

Concepts introduced in previous lectures:

- Photon noise
- Astronomical units: magnitude brightness scale, parsec
- Lagrange invariant: large field = large optics
- Airy pattern, Nyquist sampling
- Atmosphere: emission, transmission, turbulence
- Angular resolution and sensitivity in background-limited observations
- Requirements for astronomical optical systems, measurements:
 - collecting area (telescope diameter)
 - angular resolution
 - field of view
 - spectroscopy, photometry
 - astrometry
- Pupil plane, focal plane, plate scale (conversion between angle and distance)
- Refracting vs. Reflecting telescopes
- Challenges of large telescopes: holding the primary mirror

Astronomical Optics

2. Fundamentals of Telescope designs

2.2. Wide Field of View designs and aberration correction

Outline, Key concepts:

Importance of the location of focus and instruments

Main reflecting telescope designs:

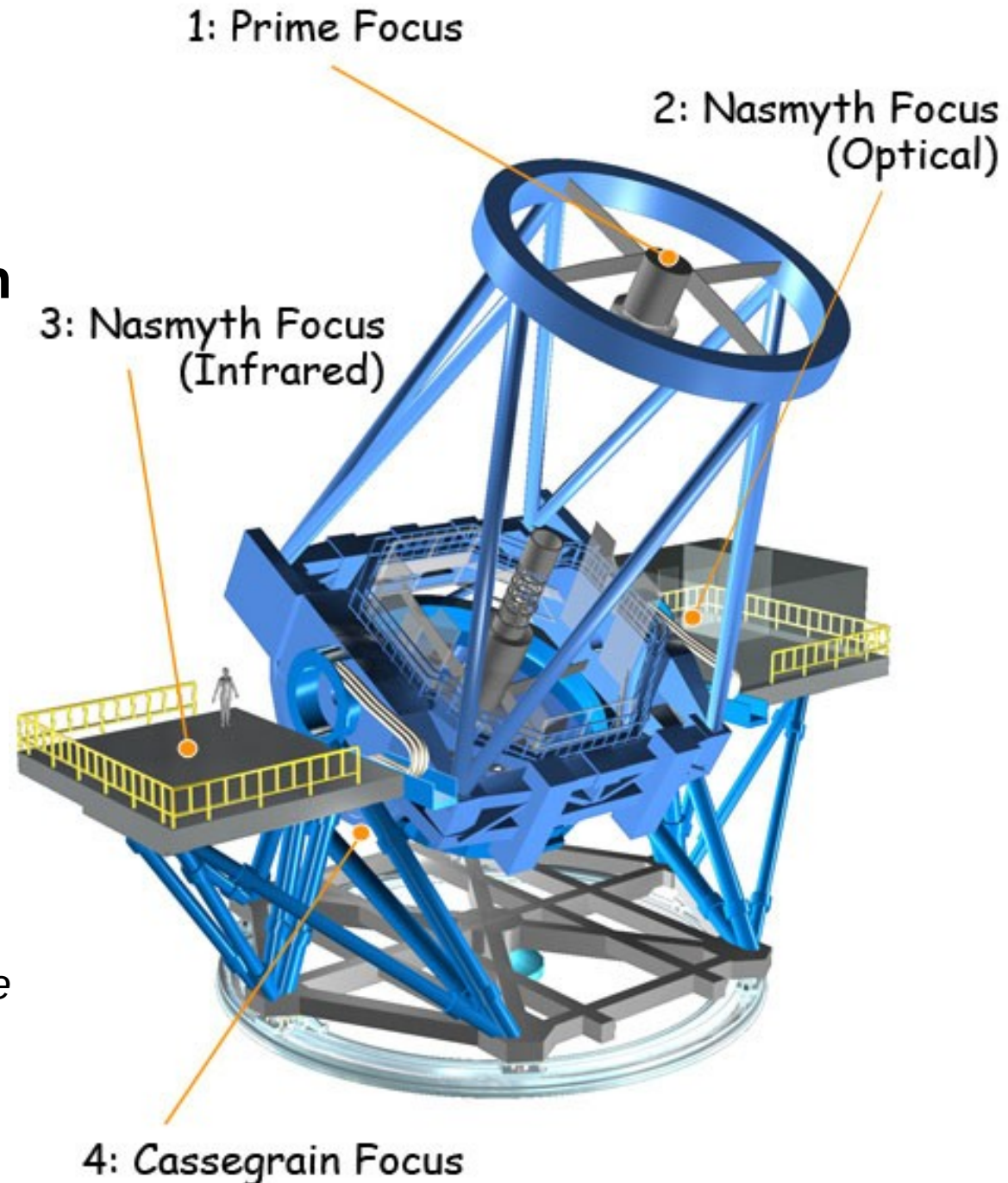
- Newtonian (parabolic mirror)
- Gregorian
- Cassegrain
- RC

Wide field telescope designs, correctors

**Location of focus
& instrument(s) is key to
telescope design**

**Telescopes are designed with
instrument(s) in mind.**

**Sometime, a specialized
telescope + instrument are
designed together.**



*Subaru telescope (8.2m):
location of the 4 telescope
focii*

Location of focus & instrument

A **wide field of view** requires a large beam, difficult to squeeze through relay optics (see Lagrange invariant)

→ prime focus is often preferred for wide field instruments, or very large central obstruction (OK if wide field is single purpose of telescope)

Examples (next few slides):

- PanSTARRS
- LBT LBC
- LSST

Heavy large/heavy instruments, or instruments requiring **outstanding stability** cannot easily be mounted on the telescope tube

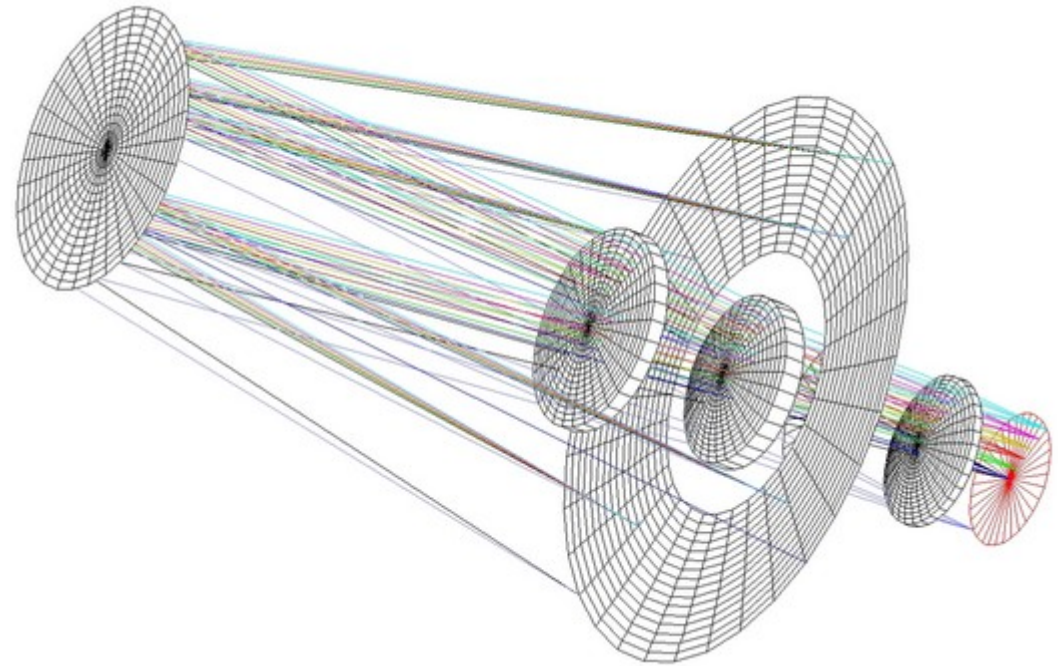
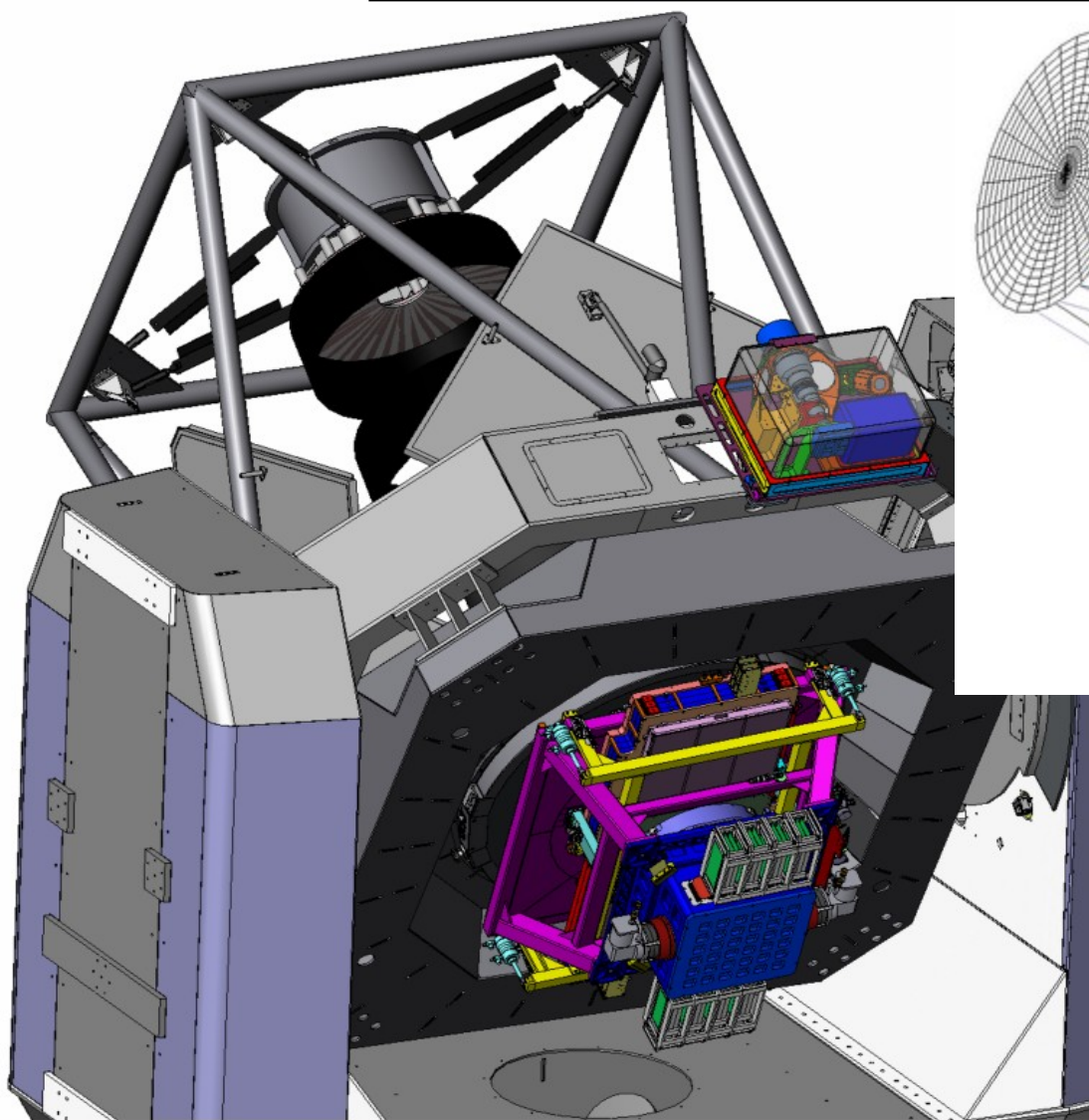
→ Nasmyth focus, or coude focus, preferred

Examples:

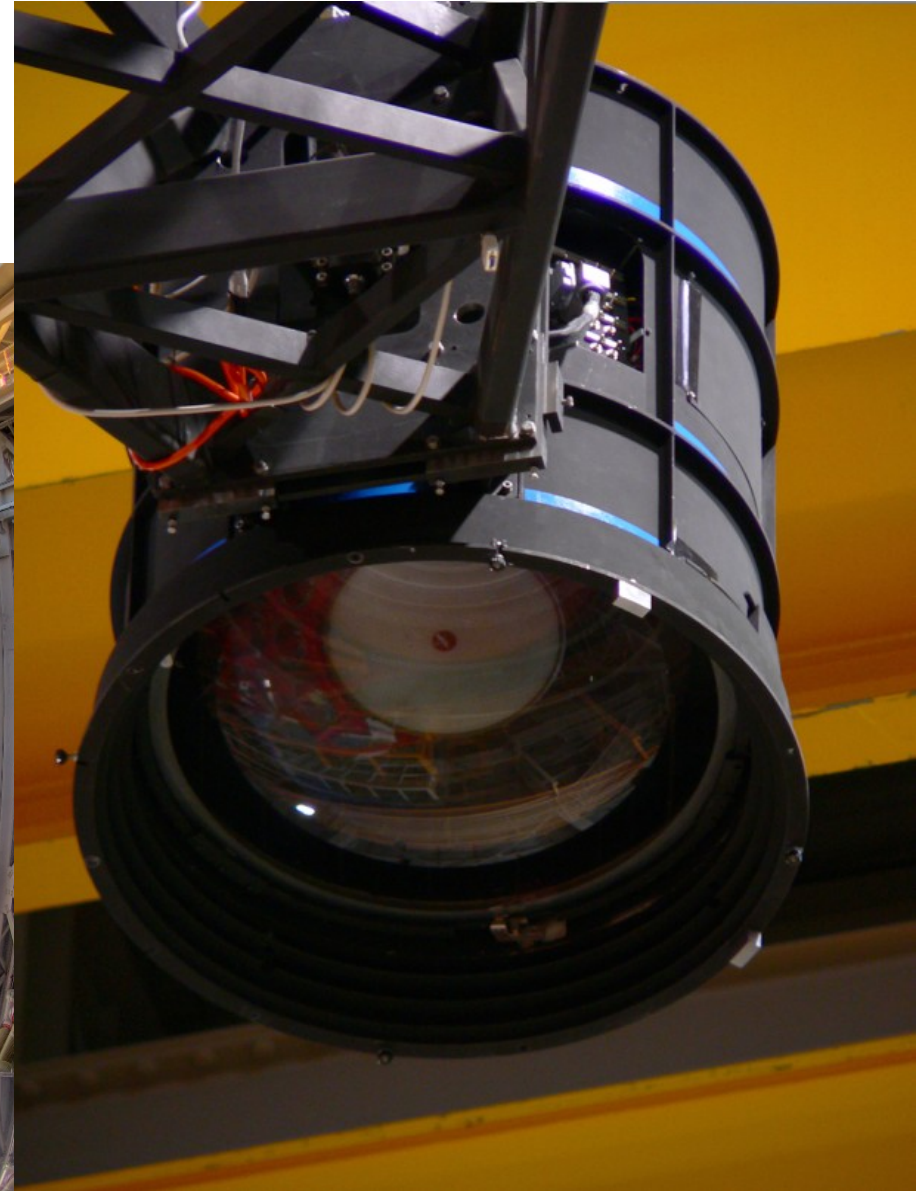
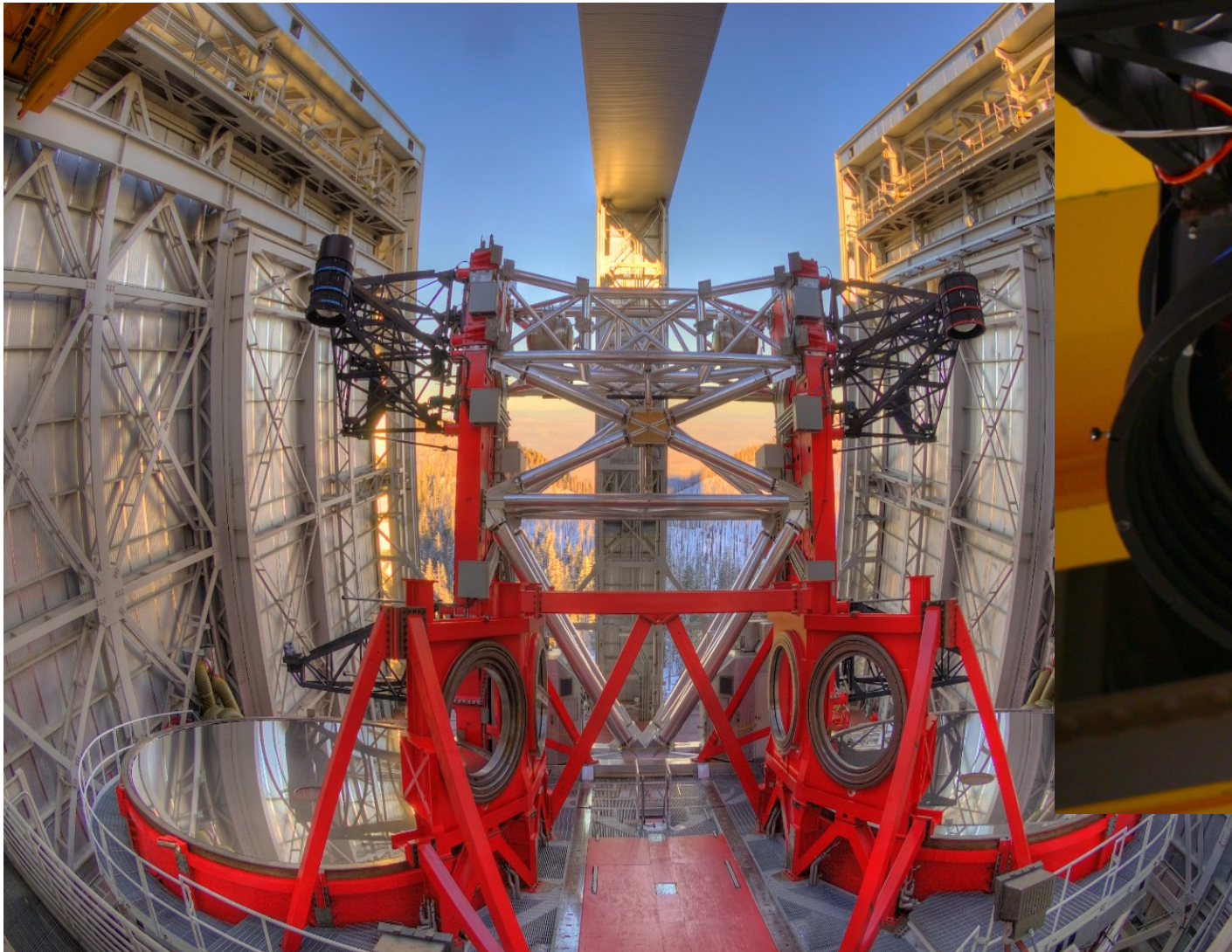
- Subaru HDS
- HARPS (requires outstanding spectroscopic stability)

