Astronomical Observing Techniques

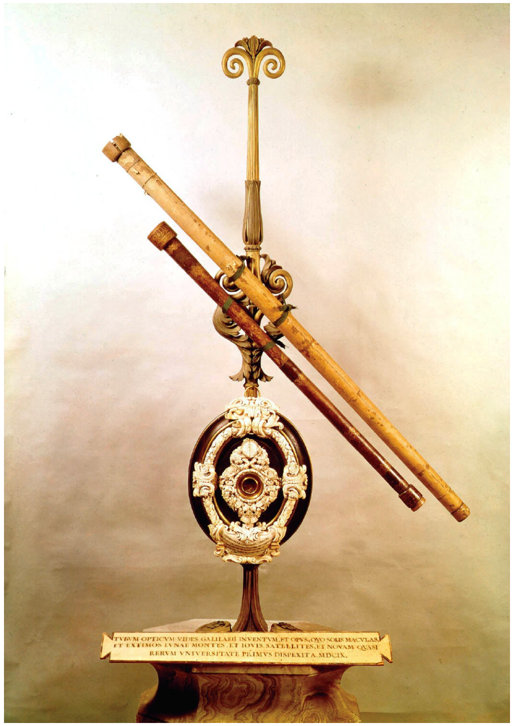
Lecture 3: Telescopes

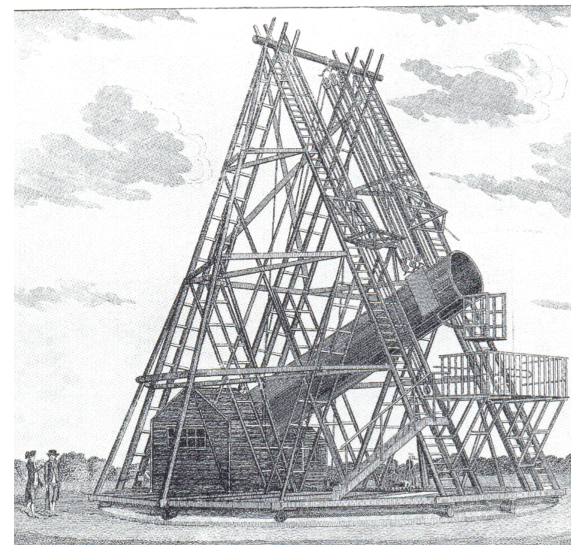
Christoph U. Keller
keller@strw.leidenuniv.nl

Outline

1. History
2. Mounts
3. Orbits
4. Telescope Optics
5. Foci
6. Mass, Size, ...
7. Radio Telescopes, Interferometers

Early Telescopes



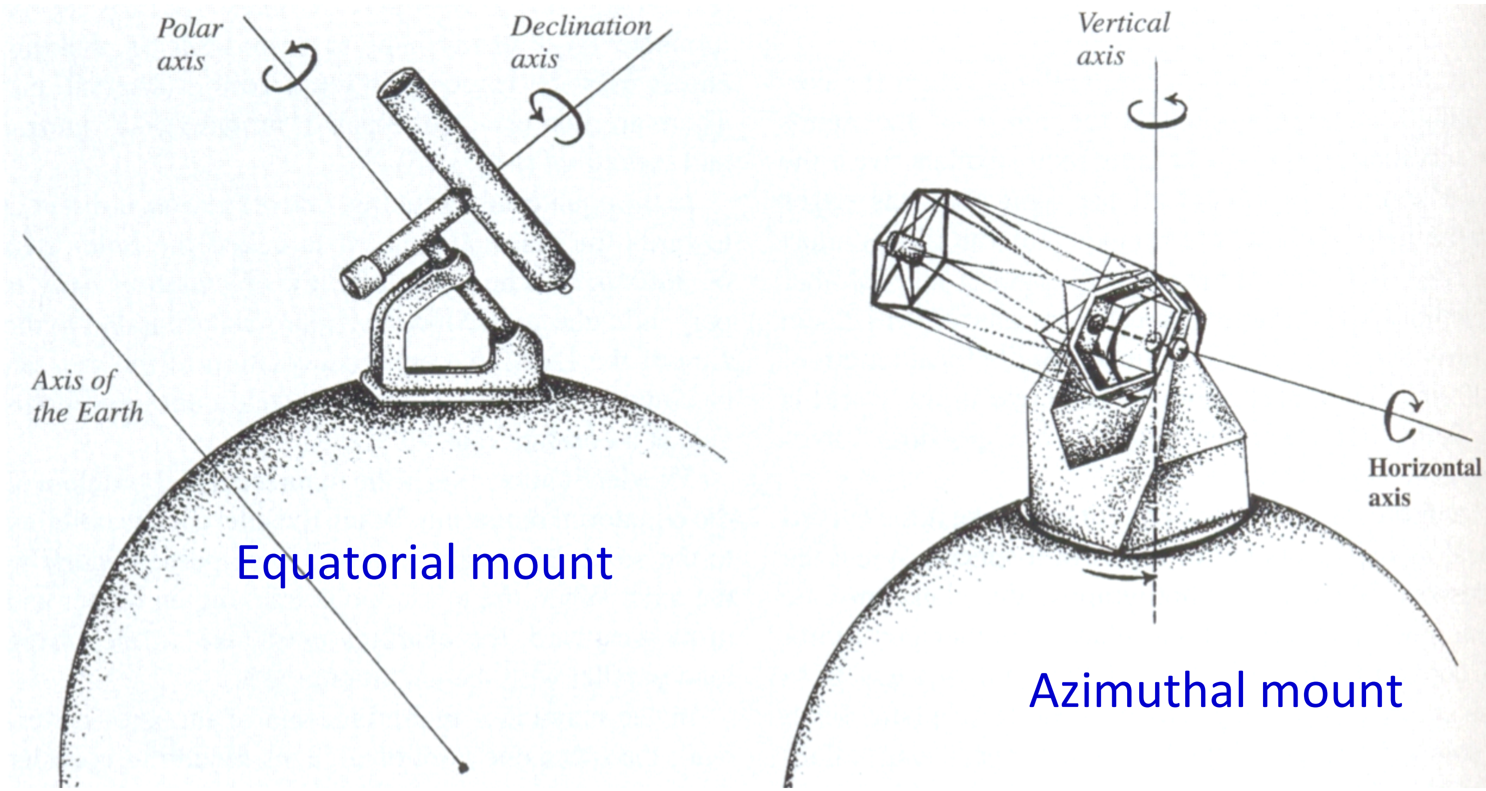


- Hans Lipperhey 1608: spy glasses
- Galileo Galilei 1609: first use in astronomy
- Kepler 1611: improved refractor

Newton 1668:
first reflector

Herschel 1789:
1.22-m diameter, 12-m long

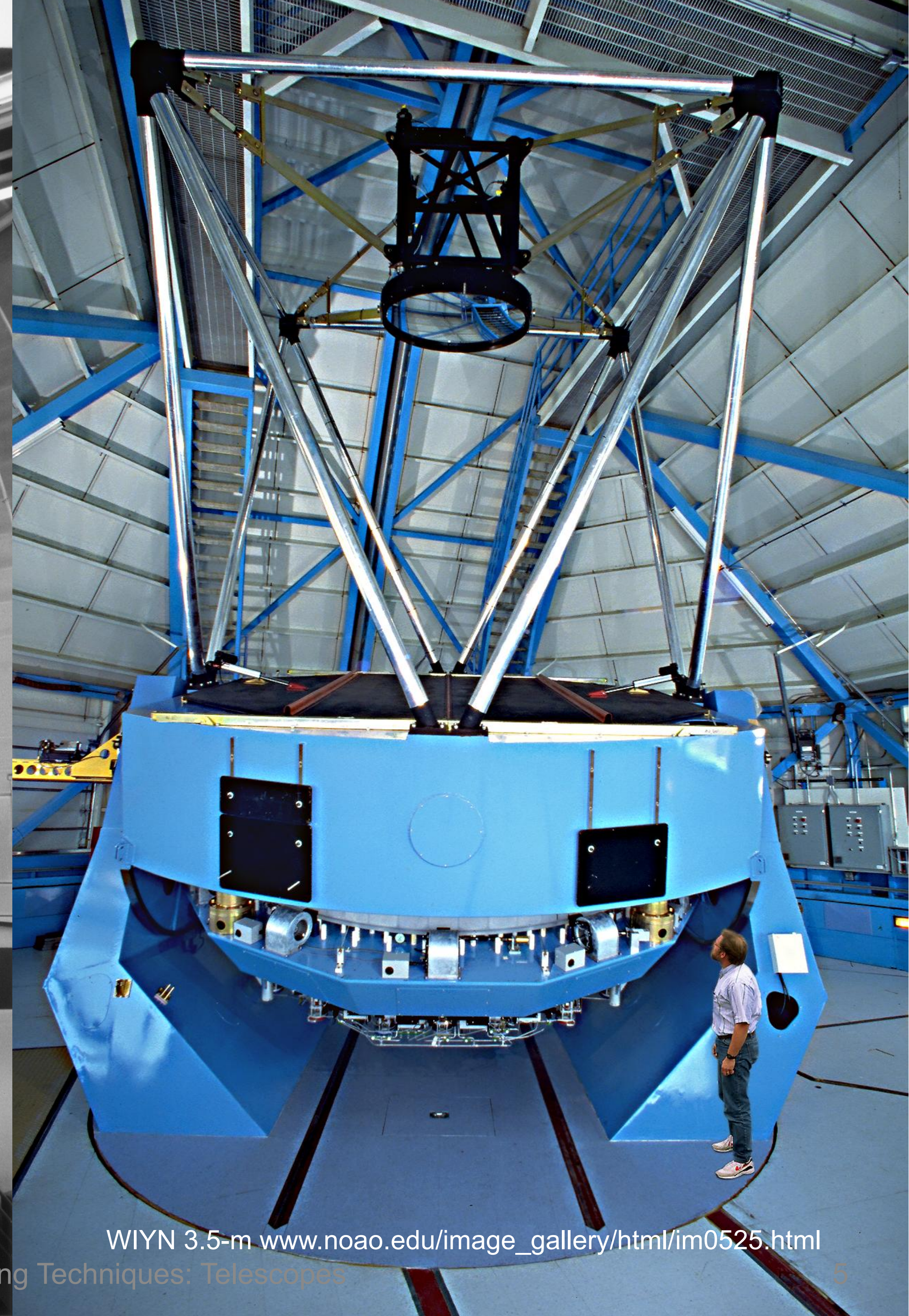
Telescope Mounts



+ single moving axis
+ constant rotation
+ no image rotation
- large, heavy
- instruments: varying gravity

+ light and symmetric
+ fixed gravity on bearings
+ two fixed-gravity ports
- two moving axes
- image rotation

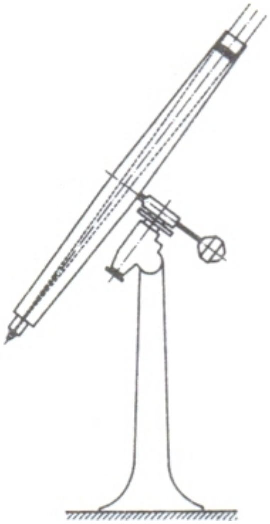
CTIO 4-m, www.noao.edu/image_gallery/html/im0132.html



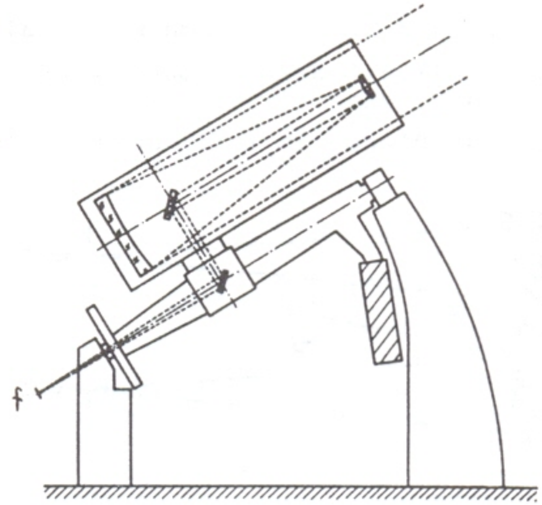
WIYN 3.5-m www.noao.edu/image_gallery/html/im0525.html

