Telescopes

OAI 2015 Lecture 06

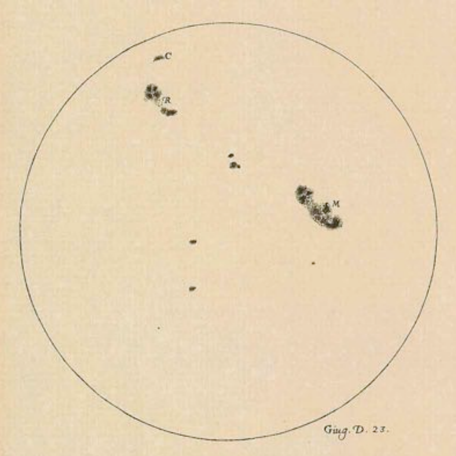
Keller and Kenworthy

Dutch Telescopes

1608

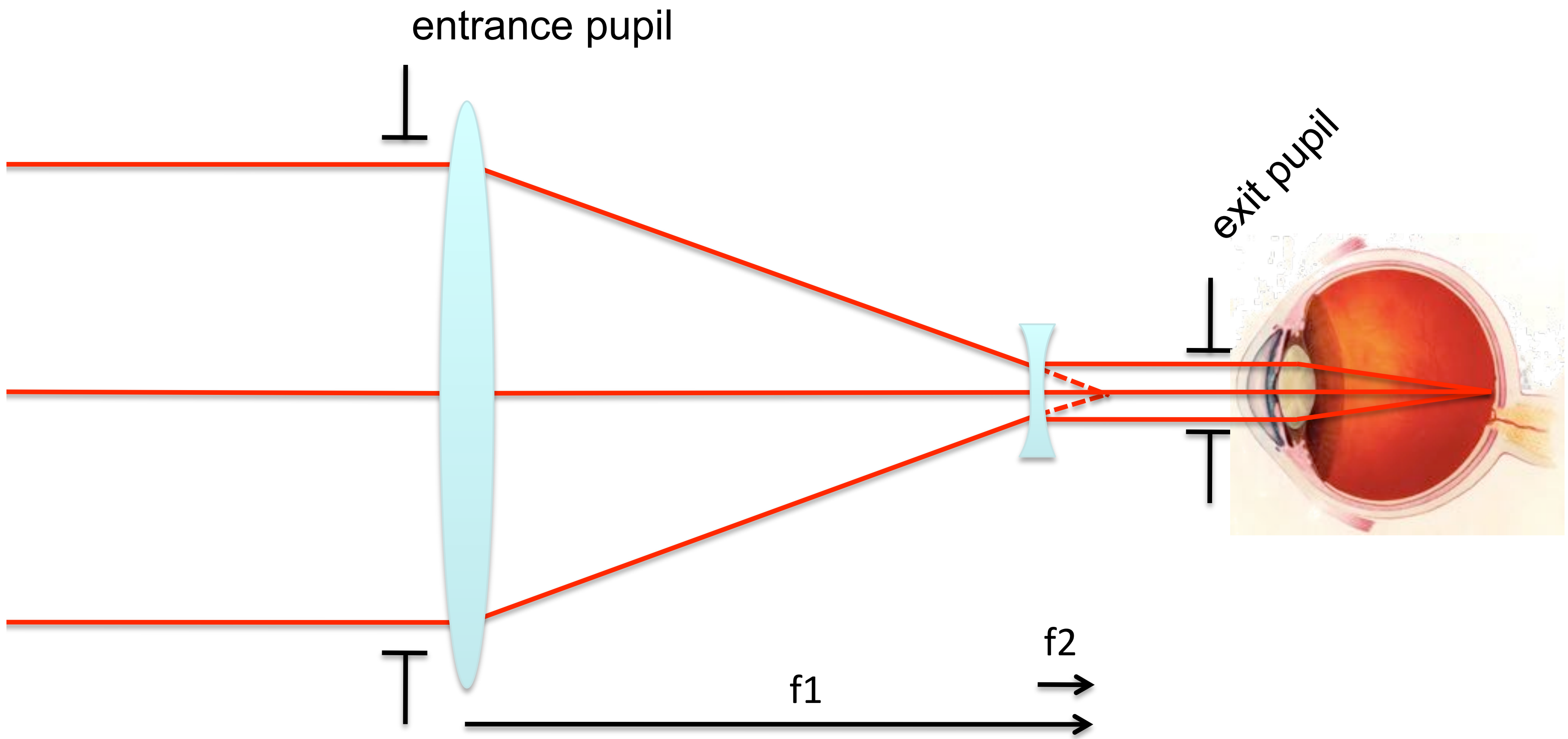
Hans Lipperhey

Dutch Telescopes



1609

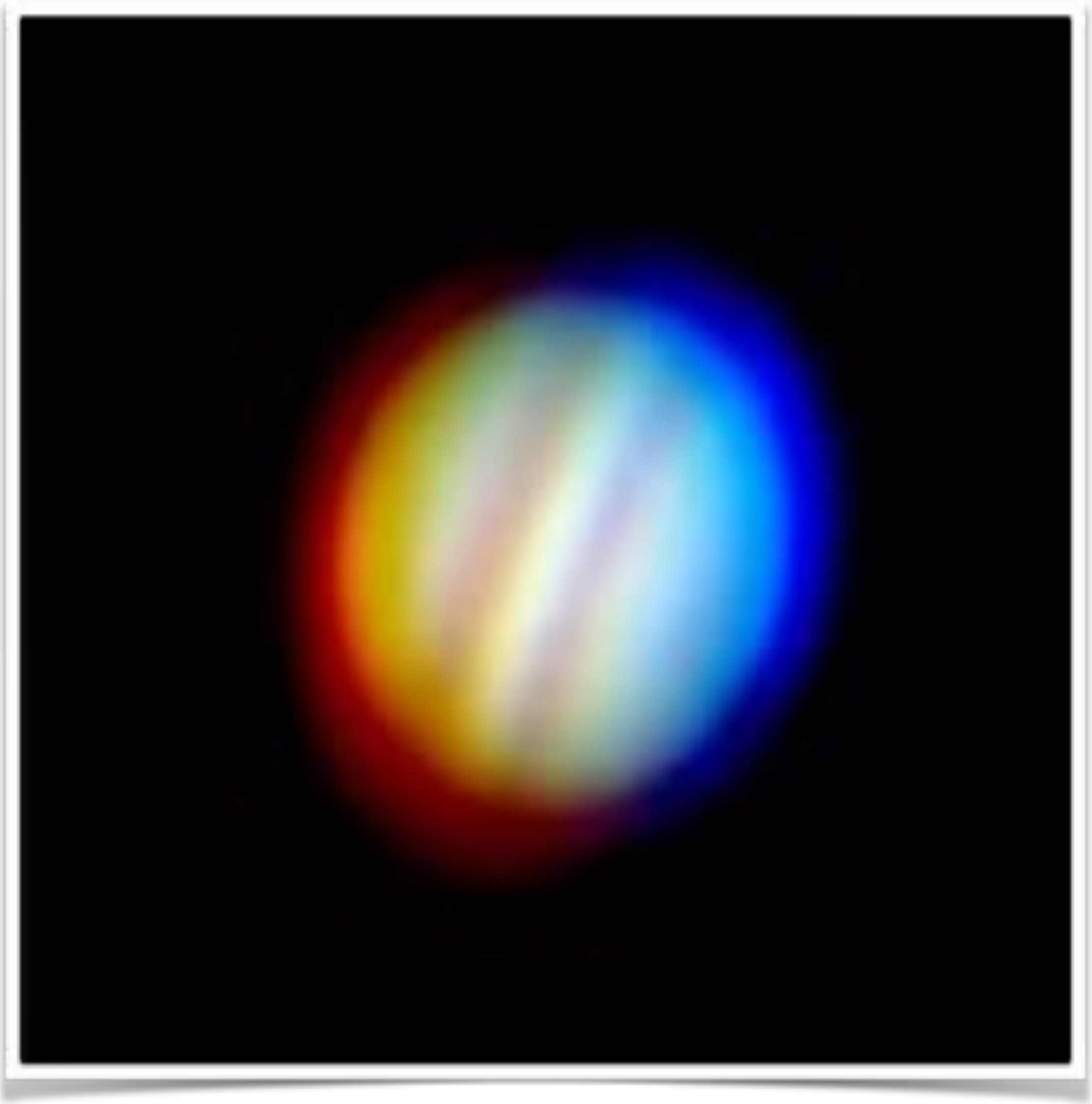
Dutch Telescopes



magnification = f1/f2

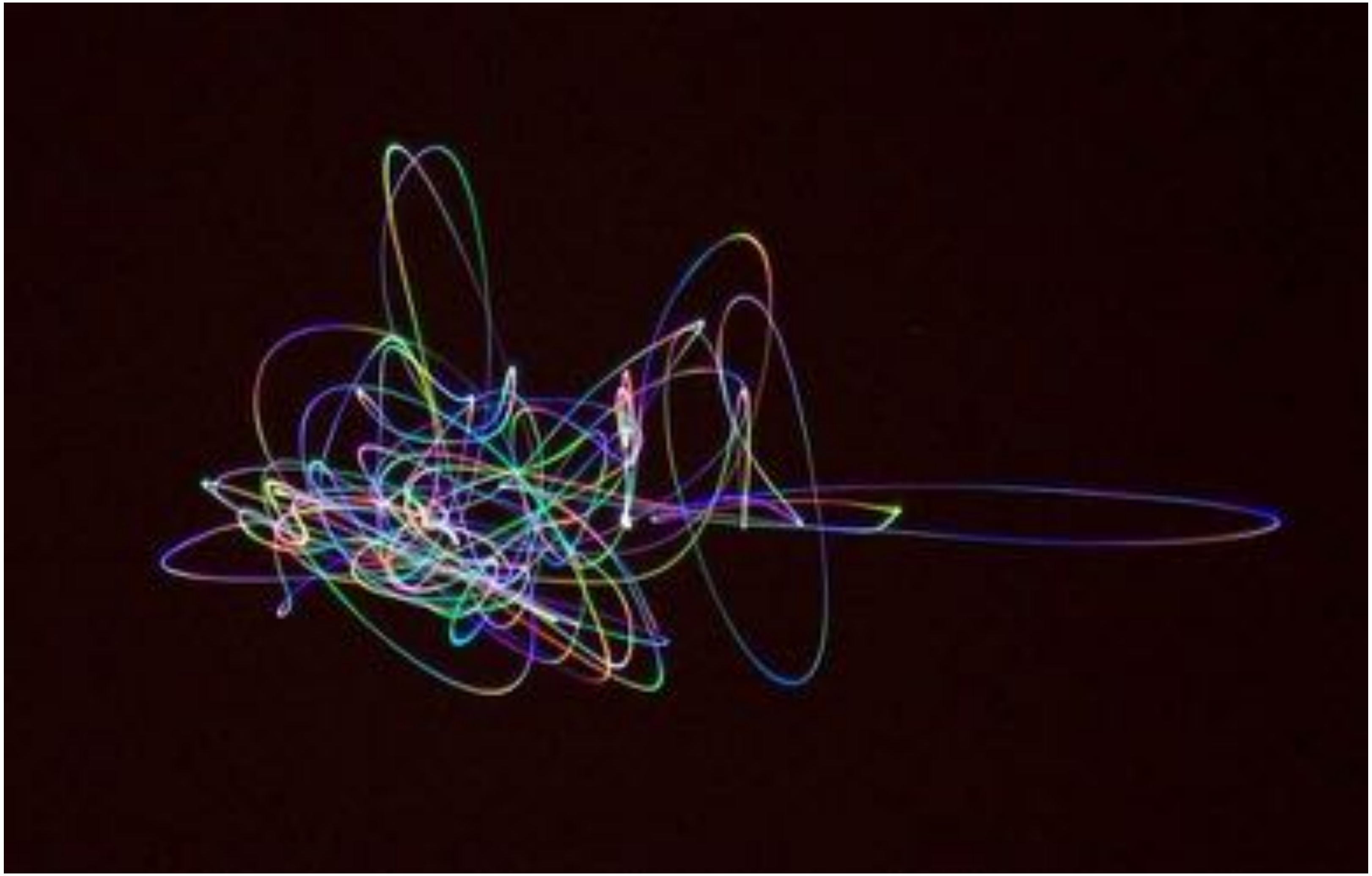
Limitations of refracting telescopes

Chromatic aberration



Limitations of refracting telescopes

Magnification requires stabilisation and guiding



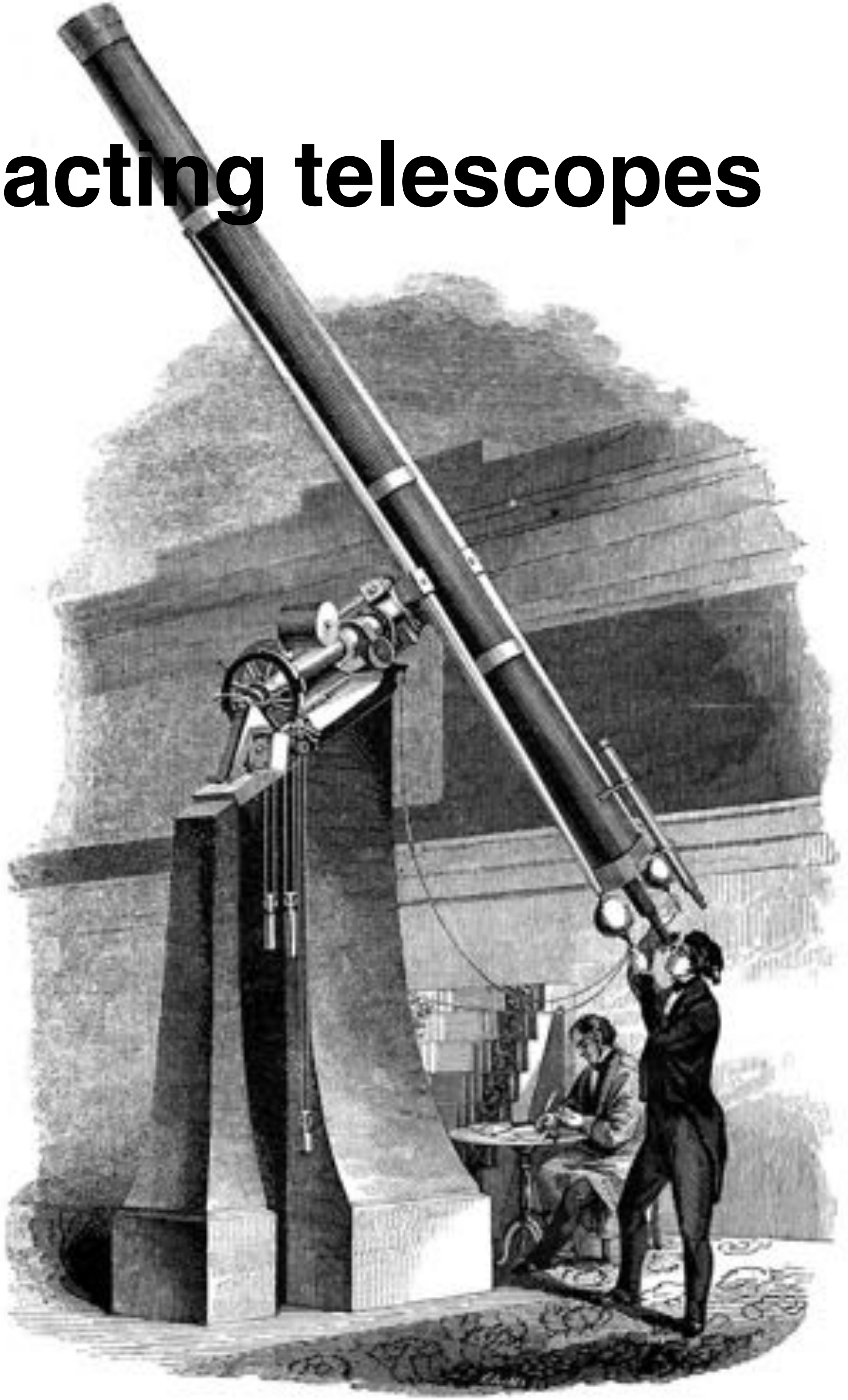
Limitations of refracting telescopes

Weight goes as D^3

Lick refractor 36 inch lens

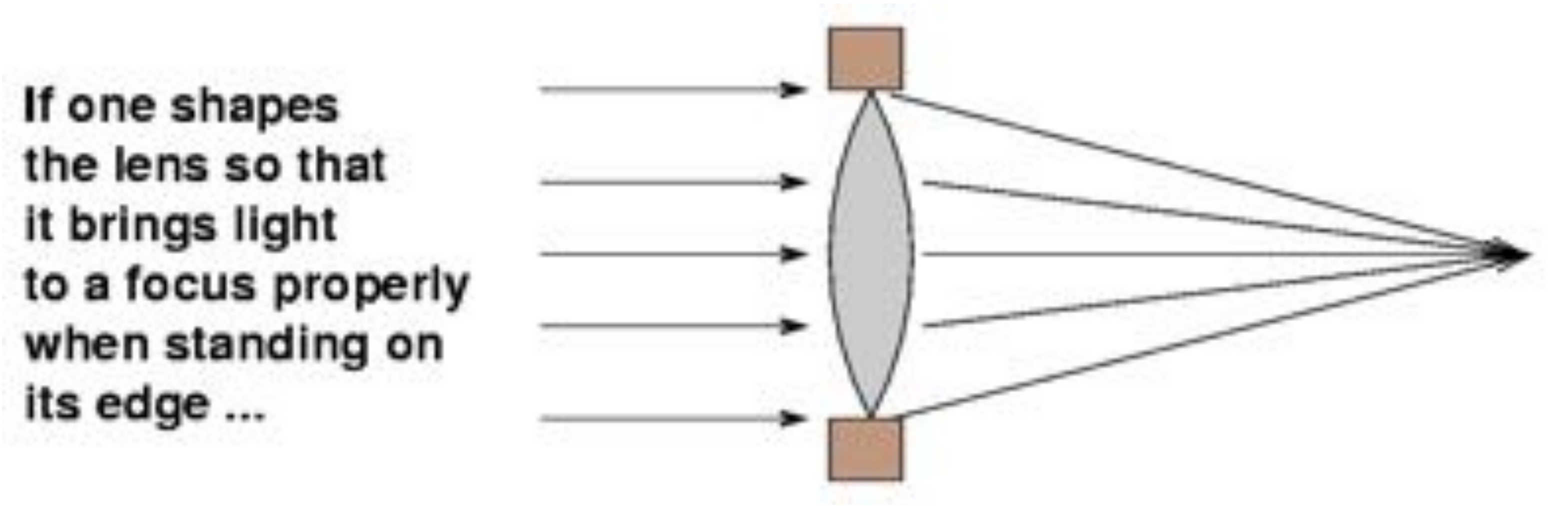
Limitations of refracting telescopes

Long telescope tubes



Limitations of refracting telescopes

Glass sags under gravity

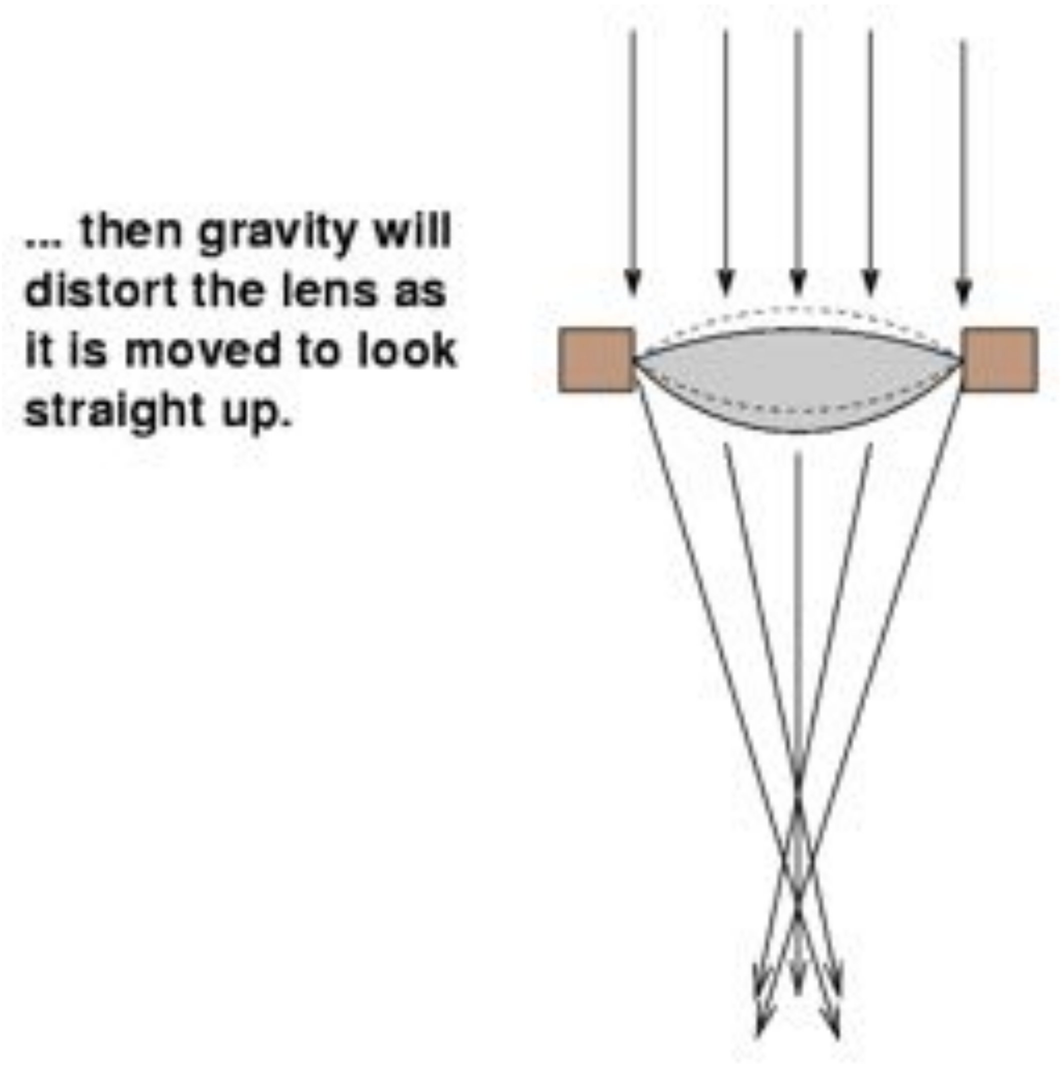


If one shapes the lens so that it brings light to a focus properly when standing on its edge ...

