Astronomical Optics

2. Fundamentals of Telescopes designs

2.1. Telescope types: refracting, reflecting

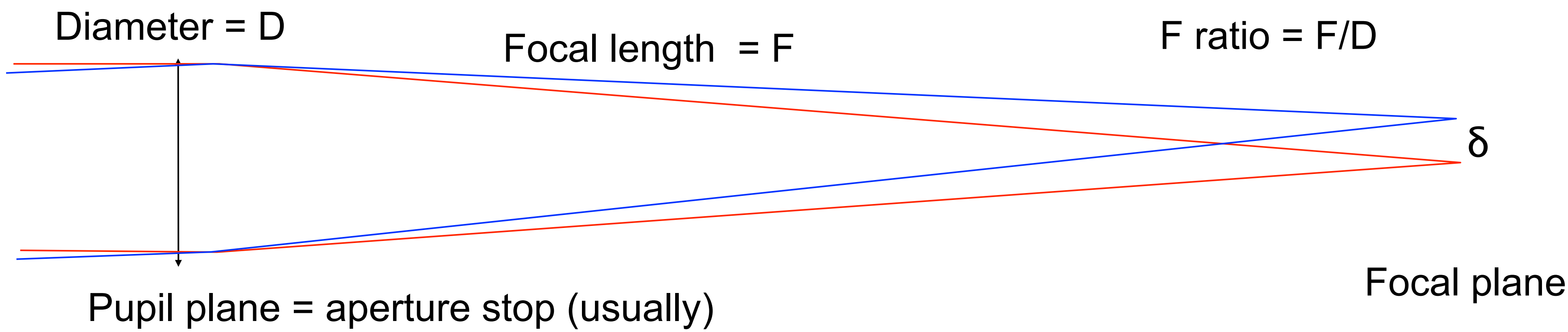
OUTLINE:

Shaping light into an image: first principles
Telescopes for different wavelengths
Telescope elements: lenses and mirrors

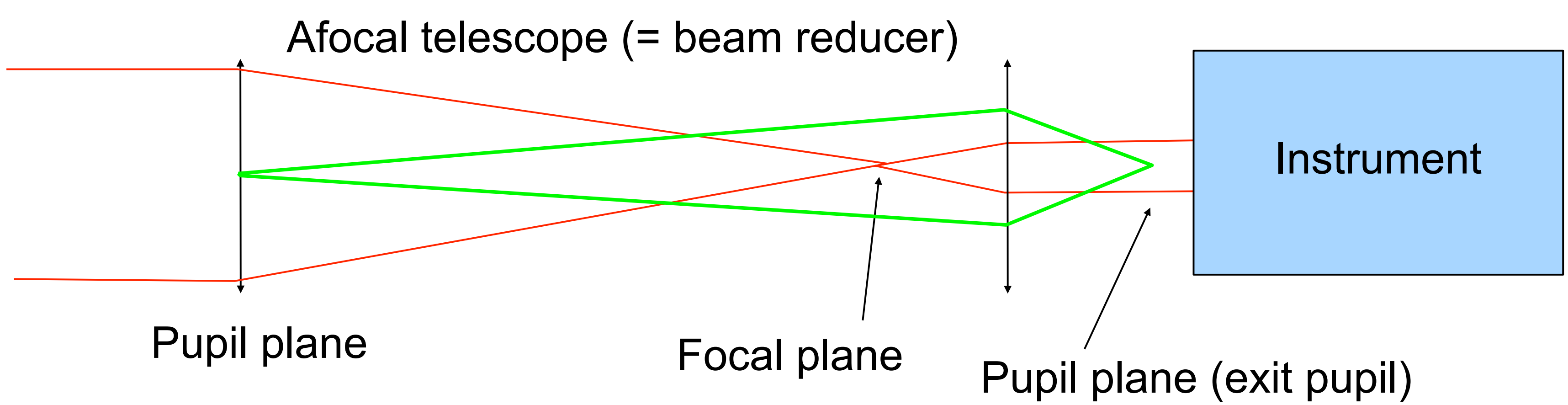
Telescope types
- refracting (lenses)
- reflecting (mirrors)

Keeping the image sharp on large telescopes: challenges

Optical principle and notations (shown here with lenses)



F gives the plate scale at the focal plane (ratio between physical dimension in focal plane and angle on the sky): δ = angle x F
F/D gives physical size of diffraction limit at the focal plane = (F/D) λ



Shaping light into an image: first principles

A telescope must bend or reflect light rays to make them converge to a small (ideally smaller that the atmospheric seeing size for ground telescopes) zone in the focal plane

At optical/nearIR wavelengths, this is done with mirrors or lenses

- choice of materials is important for lenses and mirrors
- coatings (especially for mirrors) are essential to the telescope performance
- optical surfaces of mirrors and lenses must be accurately controlled

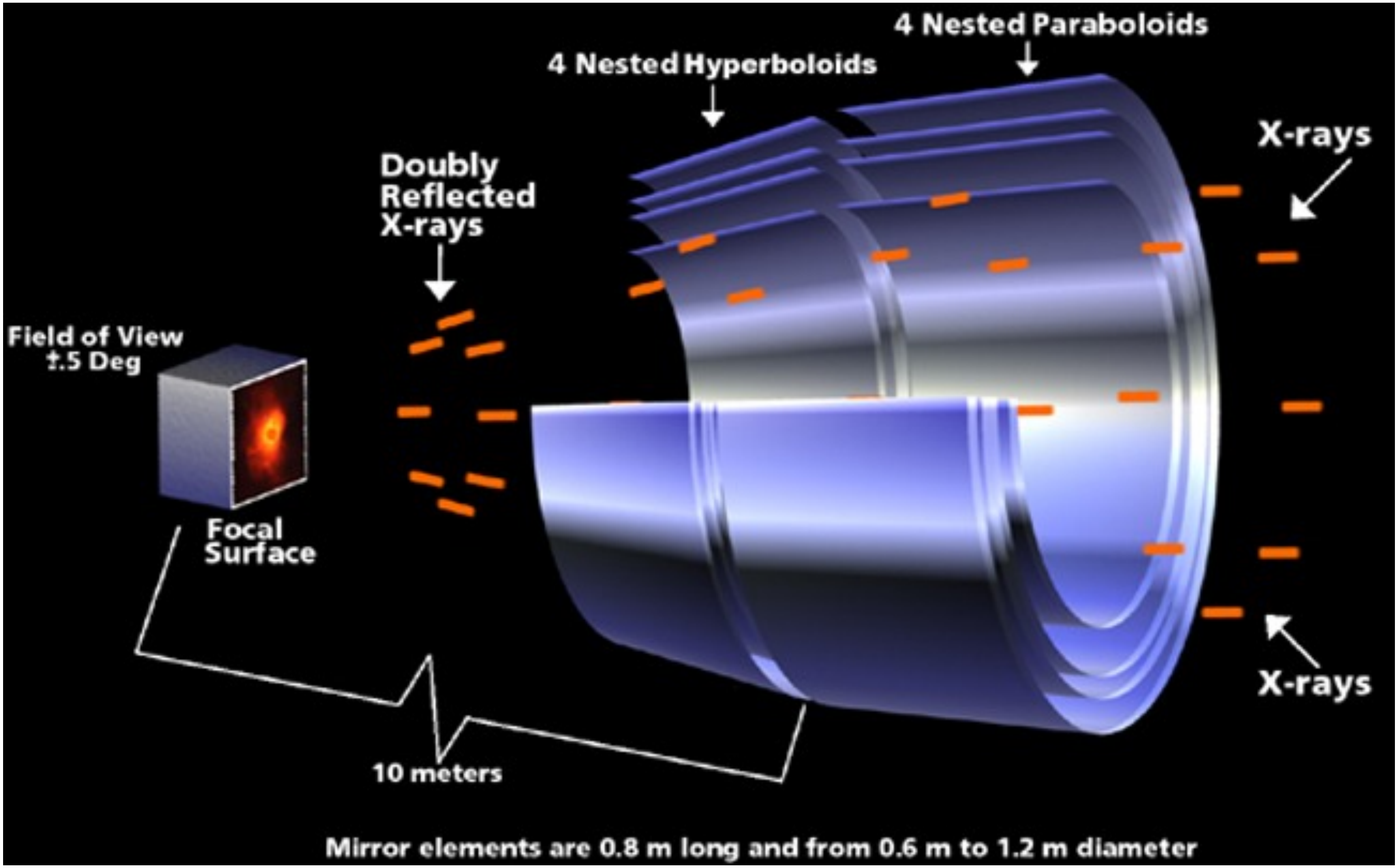
At longer wavelength (radio), metal panels or grid can be used
At shorter wavelength (UV, X ray, Gamma ray), materials are poorly reflective