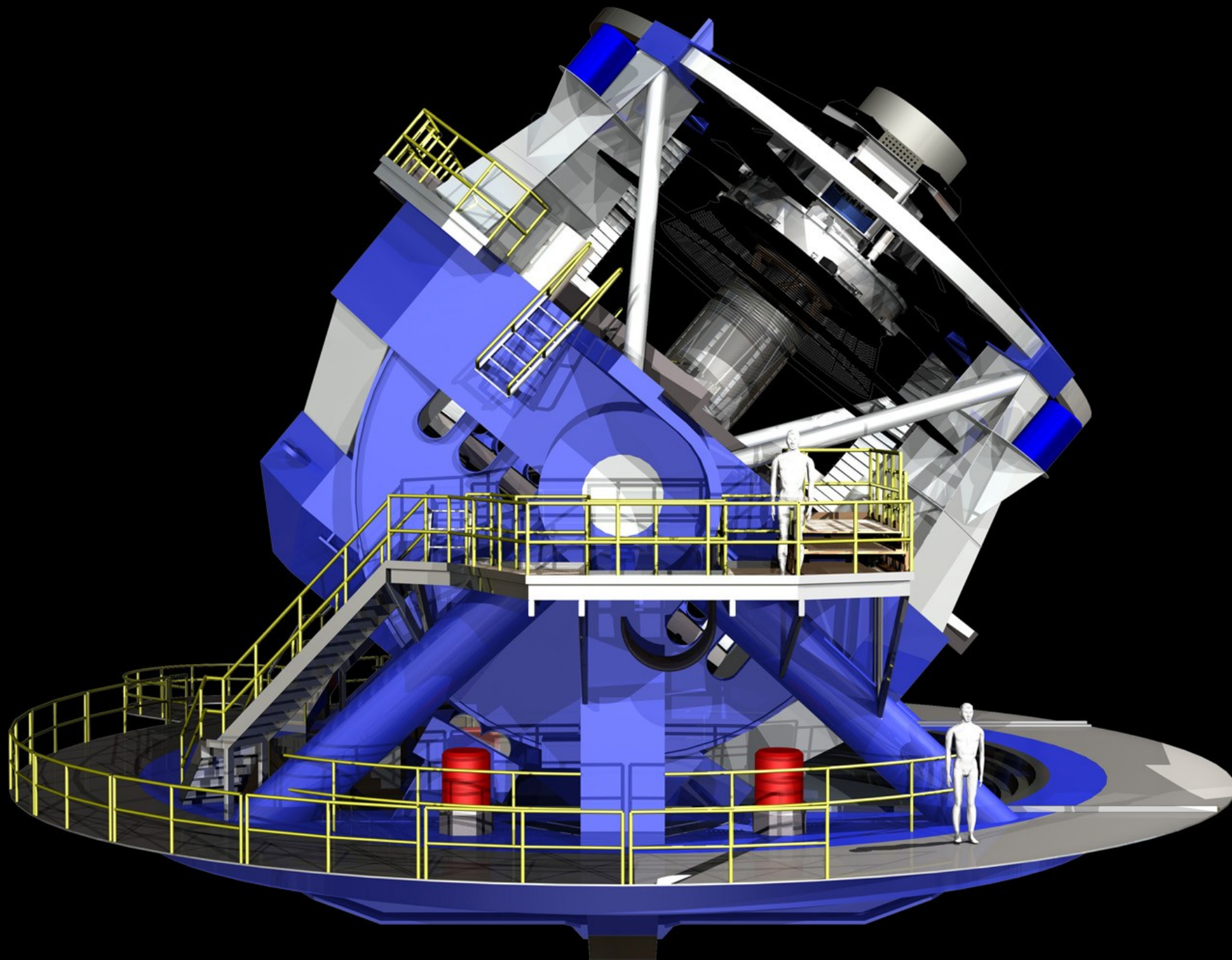
IR instruments require minimal number of reflections to limit thermal emission from optics → Cassegrain focus is preferred

Pan-STARRS : 1.8m diameter telescope, 7 sq deg field



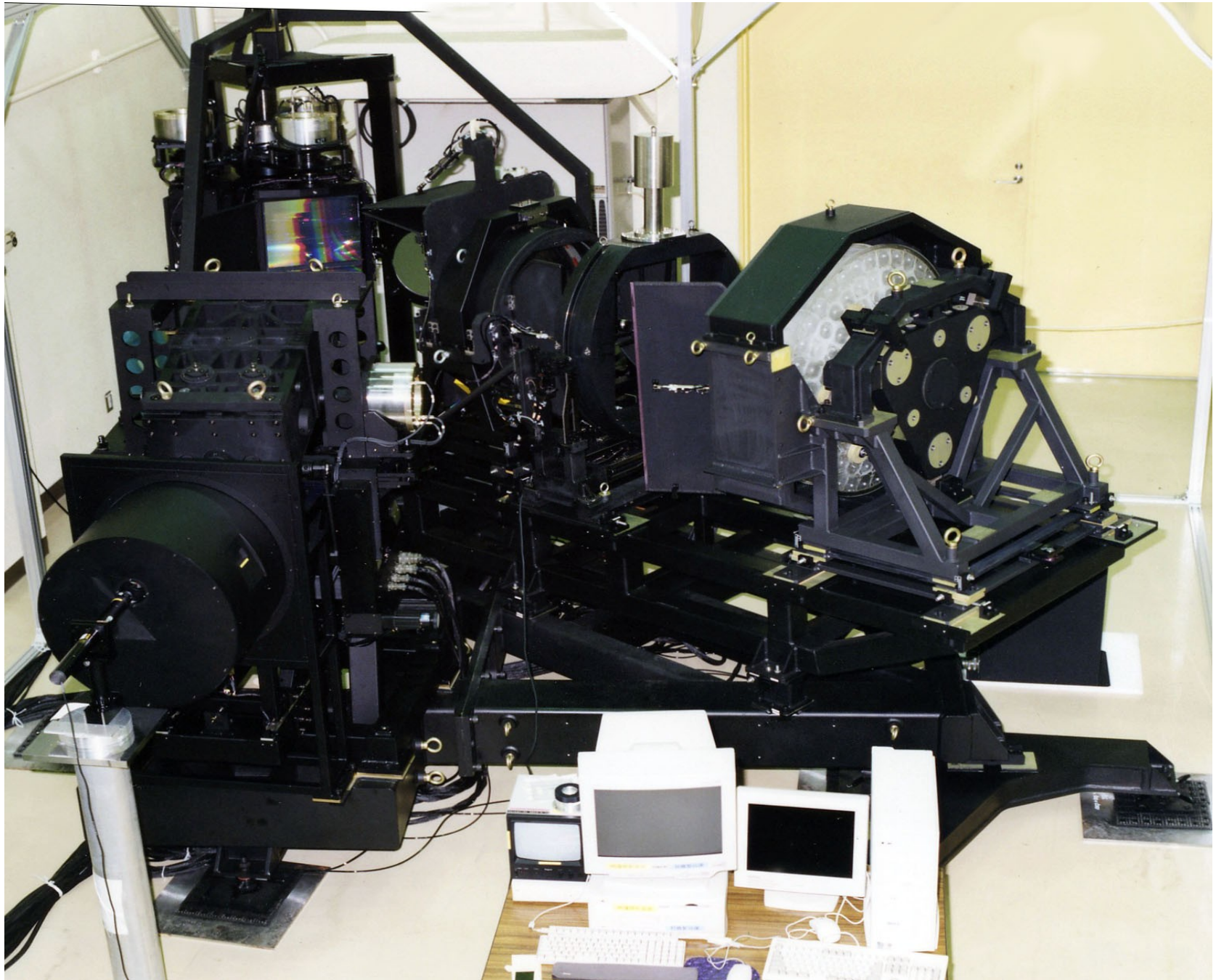
Large Binocular Telescope's wide field cameras





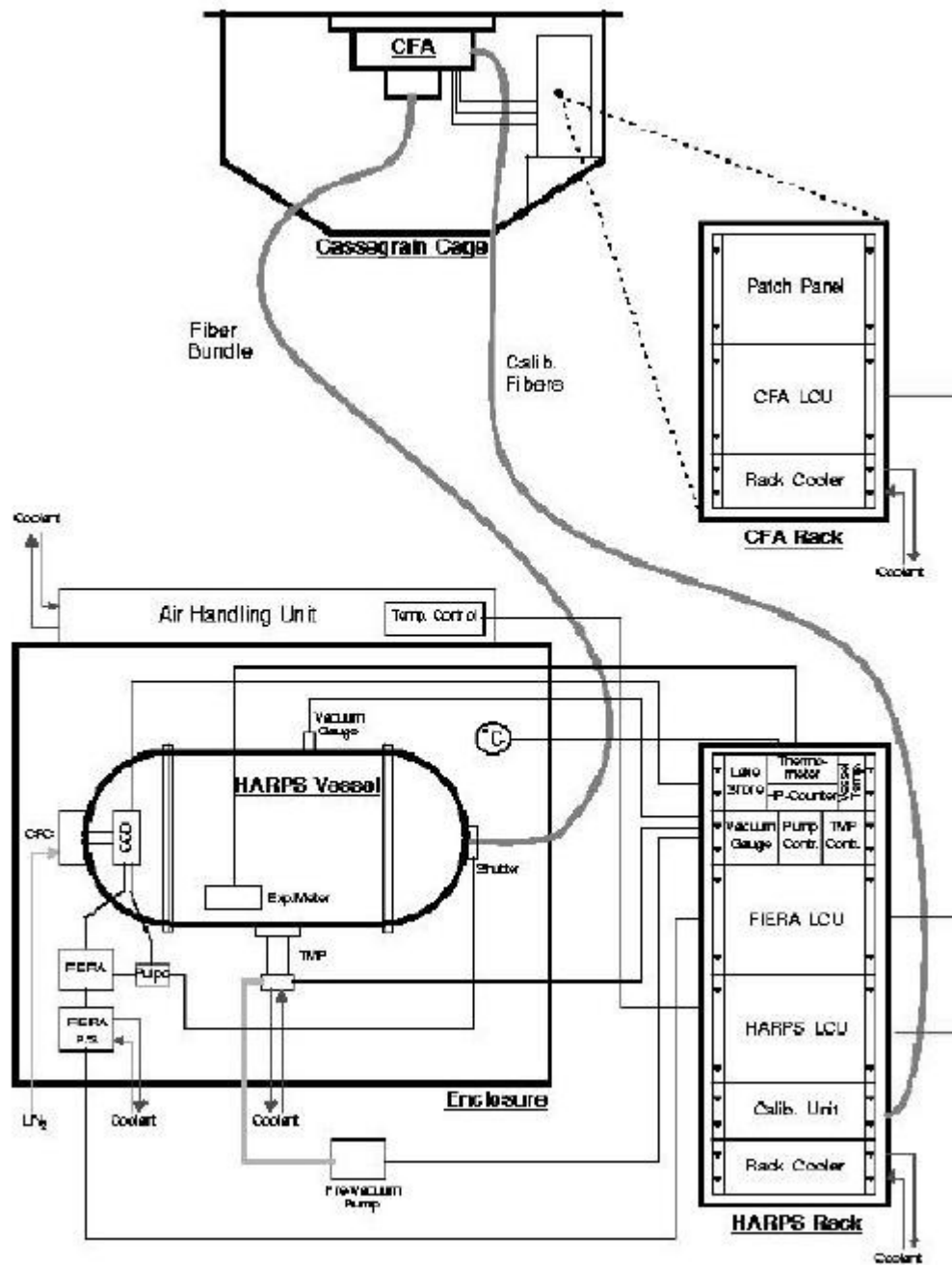
Subaru High Dispersion Spectrograph

6 metric tons, Nasmyth focus

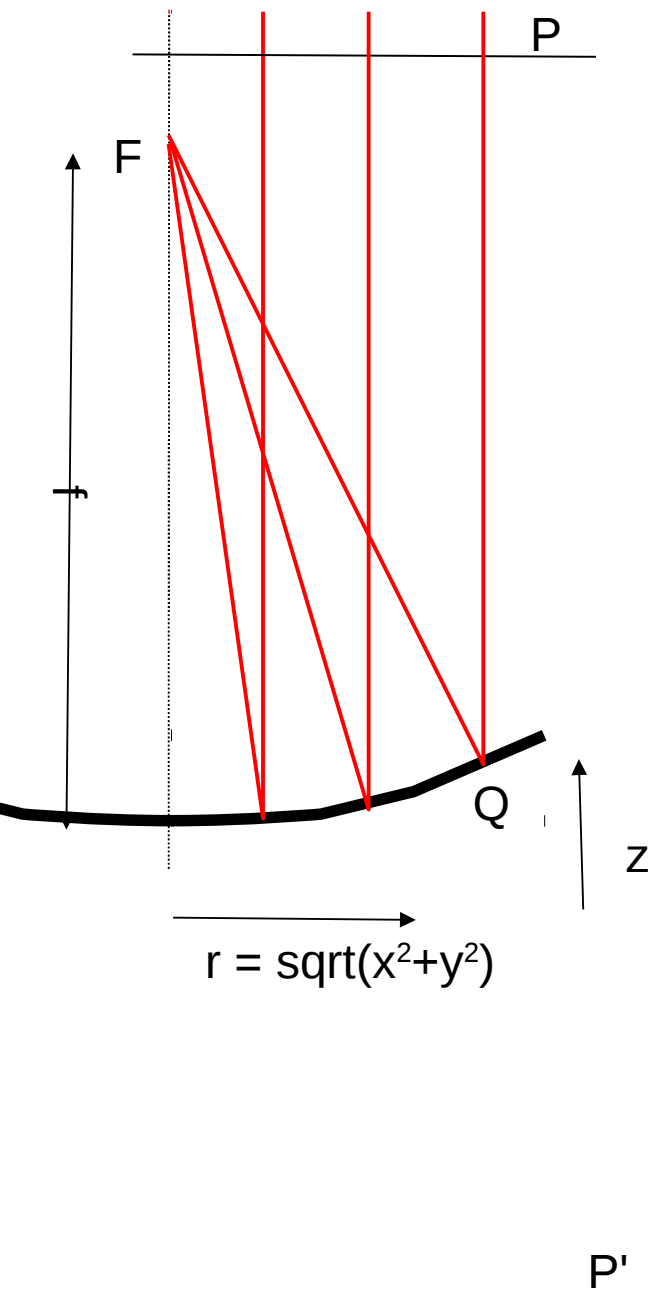


HARPS spectrograph at ESO's 3.6m

High Accuracy Radial velocity Planet Searcher



Parabola



A parabola is the **ONLY** continuous shape that will focus starlight to a point with a single mirror

$$z(x,y) = (x^2 + y^2) / (4f)$$

Why is there only one solution to this problem ?
Why is that solution a parabola ?

Fermat's principle: Light rays follow shortest path from plane P to focus F . With $OPD(x,y)$ the distance from the object to focus (= distance from plane P to point F):
 $d OPD(x,y) / dx = d OPD(x,y) / dy = 0$

Parabola is surface of equidistance between a plane P' and a point (with the plane below the mirror on the figure on the left): distance $(FQ) = \text{distance } (QP')$
 with : $(QP') + (QP) = (P'P) = \text{constant}$
 $\rightarrow (FQ) + (QP) = (QP') + (QP') = \text{constant}$

Parabola obeys Fermat's principle

Why is the solution unique ?

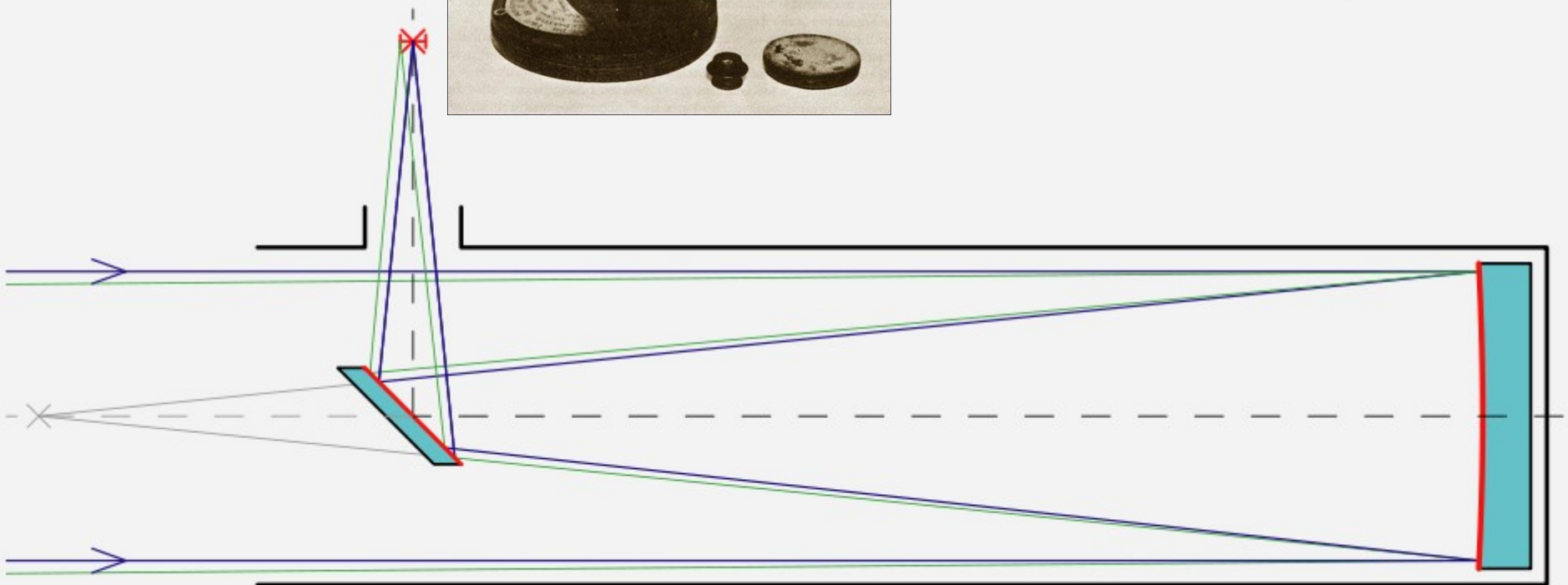
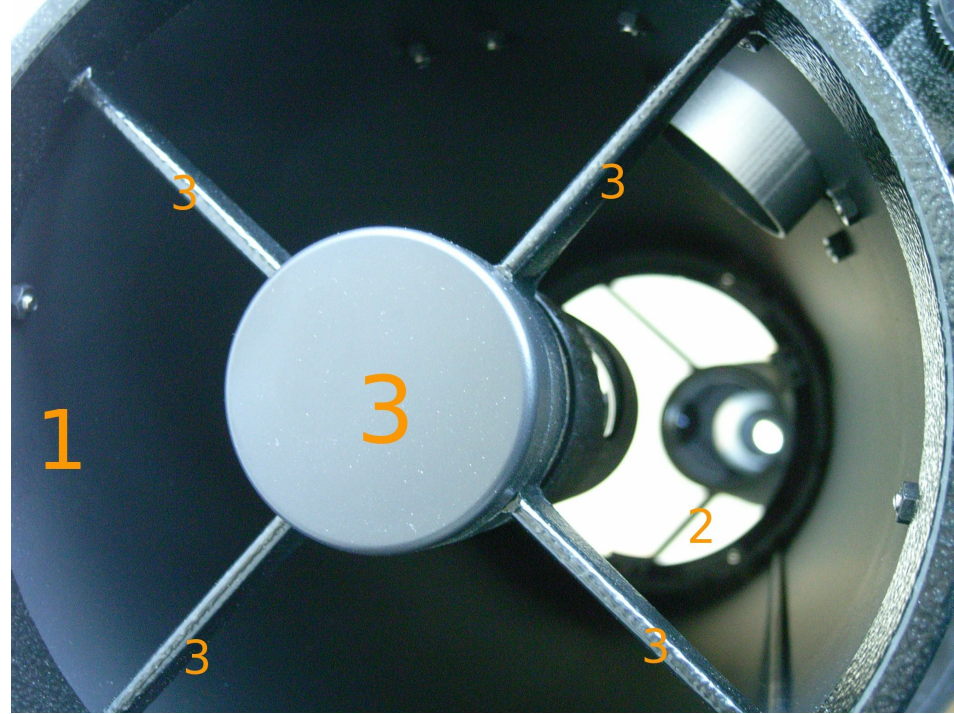
If building the mirror piecewise, with infinitively small segments, working outward from $r=0$ (optical axis), the constraint that light ray must hit focal point F is a constraint on the local slope of the mirror

$\rightarrow dz/dr = \text{function_of}(r,f,z)$

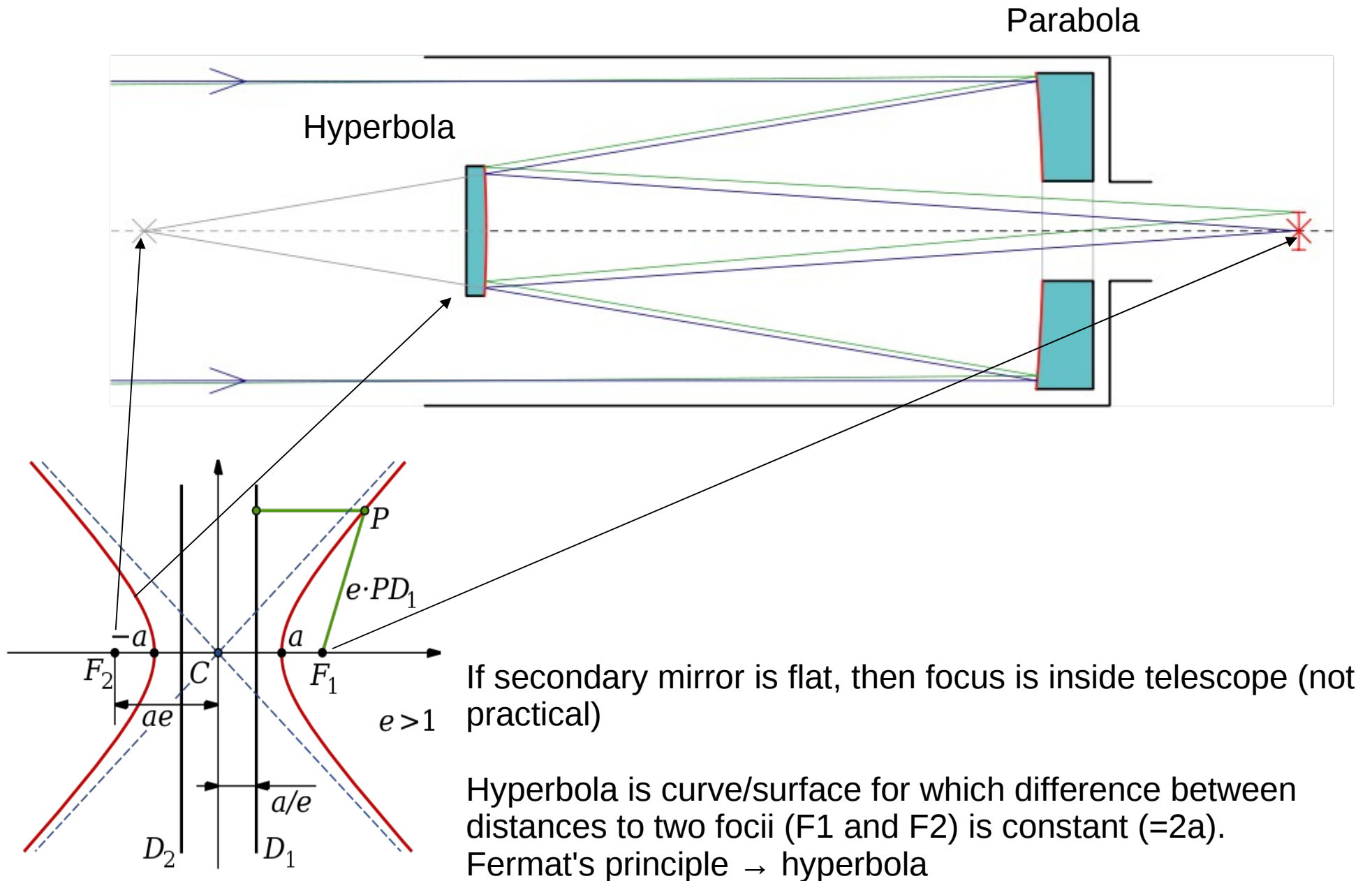
$\rightarrow$ mirror shape can be derived by integrating this equ.

