Astronomical Optics

Telescope designs for astronomy
Field of view 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

Main telescope requirements for exoplanet science
… and also other astronomical investigations

Good image quality (sharp PSF, usually smaller than seeing)

- high spatial resolution → good sensitivity (separate target from background)
- high spatial resolution → good astrometric accuracy
- with adaptive optics, angular resolution ~ λ/D: telescope diameter and angular resolution are linked. Exoplanet observations with interferometry, coronagraphy favor large telescope diameters.

High sensitivity (→ large telescope diameter)

- faint targets / high signal to noise ratio (SNR) imaging
- Radial velocity precision in photon-noise regime improves with telescope size

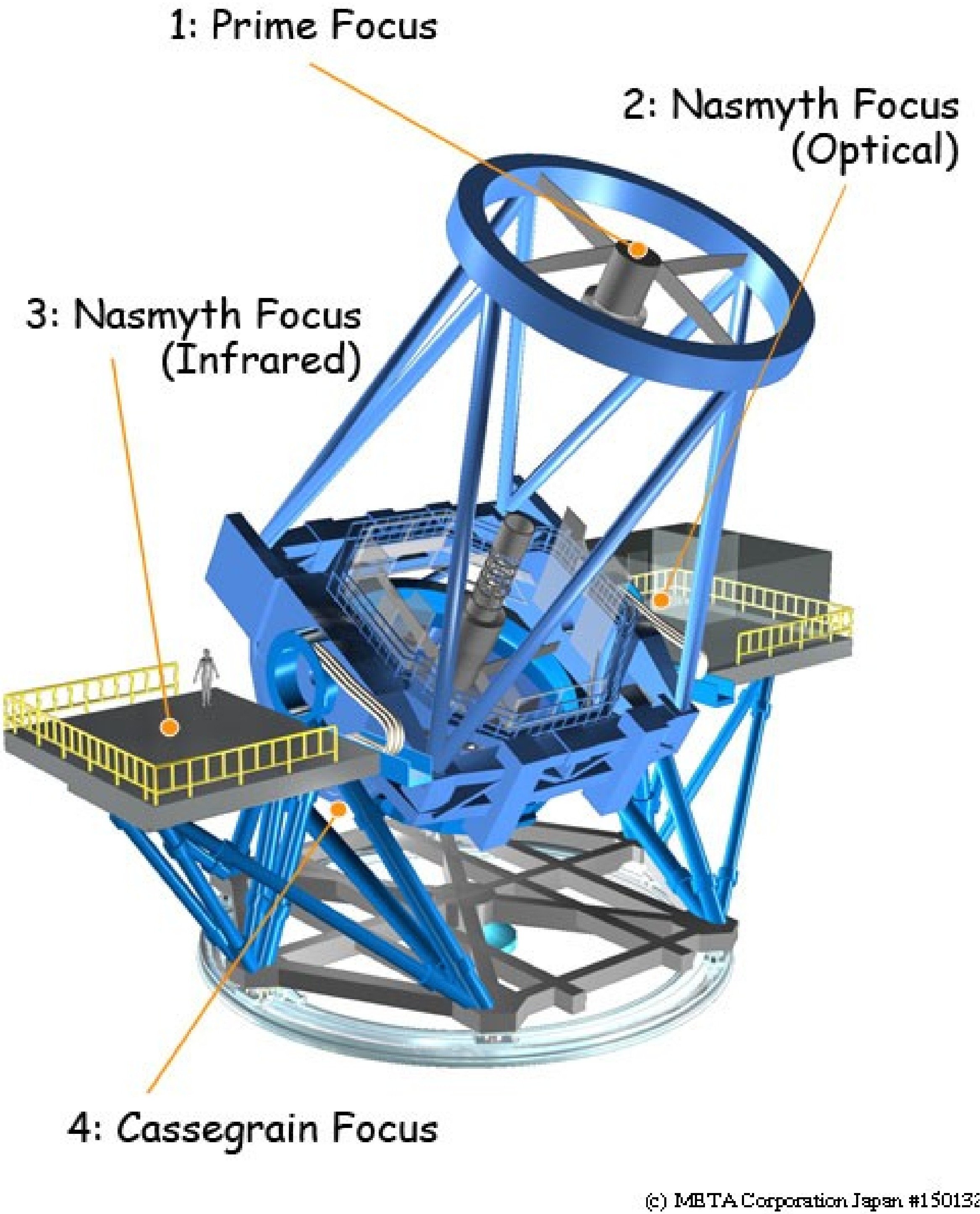
Wide field of view

- Especially important for transit surveys
- Can allow simultaneous RV measurements on several targets

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):

