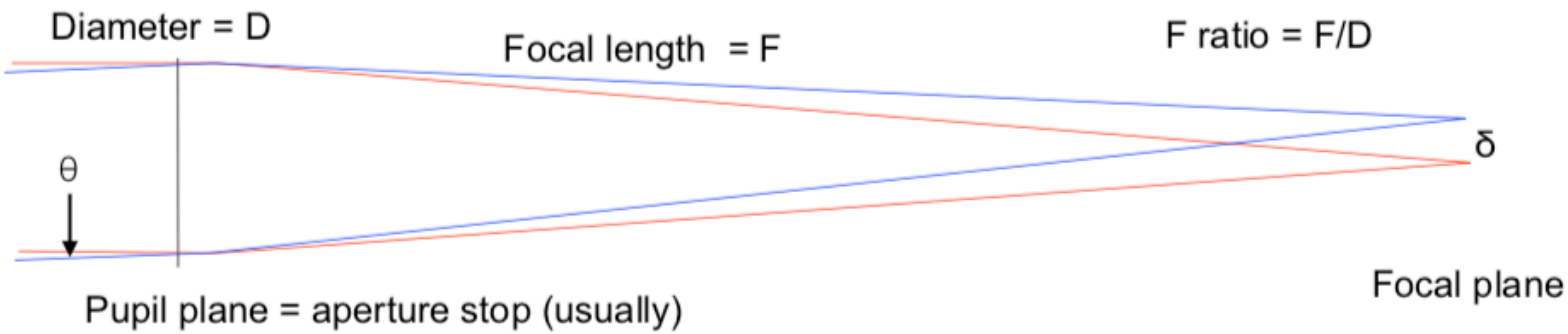


Telescope Principles



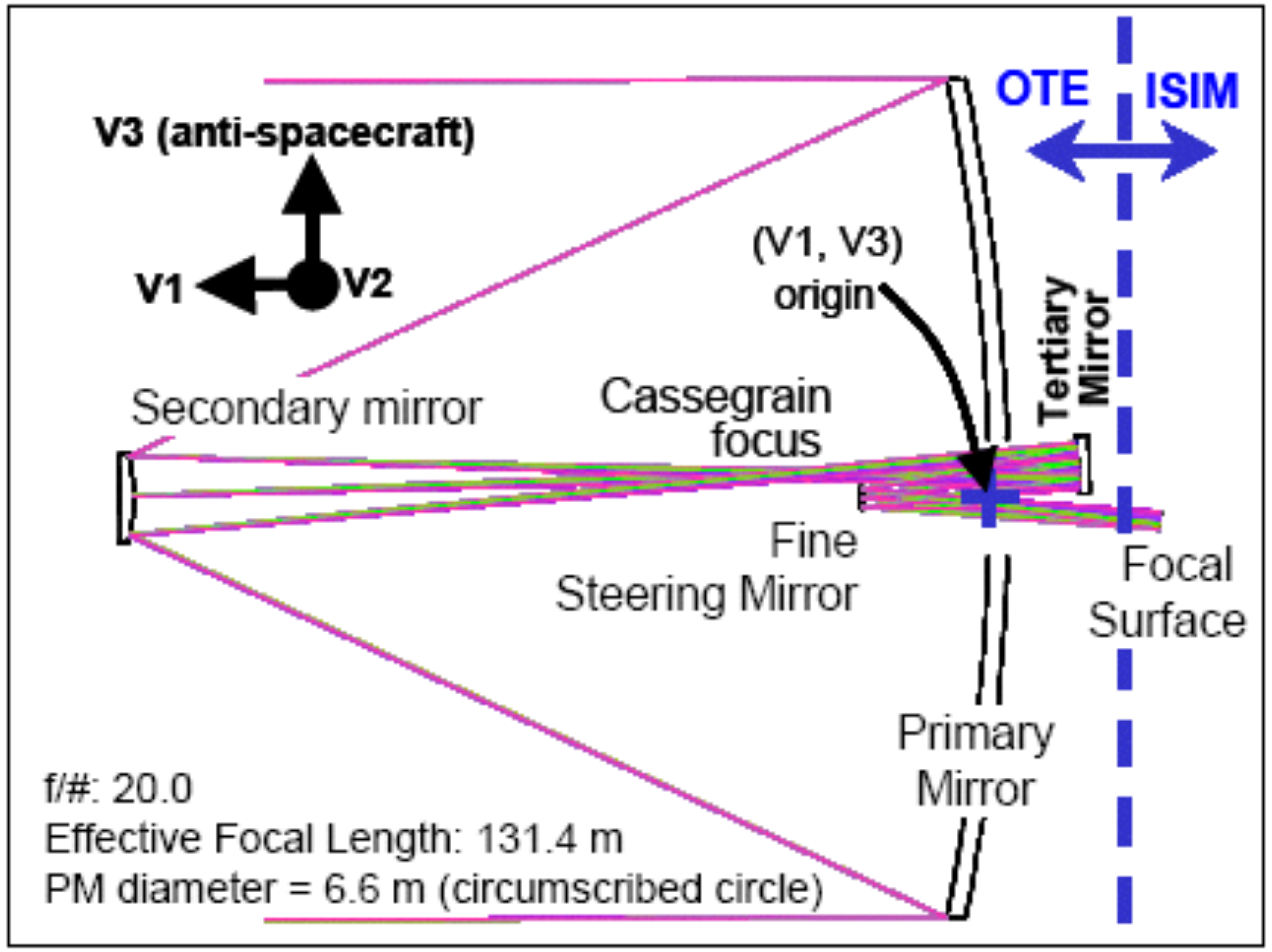
- The **Focal length (F)** determines the pixel (or plate) scale at the focal plane, the ratio between the angle on the sky and physical dimension of the detector.
  - Angular scale on-sky to physical separation on focal plane: $\boldsymbol{\delta = \theta \times F}$
    - **Plate scale: (Angle/Length), e.g., (arcsec/mm)**
  - **F/D = the "f-number" (or f/#).** So can re-express as: $\boldsymbol{\delta = \theta \times D \times (f/\#)}$