Newtonian Telescope

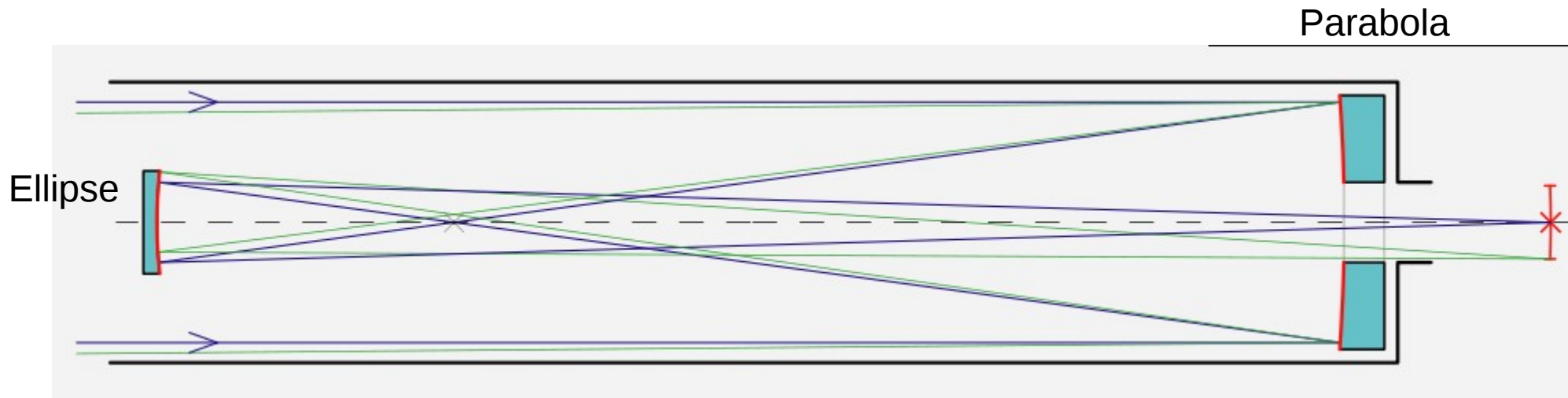
Parabolic mirror + flat secondary mirror to move image out of the incoming beam



Classical Cassegrain Telescope



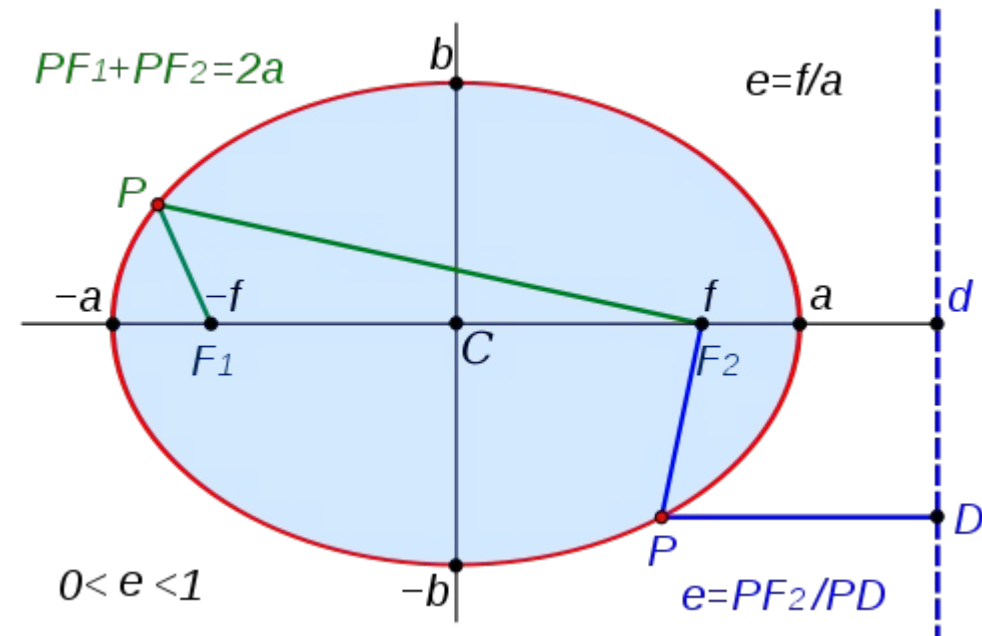
Gregorian Telescope



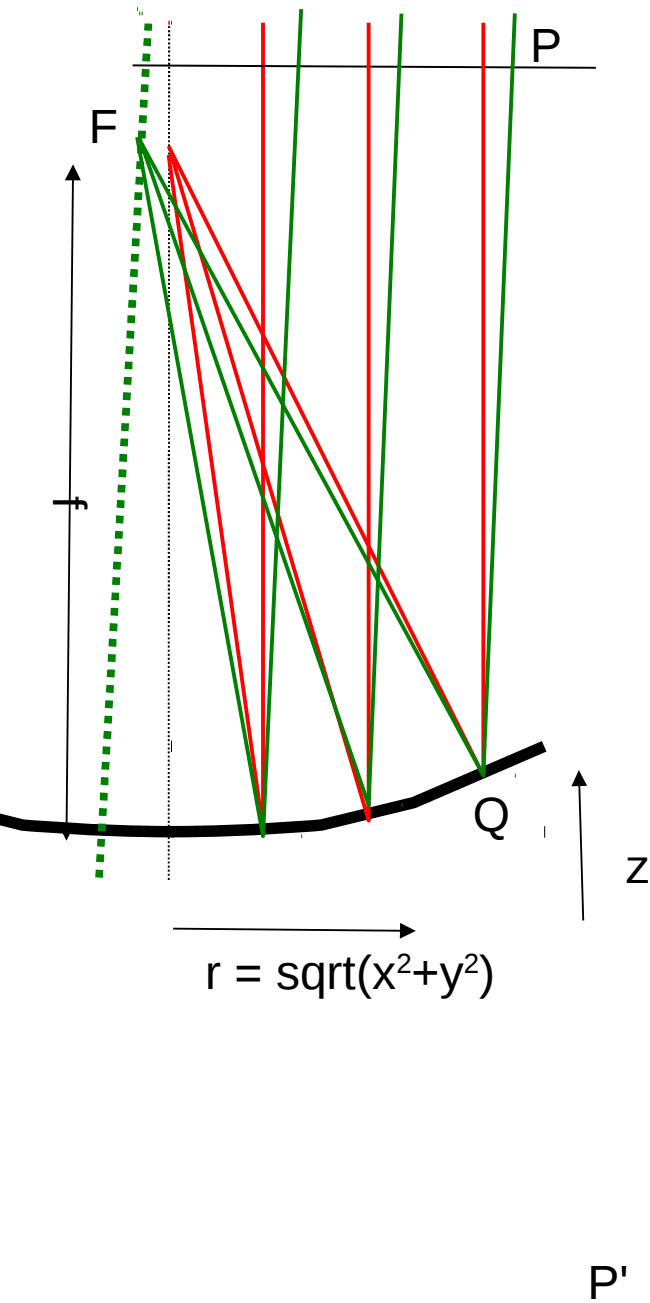
If secondary mirror is flat, then focus is inside telescope (not practical)

Ellipse is curve/surface for which sum of distances to two foci (F_1 and F_2) is constant ($=2a$).

Fermat's principle $\rightarrow$ Ellipse



Field of view problem with parabola



A parabola is the **ONLY** continuous shape that will focus starlight to a point with a single mirror

Let's look at what happens for an off-axis light source (green light rays). The new "Focus" and the off-axis angle define a new optical axis (thick green dashed line). The new axis are X, Y, and Z

Is the mirror a parabola in the form $Z = a (X^2 + Y^2)$ at the same time as being a parabola in the form $z = a (x^2 + y^2)$?

- NO, mirror is not circular symmetric in X, Y, Z coordinates
- **parabolic mirror fails to perfectly focus off-axis light into a point**

All the telescopes concepts shown previously (Newton, Gregorian, Cassegrain) suffer from aberrations which grow as distance from optical axis increases.

Field of view problem with parabola: Coma aberration

Coma is the main aberration for an parabolic mirror observing off-axis sources

For a source offset α [rad], the RMS geometrical blurr radius due to coma is:

$$r_{\text{COMA}}[\text{rad}] = 0.051 \alpha / F^2$$

Examples:

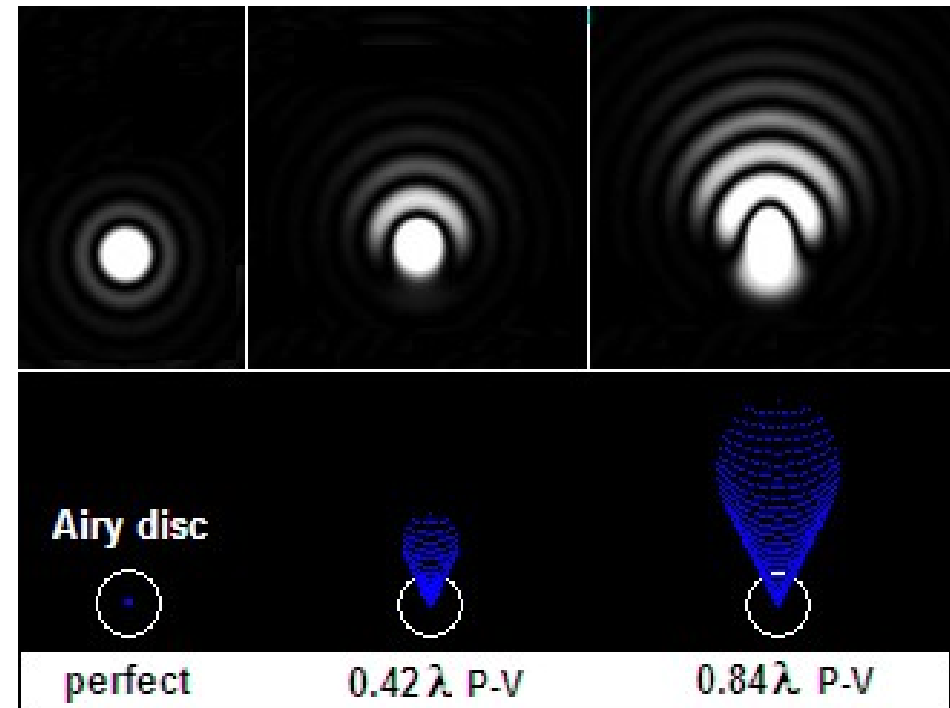
$F = f/D = 10$ telescope

$r < 0.1''$ (0.2'' diameter spot) for $\alpha = 3.3'$

$F = 5$

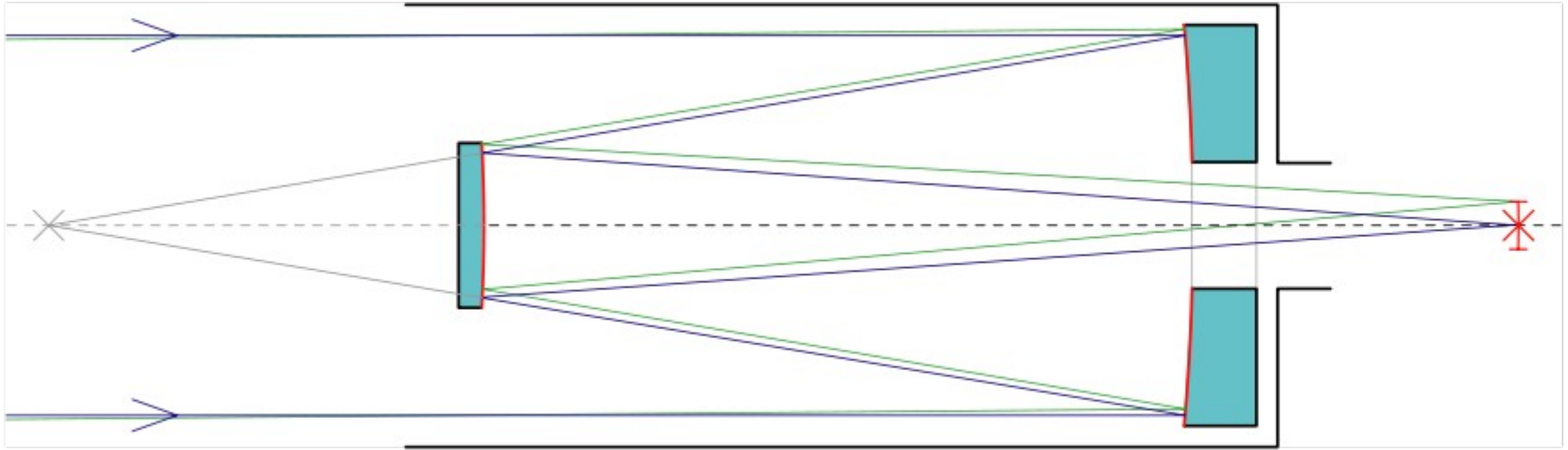
$r < 0.1''$ for $\alpha = 49''$

**Parabolic mirror telescopes are not
suitable for wide field imaging**



www.telescope-optics.net

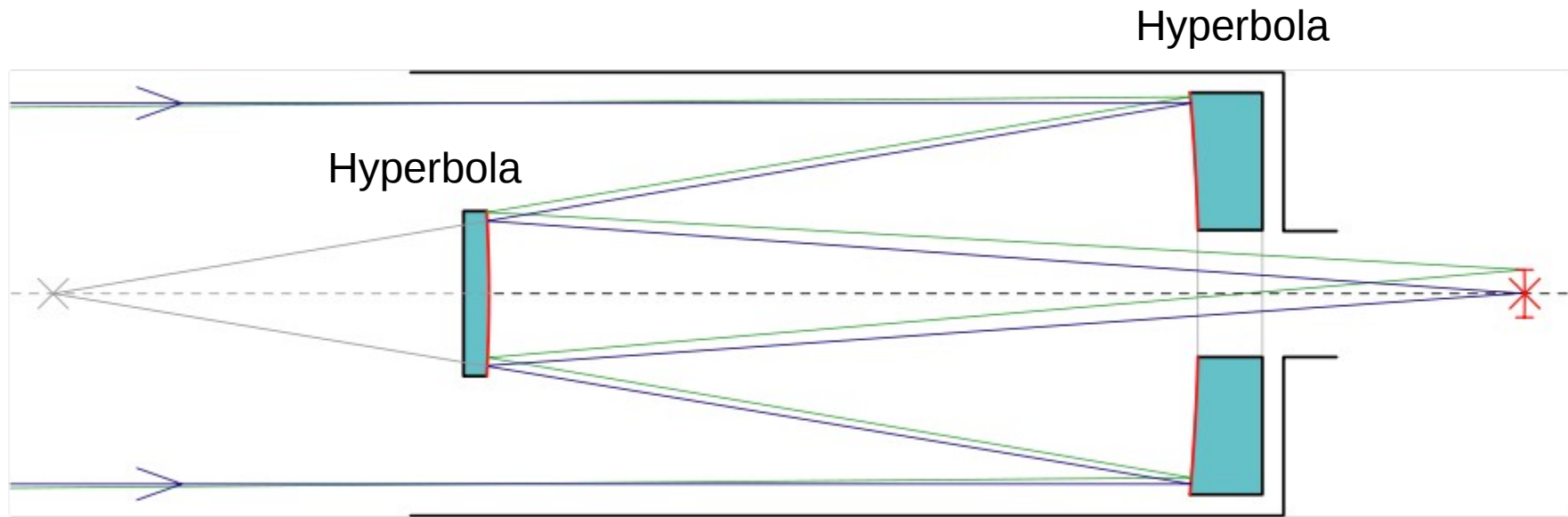
Solution to the field of view problem: >1 optical surface



With 2 mirrors, there is now an infinity of solutions to have perfect on-axis image quality.

For ANY primary mirror shape, there is a secondary mirror shape that focuses on-axis light on a point $\rightarrow$ shape of one of the 2 mirrors becomes a free parameter that can be used to optimize image quality over the field of view.

