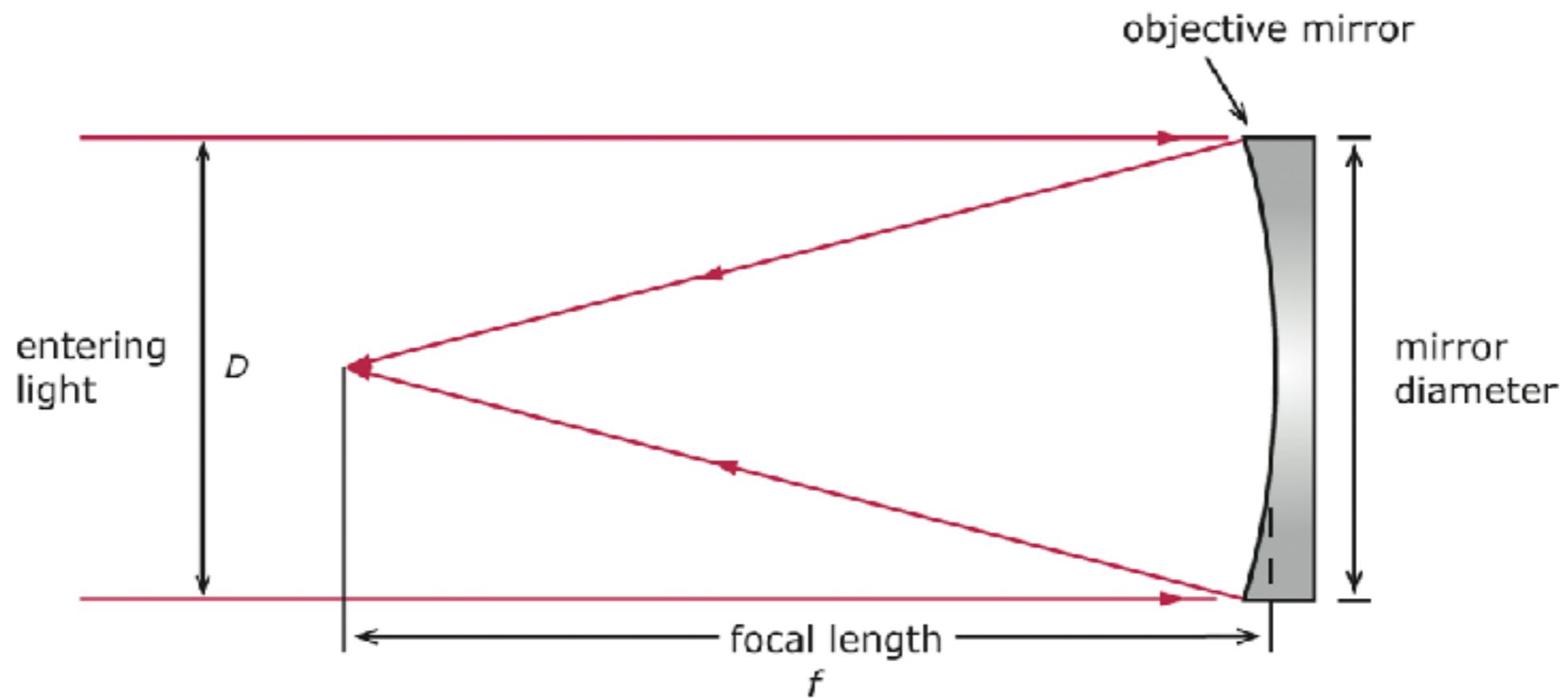


# Astronomy 503

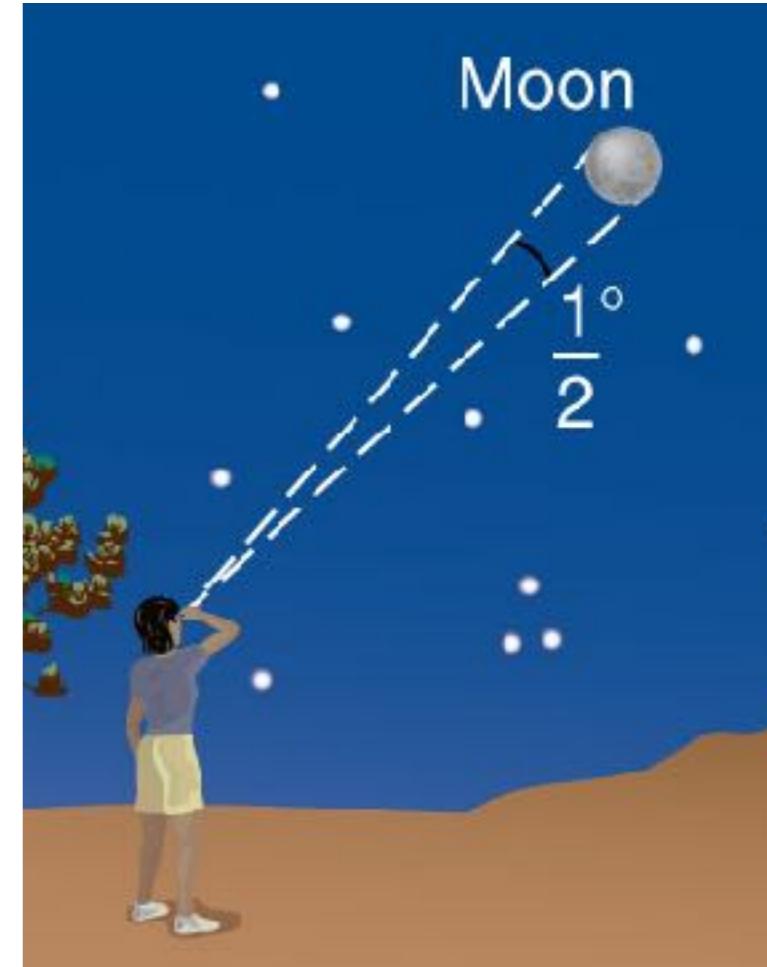
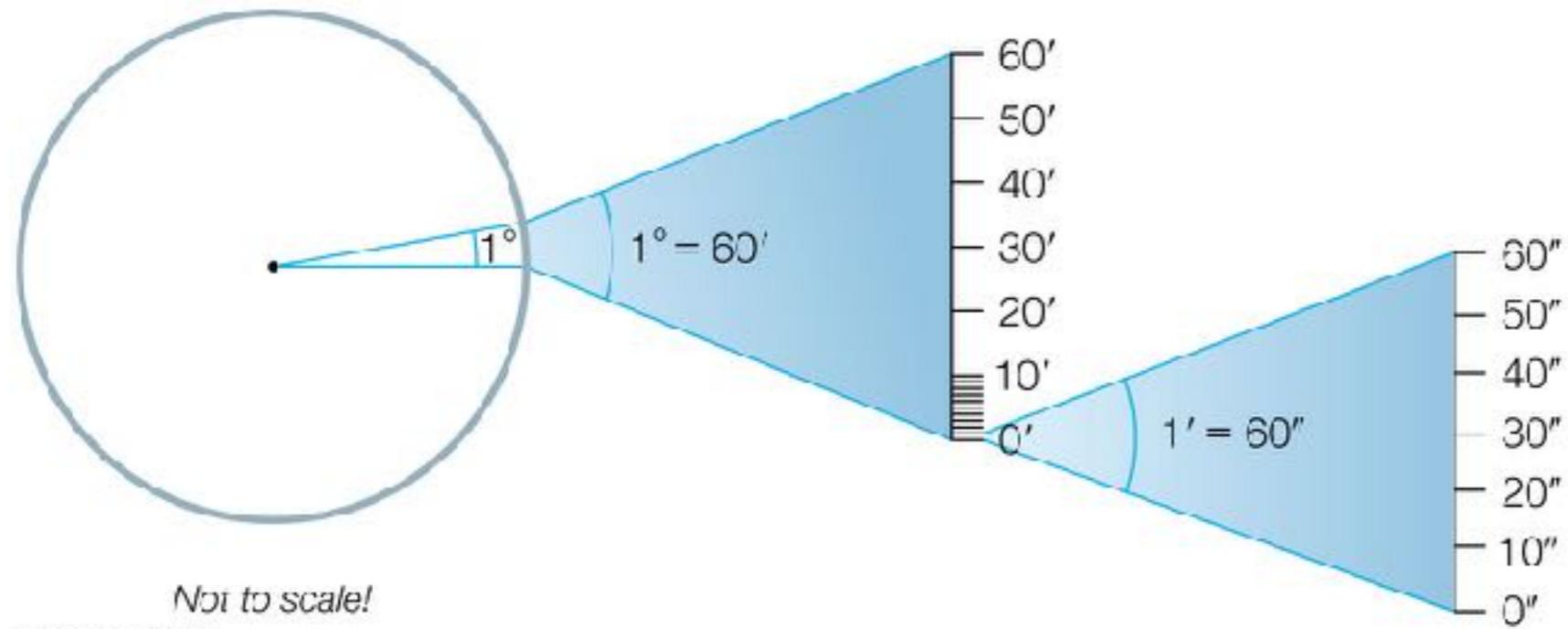
## Observational Techniques



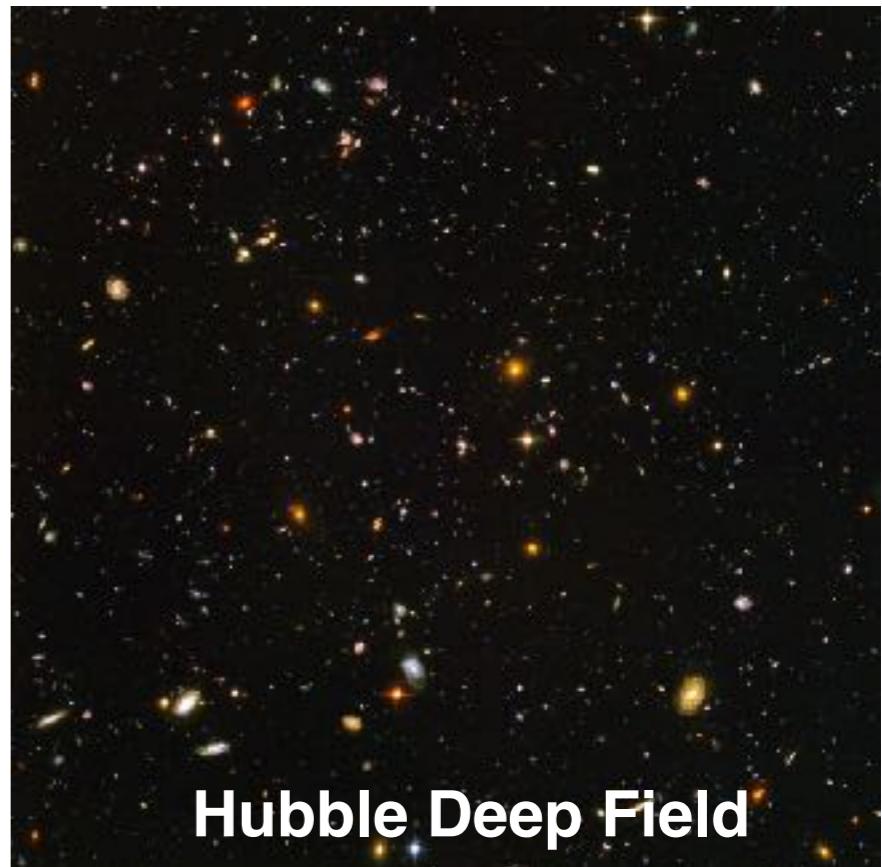
Prof. Gautham Narayan

Lecture 07: Optics

# Resolution and Angular Sizes: degrees, arcminutes, arcseconds



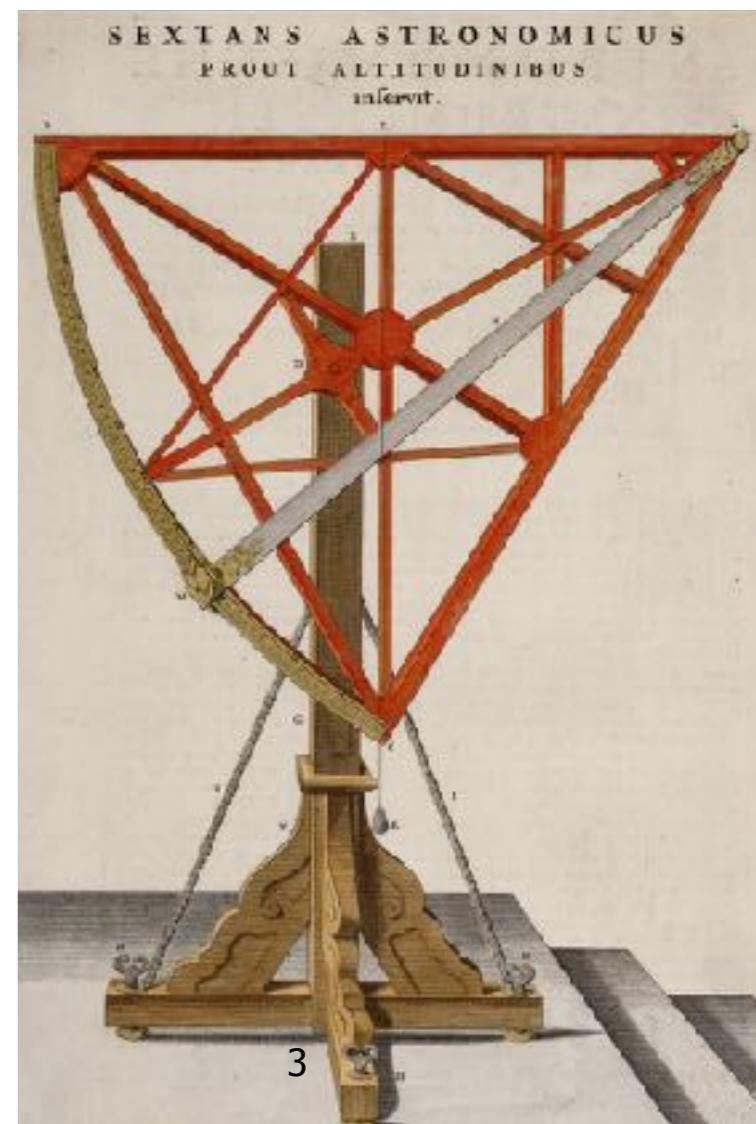
- A circle has  $360^\circ$
- The Sun and Moon are  $\frac{1}{2}^\circ$
- An arcmin is  $1/60$ th of a degree
- 20/20 human vision is  $1'$  (arcmin) resolution
- Good resolution for an optical telescope on the ground is  $1''$  (arcsec)
- Hubble/JWST resolution in space is  $0.05\text{-}0.1''$



Hubble Deep Field

# Tycho Brahe (1546–1601) the master observer

- ▶ Danish Nobleman, later exiled to Bohemia
- ▶ Lost his nose in a sword duel over who was the better mathematician. (Subsequently wore a brass prosthetic nose.)
- ▶ Observed positions of 1000 stars and the planets using a custom-made dedicated observatory with state-of-the-art equipment
  - ▶ Uraniborg – “Castle of the Heavens”
- ▶ Conducted more precise observations than had ever been done
  - ▶ Accurate to ~1 arcminute
  - ▶ x10 better than had ever been accomplished before
  - ▶ No telescopes!
- ▶ Witnessed a supernovae in 1572
- ▶ Correctly saw that the Moon orbited the Earth and tried to develop a “geo-heliocentric” system.
- ▶ Remained a Geocentrist all his life
- ▶ Johannes Kepler was his assistant and apprentice
- ▶ Died (or was murdered with mercury) after massive banquet in Prague of kidney failure, because he didn’t want to leave.
  - ▶ Observers go hard.





# Charles Messier

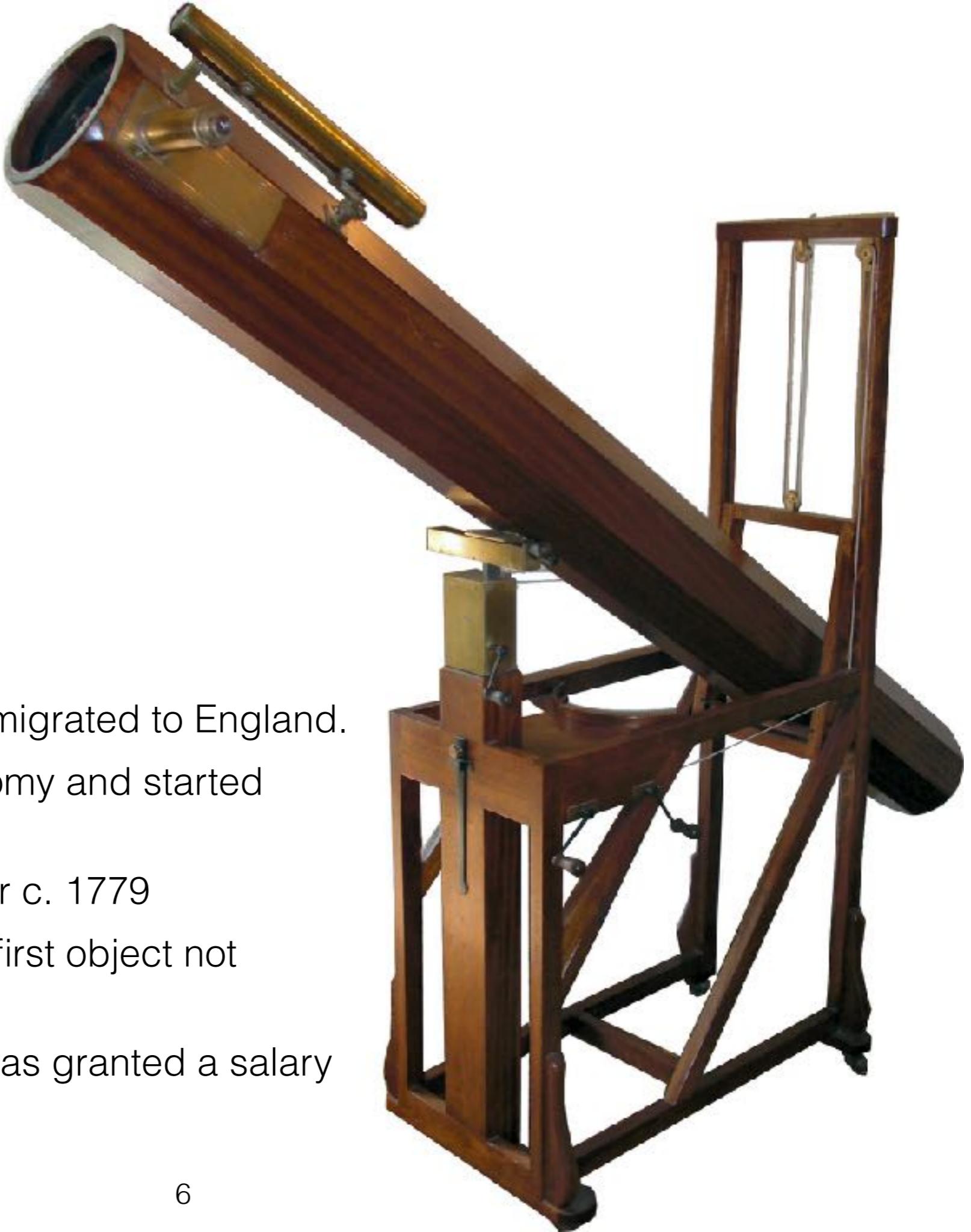
- 1730–1817
  - Devoted his life to astronomy after witnessing Haley's comet.
  - Worked for the French Naval Observatory, used a 4" refracting telescope.
  - By 1789 he had found between 13–21 comets.
  - Made the first catalog of the deep sky.

# New General Catalog = NGC



- New General Catalog of Nebulae and Clusters of Stars
- Started in 1888 by John Dreyer as a followup to Herschel's General Catalog
- 7,840 sources

# Reflectors: Herschel

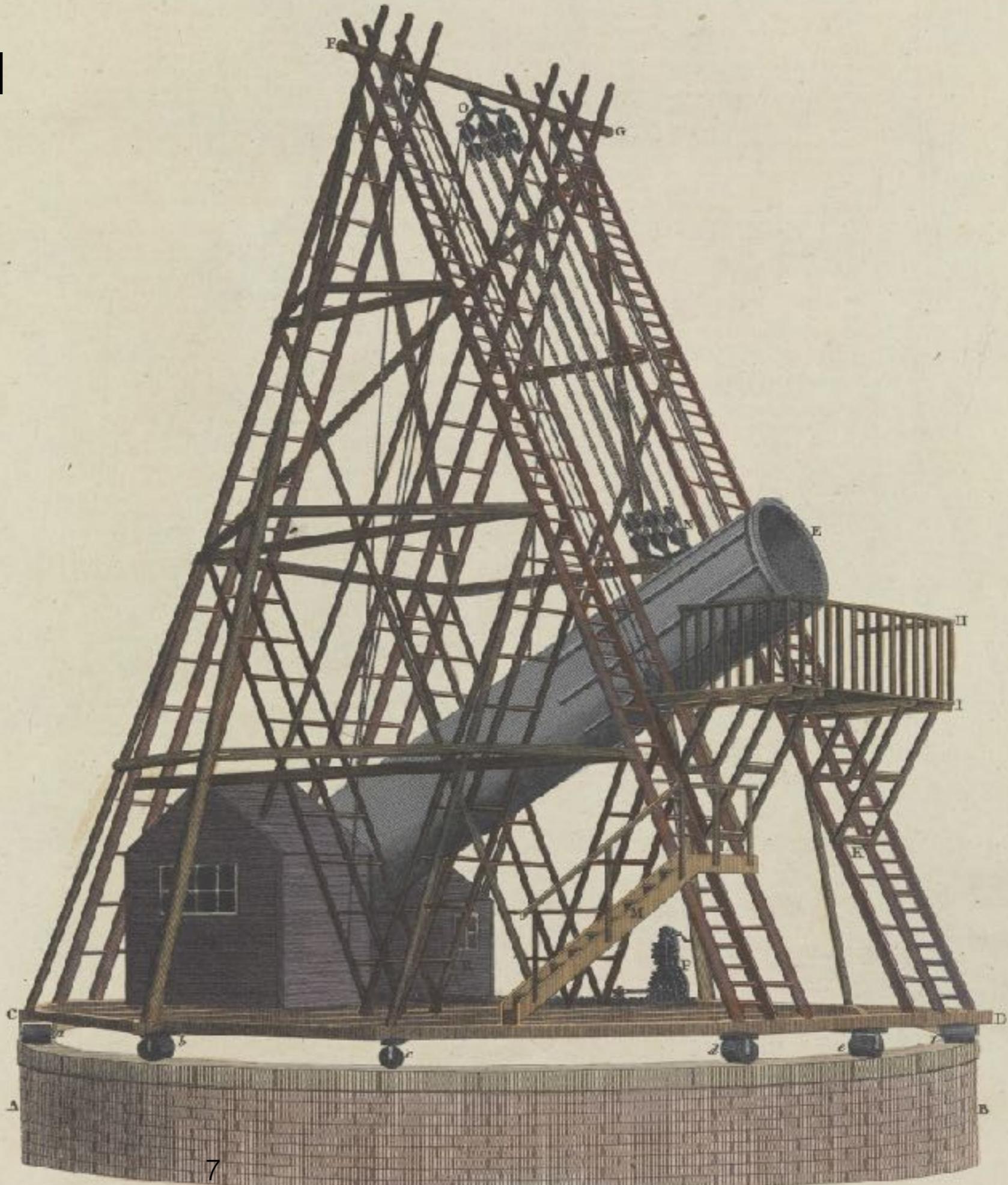


- William Herschel 1738—1822
- Was a German musician who emigrated to England.
- Became fascinated with astronomy and started building his own telescopes.
- 6.2" (16cm) Newtonian Reflector c. 1779
- Discovered Uranus (!) in 1781 (first object not known to the ancients)
- Instantly became famous and was granted a salary from the king.
- Discovered infrared radiation.

# Reflectors: Herschel

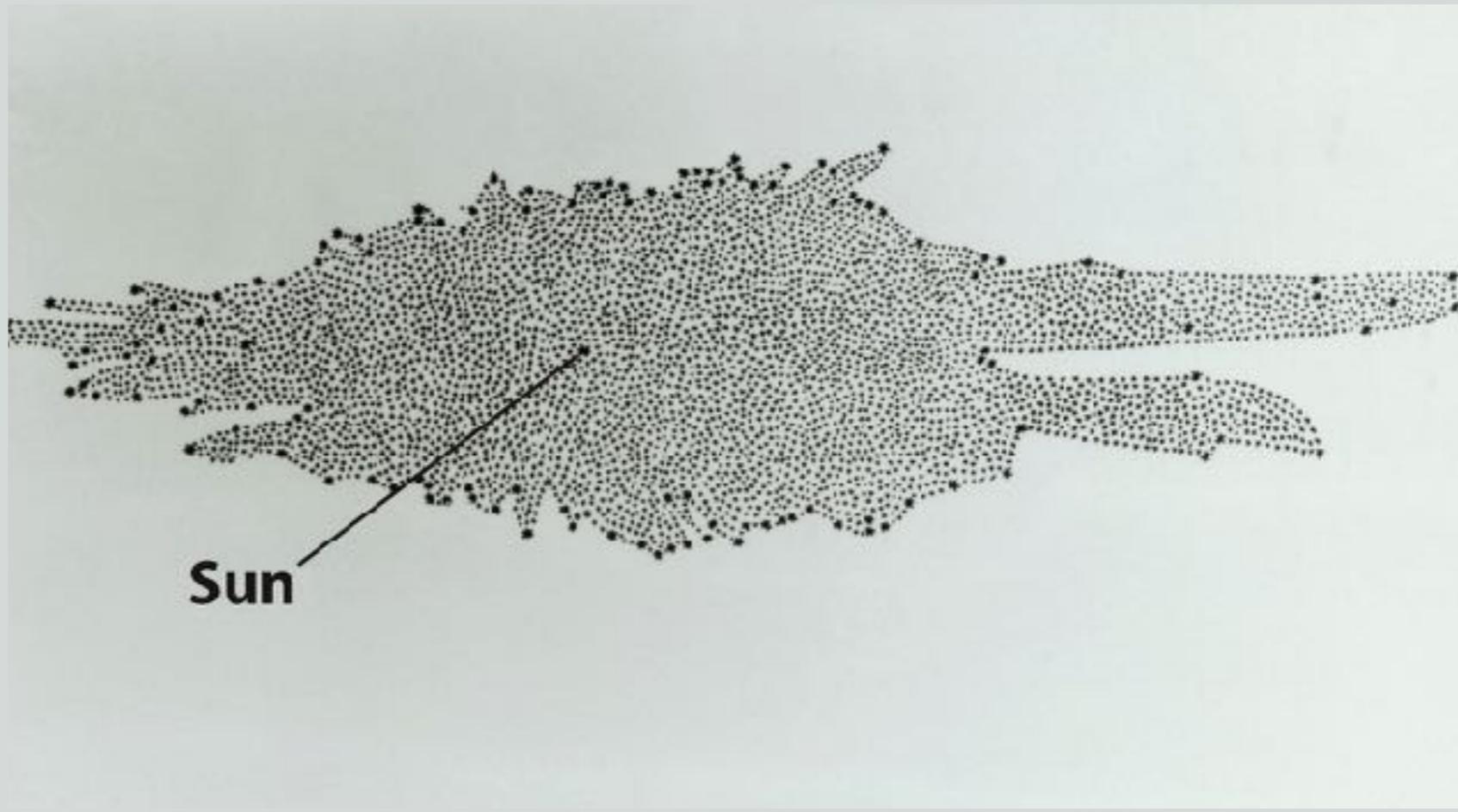


- Herschel's 40-foot telescope  
47-inch diameter (1.2m)  
completed in 1789
- Largest in the world until 1845
- Herschel used to map the  
catalog the density of stars in  
the Milky Way and our place in  
the Universe.
- Proved to be cumbersome  
and unwieldy



# Early attempts to measure the Galaxy came up short

- ▶ From 1783 to 1790 William & Caroline Herschel counted stars in 683 different directions in the sky to measure the Galaxy.
- ▶ Assumed that all stars had the same intrinsic luminosity and, thus, fainter stars were farther away.
- ▶ Concluded that it has a disk shape
  - ▶ ~15,000 light years across
  - ▶ Sun near the center



Herschels' map of the Milky Way (the Sun is approximately in the center)

# Annual parallax

Distance:  $d$

Radius of Earth's orbit:  $a$

$$a = 1.496 \times 10^{11} \text{ m (1 AU)}$$

Parallax angle:  $\theta_{par}$

Use small angle approximation:

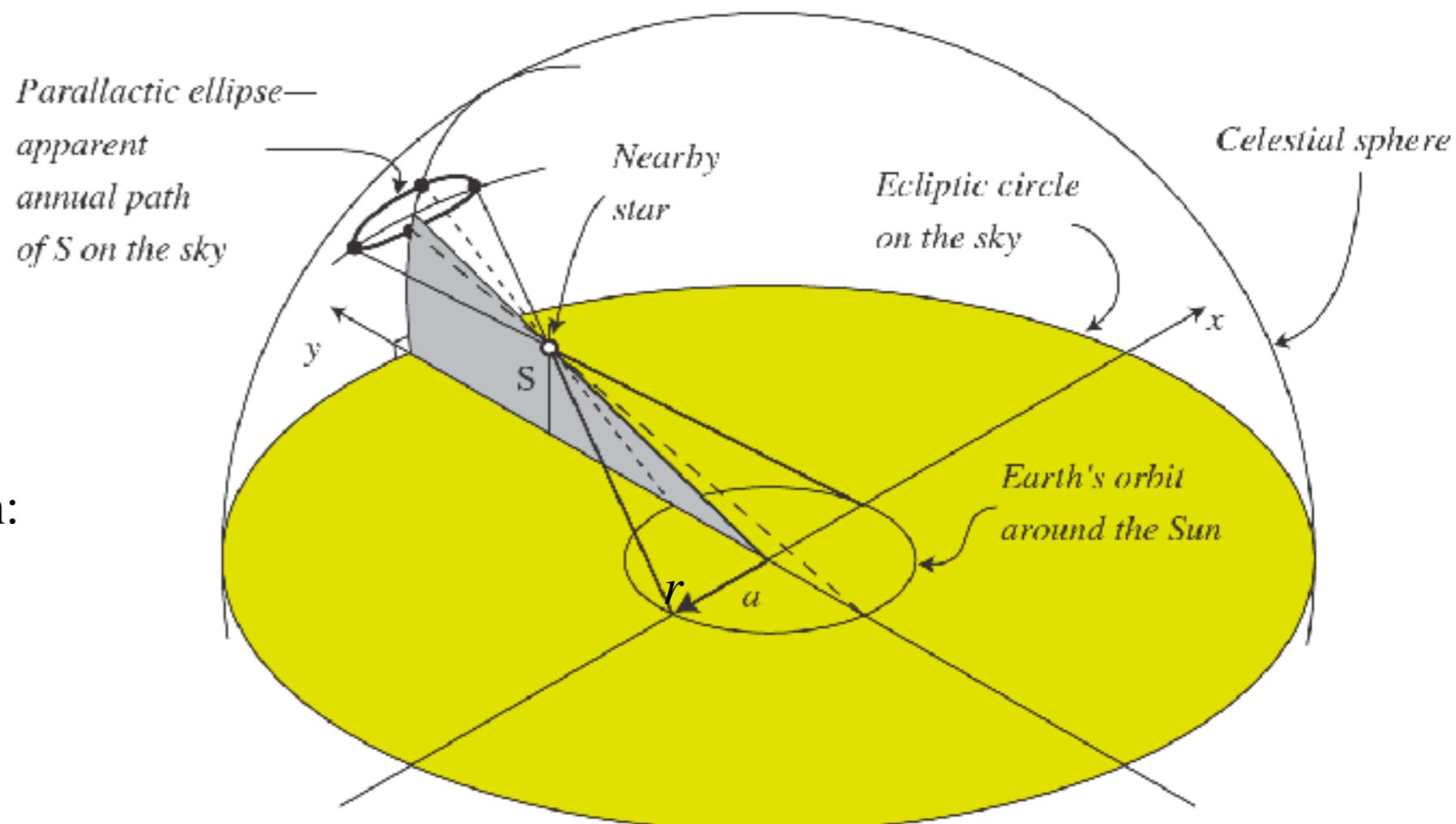
$$\tan \theta_{par} = \frac{a}{d}$$

$$\theta_{par} \approx \frac{a}{d}, \text{ for } \theta_{par} \ll 1 \text{ rad}$$

For  $\theta_{par}$  in arcsec,  $d$  in parsec

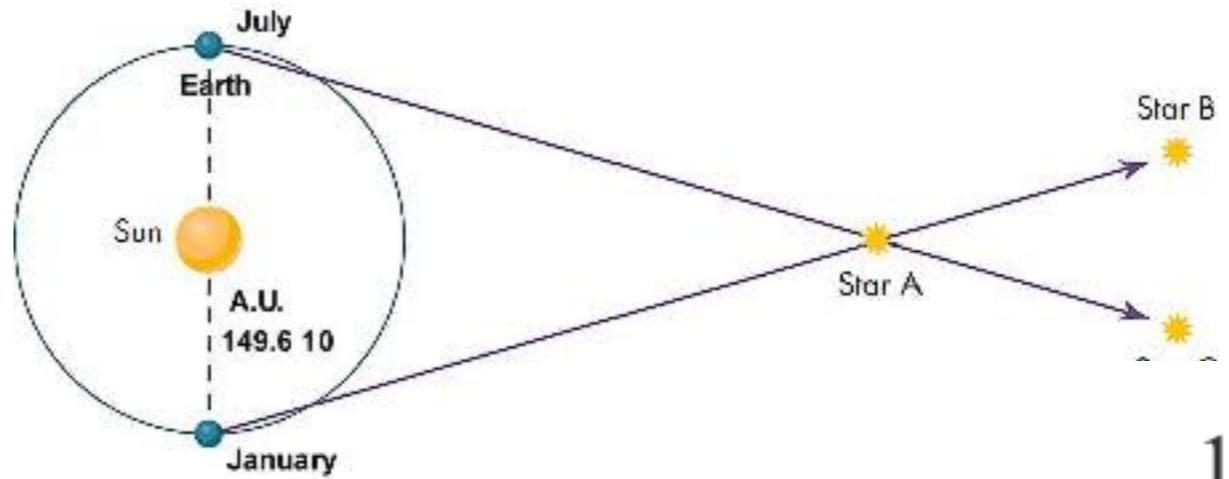
$$(1 \text{ pc} = 206,265 \text{ AU})$$

$$1 \text{ pc} = 3.26 \text{ ly}$$



$$p[\text{arcsec}] = \frac{a[\text{au}]}{r[\text{pc}]} \quad p[\text{arcsec}] = \frac{1}{r[\text{pc}]}$$

# Stellar Parallax



- The angles involved in measuring stellar parallax are very small and thus extraordinarily difficult to measure.
- The nearest star to the Sun (and also the star with the largest parallax), Proxima Centauri, has a parallax of 0.77 arcsec and is 4.25 ly (1.3 pc) away.
- This angle is approximately that subtended by an object 2 centimeters in diameter located 5.3 kilometers away.
- The lack of apparent stellar parallax was part of the evidence against the Copernican model.
- For centuries astronomers tried (and failed) to measure parallax, but still succeeded in setting lower limits and even demonstrating conclusively that the Earth was moving around the Sun.
- Eventually, in 1843, Bessel and Struve independently measured the distance to 61 Cygni (0.3", 3.5ly) and Vega (0.13", 7.7pc). Each used instruments designed and built by Fraunhofer.

$$p[\text{arcsec}] = \frac{1}{r[\text{pc}]}$$

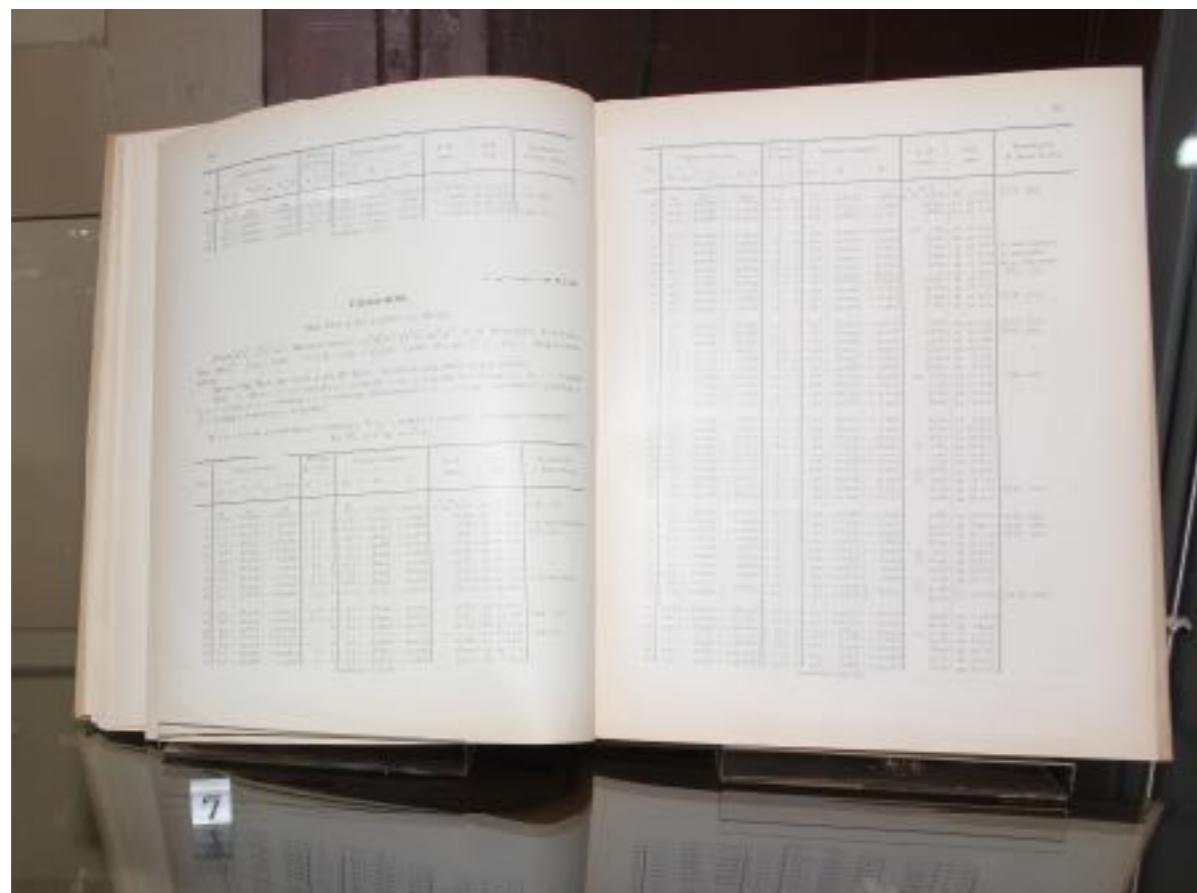
$$1 \text{ pc} = 3.26 \text{ ly}$$



# Carte du Ciel

## “Map of the Sky”

- Initiated in 1887 by Paris Observatory director Amedee Mouchez
- entire sky mapped to 11th magnitude
- map the positions of millions of stars
- 20 observatories agreed to participate
- 22,000 photographic plates
- First step, typically ~6 min exposures, to 11.5 mag
- second step, 3x20 min exposures, to 14 mag
- continues to ~1940

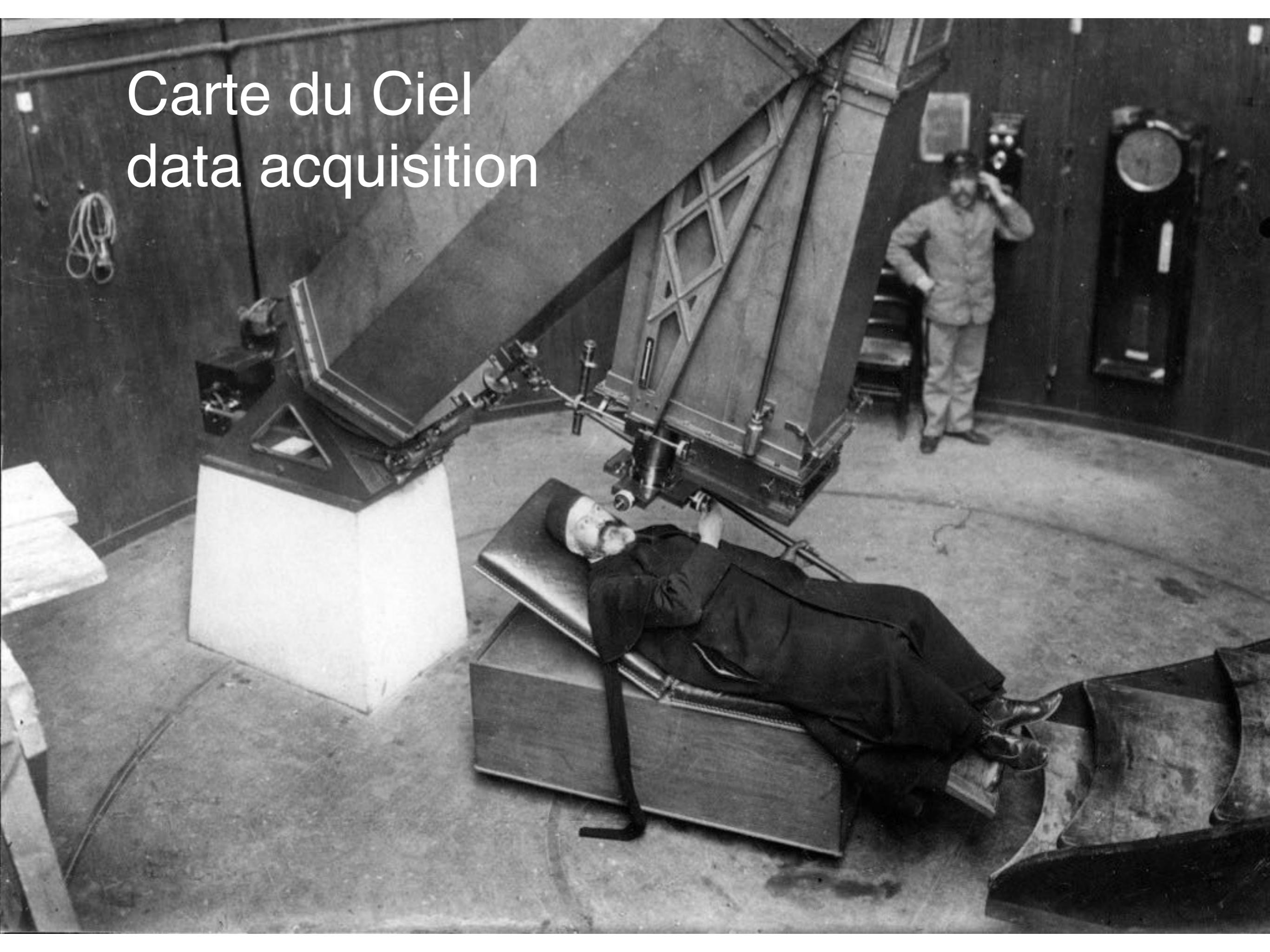


data acquisition

Participating observatories and stars measured in the context of the Astrographic Catalogue<sup>[1]</sup>

Observatory (Zone)	Declination From	Declination To	Epoch	No. of stars
Greenwich	+90°	+85°	1892–1905	179,000
Vatican	+84°	+55°	1895–1922	256,000
Catania	+54°	+47°	1894–1932	163,000
Helsingfors	+46°	+40°	1892–1910	159,000
Potsdam	+39°	+32°	1893–1900	108,000
Hyderabad north	+39°	+36°	1928–1938	149,000
Licde	+35°	+34°	1939–1960	117,000
Oxford 2	+33°	+32°	1930–1936	117,000
Oxford 1	+31°	+25°	1892–1910	277,000
Paris	+24°	+18°	1891–1927	253,000
Bordeaux	+17°	+11°	1893–1926	224,000
Toulouse	+10°	+05°	1893–1905	270,000
Algiers	+04°	-02°	1891–1911	200,000
San Fernando	-03°	-09°	1891–1917	225,000
Tacubaya	-10°	-16°	1900–1938	312,000
Hyderabad south	-17°	-23°	1914–1929	293,000
Córdoba	-24°	-31°	1909–1914	309,000
Perth	-32°	-37°	1902–1919	229,000
Perth/Edinburgh	-38°	-40°	1903–1914	139,000
Cape Town	-41°	-51°	1897–1912	540,000
Sydney	-52°	-64°	1892–1948	430,000
Melbourne	-65°	-90°	1892–1940	218,000

# Carte du Ciel data acquisition



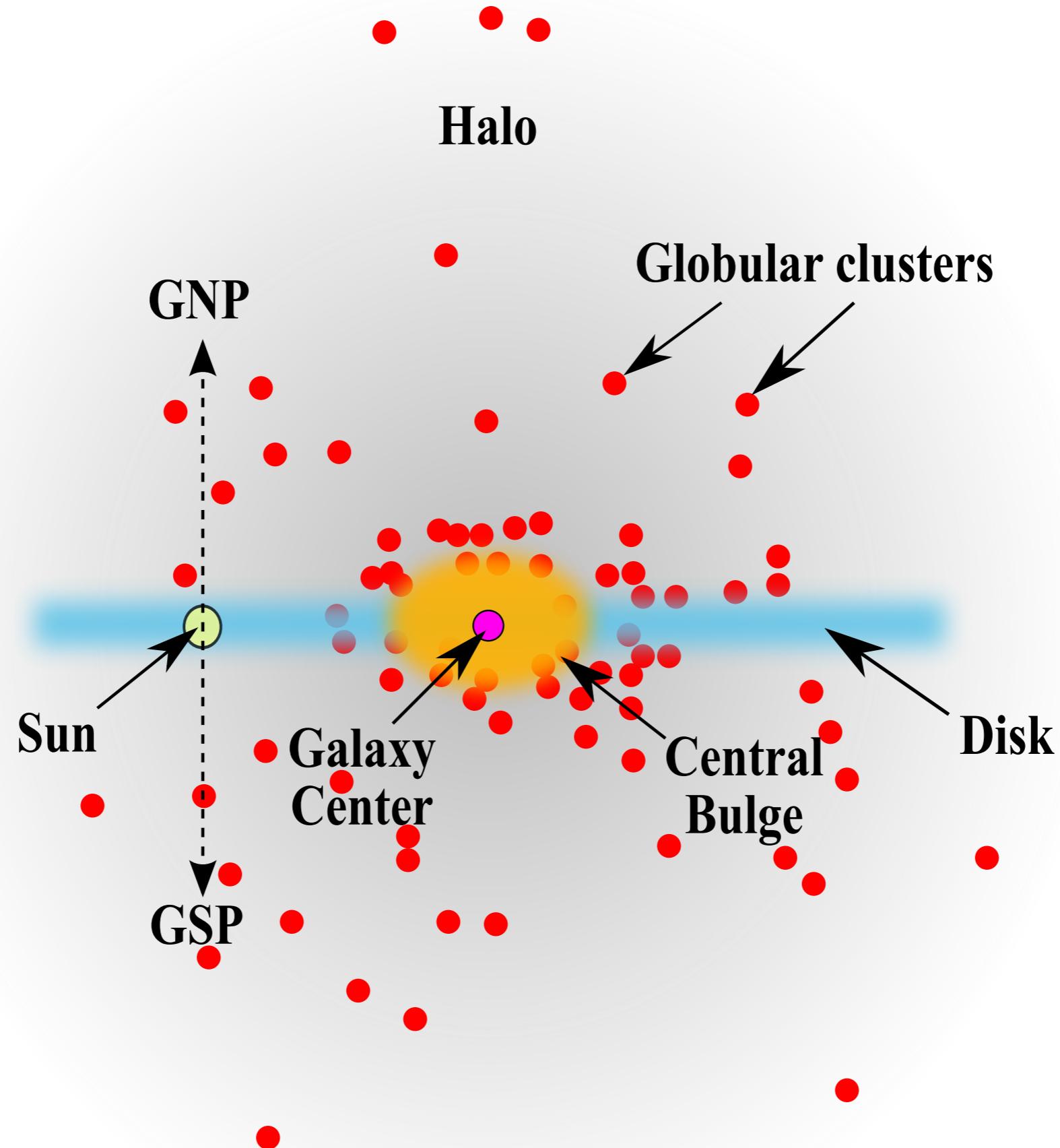
# data reduction



# Harlow Shapley

- Henrietta Swan Leavitt discovered the luminosity-period relation of Cepheid variable stars at Harvard in 1912.
- Harlow Shapley received his PhD from Princeton in 1914 working with Henry Norris Russell on understanding Cepheid variable stars and showing that they weren't binary star systems (spectroscopy!).
- He then went to work at the Mt. Wilson Observatory on the Hale 60-inch reflector — then the largest, most powerful reflector in the world.
- In 1915 he measured the distance to a single Cepheid variable star using parallax, and was thus able to calibrate their distance scale.
- Next, he started using Cepheid variable stars to measure the distances to globular clusters.
- In 1918 he measured the size of the Milky Way, increasing the size of the known Universe by x10, and showed that the Sun was *not* at the center of the Universe.
- Shapley became famous and became the director of the Harvard Observatory in 1921,





# Historical Development

- 1608: patent application by Hans Lippershey (c1570-1619), a German-born Dutch citizen, of a device with a convex and a concave lens in a tube with a magnification of about 3 times.
- 1609: Galileo Galilei (1564-1642) made his own version of the telescope and increased the magnification to 8 and 20 times.
- From the early Galilean telescope of 1.52-1.83 m (5 - 6 ft) in length, astronomical telescopes attained lengths of 4.57-6.10 m (15 - 20 ft) by the middle of the 17th century.
- 1656: Christiaan Huygens (1629-1695) made a telescope 7 meters (23 ft) long; its objective lens had an aperture of about 10 cm (~4 inches), it magnified about 100 times, and its field of view was 17 arc-minutes.
- 1672: Sir Isaac Newton showed that white light is a mixture of colored light and that every color has its own degree of refraction.
- Consequently, any curved lens will decompose white light into the colors of the spectrum, each of which will come to a focus at a different point on the optical axis. This effect, which became known as **chromatic aberration**, causes the image of a star to be surrounded by circles of different colors.
- Thus lenses had limitations for astronomy, but telescopes with long focal lengths helped to reduce these effects.

# Basic principles of optical systems

- **Geometrical optics:**

- Treats electromagnetic radiation as light rays ( $\lambda \ll$  size of optical elements)
  - Allows ray tracing analysis

- **Optical axis:**

- Line through centered optical elements.

- **Geometrical path:**

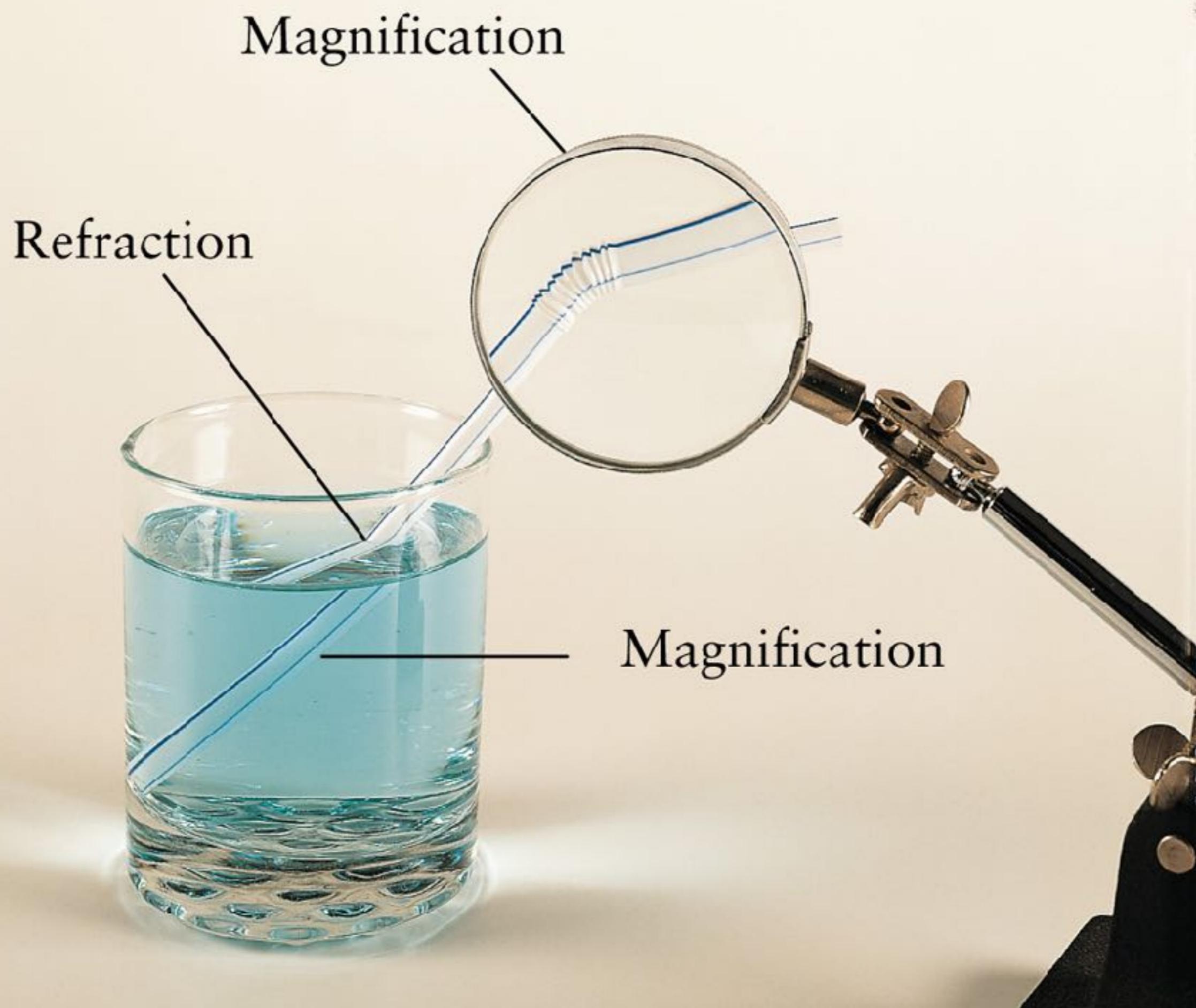
- The actual physical distance traveled by a light ray on path  $s$ .

