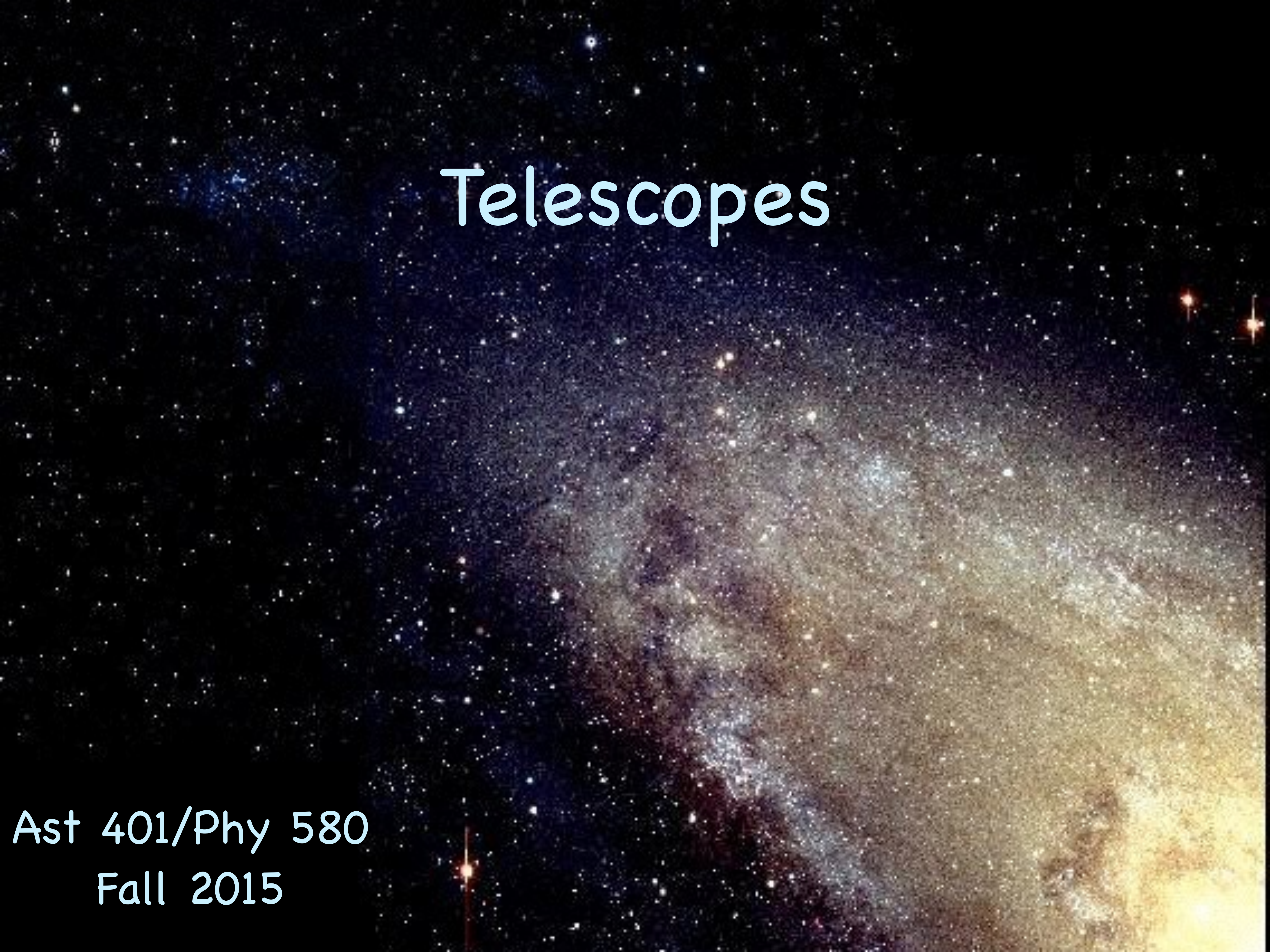

Telescopes
Ast 401/Phy 580
Fall 2015

The 6.5-meter Magellan telescopes, Las Campanas, Chile. Photo by Kathryn Neugent

The 6.5-meter MMT Observatory

6.5-meter MMT Observatory, Mt. Hopkins, Arizona. Photo by Kathryn Neugent

Two basic types of telescopes

Reflectors (mirror)

Refractors (lens)

All modern telescopes are reflectors, as the weight of a lens limits the size to 40-inches or so.

40-inch Yerkes refractor, built in 1897

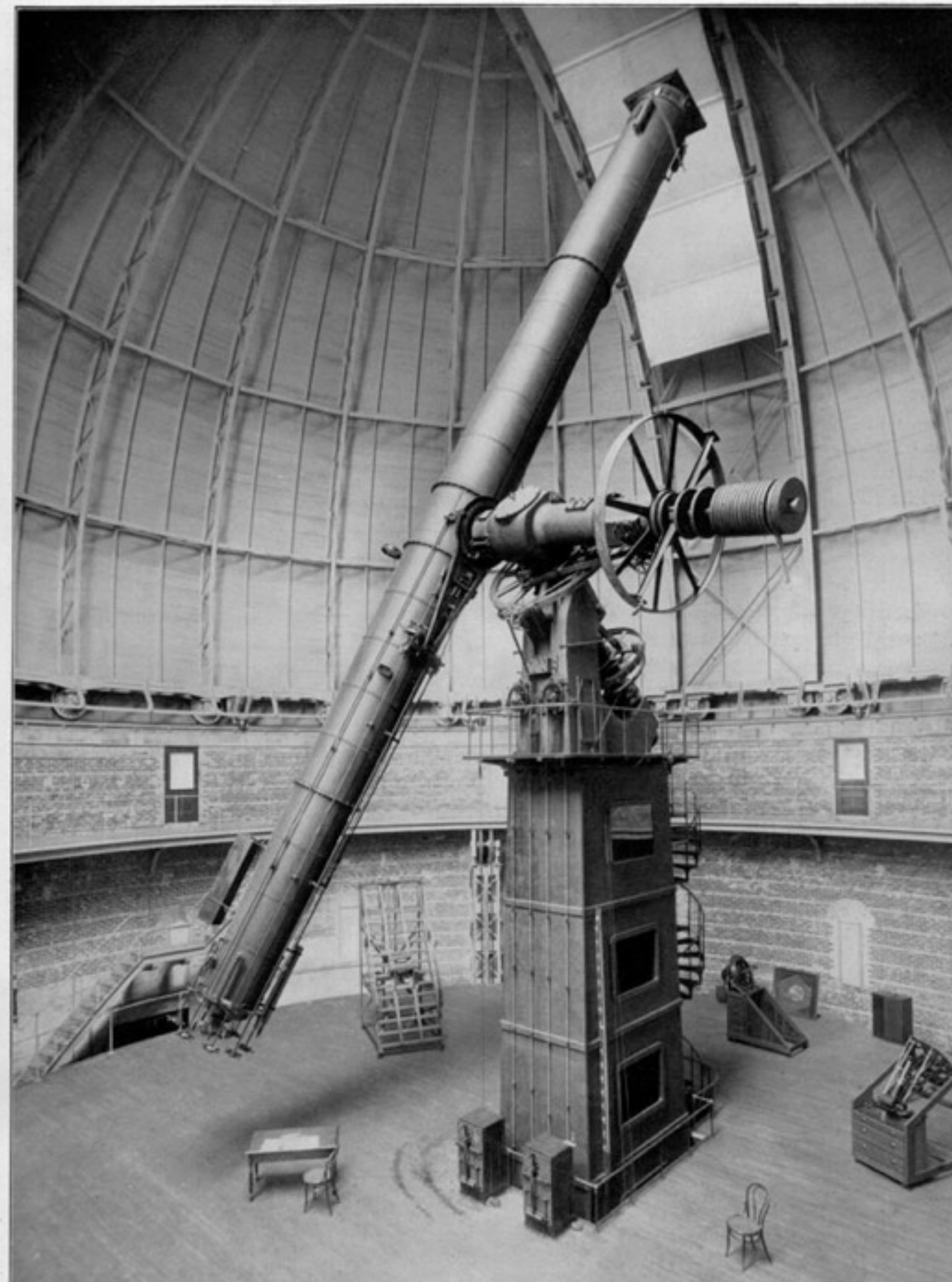
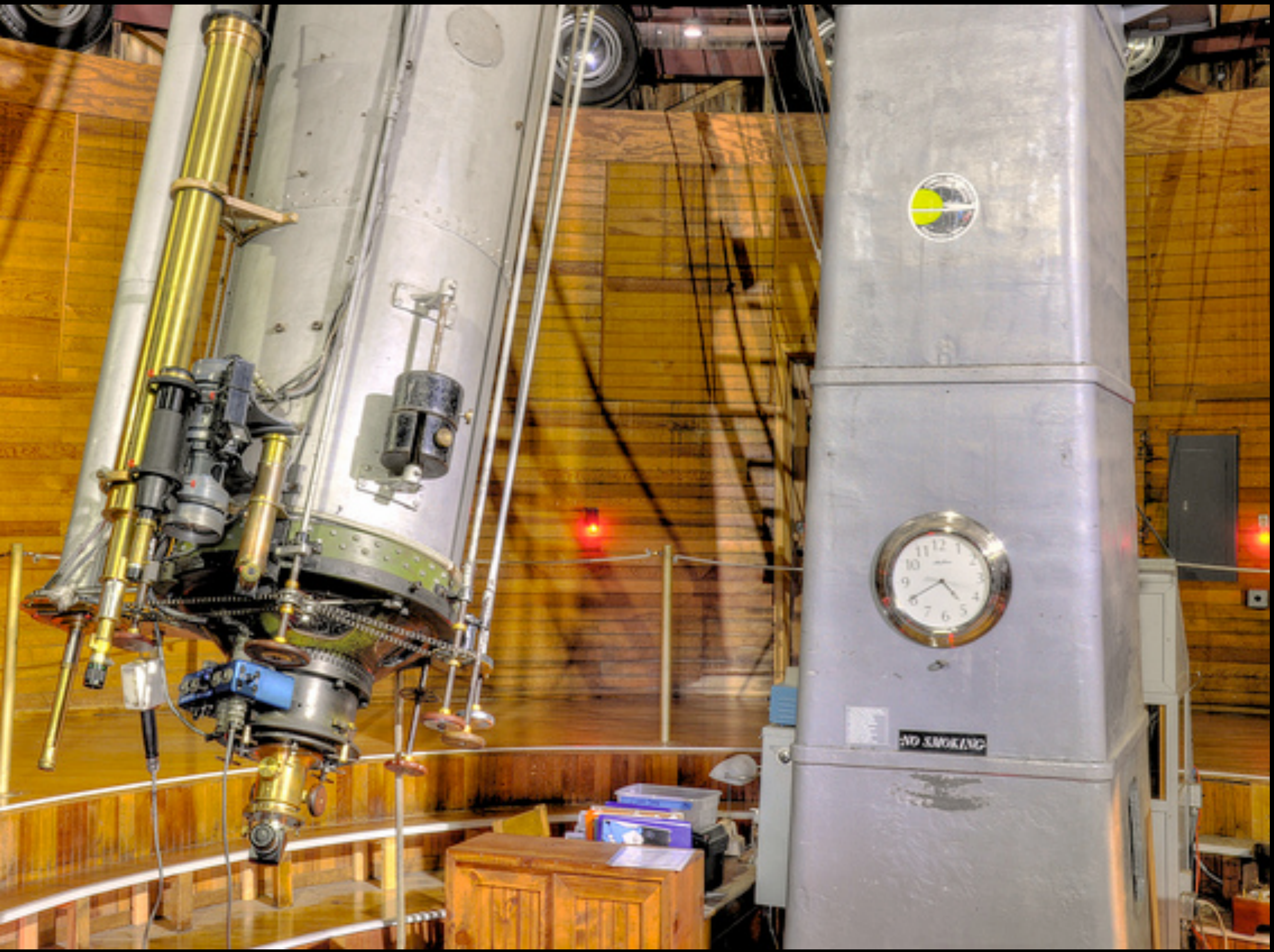
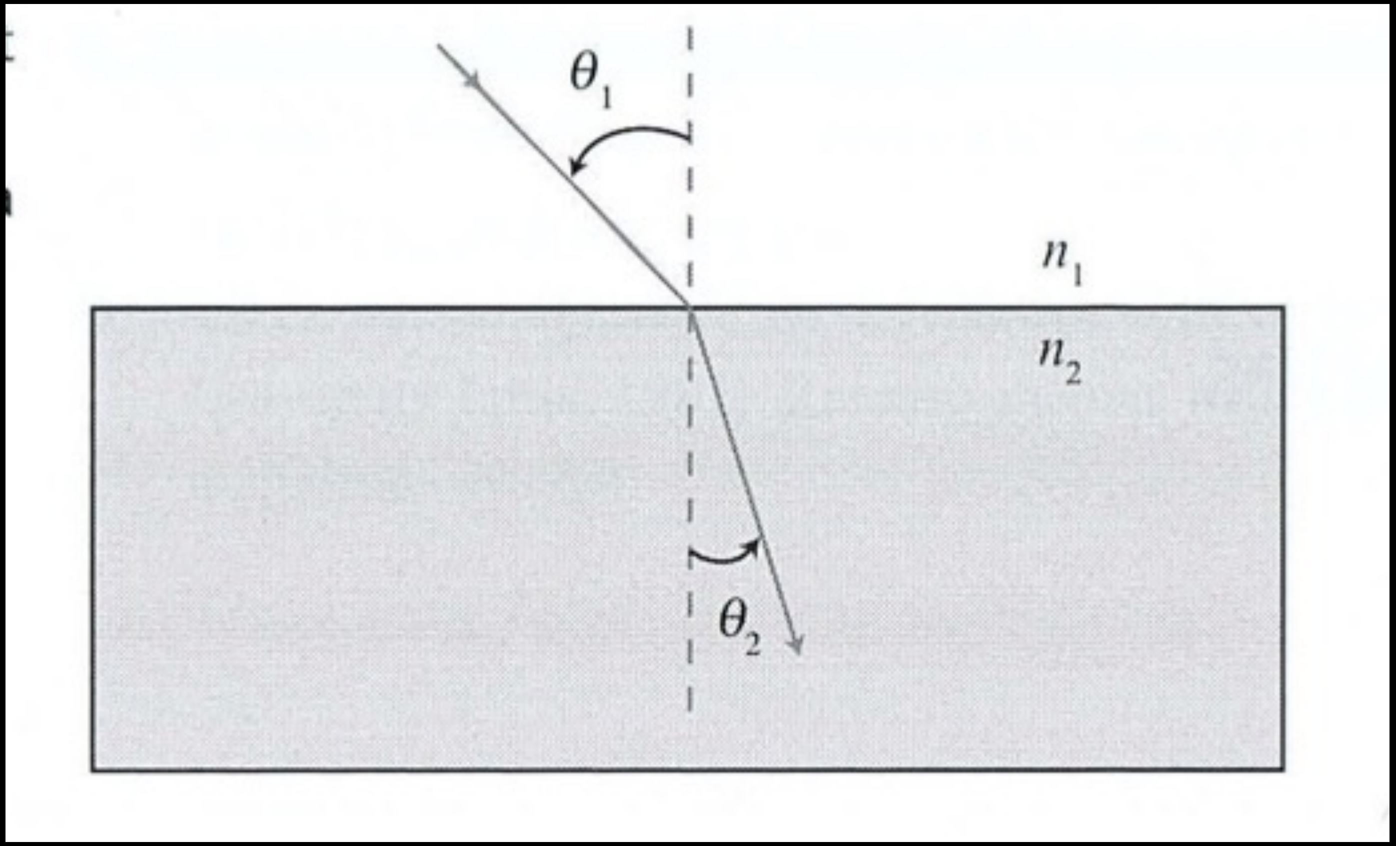