The telescope must satisfy the previous requirement over a finite field of view with high throughput

Field of view + good image quality → telescope designs with multiple elements (this will be covered in the next lecture)
High throughput over large field of view requires good coating and an optical design which can transmit the full size of the beam for any point in the field of view (no beam clipping)

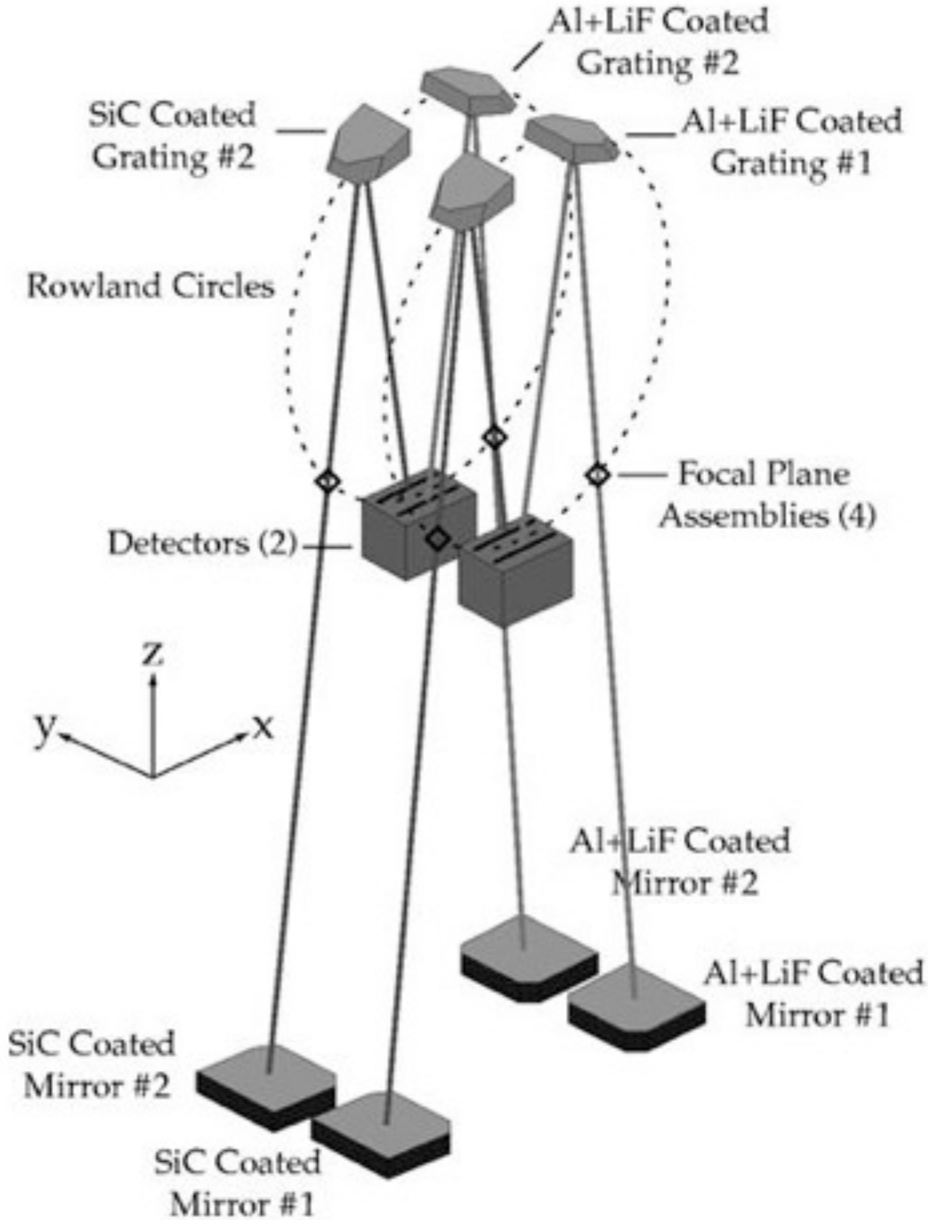
Chandra X-ray Observatory

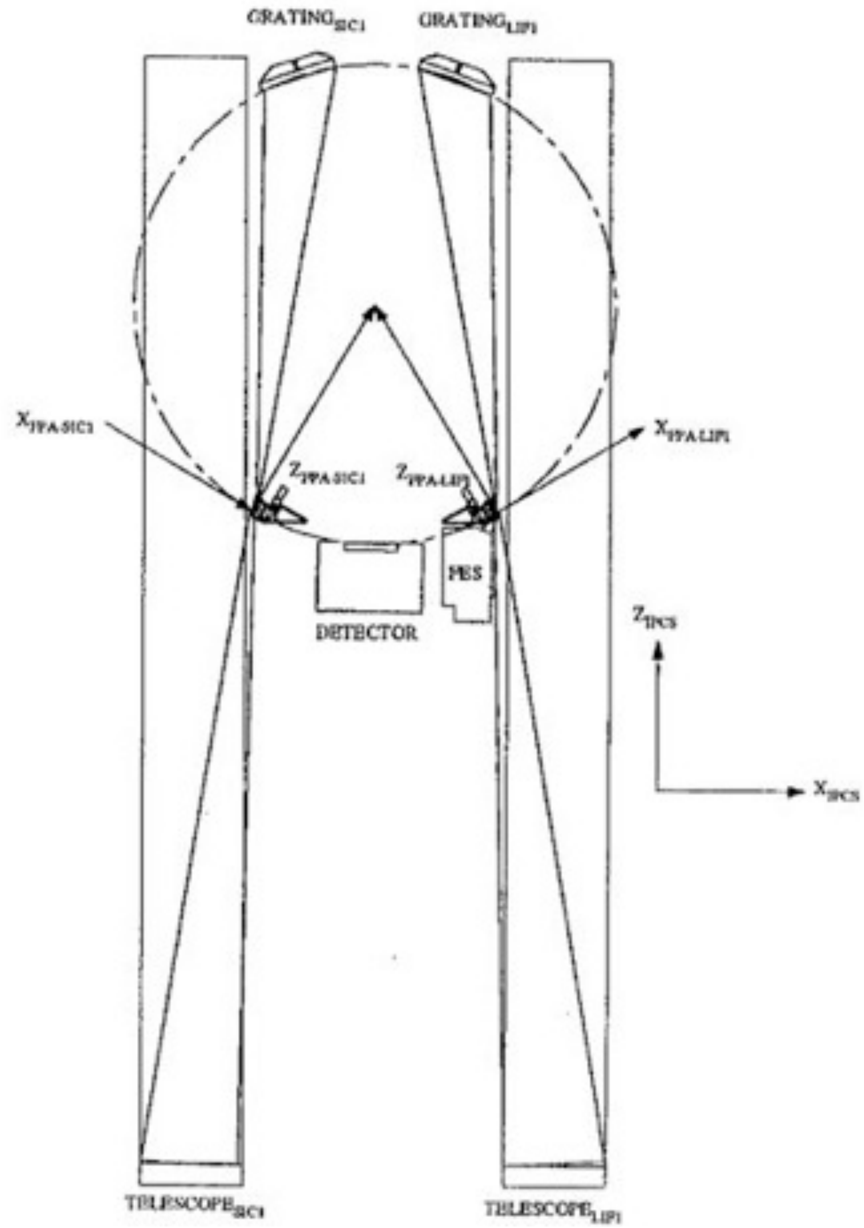
Schematic of Grazing Incidence, X-ray Mirrors



(Illustration: NASA/CXC/D.Berry)

An Ultraviolet Telescope (FUSE)