Ritchey Chretien Telescope



Primary and secondary mirror are hyperbola

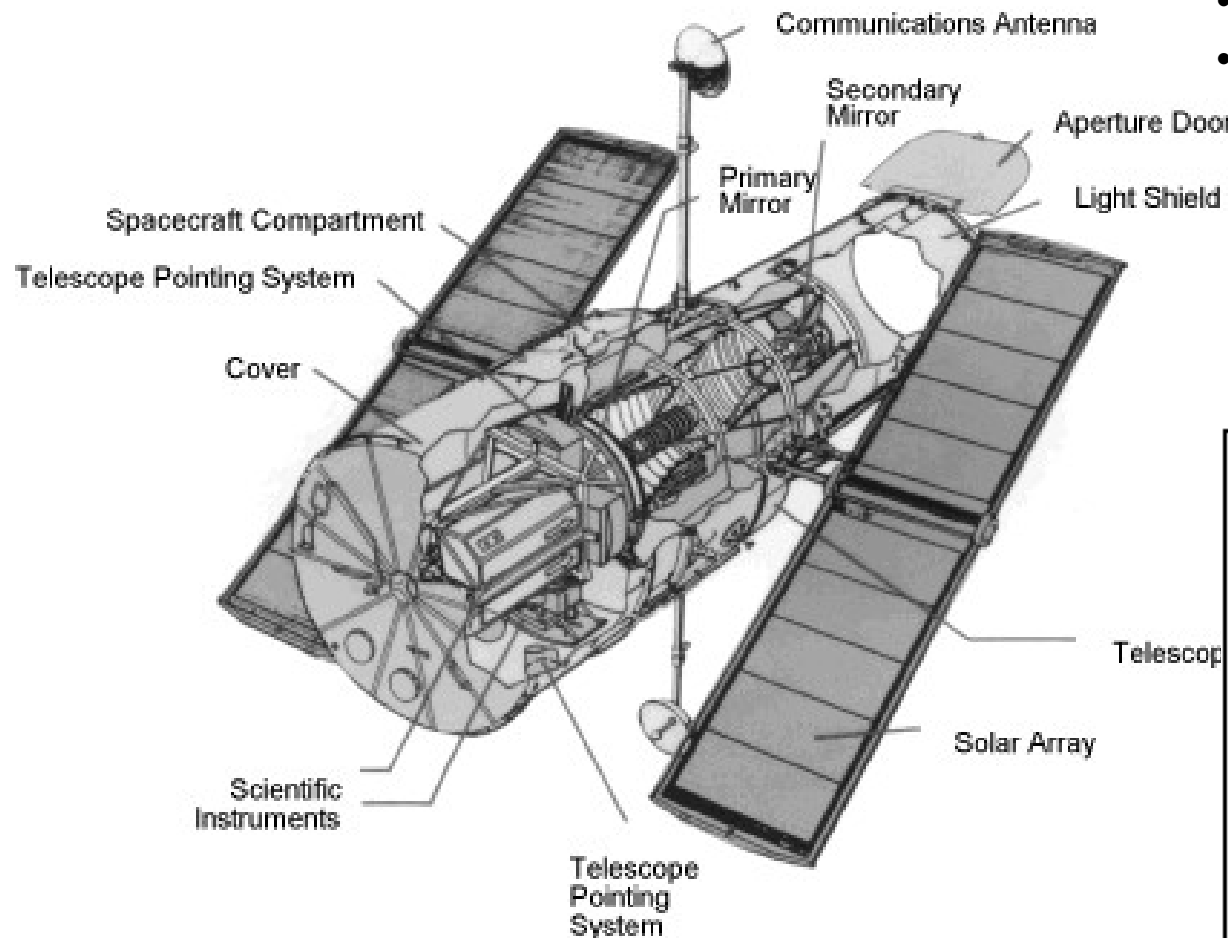
Spherical and Coma can be removed by choice of conic constants for both mirrors

→ field of view is considerably larger than with single parabola

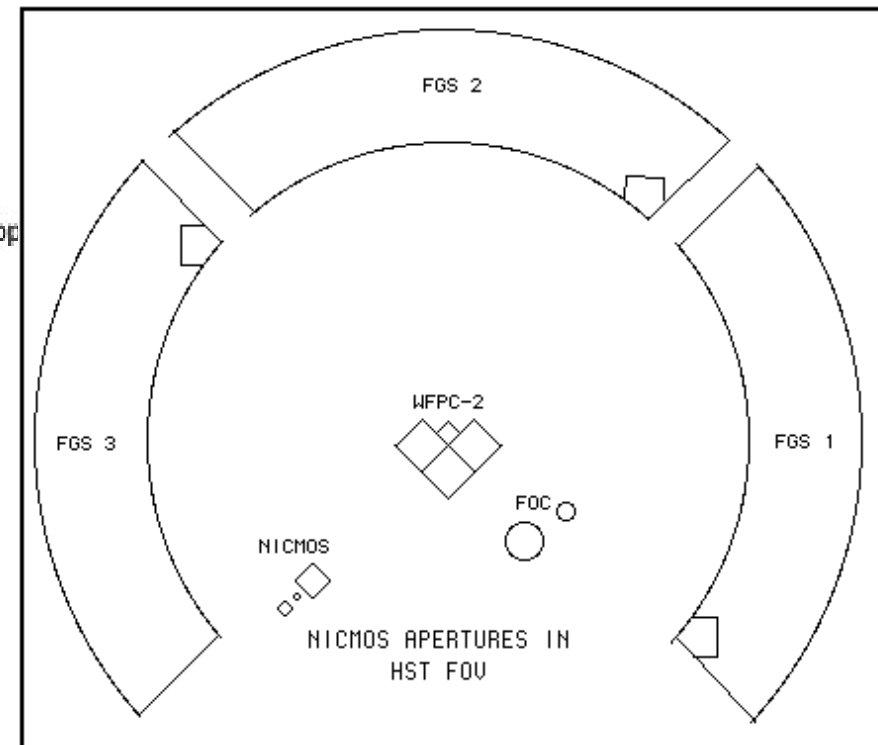
If PM and SM have same radius of curvature, field is flat

Most modern large telescopes are RC (example: Hubble Space Telescope)

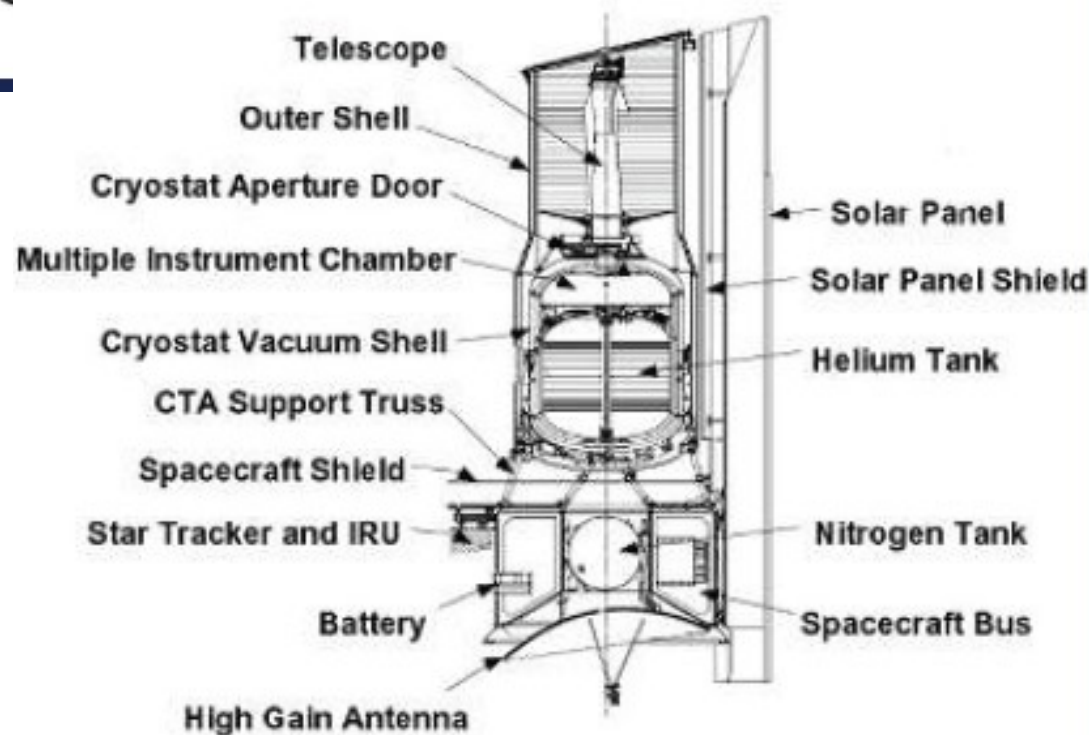
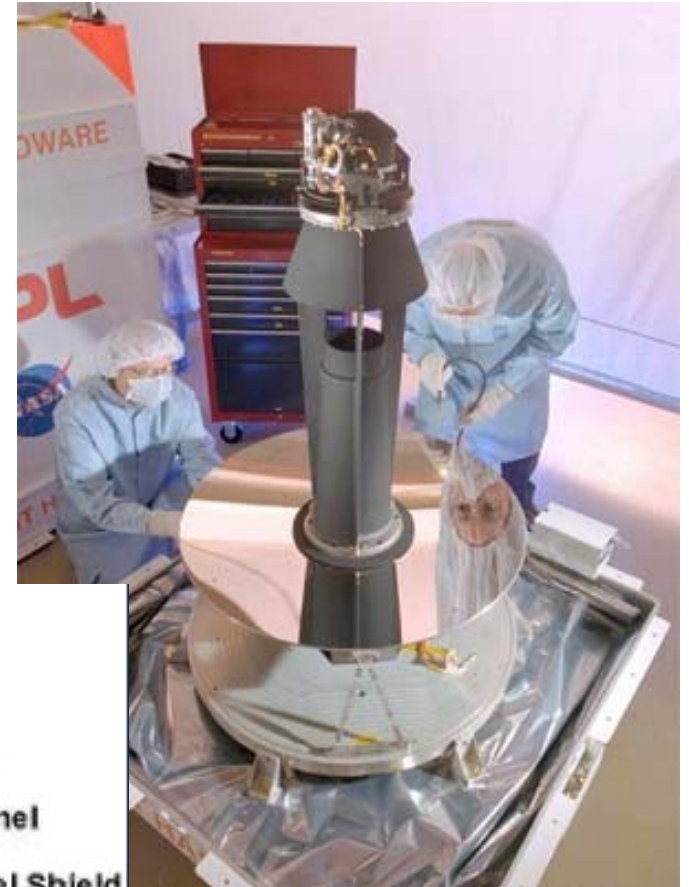
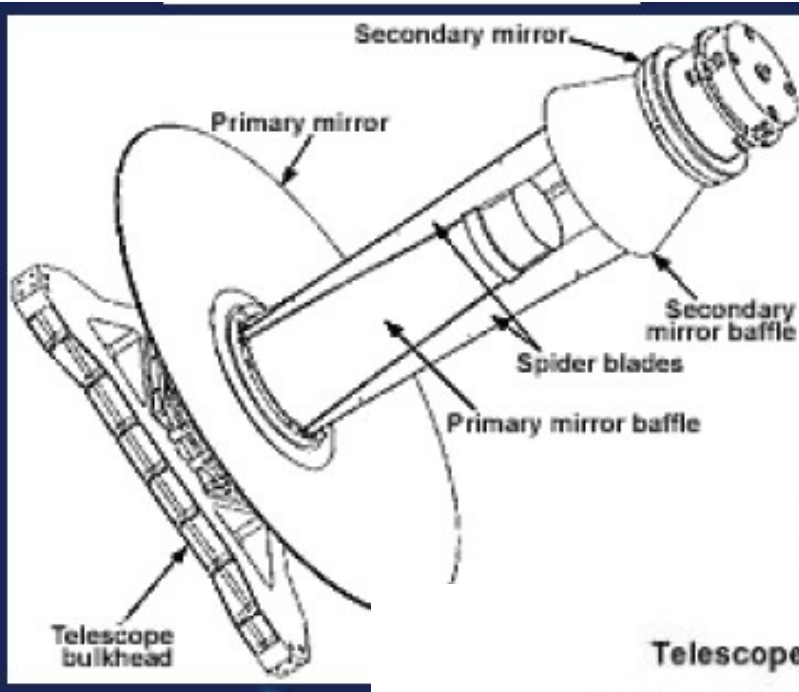
Hubble Space Telescope



- Ritchey-Chretien design
- Aplanatic – coma is corrected by satisfying the sine condition
 - Primary mirror is not quite paraboloidal
 - Secondary is hyperboloid



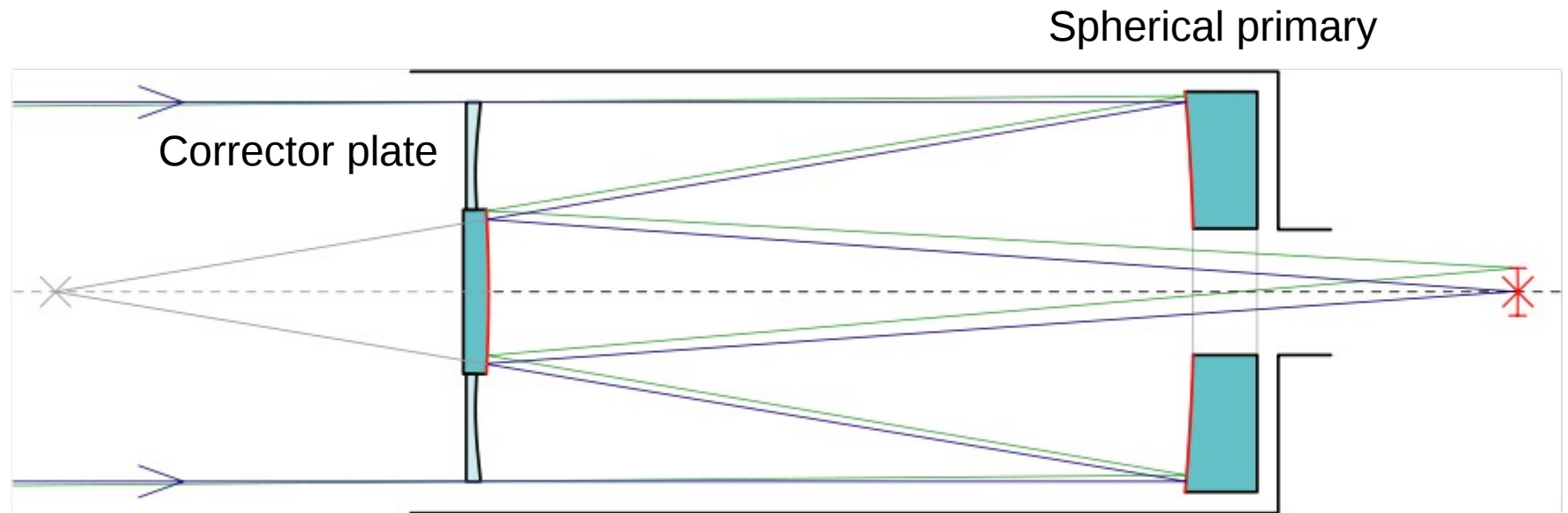
Spitzer Telescope



Ritchey-Chretien design
85 cm aperture
Cryogenic operation for low background

Schmidt-Cassegrain Telescope

SC design is a Catadioptric system : uses both refraction and reflection

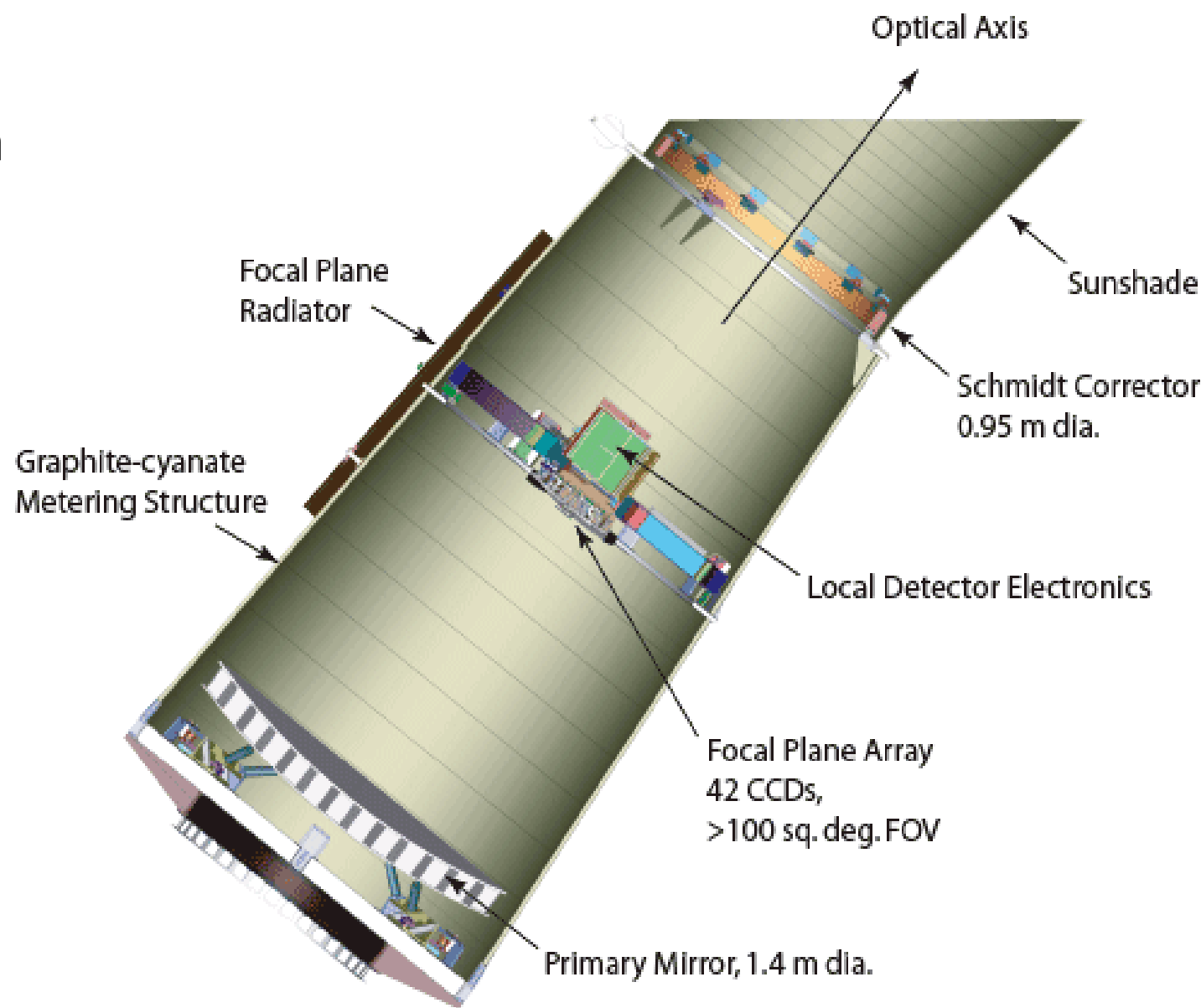


Corrector plate removes spherical aberration

Spherical aberration is field independent with a spherical mirror → correction is valid over a wide field of view

Secondary mirror can flatten the field with proper choice of radius of curvature

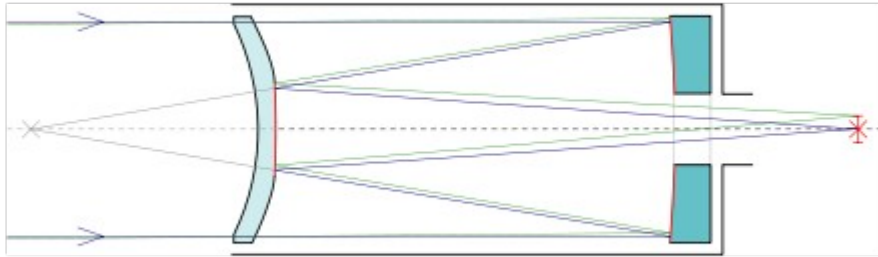
Schmidt Telescope: Kepler optical design



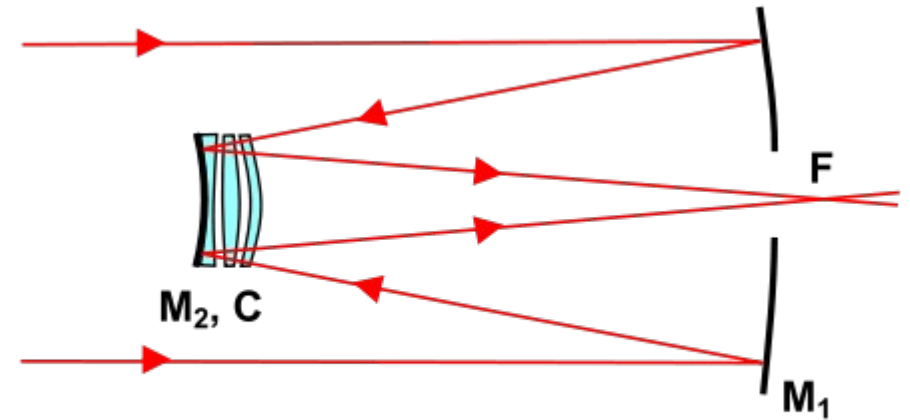
Kepler optical design: Schmidt camera for large field of view
detector at prime focus → no field flattening effect of secondary mirror
→ strong field curvature

Note that PM is larger than corrector plate !