Equatorial Telescope Mounts

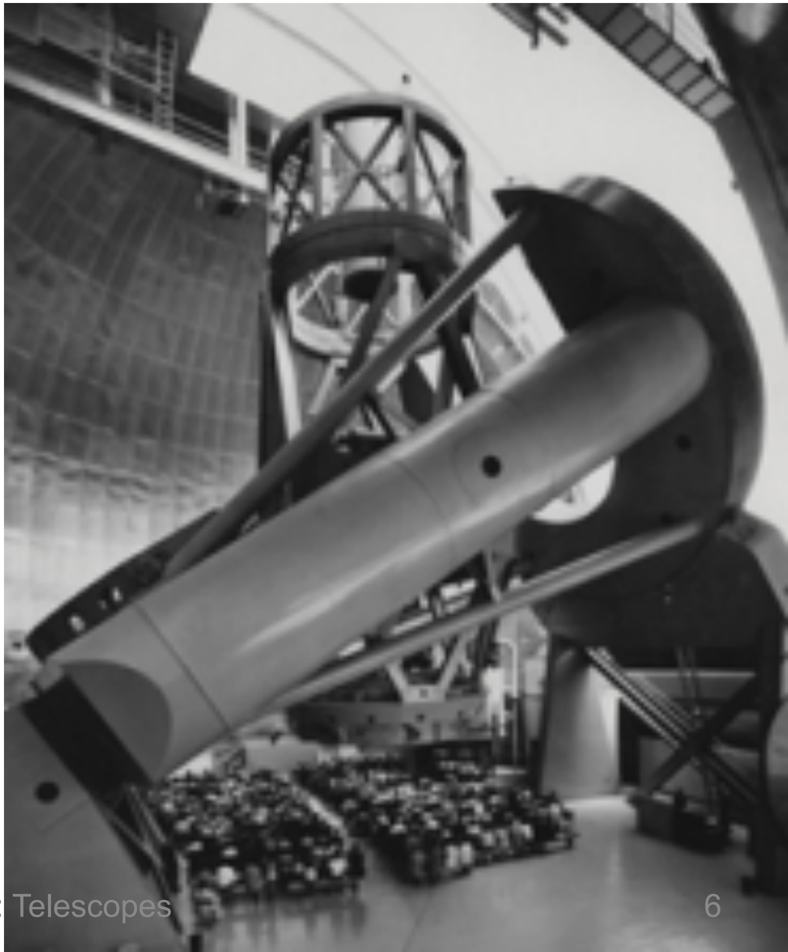
German Mount



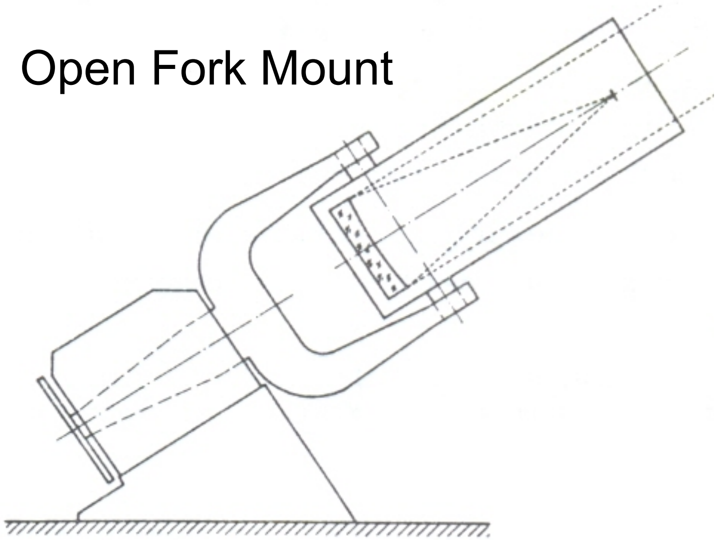
English Mount



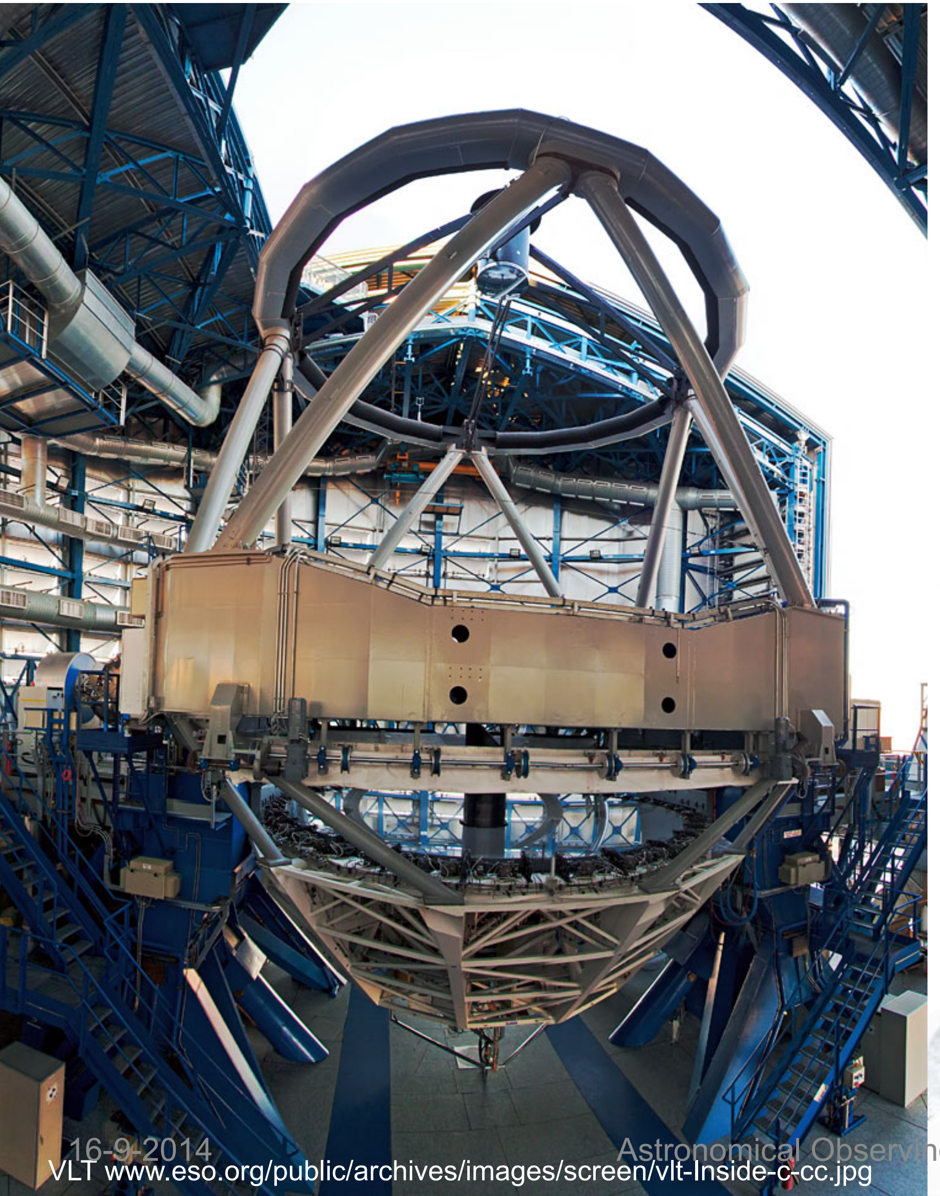
Horseshoe Mount



Open Fork Mount



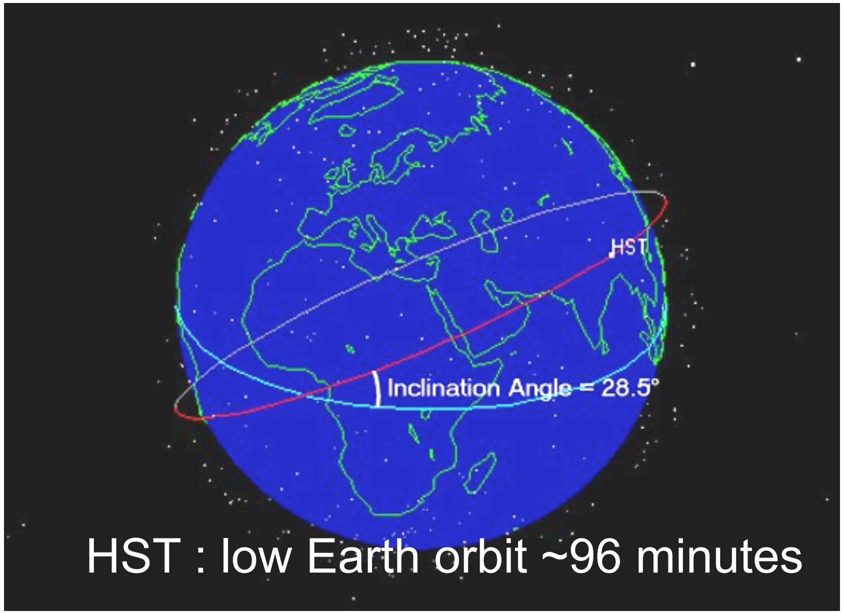
Azimuthal Telescope Mounts



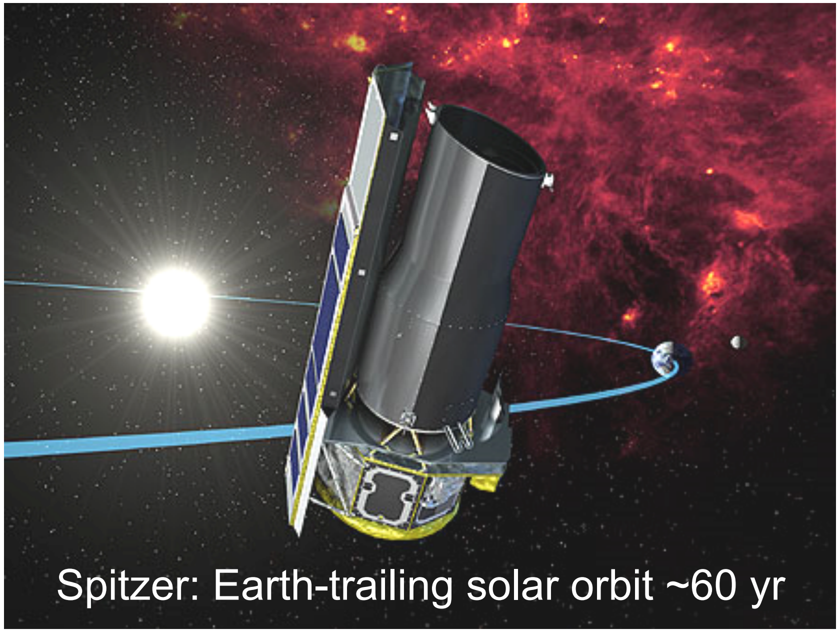
VLT www.eso.org/public/archives/images/screen/vlt-Inside-c-cc.jpg

Space Telescope Orbits

- Orbits
  - low Earth
  - sun-synchronous
  - geostationary
  - Earth-trailing
  - L2
- Orbit choice influenced by
  - communications
  - thermal background radiation
  - space weather
  - sky coverage
  - access (servicing)

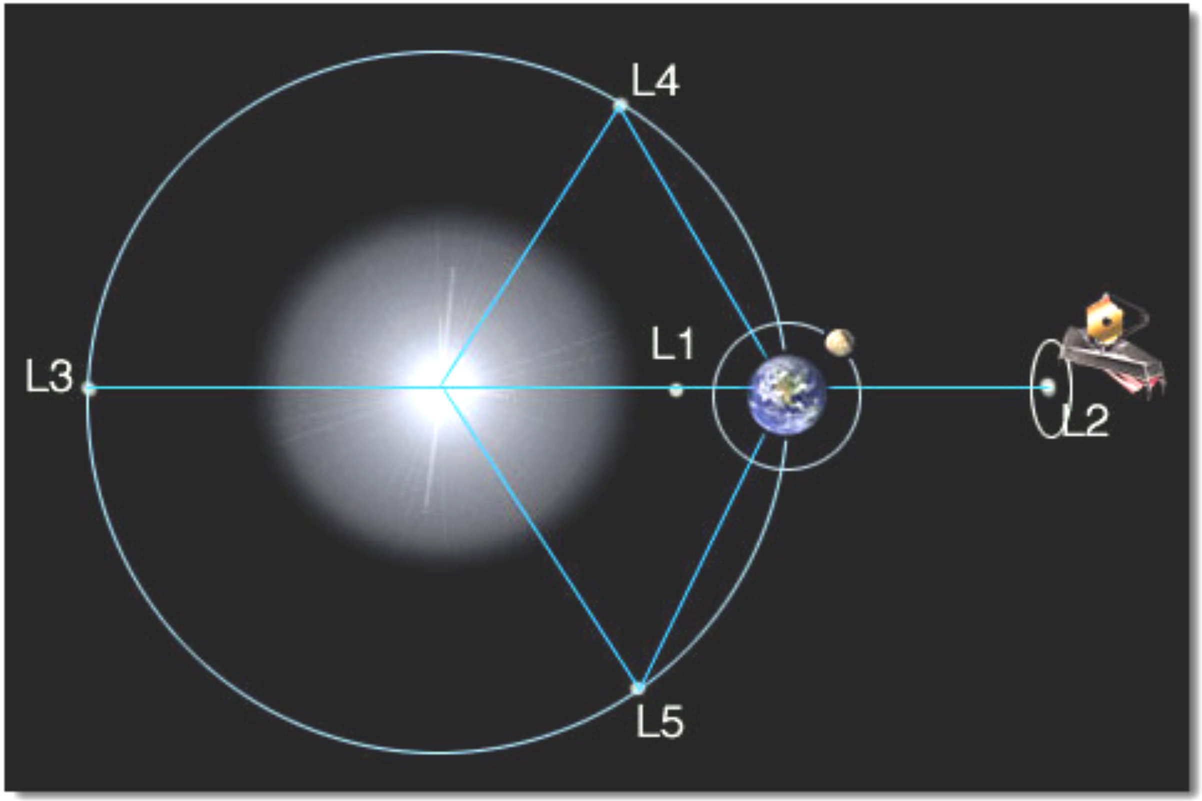


HST : low Earth orbit ~96 minutes

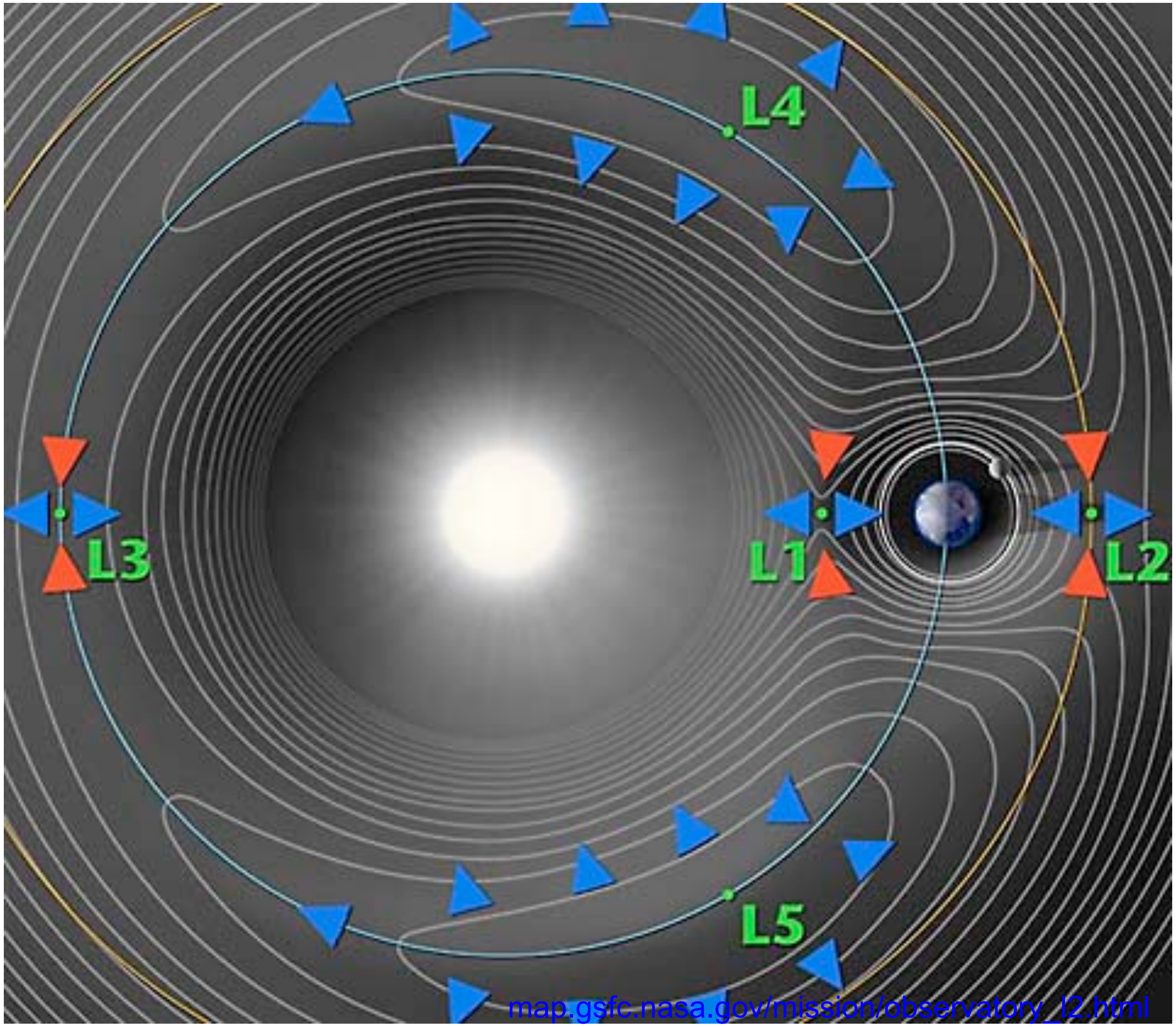

Spitzer: Earth-trailing solar orbit ~60 yr

Lagrange Points

Stable configuration in which three bodies (Sun, Earth, satellite) orbit each other, yet stay in the same position relative to each other: 5 Lagrange points

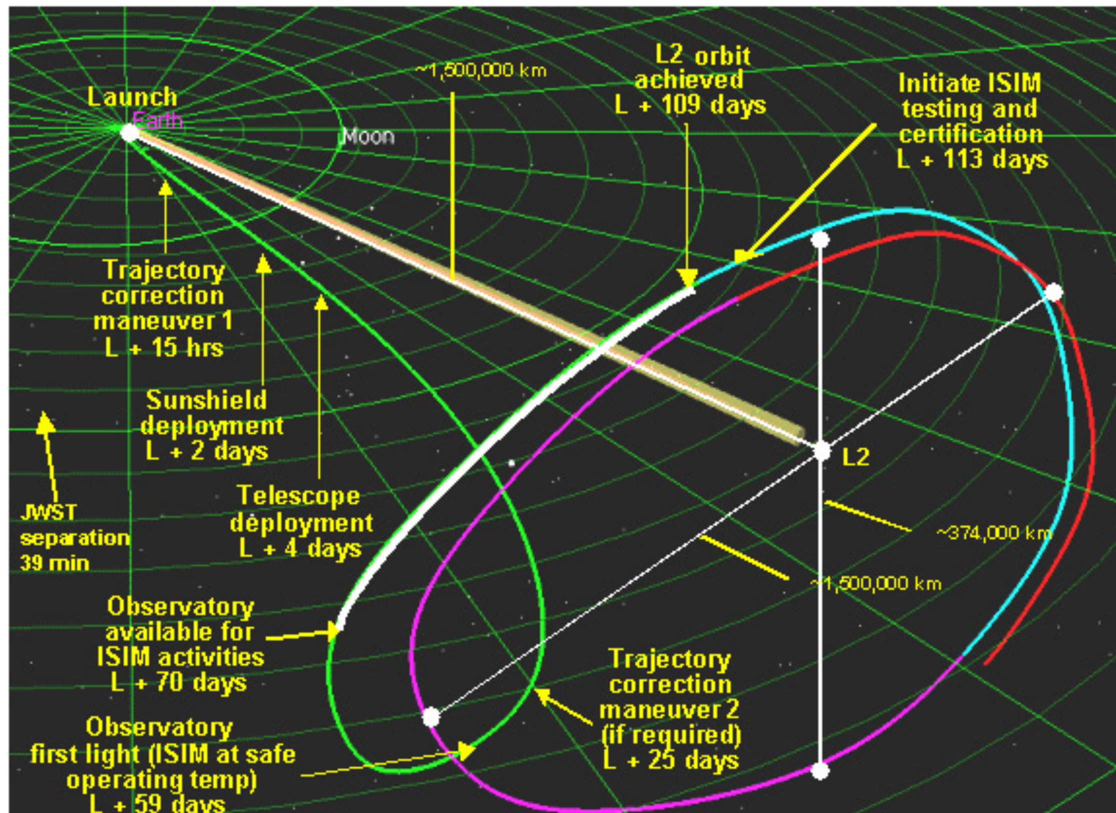


Lagrangian Point Stability

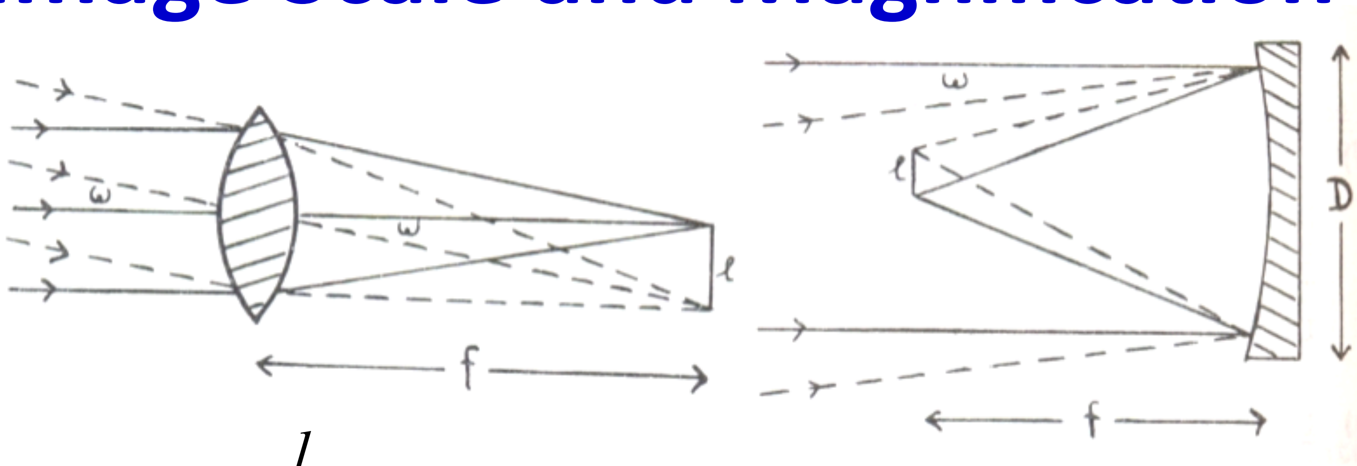


JWST, WMAP, GAIA, Herschel in orbits around L2

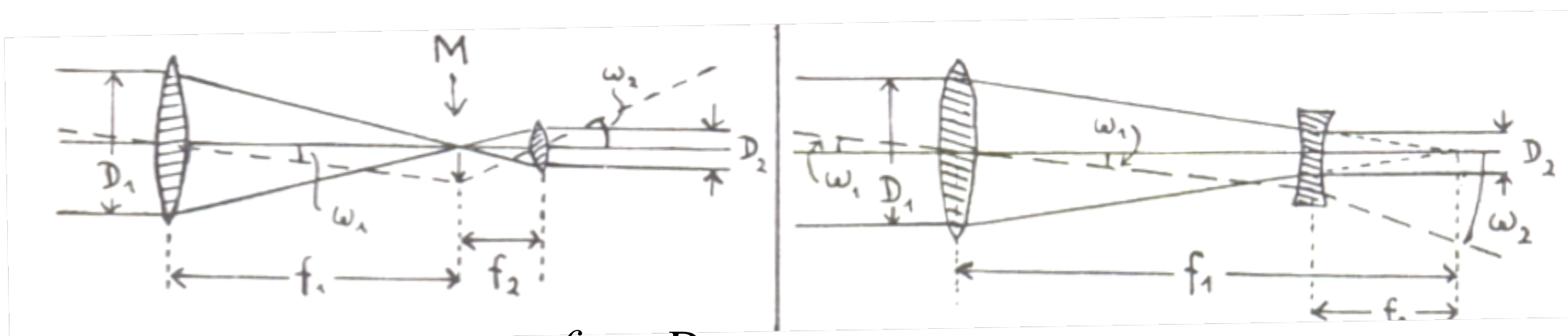
+ sun-shields
- orbit around L2
- radiation



