Telescopes

ATI Lecture 07 2017

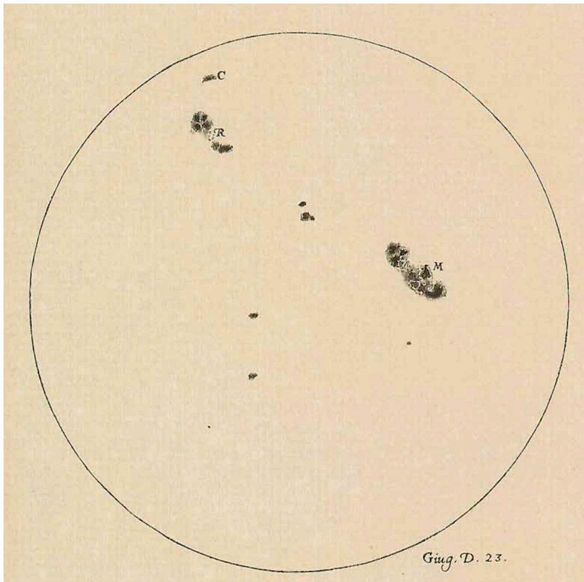
Keller and Kenworthy

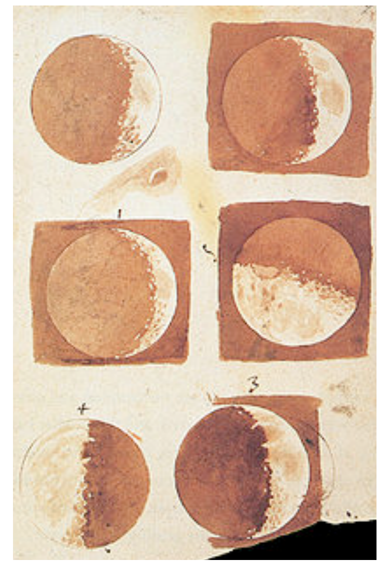
Dutch Telescopes

1608

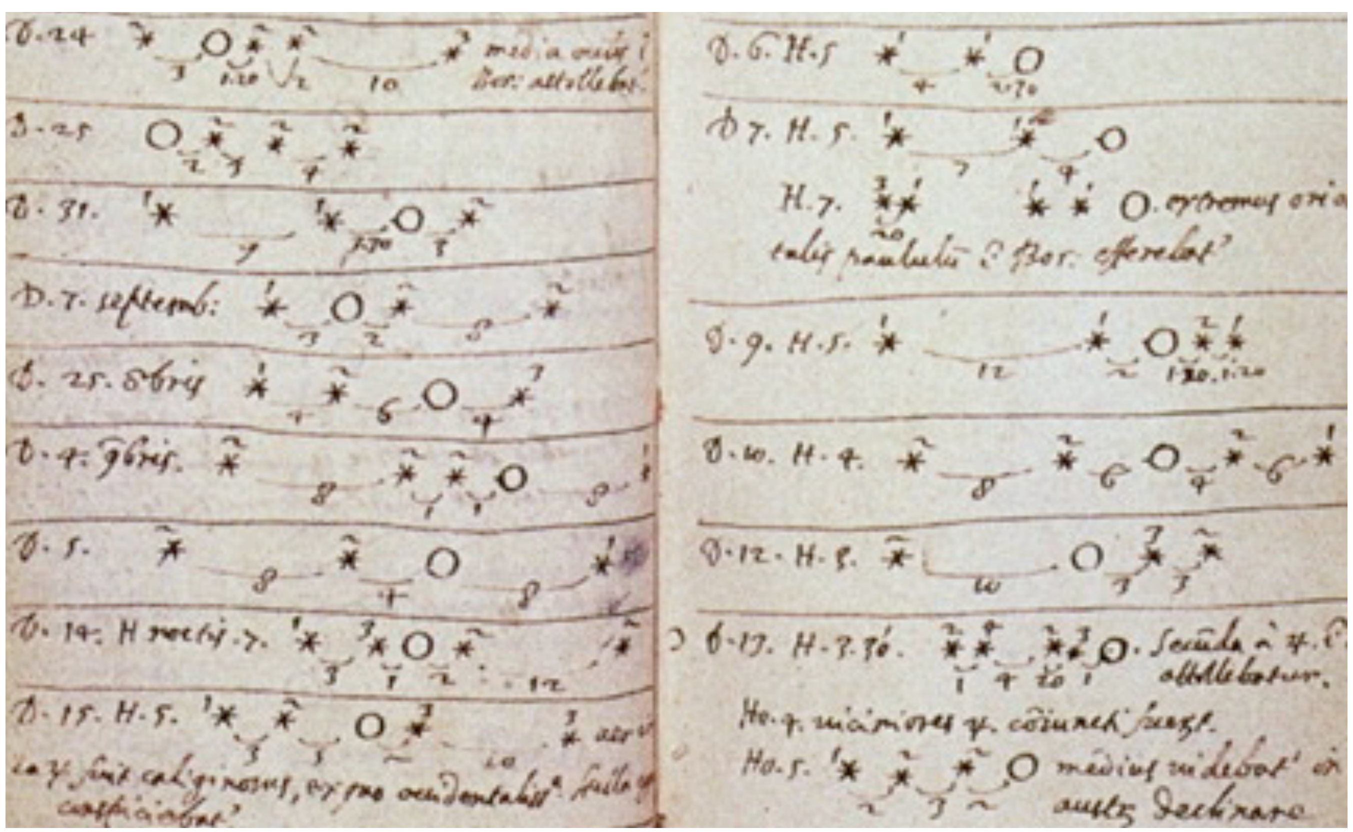
Hans Lipperhey

Dutch Telescopes

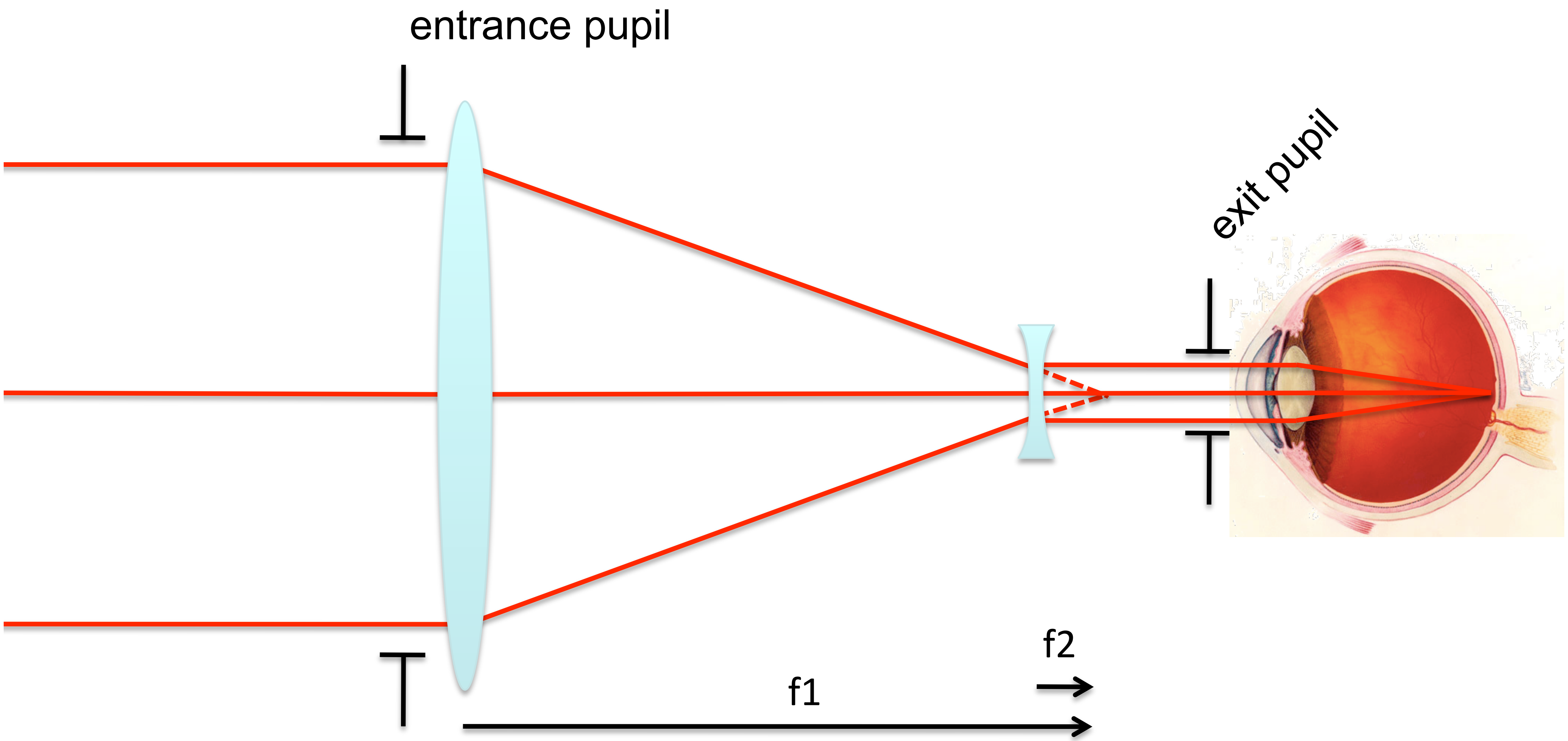




1609



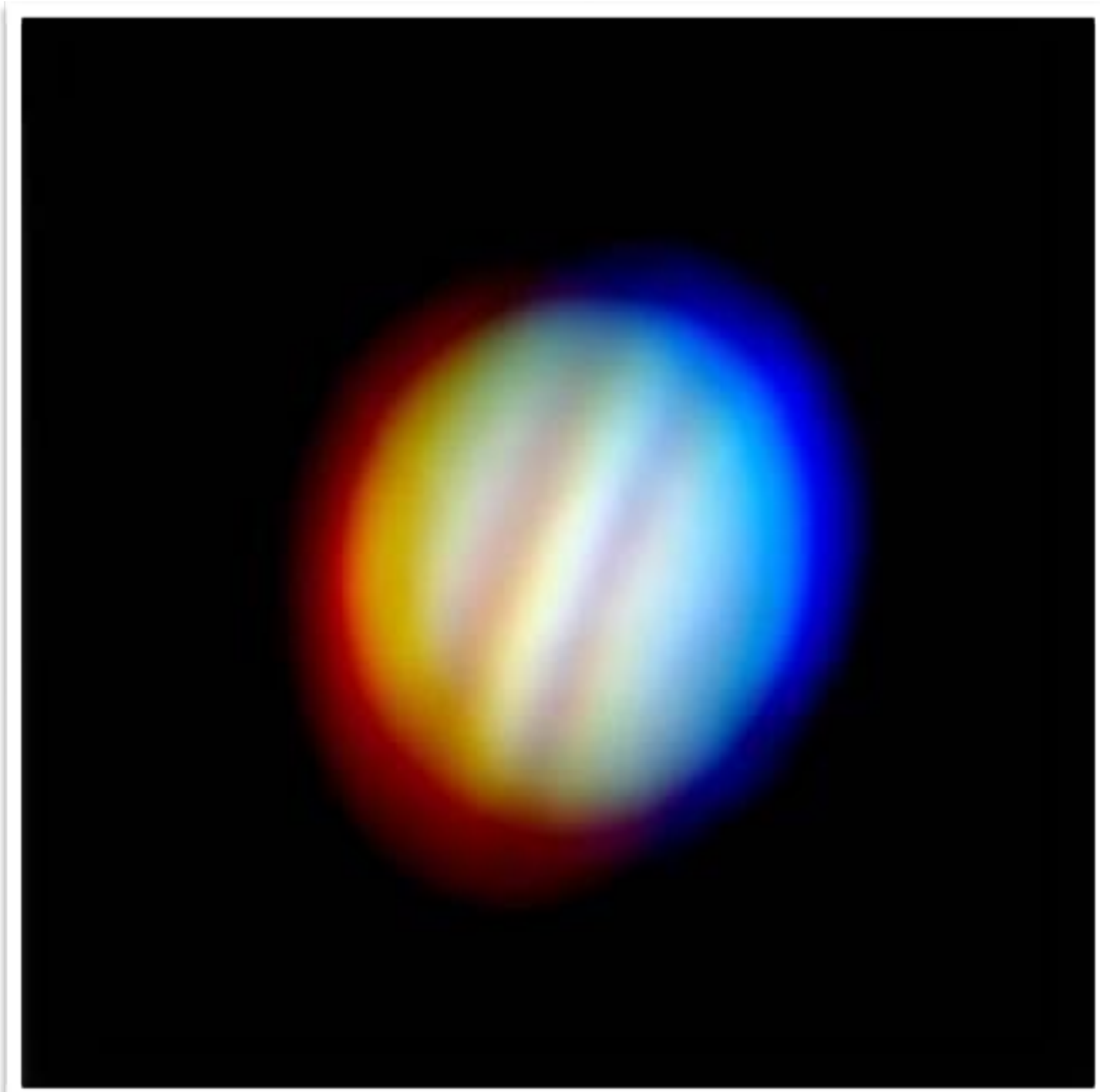
Dutch Telescopes



magnification = f1/f2

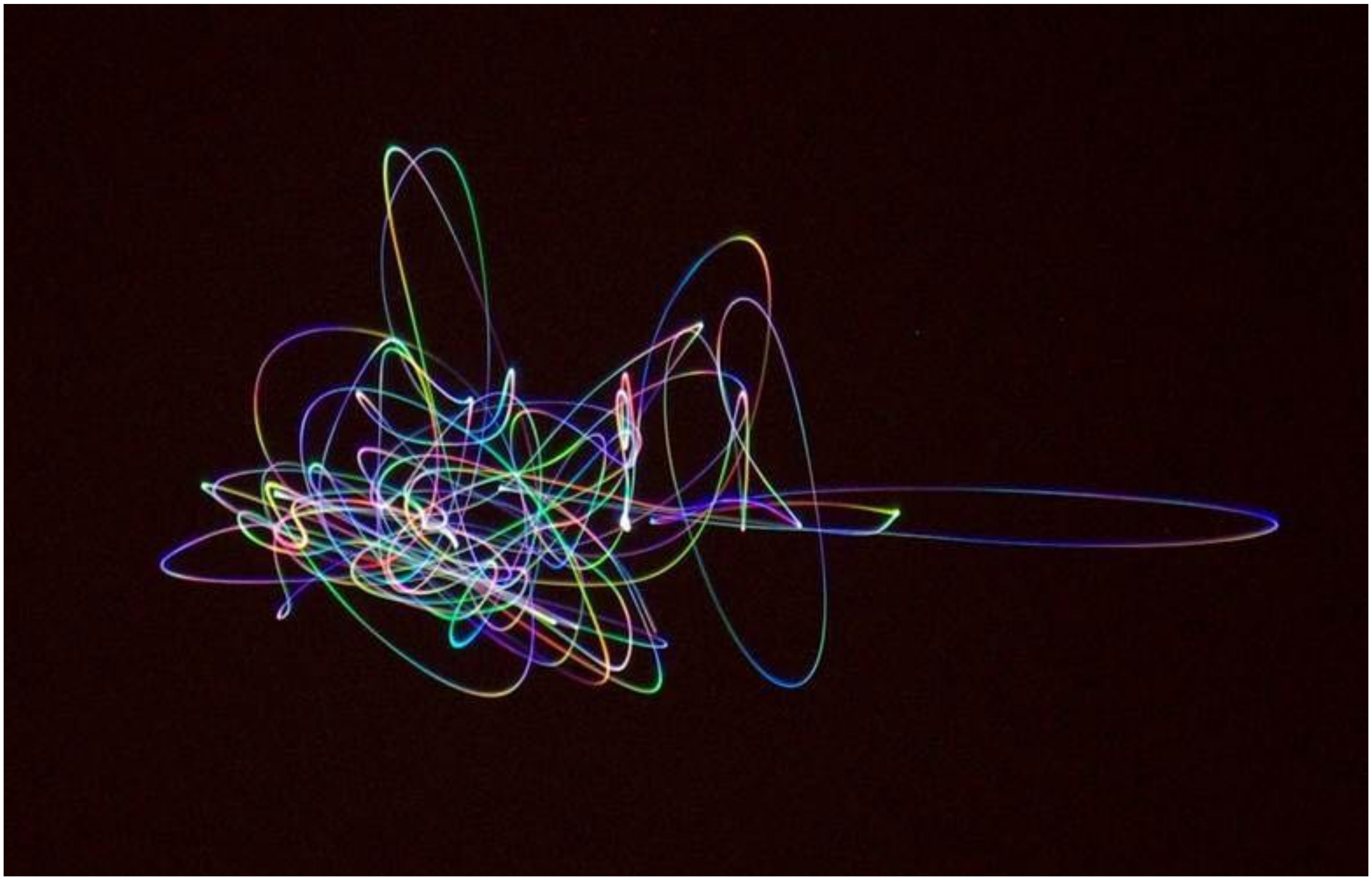
Limitations of refracting telescopes

Chromatic aberration



Limitations of refracting telescopes

Magnification requires stabilisation and guiding



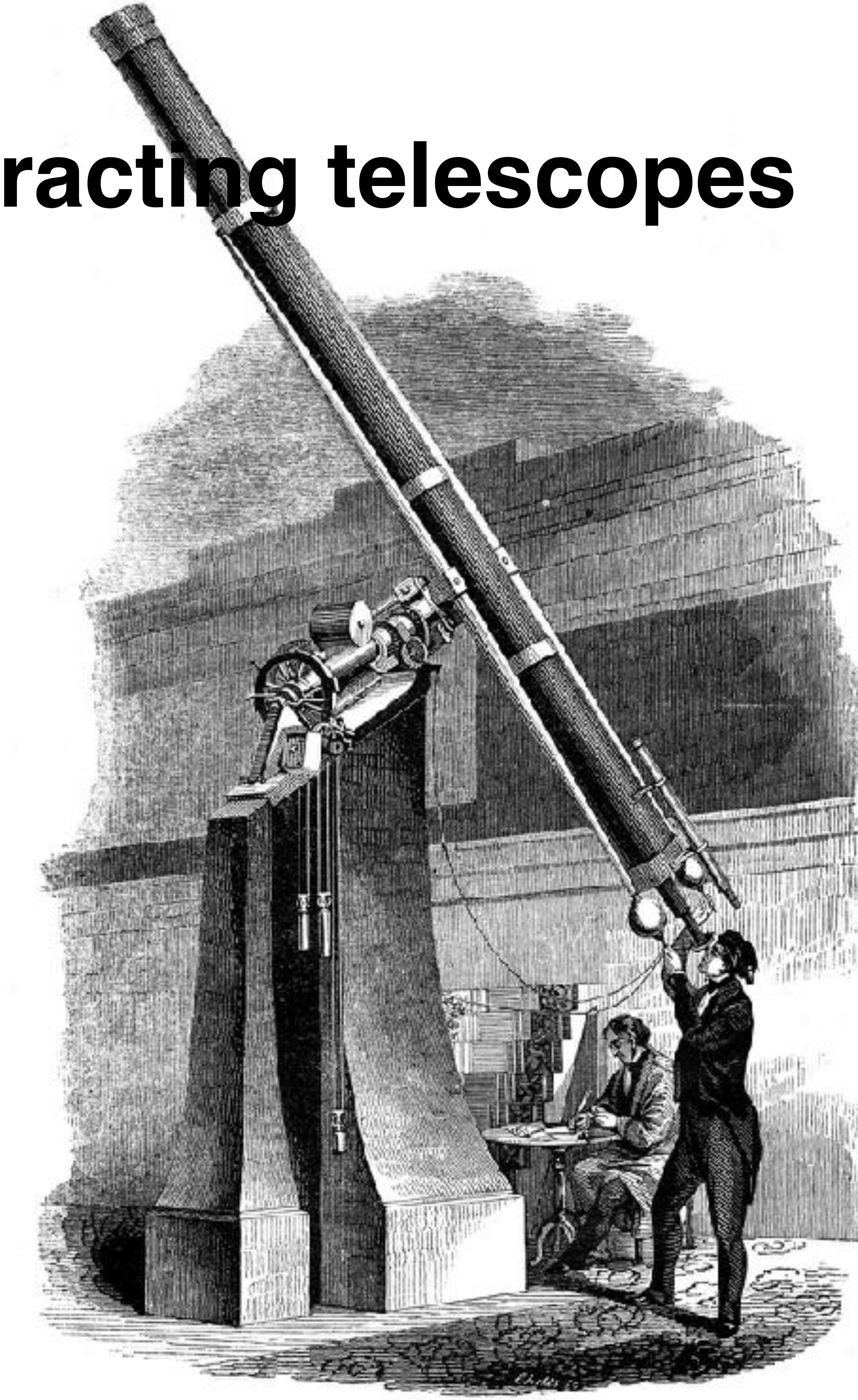
Limitations of refracting telescopes

Weight goes as D^3

Lick refractor 36 inch lens

Limitations of refracting telescopes

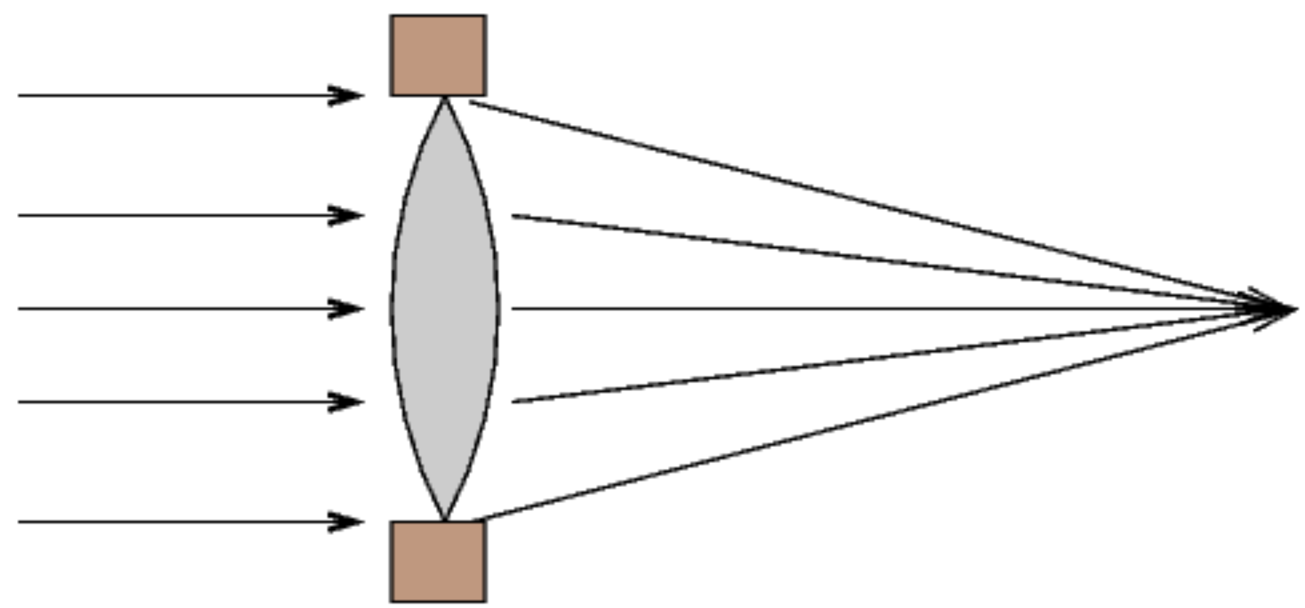
Long telescope tubes



Limitations of refracting telescopes

Glass sags under gravity

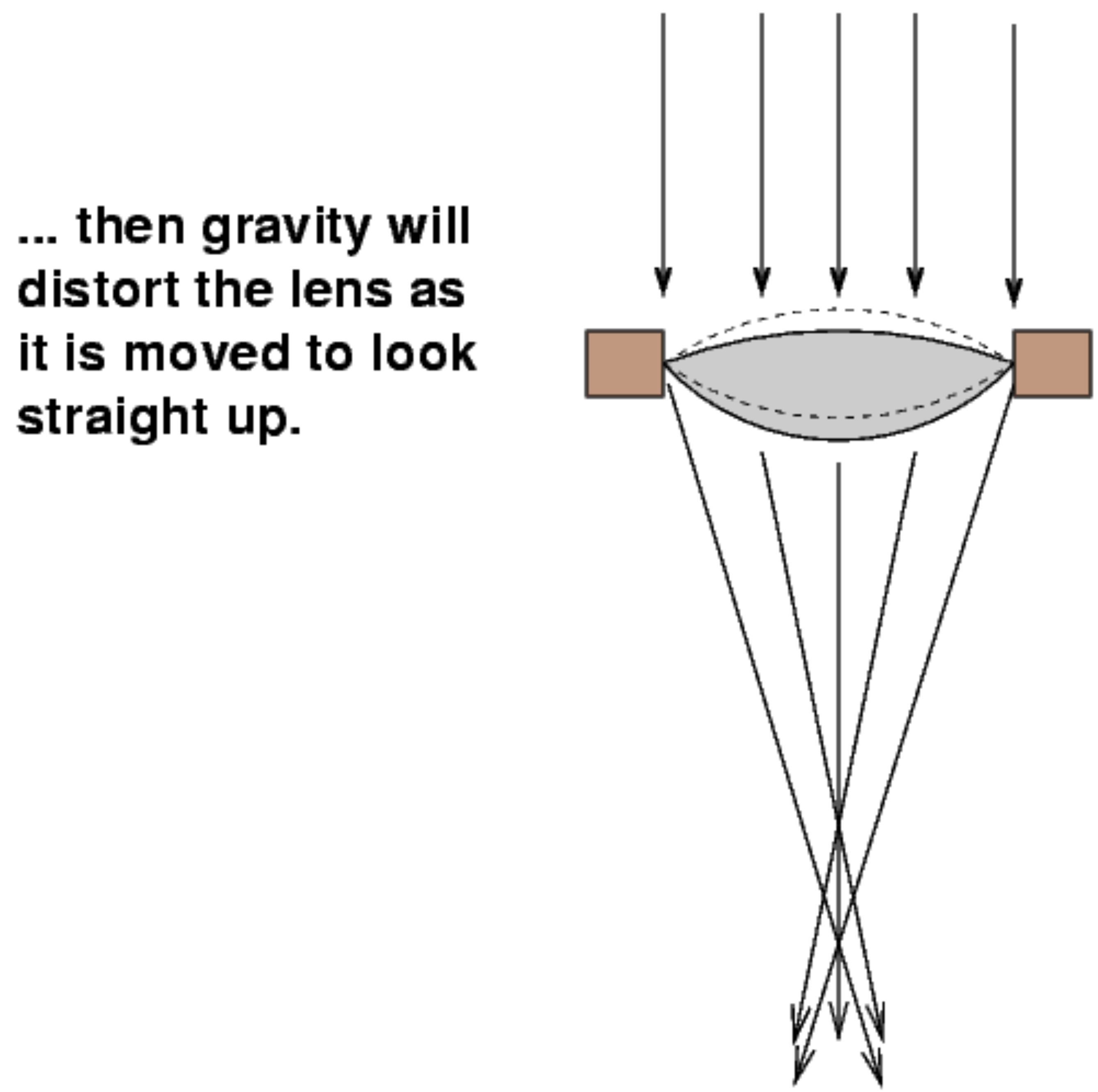
If one shapes
the lens so that
it brings light
to a focus properly
when standing on
its edge ...