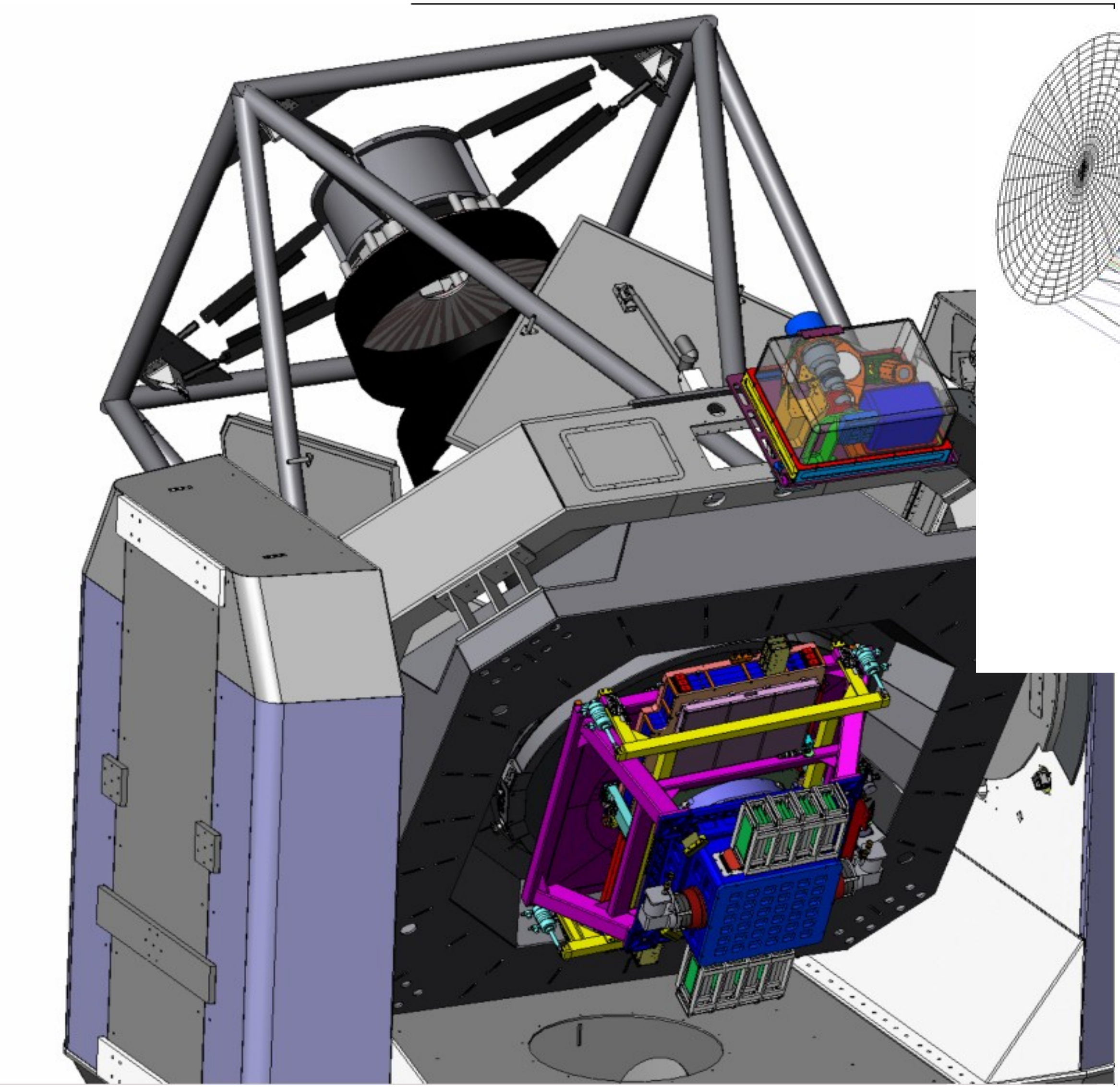
- PanSTARRS
- LBT LBC
- LSST

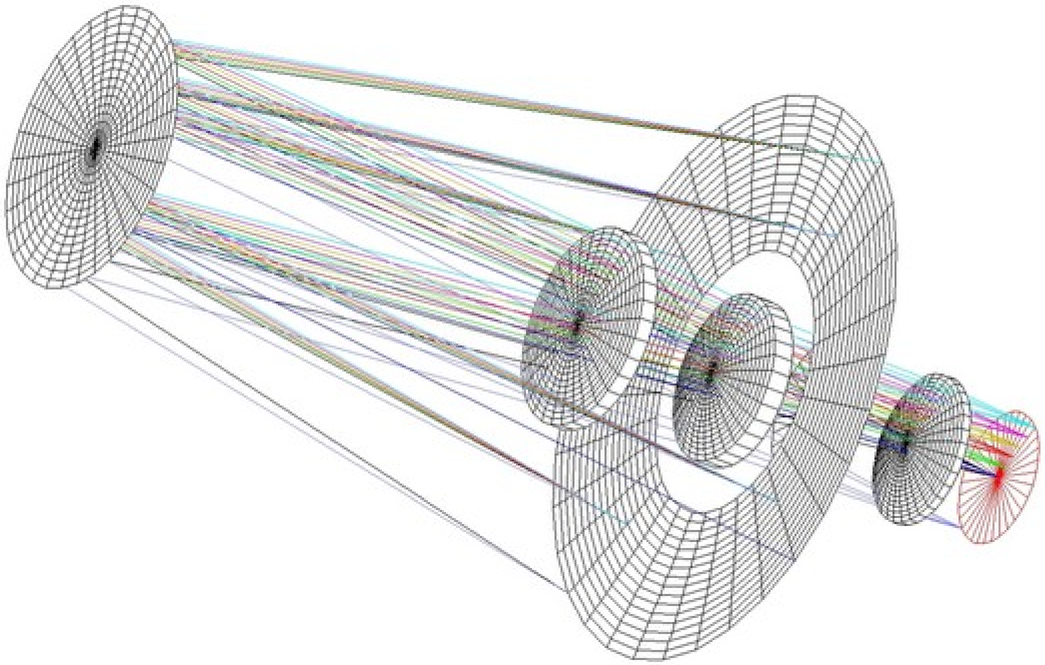
Heavy large/heavy instruments, or instruments requiring **outstanding stability** cannot easily be mounted on the telescope tube
→ Nasmyth focus, or coude focus, preferred
Examples:

- Subaru HDS
- HARPS (requires outstanding spectroscopic stability)

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

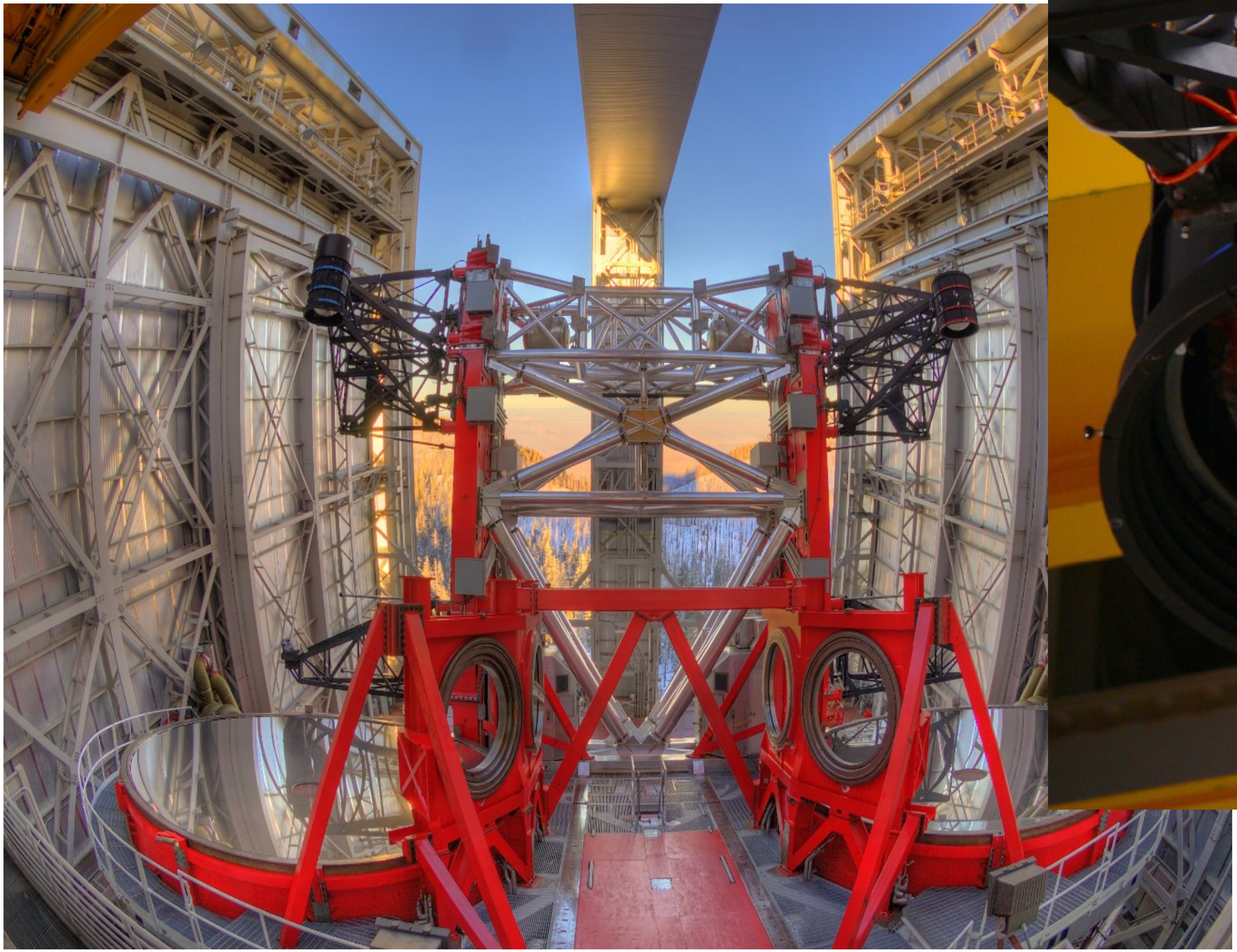
Pan-STARRS : 1.8m diameter telescope, 7 sq deg field
Integrated telescope + instrument design for wide field of view