- **Optical path:**

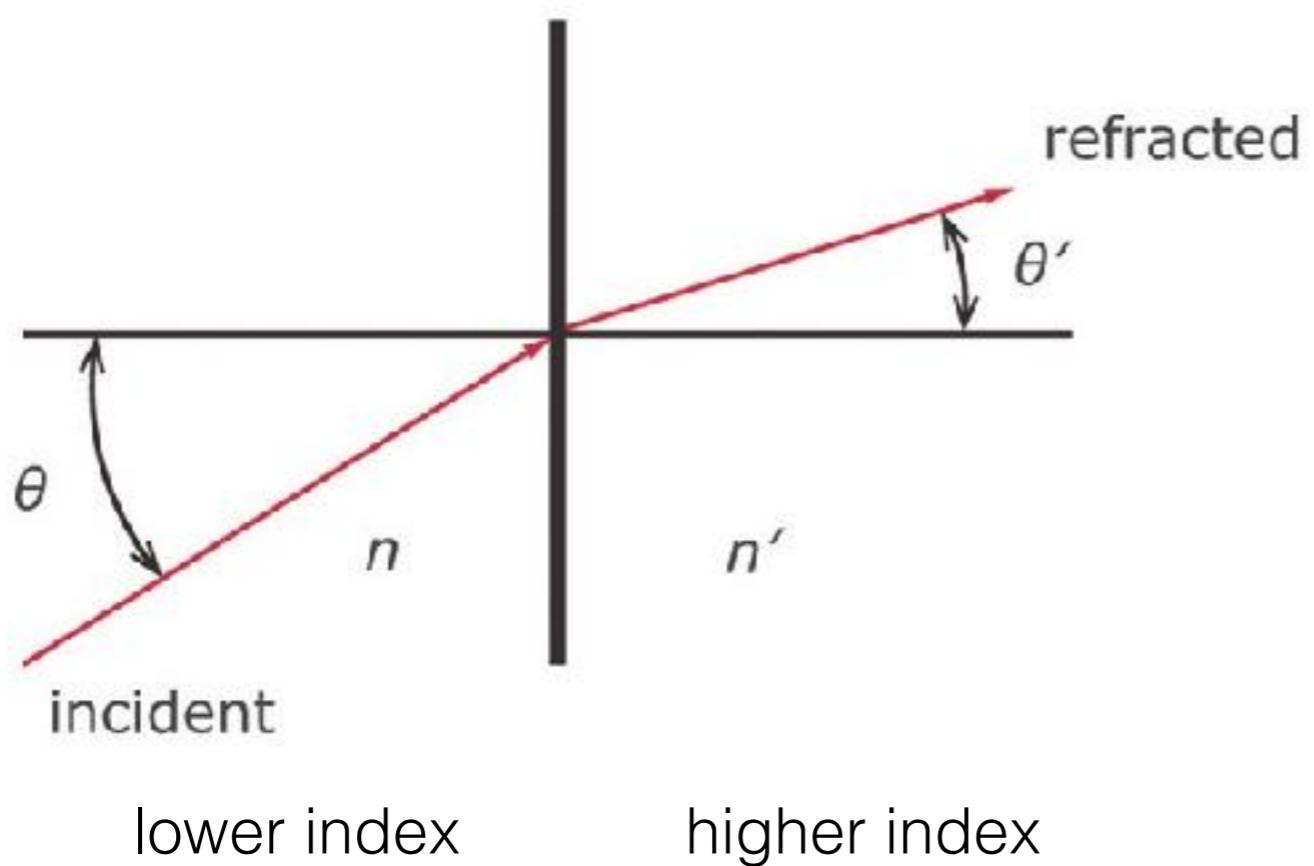
- The geometrical path multiplied by the local refractive index  $n$ :

$$\int_a^b n(s) ds$$

- **A focusing system: the paths of the rays from a point on an object to its matching image point all have the same optical path length.**



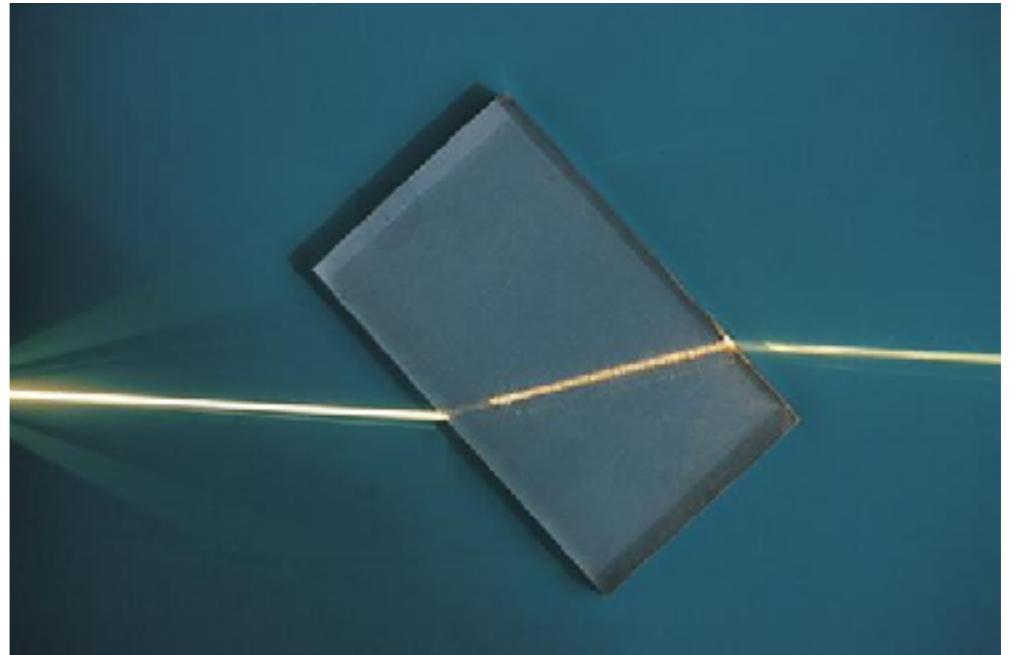
# Refraction and Snell's law



$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

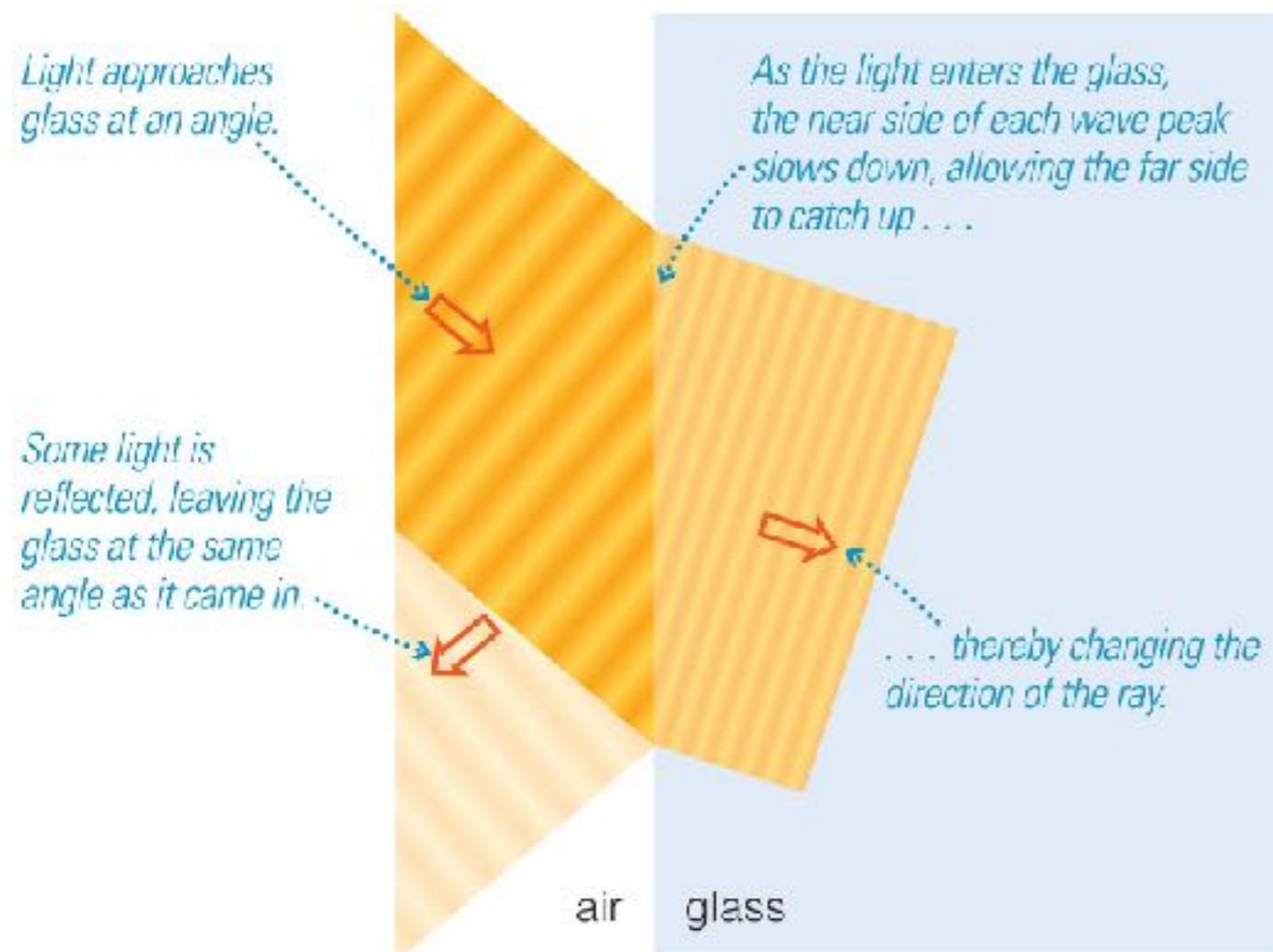
condition for total internal reflection:

$$\theta_C = \sin^{-1} \left( \frac{n_1}{n_2} \right)$$



# Refraction

Material	$n (\lambda = 588 \text{ nm})$	$d n / d \lambda (\mu\text{m}^{-1})$	$\nu_D$
Air (STP)	1.00029	$2 \times 10^{-5}$	85
Water	1.33	0.017	114
Calcium fluoride	1.435	0.027	95
Fused quartz	1.458	0.040	68
Borosilicate crown glass (BK7)	1.517	0.047	64
Flint glass (F2)	1.620	0.100	36
Dense flint glass (SF4)	1.756	0.161	28
Diamond	2.42	0.250	33



index of refraction used for Fresnel's equations and Snell's law

$$n(\lambda) = \frac{c}{v(\lambda)}$$

dielectric constant and relative permittivity used for Maxwell's equations:

$$n = \sqrt{\epsilon}$$

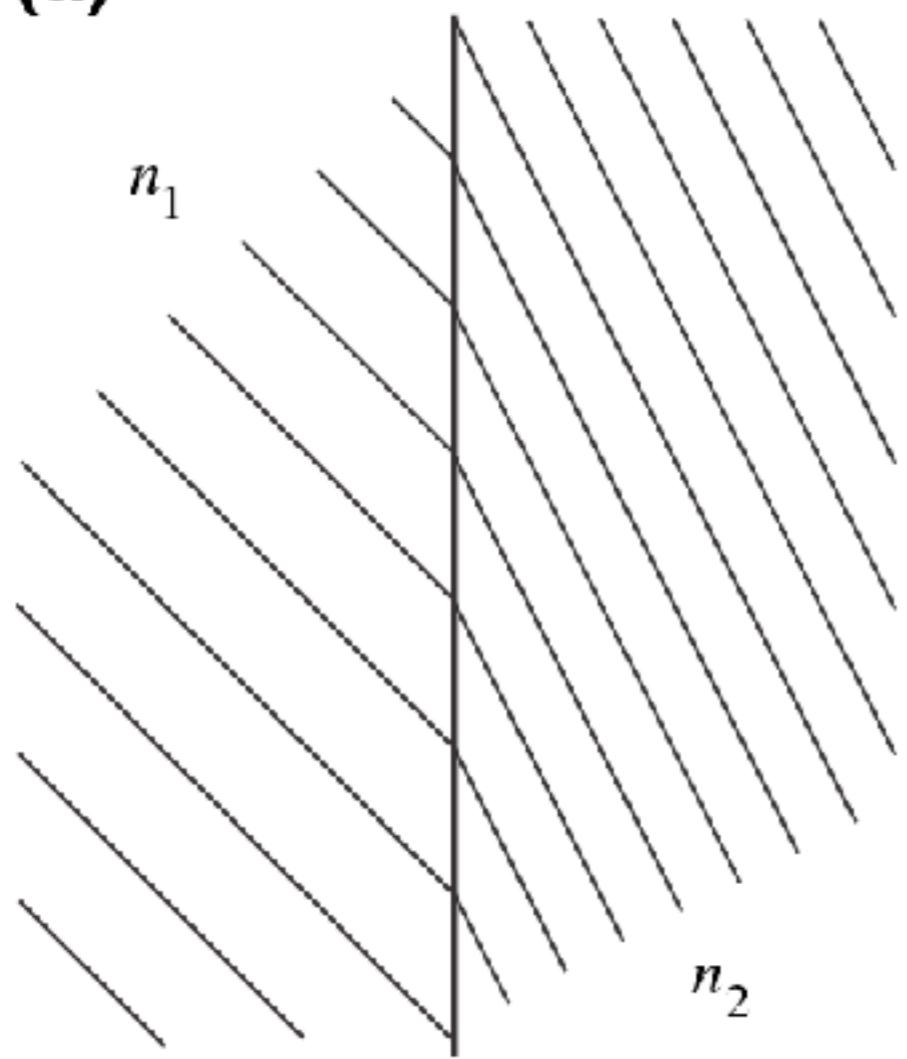


# Fresnel's Equations

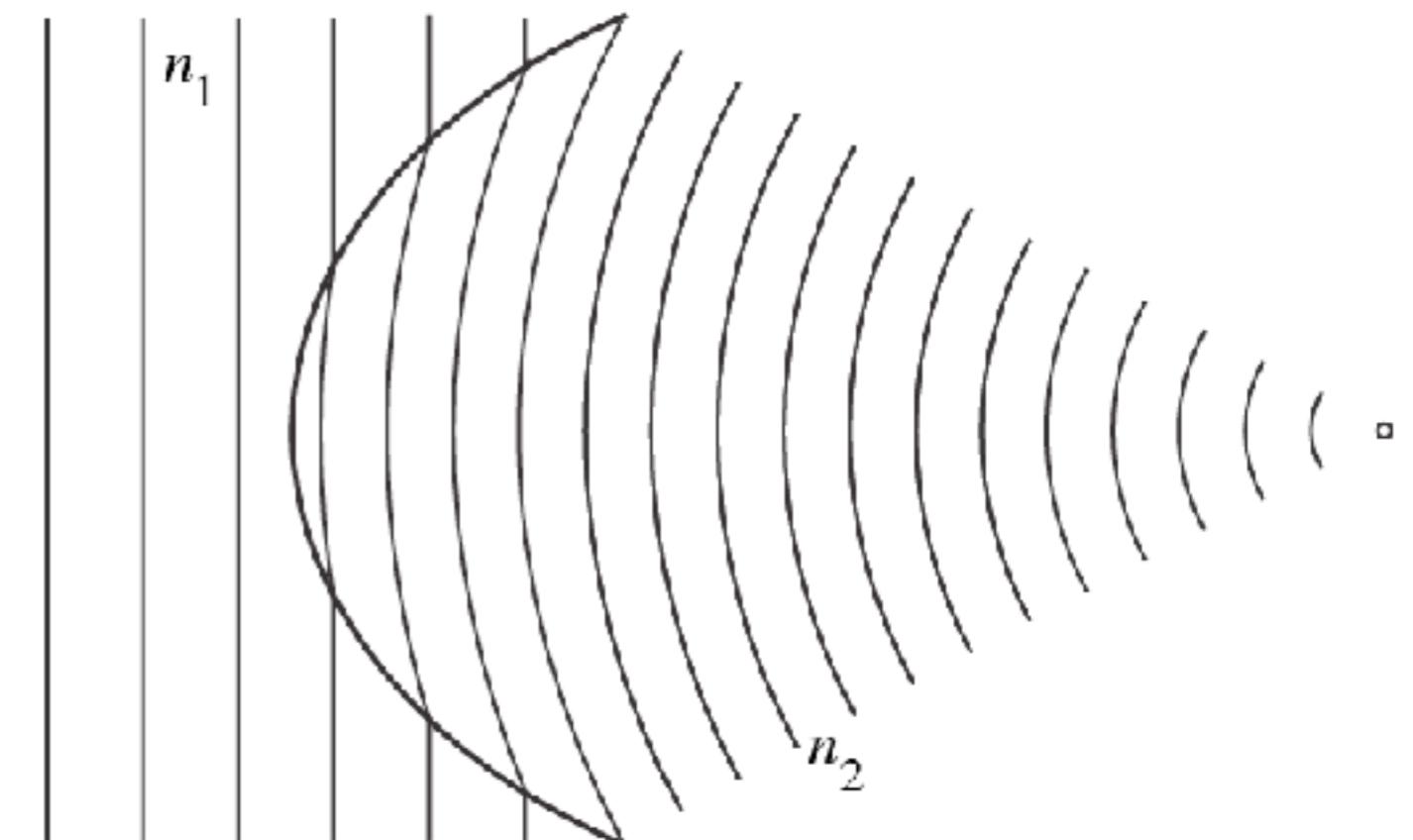
Reflection from a surface

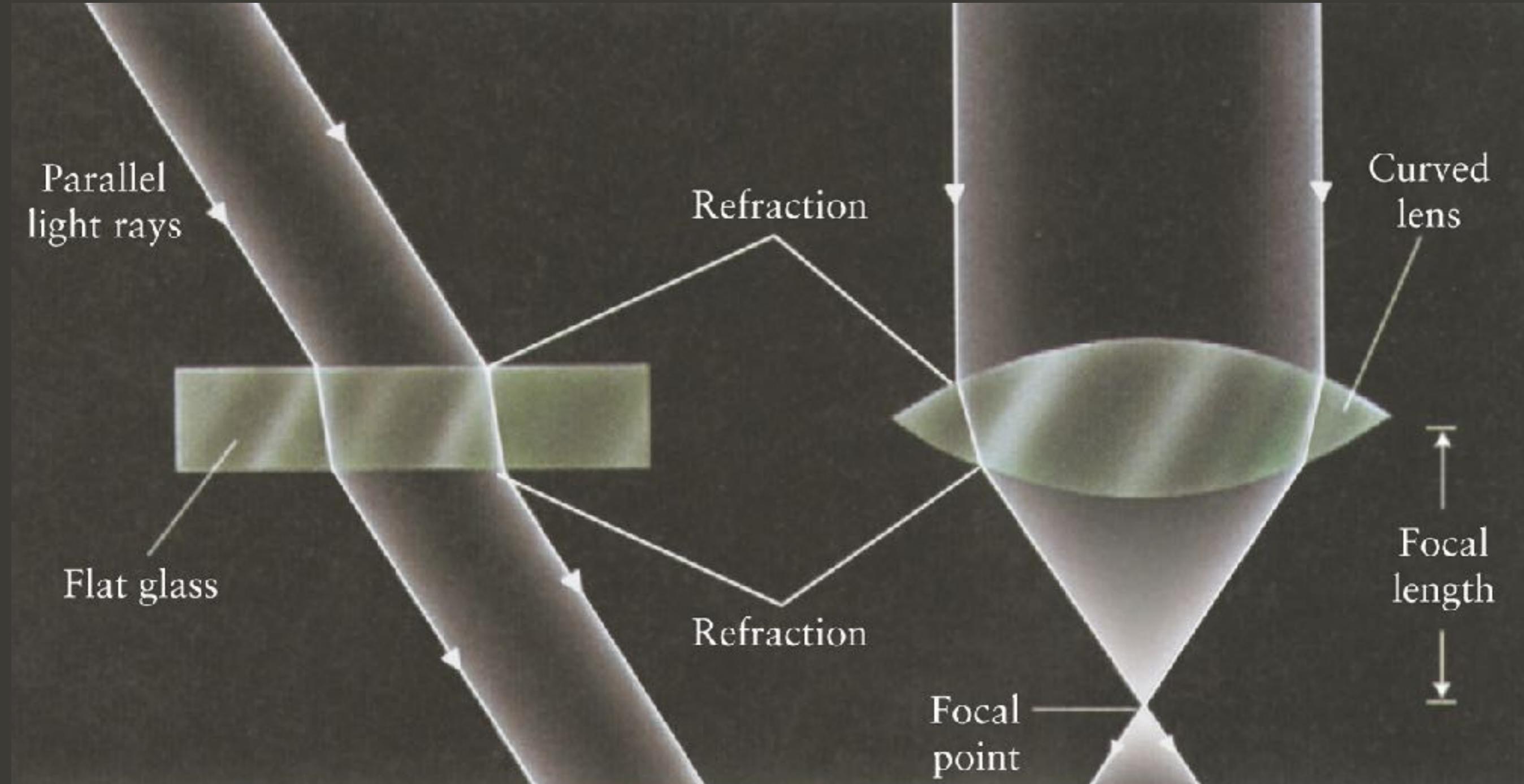
$$R = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2$$

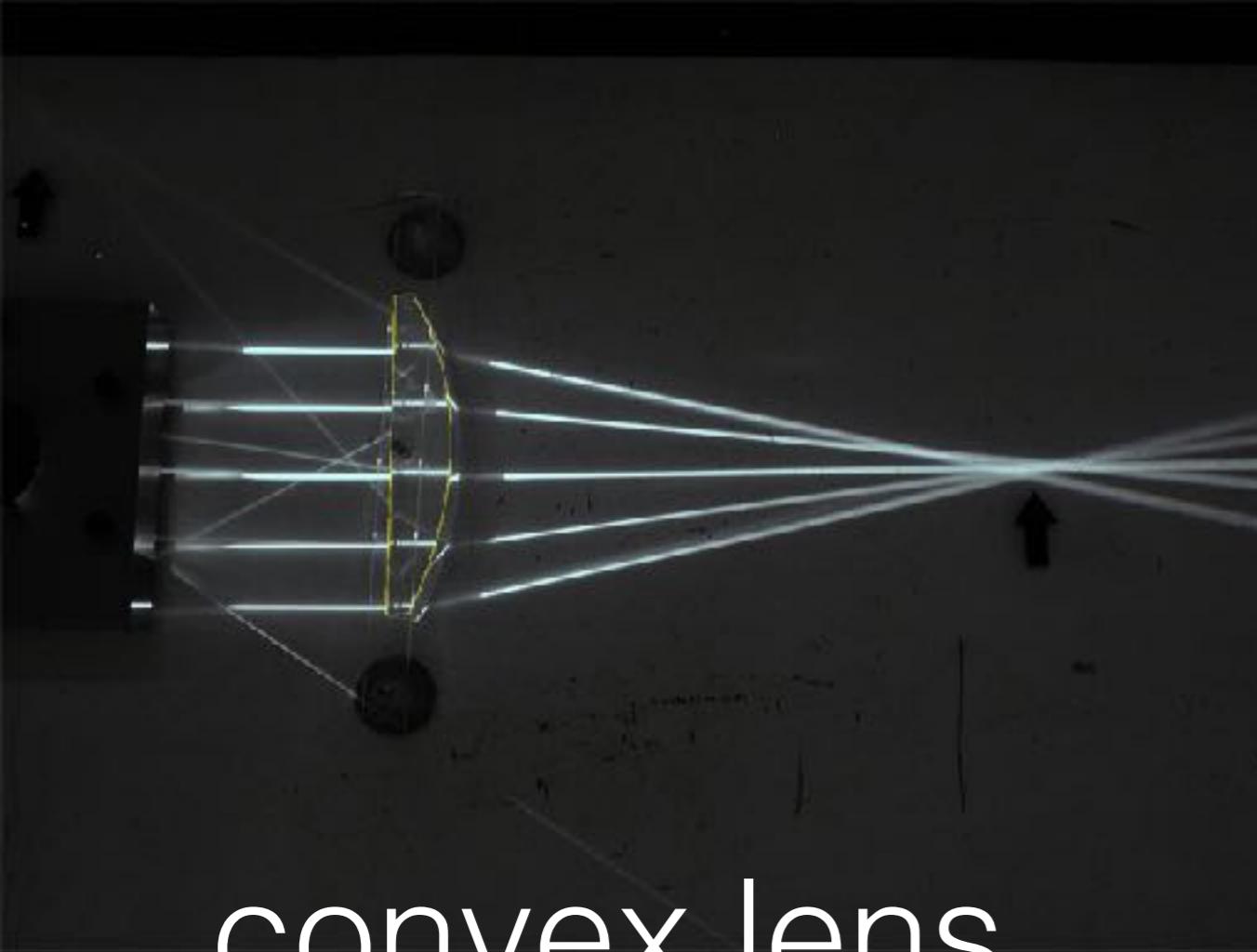
**(a)**



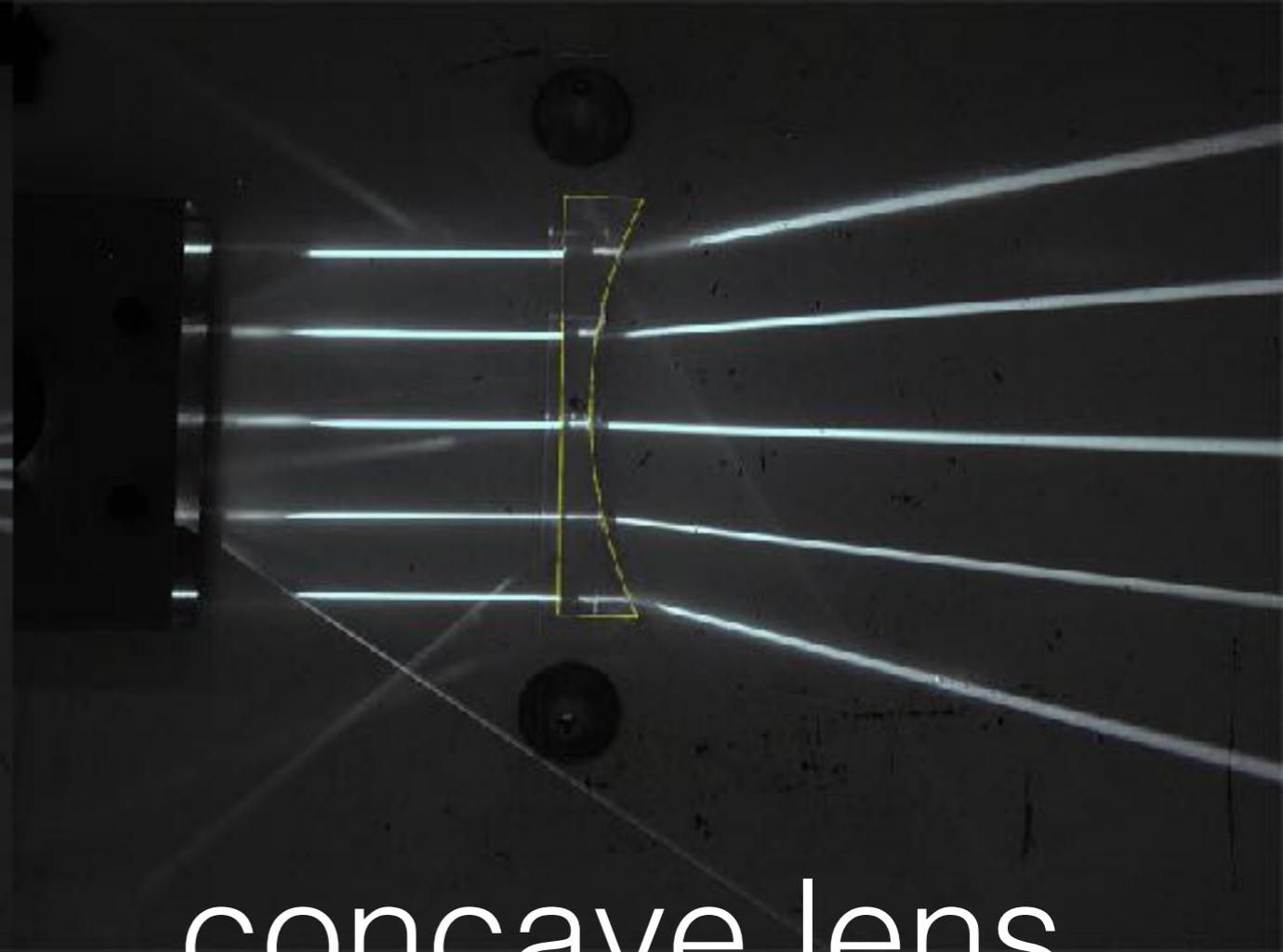
**(b)**





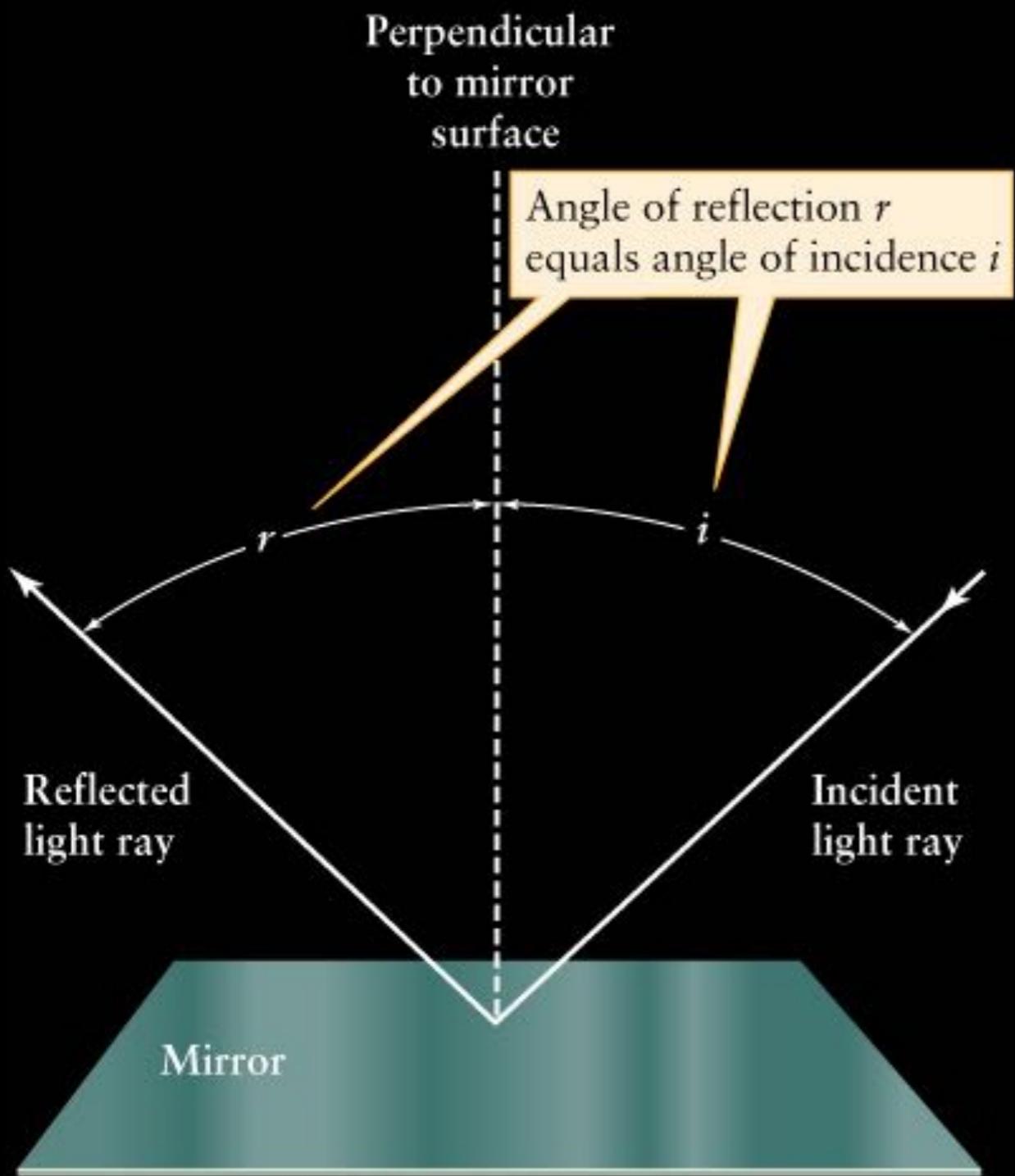


convex lens

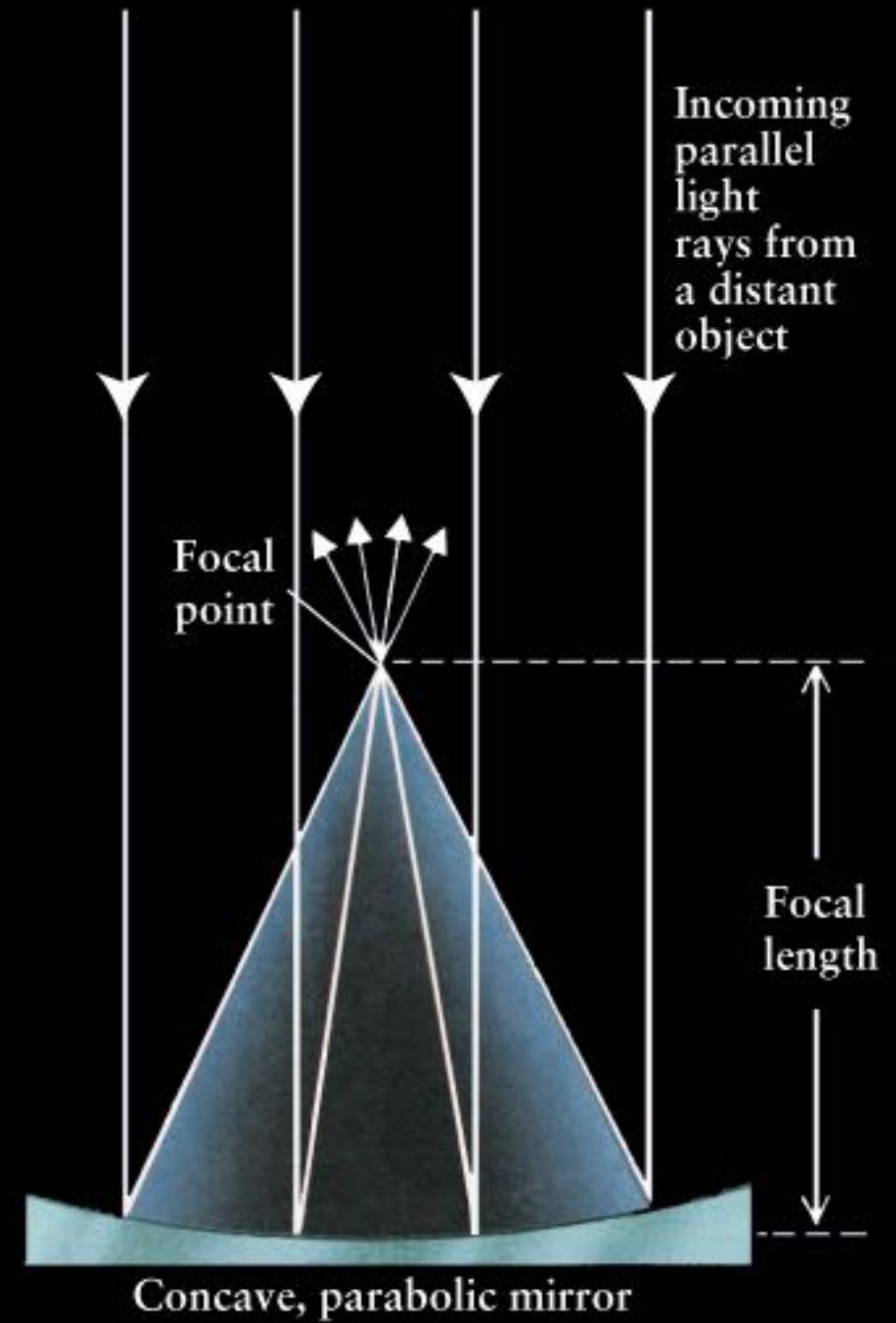


concave lens

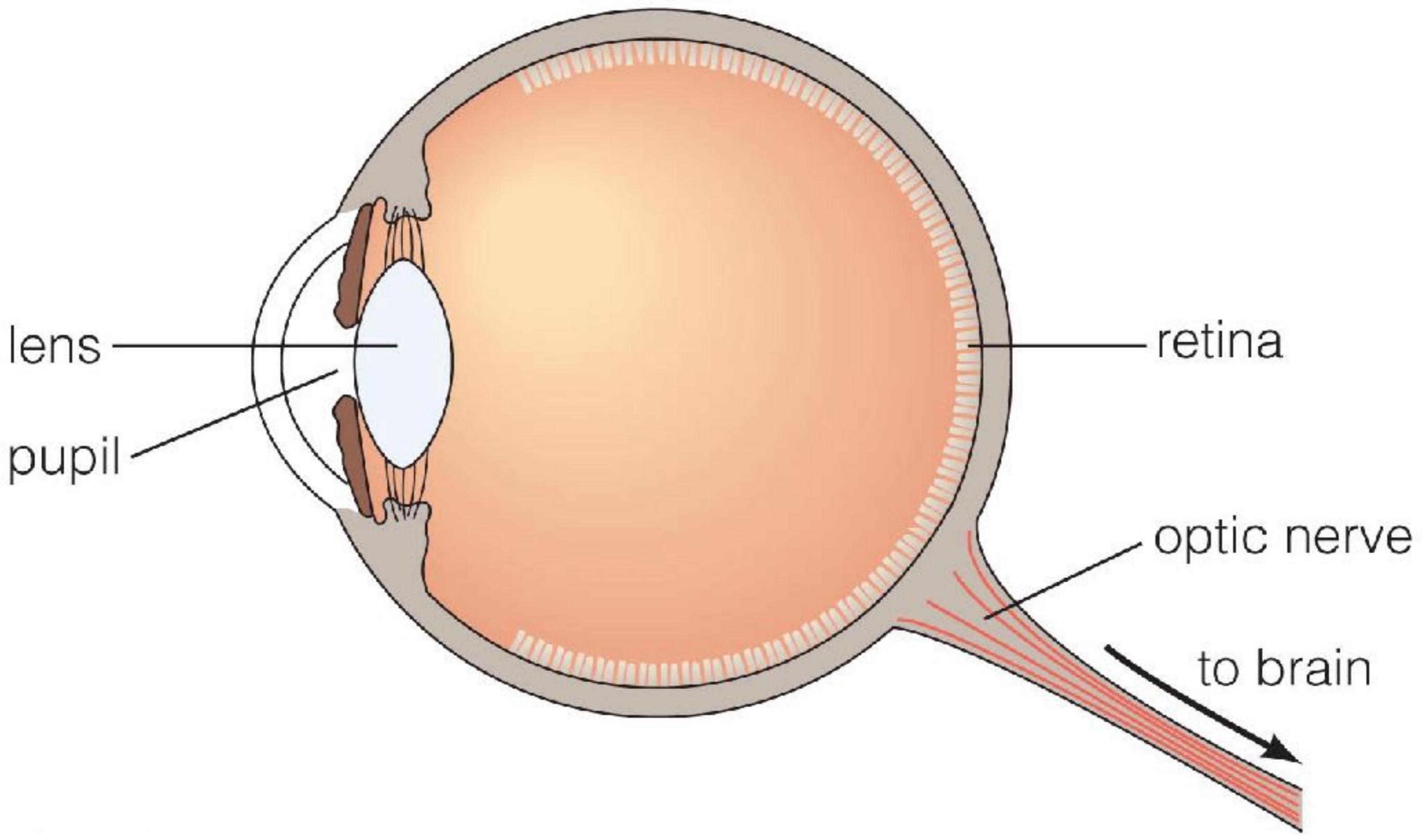
# mirrors

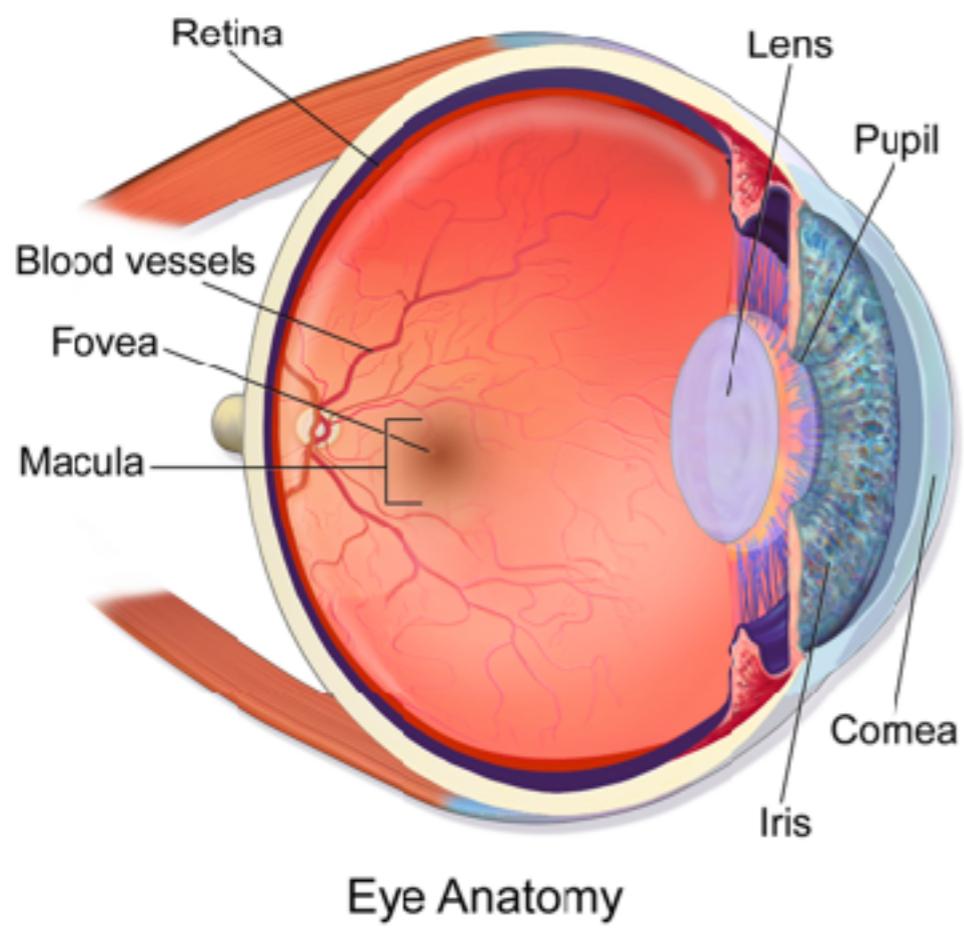


Reflection off of a flat surface

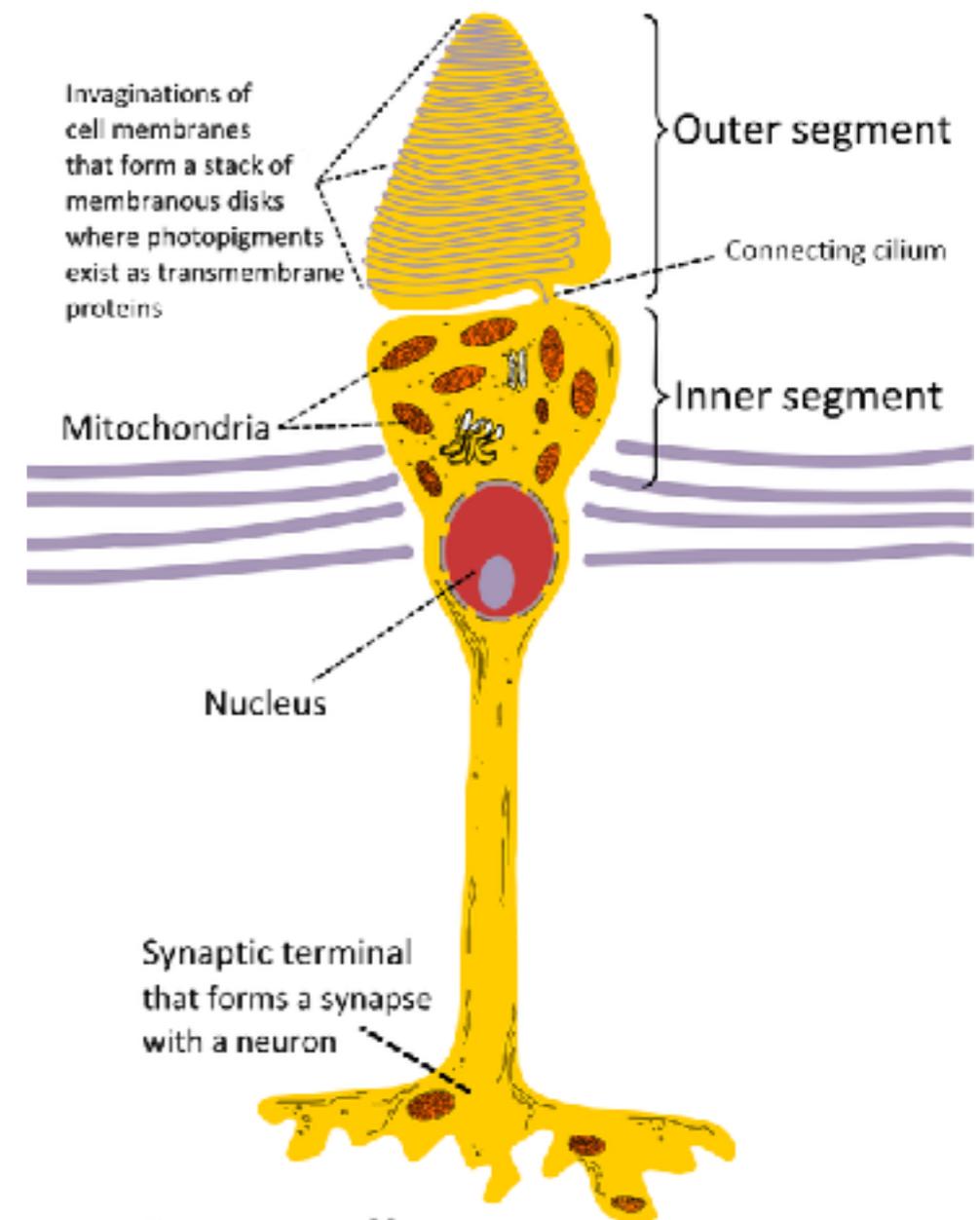


Reflection off of a curved surface

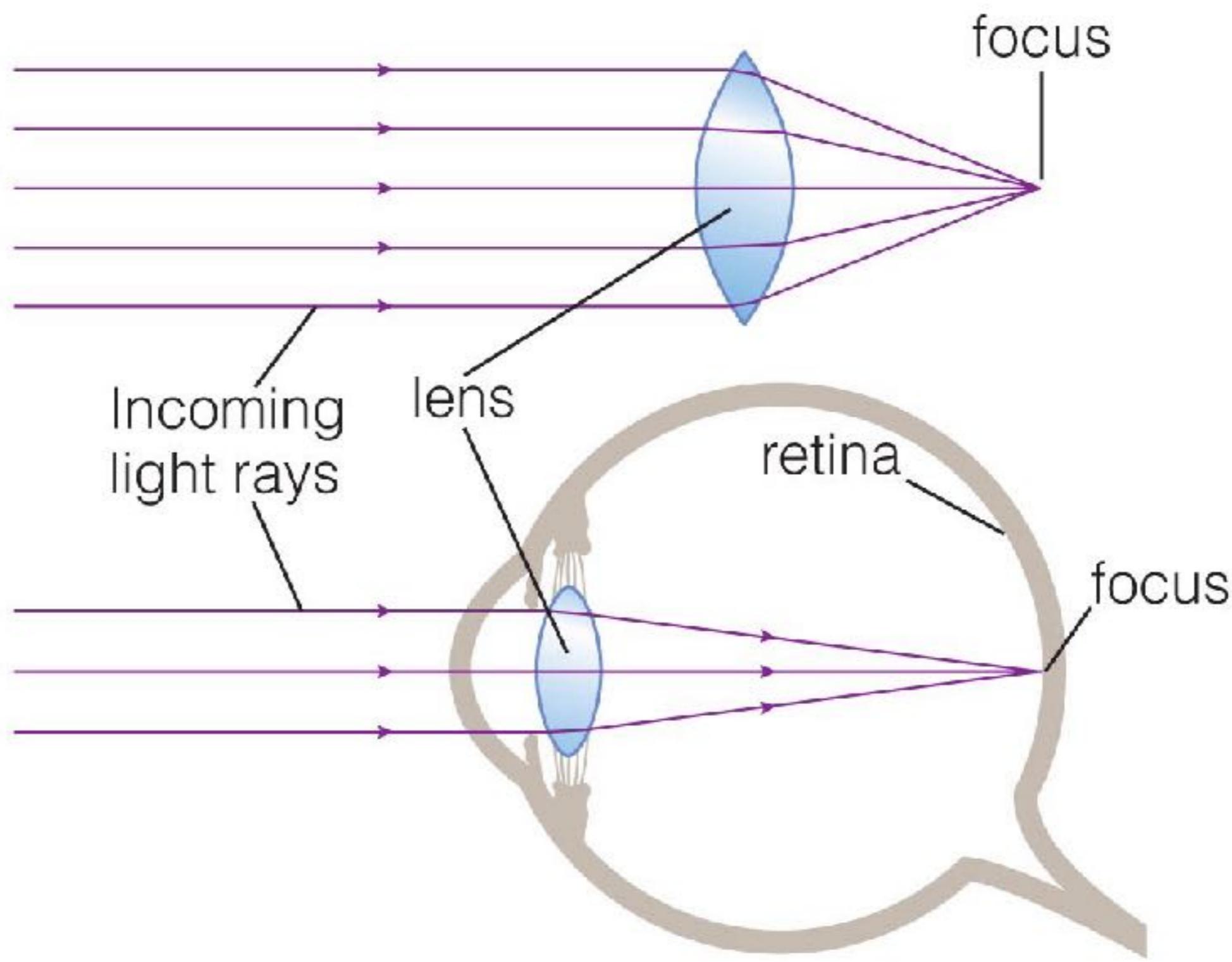


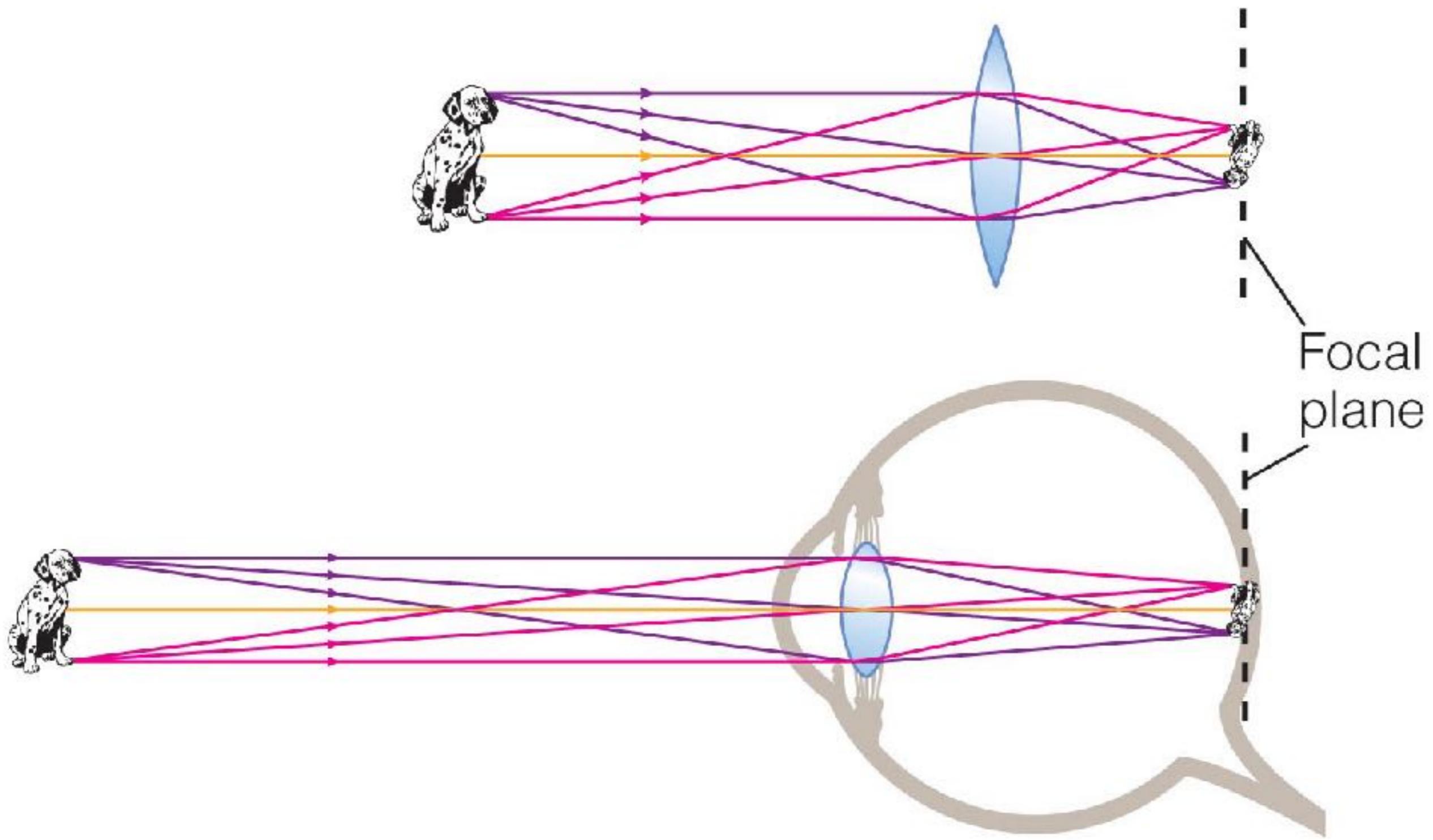


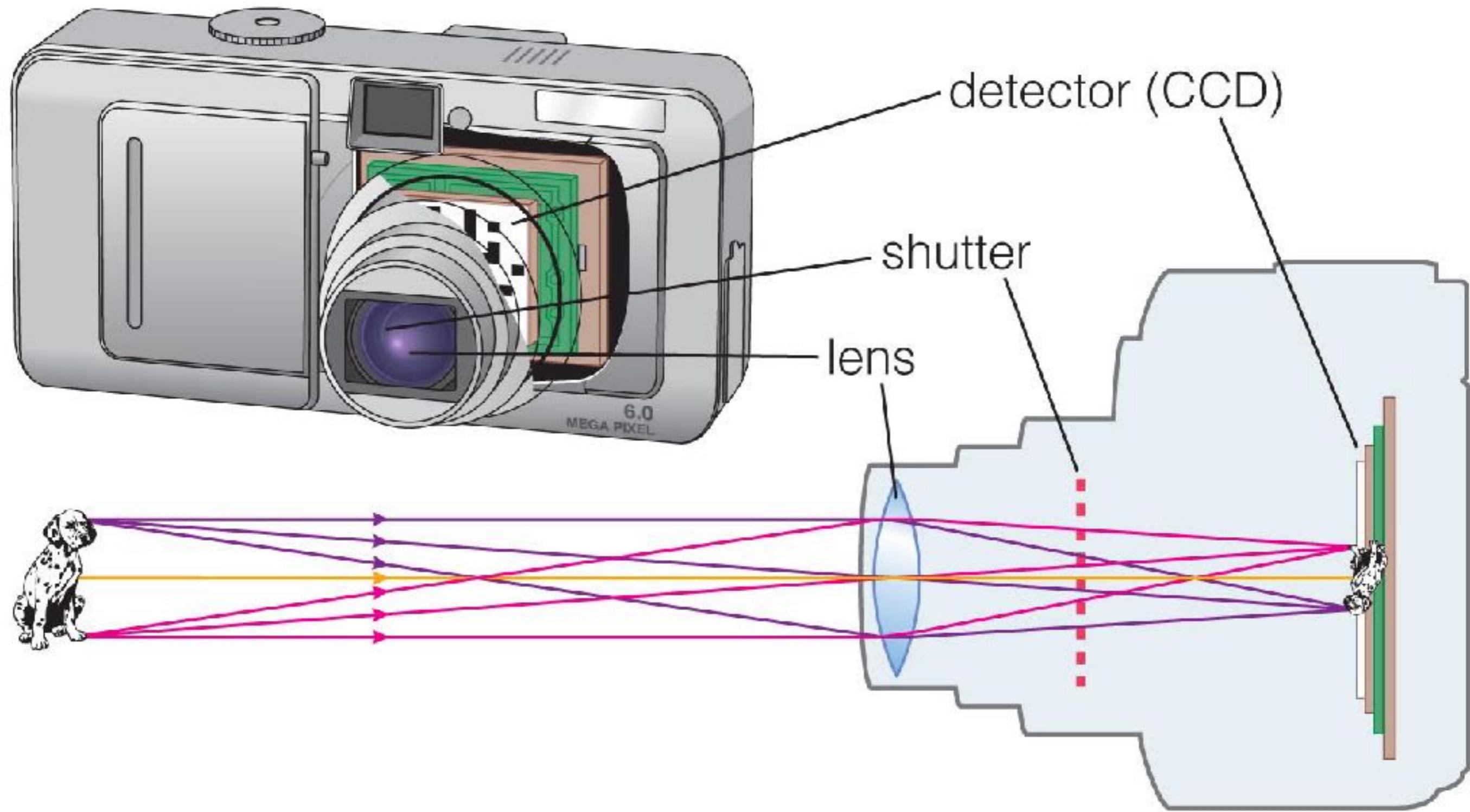
# Human Eye



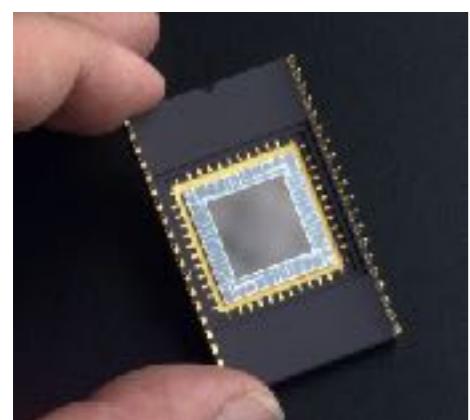
**Cone cell**





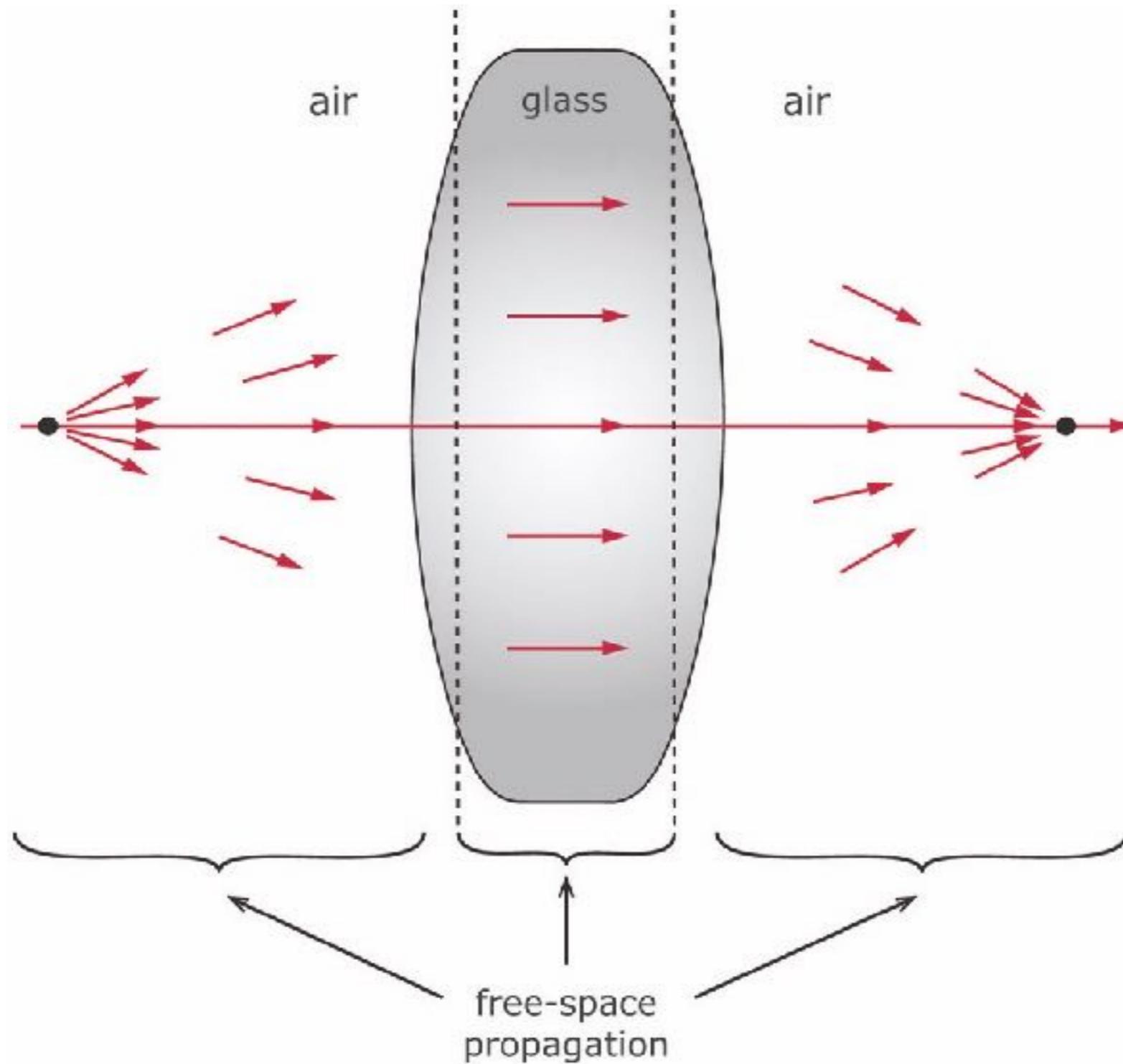


# Optical Detector Comparison

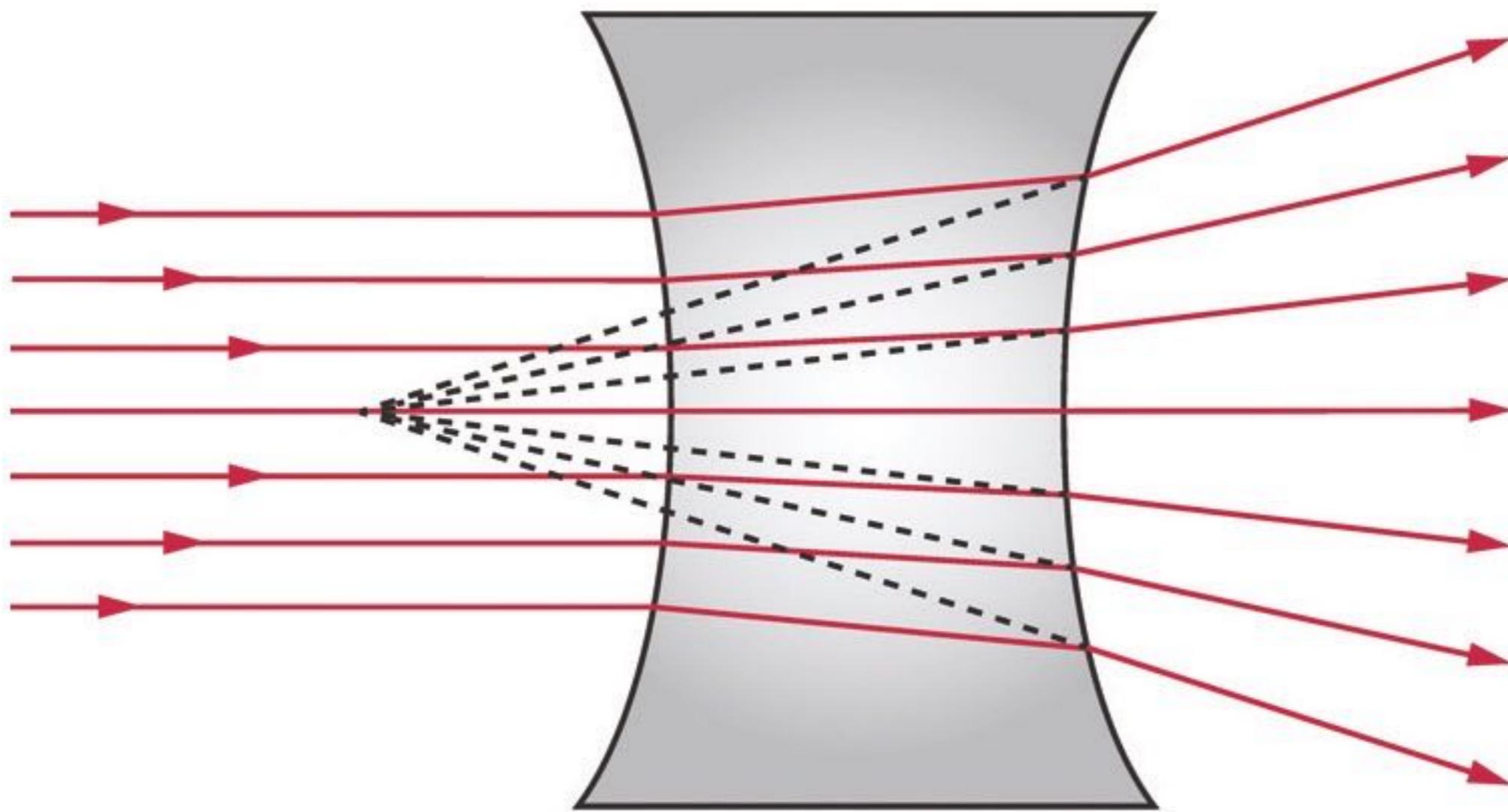


Detector	physical size	resolution elements	QE	Integrate?	Readout time	linear?	precision
Human Eye	12 mm x 12 mm	1M	6%	no	instant	no	2%
Photograph	356 mm x 356 mm	1.3G	3%	yes	fast	no	8%
CCD	61 mm x 61 mm	16M	70%	yes	slow	yes	0.05%

BUT ... can build a mosaic array of CCDs ...



The operation of a simple lens.  
It operates by using a transparent material with an index of refraction greater than the surrounding air.



A negative lens with concave surfaces forms a virtual image  
— it looks like light is coming from a point but it is not

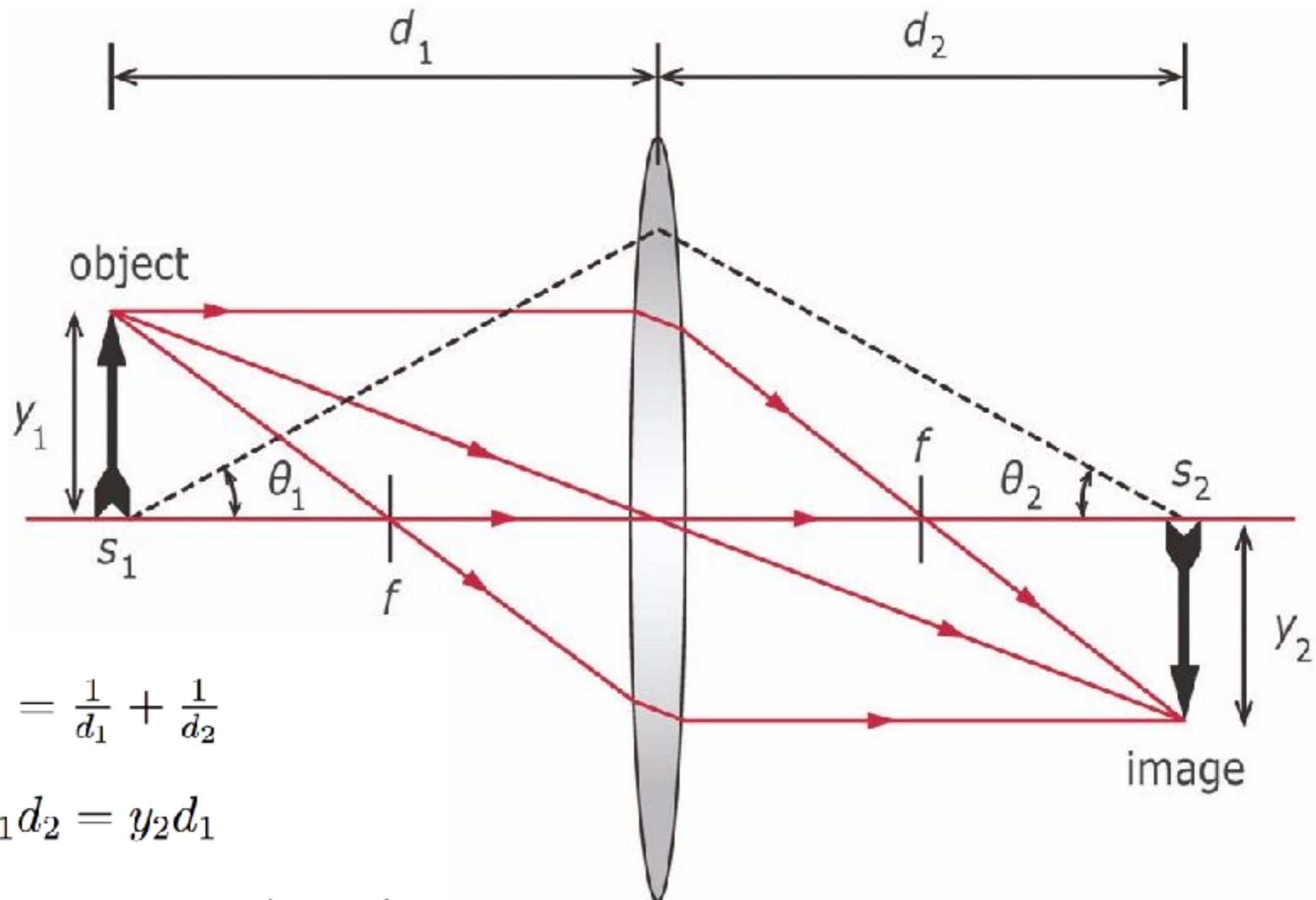
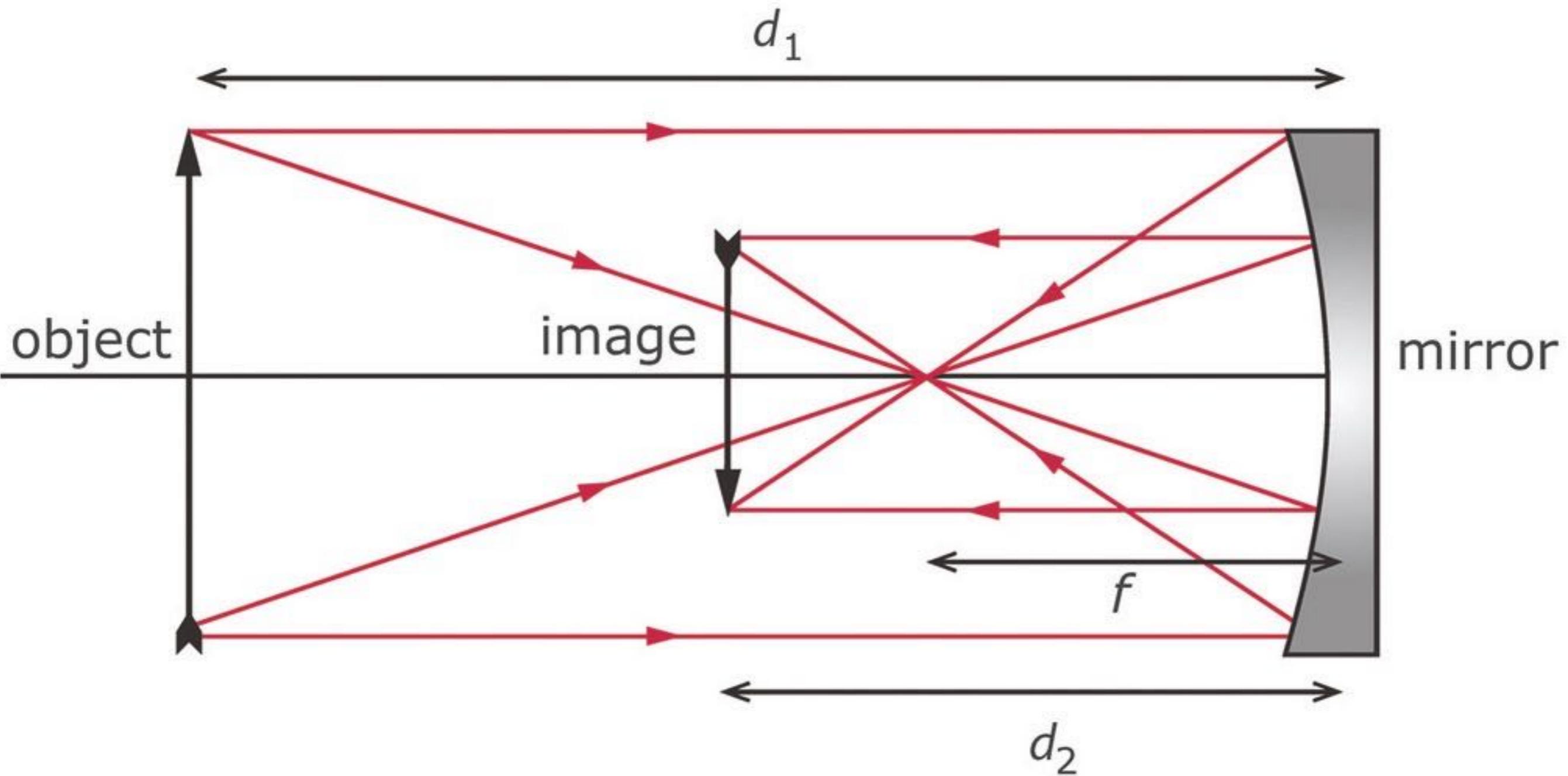


Image formation by a positive lens.