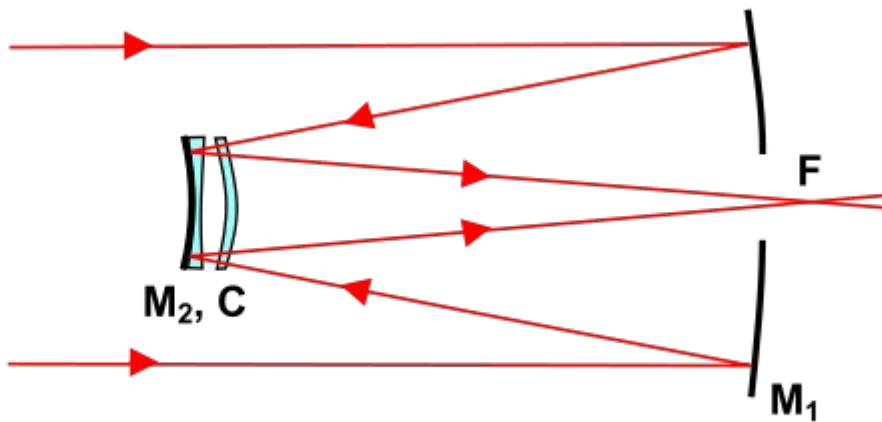
Other Catadioptric telescope designs



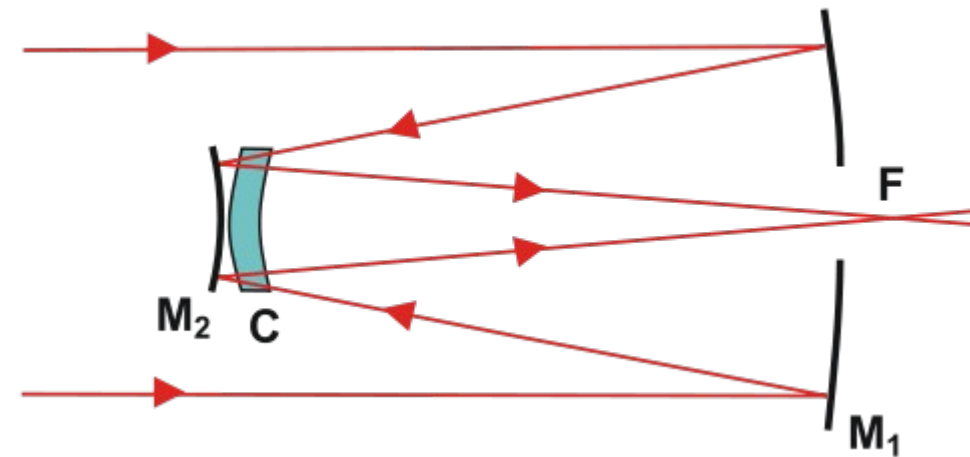
Maksutov-Cassegrain



Argunov-Cassegrain



Klevtsov-Cassegrain



Sub-aperture Maksutov-Cassegrain

Maksutov-Cassegrain



Types of aberrations in optical systems

Wavefront errors

Spherical aberration

On-axis aberration, difference between a sphere and a parabola. Telescope focus is function of radius in pupil plane

Coma

Off-axis aberration

Astigmatism

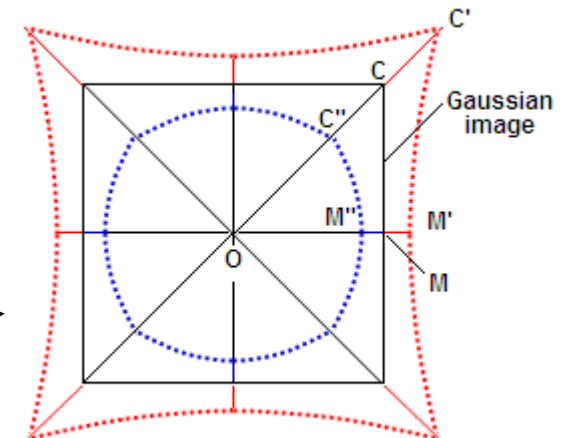
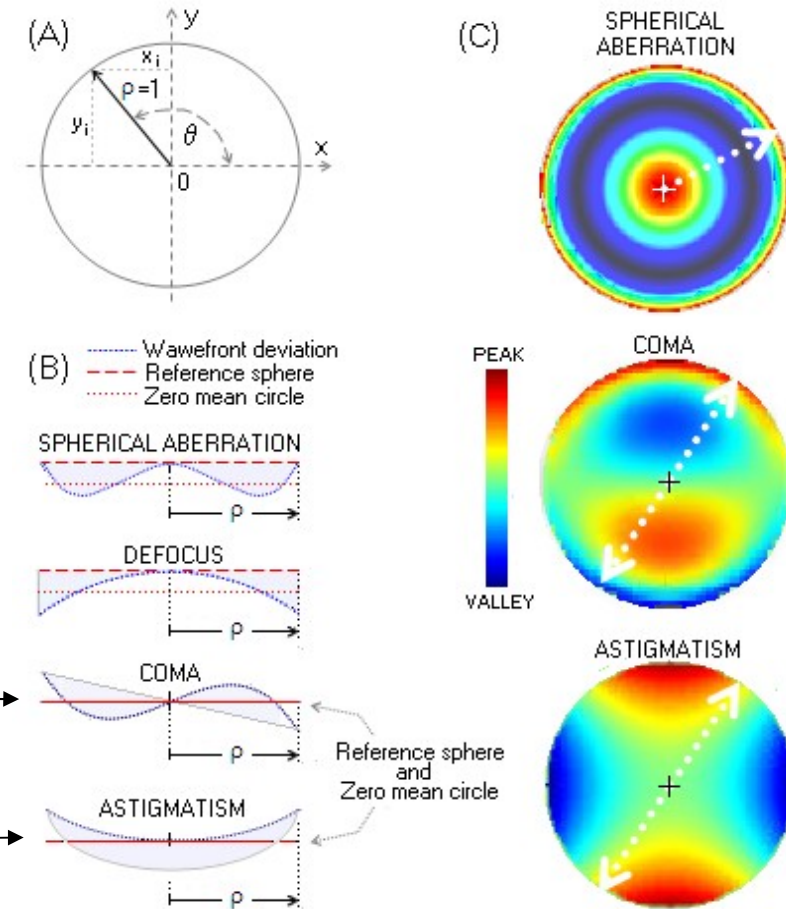
Off-axis aberration. Focal length is different along x and y axis

Field curvature

Sharpest image surface is not a plane, it is curved → a flat detector will not be in focus at all distances from optical axis

Field distortion

Chromatic aberration



Types of aberrations in optical systems: Seidel aberrations

Seidel aberrations are the most common aberrations:

Spherical aberration

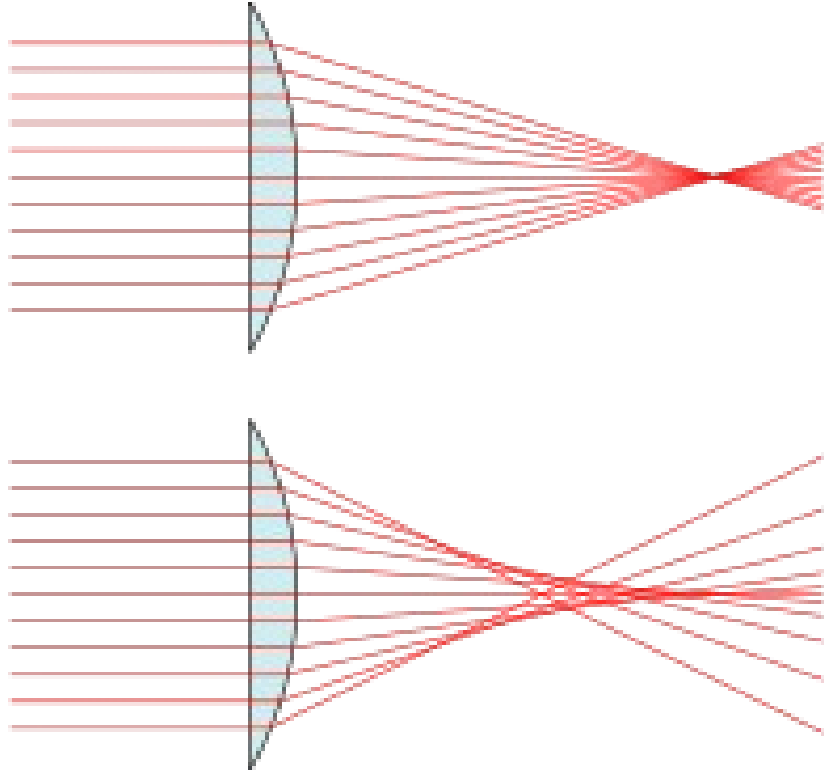
Coma

Astigmatism

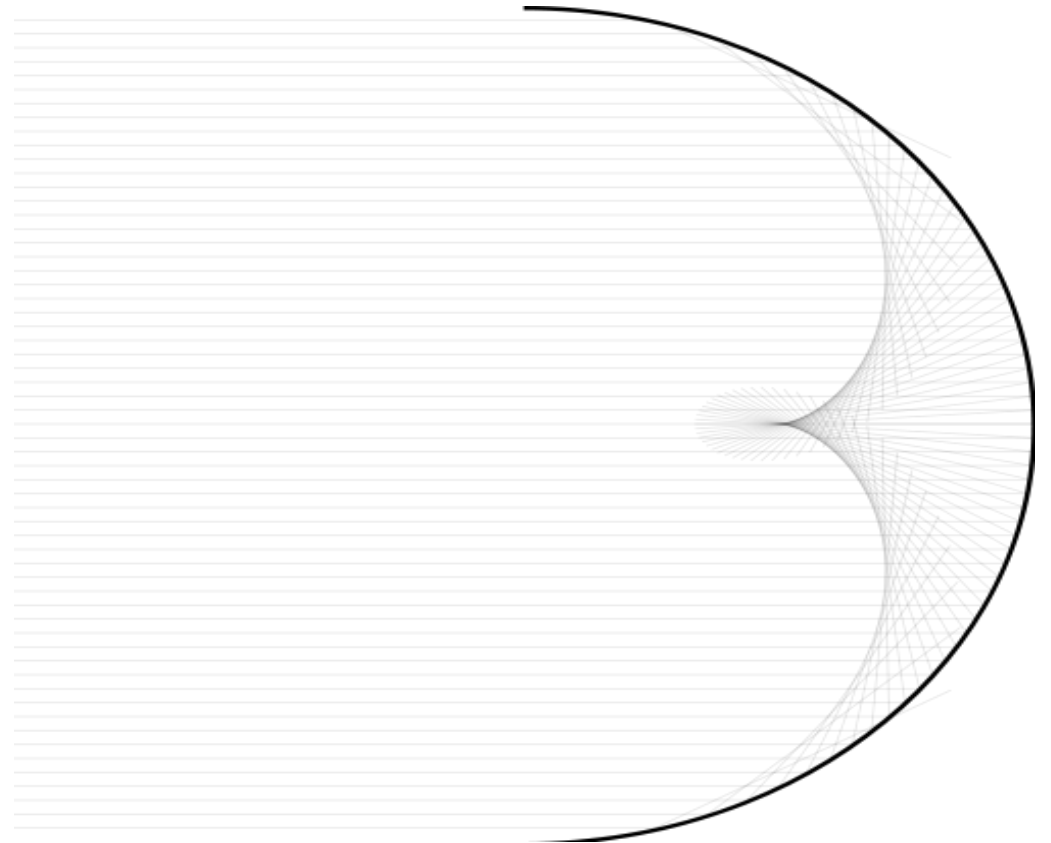
Field curvature

Field distortion

Spherical aberration (Geometric optics)

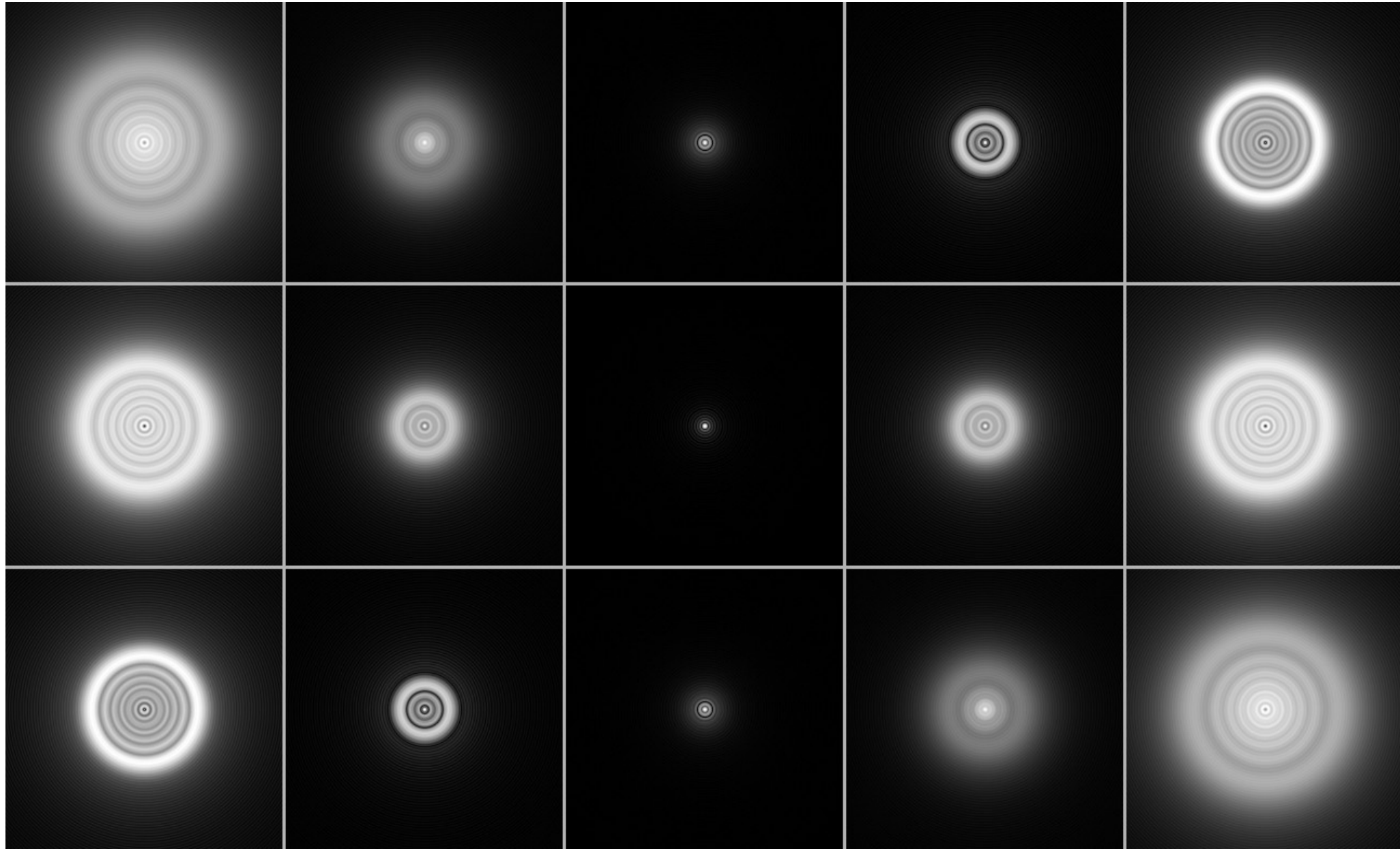


Lens: aspherical (top), spherical (bottom)

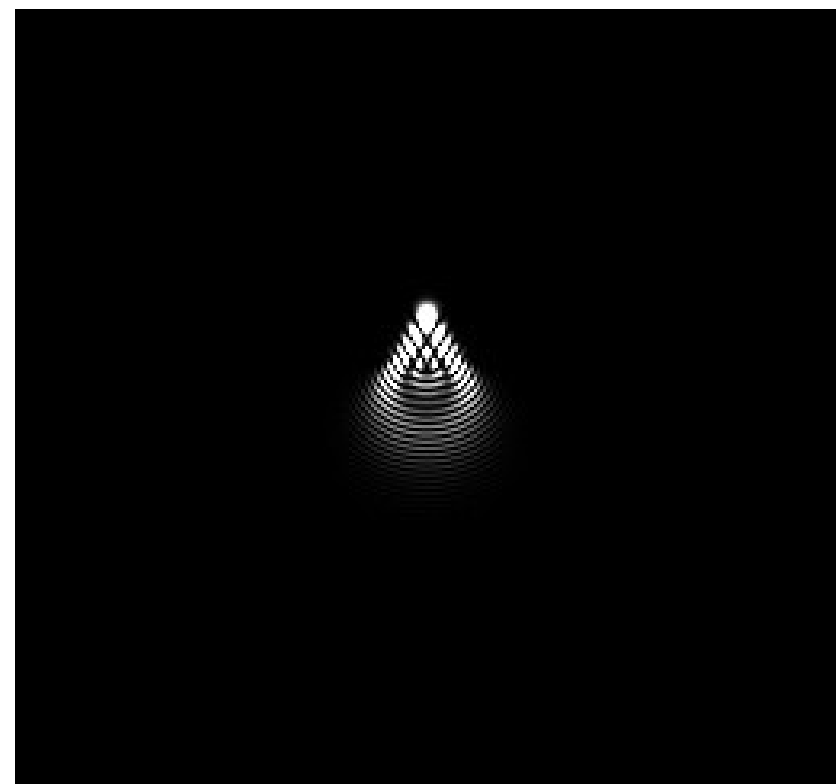
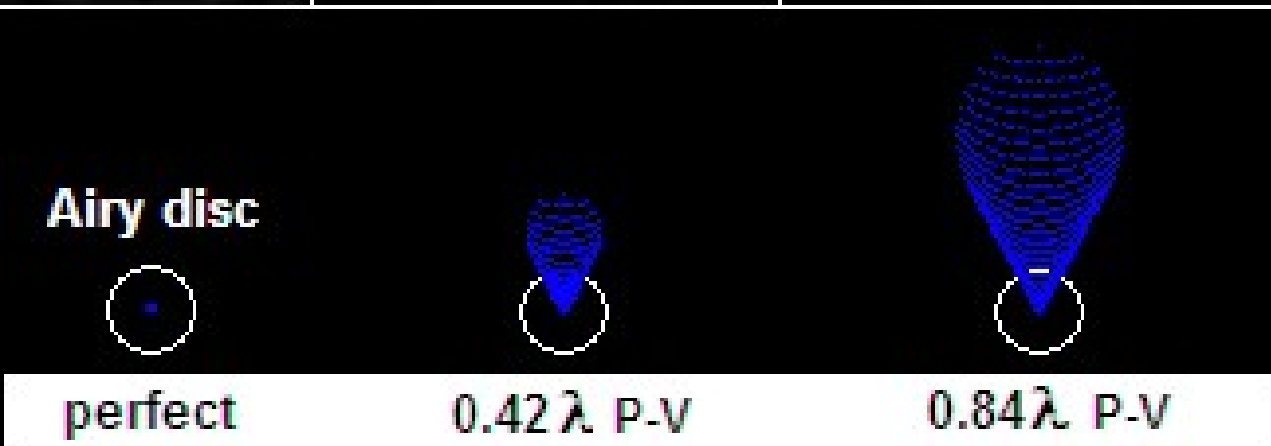
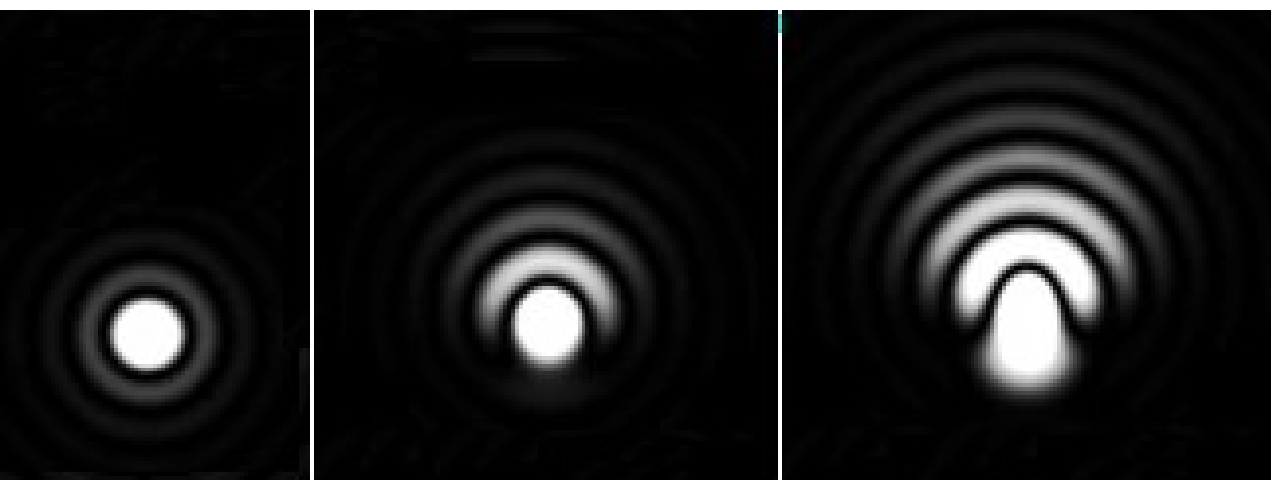


