

Telescopes

ATI Lecture 08 2016
Keller and Kenworthy

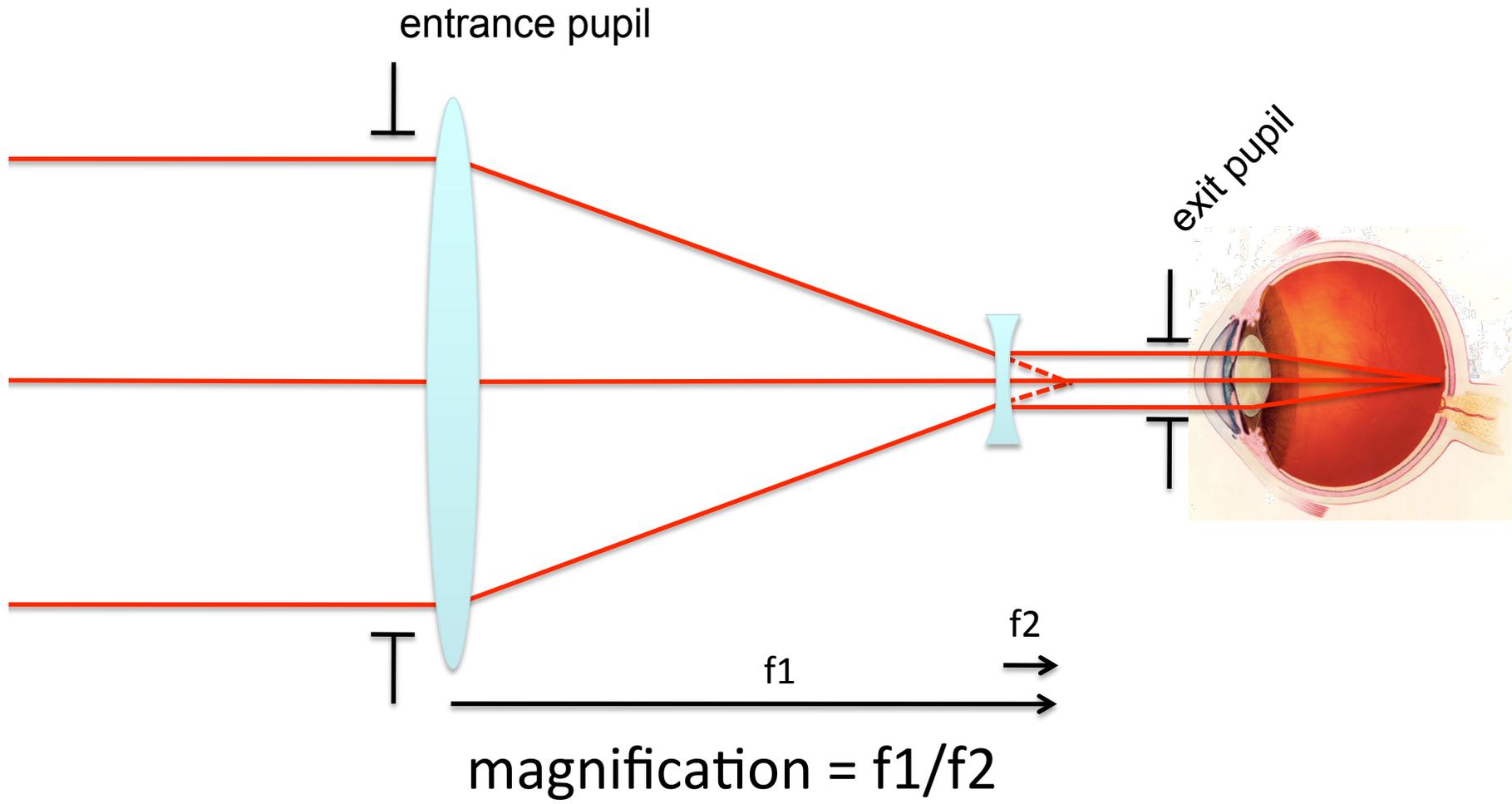
Dutch Telescopes

1608



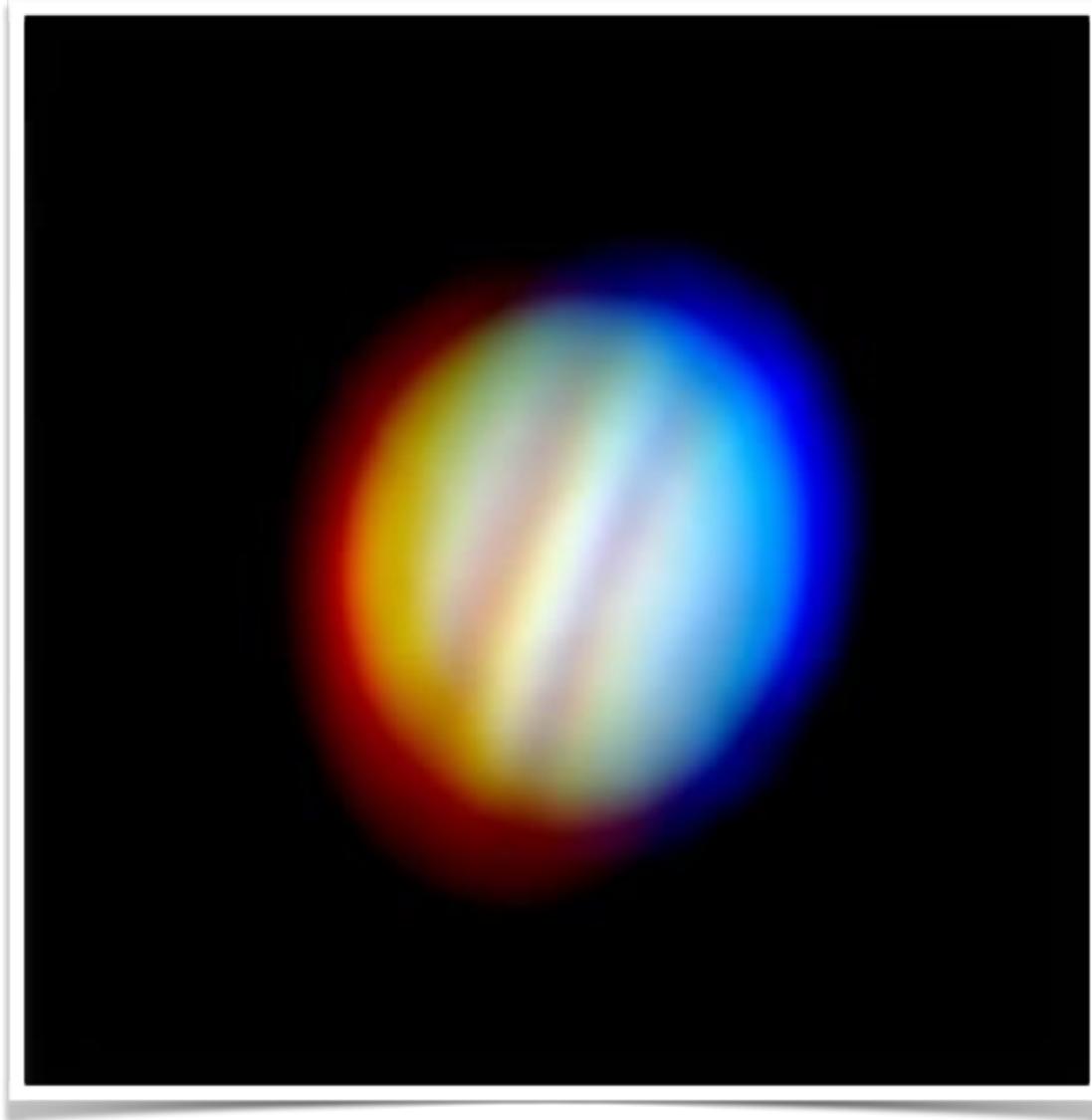
Hans Lipperhey

Dutch Telescopes



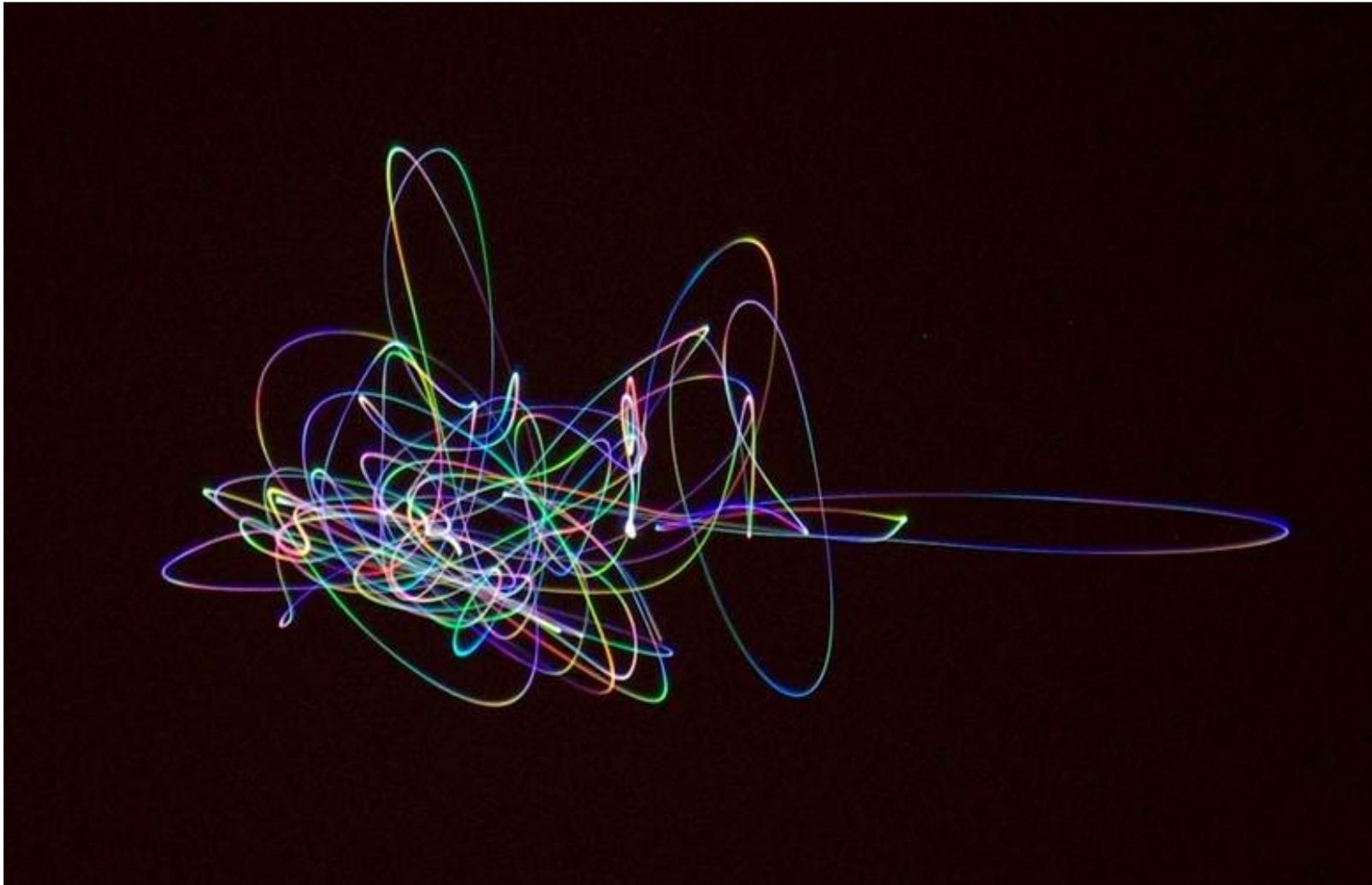
Limitations of refracting telescopes

Chromatic aberration



Limitations of refracting telescopes

Magnification requires stabilisation and guiding



Limitations of refracting telescopes

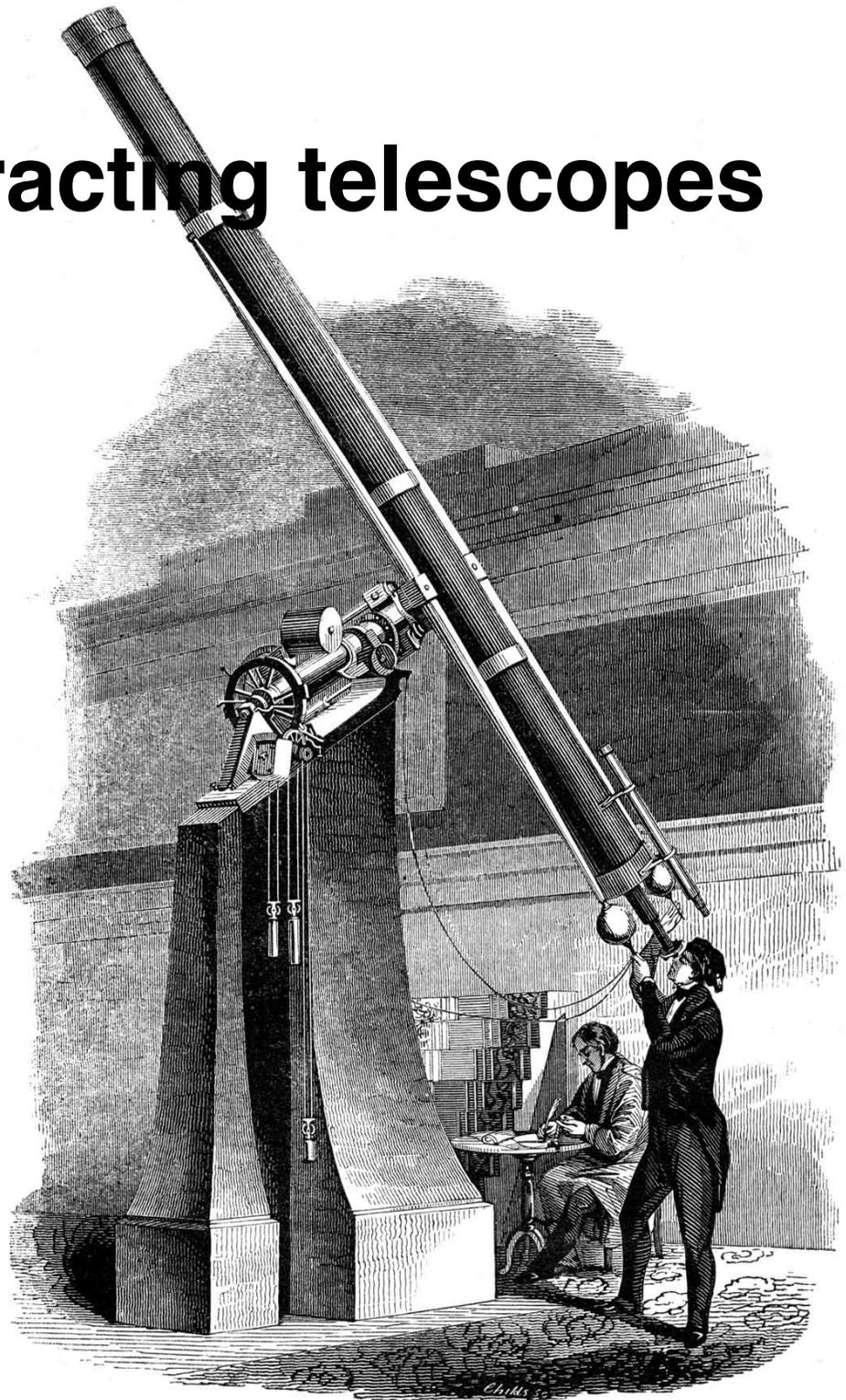
Weight goes as D^3



Lick refractor 36 inch lens

Limitations of refracting telescopes

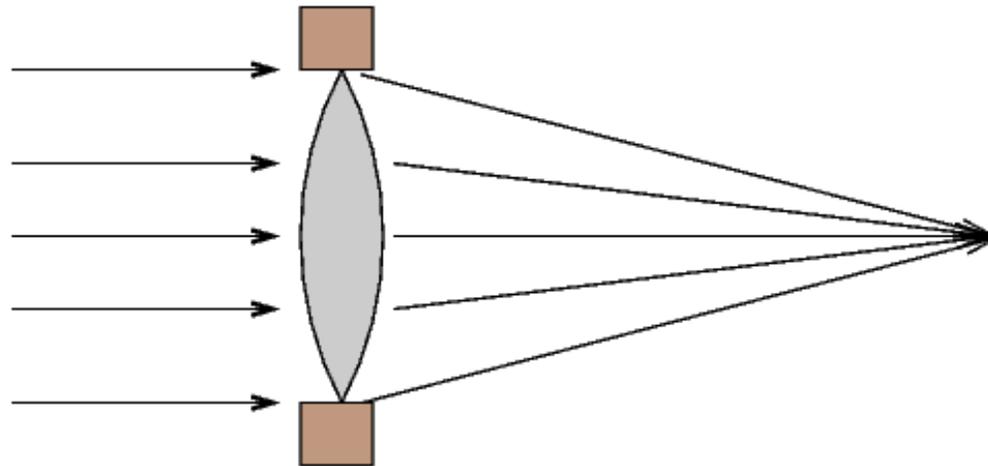
Long telescope tubes



Limitations of refracting telescopes

Glass sags under gravity

If one shapes the lens so that it brings light to a focus properly when standing on its edge ...

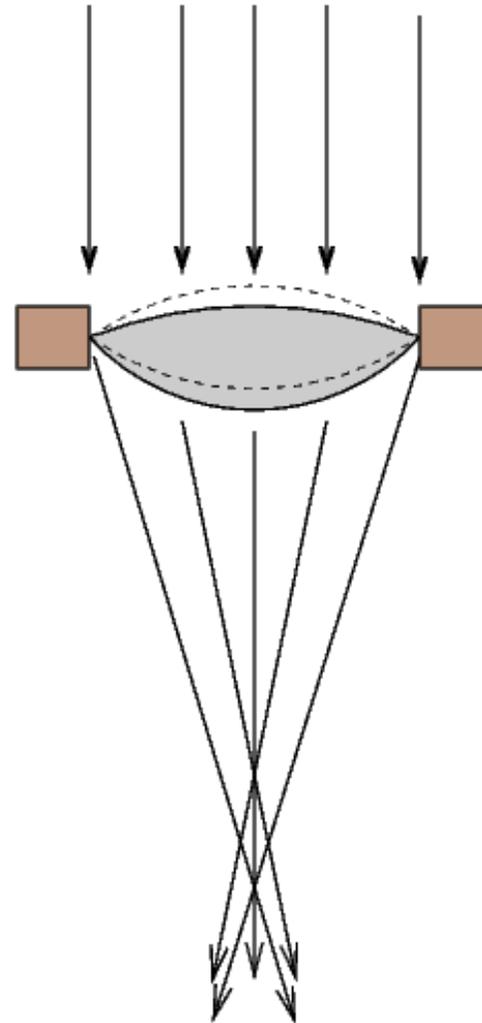


http://spiff.rit.edu/classes/phys301/lectures/optical_tel/optical_tel.html

Limitations of refracting telescopes

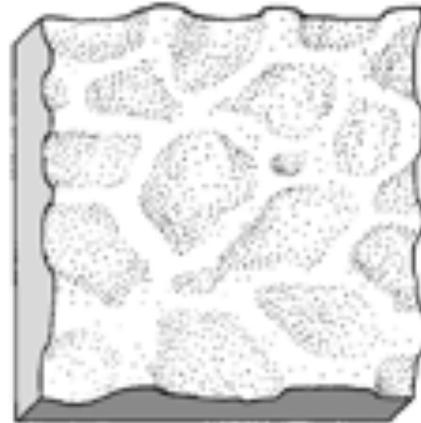
Glass sags under gravity

... then gravity will distort the lens as it is moved to look straight up.