R is the radius of curvature. + = convex, - = concave

Thin lens formula.

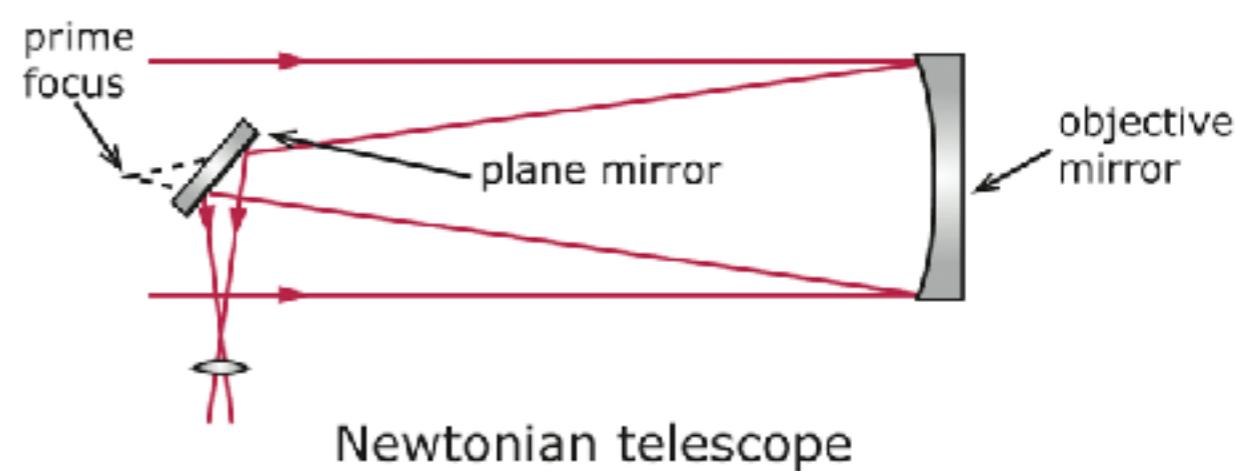
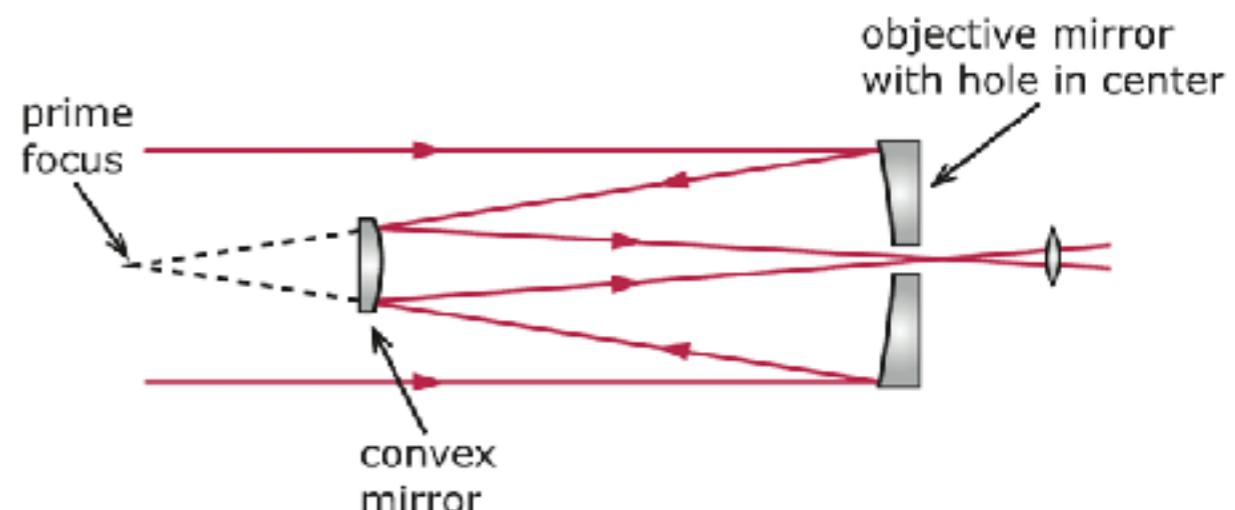
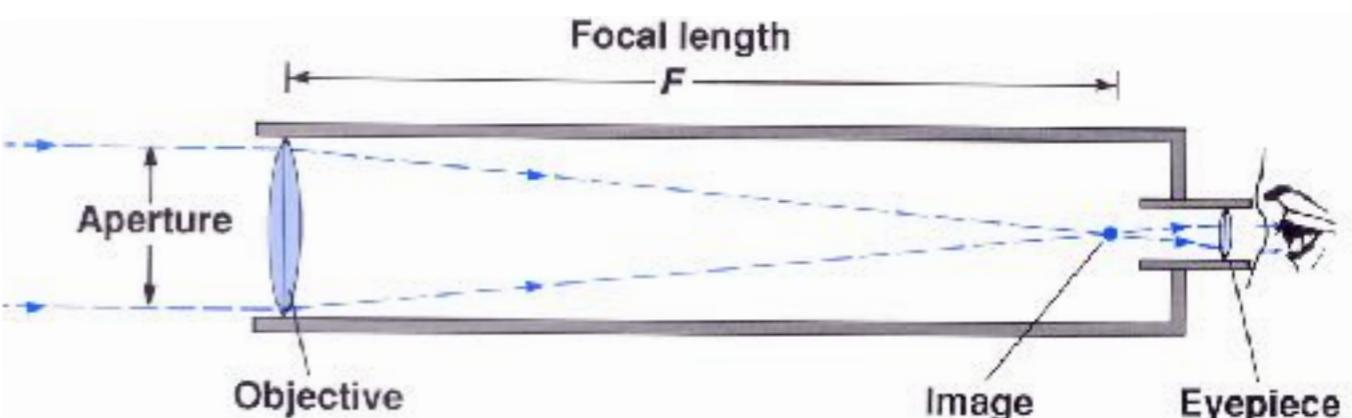


A concave mirror has image properties similar to those of a positive lens

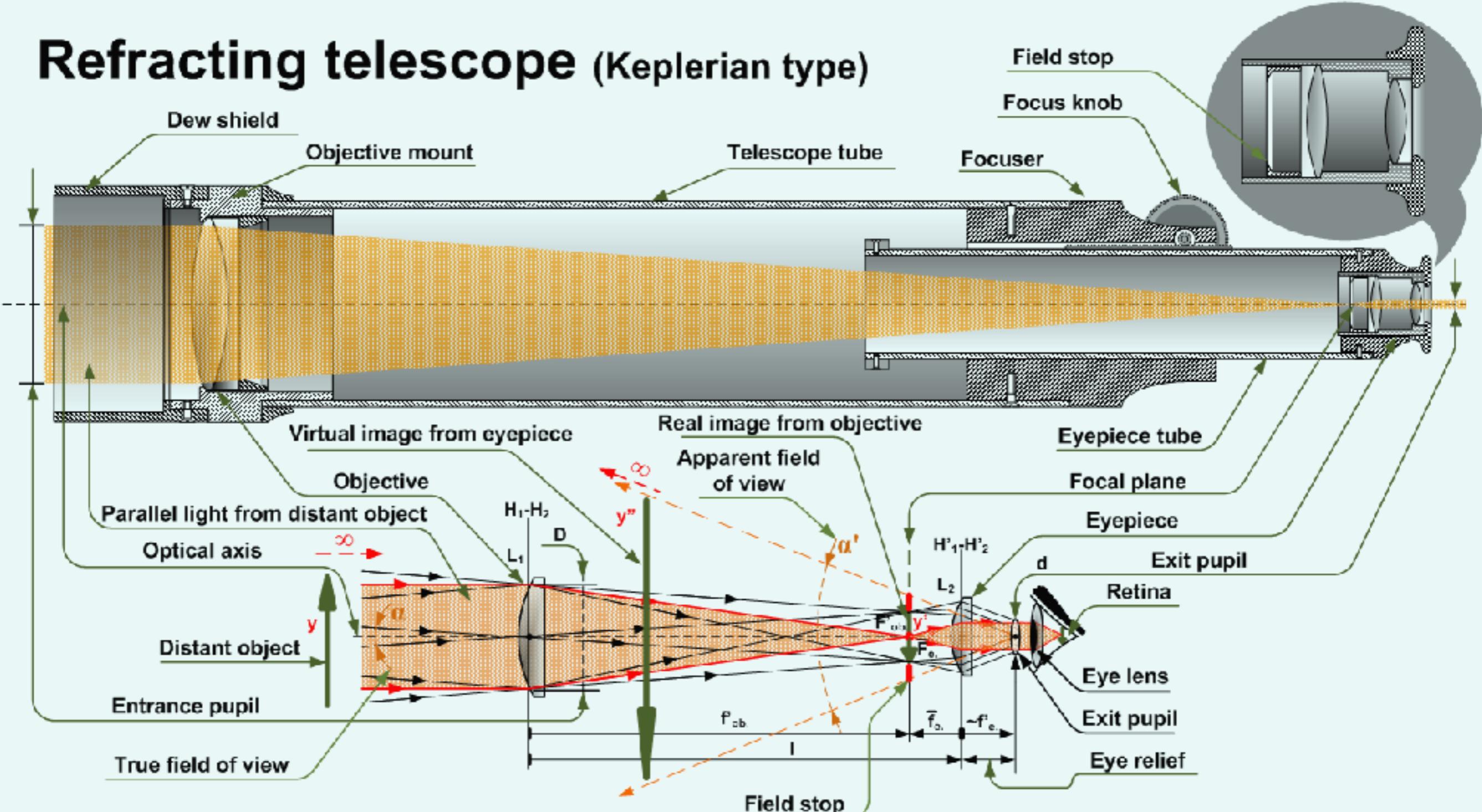
# Telescope designs

fall into one of 3 basic types:

- **Refractive** (uses lenses);
- **Reflective** (uses mirrors);
- Hybrid (a combination of mirrors and lenses).



# Refracting telescope (Keplerian type)



$$\text{Telescope magnification: } M = \frac{\tg \alpha'}{\tg \alpha} = \frac{f'_{ob.}}{f_{e.}} = \frac{D}{d}$$

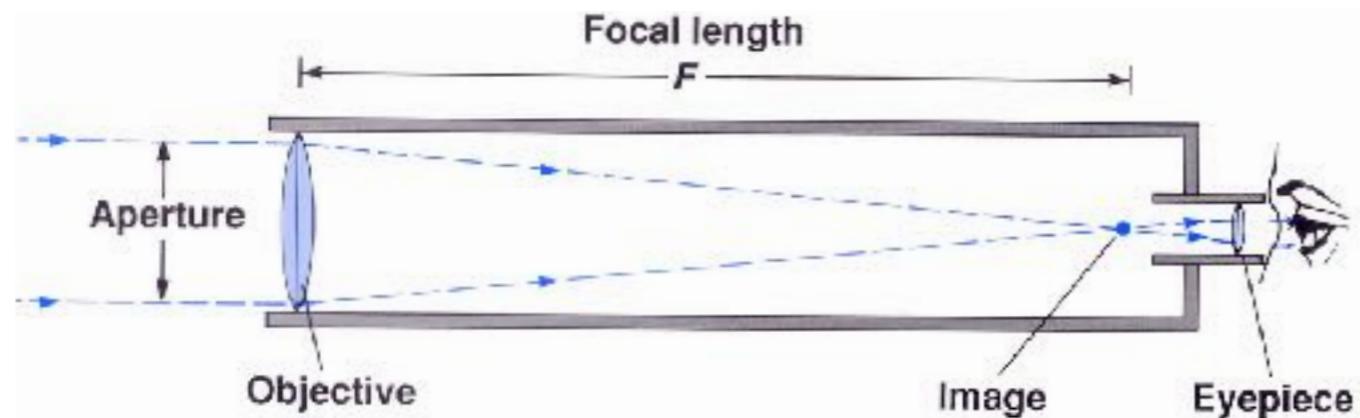
# Simple example



# Simple example

focal length  $F = 4572 \text{ mm}$

objective aperture diameter  $D = 305 \text{ mm}$



$$f/\# = F/D = "f/14.5"$$

$$\begin{aligned} \text{magnification} &= \text{focal length} / \text{eyepiece length} \\ &= 4571\text{mm}/15\text{mm} = 300 \end{aligned}$$

$$\begin{aligned} \text{field of view ("FOV")} &= \\ &= \text{opening angle of eyepiece} / \text{mag} \\ &= 82^\circ/300 = 0.3^\circ \end{aligned}$$

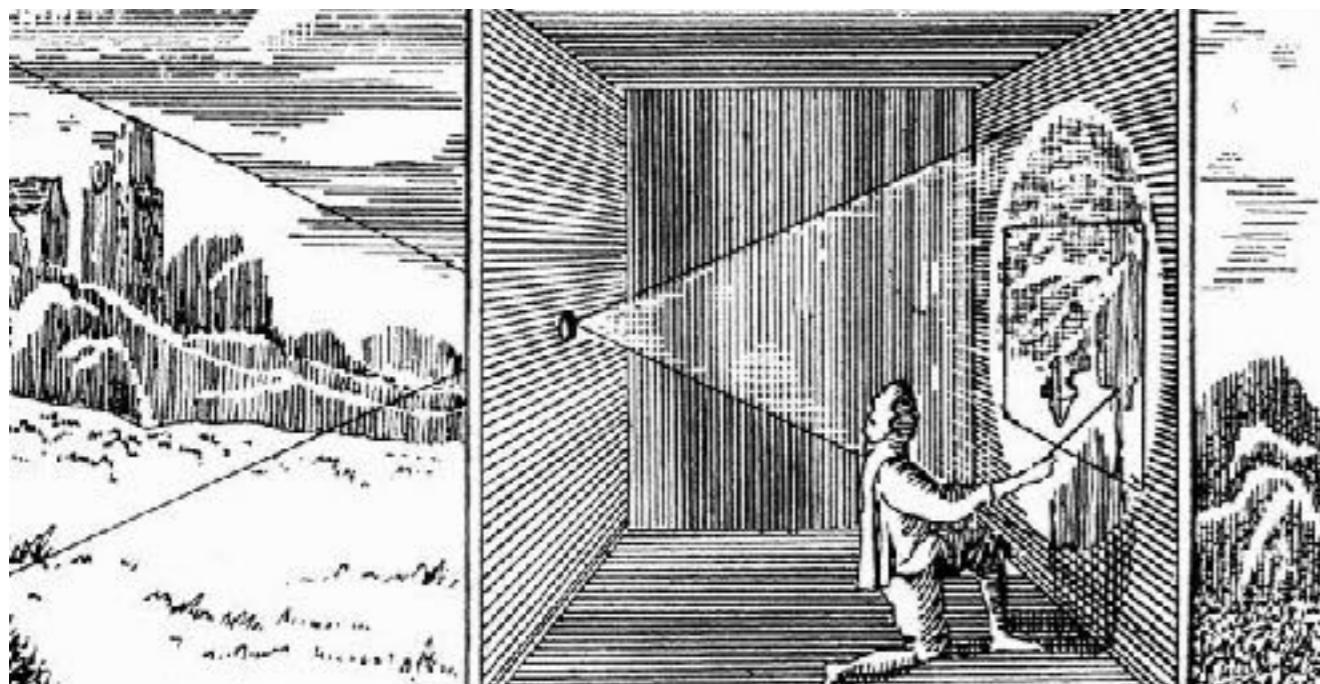




# PINHOLE CAMERA/CAMERA OBSCURA

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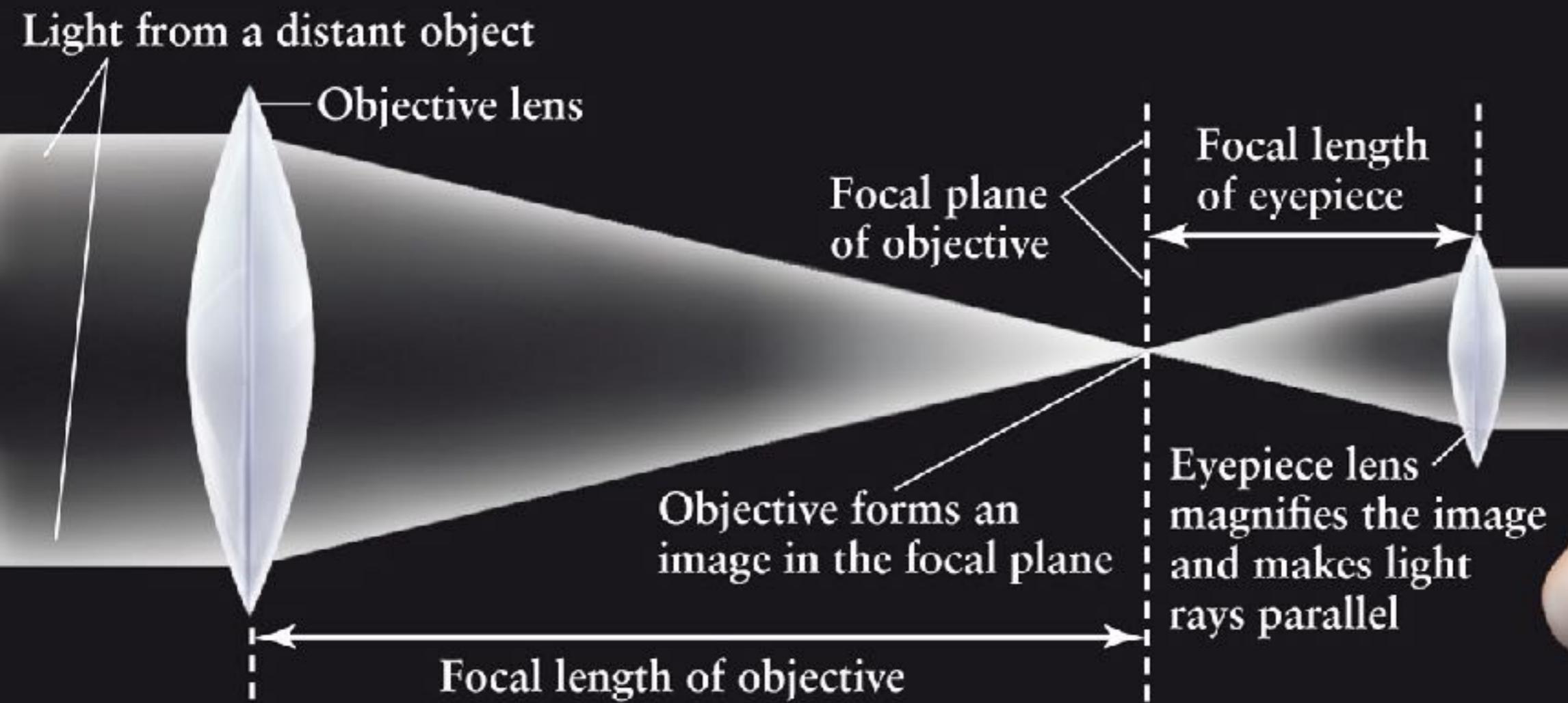
- ▶ Simplest camera; creates 1-1 mapping between object and image
- ▶ Problem: small hole limits light transmission, enlarging hole degrades 1-1 mapping and image quality.





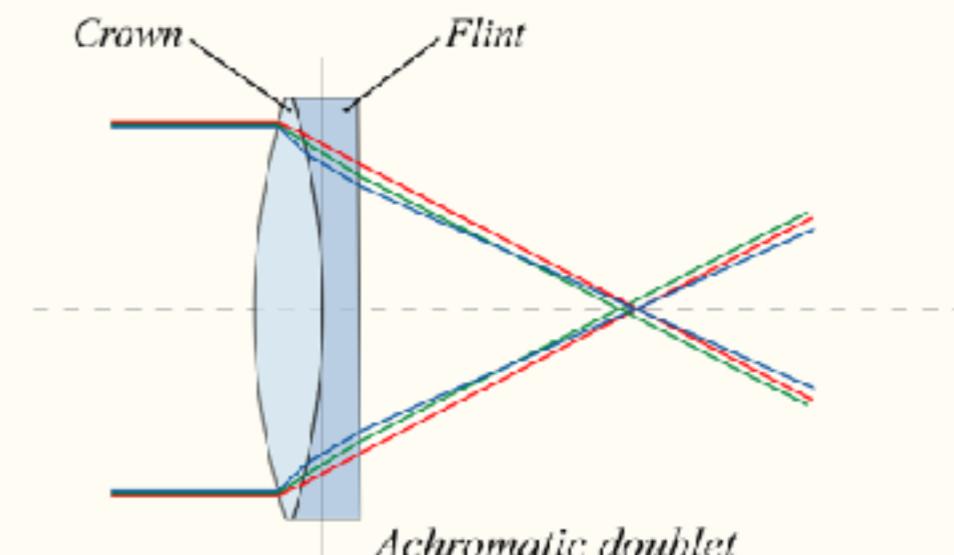
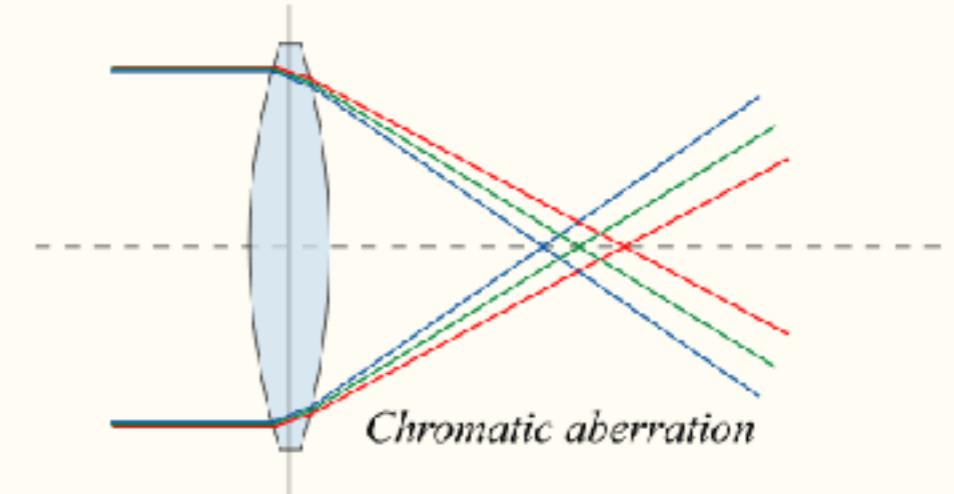
<https://www.youtube.com/watch?v=X-CRKOtIceg>



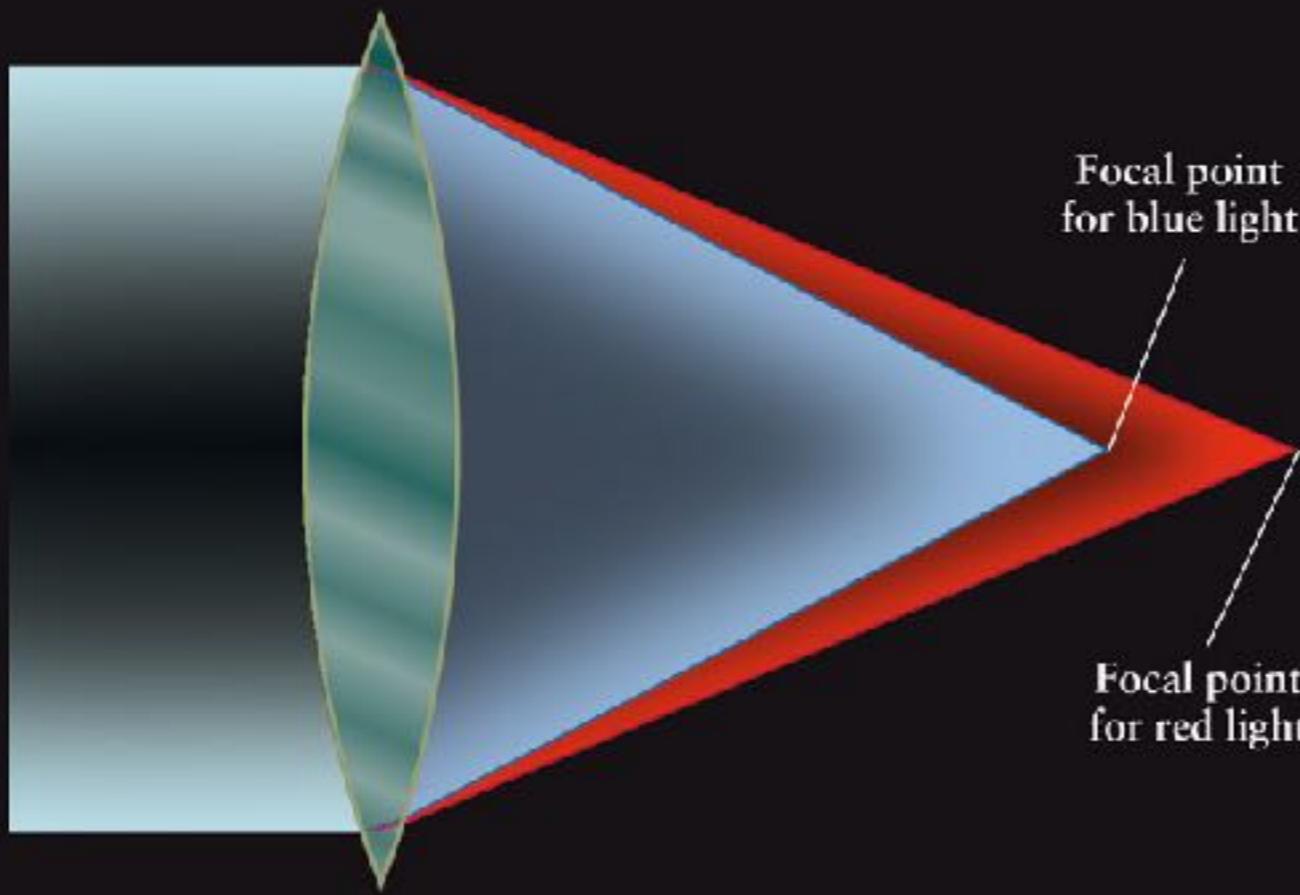


# Limits to refracting telescopes

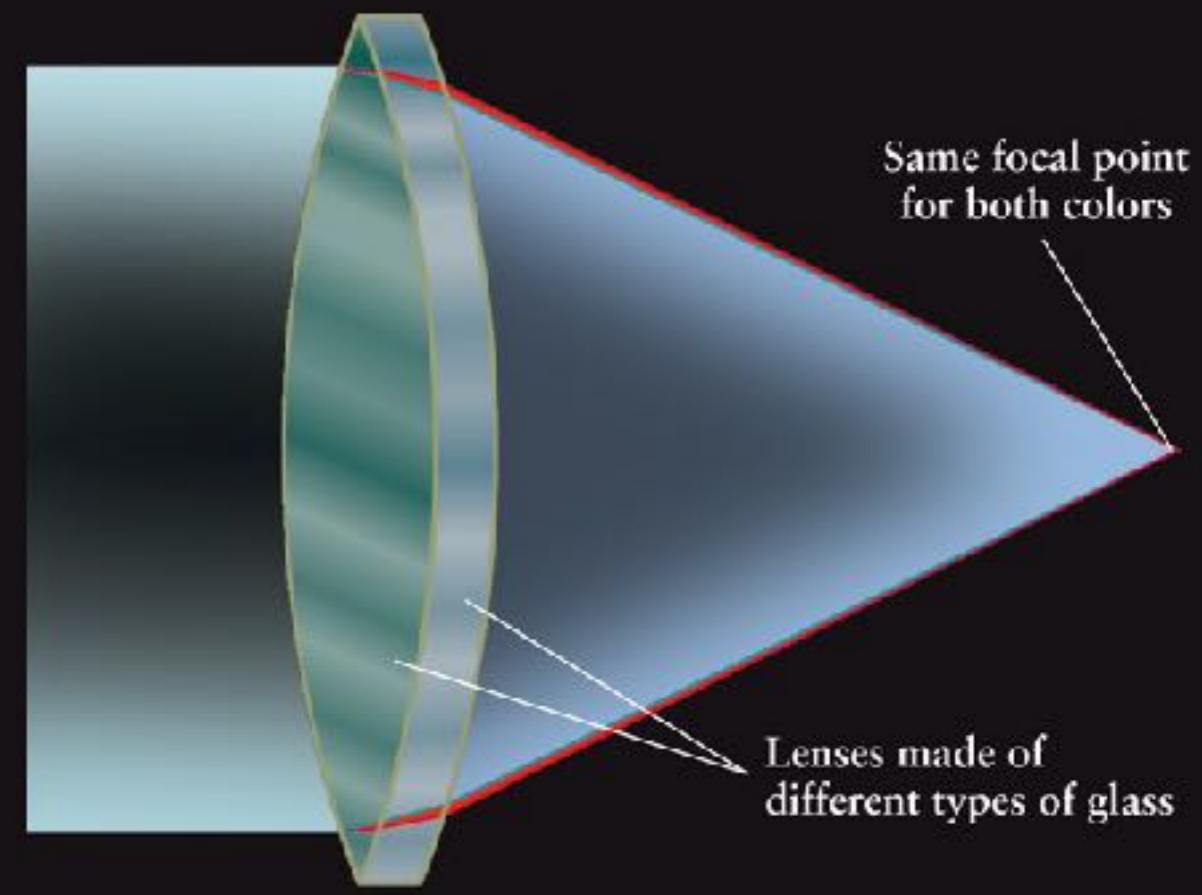
- Problems with refractors:
  - Chromatic aberration – limits to the extent it can be corrected perfectly. Focus can be off by inches for a typical 12" refractor !
  - Reflection losses at each surface. Optics need to be anti-reflection coated with a broad band.
  - Transmission losses (especially UV). Light must pass through the lens, so can't have defects (e.g. air bubbles).
  - Long focal lengths (to mitigate chromatic aberration) require large domes.
  - Heavy convex lenses, hung on the end of the optical tube make for a difficult mechanical problem – gravitational support and deformation issues.



lenses usually require an additional lens to correct for chromatic aberration



The problem: chromatic aberration



The solution: use two lenses





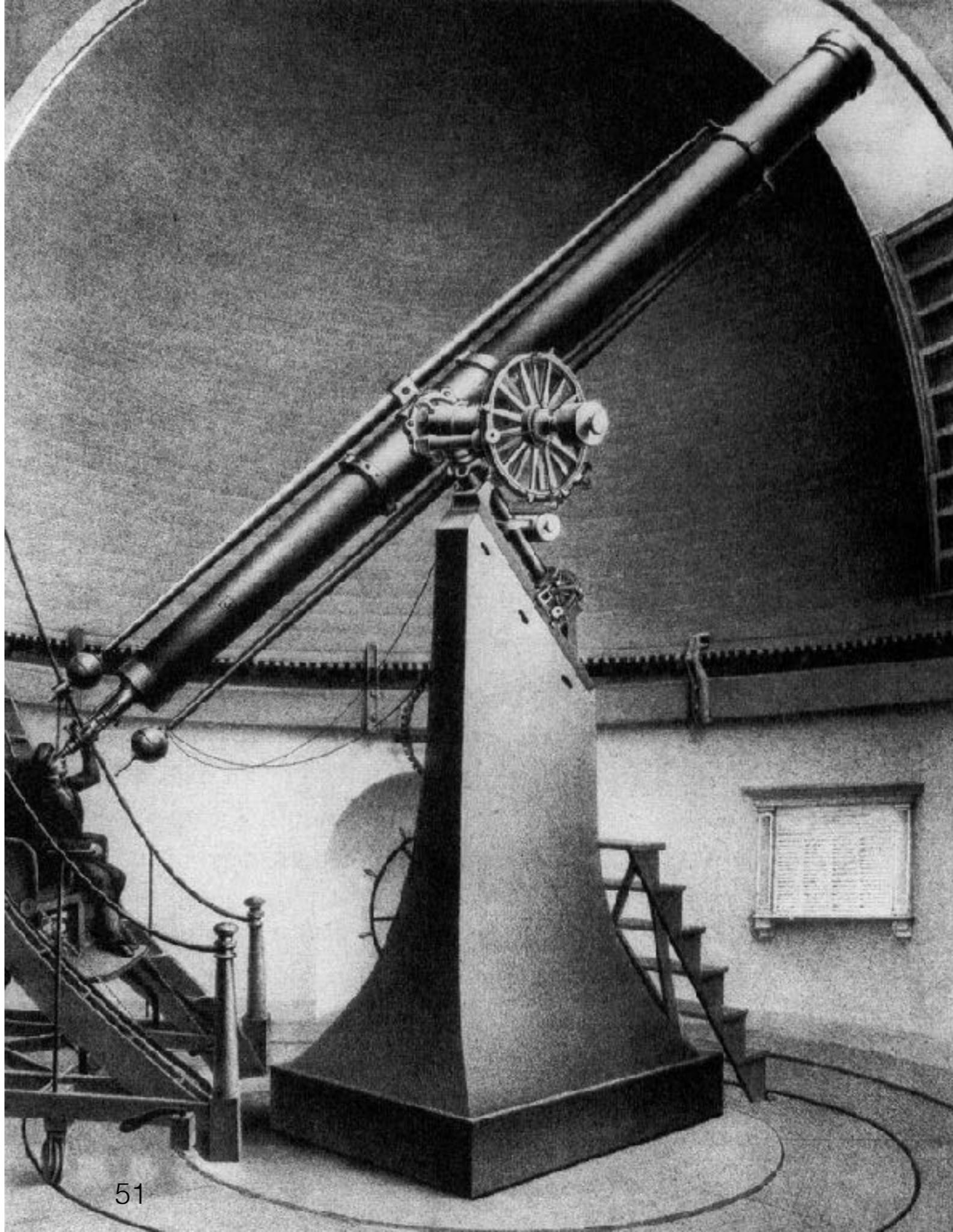
# Refractors: Great 9-inch Dorpat Refractor



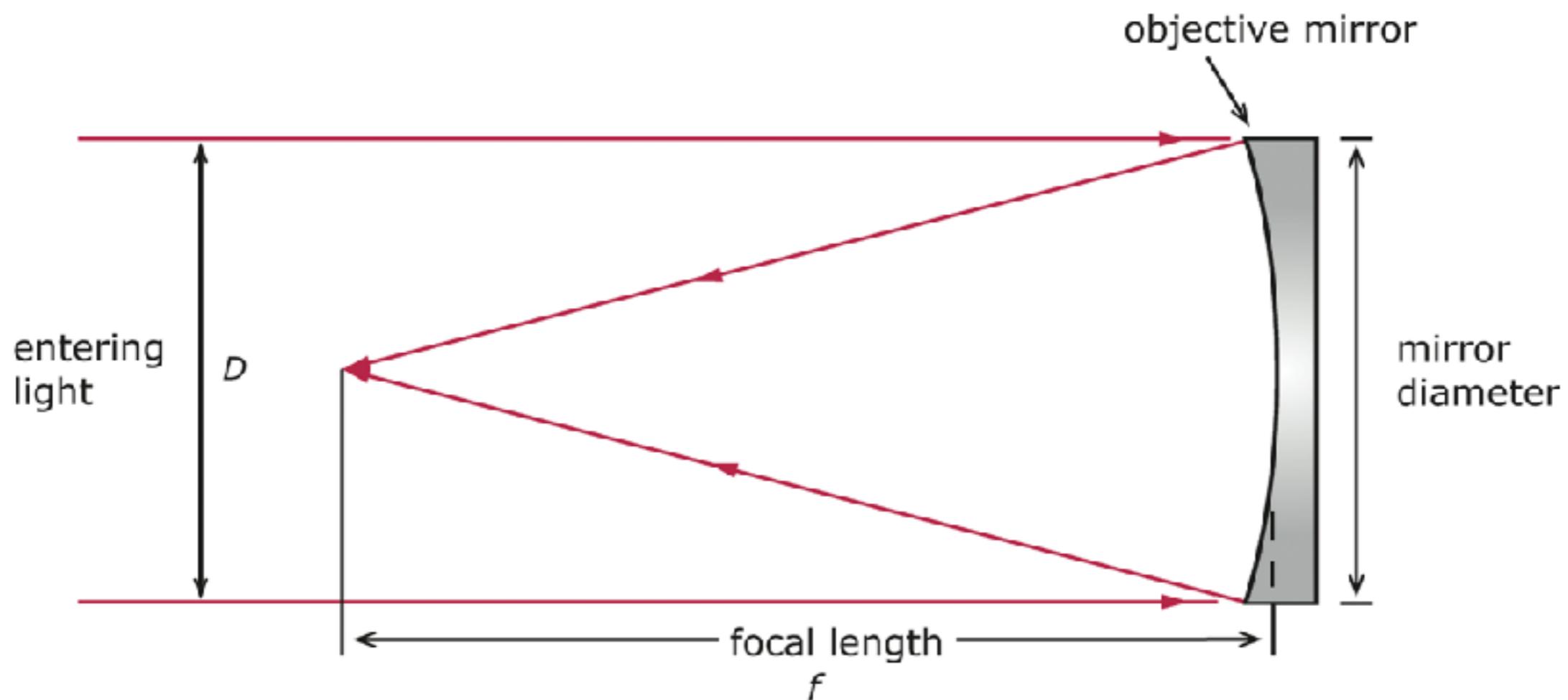
- Built in 1824 by Joseph von Fraunhofer (who started the field of astrophysics with his spectroscopic work in 1814), it was installed at Tartu (Dorpat) Observatory in Estonia.
- The 9.6" was the first modern achromatic refractor and the largest refractor in the world.
- Also developed the first modern (German) equatorial mount with clock drives
- While reflectors were much bigger (47"!), the refractors were much better.
- Ushered in the era of the Great Refractors but Fraunhofer died at age 39.

# Refractors: Harvard

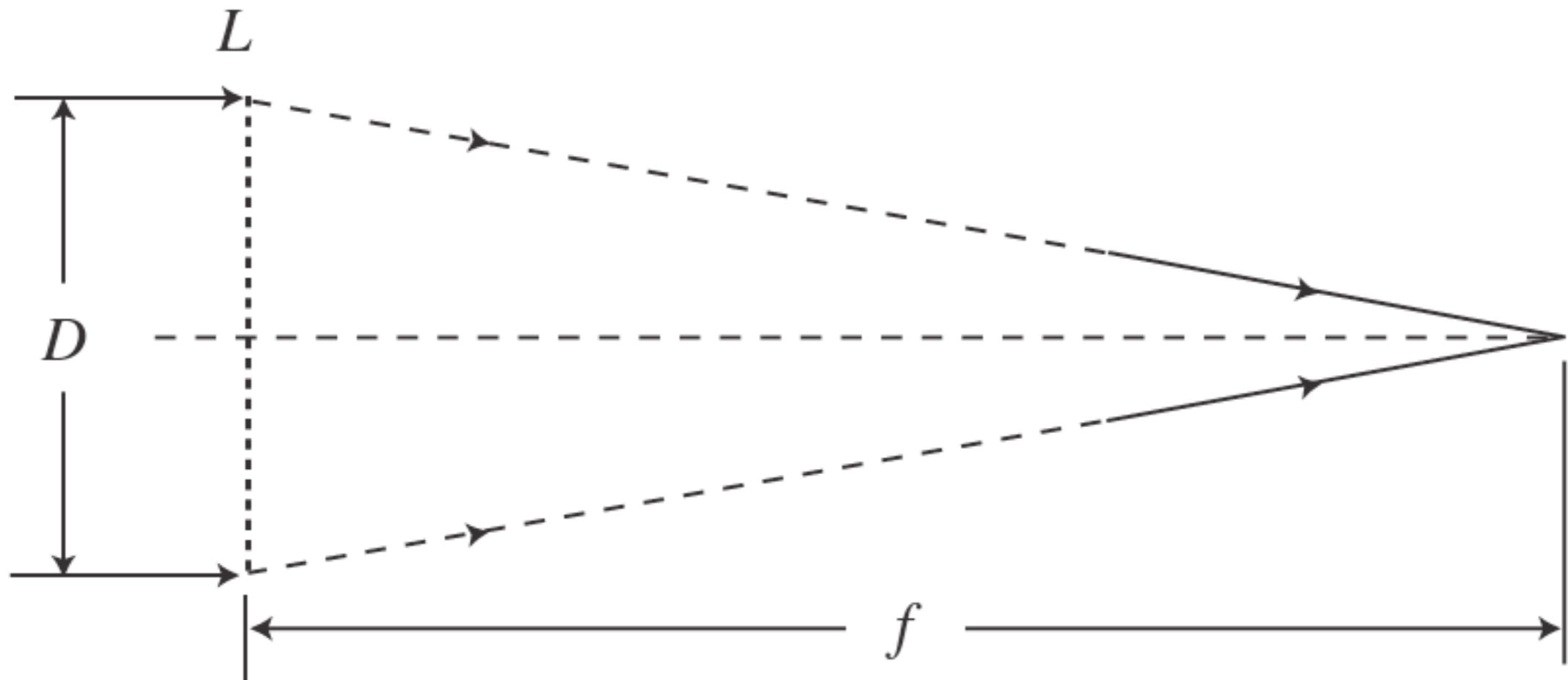
- There were no state-of-the art telescopes in the US.
- Finally, Harvard built a 15-inch refractor in 1847. It was equal to the best telescope in the world at the time (1839—Russia).
- Director William Bond and photographer James Wheeler were among the first to start using photography.



# A Prime Focus Telescope

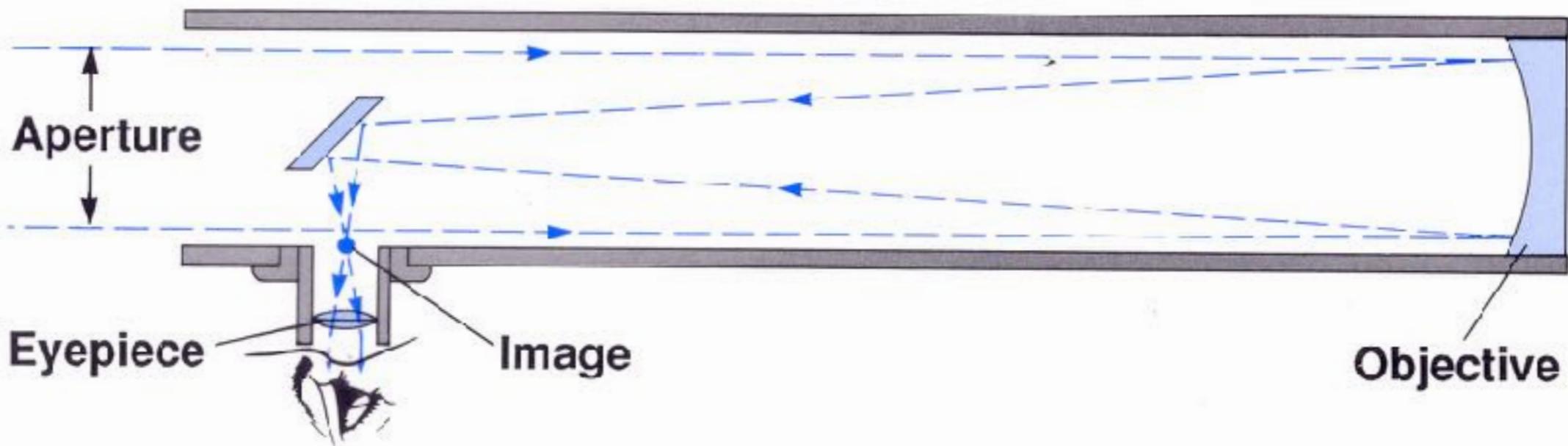
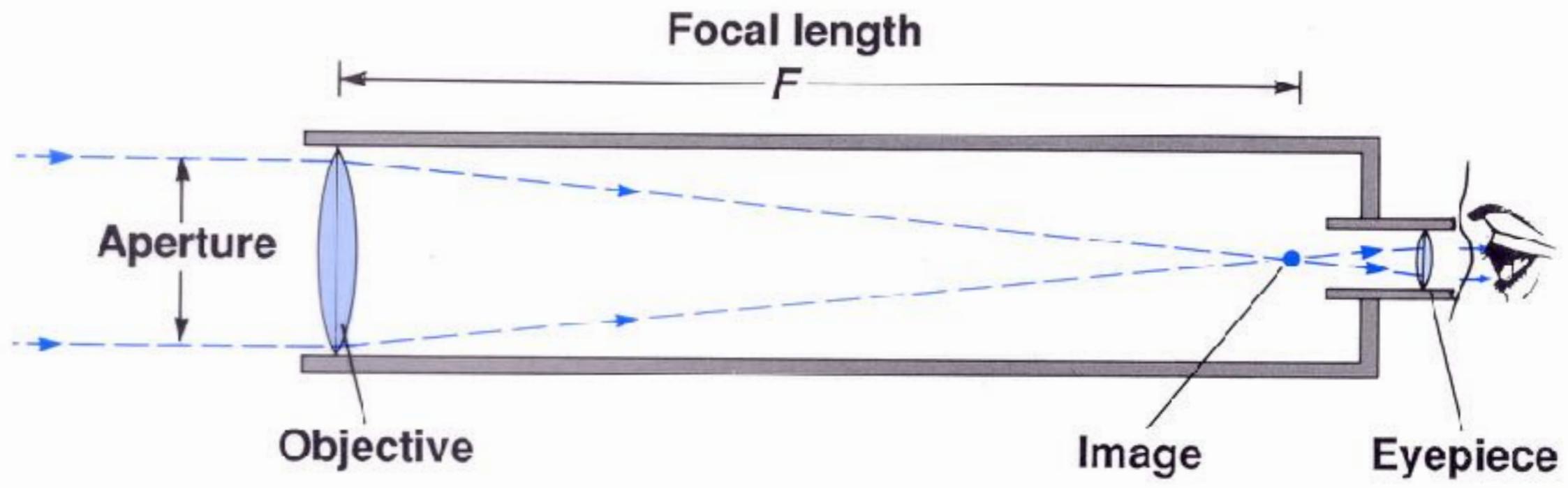


equivalent single element refractive telescope



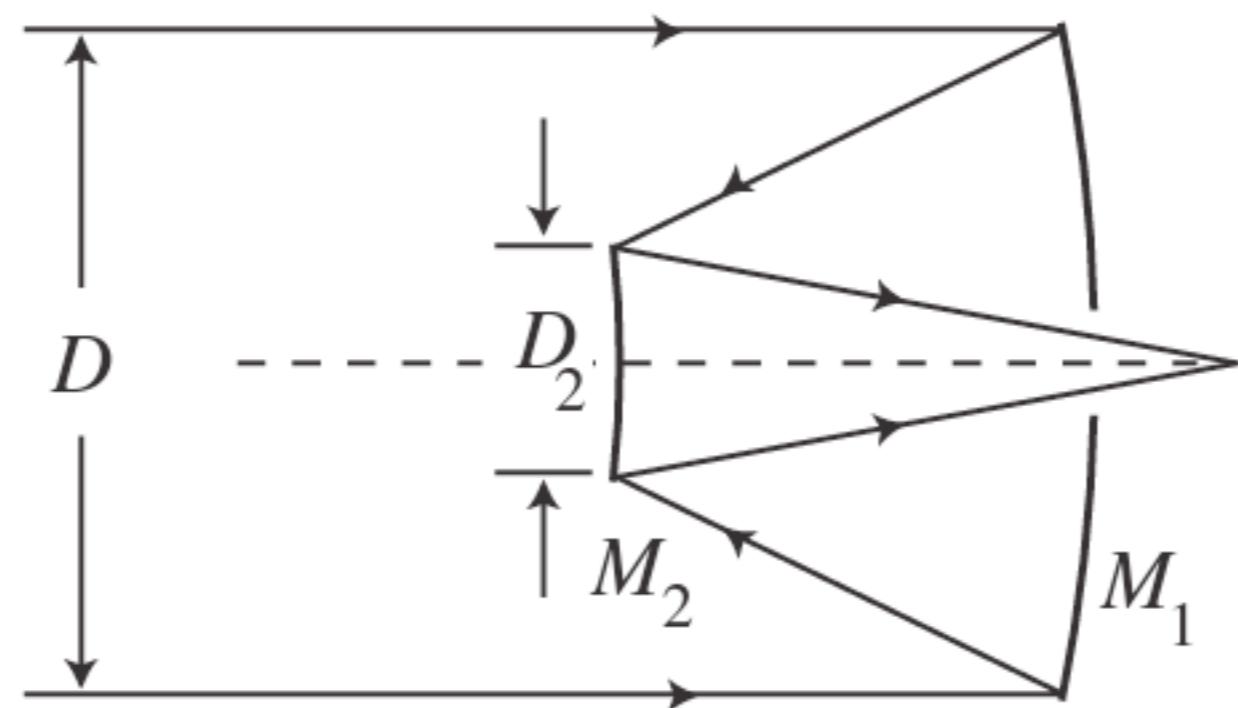
$$\text{focal ratio} = \text{"f/#"} = \frac{f}{D} = \frac{\{\text{focal length}\}}{\{\text{diameter of entrance aperture}\}}$$

# Refractor

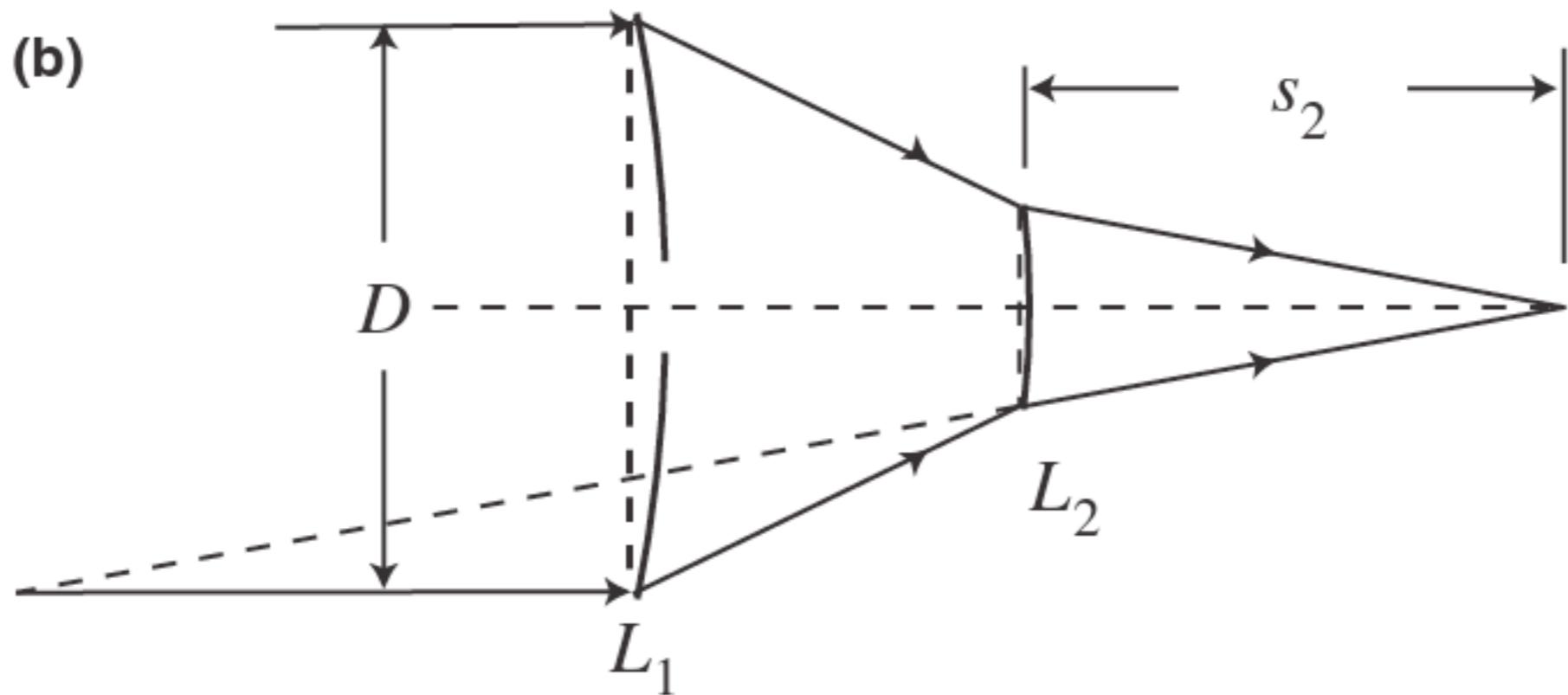


# Reflector

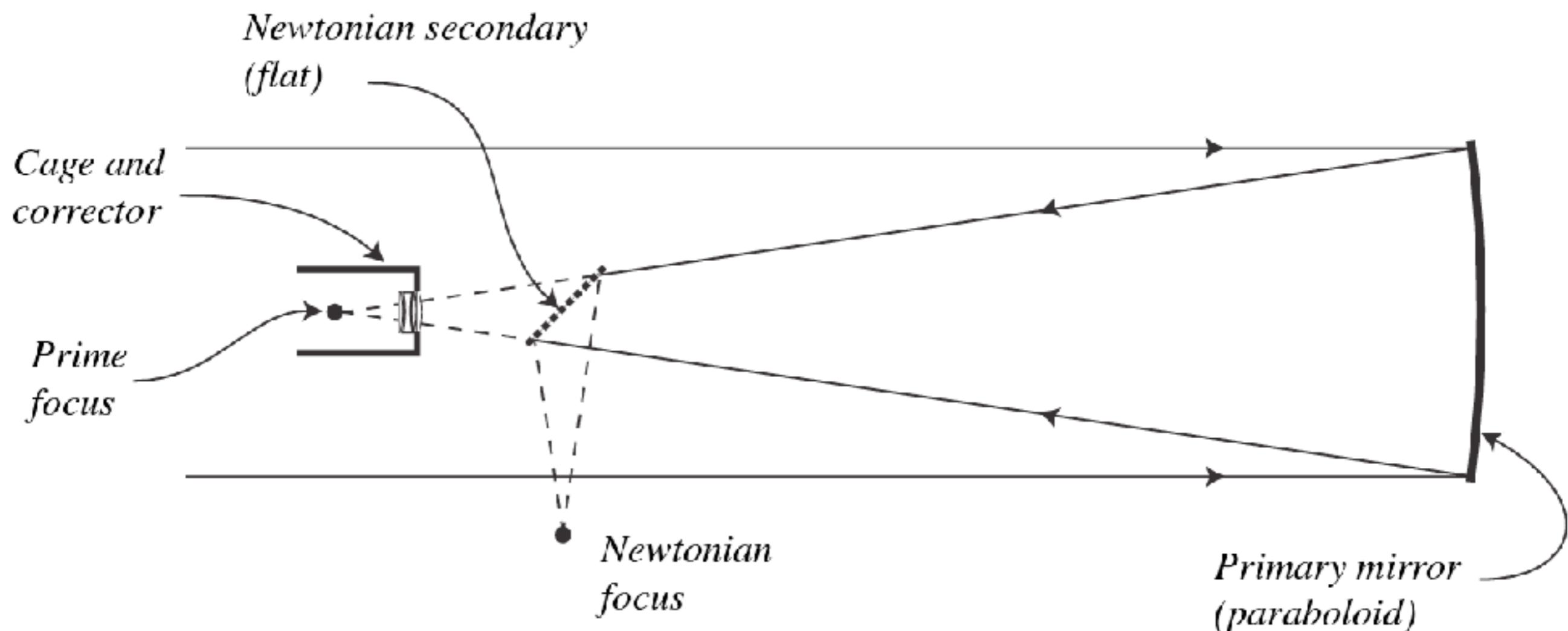
# reflective telescope



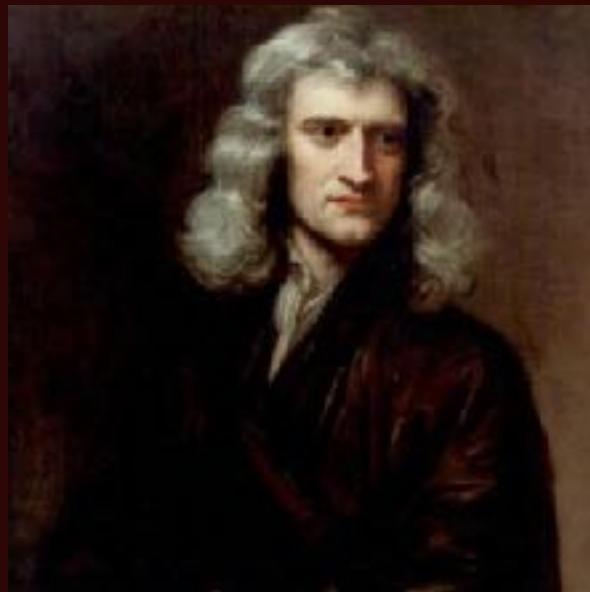
# equivalent refractive telescope



# Newtonian Telescope



# Reflectors: Newton



- 1642—1726
- 1.3-inch aperture c. 1668
- Spherical mirror was made of speculum
- Built it to prove his theory that white light is made of the spectrum of colors and explain chromatic aberration



# Leviathan of Parsonstown

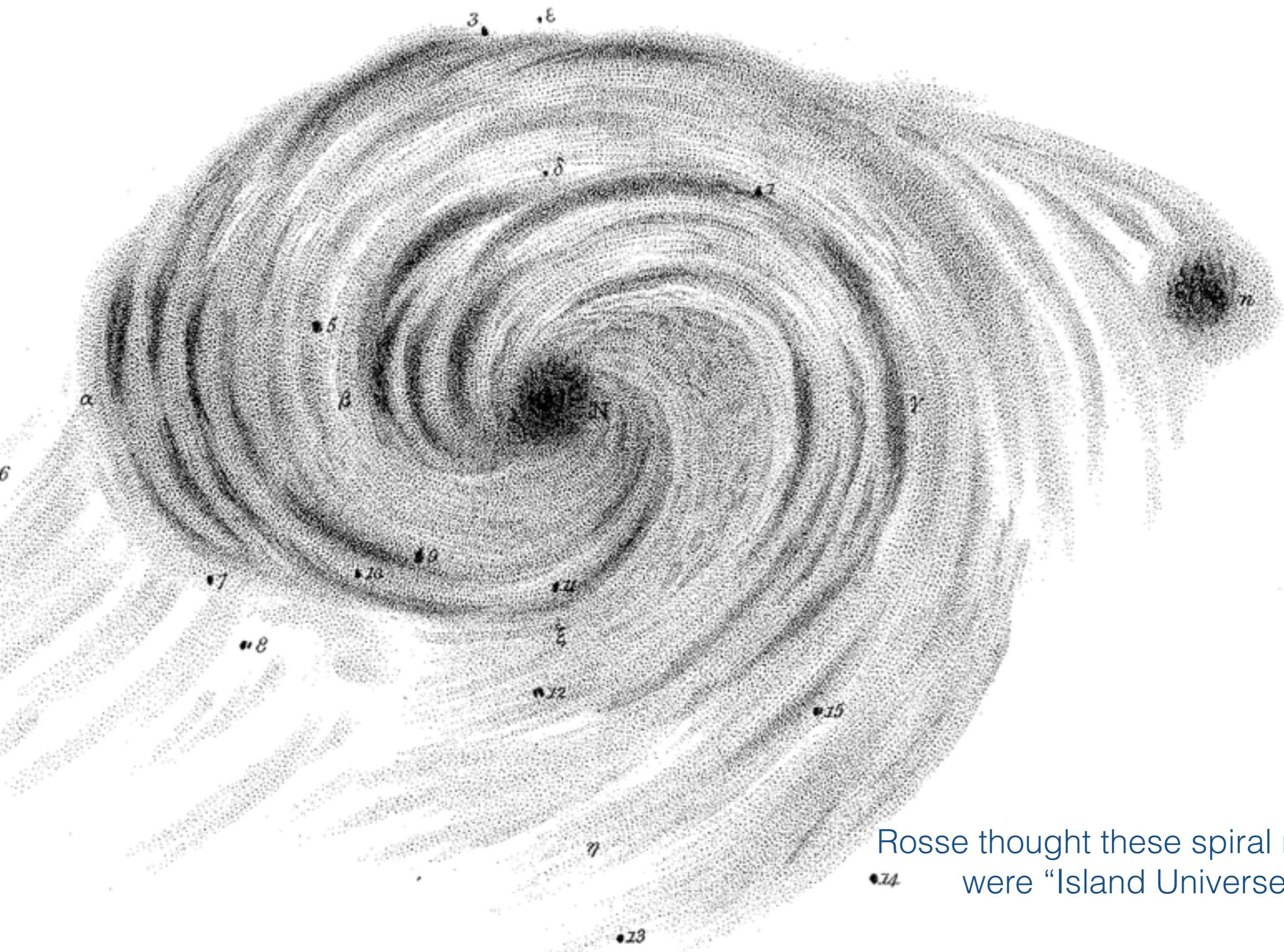
William Parsons (1800-1867) 3rd Earl of Rosse

72" (1.8m) Newtonian telescope in Ireland

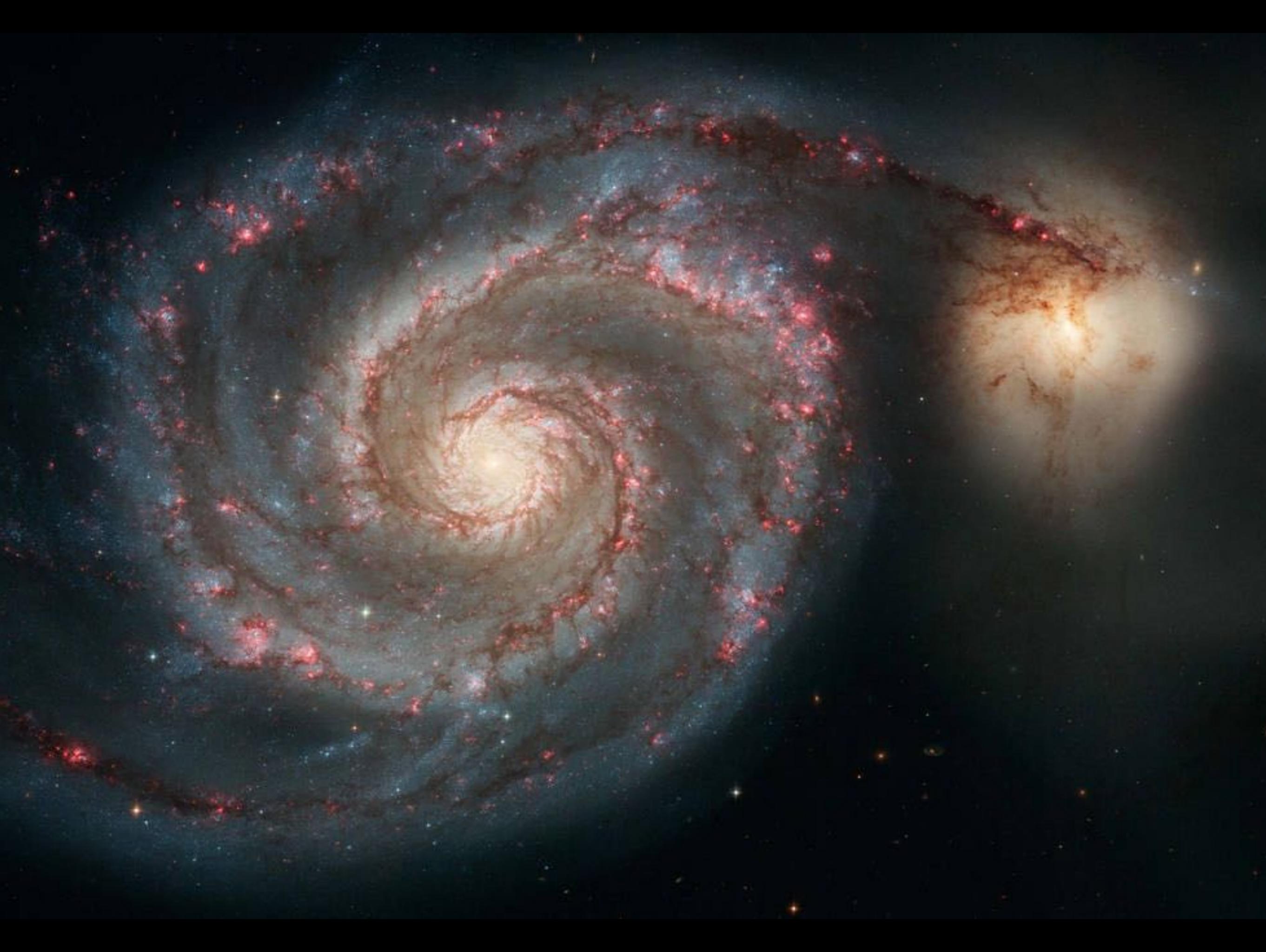
Largest in the world from 1845—1917



# Sketch of M51 by Lord Rosse in 1845



Rosse thought these spiral nebulae  
were “Island Universes”



# Mirrors: I

Why didn't they just build telescopes out of mirrors?