PLANCHE 1. — RÉFRACTEUR DE 1 m, 02 DE L'OBSERVATOIRE DE YERKES.
PLATE 1. — THE 40-INCH REFRACTOR OF YERKES OBSERVATORY.



Clark 24-inch refractor, Lowell Observatory

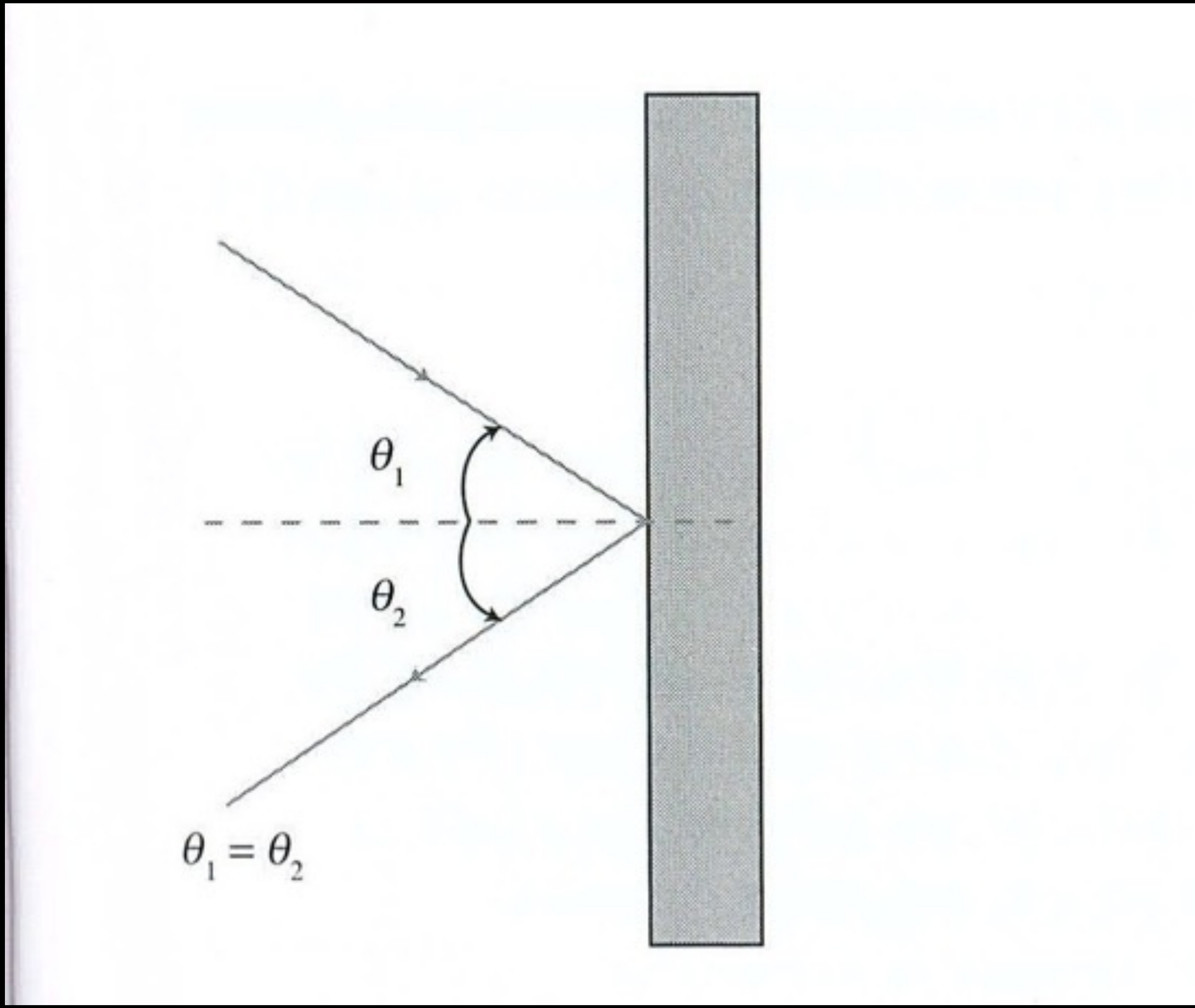
Some basics



Snell's law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$, where n_1 is the index of refraction of medium 1, and θ_1 is the angle of incidence relative to the normal at medium 1.

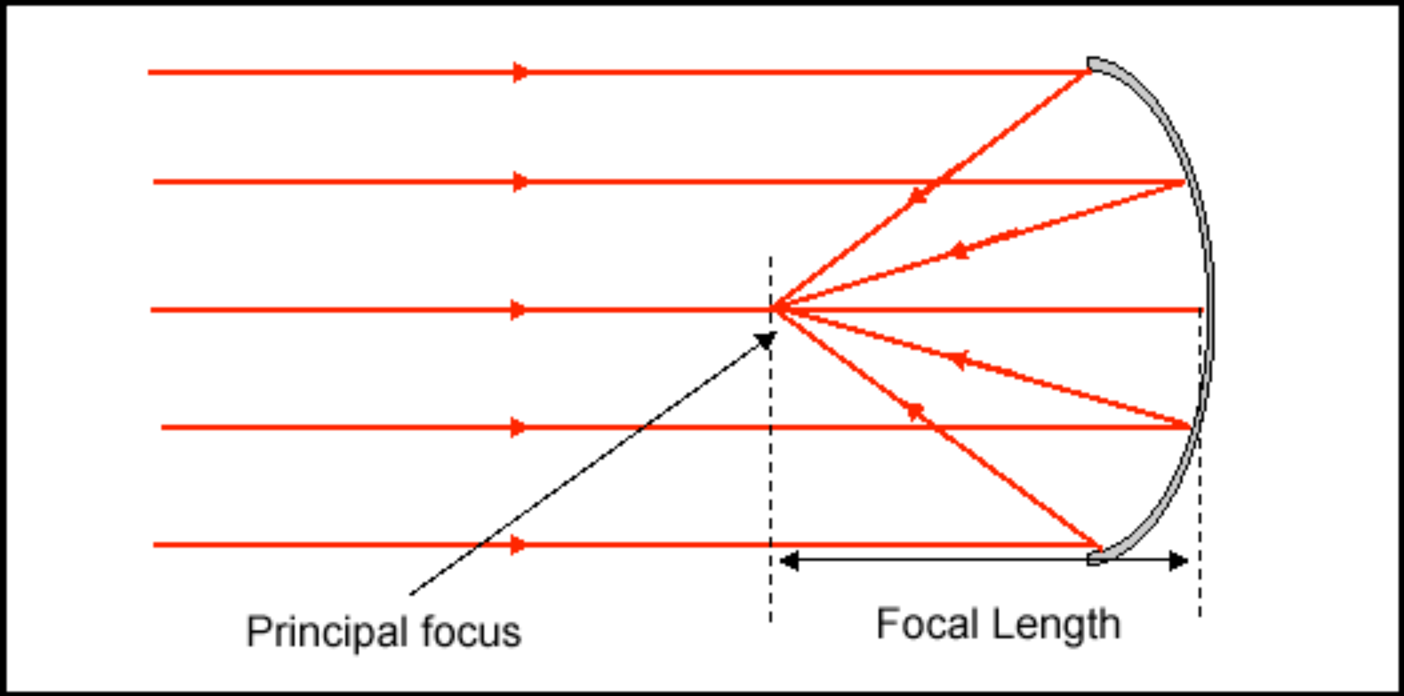
Some basics

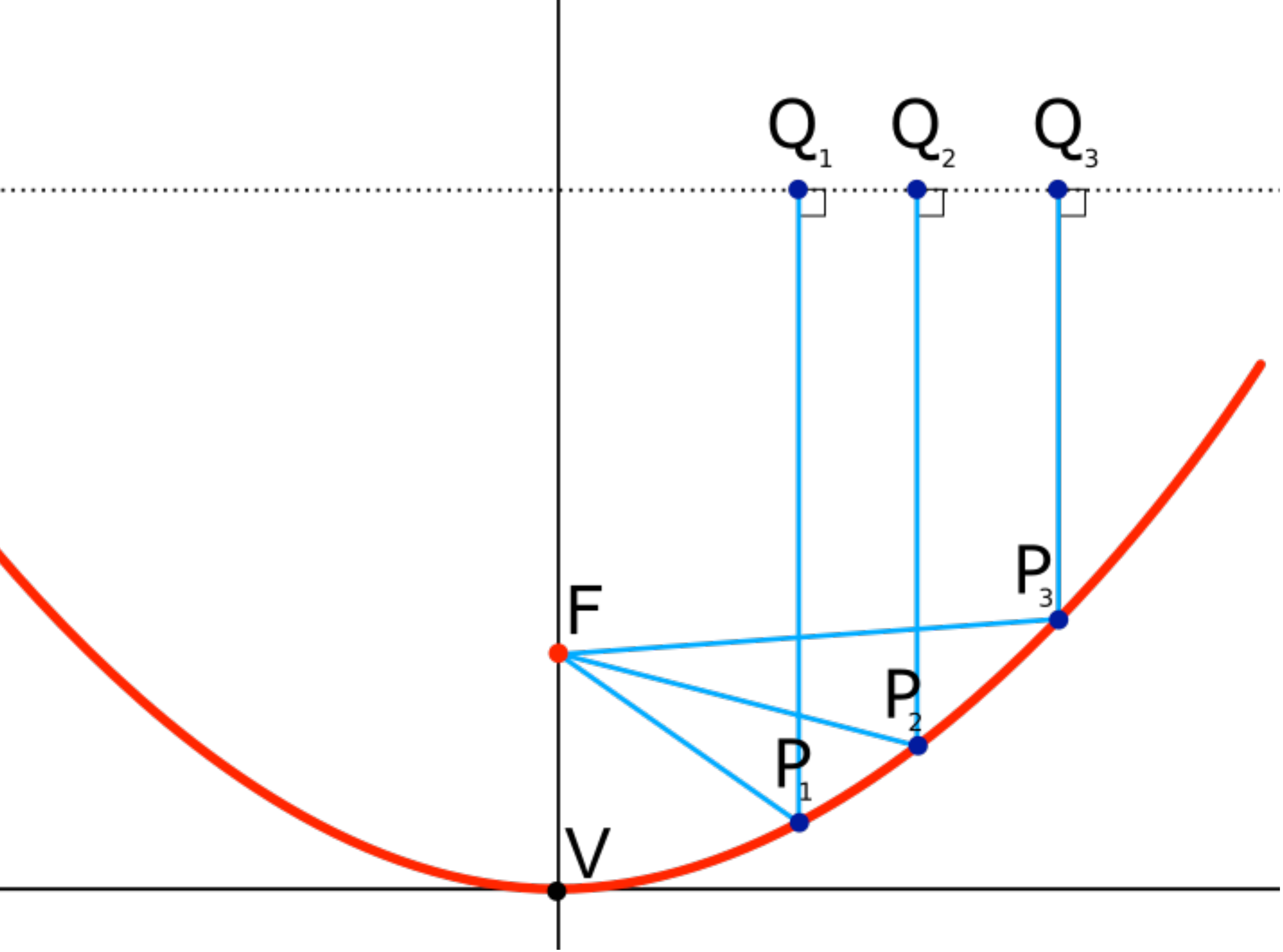
Law of reflection: angle of incidence = angle of reflection.



Some basics

Astronomical objects are so far away that their light is parallel. If our telescope mirror is in the shape of a paraboloid, the on-axis light will be brought to a perfect focus.