Telescope Optics:
Image Scale and Magnification

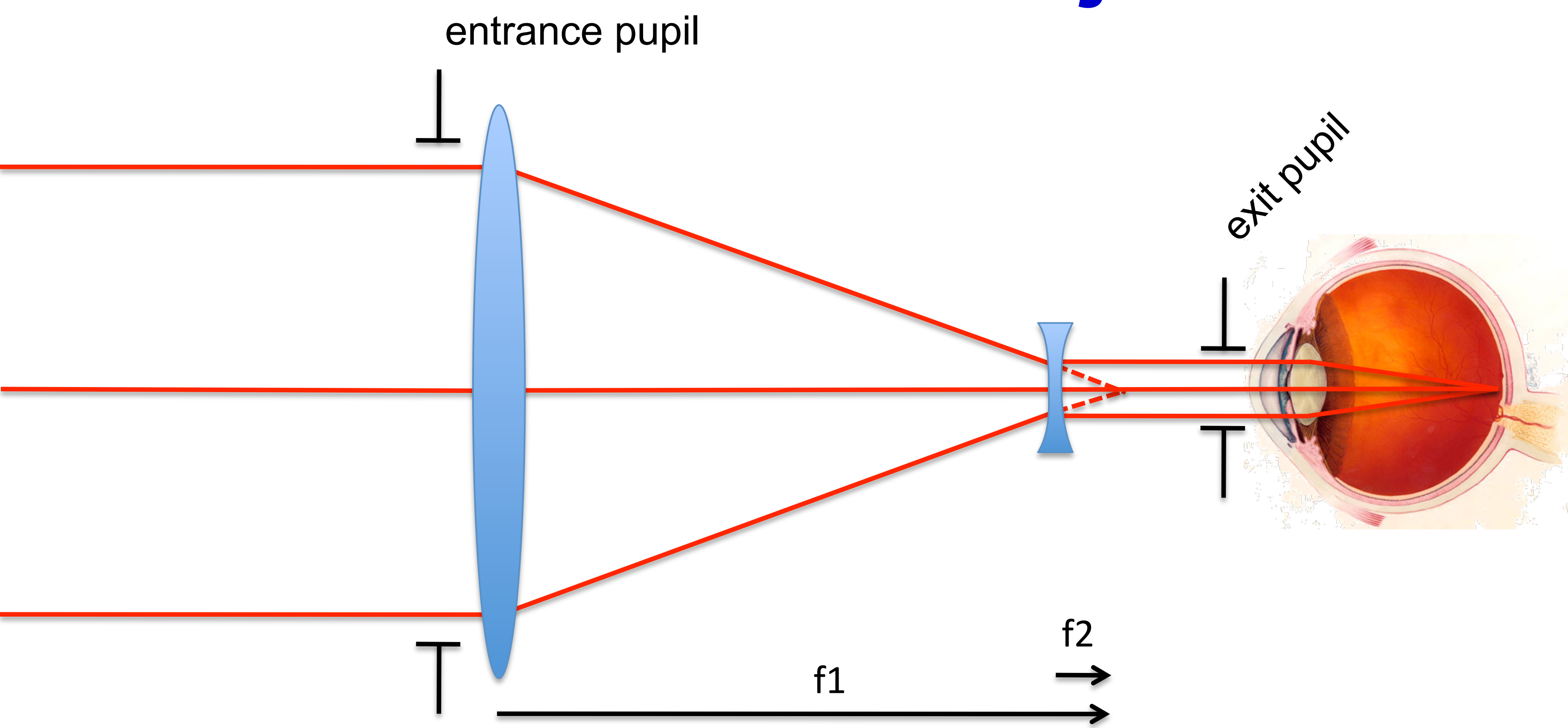


Scale: $\tan\omega = \dfrac{l}{f}$ and for small ω: $l \approx 0.0175\,\omega f$



Magnification: $$V = \frac{f_1}{f_2} = \frac{D_1}{D_2} = \frac{\omega_2}{\omega_1}$$

Hollandsche Kijker

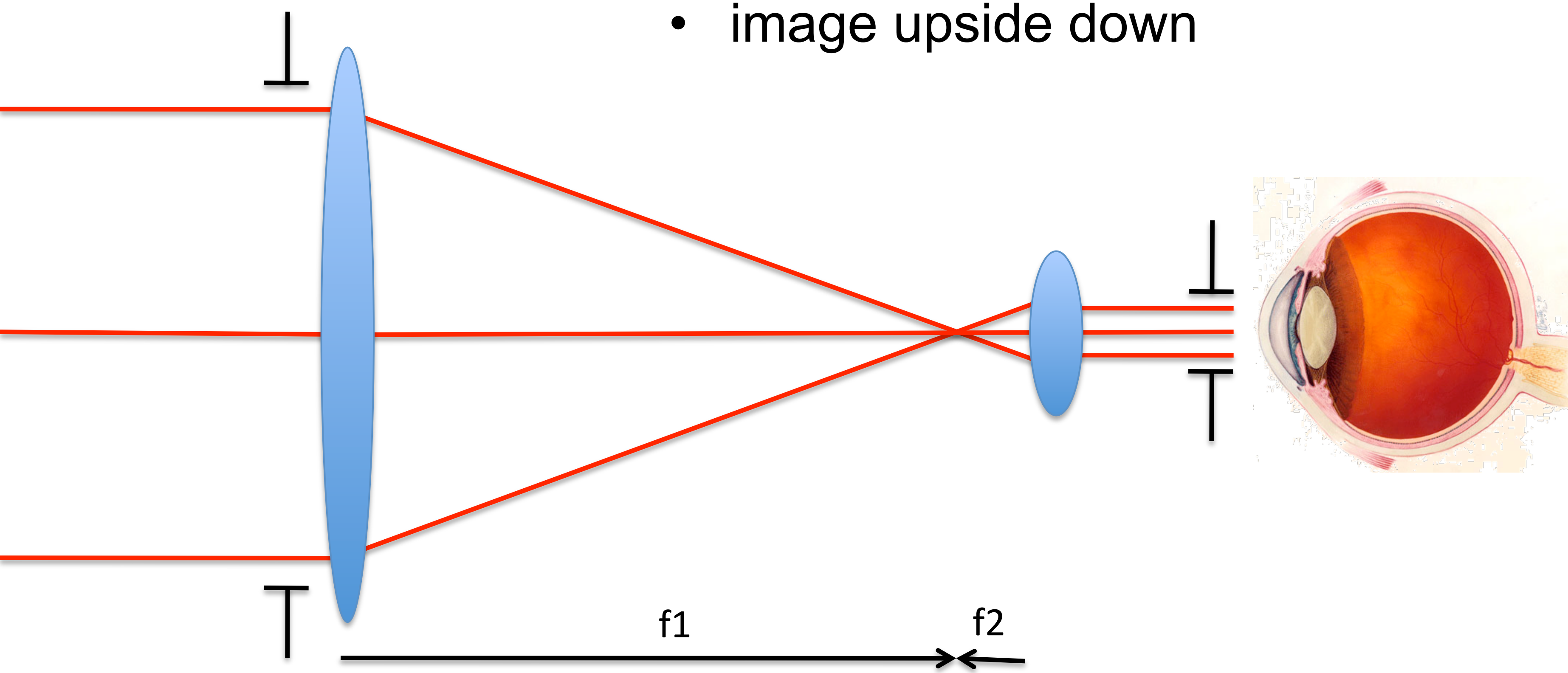


magnification = f1/f2

limitations: field, chromatic aberrations

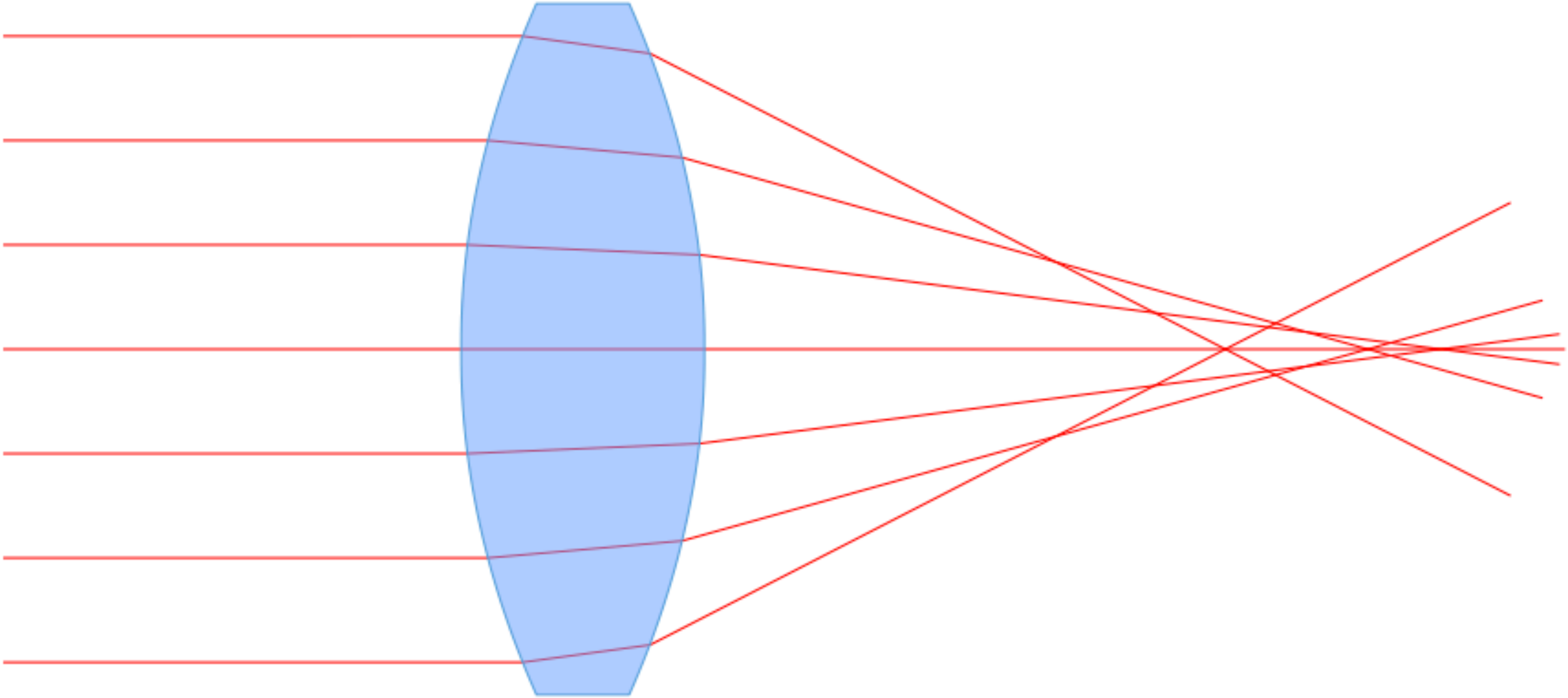
Kepler Refractor

- larger FOV
- image upside down



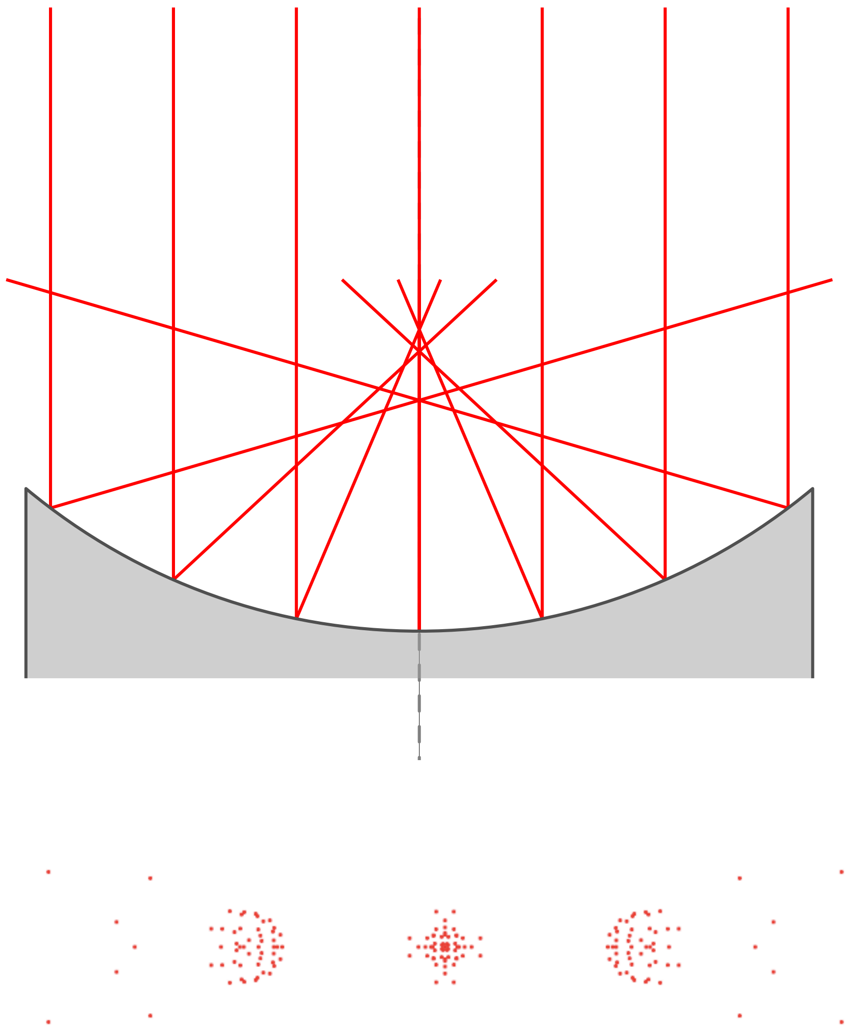
magnification = f1/f2

Spherical Lenses



Spherical Aberration: Beams away from center have shorter focal lengths

Spherical Mirrors

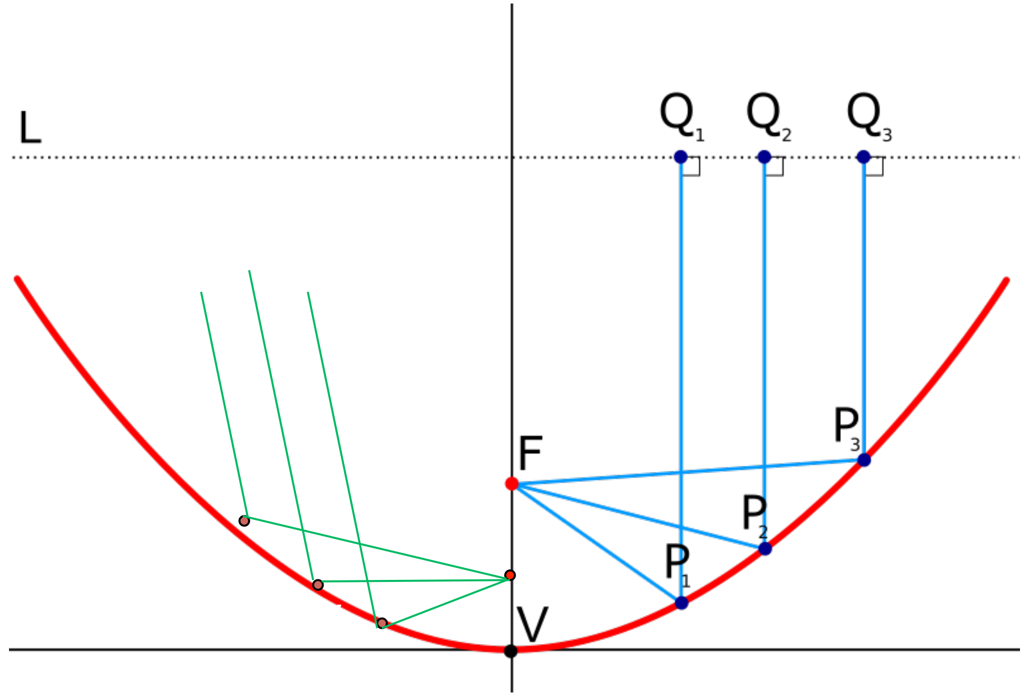


- provide large field of view (FoV)
- rays more distant from optical axis have a different focal point
- aberrations
- limited size
- limited curvature

Parabolic Mirrors

Parabolic primary mirrors focus all rays from the same direction to one point.