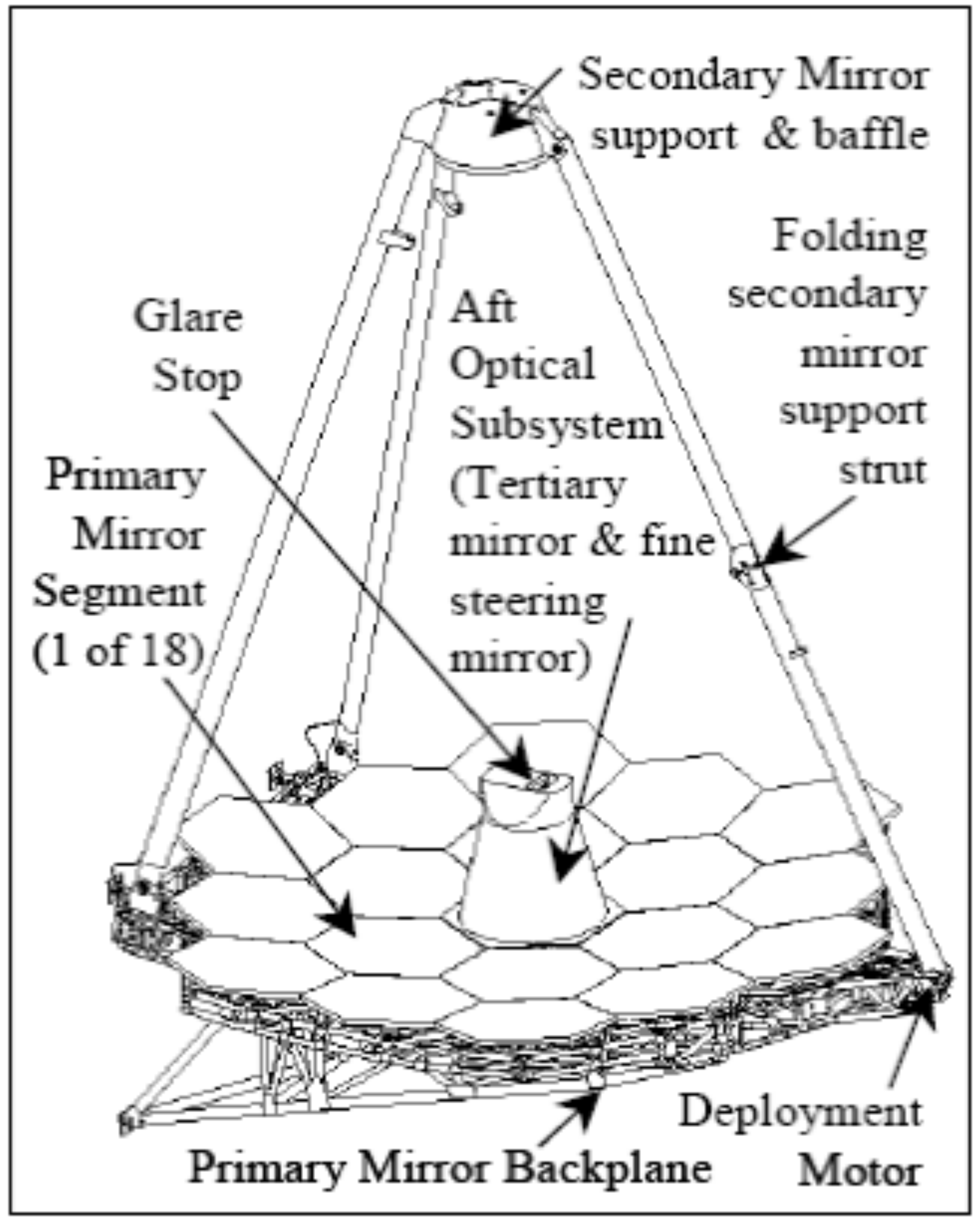
Telescope Principles

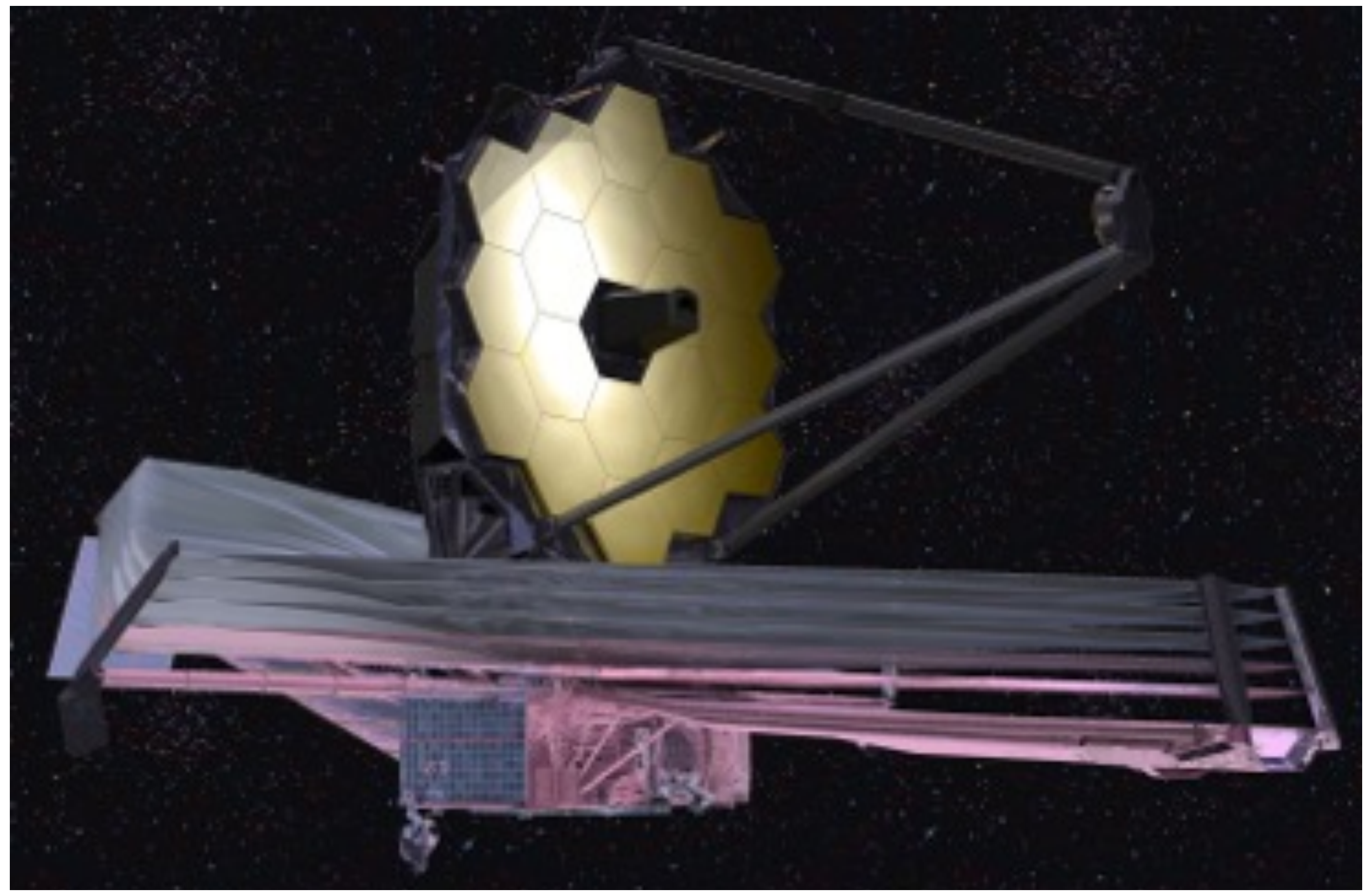


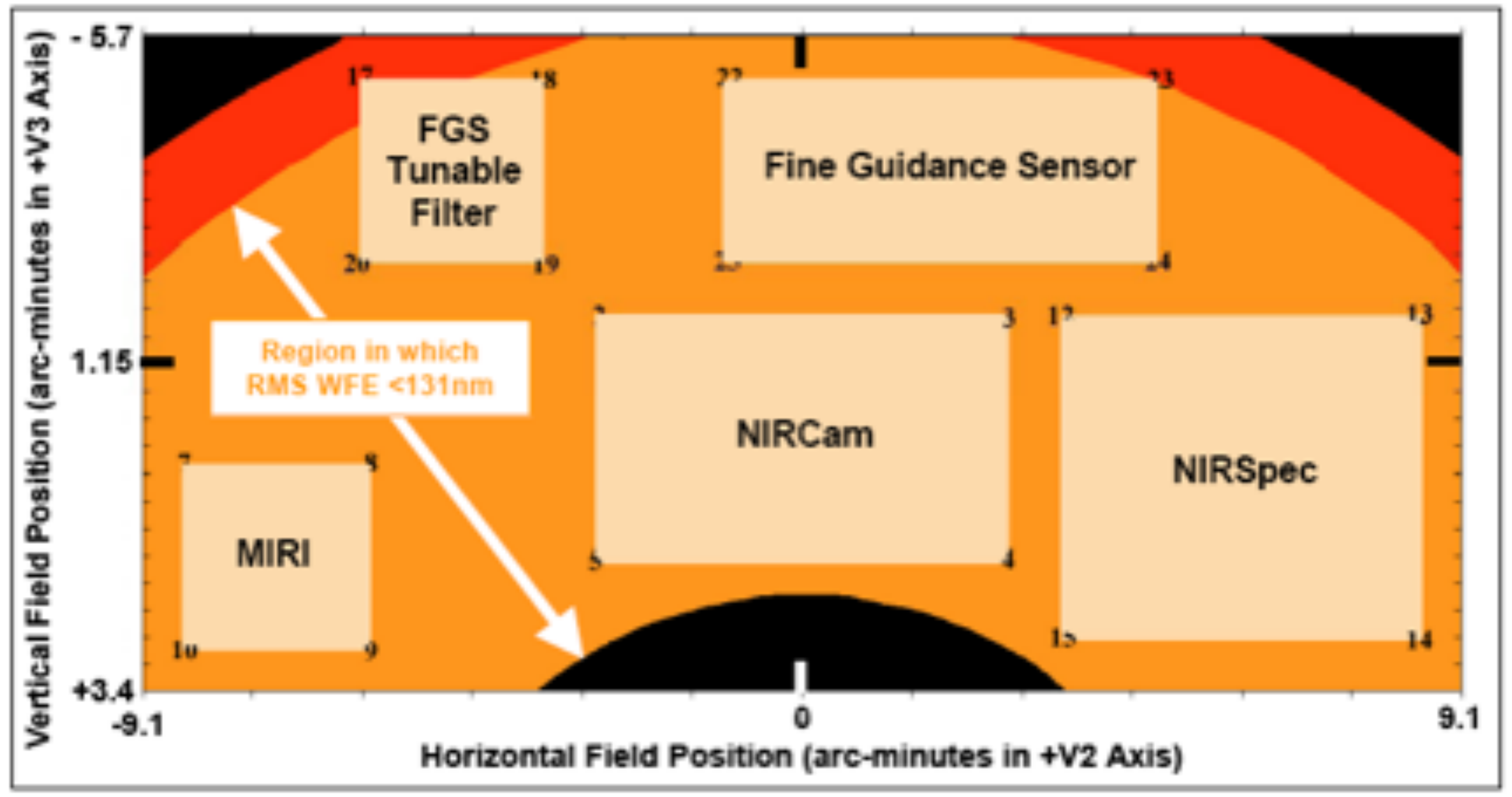
- Examples:
  - **<u>Dark Energy Survey (DES) (Optical)</u>**:
    - 4-m Blanco telescope with f/# = 2.7
      - F ~ 2.7 x D = 11-m
    - δ = (1”) (F) ~ (4.85e-6 radians) (11-m) = 53 um (per arcsec)
    - DES CCD’s are 15 x 15 um pixels, or 15/53 = 0.28” square pixels. Best **point-spread function (PSF)** at Blanco is ~0.5”, so ~2-pixels wide.
    - Optical telescopes are not at “diffraction-limit” typically limited by atmospheric “seeing”, most optical systems over-sample the PSF.

JWST: Three Mirror Anastigmat (TMA)