At the time, they only had **speculum**, which was an expensive and heavy alloy made of copper and tin.

The surface was difficult to cast, difficult to polish, and tarnished quickly, meaning it had to be re-polished constantly.

The resulting surfaces reflect only ~50% of the light.

Nevertheless, people did make the largest telescopes with these, but the logistics of such large, cumbersome, and inefficient structures hampered further development.

William Herschel's 1.2 meter speculum primary mirror from the 200 foot telescope



# Mirrors: II

## Silvered glass

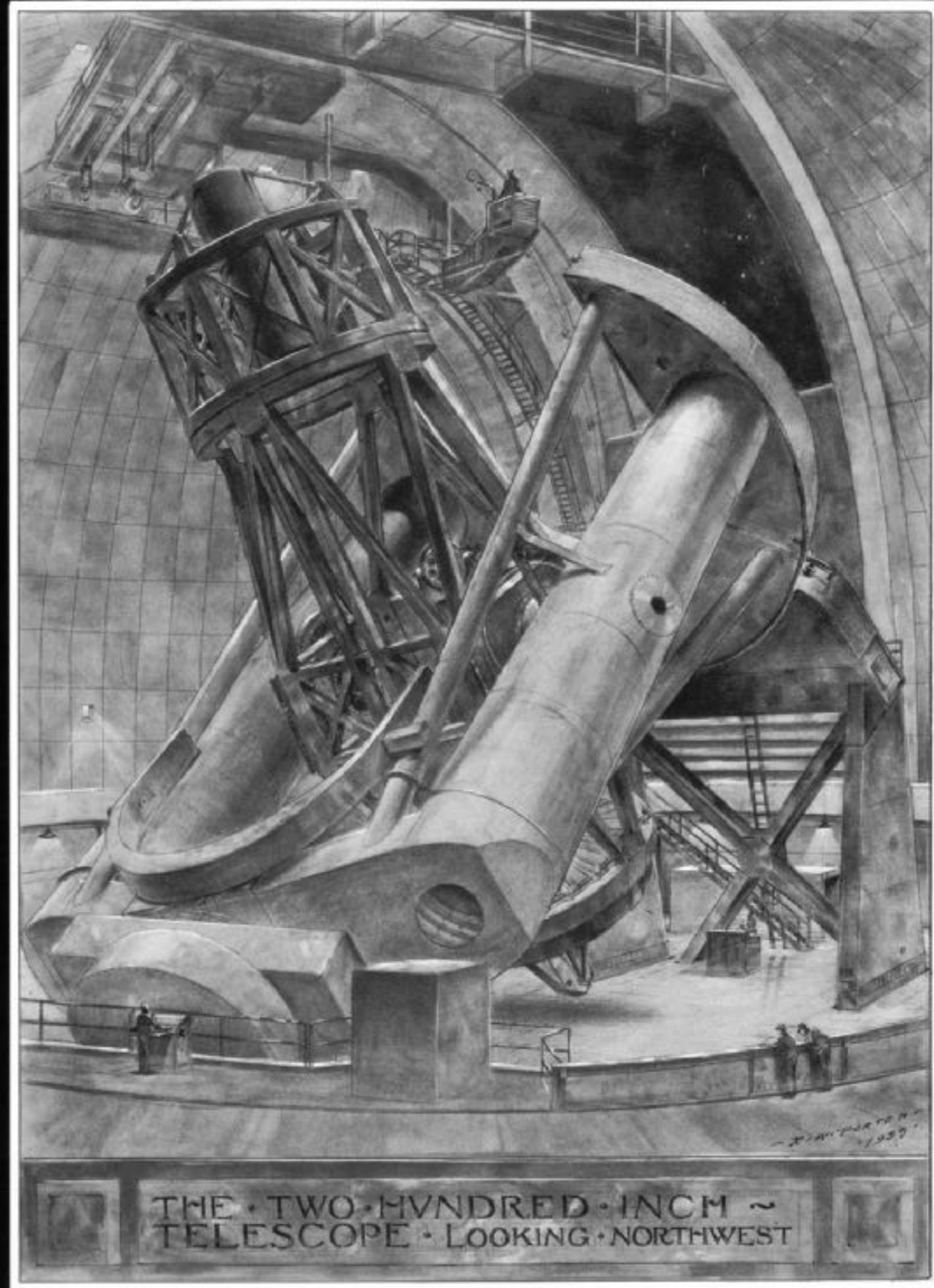
- Towards the end of the 19th century, advances in chemistry allowed astronomers to deposit a thin layer of silver on glass to make high-quality mirrored surfaces.
- Glass could be easily figured into the right shape and polished to a high degree of accuracy.
- The first such telescopes were built by amateur astronomer Dr. Andrew Common in the 1870-80s, who eventually built a 36" reflector.
- This technique culminated in the Hale 60" telescope on Mt. Palomar in 1908.
- Later, in 1930, aluminum was able to be deposited. This is now the standard modern practice.



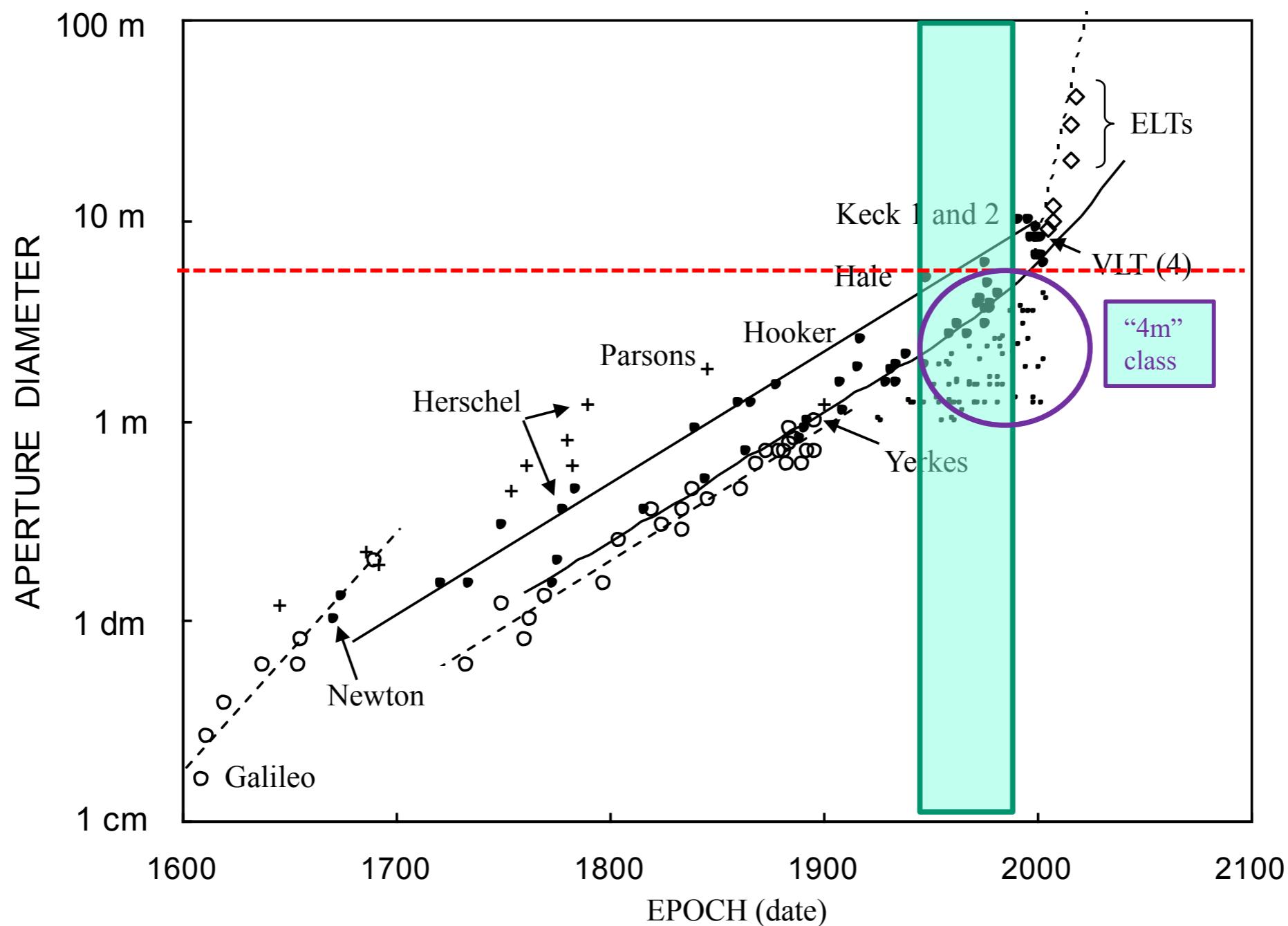
82" Struve Telescope primary mirror circa 1935

# Hale 200-inch Telescope on Mt Palomar

- Planning began 1928
- Mirror casting began 1934
- Dedication in 1948
- 1949 first light. First observer was Edwin Hubble
- 1958  $H_0$  refined by Allan Sandage
- 1963 QSOs discovered by Maarten Schmidt
- 1960s — First IR detectors
- 1970s — First CCDs
- First major telescope with AO
- Largest telescope in the world for 45 years



# HALE TELESCOPE 200" ERA (1949-1993)



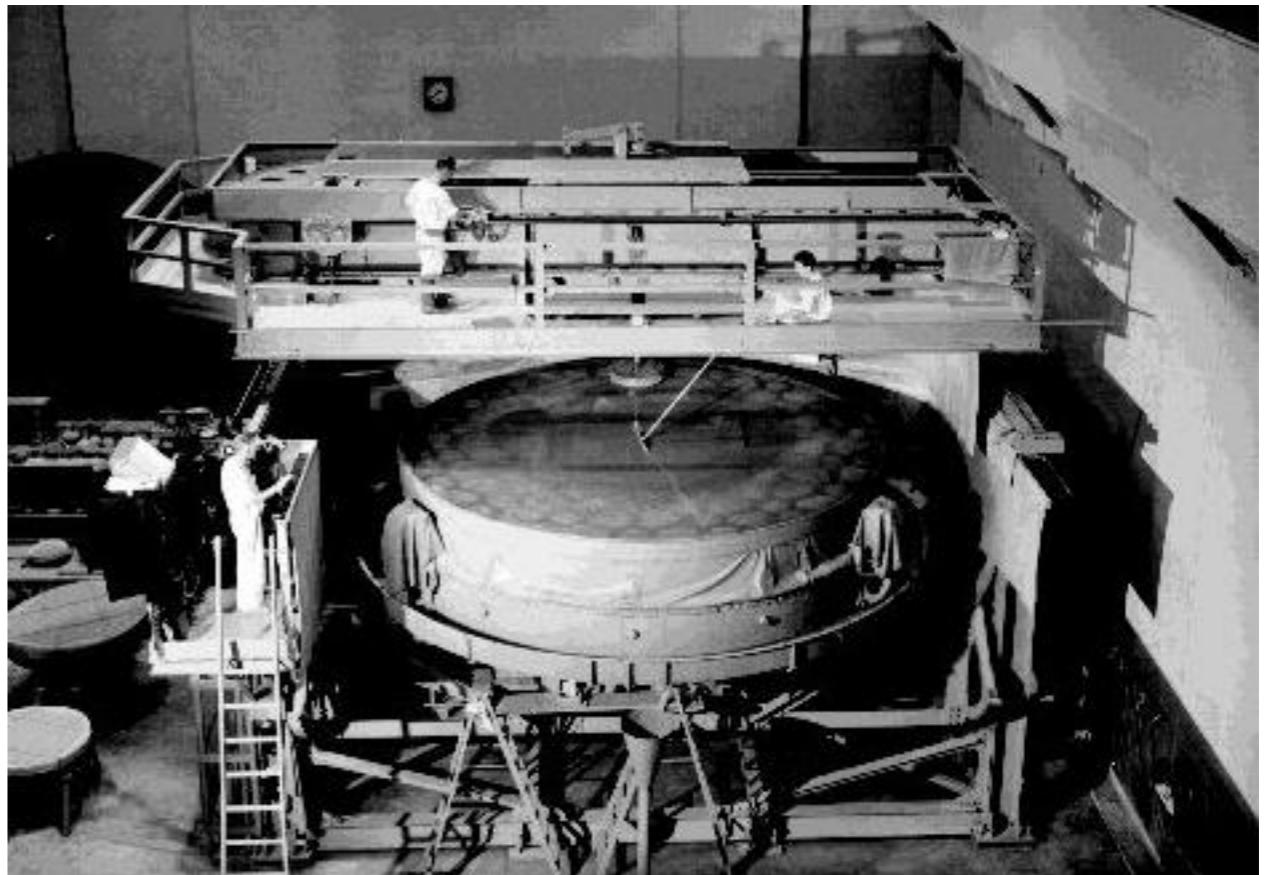
(McLean 2008)

Lecture #13 ©

# BUILDING BIGGER TELESCOPES IS RUNNING UP AGAINST MECHANICAL LIMITS



(Mirror blank; Credit: Palomar Observatory/Caltech)



(Grinding/polishing; Credit: Palomar Observatory/Caltech)

Gravitational flexure is proportional to  $D^4$  – for mirror diameter  $D$ .



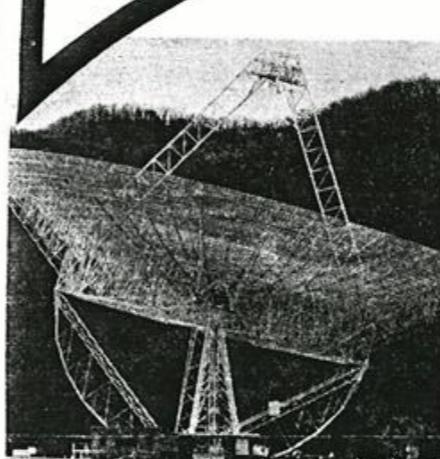
# 300-ft Greenbank telescope (1988)



([www.nrao.edu](http://www.nrao.edu))

*America's most powerful radio telescope IS ...*

**ZAPPED!**  
... by hostile space aliens!



BEFORE ▲

Space aliens zapped the enormous radio telescope at Green Bank, W. Va., with a powerful laser to keep scientists from monitoring their activities in the northern hemisphere!

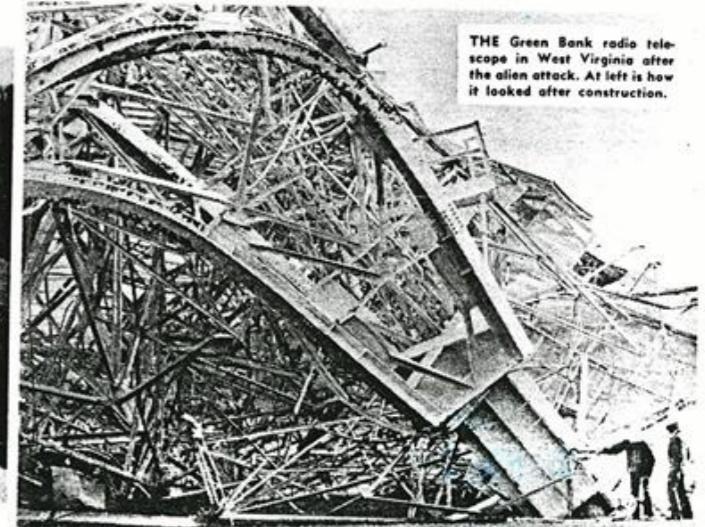
That's the claim of Swiss astronomer Peter Voidsard, who says the destruction of the 300-foot instrument on November 15 qualifies as the boldest act of extraterrestrial aggression in the history of the world.

"We know that extraterrestrials have shot down planes and abducted people but this is the first time they have been brazen enough to destroy a government research facility," the expert told newsmen.

By RAGAN DUNN

in Geneva. "The Americans must have been learning too much about them," he continued. "There is no other rational explanation for such a strike as this. In some circles, it might be considered an act of war."

Dr. Voidsard's report sent



AFTER ►

shockwaves throughout the world's scientific community. But the handful of men who can talk about the Green Bank disaster with authority refused to describe the incident as anything more than "a mystery."

There is no doubt that the instrument — which could detect objects almost two-thirds of the way to the edge of the visible universe — was essential to monitoring extraterrestrial activity in the northern skies.

"Suddenly it collapses in the dead of night. What are we supposed to think? That the telescope just fell apart?" French radio astronomer Marc Kraemer was inclined to agree with Dr. Voidsard but warned against jumping to conclusions.

"I firmly believe that we can

prove extraterrestrials toppled the telescope at Green Bank," he said. "But let's wait until all the evidence is in."

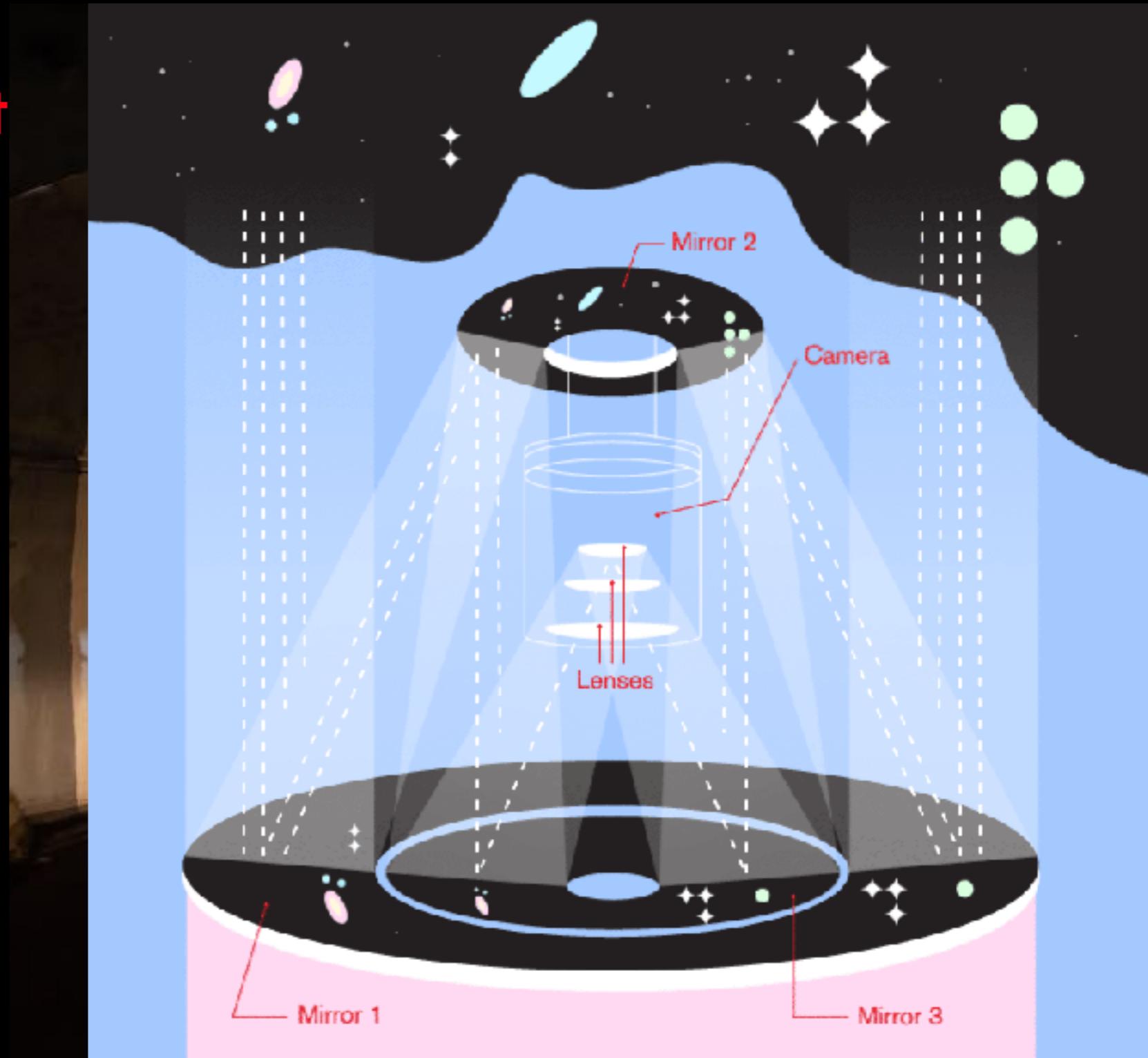
"Then we can take whatever steps are necessary to prevent things like this from happening in the future."

prove extraterrestrials toppled the telescope at Green Bank," he said. "But let's wait until all the evidence is in."

"Then we can take whatever steps are necessary to prevent things like this from happening in the future."

# What's special about Rubin Observatory

- Rubin isn't going to have the biggest telescope
  - We want more area to collect more light and see fainter, farther sources
  - ... but, we want to also cover as much area on the sky as possible - a “synoptic survey”



8m Class  
Telescope



LSST

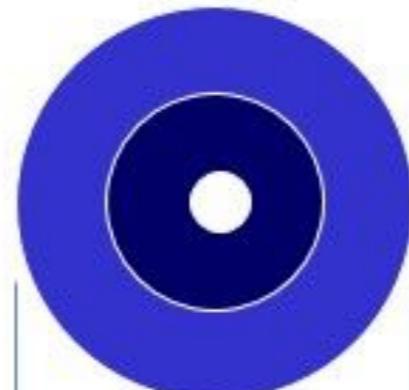


Z. Ivezic,

Primary Mirror  
Diameter

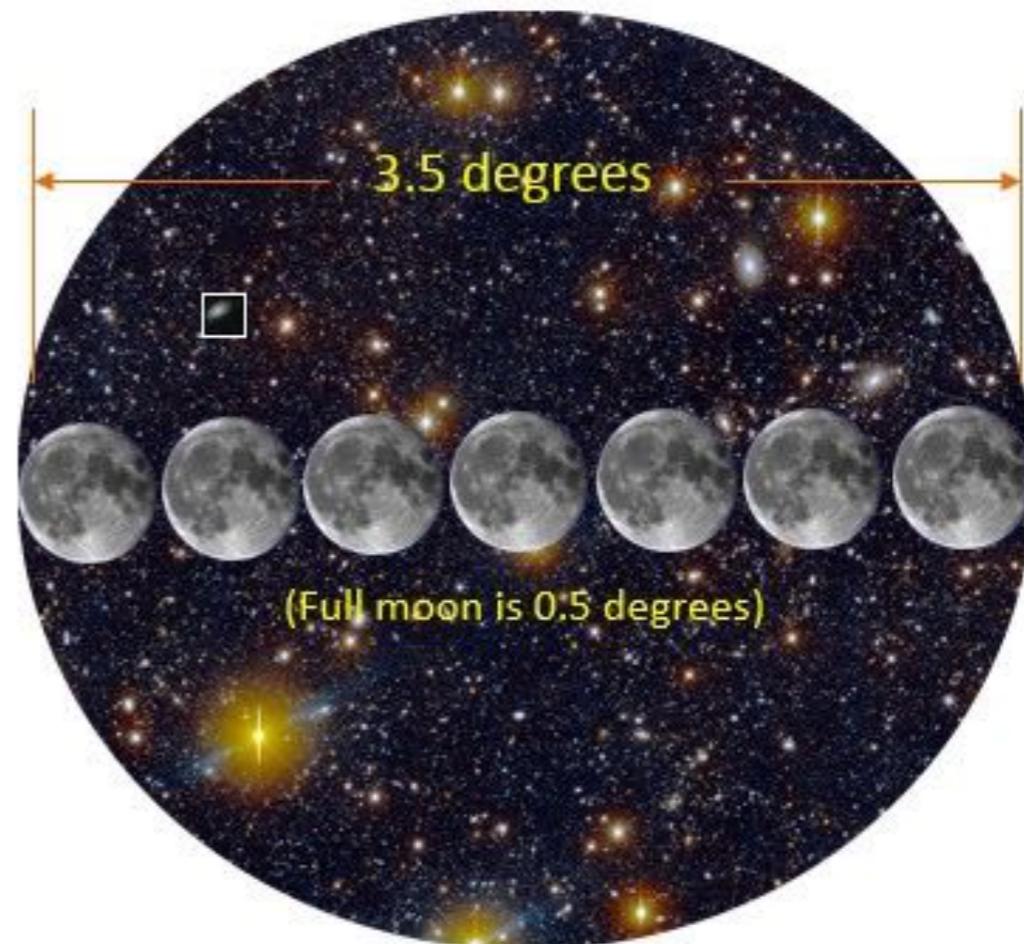
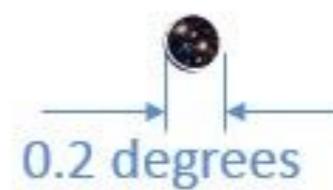


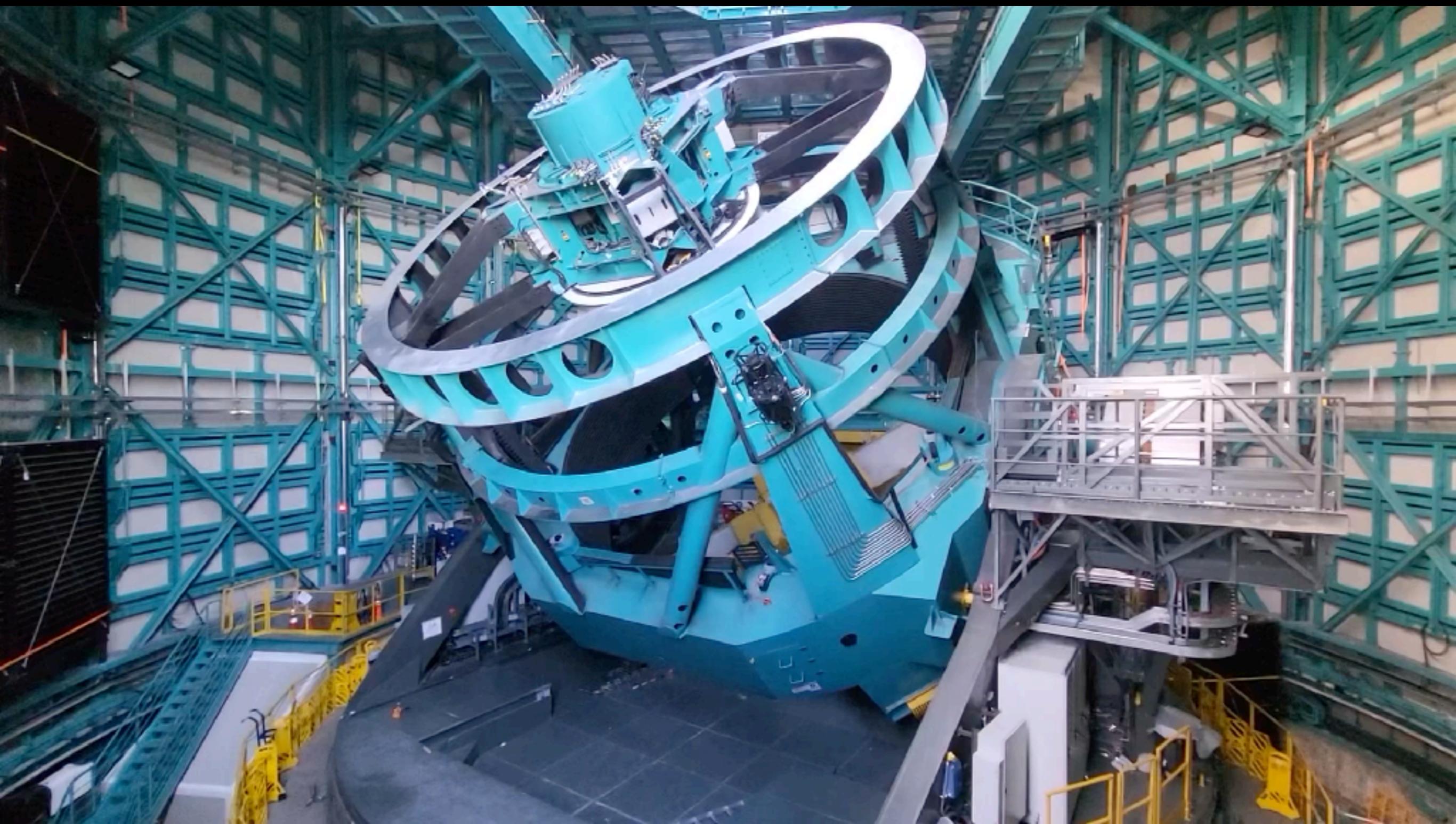
8 m

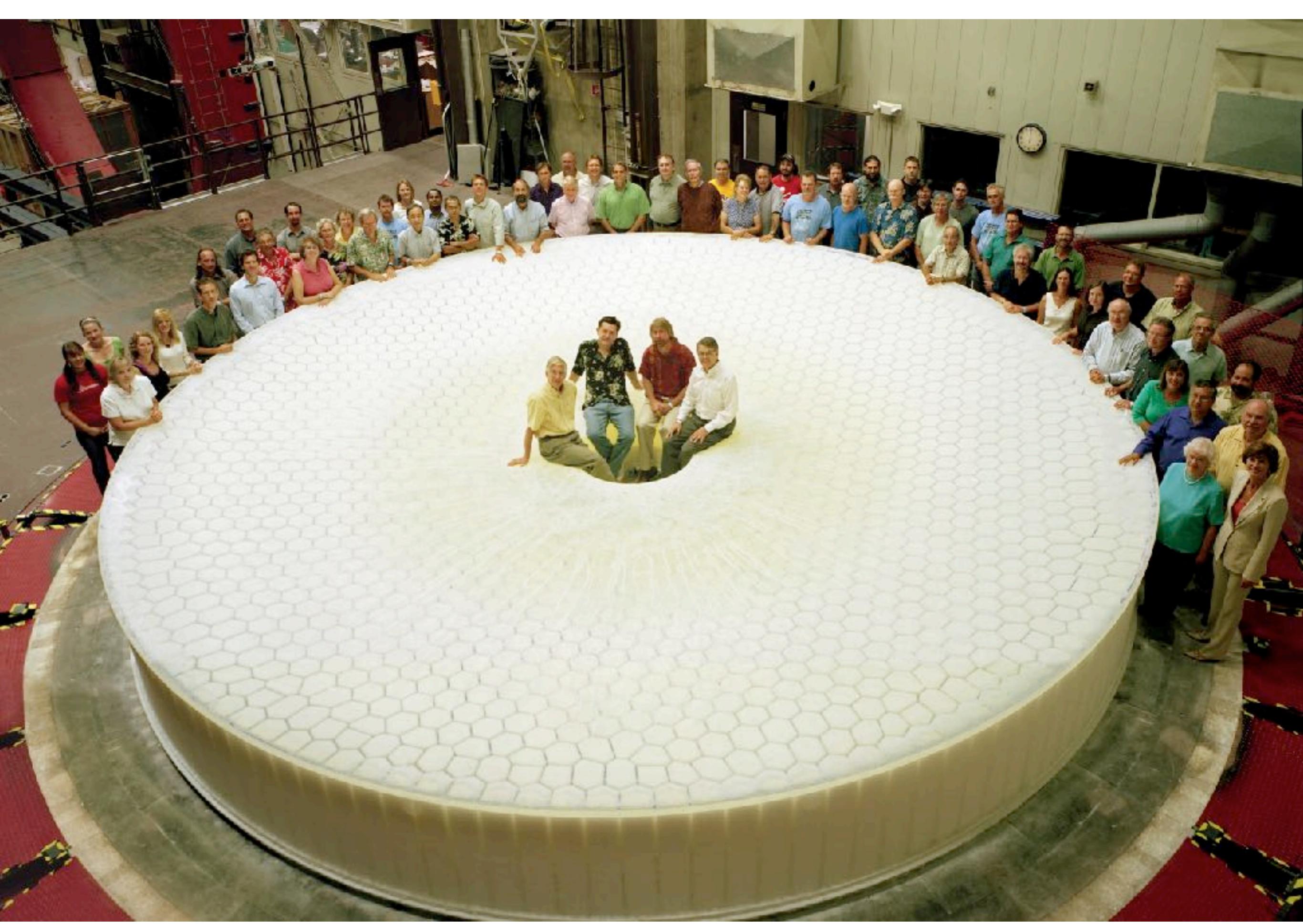


8.4 m

Field of  
View





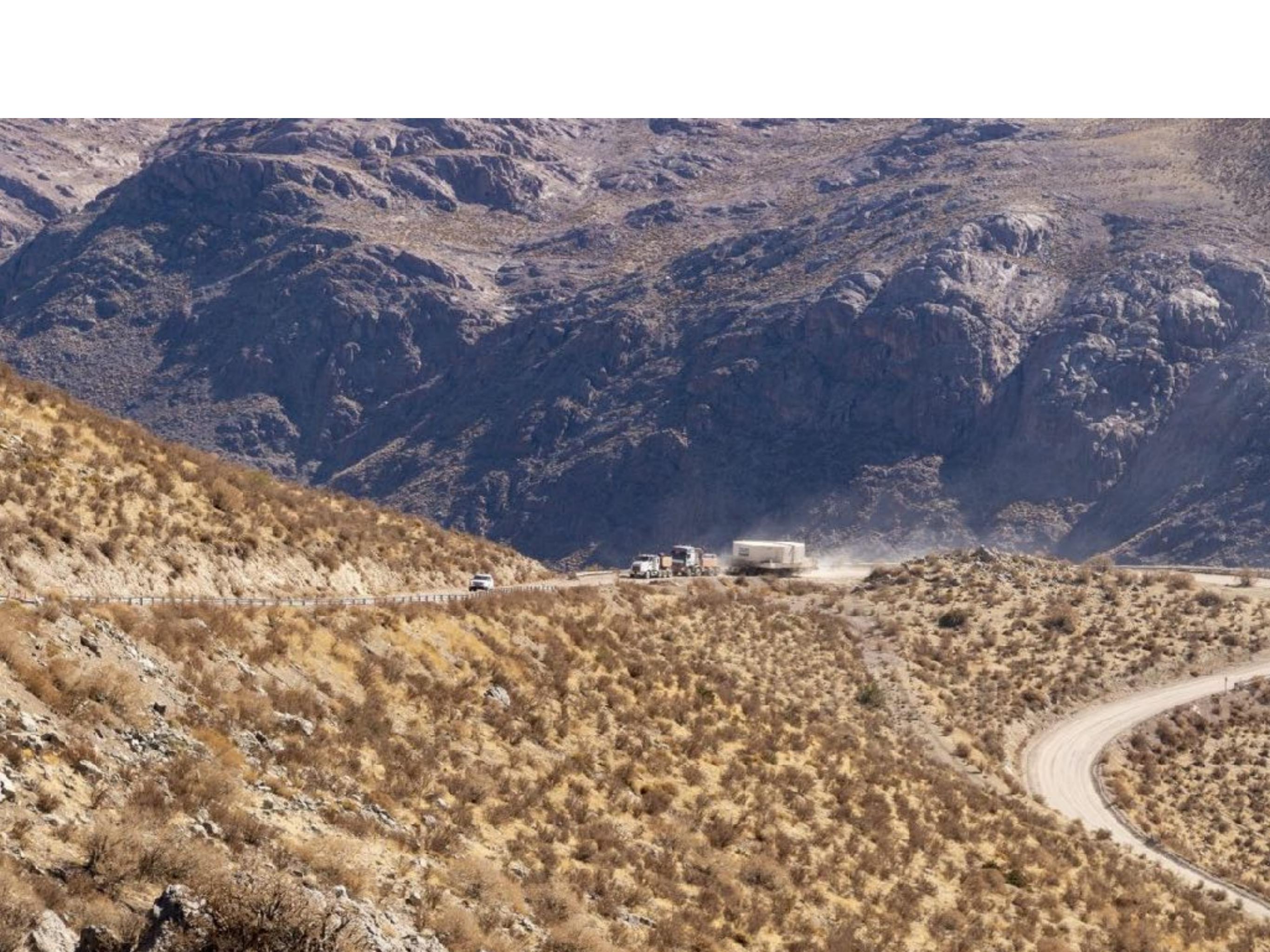


Túnel  
Puclaro

VON ARDENNE

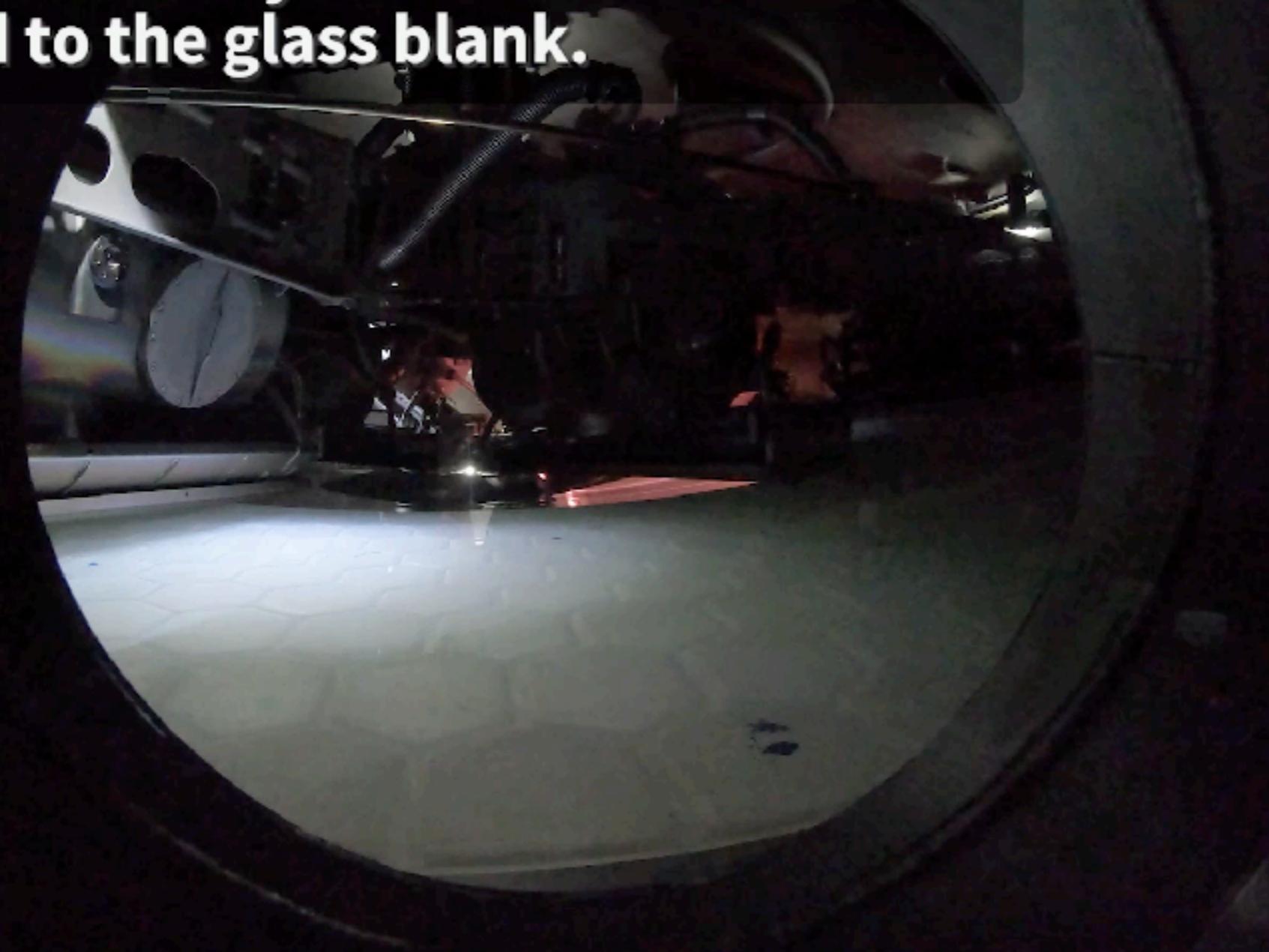
60

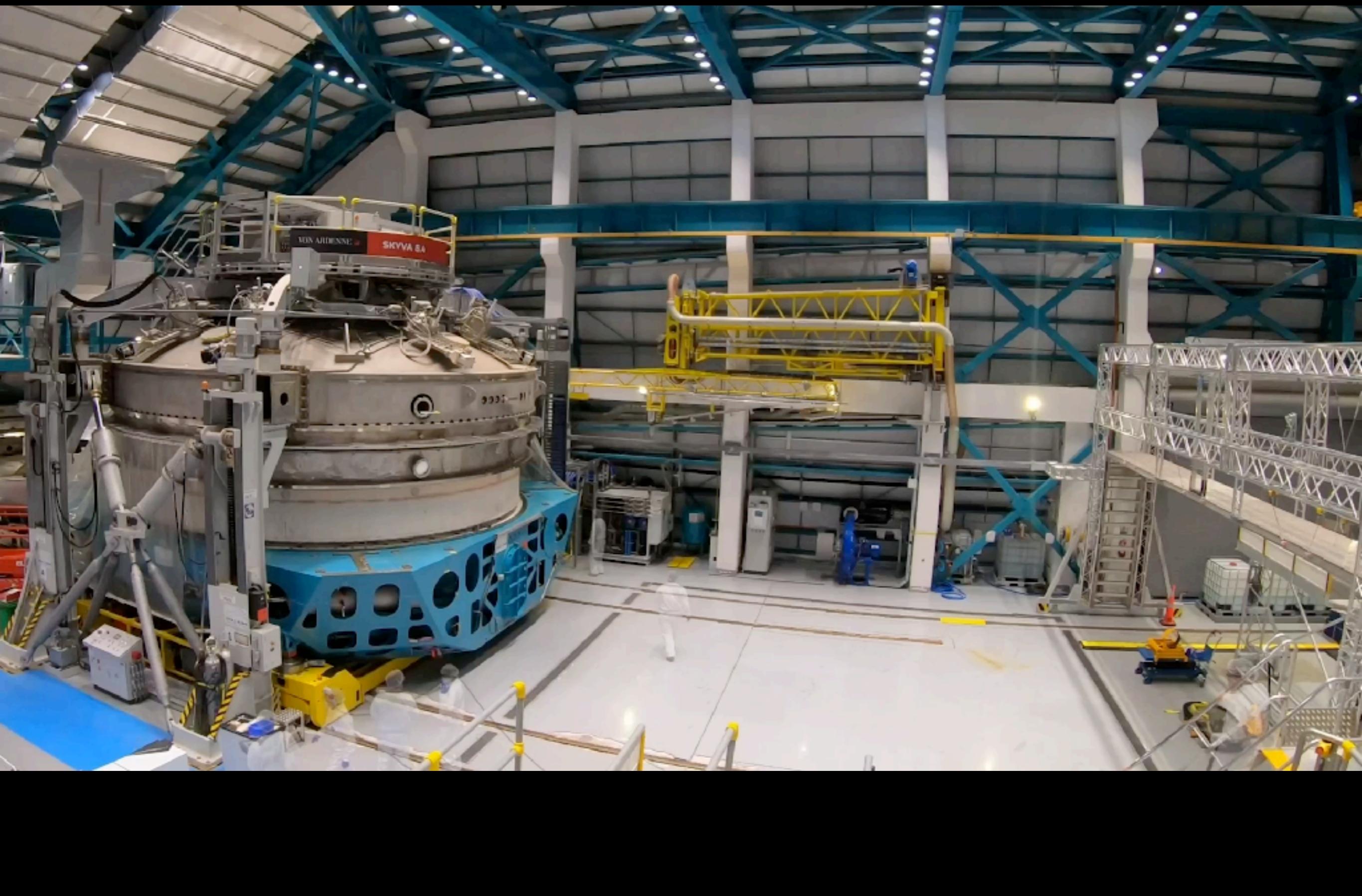
INTERIOR  
TUNNEL



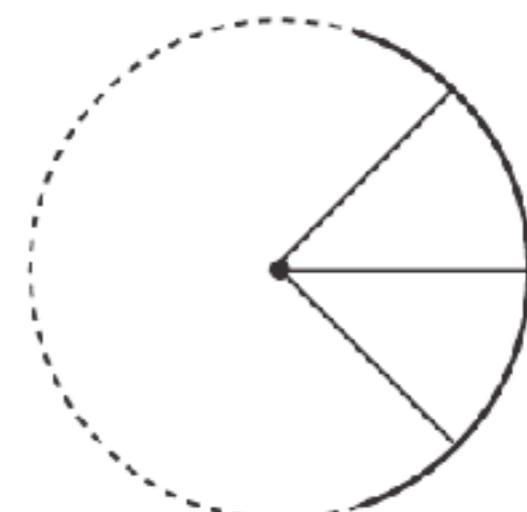
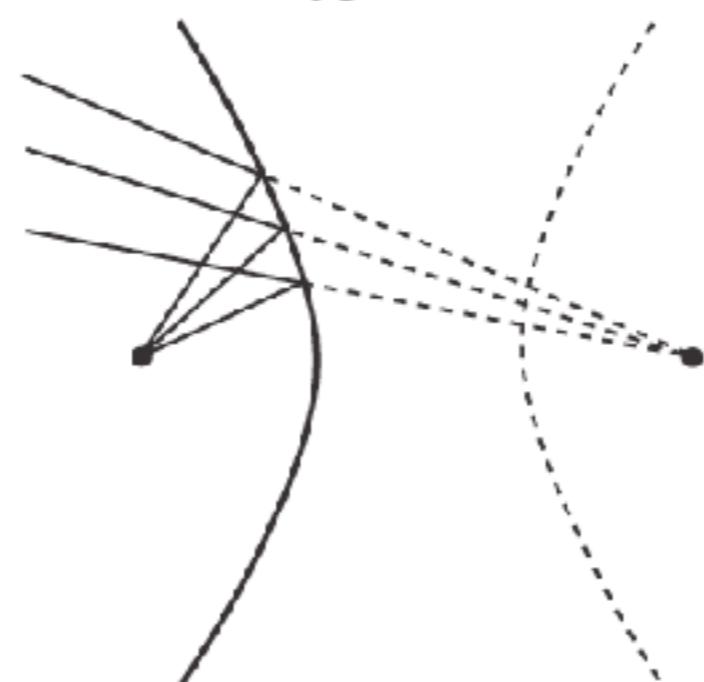
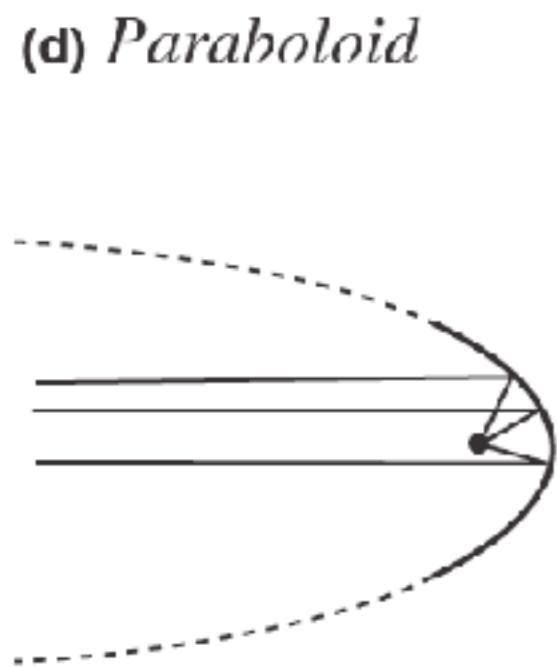
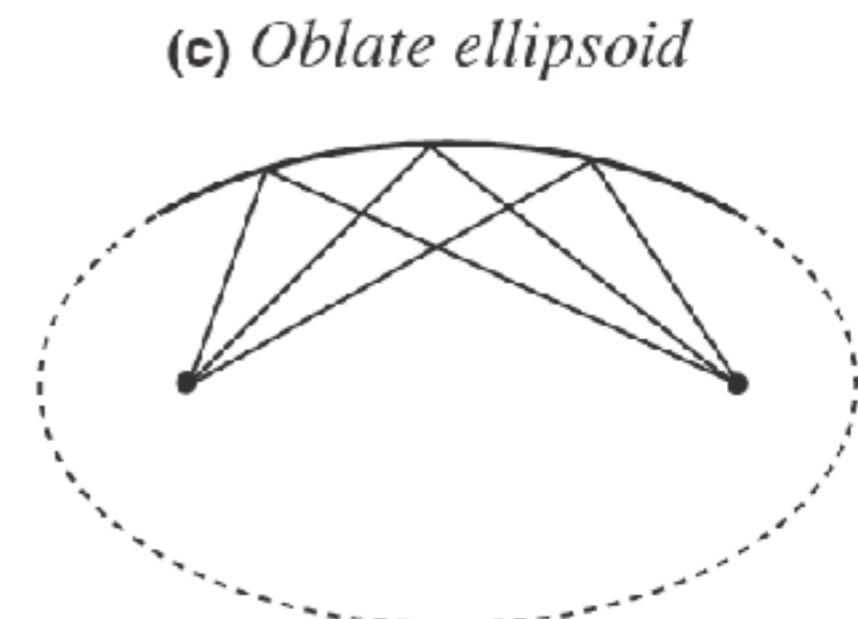
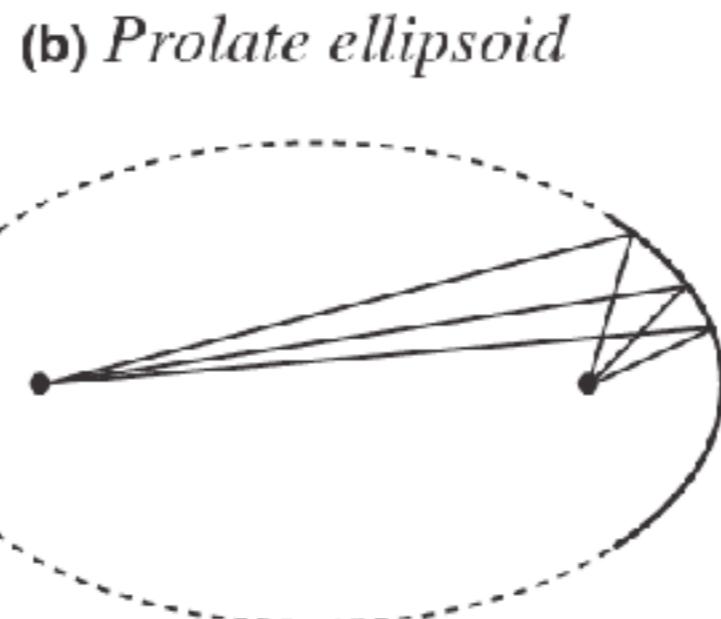
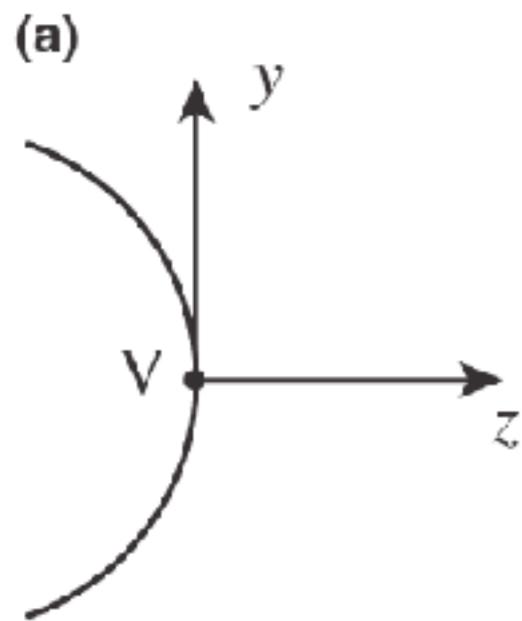


**First, an adhesion layer of nickel-chromium was applied to the glass blank.**

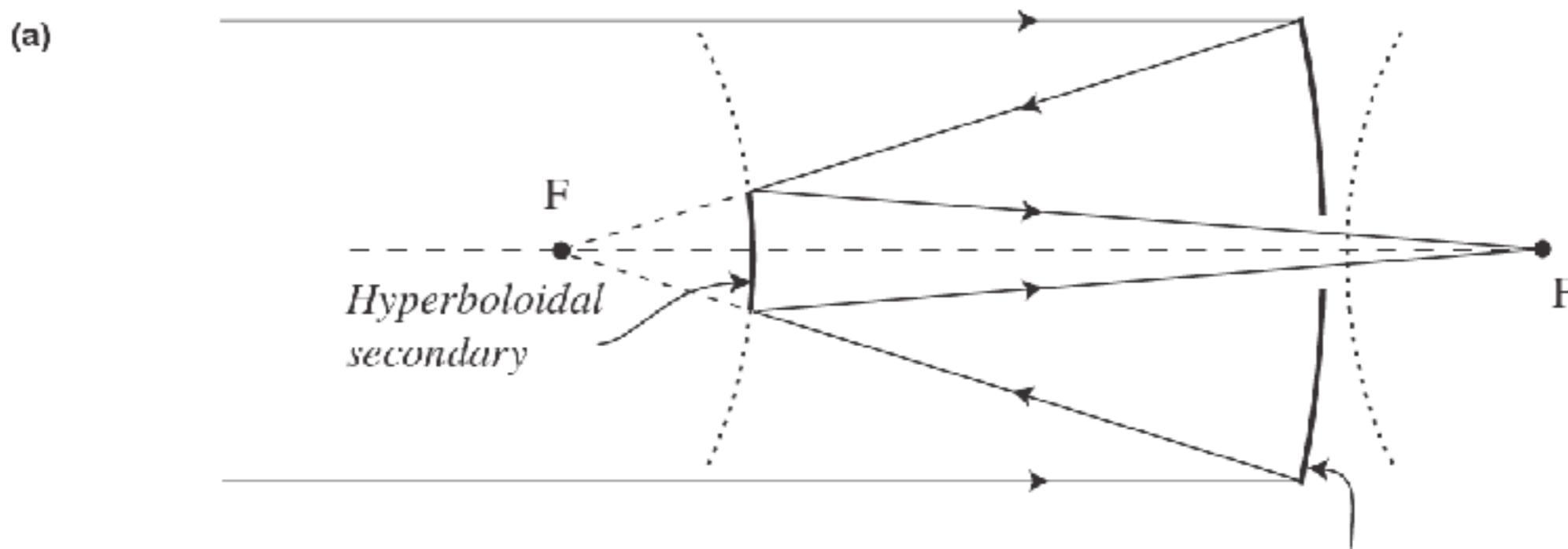




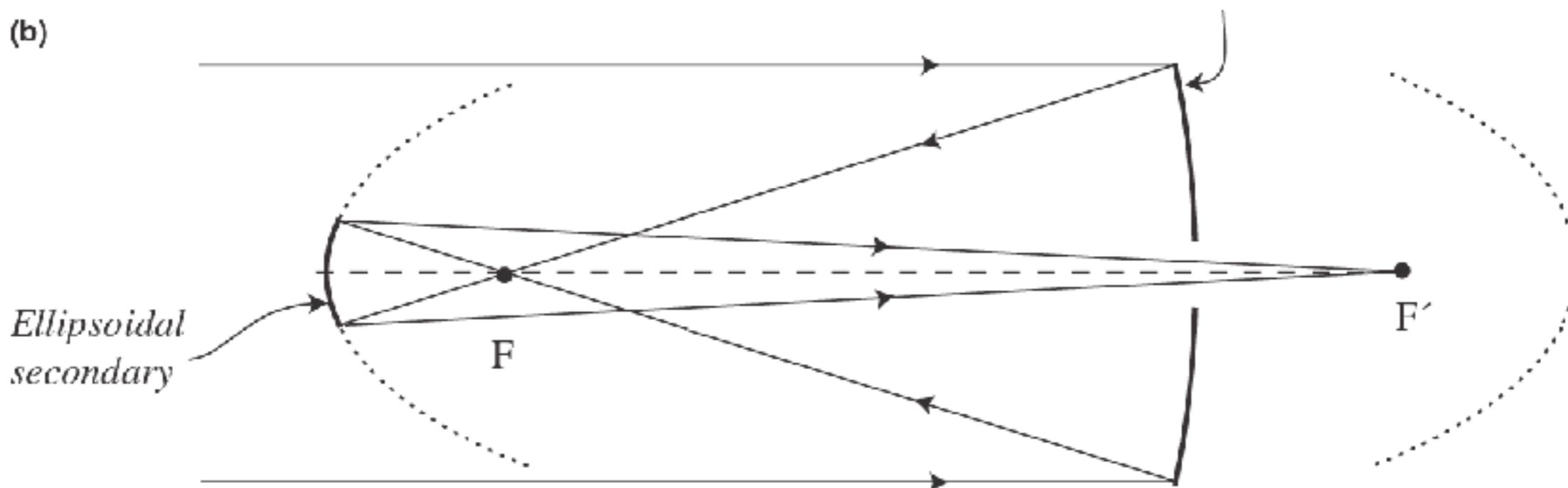
# conic sections of mirrors



# Most common telescopes

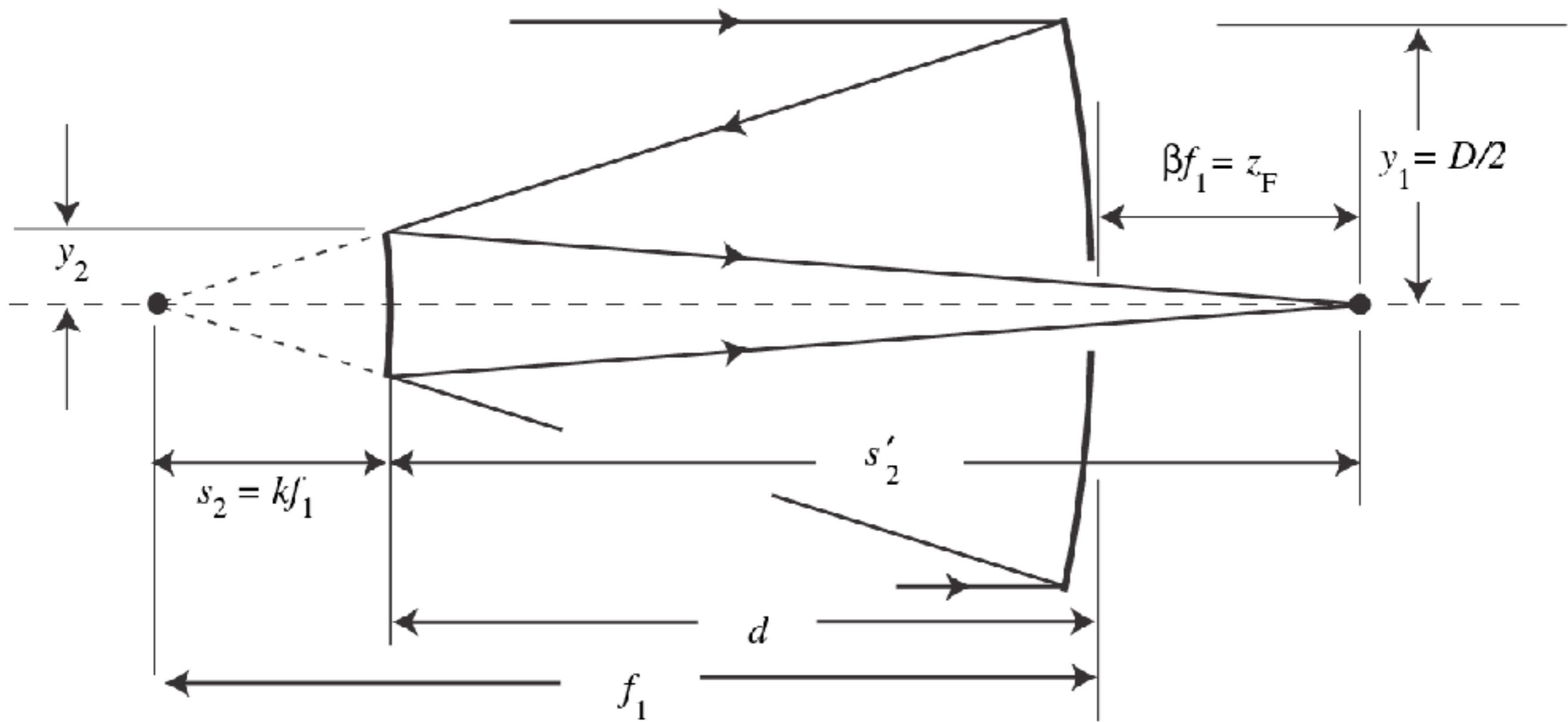


**Cassegrain**



**Gregorian**

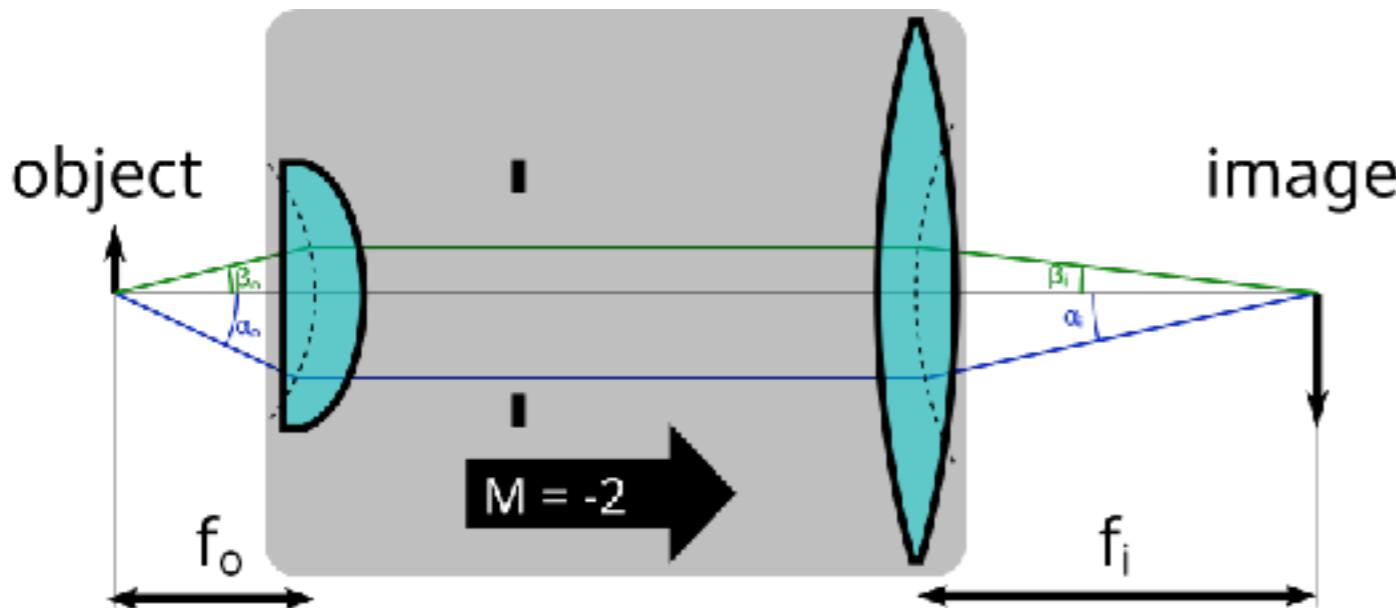
# Parameters for a two-mirror telescope



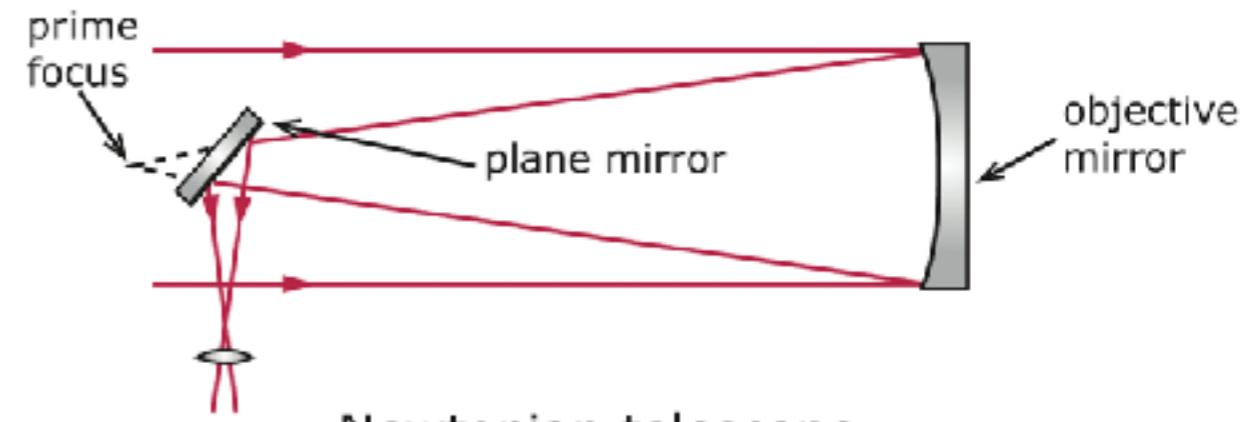
# Basic telescope types

These are all based on Fermat's Principle.