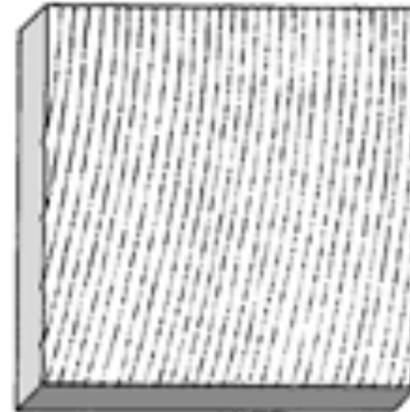


Limitations of refracting telescopes

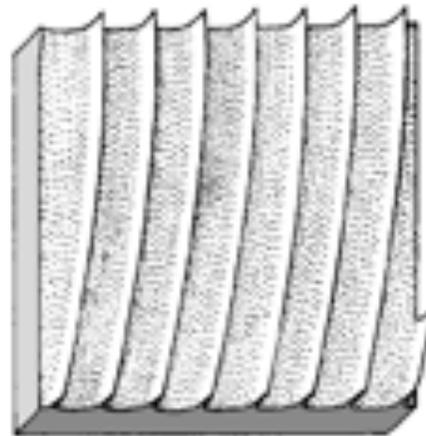
Glass homogeneity is difficult to maintain



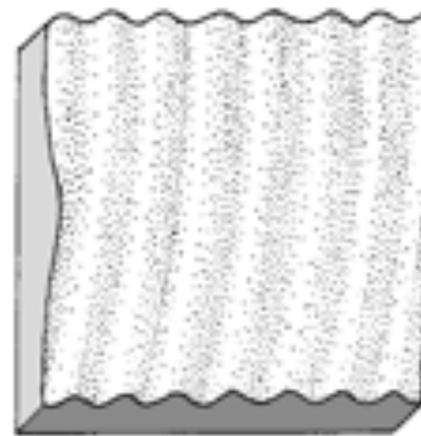
Malleations



Striae

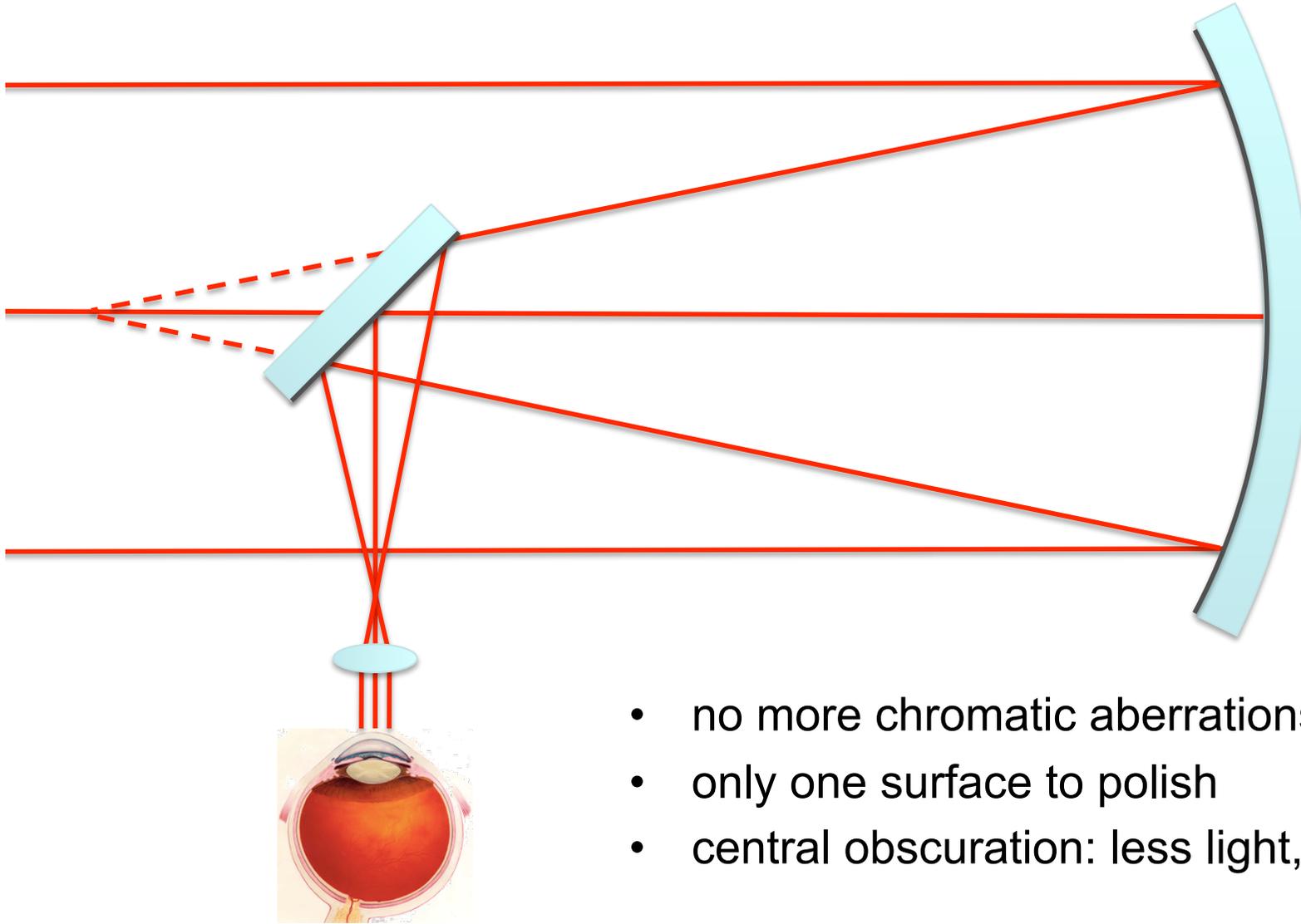


Lamellar Ribs



Ribs

Newtonian Telescope



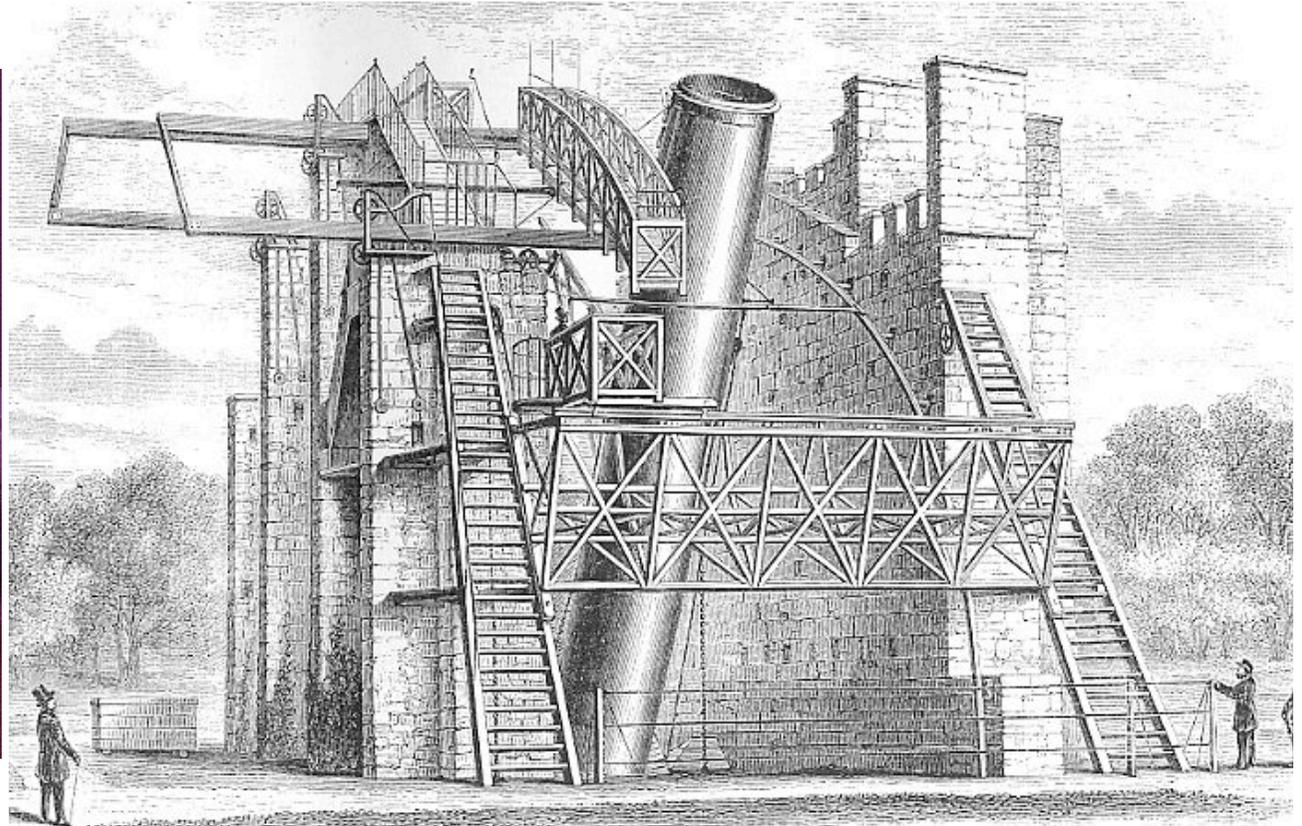
- no more chromatic aberrations
- only one surface to polish
- central obscuration: less light, diffraction

Newtonian Telescope

1668

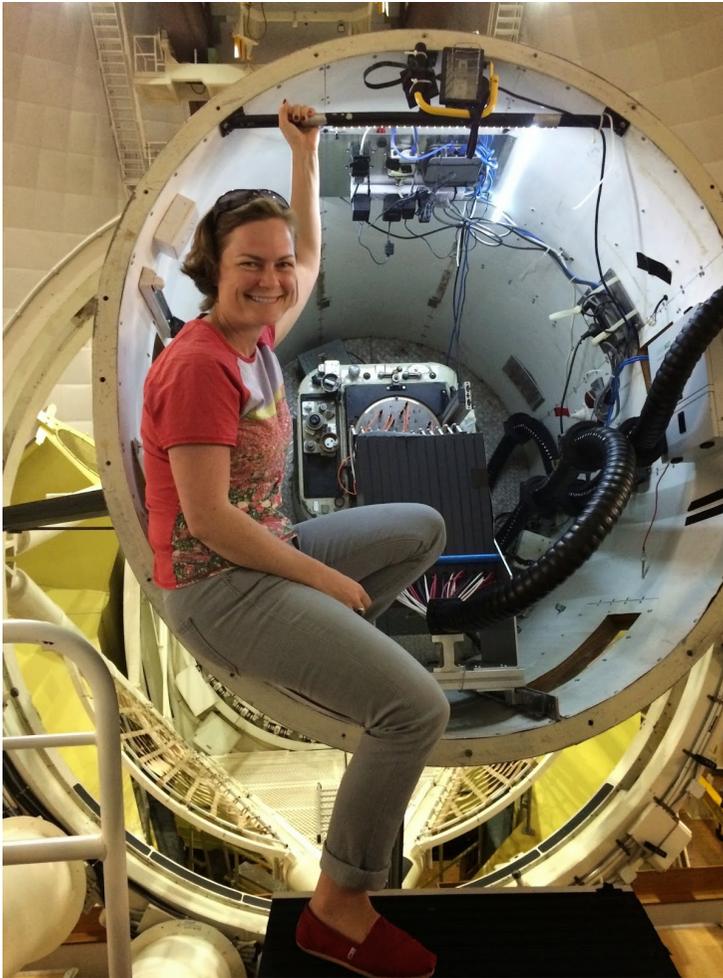


1842

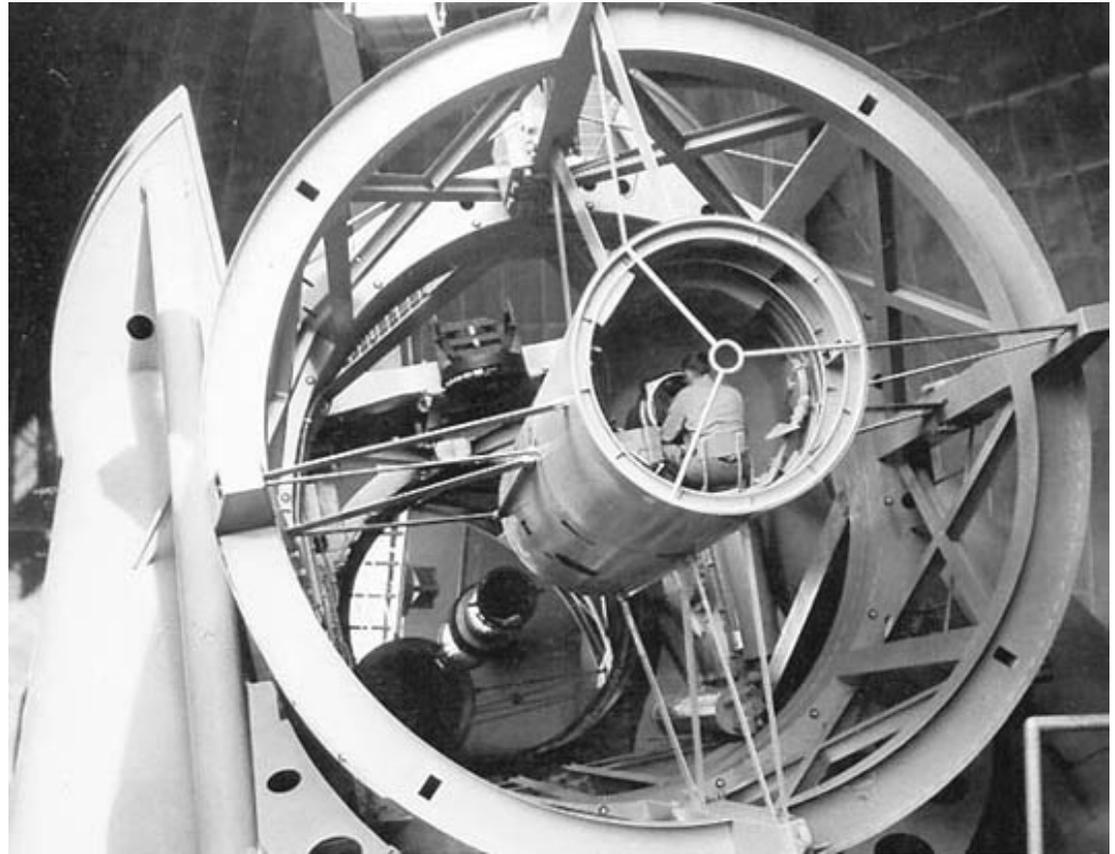


Introducing a Secondary Mirror

Primary focus is awkward to get to



(c) Amanda Bauer



Adding a secondary mirror can relay the focus to a more convenient location!

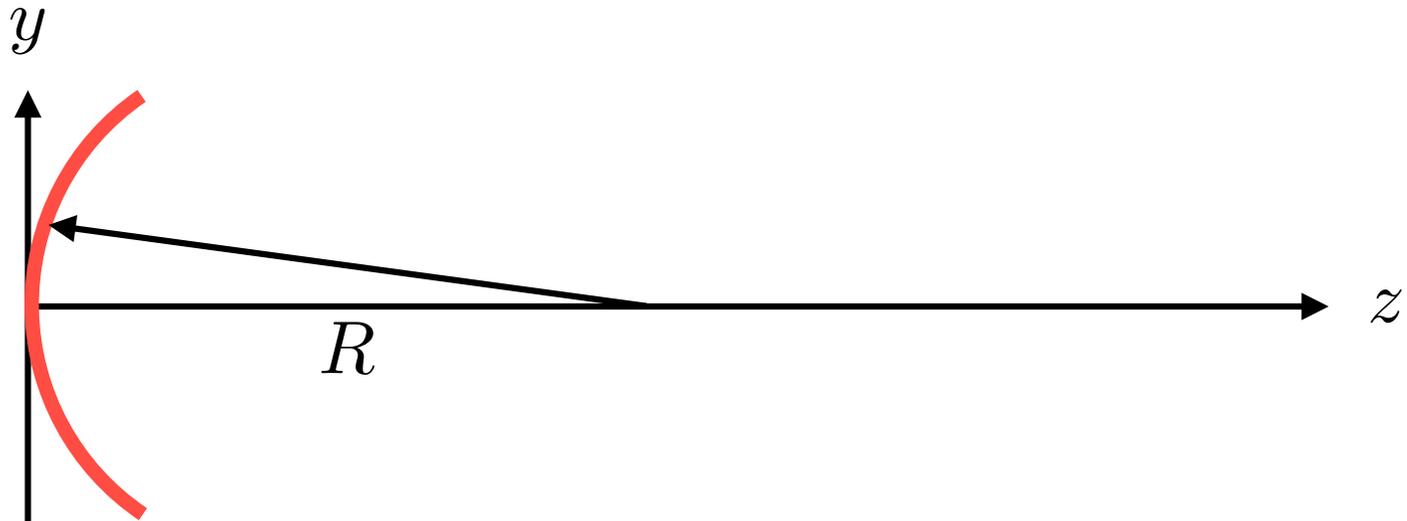
The family of conic mirrors

All these curves can be parameterised with one equation:

$$y^2 - 2Rz + (1 - e^2)z^2 = 0$$

Conic constant K is defined as:

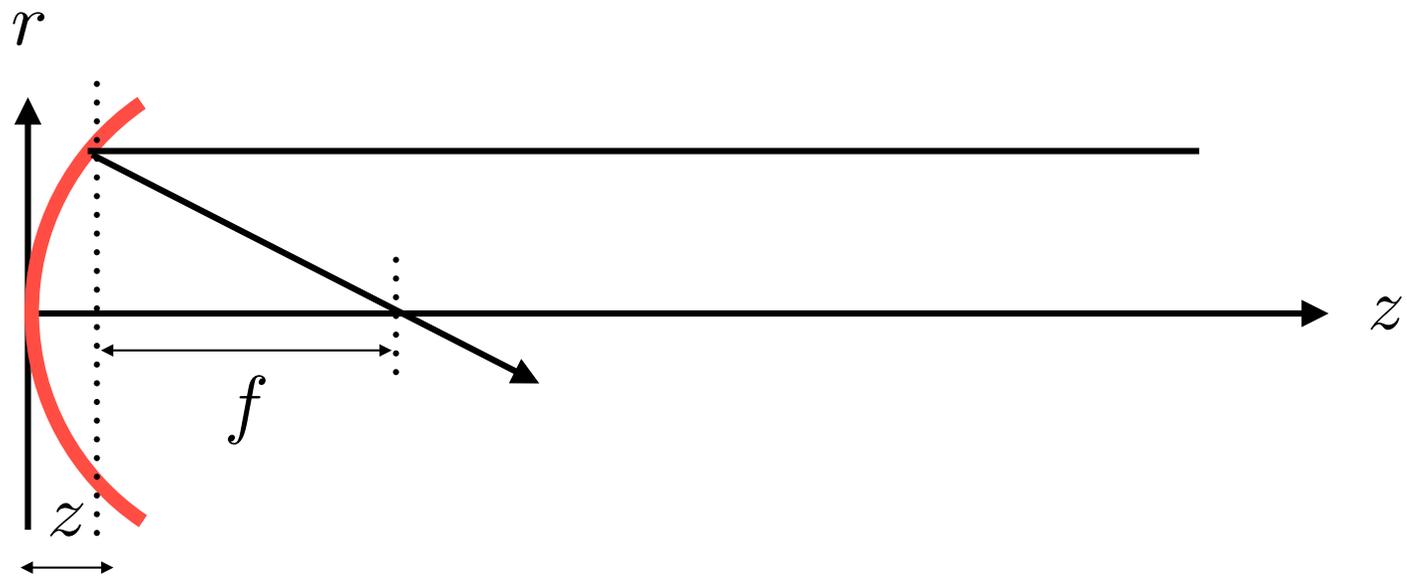
$$K = -e^2$$



focal distance with r

For all conics, the rays come to a focus at distance z:

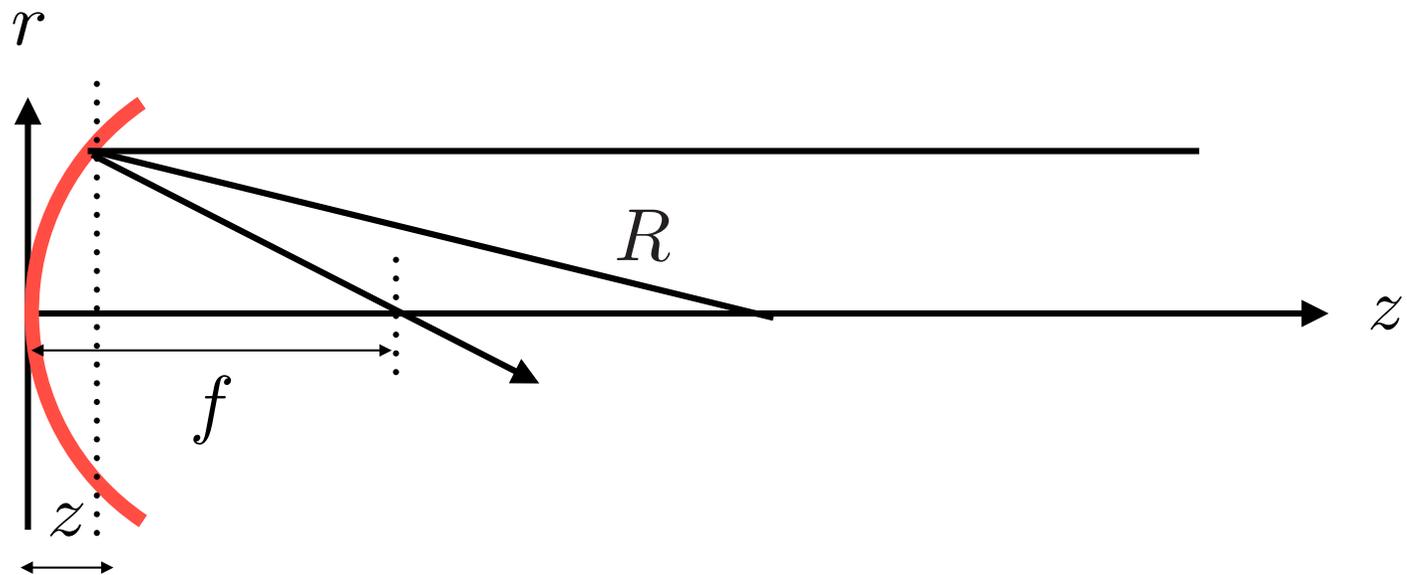
$$z = \frac{R}{1 + K} \left[1 - \left(1 - \frac{r^2}{R^2} (1 + K) \right)^{1/2} \right]$$



focal distance with r

You can expand the power series
and keep only the first two terms:

$$f = \frac{R}{2} - \frac{(1 + K)r^2}{4R} - \frac{(1 + K)(3 + K)r^4}{16R^3} - \dots$$