But: different directions have different focal points.

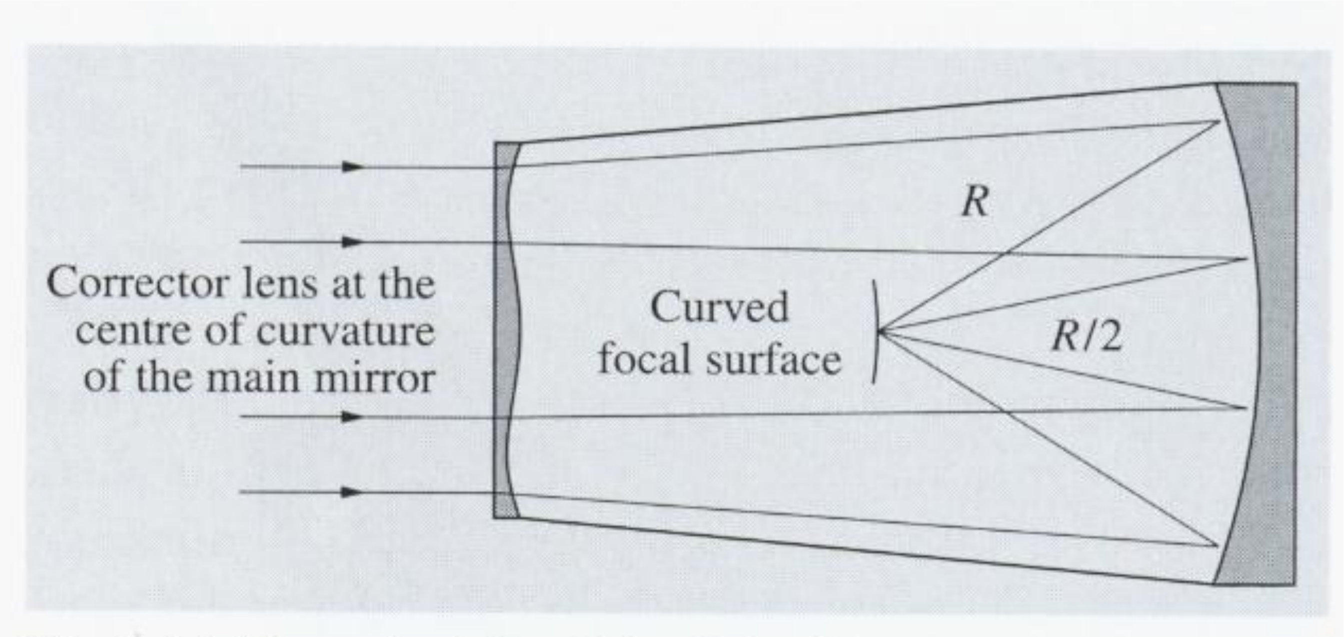


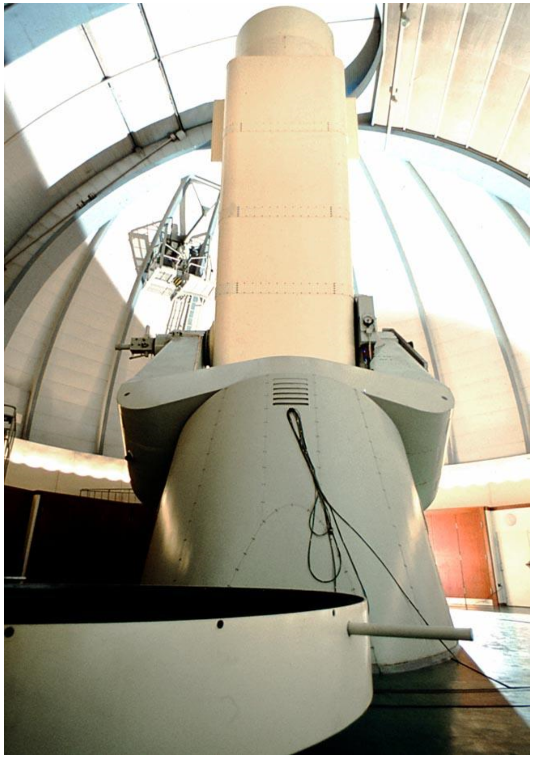
→ Field of view limited by aberrations: the bigger the mirror the bigger the difference [parabola – sphere] near the edge → bigger telescopes have smaller FOVs (~<1 deg)

Schmidt Telescope

Idea:

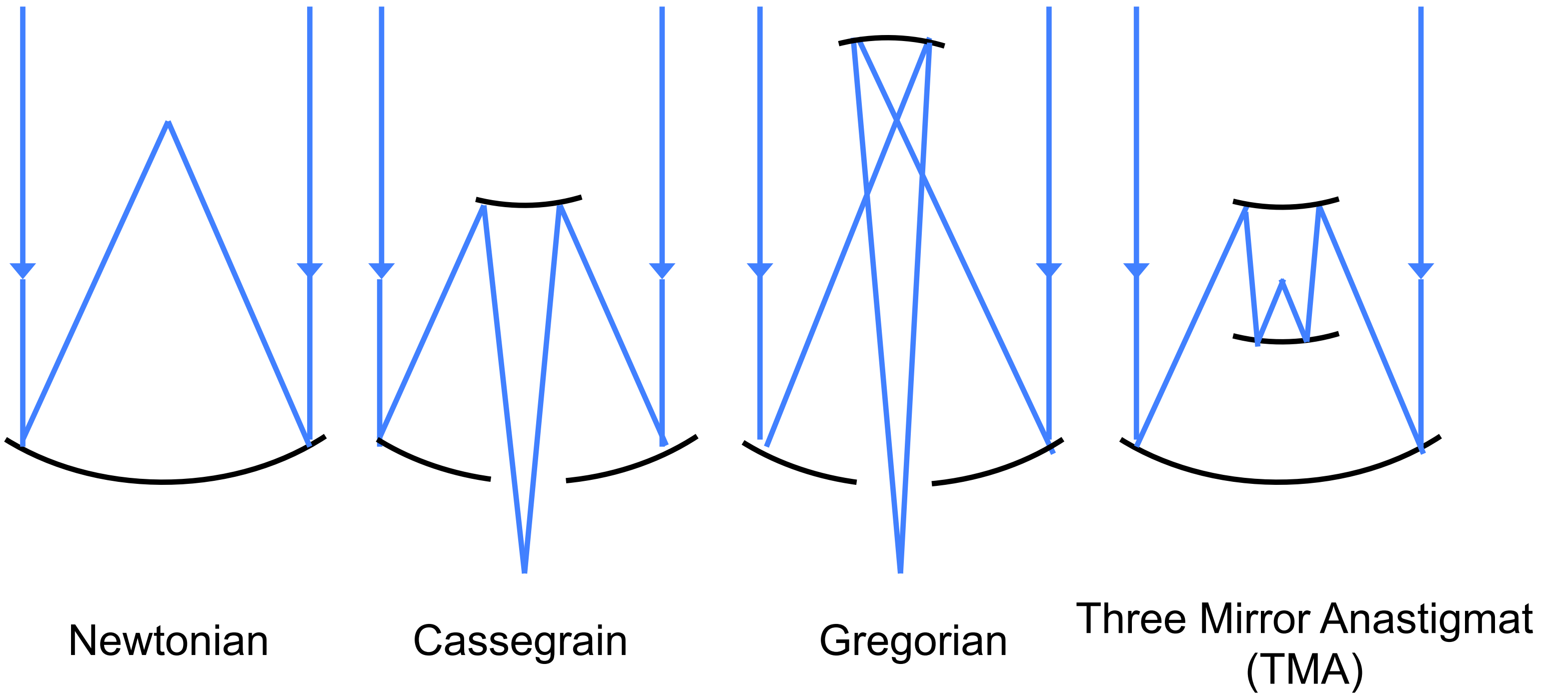
1. Use spherical primary mirror for maximum field of view (>5 deg) → no off-axis asymmetry *but* spherical aberrations
2. correct spherical aberrations with corrector lens.





Two meter Alfred-Jensch-Telescope in Tautenburg, the largest Schmidt camera in the world.

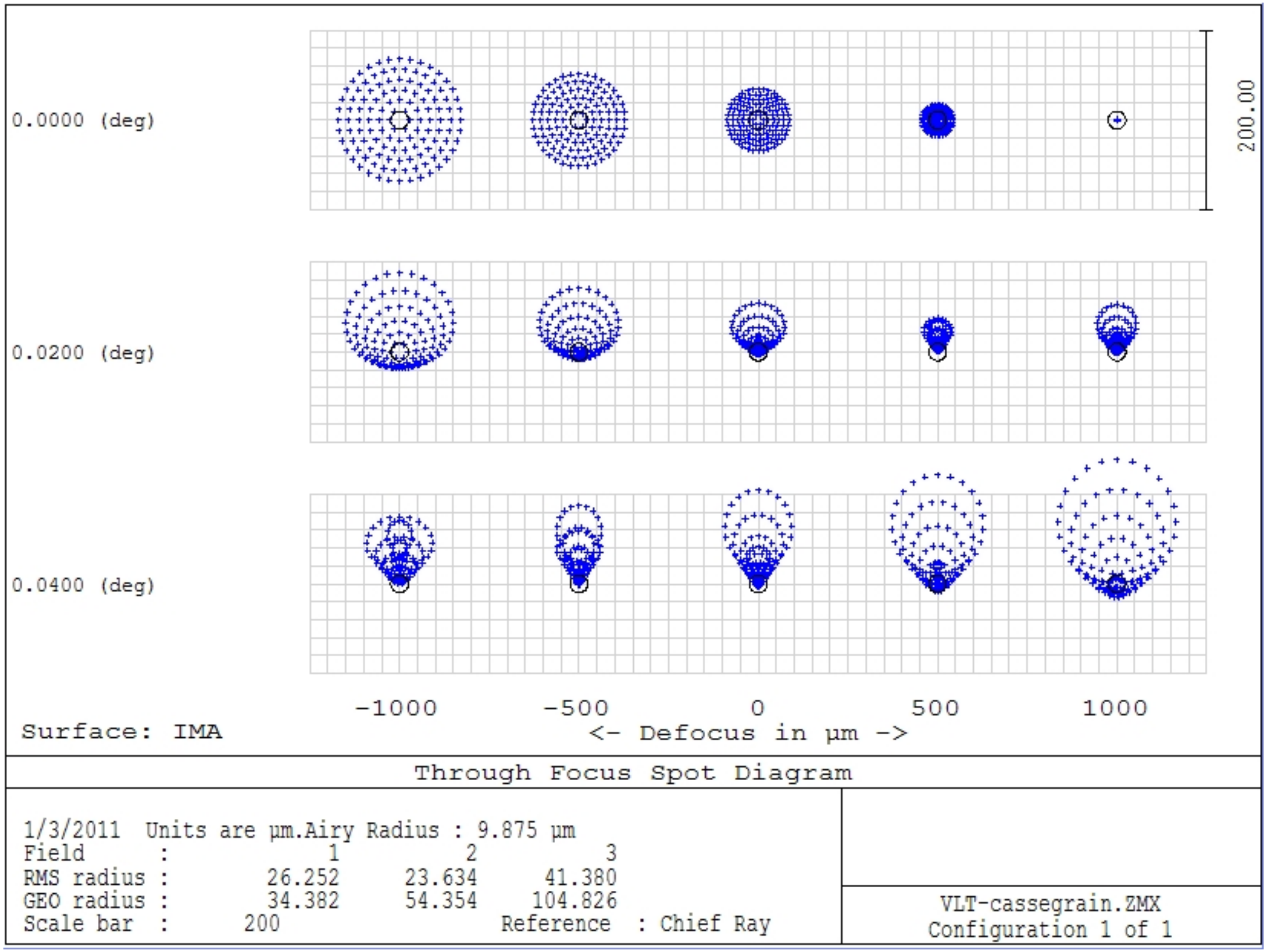
Two-Mirror Telescopes



Cassegrain Telescope

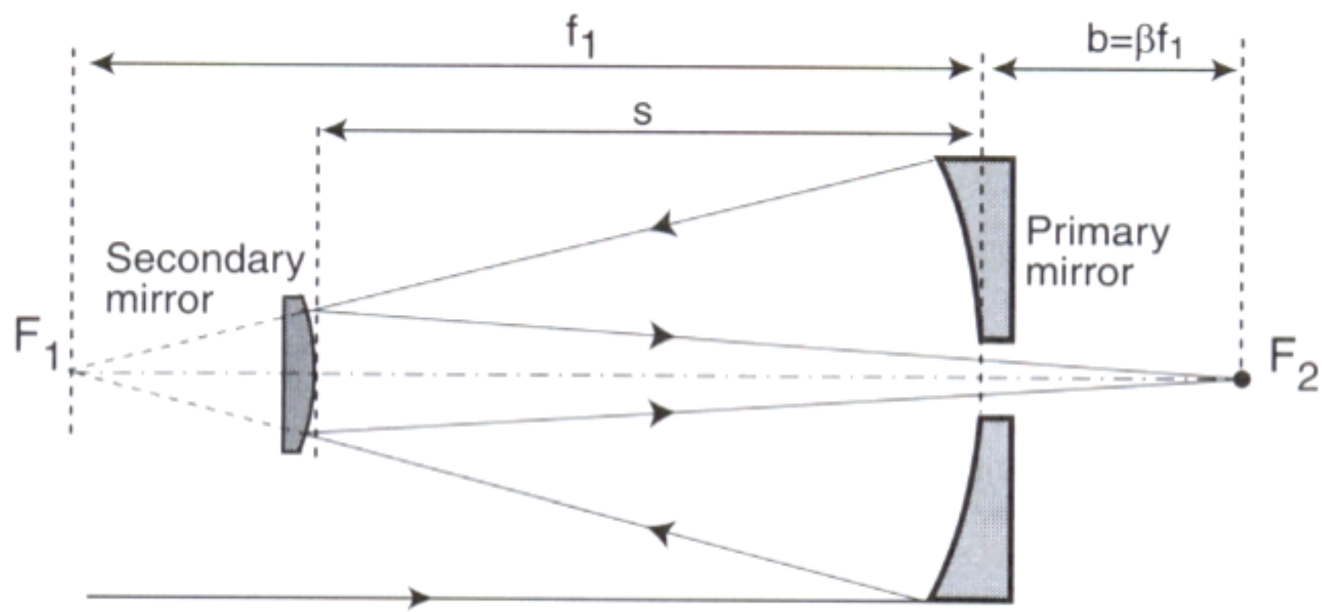
VLT as classical Cassegrain

$K_1 = -1$
$K_2 = -1.62$



Ritchey-Chrétien Configuration

Modification of Cassegrain configuration (parabolic primary, elliptical secondary): Hyperbolic primary mirror (almost parabola) and hyperbolic secondary mirror eliminates (some) optical errors (3rd order coma and spherical aberration).

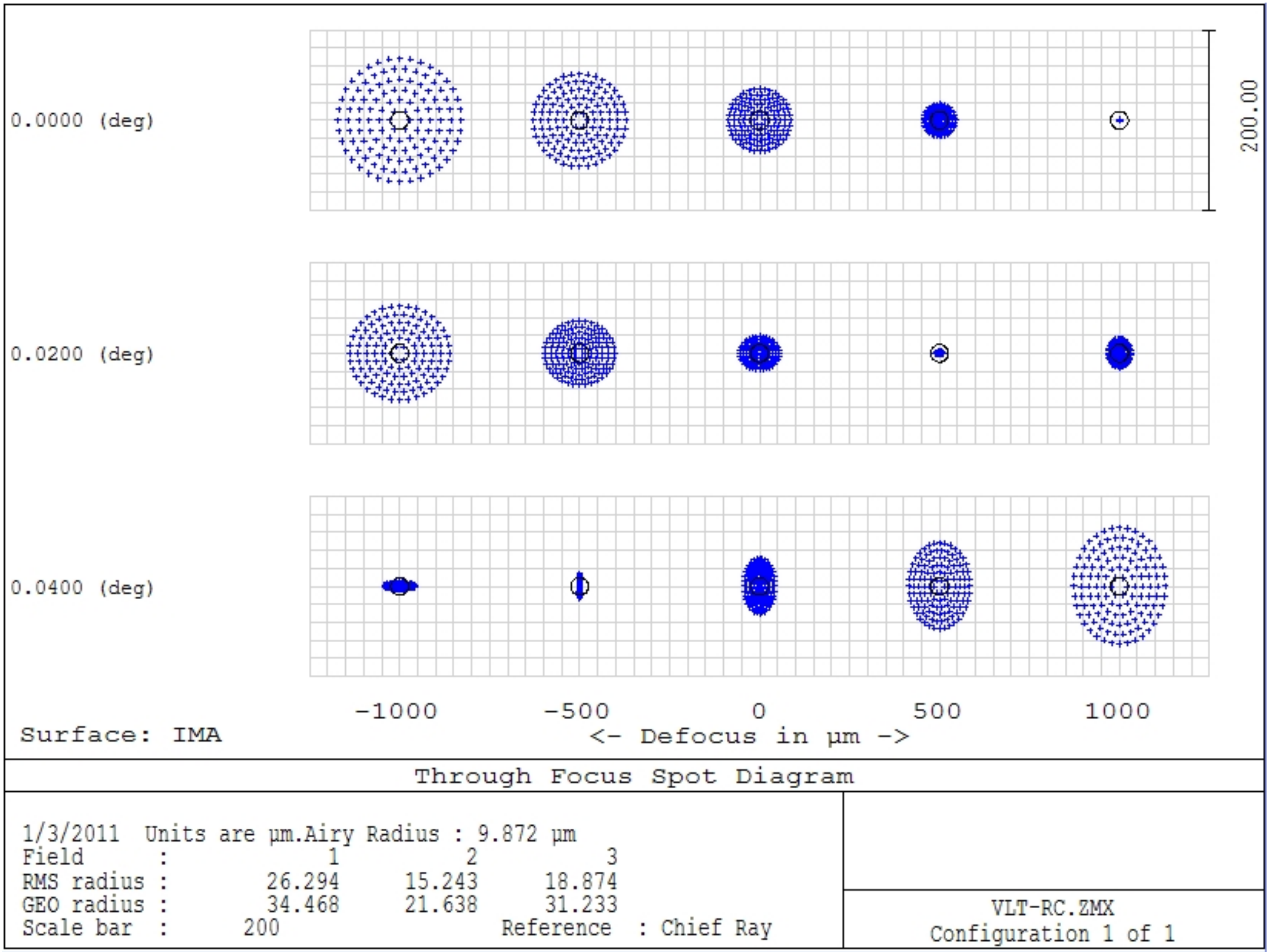


→ large field of view & compact design (for a given focal length)