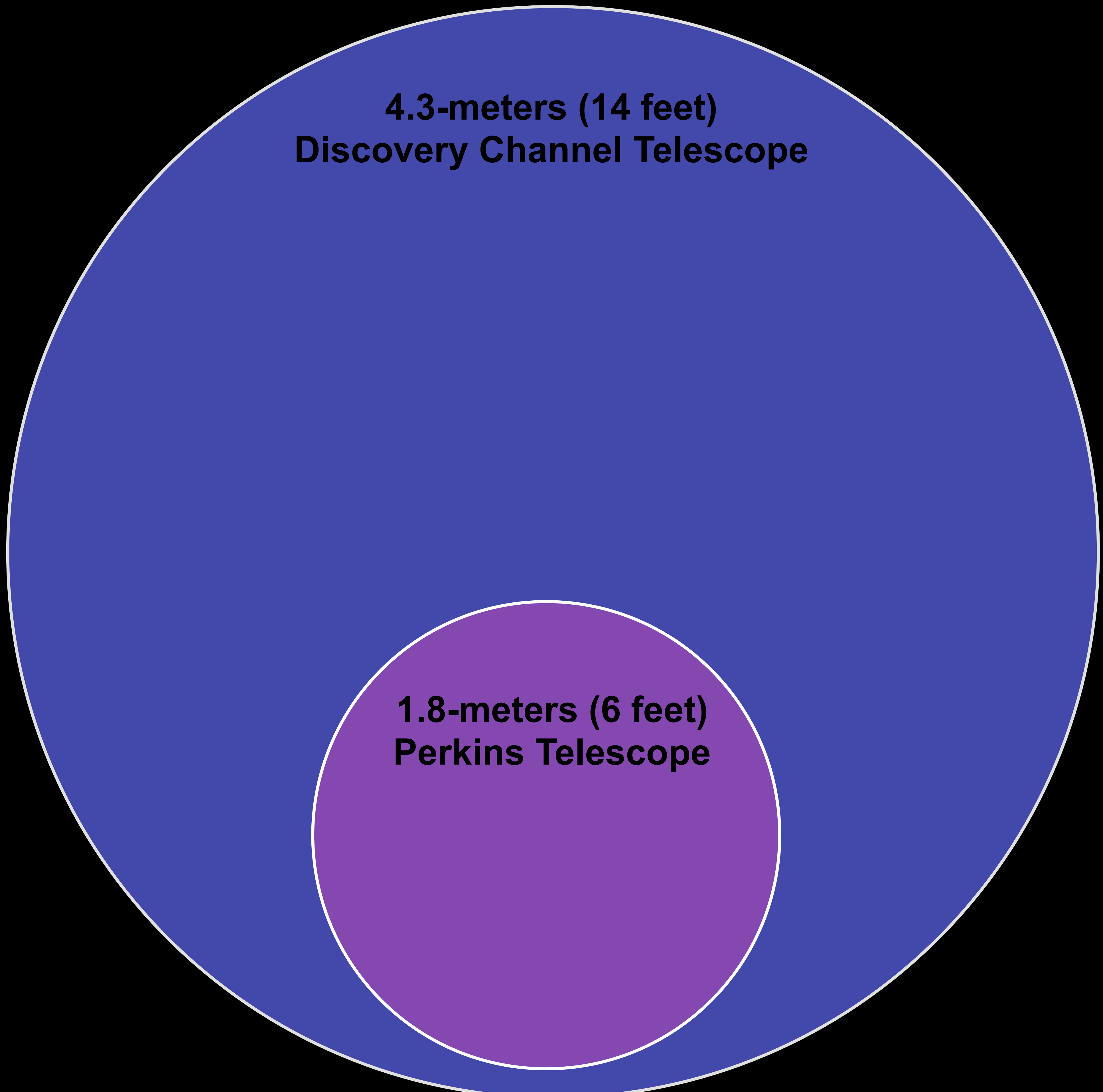


Q_1
Q_2
Q_3
P_3
F
P_2
P_1
V

Light-gathering power

A telescope acts as a "light-bucket", gathering photons. The bigger the mirror (or lens) the more light it gathers.

The pupil in your eye is about 6mm in diameter when it's dark. Compare this to the 0.5-m Lutz telescope: $(0.5\text{-m} \times 1000\ \text{mm/m})^2/6^2 = 7000$. The Barry Lutz telescope gathers about 7000 x more light than your eye. All other things being equal you should be able to see about $-2.5 \log(7000) = 9.5$ mags fainter (so, about 15-16th mag).


4.3-meters (14 feet)
Discovery Channel Telescope
1.8-meters (6 feet)
Perkins Telescope

Telescope properties

Mirror diameter D.

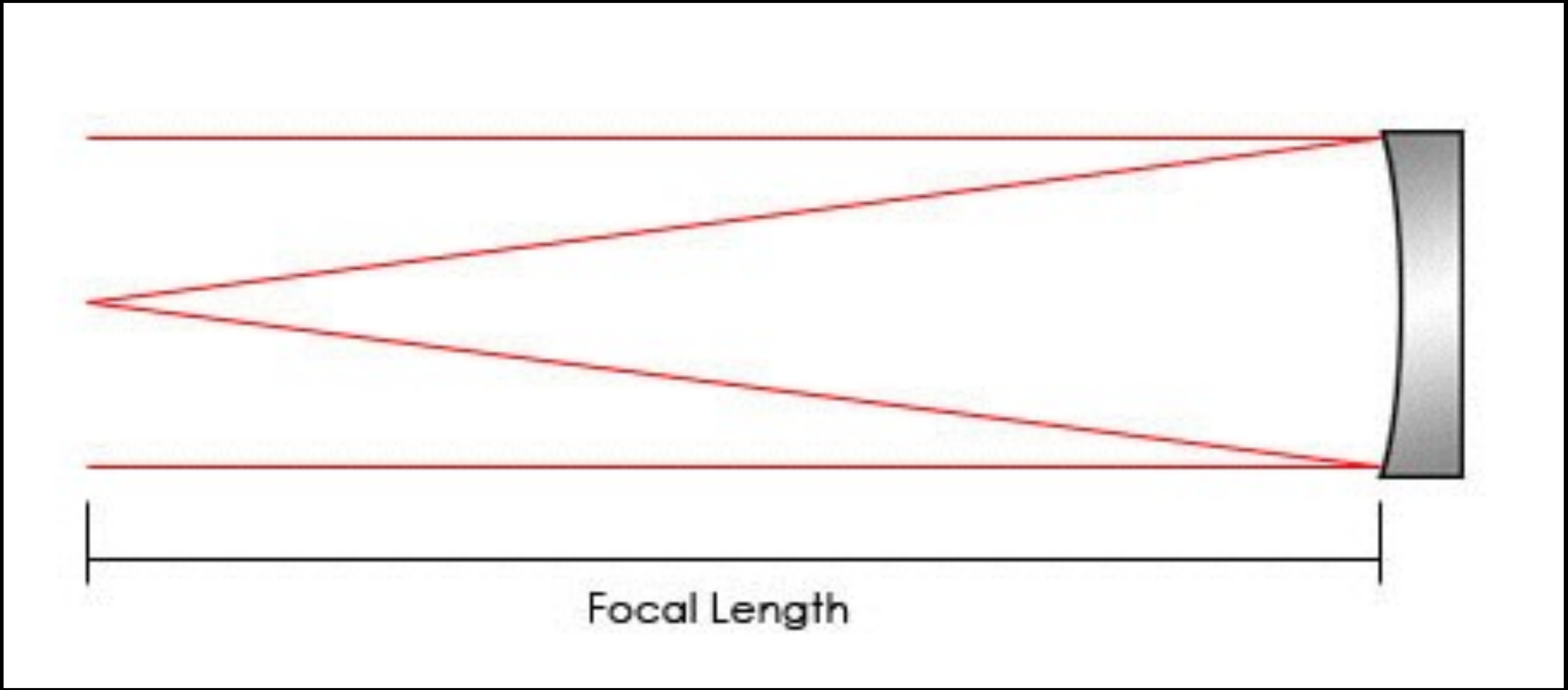
Focal length F.

f-ratio = F/D, typically f/2.5 (“fast”) to f/10 (“slow”). (These f-numbers are the same with your camera.) Most modern Cassegrain systems f/5-8.

The longer the focal length, the BIGGER the image. (It will also be fainter, because number of photons is conserved.)

Image scale? How many arcsecs per mm or pixels?

Telescope properties



Telescope properties

Want the number of arcsecs per pixel. Scale is $1/(F\theta)$. For θ, use 1" (in radians), 1/206265. So, scale is 206265/F in terms of arcsecs/mm if F is in mm. Now we need the number of mm/pixel. Usually we know the pixel size of a CCD in microns (μm). So, we are left with the formula in the book, Scale = 206.265 x pixel size (μm) /F (mm).

Side-bar: 206265

I keep using the number 206265. It's the number of AUs in a parcsec. Now we're using it here to derive a plate scale. Where does it come from?

There are 3600 arcseconds per degree. There are 180 degrees in π radians. $3600 \times 180^{\circ}/\pi = 206265$. So if you're trying relate distances and an arcsecond, you should remember this number (or at least how to derive it).

A camera lens is described as having an 20mm focal length with an f-ratio of 3.5. What's the diameter of the lens?

a) 20mm / 3.5 = 5.7mm

b) 20mm x 3.5 = 70mm

c) 20 mm

d) 3.5 furlongs

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Lowell Observatory's 4.3-m DCT has an f-ratio of 6.5. What is the focal length?

a) 4.3m x 6.5 = 28 meters

b) 4.3m / 6.5 = 66 cm

c) 4.3m

d) 6.5 fathoms

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Telescope properties

Surface brightness:

How much light is recorded in each pixel from an extended object (such as a galaxy, or the sky) depends on the surface brightness of the object (how many magnitudes/arcsec^2) and the f-ratio for a given CCD camera; nothing more! Isn't that amazing? Be prepared to derive this fact.

Telescope properties

Limiting magnitude:

How faint can you reach with a given telescope and instrument? It partially, but not completely, depends upon your patience. Slipher and other astronomers in the early 1900s might expose a photographic plate for several nights! In the end, the question is a signal-to-noise ratio question. We will discuss this more extensively when we get to CCDs.

Telescope properties

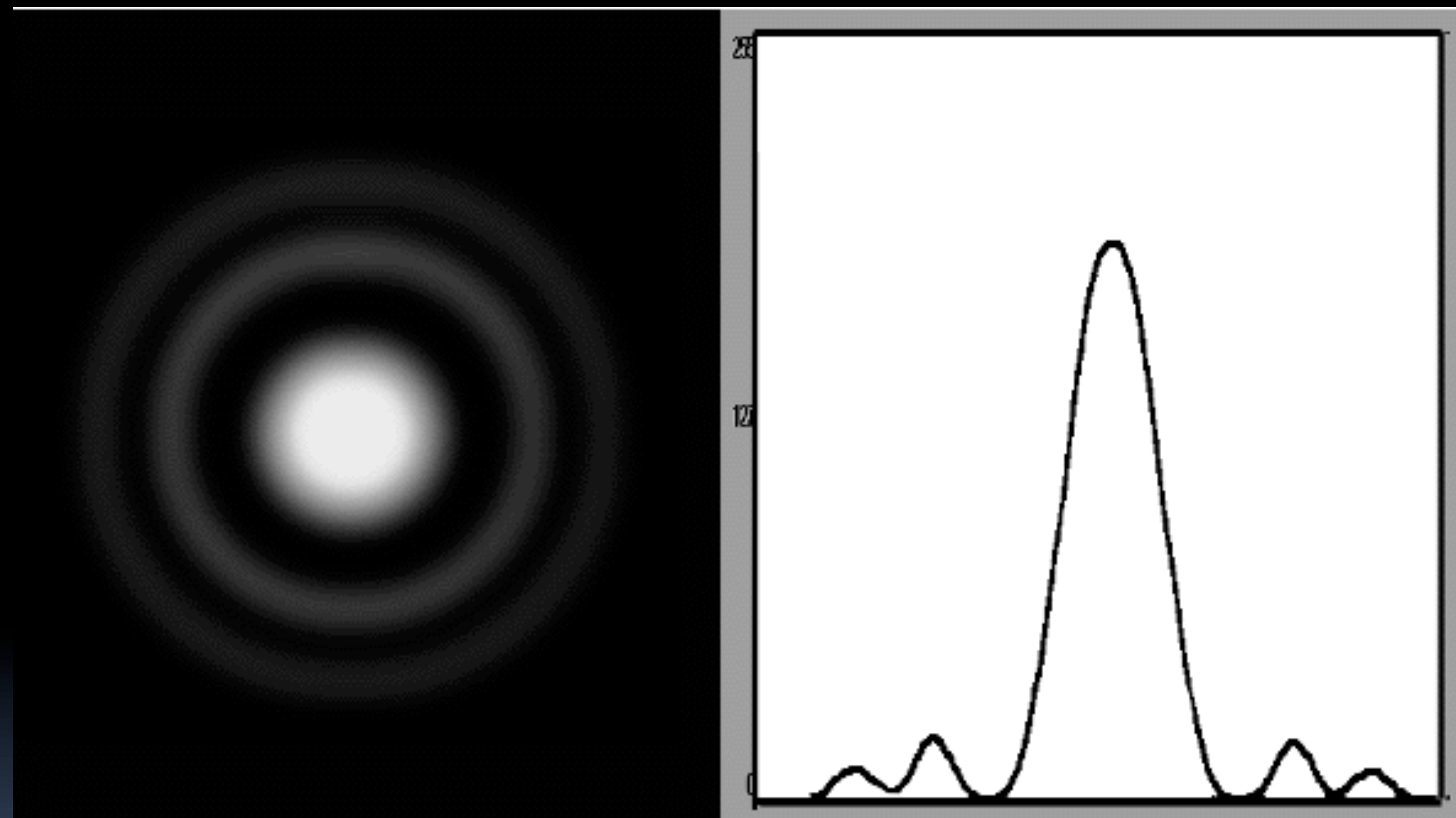
Angular resolution:

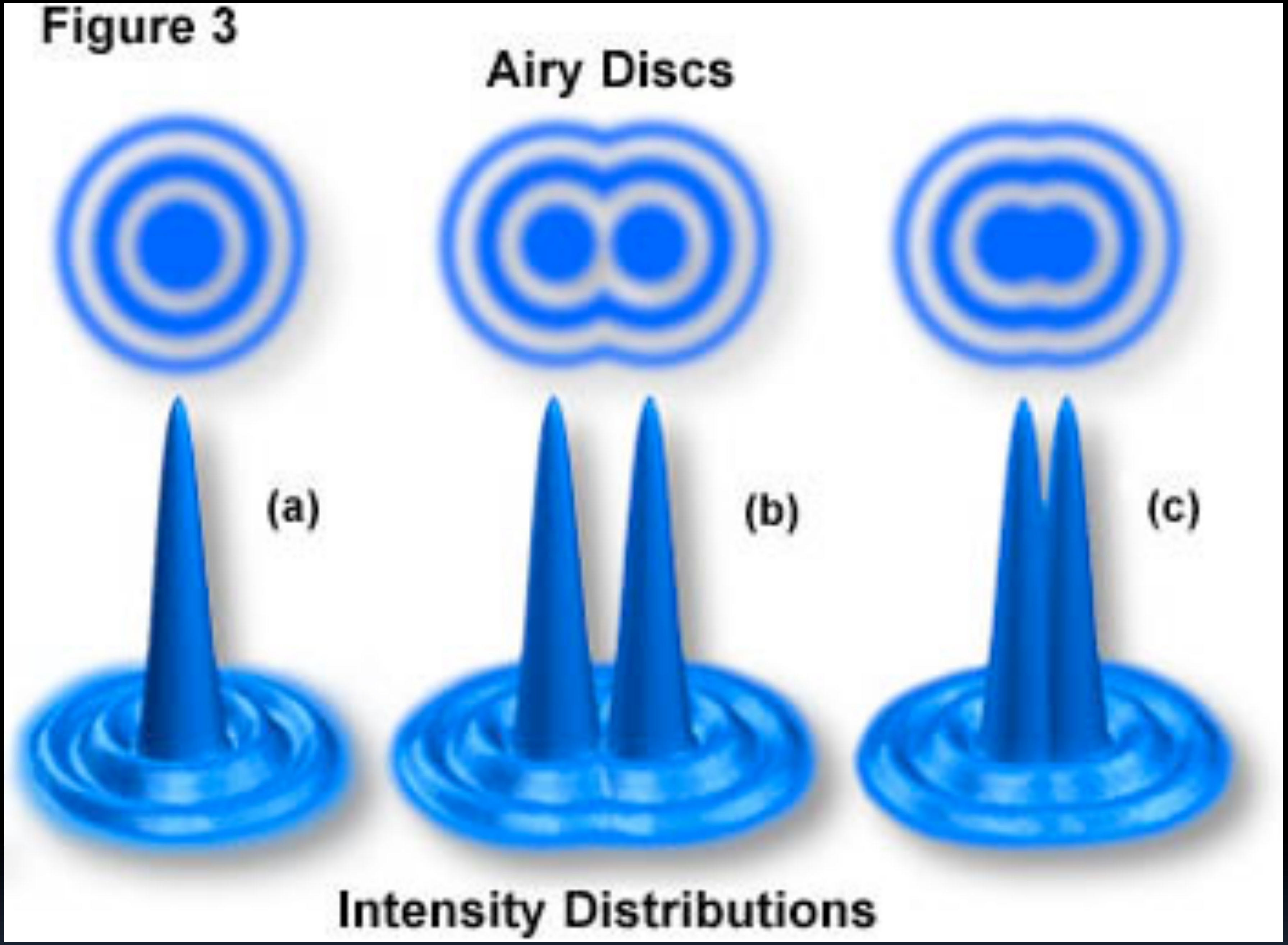
Fineness of detail in an image is usually dominated by the atmosphere. But there are intrinsic limits as well, set by physics.

Airy Disk

Because of diffraction, telescopes can’t image the hemisphere of a star.

The image of the star is a “bulls eye” pattern (i.e. an Airy disk).





One Star

Two Resolved Stars

Two Unresolved Stars

Telescope properties

Angular resolution. Most people adopt the "Rayleigh criterion":

$\sin\theta = 1.22 \ \lambda/D$,

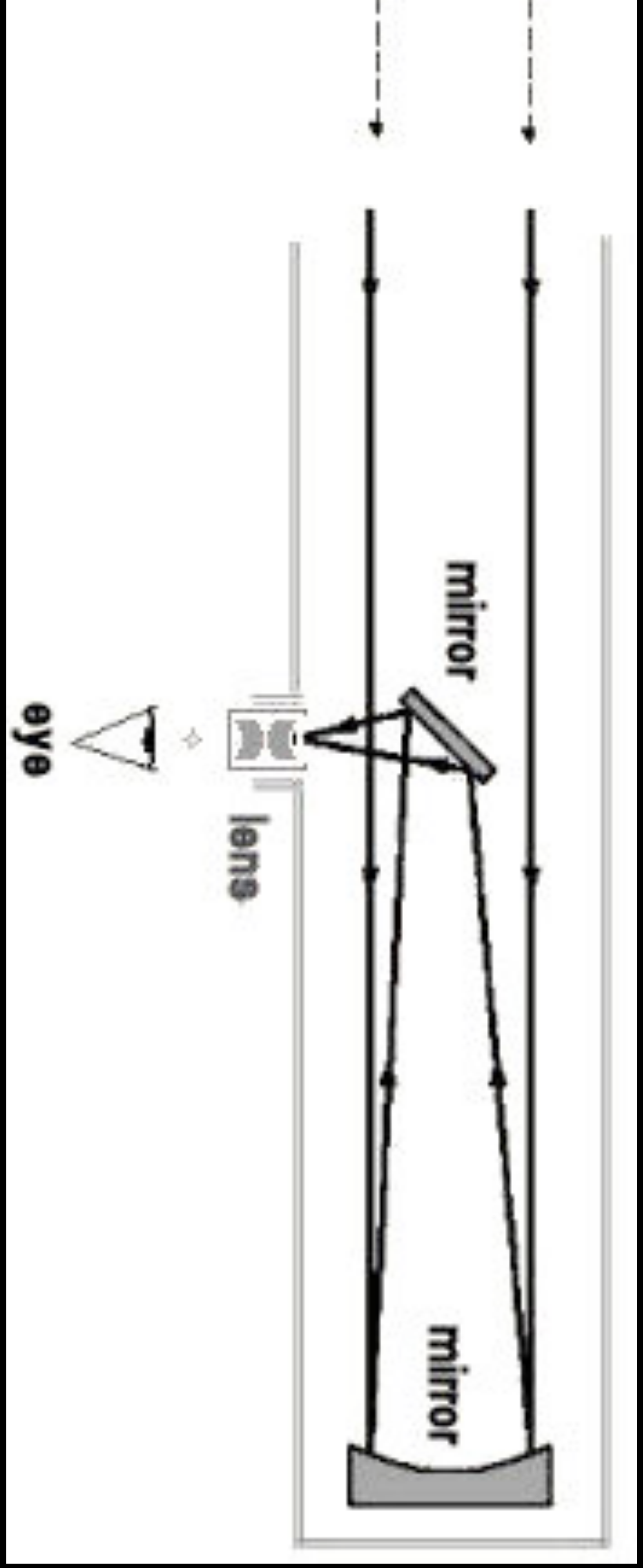
where λ (the wavelength) and D (the mirror diameter) must be in the same units. (Remember that 1Å = 1×10^{-10} meters.)

Bigger telescope mirror, better (smaller) resolution. Longer wavelenths, worse resolution.

Types of Telescopes

Newtonian telescopes:

These have a flat mirror that takes the light and directs it out the side. Most of the older 4-8-inch telescopes were of this design:


mirror
eye
lens
mirror

ORION

Types of Telescopes

The largest was the Newtonian platforms on the Mt Wilson 60- and 100-inch telescopes.

Types of Telescopes

Prime focus:

Light comes to a focus up near the top of the tube. There's a cage there large enough to hold an instrument. Observers used to ride up there with photographic plates.

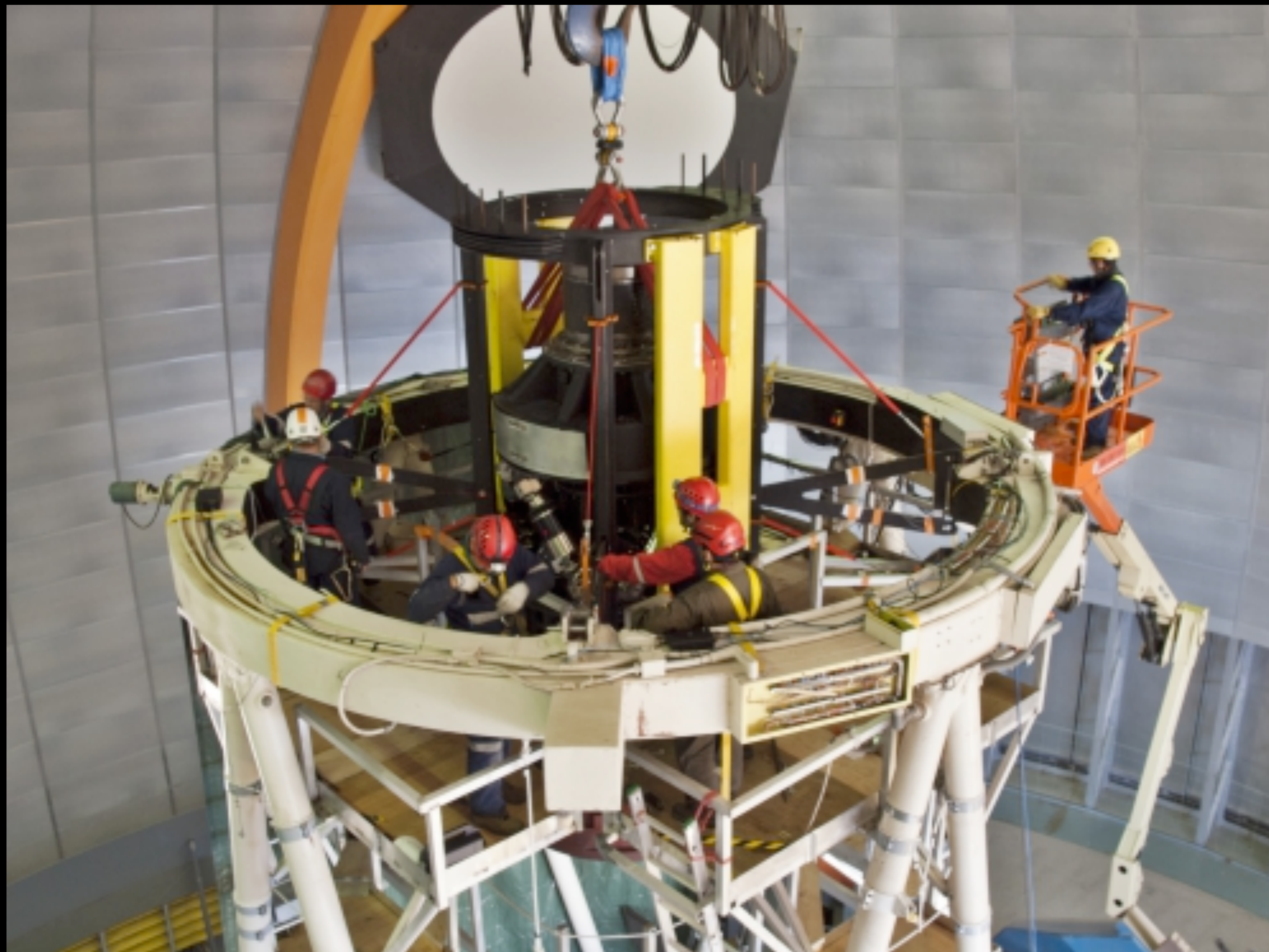
The Palomar 200-inch telescope.

Edwin Hubble in the prime focus cage of the 200-inch

Astronomer Jesse Greenstein exiting the prime focus cage.

Types of Telescopes

Prime focus is very "fast", usually f/2 or 3. So, the image scale isn't very good (larger number of arcseconds per pixel than in a slower beam) but there's more light per pixel. However...you can't cram a very large instrument up there in the air. Although people try...