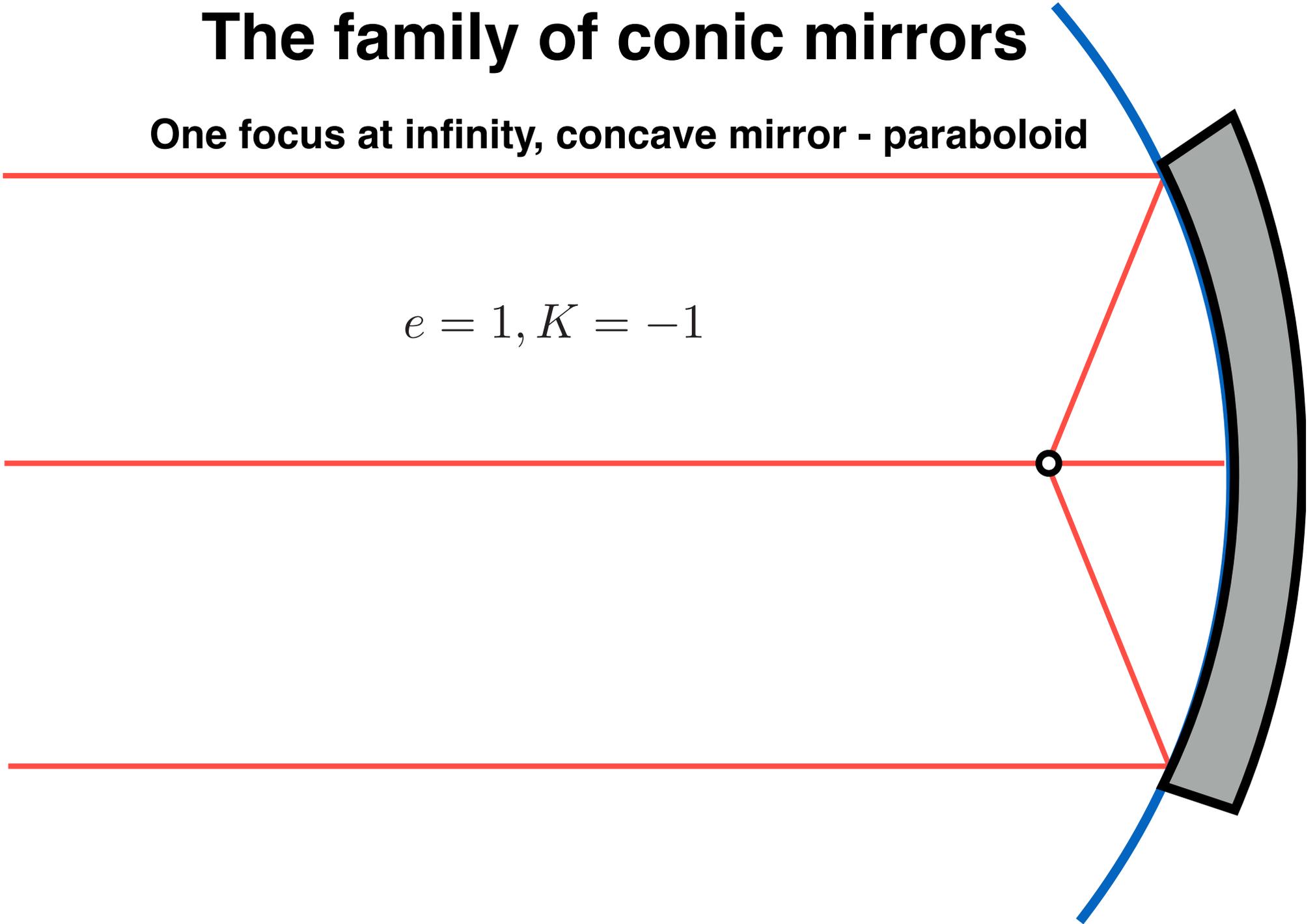


unless $K=-1$, the focal distance f changes with radius r and you have
SPHERICAL ABERRATION

The family of conic mirrors

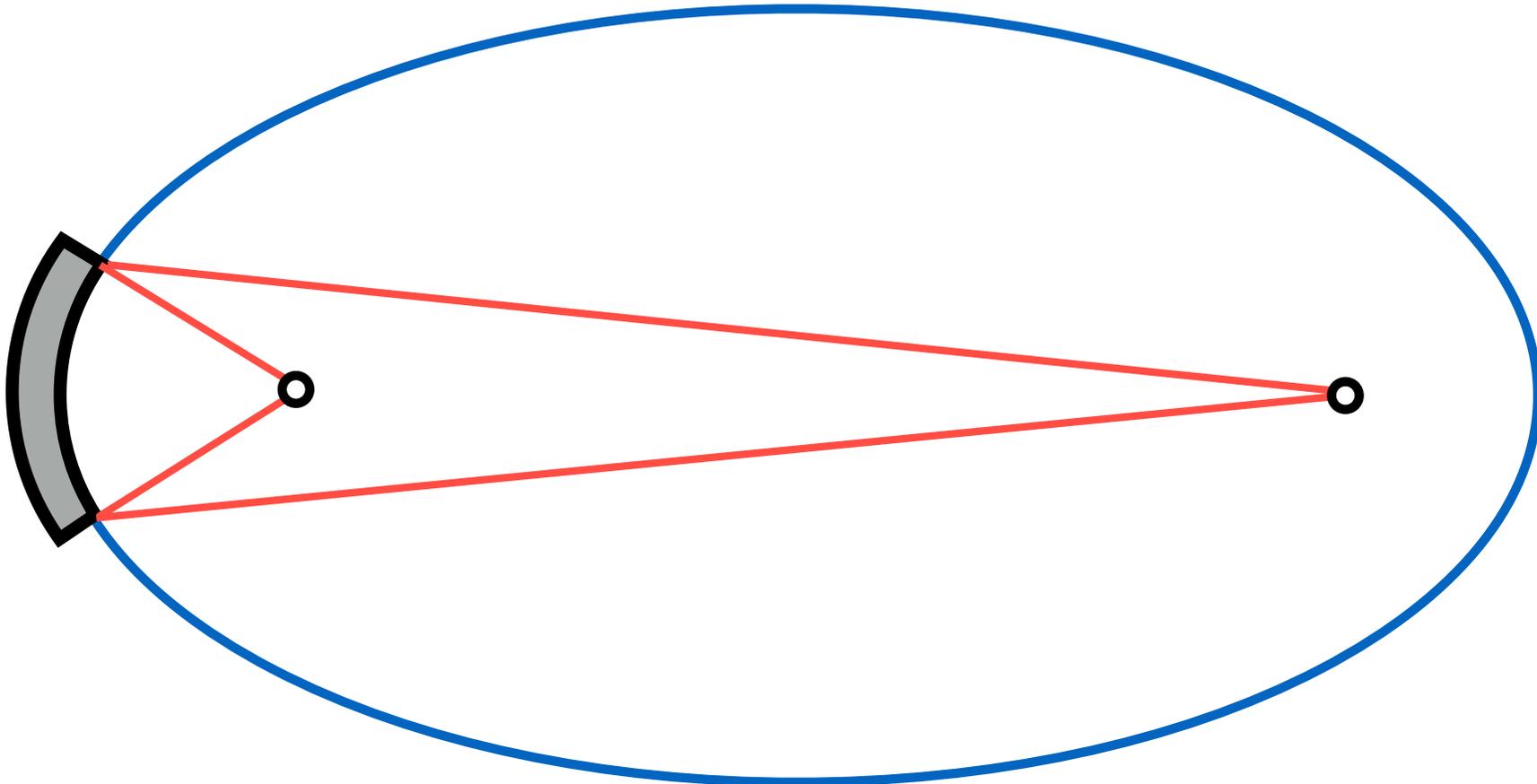
One focus at infinity, concave mirror - paraboloid

$$e = 1, K = -1$$



The family of conic mirrors

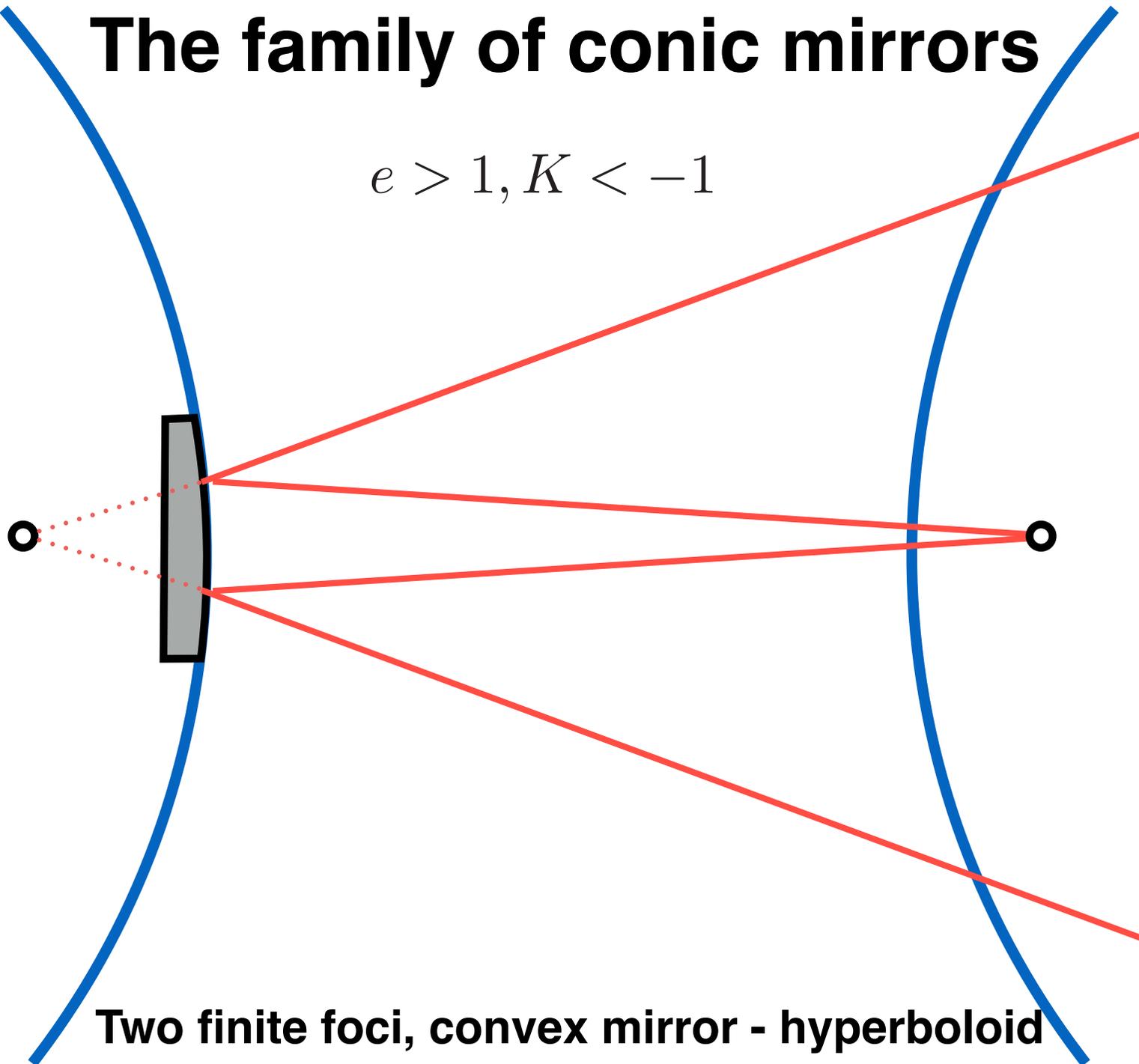
Two finite foci, concave mirror - ellipsoid



$$0 < e < 1, -1 < K < 0$$

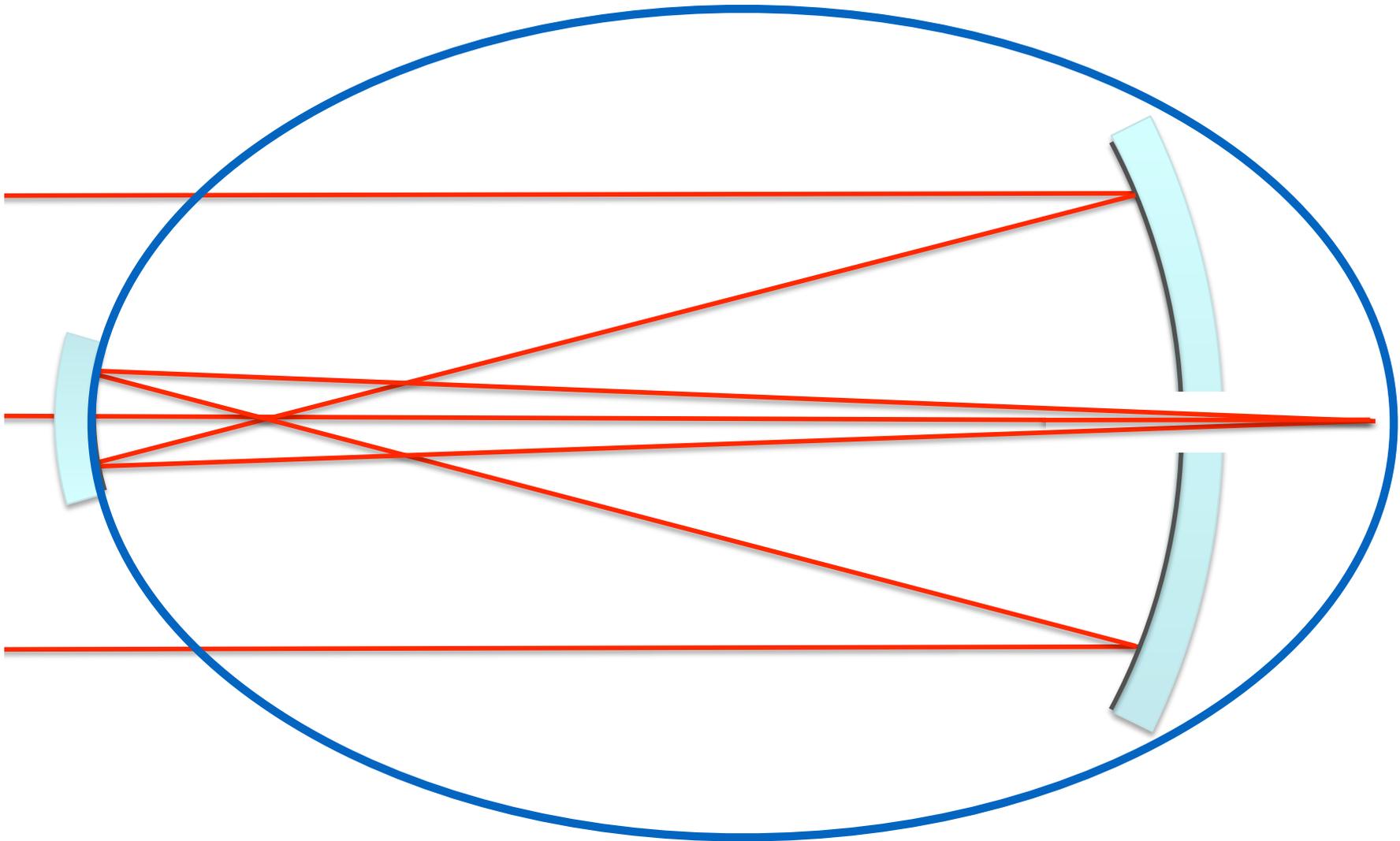
The family of conic mirrors

$$e > 1, K < -1$$

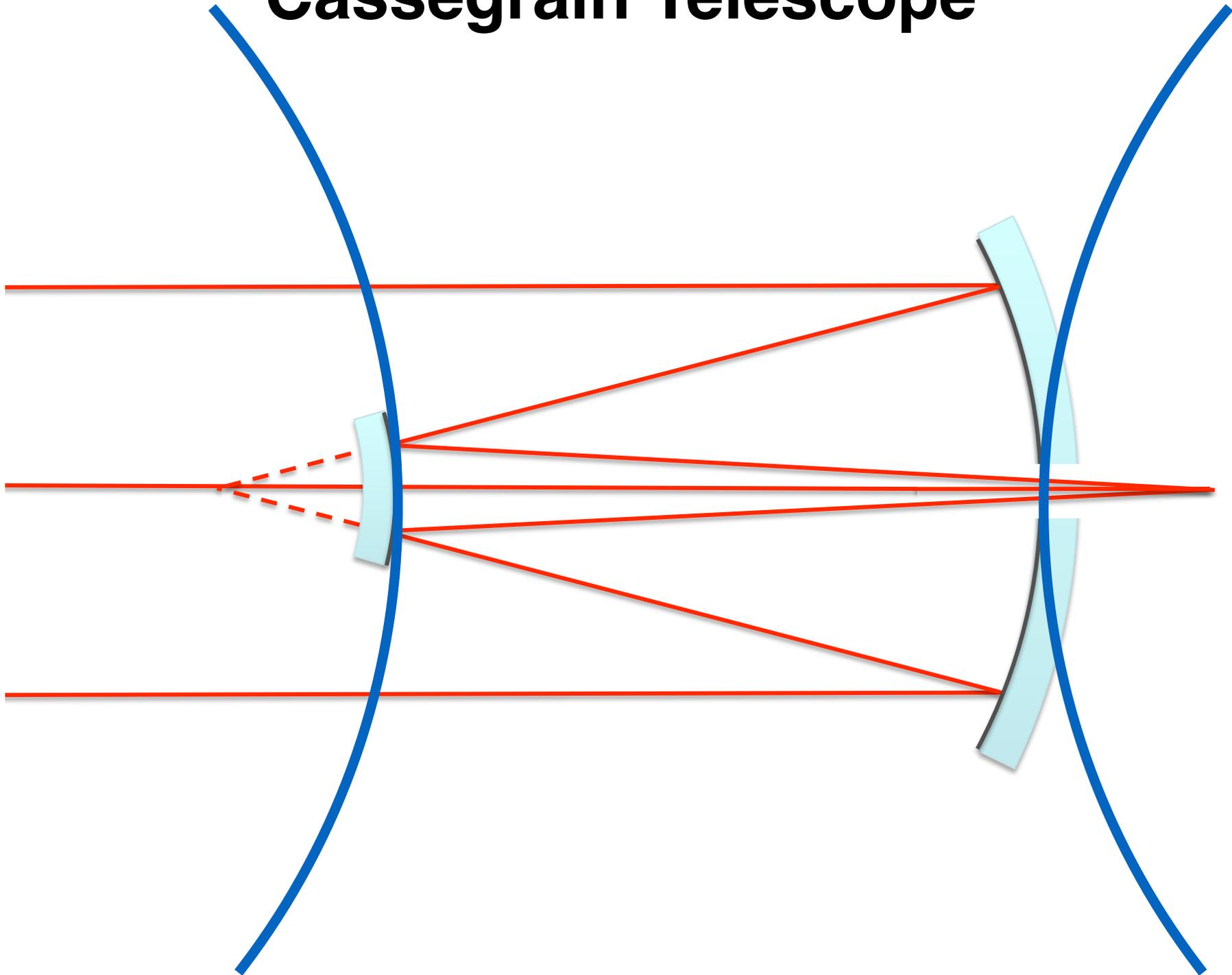


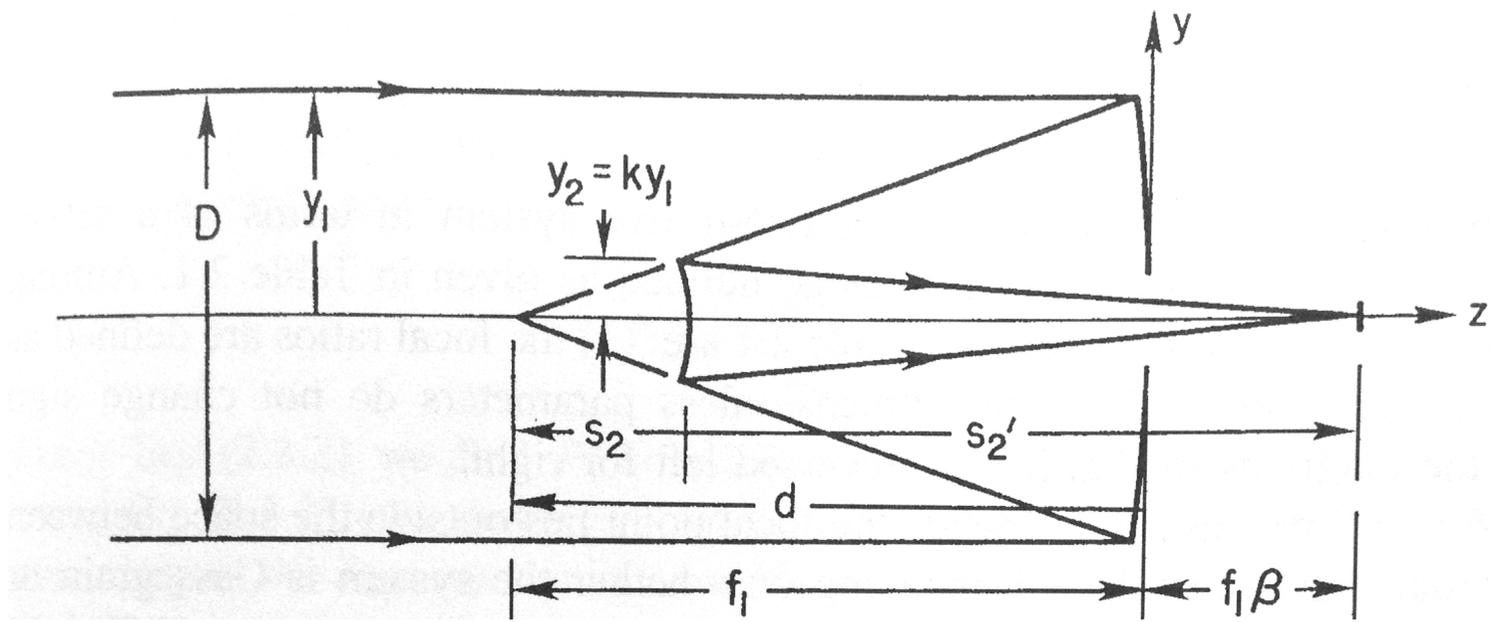
Two finite foci, convex mirror - hyperboloid