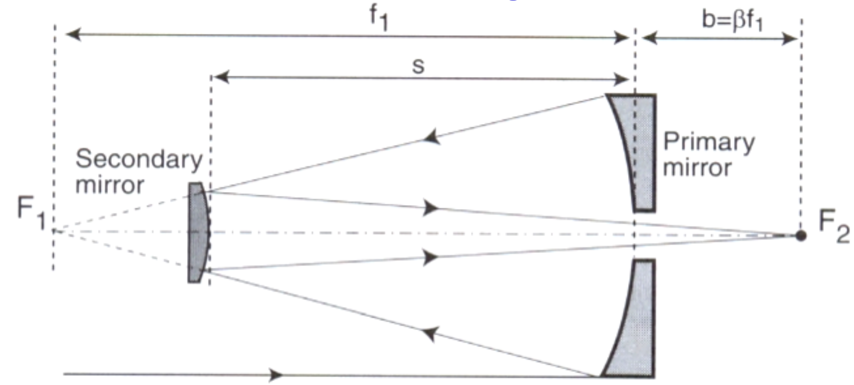
Ritchey-Chrétien Telescope

VLT

K_1 = -1.0046
K_2 = -1.66926

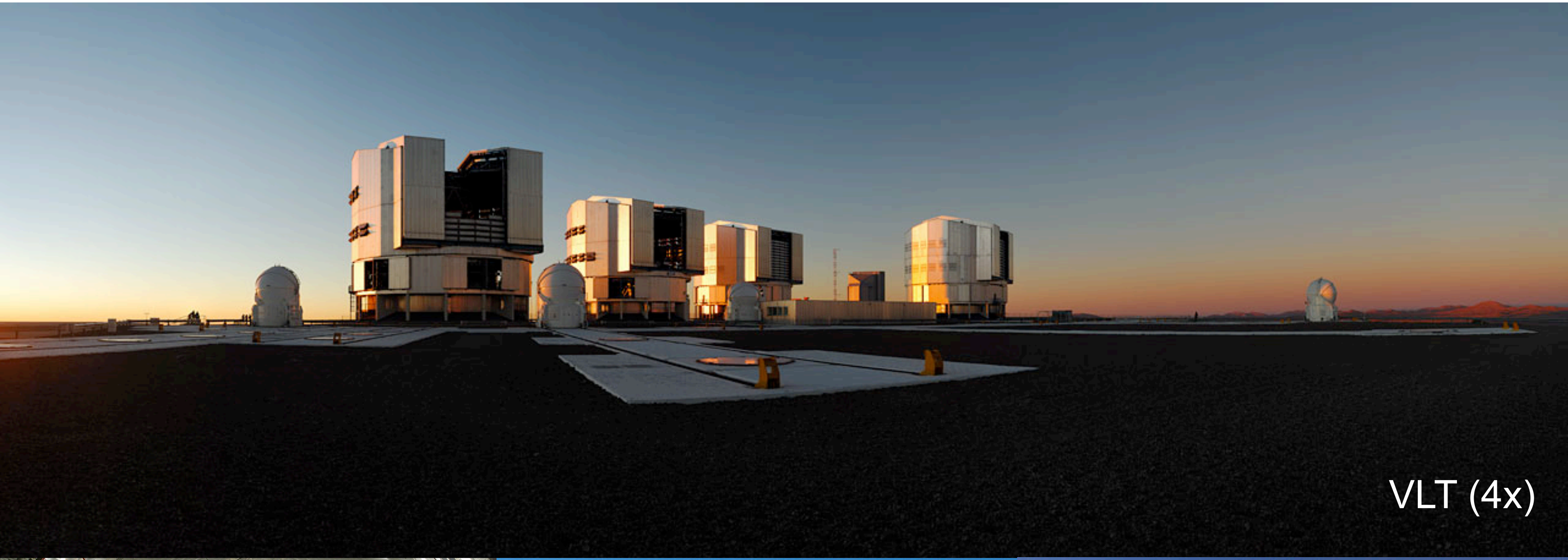


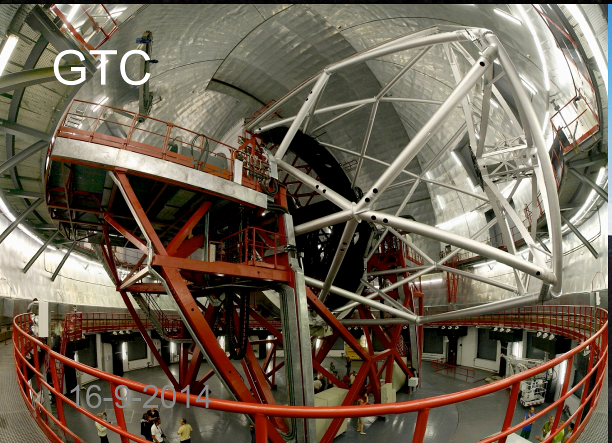
Parameters of a Ritchey-Chrétien Telescope

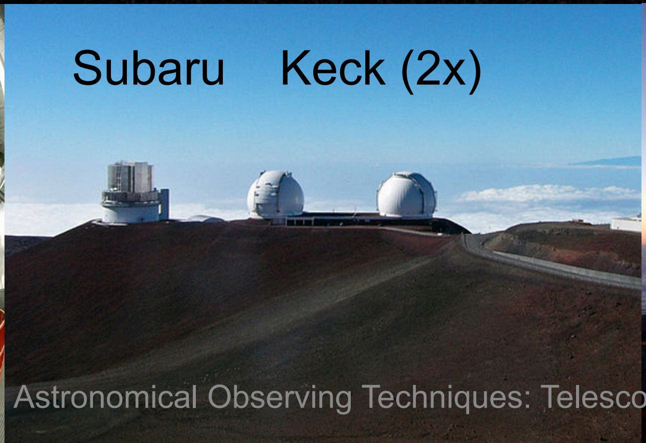


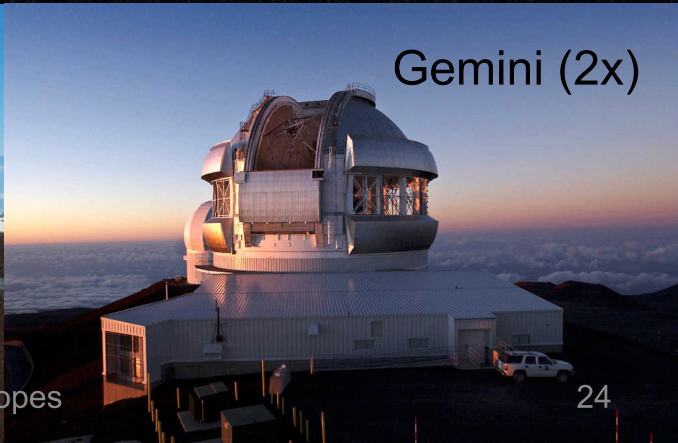
Optical parameters	
Primary mirror diameter	D_1
Primary mirror f-ratio	N_1
Primary mirror focal length	$f_1 = N_1 D_1$
Backfocal distance	$b = \beta f_1$
Normalized back focal distance	$\beta = b/f_1$
Magnification of secondary mirror	$m = f/f_1$
Primary–secondary separation	$s = (f - b)/(m + 1)$
Secondary mirror focal length	$f_2 = m(f_1 + b)/(m^2 - 1)$
Primary mirror conic constant	$\kappa_1 = -1 - \frac{2(1+\beta)}{m^2(m-\beta)}$
Secondary mirror conic constant	$\kappa_2 = -\left(\frac{m+1}{m-1}\right)^2 - \frac{2m(m+1)}{(m-\beta)/(m-1)^3}$
Secondary mirror dia. (zero field)	$D_2 = D_1(f_1 + b)/(f + f_1)$
Obscuration ratio (no baffling)	D_2/D_1
Final f-ratio	N
Final focal length	$f = ND_1 = \frac{f_1 f_2}{f_1 + f_2 - s}$
Field radius of curvature	$\frac{f_1 f^2 (f_1 - s)}{f f_1^2 + s(f^2 - f_1^2)}$
Aberrations	
Angular astigmatism	$\frac{\theta^2}{2F} \frac{m(2m+1)+\beta}{2m(1+\beta)}$
Angular distortion	$\theta^3 \frac{(m-\beta)}{4m^2(1+\beta)^2}(m(m^2 - 2) + \beta(3m^2 - 2))$
Median field curvature	$\frac{2}{R_1} \frac{(m+1)}{m^2(1+\beta)}(m^2 - \beta(m - 1))$

Ritchey-Chrétien Telescopes



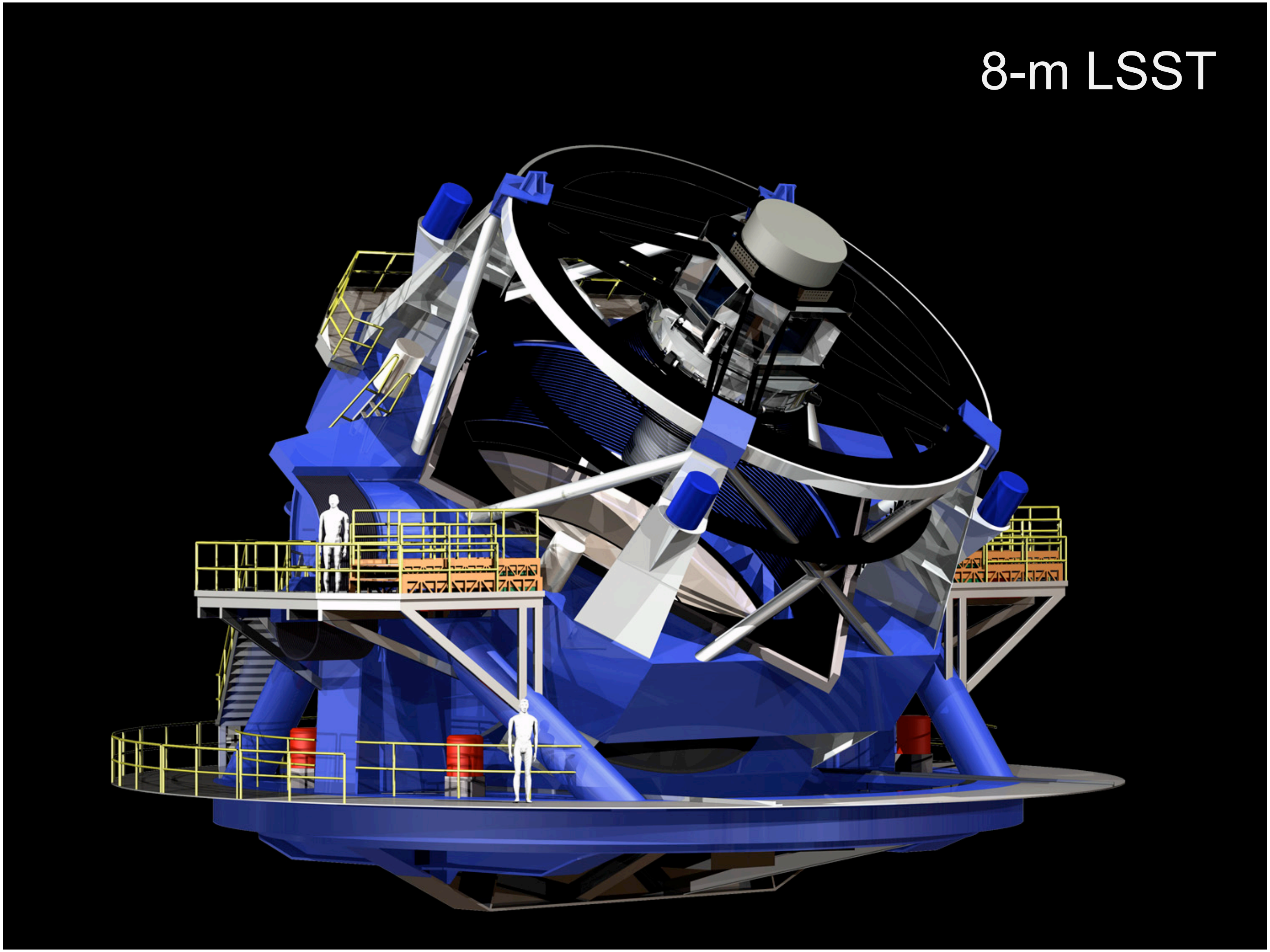




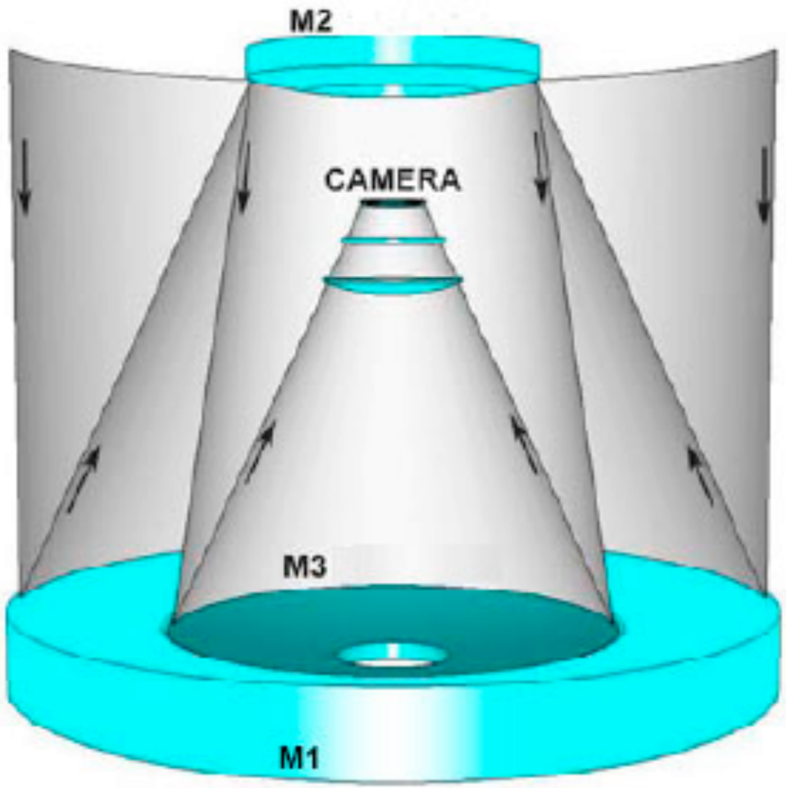


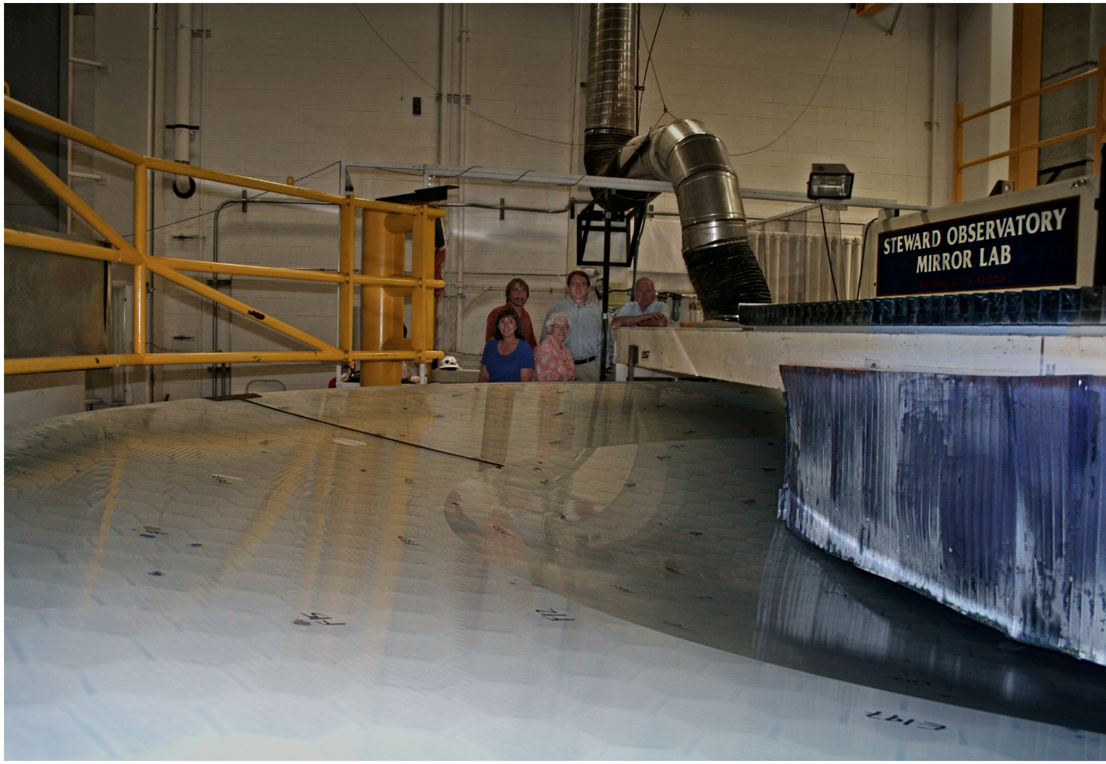
Ritchey-Chrétien Telescope

Three-Mirror Wide-Field Telescope



TMA





Large Synoptic Survey Telescope (LSST)