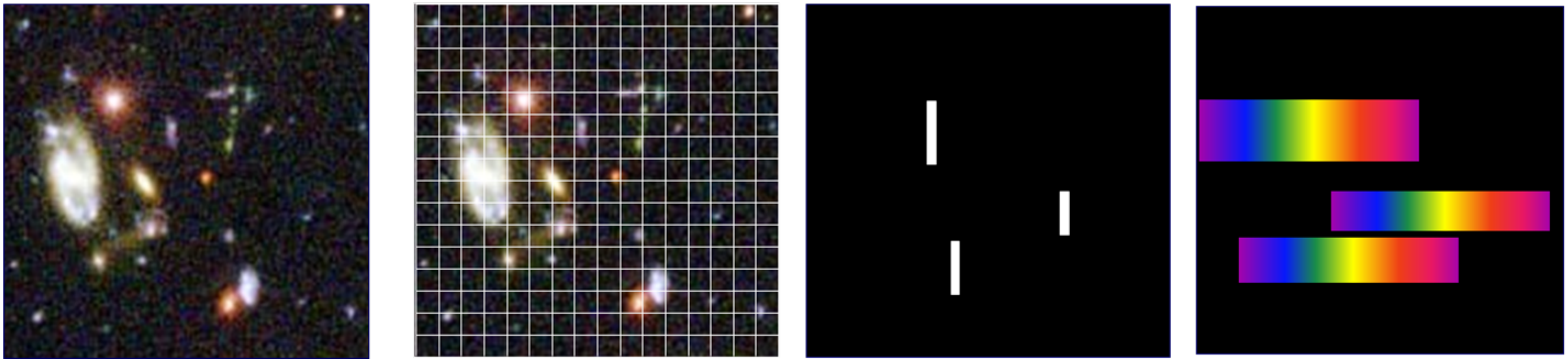




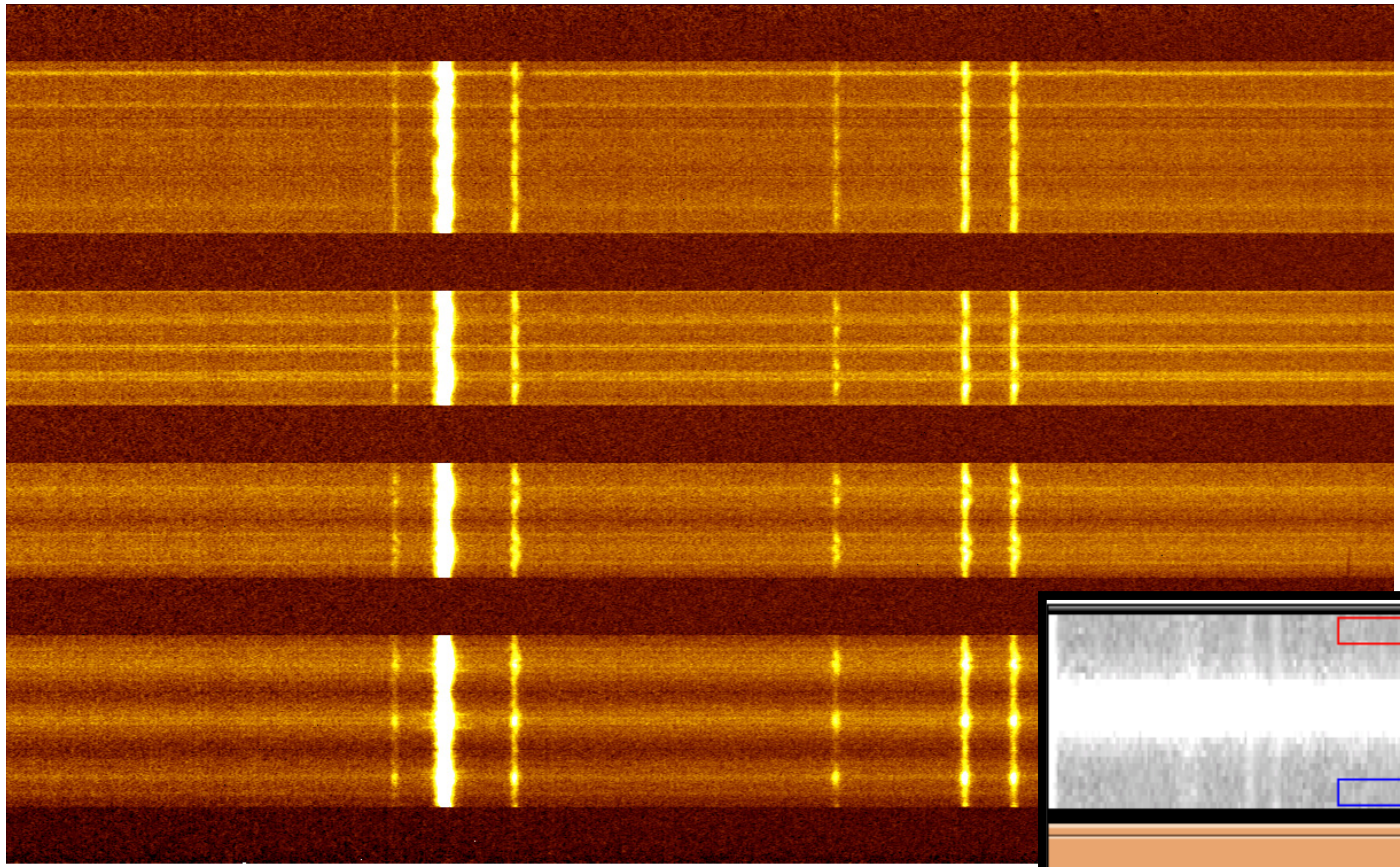


Slits and Spectroscopy

- Introduce a “slit” mask at the focal plane (in front of camera) that only accepts light from objects that you want to measure spectra for
  - For multi-slit spectroscopy requires a round of pre-imaging, so that you can physically make a mask appropriate for your field



Example Spectra on a CCD



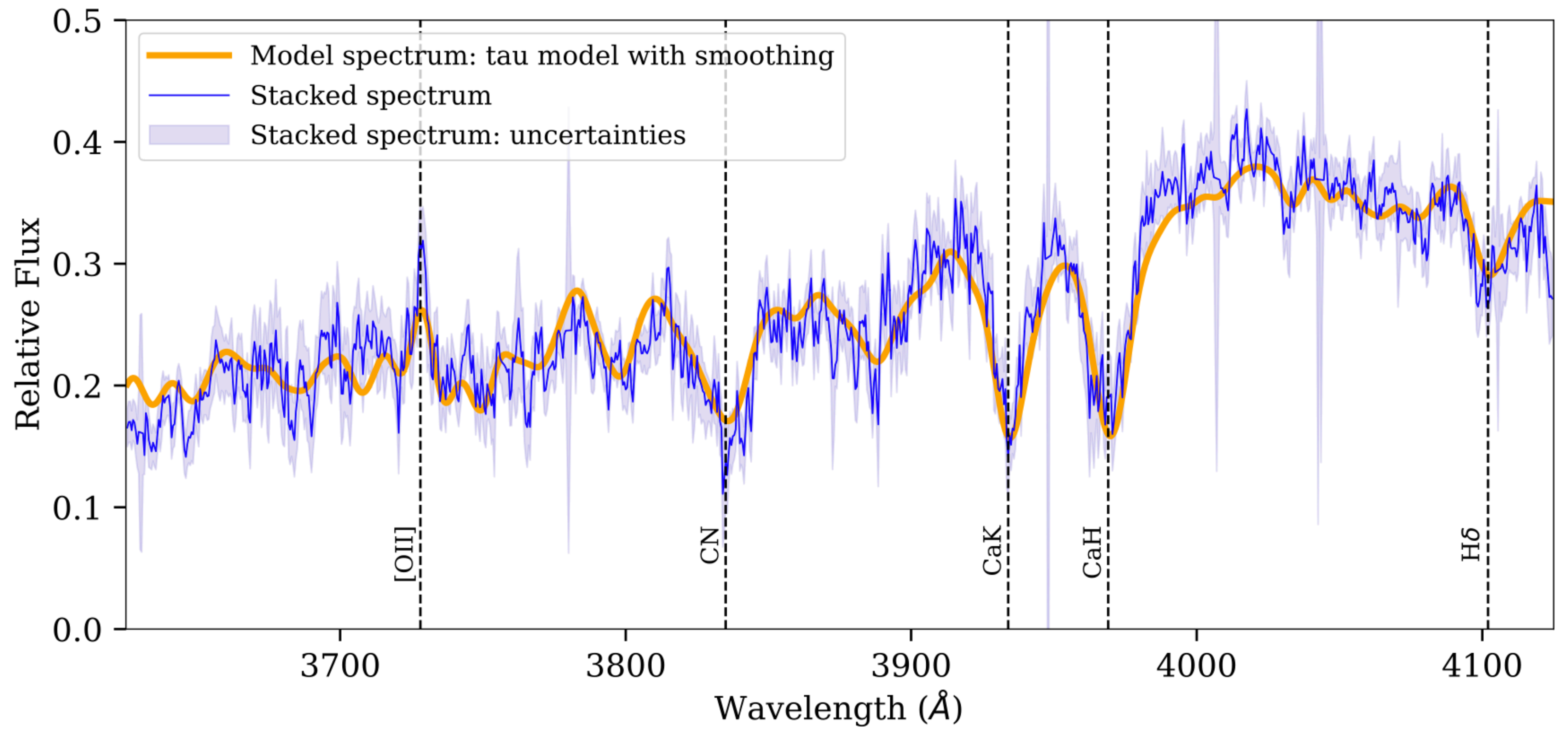


Figure 10. Stacked spectrum analysis for the 28 passive galaxies across 5 clusters reported in this paper. The light blue band corresponds to 68% confidence interval based on a linear combination of statistical and systematic uncertainties in the stack. Orange spectrum corresponds to an exponential tau model of star formation that is 1.7 Gyr old, at a metallicity log $(Z/Z_\odot) = +0.33$ (see Section 5.5 for a more detailed description). Dotted lines correspond to rest frame [OII], CN, Ca II H&K, and Hδ features.