Gregorian Telescope

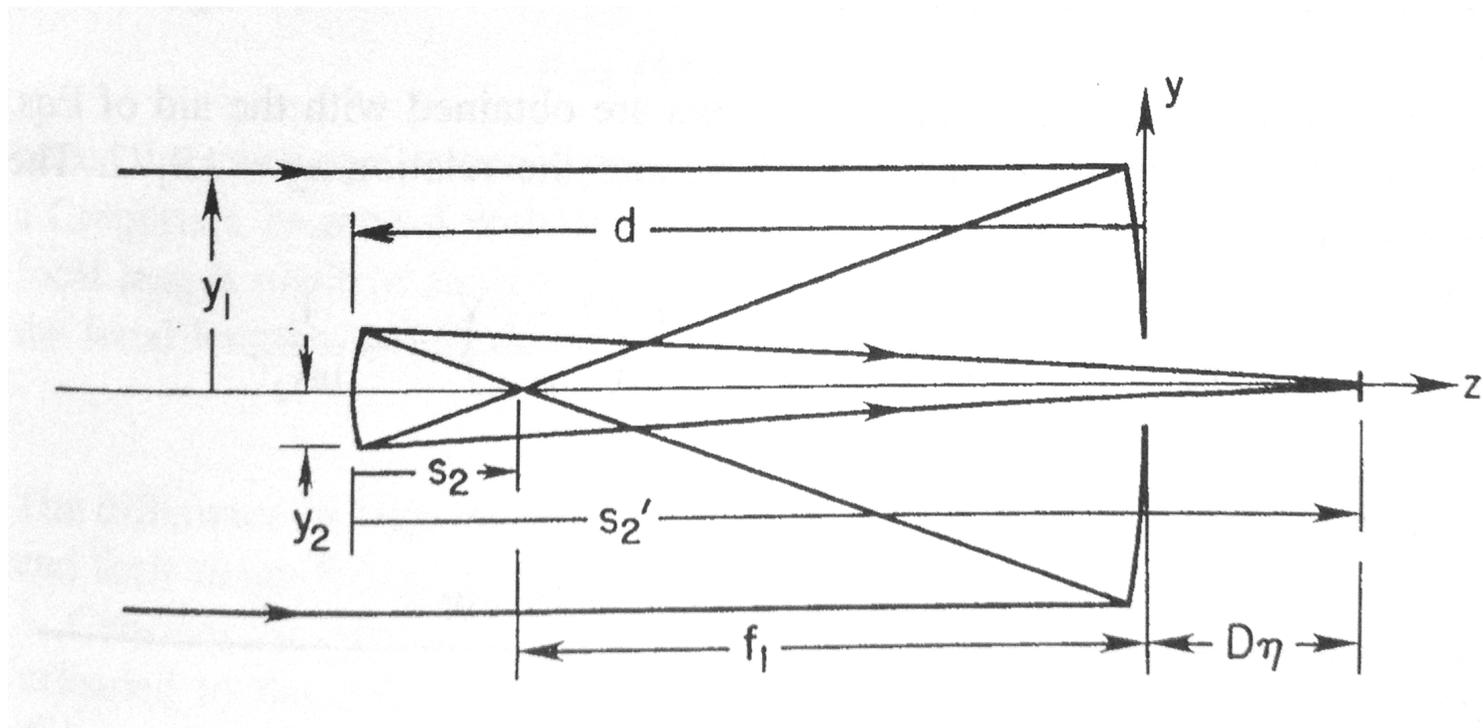


Cassegrain Telescope





Normalized Parameters for Two-Mirror telescopes



Normalized Parameters for Two-Mirror telescopes

$k = y_2/y_1 =$ ratio of ray heights at mirror margins

$\rho = R_2/R_1 =$ ratio of mirror radii of curvature

$m = -s'_2/s_2 = f/f_1 =$ transverse magnification of secondary

$f_1\beta = D\eta =$ back focal distance, or distance from vertex of primary mirror to final focal point

β and η , back focal distance in units of f_1 and D , respectively

$F_1 = |f_1|/D =$ primary mirror focal ratio

$W = (1 - k)f_1 =$ distance from secondary to primary mirror = location of telescope entrance pupil relative to the secondary when the primary mirror is the aperture stop

$mkf_1 =$ distance from secondary to focal surface

$F = |f|/D =$ system focal ratio, where f is telescope focal length

$$m = \frac{\rho}{\rho - k} \quad \rho = \frac{mk}{m - 1} \quad k = \frac{1 + \beta}{m + 1}$$

Cassegrain Telescope

Short telescope with long focal length

Effective focal length:

$$f_{eff} = \frac{f_1 f_2}{f_1 - f_2 - d}$$

Secondary magnification:

$$m = f_{eff} / f_1 = s'_2 / s_2$$

And so....

$$f_{eff} = d + b + md$$

Field curvature in all two-mirror telescopes

$$\frac{1}{r_f} = \frac{1}{R_1} - \frac{1}{R_2}$$

Concave focal plane towards the sky

Classical Cassegrain

Classical Cassegrain balances K_1 and K_2 to remove
SPHERICAL ABERRATION

$$K_1 = -1$$

Paraboloidal primary

$$K_2 = - \left(\frac{m + 1}{m - 1} \right)^2$$

Hyperboloidal secondary

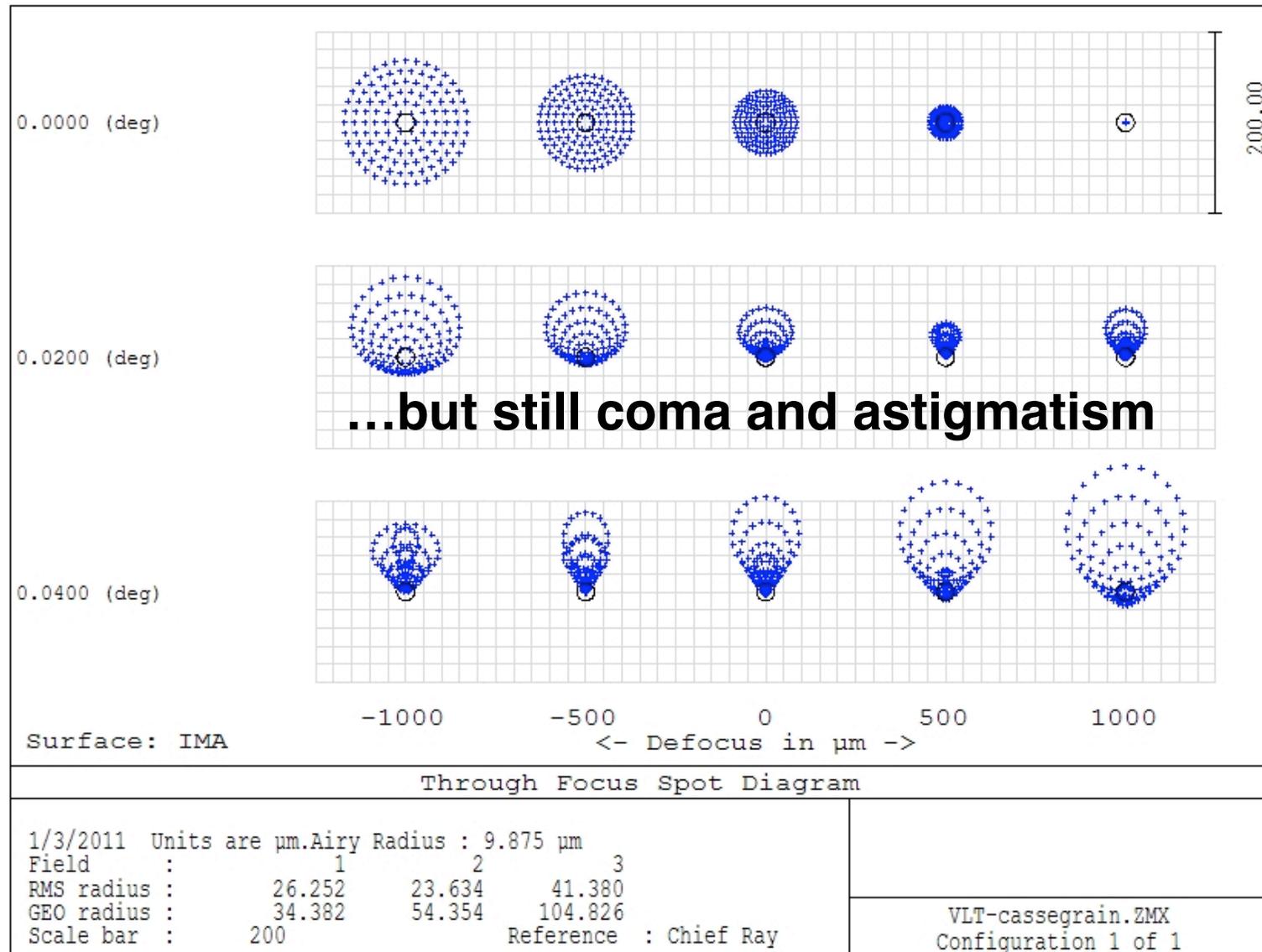
...but still coma and astigmatism

Classical Cassegrain

Classical Cassegrain balances K_1 and K_2 to remove
SPHERICAL ABERRATION

VLT as
classical
Cassegrain

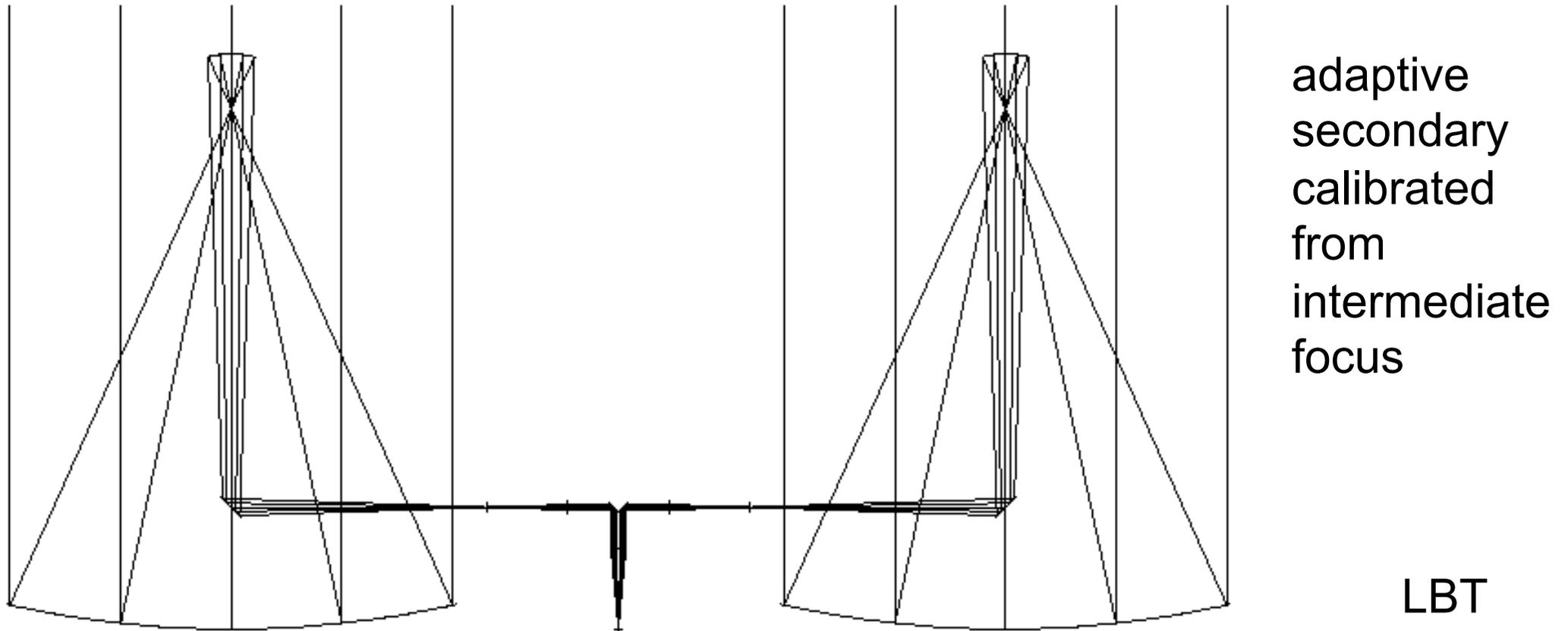
$K_1 = -1$
 $K_2 = -1.62$



Gregorian astronomical telescopes

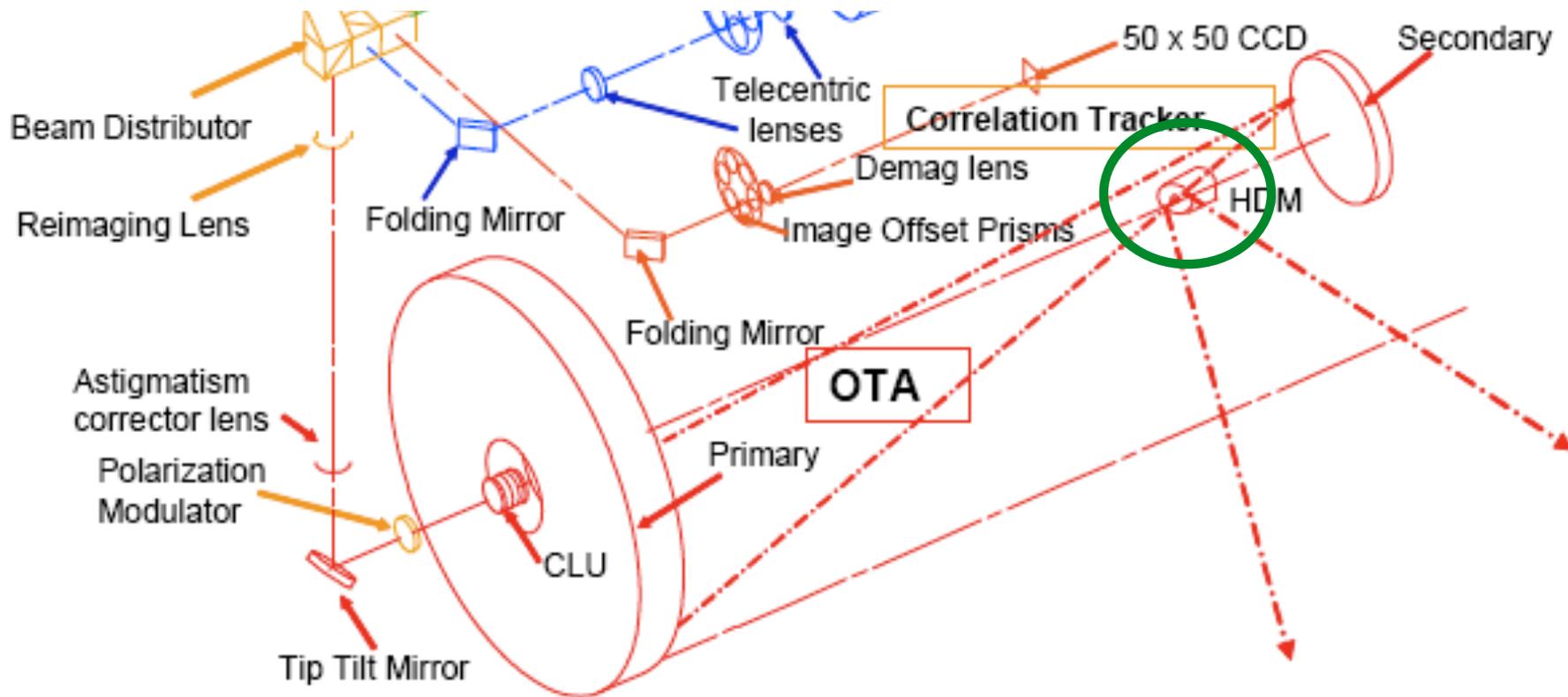
Classical Gregorian uses elliptical secondary

Much longer than equivalent Cassegrain! So why use it?



Gregorian solar telescopes

Much longer than equivalent Cassegrain! So why use it?



Focus at primary mirror means that you can have a **HEAT STOP**

Ritchey-Chrétien Telescope

Infinite combination of K_1 and K_2 for zero spherical

Can cancel spherical and coma with the right values

$$K_1 = -1 - \frac{2(1 + \beta)}{m^2(m - \beta)}$$

and:

$$K_2 = - \left(\frac{m + 1}{m - 1} \right)^2 - \frac{2m(m + 1)}{(m - \beta)(m - 1)^3}$$

Ritchey-Chrétien Telescopes

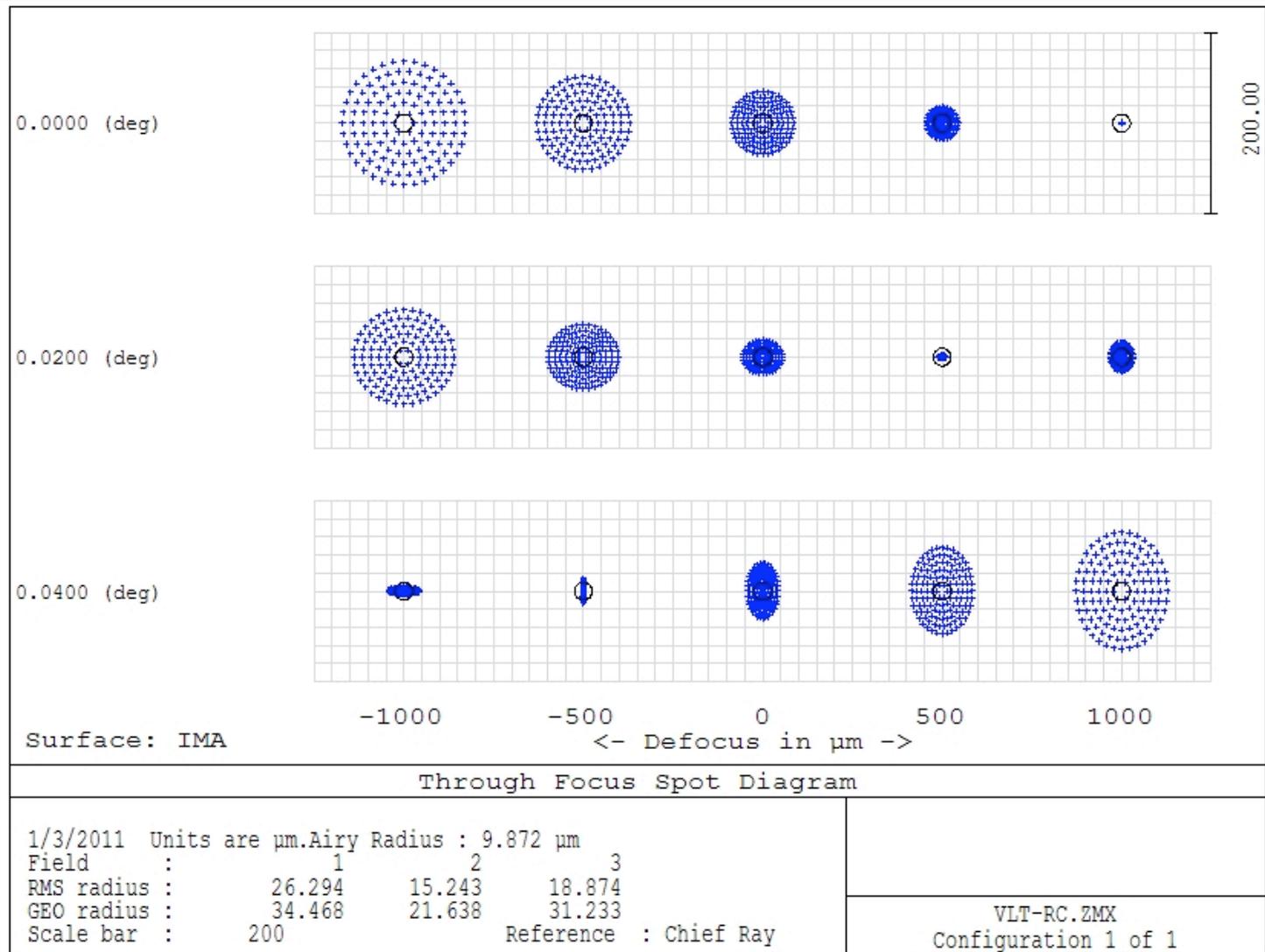


Ritchey-Chrétien Telescope

Infinite combination of K1 and K2 for zero spherical

VLT

$K_1 = -1.0046$
 $K_2 = -1.66926$



Making the conics

Conic	Testing	Why?
Spherical	Very easy	Single conjugate point easy for interferometer
Paraboloidal	Easy	Double pass with a mirror can test like spherical
Ellipsoidal	Easy	Two foci, but one mirror to get back to conjugate
Hyperboloidal	Difficult	Need a Hindle sphere test - no accessible focus