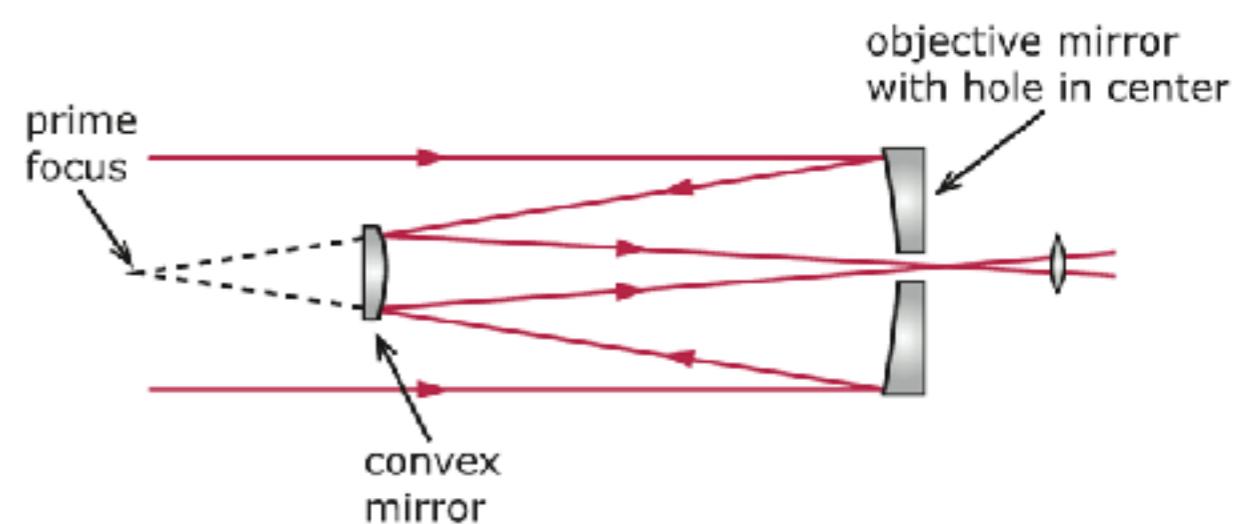
The Ritchey-Cretien looks like the Cassegrain, but abandons the conic sections and instead is optimized around the Abbe Sine Condition:



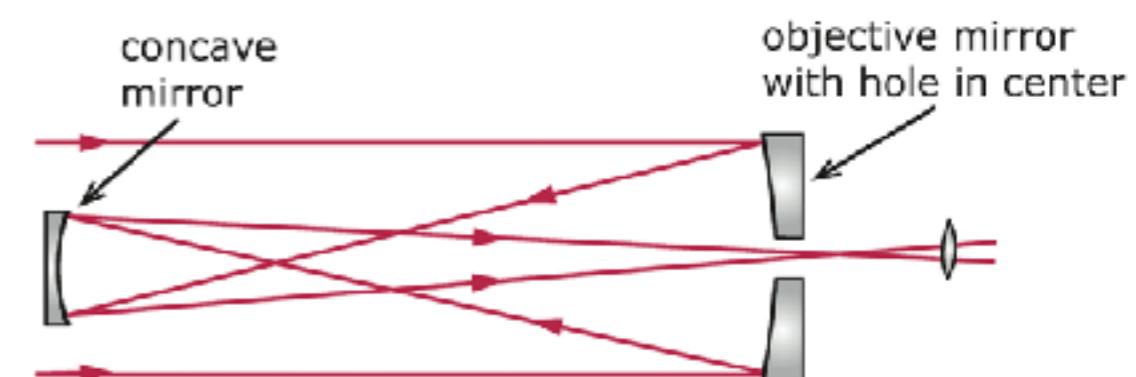
$$\frac{\sin \alpha_o}{\sin \alpha_i} = \frac{\sin \beta_o}{\sin \beta_i} = |M|$$



Newtonian telescope



Cassegrain telescope

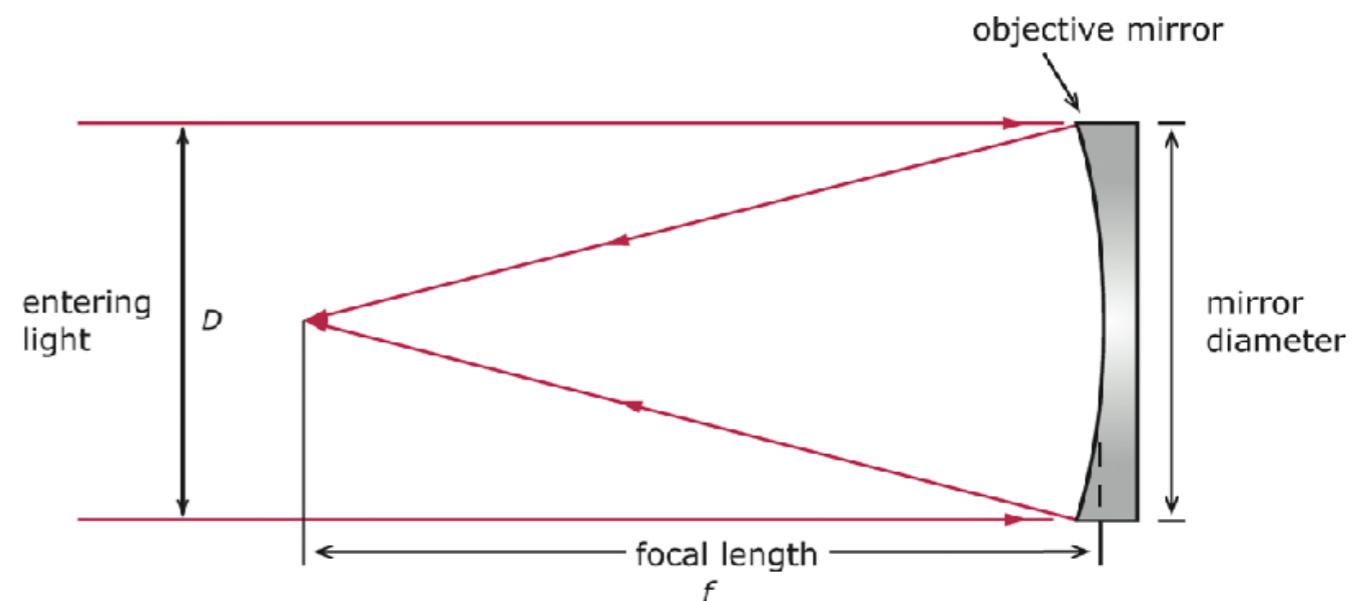


Gregorian telescope

## Diffraction limit

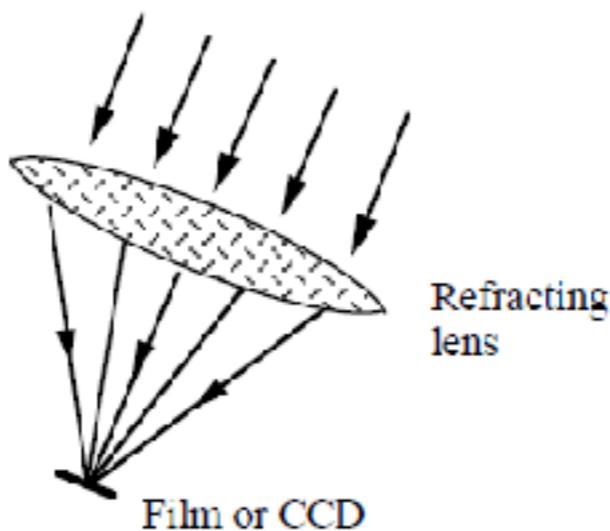
$$\theta \simeq 1.22 \frac{\lambda}{D}$$

focal length  
f-number =  $f/D$

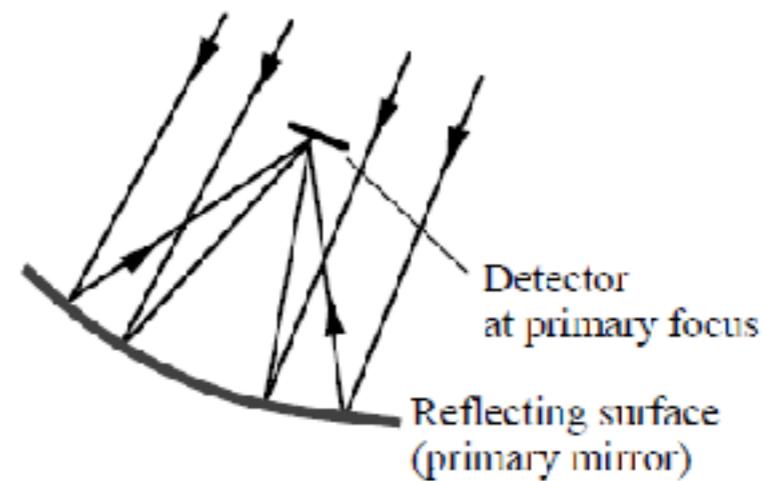


optical accuracy requirements  
RMS  $< \lambda/10$

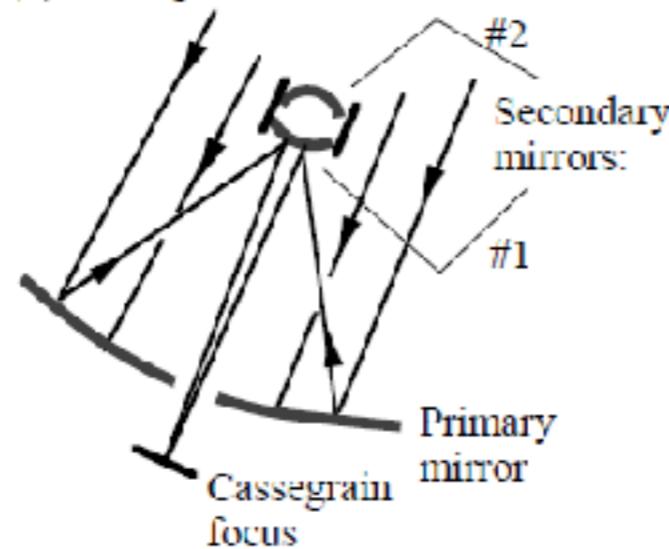
(a) Refracting lens



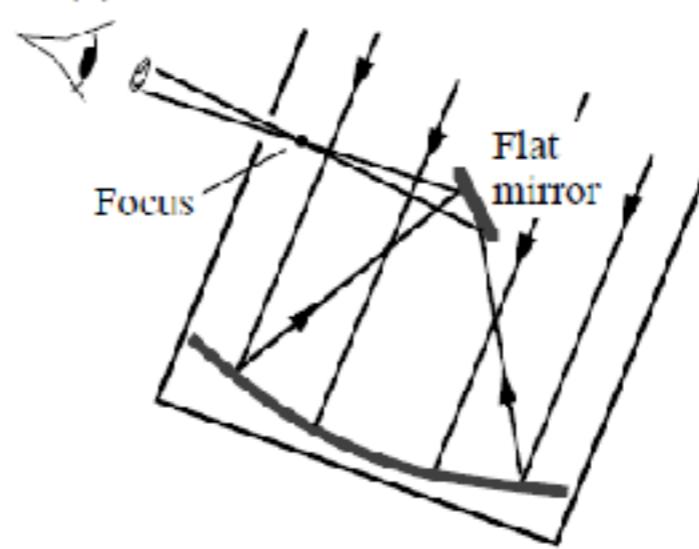
(b) Reflector: primary focus



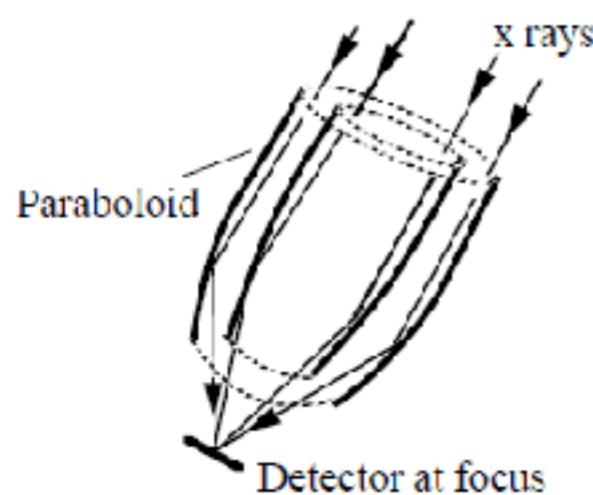
(c) Cassegrain focus



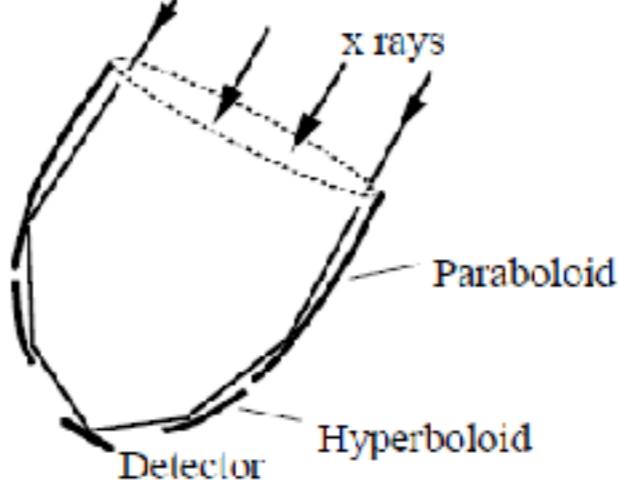
(d) Newtonian focus



(e) Grazing-incidence reflector (x rays)

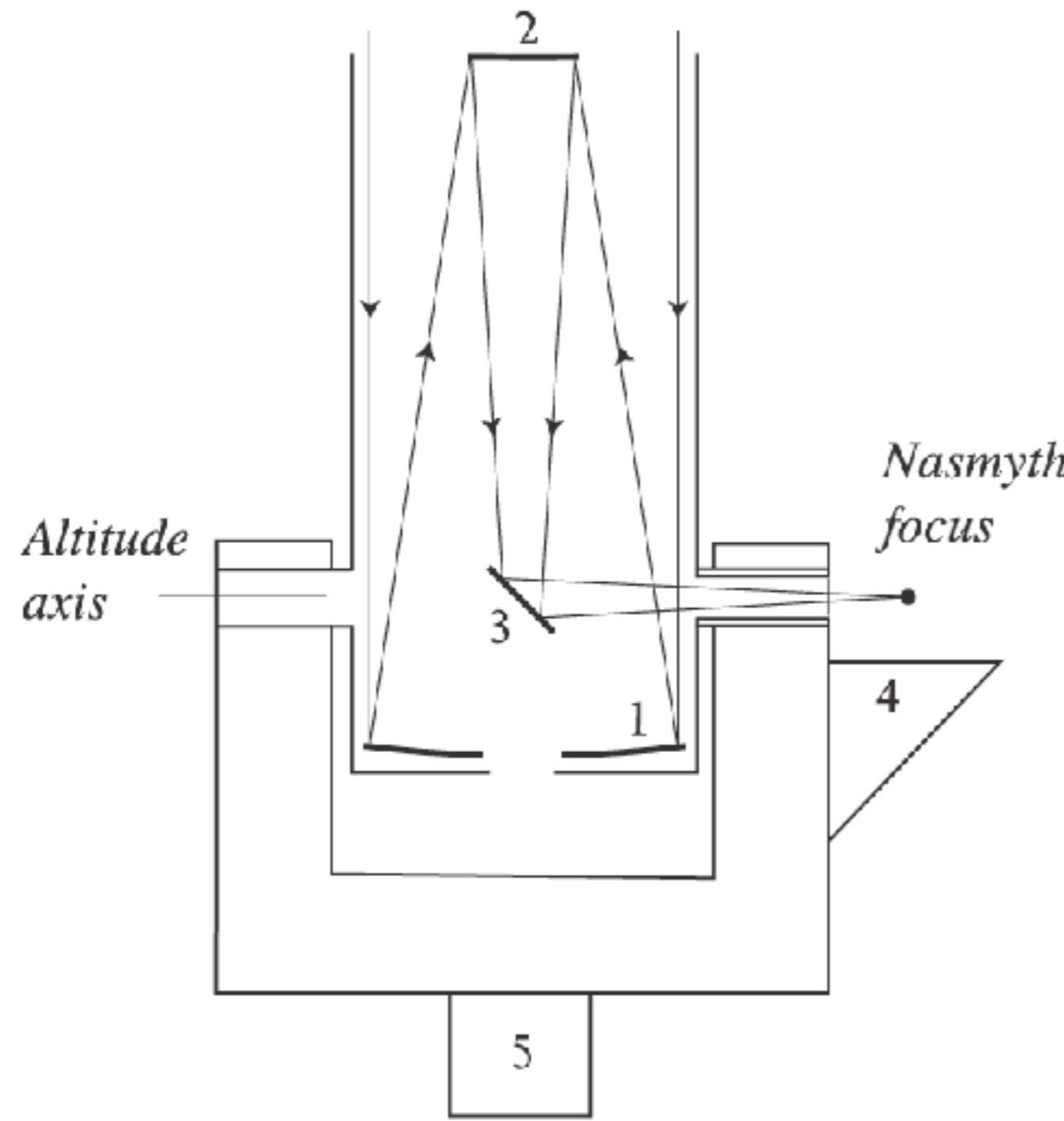


(f) Grazing-incidence focusing

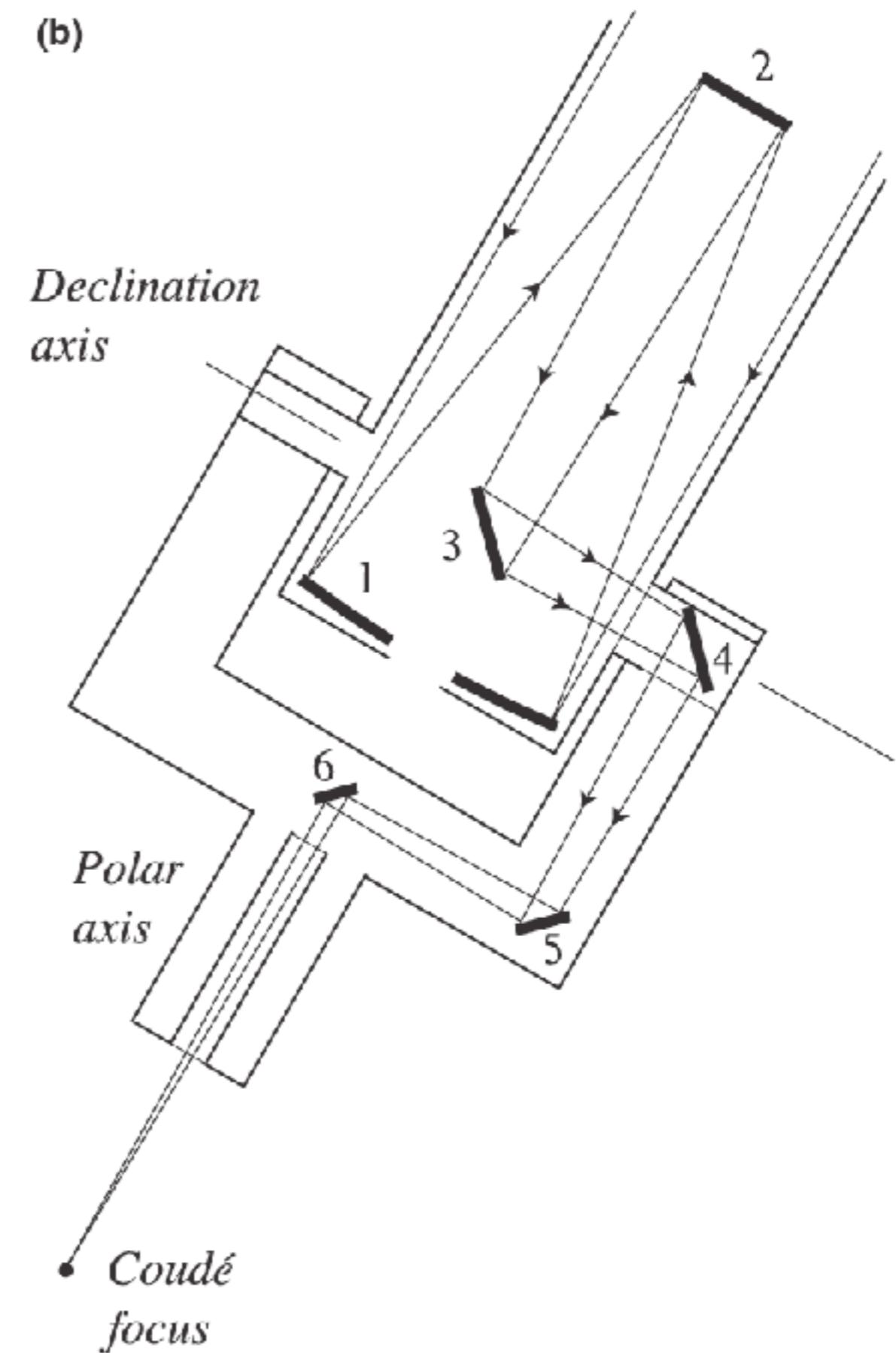


# Other foci

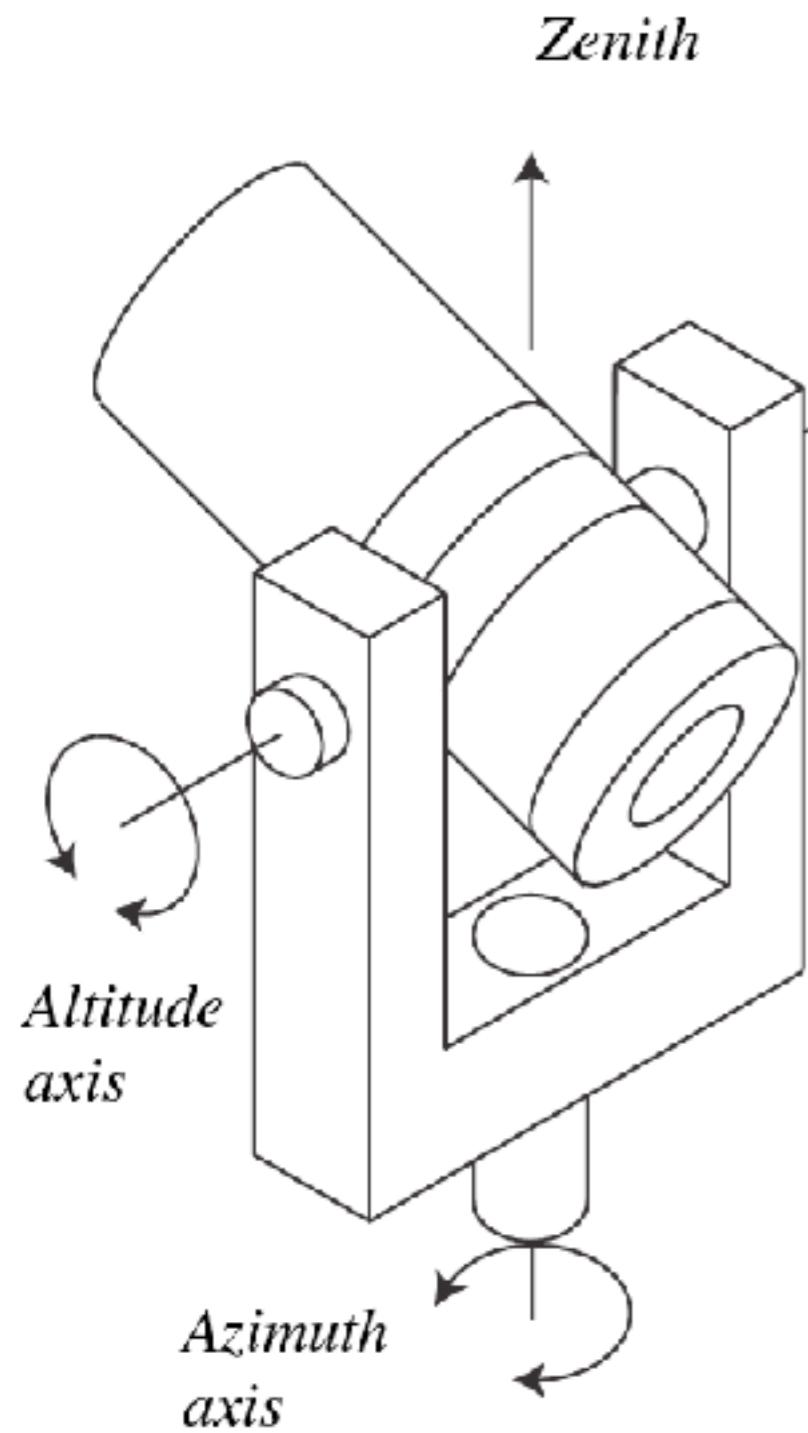
(a)



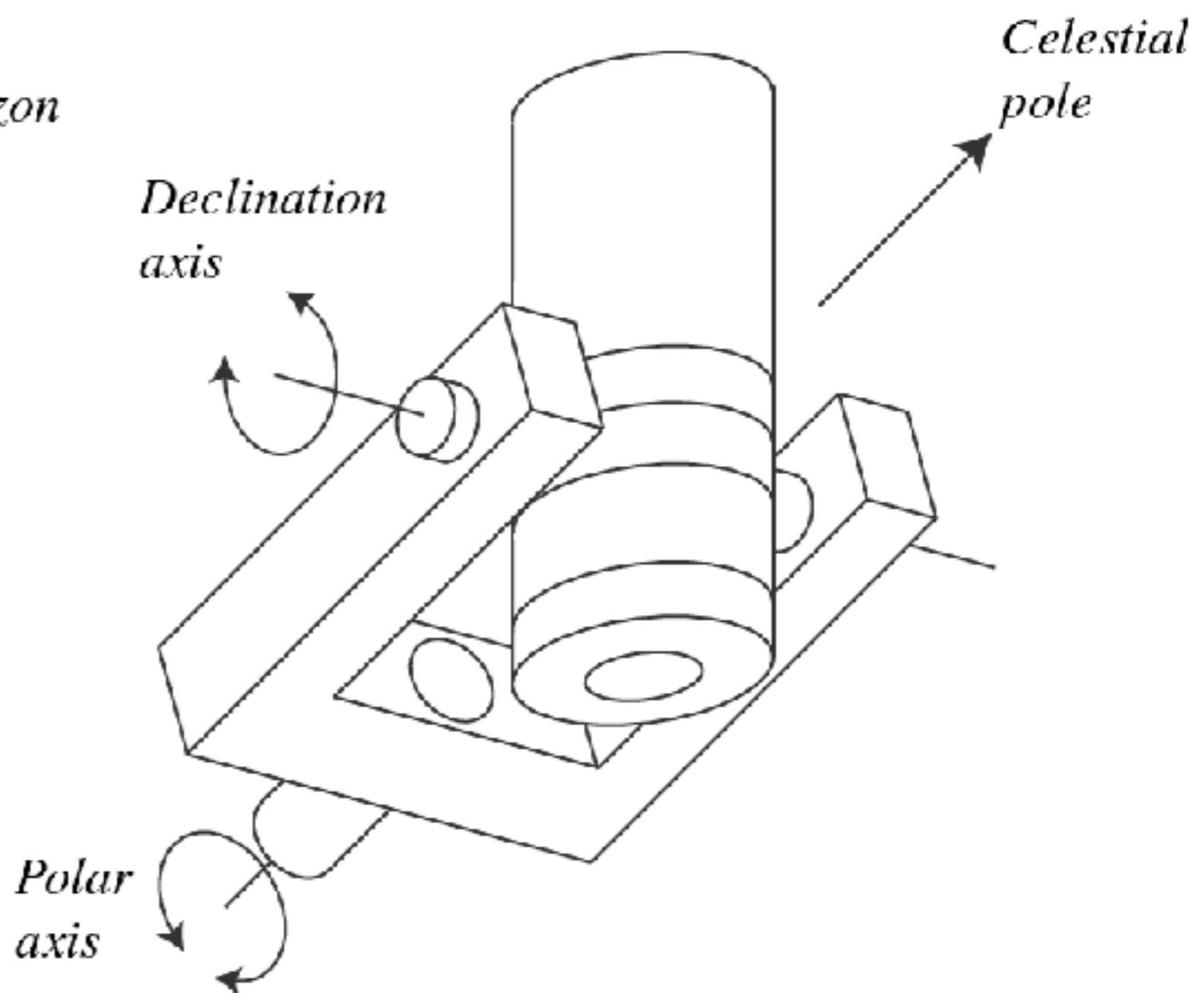
(b)



# Telescope Mounts



altazimuth



equatorial

# Mounts: Zenith



spinning mercury mirror

## Mounts: Zenith



Arecibo Observatory  
1000 ft ; 305 m aperture  
spherical reflector

## Mounts: Zenith



Arecibo Observatory  
1000 ft ; 305 m aperture  
spherical reflector

## Mounts: Transit (fixed AZ)



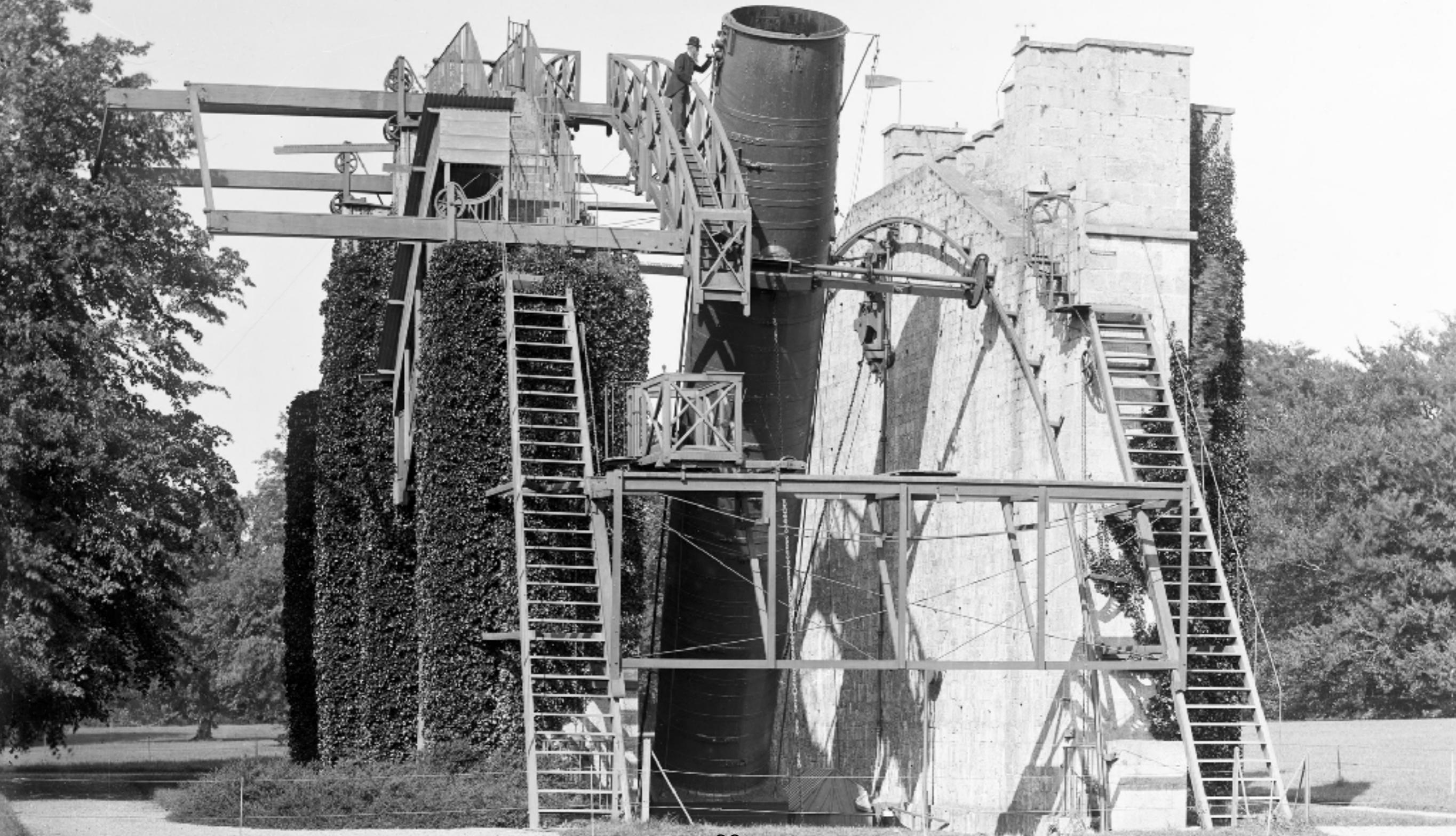
# Mounts: Transit (~limited motion in AZ)

Leviathan of Parsontown

72-inch (1.8m) aperture

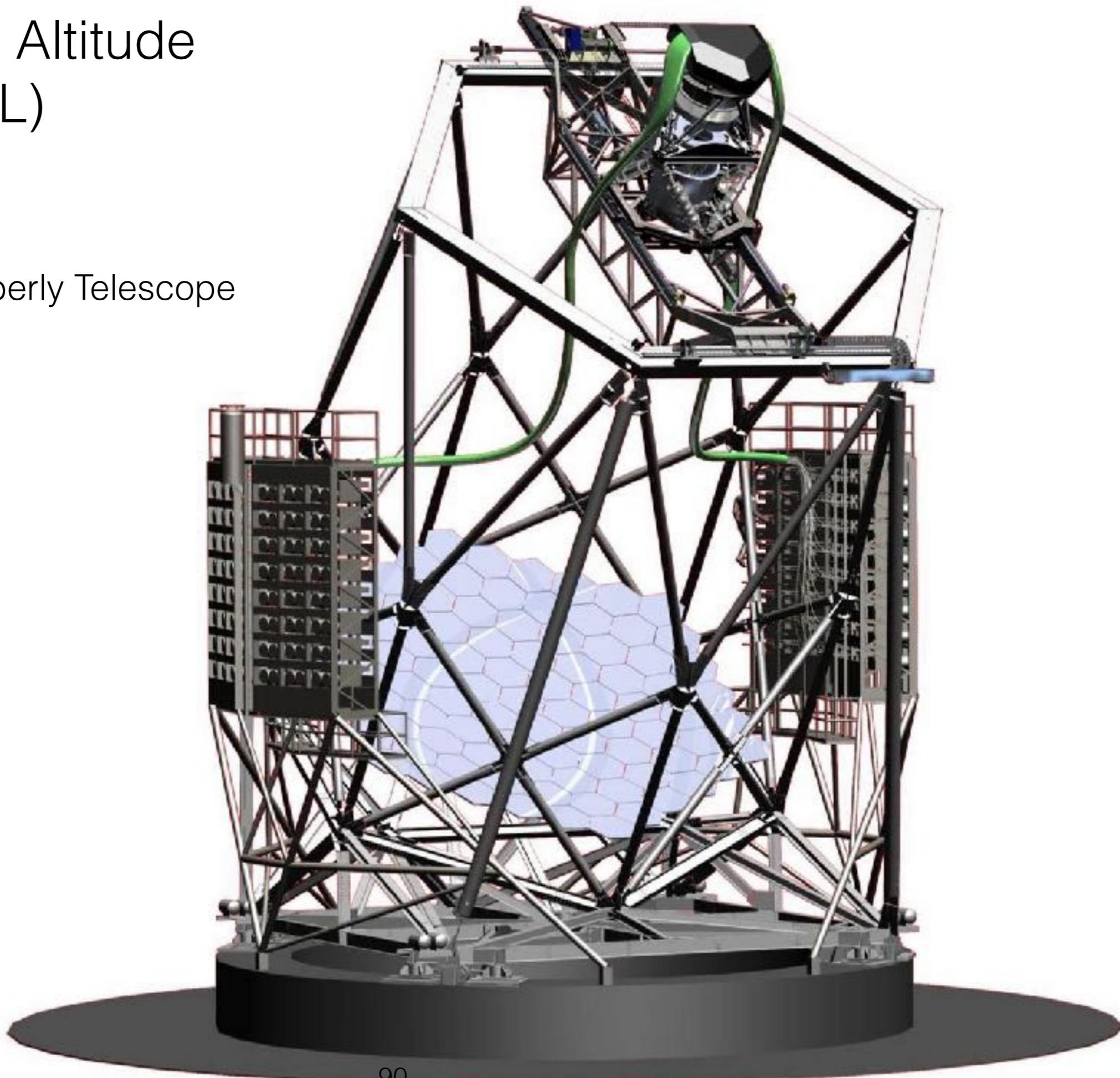
Largest in the world from 1845-1917

Only 1 hr (15 deg) range of motion in AZ



# Mounts: Fixed Altitude (fixed EL)

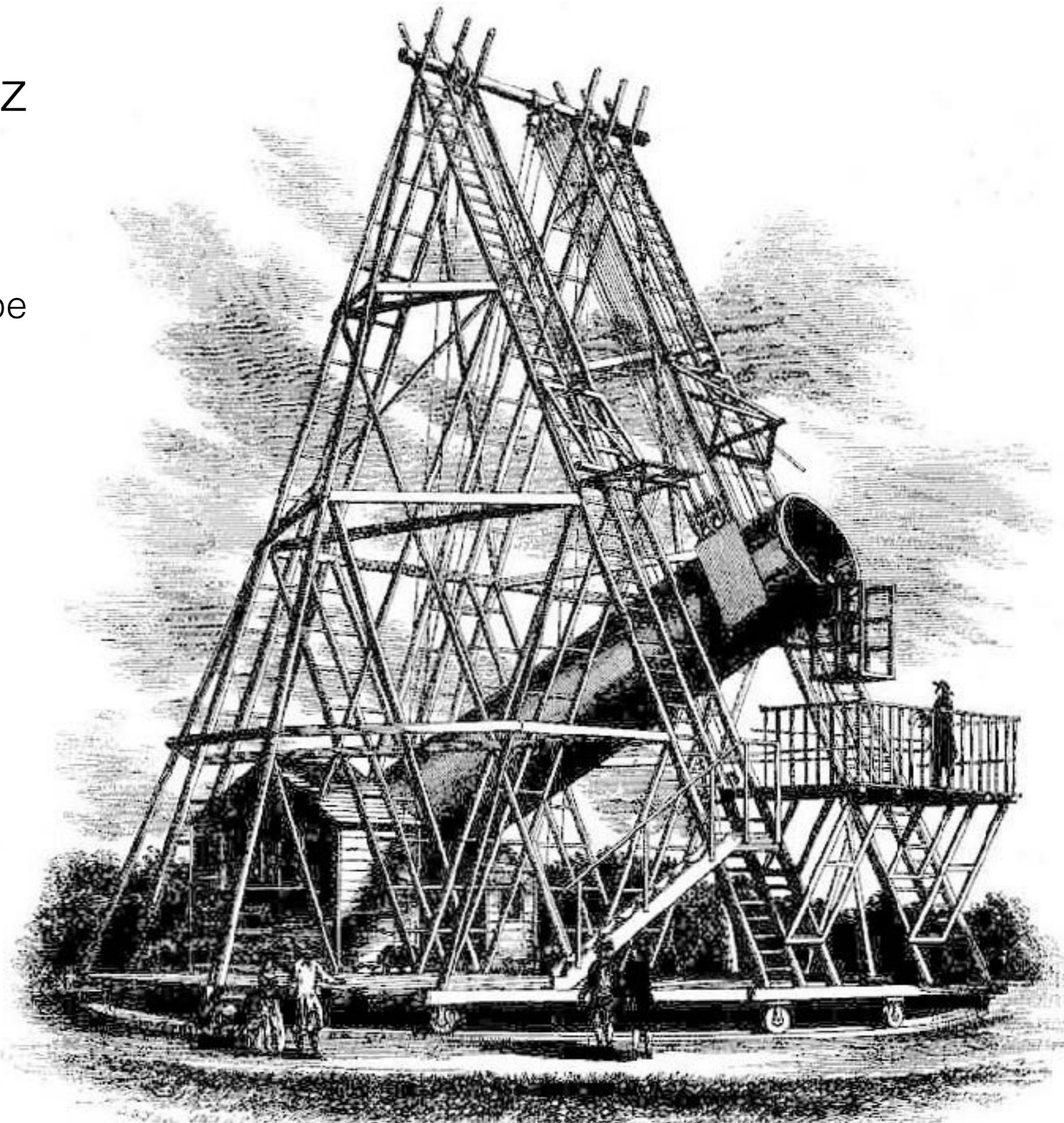
e.g. 9.2m Hobby-Eberly Telescope



## Mounts: Alt-Az

Herschel's 40-foot telescope  
47-inch diameter (1.2m)  
completed in 1789

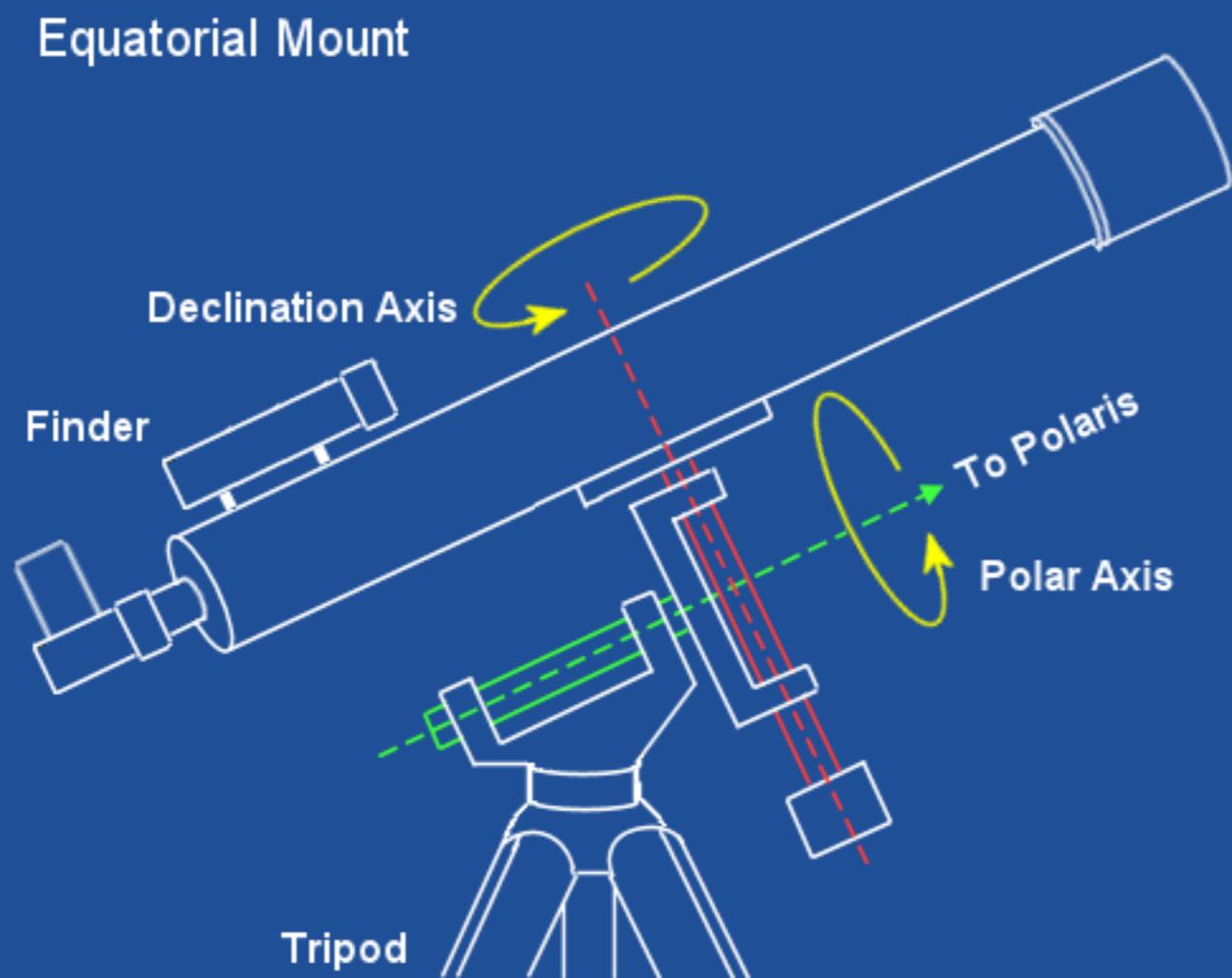
proved to be cumbersome  
and unwieldy



## Mounts: Alt-Az



# Mounts: Equatorial



# Mounts: Equatorial

University of Illinois 12"  
Built in 1896  
National Historic Landmark

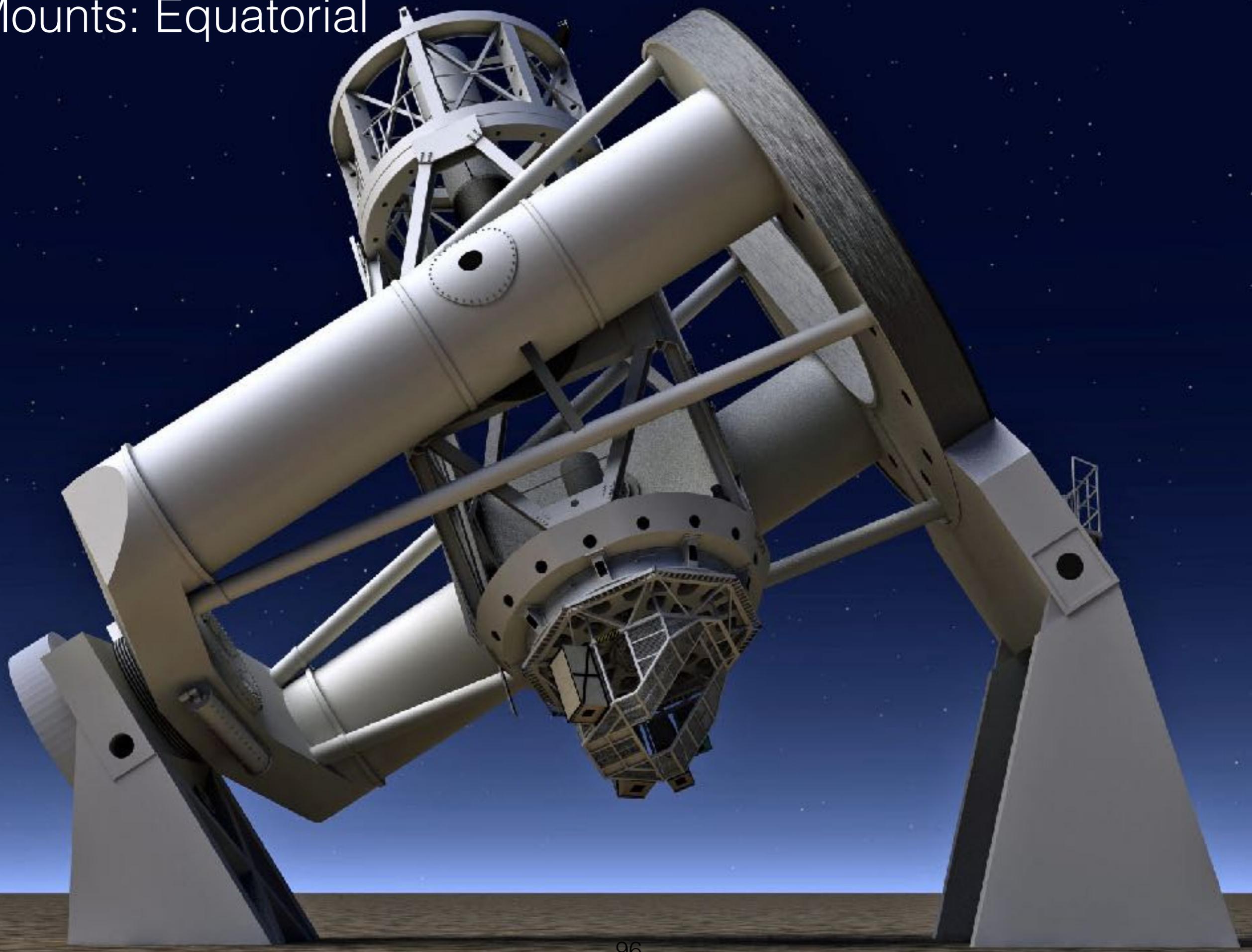


# Mounts: Equatorial

Palomar Hale 200"  
Largest telescope built with an equatorial mount



## Mounts: Equatorial



# Mounts: Alt-Az

## BTA-6m

- Built by the USSR in 1976
- 6m at 2000m in the Caucuses
- First modern telescope to use an Alt-Az mount (and computer control)
- “BTA” = “Large Altazimuth Telescope”
- Mirror, optical design, dome, site, instruments ... nothing worked.
- Palomar remained “largest effective aperture” until Keck in 1992
- Ahead of it's time ? ... or piece of junk ?

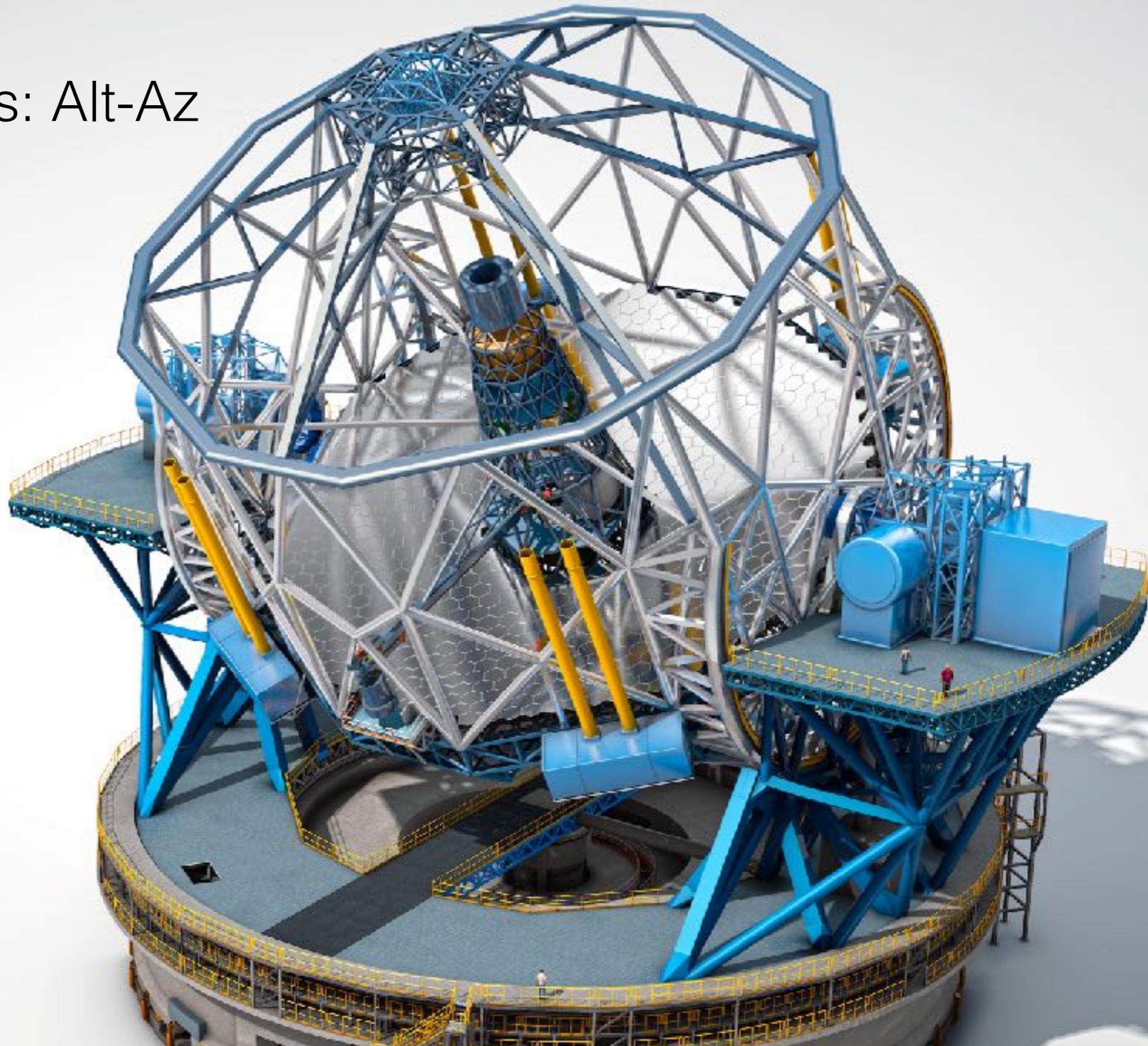
# Mounts: Alt-Az

4.2m William Herschel Telescope built in 1987

- Since ~1980, all major telescope built with altazimuth mounts
- Difficulties:
  - need computer control (trivial nowadays)
  - the PA of the image rotates on the sky.
  - Difficult to observe zenith
- Advantages:
  - lighter = less steel = cheaper

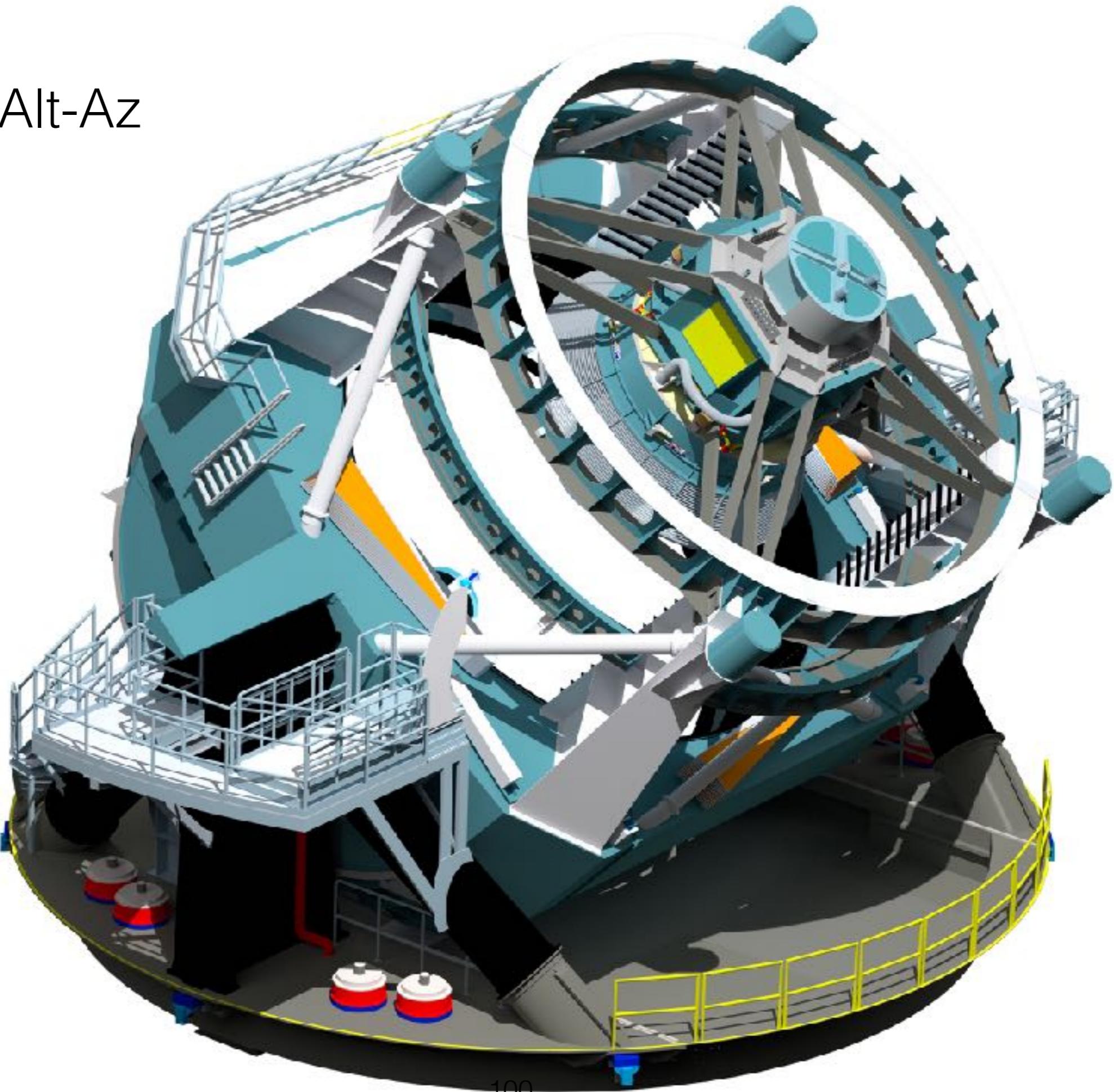


Mounts: Alt-Az



European Extremely Large Telescope

Mounts: Alt-Az



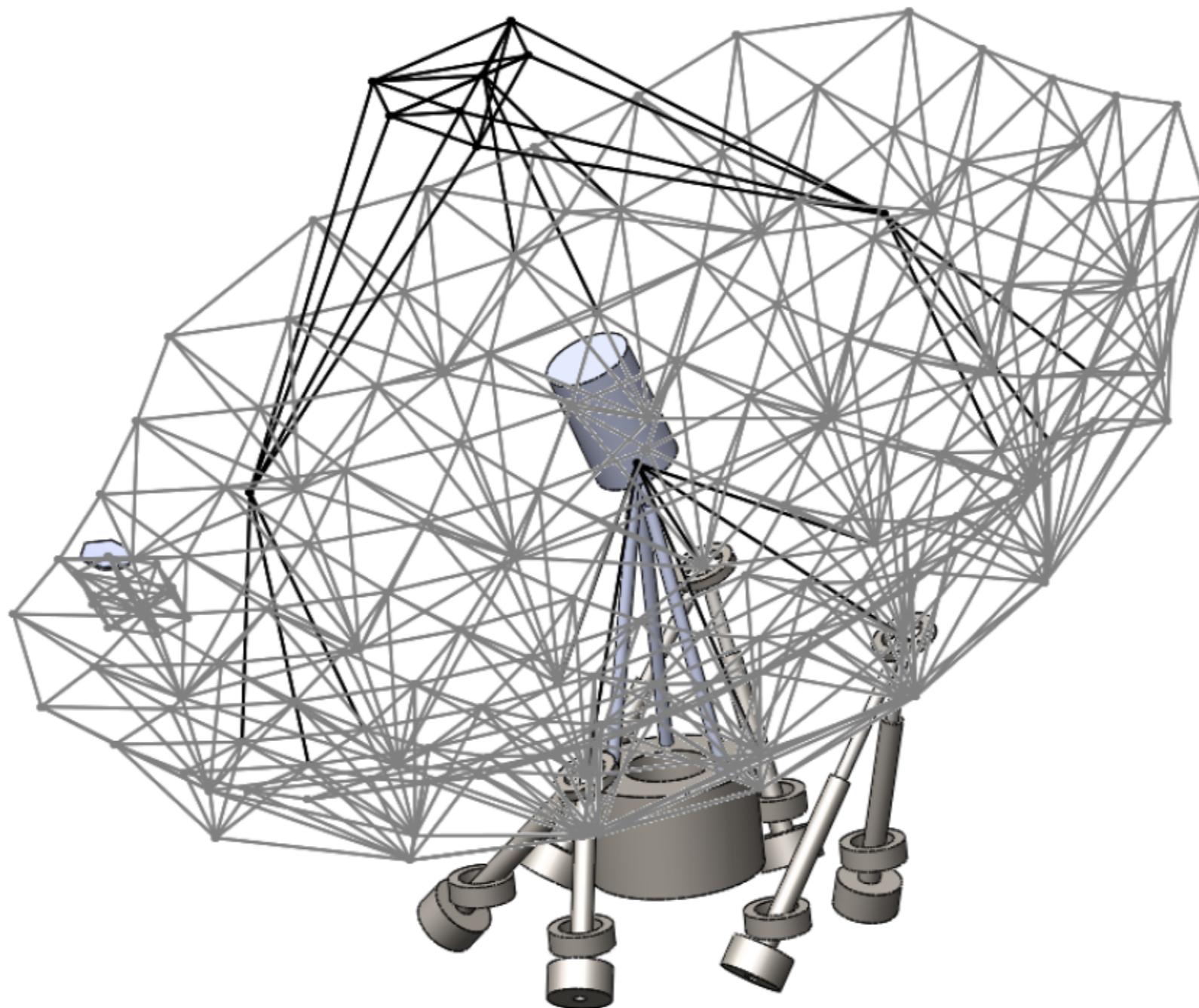
Rubin

# South Pole Telescope

Alt-Az or Equatorial mount ?