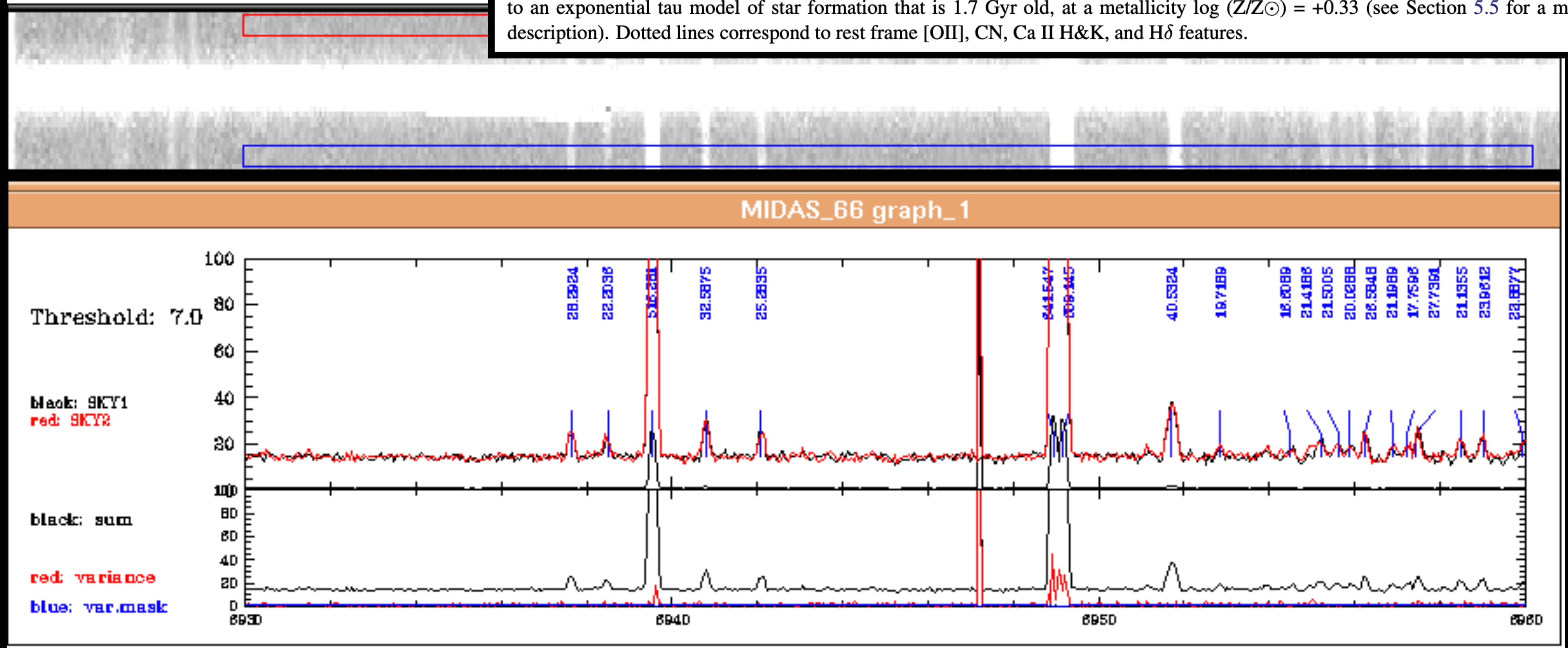


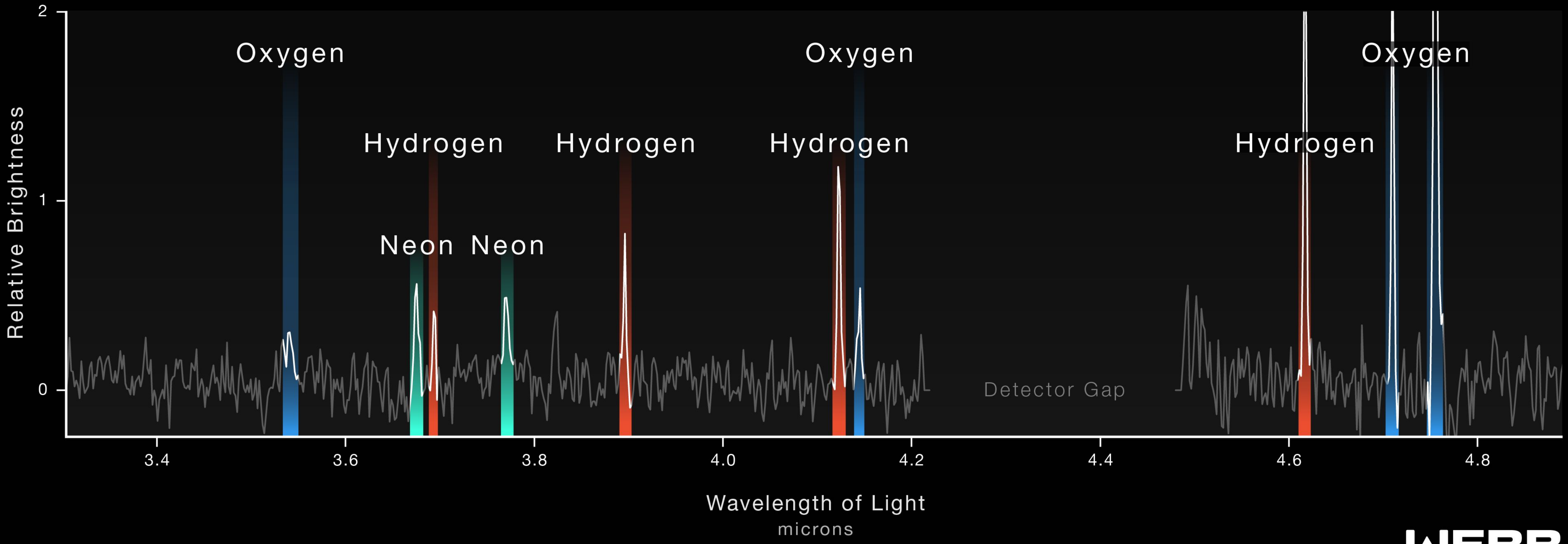
Fig. 1: Extraction and line identification. The upper display shows the pipeline-delivered 2D spectrum with slit coordinate in vertical direction. Blue and red frames mark the lower and upper sky windows. Bright and faint sky emission lines are readily visible. The lower graph has been used to identify emission lines. The black and red lines mark the *extracted* SKY windows. There is also a SKY plot at reduced intensity (factor 10) to show the brightest line profiles. The lowermost graph has the combined signal (SKY1+SKY2) and the difference spectrum (abs[SKY1-SKY2]). The difference (error) plot has been used to discriminate the extremely bright feature at 6947 (being due to a residual cosmic).

DISTANT GALAXY BEHIND SMACS 0723

WEBB SPECTRUM SHOWCASES GALAXY'S COMPOSITION

NIRCam Imaging

NIRSpec Microshutter Array Spectroscopy



WEBB SPACE TELESCOPE

Coupling

- ***IMACS***: Extremely versatile wide-field (15-27 arcmin) imaging multi-object spectrograph.
- ***FIRE***: Infrared echellette providing R~6,000 cross-dispersed spectra covering the entire near-IR.
- ***FourStar***: a wide-field 11’x11’ JHK imager using 4 Rockwell Hawaii IIRG arrays
- ***MagE***: an R~6,000 optical echellette spectrograph

- f/5 -

- ***Megacam***: 36 CCD mosaic camera FOV 25‘x25’

- f/16 AO -

- ***VisAO***: Adaptive Optics visible camera
- ***CLIO2***: 1-5 micron near-IR imager, coronagraph, and spectrograph

- f/11 -

- ***MIKE***: a high-throughput dual channel echelle spectrograph.
- ***LDSS3***: imaging multi-object spectrograph