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

Limitations of refracting telescopes

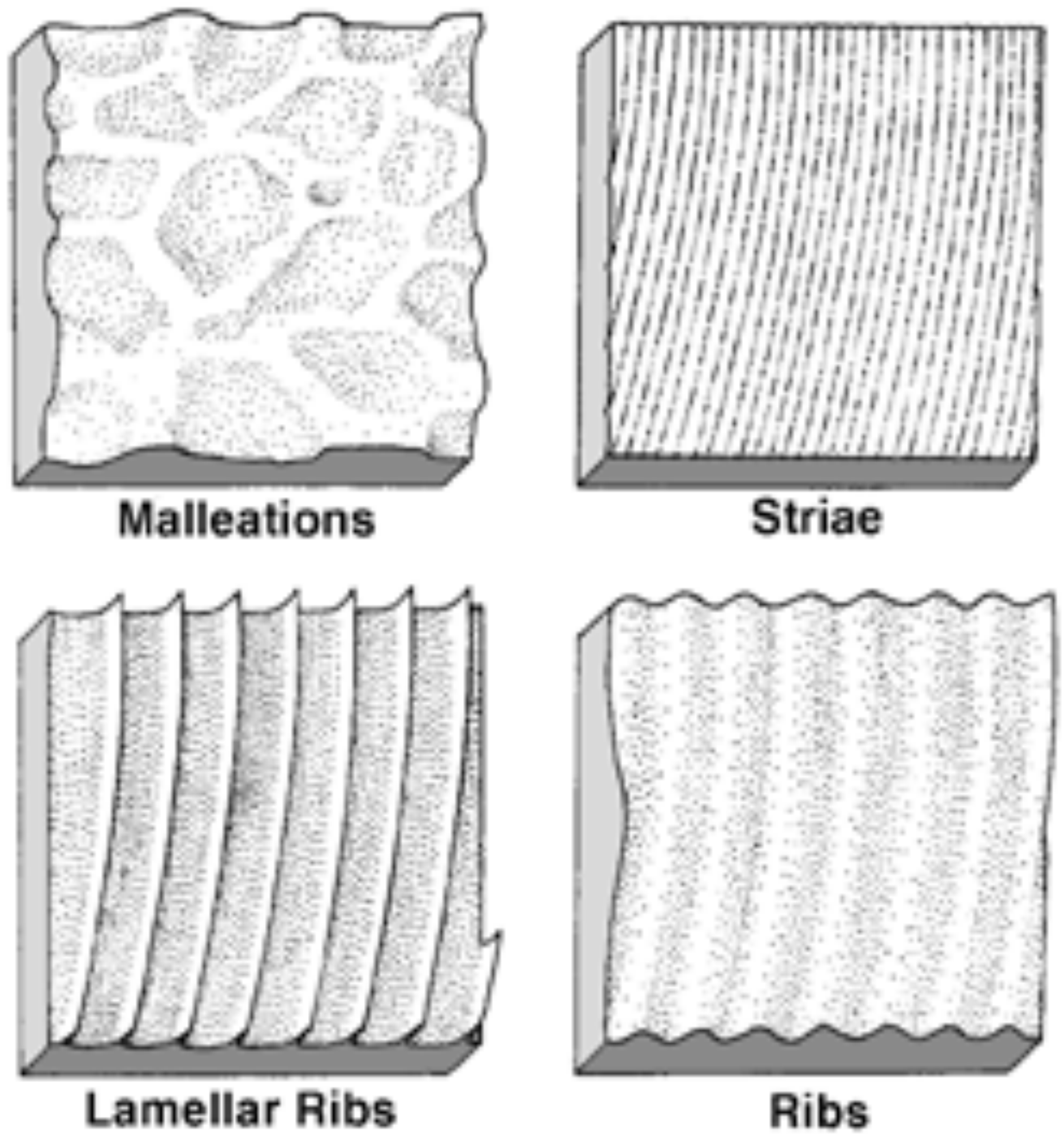
Glass sags under gravity



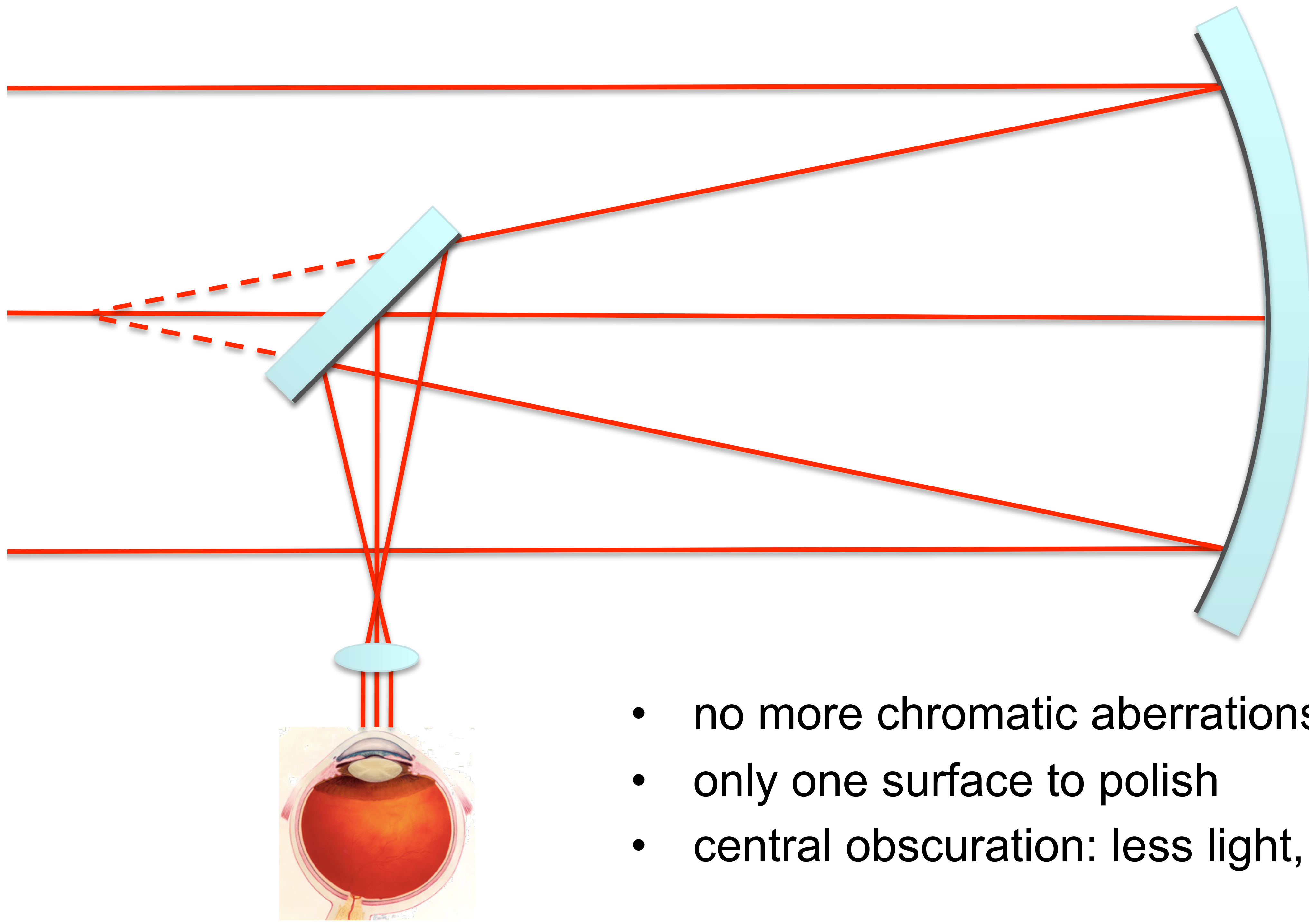
http://spiff.rit.edu/classes/phys301/lectures/optical_tel/optical_tel.html

Limitations of refracting telescopes

Glass homogeneity is difficult to maintain



Newtonian Telescope

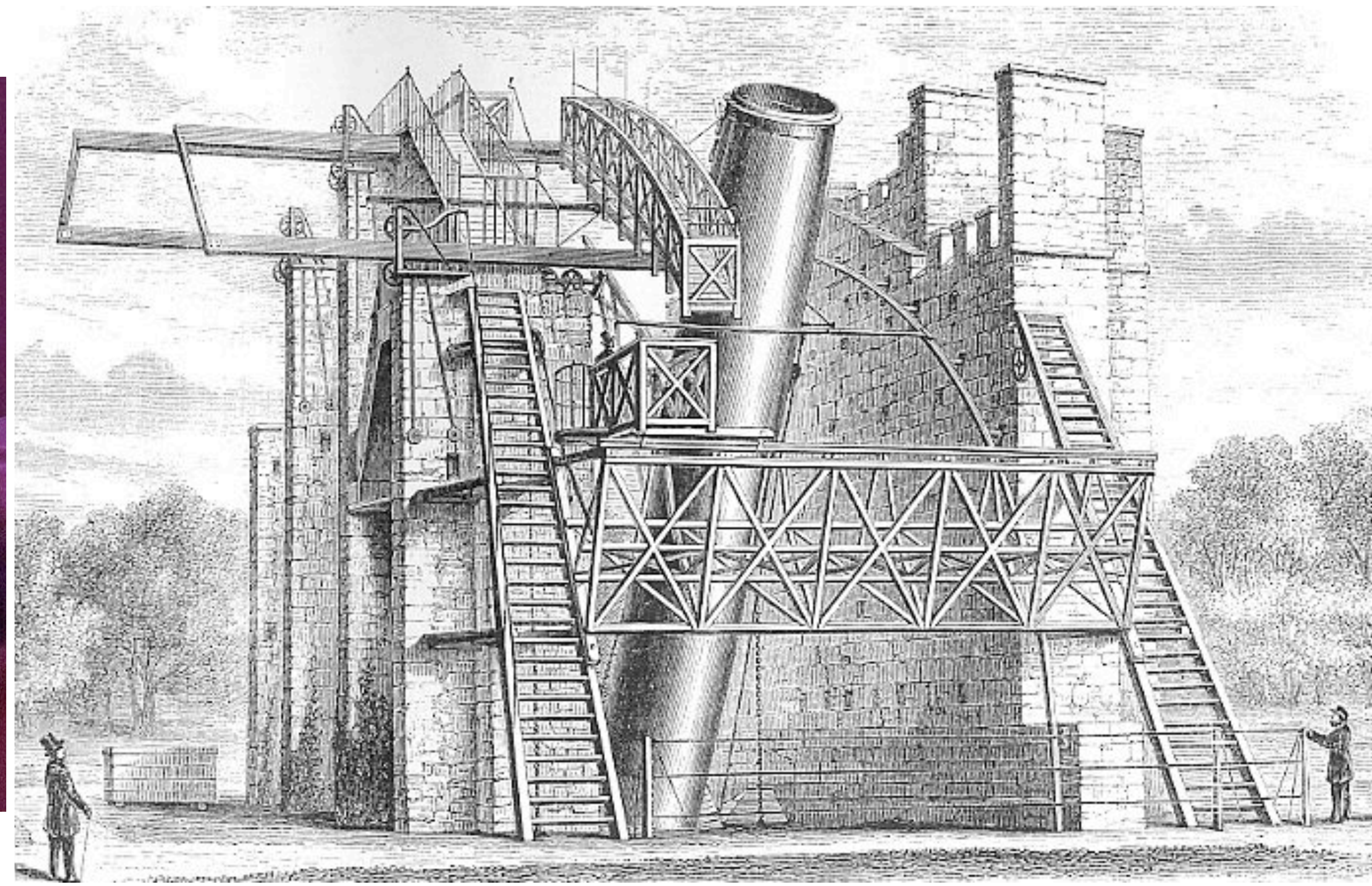


- no more chromatic aberrations
- only one surface to polish
- central obscuration: less light, diffraction

Newtonian Telescope

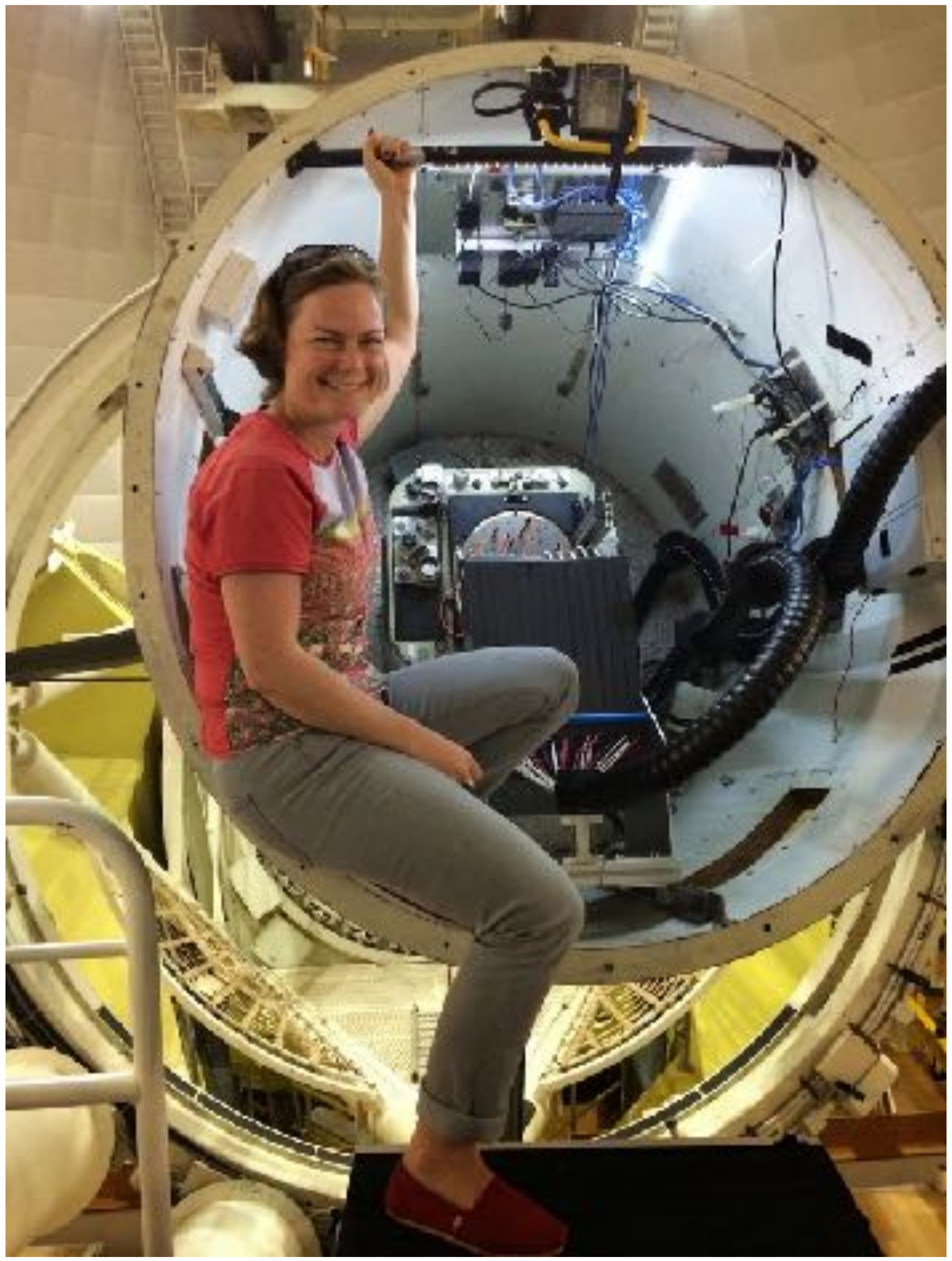
1668

1842

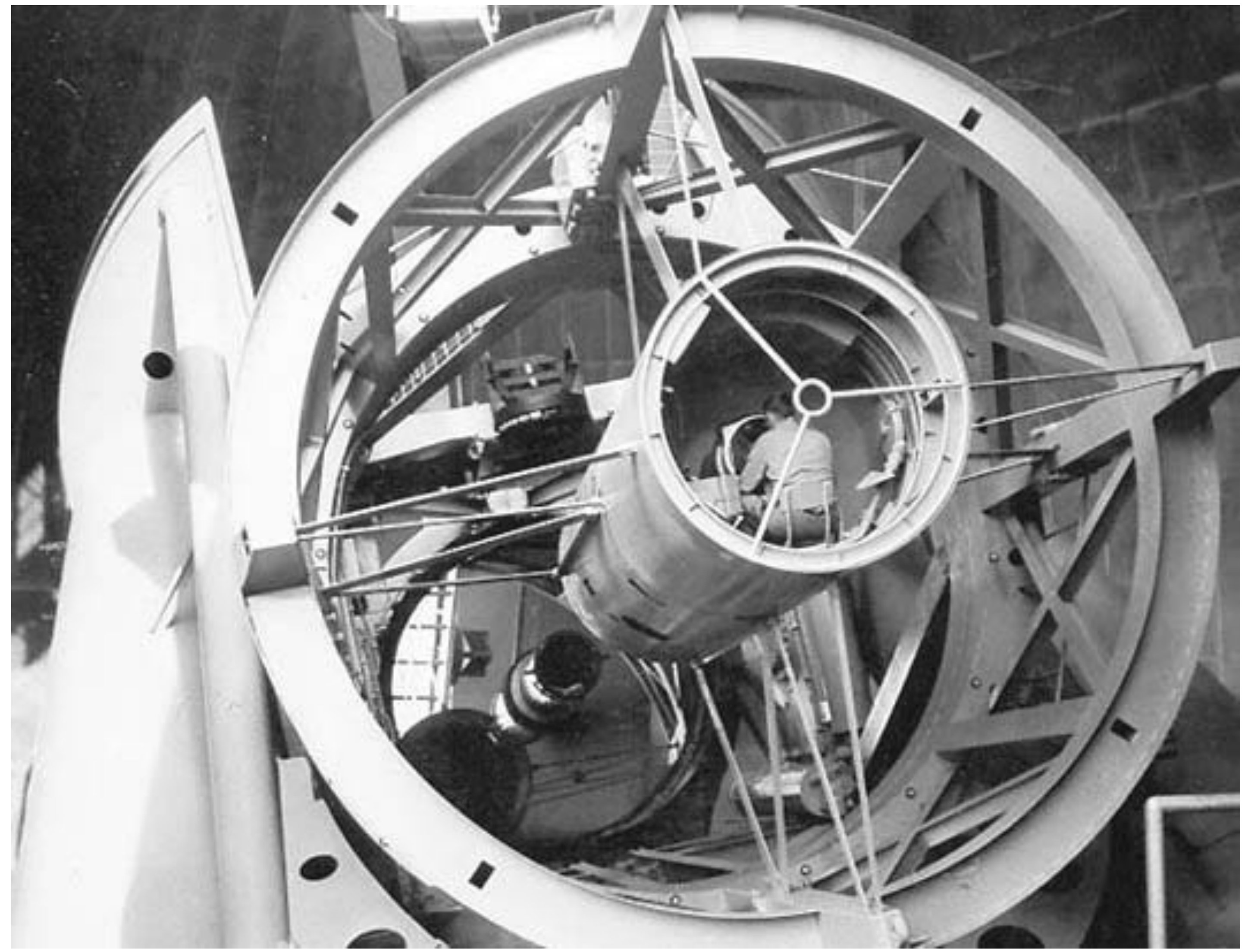


Introducing a Secondary Mirror

Primary focus is awkward to get to



(c) Amanda Bauer



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

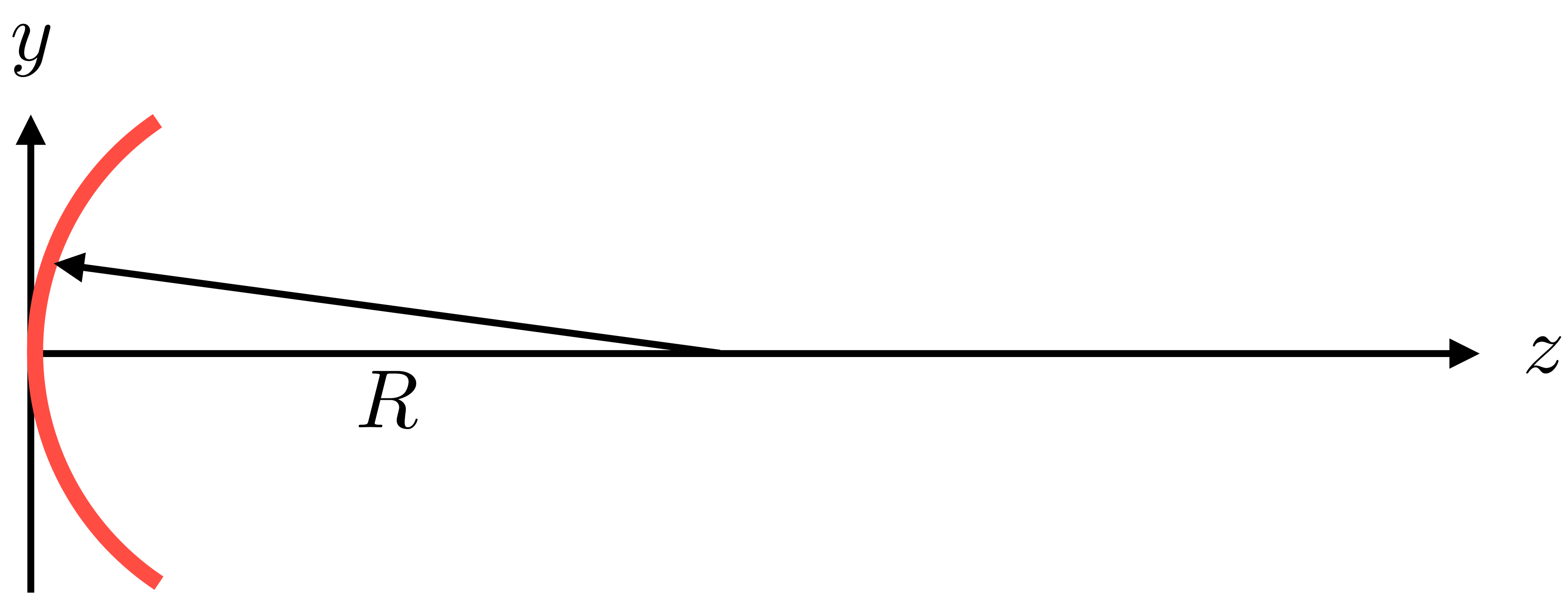
The family of conic mirrors

All these curves can be parameterised with one equation:

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

Conic constant K is defined as:

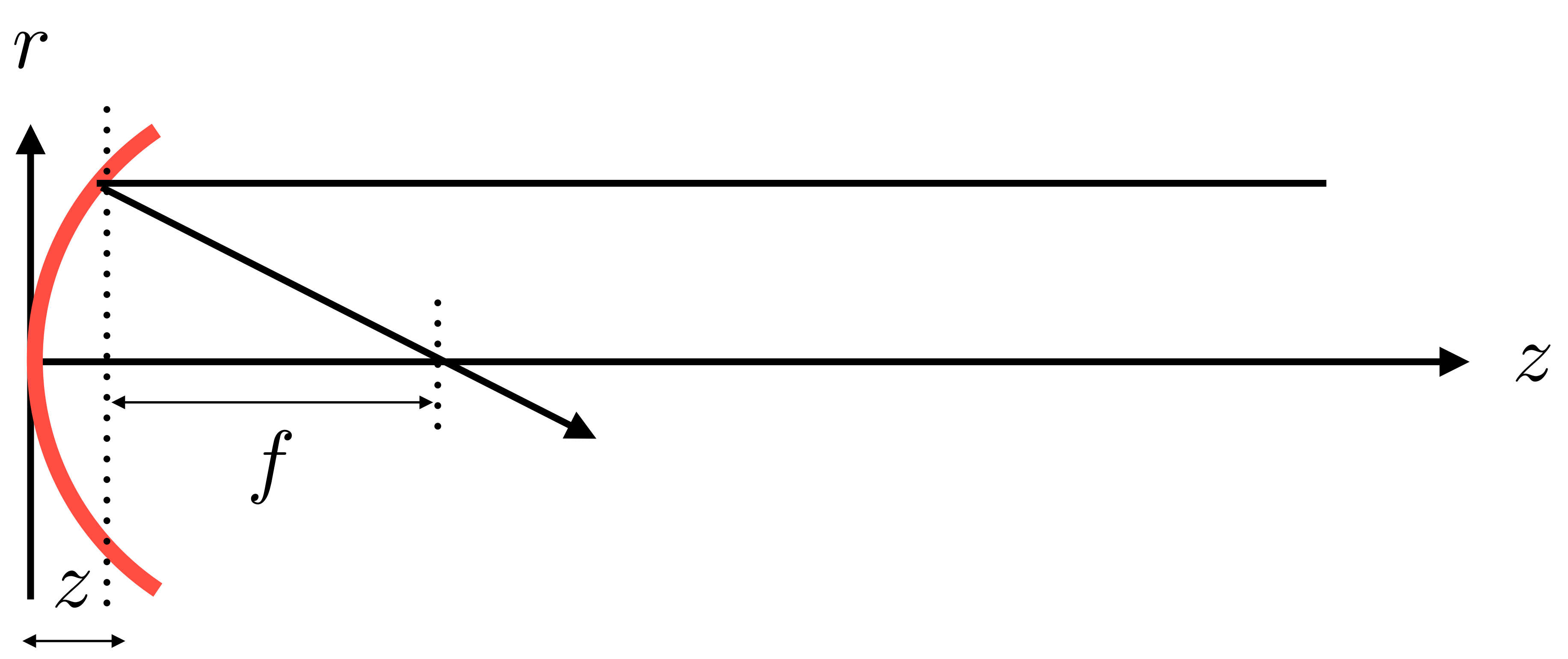
$$K = -e^2$$



focal distance with r

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

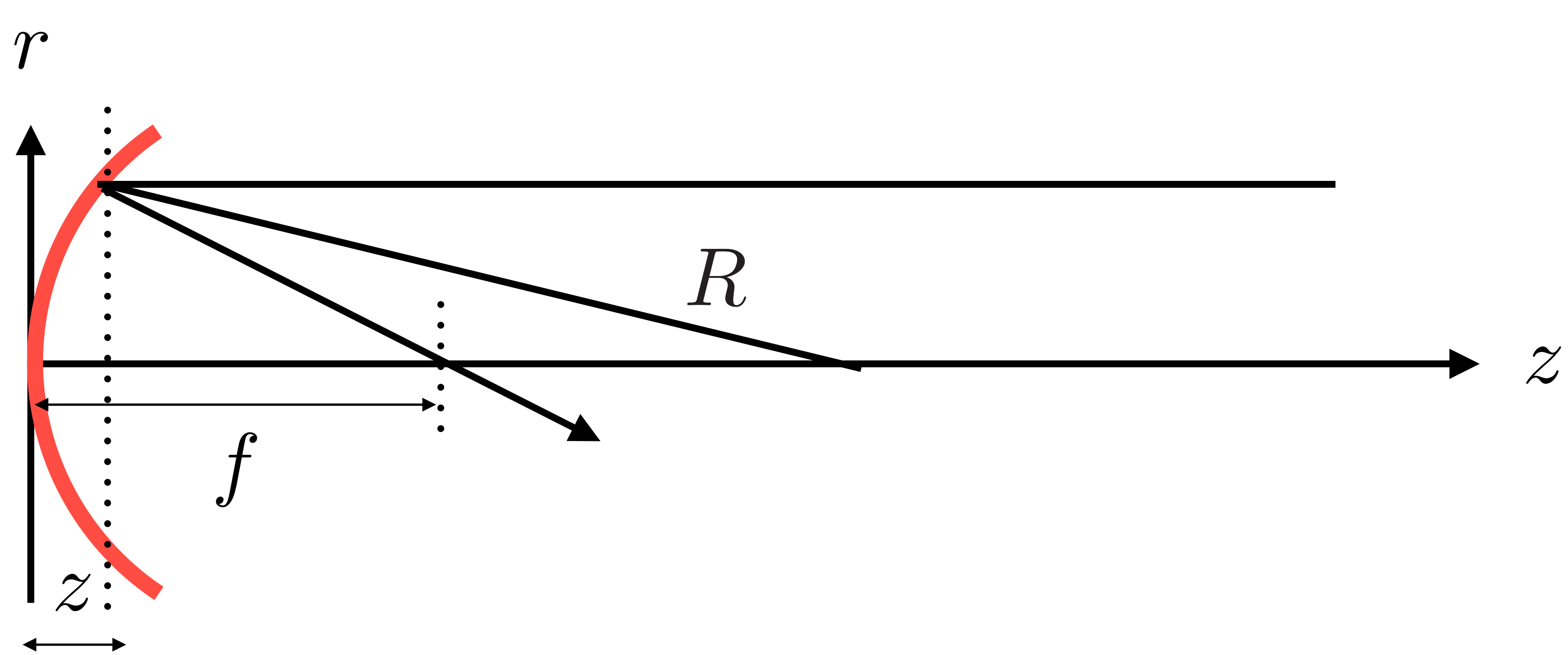
$$z = \frac{R}{1+K}\left[1-\left(1-\frac{r^2}{R^2}(1+K)\right)^{1/2}\right]$$



focal distance with r

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

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

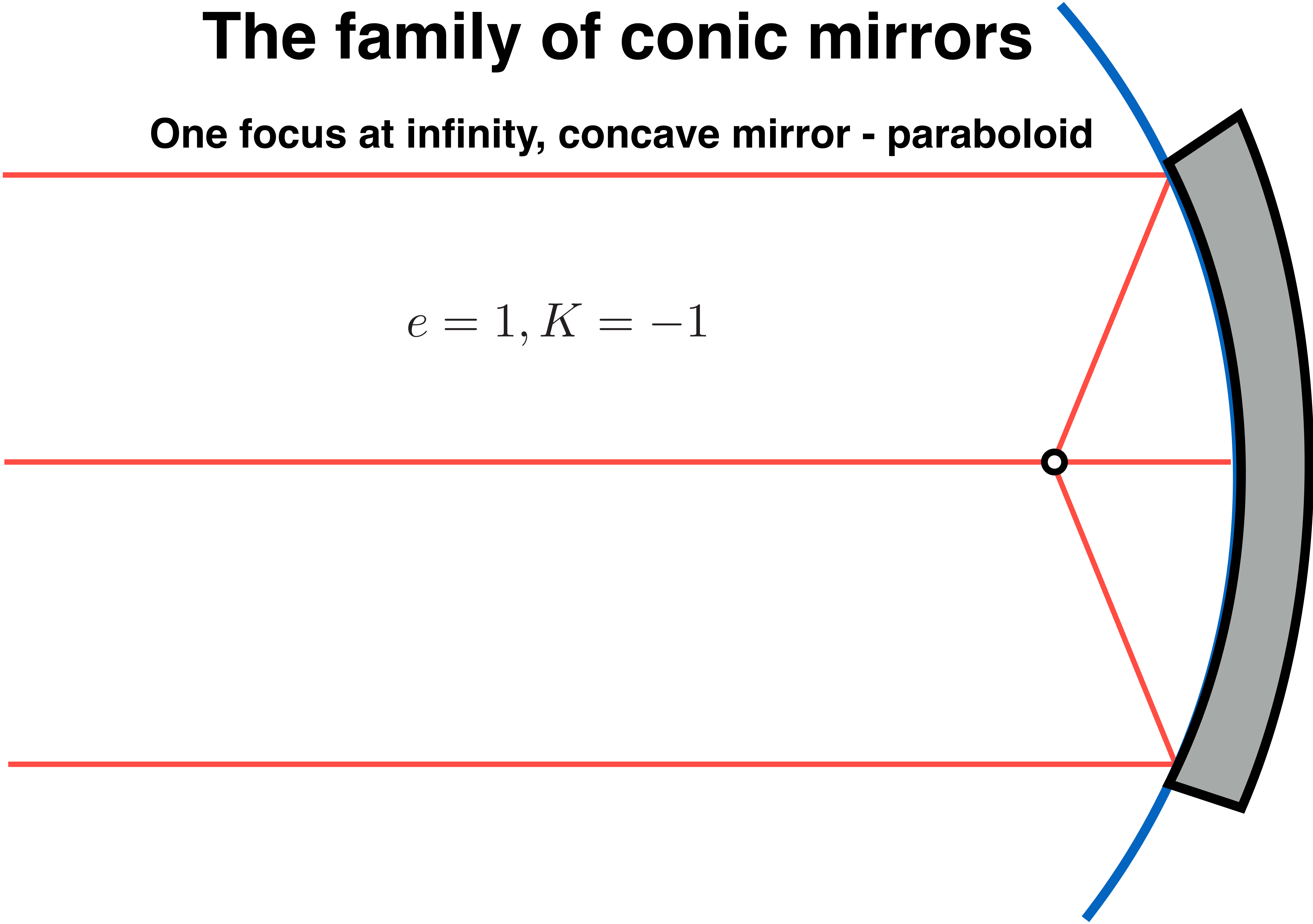


unless K=-1, the focal distance f changes with radius r and you have SPHERICAL ABERRATION

The family of conic mirrors

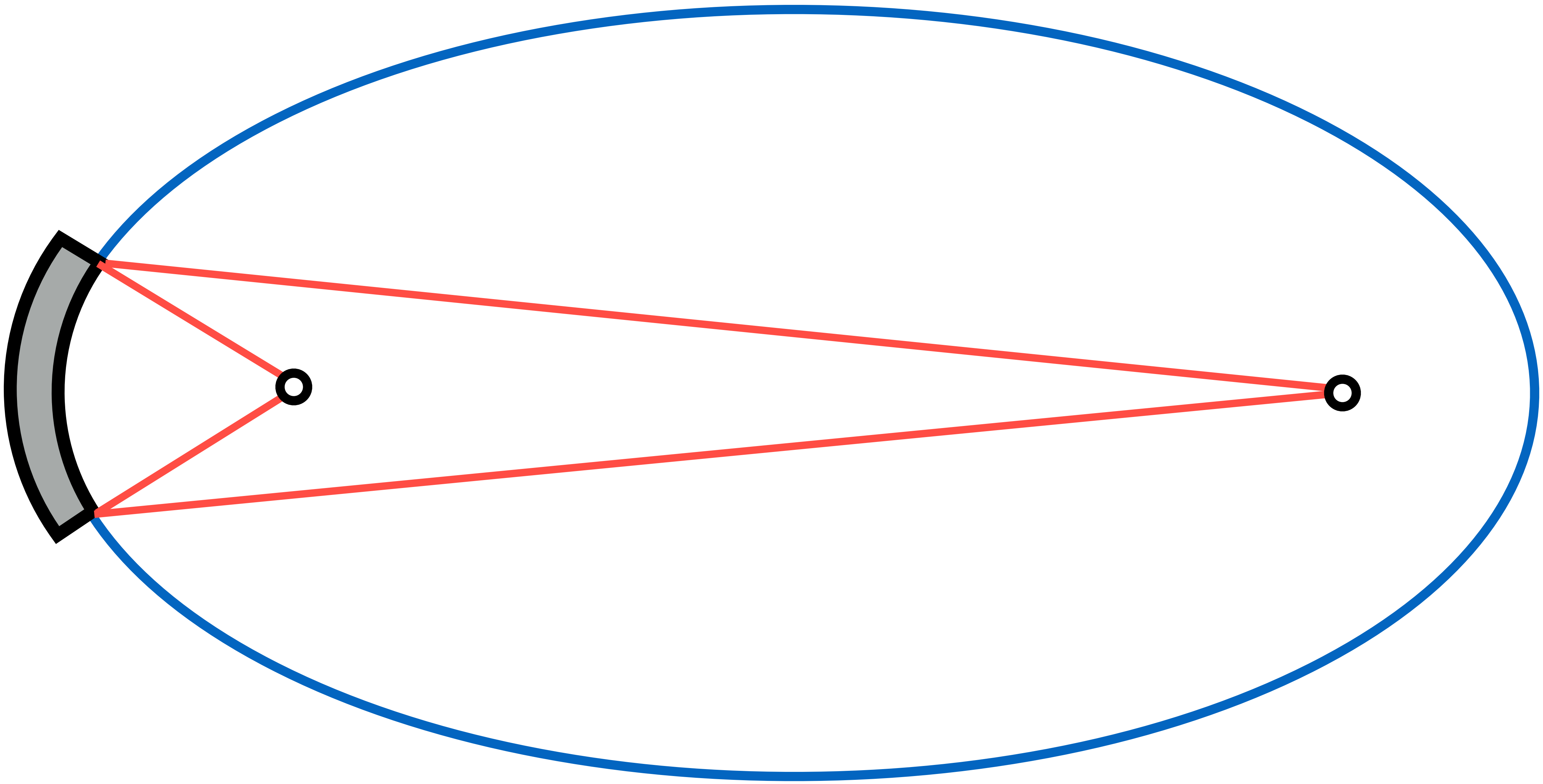
One focus at infinity, concave mirror - paraboloid

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



The family of conic mirrors

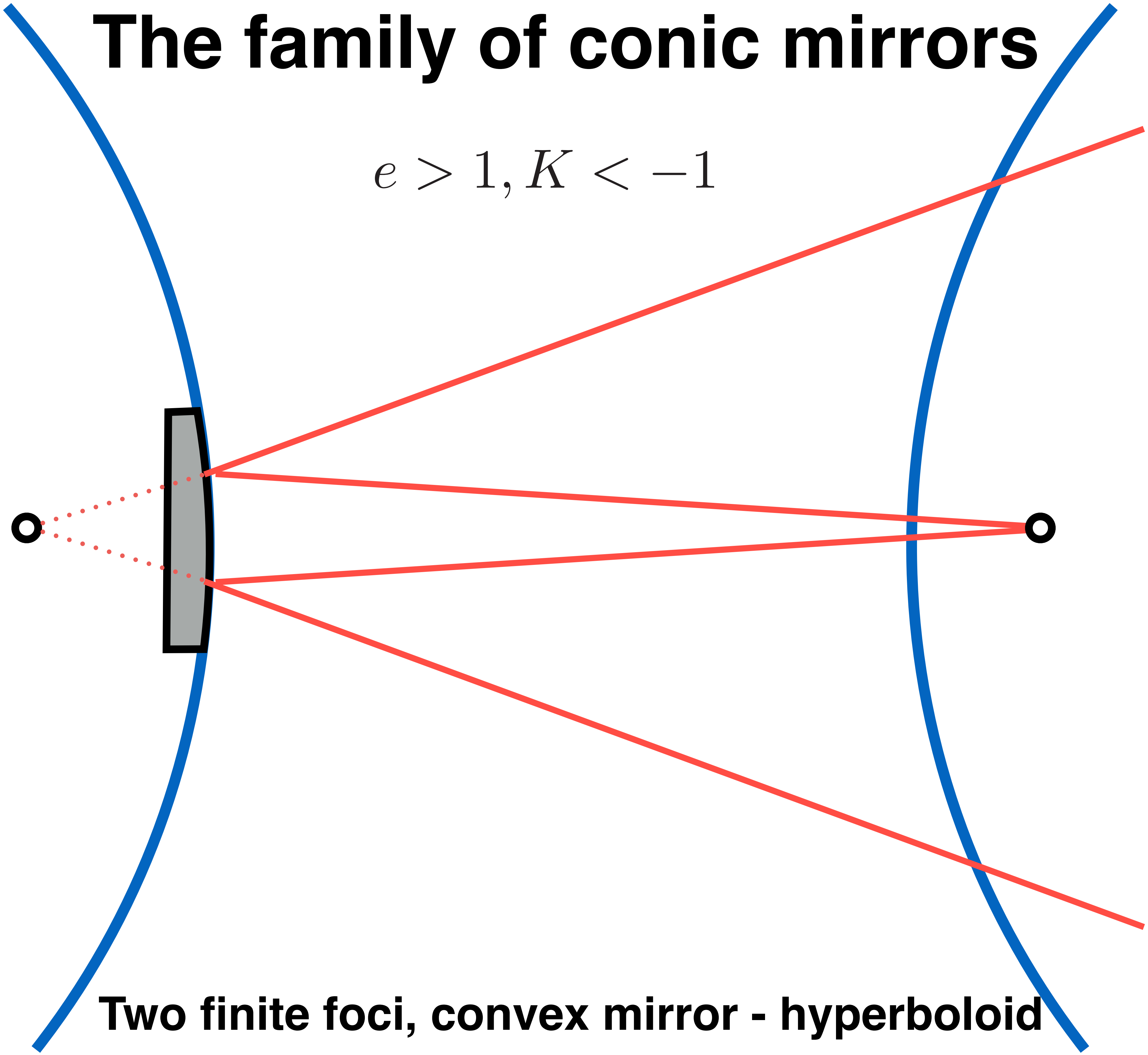
Two finite foci, concave mirror - ellipsoid



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

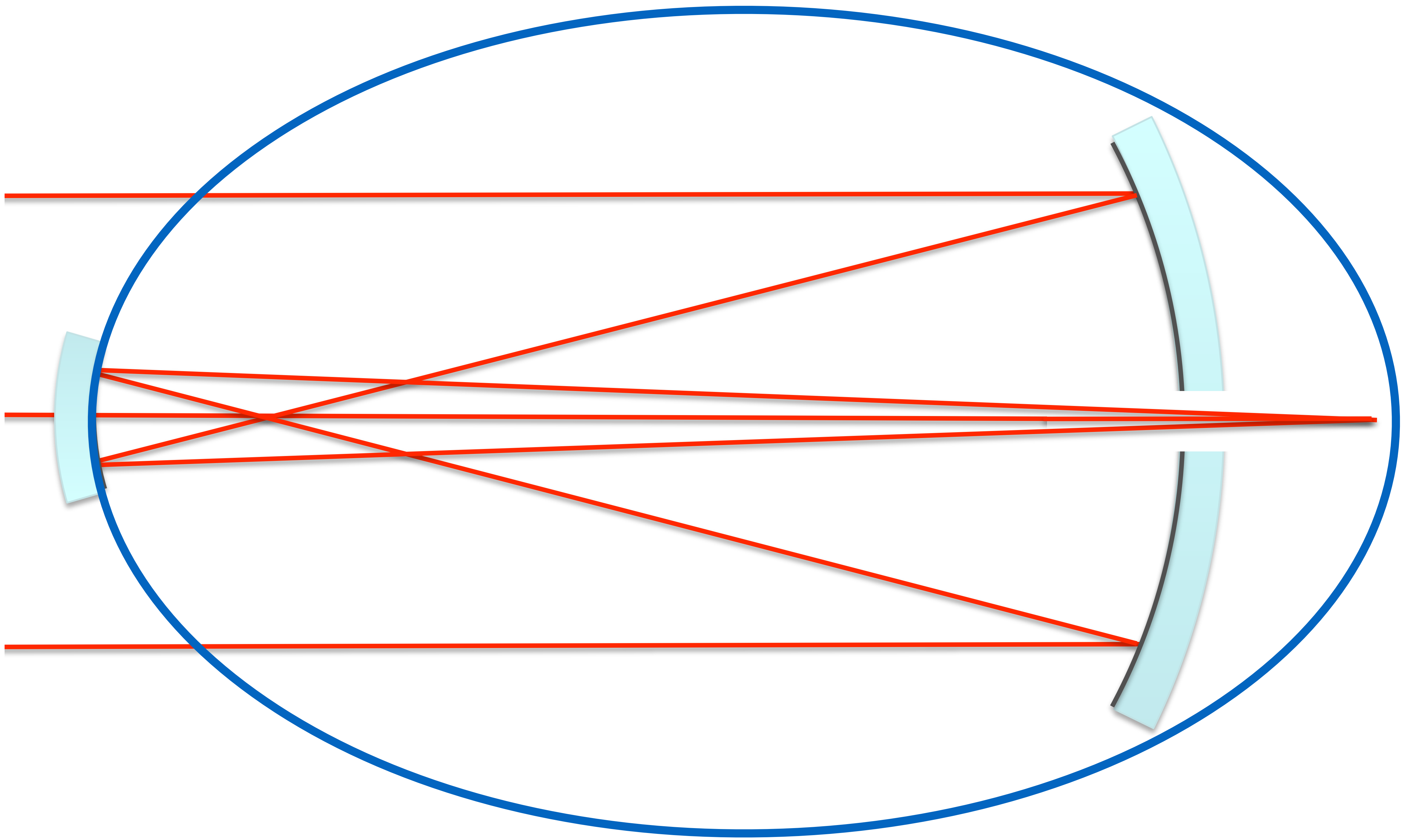
The family of conic mirrors

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

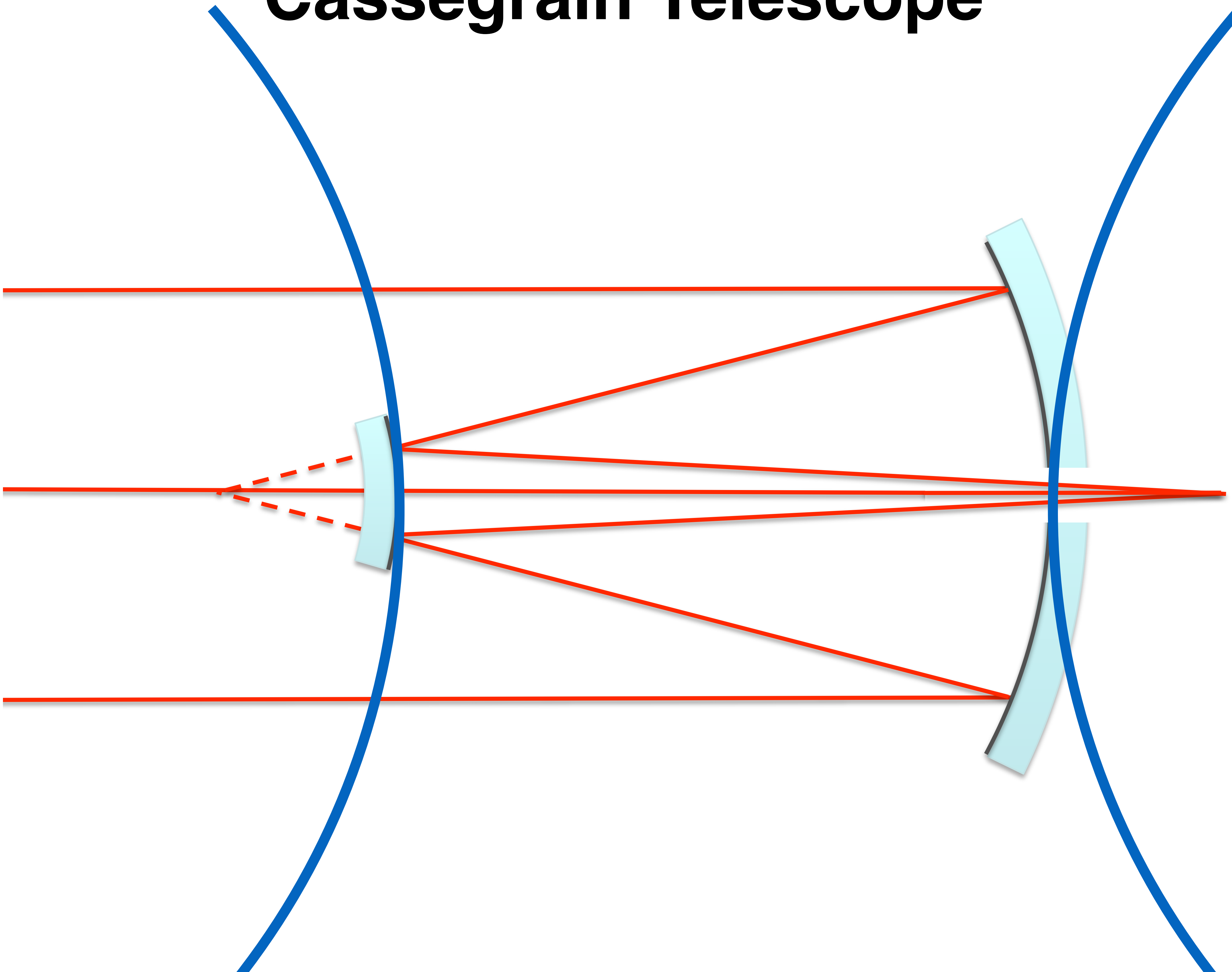


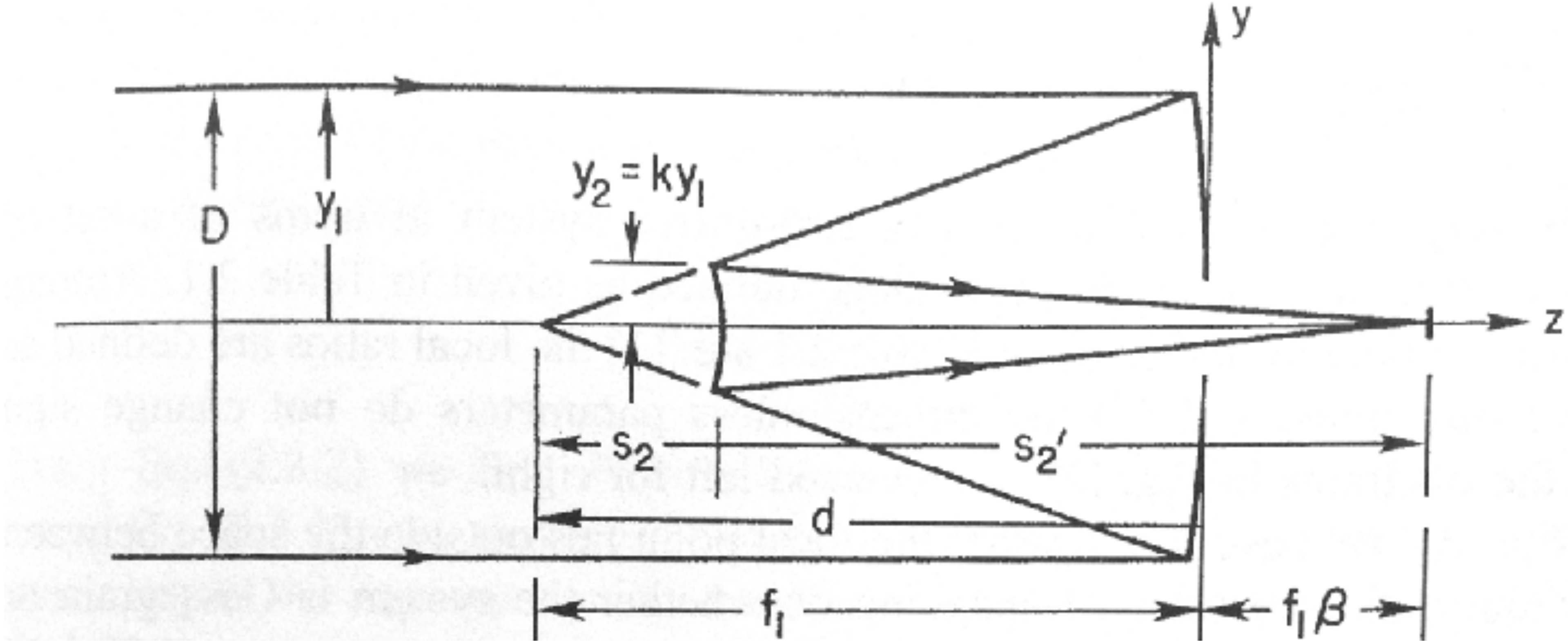
Two finite foci, convex mirror - hyperboloid