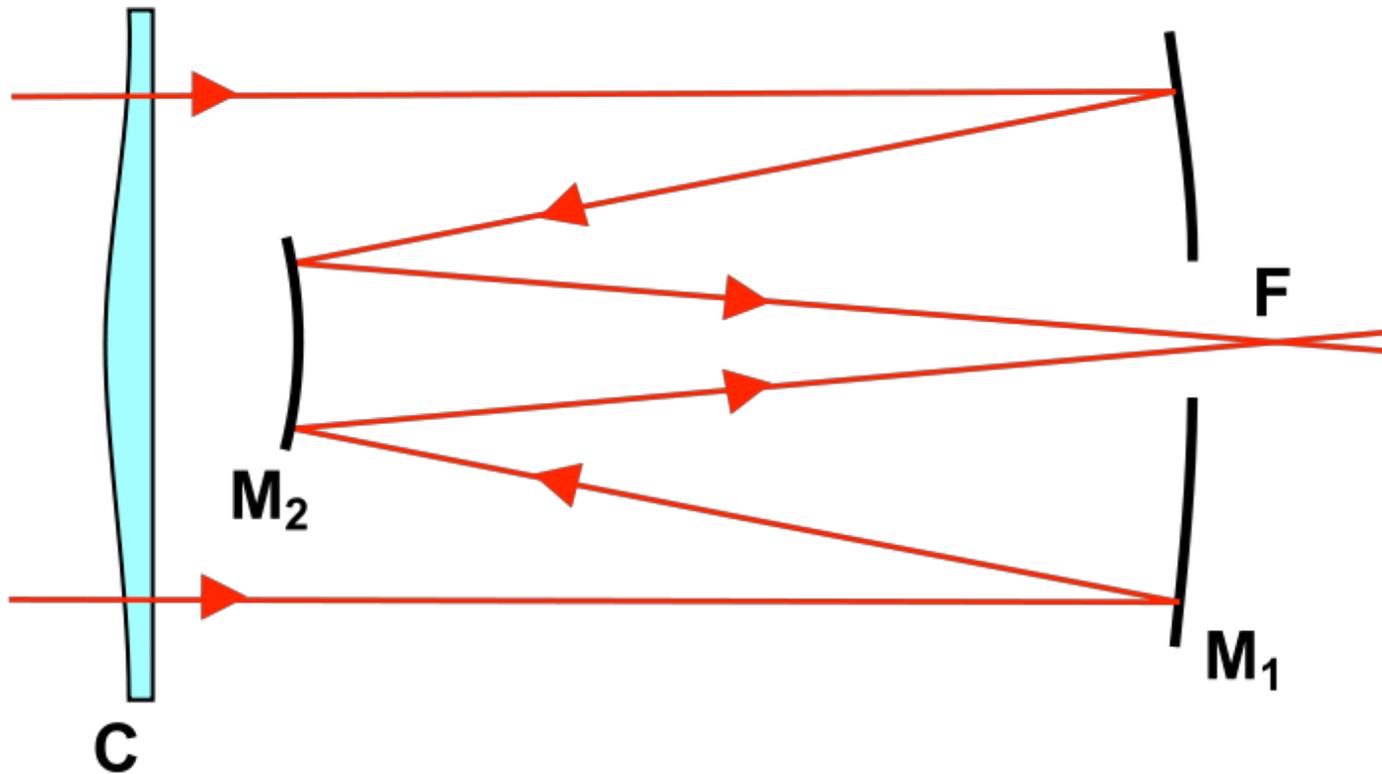
Two Mirror Telescope aberrations

On-axis aberrations are SPHERICAL

**Off-axis aberrations include:
coma, astigmatism, and field distortion**

Wide field telescopes

Maksutov corrector plate widens the field of view



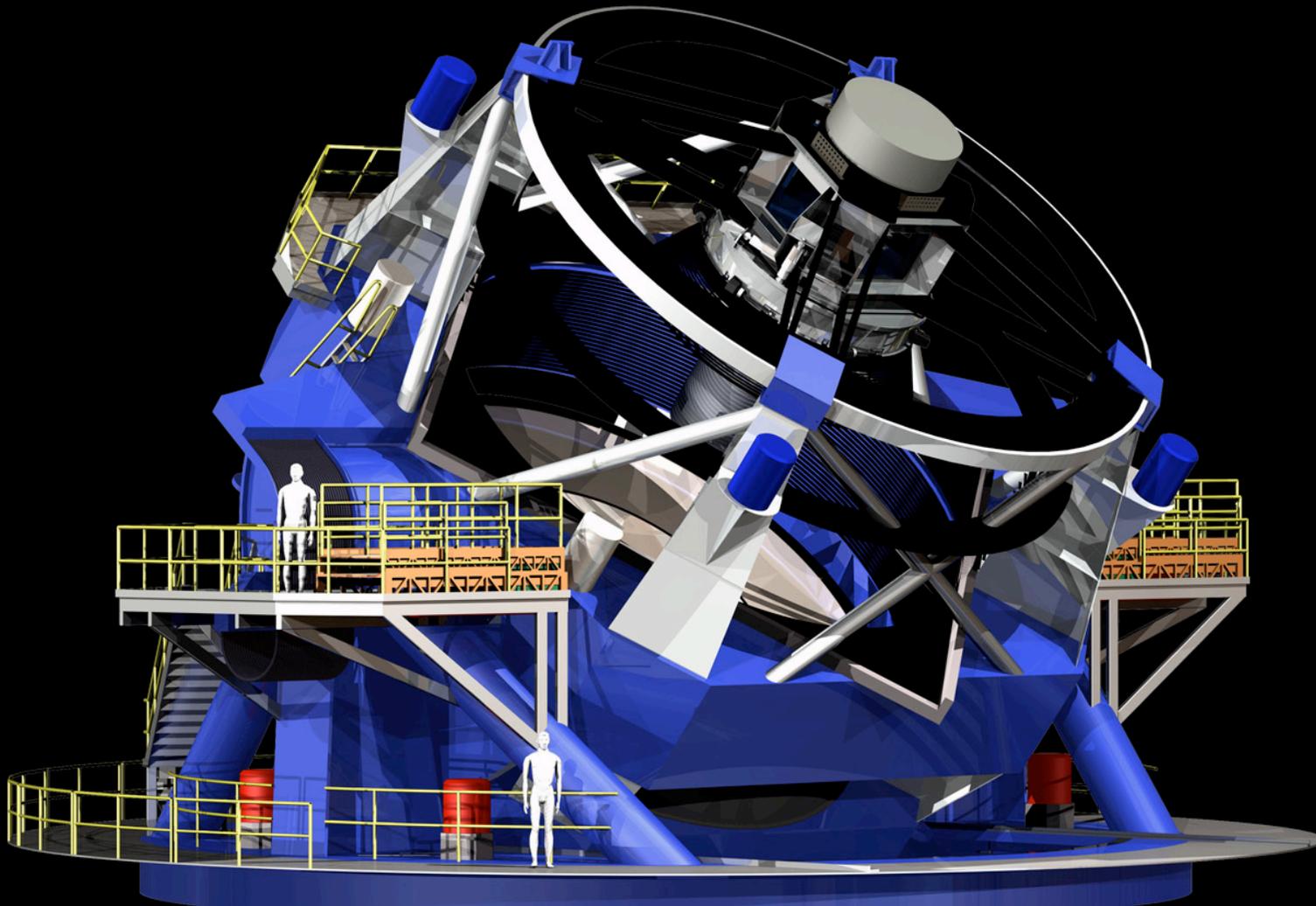
Schmidt-Cassegrain

Wide field telescopes

Three Mirror Anastigmat (TMA)

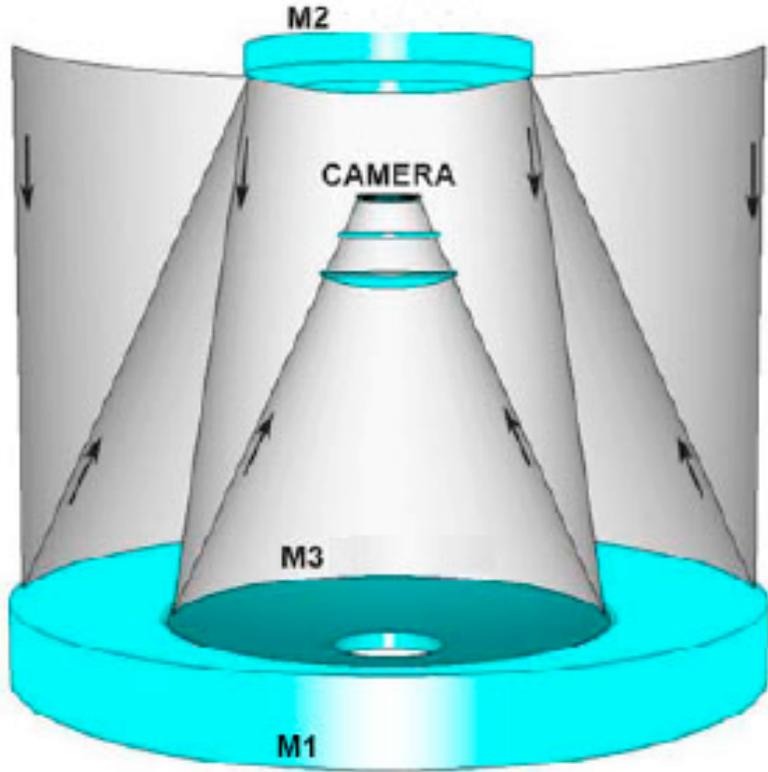
fixes spherical, coma, astigmatism with three conic constants

Large Synoptic Survey Telescope (LSST)

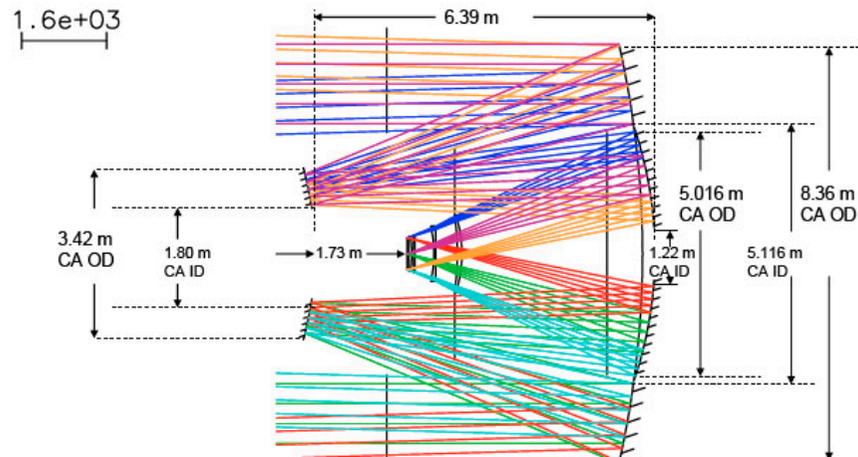


Wide field telescopes

M1 and M3 polished out of same blank!

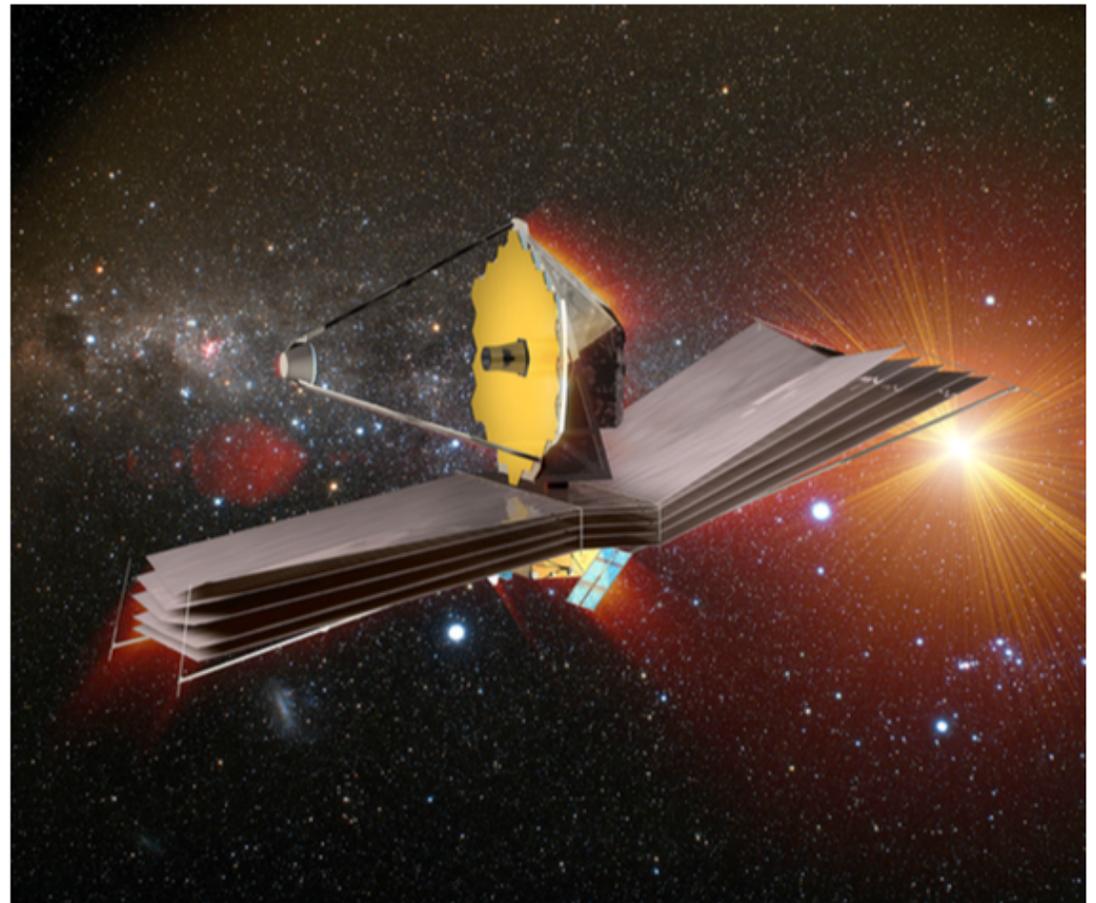
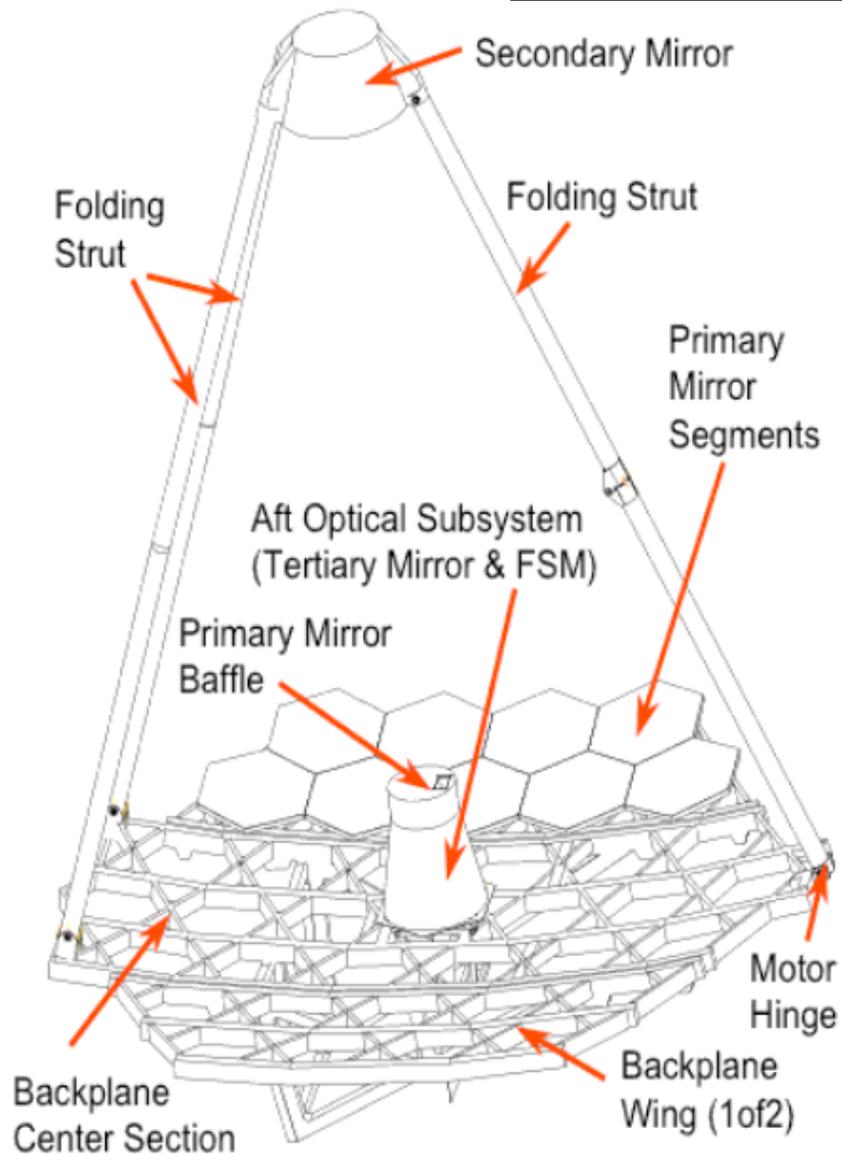


LSS



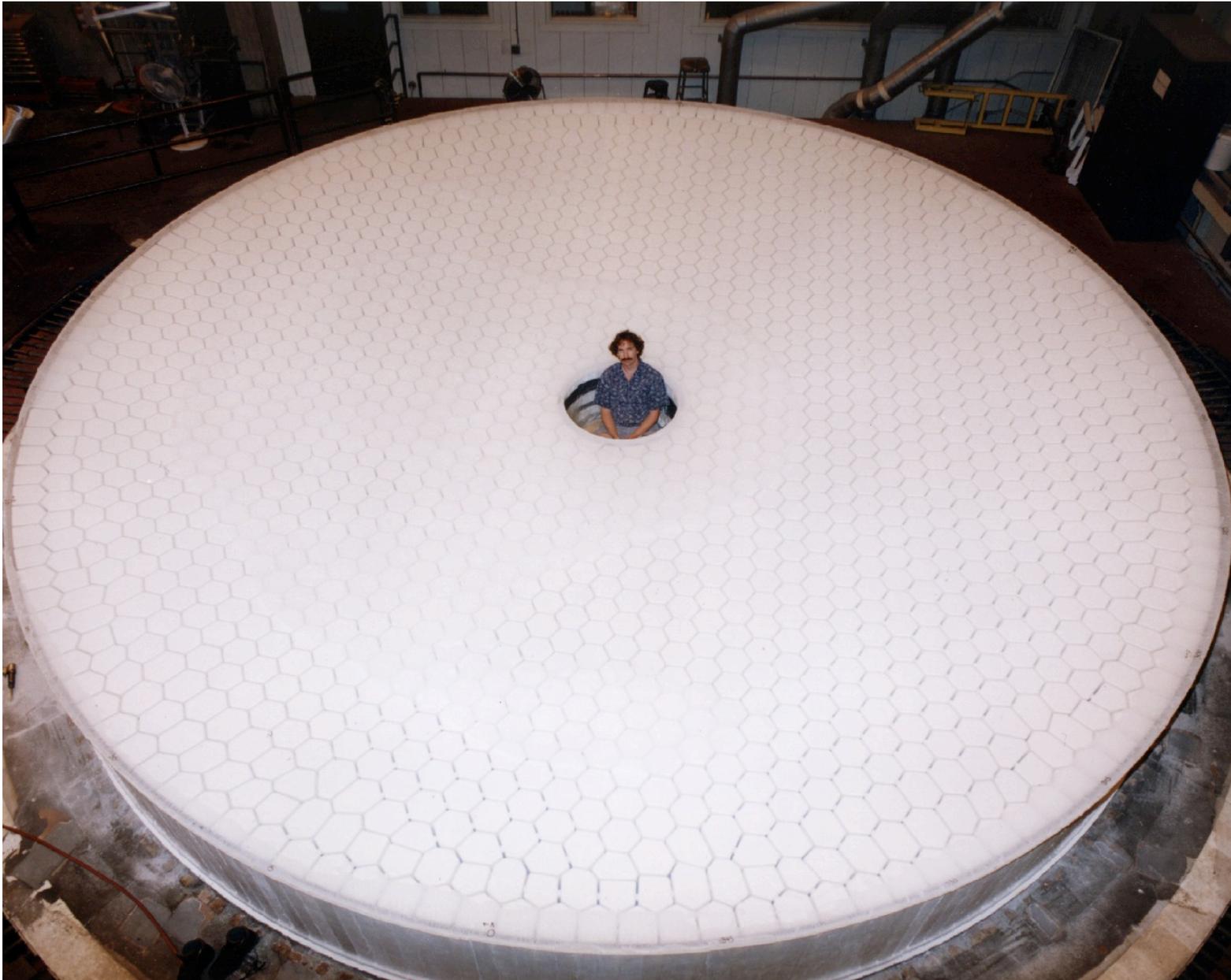
Wide field telescopes

James Webb Space Telescope (JWST)