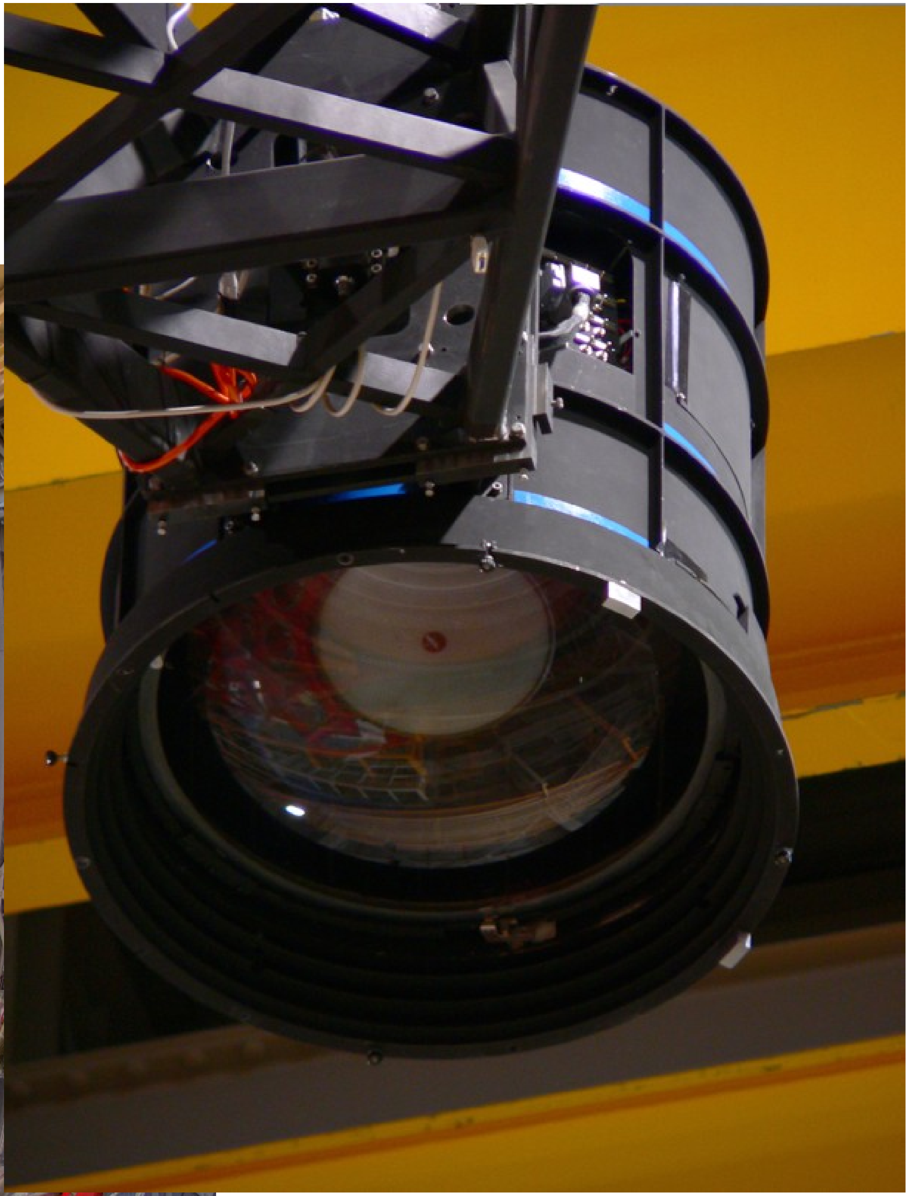


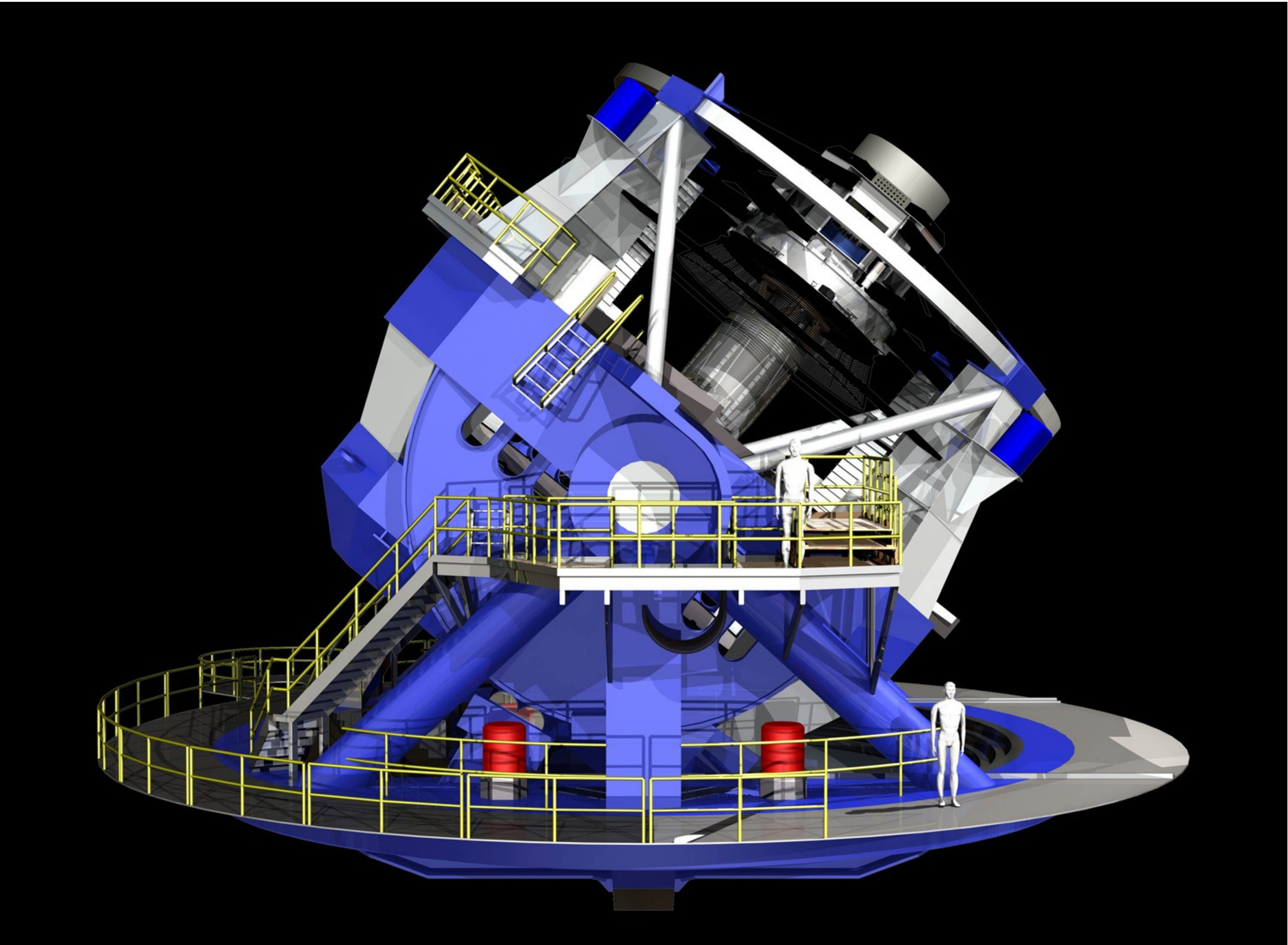


Large Binocular Telescope's wide field cameras

Large imaging camera