Gregorian Telescope

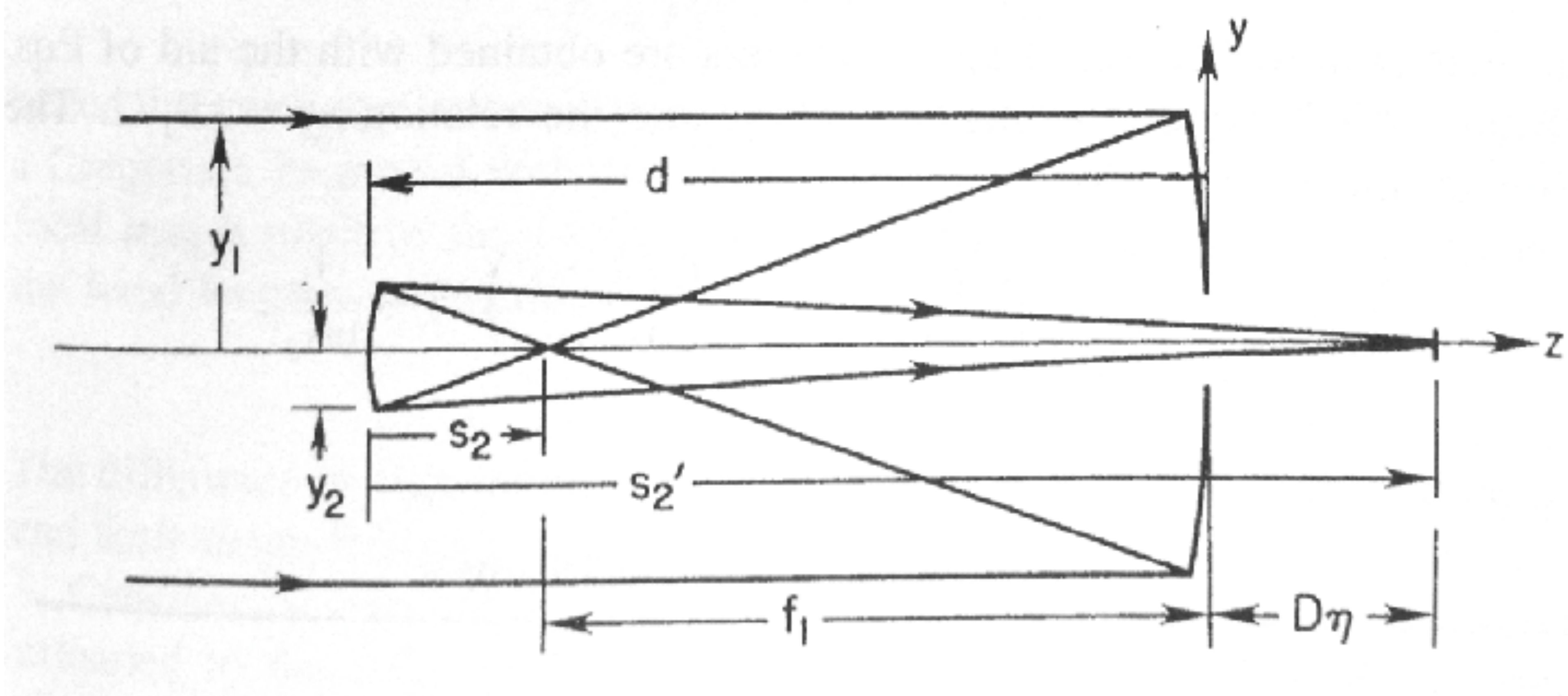


Cassegrain Telescope





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

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

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

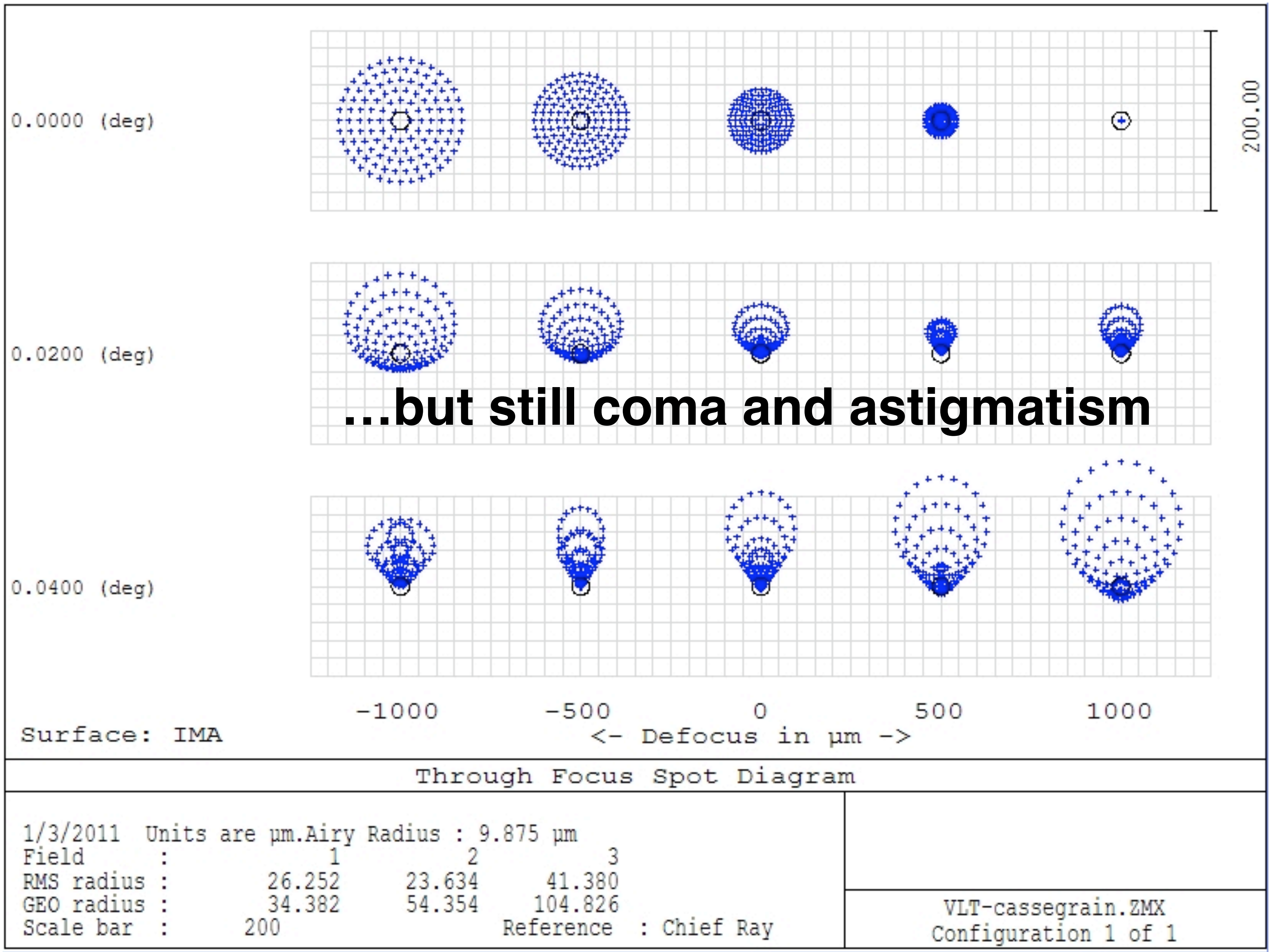
…but still coma and astigmatism

Classical Cassegrain

Classical Cassegrain balances K_1 and K_2 to remove SPHERICAL ABERRATION

VLT as classical Cassegrain

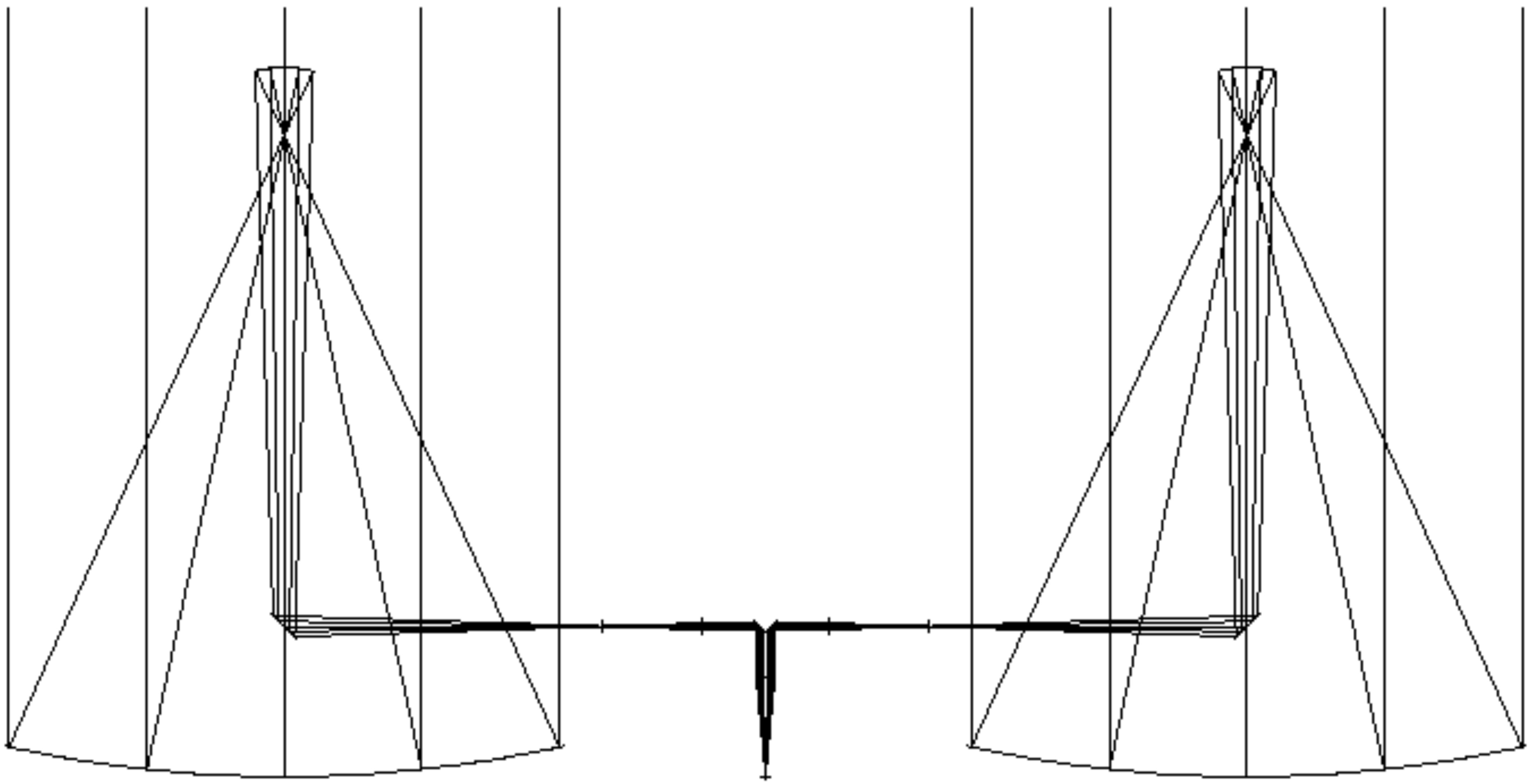
$K_1 = -1$
$K_2 = -1.62$



Gregorian astronomical telescopes

Classical Gregorian uses elliptical secondary

Much longer than equivalent Cassegrain! So why use it?

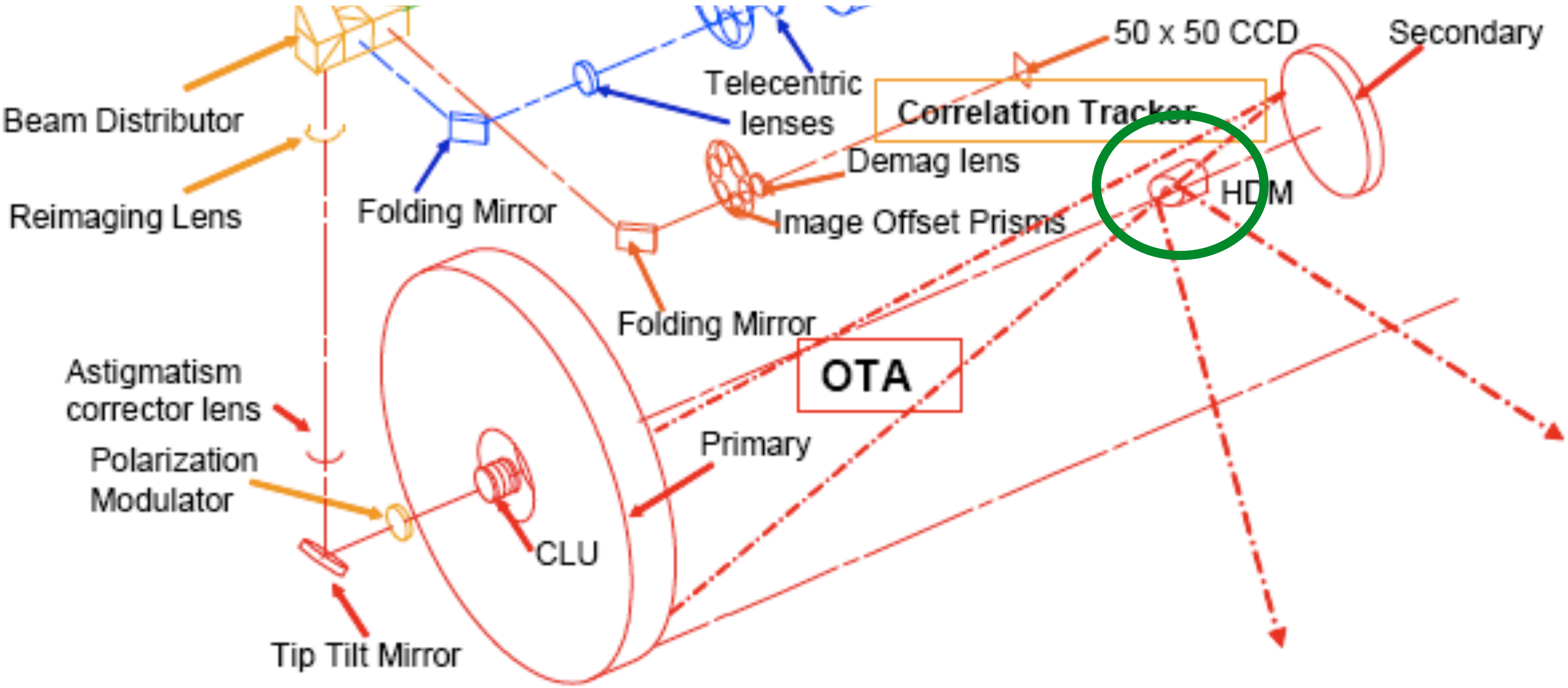


adaptive secondary calibrated from intermediate focus

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 K_1 and K_2 for zero spherical

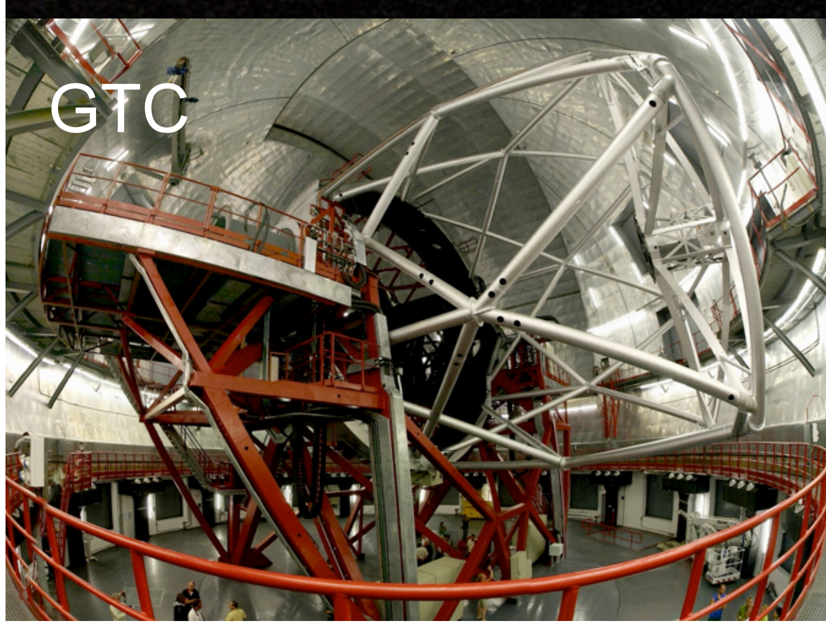
Can cancel spherical and coma with the right values

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

and:

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

Ritchey-Chrétien Telescopes

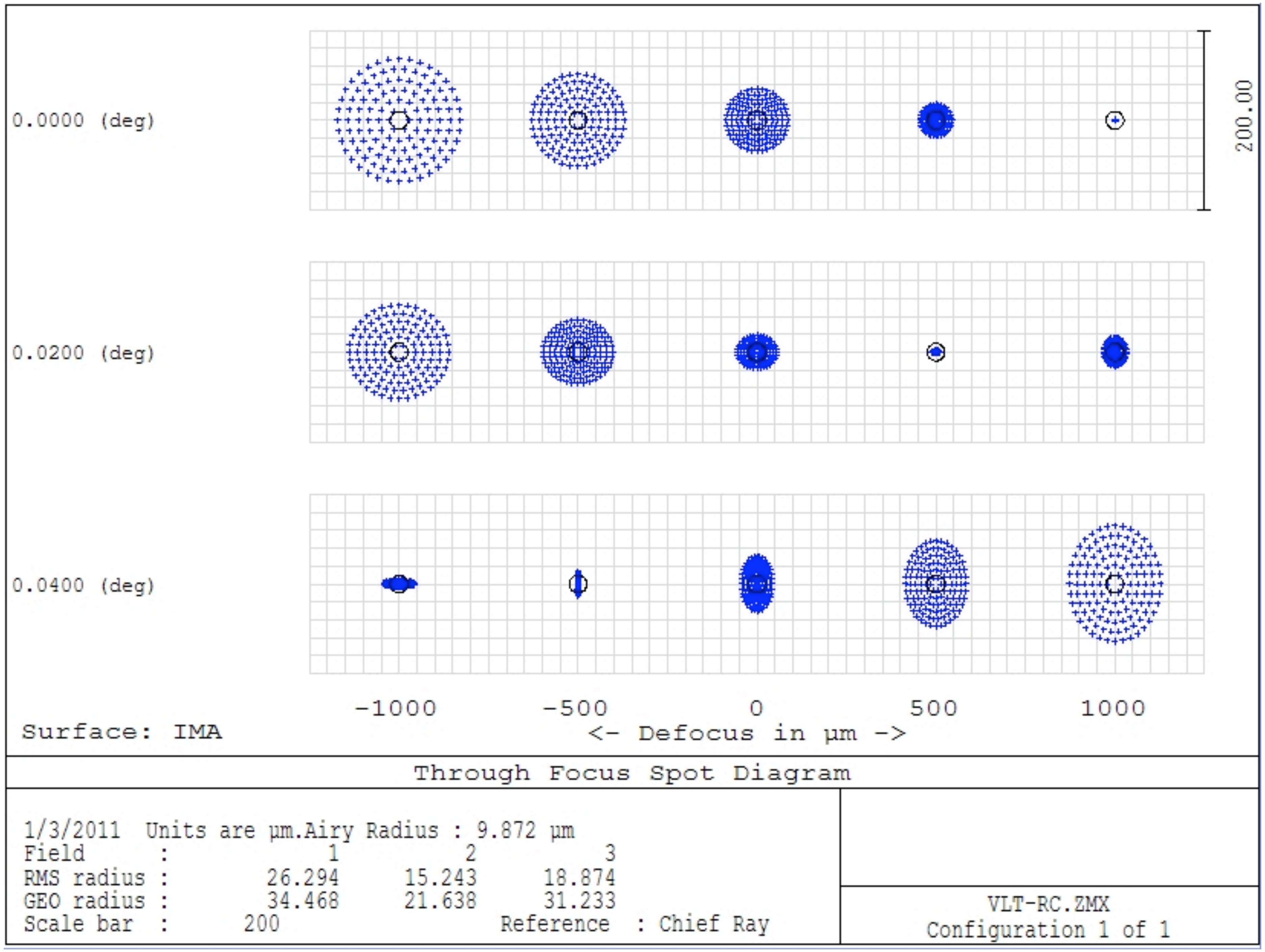


Ritchey-Chrétien Telescope

Infinite combination of K_1 and K_2 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

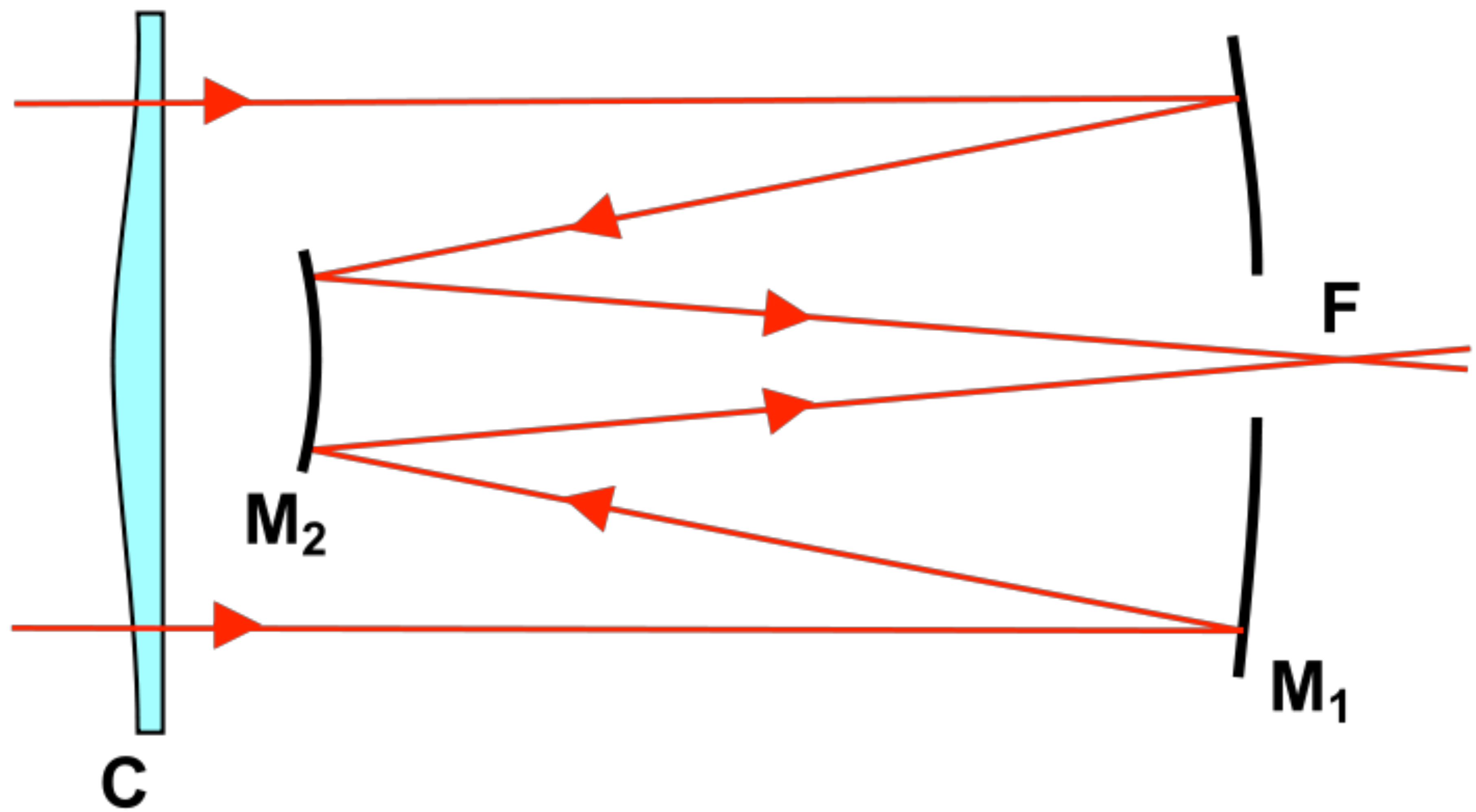
Two Mirror Telescope aberrations

On-axis aberrations are SPHERICAL

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

Wide field telescopes

Schmidt corrector plate widens the field of view

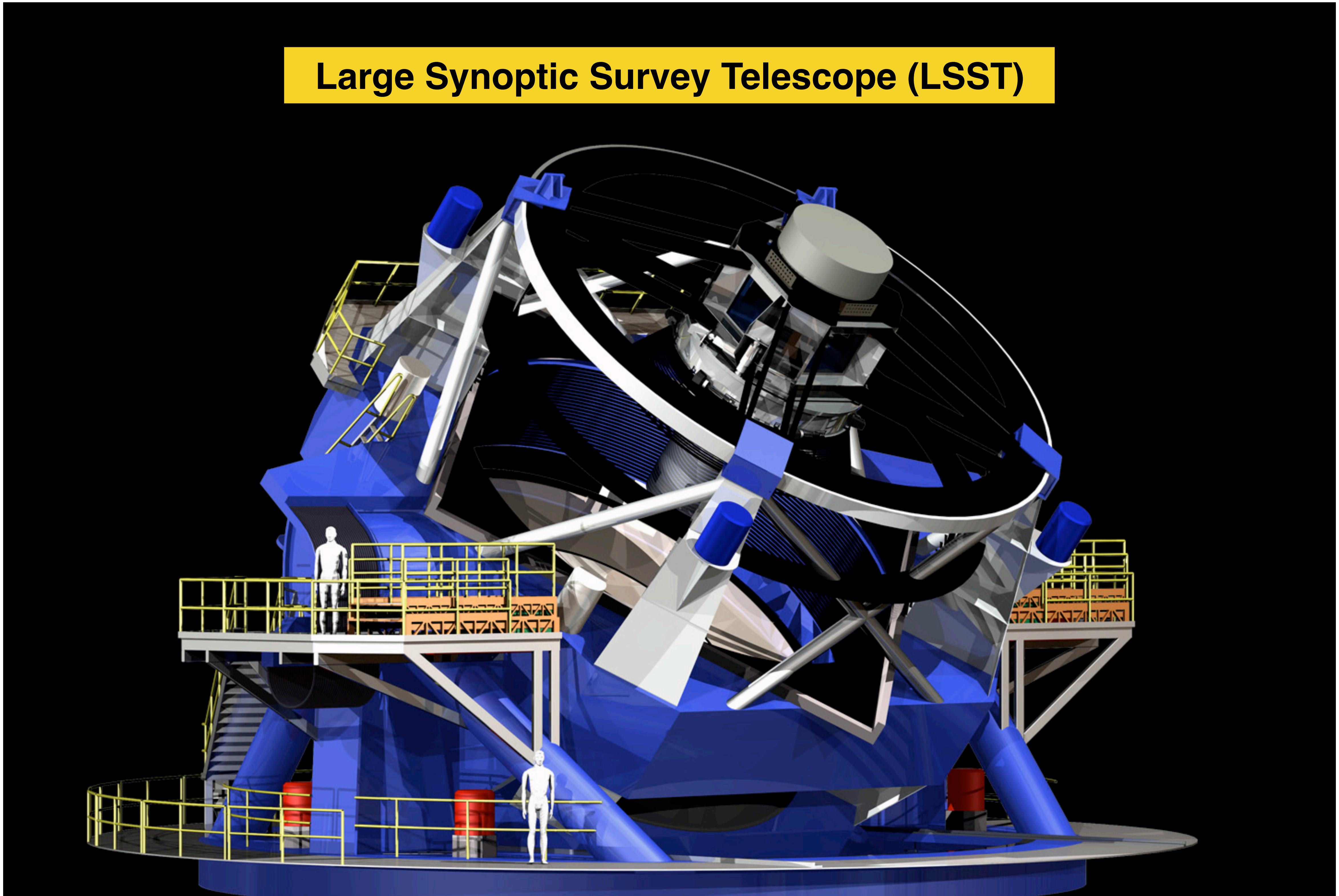


Schmidt-Cassegrain

Wide field telescopes

Three Mirror Anastigmat (TMA)