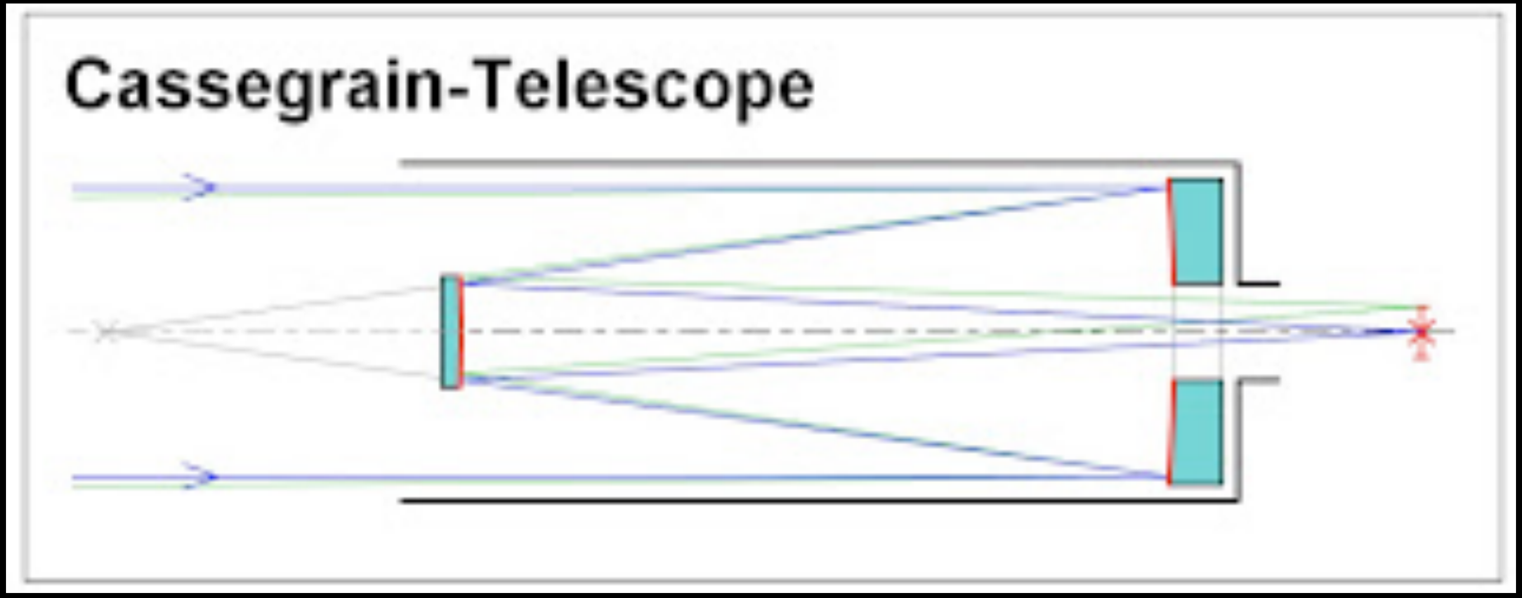


The Dark Energy Camer at CTIO: 4 tons! 520 million pixels (about 500x that of the Lutz camera)

4-meter Mayall telescope on Kitt Peak

Cassegrain and Ritchey-Chretien telescopes

Most (but not all) telescopes in the 0.5-6.5 meter classes instead have an instrument mounted down BELOW the primary mirror. A secondary mirror directs the light down through a hole in the primary.



The 1-meter Swope telescope on Las Campanas in Chile. CCD camera is attached below the primary mirror. Dr. Nidia Morrell is shown for scale.

Cassegrain and Ritchey-Chretien telescopes

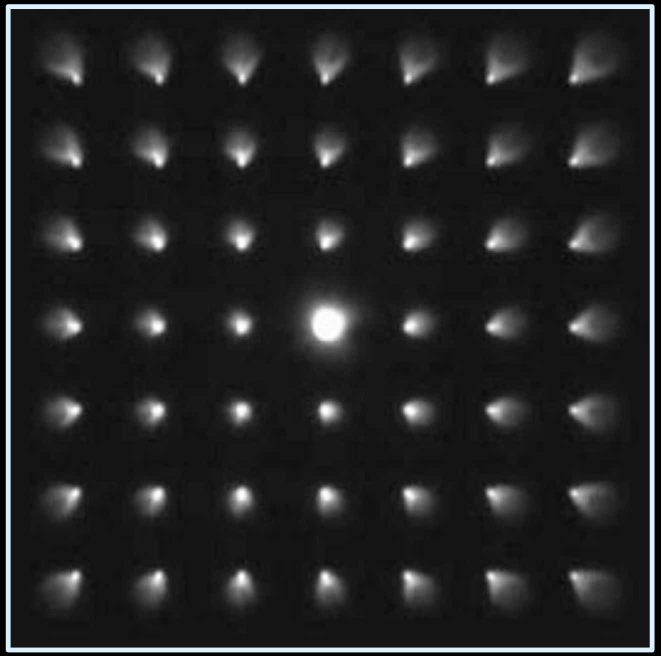
In a classical Cassegrain system, the primary is a concave parabola and the secondary had a convex, hyperbolic shape.

Main problem is an aberration called coma: anywhere off-axis stars are enlongated pointing away from the center. Same problem actually affects uncorrected prime-focus. Often a corrector (bunch of lenses) were inserted to correct for this, but problems associated with that.

Coma Aberration

Particularly serious in images formed by parabolic mirrors

Star images near center of picture are sharp, round dots, whereas those near the corners, which are formed by light entering the telescope off axis, are distorted into commas pointing toward the center of the picture



An example of off-axis coma typical in reflective optical systems.

Cassegrain and Ritchey-Chretien telescopes

The way around this was invented in 1910 by George Ritchey and Henri Chretien. Both the primary and the secondary are hyperbolic. These suffer NO coma…but the focal surface is curved.

Nearly all modern "Cassegrain" telescopes are of the Ritchey-Chretien design, including the Barry Lutz 0.5-m and the 4.3-meter DCT.

Nasmyth-Cassegrain

Nasmyth telescopes are like Ritchey-Chretien telecopes in that both the primary and secondary mirrors are hyperbolic and hence no coma. But a flat tertiary mirror then takes the light and directs it out to a Nasmyth platform on the side. You can put very heavy instruments there.

Hydra on the 3.8-meter WIYN telescope

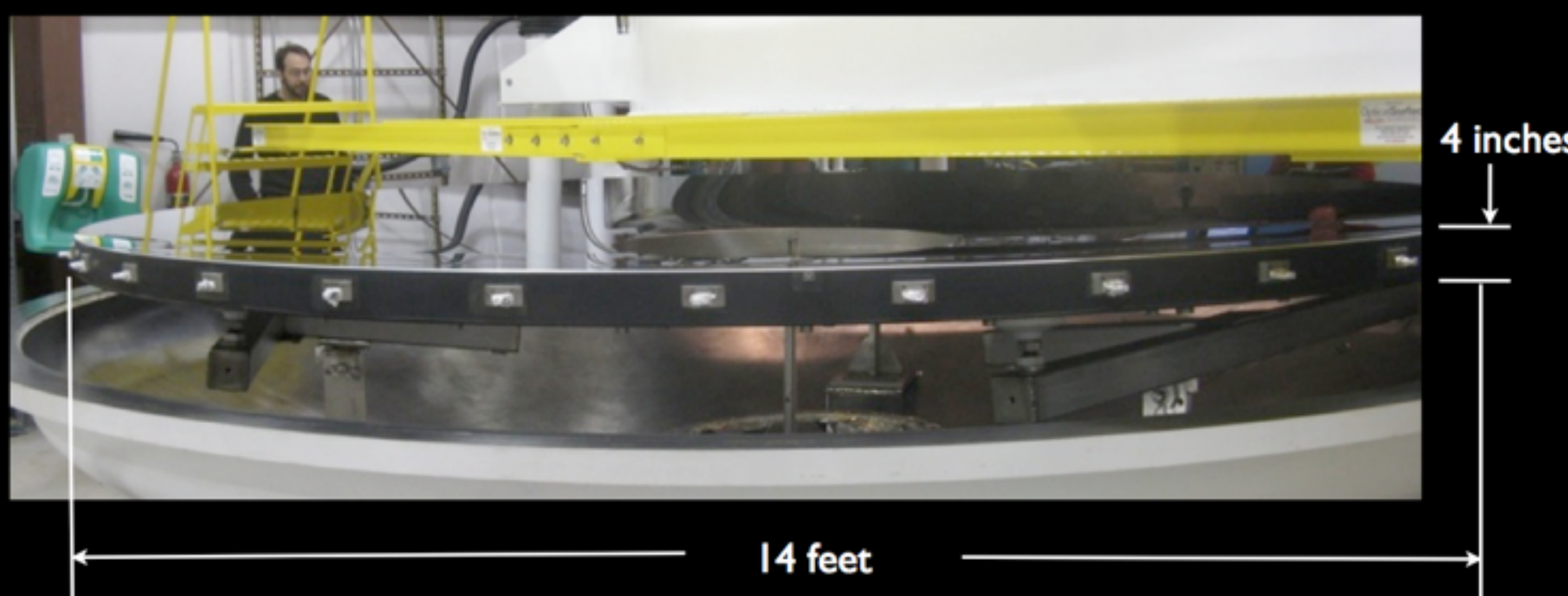
Nasmyth port at Magellan. Dr. Kathy Eastwood shown for scale.

Nasmyth-Cassegrain

But be prepared to rotate that instrument! True for all alt-az telescopes.

Floppy mirrors and wave-front sensing

In the "bad old days" telescope mirrors were THICK. The Kitt Peak 4-meter mirror is 2 feet thick. By contrast the DCT 4.3-meter mirror is 4 inches thick!