includes corrector for wide field of view

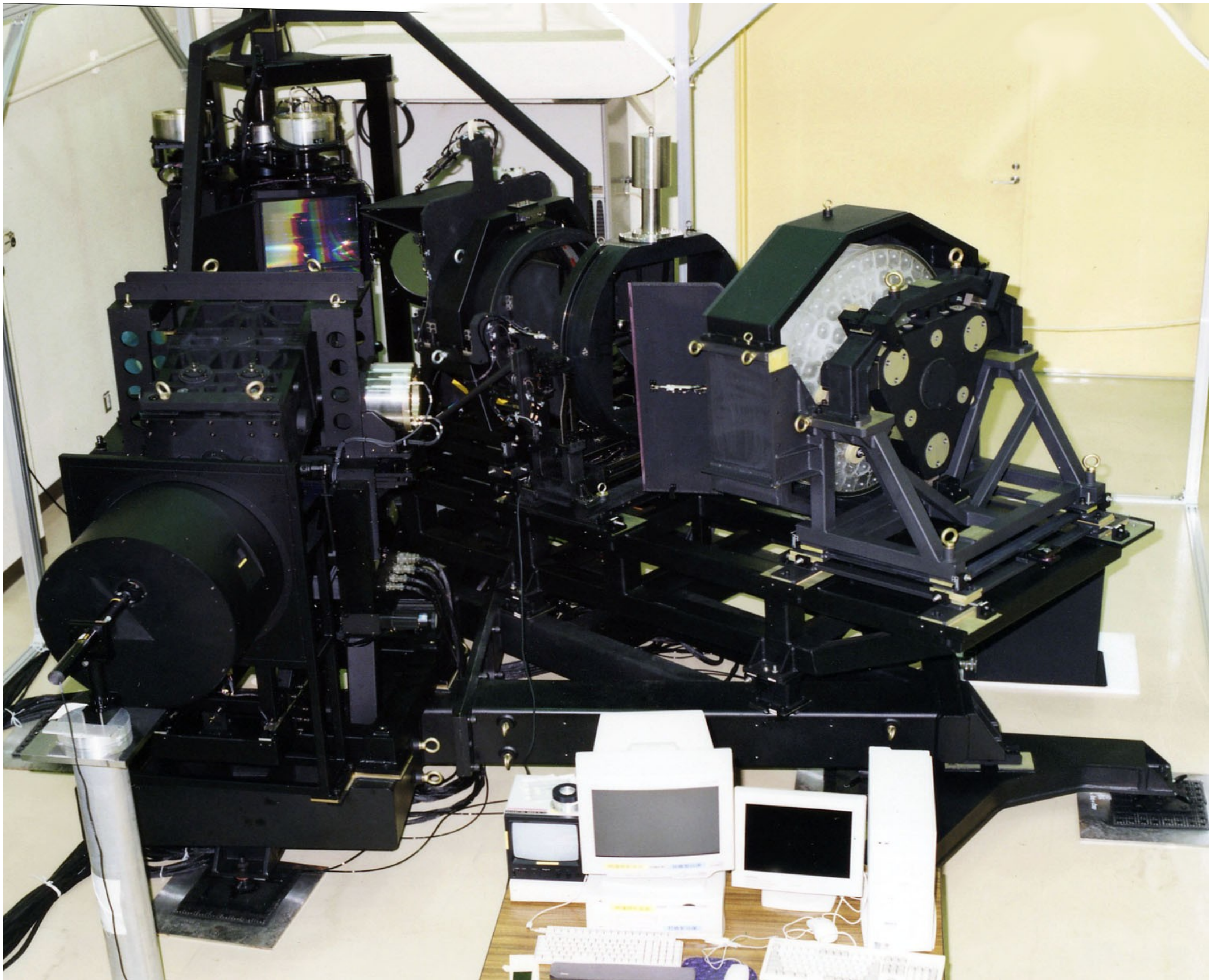






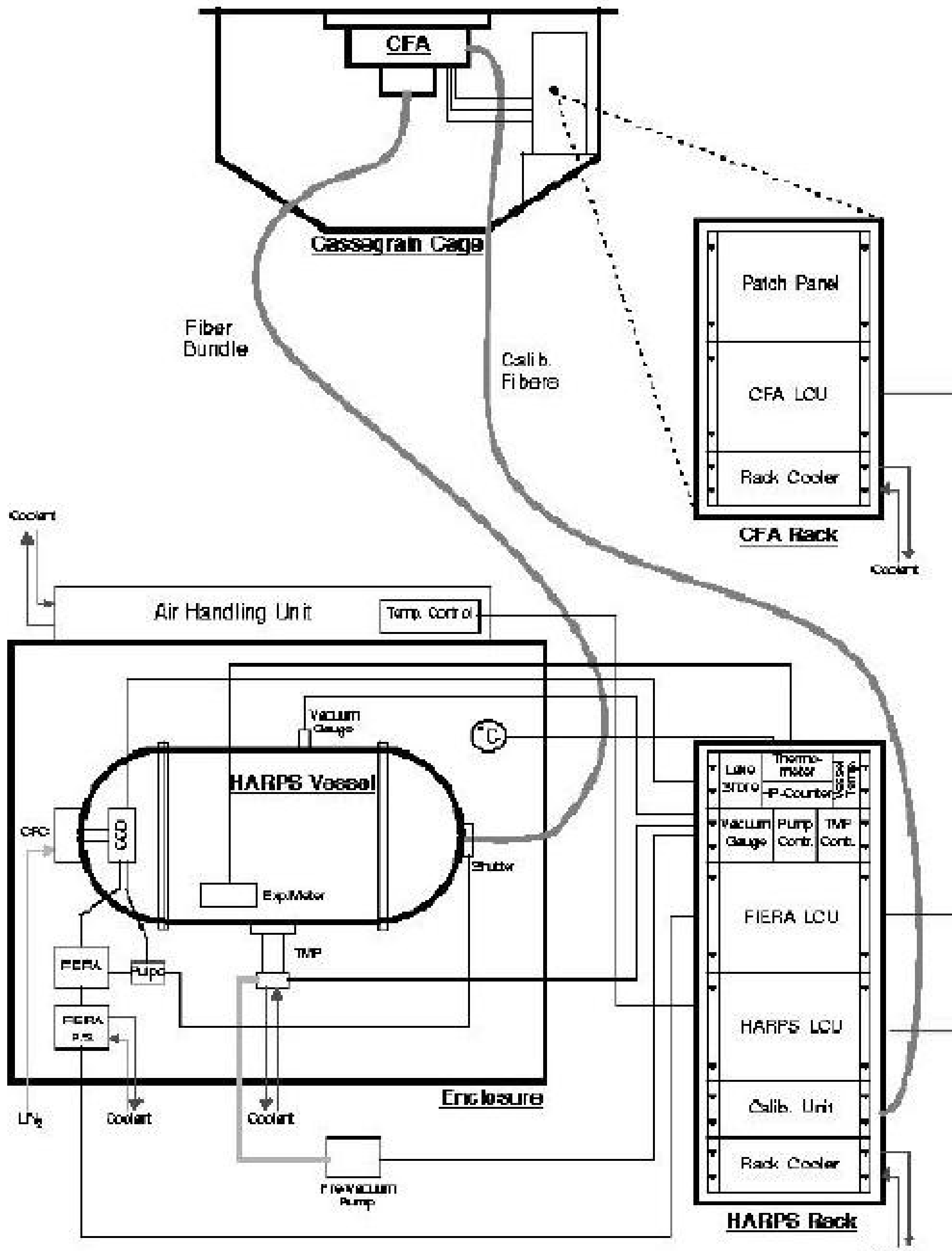
Subaru High Dispersion Spectrograph