Largest Monolithic Mirrors

Spin-casting mirrors in Arizona



Glass loaded into the mold



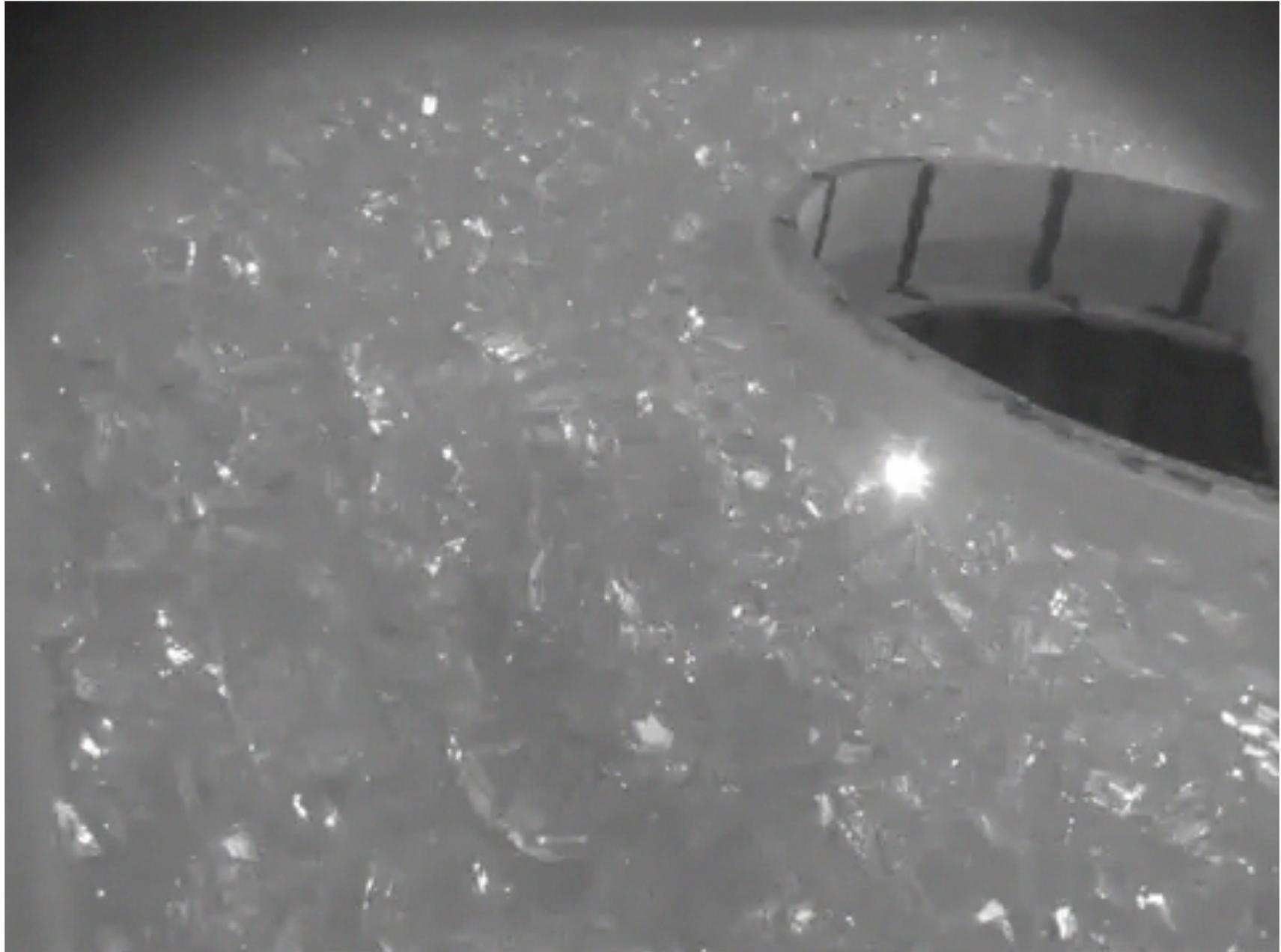
Photo by Ray Bertram

GMTO / Ray Bertram

SOML Spinning Oven

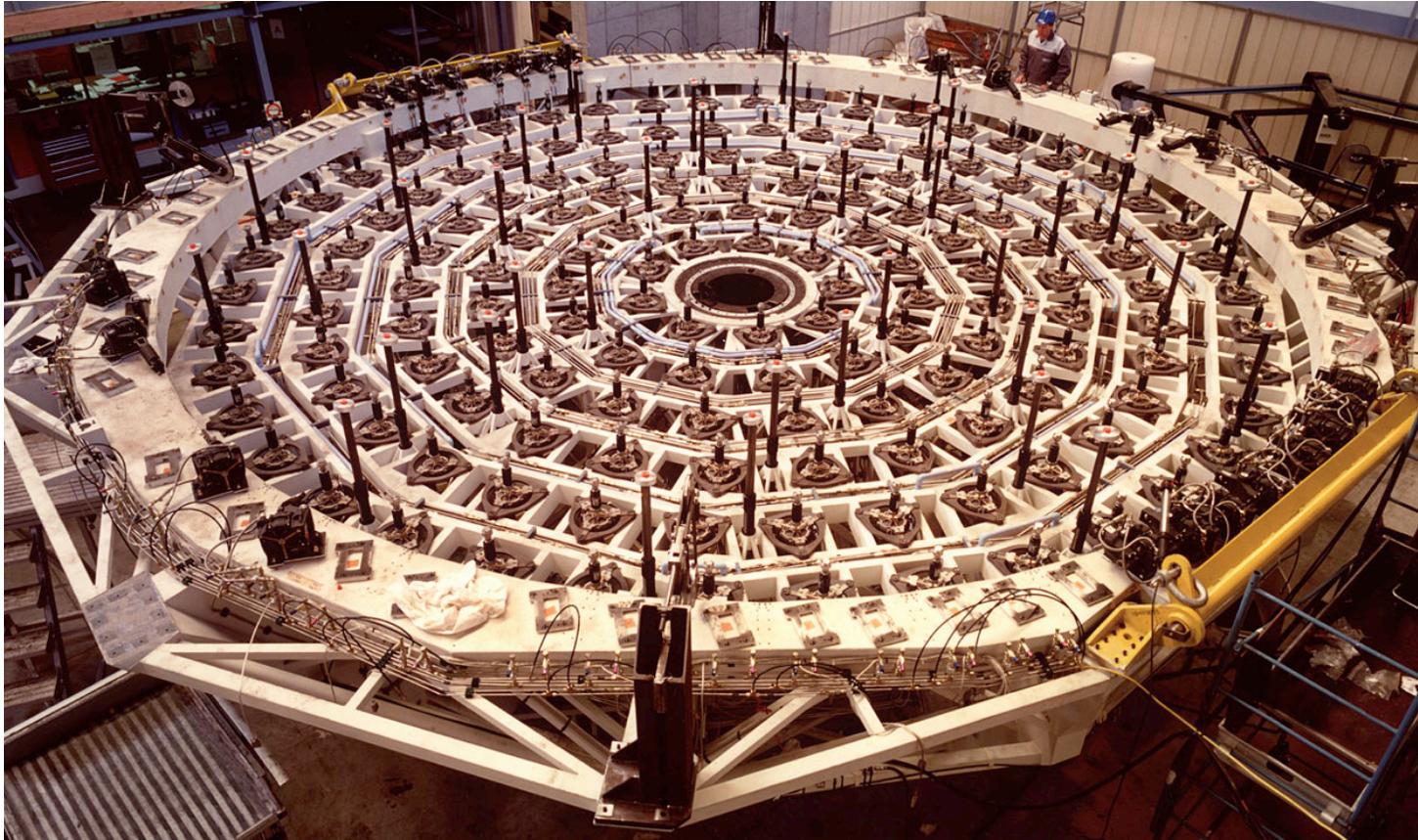


GMT mirror 4 in 2015



Cooling Primary Mirrors

Thin primary mirrors deform, so active support required



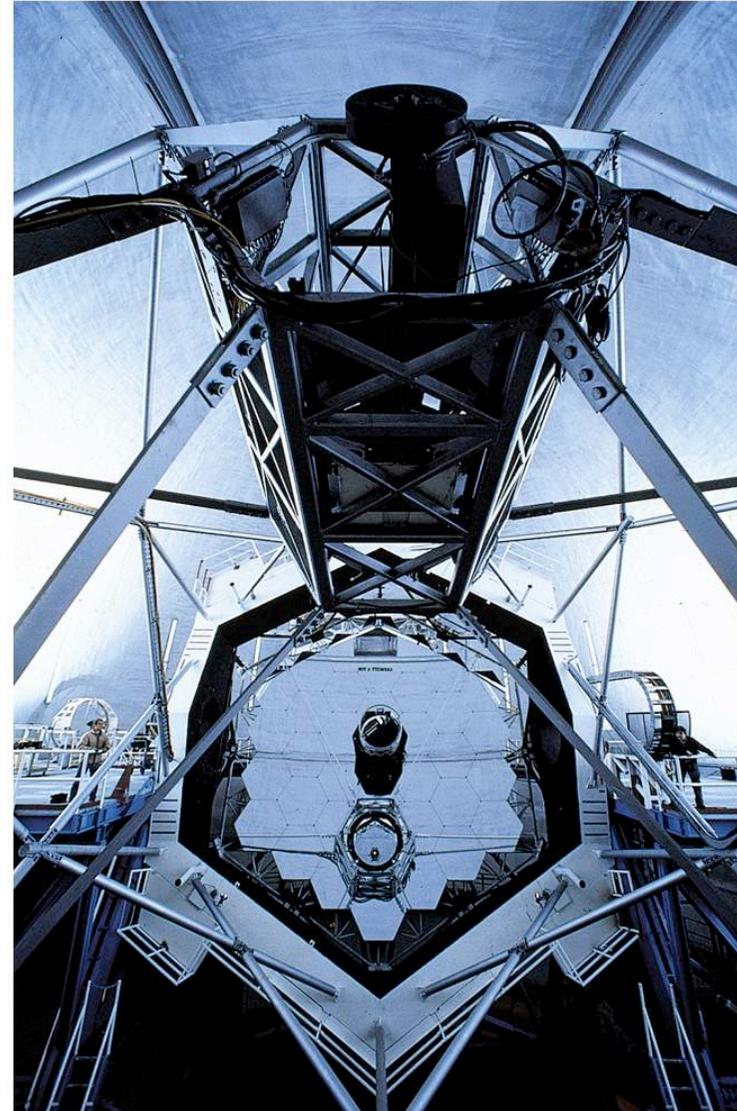
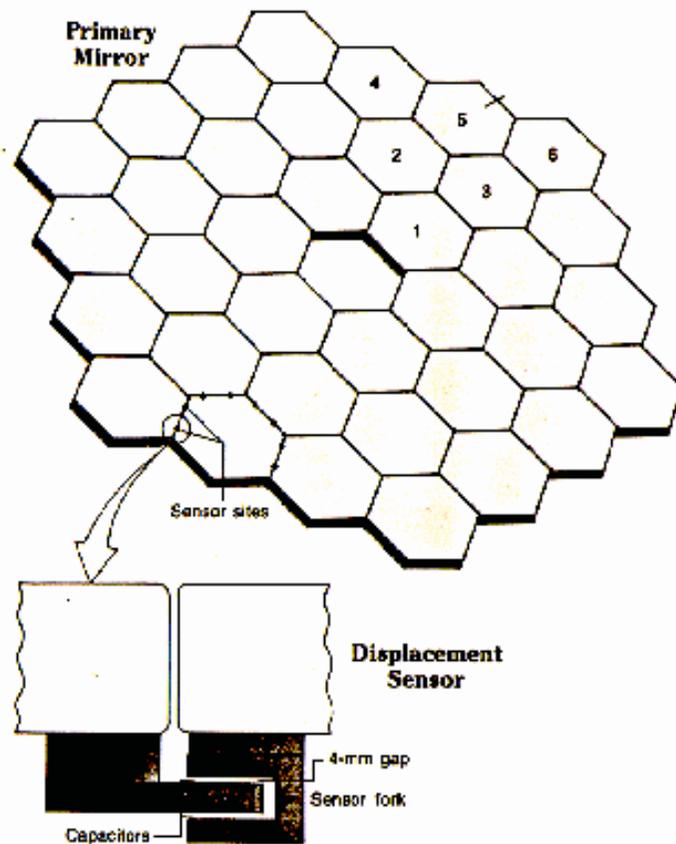
Temperature control with air jet cooling

Arizona Mirror Laboratory

Segmented Primary Mirrors

Individual mirrors easy to manufacture

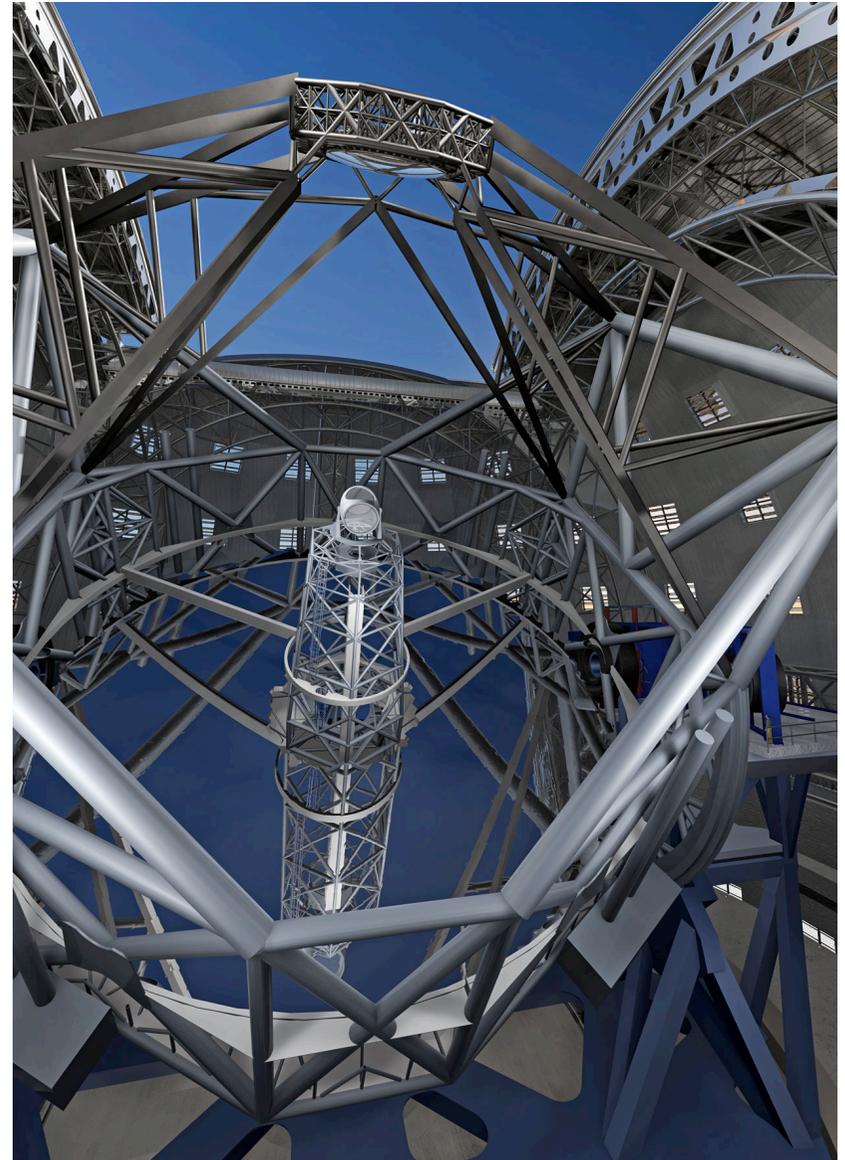
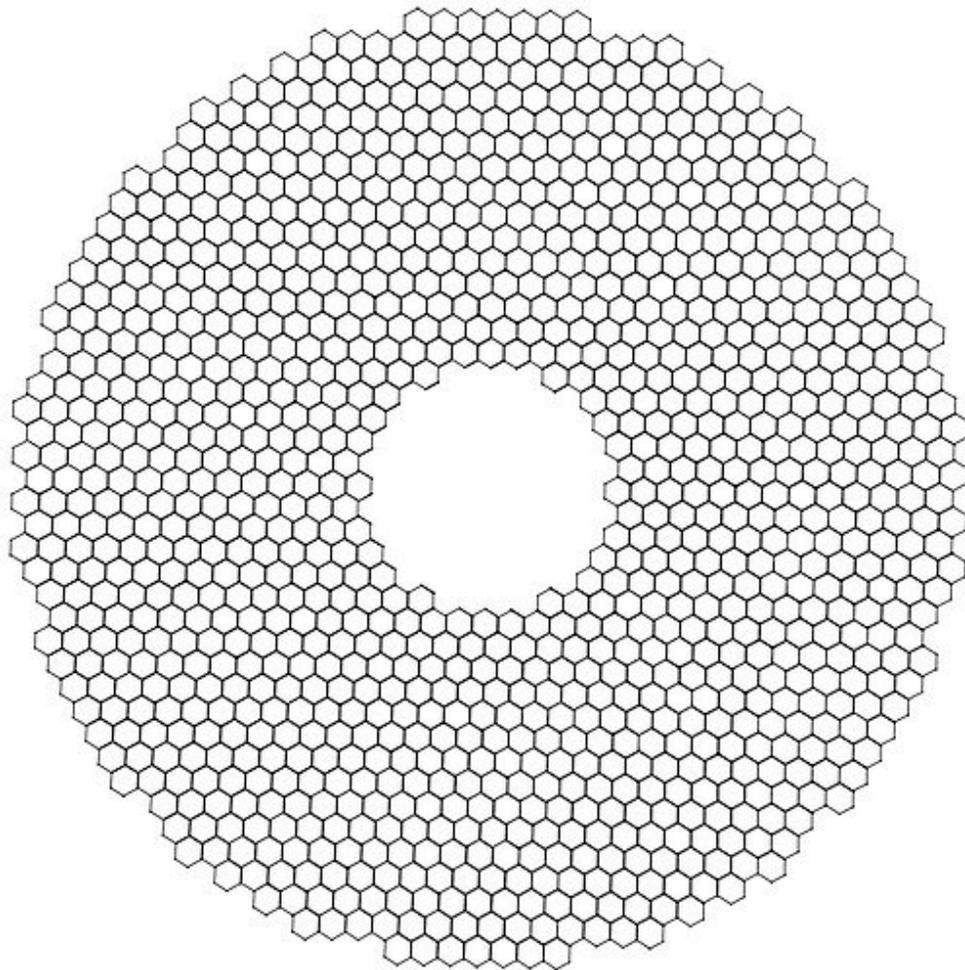
Keck I and II



Segmented Primary Mirrors

Individual mirrors easy to manufacture

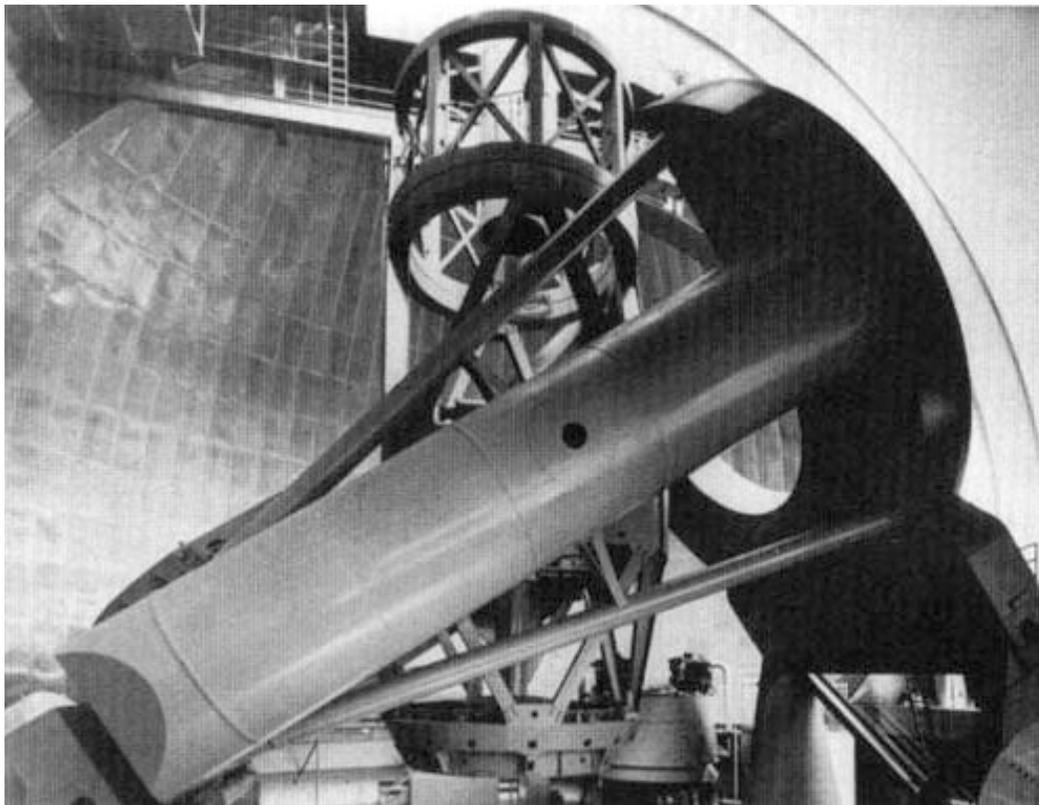
E-ELT: 984 1.4-m segments



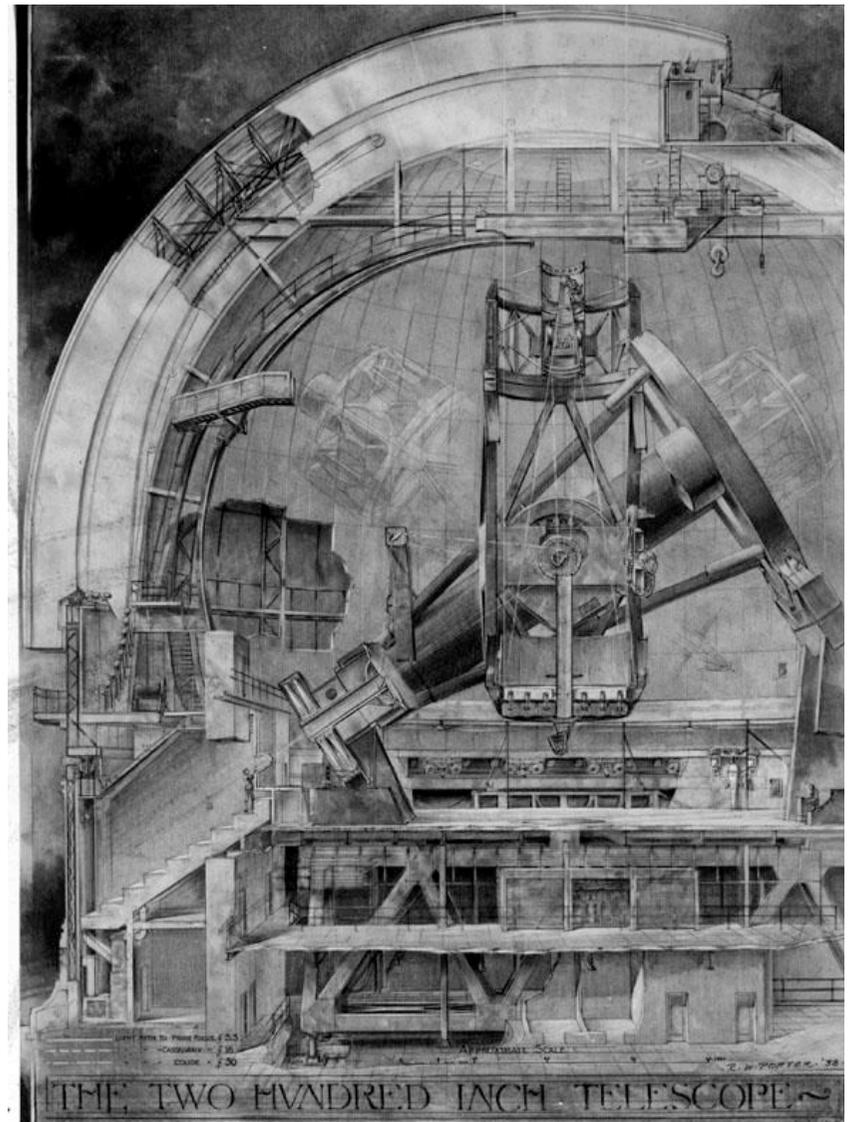
Equatorial Mounts

Only one axis to guide

- equatorial (RA, dec)