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

Limitations of refracting telescopes

Glass sags under gravity

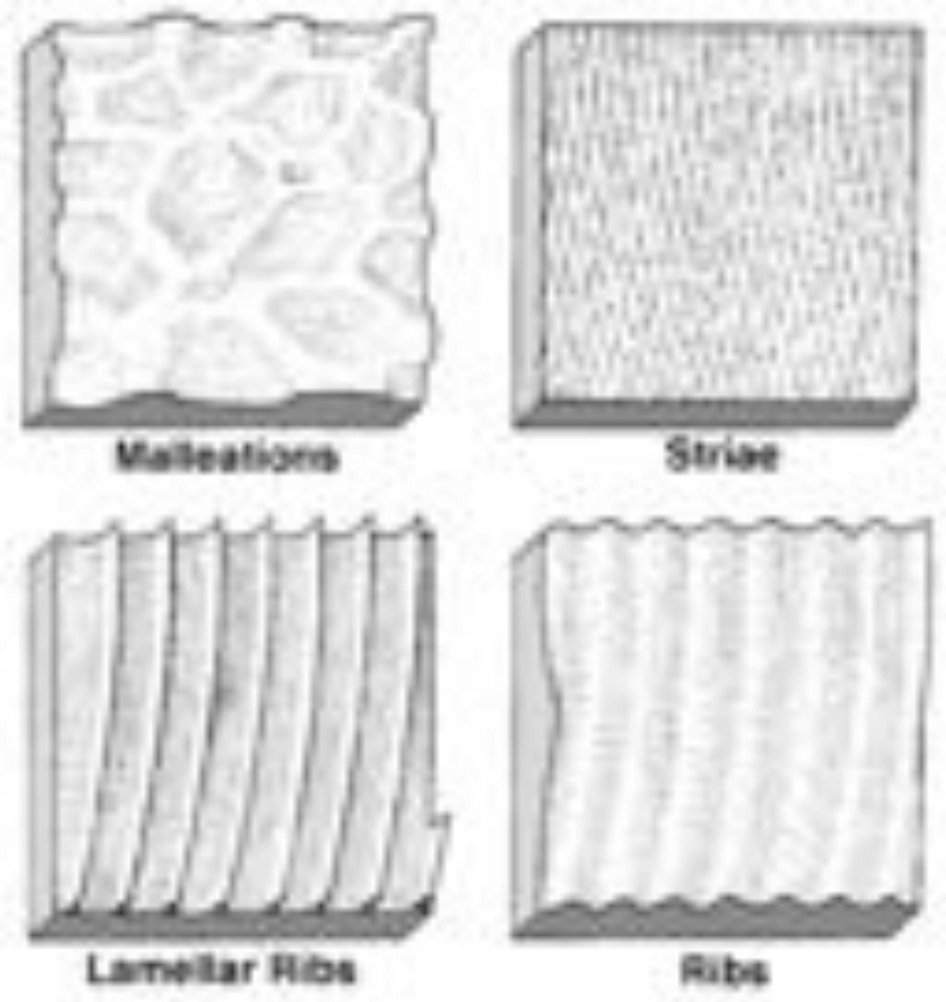


... then gravity will distort the lens as it is moved to look straight up.

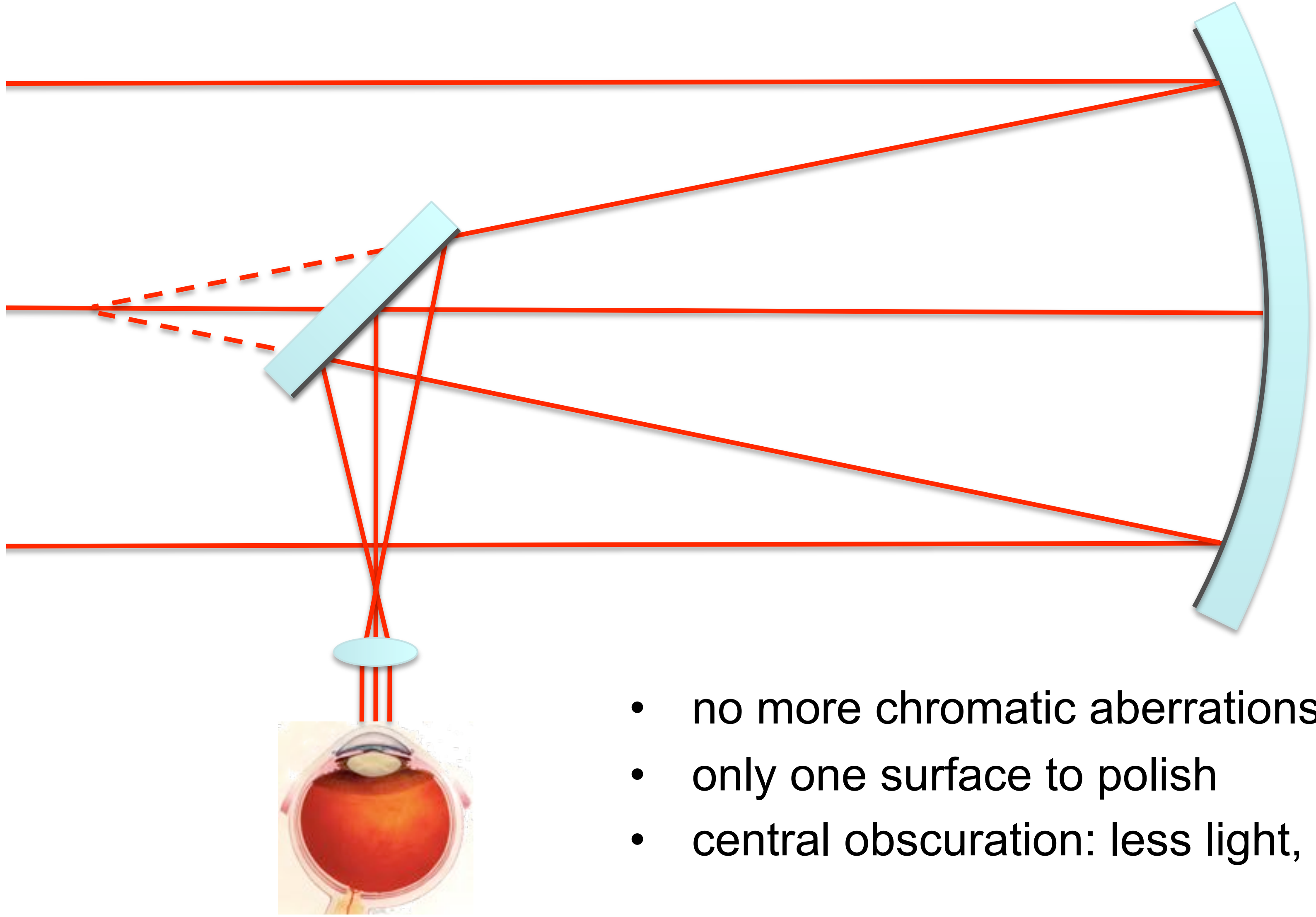
http://spiff.rit.edu/classes/phys301/lectures/optical_tel/optical_tel.html

Limitations of refracting telescopes

Glass homogeneity is difficult to maintain



Newtonian Telescope

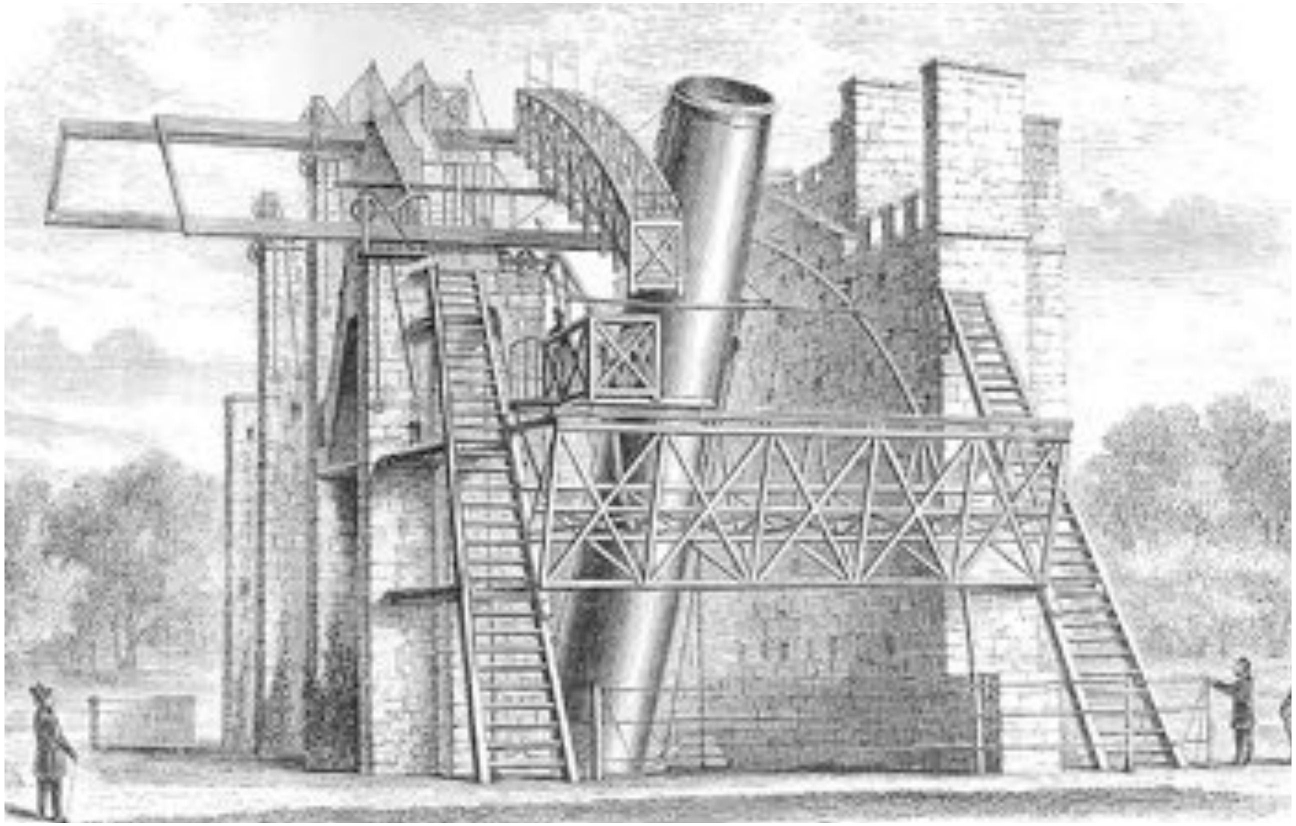


- no more chromatic aberrations
- only one surface to polish
- central obscuration: less light, diffraction

Newtonian Telescope

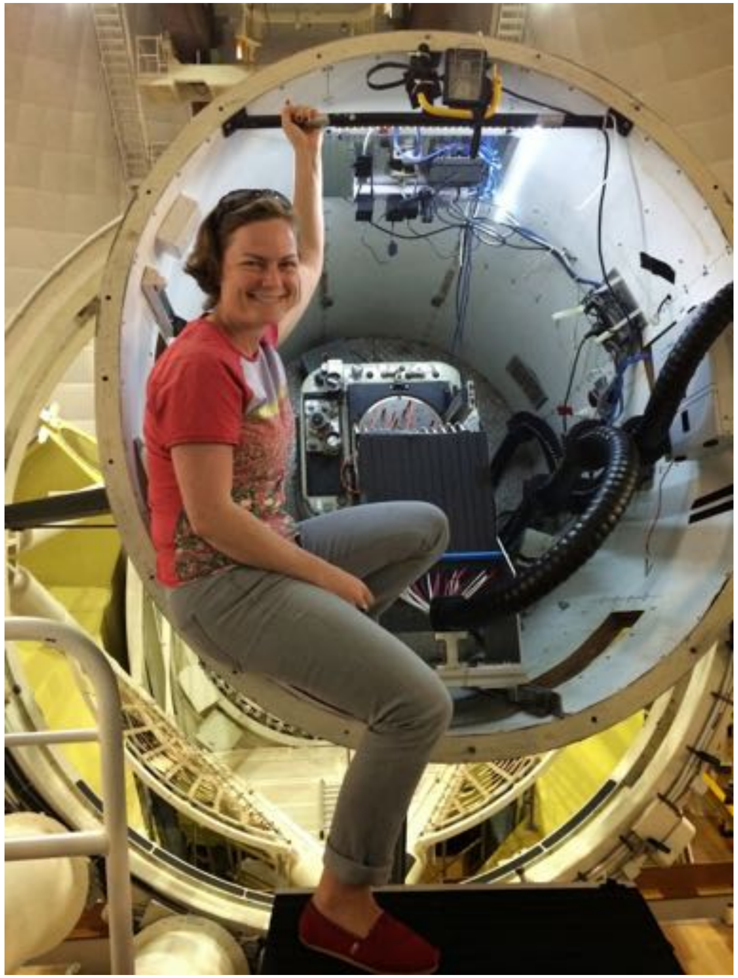
1668

1842

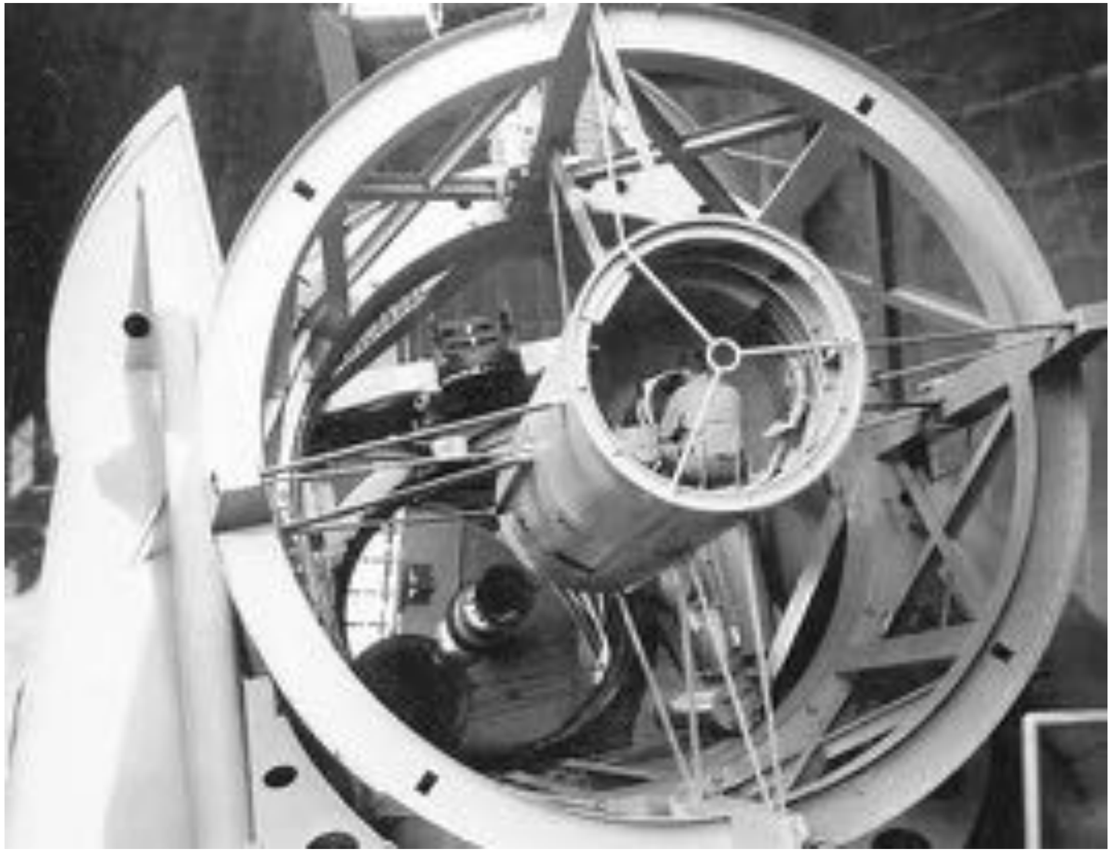


Introducing a Secondary Mirror

Primary focus is awkward to get to



(c) Amanda Bauer



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

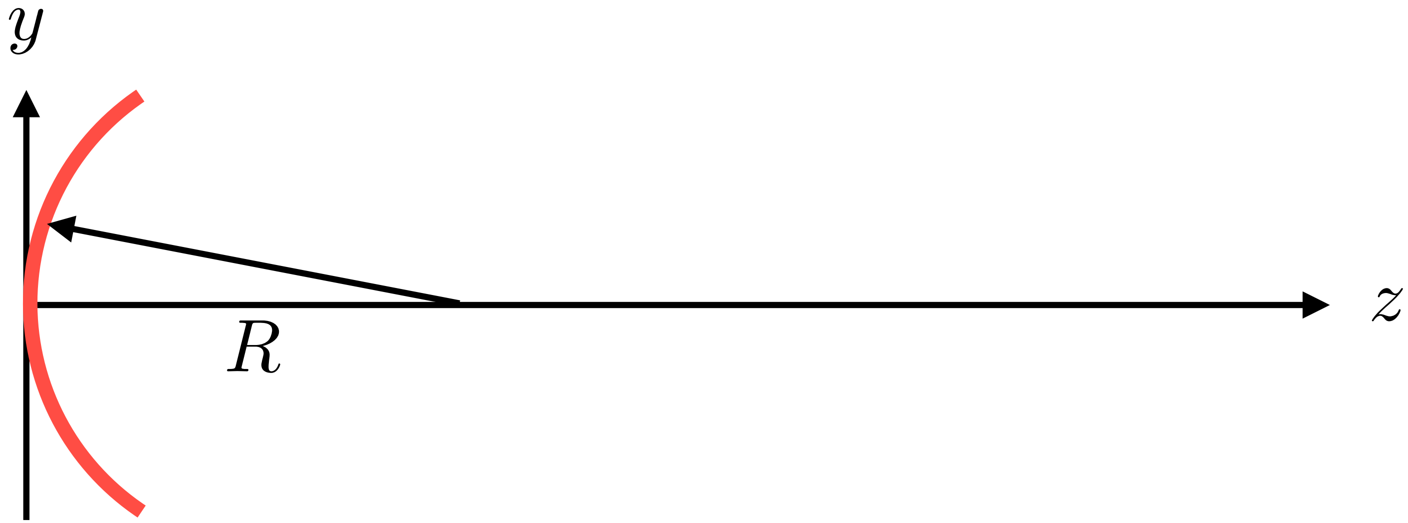
The family of conic mirrors

All these curves can be parameterised with one equation:

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

Conic constant K is defined as:

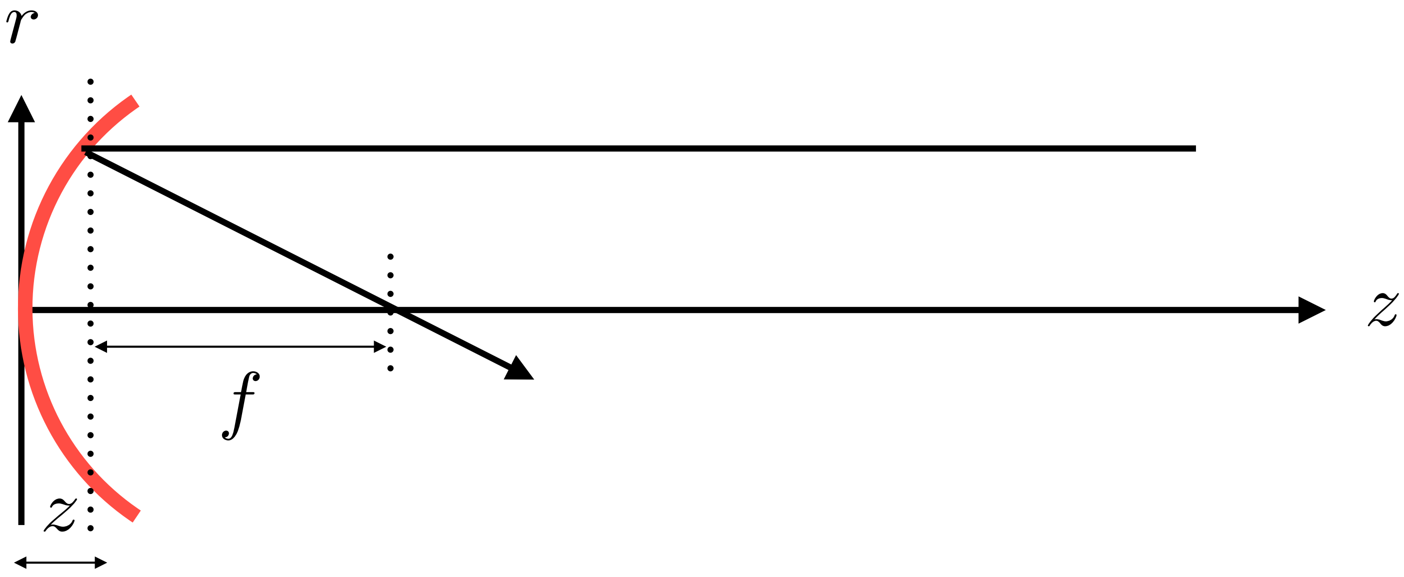
$$K = -e^2$$



focal distance with r

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

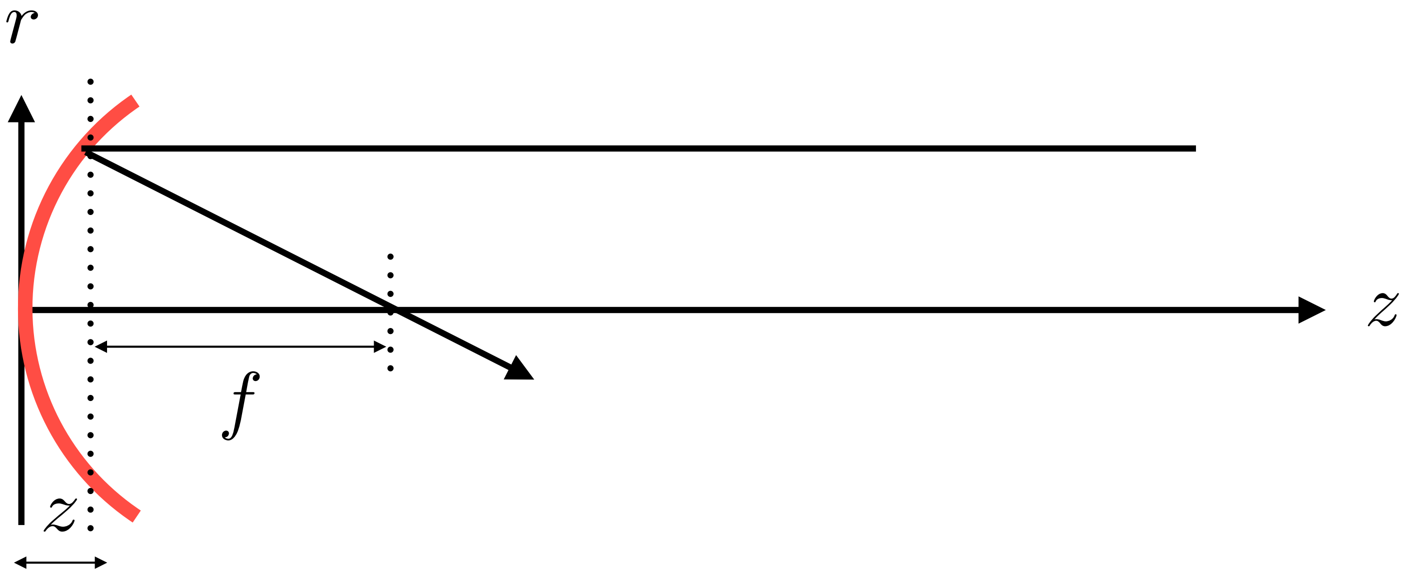
$$z = \frac{R}{1+K}\left[1 - \left(1 - \frac{r^2}{R^2}(1+K)\right)^{1/2}\right]$$



focal distance with r

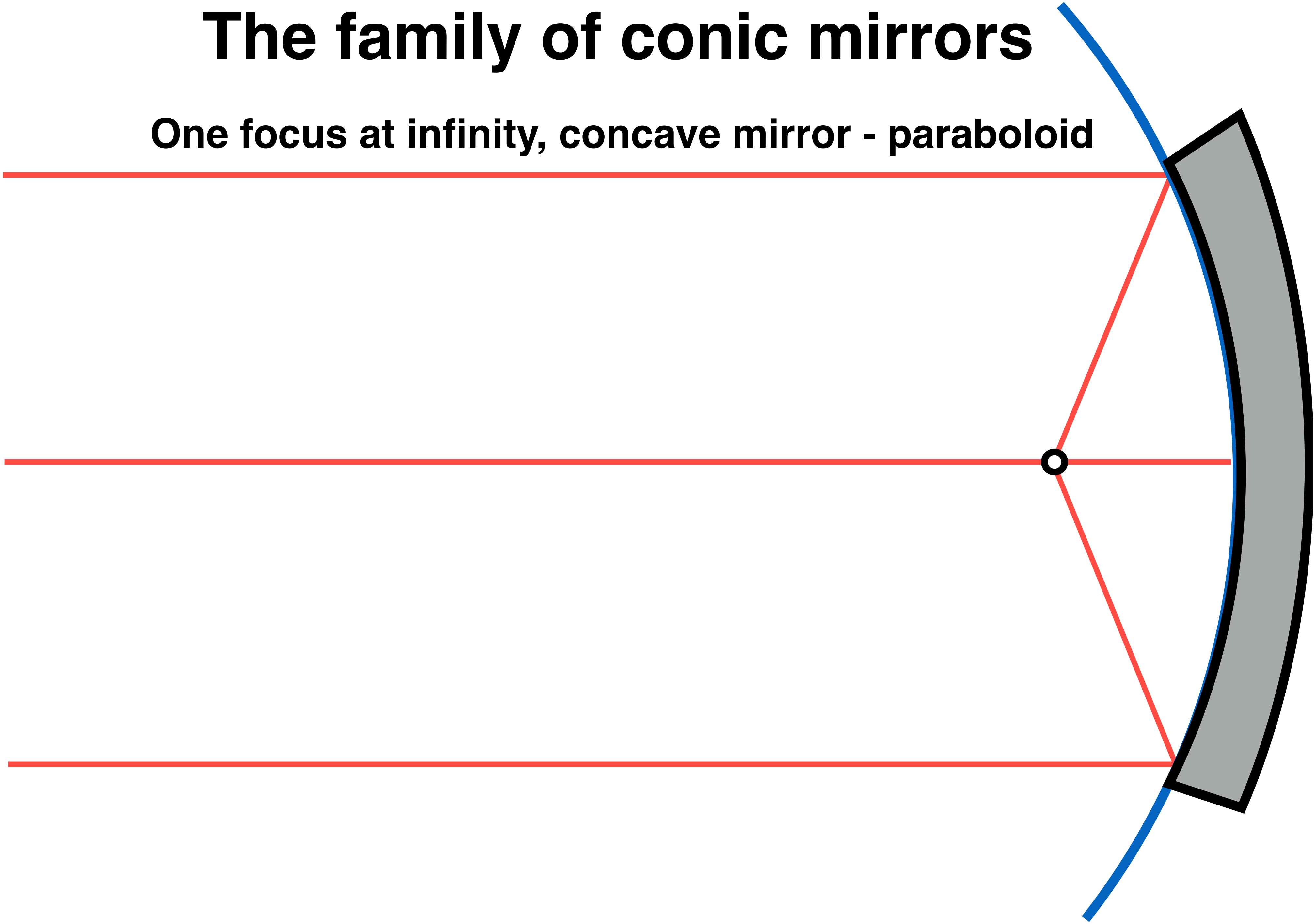
You can expand the power series and keep only the first two terms:

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



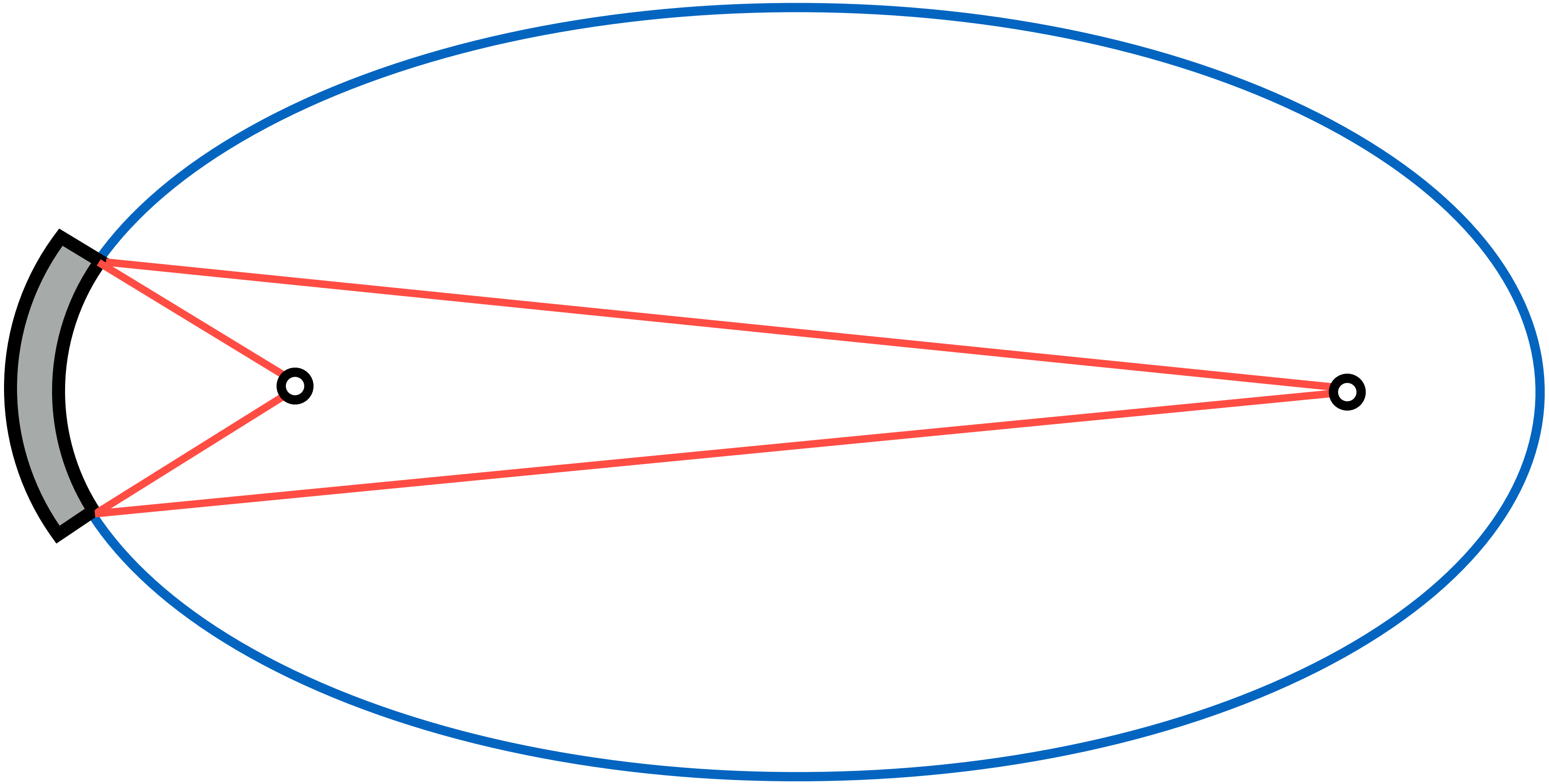
The family of conic mirrors

One focus at infinity, concave mirror - paraboloid

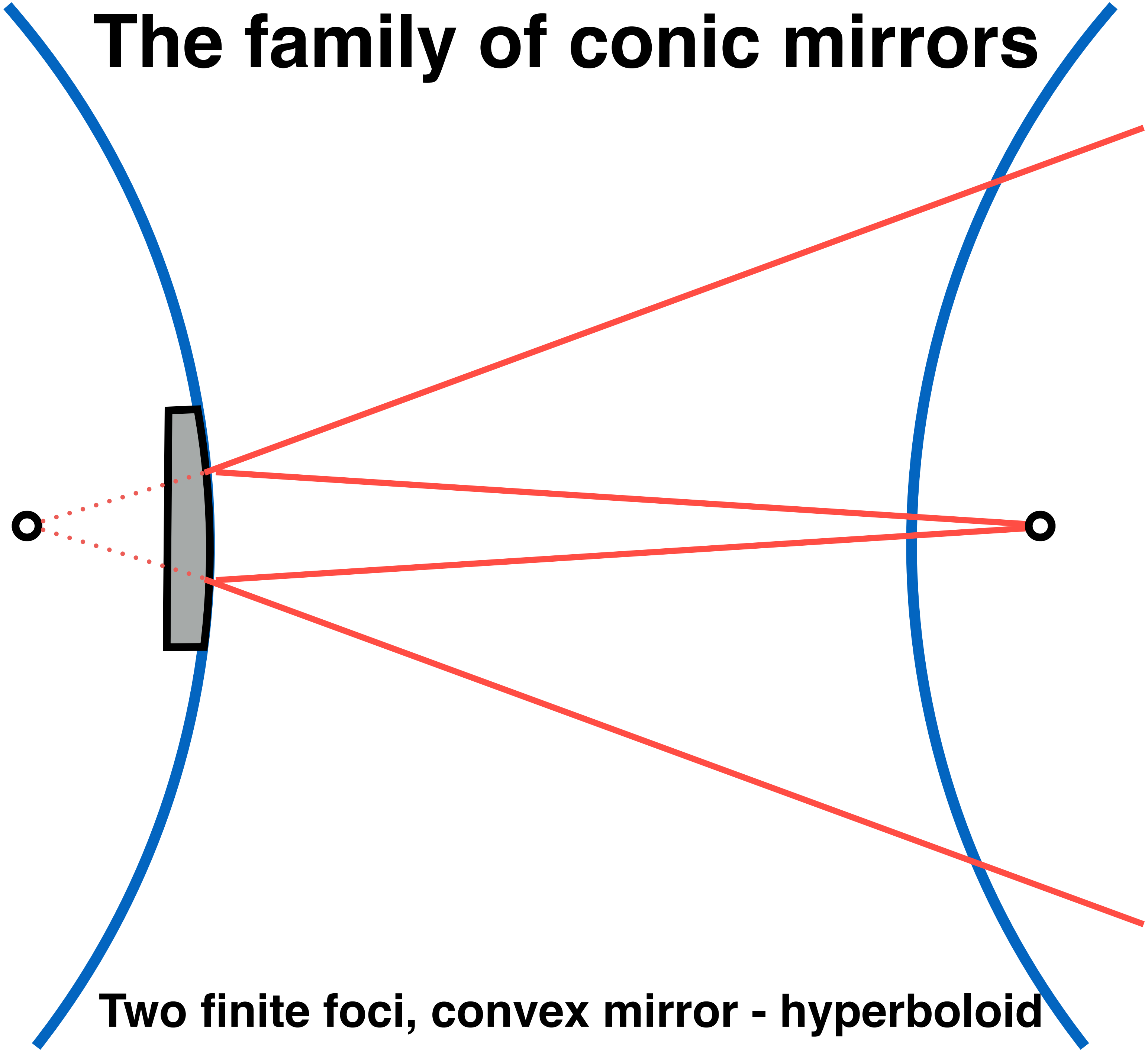


The family of conic mirrors

Two finite foci, concave mirror - ellipsoid

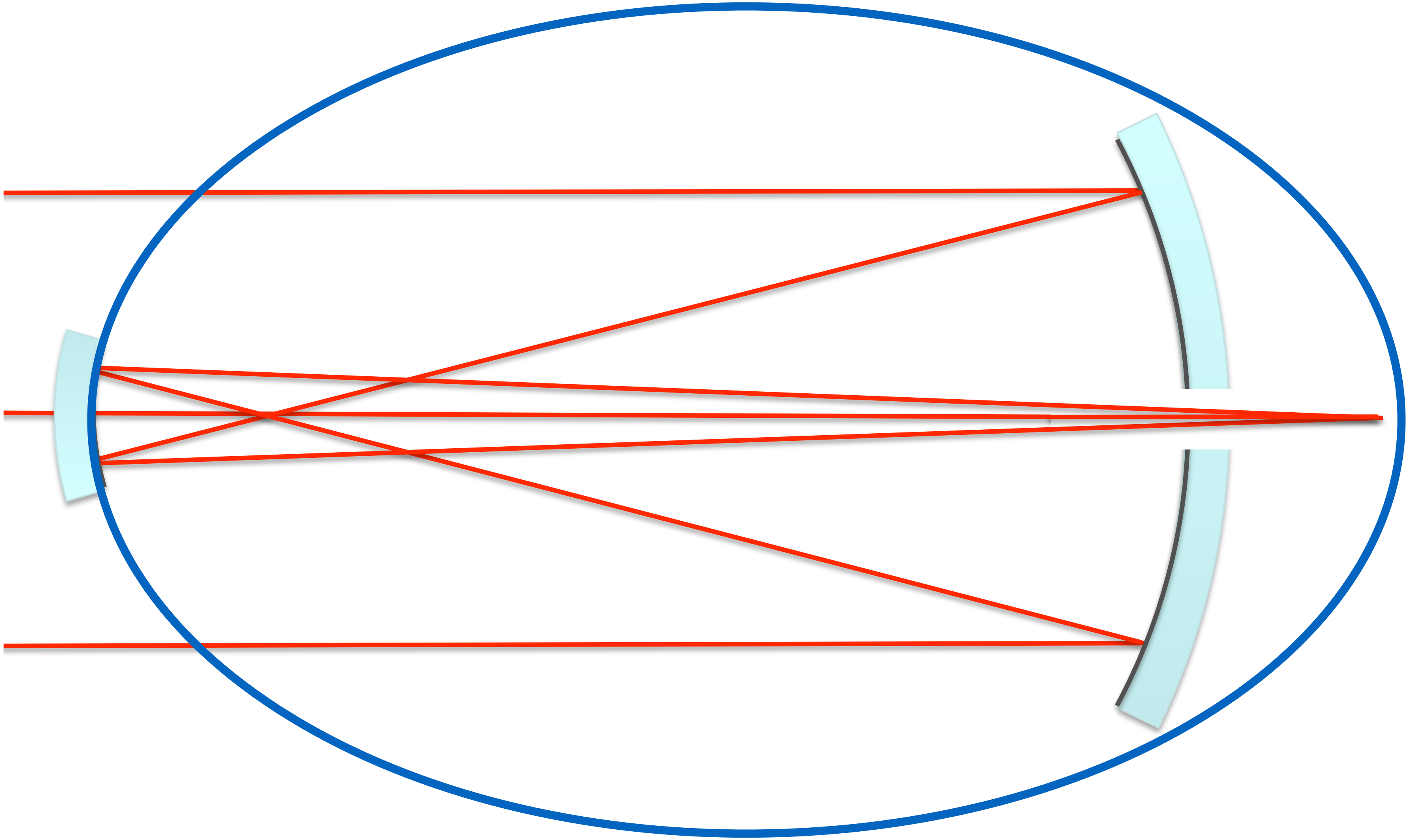


The family of conic mirrors

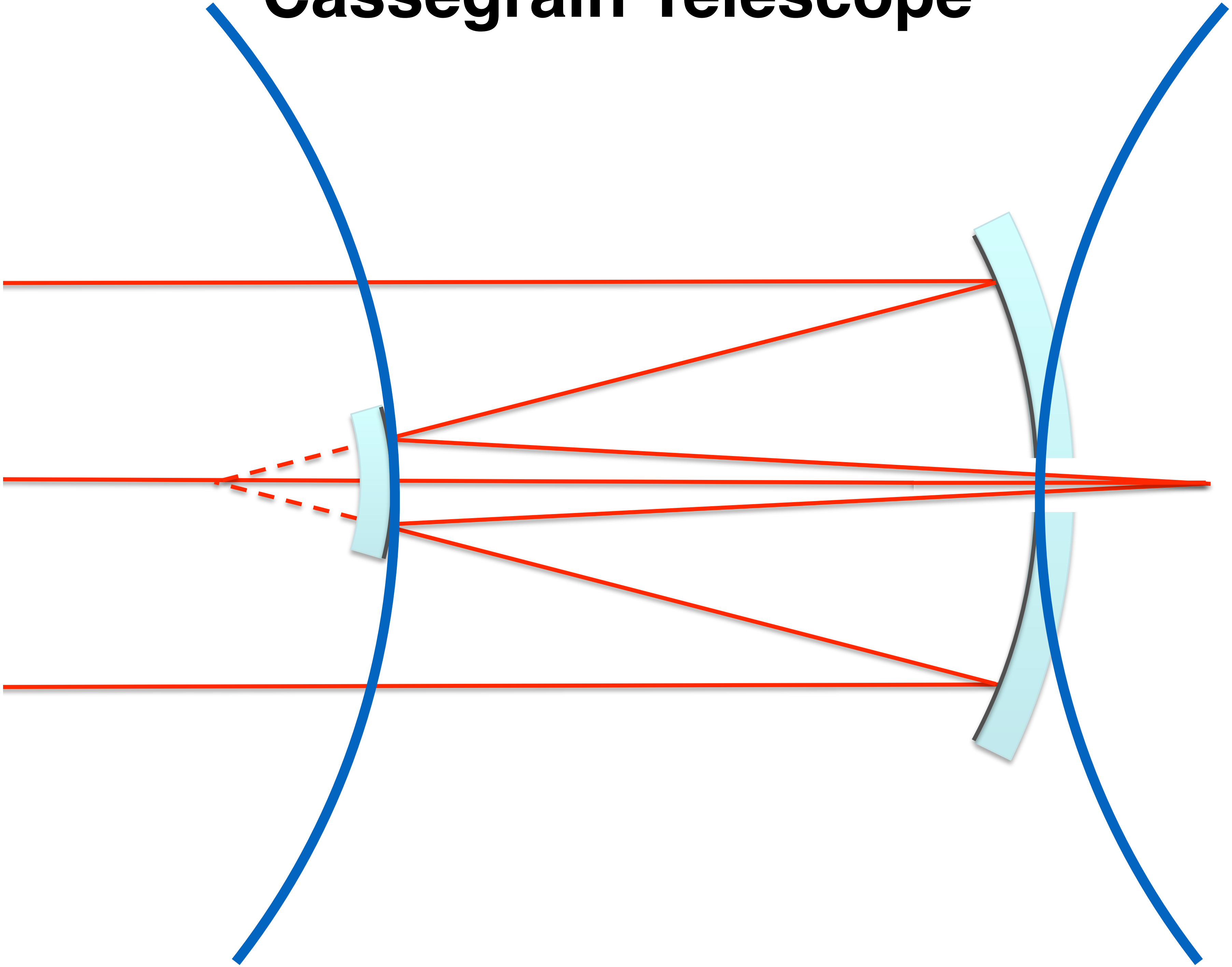


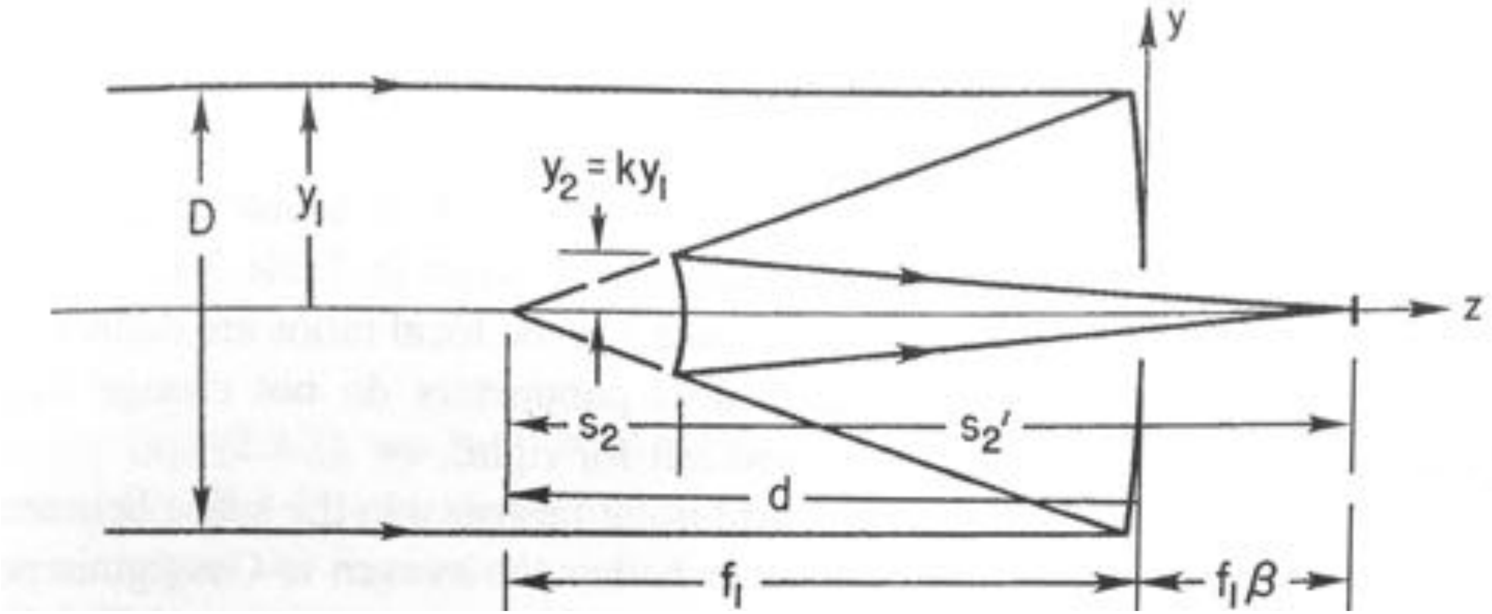
Two finite foci, convex mirror - hyperboloid

Gregorian Telescope

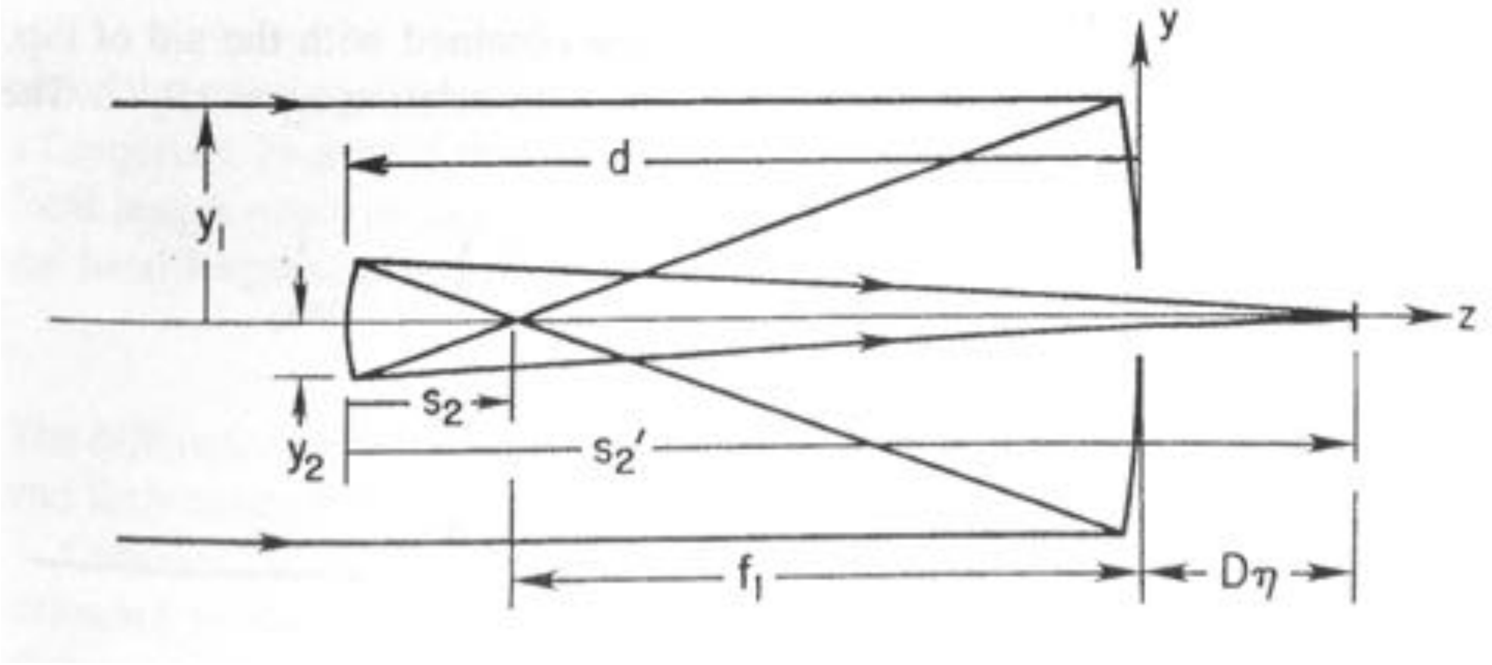


Cassegrain Telescope

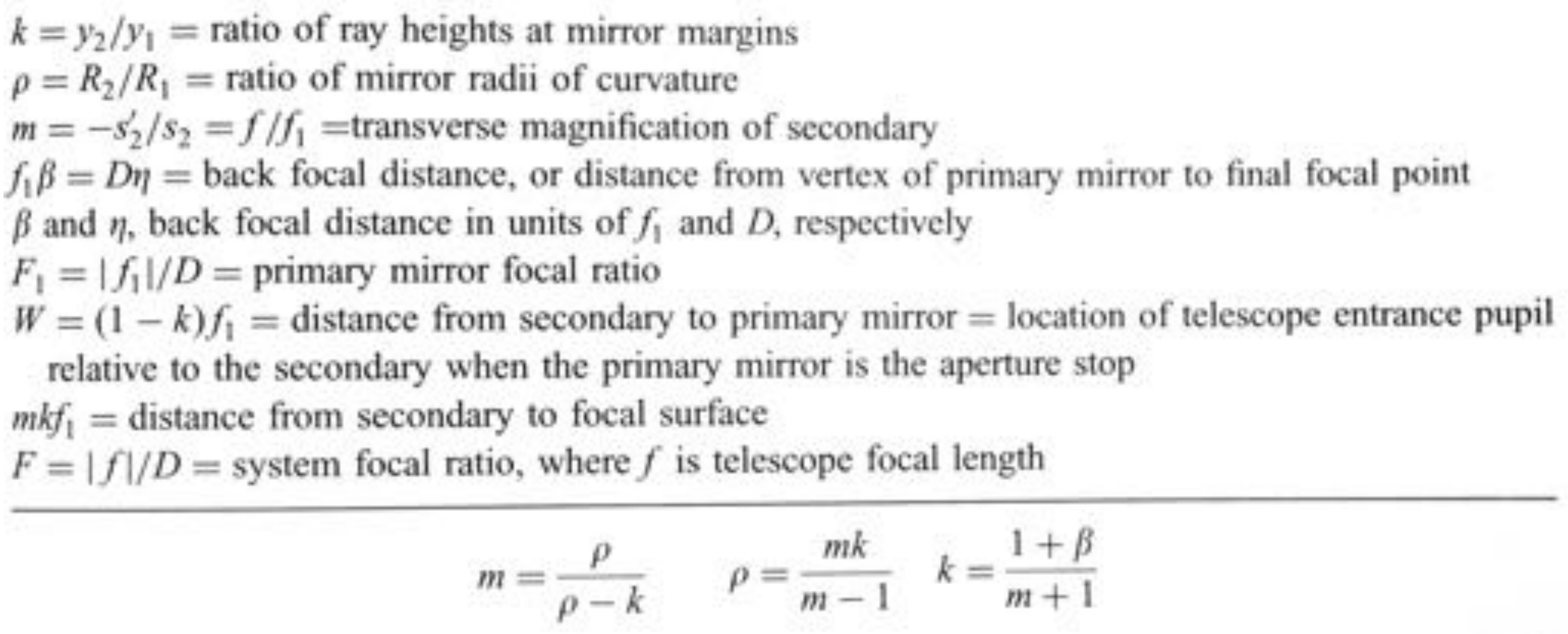




Normalized Parameters for Two-Mirror telescopes



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

---

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

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

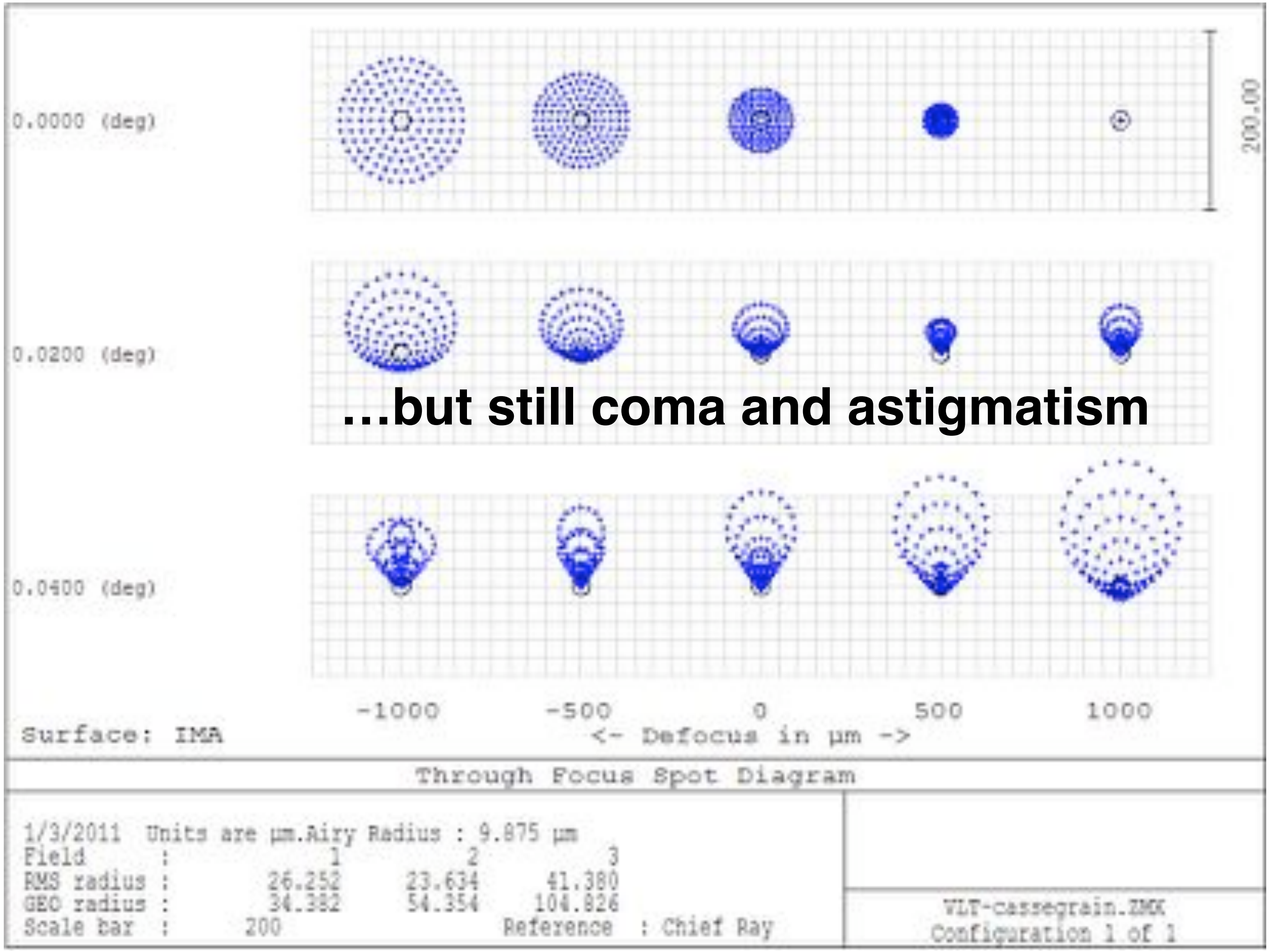
…but still coma and astigmatism

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



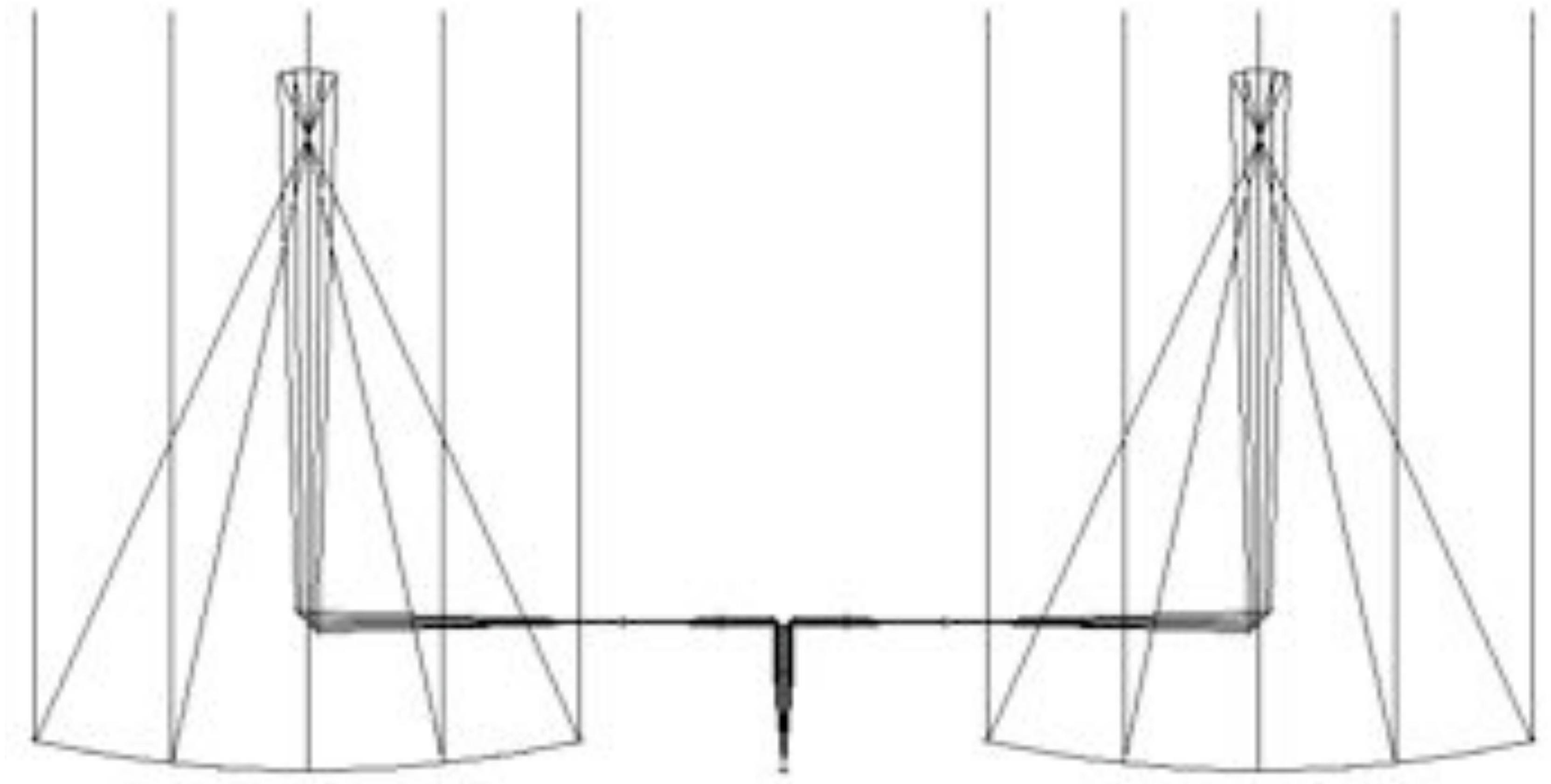
…but still coma and astigmatism

```
Through Focus Spot Diagram

1/3/2011  Units are µm.Airy Radius : 9.875 µm
Field      :          1          2          3
RMS radius :     26.252     23.634     41.380
GEO radius :     34.382     54.354    104.826
Scale bar  :      200            Reference   : Chief Ray

VLT-cassegrain.ZMX
Configuration 1 of 1
```

Gregorian astronomical telescopes

Classical Gregorian uses elliptical secondary

Much longer than equivalent Cassegrain! So why use it?