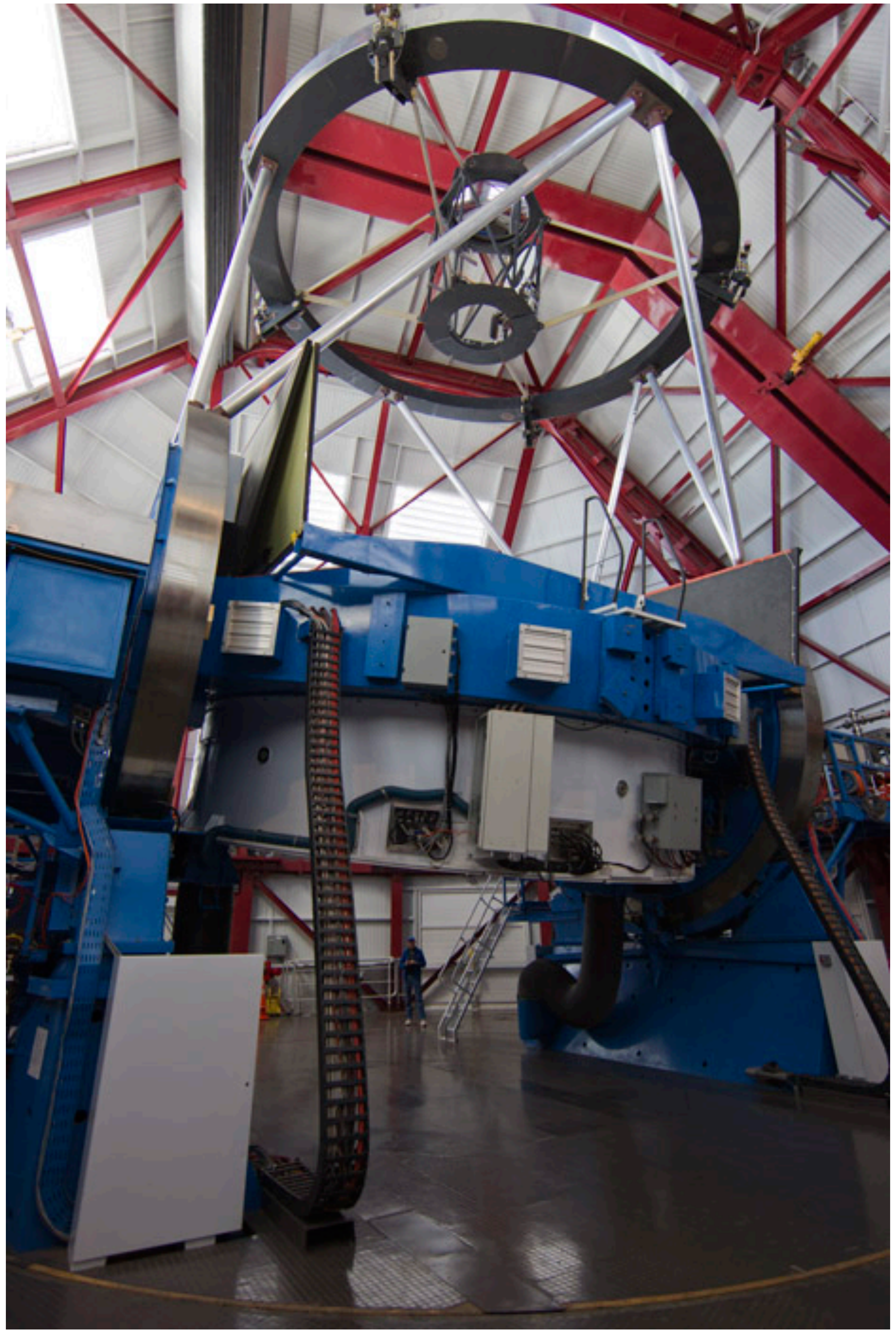
- f/11 PI -

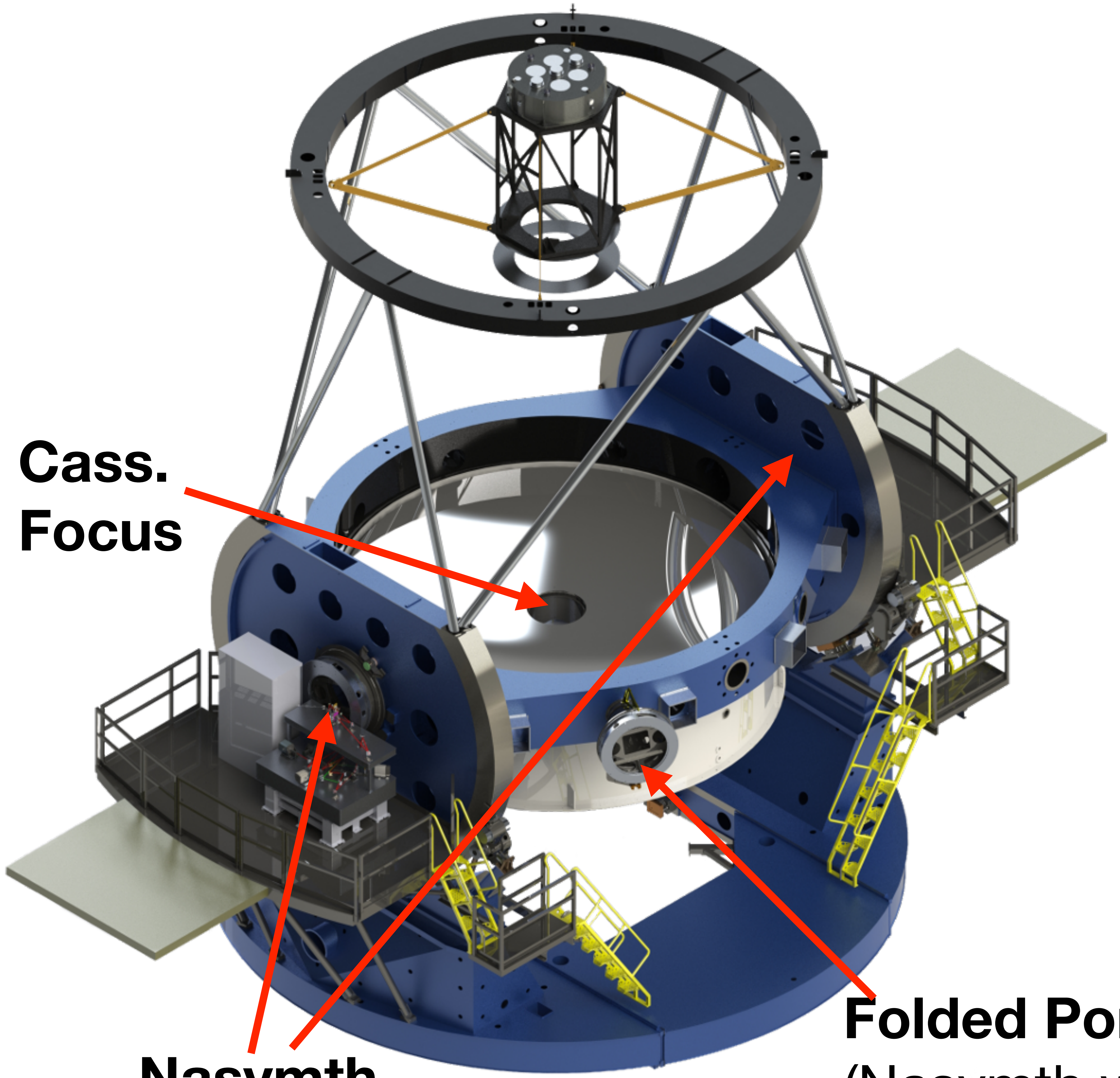
- ***PFS***: a high precision RV spectrograph.
- ***M2FS***: a low/medium/high resolution fiber-fed multi-object spectrograph.
- ***PISCO***: a simultaneous multi-band imager.
- ***POETS***: a portable high speed imager.

Baade **Clay**

2017 Instrument Suite

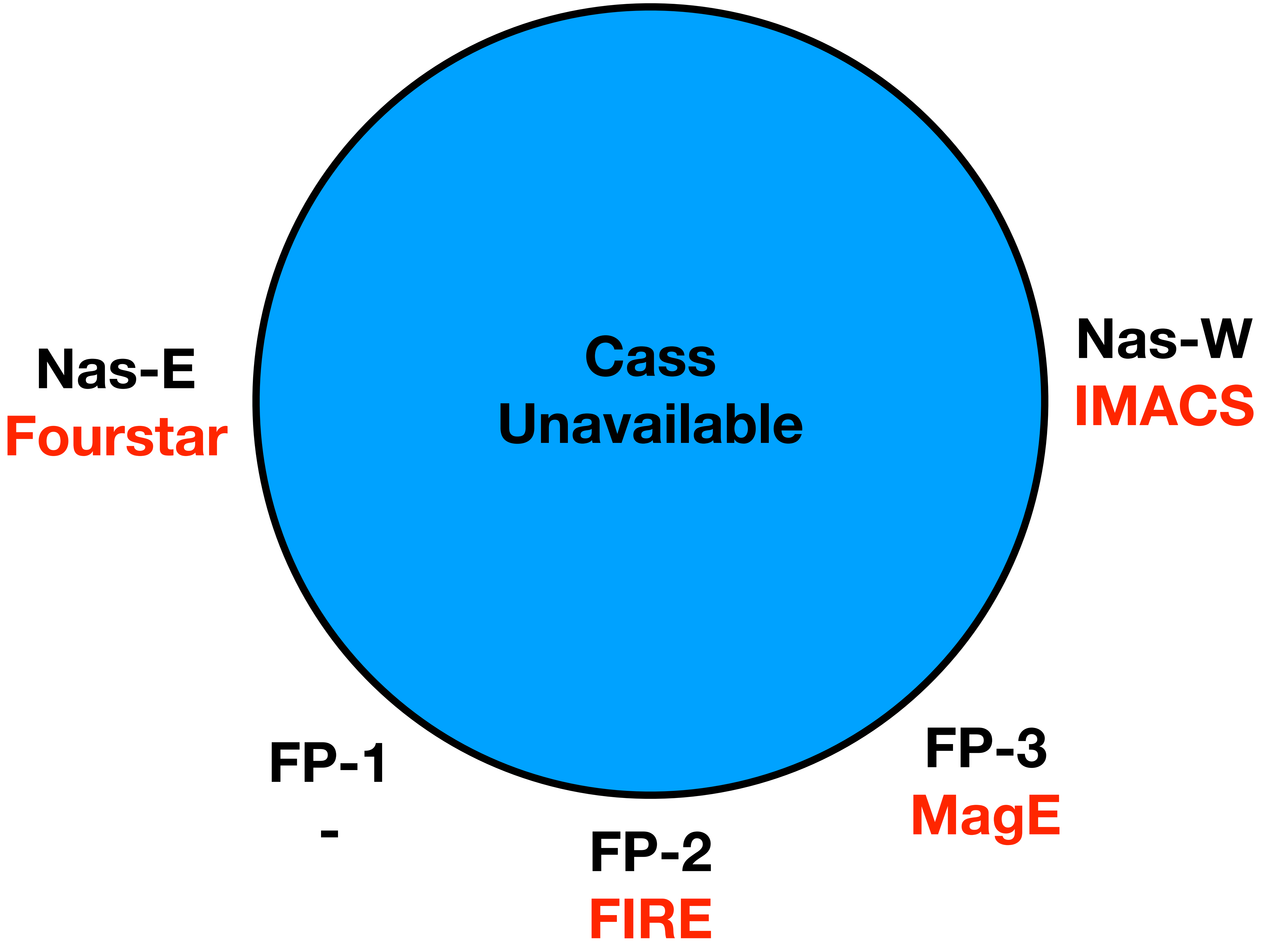
Magellan Instruments:

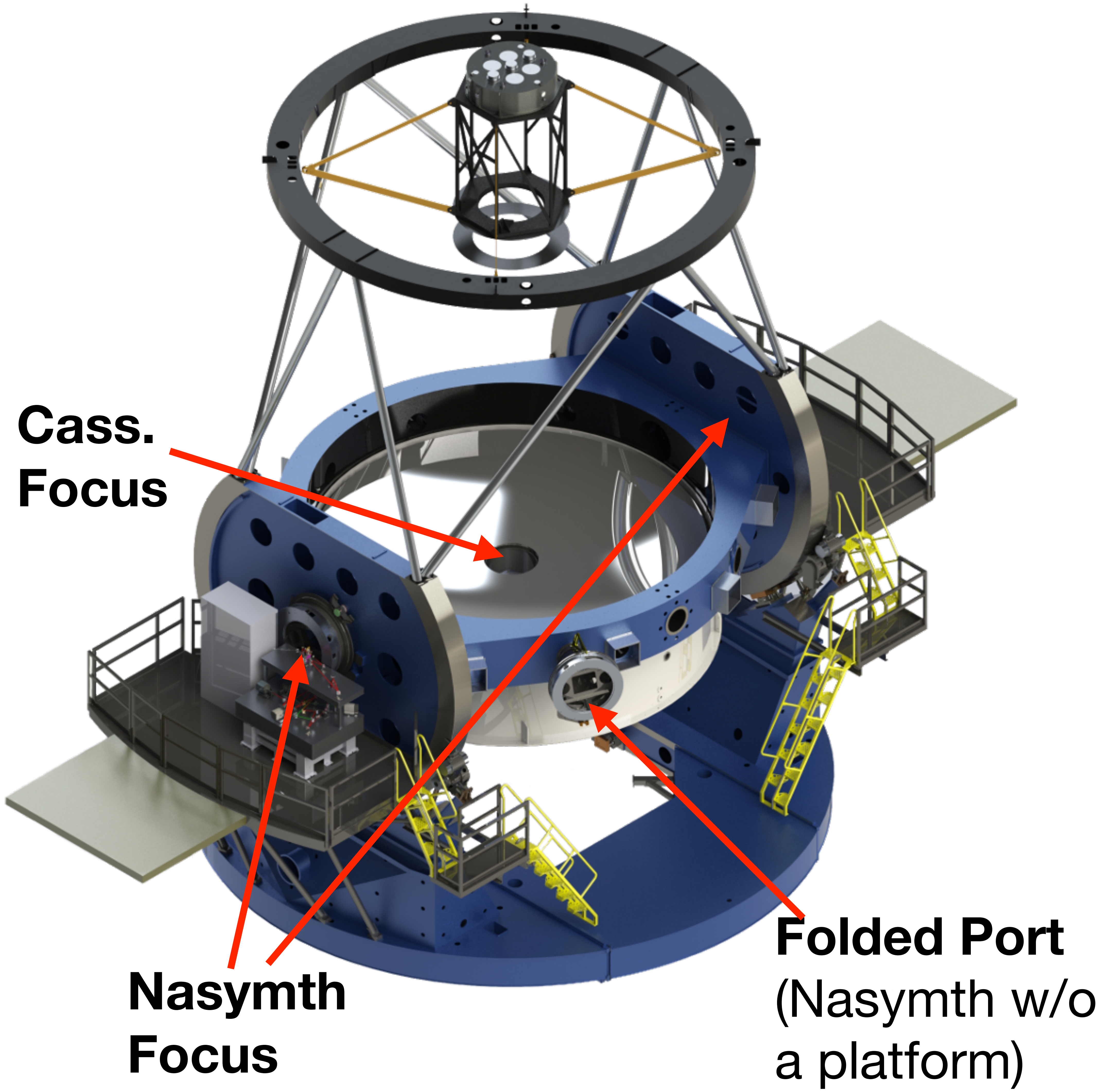




Magellan Instruments: Baade Telescope

Facility Instruments in Red
PI Instruments in Purple

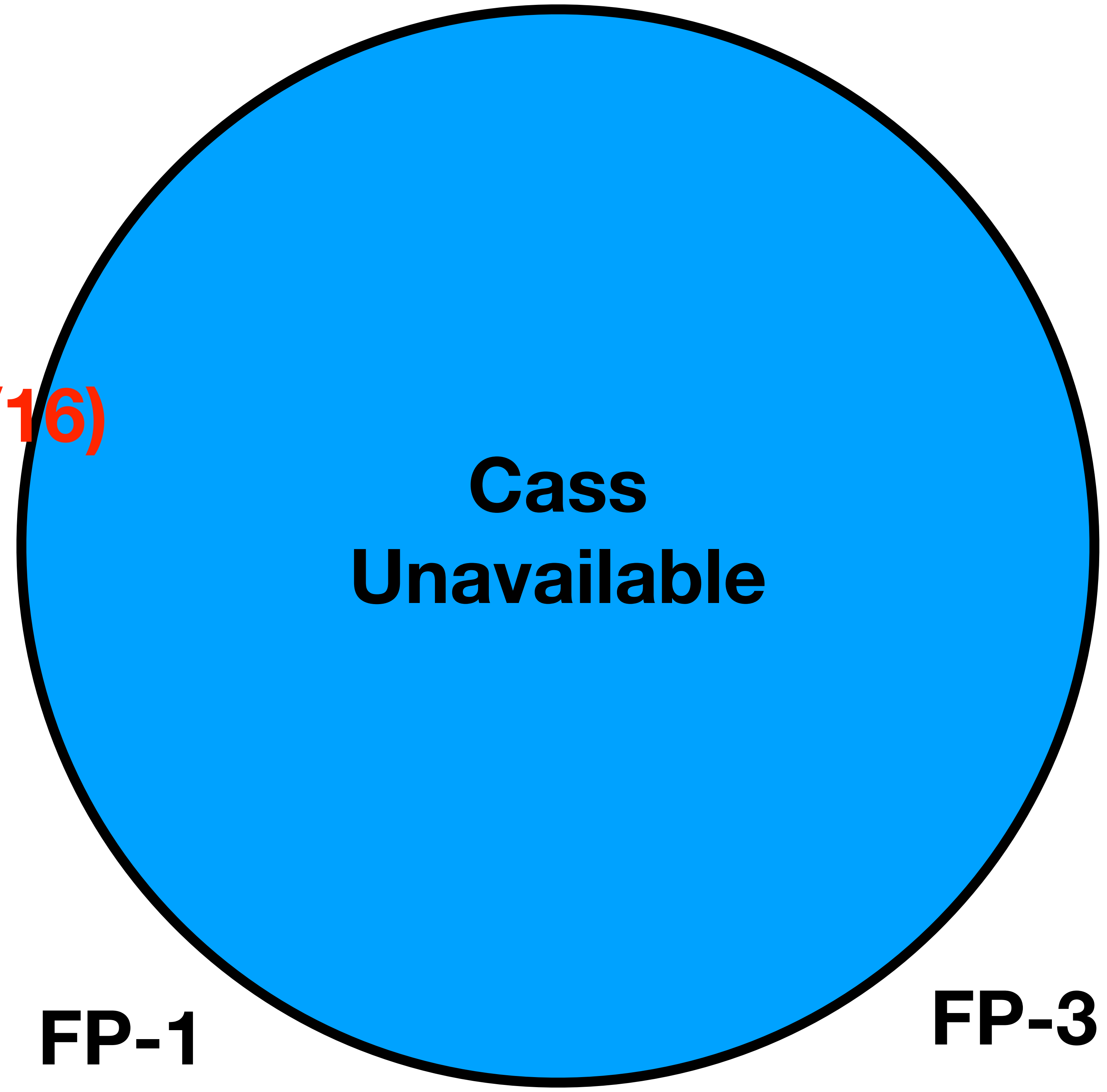




Magellan Instruments: Clay Telescope

Facility Instruments in Red
PI Instruments in Purple

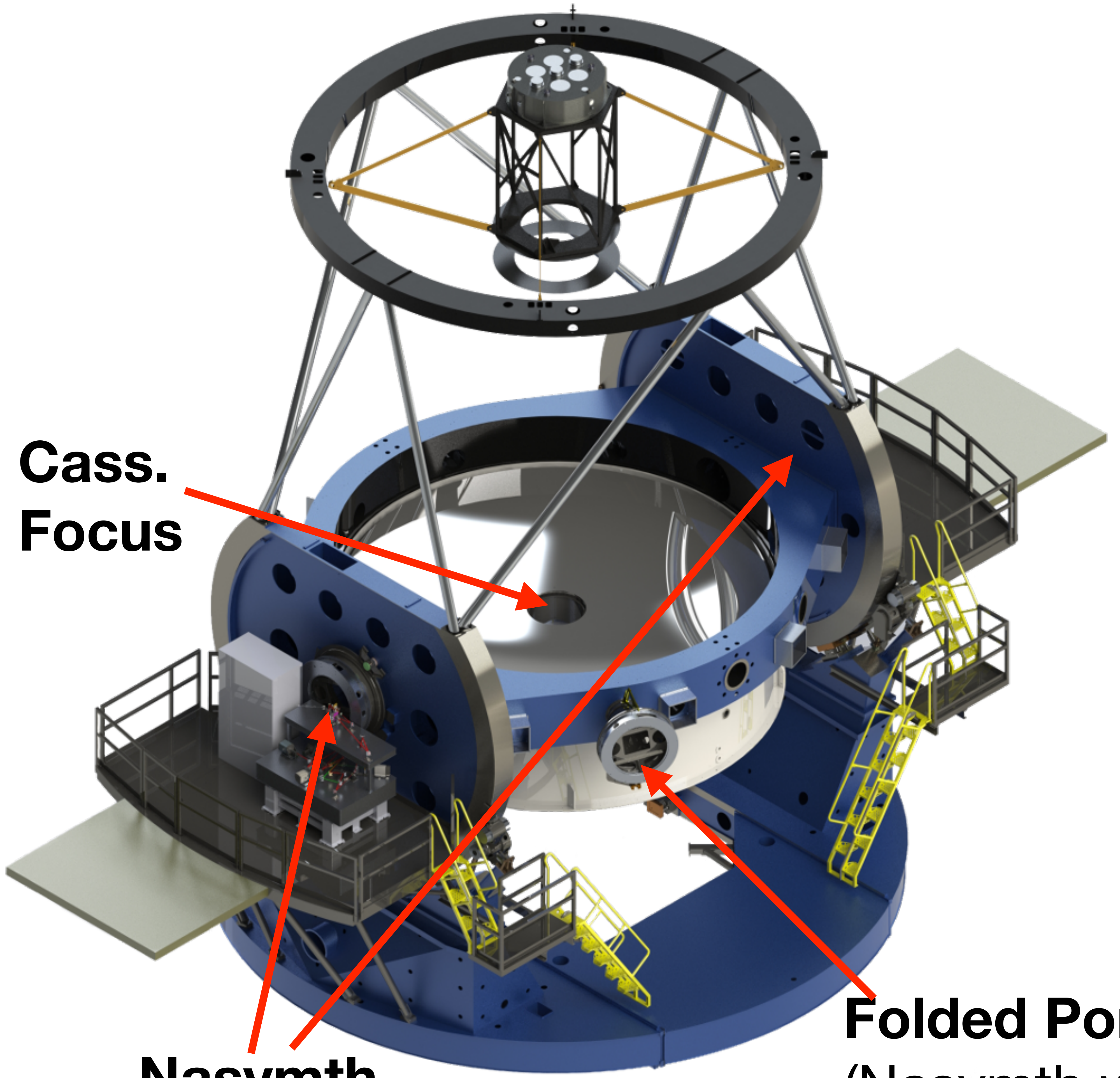
Nas-E
MIKE
MagAO (f/16)
PFS
M2FS
PISCO
POETS