6 metric tons, Nasmysh focus



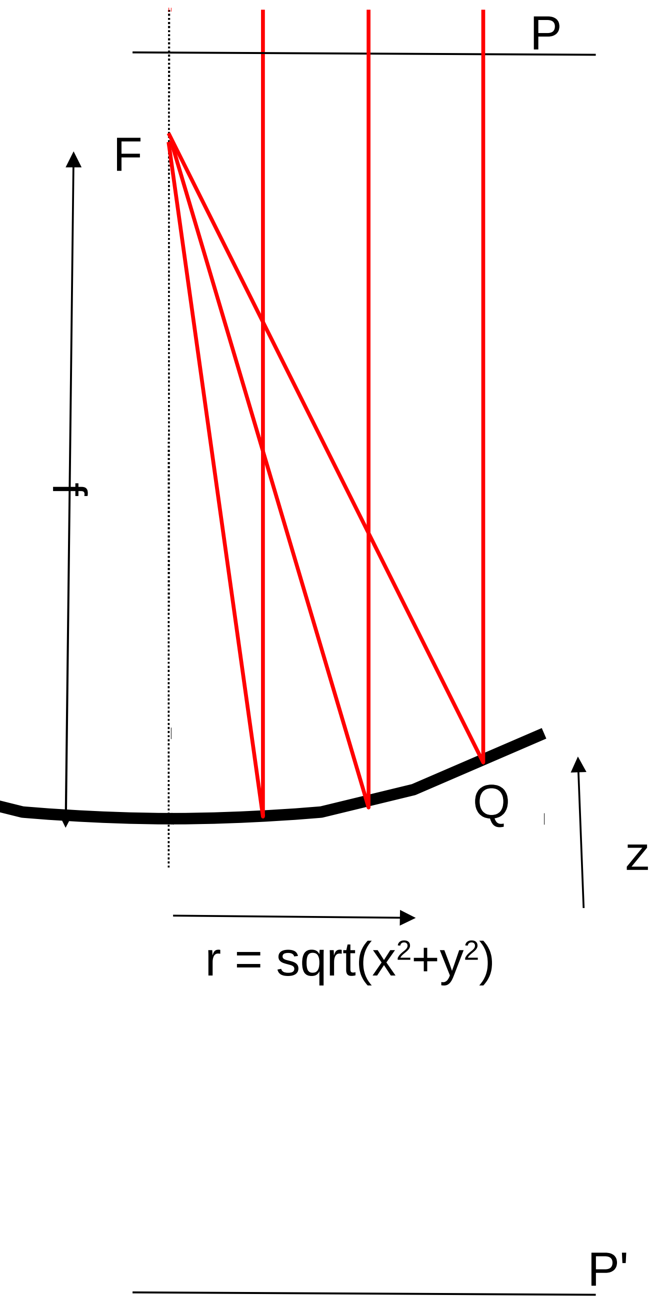
HARPS spectrograph at ESO's 3.6m

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 ?