Hale 200" @ Palomar



Equatorial Mounts

Only one axis to guide

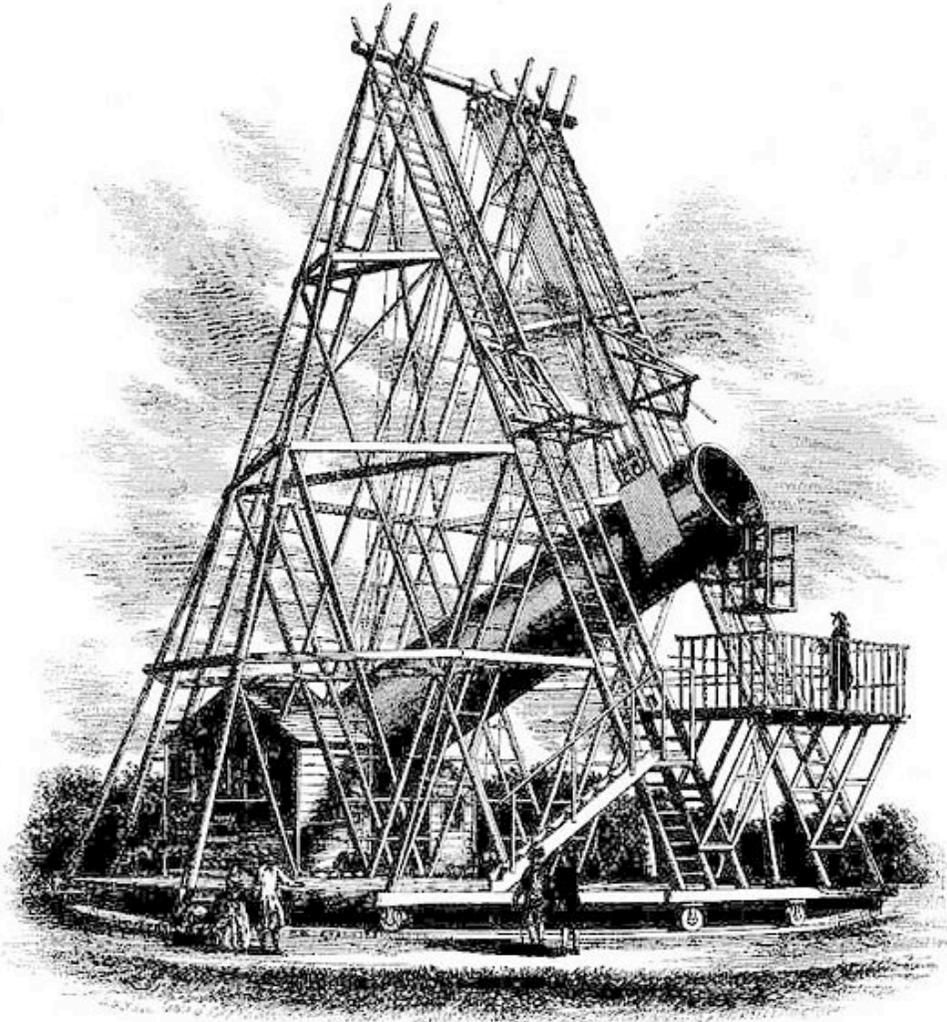
- equatorial (RA, dec)



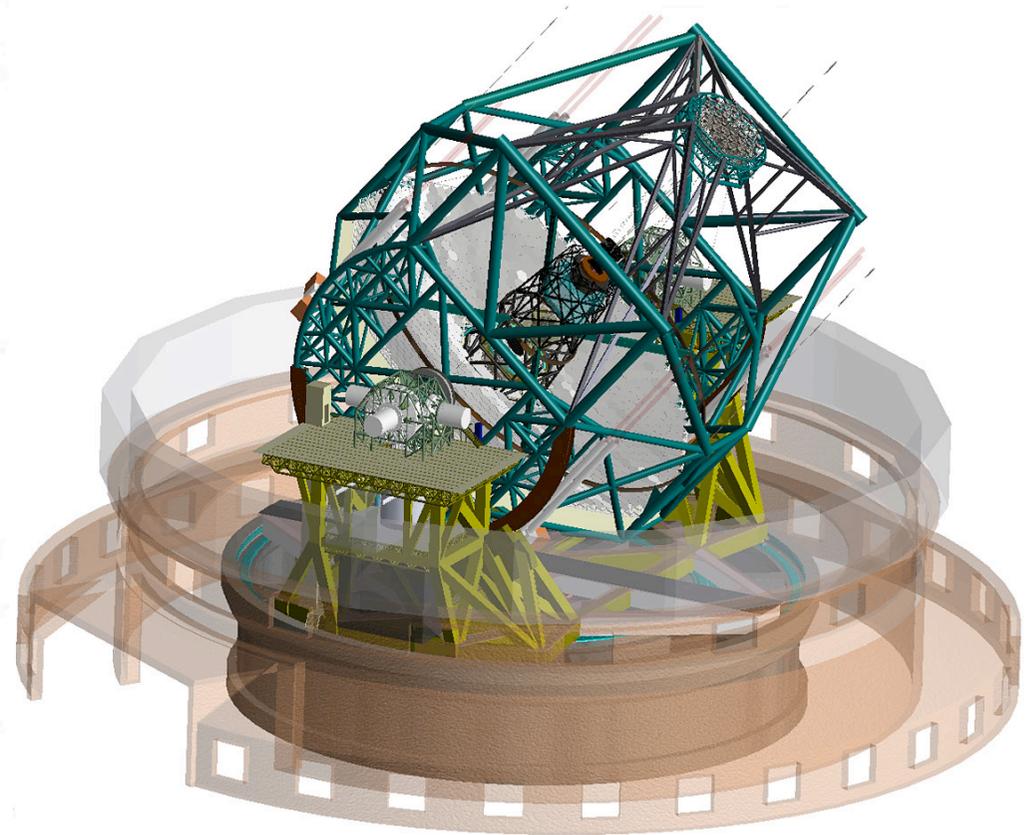
Alt-Az mounts

Computer controllers make this preferred option

Zenith inaccessible due to azimuth drive speed



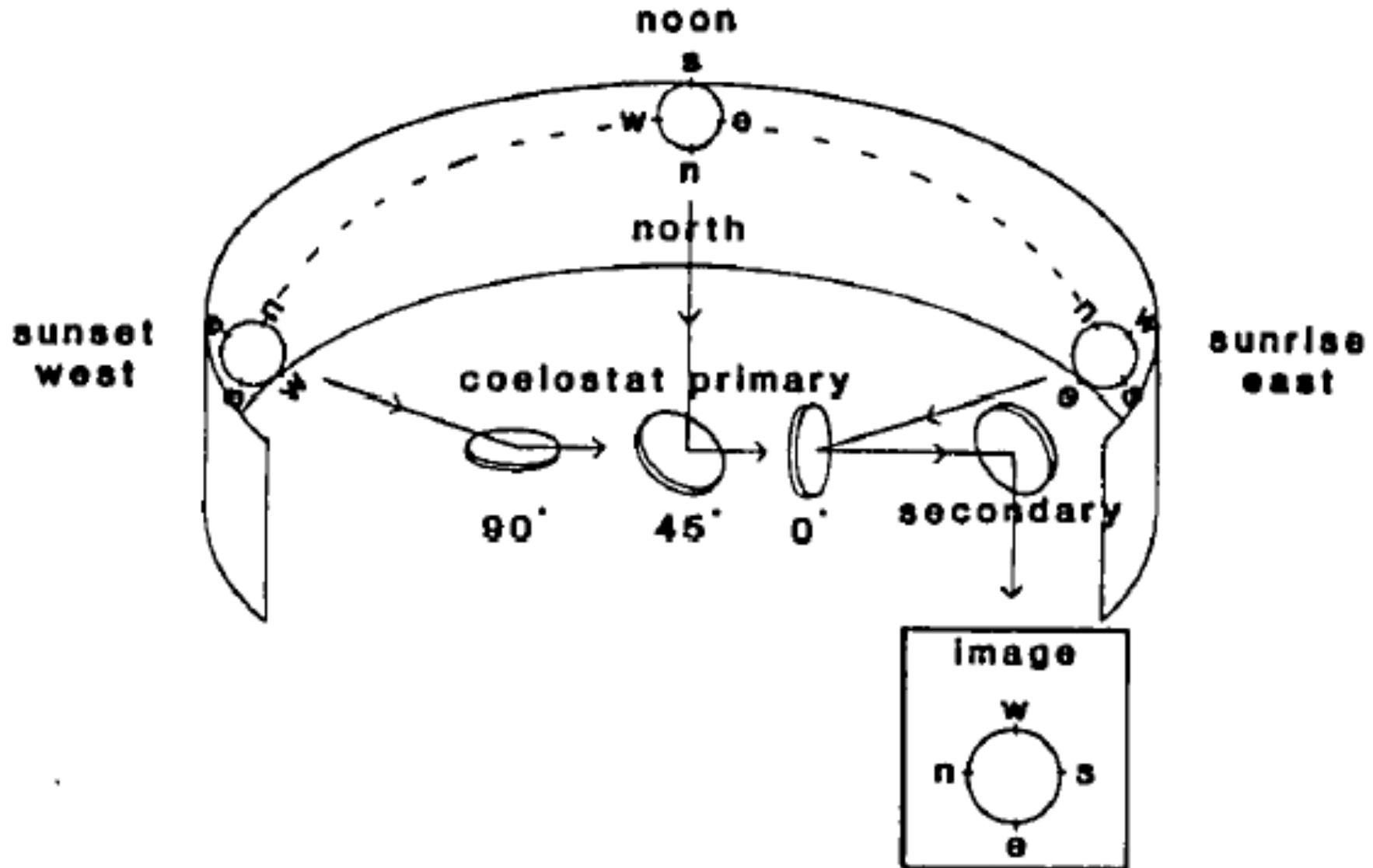
Herschel 1789



E-ELT (2026)

Derotation

Sky rotates with hour angle



Rotation speed is variable

Sky rotates with hour angle

- δ = source declination
- φ = telescope latitude

- alt-az at Cassegrain focus:

$$\cos \vartheta_{\text{Cass}} = \frac{\sin \varphi - \sin(\text{alt}) \sin \delta}{\cos(\text{alt}) \cos \delta}$$

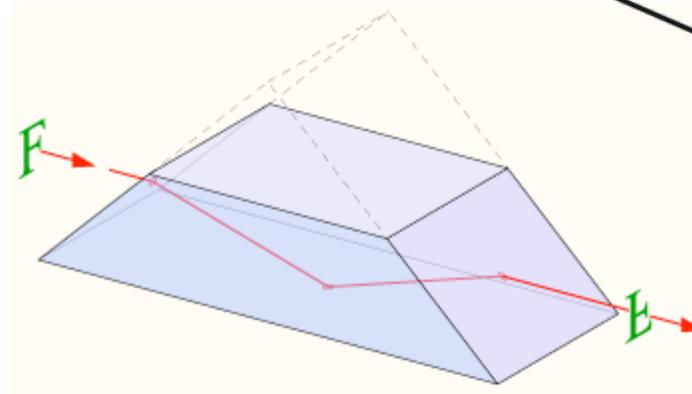
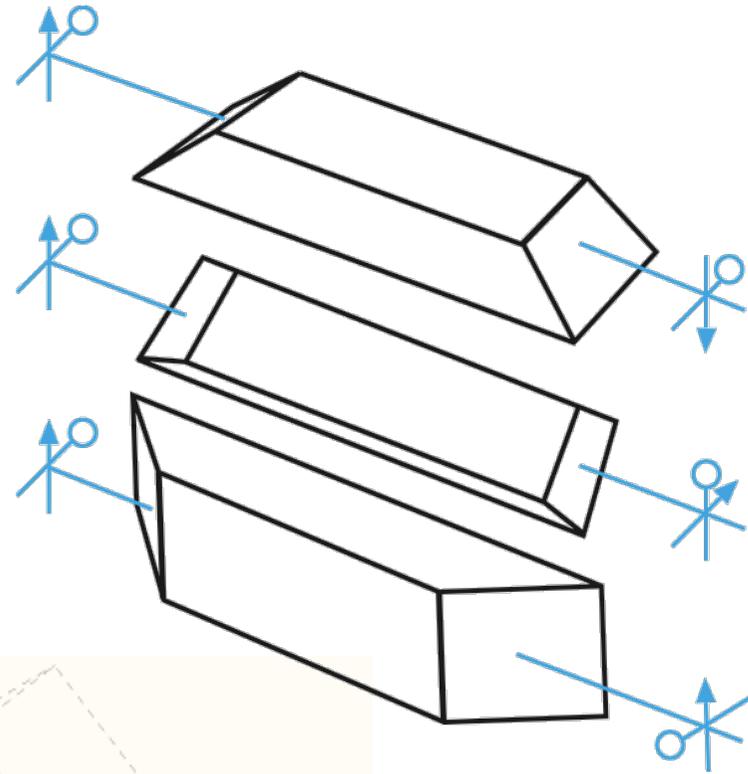
- alt-az at Nasmyth (or Coudé) platform:

$$\vartheta_{\text{Nasmyth}} = \text{alt} - \vartheta_{\text{cass.}} \quad (- \text{az})$$

Derotating the field of view

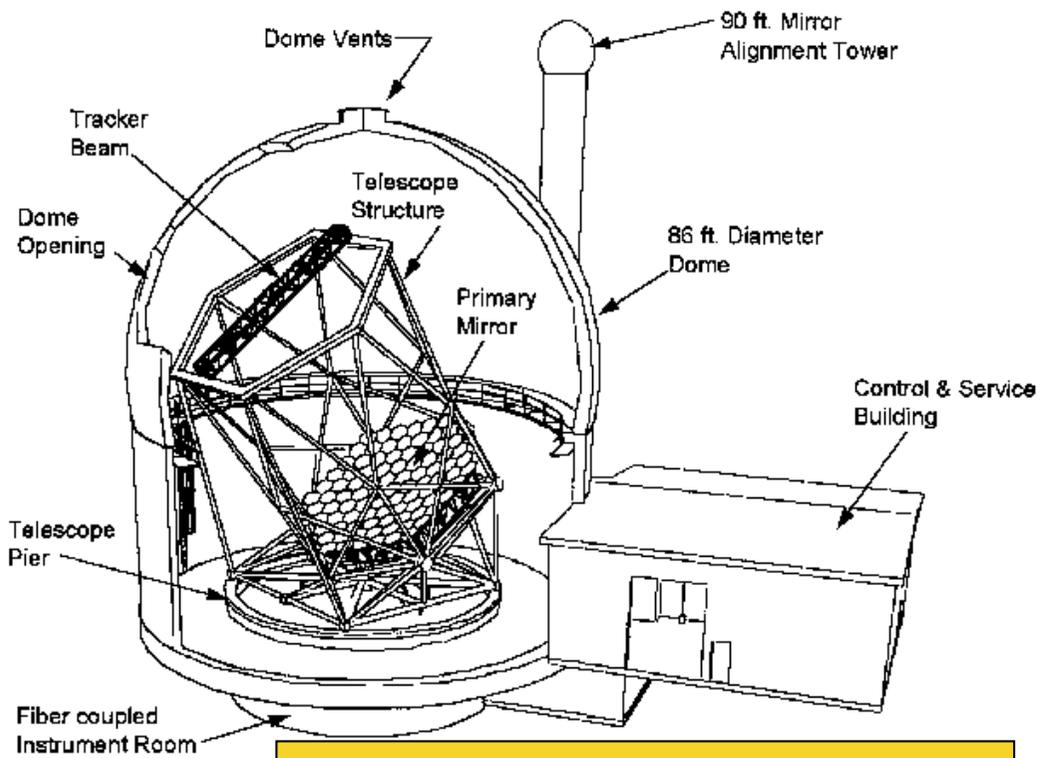
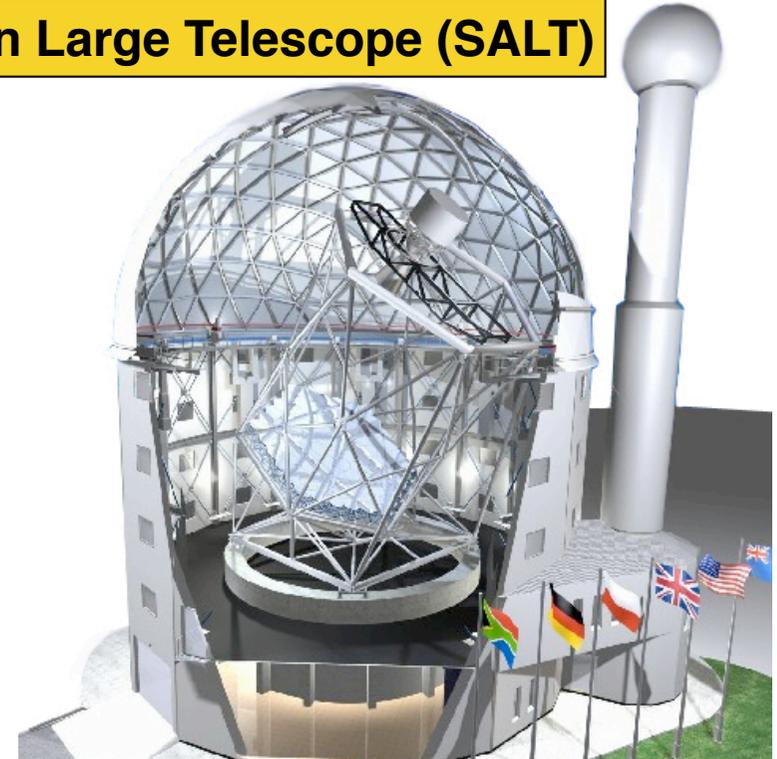
Sky rotates with hour angle

- rotate entire instrument
- derotator
 - K-mirror
 - Dove prism
 - anything rotatable with an odd number of reflections

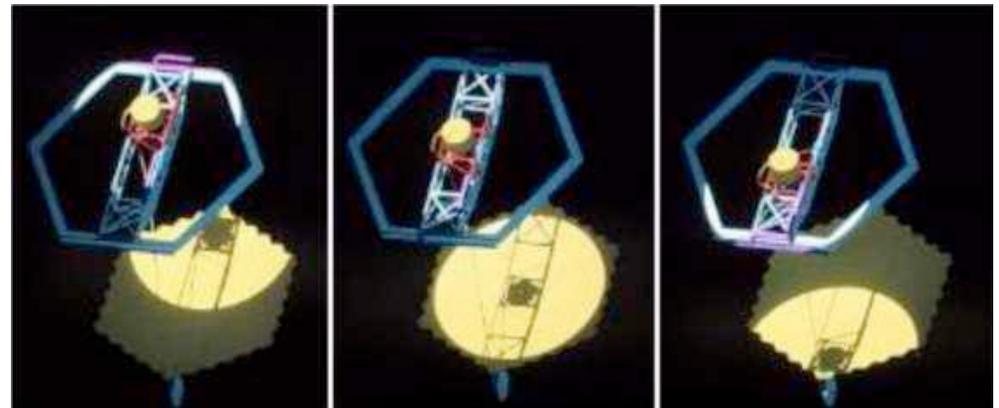


Fixed elevation telescopes

Southern African Large Telescope (SALT)



Hobby-Everyly Telescope (HET)