FP-1
-

FP-2
-

FP-3
-



Magellan Instruments

- See: https://www.lco.cl/magellan-instruments/

Instrument suite:

Telescope	Instrument	Type	Wavelength	Wavelength range	FOV (arcmin)	R (for spectrographs)	Pixelscale, arsec/pix
6.5-m Magellan Baade	IMACS	imager / multislit spectrograph	optical	365-1000 nm	14' or 24-27'	500 .. 20000	0.11 or 0.2
	FOURSTAR	imager	infrared	1000 - 2510 nm	10.8 x 10.8'	-	0.16
	FIRE	spectrograph	infrared	820 - 2510 nm	7" slit	500 .. 6000	0.18
	MAGE	spectrograph	optical	310 .. 1100 nm	10" slit	4000 .. 8000	0.3
6.5-m Magellan Clay	LDSS3	imager / multislit spectrograph	optical	360 .. 1100 nm	8.3' (diameter)	850 .. 1900	0.189
	MIKE	spectrograph	optical	320 .. 1000 nm	5" slit	22000 .. 83000	
	PFS	spectrograph	optical	388..668 nm	3.7" slit	38000 .. 127000	
	M2FS	double-arm fiber spectrograph	optical	370 .. 1050 nm	30'	1500 .. 34000	
	MEGACAM	imager	optical	350 .. 900 nm	25'	-	0.08
	VISAO	imager / Adaptive optics	optical	600 .. 1000 nm	8"x8"	-	0.008
	CLIO	imager / Adaptive optics	infrared	1000 .. 5300 nm	16" x 8" 28" x 14"	-	0.016 0.027

For Next Week

- Homework 1 is due on Tues Mar-26 at 5pm, right before class
    - On class schedule on wiki:
    - Submit on Canvas (with hopefully right link)
- Office hours will start next week!
    - **Brad: Thurs -12-1pm ERC 589**
    - Dillon and Rohan (TBD)
- Next Thursday’s class:
    - Intro to SEO lecture co-taught by Amanda Pagul and Marc Berthoud
    - After class (TBC), Marc will be running through some remote SEO tutorials/ demos for those who are interested.

END

Absolute Magnitudes

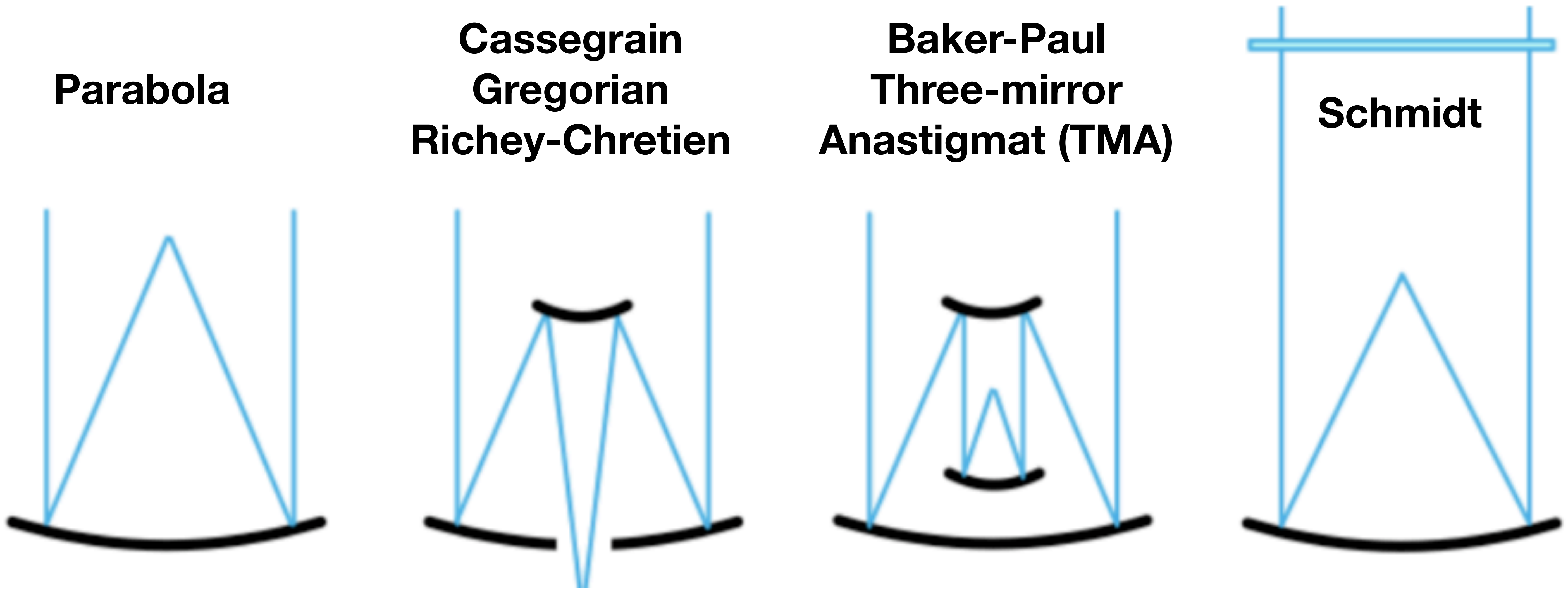
- So far, the magnitudes we've discussed have been based on flux, i.e., they are apparent magnitudes, not intrinsic property of the objects, which will depend on distance
- **Absolute Magnitude, M:** Apparent magnitude if the object were at a distance of 10-parsec
- **Distance Modulus:**

$$m - M = -2.5\log\left(\frac{F(d)}{F(10\mathrm{pc})}\right)$$

$$= -2.5\log\left(\frac{L/4\pi d^2}{L/4\pi(10\mathrm{pc})^2}\right)$$

$$= 5\log\left(\frac{d}{10pc}\right) = 5\log(d[pc]) - 5$$

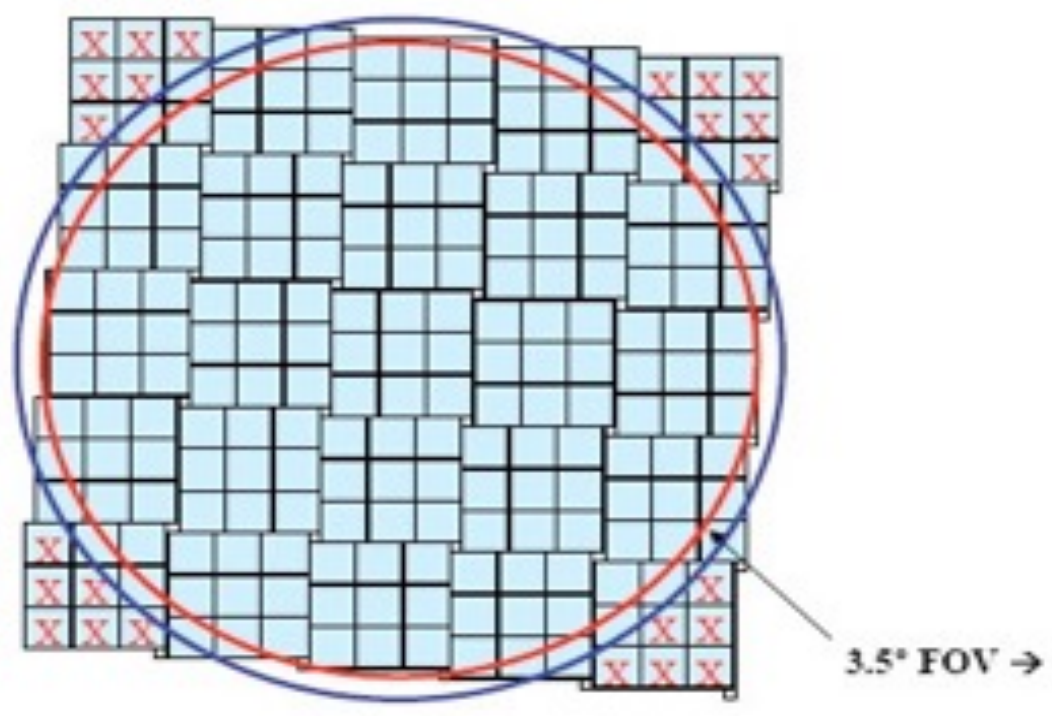
Correcting Aberrations

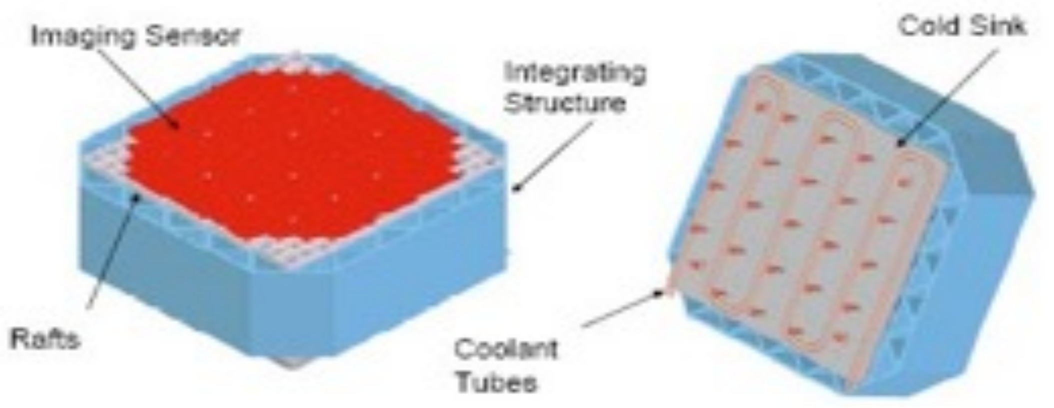


- Generally possible to correct for one aberration per optical surface
- **Parabolic** mirror: corrects spherical aberration
- **Cassegrain** or **Gregorian** (2-mirror) corrects for only spherical aberation
- **Richey-Chretien** (2-mirror) corrects spherical aberration and coma by using a hyperbolic primary (in place of parbolic primary in Cassegrain ssystem)
  - Most modern telescopes are RC, e.g., Hubble, Keck, VLT
- **Baker-Paul / TMA** (3-mirror) corrects for spherical aberration, coma, and astigmatism
  - Gives wider field-of-fiew, e.g., LSST, JWST, WFIRST, SP-TMA
- **Schmidt** telescope (spherical mirror+thin lens/corrector plate)
  - Efficient way to achieve large field-of-view with only one reflector (e.g., Kepler)