Light Gathering Power and Resolution

Light gathering power

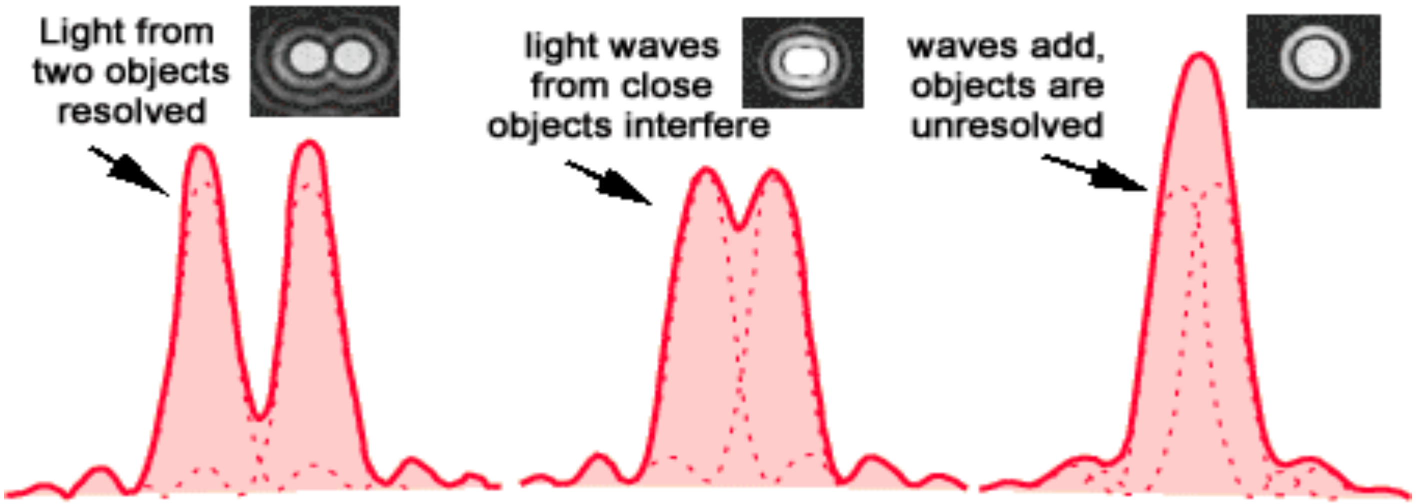
For extended objects: $S/N \propto \left(\frac{D}{f}\right)^2$ (see lecture on S/N)

For point sources: $S/N \propto D^2$

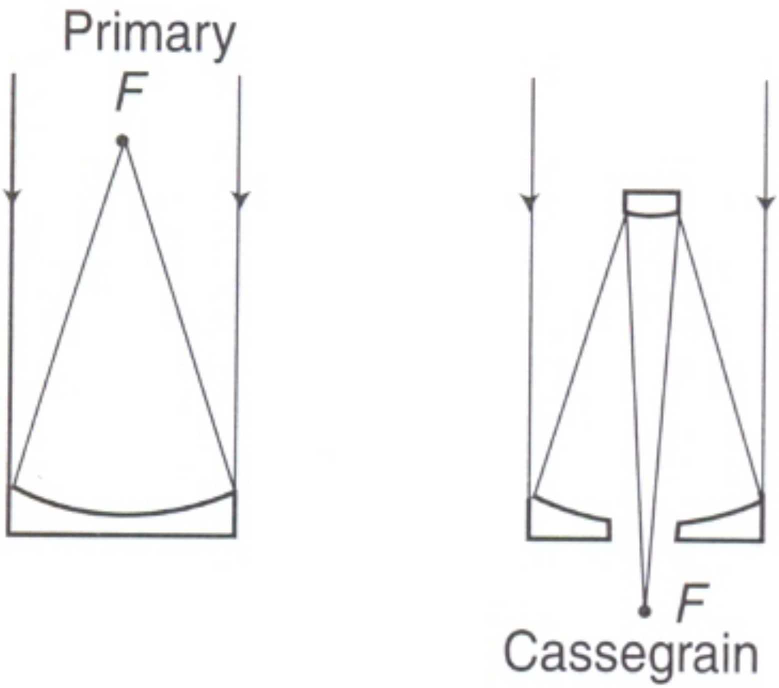
Angular resolution

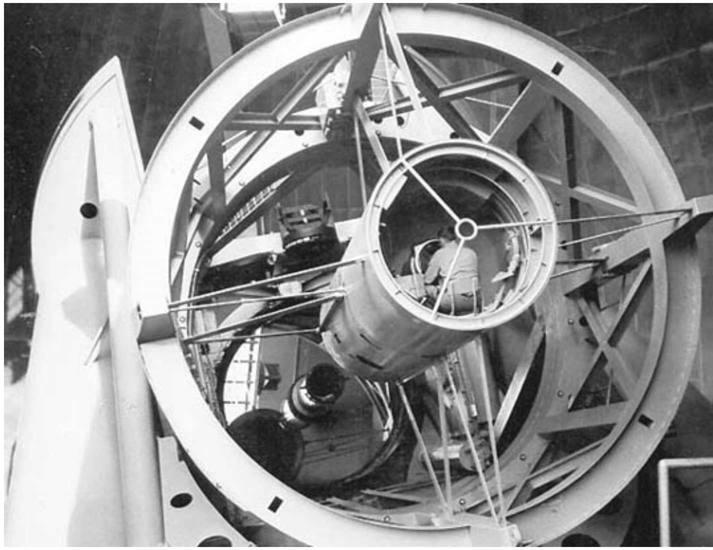
$$\sin\Theta = 1.22\frac{\lambda}{D} \quad \text{or} \quad \Delta l = 1.22\frac{f\lambda}{D}$$

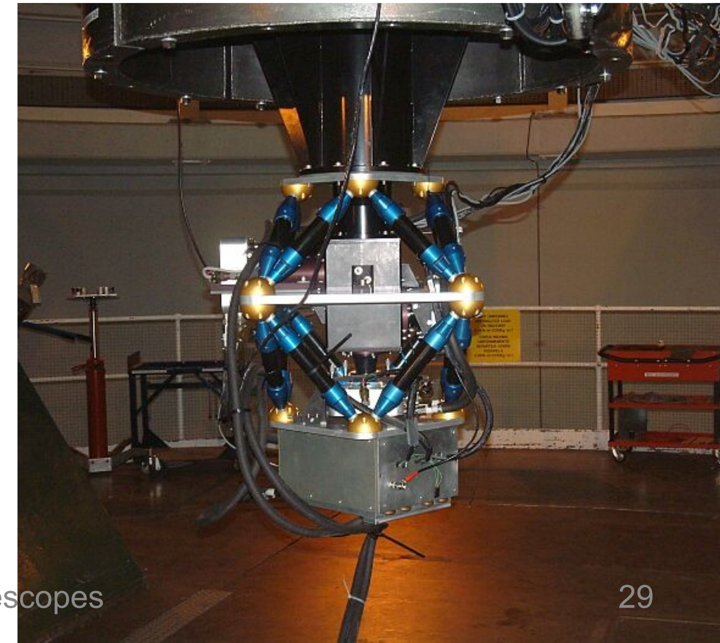
(given by the Rayleigh criterion)



Telescope Foci – where to put the instruments



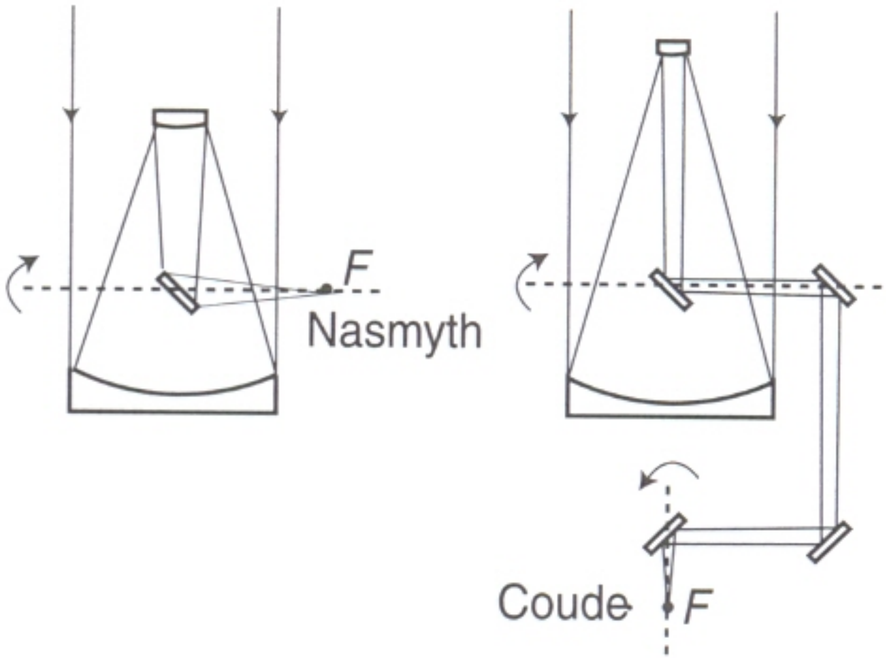




Prime focus – wide field, fast beam but difficult to access and not suitable for heavy instruments

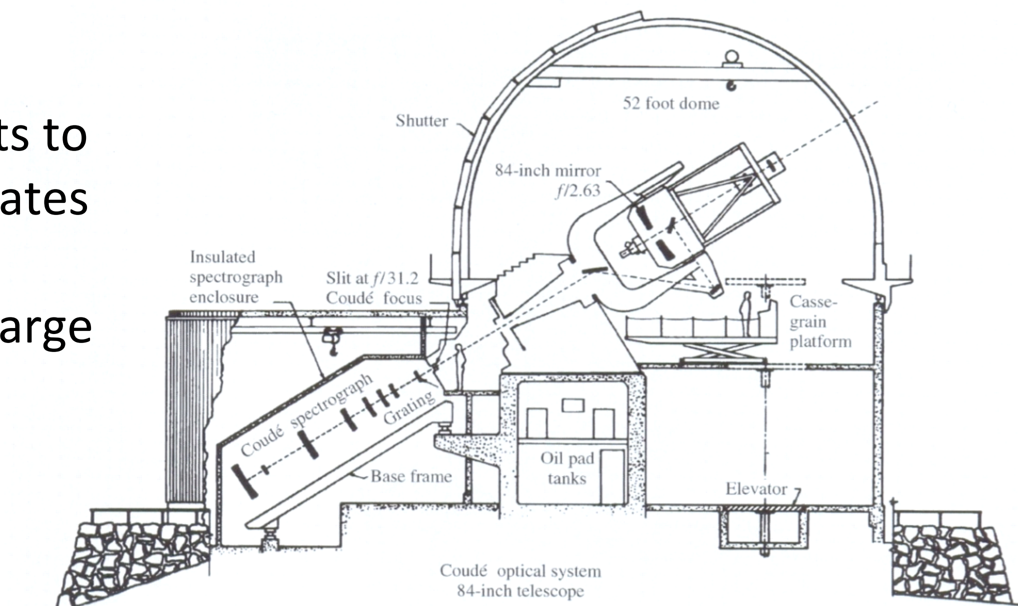
Cassegrain focus – moves with telescopes, small field

Telescope Foci – where to put instruments (2)



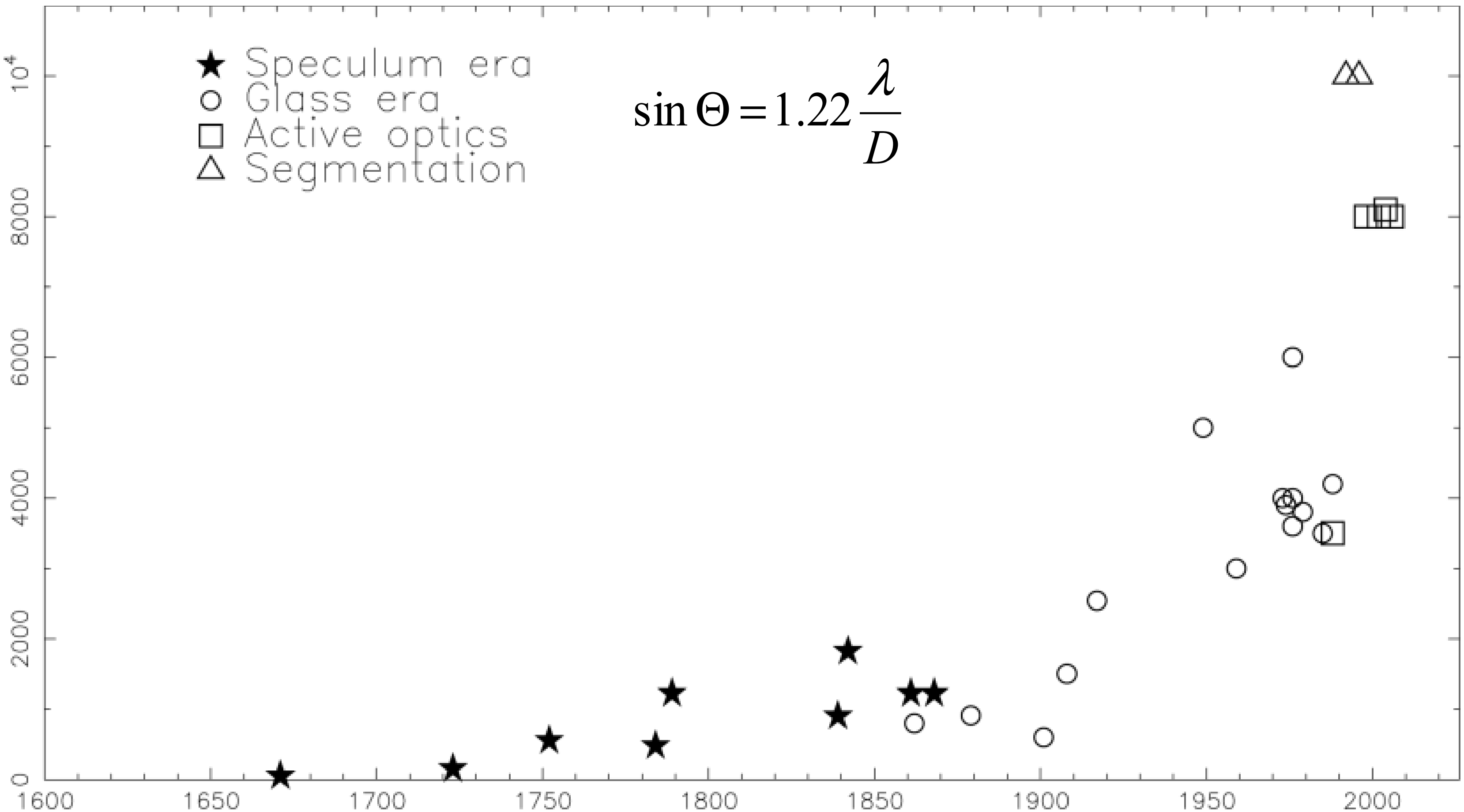
Nasmyth – ideal for heavy instruments to put on a stable platform, but field rotates

Coudé – very slow beam, usually for large spectrographs in the "basement"

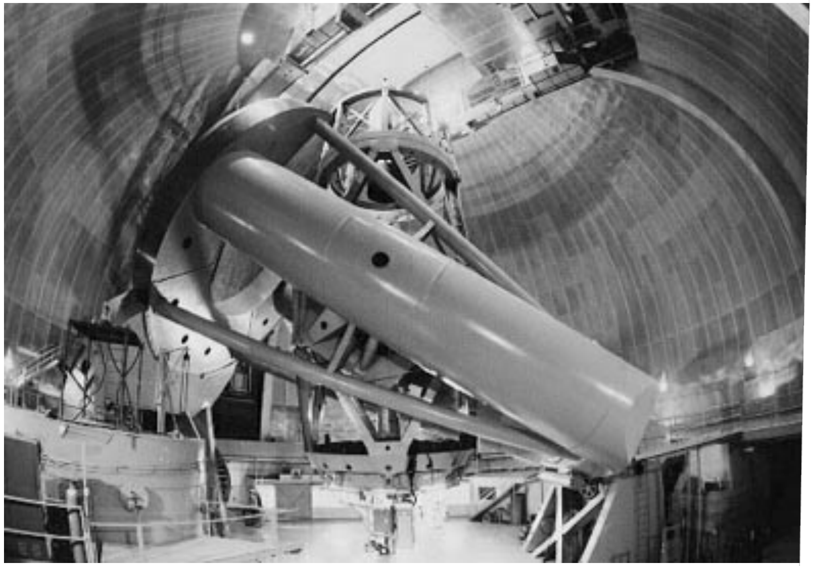


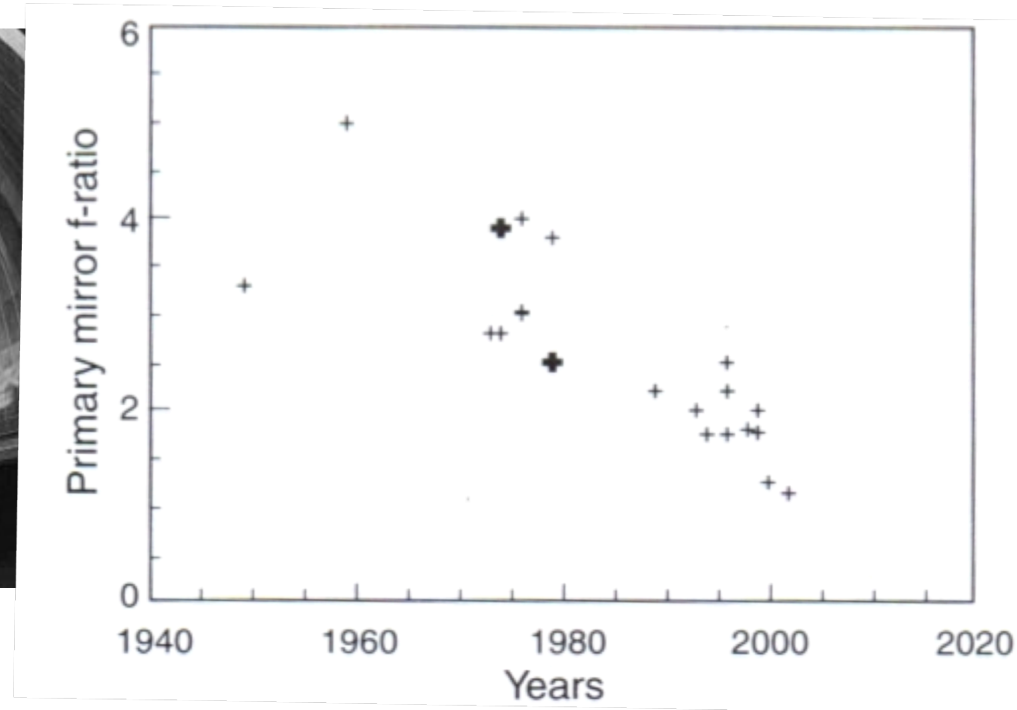
Mass, Size, etc.