Spherical mirror

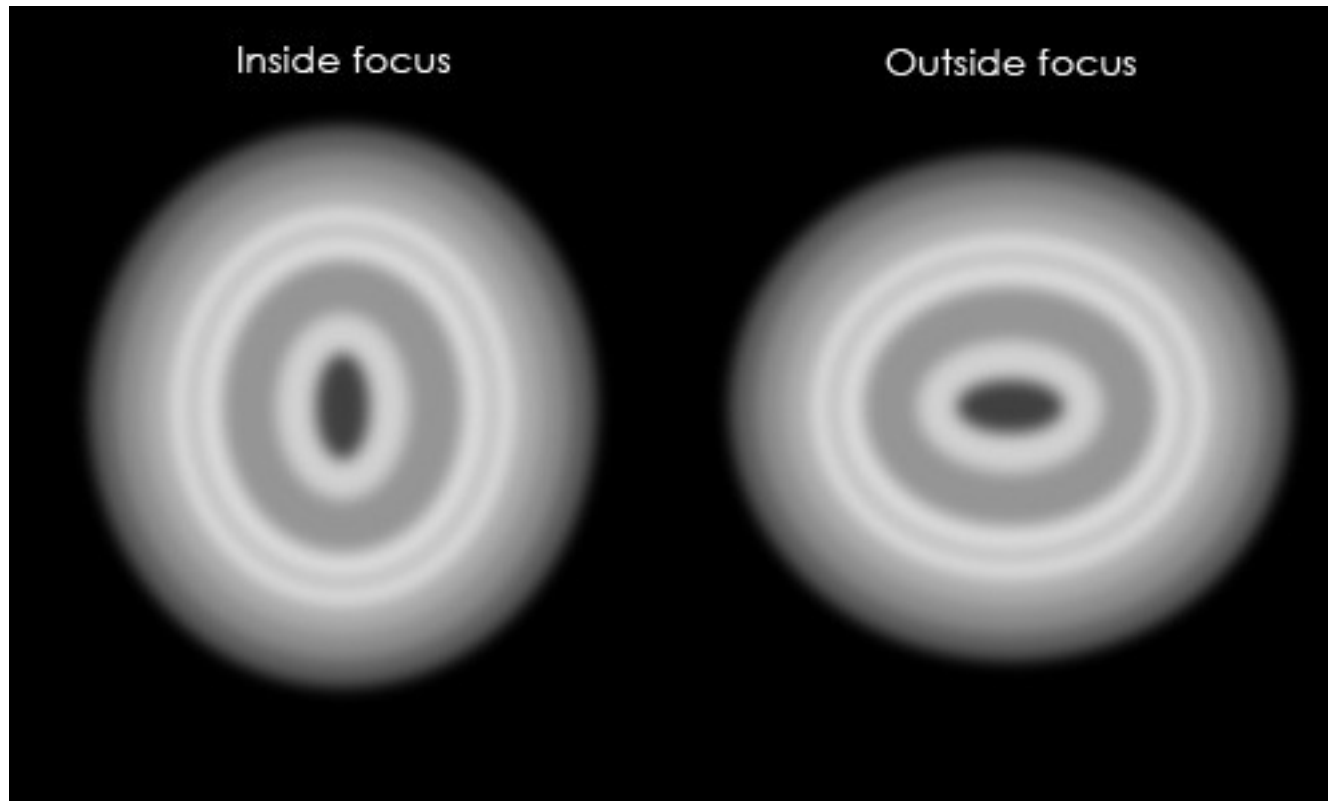
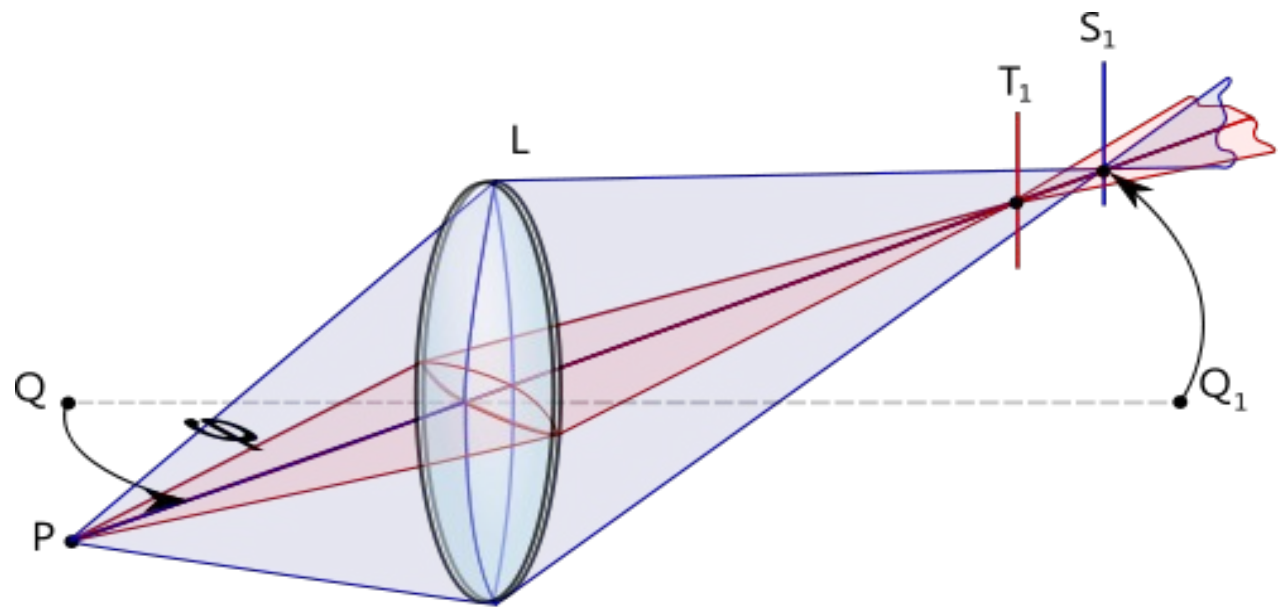
Spherical aberration (diffraction)



Coma



Astigmatism



1	2	3	4	5	6
ABERRATION	n	m	ZERNIKE CIRCLE POLYNOMIAL $V(\rho)\cos(m\theta)$	ZERNIKE ABERRATION TERM $Z_n^m(\rho, \theta)/\omega = [2(n+1)/(1+\delta_{m0})]^{0.5} V(\rho)\cos(m\theta)$	RMS WAVEFRONT ERROR $\omega = Z_n^m(1, 0) / [2(n+1)/(1+\delta_{m0})]^{0.5}$
Tilt (Distortion)	1	1	$\rho\cos\theta$	$2\rho\cos\theta$	2
Defocus (Field curvature)	2	0	$2\rho^2-1$	$\sqrt{3}(2\rho^2-1)$	$1/\sqrt{3}$
Primary spherical	4	0	$6\rho^4-6\rho^2+1$	$\sqrt{5}(6\rho^4-6\rho^2+1)$	$1/\sqrt{5}$
Secondary spherical (balanced 6th/4th)	6	0	$20\rho^6-30\rho^4+12\rho^2-1$	$\sqrt{7}(20\rho^6-30\rho^4+12\rho^2-1)$	$1/\sqrt{7}$
Primary coma	3	1	$(3\rho^3-2\rho)\cos\theta$	$\sqrt{8}(3\rho^3-2\rho)\cos\theta$	$1/\sqrt{8}$
Secondary coma	5	1	$(10\rho^5-12\rho^3+3\rho)\cos\theta$	$\sqrt{8}(10\rho^5-12\rho^3+3\rho)\cos\theta$	$1/\sqrt{8}$
Primary astigmatism	2	2	$\rho^2\cos 2\theta$	$\sqrt{6}\rho^2\cos 2\theta$	$1/\sqrt{6}$
Secondary astigmatism	4	2	$(4\rho^4-3\rho^2)\cos 2\theta$	$\sqrt{10}(4\rho^4-3\rho^2)\cos 2\theta$	$1/\sqrt{10}$

Wavefront errors: Zernike Polynomials

Zernike polynomials are the most standard basis for quantifying aberrations:

- analytical expressions
- orthonormal basis on a circular aperture → makes it easy to decompose any wavefront as a sum of Zernike polynomials
- the first Zernike polynomials correspond to the most common optical aberrations

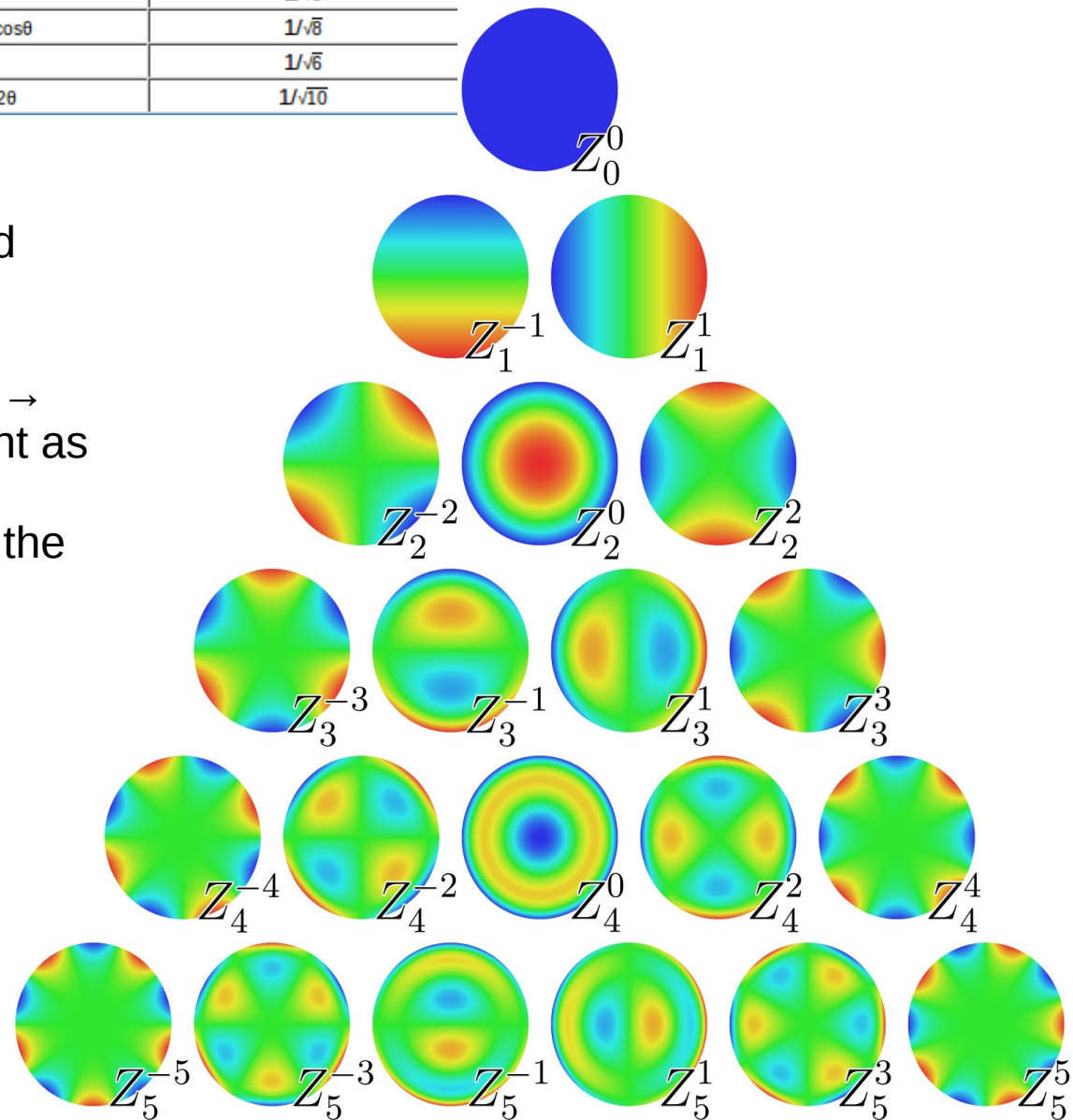
For example:

pointing → tip and tilt

telescope focus, field curv → focus

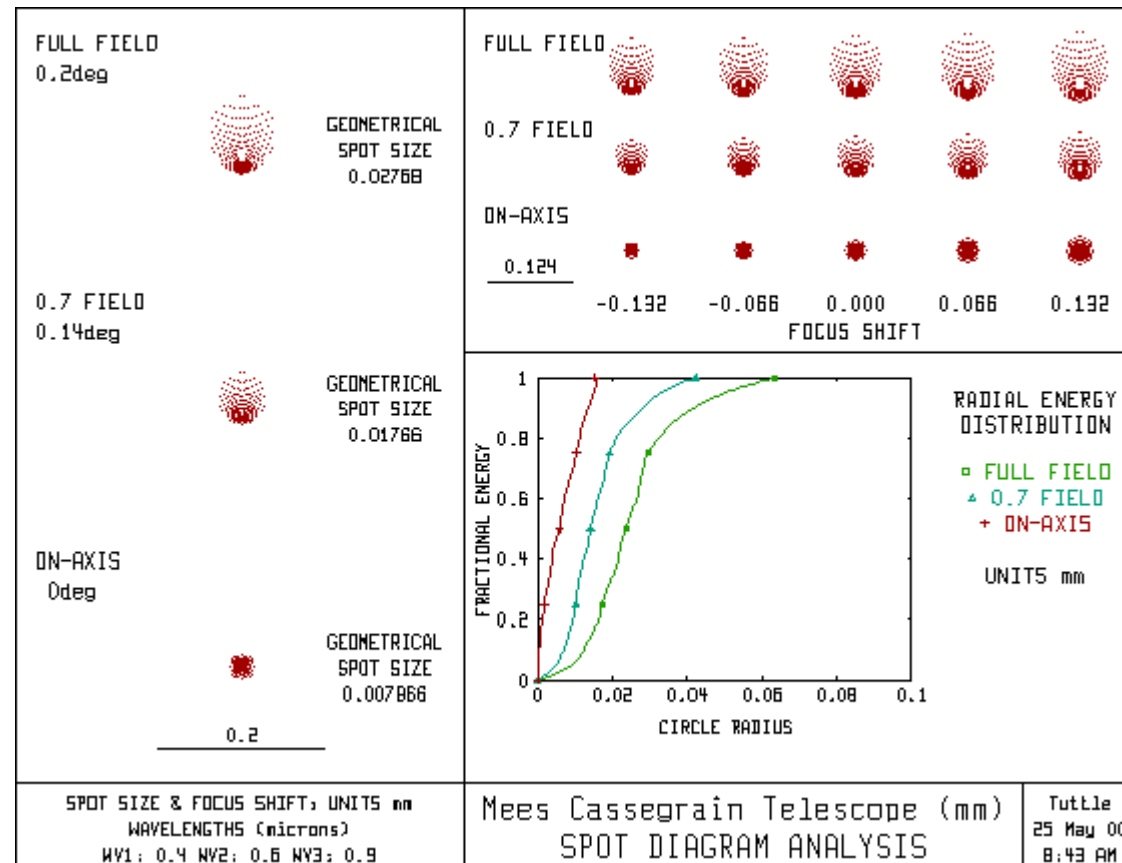
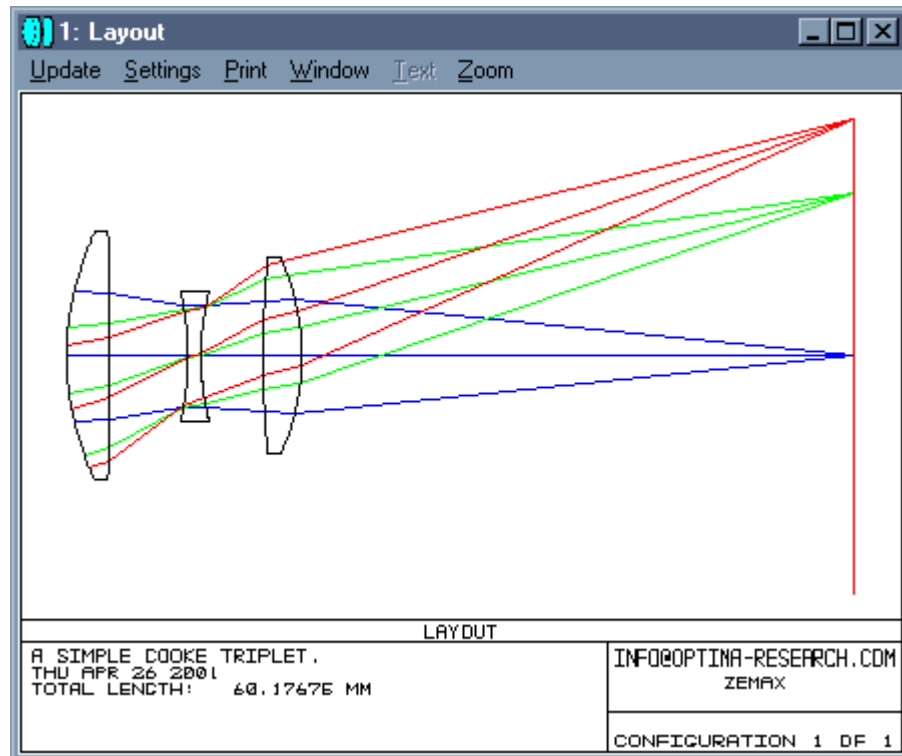
tilt a lens → astigmatism

parabolic mirror used off-axis → coma



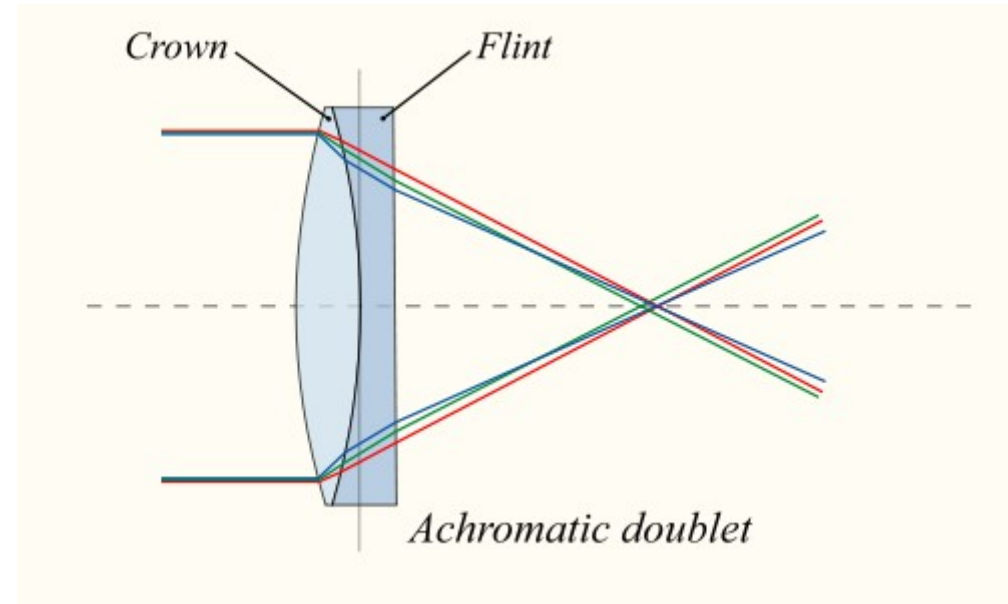
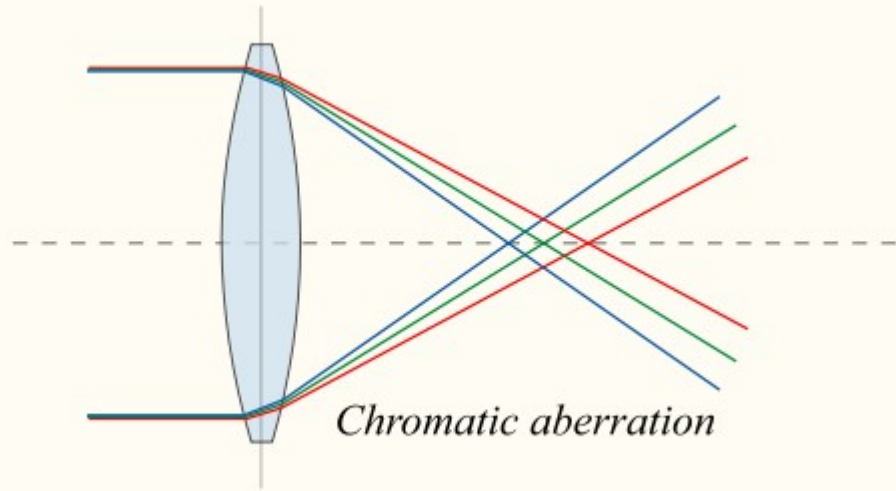
Wavefront errors

Wavefront errors are usually computed by raytracing through the optical system. Optical design softwares do this (Zemax, Code V, Oslo, etc...). Optical design software is used to minimize aberrations if given a well defined set of parameters to optimize.