Large Synoptic Survey Telescope

200 4k x 4k detectors

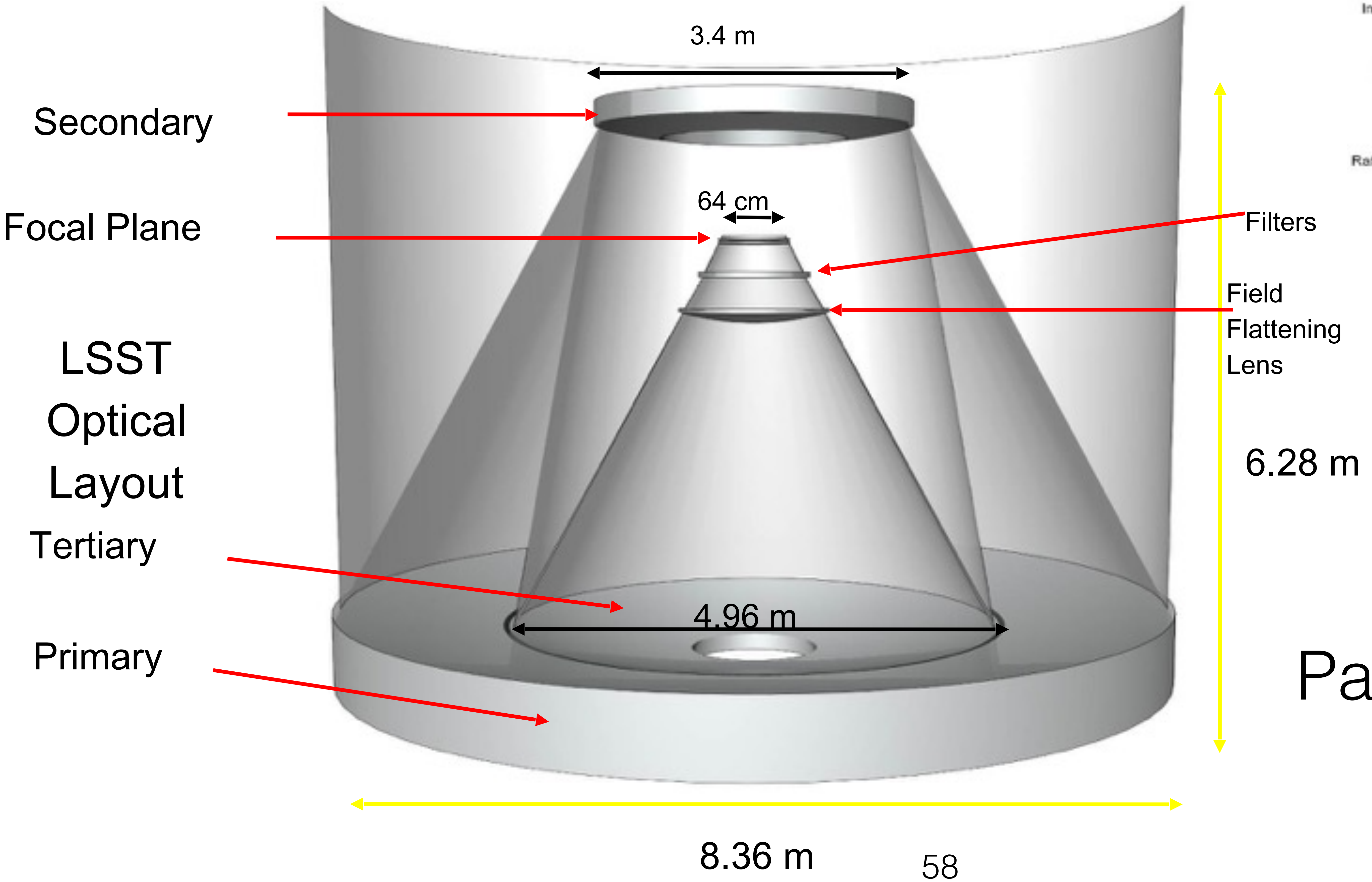




3.5° field of view for all-sky survey

Primary and Tertiary mirrors to be made at Arizona *on the same substrate*

LSST Optical Layout



Paul-Baker Design

Telescopes: Putting it all together

- Physical Size:
  - Keep f/# small (<~2) to keep telescope size small; for 6-10 m class telescope want f# < ~2 to keep overall telescope of reasonable size
  - Small f/# (<~2) also keeps focal plane reasonable size to fit in a cryostat. For example, CD/TMA for SO/CMB-S4 has a ~2-m diameter focal plane with ~5-mm pixels (i.e., with pixel-size >1.2 (f/#) λ)
- Surface quality:
  - Keep RMS surface accuracy of mirrors < λ/40 to minimize loss in the main beam
    - Ruze formula: Loss = $1 - \exp[-(4\pi\sigma_{rms} / \lambda)^2]$, with σ_{rms} = RMS surface variation
    - e.g., for λ=1-mm and $\sigma_{rms} = \lambda/40 = 25$-um -> 10% loss
- Mechanical Support:
  - Deflection of circular plate ~ $(\text{diameter})^4 / (\text{thickness})^2 = D^4 / t^2$
  - So need $t \sim D^2$ to keep deformation constant i.e., going from D=1-m to 10-m, requires a 100x stiffer support!
- Thermal Gradients
  - Keep thermal graidents across the mirror low, e.g., a 5-K gradient would lead to a 20-um deflection, either during observations or during machining

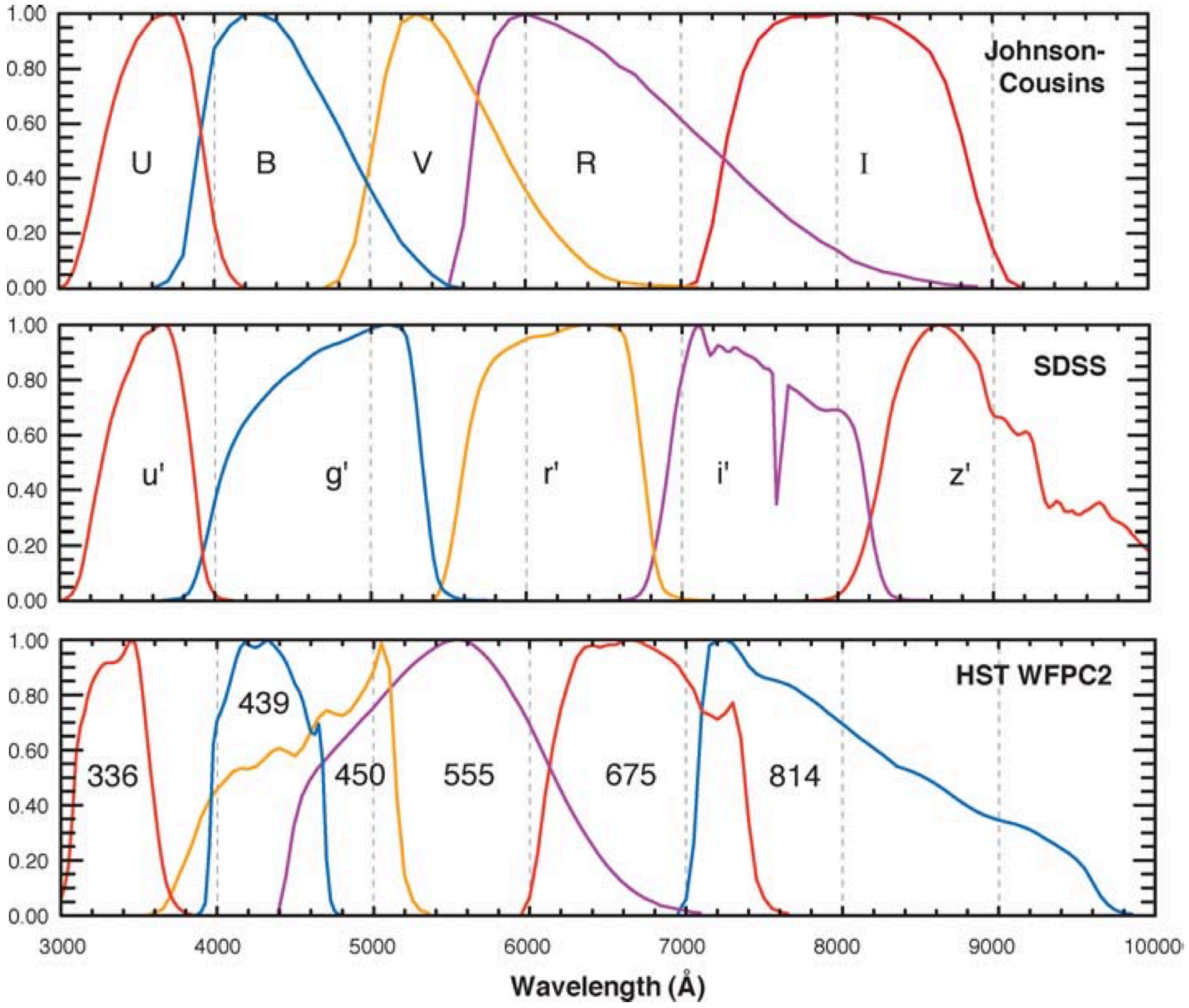


Figure 1 Schematic passbands of broad-band systems.