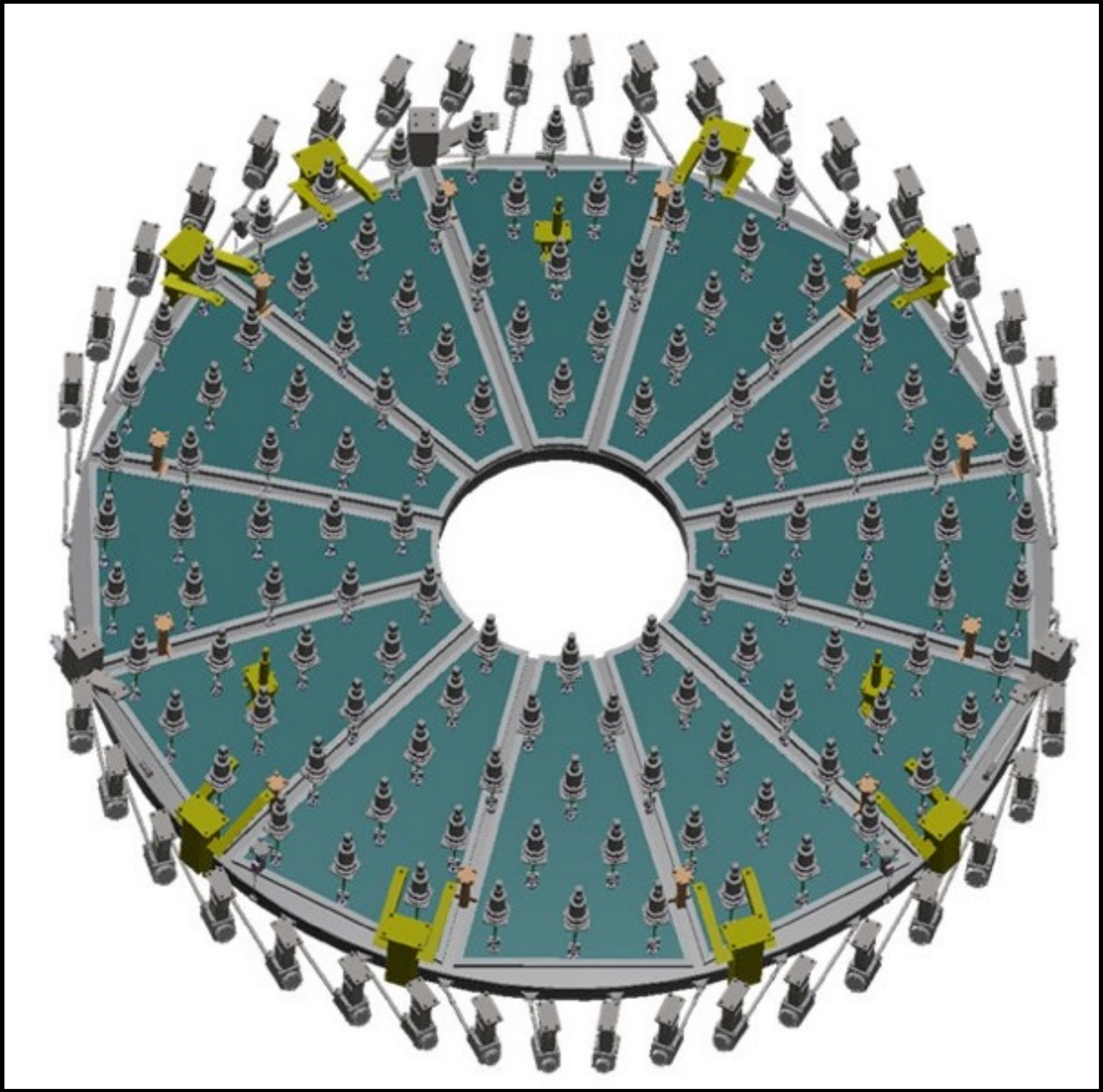


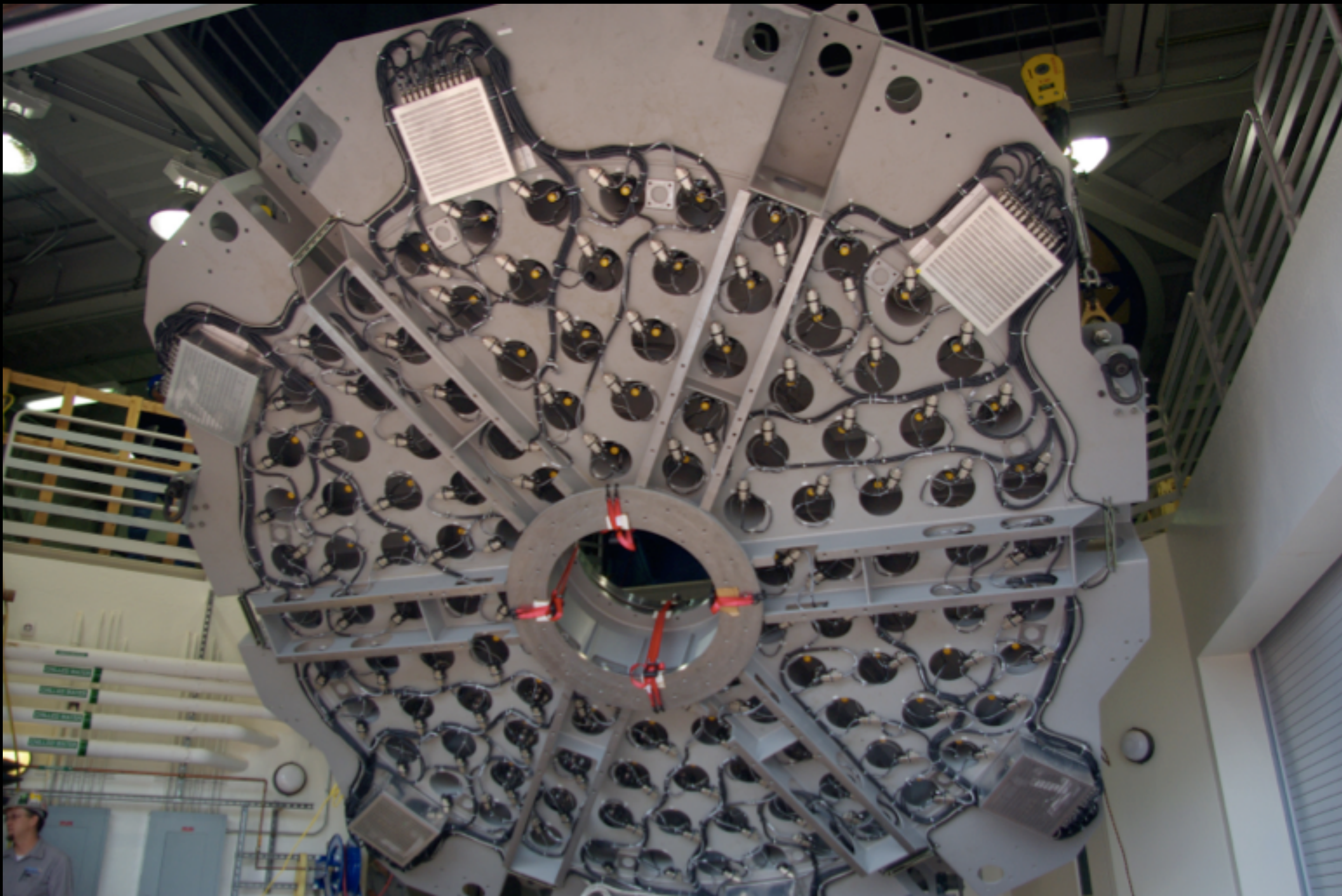
Floppy mirrors and wave-front sensing

But thick mirrors have a thermal constant of days (maybe weeks!). Thin mirrors are much better. But how do you make a thin mirror stiff? You don't. Instead, you put a bunch of actuators on the back, and push on the mirror just so as you move around the sky. You use wave-front sensing to "tune" the shape of the mirror, either using values you've determined during testing (look-up table) or do the wave-front sensing in real time.

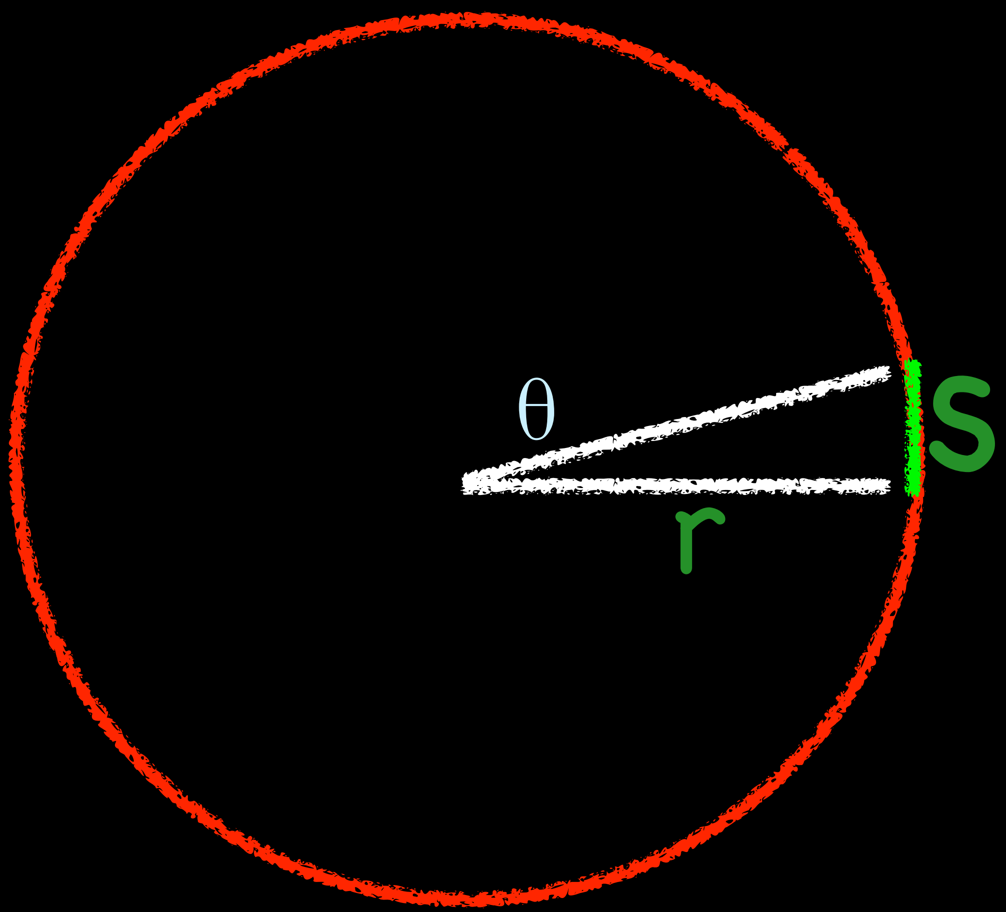
You "tune out" coma, spherical abberation, astigmatism, trefoil, etc.

The Active Optics System





How Do We Calculate Scale?



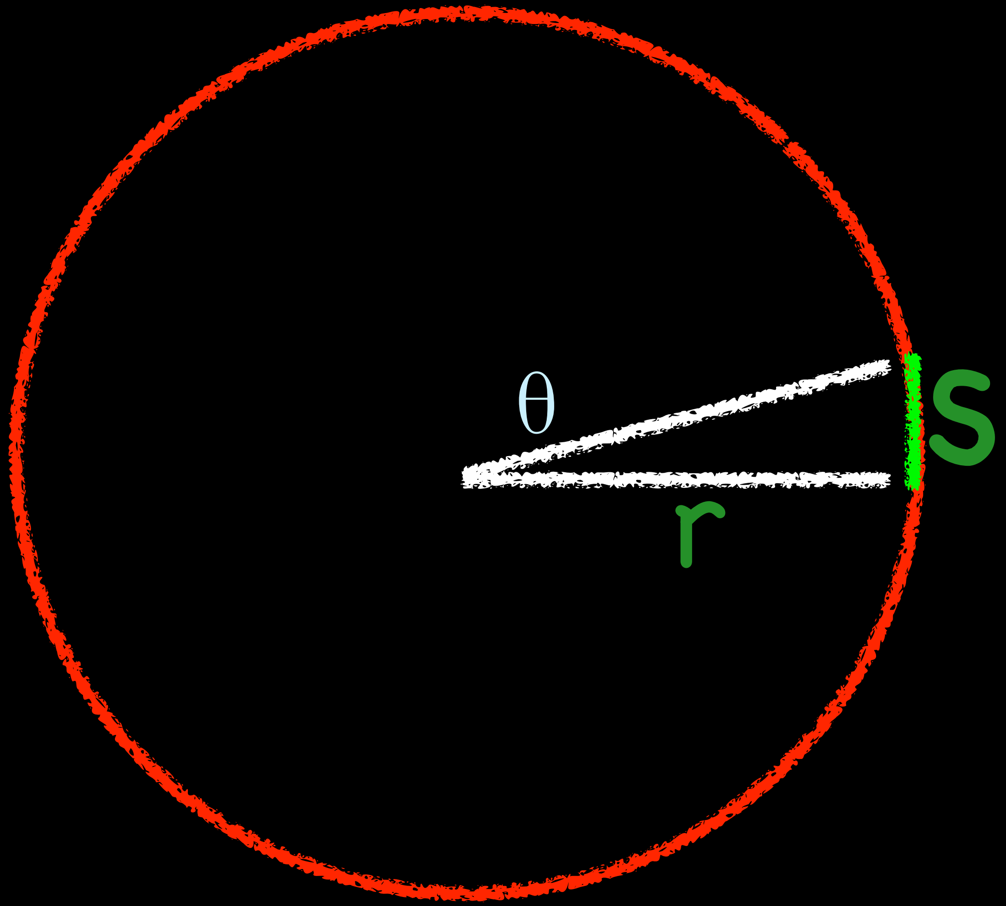
$$s = r\theta$$

The distance s in the focal plane is equal to the angle θ times the focal length r.

If the focal plane isn't curved, this still works via the small angle approximation

How Do We Calculate Scale?

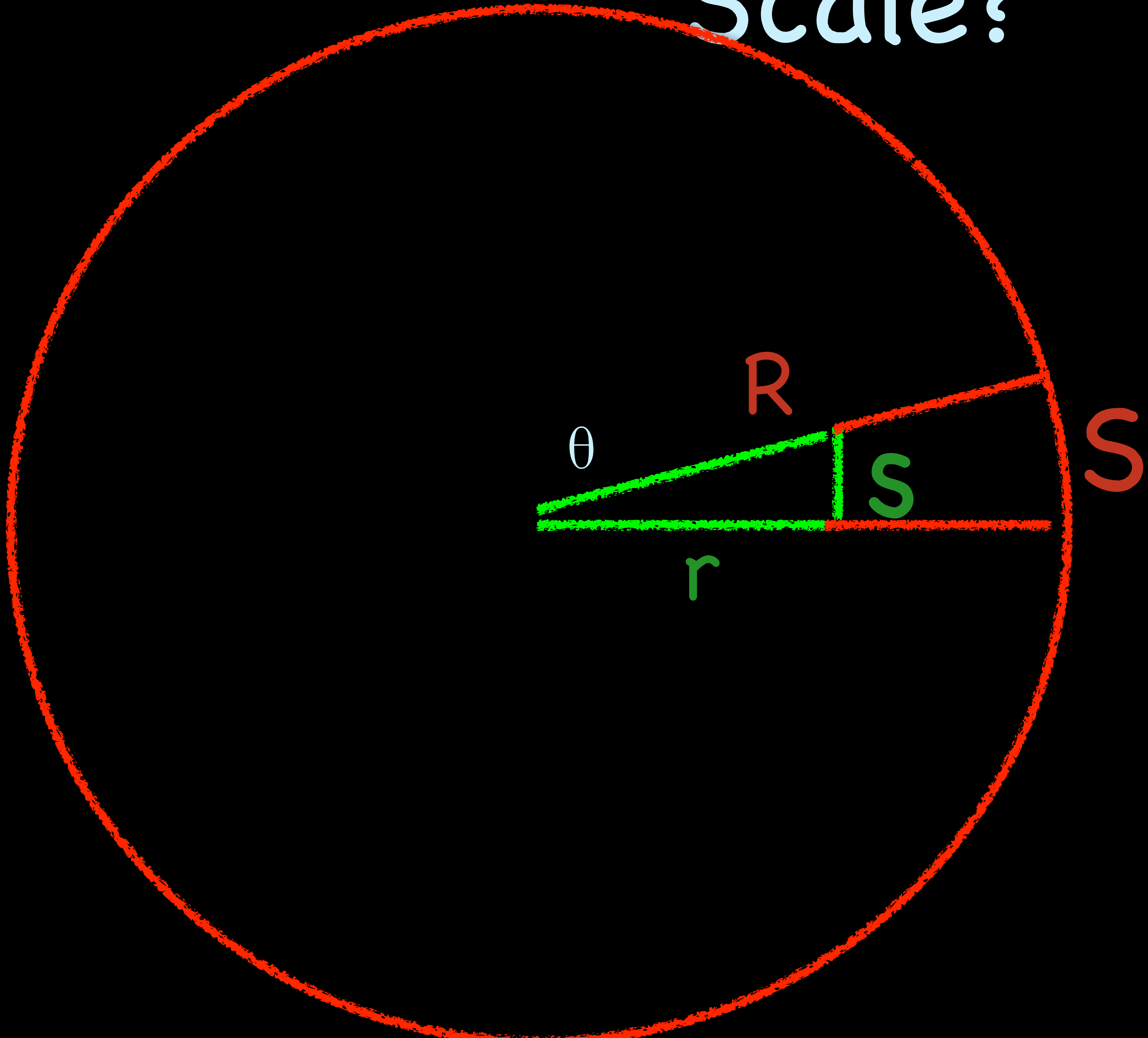
$$s = r\theta$$



So, 1 arcsec seperation will have a larger physical seperation s the longer the focal length r.

How Do We Calculate Scale?

$$s = r\theta$$



How Do We Calculate Scale?

So, PHYSICALLY (mm) how much does 1 arcsecond translate to? Depends ONLY ON FOCAL LENGTH!

Focal length x 1/206265

If you know the mirror diameter and f-ratio, remember that the Focal Length = diameter x f-ratio.