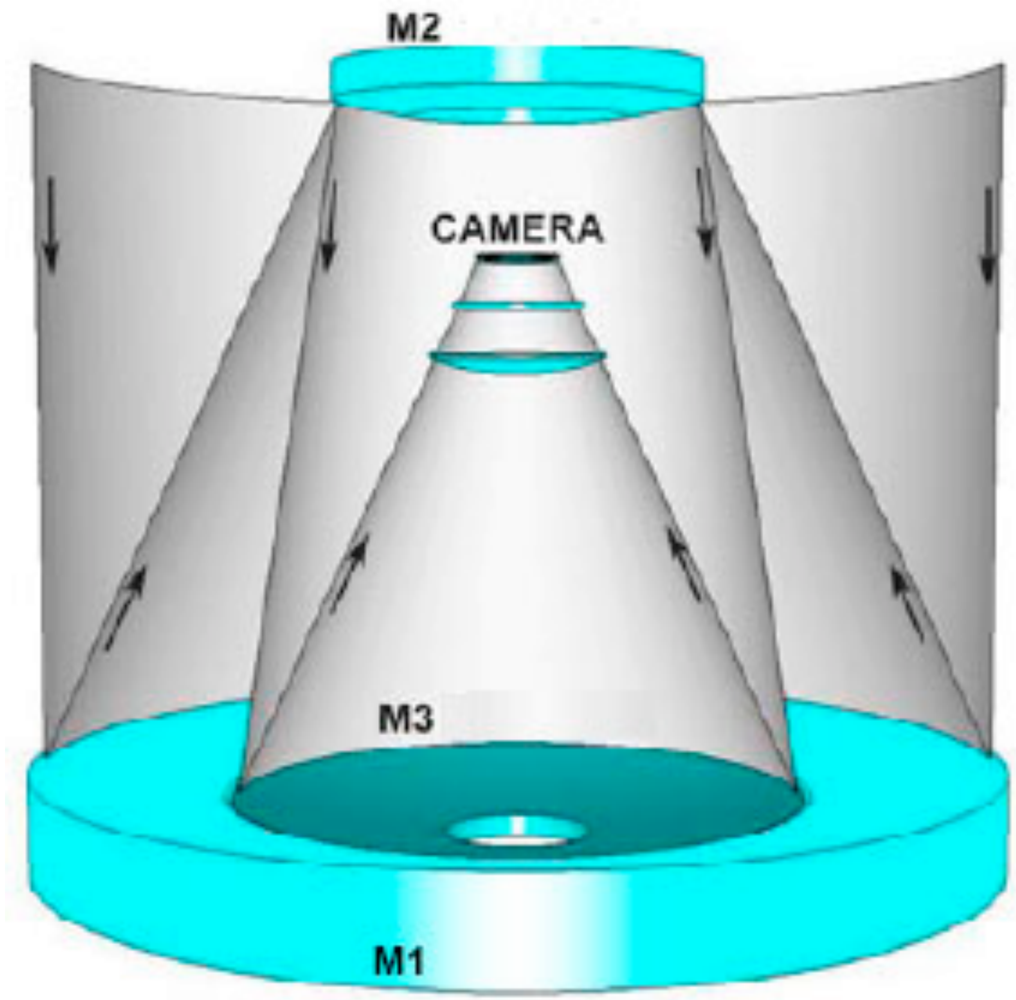
fixes spherical, coma, astigmatism with three conic constants

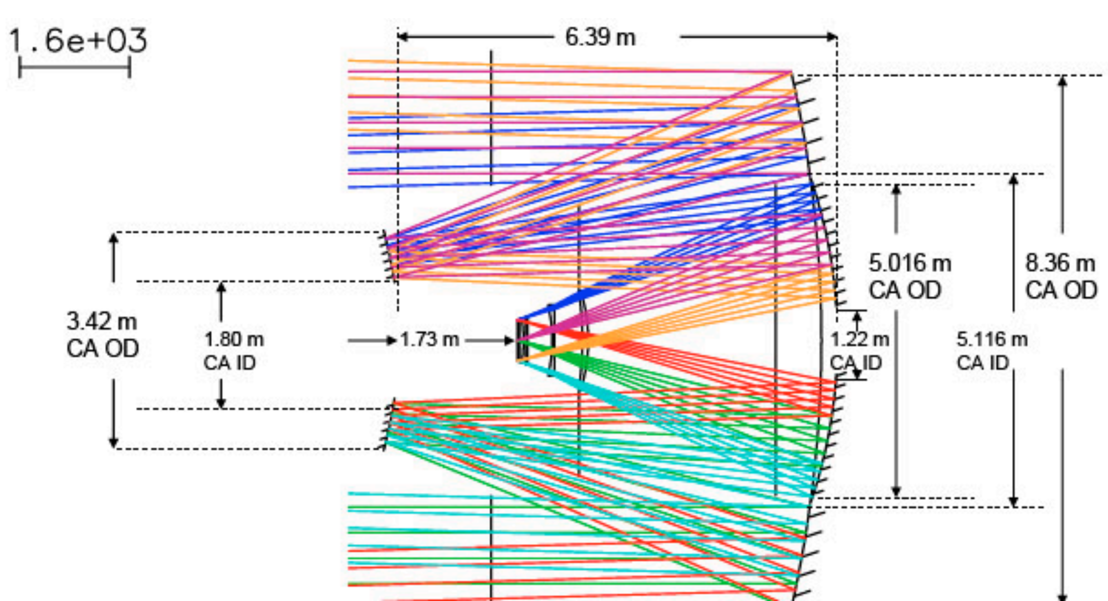


Wide field telescopes

M1 and M3 polished out of same blank!

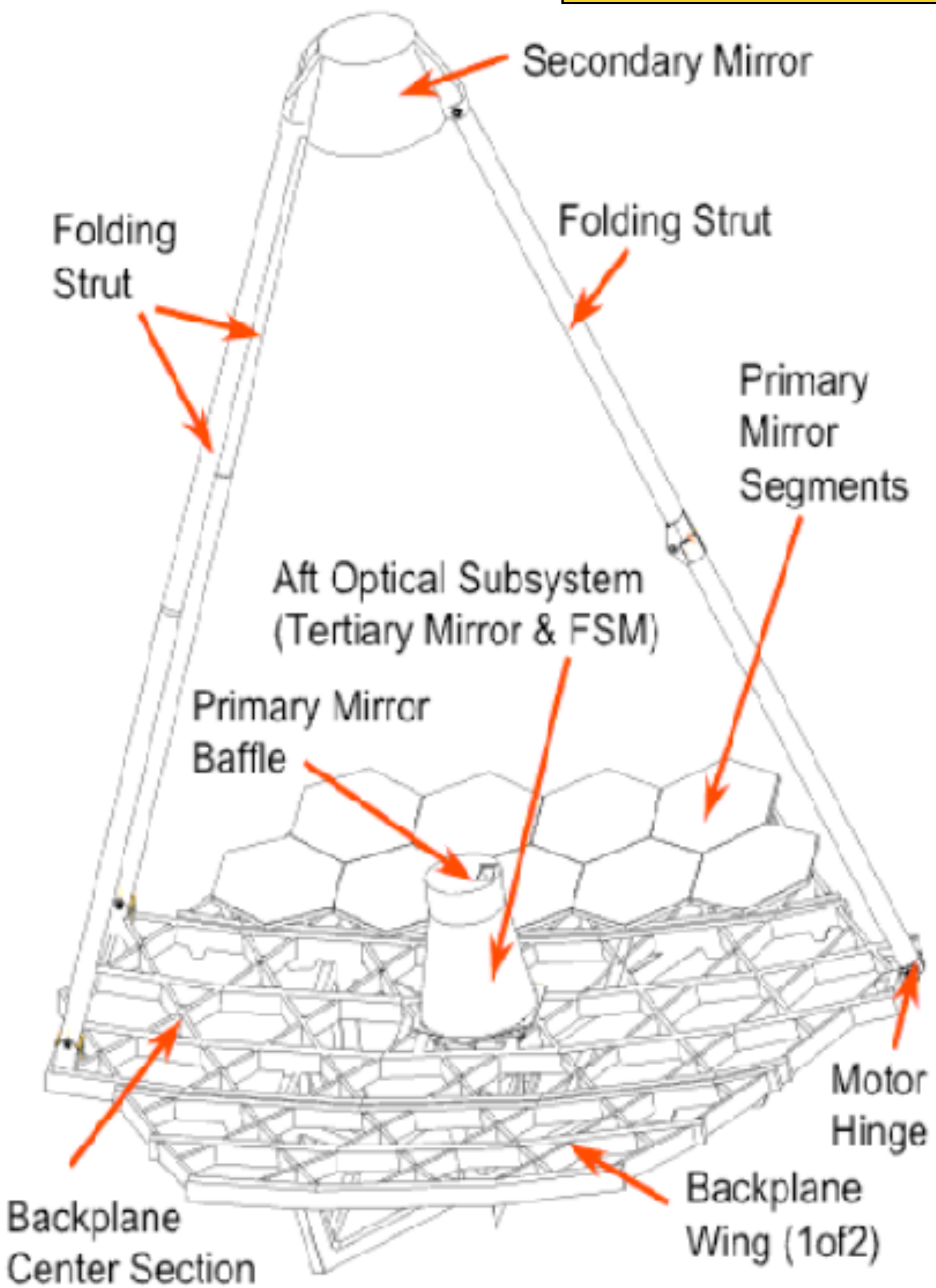
LSST

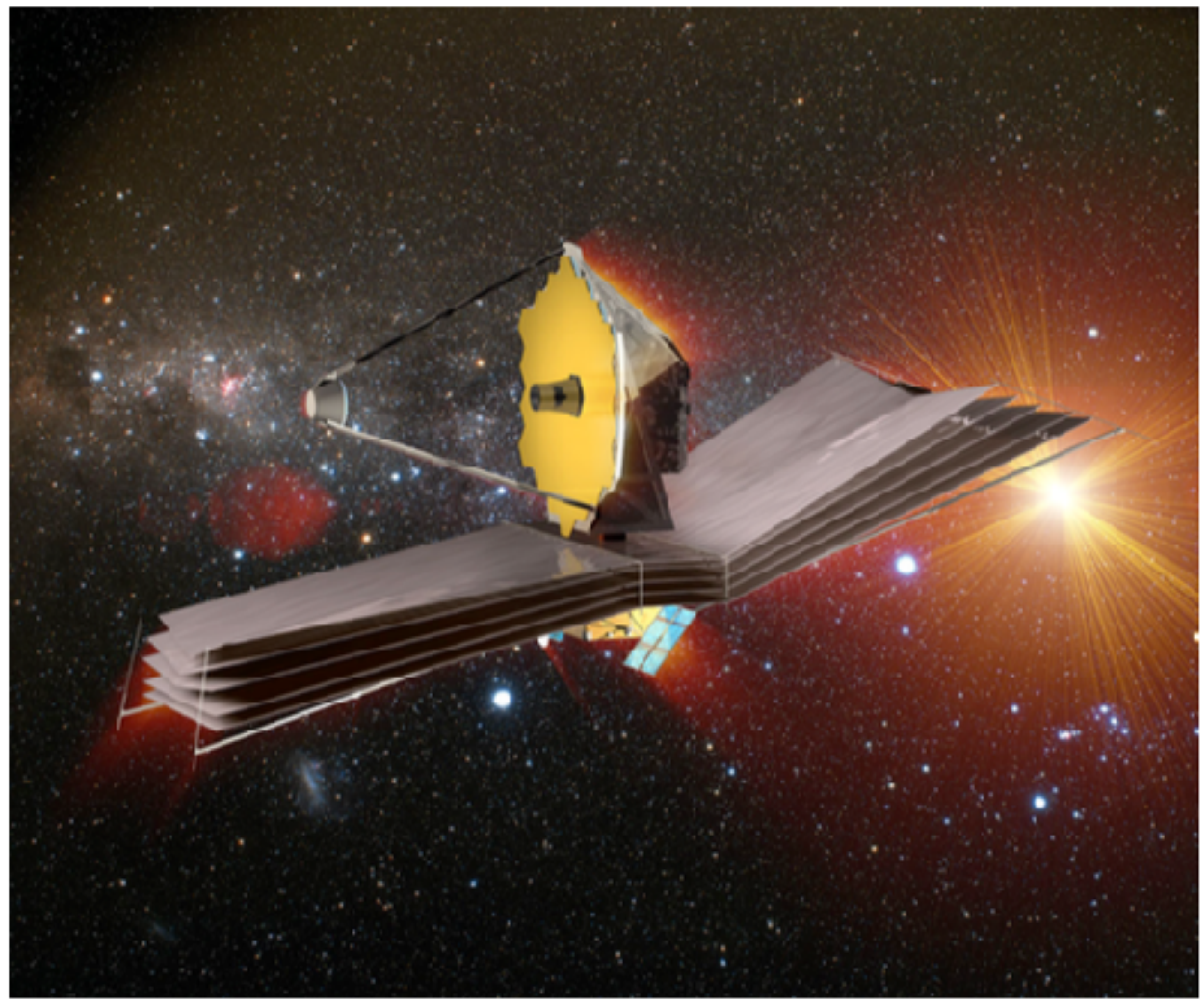




Wide field telescopes

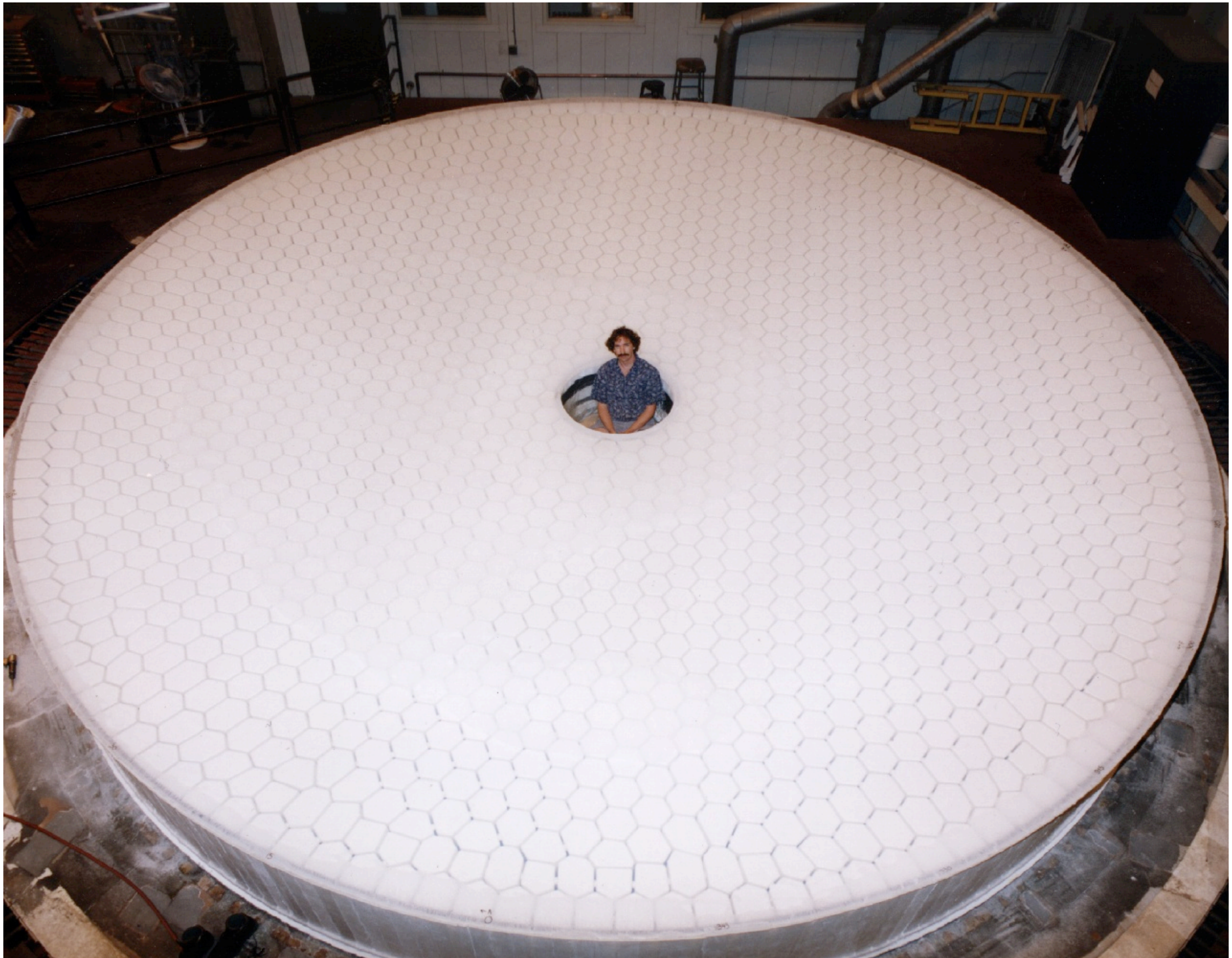
James Webb Space Telescope (JWST)