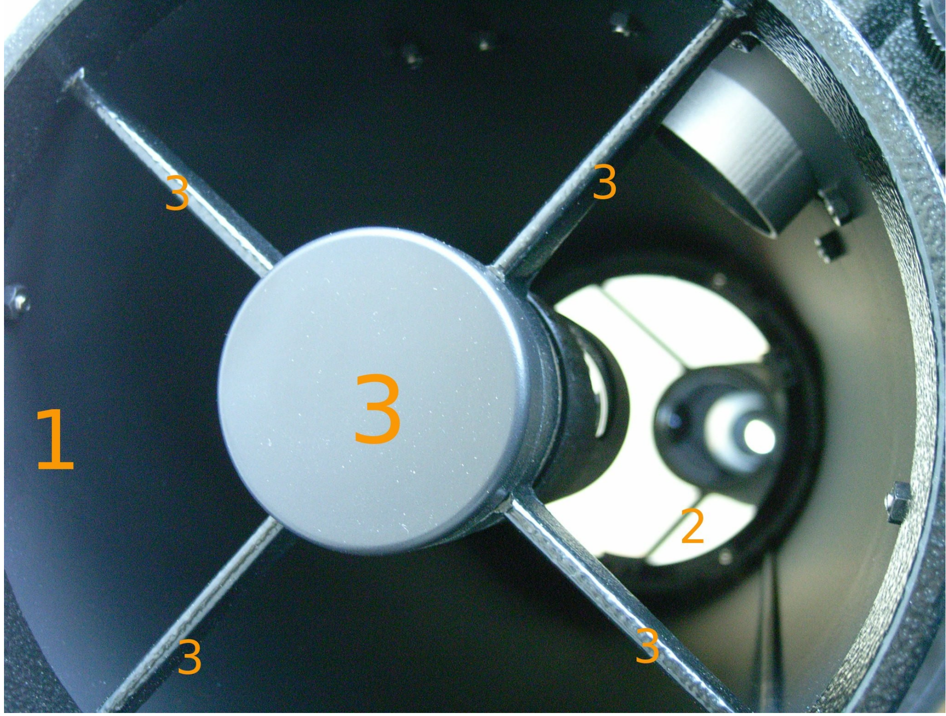
Fermat's principle: Light rays follow shortest path from plane P to focus F. With OPD(x,y) the distance from the object to focus (= distance from plane P to point F):
d OPD(x,y) / dx = d OPD(x,y) / dy = 0

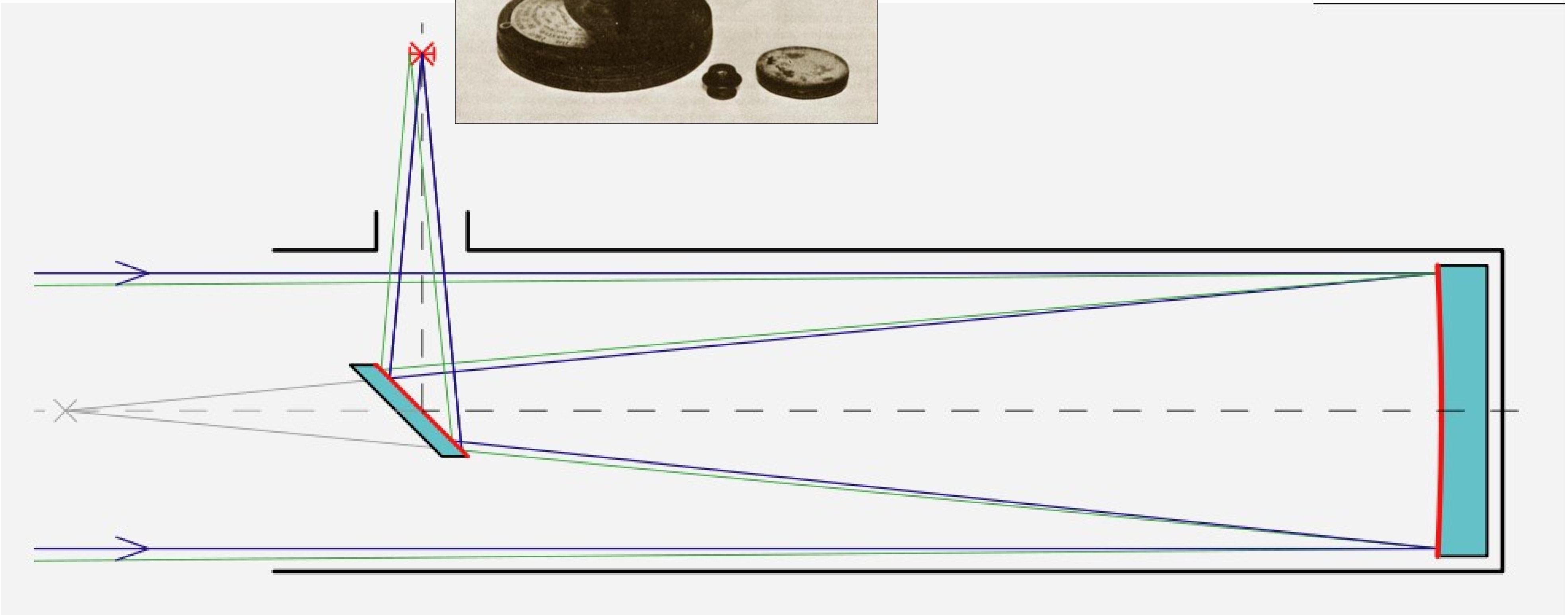
Parabola is surface of equidistance between a plane P' and a point (with the plane below the mirror on the figure on the left): distance (FQ) = distance (QP')
with : (QP') + (QP) = (P'P) = constant
→ (FQ) + (QP) = (QP') + (QP') = constant
Parabola obeys Fermat's principle

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
→ dz/dr = function_of(r,f,z)
→ mirror shape can be derived by integrating this equ.