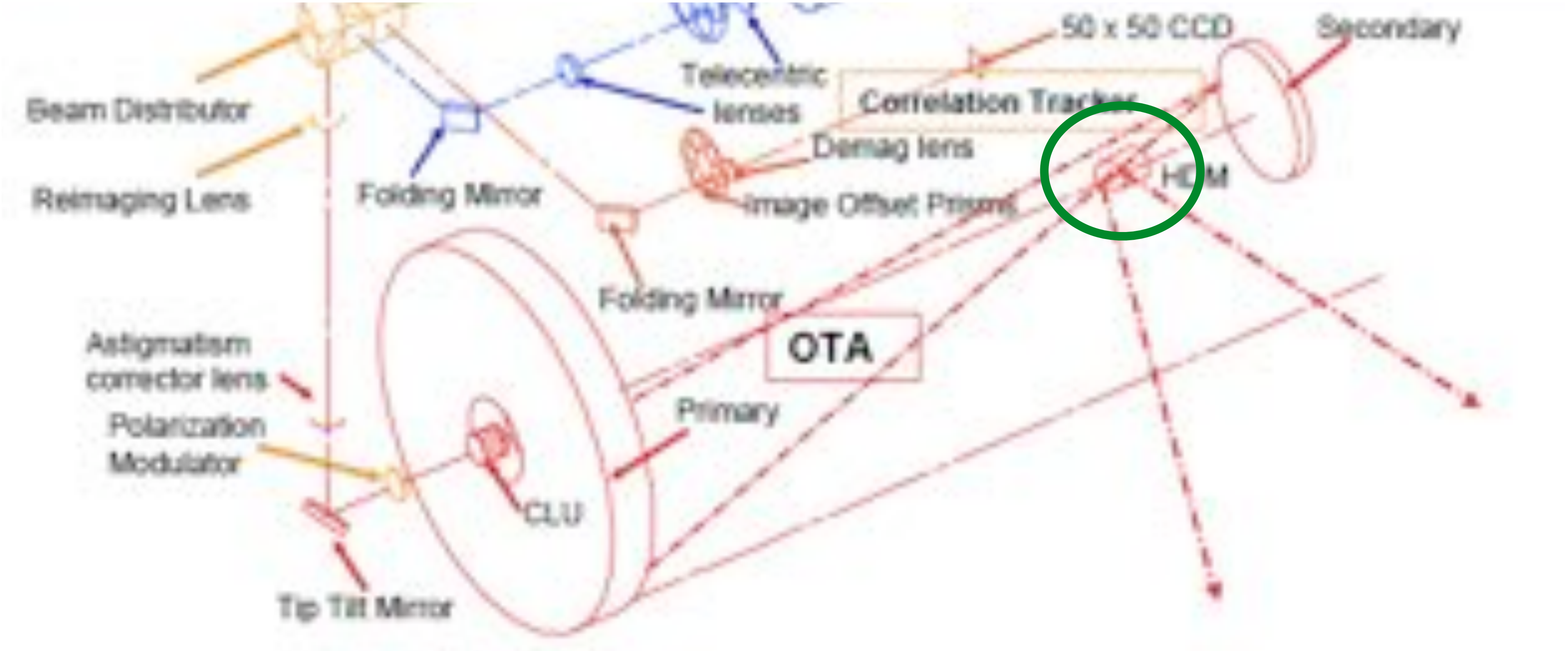


adaptive
secondary
calibrated
from
intermediate
focus

LBT

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 K1 and K2 for zero spherical

Can cancel spherical and coma with the right values

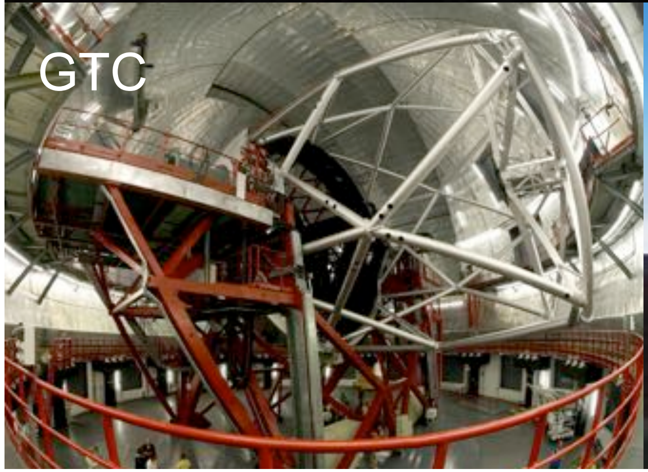
$$K_1 = -1 - \frac{2(1+\beta)}{m^2(m-\beta)}$$

and:

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

Ritchey-Chrétien Telescopes


VLT (4x)


GTC


Subaru Keck (2x)

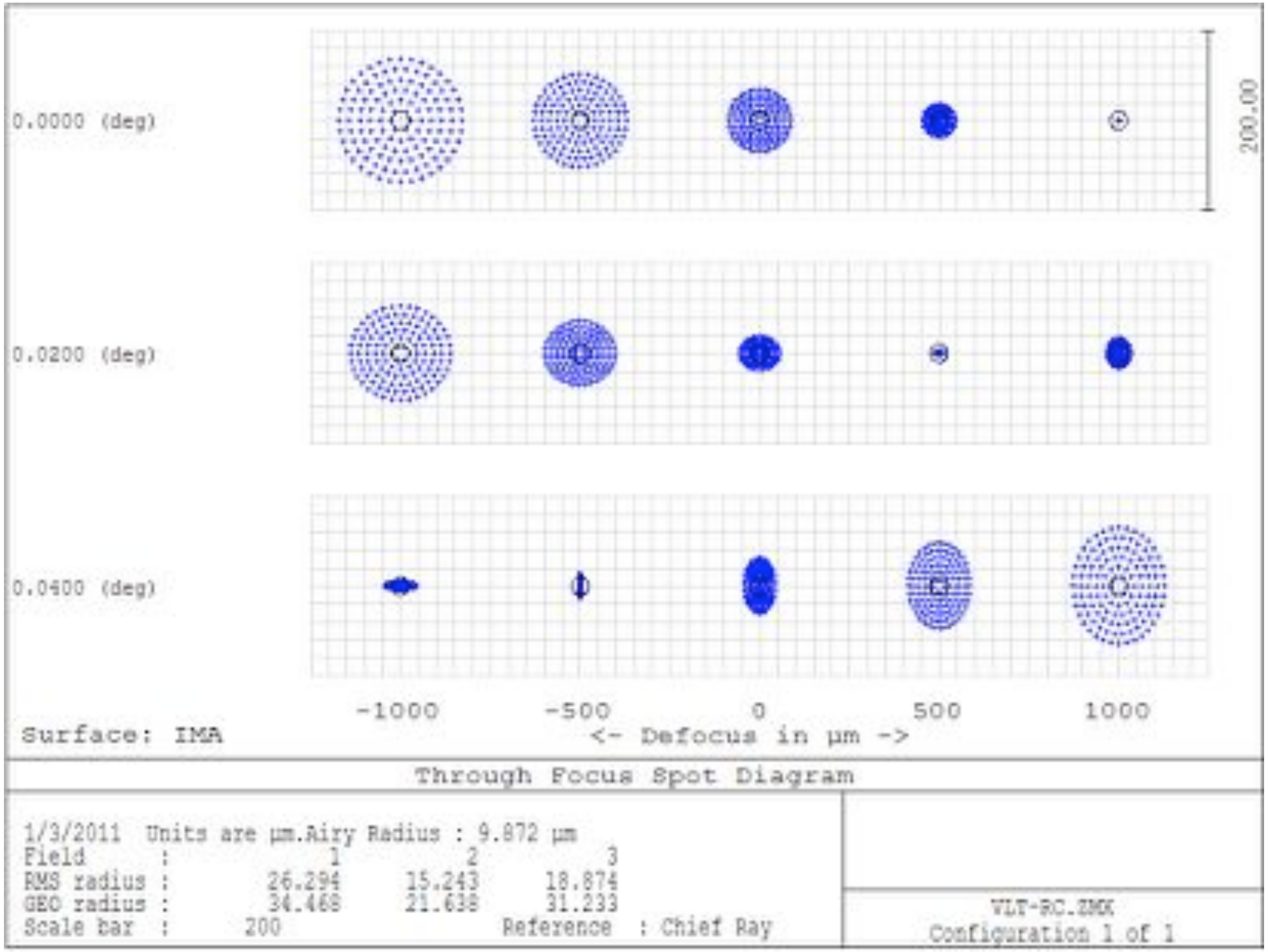

Gemini (2x)

Ritchey-Chrétien Telescope

Infinite combination of K1 and K2 for zero spherical

VLT

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



```
1/3/2011  Units are µm.Airy Radius : 9.872 µm
Field      :          1          2          3
RMS radius :     26.294     15.243     18.874
GEO radius :     34.468     21.638     31.233
Scale bar  :    200               Reference   : Chief Ray
```

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

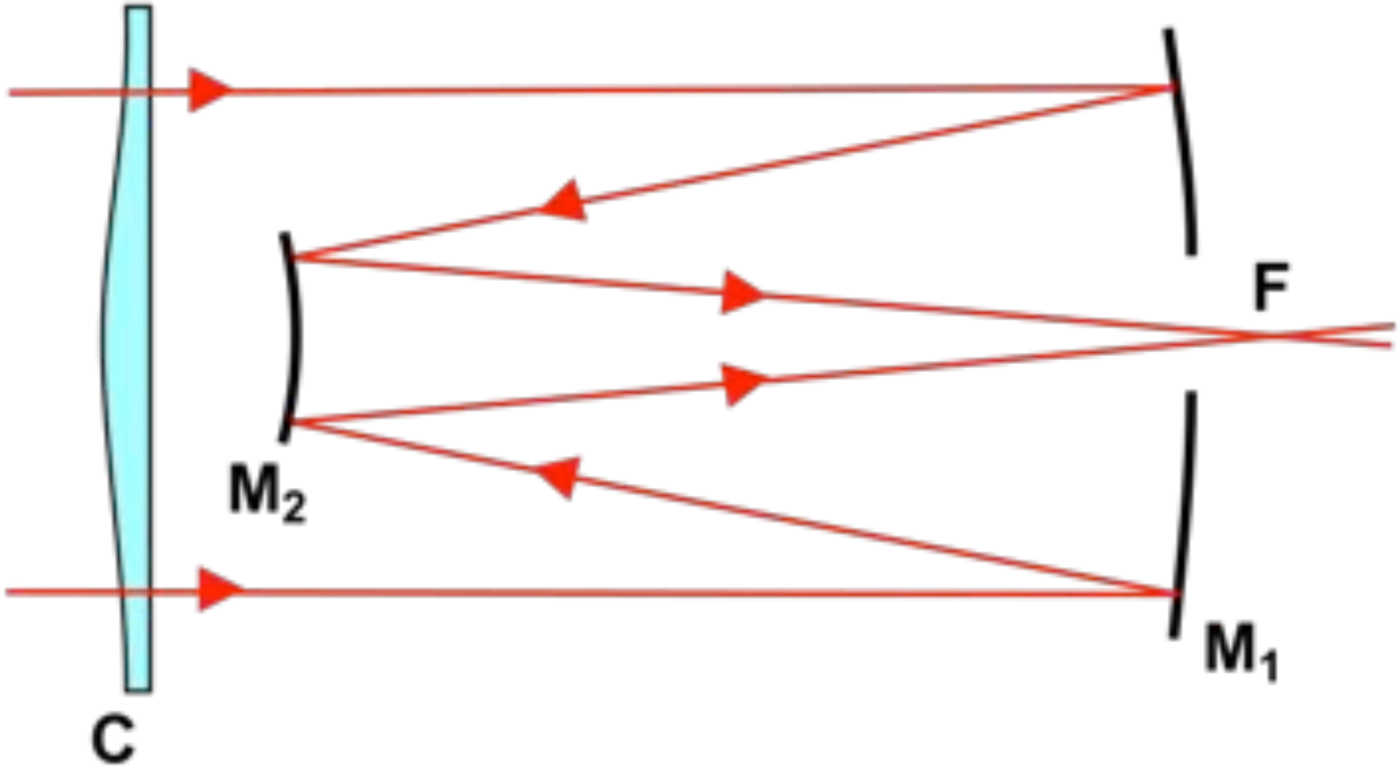
Two Mirror Telescope aberrations

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

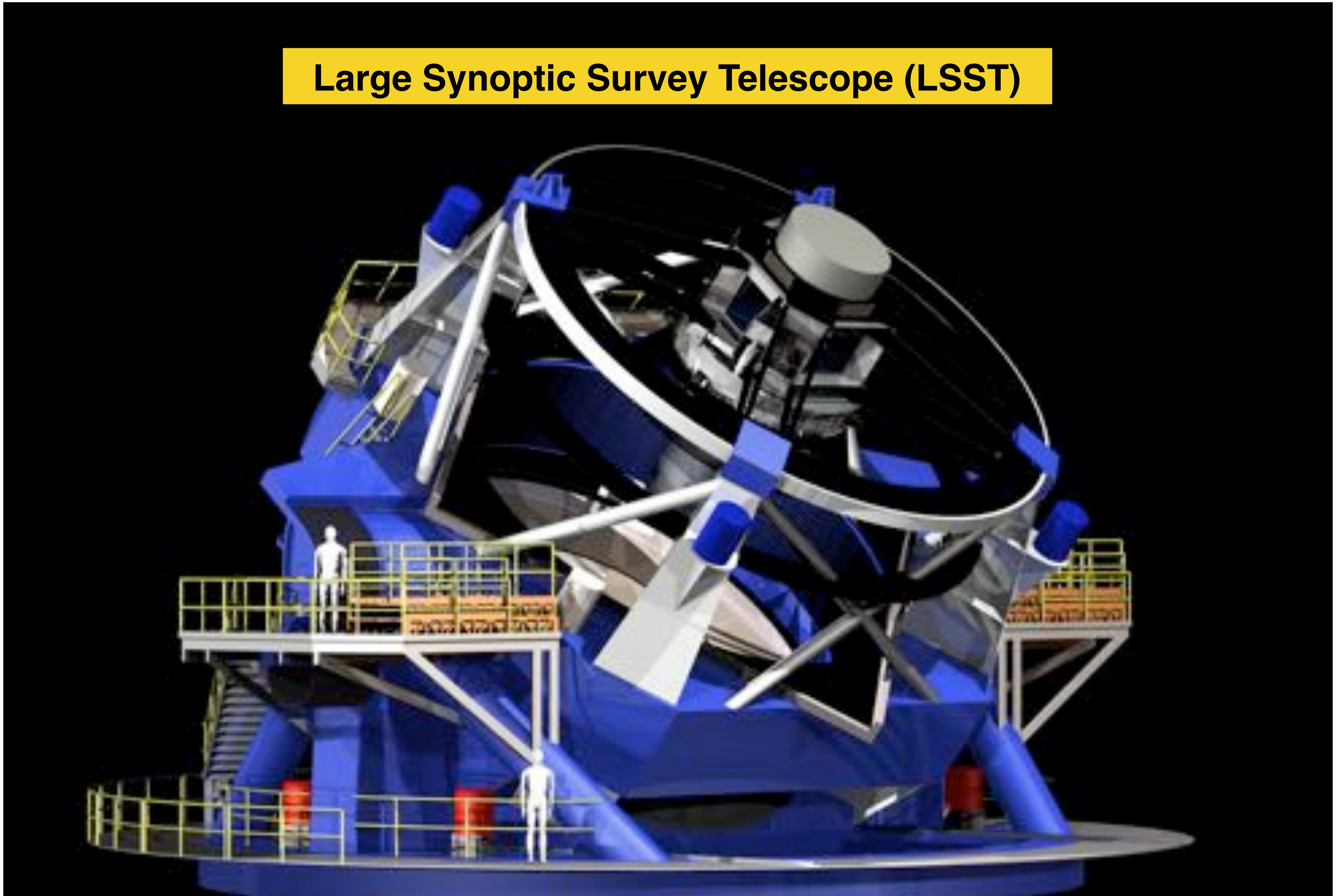


Schmidt-Cassegrain

Wide field telescopes

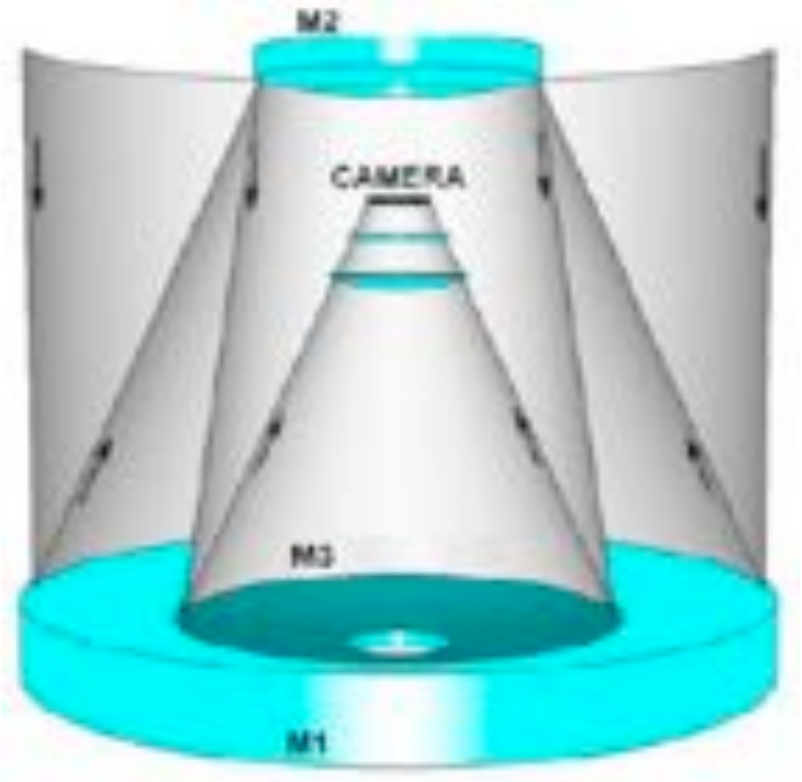
Three Mirror Anastigmat (TMA)

fixes spherical, coma, astigmatism with three conic constants

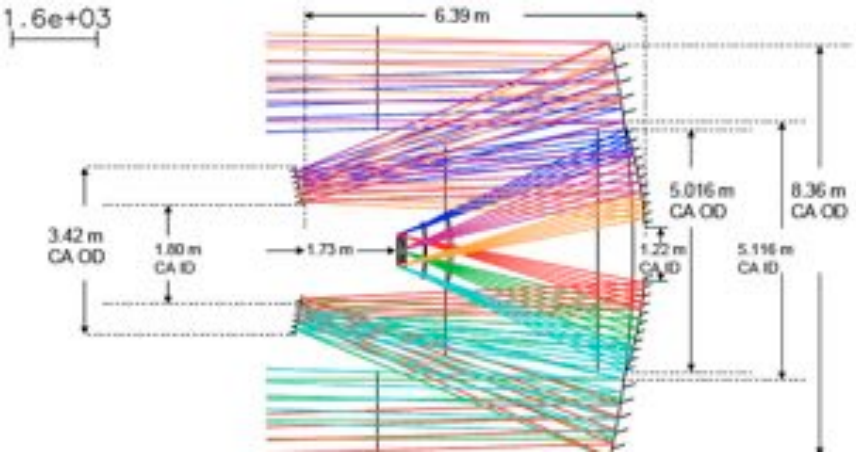


Wide field telescopes

M1 and M3 polished out of same blank!