# Mounts: Hexapod



Chajnantor Submillimeter Survey Telescope

# The South Pole



# The South Pole Telescope



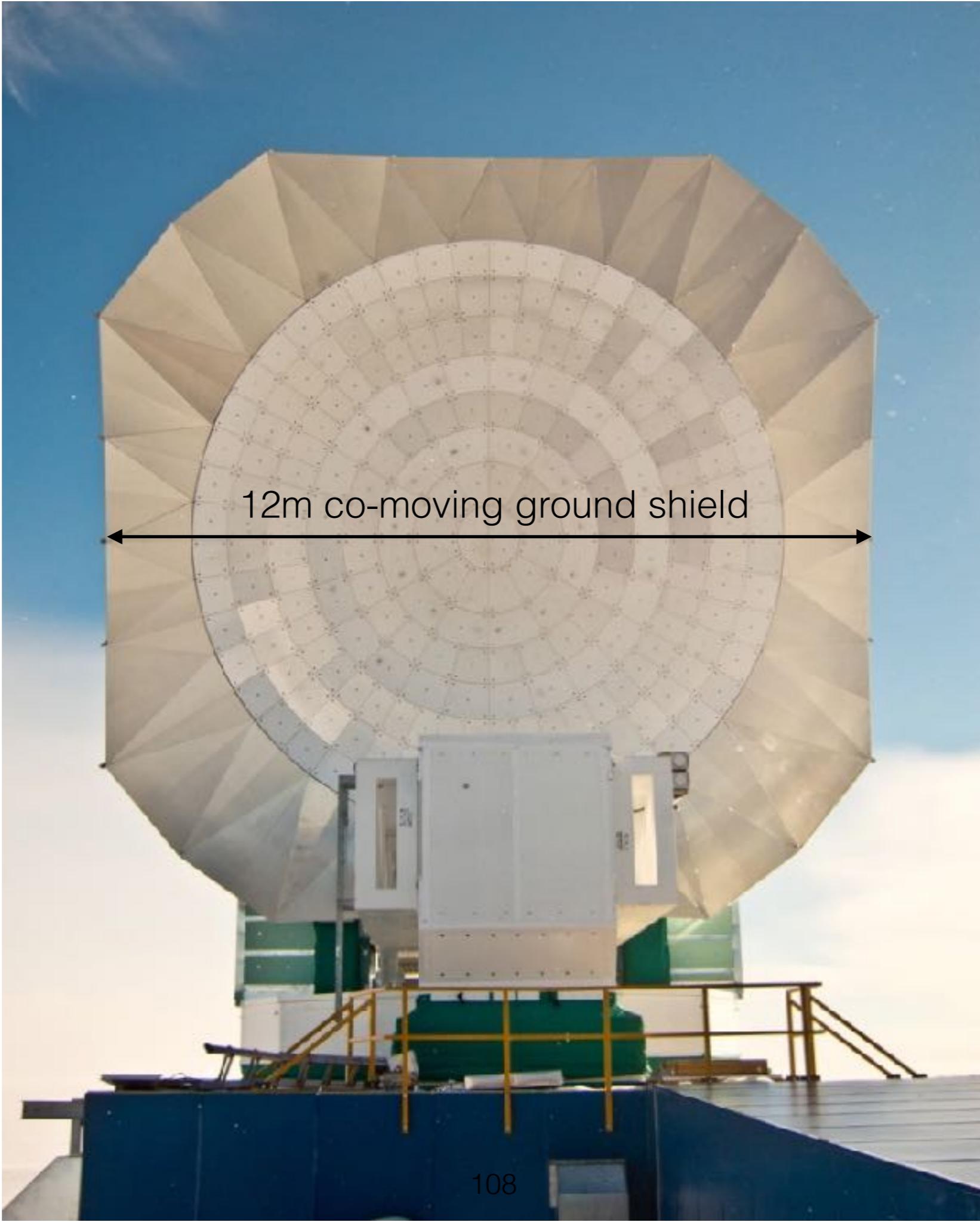
# The South Pole Telescope

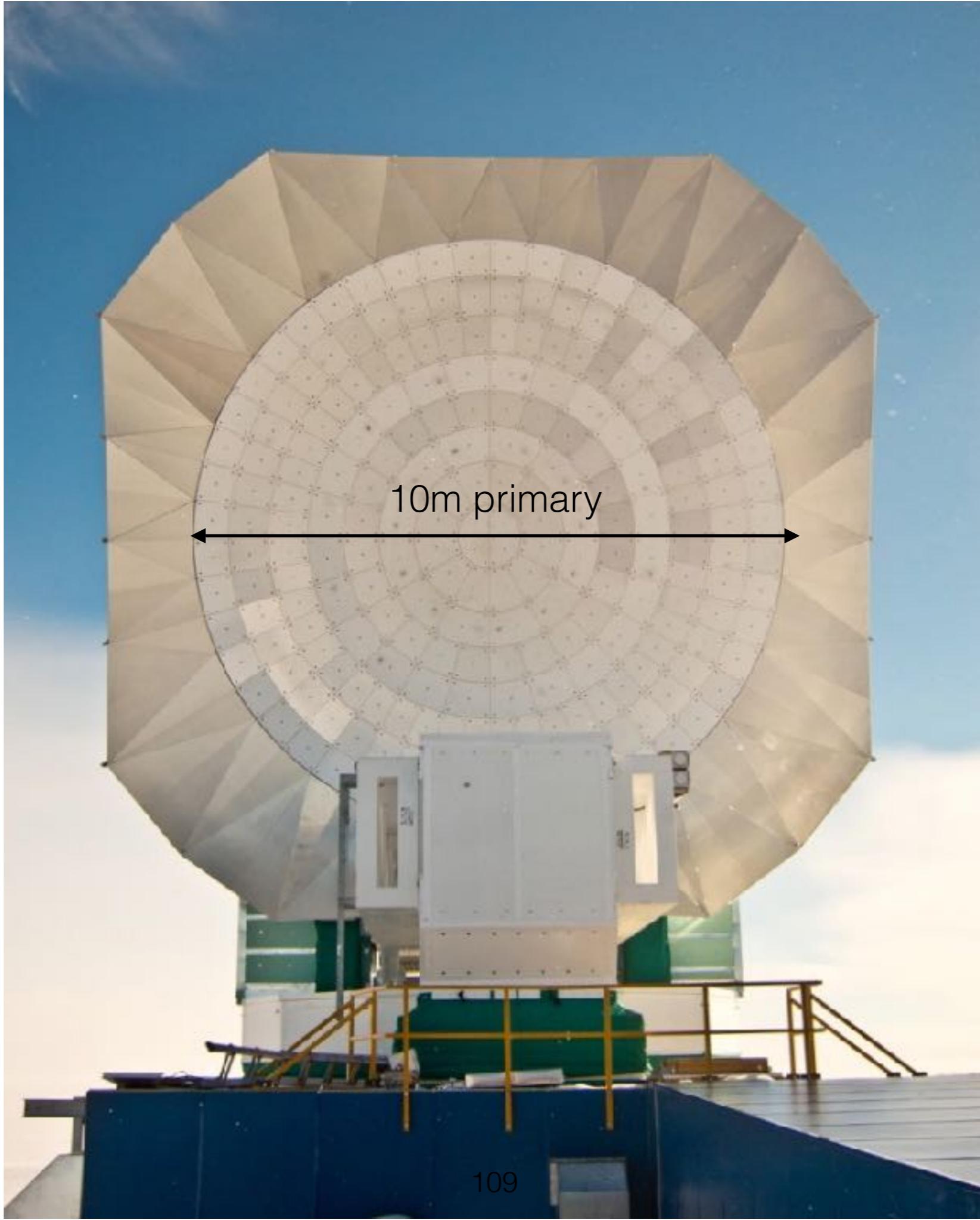


# The South Pole Telescope Mirror











# Optics

Very clean, low-noise, optical design:

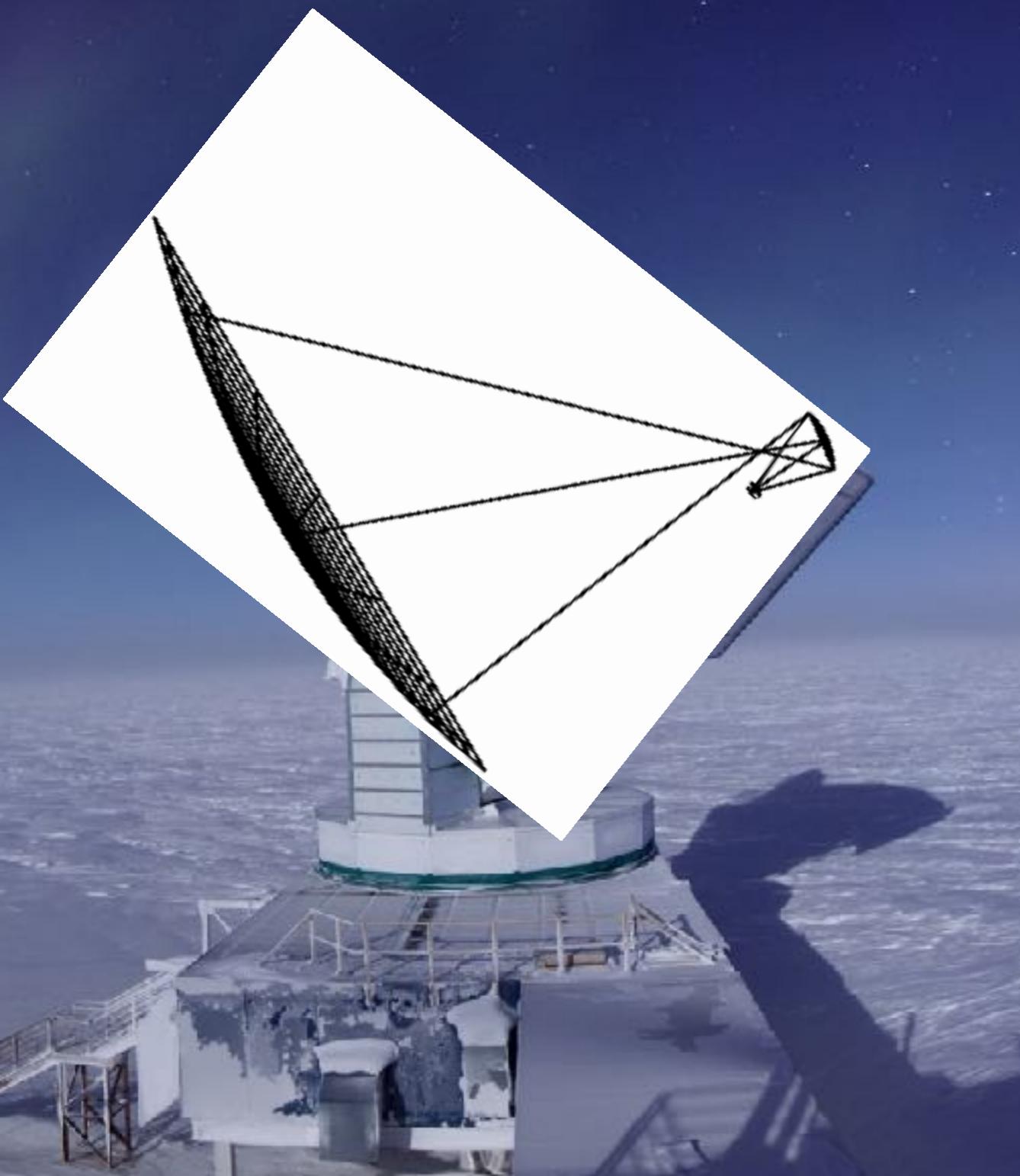
- Cold (10K) secondary acts as the stop
- Under-illuminated primary mirror (8m)
- Co-moving ground shield



# Optics

Very clean, low-noise, optical design:

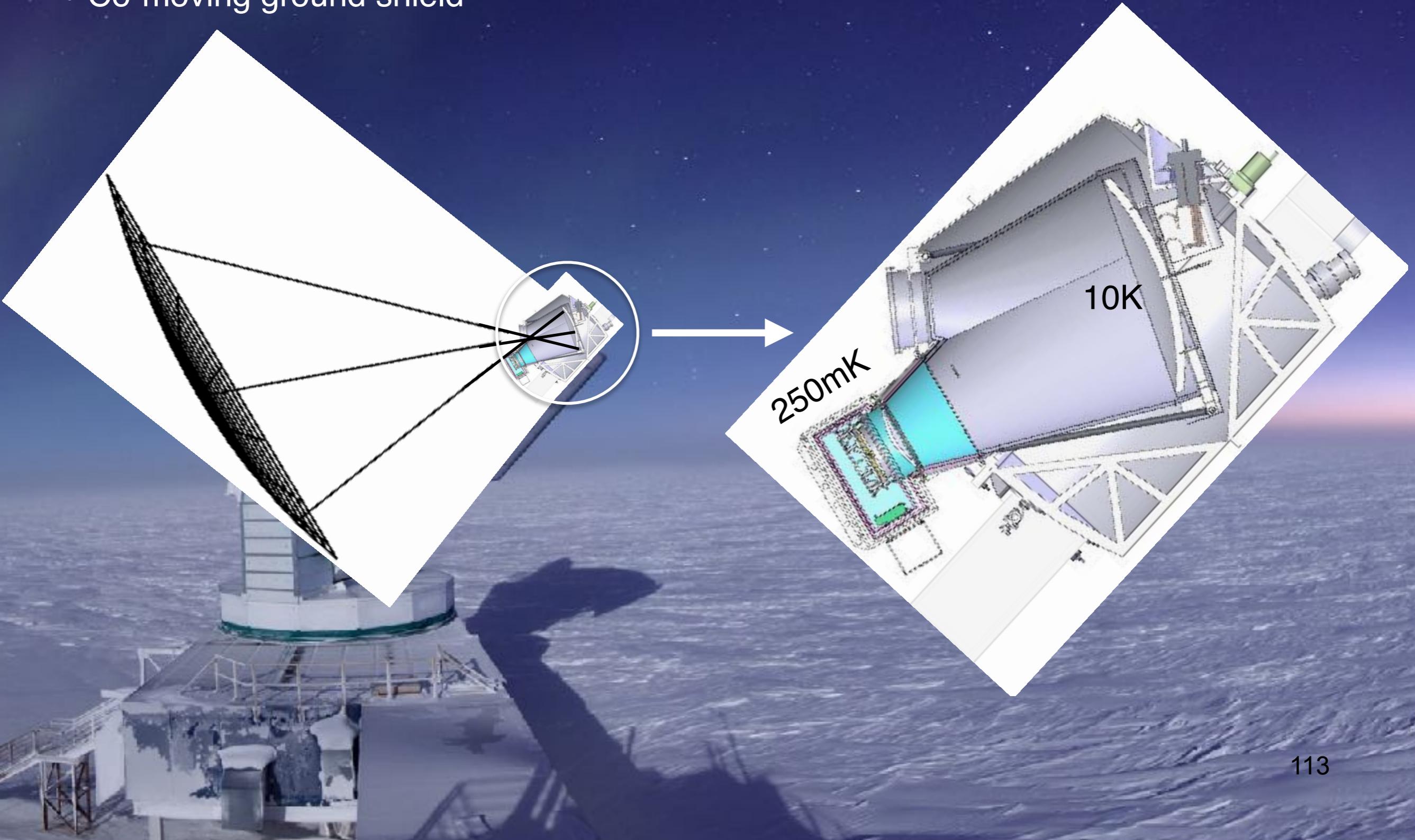
- Cold (10K) secondary acts as the stop
- Under-illuminated primary mirror (8m)
- Co-moving ground shield



# Optics

Very clean, low-noise, optical design:

- Cold (10K) secondary acts as the stop
- Under-illuminated primary mirror (8m)
- Co-moving ground shield

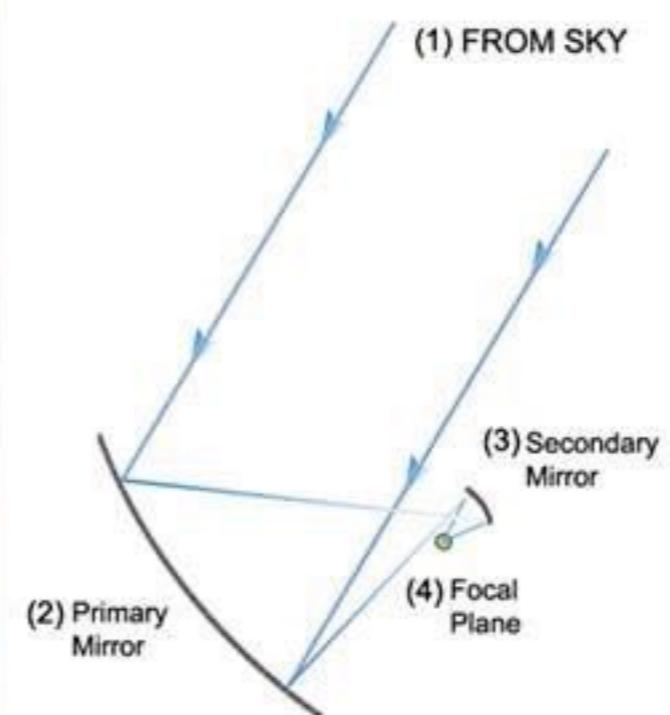


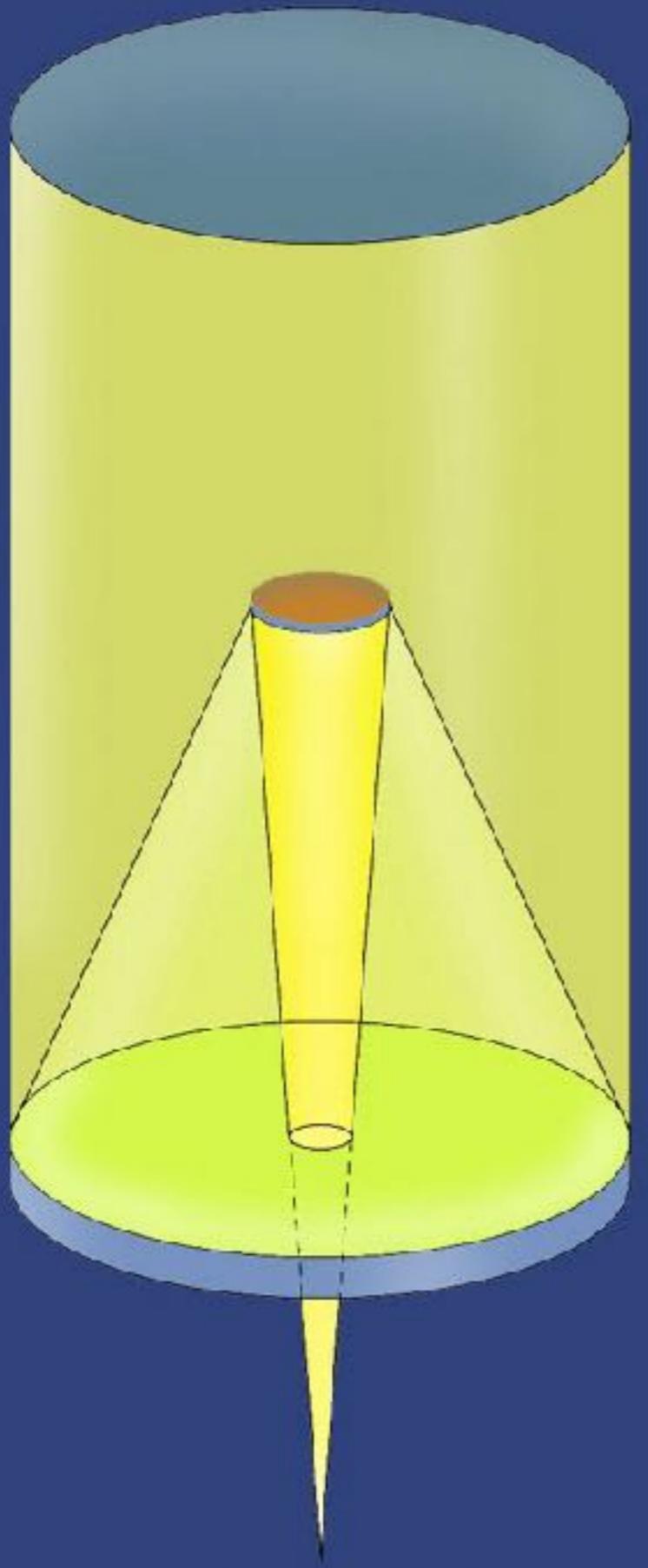


...continue to top of field, then repeat

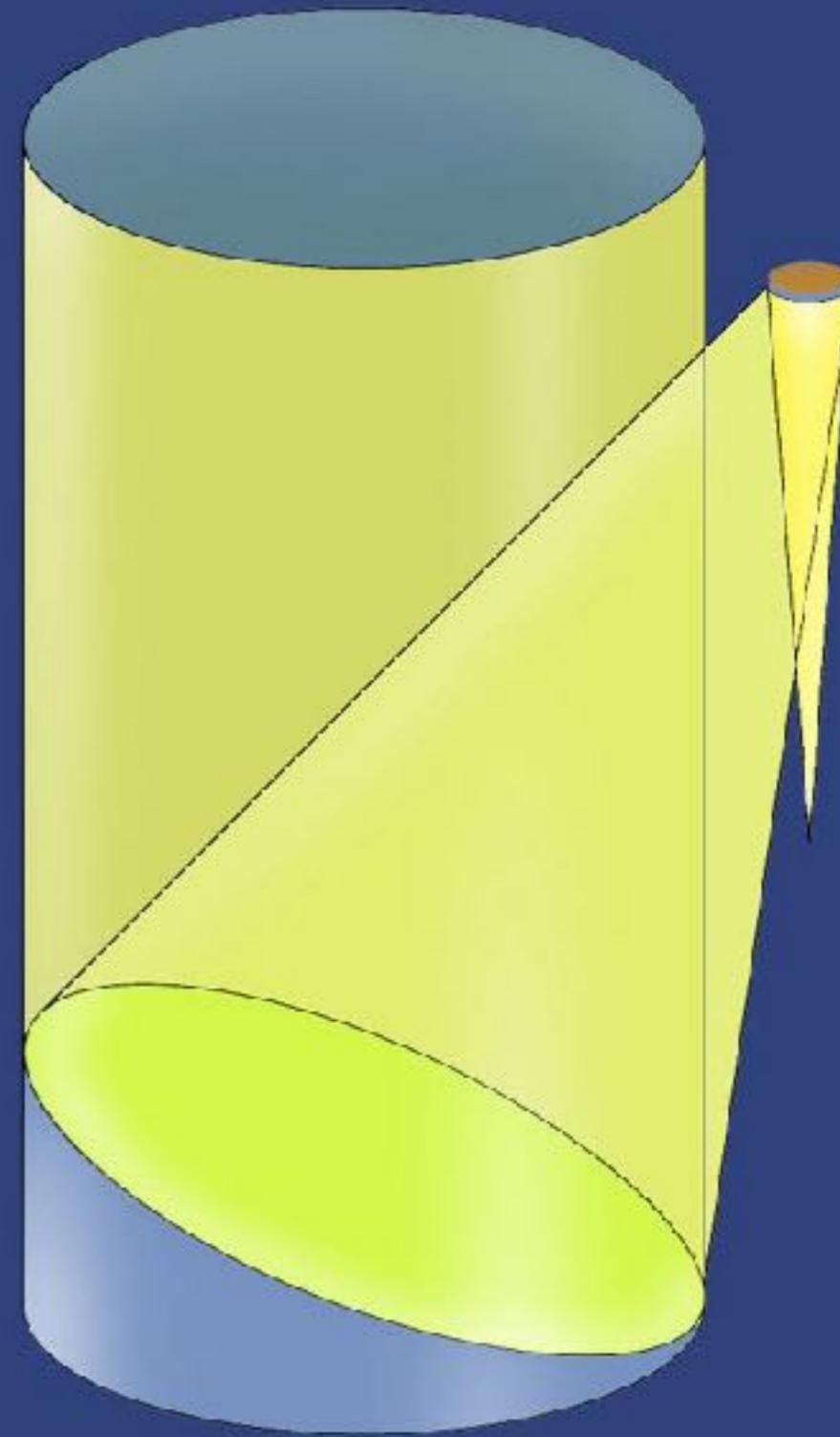


start of an observation

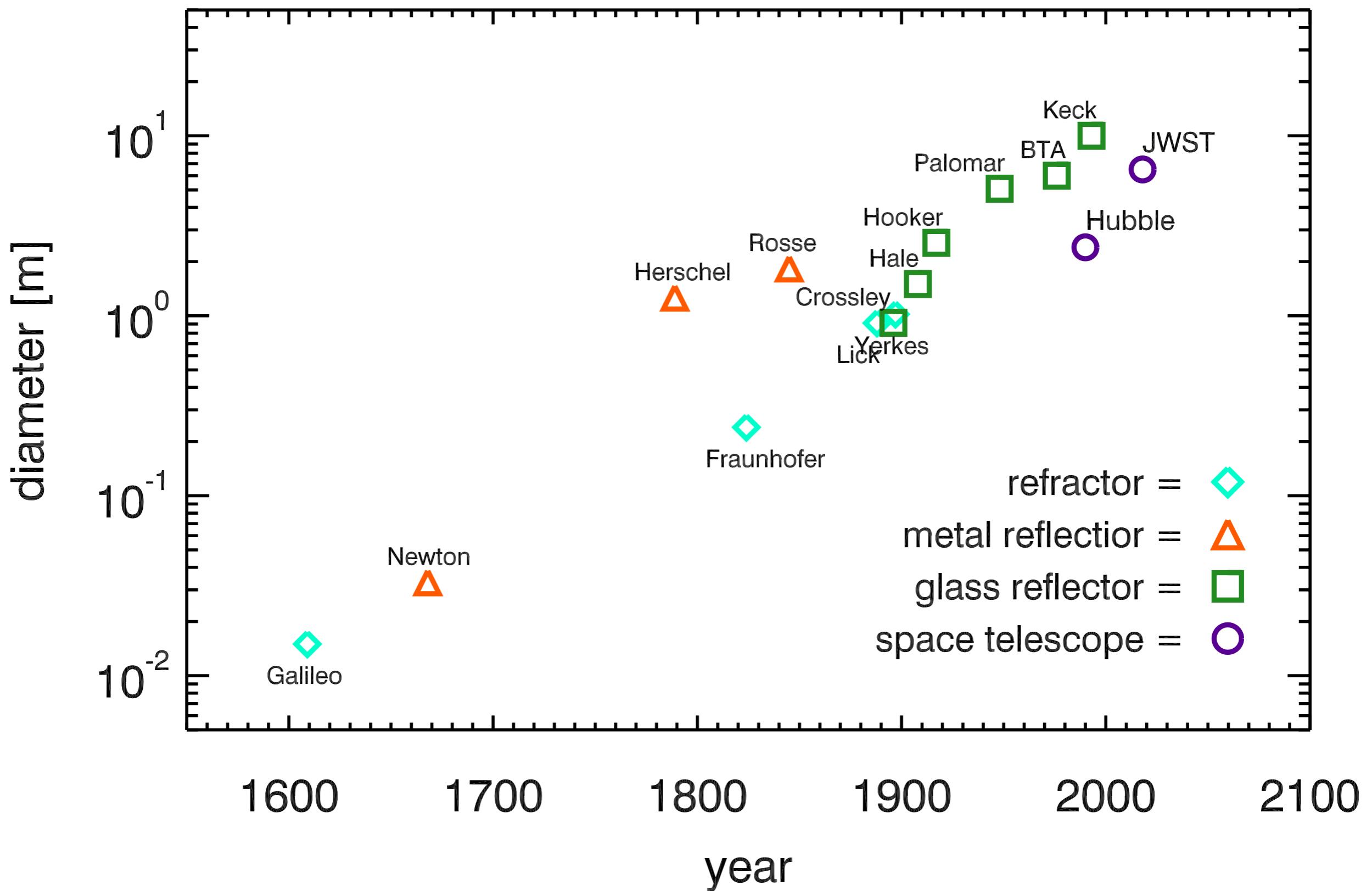




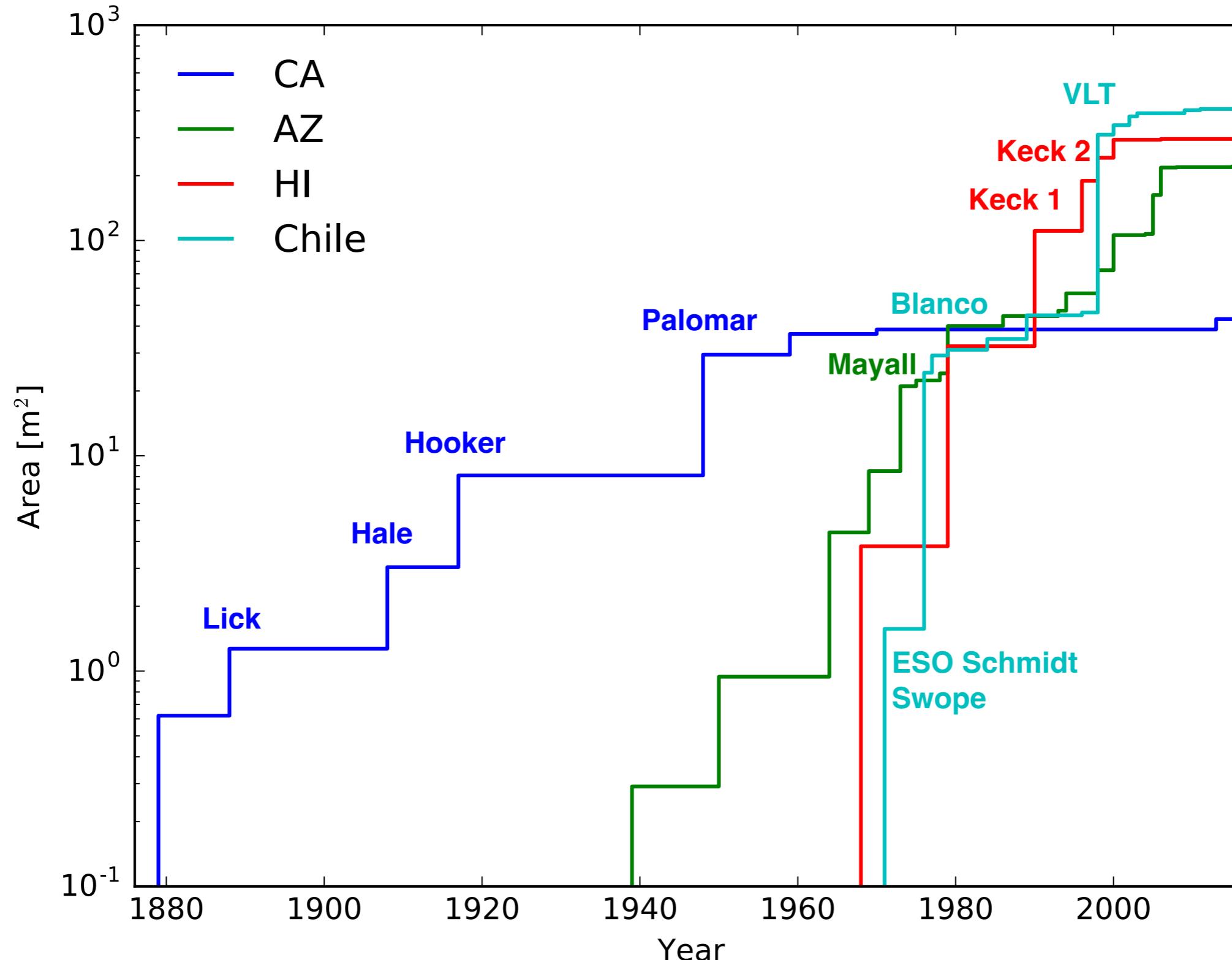
On-axis telescope



Off-axis telescope

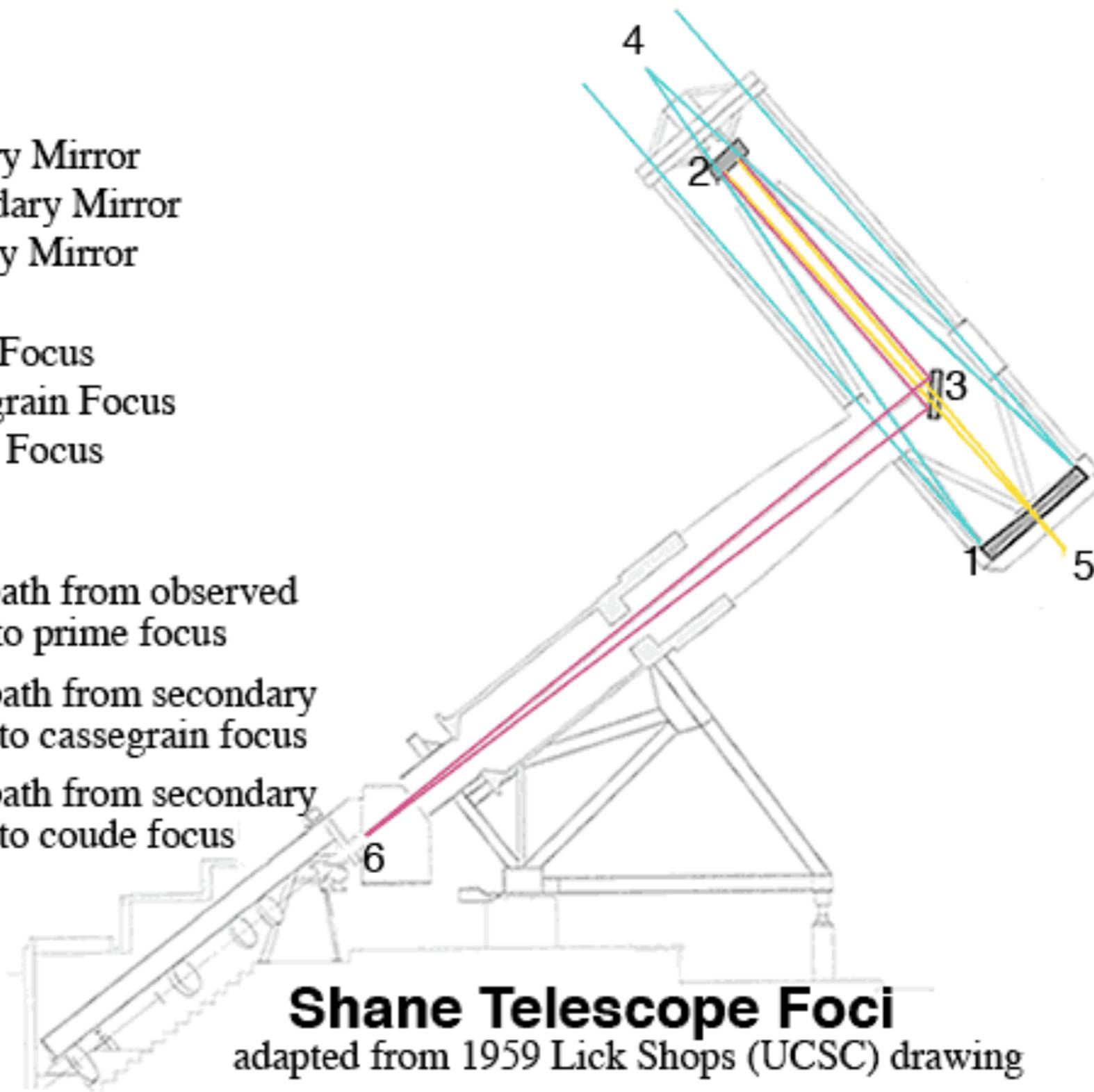


# Major Ground-Based Optical Telescopes Around the World



- 1 Primary Mirror
- 2 Secondary Mirror
- 3 Tertiary Mirror
- 4 Prime Focus
- 5 Cassegrain Focus
- 6 Coude Focus

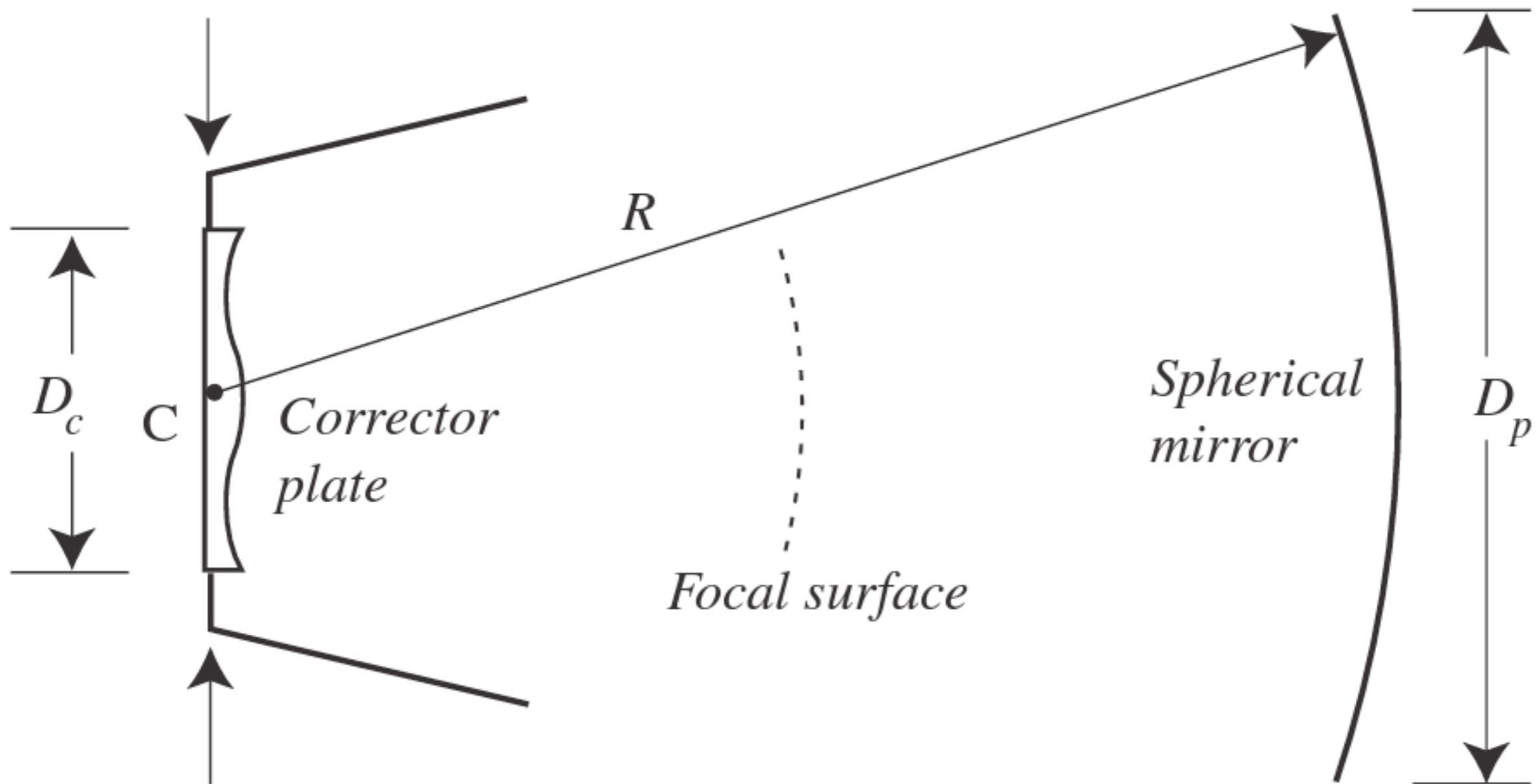
- Light path from observed object to prime focus
- Light path from secondary mirror to cassegrain focus
- Light path from secondary mirror to coude focus



# Schmidt Telescope

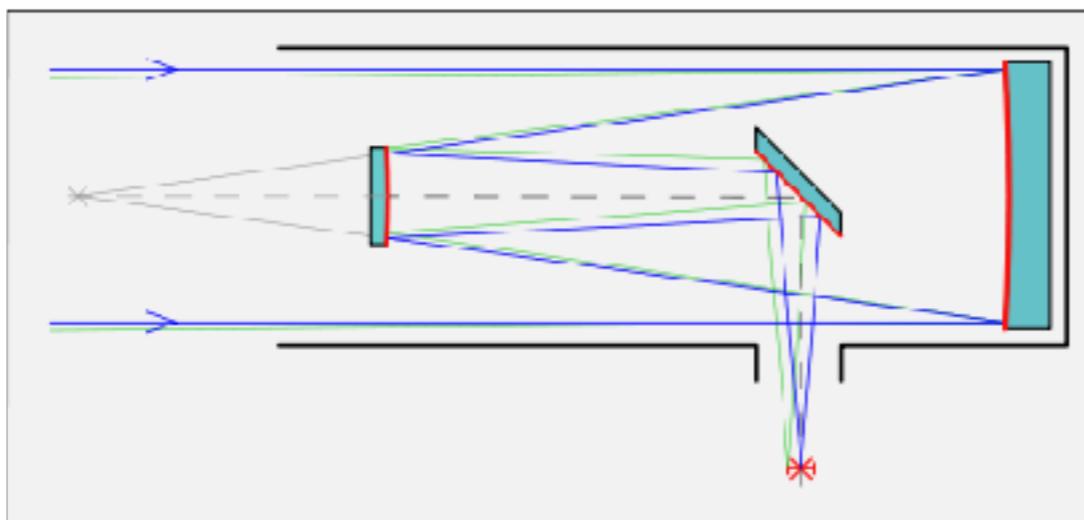
(a)

*Aperture stop*

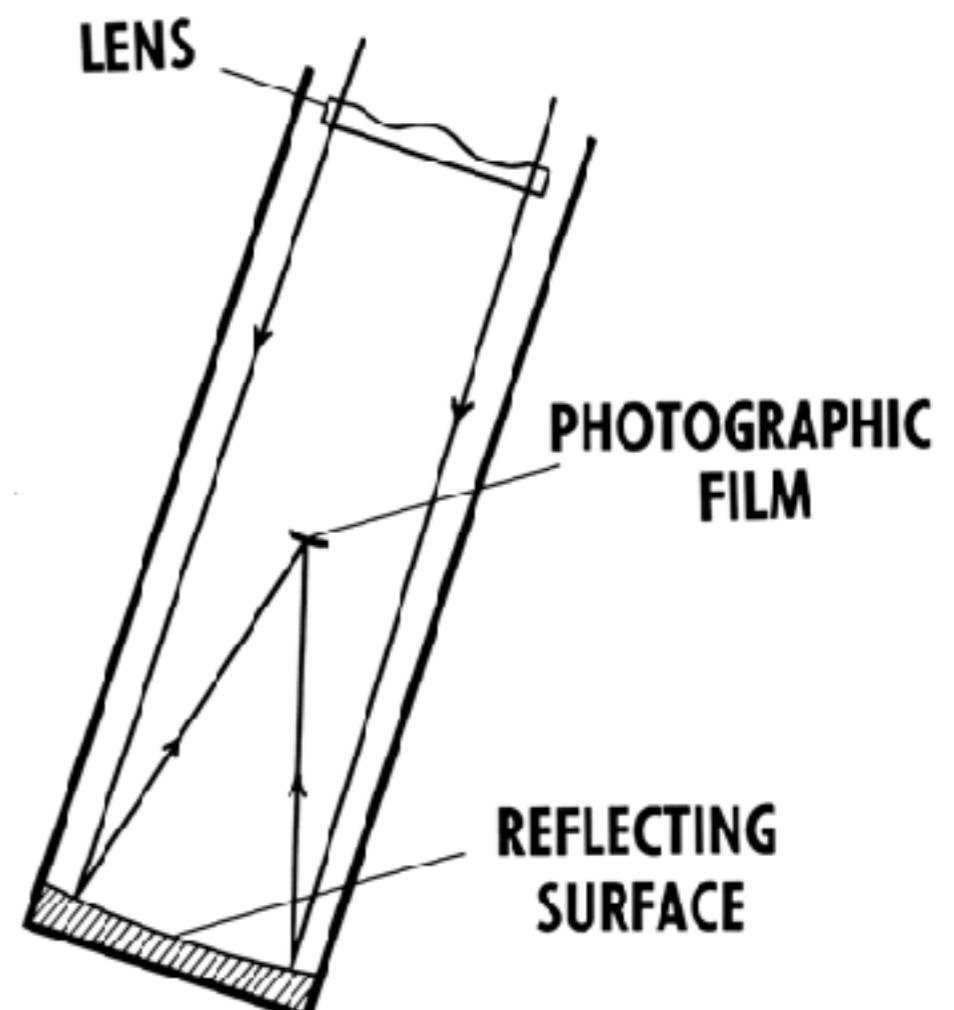


# Hybrids, correctors, and tertiaries

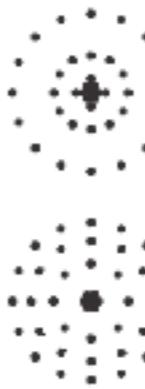
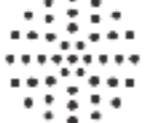
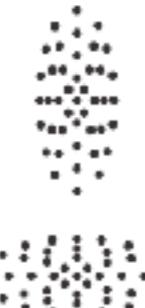
- The **Schmidt telescope** has a primary mirror with a spherical surface and a spherical aberration corrector.
  - Focal surface is significantly curved.
- To make use of the Prime Focus of a large telescope for wide-field imaging requires additional optics in front of the camera.
  - **Prime focus correctors** are high performance refractive elements for this purpose.
- **Tertiary mirrors:**
  - Nasymth (alt-az) and coude (equatorial).
  - Stationary focal point.



(Nasmyth/Coude optics; CC)



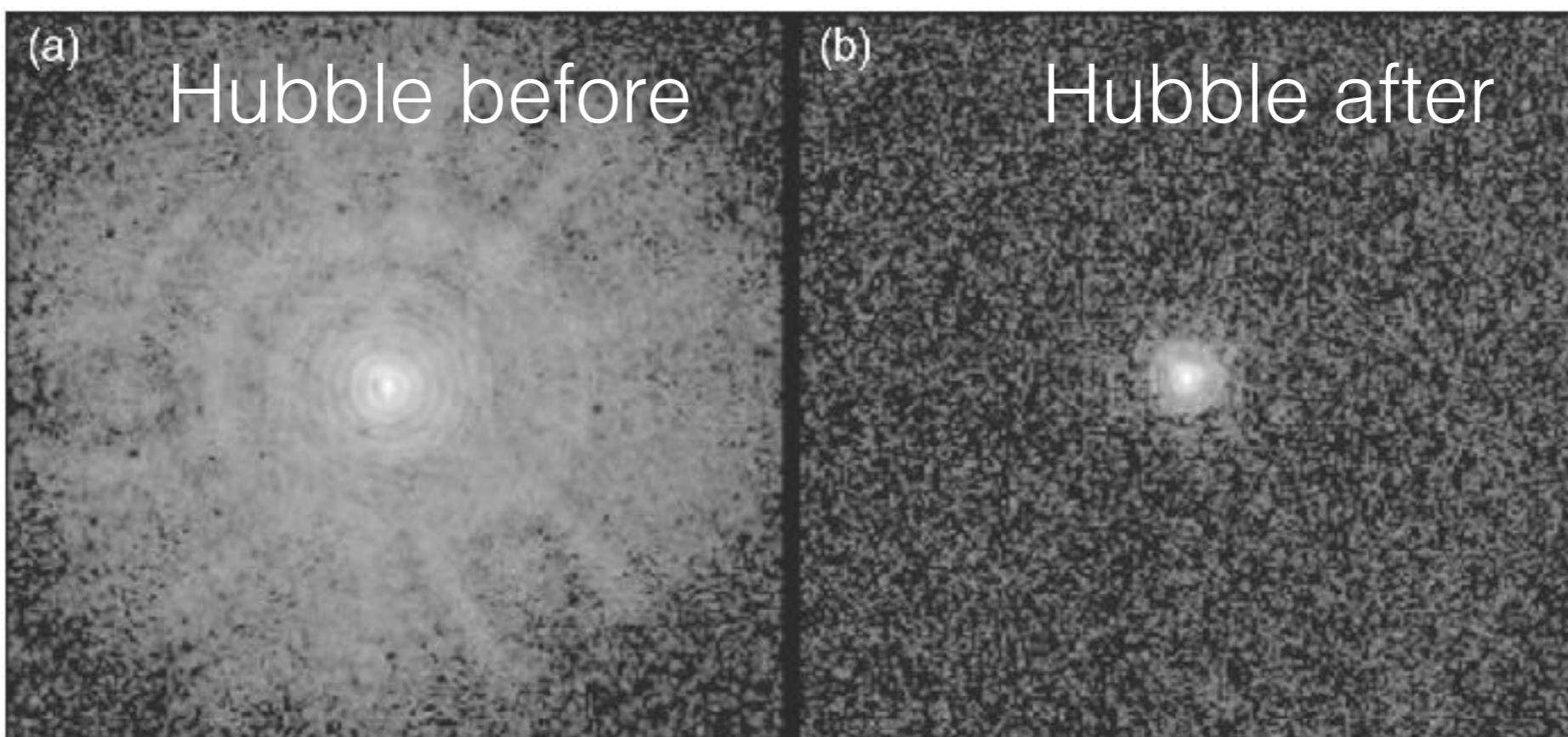
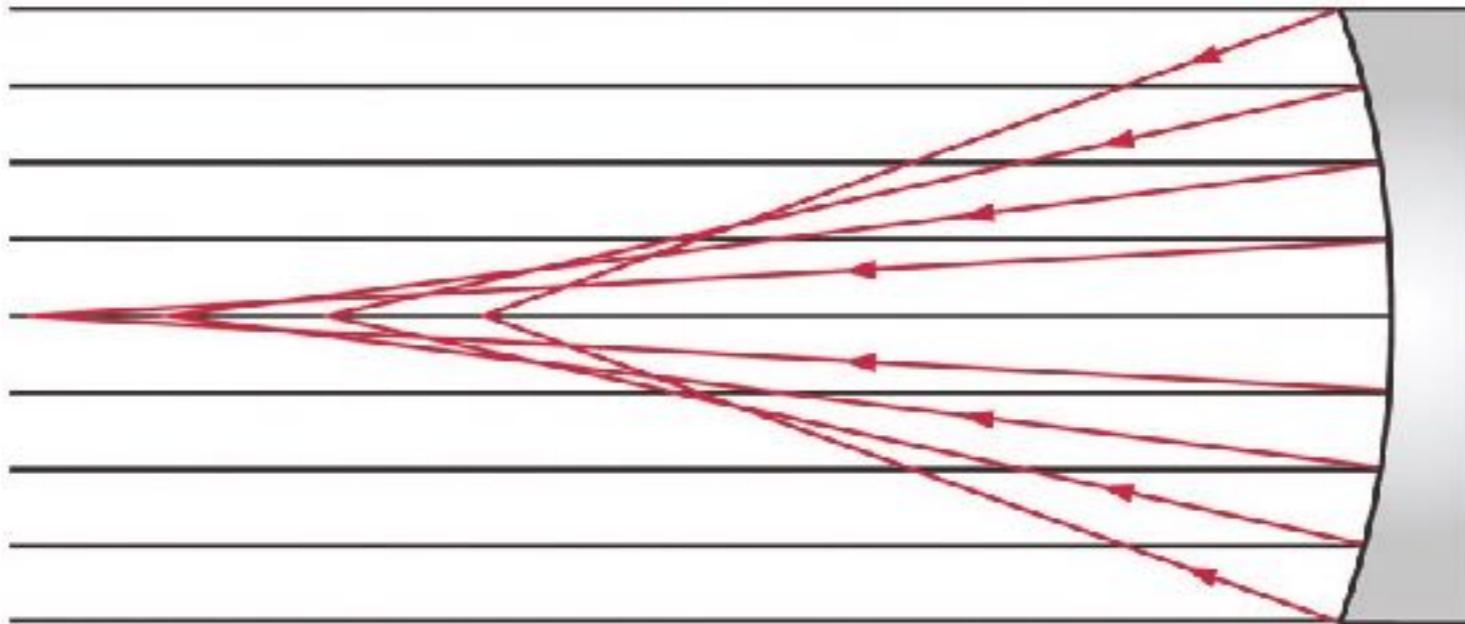
# Optical Aberrations

	<i>On-axis focus</i>	<i>On-axis defocus</i>	<i>Off-axis</i>	<i>Off-axis defocus</i>
spherical aberration <i>SA</i>				
<i>Coma</i>				
<i>Astigmatism</i>				
<i>Curvature of field</i>				

# Spherical aberration

e.g. spherical reflectors

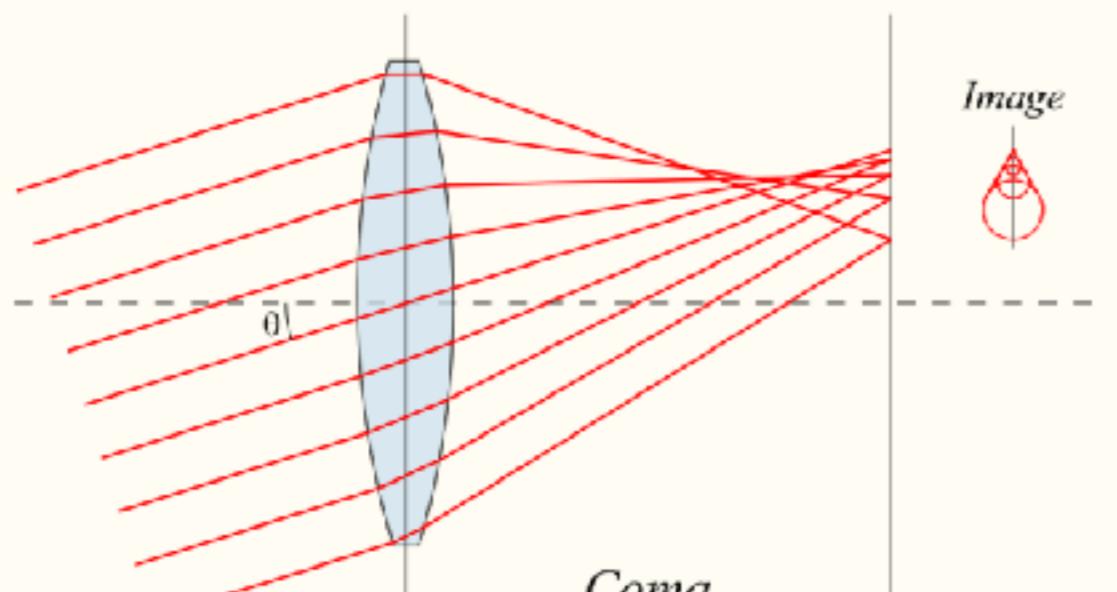
Off-axis rays don't trace properly to form an image  
produces blurred halo around image



# Coma

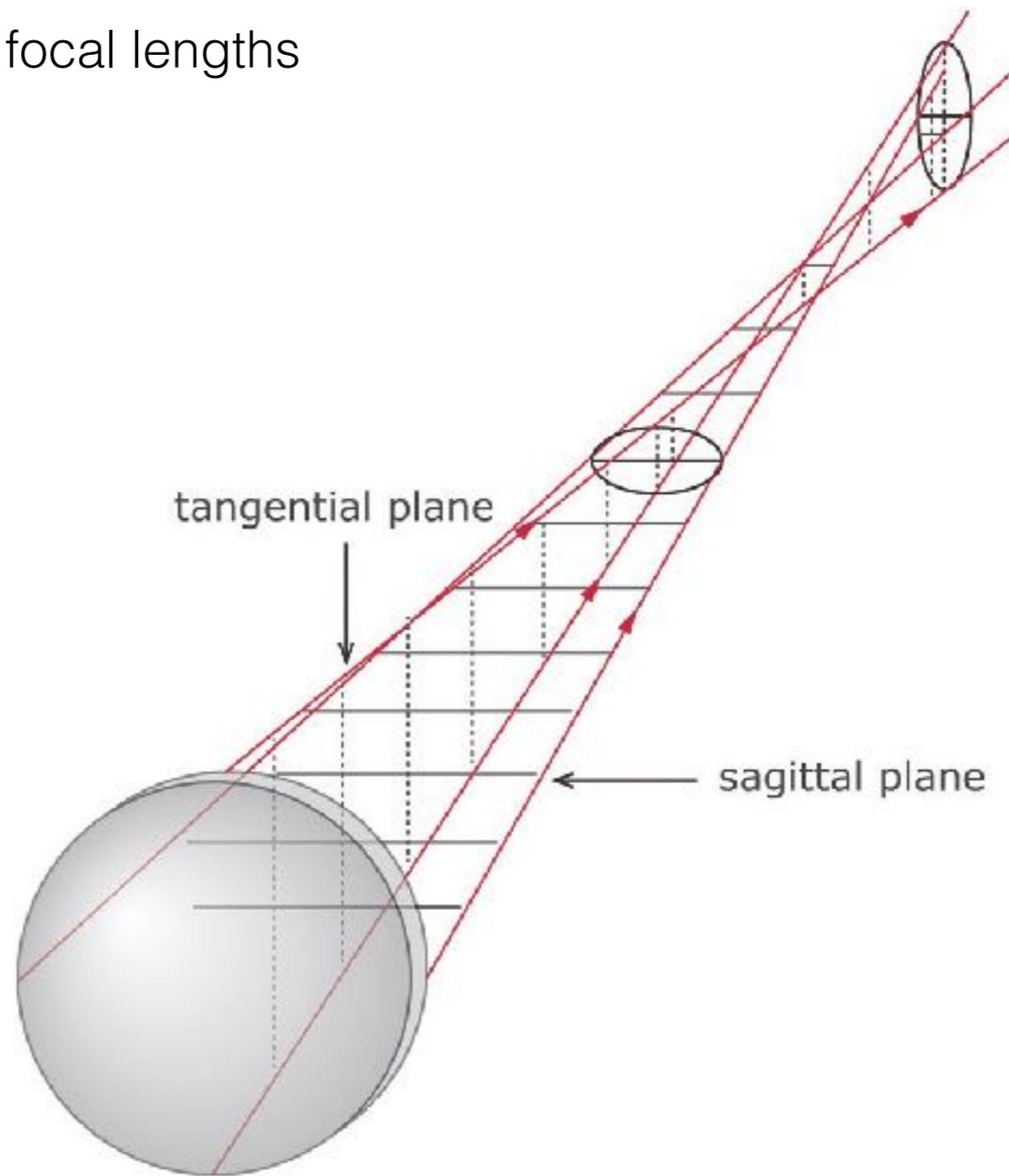
e.g. paraboloid

Off-axis rays don't trace properly to form an image  
produces blurred halo around image



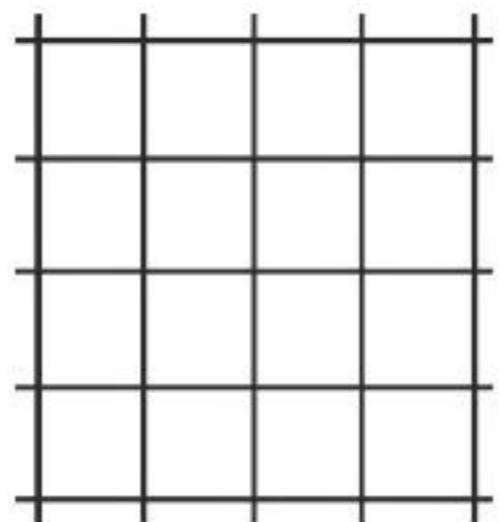
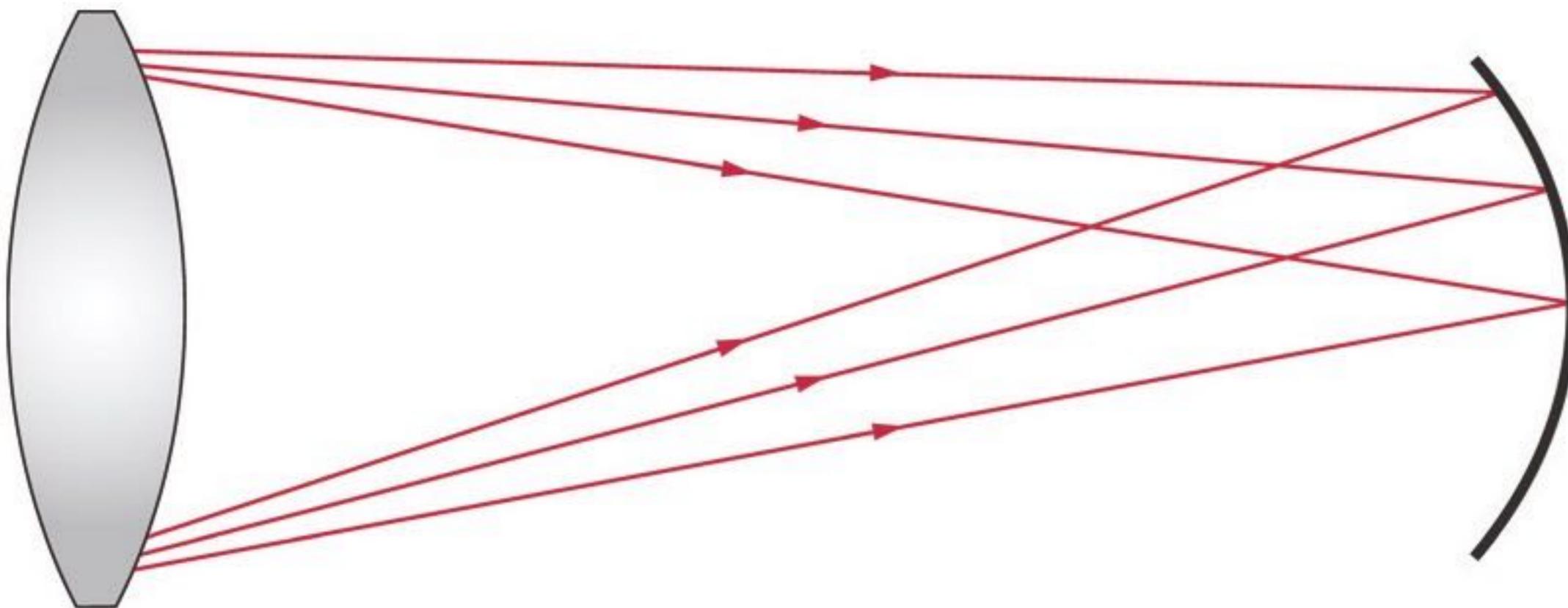
# Astigmatism

x- and y- planes have different focal lengths



# Curvature of field

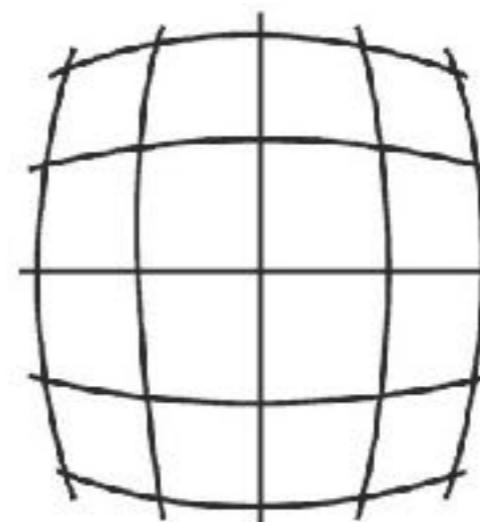
Focal plane is curved.



object

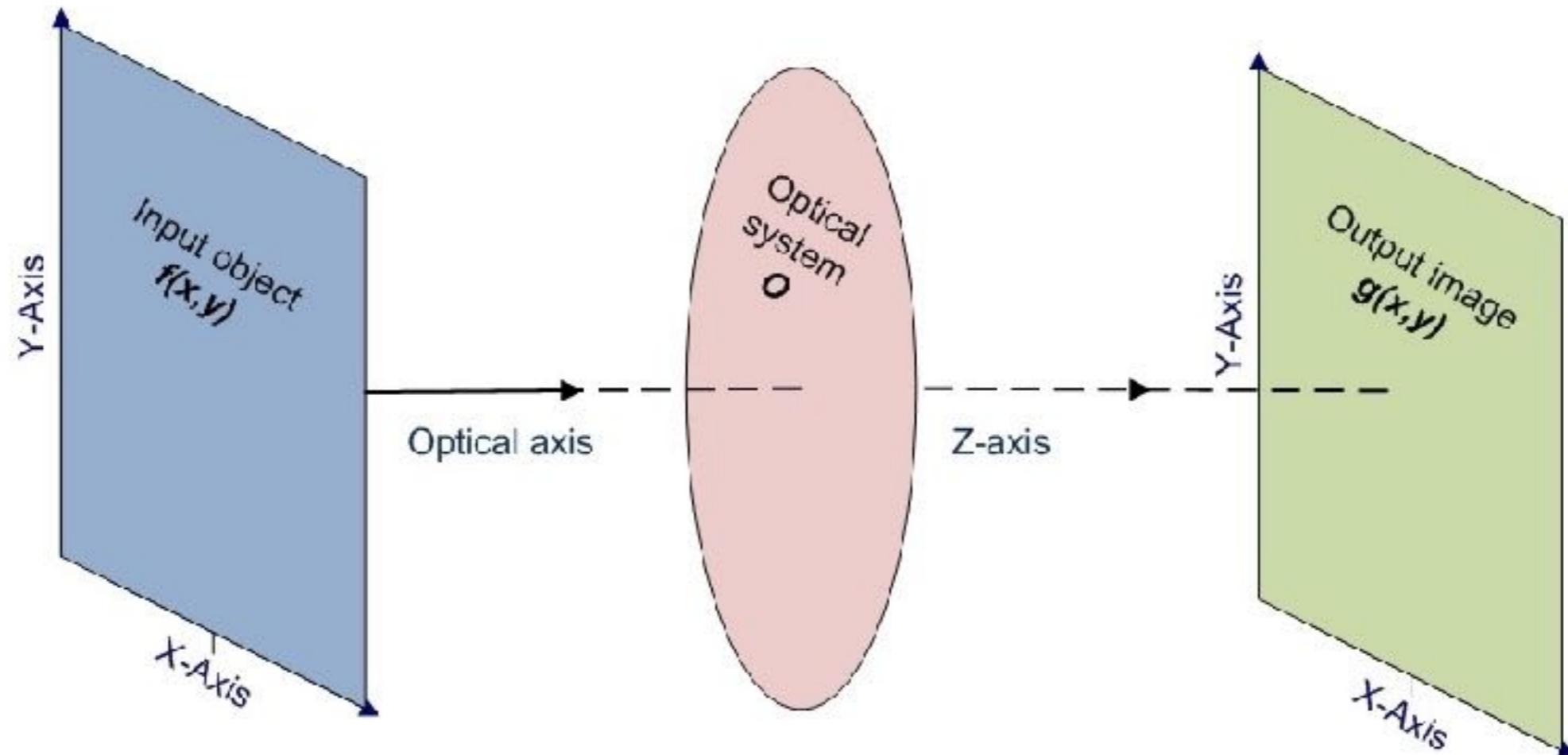


pincushion  
distortion



barrel  
distortion

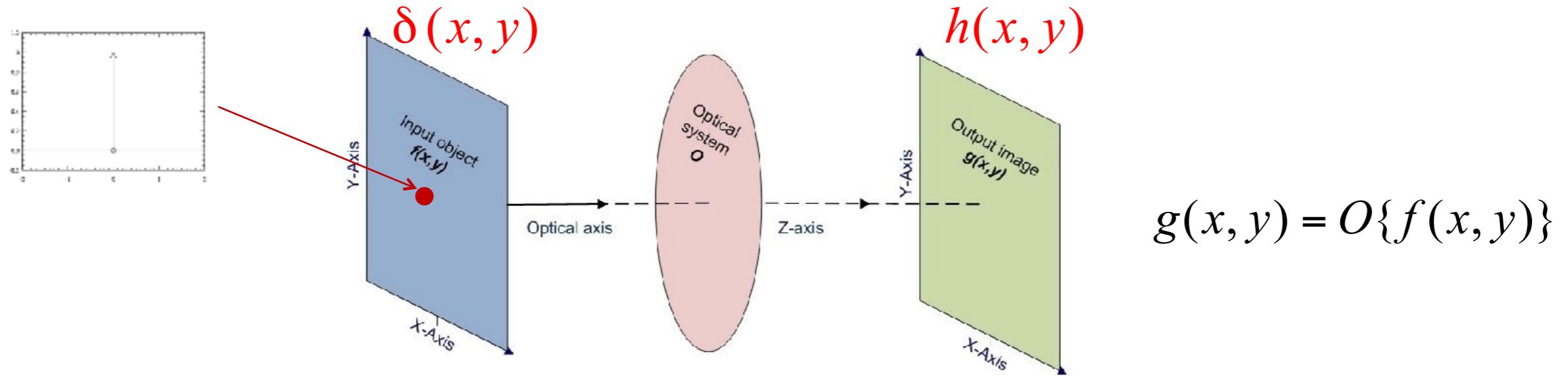
# Imaging systems



- Can represent the action of 2-d imaging system by a general ***imaging operator***  $g(x,y)=O(f(x,y))$
- An important component of our overall data model.