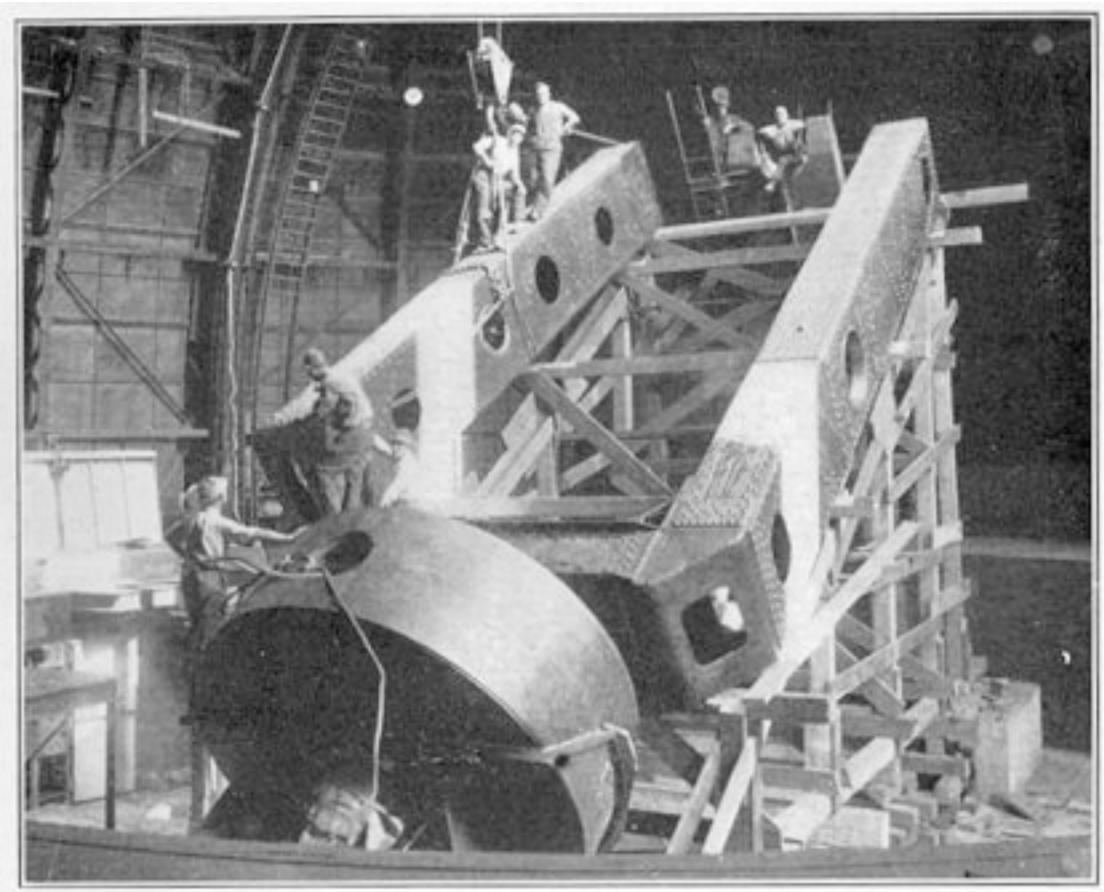




The Mt. Wilson Hooker Telescope

Equatorial Mount

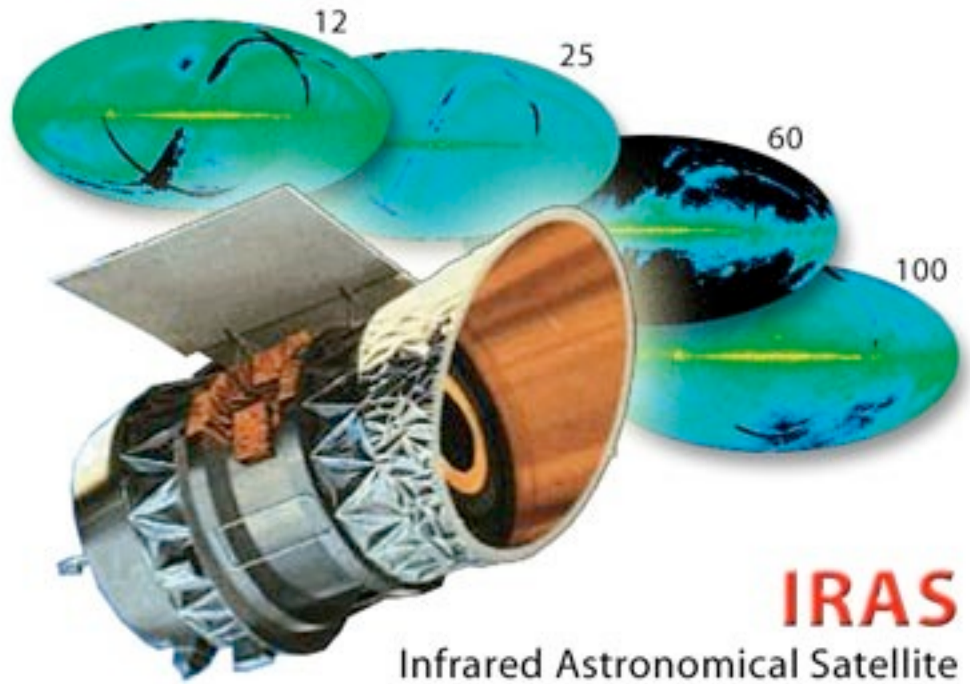
Long Focal Length Primary



An early Infrared Telescope

Key feature is a cooled optical design.

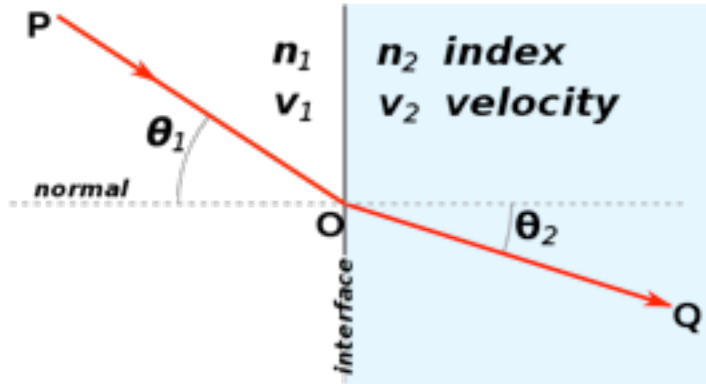
All-sky mapping at 12, 25, 60, 100 um.



Radio Telescope

Optics are easier when the light is 20-200 cm wavelength!

Refracting telescopes (lenses)



Lenses are easy to manufacture when small
First telescopes were refractors (Galileo)

Refractors suffer from serious limitations:

- chromaticity
  - refraction index is chromatic: a simple lens has a focal length which changes with wavelength
  - achromatic lens designs use combination of several materials to reduce chromaticity
- Difficult to implement for large telescopes:
  - lens thickness increases with diameter, and needs to be held at its edges
  - lens is located at the front of the telescope: center of mass is close to the top of the telescope (top-heavy)

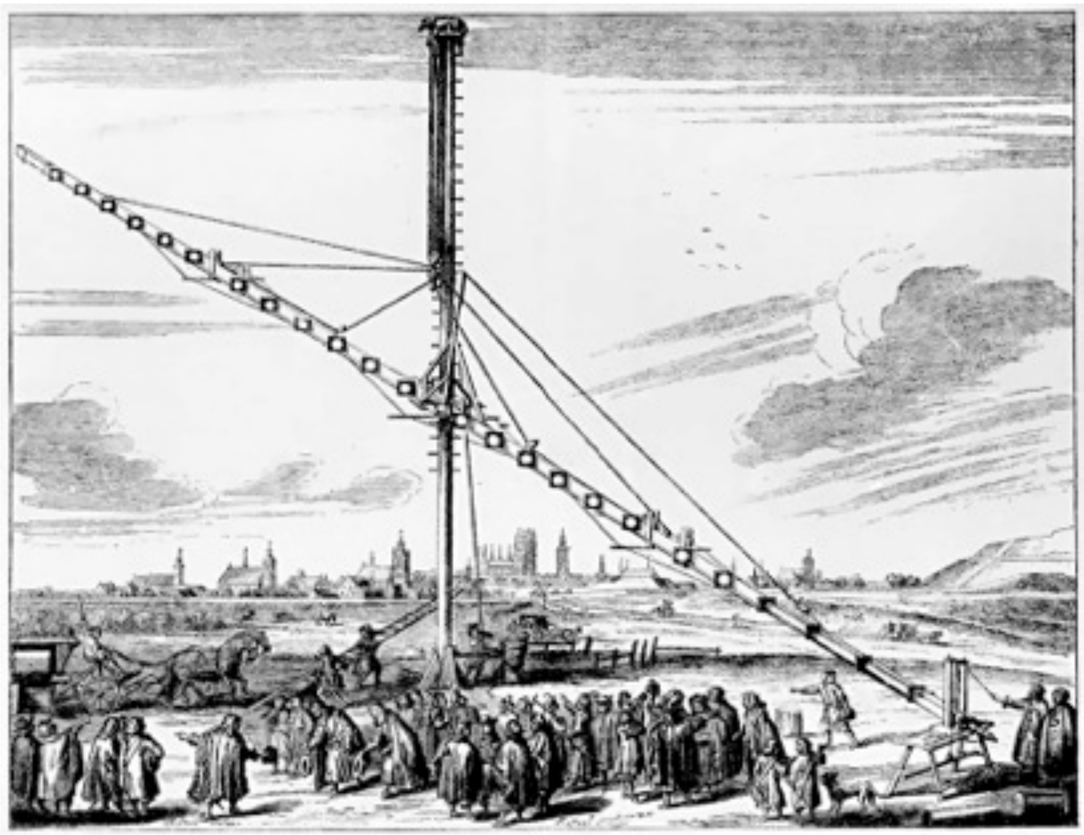
Galileo's telescope (1609)