Largest Monolithic Mirrors

Spin-casting mirrors in Arizona

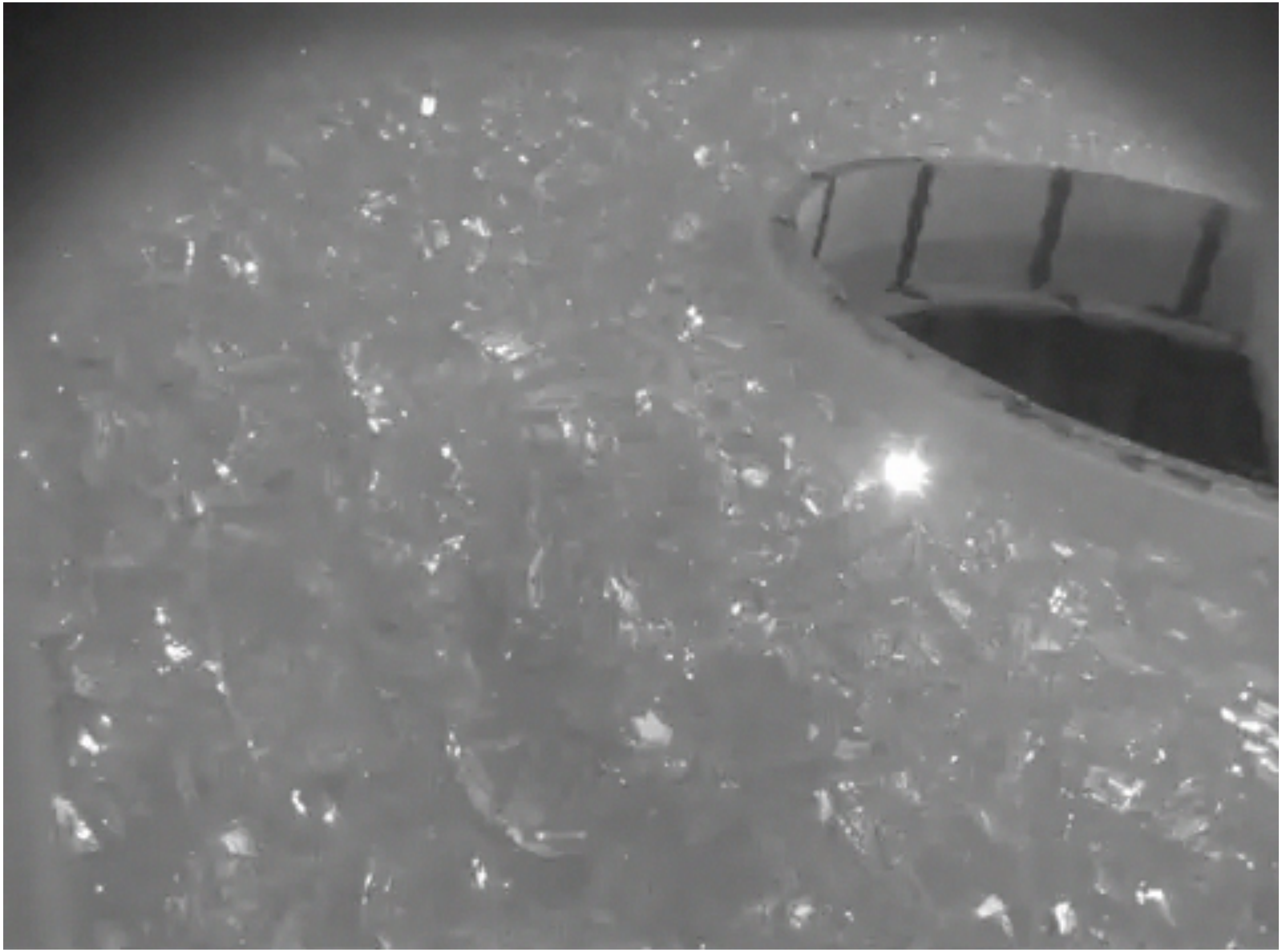


Glass loaded into the mold

GMTO / Ray Bertram

SOML Spinning Oven

GMT mirror 4 in 2015

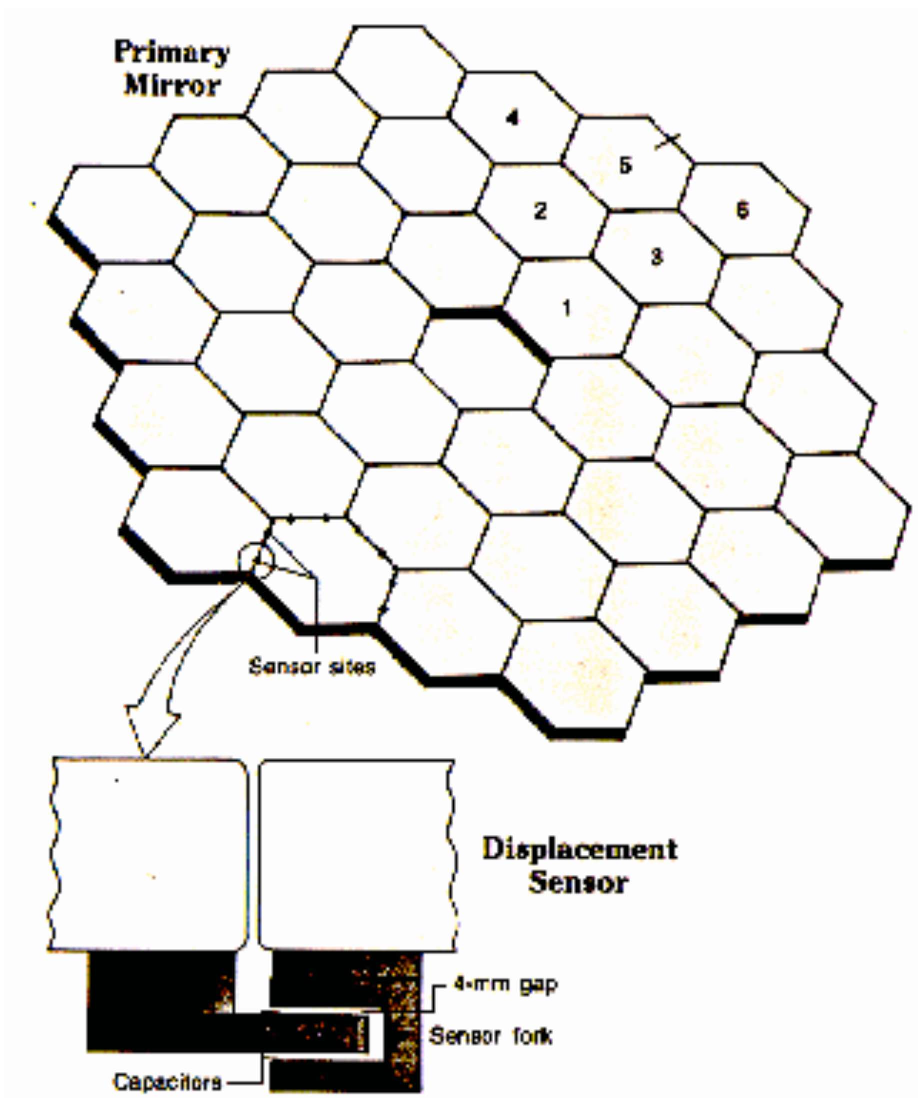


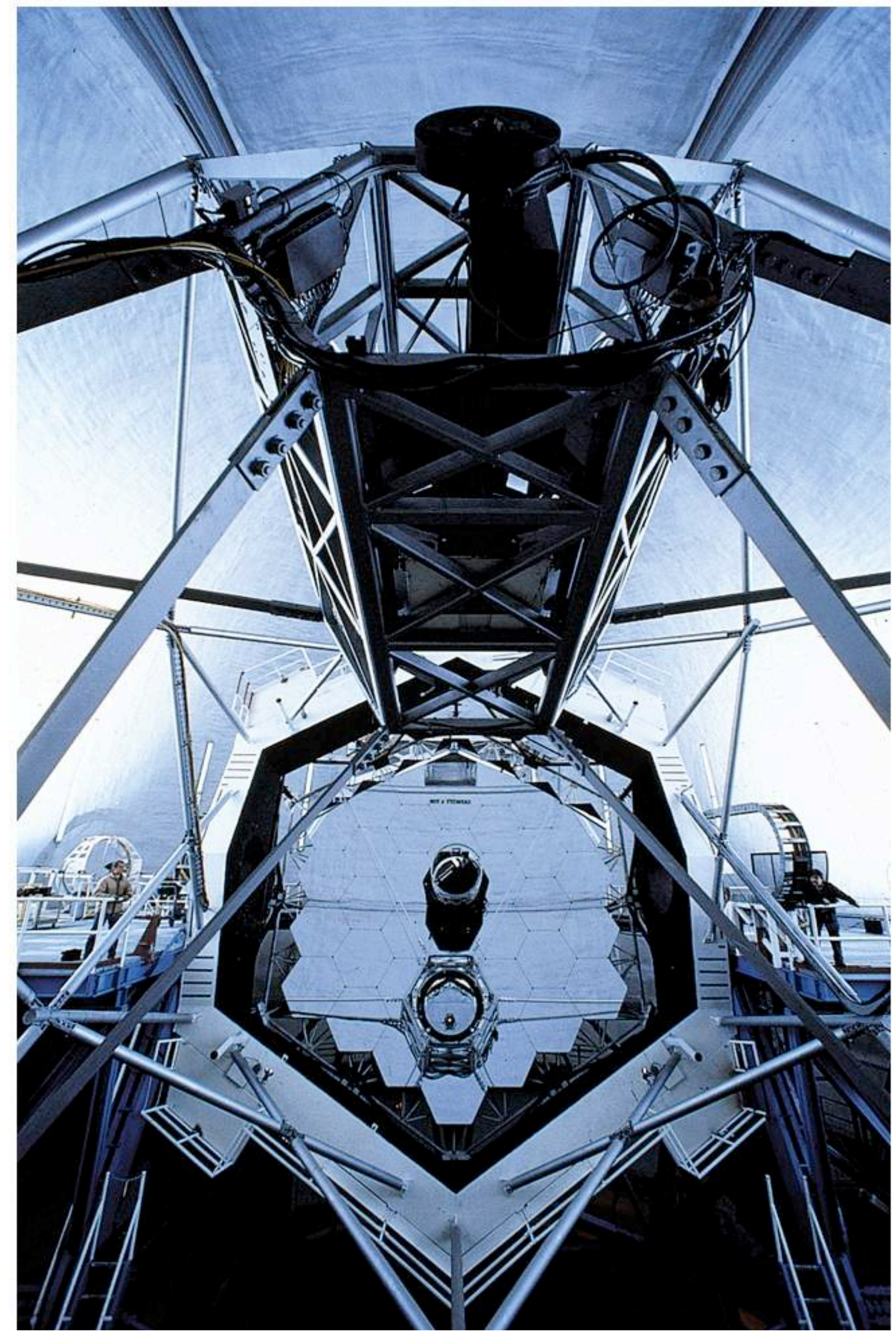
John Hill / University of Arizona

Segmented Primary Mirrors

Individual mirrors easy to manufacture

Keck I and II

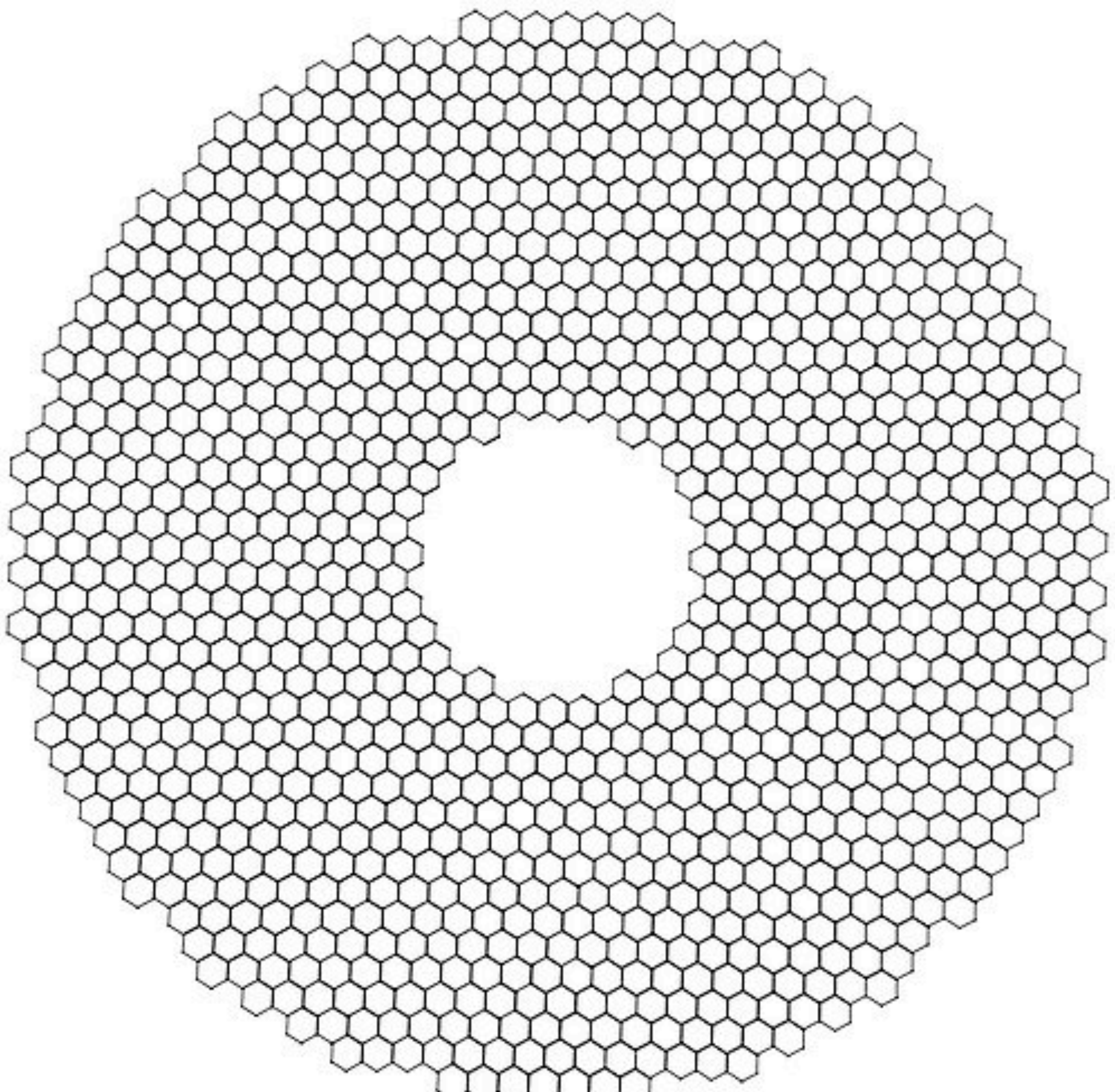


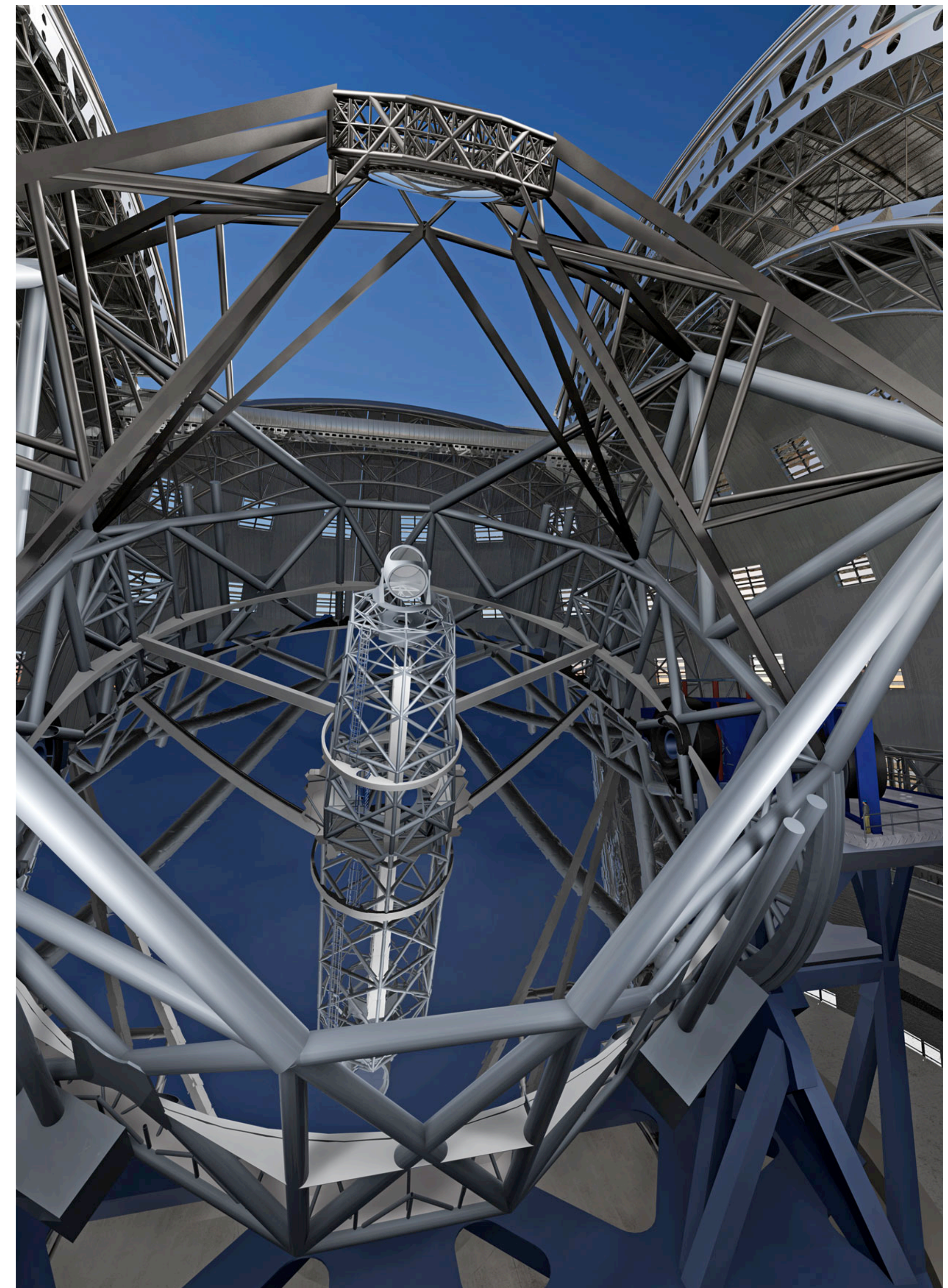


Segmented Primary Mirrors

Individual mirrors easy to manufacture

E-ELT: 984 1.4-m segments

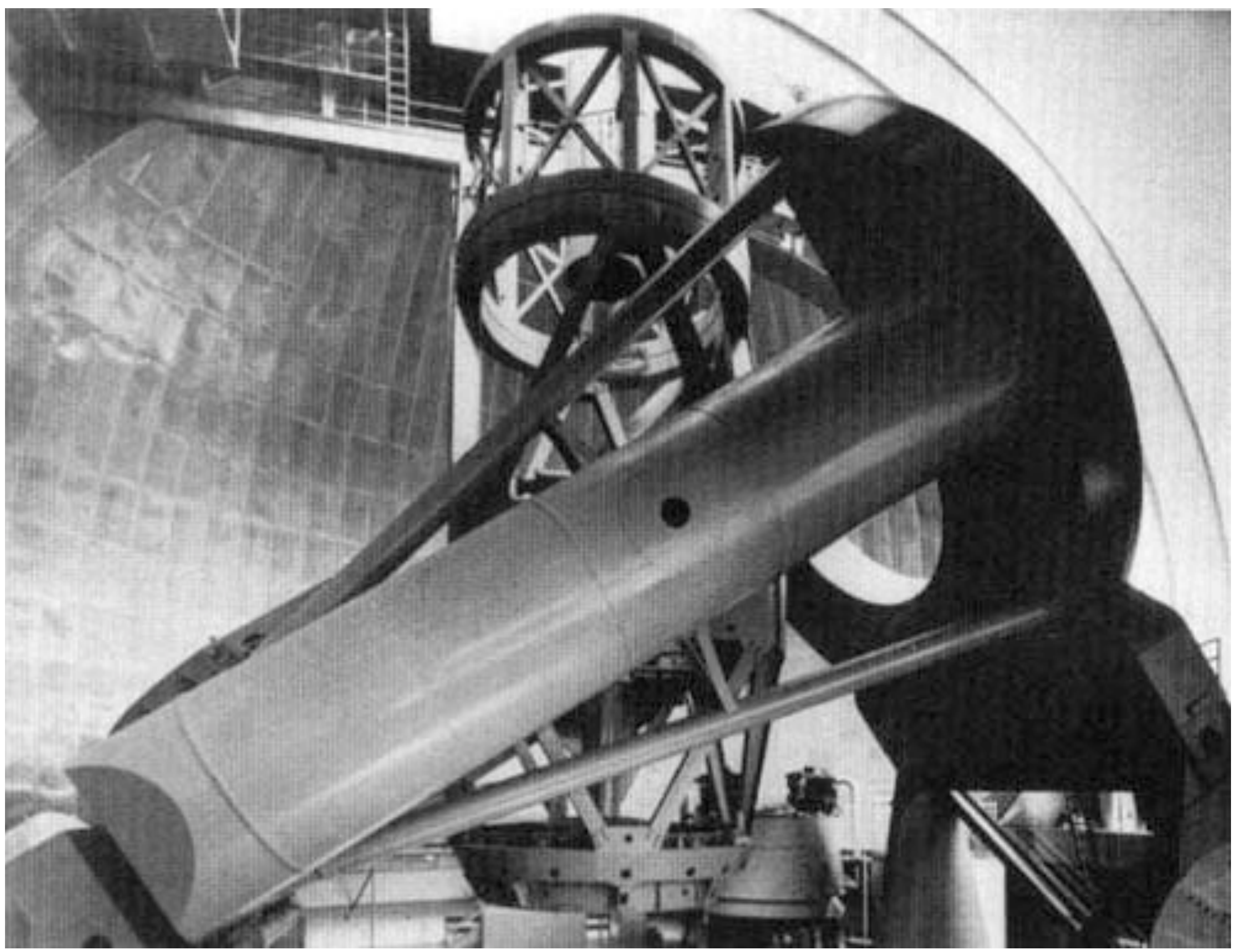




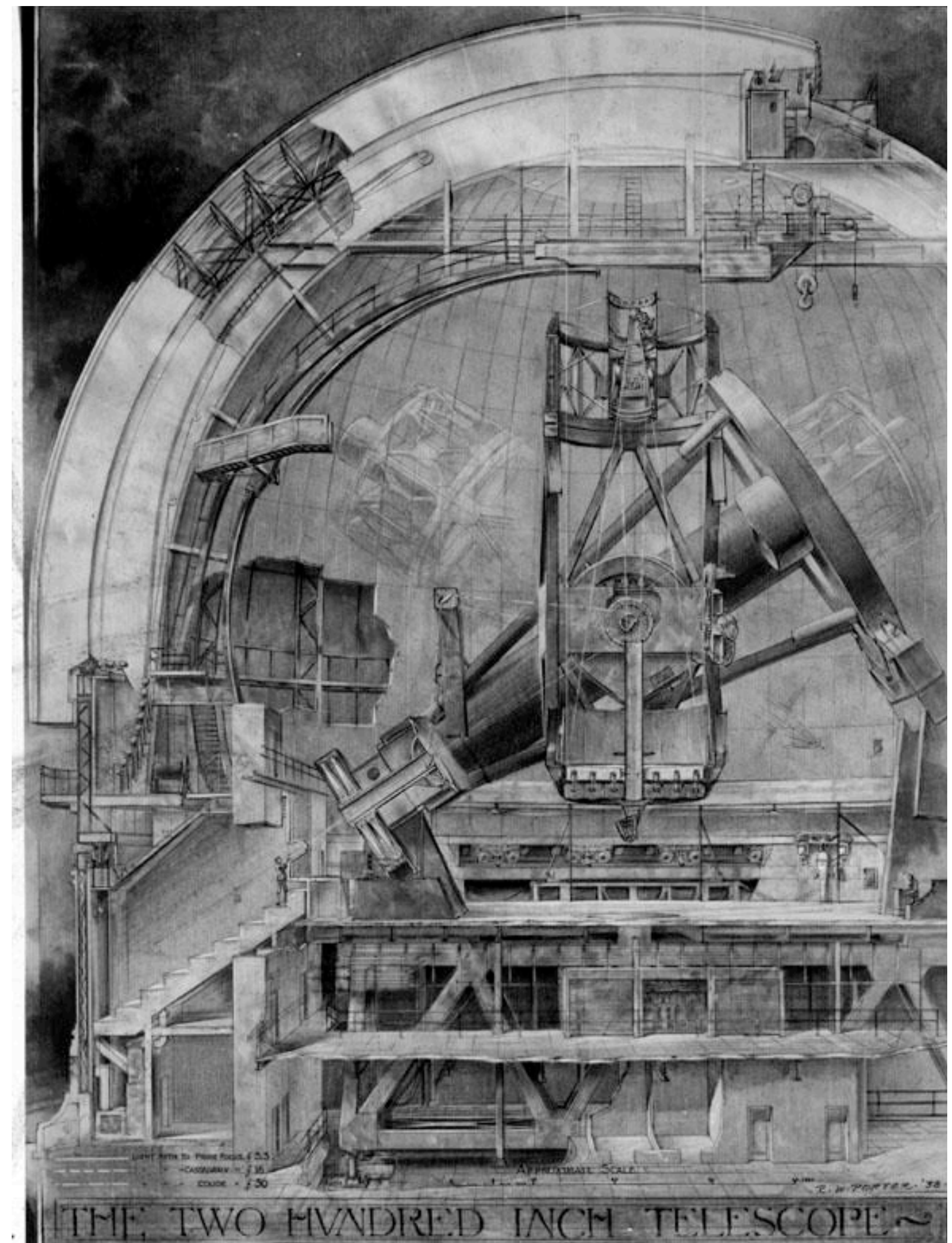
Equatorial Mounts

Only one axis to guide

- equatorial (RA, dec)