# The point-spread function (PSF)

120



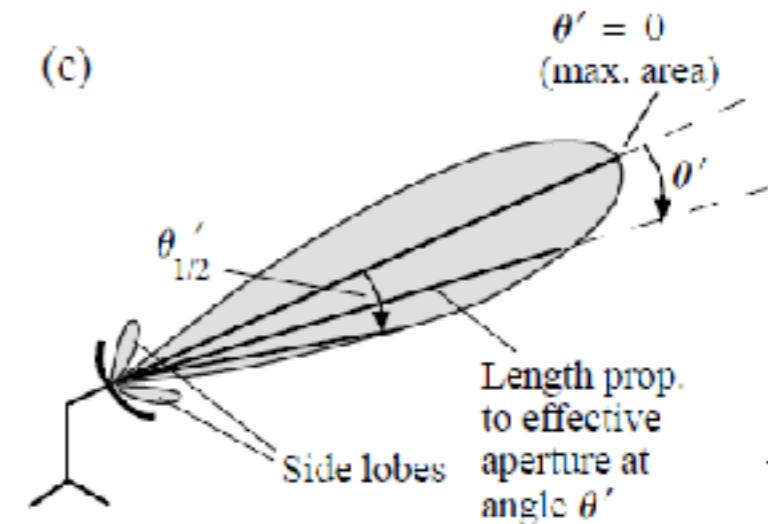
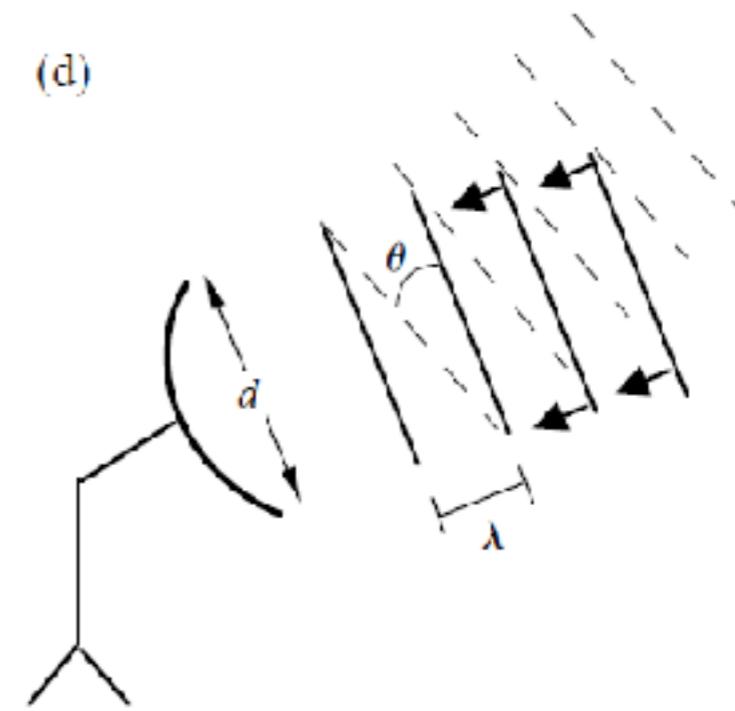
- The response of the imaging operator to a point source impulse function (Dirac delta function) at the origin:

$$h(x, y) = O\{\delta(x, y)\}$$

# Telescope angular response function

129

- In practice, telescopes have finite angular resolution.
- **Why is the PSF not a delta function ?**
- **Diffraction:**
  - Due to the wave nature of electromagnetic radiation
  - **Not** included in the **geometric optics approximation** (i.e. the *light ray* model)
- **Propagation effects** (e.g. refractive turbulence along incident path).
- **Optical errors**
- **Scattering**
- We will denote as  $P(\theta', \phi', v)$ , where  $(\theta', \phi')$  are measured relative to the optical axis (here assumed the same as pointing direction):
- ***Caution: - need to take care with units of response function:***
  - Acting on electric field of incident EM wave,  $E$ , or
  - Acting on intensity of incident EM wave  $|E|^2$  (power pattern)

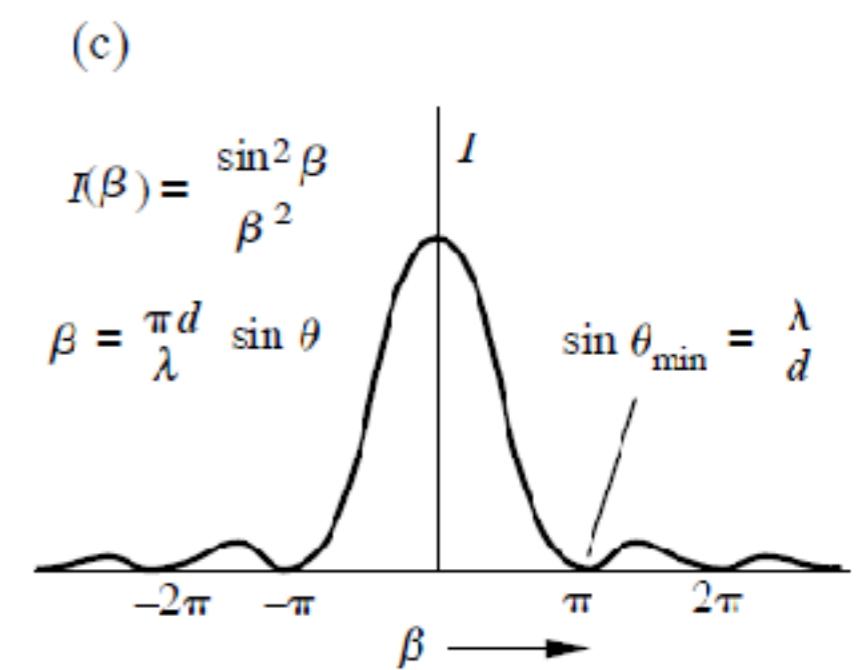
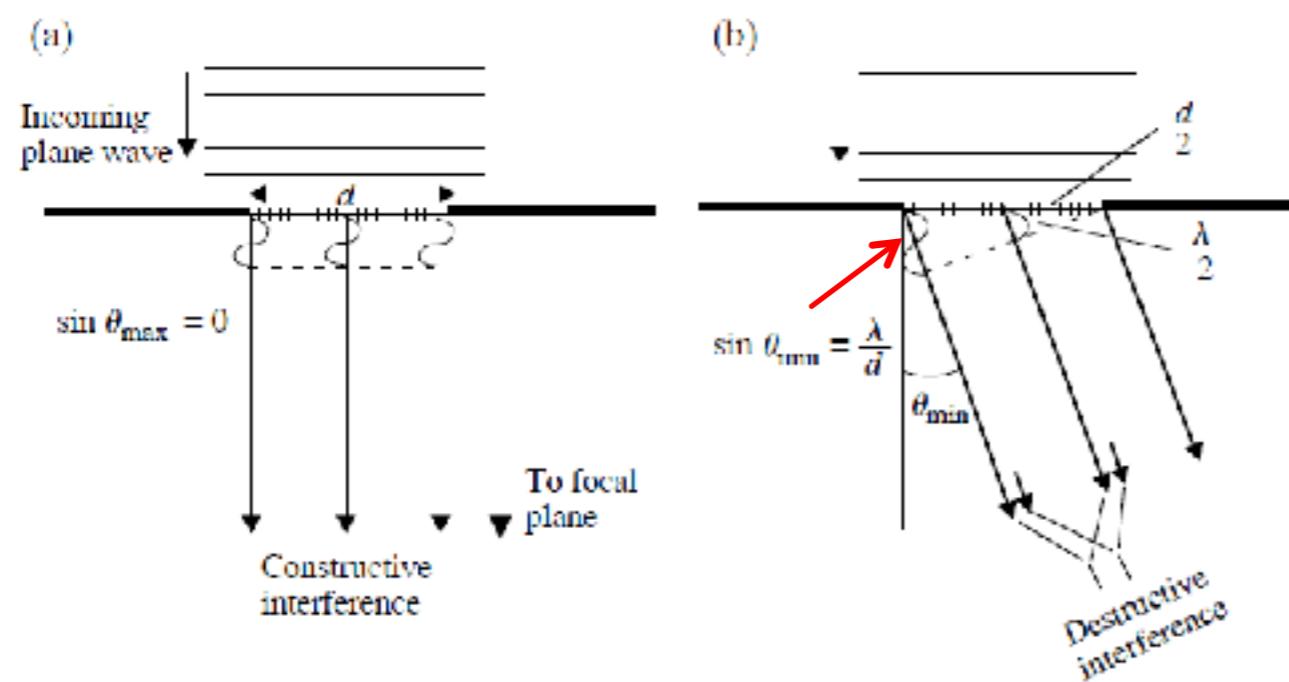
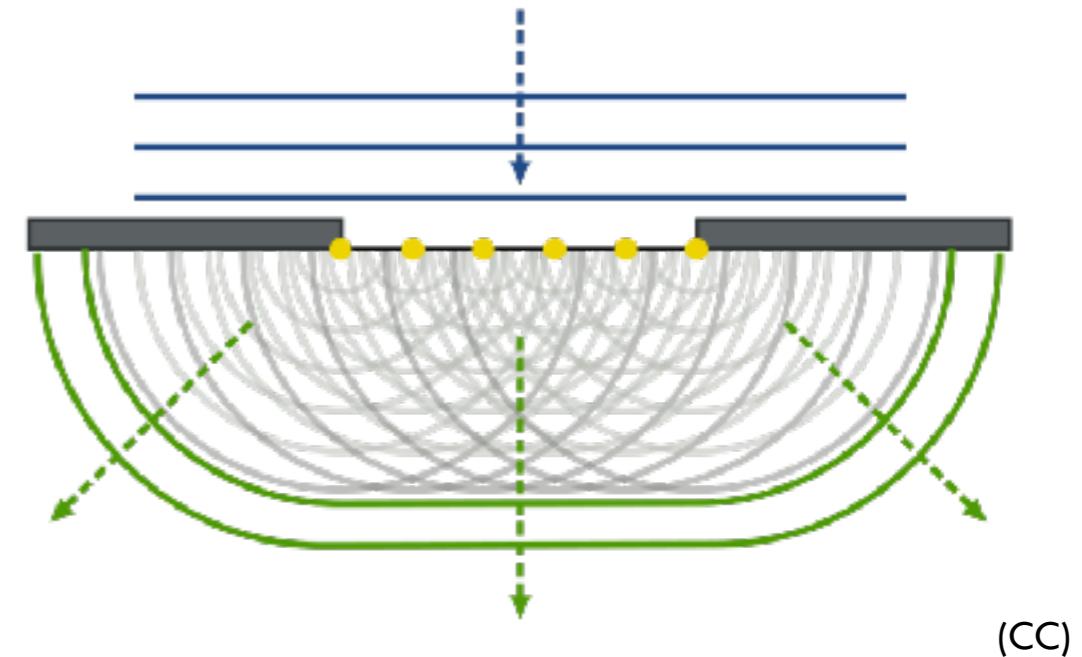


(Bradt 2004)

# Diffraction – an intuitive approach

130

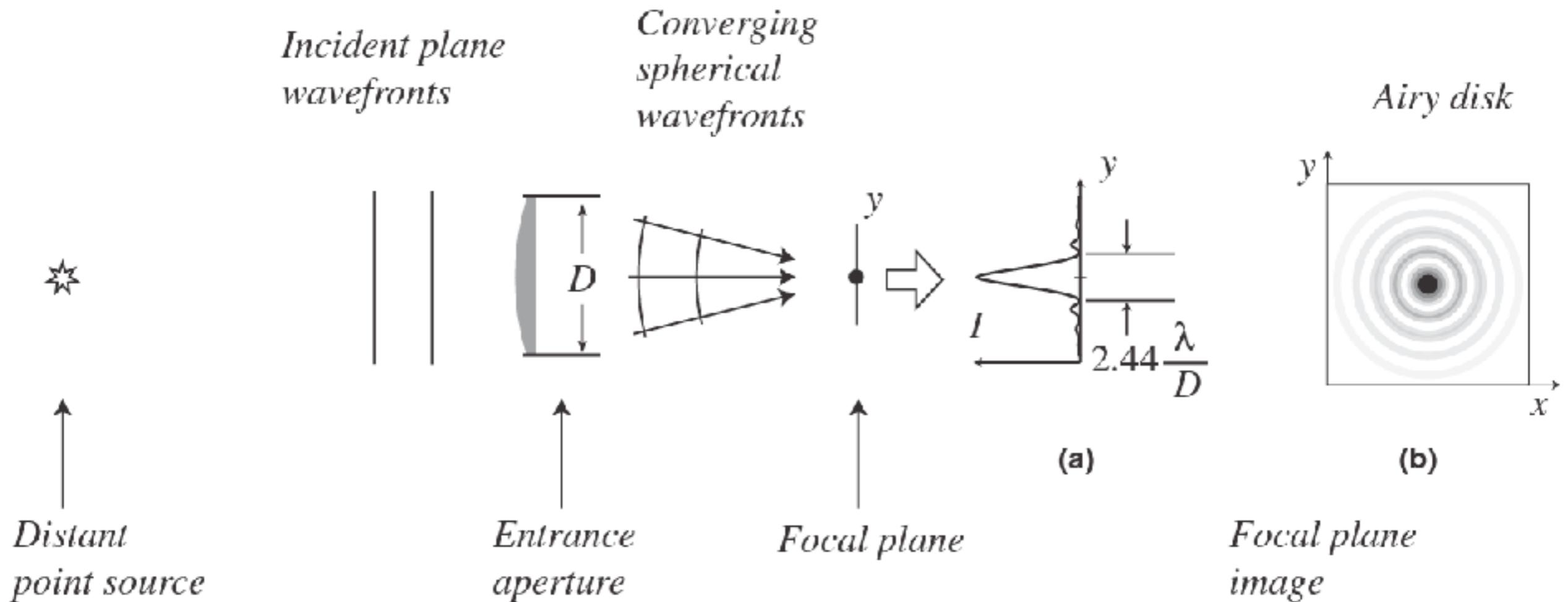
- Diffraction places the intrinsic limit on angular resolution
- The **Huyghens-Fresnel** principle:
  - ▣ *Each point on an advancing wavefront becomes the source of a secondary Huyghens wavelet that radiates spherically.*



(Bradt 2004)

(Bradt 2004)

# Diffraction limit



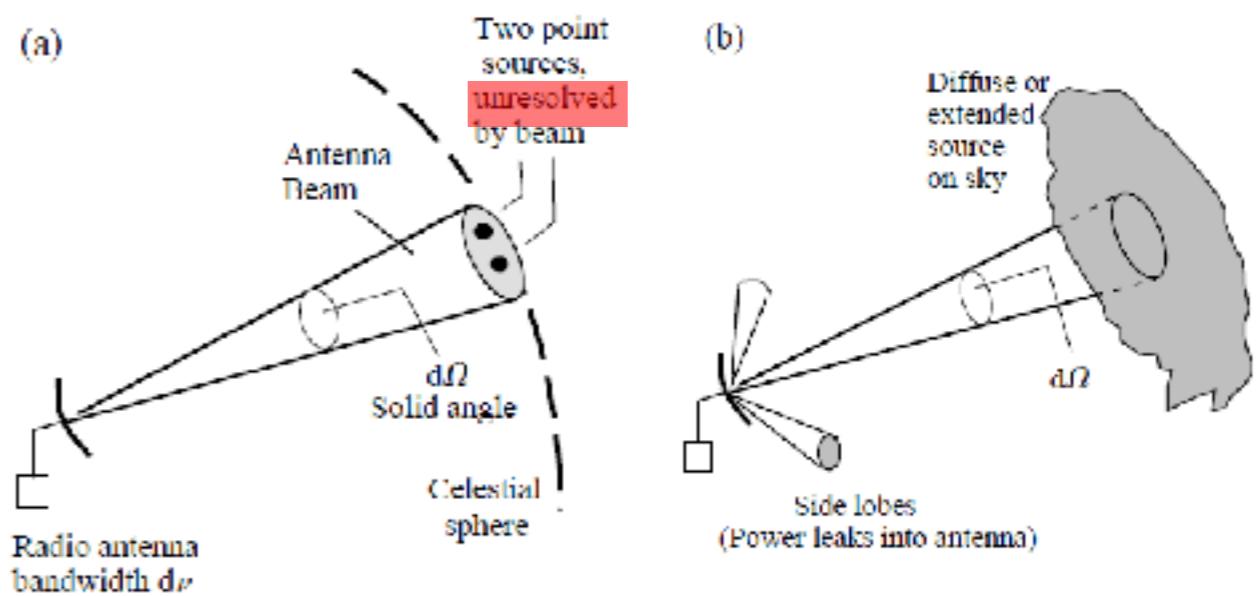
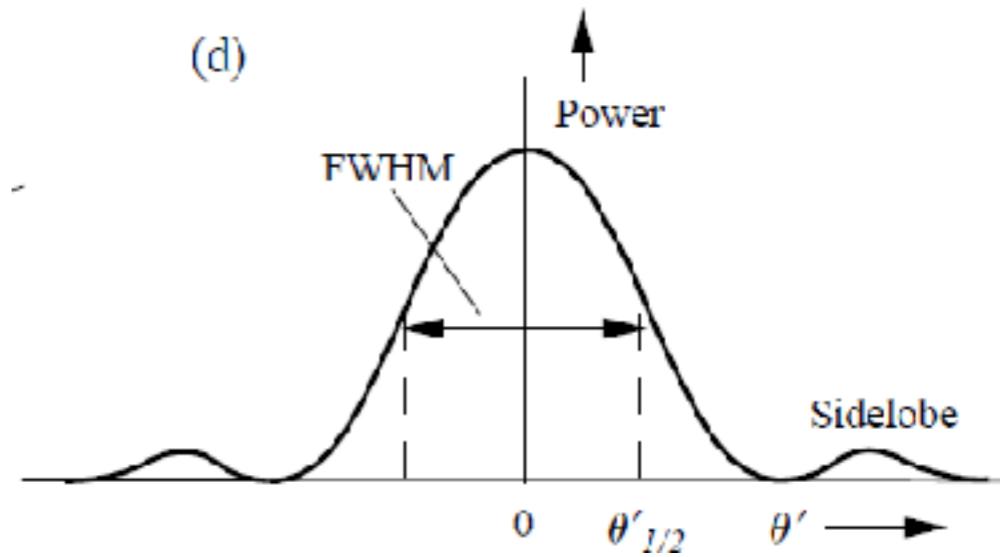
$$\theta \simeq 1.22 \frac{\lambda}{D}$$

optical accuracy requirements  
 $\text{RMS} < \lambda/10$

# PSF properties

132

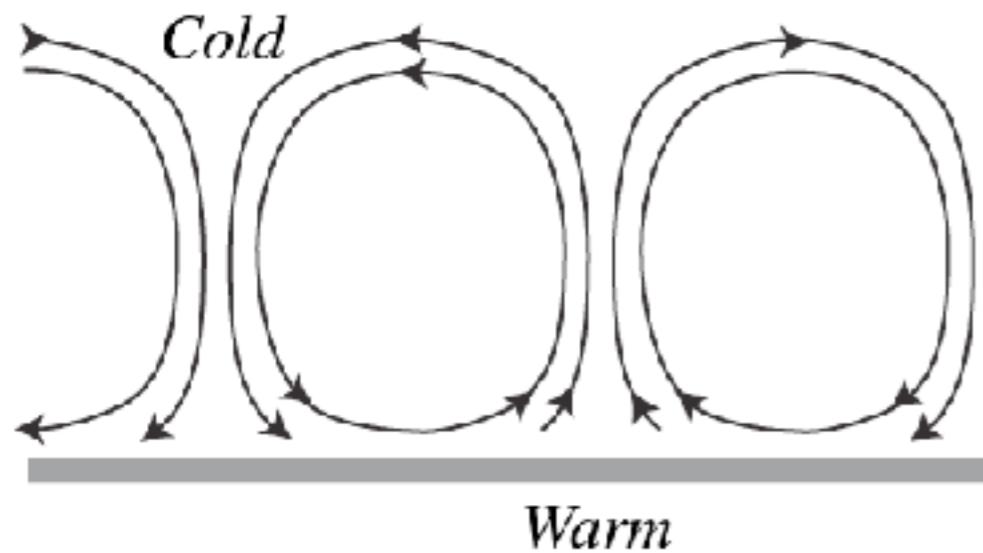
- A beam pattern (or PSF) has some key qualitative properties:
  - **Beam solid angle** – the total solid angle of the beam.
  - **Main lobe** (or main beam) – central lobe of the response pattern.
  - **Angular resolution** – a measure of the angular width of the main lobe;
    - Also, the minimum **angular separation** that can be resolved between two point sources.
  - **Sidelobes** – angular response lobes outside the main lobe.
  - **Efficiency**
    - The ratio of the main lobe solid angle to the total beam solid angle.



(Bradt 2004)

# Atmosphere

(a)



no turbulence

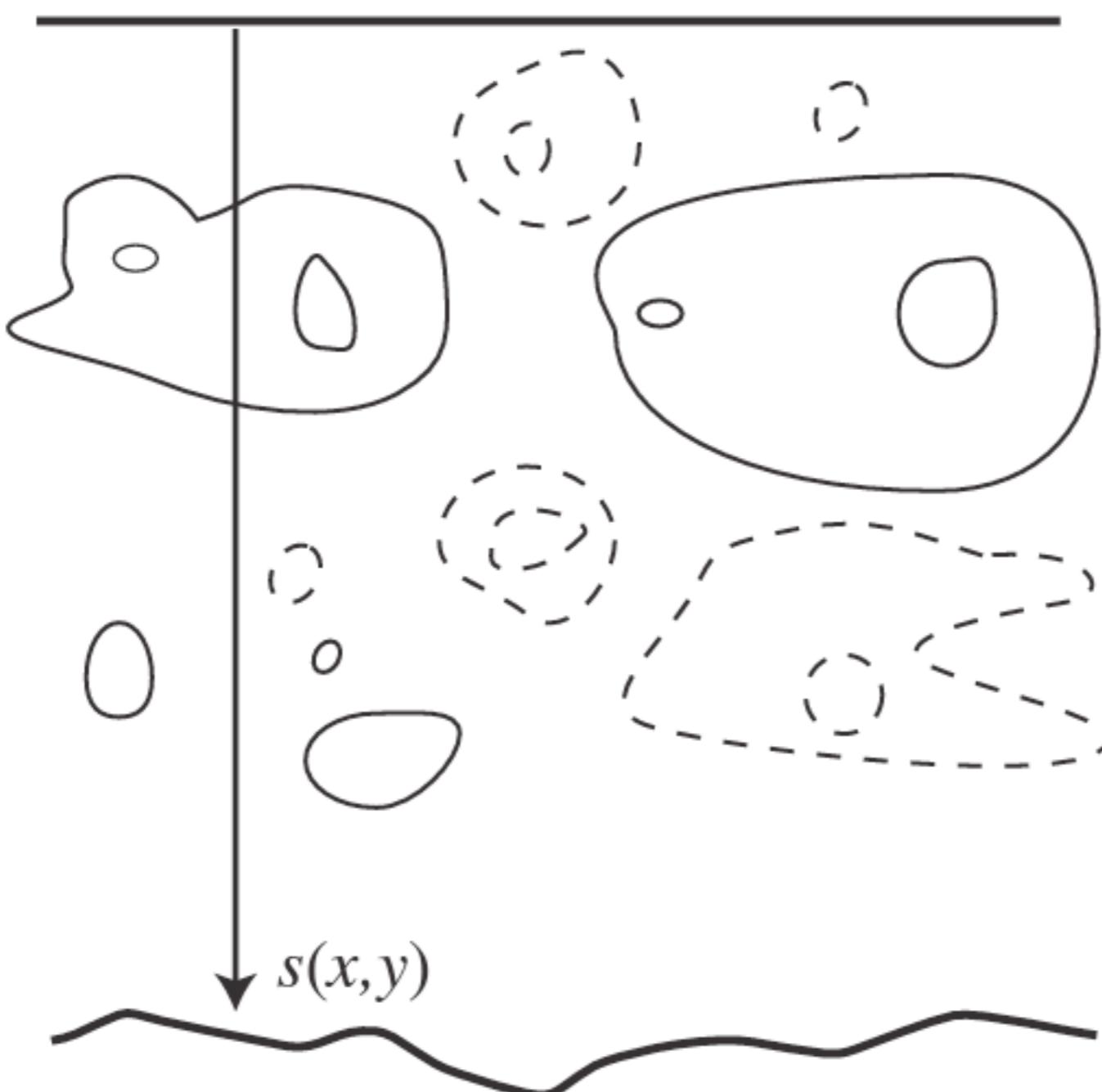
~1 km height

(b)



turbulence

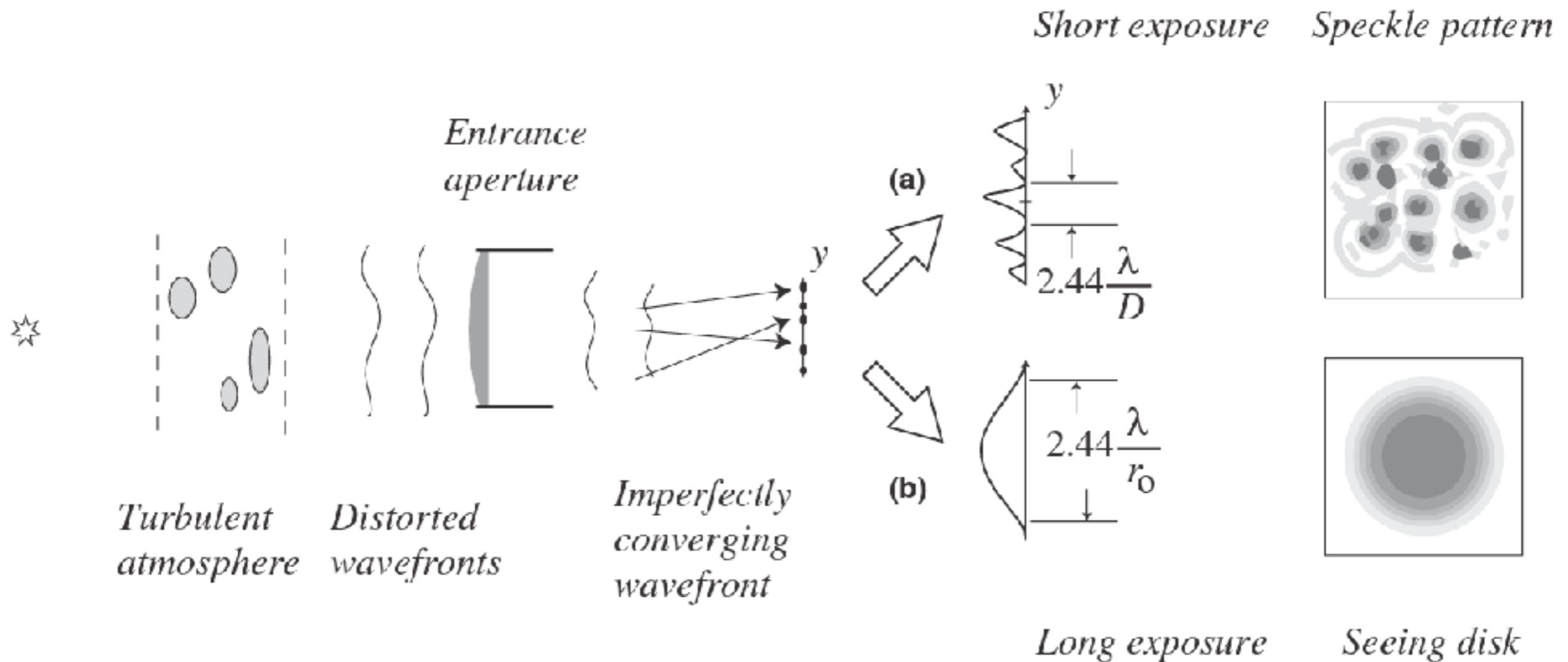
(a)

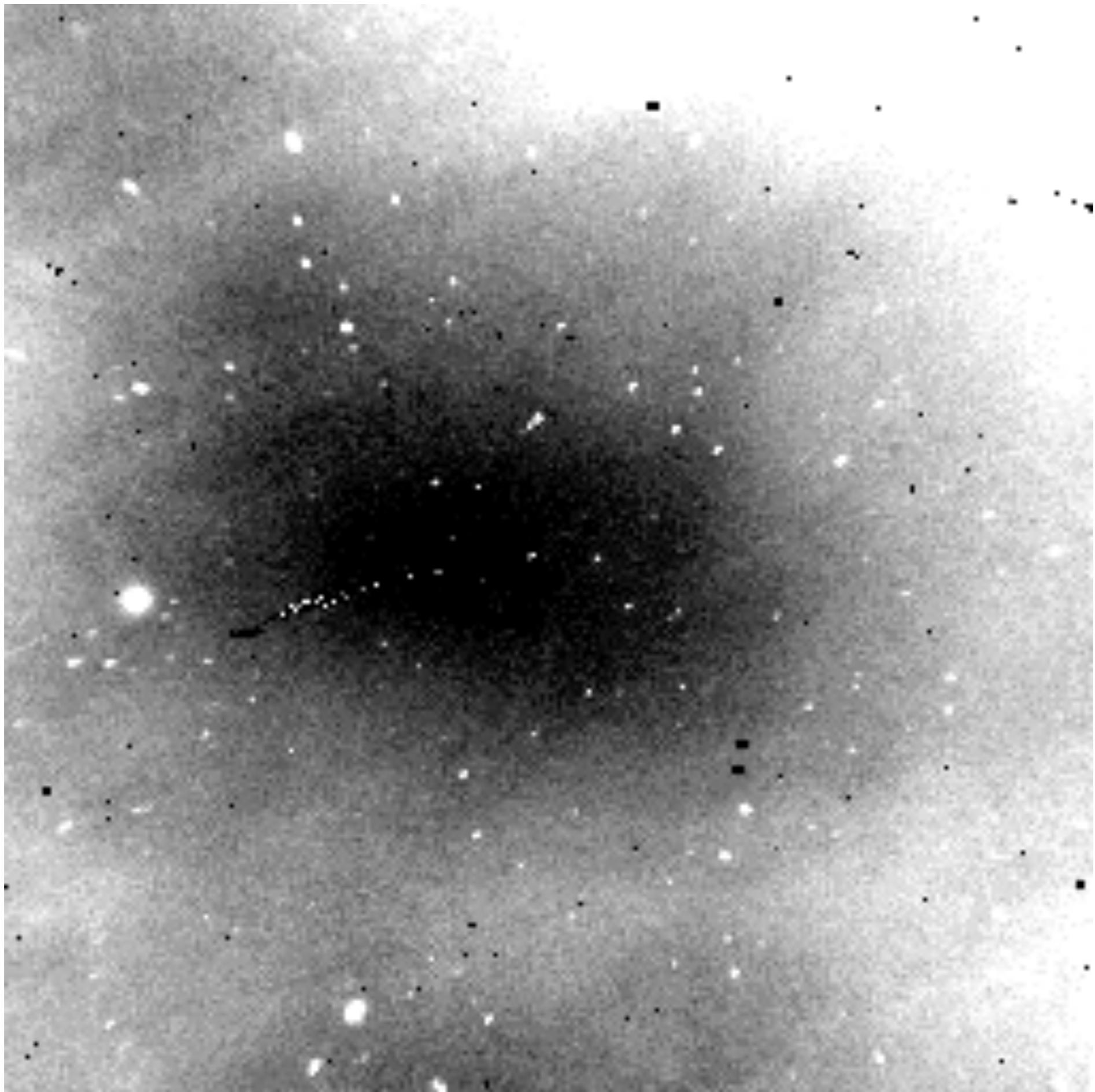


*Plane  
wavefront*

*Distorted  
wavefront*

# seeing

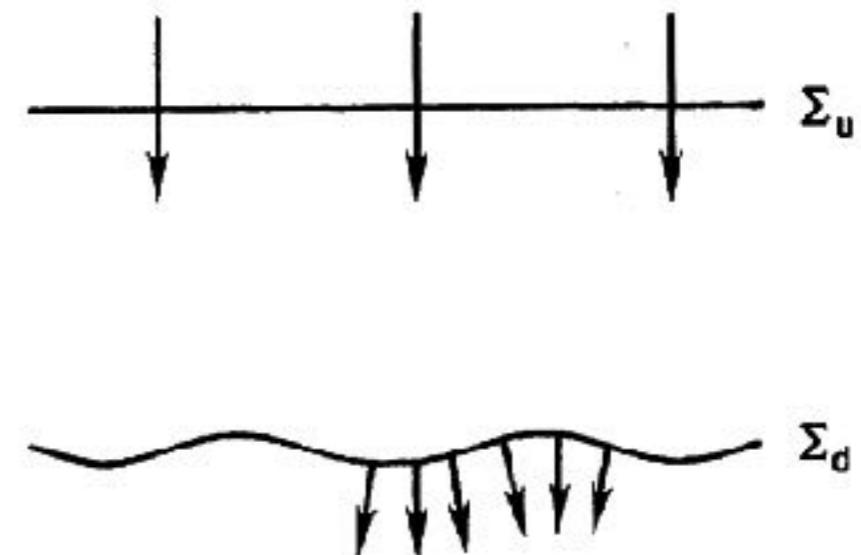
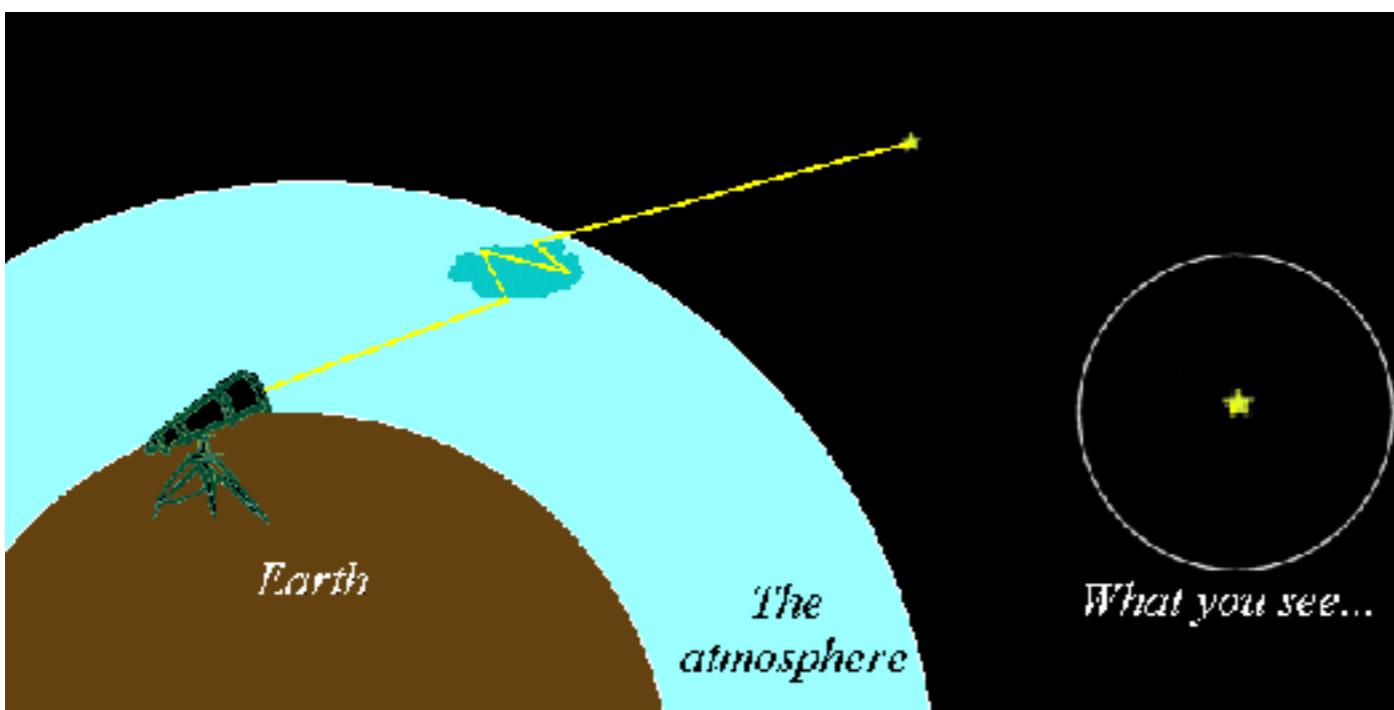




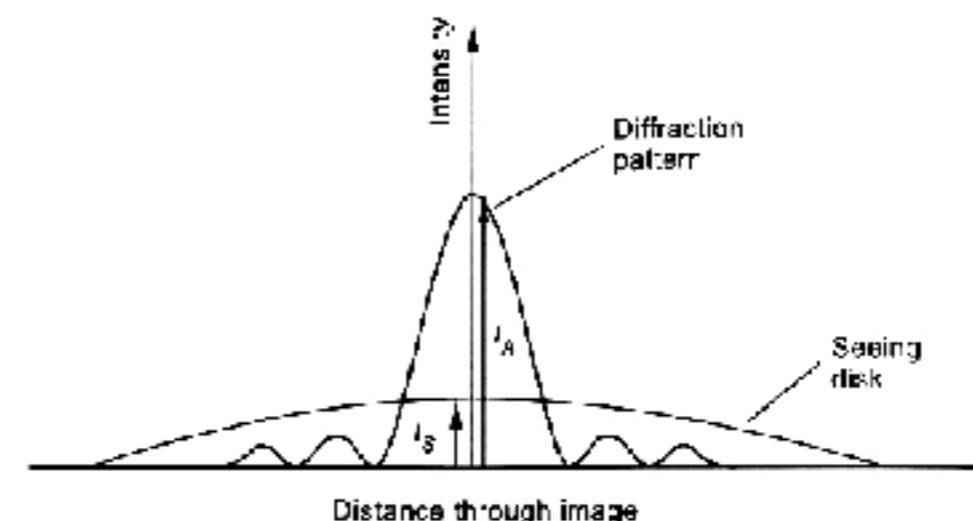


## NOT QUITE ON EARTH AS IT IS IN HEAVEN: SEEING

- ▶ Can big very large mirrors on Earth, and launching rockets is expensive, so why bother putting smaller telescopes in space?



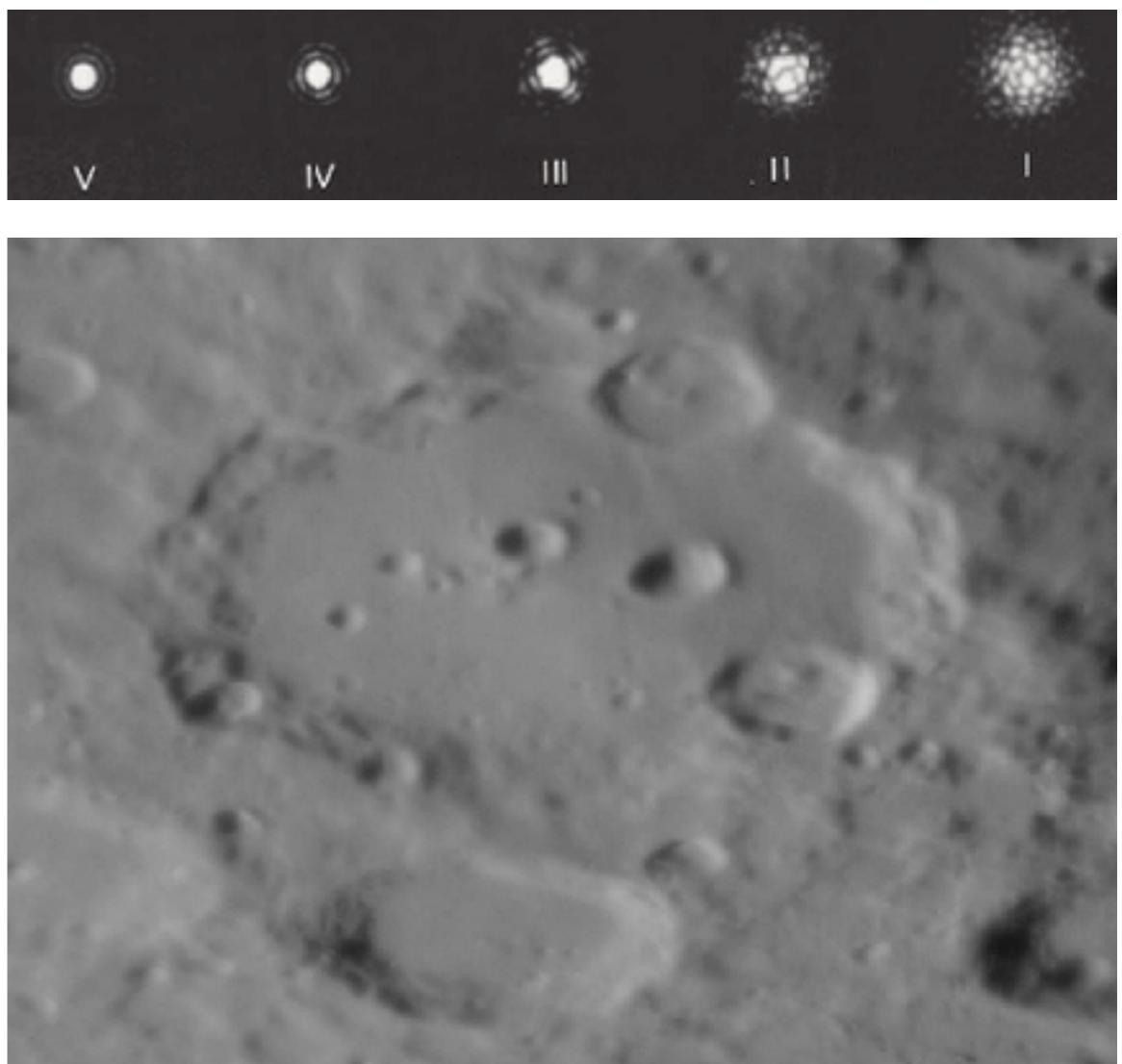
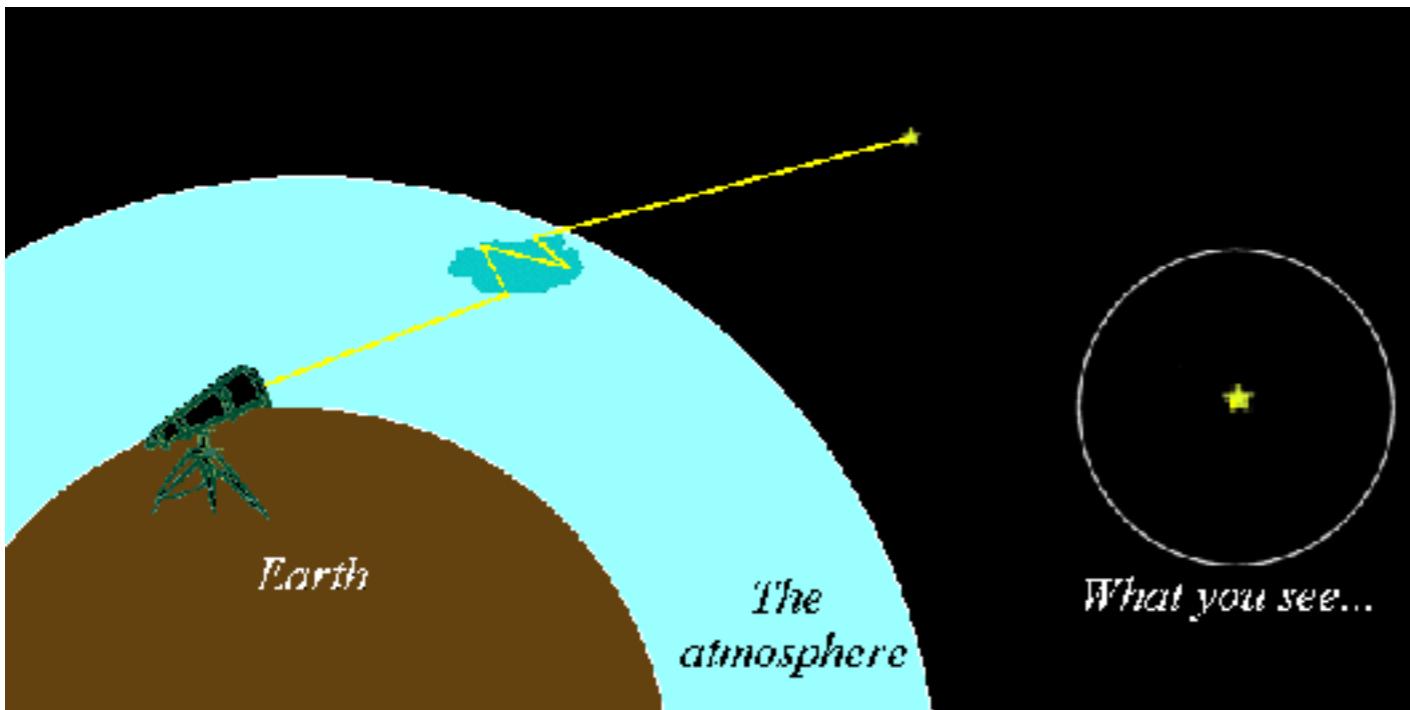
**Fig. 16.1.** Cross sections of undistorted wavefront  $\Sigma_u$  at top of atmosphere and distorted wavefront  $\Sigma_d$  at ground, after passage through turbulent atmosphere.

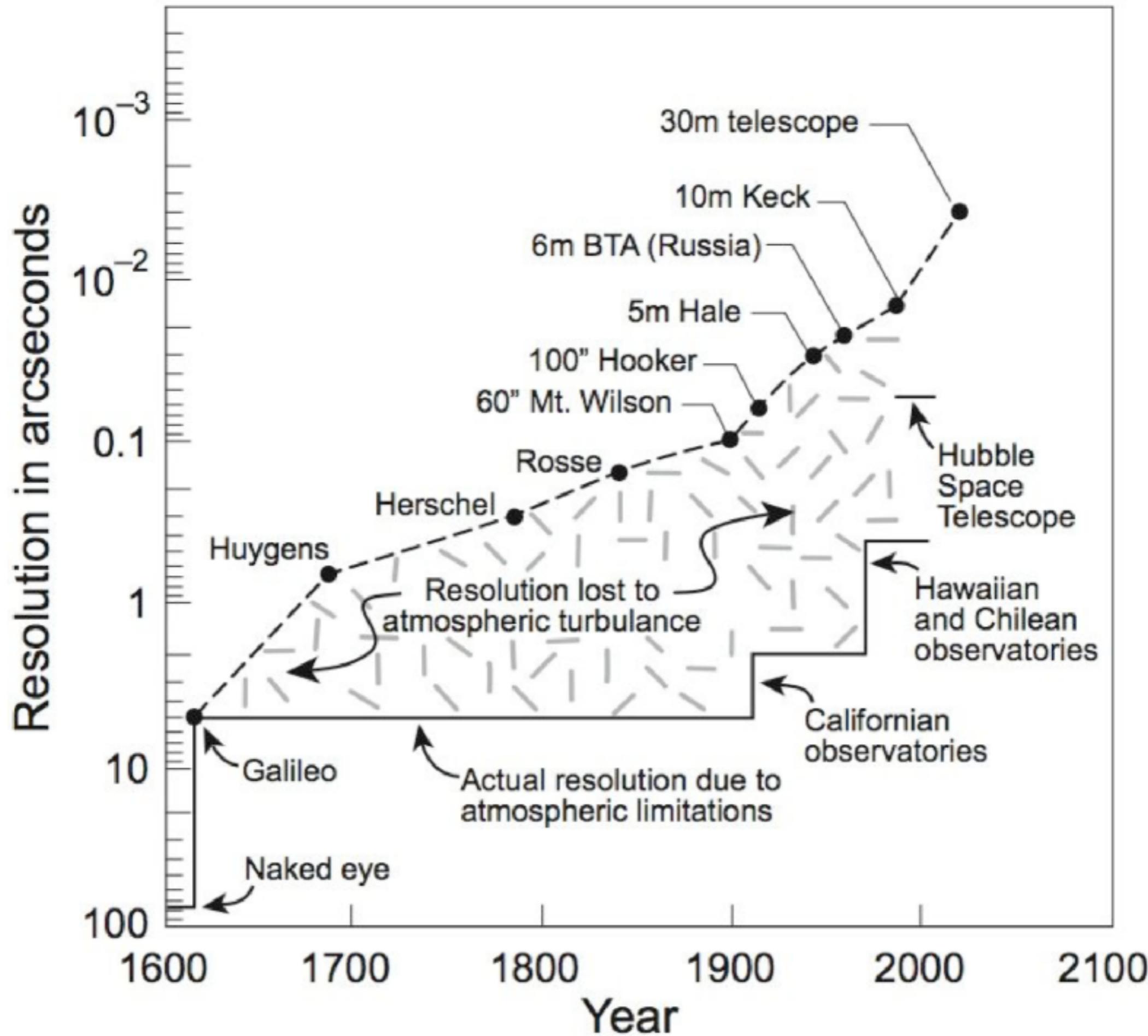


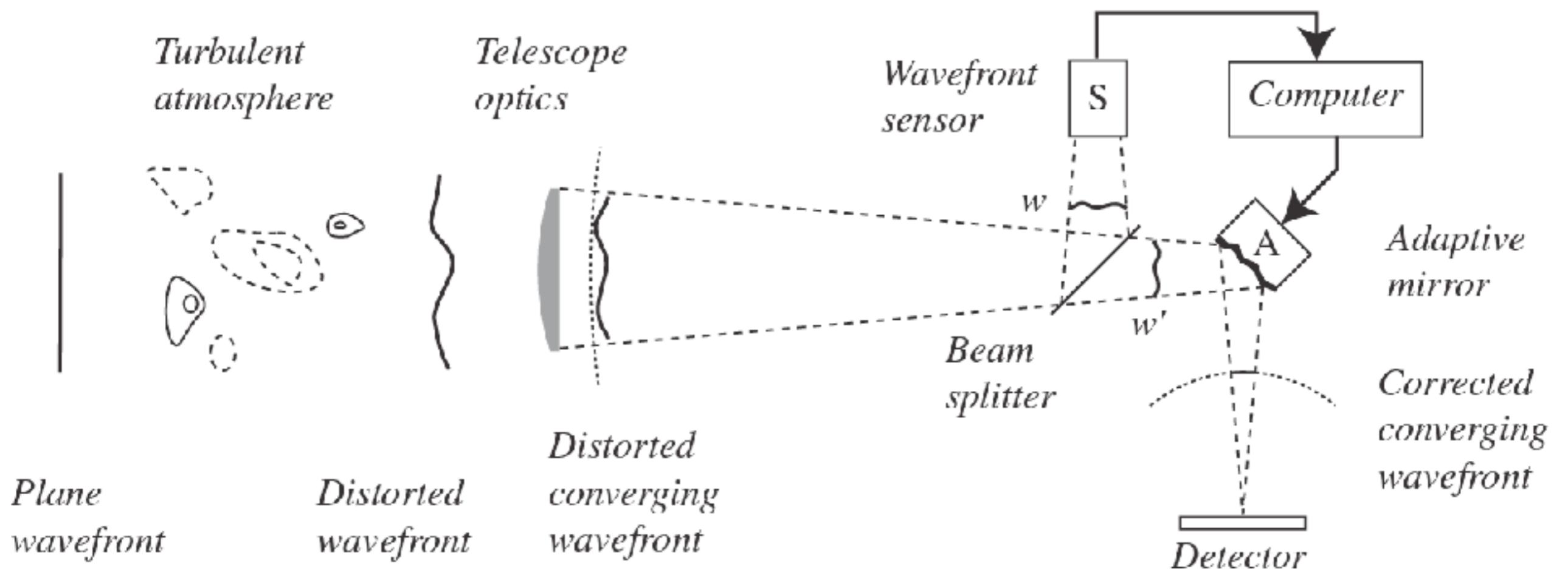
**Figure 19.8.** The seeing disc of a star is superposed in the theoretical diffraction pattern in the image plane. The ratio of the peak intensities,  $I_S/I_A$ , is referred to as the Strehl index.

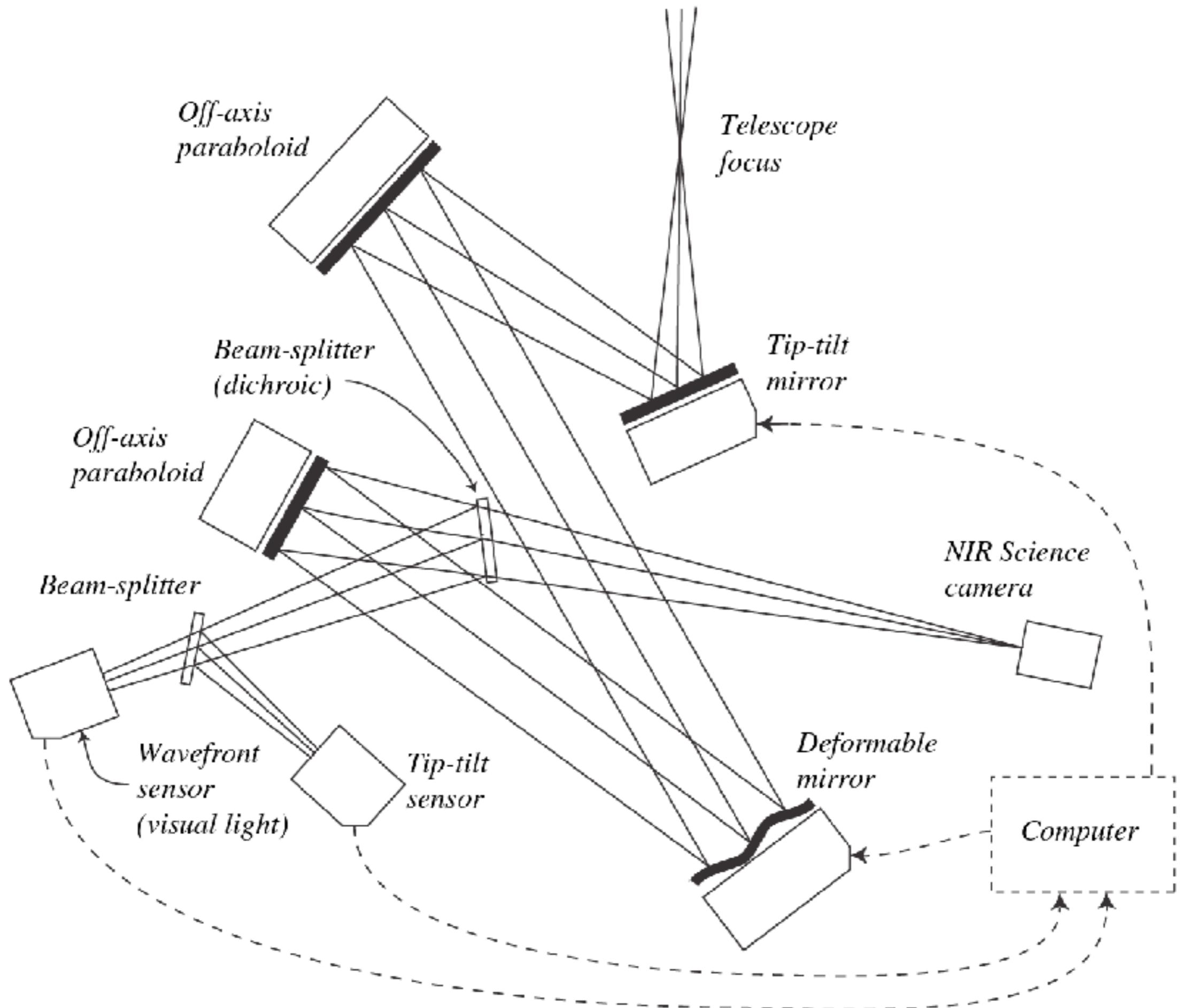
## NOT QUITE ON EARTH AS IT IS IN HEAVEN: SEEING

- ▶ Can big very large mirrors on Earth, and launching rockets is expensive, so why bother putting smaller telescopes in space?