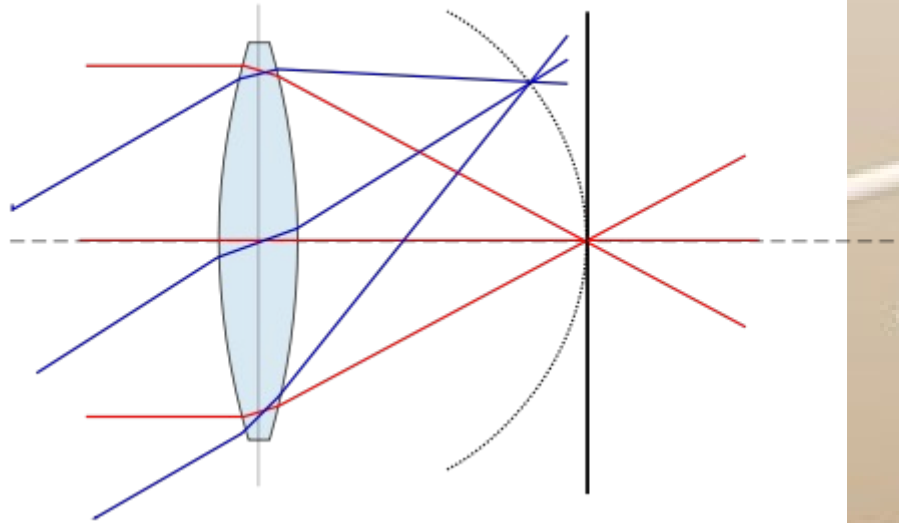
Chromatic aberrations

Chromatic aberrations only affect lenses (not mirrors)

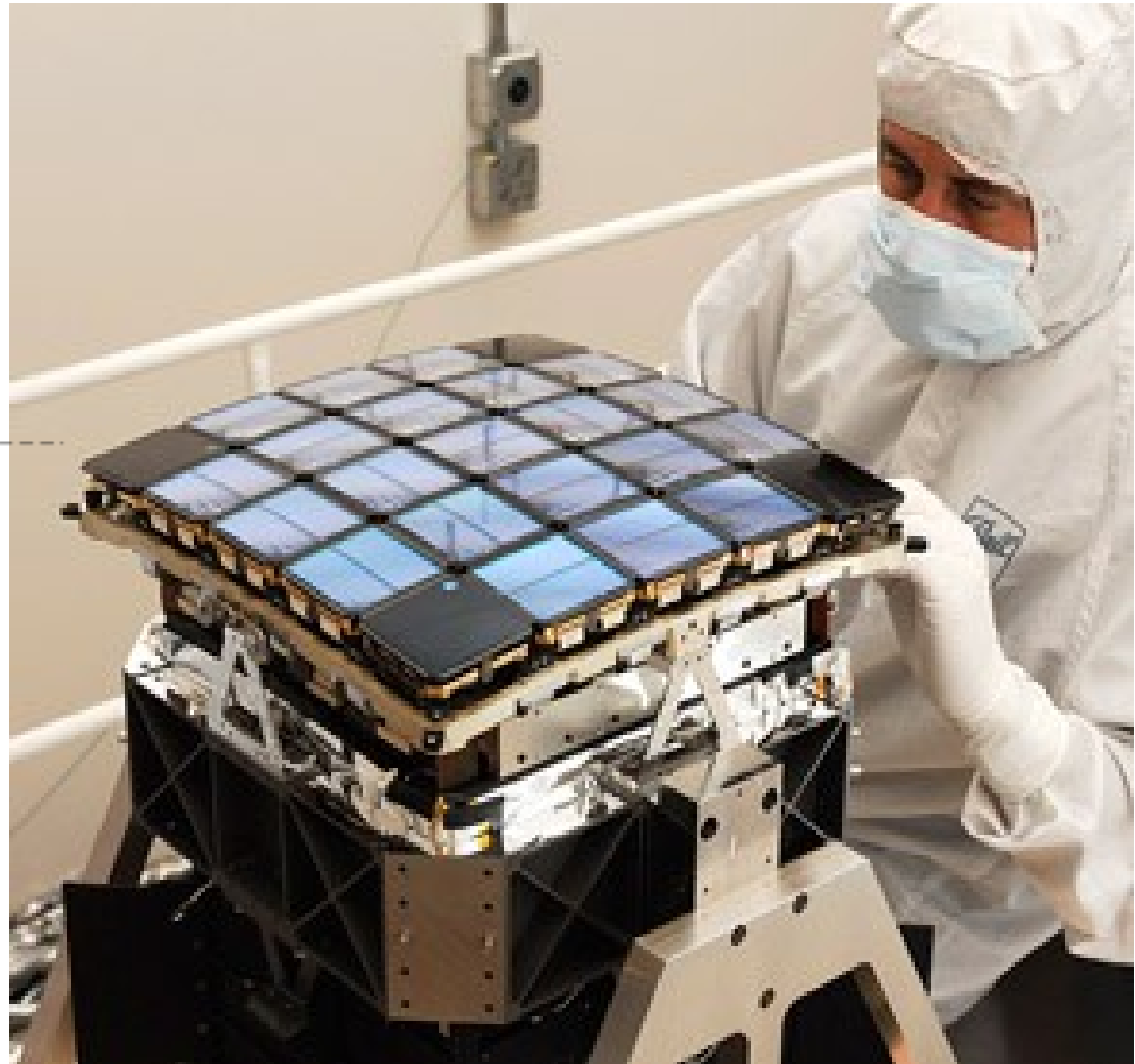


Can be reduced by combining different types of glass, which have different index of refraction as a function of wavelength

Field curvature



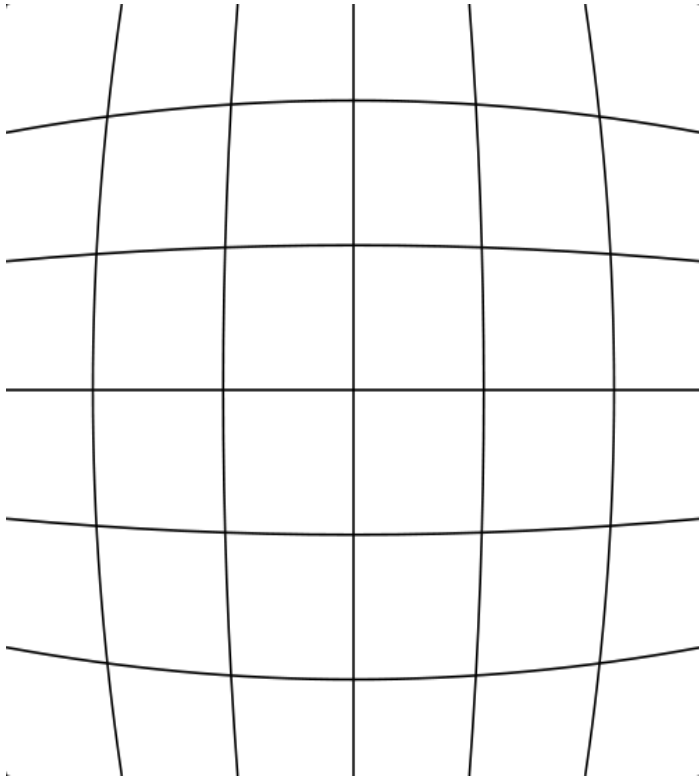
Most detectors are flat:
field curvature produces focus
error across the detector



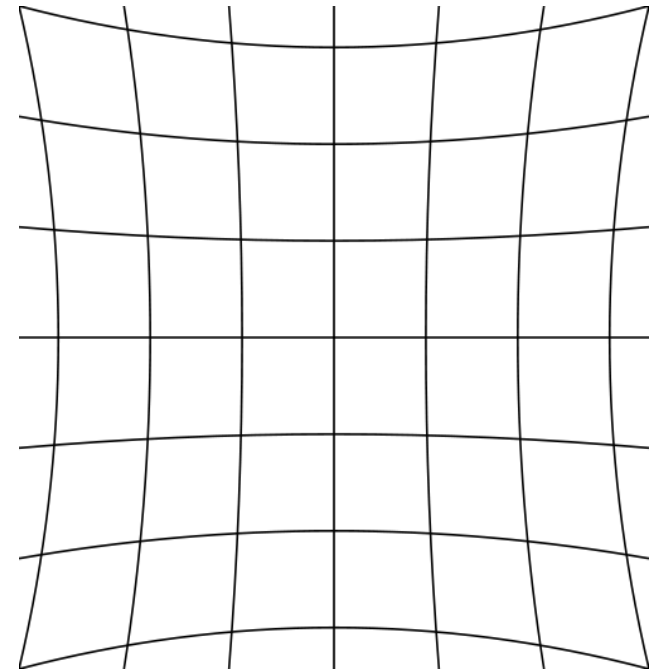
Focal plane array for Kepler mission
The detectors are mounted to match the
strong field curvature

Distortion errors

Makes the correspondance between sky angular position and detector coordinate complicated / non linear.



barrel distortion



pincushion distortion

Design considerations

Wavefront errors should be minimized by the telescope design and can also be reduced with a field corrector (usually refractive optics). Systems with very large field of views all have refractive field correctors, as the number of optical surfaces required to achieve suitable correction is too large for a all-reflective design to be practical.

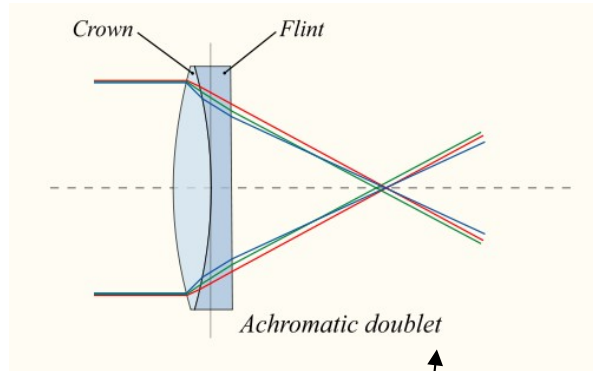
Field curvature can be minimized by a refractive corrector. Sometimes, it is simpler to build a curved focal plane detector than optically correct field curvature (see example on the right)

Field distortion is usually not a concern, as it is known and can be accounted for in the analysis of the images.

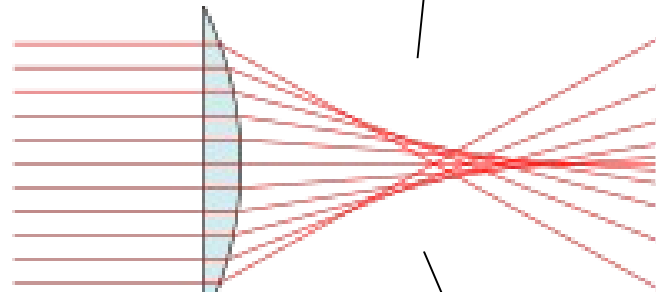
Chromatic aberration is not an issue with reflecting telescopes, but is a design constraint for refractive wide field correctors.

Having to simultaneously minimize wavefront errors, field curvature, (field distortion ?) and chromatic aberrations over a wide field of view requires careful optical design and usually complex multi-element refractive correctors and/or unusual optical designs.

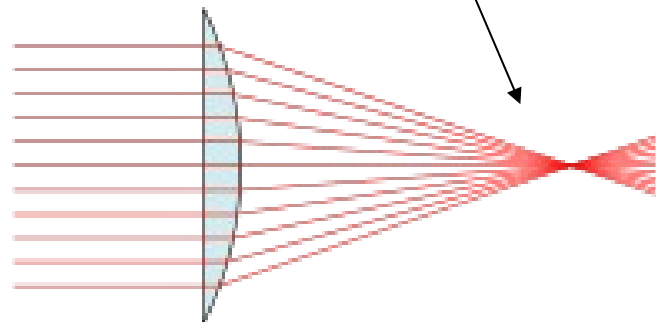
Example: lens design



solve chromatic aberration

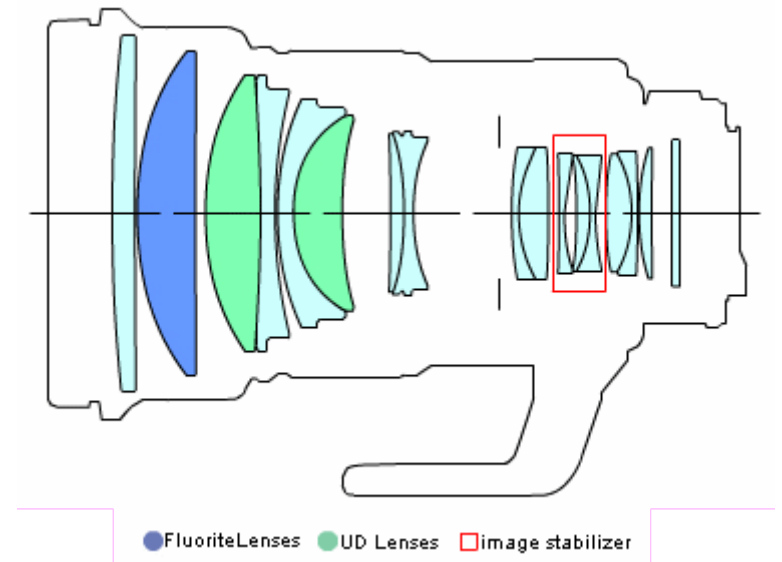


solve spherical aberration



aspheric lens

minimize chromatic aberration and wavefront aberration over a large field of view:



Canon 200mm F2 lens

Example: SuprimeCAM corrector (Subaru Telescope)

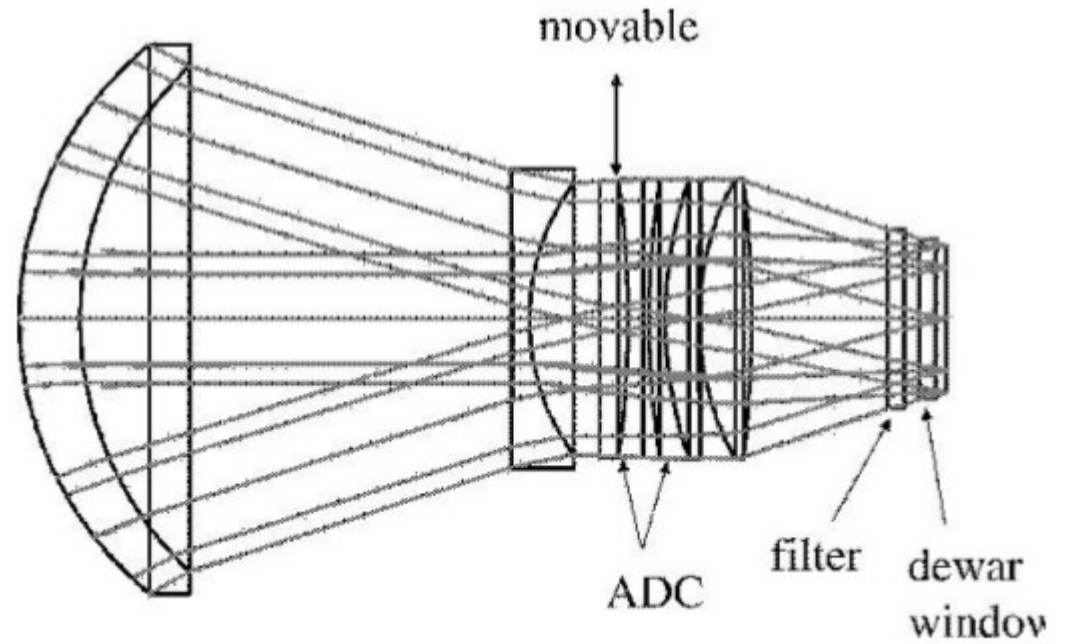
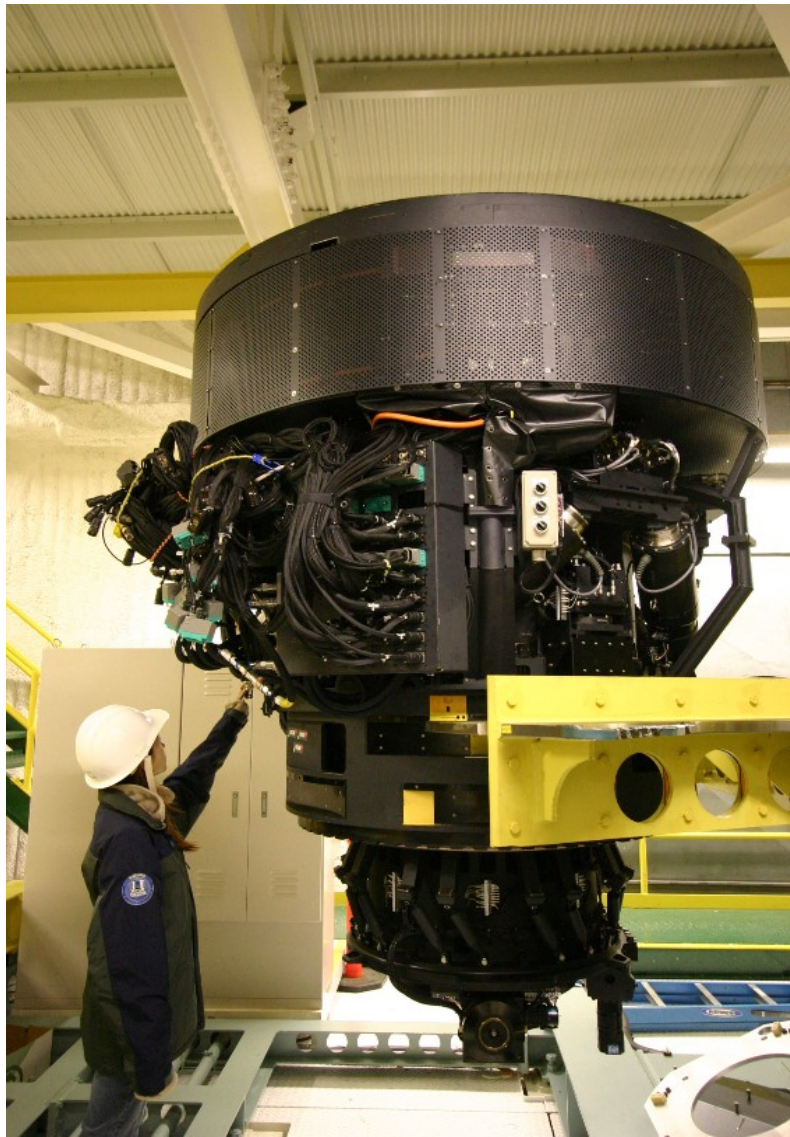


Fig. 14. Prime-focus corrector for Suprime-Cam based on a three-lens corrector design (Wynne 1965), but optimized with additional optical components for ADC.