How Do We Calculate Scale?

Usually we want to know the number of arcseconds per mm (or per pixel). So, we really want the inverse of that. But start by asking how many mm 1 arcsecond projects too. If you want something involving pixels, then use the size of a pixel. Dimensional analysis also helps....

arcsec/mm x 13.5 microns/pixel x 1mm/1000 microns will leave you with arcsec / pixel

Right? Right!

QUIZ

The camera on the 4.3-meter f/6.5 DCT telescope has 6800 x 6800 15µm pixels.

1. What is the image scale (arcseconds/pixel)?
2. What is the field of view (arcmins x arcmins)?
3. If you get 1000 counts/sec in the V-band from a star with the DCT, how many would you get with the 0.51-m Lutz telescope?

QUIZ

The camera on the 4.3-meter f/6.5 DCT telescope has 6800 x 6800 15μm pixels.

1. What is the image scale (arcseconds/pixel)?

   First calculate how many microns/arcsecond: $s=r\theta$.
   $r=6.5 \times 4.3 = 28.0$ meter $= 2.8\times10^4$ mm.
   $\theta=1/206265$. So $s = 0.135$mm or 135μm/arcsec.
   Thus 15μm/pixel / 135μm/arcsec = 0.11 arc/pixel.

QUIZ

The camera on the 4.3-meter f/6.5 DCT telescope has 6800 x 6800 15µm pixels.

2.What is the field of view (arcmins x arcmins)?

6800 pixels x 0.111 arcsec/pixel = 755 arcsec = 12.6 arcmin. So, FOV is 12.6’ x 12.6

QUIZ

The camera on the 4.3-meter f/6.5 DCT telescope has 6800 x 6800 15µm pixels.

3. If you get 1000 counts/sec in the V-band from a star with the DCT, how many would you get with the 0.51-m Lutz telescope?

1000 x (0.51/4.3)2 = 14 counts/sec

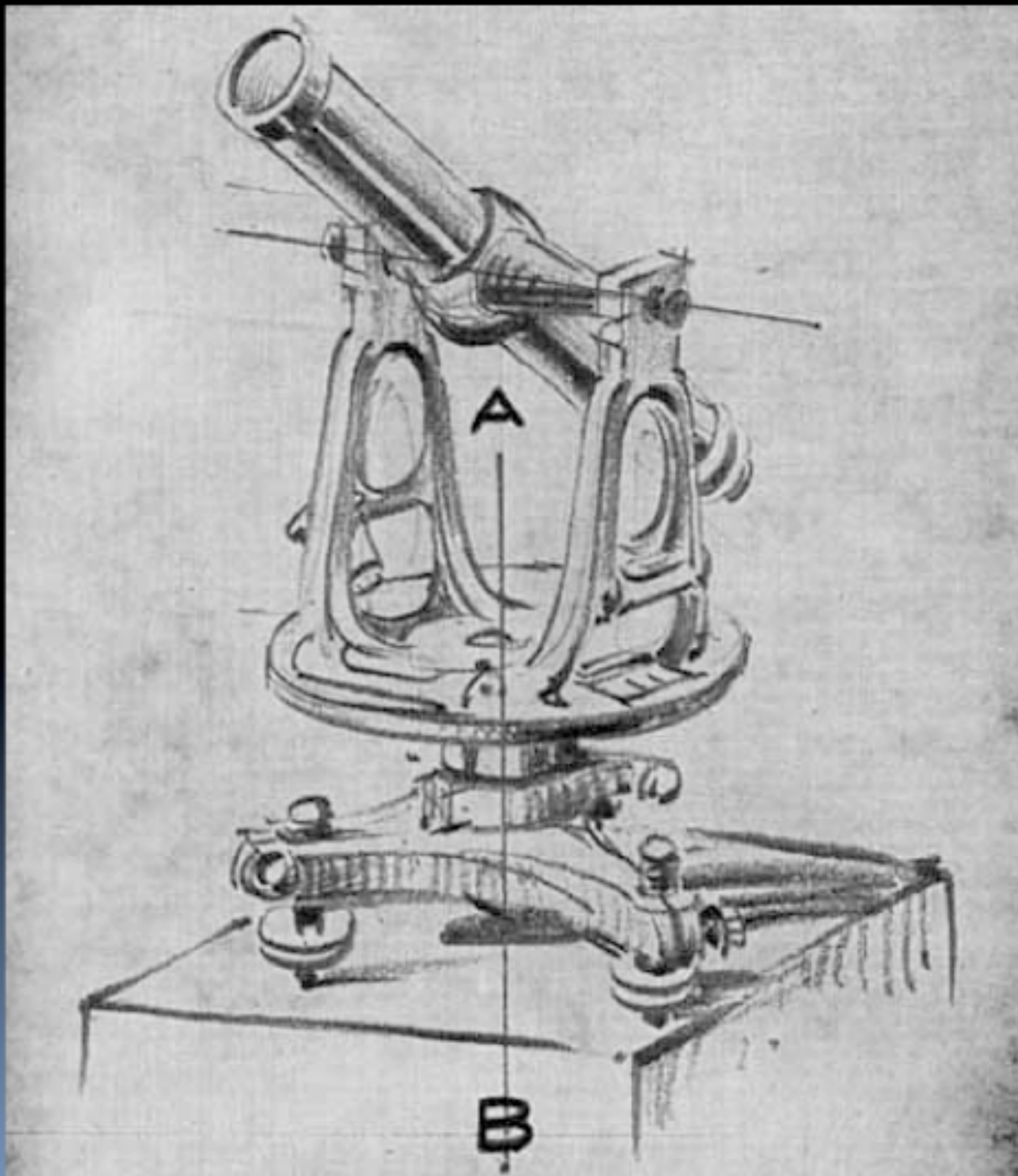
Telescope Mounts

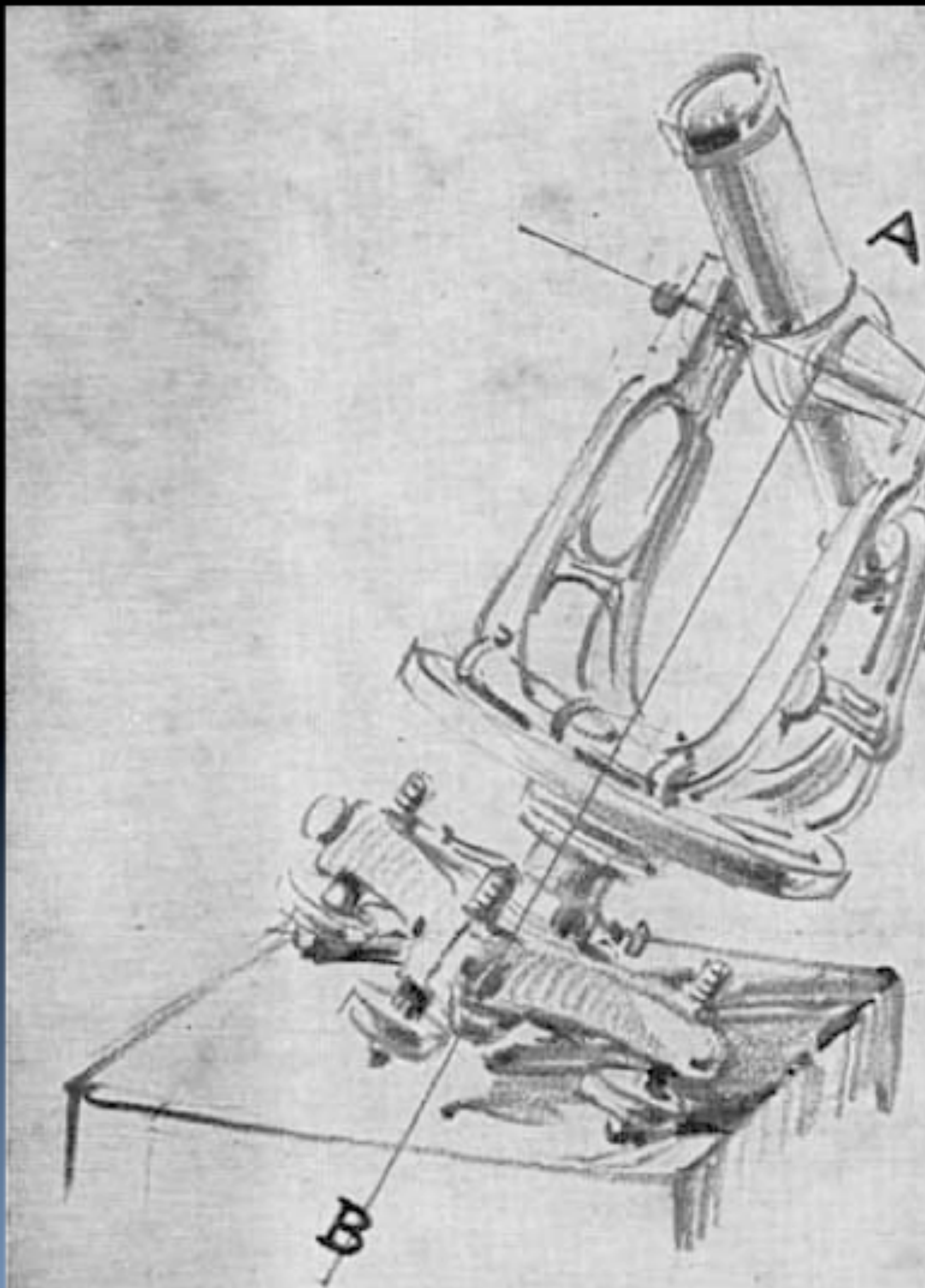
Supports telescope

Enables telescope to follow motion of the night sky

Two major types:

- ★ Alt-Az
- ★ Equatorial (lots of variations)





Alt-Az

Equatorial

Equatorial vs. Alt-Az Mounts

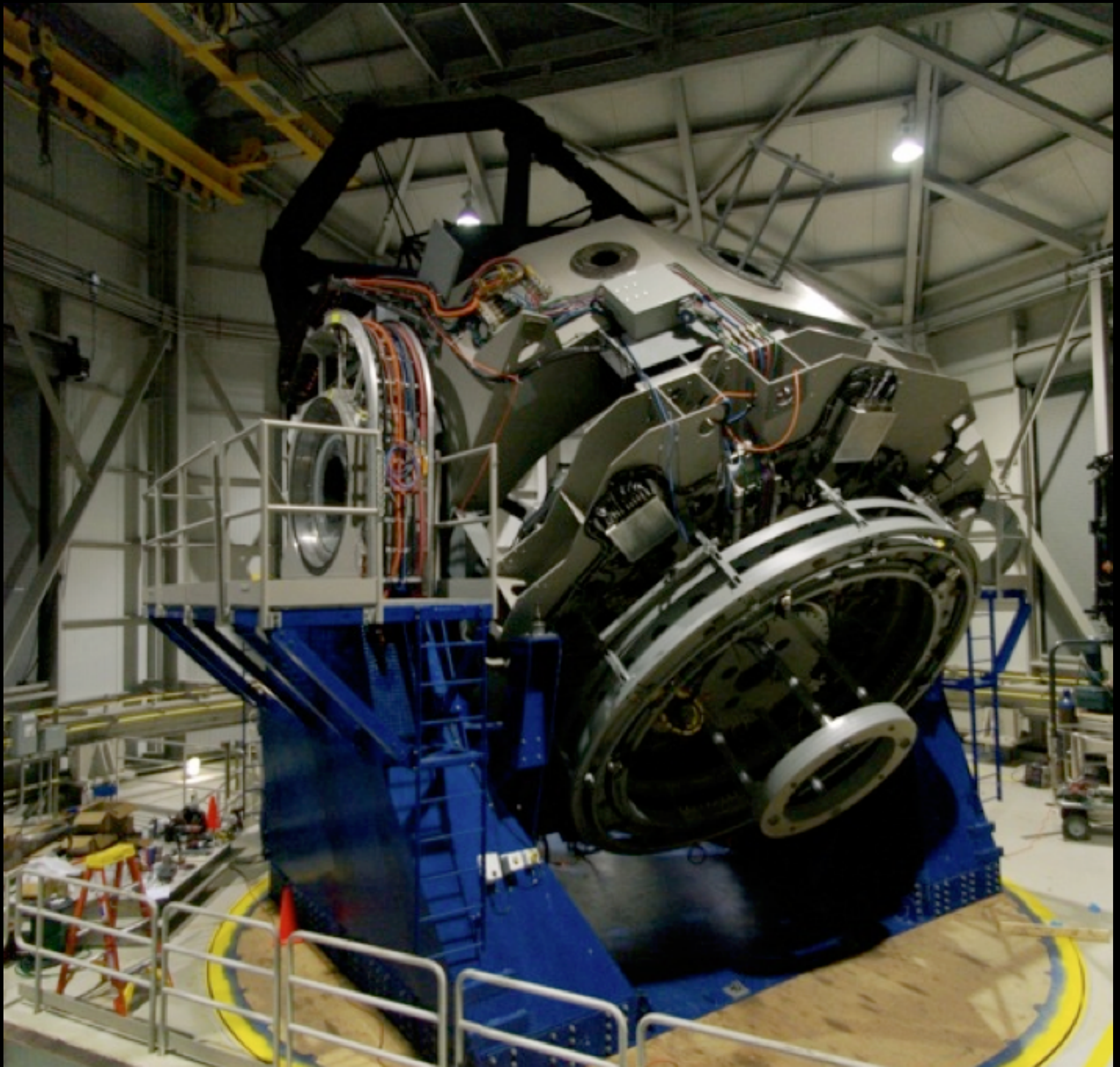
Equatorial

- Mechanically complex
- Two Axes
  - Equatorial (Right Ascension)
  - Perpendicular (Declination)
- Track object in sky at uniform speed with equatorial axis
- Image does not rotate in focal plane