D=37 mm
m=20

Yerkes obs. refractor (1-m diameter, 1900)

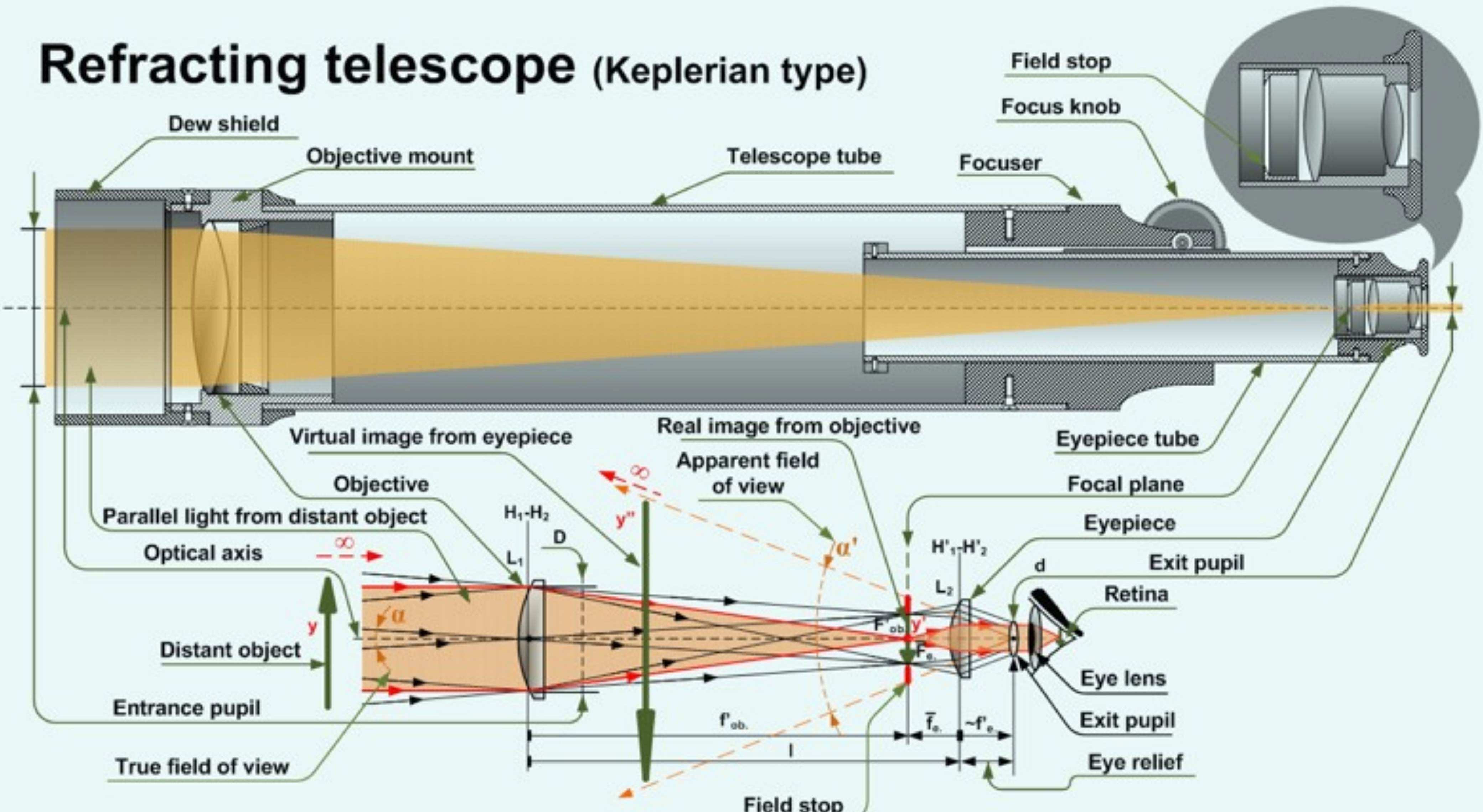
Refracting telescopes (lenses)

Chromaticity problem can be mitigated by adopting long focal length → Refracting telescopes used to be very long and narrow field of view
More recently, developments in lens design and manufacturing technology have led to high quality short refractors → Refractors are still used in astronomy for wide field small diameter systems, and the same technology is used to correct for aberrations in wide field reflecting telescopes.



Johann Hevelius 45m long telescope (1673)

Modern wide angle lens



Telescope magnification: $M = \frac{tg\alpha'}{tg\alpha} = \frac{f'ob.}{fe.} = \frac{D}{d}$

Reflecting telescopes (mirrors)

Challenges:

Light bounces back toward the object: focal plane in front of the telescope, or secondary mirror needs to be used to send light to instrument / viewer.

Mirrors have ~4x tighter optical surface tolerances than lenses

For surface defect h, wavefront error is 2h in reflection, h(n-1) in refraction

→ mirrors often need to be made non-spherical with <100nm surface accuracy

Mirrors need to be reflective

At first, mirrors were made of metal, then glass

Advantages:

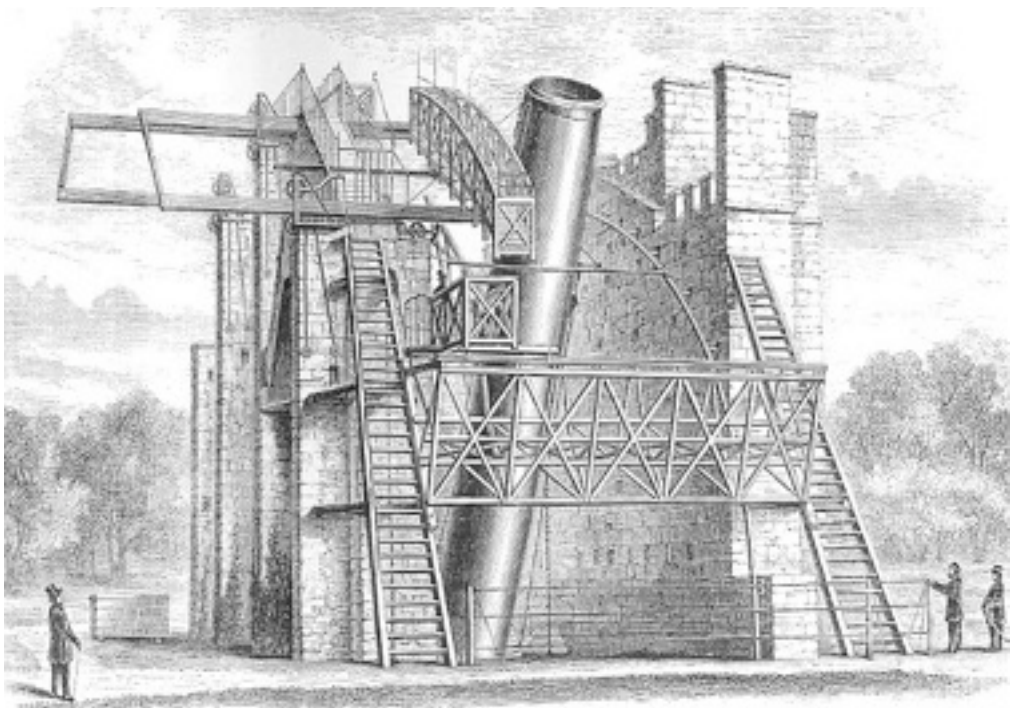
- achromatic by design (reflection is achromatic)

- Ideally suited for large telescopes:
    - Mirror is supported from the bottom, and can be thin with active control
    - Mirror is located at the back of the telescope: center of mass is low
    - Telescope tube can be relatively short (F ratio of modern large telescopes is ~1 to 2)

Early reflecting telescopes (metal mirrors)

Hershel's telescope primary mirror (1.2m) (1875-1879)

Newton's telescope (1668-1672)