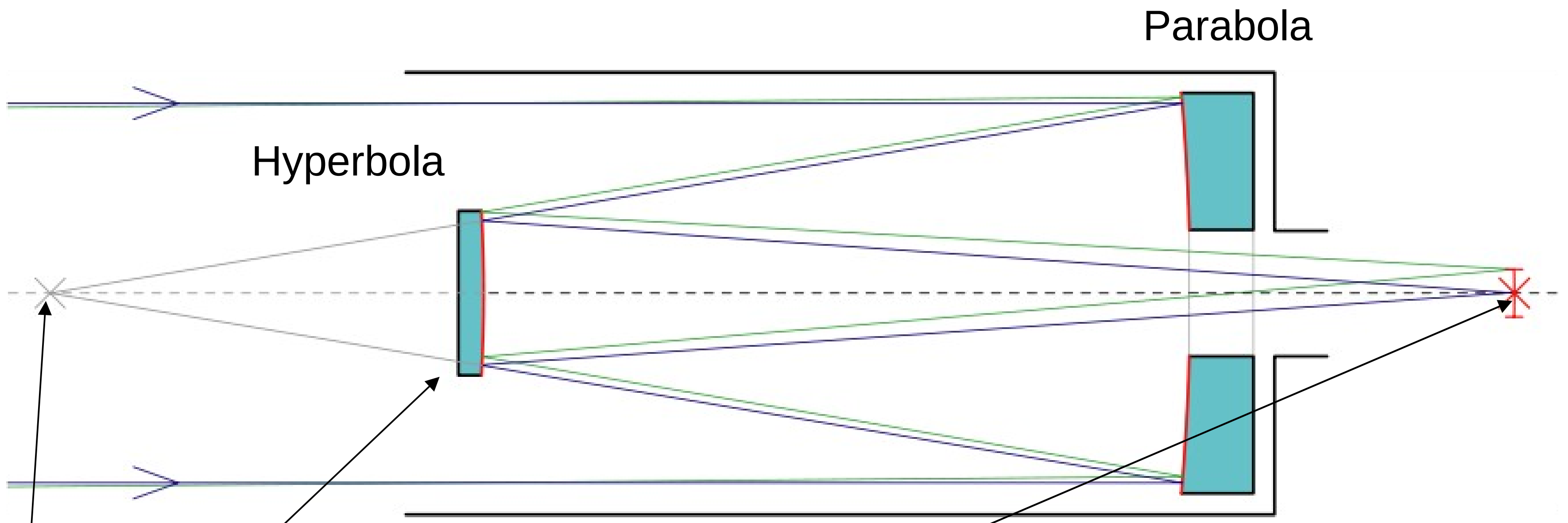
Newtonian Telescope

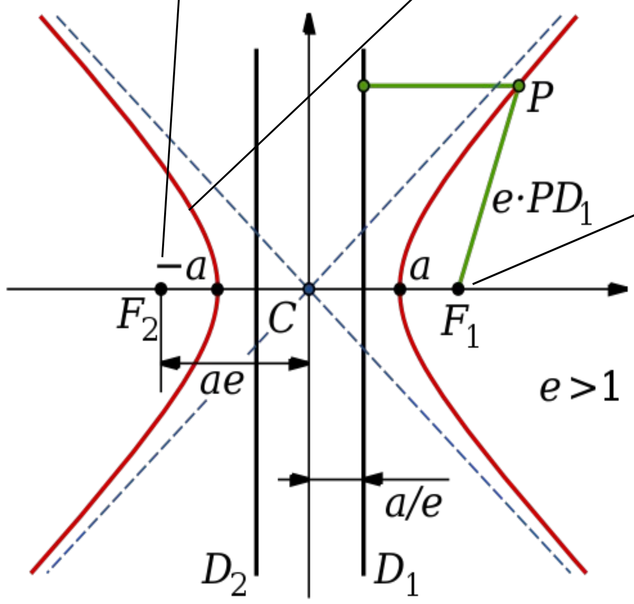
Parabolic mirror + flat secondary mirror to move image out of the incoming beam





Classical Cassegrain Telescope

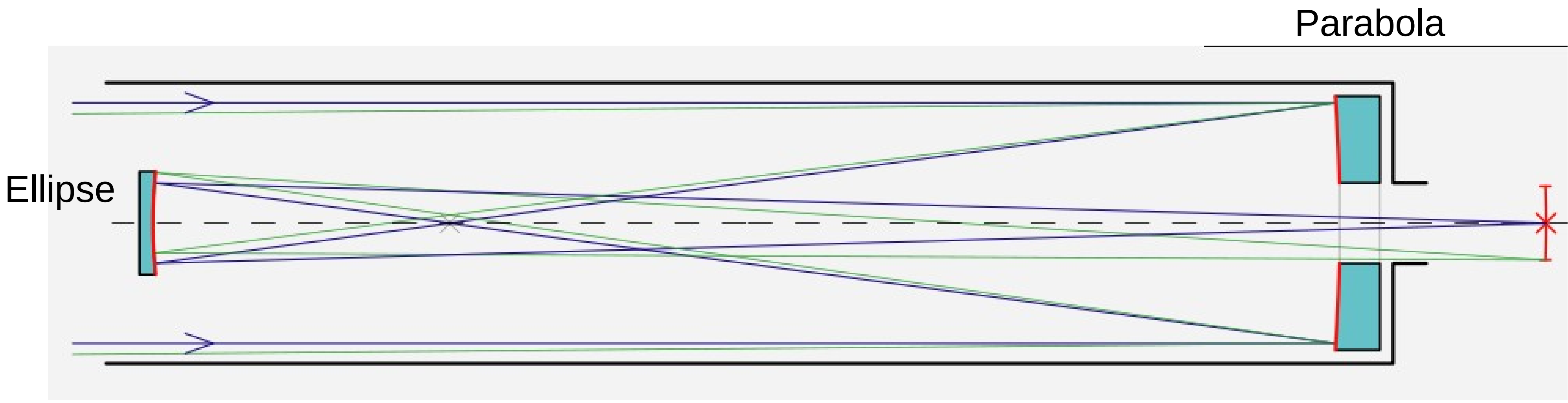




If secondary mirror is flat, then focus is inside telescope (not practical)

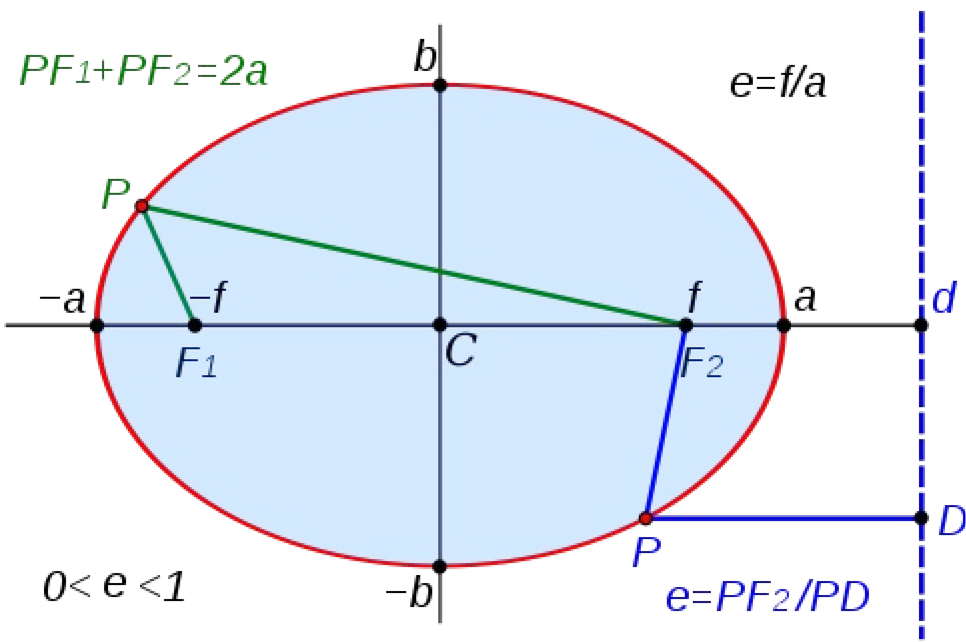
Hyperbola is curve/surface for which difference between distances to two focii (F1 and F2) is constant (=2a). Fermat's principle → hyperbola