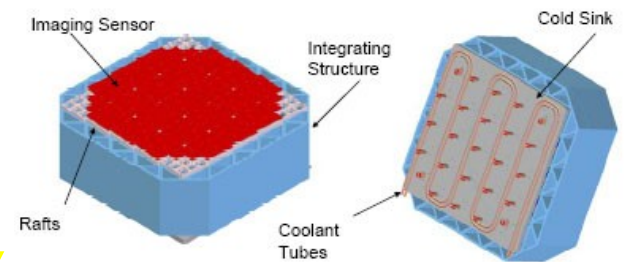
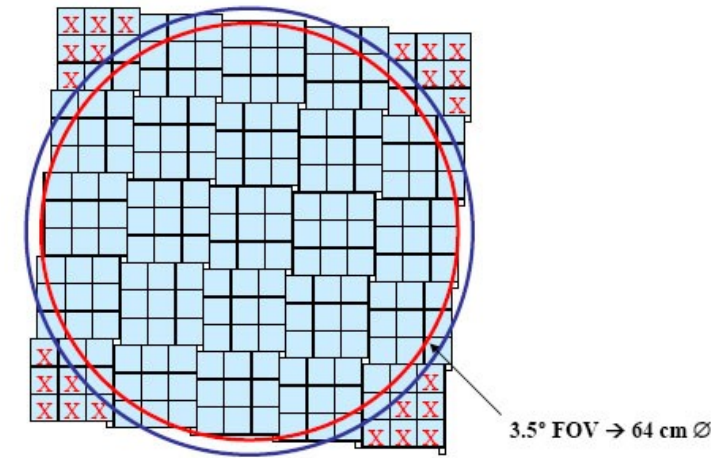
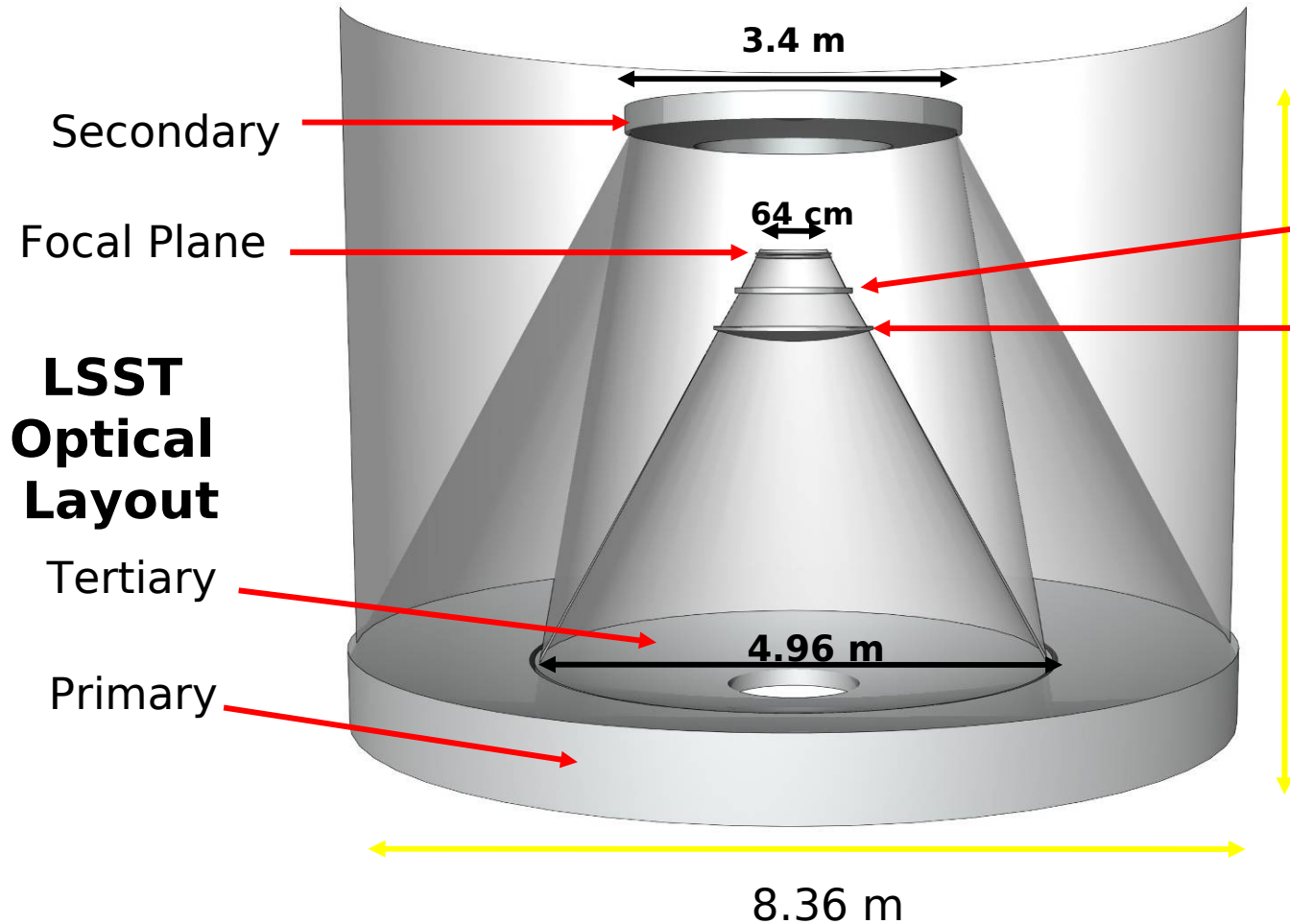


LSST

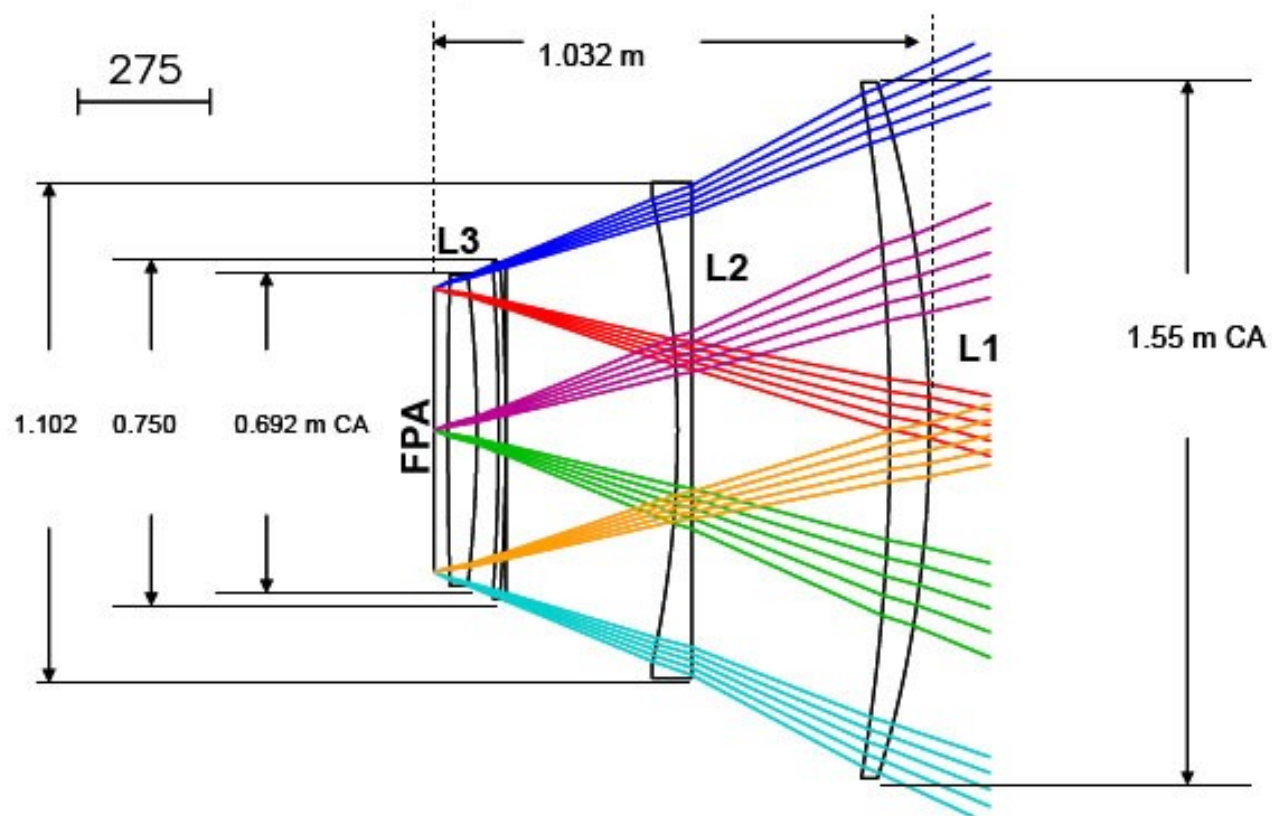
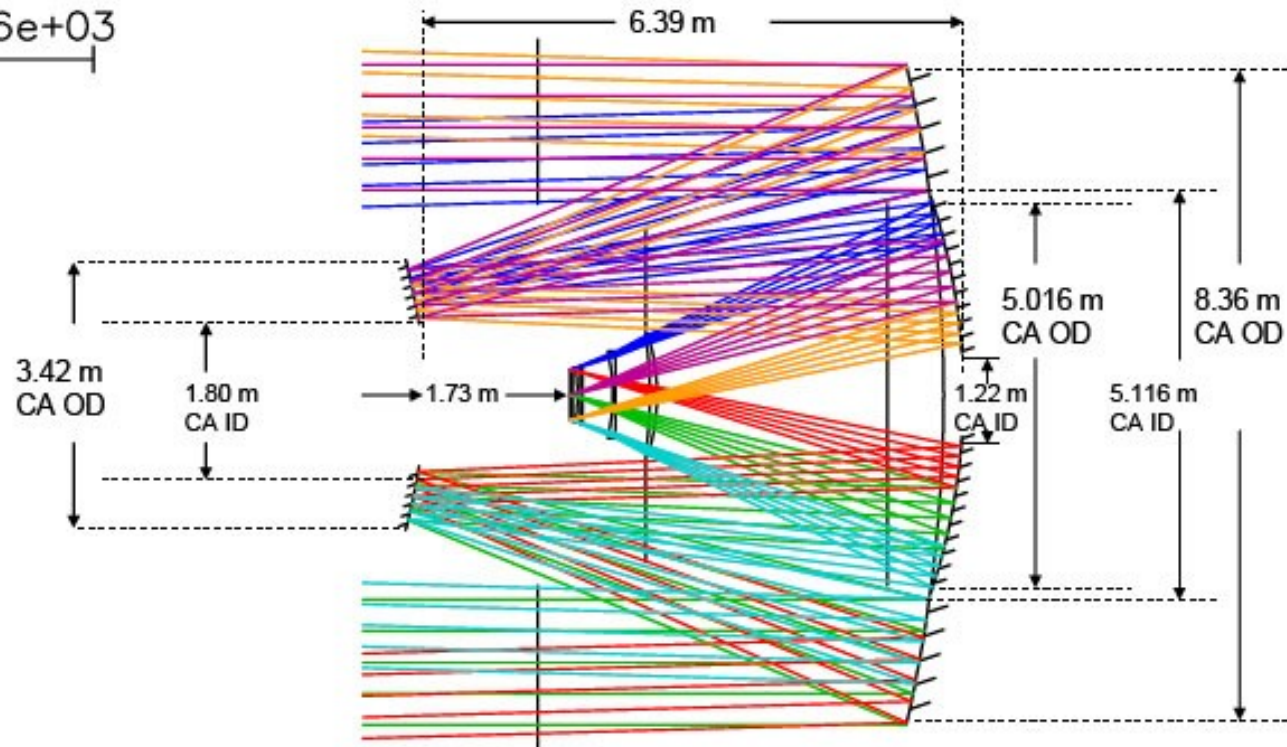
3.5° field of view for all-sky survey

Primary and Tertiary mirrors to be made at UA *on the same substrate*

200 4k x 4k detectors



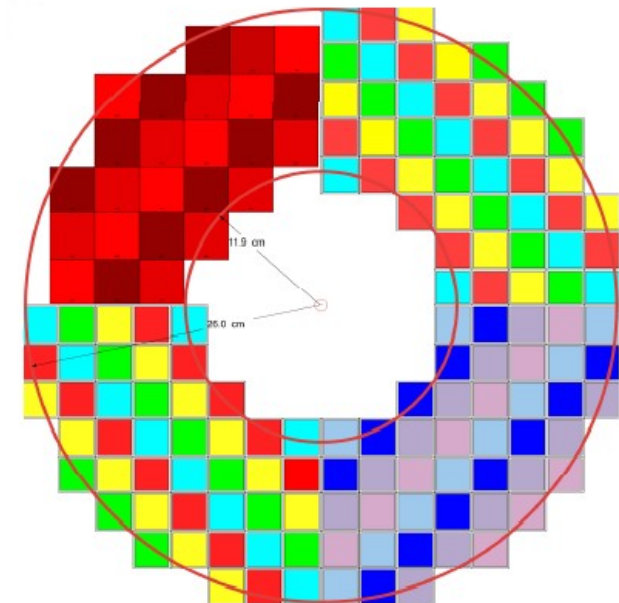
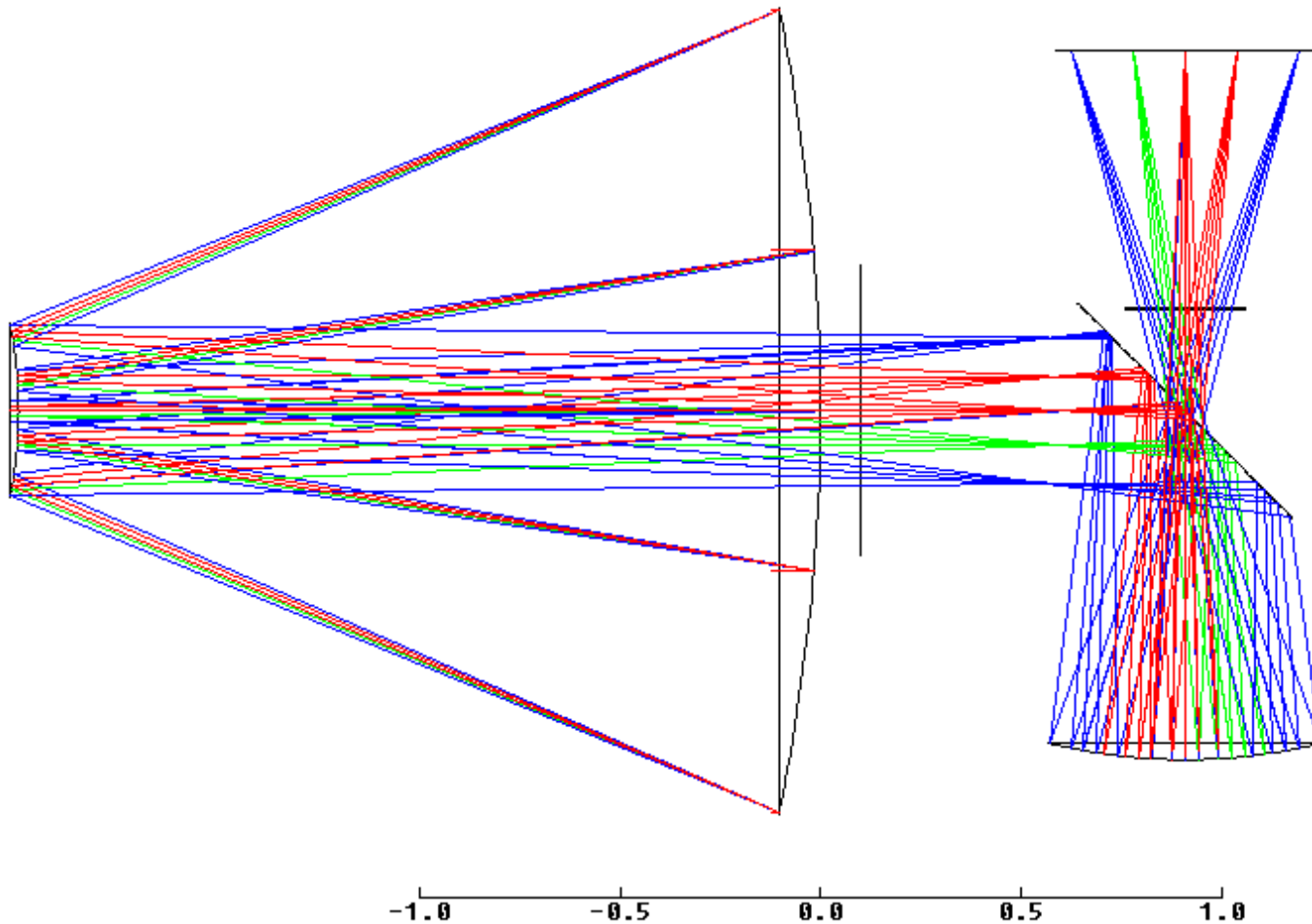
1.6e+03



TMA (Three Mirror Anastigmat)

SNAP, annular FOV, 1.4 sq degrees,
2 m aperture, diffraction limited for $> 1 \mu\text{m}$

1 Gpixel



7 HgCdTe Filter 1
9 HgCdTe Filter 2
9 HgCdTe Filter 3

10 CCD-red Filter blue
10 CCD-red Filter green
12 CCD-red Filter yellow
12 CCD-red Filter red

JWST TMA

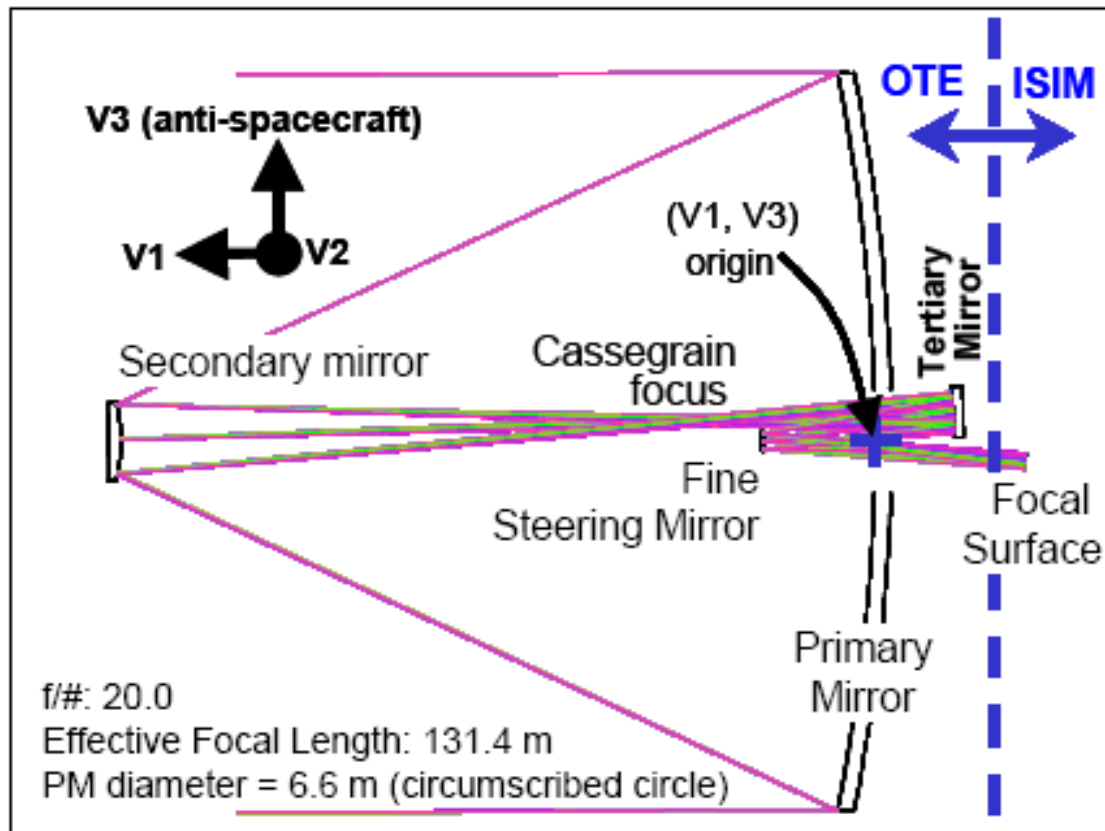


Figure 11 JWST Observatory Telescope Optical Layout