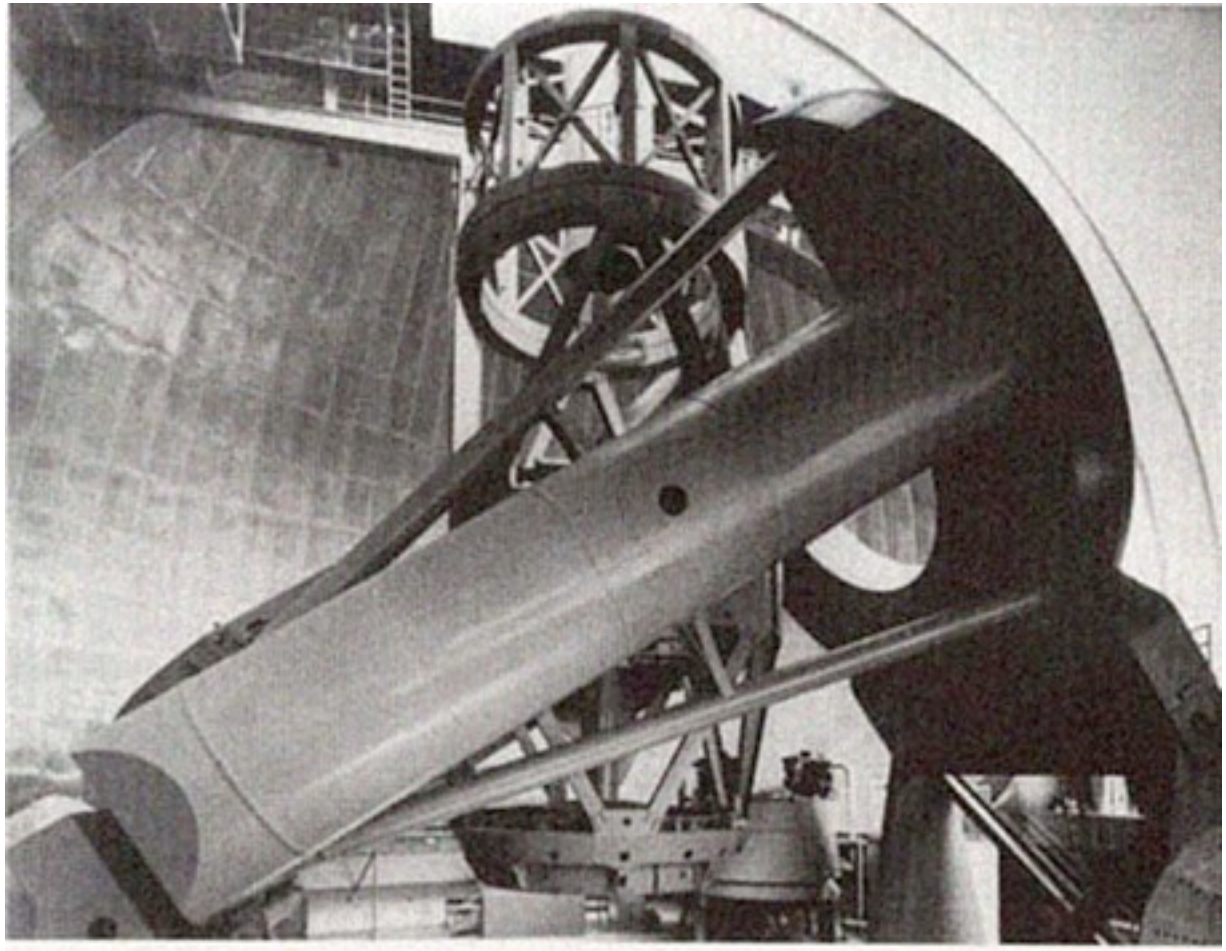
Birr Castle 1.8m telescope (metal mirror, 1845)

Tracking the Stars

Long exposures require a mount that can track the stars across the sky.

Early-mid 20th century telescopes were all equatorial mounts.

Almost all modern large telescopes are elevation-azimuth mounts.

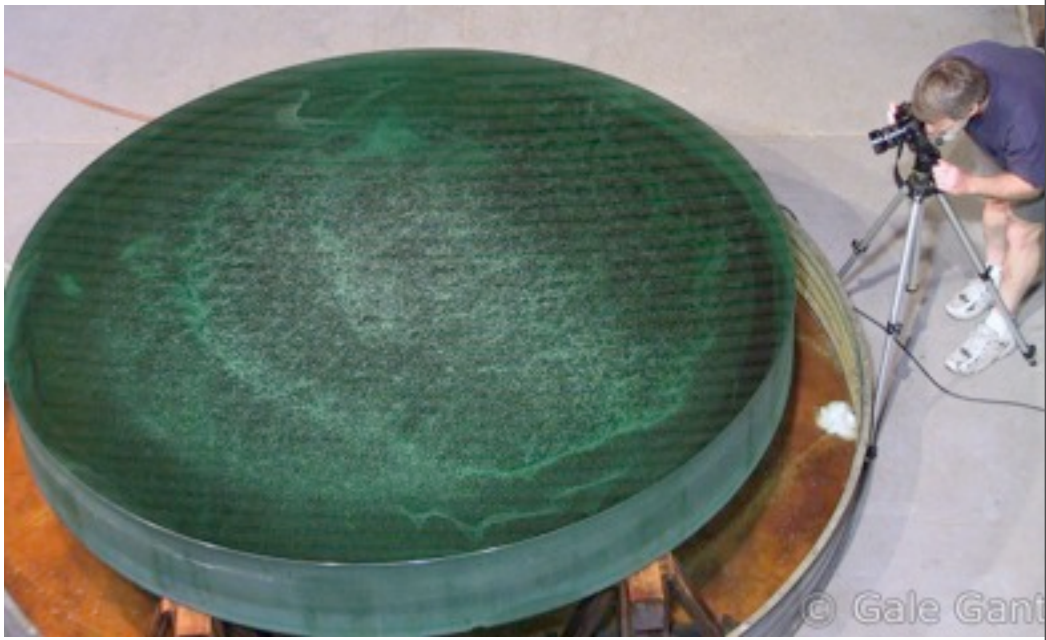


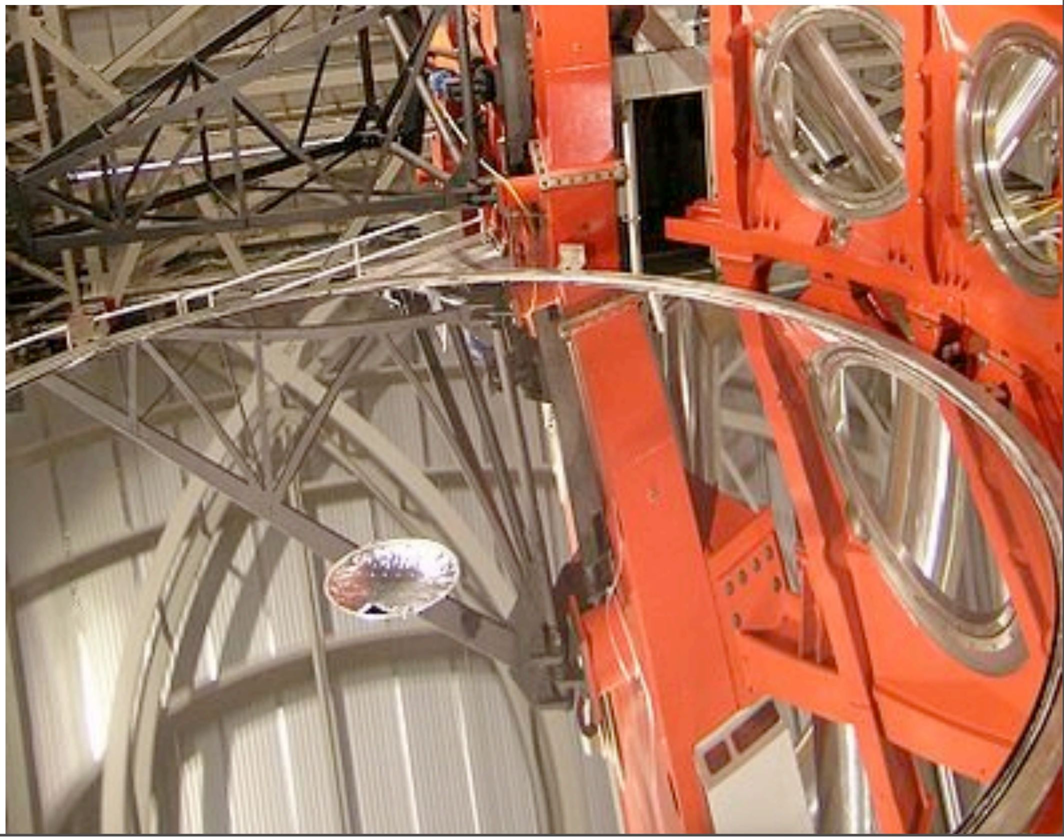
Mt. Palomar's 200-inch Hale Telescope, pointing to the zenith, as seen from the east side.

Primary Mirror: Big and Fast

The primary mirror size determines how many photons a telescope receives.

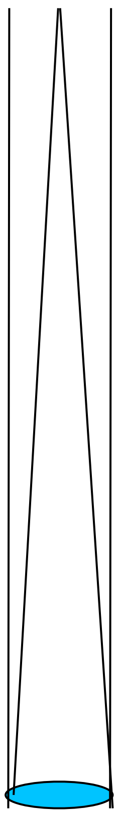
A larger telescope can also (in principle) form a sharper image.