Coelostat

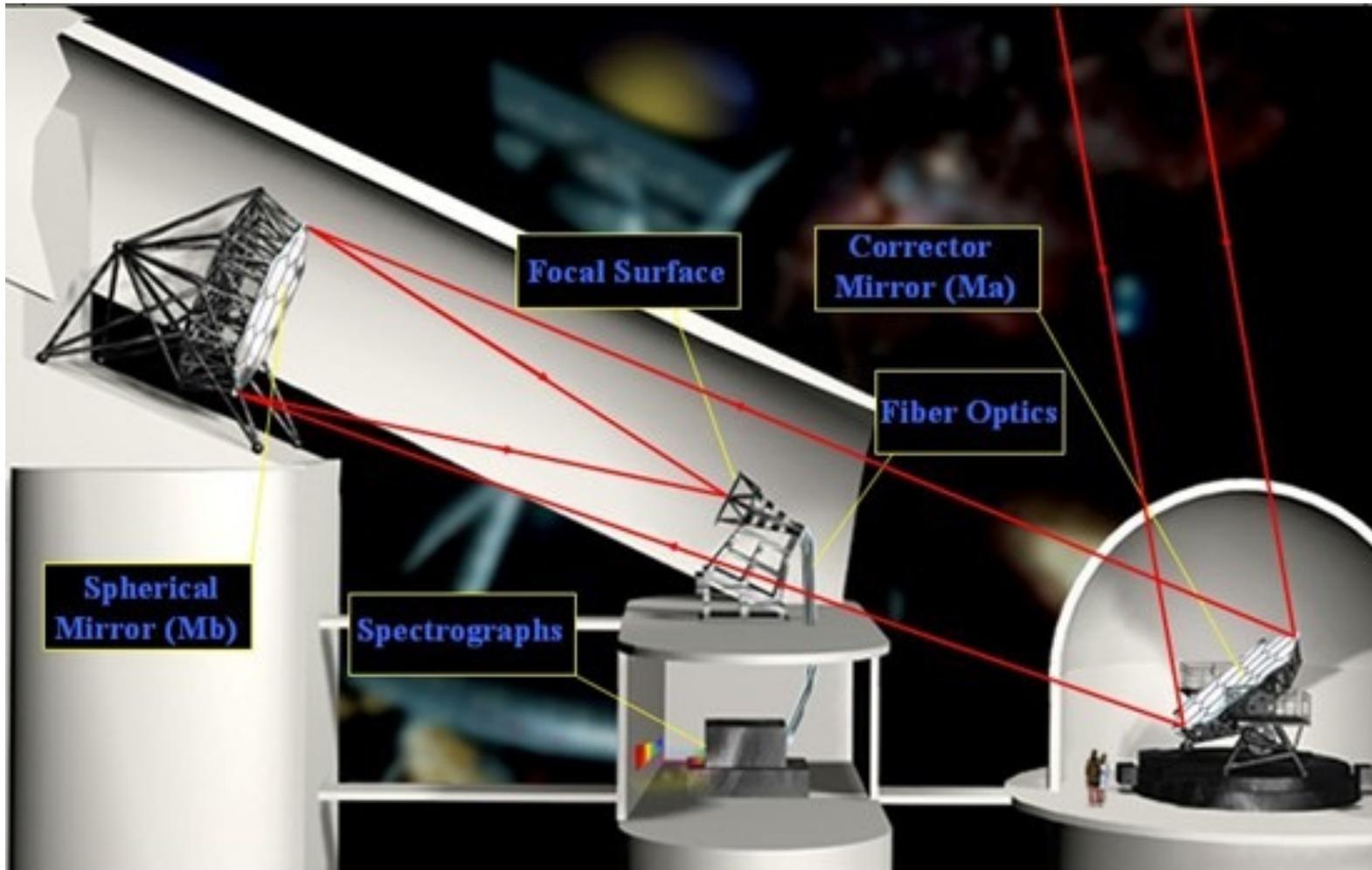
Only one mirror to steer across sky



LAMOST (China)

Coelostat

Only one mirror to steer across sky

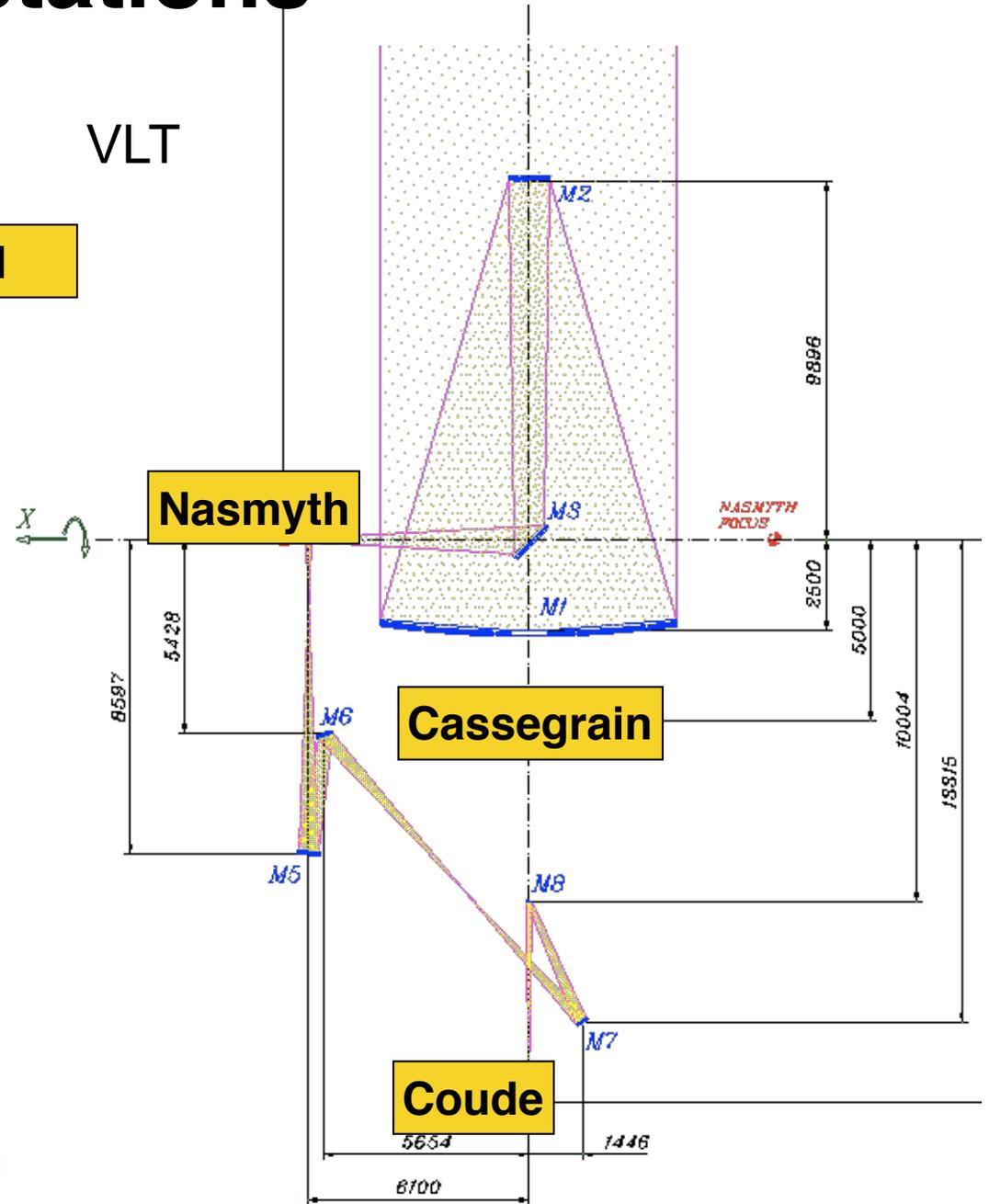
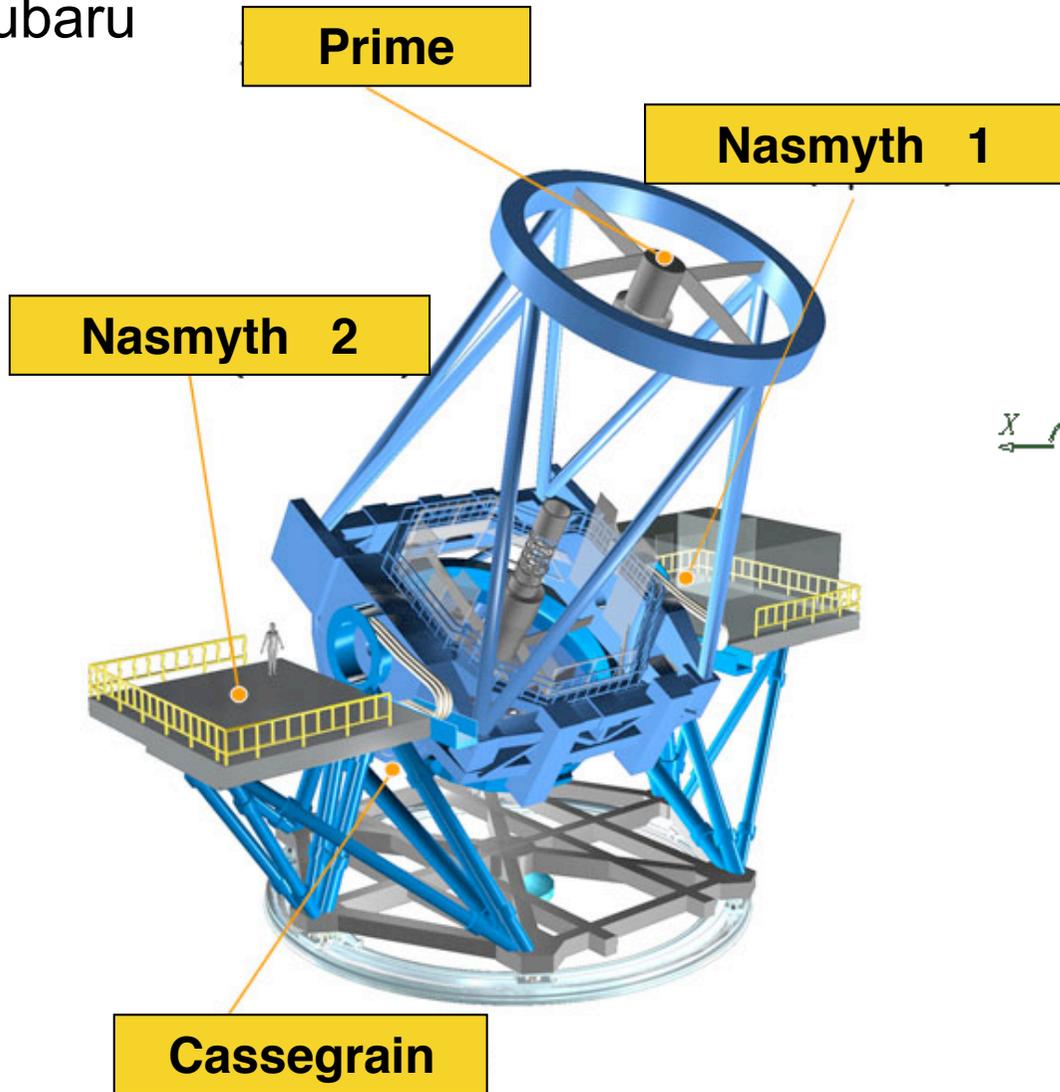


LAMOST (China)

Focal stations

Subaru

VLT



Focal stations

Sky rotates with hour angle



Nasmyth 2

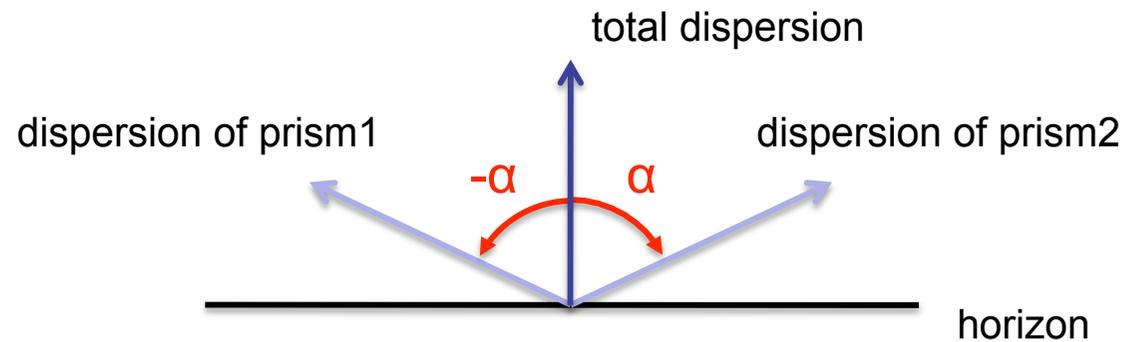
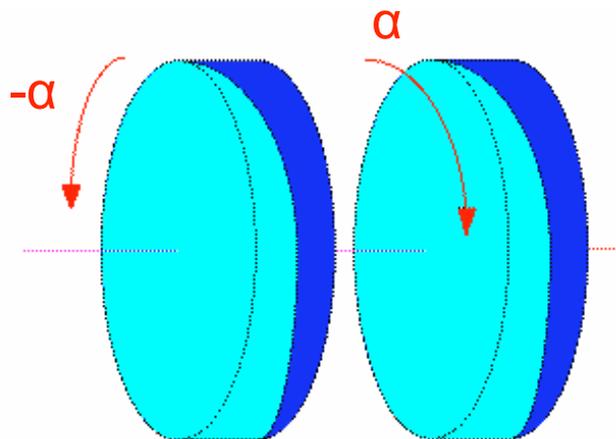
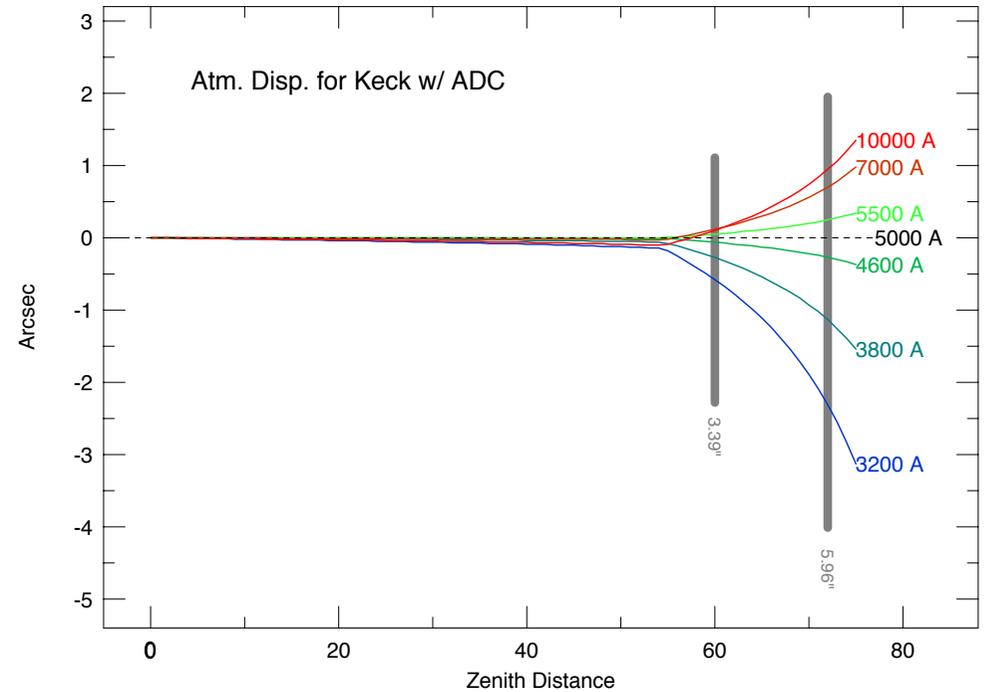
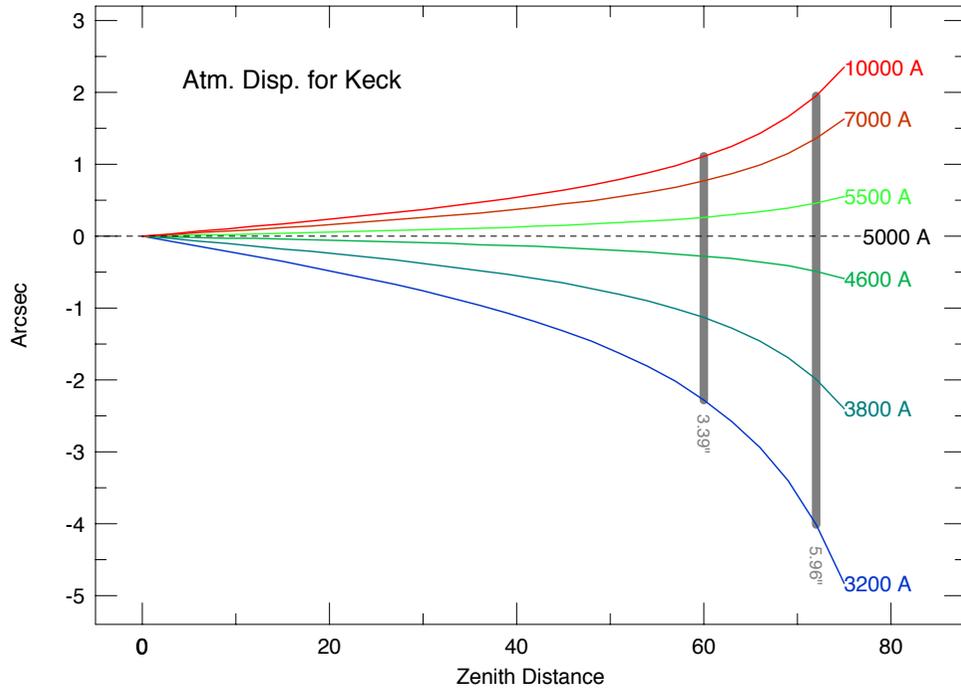
Nasmyth 1

Tertiary mirror

VLT

Atmospheric Dispersion Corrector

Atmosphere is a prism at non-zenith angles

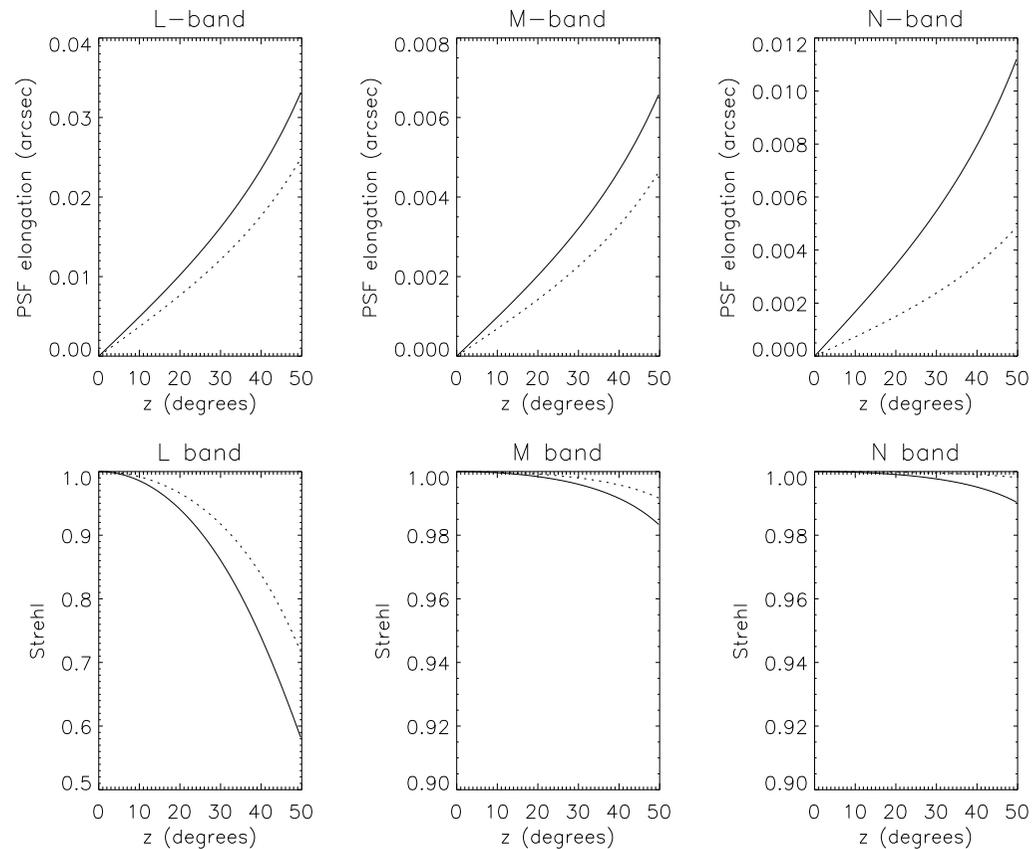


Atmospheric Dispersion Corrector

This is a problem for coronagraphs on ELTs!

Band	λ_{centre} (μm)	$\Delta\lambda$ (μm)
L	3.78	0.70
M	4.68	0.20
N	10.5	1.50

Table 2. Centre wavelengths and bandwidths for three representative filters used to calculate the effect of atmospheric dispersion in the mid-IR on the 42-m E-ELT.



Kendrew 2008 SPIE

Figure 2. Effect of atmospheric dispersion across the bandwidths of typical broad-band filters, as defined in Table 2, as a function of zenith distance, around 3.8, 4.7 and 10.5 μm (L-, M- and N-bands) and for the 2 representative sites. Top row: dispersion across the bands in arcseconds. Bottom row: resultant Strehl loss from uncorrected dispersion. The solid line is for a regular site (Paranal), the dashed line for a high and dry site (Macon).