Alt-Az

- Mechanically simple
- Two Axes
  - Azimuth
  - Altitude
- Track object in sky at variable rates with az & alt axes
- Image rotates in focal plane (need a de-rotator)

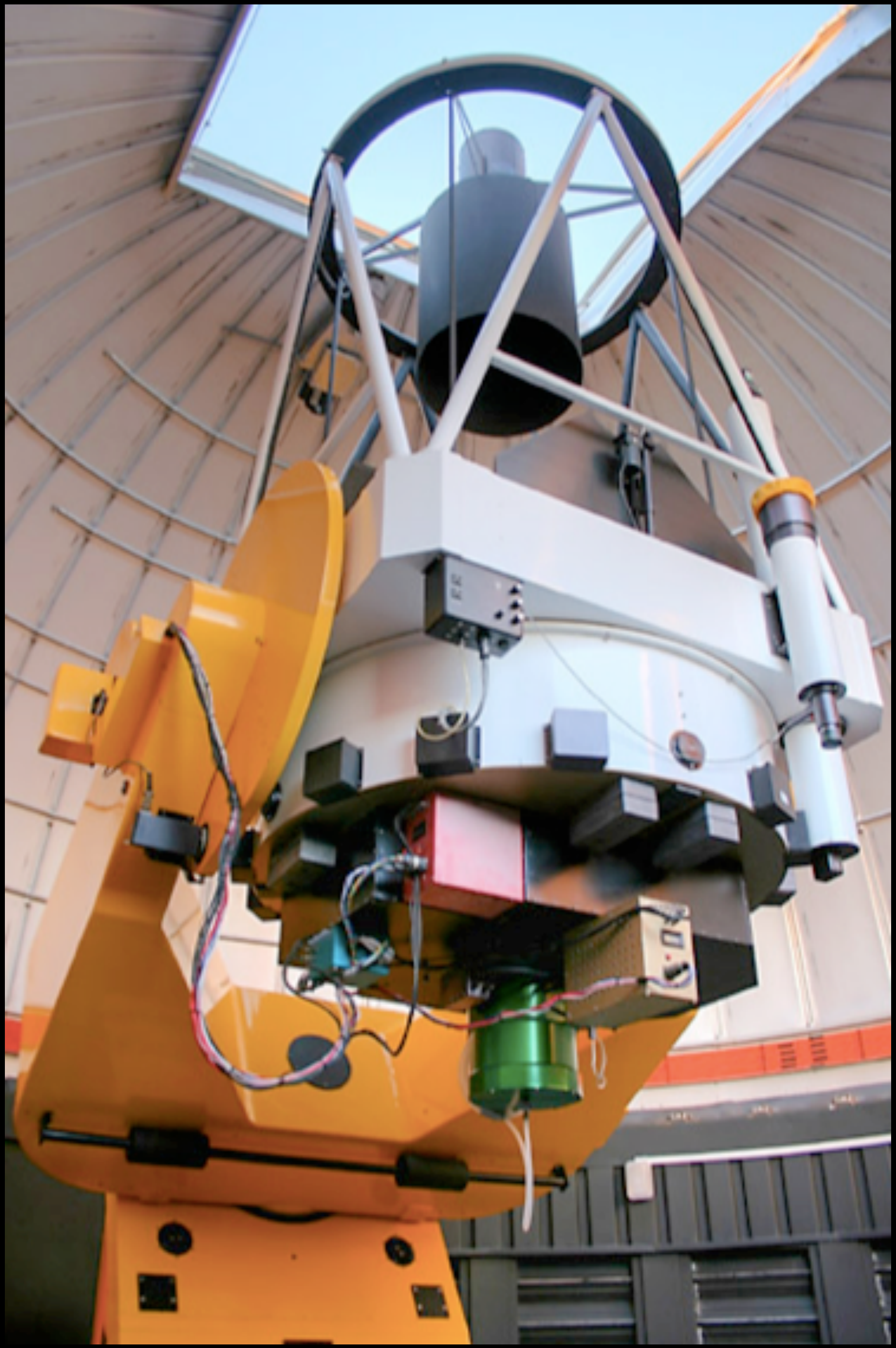
All modern large telescopes are alt-az

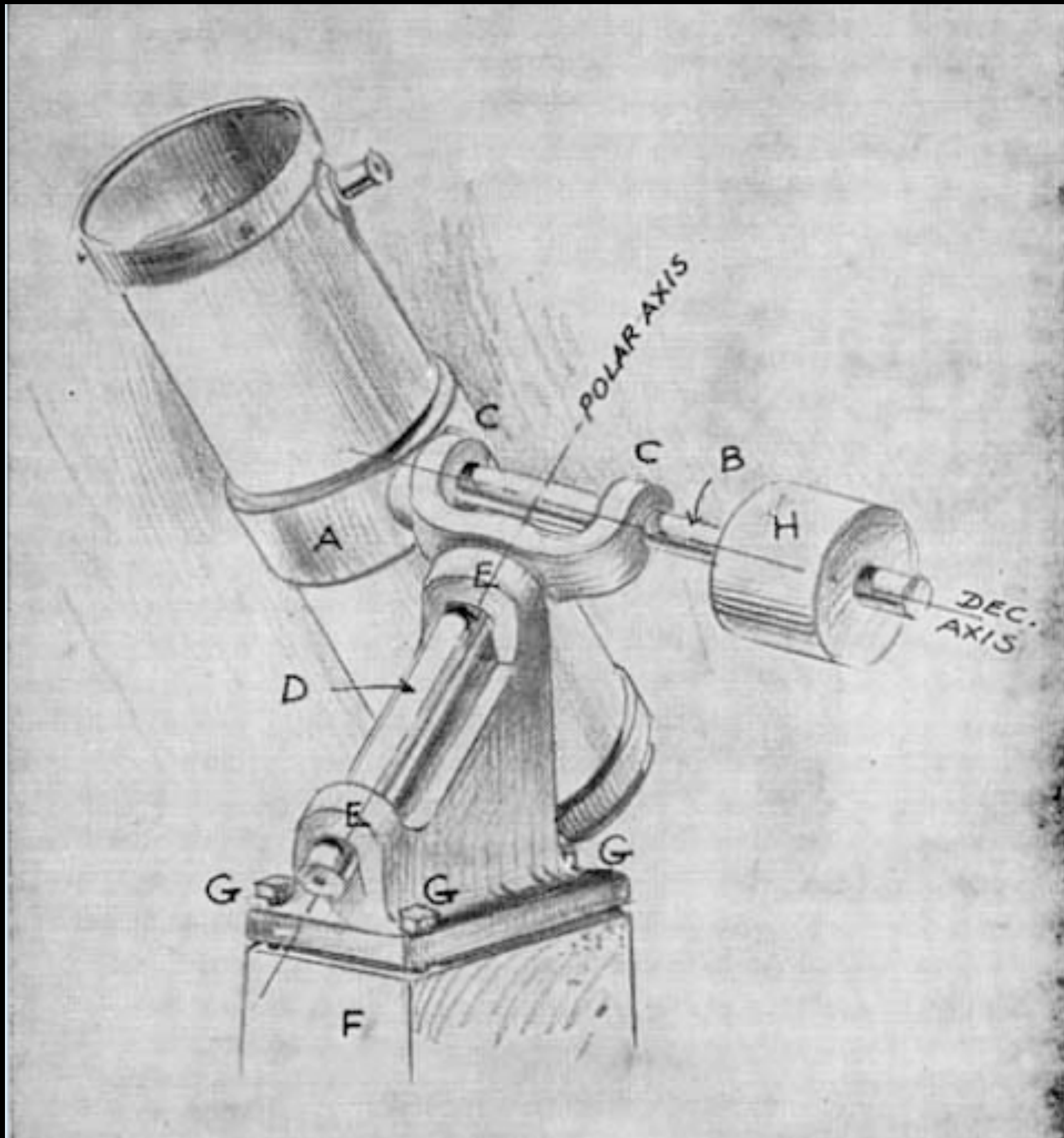


4.3-meter Discovery Channel Telescope

Equatorial horseshoe (Mayall 4-meter)

Equatorial fork mount





German Equatorial mount

If equatorial telescopes are more mechanically complex than alt-az, why is it that all of the large telescopes built in the 1960s and 1970s were equatorial while all modern large telescopes at alt-az?

A. Telescope engineers stuck in their ways.

B. Didn't think of it.

C. Needed faster computers.

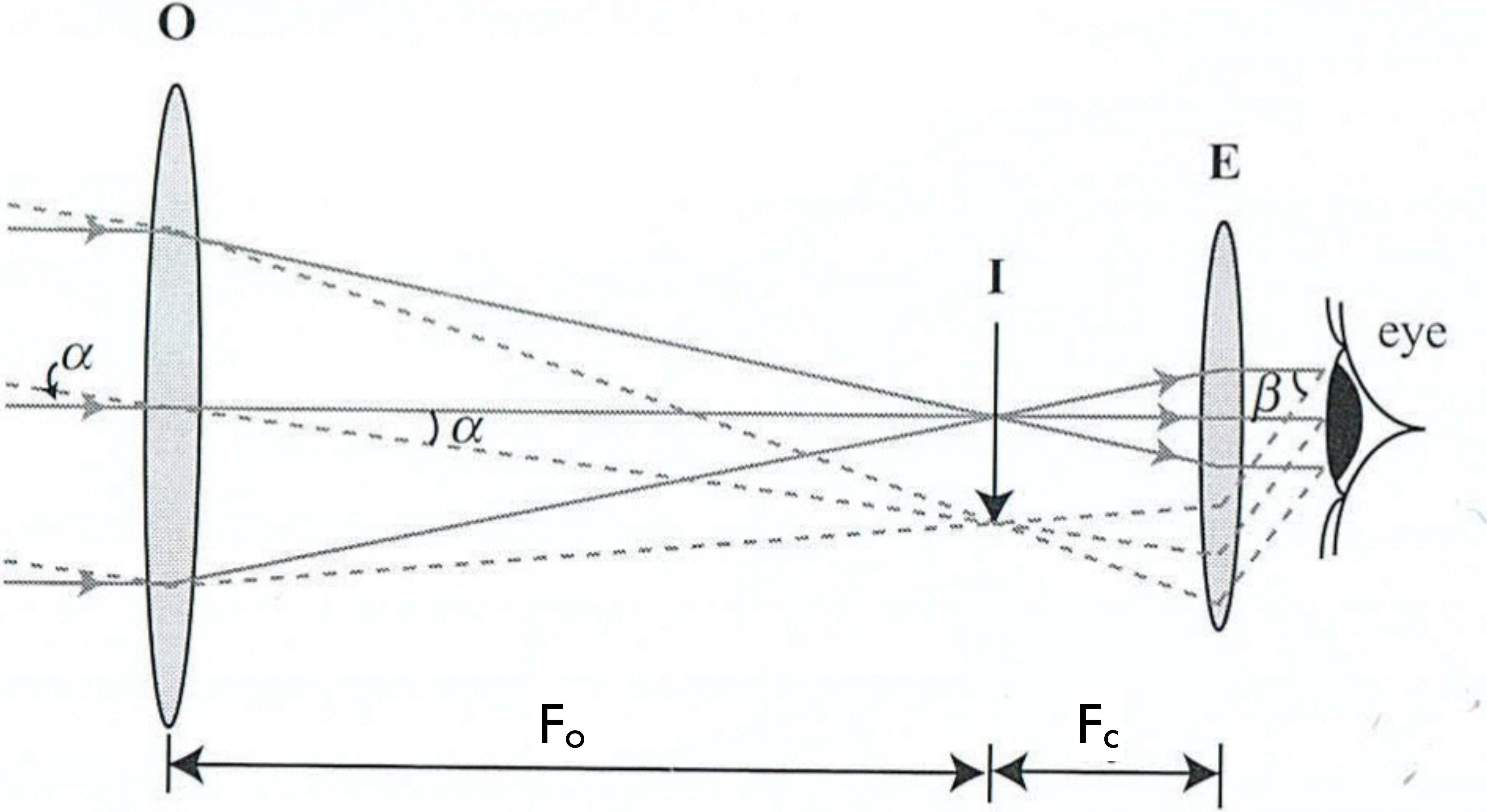
D. Liked to spend more money on bigger domes.

Eyepieces

When you **look** through a telescope, **why** do you have to use an eyepiece? The telescope forms an image, after all, in a focal plane. Why can't you just stick your eye there and look at it?

Eyepieces

Your eye has a lens. So, you need parallel light. If we think of an eyepiece as a single lens (they're not), then what it does is act as a "magnifying glass" to examine the image in the focal plane, turning the light parallel.



Magnification = β / α = f_o/f_c

Eyepieces

Consider the BLT. It has a focal length (F_o) of 4115mm. If you use it with a "standard" eyepiece of focal length 1" (25.4mm, f_c) what is the magnification?

$M = F_o/F_c$

$M = 4115 / 25.4 = 162$. So, things look "closer" by 162 times!

Homework_5 due 10/6

Answer 1-5 about the Barry Lutz telescope, based on the following characteristics. SHOW YOUR WORK!

- Primary mirror: 0.51-meter
- Focal length: 4115 mm
- CCD is a 1024x1024 array with 13μm x 13μm pixels

1) What is the f-ratio of the telescope?

2) What is the image scale ("/pixels) of the CCD?

3) At opposition, Jupiter subtends about 50". How many pixels?

4) What is the field-of view of the CCD camera?

5) What is the theoretical resolution of the Lutz telescope at 5100Å? What limits this in practice?