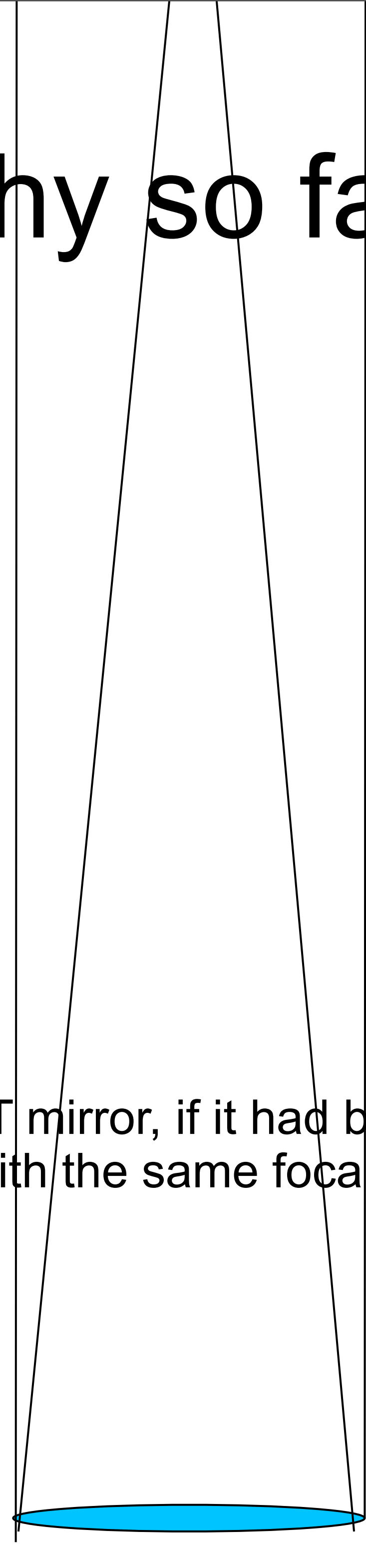


Why so fast?

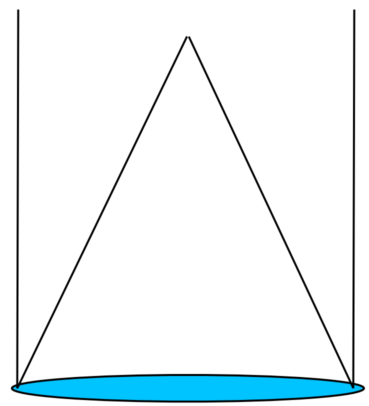
The Hooker 2.5 m with an
f/5 Primary mirror



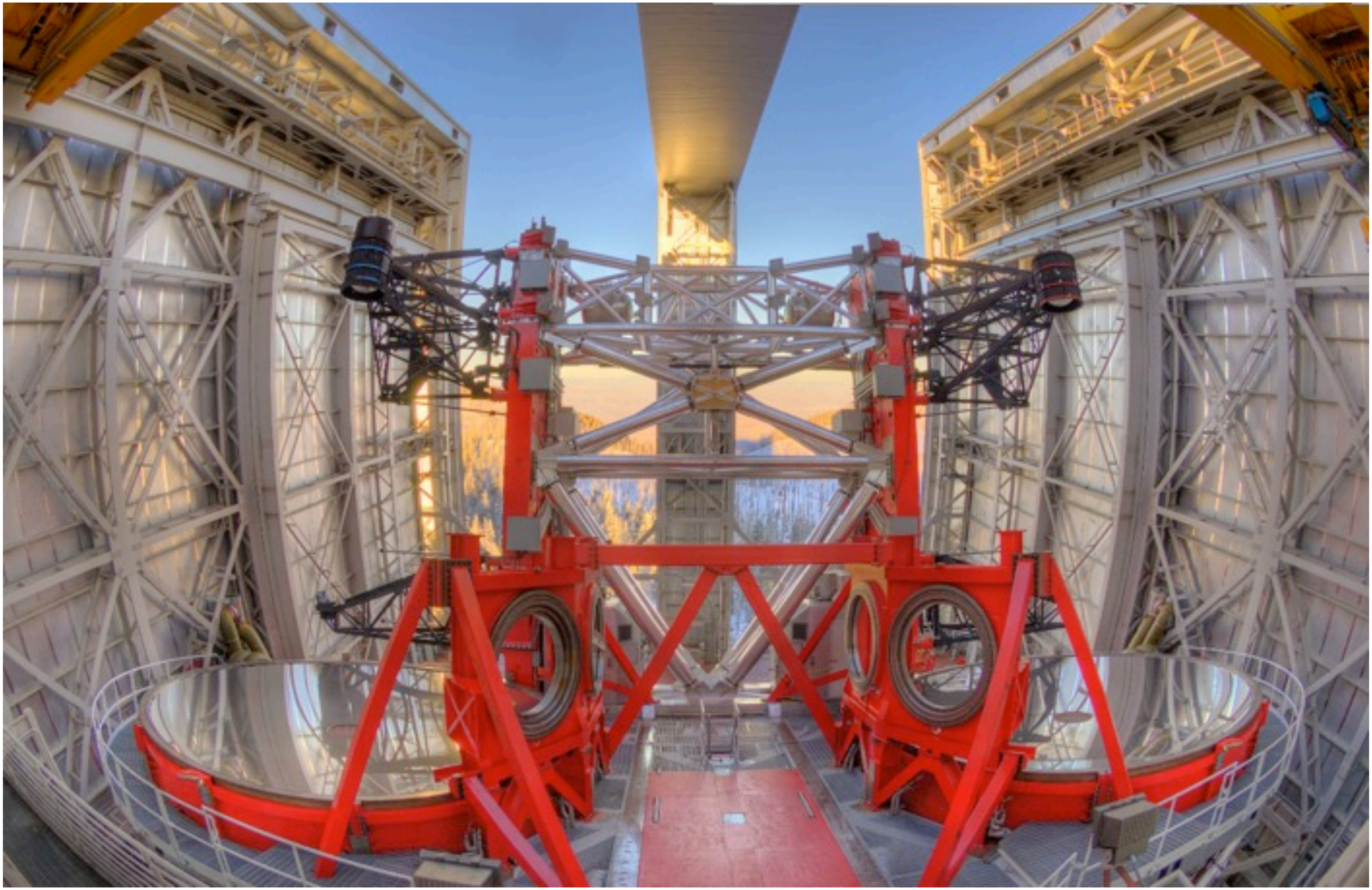
The LBT mirror, if it had been
made with the same focal ratio.



The LBT mirror, as designed with
an f/1.1 primary.



Modern reflecting telescopes (glass mirrors)



Large Binocular Telescope (LBT): 2x 8.4 m

Very Large Telescope (VLT): 4x 8 m + 1.8m aux. telescopes

Mauna Kea, Hawaii: 4 telescope 8 m to 10 m

Optical quality ↔ Image quality

How good does the telescope primary mirror need to be ?

<u>Ground-based telescopes:</u>
Optics need to produce an image which is sharper that the atmosphere delivers
In optical, very good site / very good night: seeing = 0.3”
On large telescope (8m), this is equivalent to ~1 μm of wavefront error (0.5 μm on the mirror surface)
→ Primary mirror surface should be good to ~100nm
for high spatial frequencies, this is achieved through figuring and polishing of the surface
for low spatial frequencies, this is achieved by active optics

<u>Space-based telescopes:</u>
Optics need to produce a diffraction limited image
In optical, mirror surface should ideally be ~1/40 of a wave (1/20 of a wave wavefront) ~ 10nm

Note: for some applications (wide field imaging for example), the telescope may not be required to reach diffraction limit

Example: Kepler telescope (NASA), 0.95m aperture, but 10” size image. Does high precision photometry of stars to detect planetary transits.

Challenges associated with large telescopes: Maintaining optical surface on large primary mirror

Larger size requires fundamental changes in the telescope design
Maintaining good optical surface on large telescopes cannot be achieved passively, as it used to be done on small telescopes

plate stiffness:

$\underline{D} = E/(1-v^2) \times (t^3 / 12)$

E = Young modulus
t = plate thickness
v = Poisson's ratio

Mirror surface deformation is proportional to $q\,(N/A)^{-2}\,\underline{D}^{-1}$
$q = \rho t$ = areal density (proportional to t for simple plate)
N/A = actuator density (number of support points N per unit area A)

For a simple plate and a fixed number of support points:
N/A goes as power -2 of telescope diameter D
$\underline{D}$ goes as t^3 → deformation goes as : $D^4 \times t^{-2}$

Keeping the deformation constant requires $t \sim D^2$
A 1m diameter mirror, 10cm thick would have the same deformation as a 5m diameter mirror with a 2.5m thickness
Large mirror mass → even larger telescope structure mass

Challenges associated with large telescopes: Thermal issues for a large primary mirror

A difference in temperature between the mirror and ambient air is bad for astronomy: it creates turbulence just above the mirror and makes the image less sharp

PROBLEM: the air temperature is constantly changing, and the mirror needs to follow it closely → thermal time constant for the mirror needs to be short → thick massive mirrors are problematic !