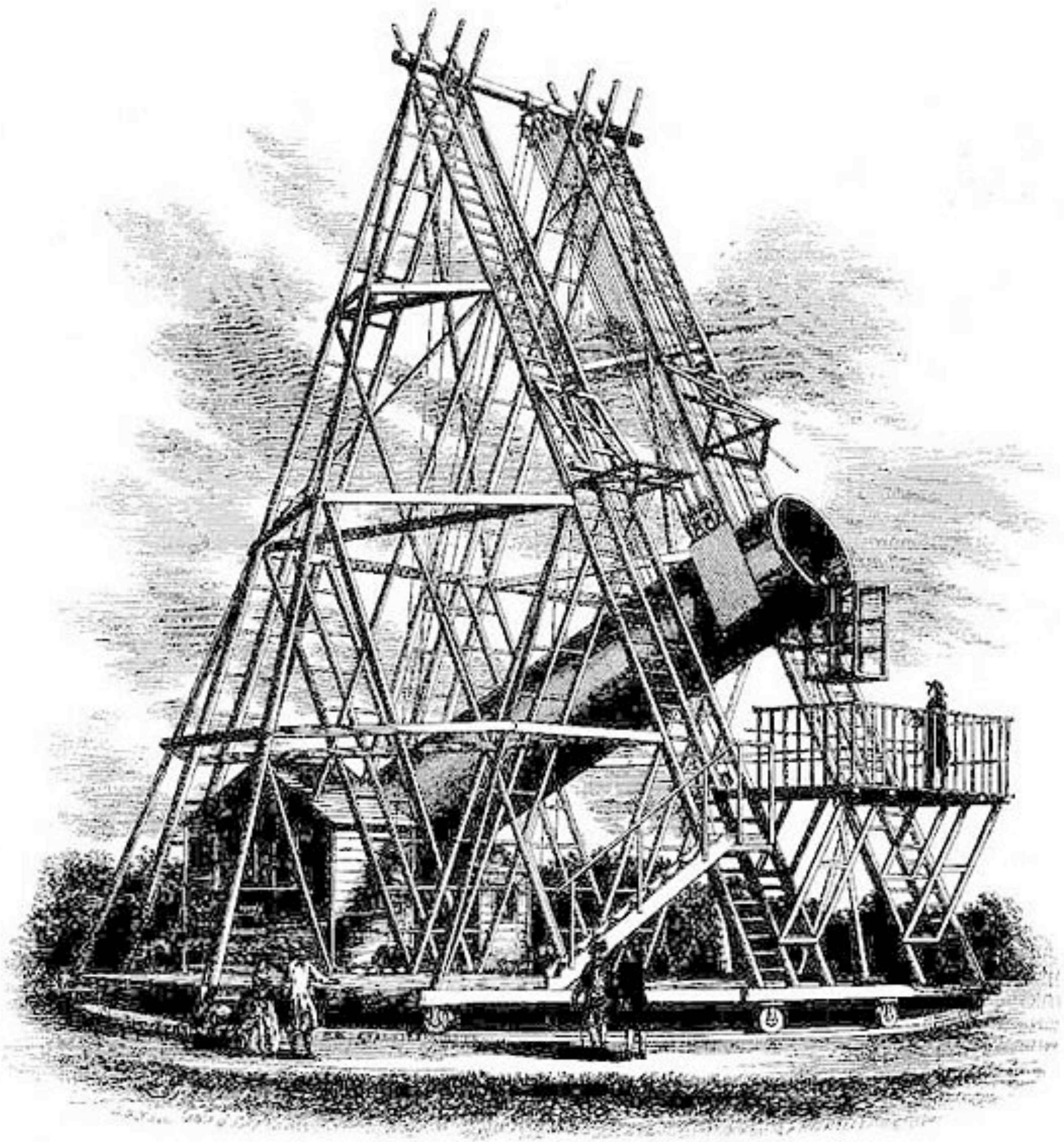
Hale 200" @ Palomar



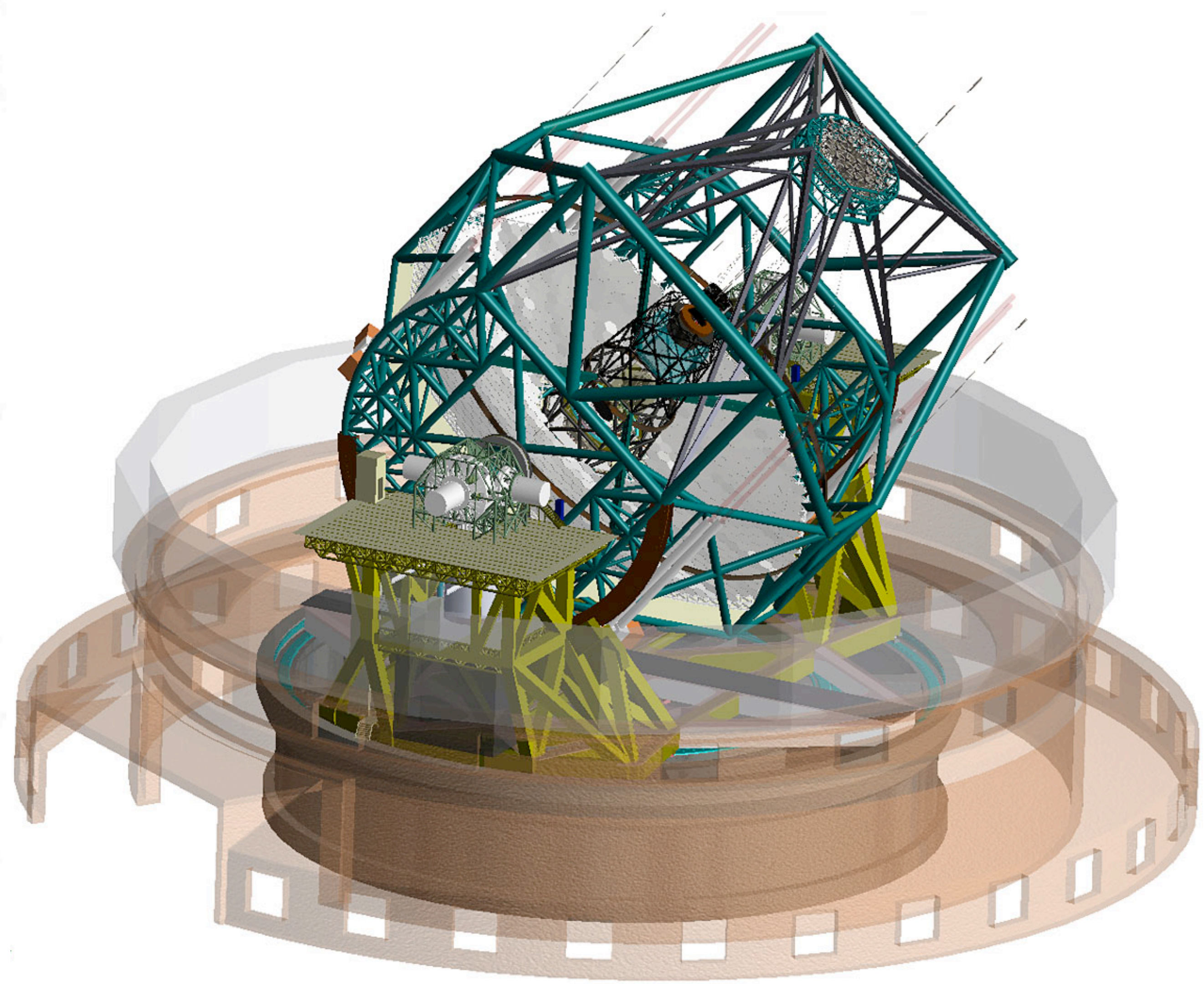
Alt-Az mounts

Computer controllers make this preferred option

Zenith inaccessible due to azimuth drive speed



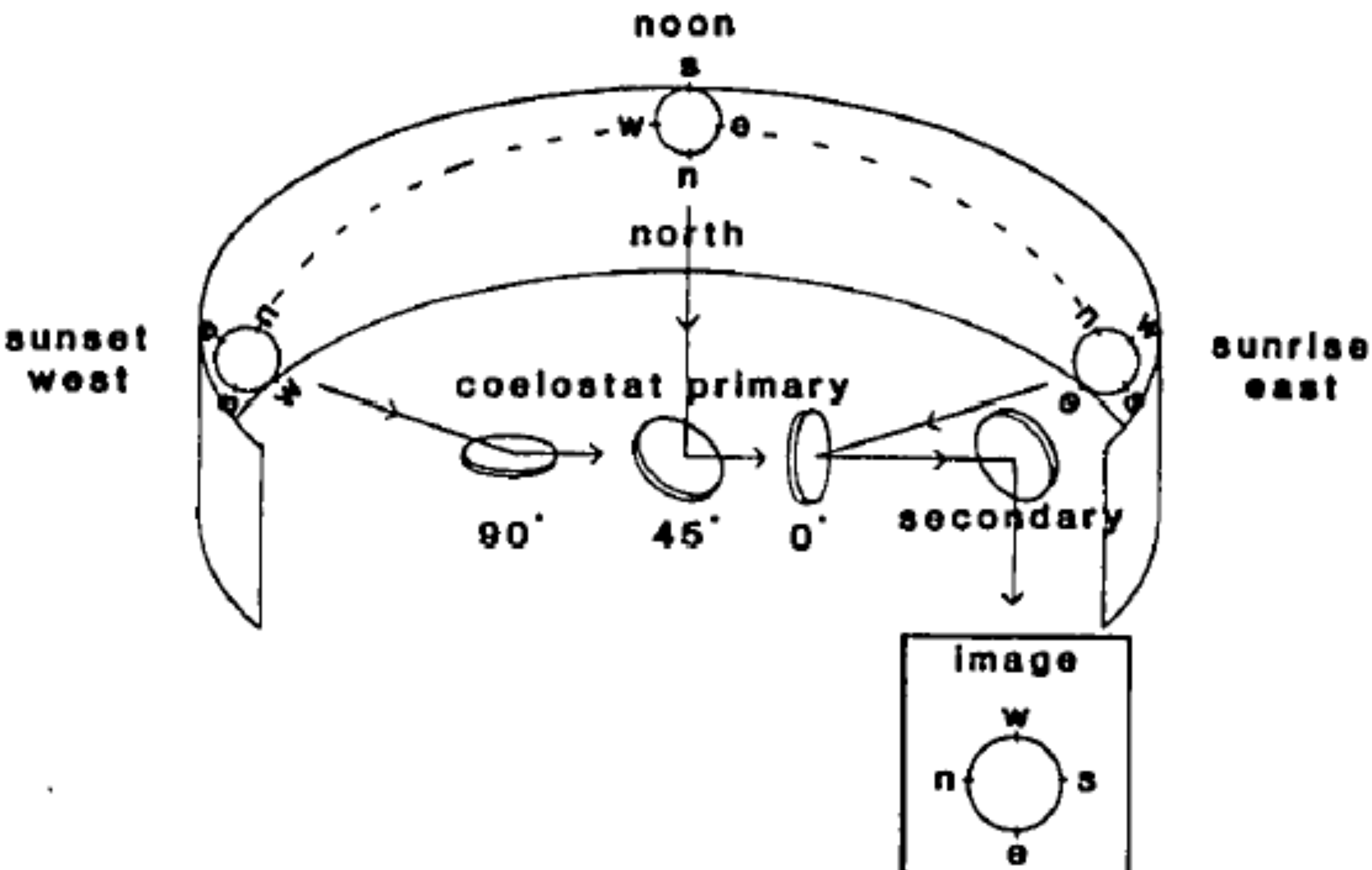
Herschel 1789



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:

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

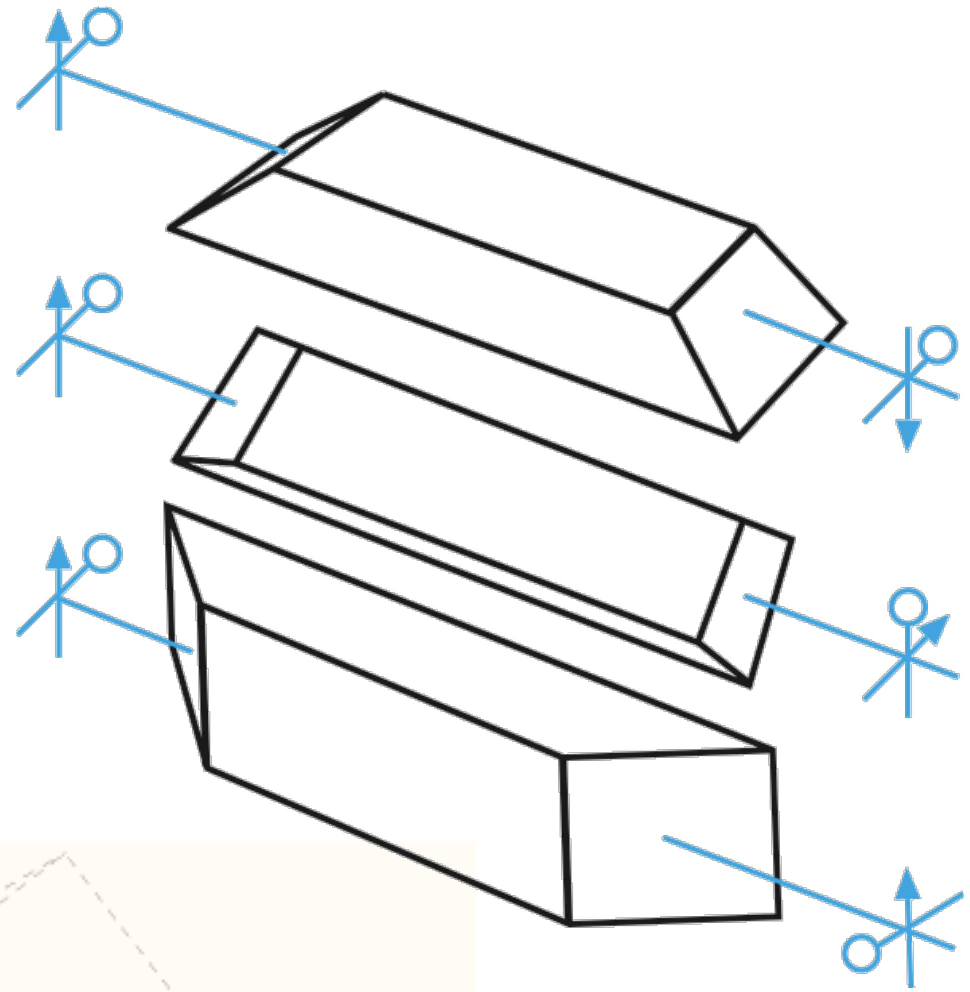
- alt-az at Nasmyth (or Coudé) platform:

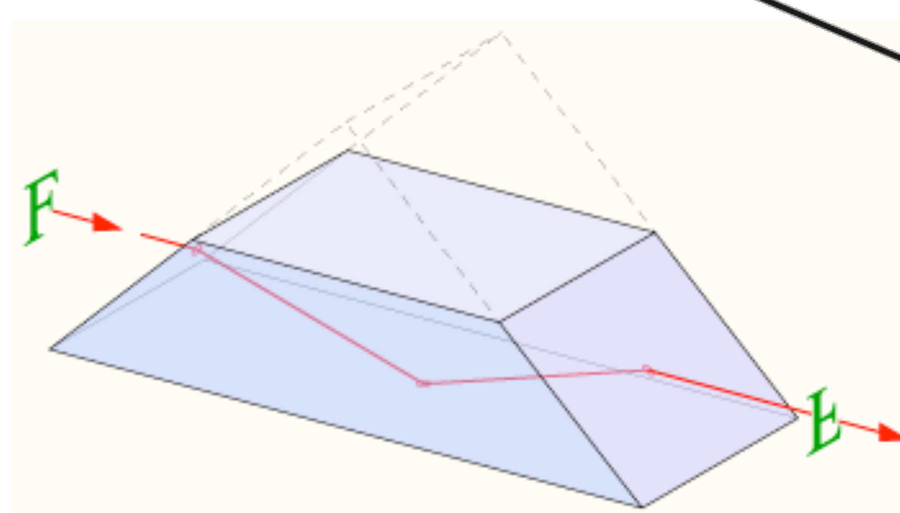
$$\vartheta_{\mathrm{Nasmyth}} = alt - \vartheta_{\mathrm{cass.}} \; (- \, az)$$

Derotating the field of view

Sky rotates with hour angle

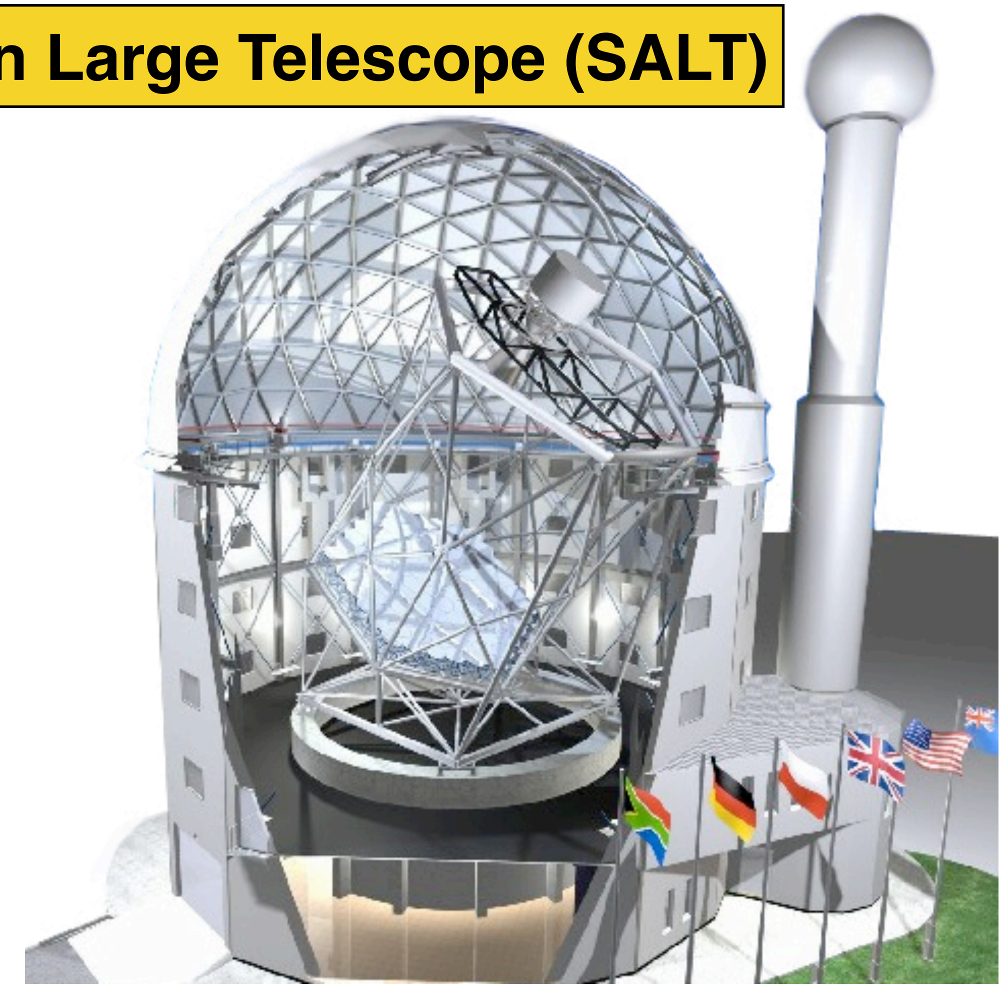
- rotate entire instrument
- derotator
  - K-mirror
  - Dove prism
  - anything rotatable with an odd number of reflections

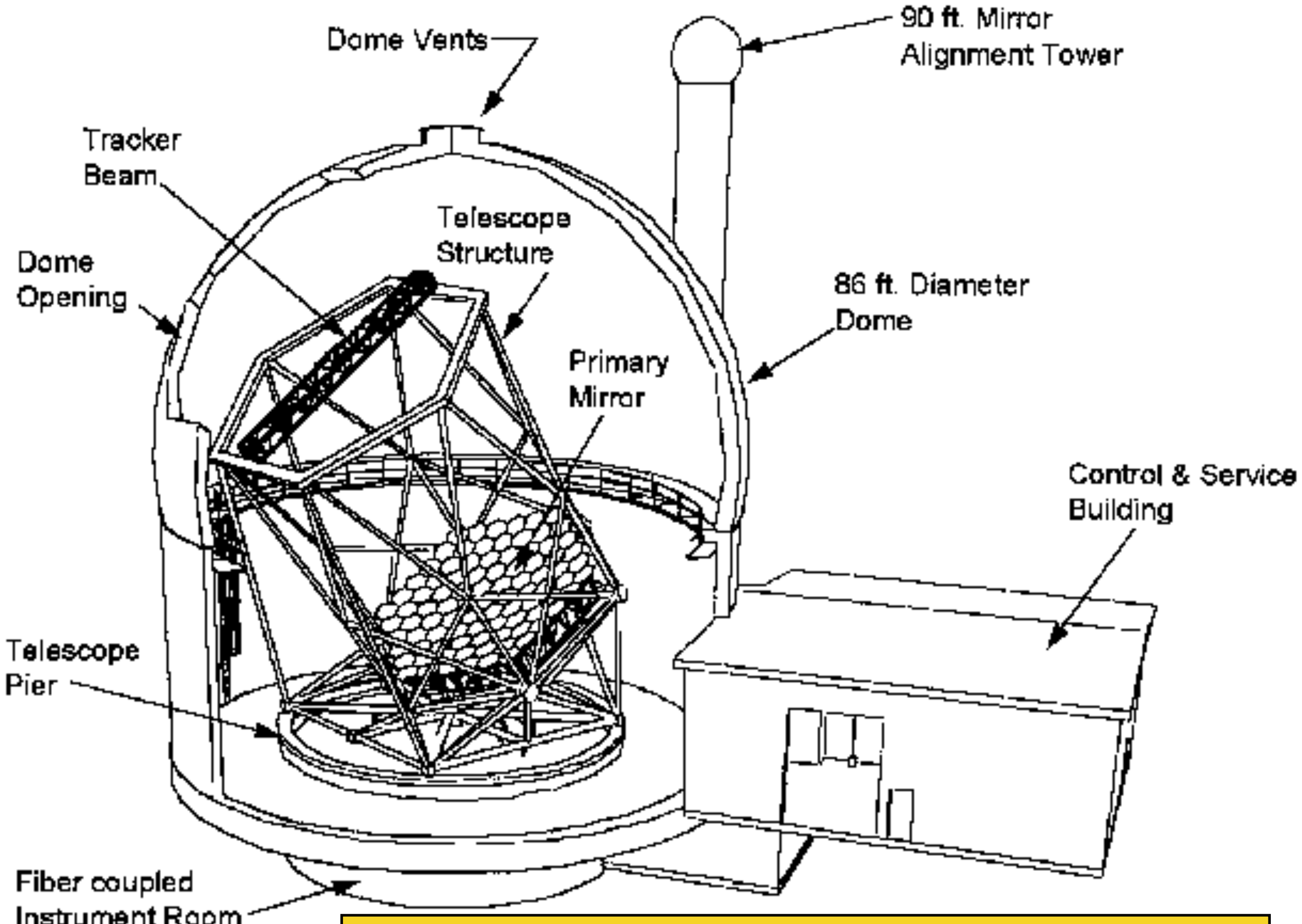




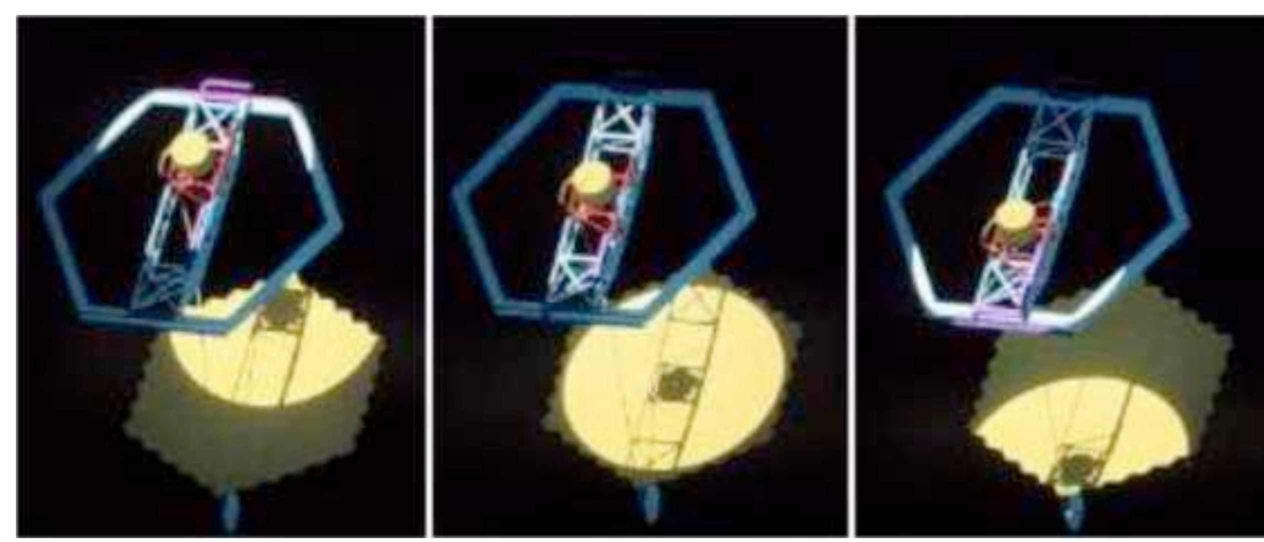
Fixed elevation telescopes

Southern African Large Telescope (SALT)





Hobby-Everly Telescope (HET)



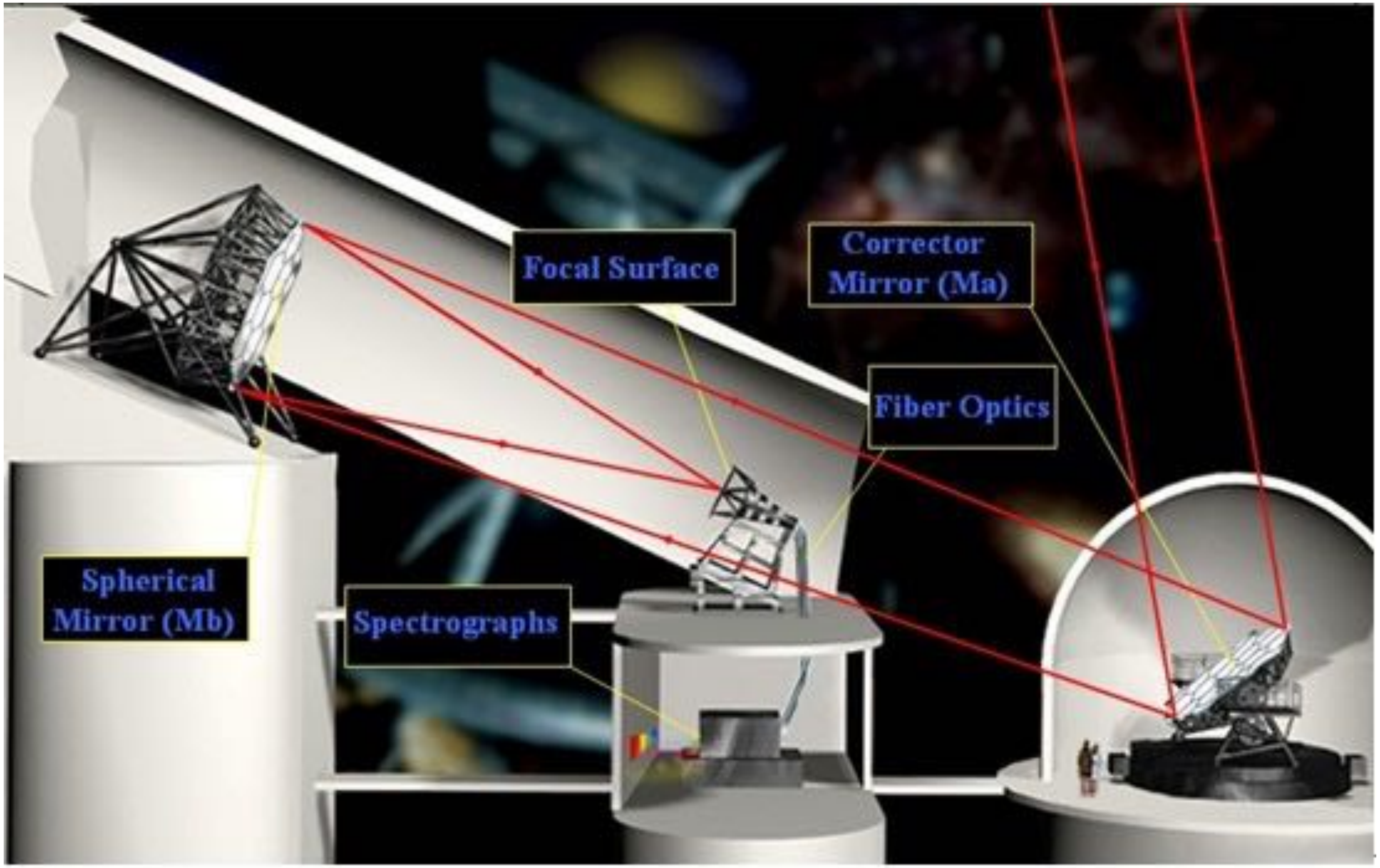
Coelostat

Only one mirror to steer across sky

LAMOST (China)

Coelostat

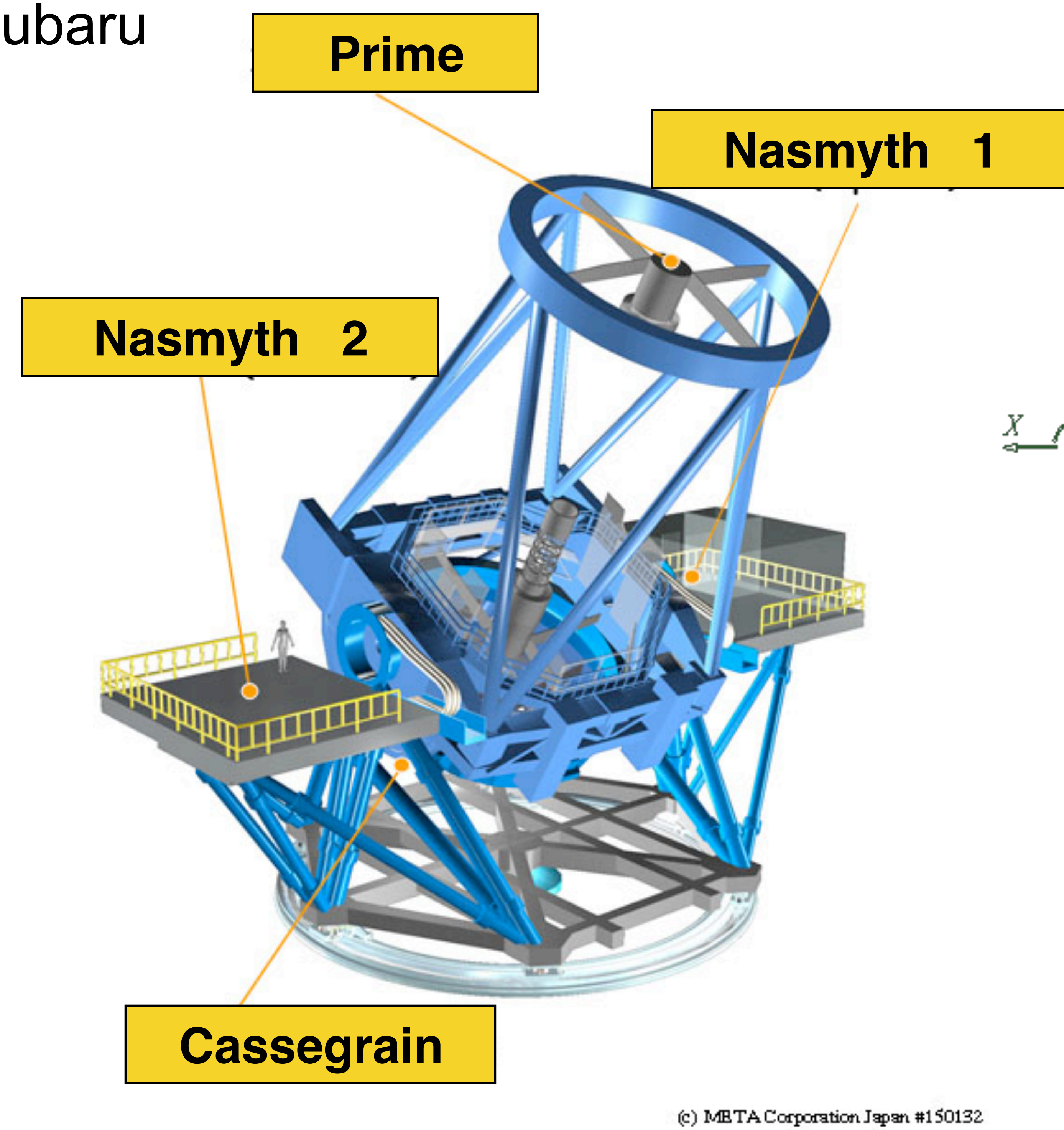
Only one mirror to steer across sky



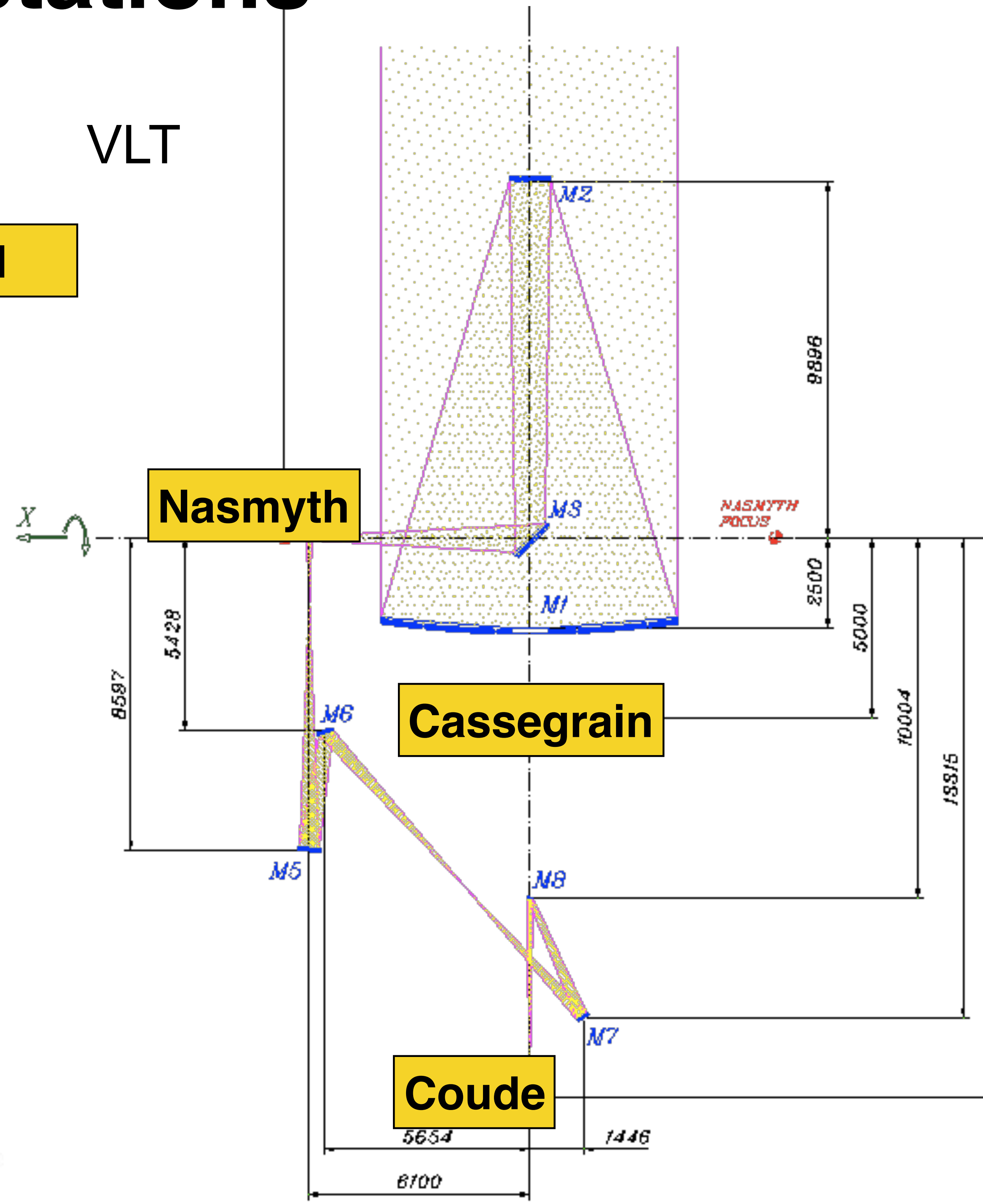
LAMOST (China)