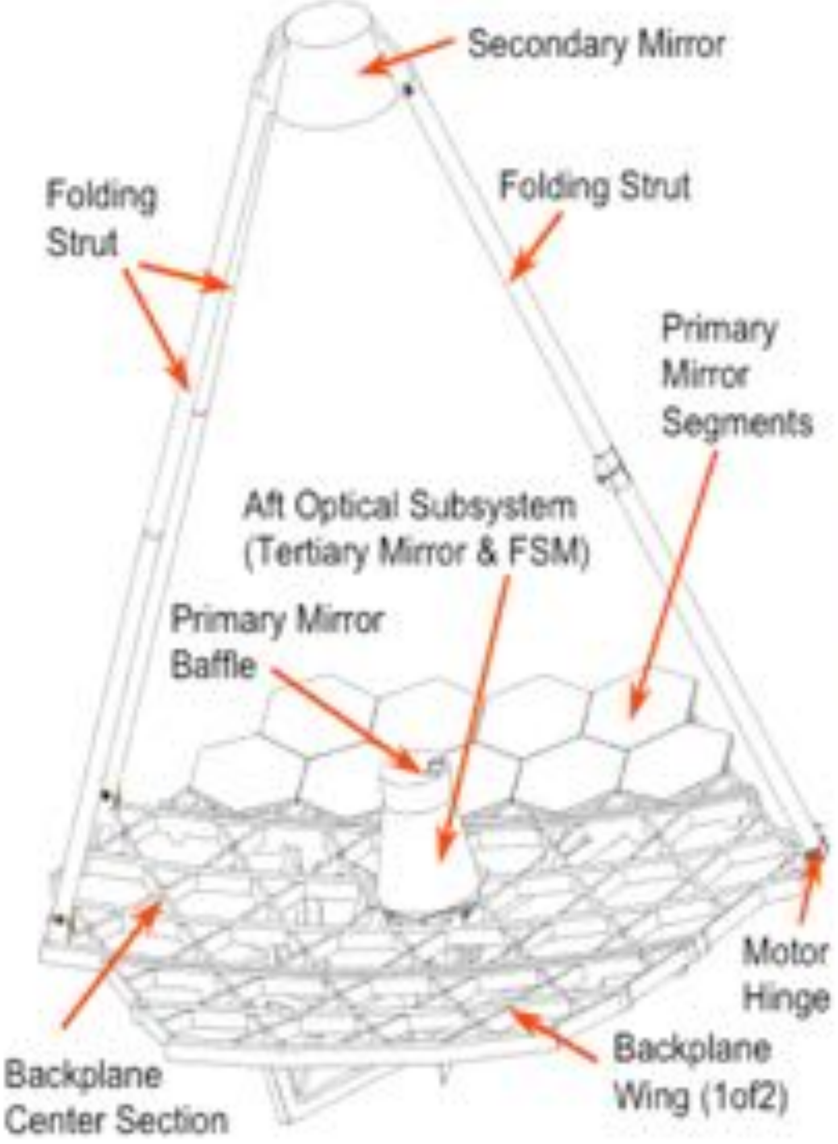


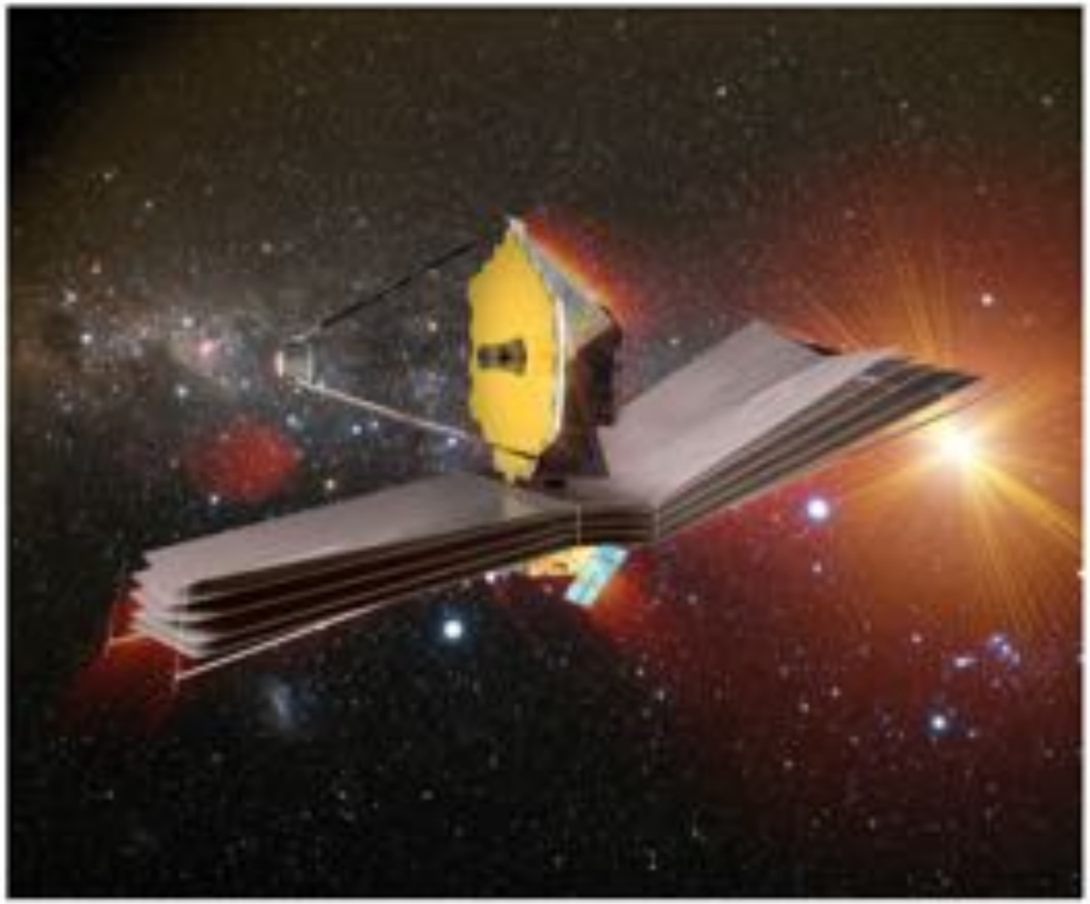
LSS



Wide field telescopes

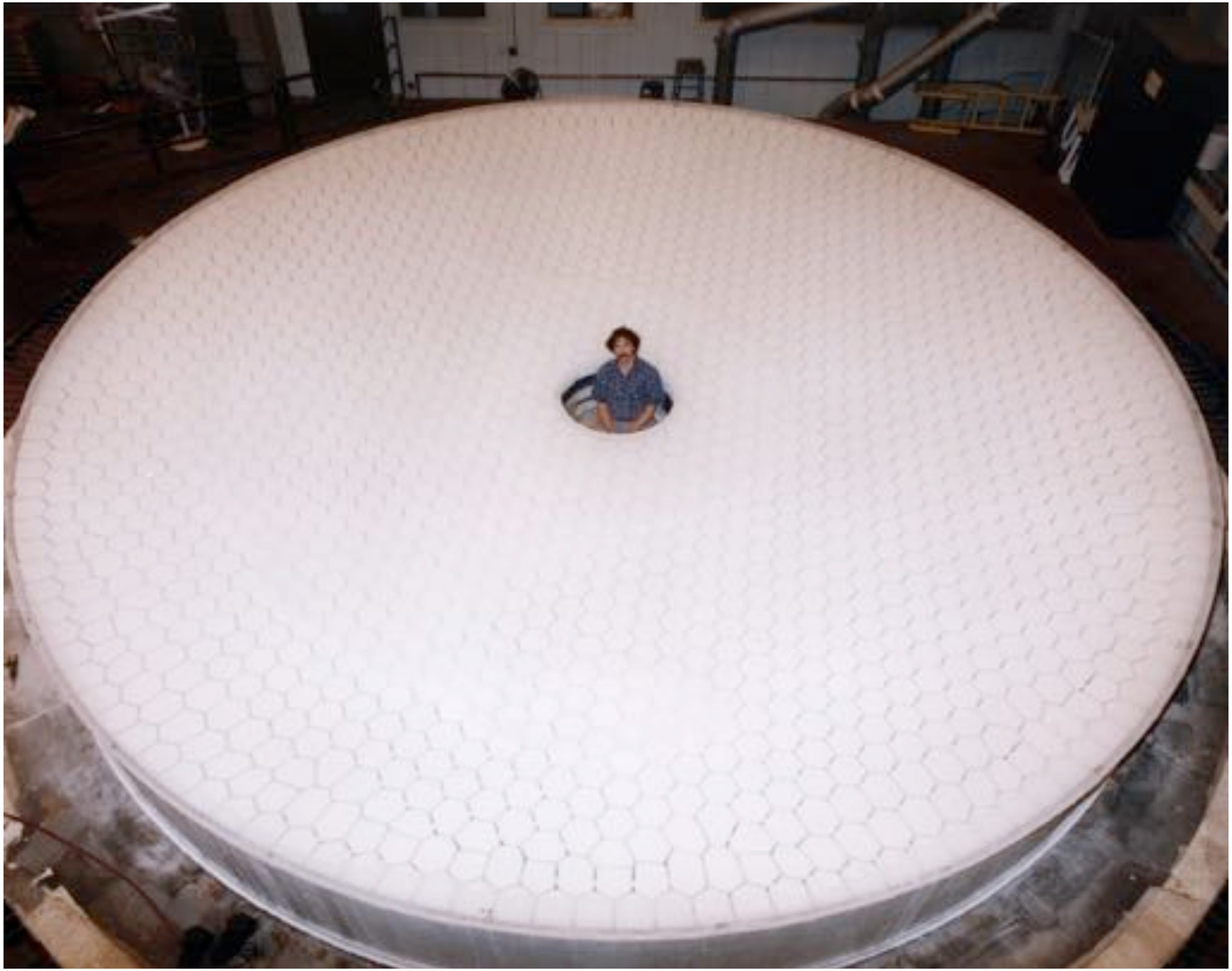
James Webb Space Telescope (JWST)





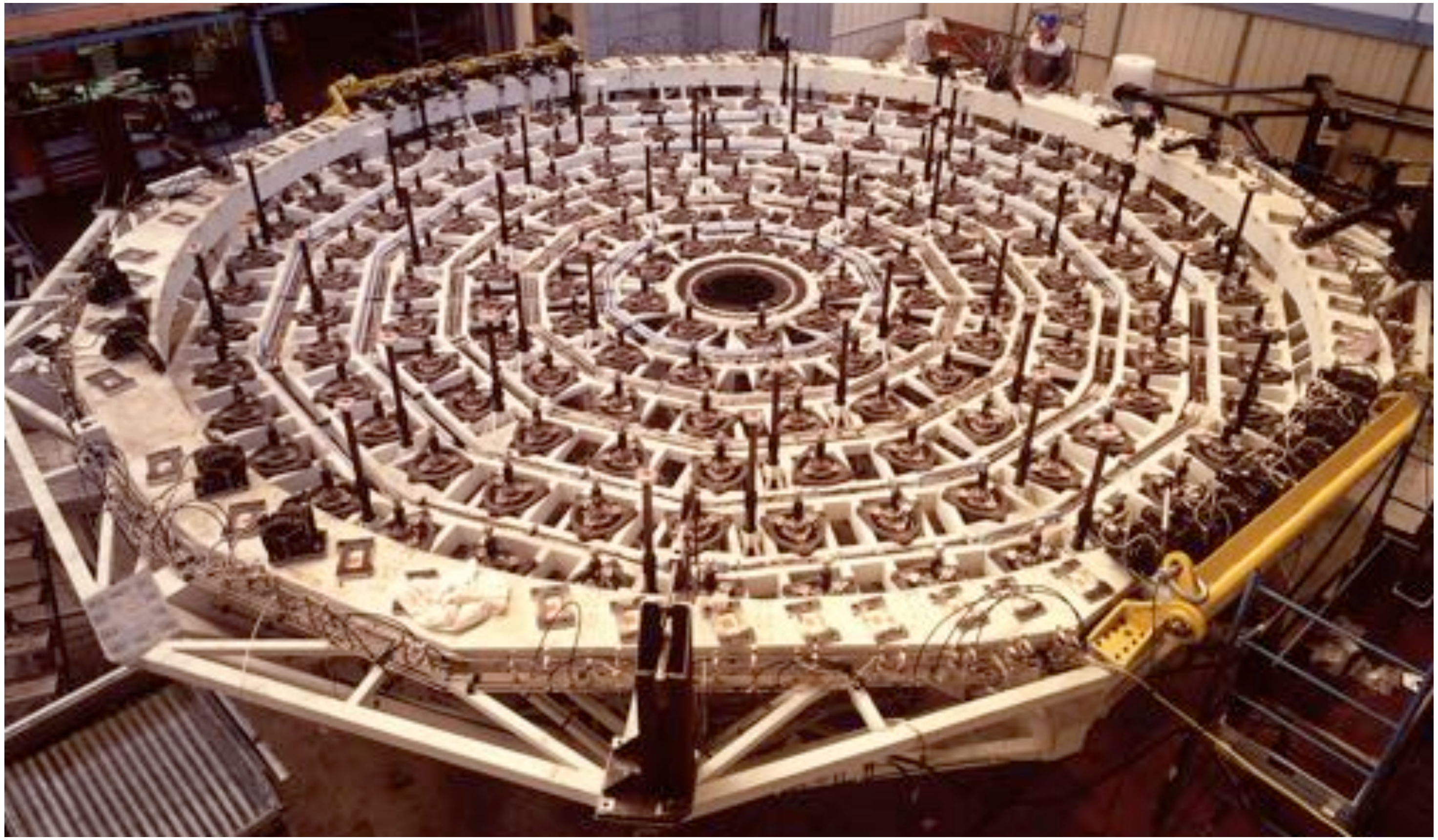
Largest Monolithic Mirrors

Spin-casting mirrors in Arizona



Cooling Primary Mirrors

Thin primary mirrors deform, so active support required



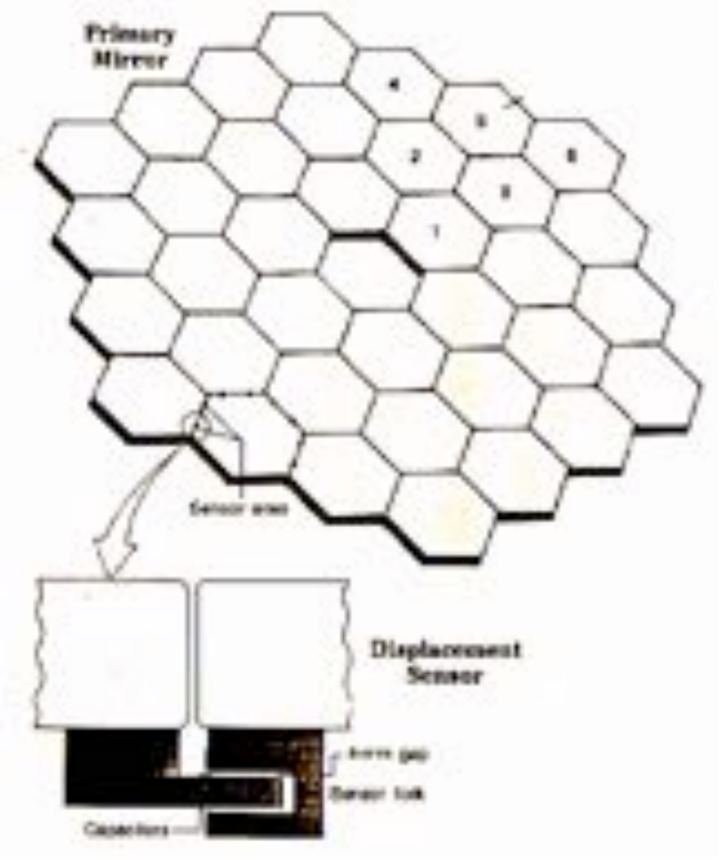
Temperature control with air jet cooling