SEEING AT CFHT 1027

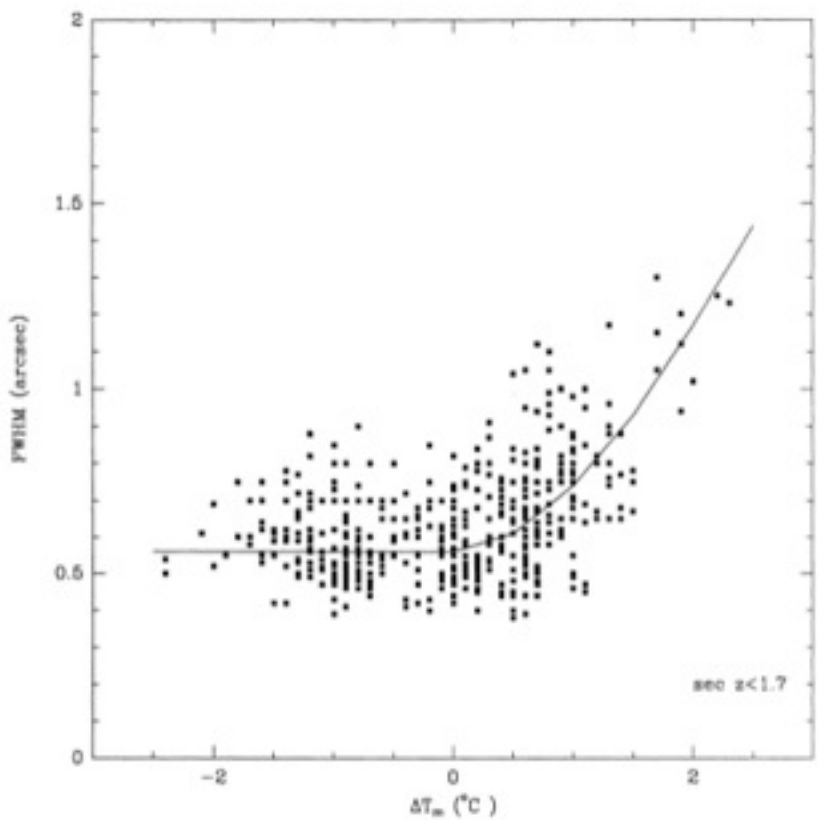


FIG. 6–Image spread as a function of the mirror-to-air temperature difference. The line is the expected relation for a spread of 0″.56 due to optics and average natural seeing and a mirror seeing of 0″.40/°C$^{6/5}$ when $\Delta T_m > 0$.

Racine et al. 1991 (3.6-m Canada France Hawaii Telescope)

Larger size telescopes were made possible by fundamental changes in the primary mirror design

Honeycomb mirrors

Honeycomb stiffness:

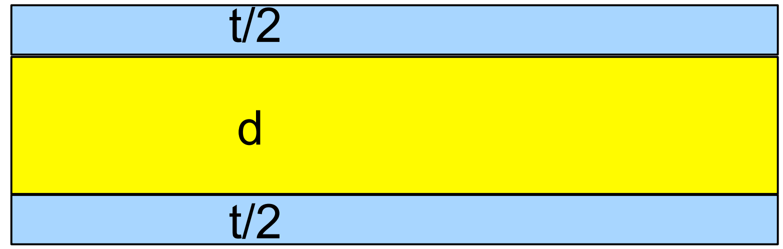
$\underline{D} \sim E/(1-v^2)\ \ x\ \ ((2/3)x(d/2+t/2)^3 - d^3/12)$

t/2 = top plate thickness = bottom plate thickness

d = core thickness

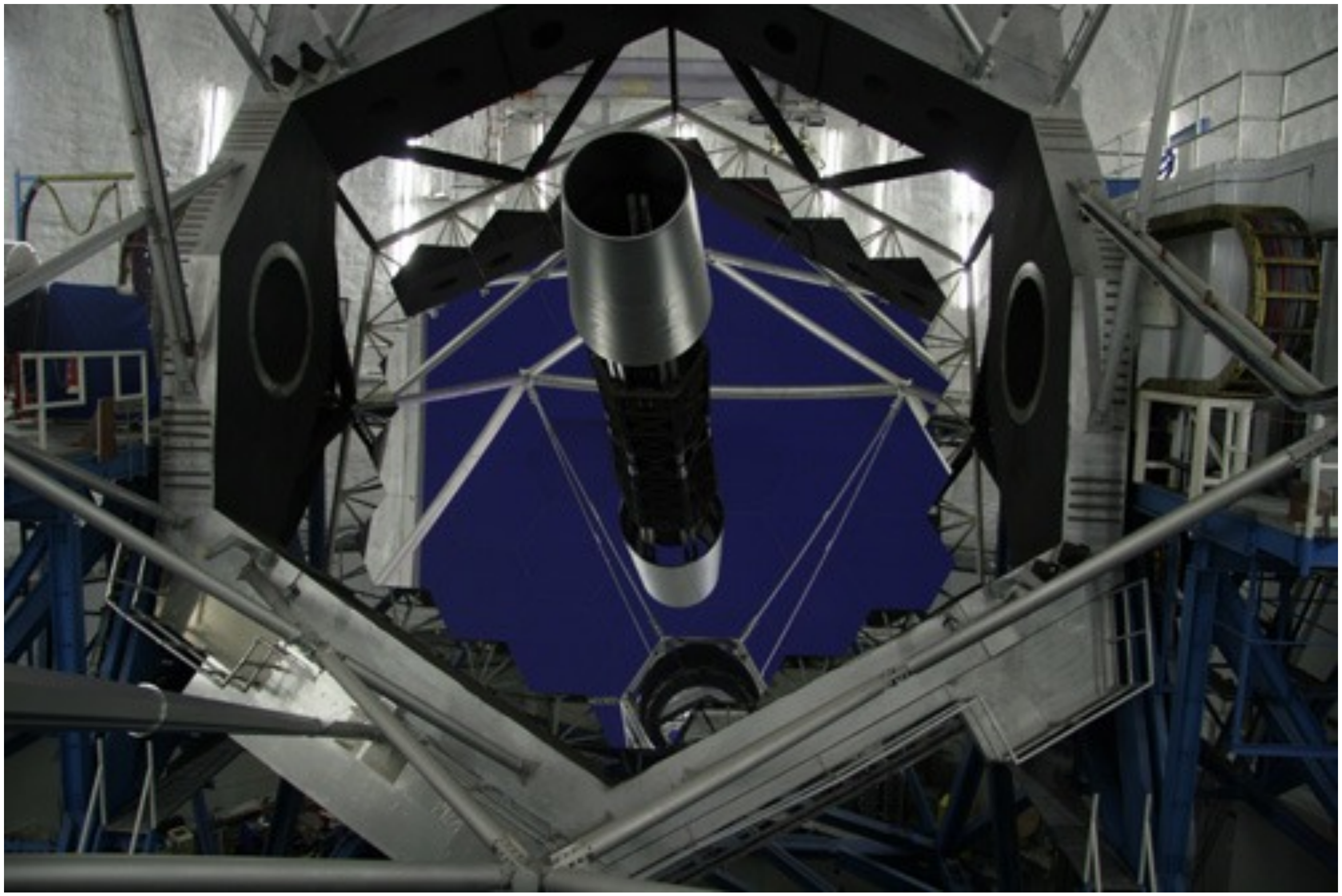
→ allows high stiffness without increasing mass

→ reduced thermal time constant by circulating air inside the mirror



Larger size telescopes were made possible by fundamental changes in the primary mirror design