# Modern mirrors



*Classical*



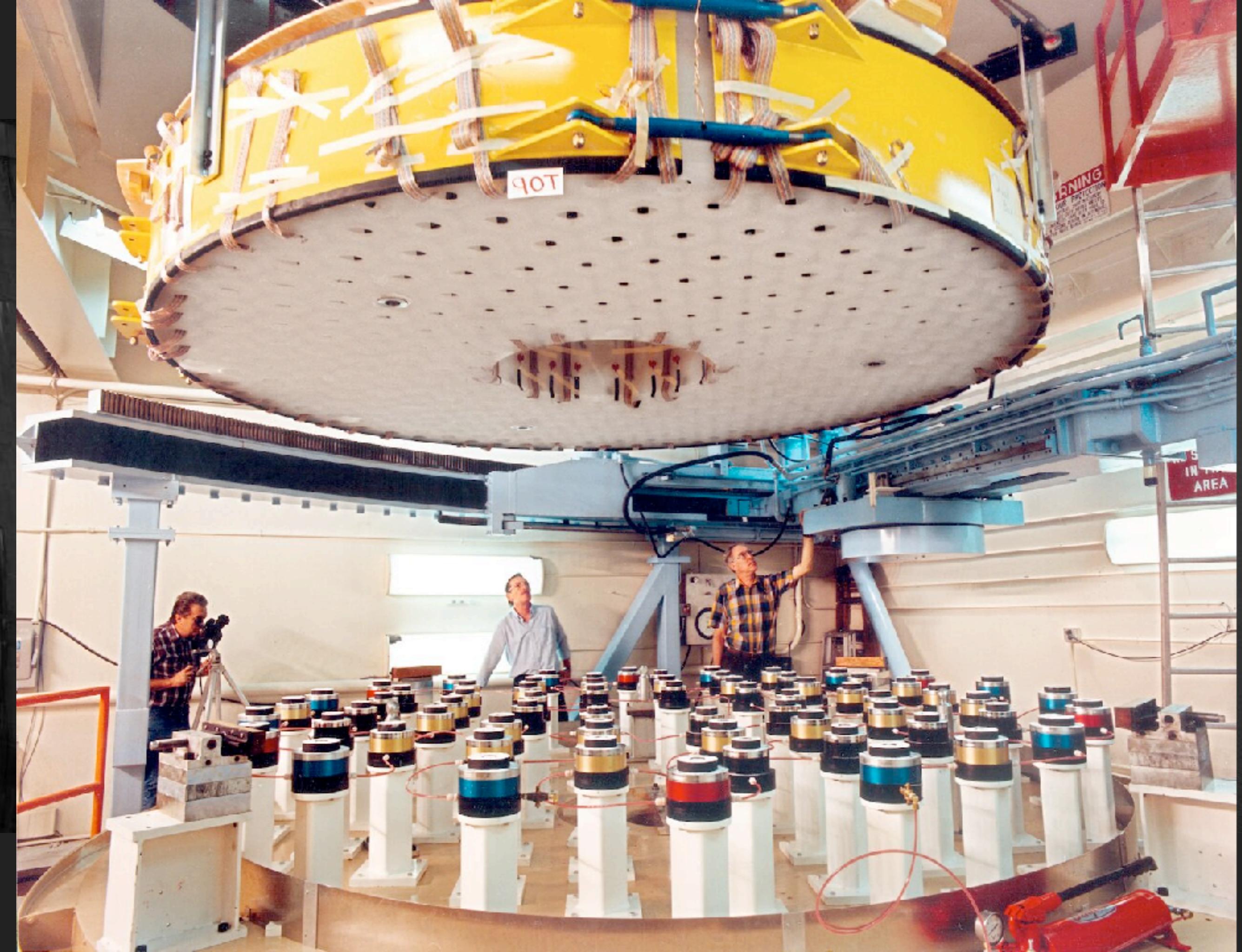
*Honeycombed*



*Meniscus*

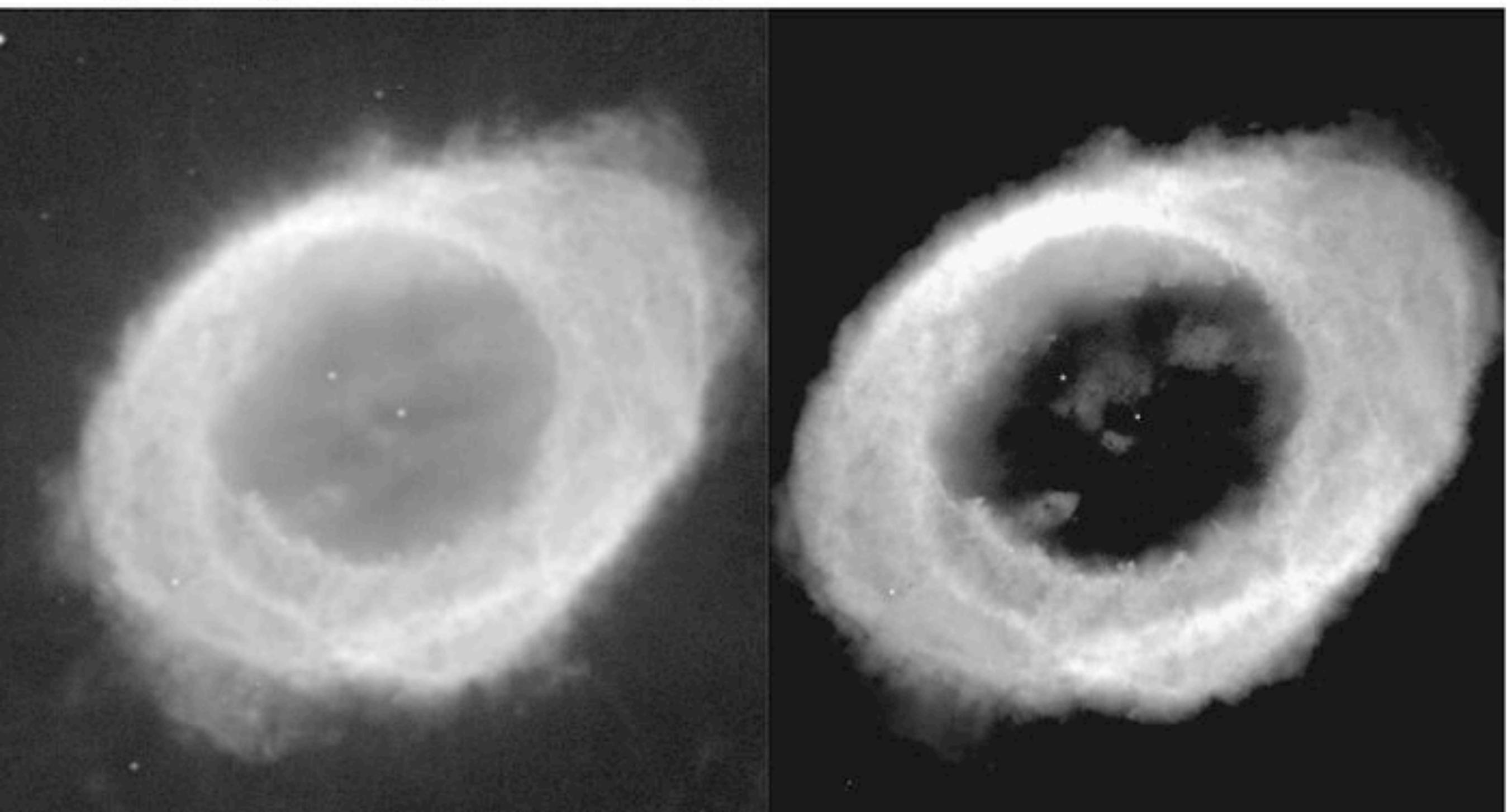


*Segmented*



- WIYN Image  
(rapid guiding correction)

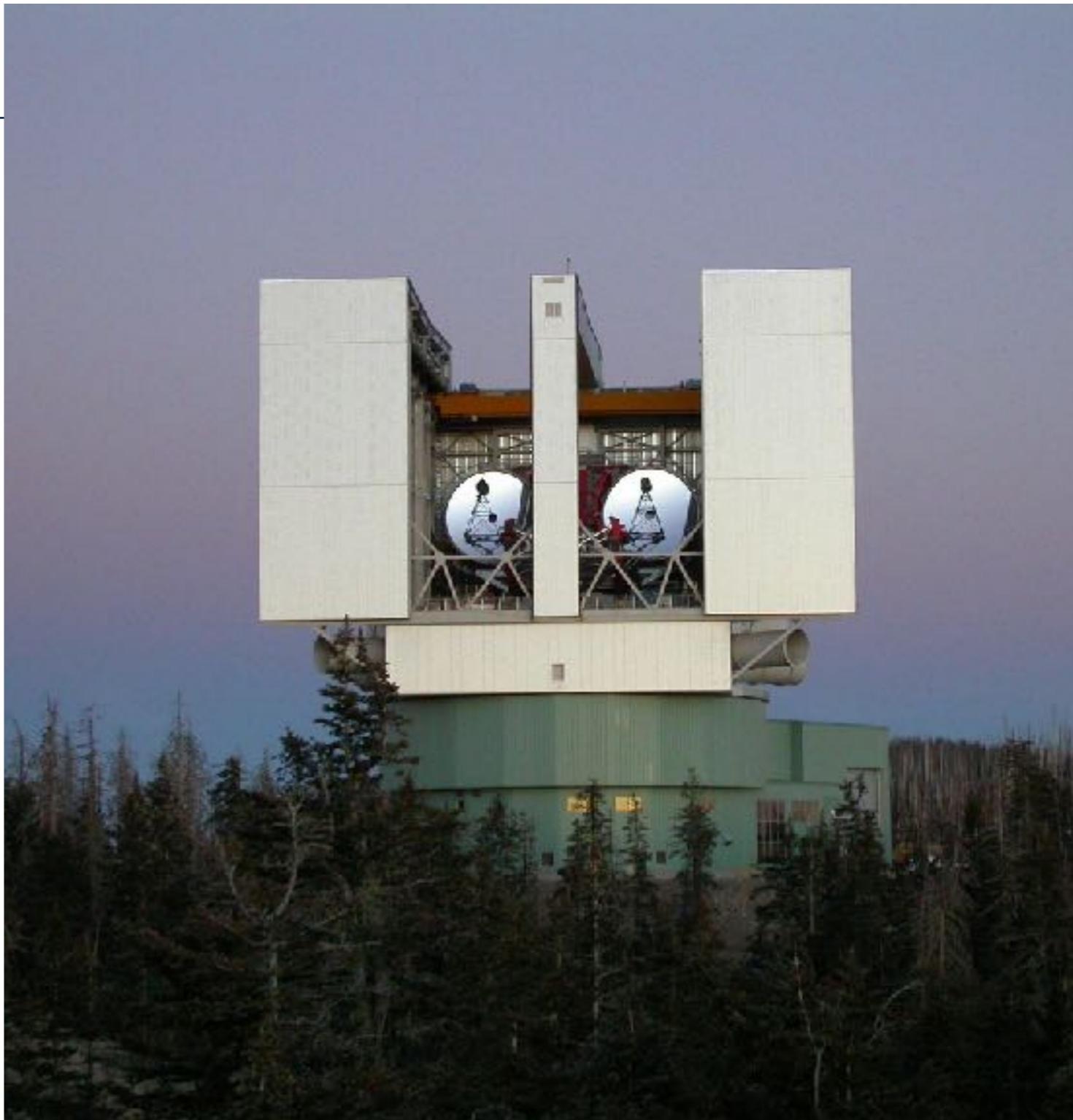
Hubble Image

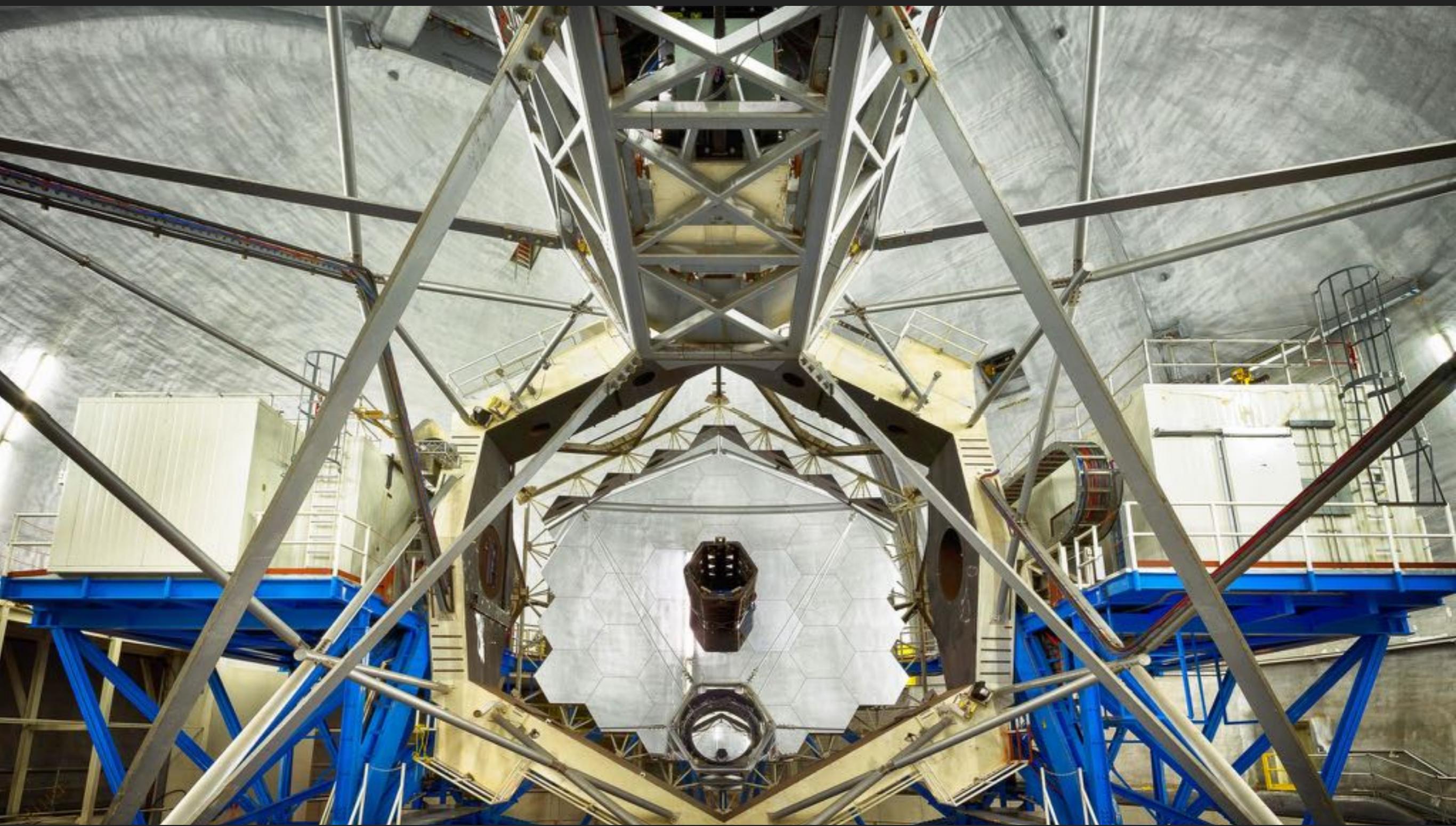


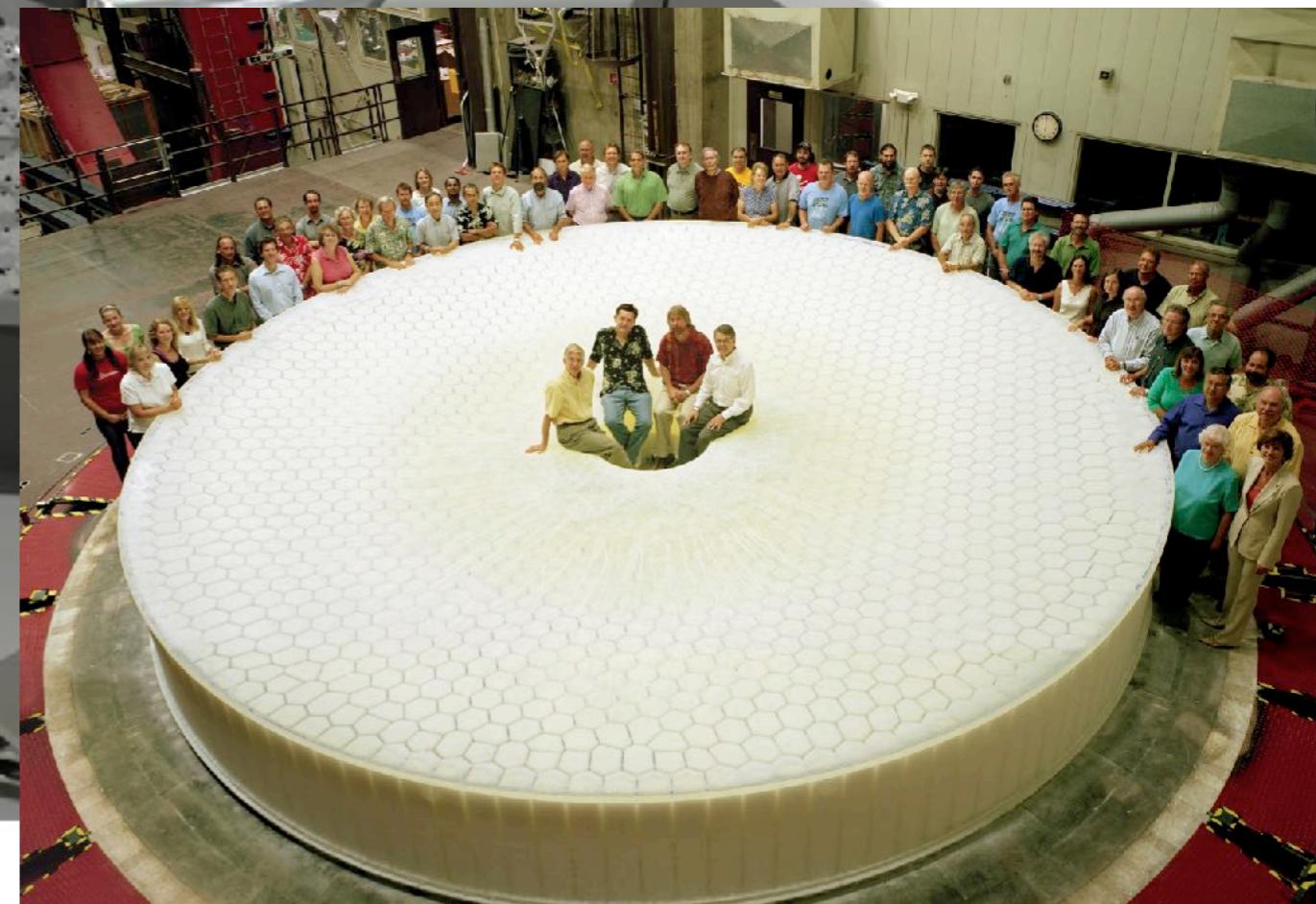
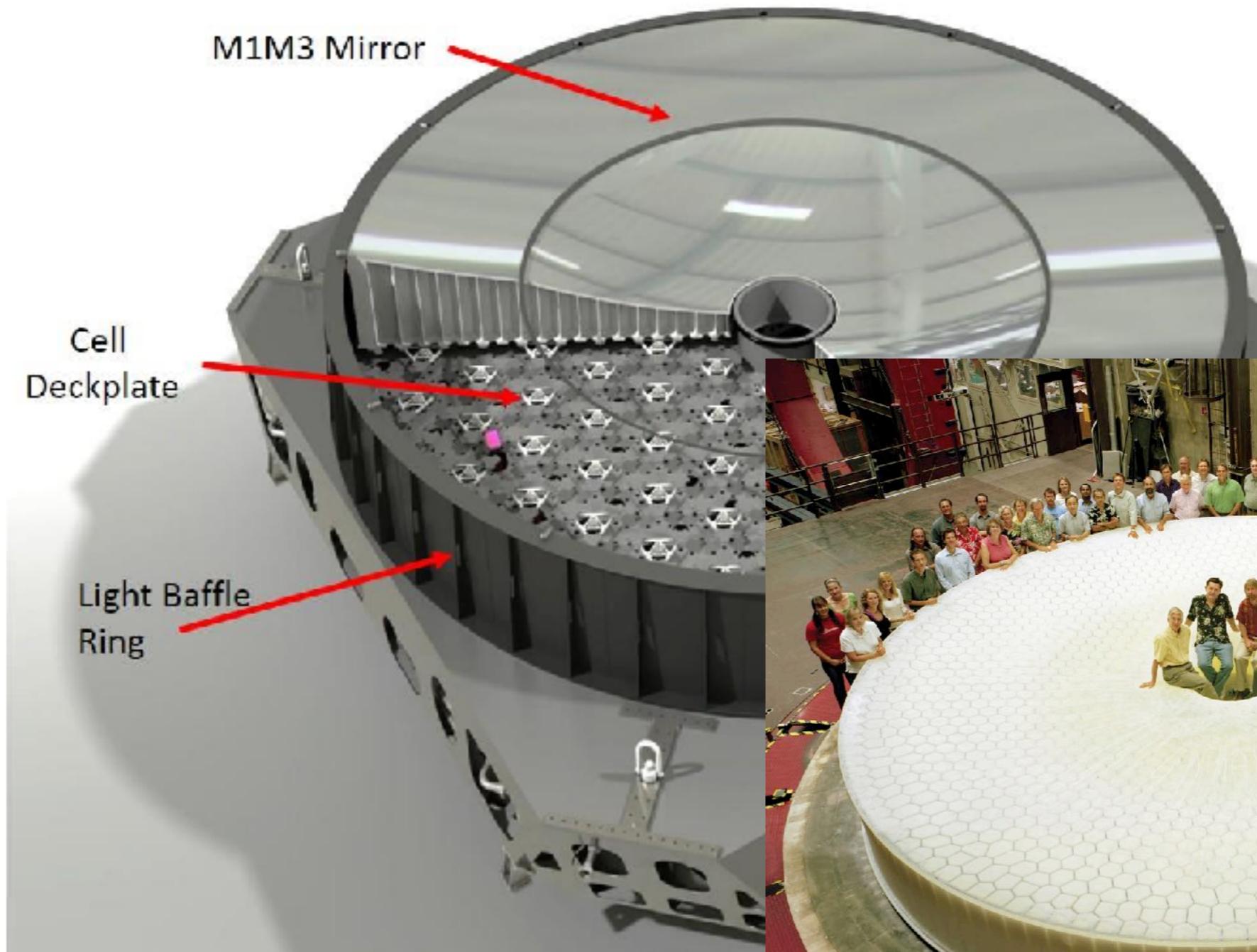
## NEW MIRROR TECH

---

- ▶ Three major categories of new technology:
- ▶ Segmented mirrors – smaller monolithic disks of thin polished glass, with position actuators, and gap sensors.
- ▶ Multiple mirrors – combining the light from smaller individual mirrors.
- ▶ Honeycomb mirrors - a thick mirror with large pockets of mass removed from the back to make the mirror lightweight yet very stiff. Spun in furnace to parabolic shape.







# National New Technology Telescope

Roger Angel / U. Arizona : multiple mirrors

Jerry Nelson / UCSC : segmented mirrors

"The Hale Telescope was very innovative for its day, but in terms of advancing the state of the art--or at least pushing the available technology to its limits--it's been downhill ever since for optical telescopes. It is time for a forward step, not just making improvements in an old design."

—Jerry Nelson

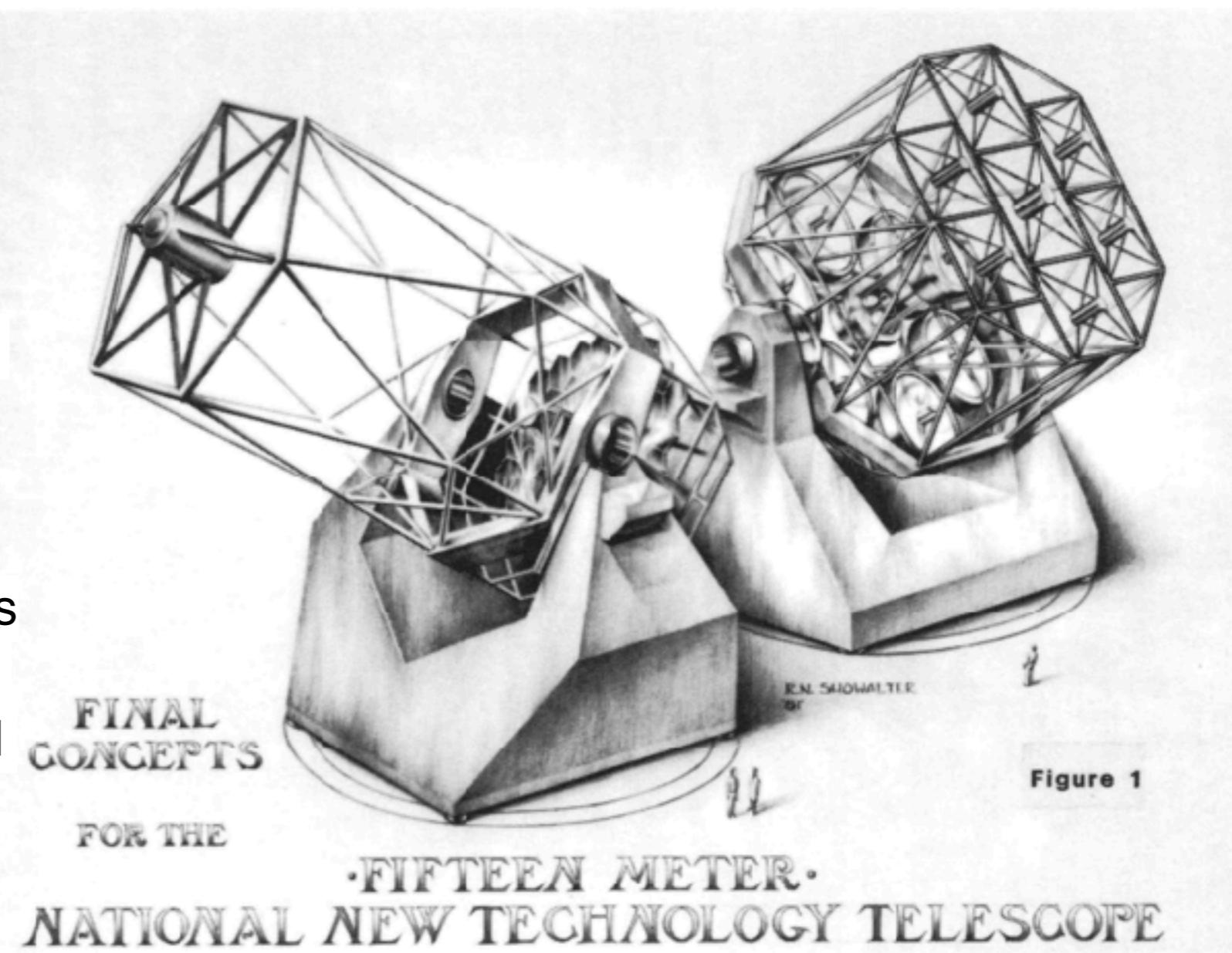
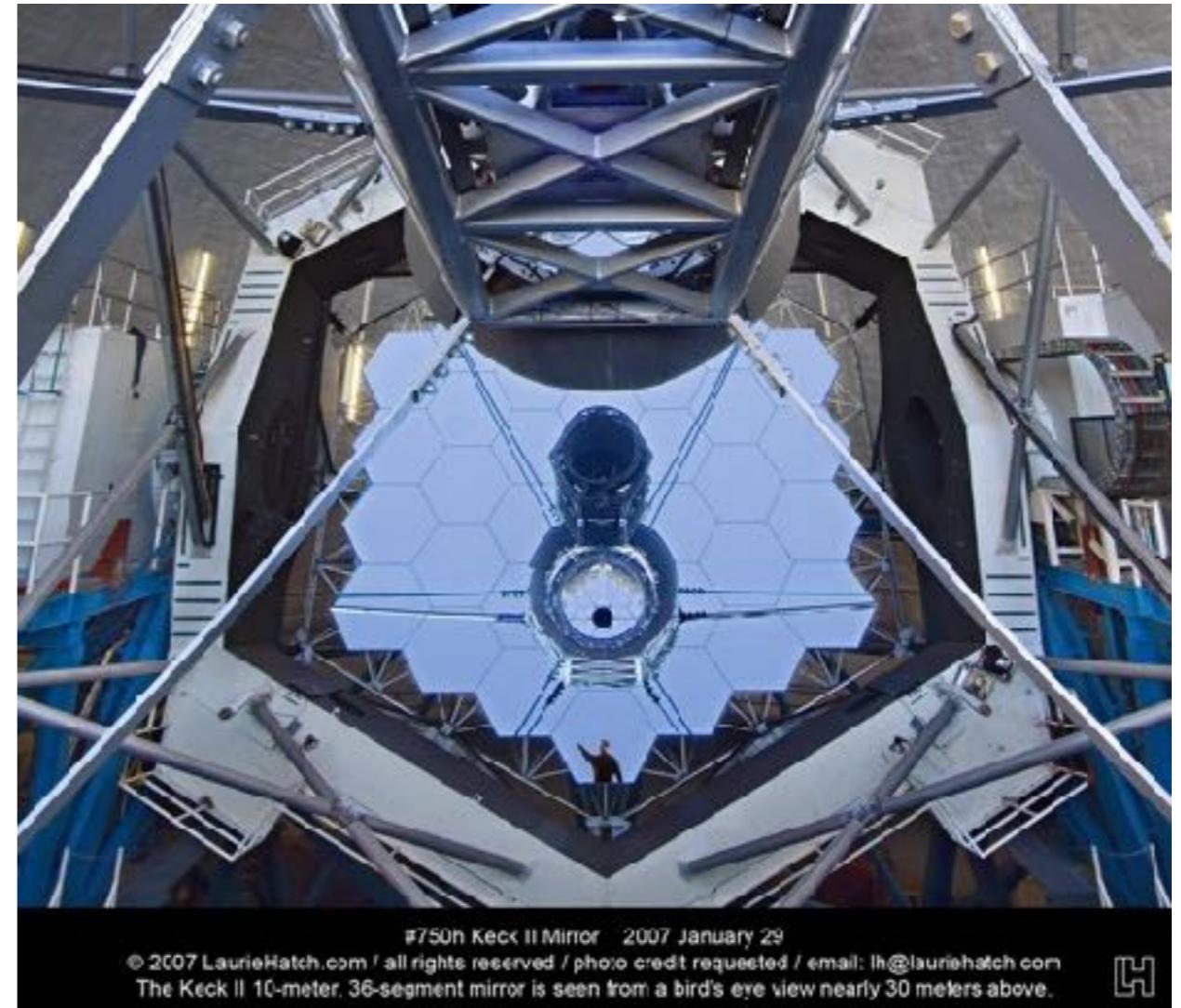


Figure 1

# Advances in mirror technology

150

- Three major categories of new technology:
- **Segmented mirrors** — smaller monolithic disks of thin polished glass, with position actuators, and gap sensors.
- **Meniscus mirrors** — large monolithic disks of solid glass that are thin, flexible, and must be actively controlled to maintain shape.
- **Honeycomb mirrors** - a thick mirror with large pockets of mass removed from the back to make the mirror lightweight yet very stiff. Spun in furnace to parabolic shape.



#750h Keck II Mirror 2007 January 29  
© 2007 LaurieHatch.com / all rights reserved / photo credit requested / email: lh@laurelhatch.com  
The Keck II 10-meter, 36-segment mirror is seen from a bird's eye view nearly 30 meters above.



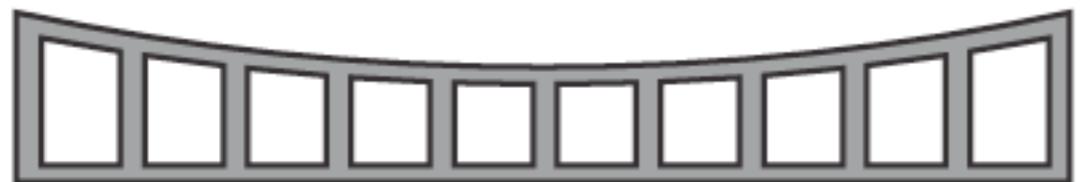
(10-m Keck II primary; W.M. Keck Telescope)

+ Computers !!!

# Advances in mirror technology



*Classical*



*Honeycombed*



*Meniscus*



*Segmented*

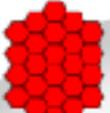
**Classical mirrors** – Large monolithic disks of polished glass with an aluminized first surface.

**Honeycomb mirrors** - a thick mirror with large pockets of mass removed from the back to make the mirror lightweight yet very stiff. Spun in furnace to parabolic shape.

**Meniscus mirrors** – large monolithic disks of solid glass that are thin, flexible, and must be actively controlled to maintain shape.

**Segmented mirrors** – smaller monolithic disks of thin polished glass, with position actuators, and gap sensors.

**Great Paris Exhibition Telescope**  
(lens at the same scale)  
Paris, France (1900)



**Yerkes Observatory**  
(40" refractor  
lens at the same scale)  
Williams Bay,  
Wisconsin (1893)



**Hooker (100")**  
Mt Wilson,  
California  
(1917)

**Hale (200")**  
Mt Palomar,  
California  
(1948)



**Multi Mirror Telescope**  
Mount Hopkins, Arizona



**BTA-6 (Large Altazimuth Telescope)**  
Zelenchuksky, Russia  
(1975)



**Large Zenith Telescope**  
British Columbia, Canada  
(2003)

**Gala**  
Earth-Sun L2 point  
(2014)



**James Webb Space Telescope**  
Earth-Sun L2 point  
(planned 2018)

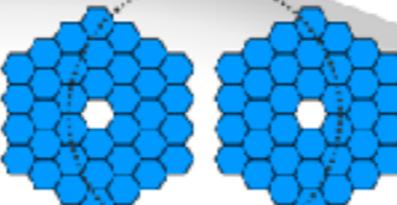


Tennis court at the same scale

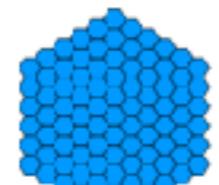
**Large Sky Area Multi-Object Fiber Spectroscopic Telescope**  
Hebei, China (2009)



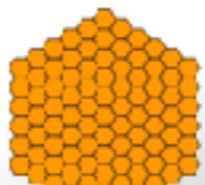
**Gran Telescopio Canarias**  
La Palma, Canary Islands, Spain (2007)



**Keck Telescope**  
Mauna Kea, Hawaii (1993/1996)



**Hobby-Eberly Telescope**  
Davis Mountains, Texas (1996)



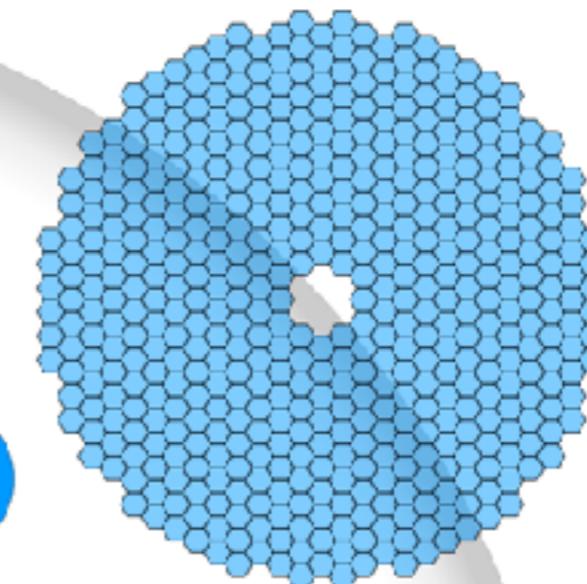
**Southern African Large Telescope**  
Sutherland, South Africa (2005)



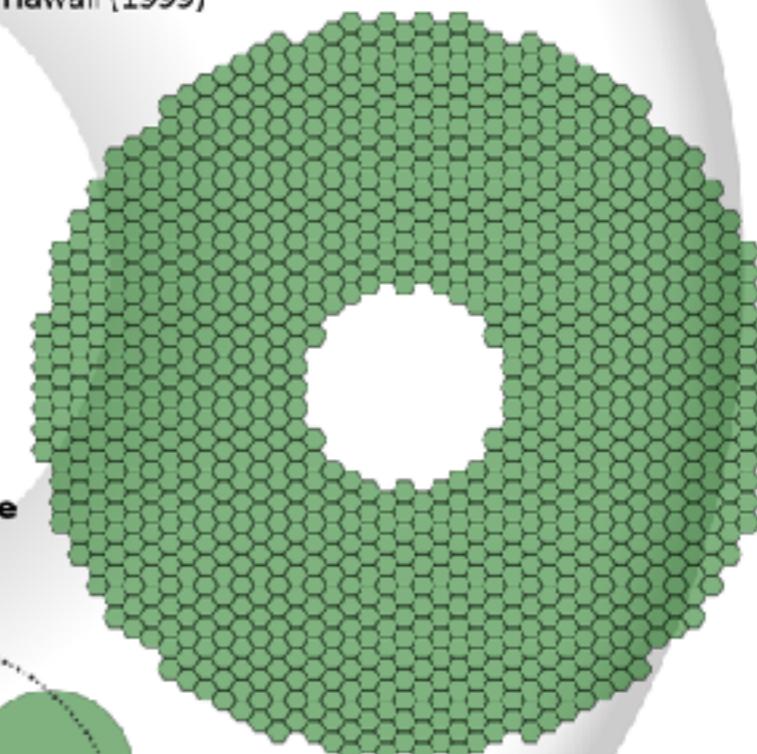
**Gemini North**  
Mauna Kea, Hawaii (1999)



**Subaru Telescope**  
Mauna Kea, Hawaii (1999)



**Thirty Meter Telescope**  
Mauna Kea, Hawaii (planned 2022)

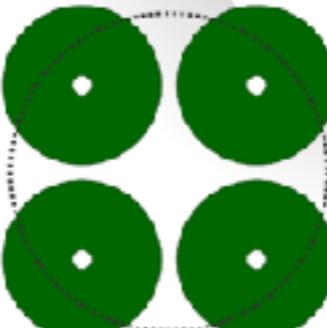


**Gemini South**  
Cerro Pachón, Chile (2000)



**Large Binocular Telescope**  
Mount Graham, Arizona (2005)

**Large Synoptic Survey Telescope**  
El Peñón, Chile (planned 2020)



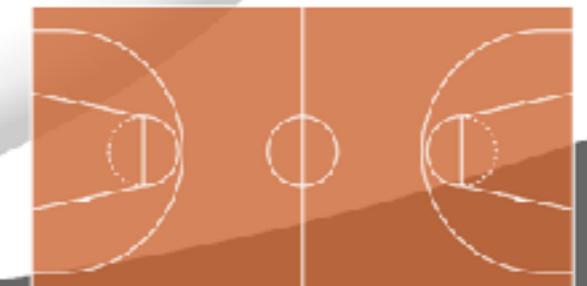
**Very Large Telescope**  
Cerro Paranal, Chile (1998-2000)



**European Extremely Large Telescope**  
Cerro Armazones, Chile (planned 2022)

Human at the same scale

0 5 10 m  
0 10 20 30 ft



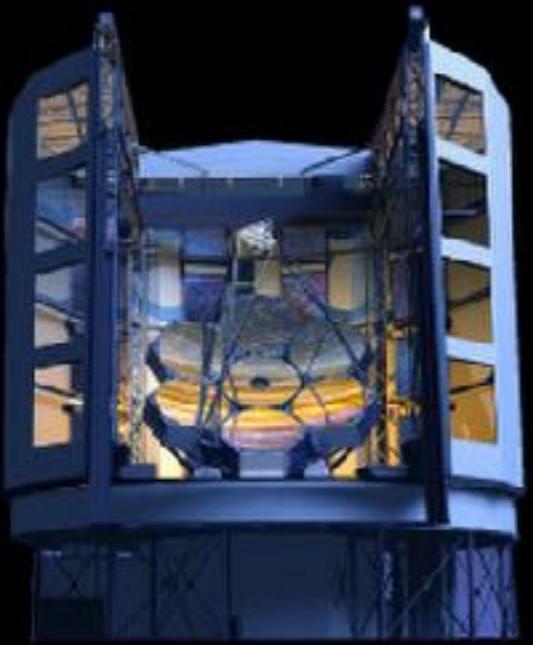
Basketball court at the same scale

Overwhelmingly Large Telescope (cancelled)

Arecibo radio telescope at the same scale

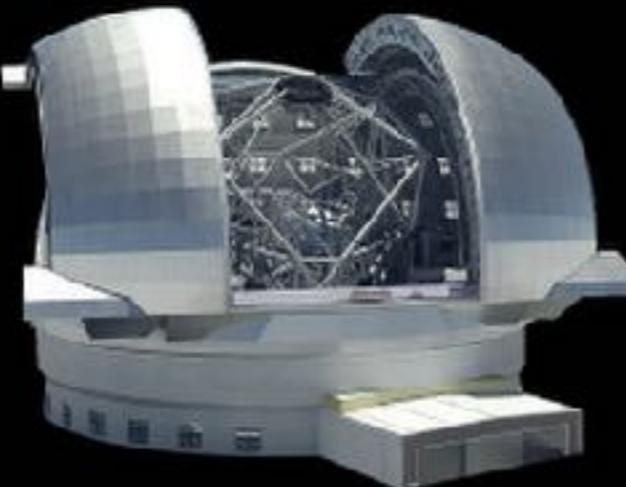
# BIGGEST SCOPES

As of 2013, the largest reflecting telescope in the world is the Gran Telescopio Canarias in La Palma, Spain, with a mirror diameter of 34.2 feet (10.4 meters). Within a decade, much larger telescopes will be coming online.



## GIANT MAGELLAN TELESCOPE

**MAIN MIRROR DIAMETER:**  
80 feet (24.5 m)  
**MIRROR SEGMENTS:** 7  
**LOCATION:** Las Campanas Observatory, Chile  
**PLANNED OPERATIONAL START:**  
2020



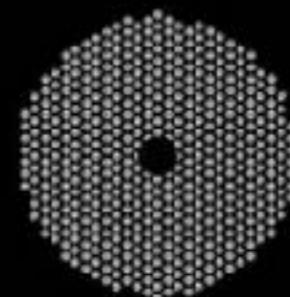
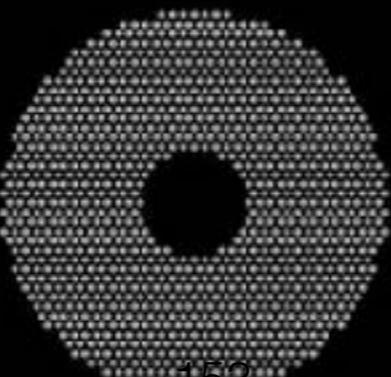
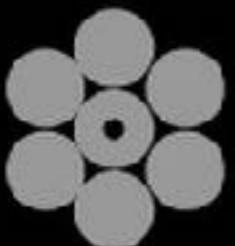
## EUROPEAN EXTREMELY LARGE TELESCOPE

**MAIN MIRROR DIAMETER:**  
129 feet (39.3 m)  
**MIRROR SEGMENTS:** 798  
**LOCATION:** Cerro Armazones, Chile  
**PLANNED OPERATIONAL START:** early 2020s



## THIRTY METER TELESCOPE

**MAIN MIRROR DIAMETER:**  
98 feet (30 m)  
**MIRROR SEGMENTS:** 492  
**LOCATION:** Mauna Kea, Hawaii  
**PLANNED OPERATIONAL START:**  
early 2020s



Telescope	Location	Aperture	type	Year
Galileo 1st	Italy	1.5 cm	refracting	1609
Galileo final	Italy	2.6 cm	refracting	1612
Yerkes	Wisconsin	40" ; 1 m	refracting	1897
Hale	Mt. Wilson, CA	60" ; 1.5 m	reflecting	1908
Hooker	Mt. Wilson, CA	100" ; 2.5 m	reflecting	1917
Hale	Palomar, CA	200" ; 5 m	reflecting	1948
Keck	Mauna Kea, HI	10 m	reflecting, segmented	1993
Hubble	space	2.4 m	reflecting	1990
JWST	space	6.5 m	reflecting, segmented	2021 (?)





Photo credit: Heidi B. Hammel, Imke de Pater, Keck Observatory

## Uranus on 9 July 2004

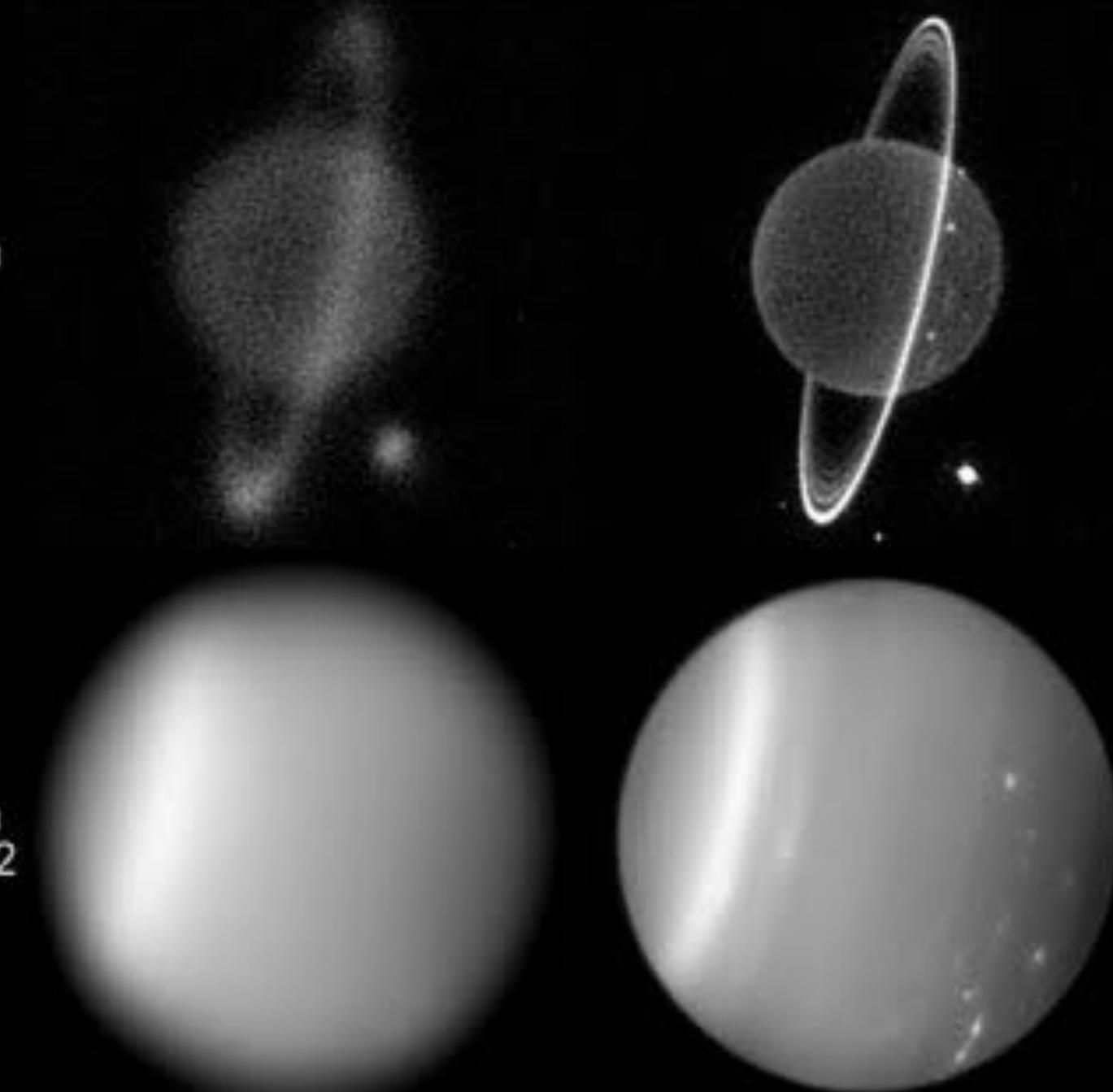
The Power of Keck's Adaptive Optics

AO System OFF

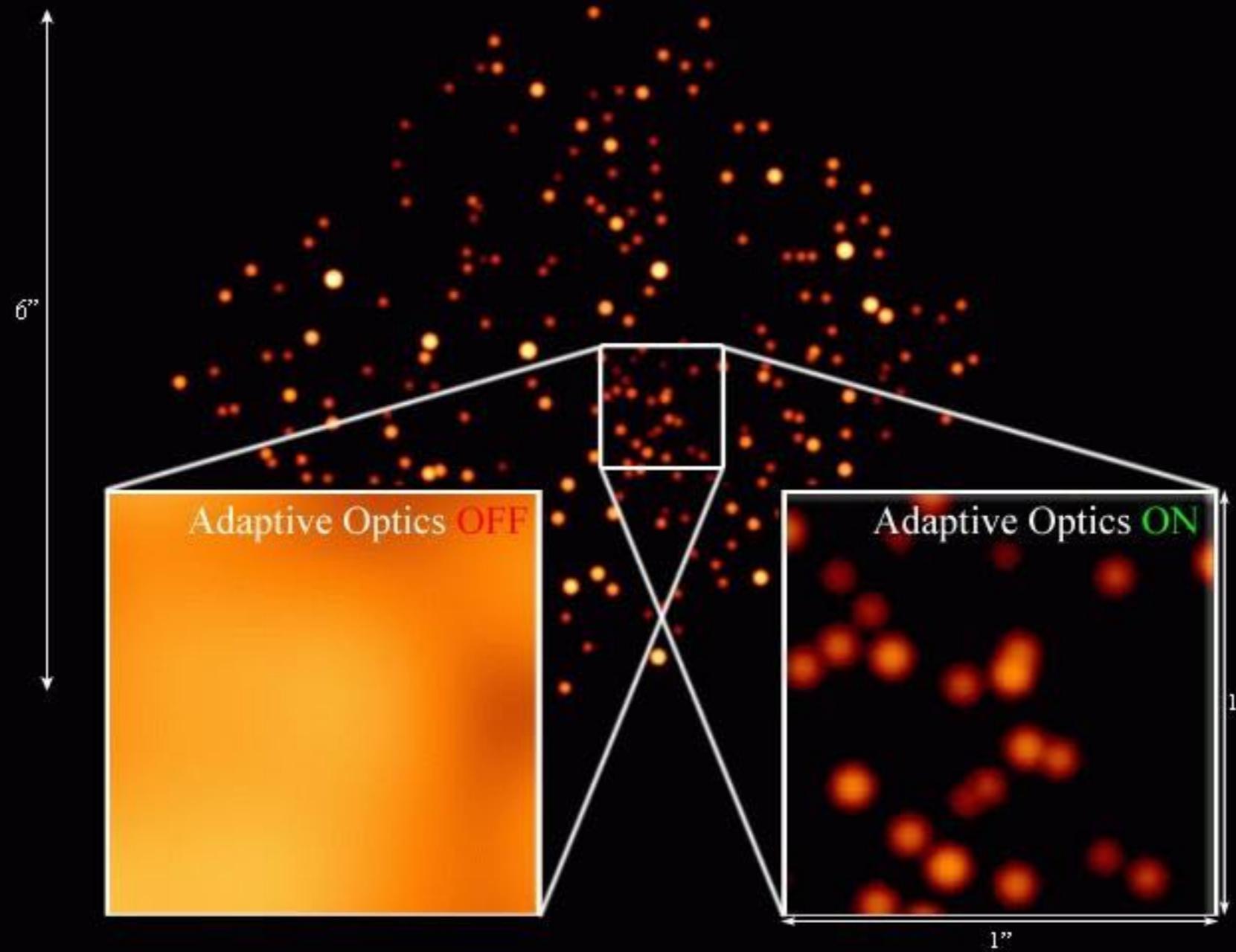
AO System ON

2.2  $\mu\text{m}$

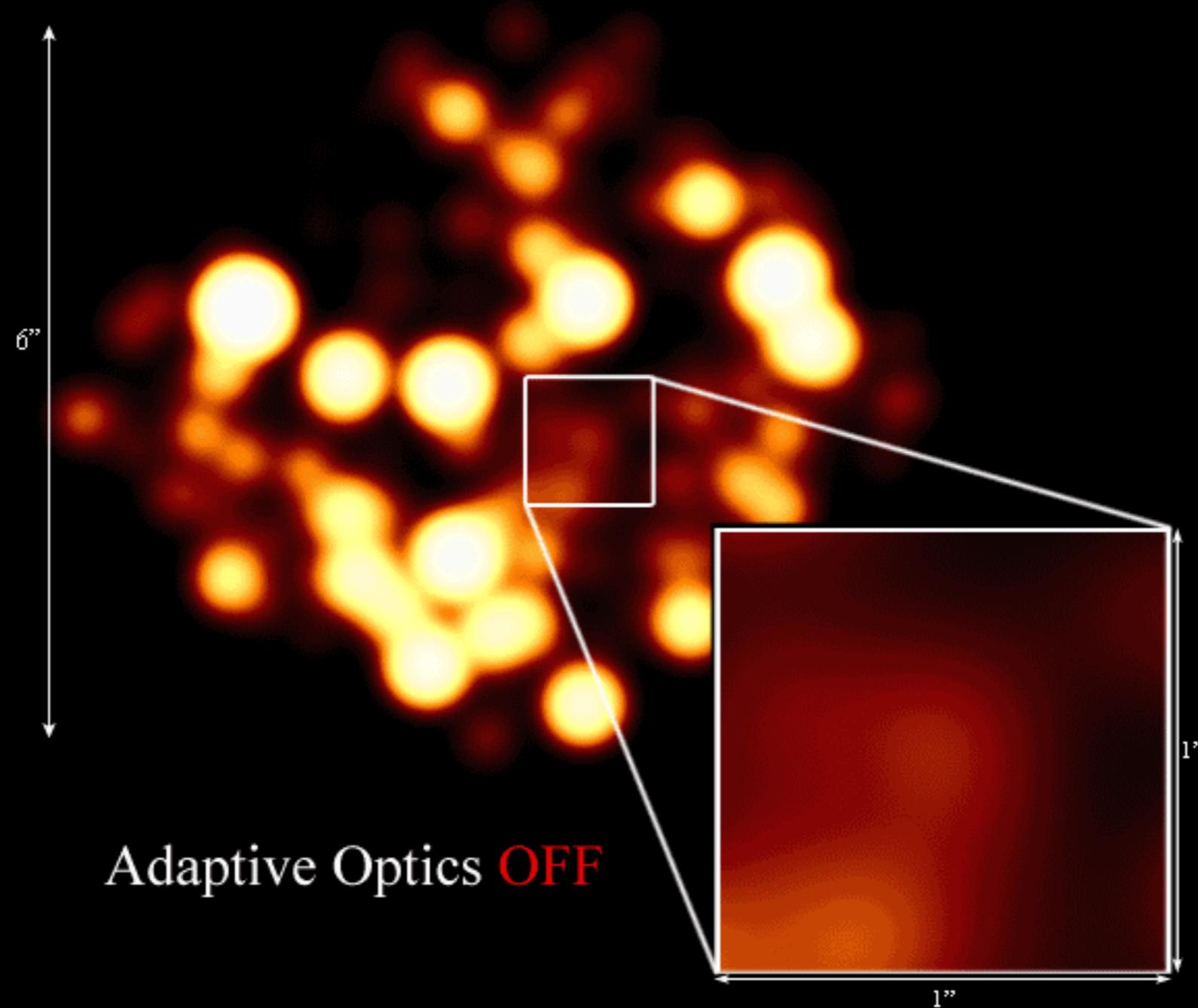
1.6  $\mu\text{m}$   
zoom x2



## The Galactic Center at 2.2 microns



# The Galactic Center at 2.2 microns



# Meniscus mirrors: VLT



- 4 x 8 m telescopes
- Each with monolithic glass meniscus primary mirror ( $f/1.8$ ) which is so thin for its size that the mirror requires "active" rather than "passive" mechanical support.
- Hundreds of adjustable "pistons" placed against the back of the mirror exert small forces that compensate for distortions of the figure of the mirror due to gravitational stress, thermal effects, wind-buffeting and slowly-varying atmospheric blurring.
- Mirror support needs to be up-dated a few times per second.



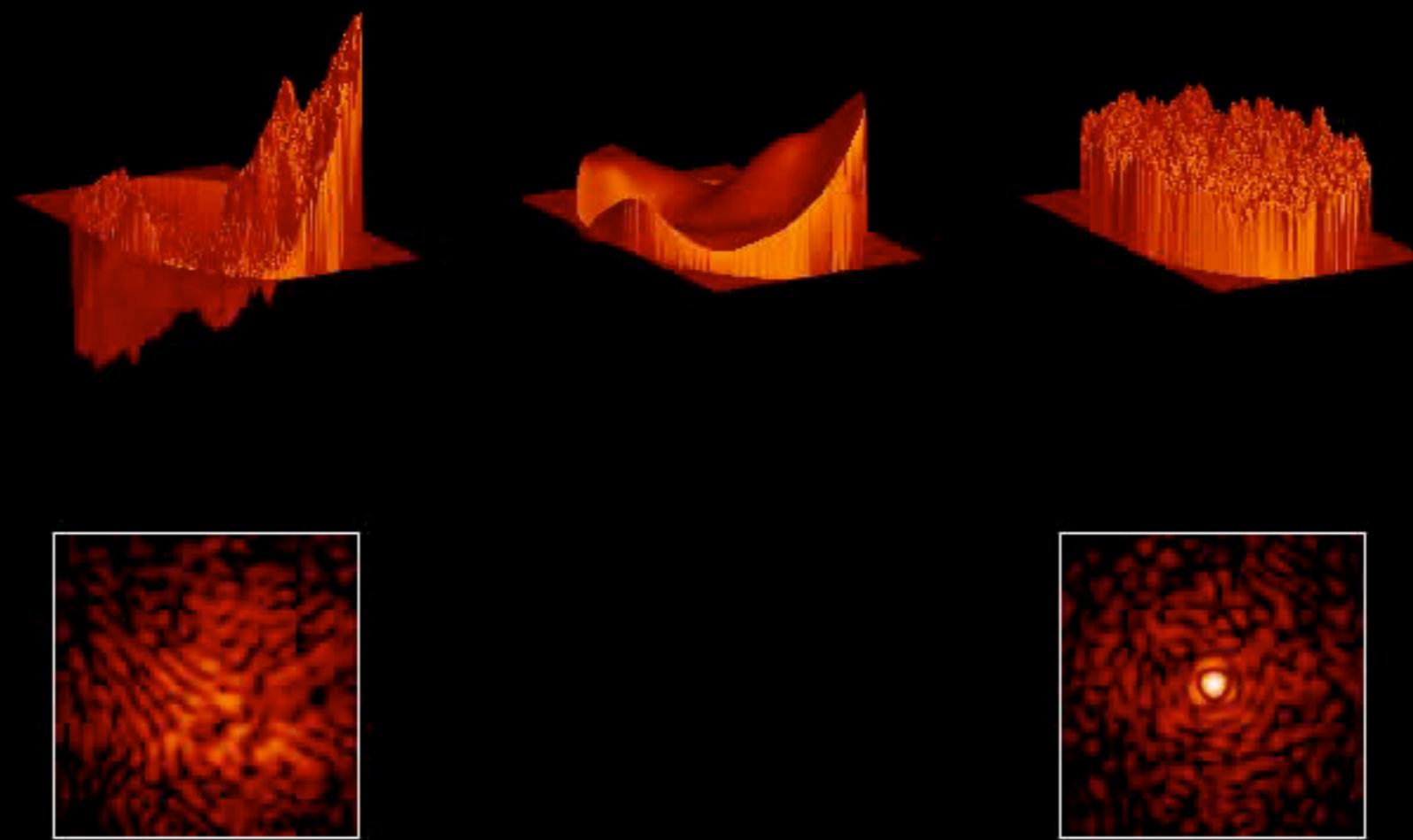
# Ritchey–Chrétien telescopes

- Ritchey–Chrétien (R-C) telescopes specialized variant of the Cassegrain telescope.
- A hyperbolic primary mirror and a hyperbolic secondary mirror designed to eliminate off-axis optical errors (coma).
- The R-C has a wider field of view free of optical errors compared to a more traditional reflecting telescope configuration.
- Since the mid 20th century, a majority of large professional research telescopes have been R-C configurations; some well-known examples are the Hubble Space Telescope, the Keck telescopes and the ESO Very Large Telescope.





Keck/UCLA Galactic Center Group



# Two-dimensional Fourier transforms

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A direct generalization from 1-d:

$$f(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(\xi, \eta) e^{-i2\pi(x\xi + y\eta)} d\xi d\eta$$

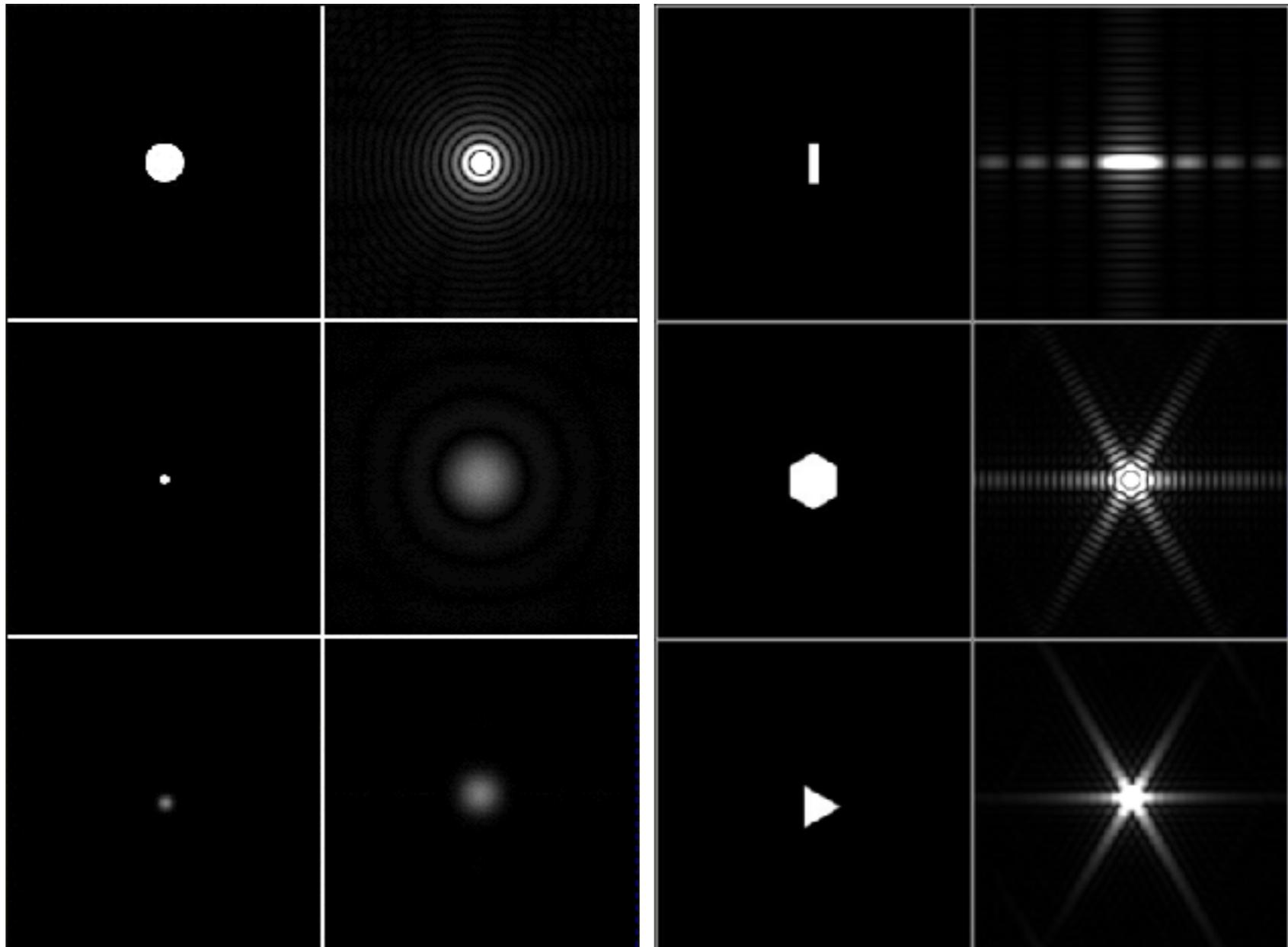
$$F(\xi, \eta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) e^{+i2\pi(x\xi + y\eta)} dx dy$$

In vector form:

$$f(\vec{x}) = \int \int_{-\infty}^{\infty} F(\vec{s}) e^{i2\pi \vec{s} \cdot \vec{x}} d^2 s$$

$$F(\vec{s}) = \int \int_{-\infty}^{\infty} f(\vec{x}) e^{-i2\pi \vec{s} \cdot \vec{x}} d^2 \vec{x}$$

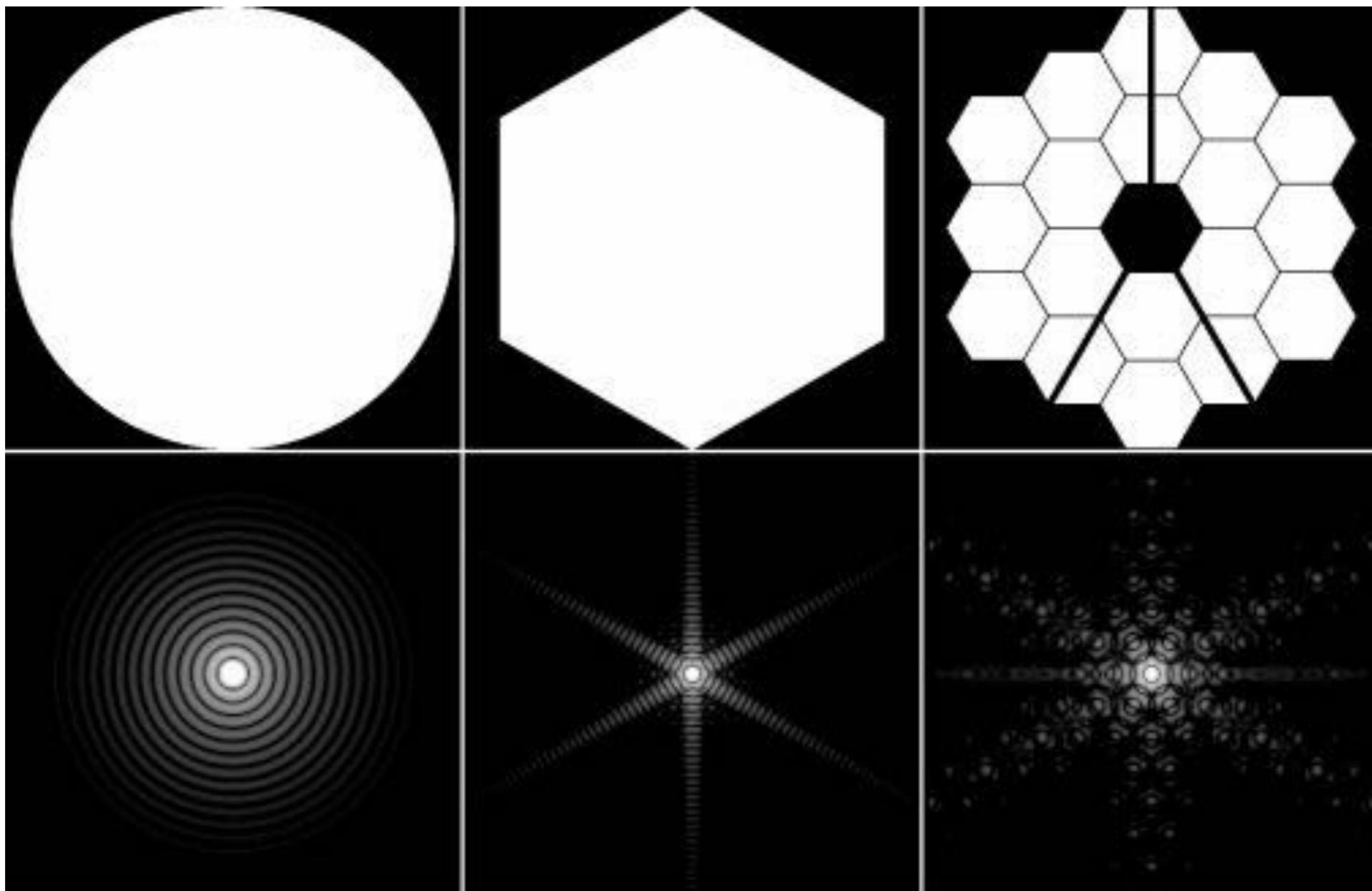
Can simplify greatly if  
separable or symmetric.



(CC)

# Sample PSFs

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(NASA/JWST)