Focal stations

Subaru

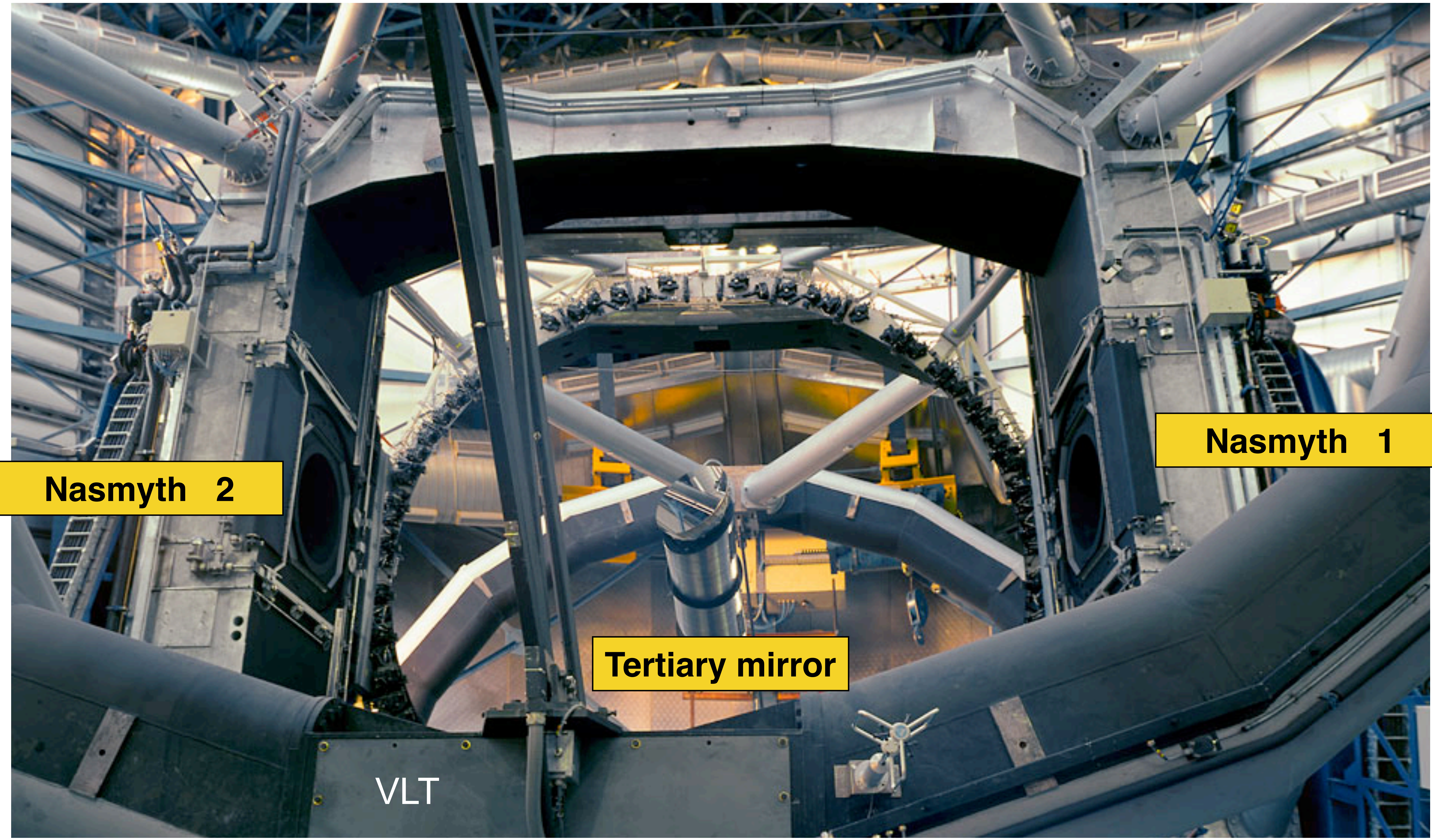


VLT

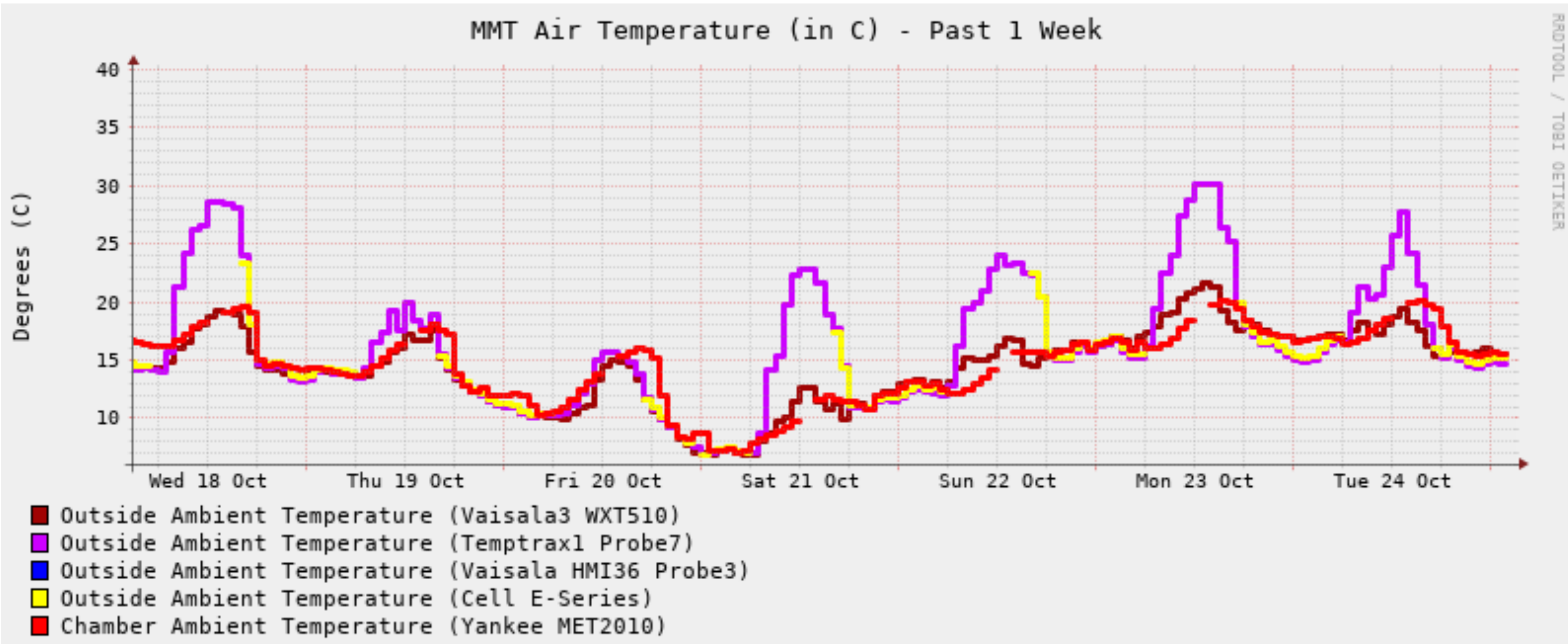


Focal stations

Sky rotates with hour angle

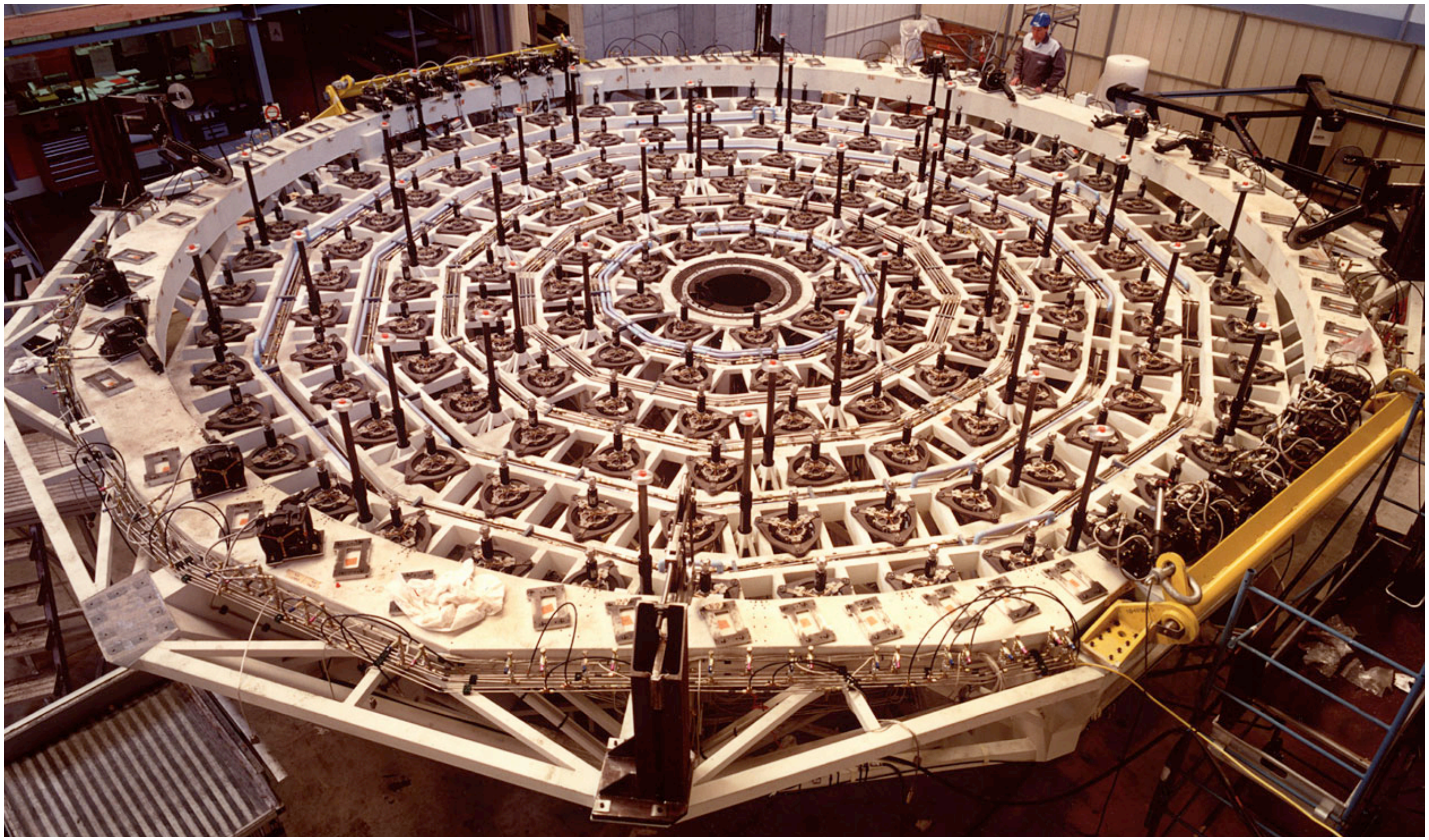


Outside air cools much faster than large telescope mirrors



http://hacksaw.mmto.arizona.edu/engineering/rrd/vaisala3/1wk.php

Warm mirror and cold night air mix to form ‘mirror seeing’

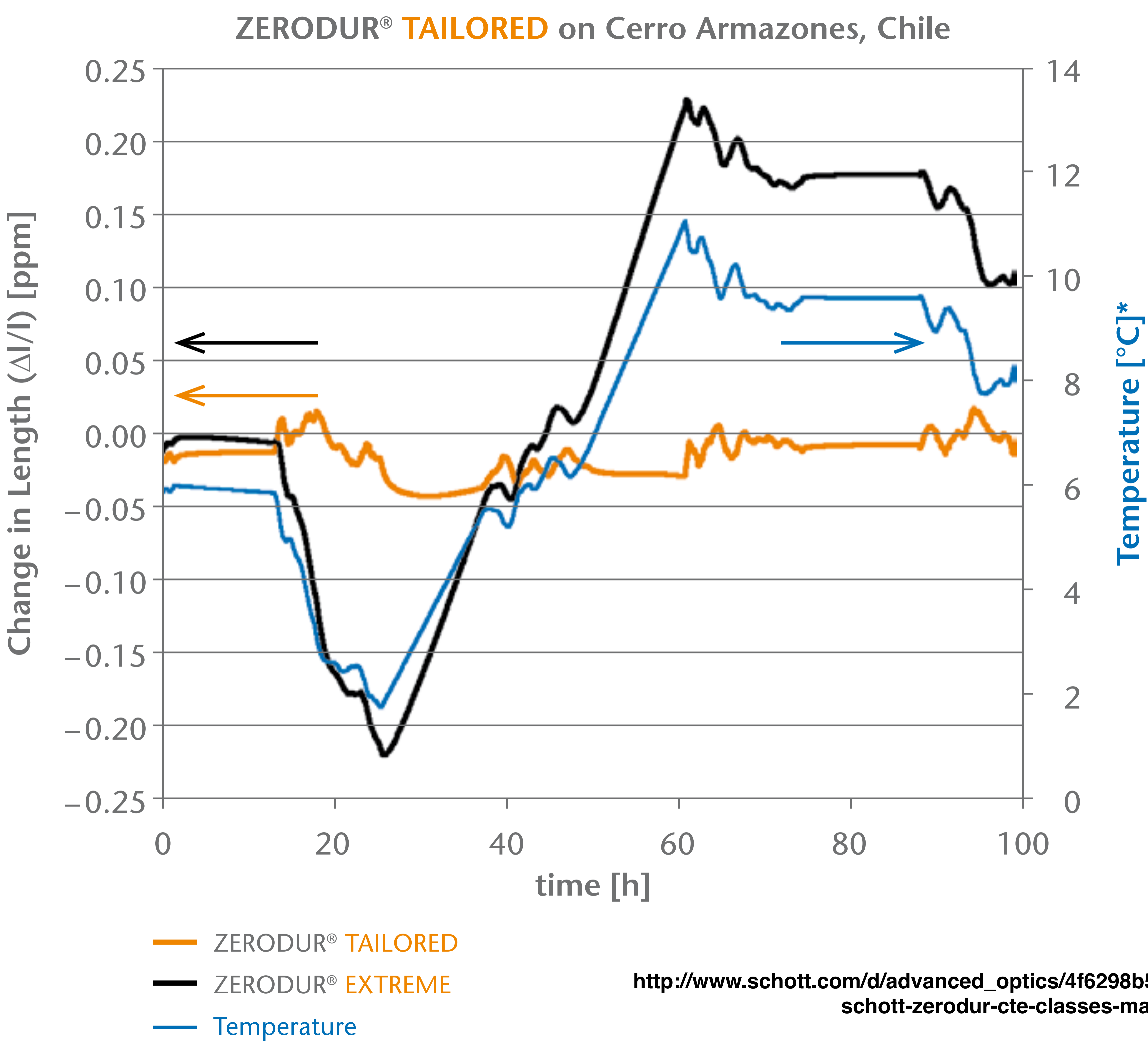


Temperature control with air jet cooling

Arizona Mirror Laboratory

ZERODUR from SCHOTT

One of the lowest Coefficient of Thermal Expansions (CTEs)

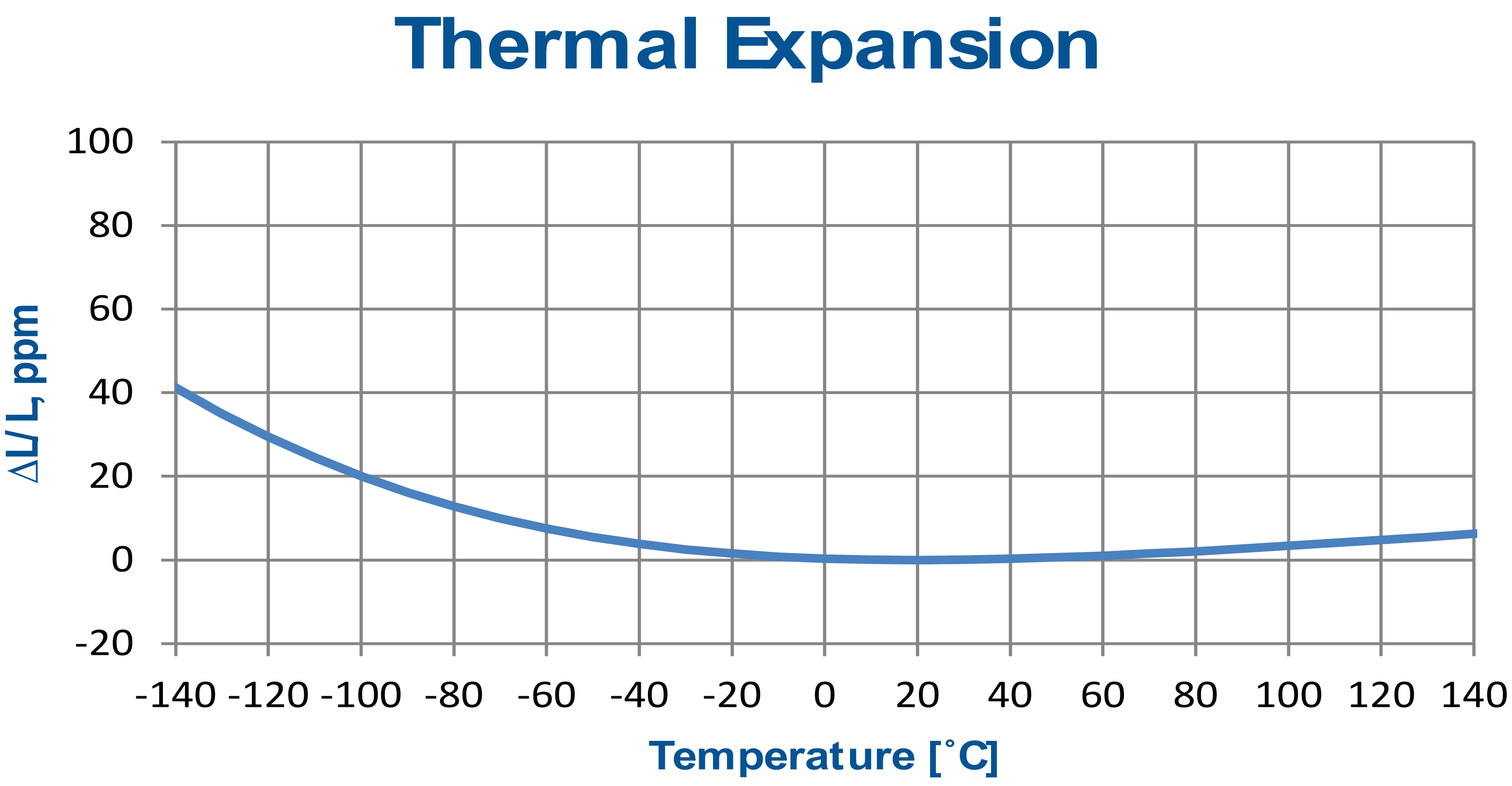


Operating range: 0 to 50 deg C

http://www.schott.com/d/advanced_optics/4f6298b5-9f89-4da8-8d8c-3e5190dca4b4/1.0/schott-zerodur-cte-classes-may-2013-eng.pdf

Ultra-Low Expansion (ULE) glass

Fused silica doped with titanium to make CTE close to 0 at room temps (Corning) some 20 times lower CTE than regular float glass



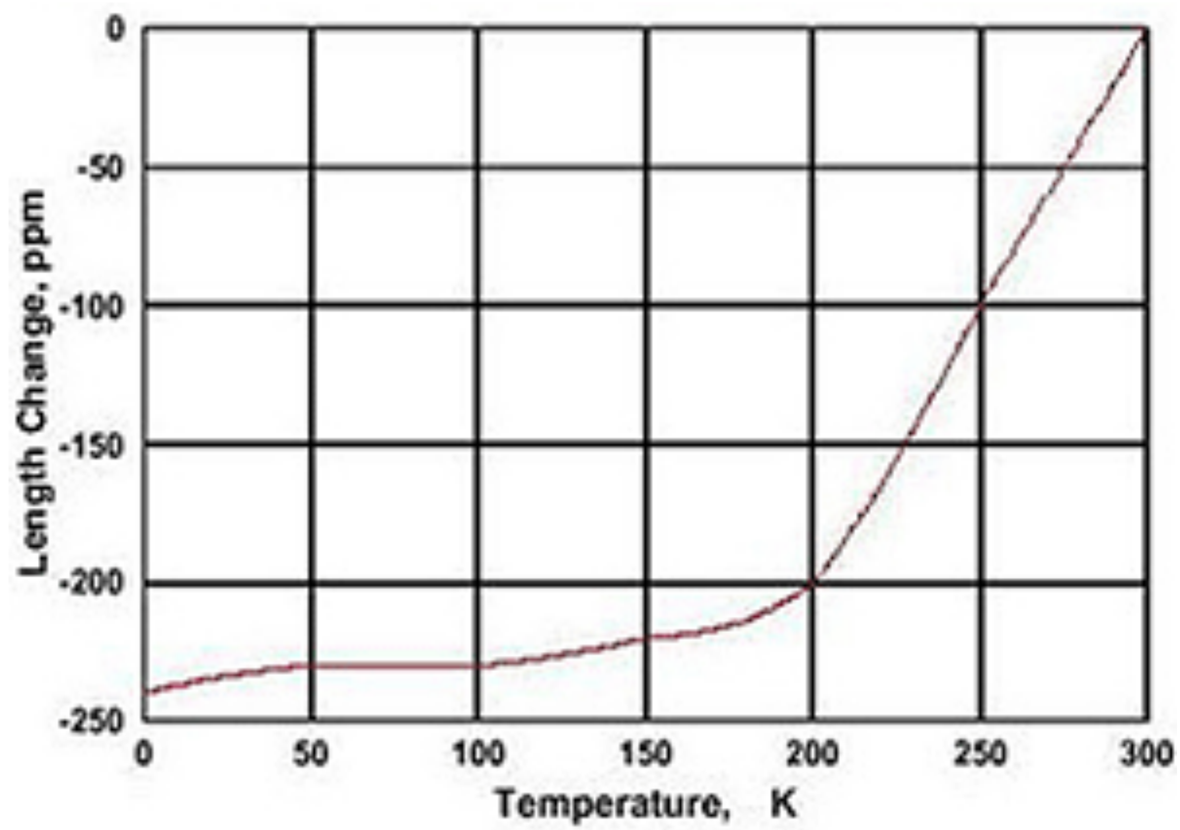
https://www.corning.com/media/worldwide/csm/documents/7973%20Product%20Brochure%202015_07_21.pdf

Lightweighting with Silicon Carbide

Operating range:
0 to 200 K

Ideal for space based operations

Difficult to polish



http://www.northropgrumman.com/BusinessVentures/AOAXinetics/AdvancedSystems/Pages/SiliconCarbide.aspx

Comparison of CTEs