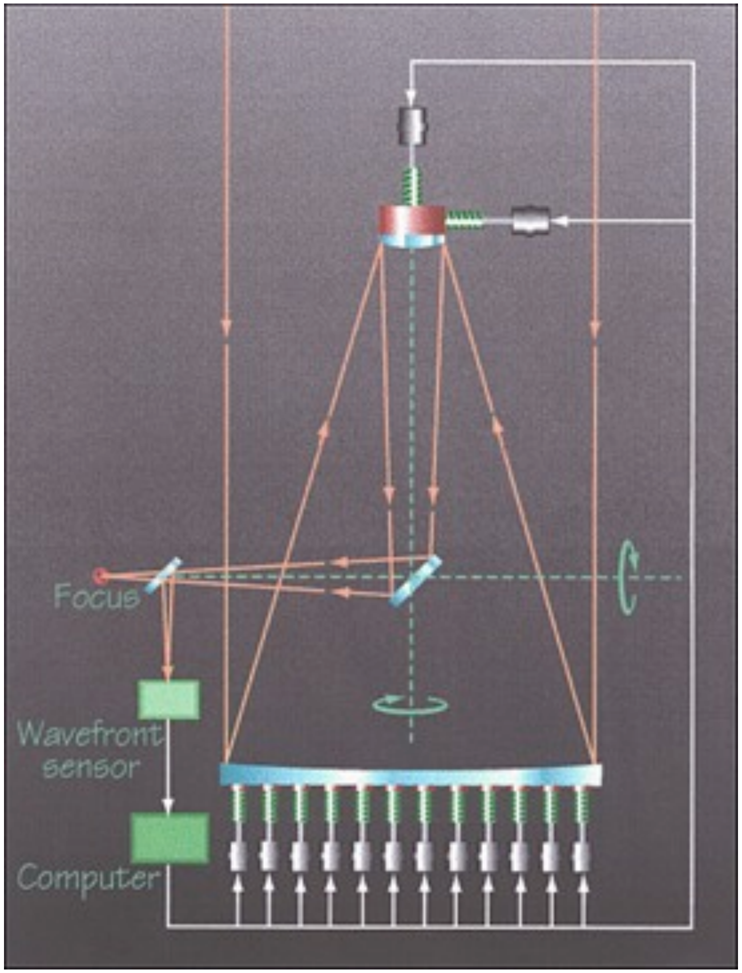
Segmented mirrors
The mirror is made of segments individually controlled in position



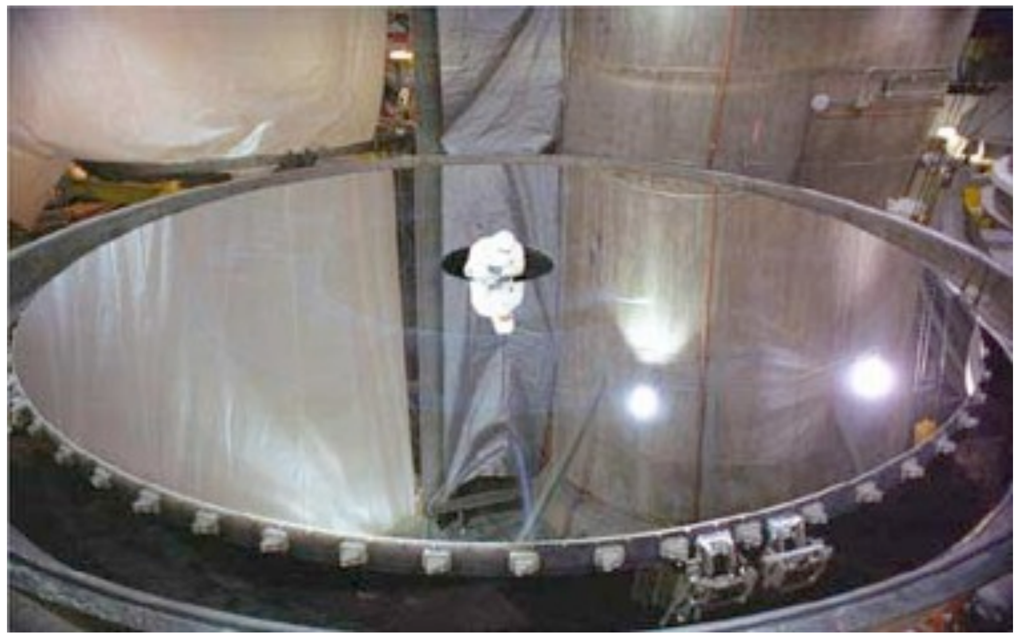
KECK telescope: hexagonal segments form the primary mirror

Larger size telescopes were made possible by fundamental changes in the primary mirror design

Active optics to enable thin mirror telescopes
The telescope mirror shape is actively controlled by computers driving force actuators
→ thinner mirrors can be used

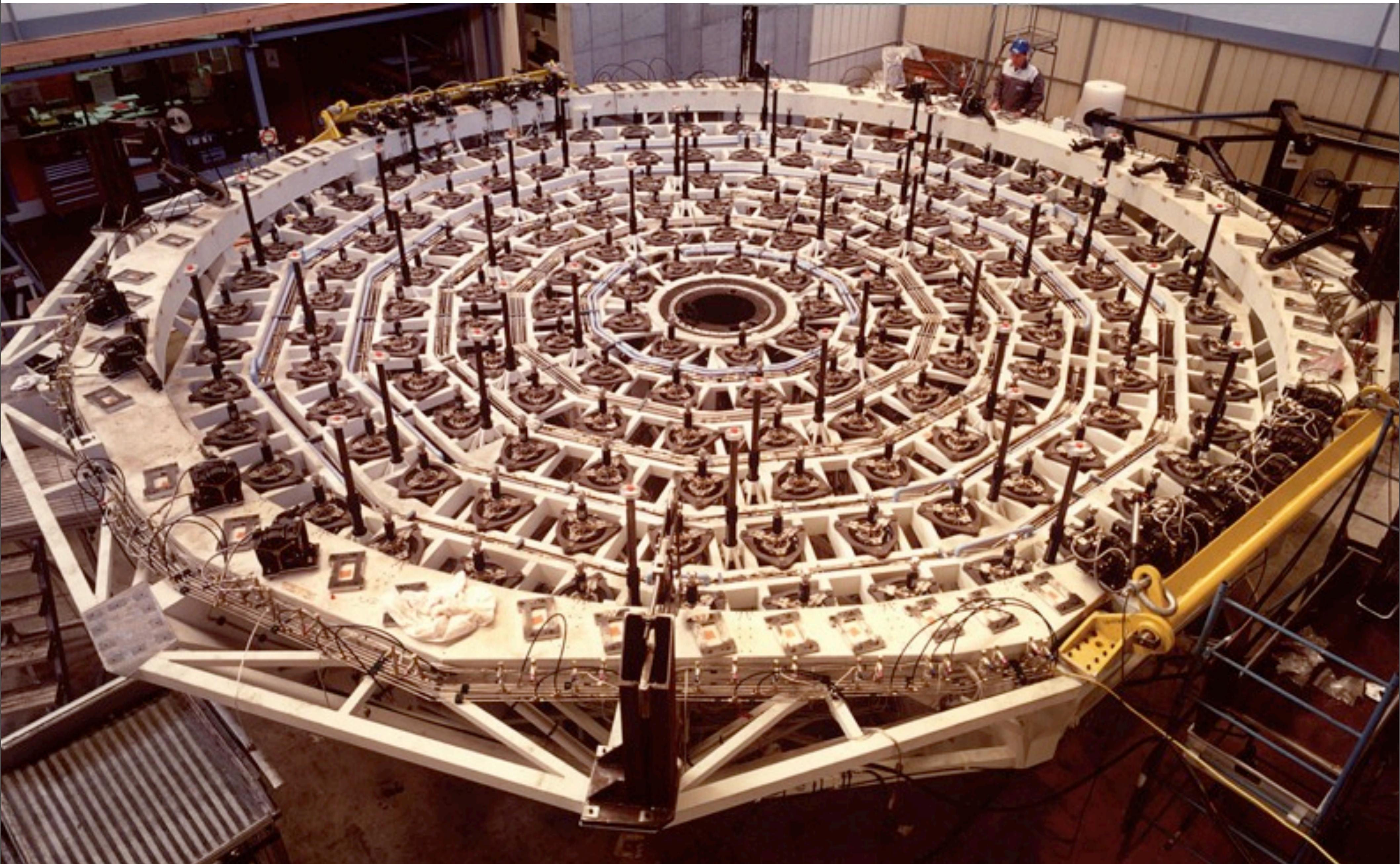


Courtesy of ESO



Gemini Telescope mirror: 8m diameter, 20cm thick

All large modern telescope include computer-controlled active optics



VLT mirror cell for 8m mirror, ~20cm thick

Vibrations, Dome

Vibrations are mostly introduced by wind, but can also be generated by telescope drive motors

The telescope structure must be as stiff as possible

stiff = high frequency resonances = small amplitude resonances

Lowest resonance frequencies on large telescopes are ~10 Hz

Active correction is possible (vibrations can be measured optically or with accelerometers)

Dome must be carefully designed:

Dome must let air flow through telescope to avoid temperature gradients

Dome must block wind before it exites telescope structure resonances

Gemini Telescope dome includes side vents
low wind: open
high wind: closed