Arizona Mirror Laboratory

Segmented Primary Mirrors

Individual mirrors easy to manufacture

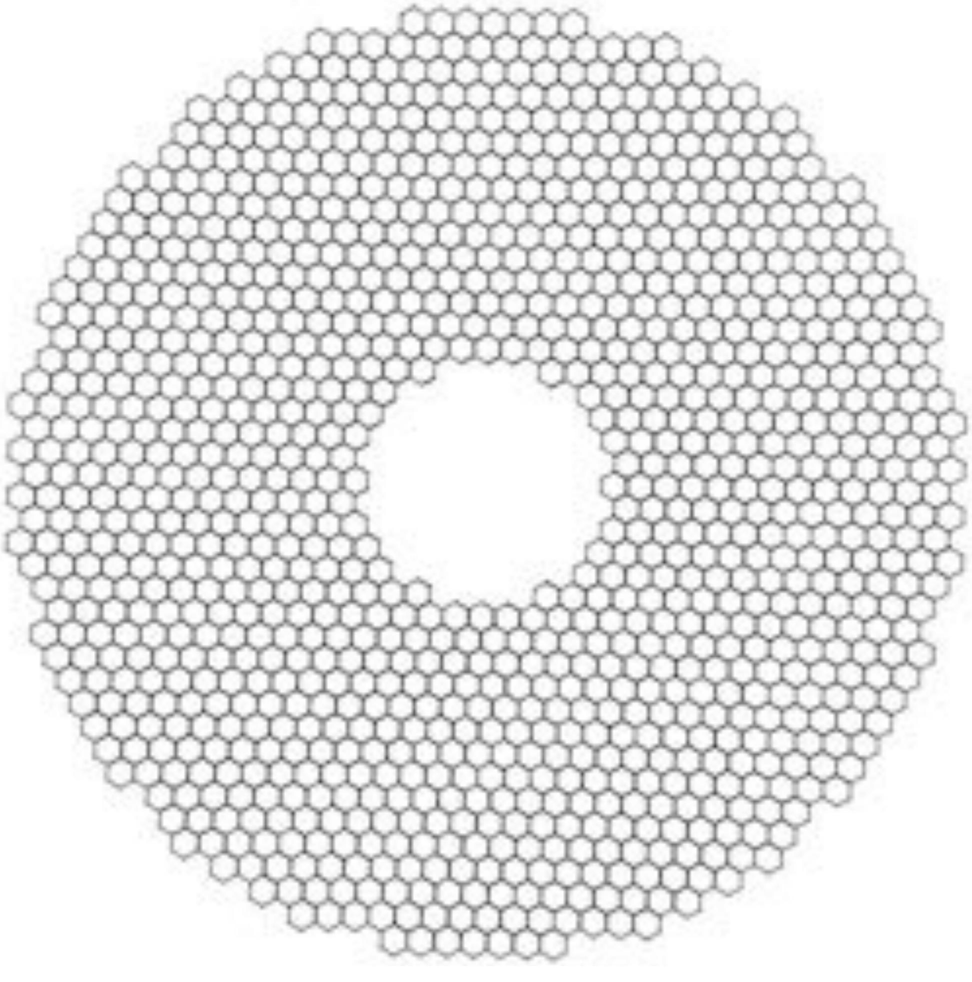
Keck I and II

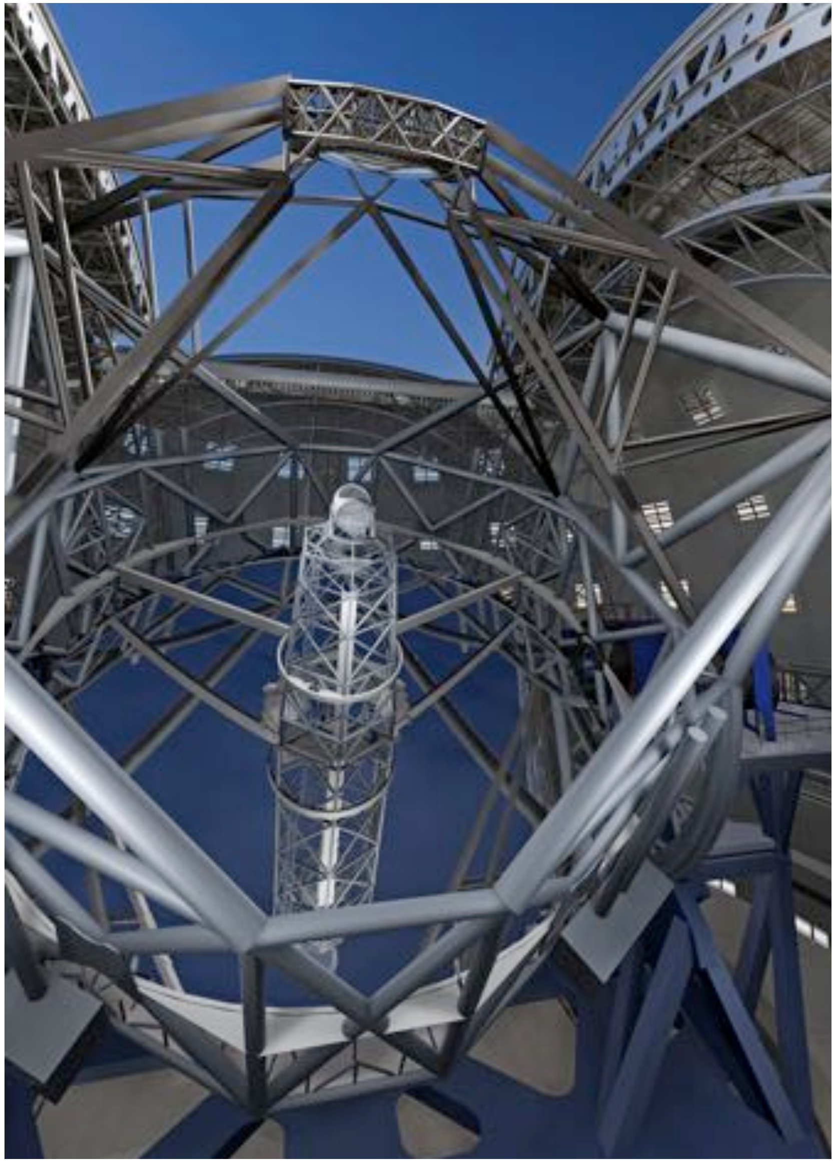


Segmented Primary Mirrors

Individual mirrors easy to manufacture

E-ELT: 984 1.4-m segments



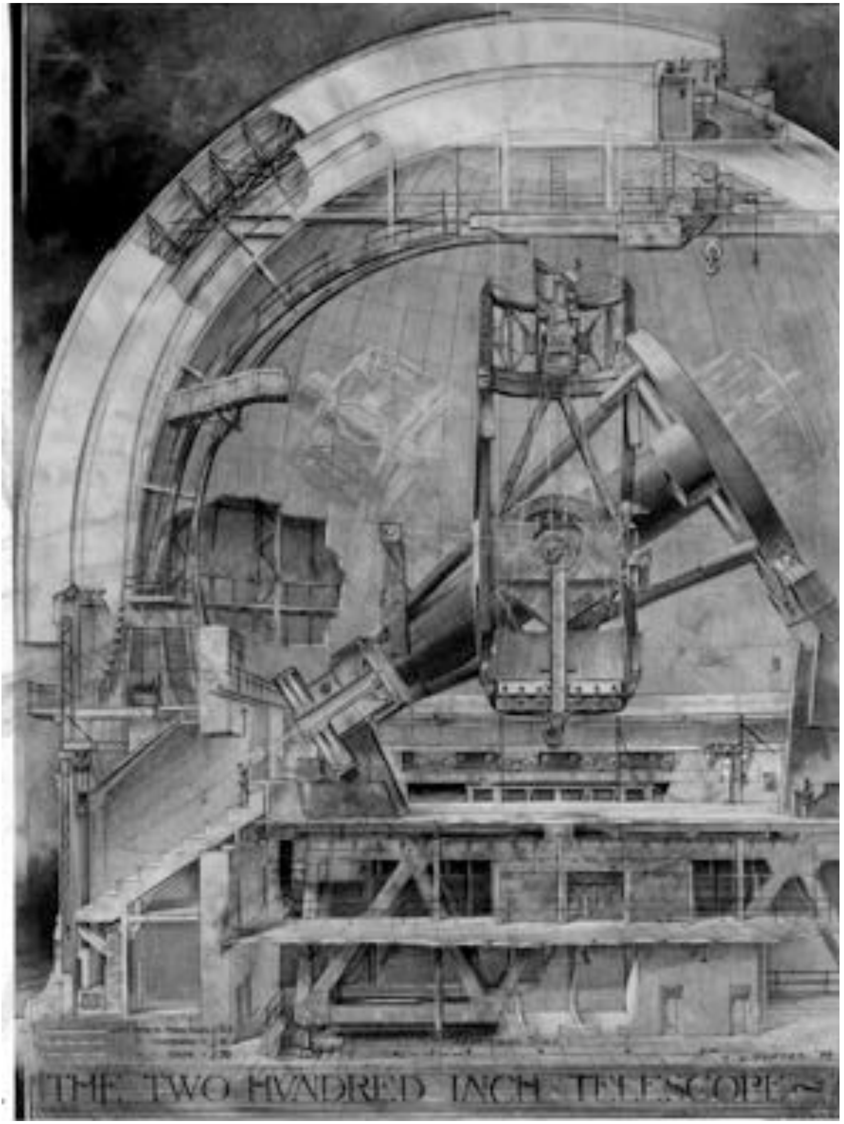


Equatorial Mounts

Only one axis to guide

- equatorial (RA, dec)

Hale 200” @ Palomar



Equatorial Mounts

Only one axis to guide

- equatorial (RA, dec)

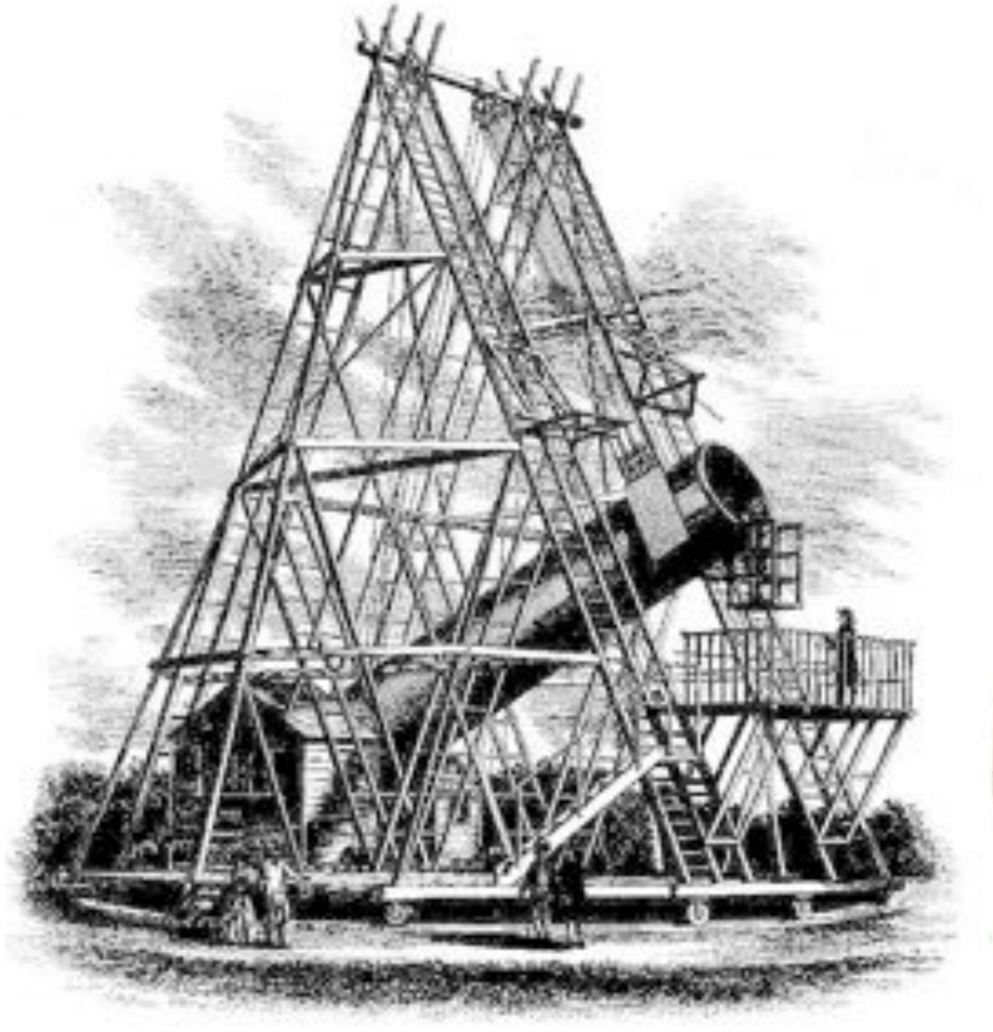
Dutch Open Telescope

ESO 3.6m telescope

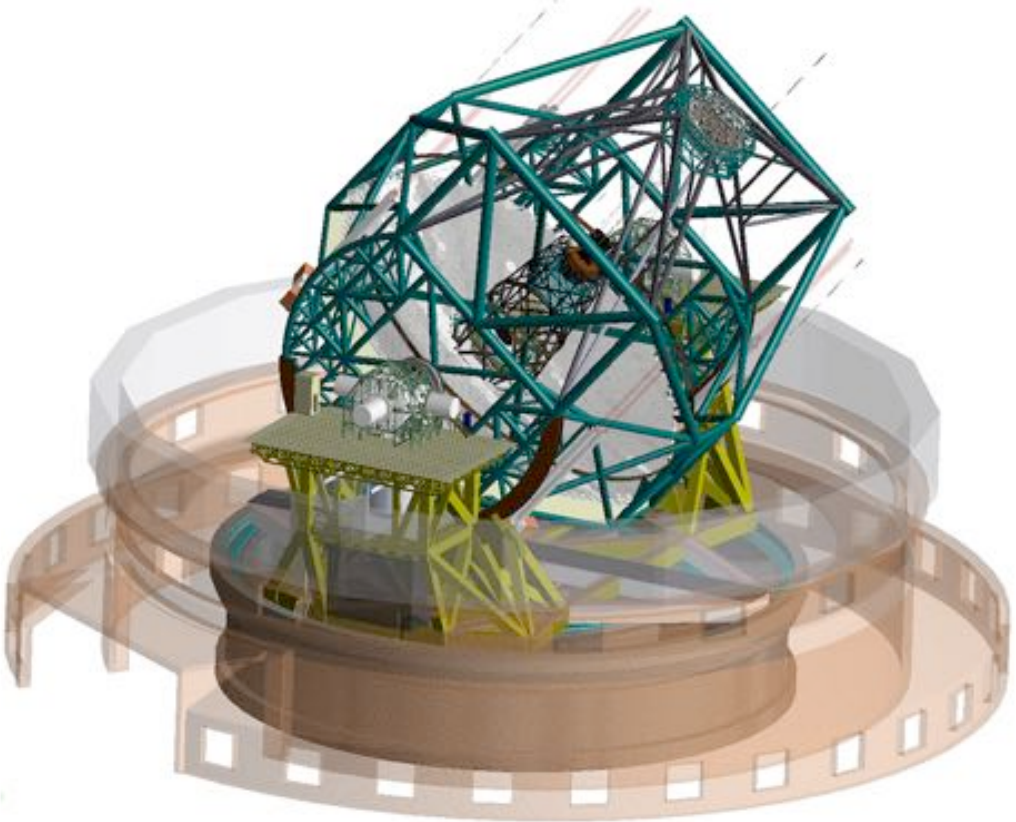
Alt-Az mounts

Computer controllers make this preferred option

Zenith inaccessible due to azimuth drive speed



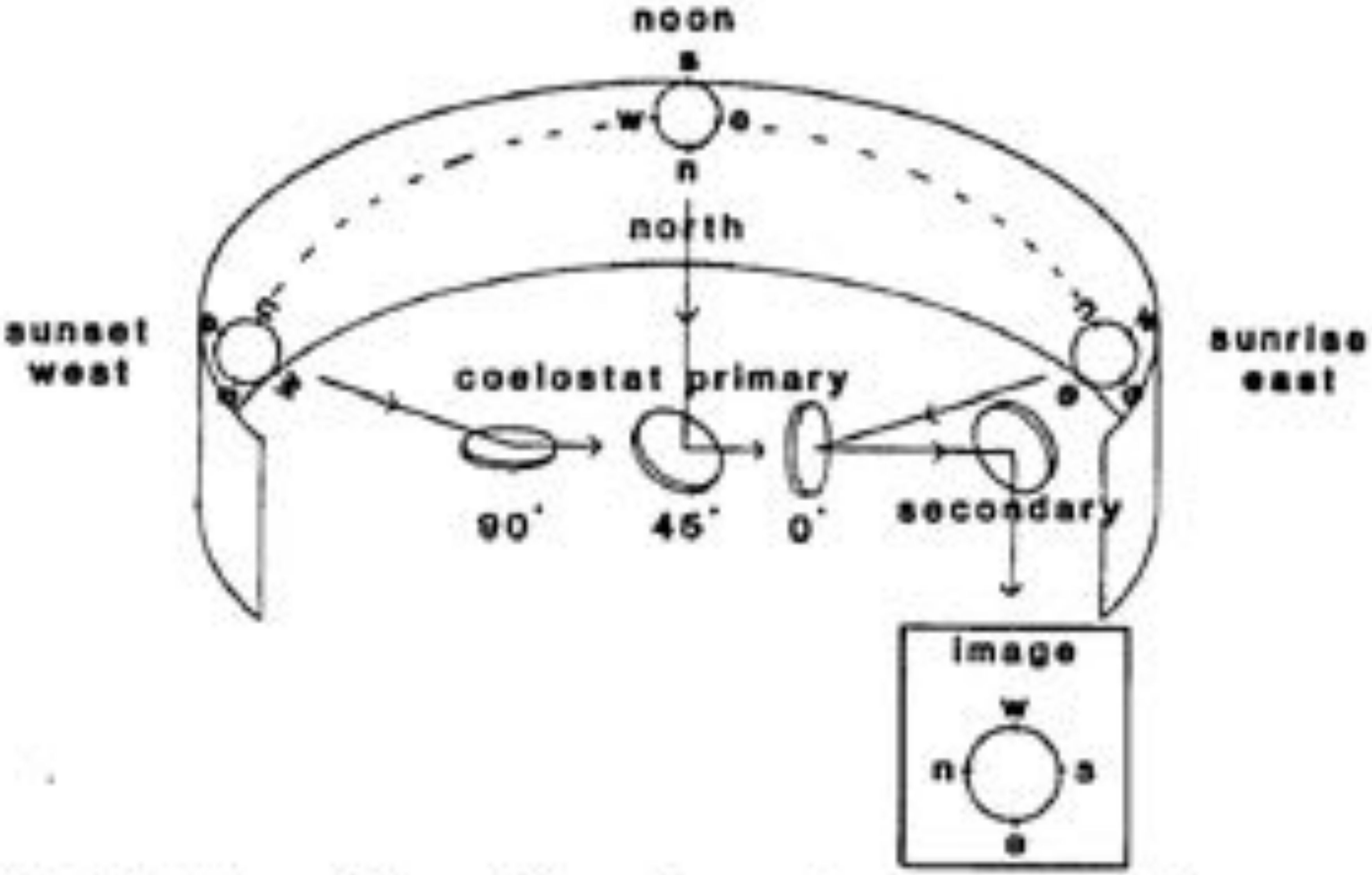
Herschel 1789



E-ELT (2026)

Derotation

Sky rotates with hour angle



Rotation speed is variable

Sky rotates with hour angle

- δ = source declination
- φ = telescope lattitude

- alt-az at Cassegrain focus:

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

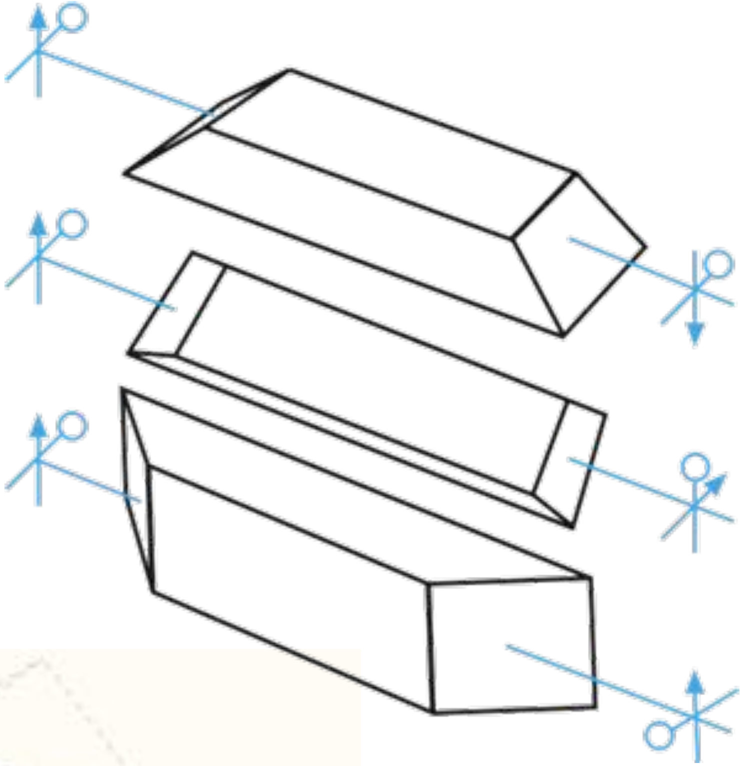
- alt-az at Nasmyth (or Coudé) platform:

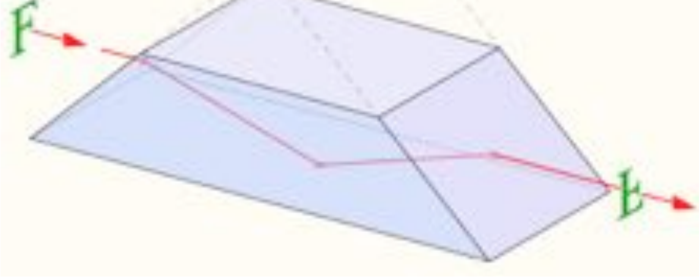
$$\vartheta_{\mathrm{Nasmyth}} = alt - \vartheta_{\mathrm{cass.}} \ (- \, az)$$

Derotating the field of view

Sky rotates with hour angle

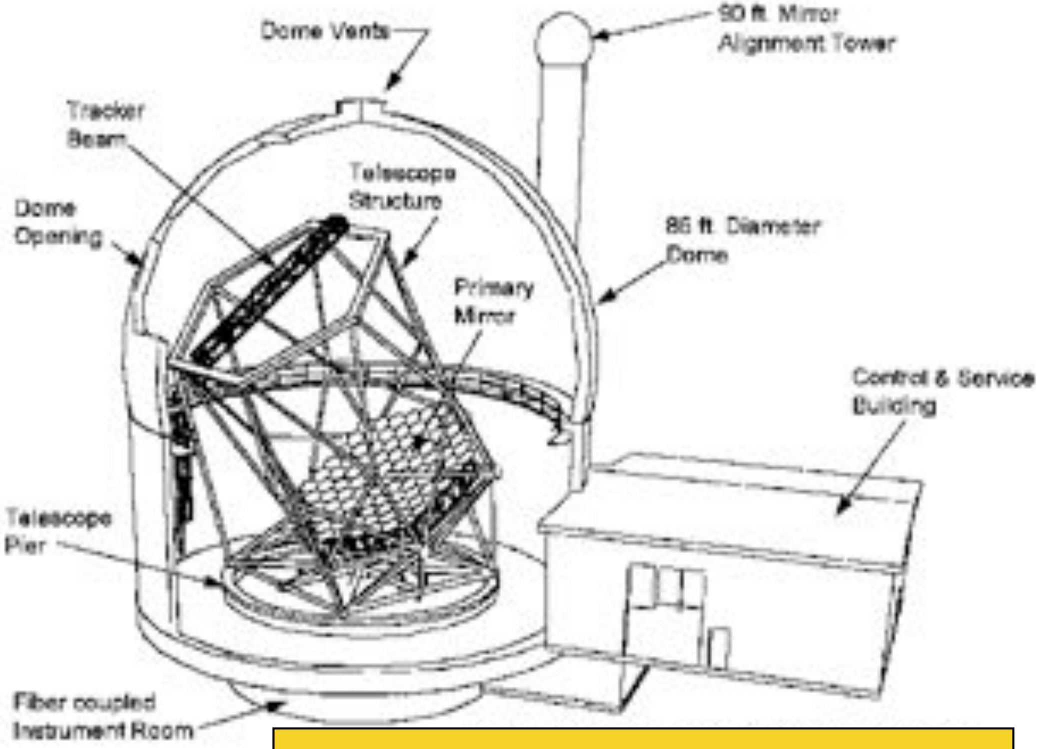
- rotate entire instrument
- derotator
  - K-mirror
  - Dove prism
  - anything rotatable with an odd number of reflections