The Growth of Telescope Collecting Area



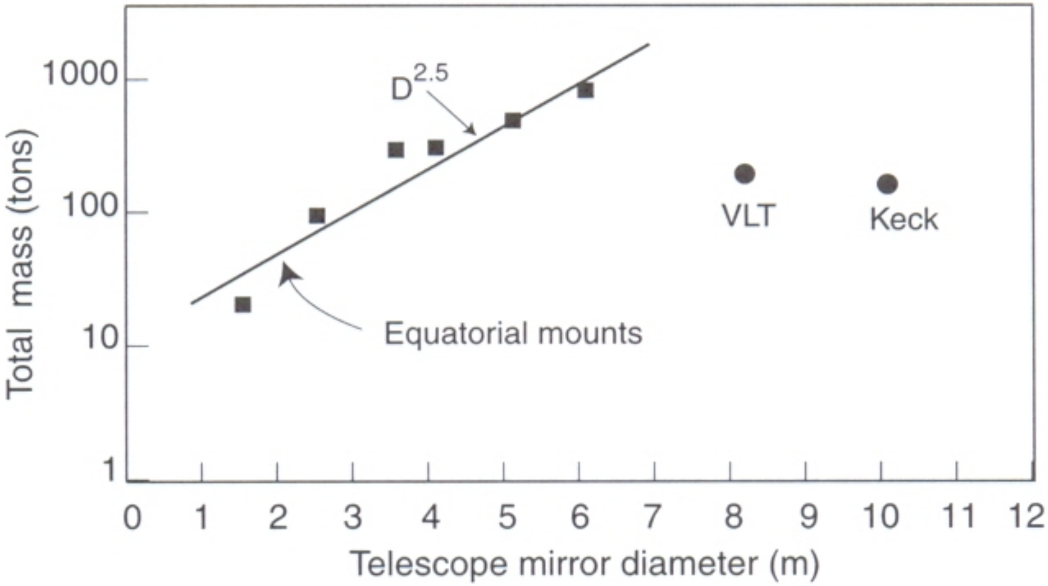
Size Limitations





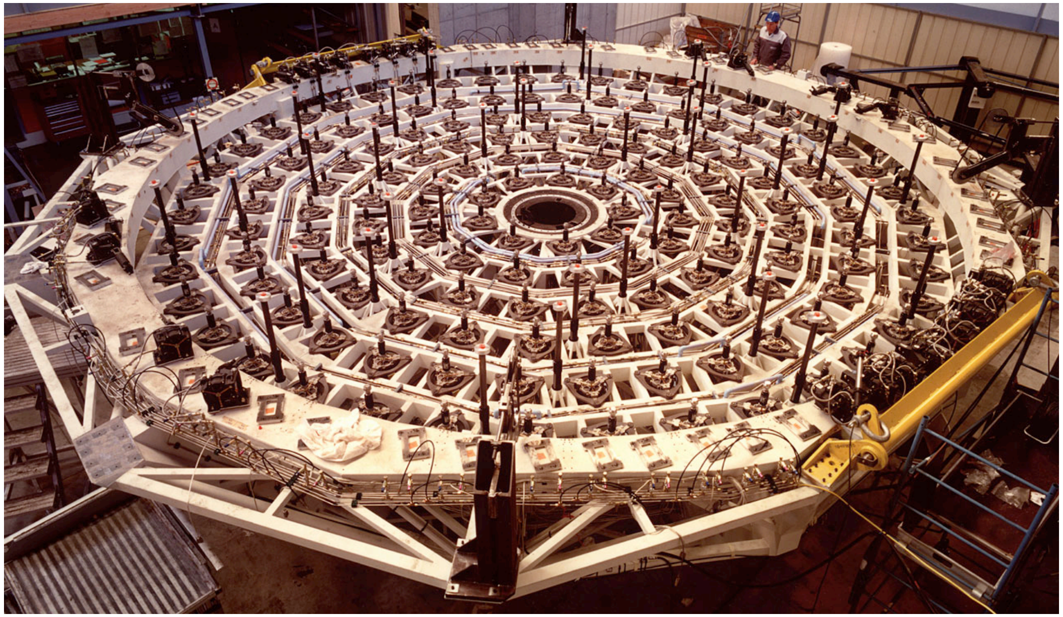
- faster mirrors → smaller telescopes → smaller domes
- faster mirrors require:
  - new polishing and testing techniques
  - more accurate alignment

Mass Limitations

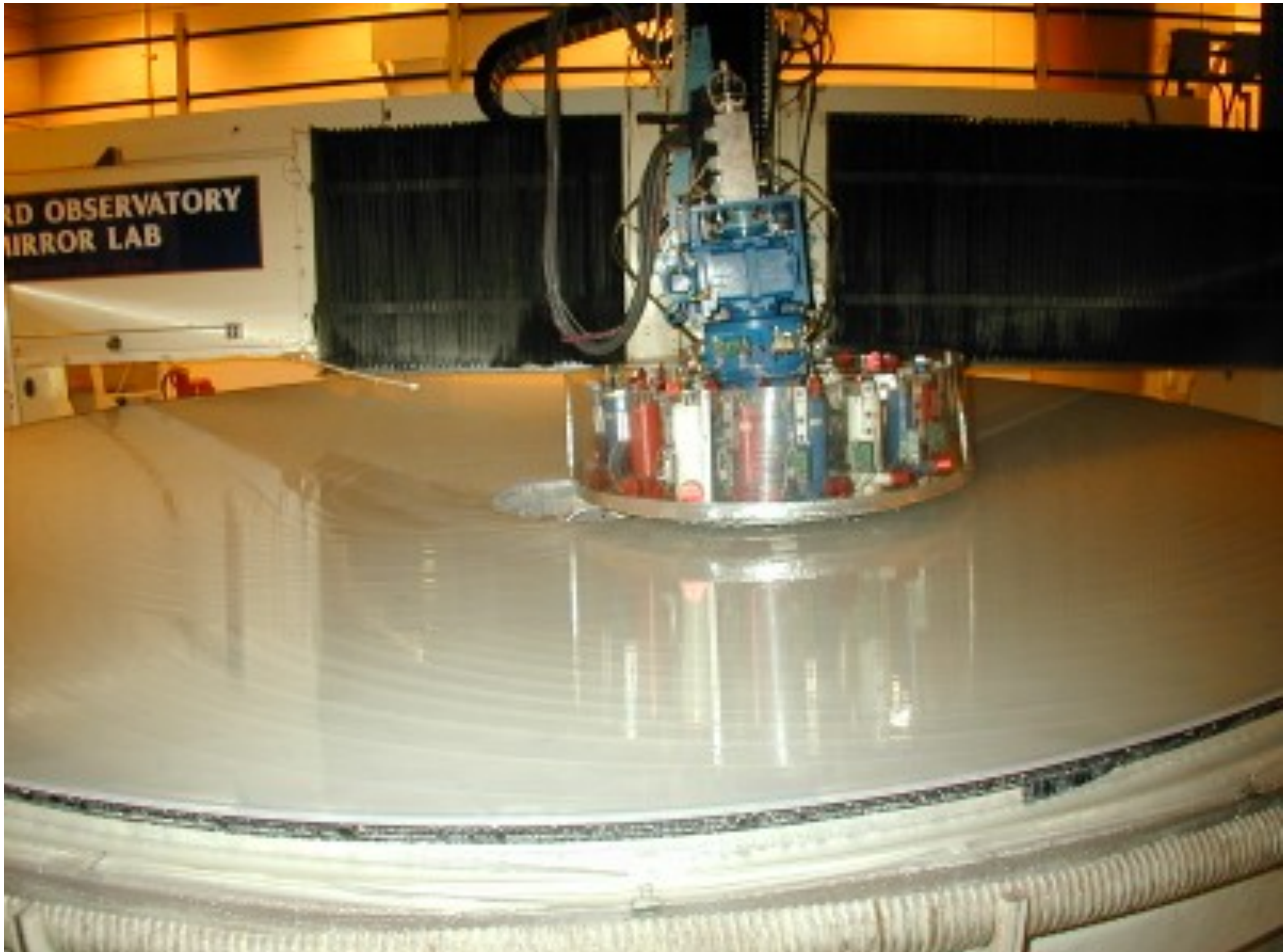


bigger mirrors require

- thinner / segmented mirrors
- active support



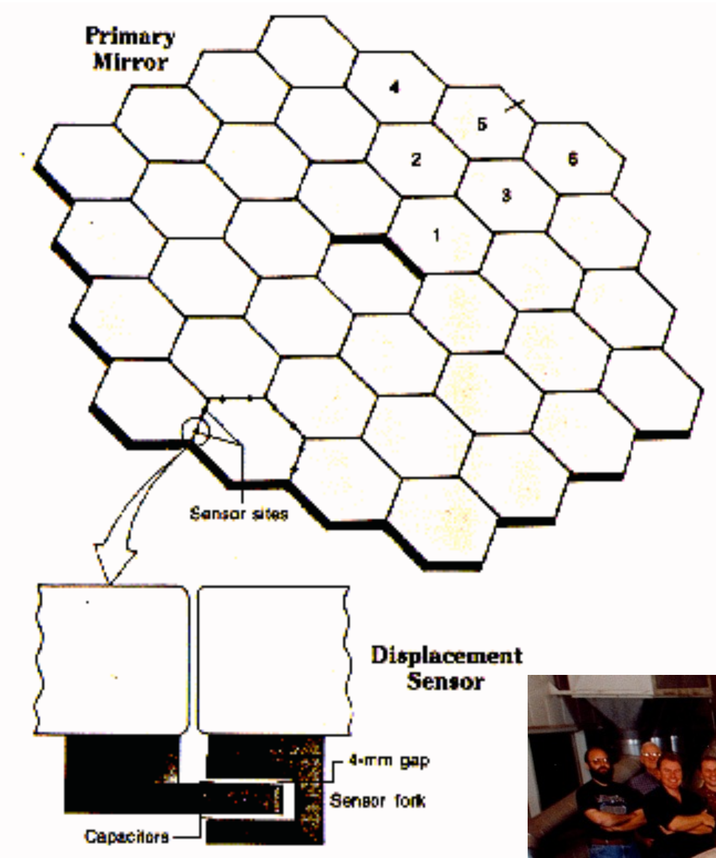
Mirror Polishing

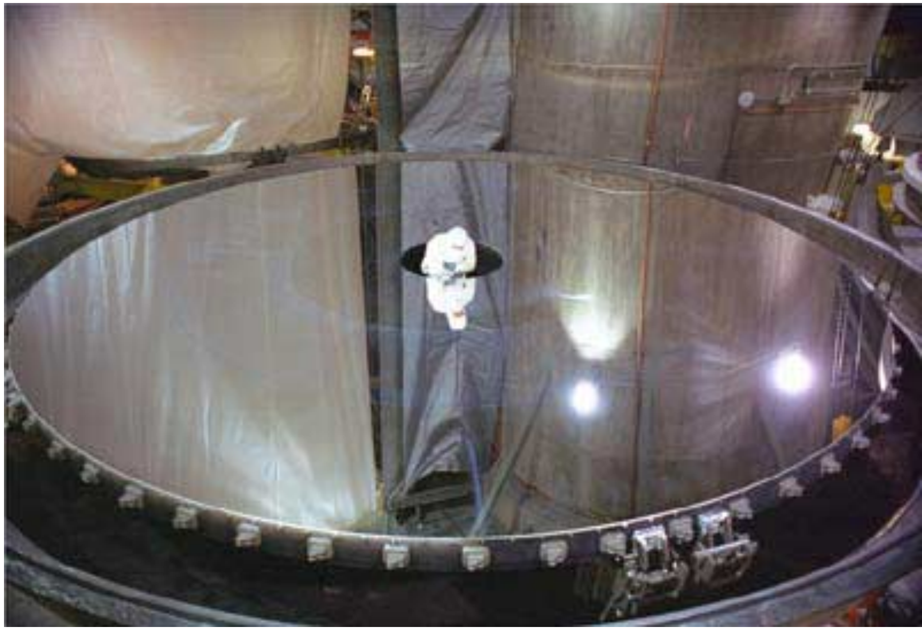


Polishing a 6.5-m mirror on the Large Optical Generator (LOG) using the stressed-lap polishing tool. The lap changes shape dynamically as it moves radially from center-to-edge of the mirror to produce a paraboloid.

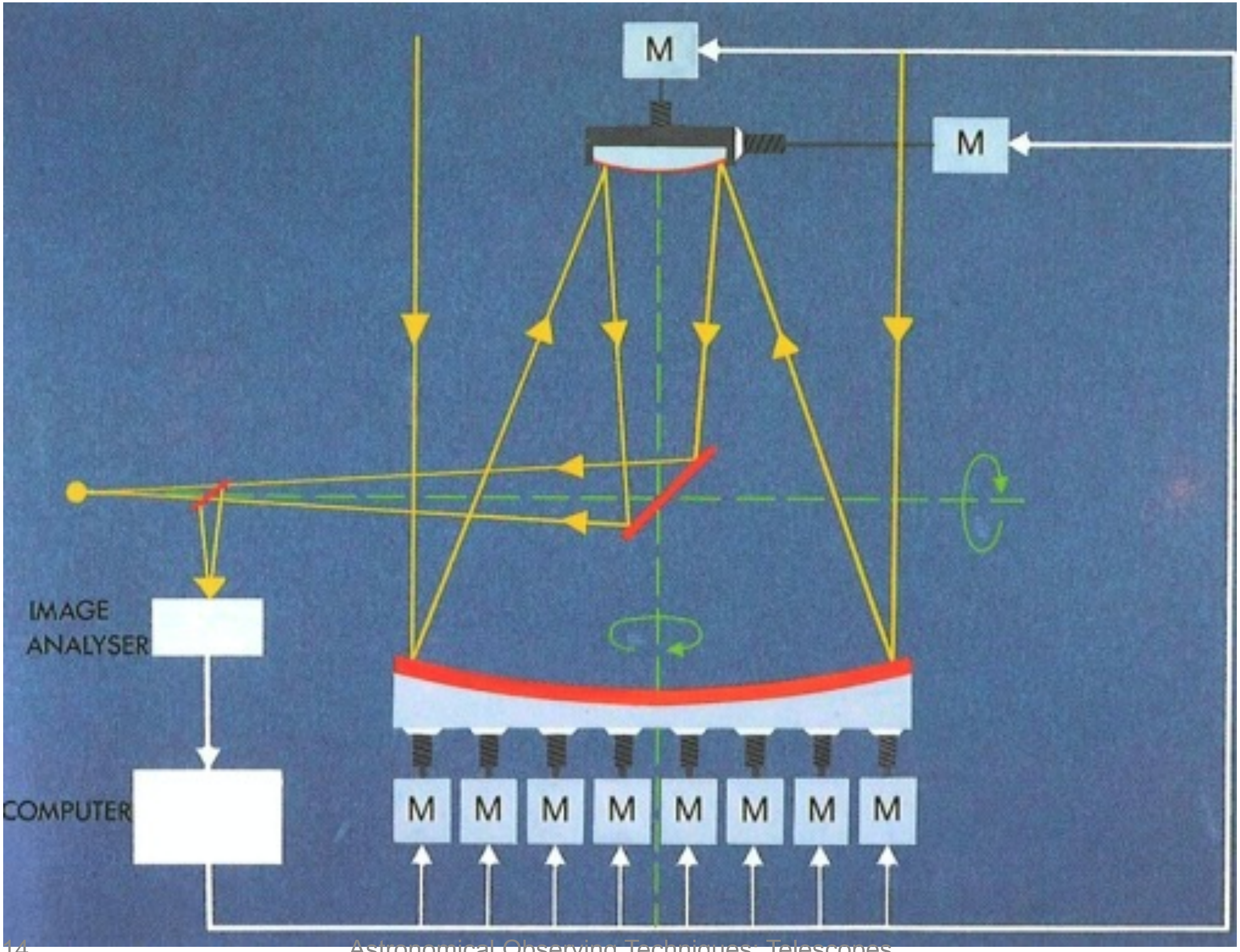
http://mirrorlab.as.arizona.edu/TECH.php?navi=poli

Segmented, Thin and Honeycomb Mirrors

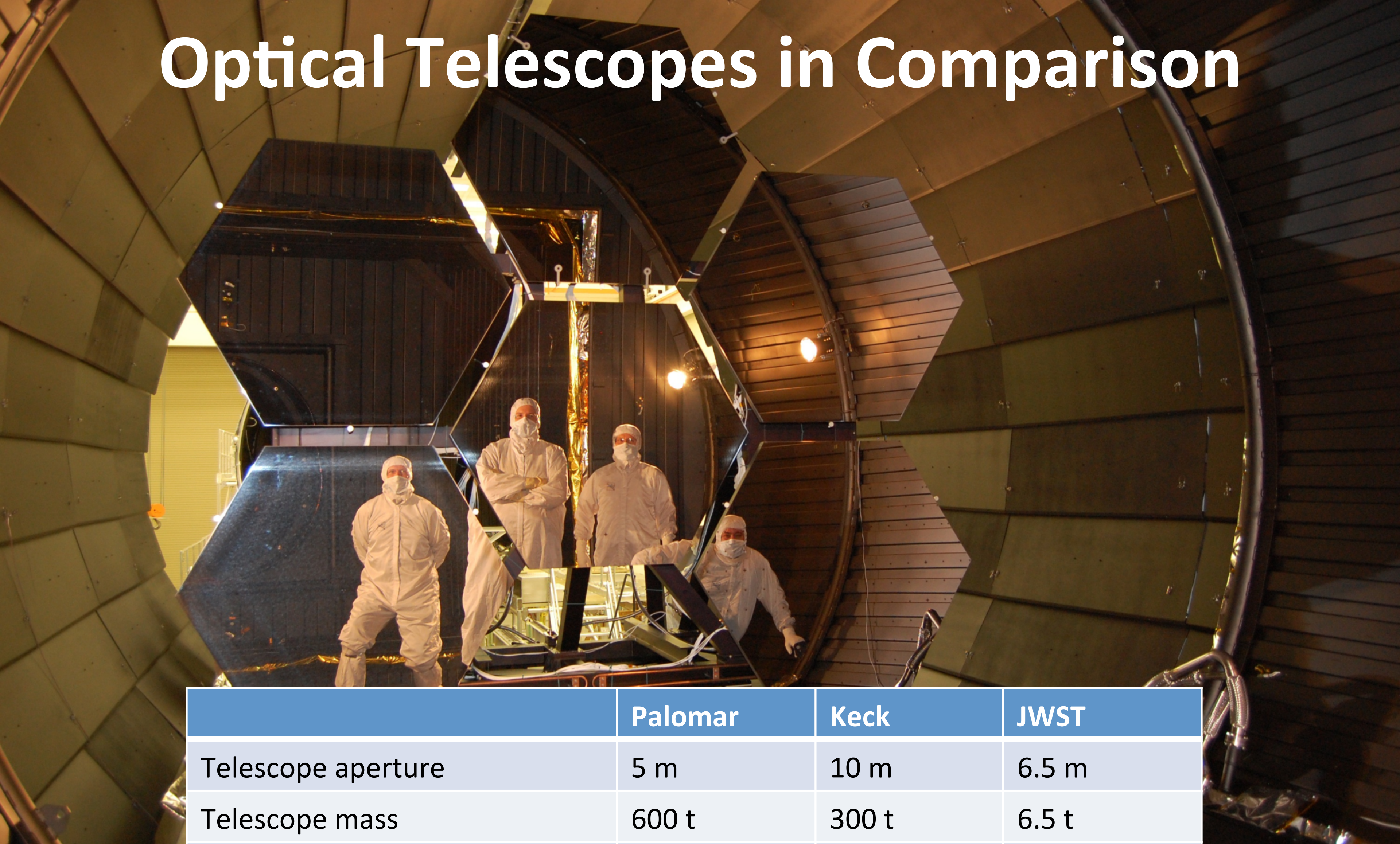




Active Optics (Mirror Support)



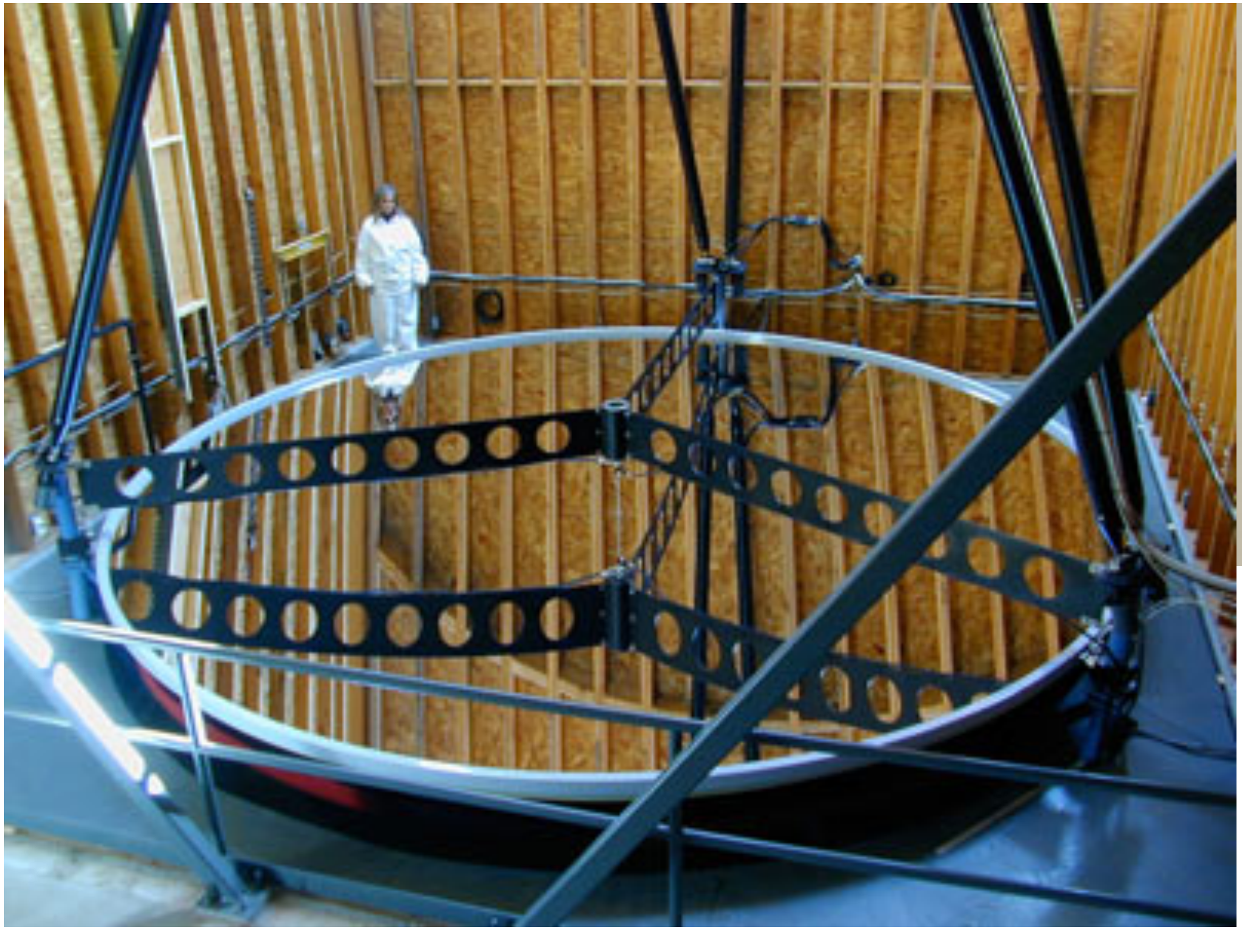
Optical Telescopes in Comparison

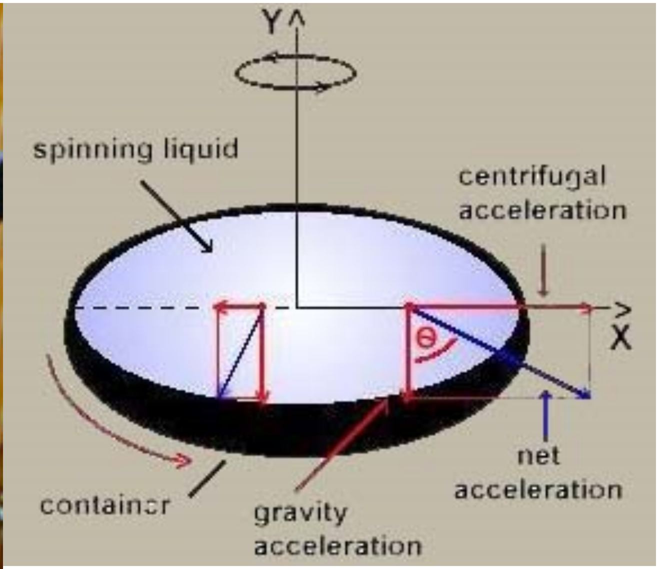


	Palomar	Keck	JWST
Telescope aperture	5 m	10 m	6.5 m
Telescope mass	600 t	300 t	6.5 t
# of segments	1	36	18
Segment size	5 m	1.8 m	1.3 m
Mass / segment	14’500 kg	400 kg	20 kg

Liquid Mirror Telescopes

- First suggestion by Ernesto Capocci in 1850
- First mercury telescope built in 1872 with a diameter of 350 mm
- Largest mirror: diameter 3.7 m





Radio Telescopes

Dishes similar to optical telescopes but with much lower surface accuracy

Arecibo, Puerto Rico – the largest (305m) single-aperture telescope

Effelsberg, Germany – 100m fully steerable telescope

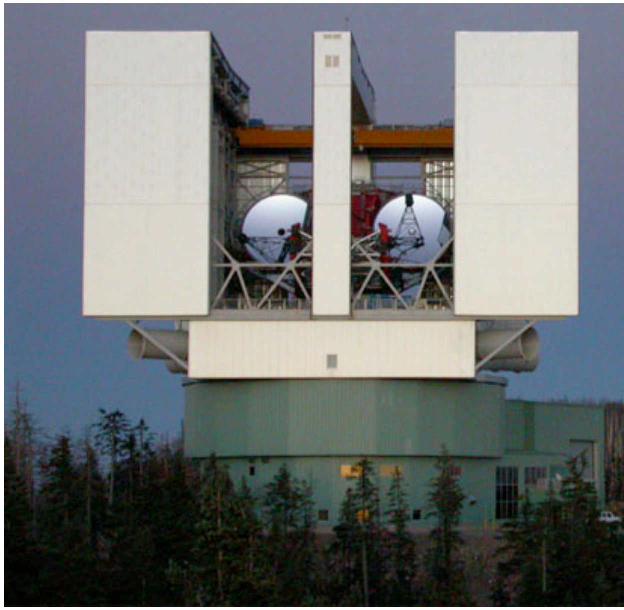
Greenbank, USA – after structural collapse (now rebuilt)

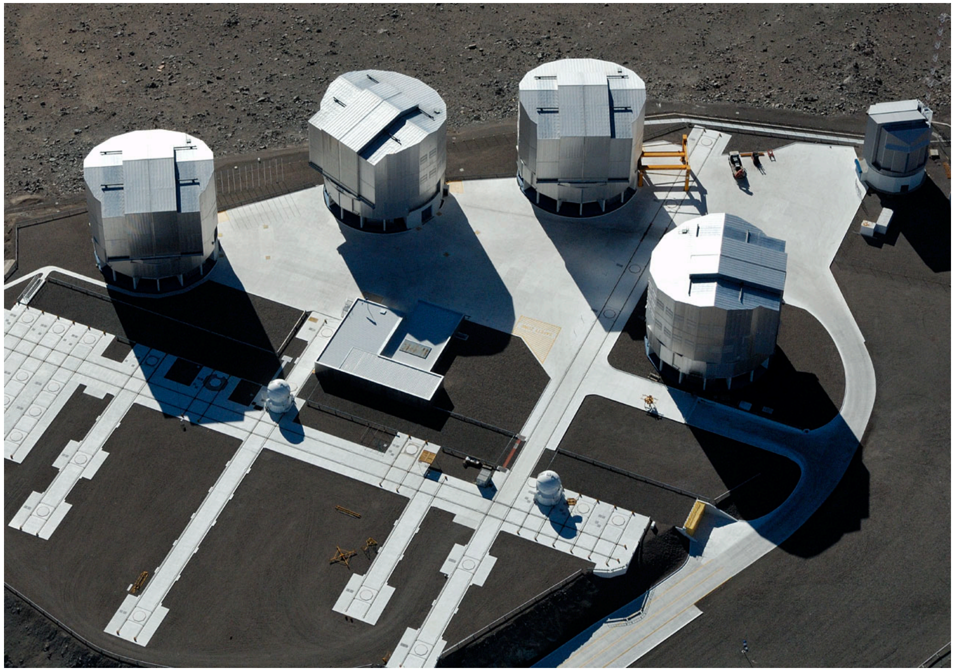
Arrays and Interferometers

Optical Interferometers

Keck

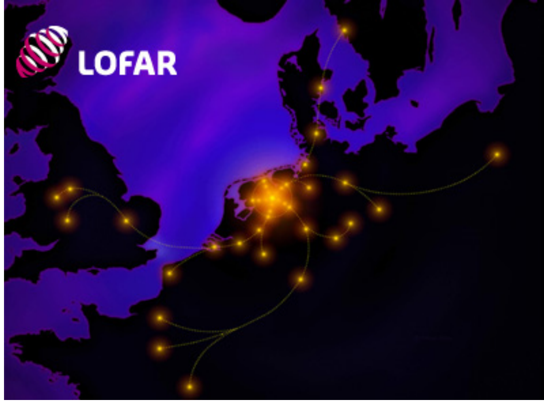
LBT



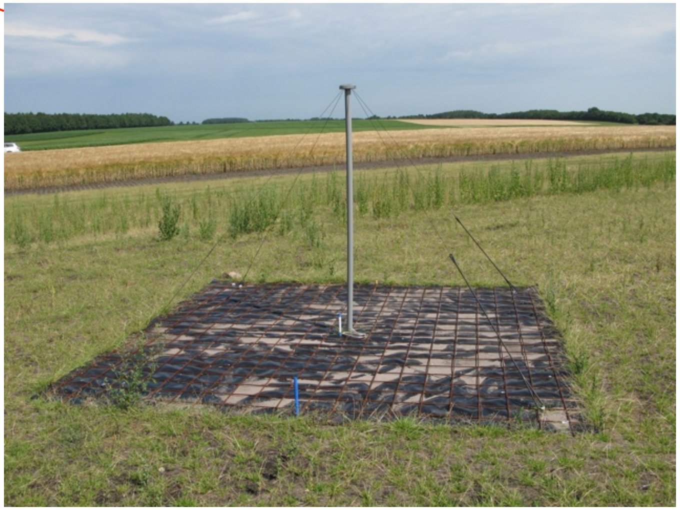


VLTI

LOFAR in the Netherlands



- LOw Frequency ARray uses two types of low-cost antennae:
  - Low Band Antenna (10-90 MHz)
  - High Band Antenna (110-250 MHz).



- Antennae are organized in 36 stations
- over ~100 km. Each station contains
- 96 LBAs and 48 HBAs
- Baselines: 100m – 1500km
- Main LOFAR subsystems:
- sensor fields
- wide area networks
- central processing systems
- user interfaces

X-ray Telescopes

• X-rays impinging perpendicular on any material are largely absorbed rather than reflected

• telescope optics based on glancing angle reflection (rather than refraction or large angle reflection)

• typical reflecting materials for X-ray mirrors are gold and iridium (gold has a critical reflection angle of 3.7 deg at 1 keV).

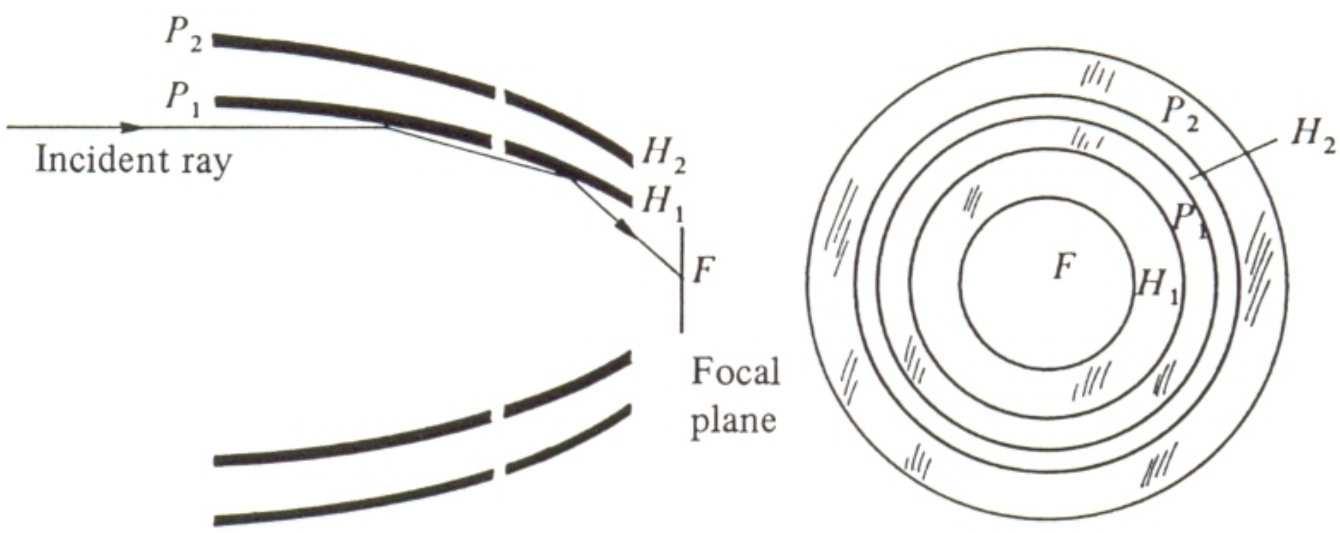


Fig. 4.33. Side and front views of a Wolter X-ray telescope. P and H denote