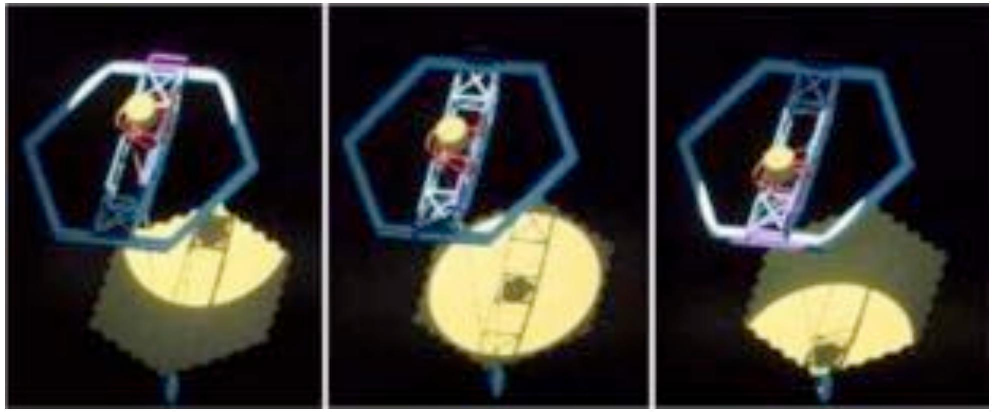


Fixed elevation telescopes

Southern African Large Telescope (SALT)



Hobby-Everly Telescope (HET)



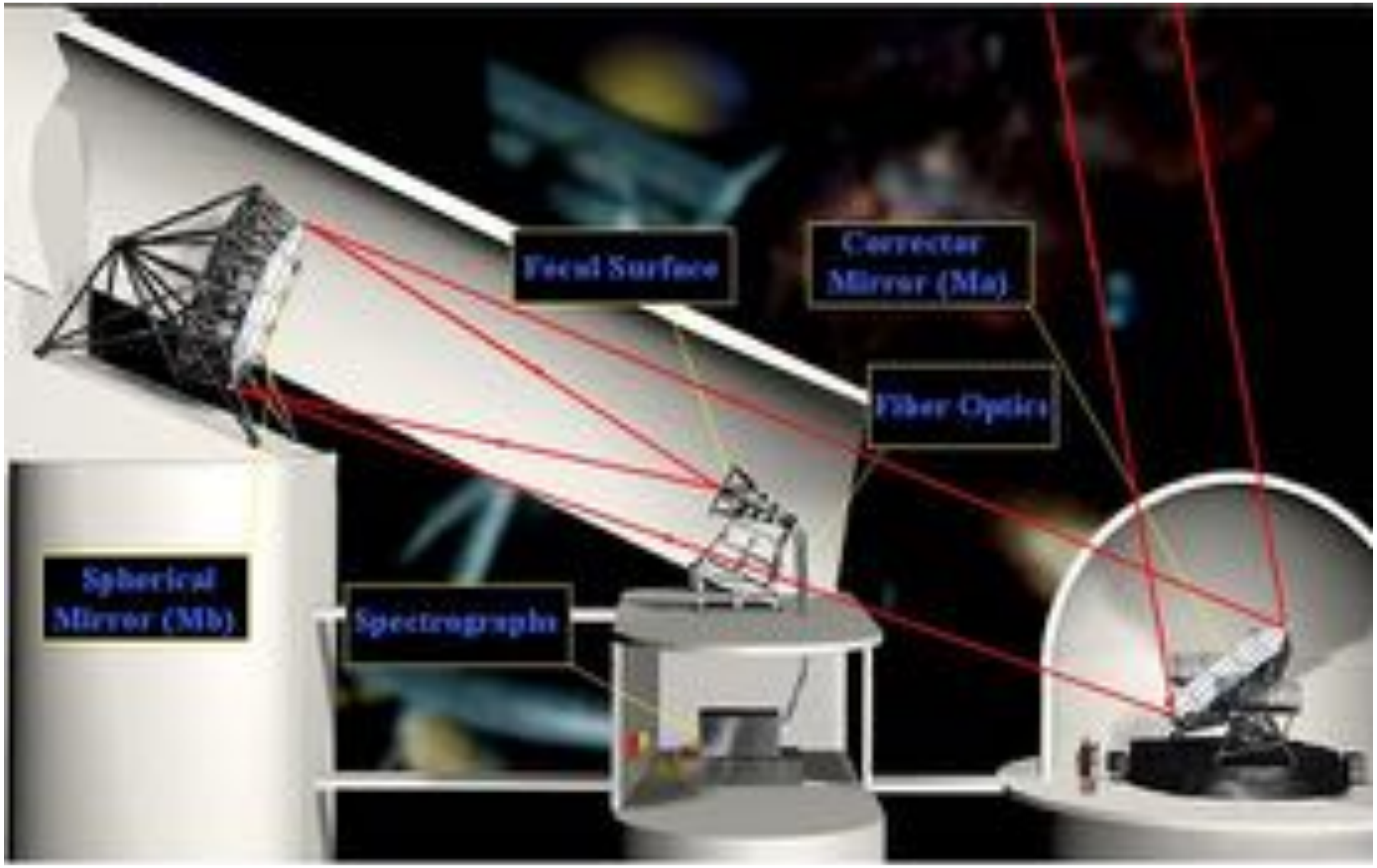
Coelostat

Only one mirror to steer across sky

LAMOST (China)

Coelostat

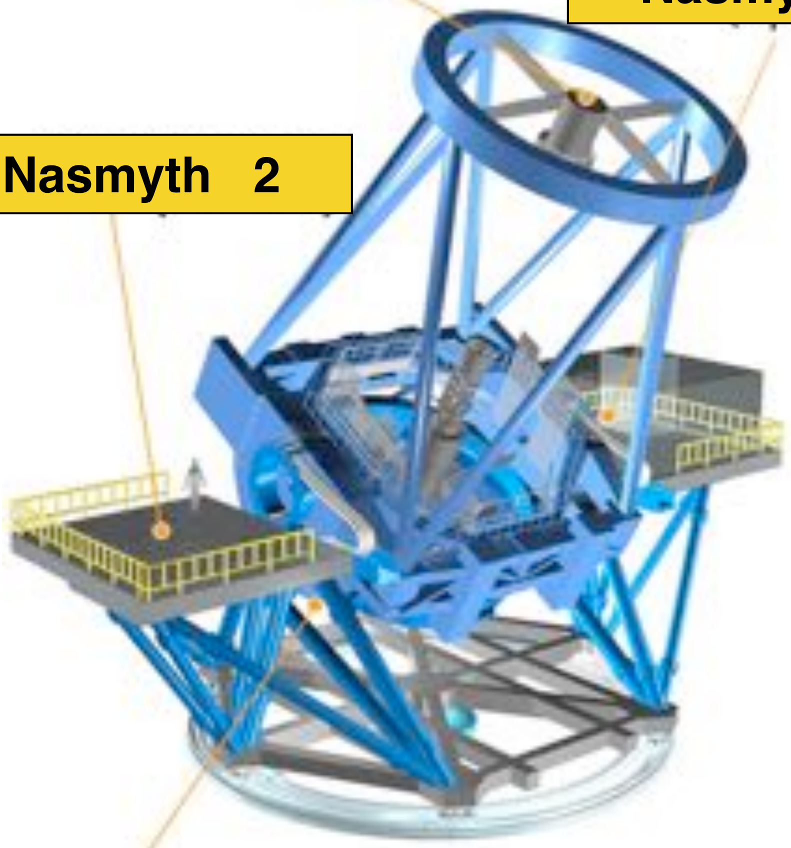
Only one mirror to steer across sky



LAMOST (China)

Focal stations

Subaru



Prime

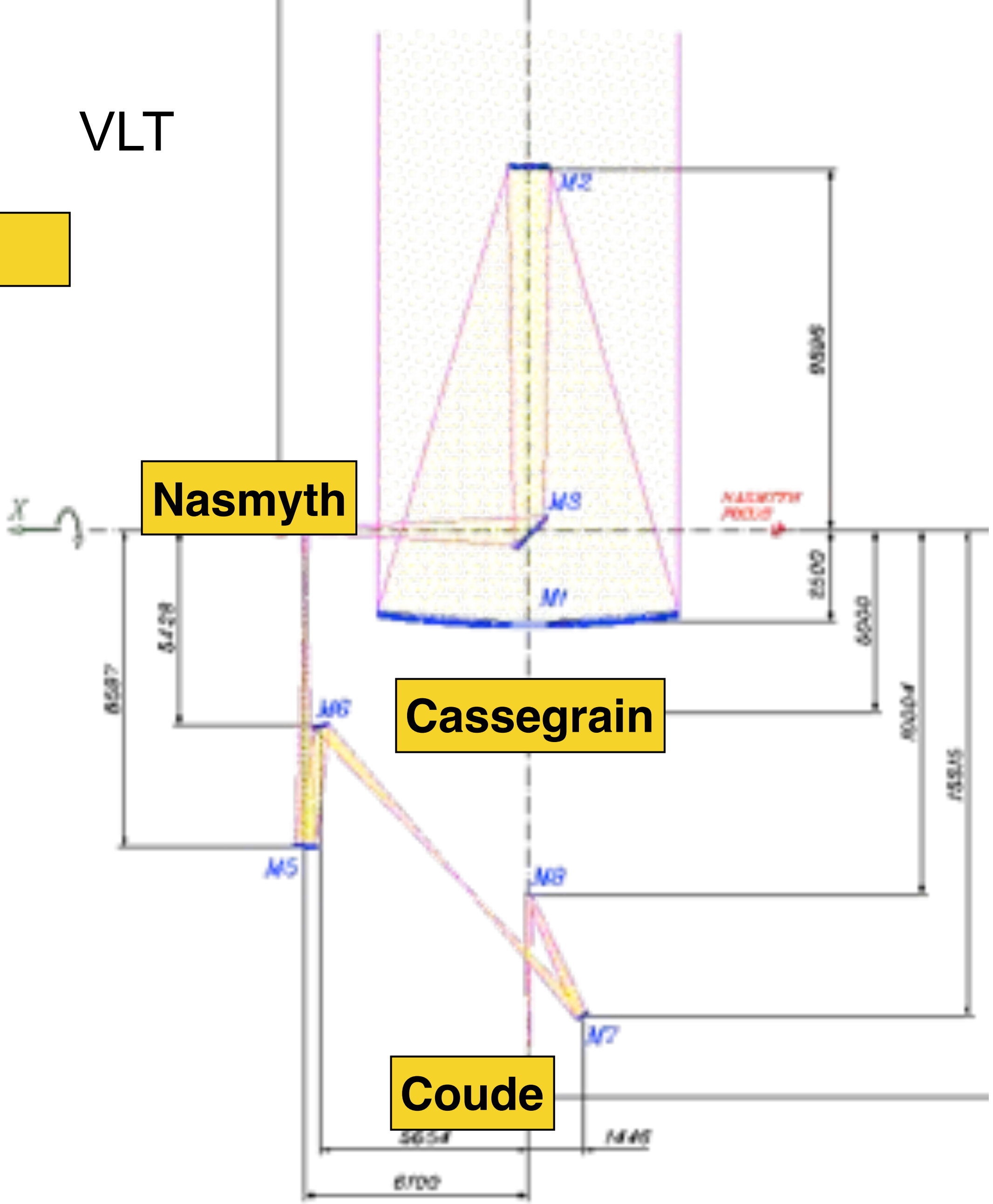
Nasmyth 1

Nasmyth 2

Cassegrain

(c) MELCO Corporation Japan

VLT



Nasmyth

Cassegrain

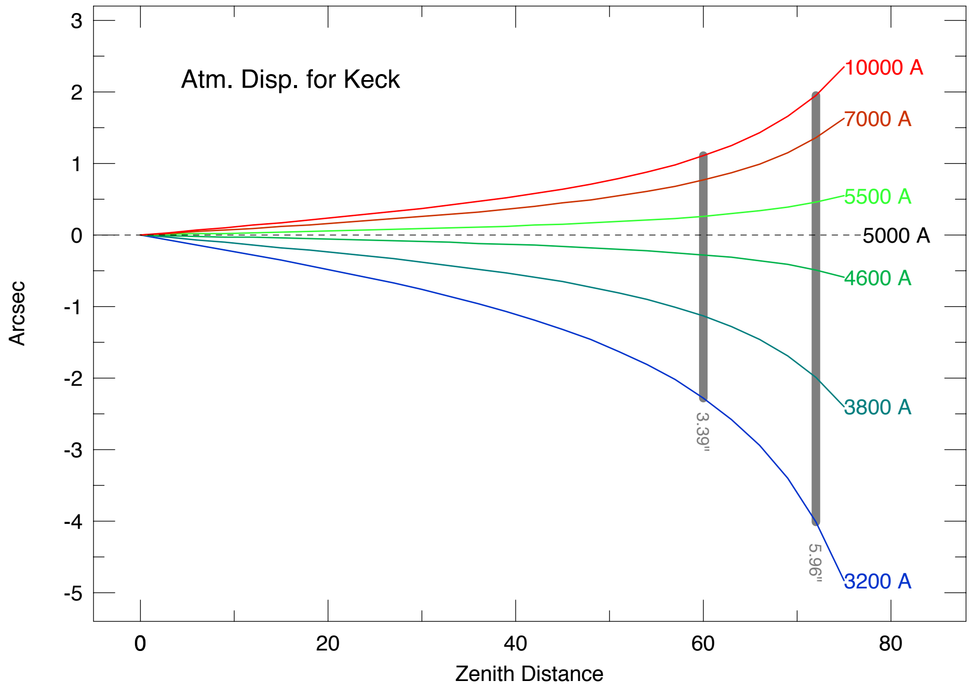
Coude

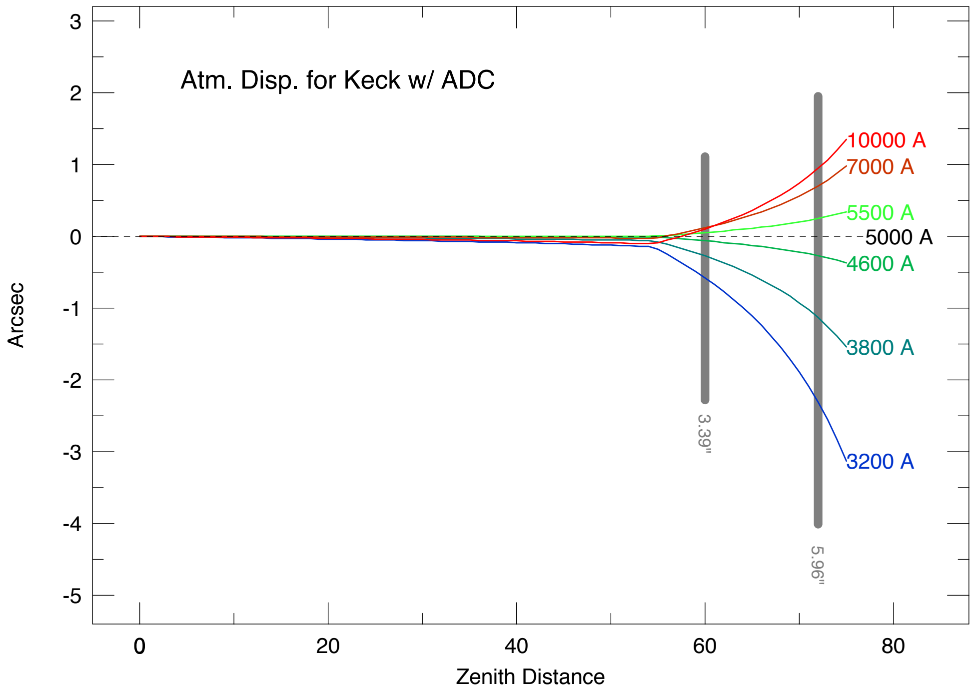
Focal stations

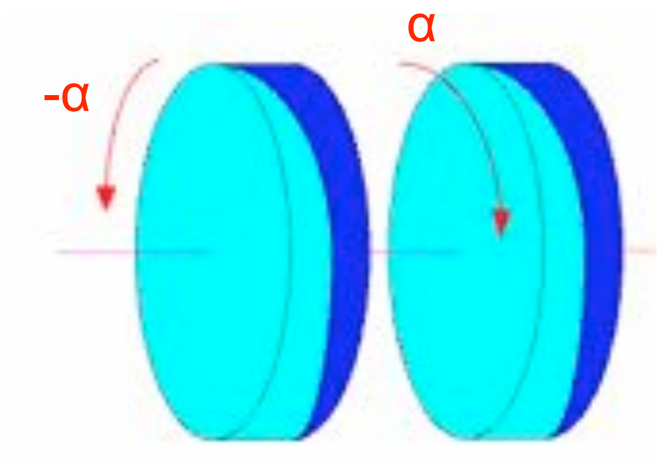
Sky rotates with hour angle

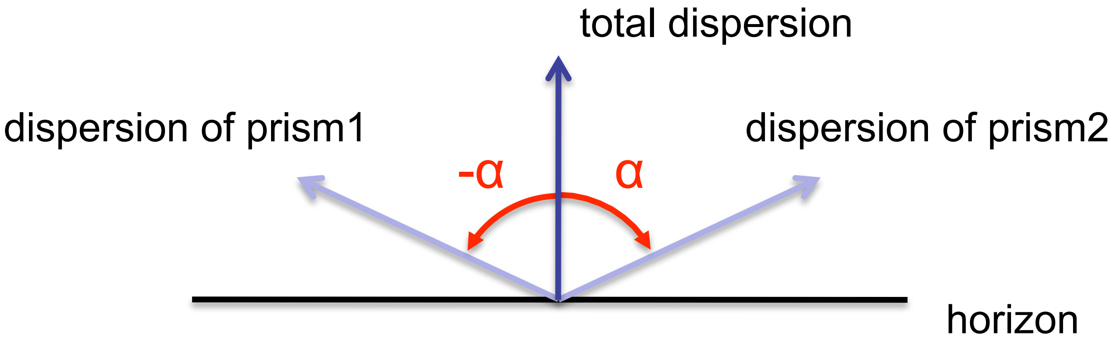
Atmospheric Dispersion Corrector

Atmosphere is a prism at non-zenith angles









total dispersion

dispersion of prism1

dispersion of prism2

-α

α

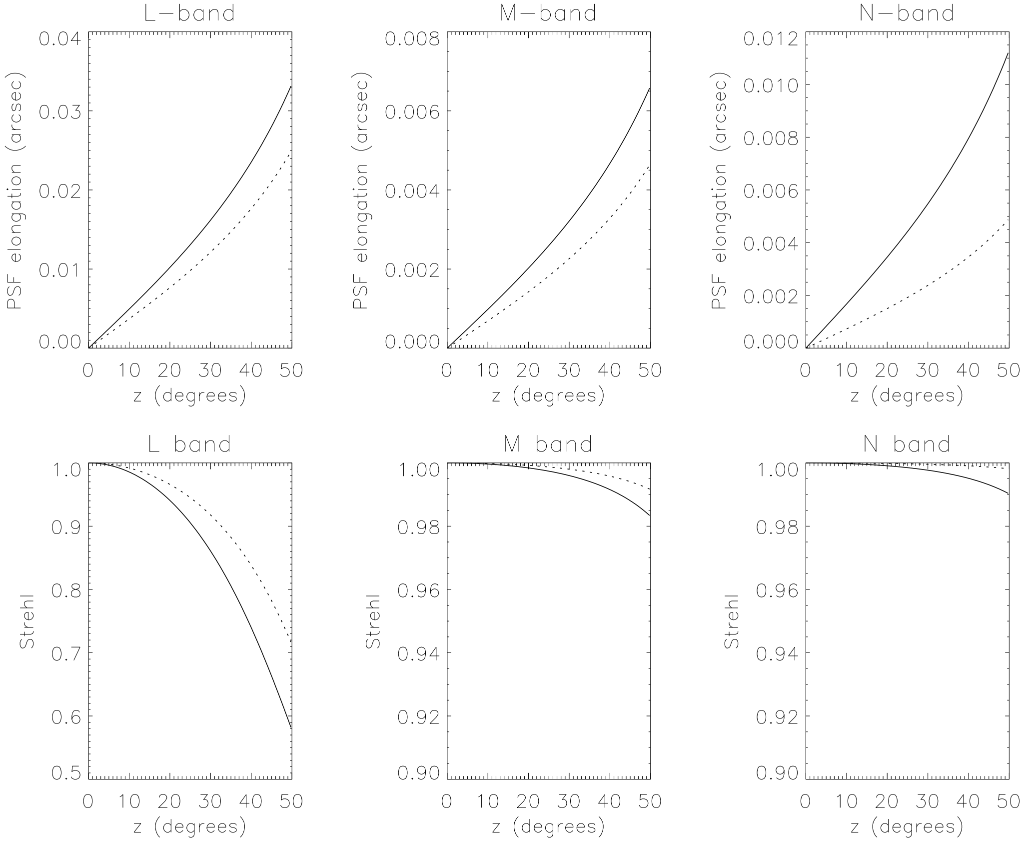
horizon

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).