Gregorian Telescope

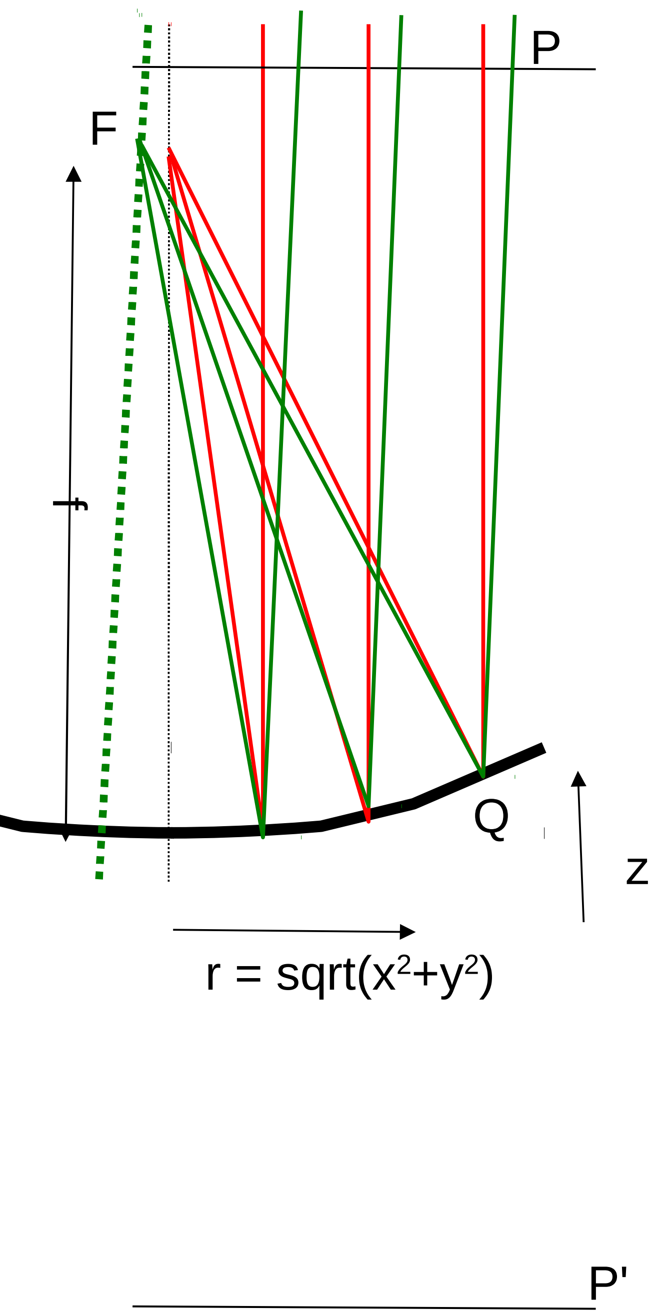


If secondary mirror is flat, then focus is inside telescope (not practical)

Ellipse is curve/surface for which sum of distances to two focii (F1 and F2) is constant (=2a).
Fermat's principle → 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 symetric 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

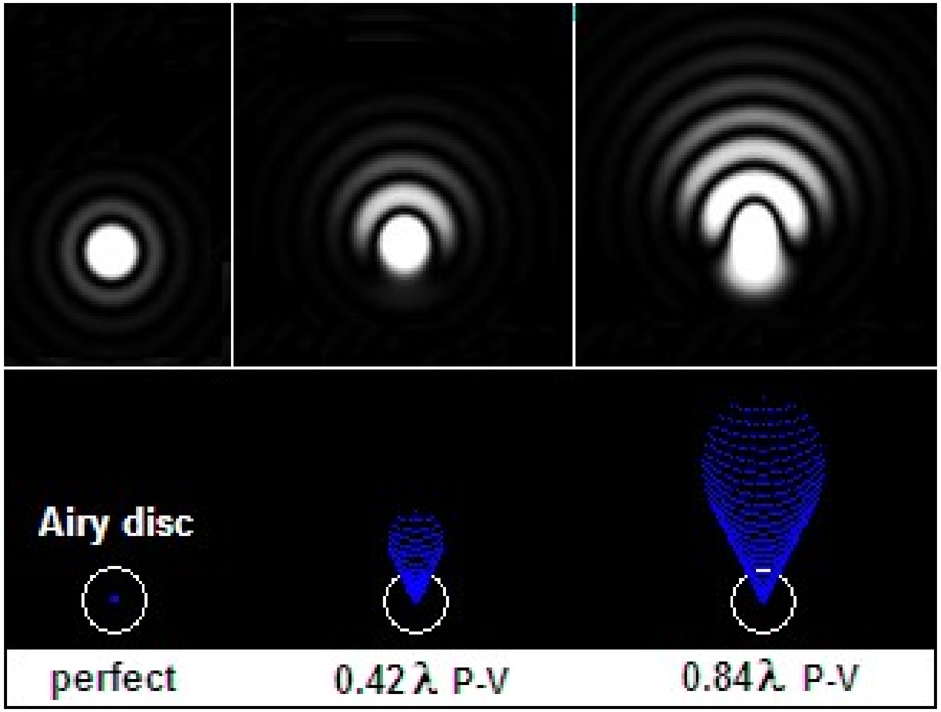
For a source offset α [rad], the RMS geometrical blurr radius due to coma is:

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

Examples:
F = f/D = 10 telescope
r < 0.1” (0.2” diameter spot) for α=3.3'

F = 5
r < 0.1” for α=49”

Parabolic mirror telescopes are not suitable for wide field imaging



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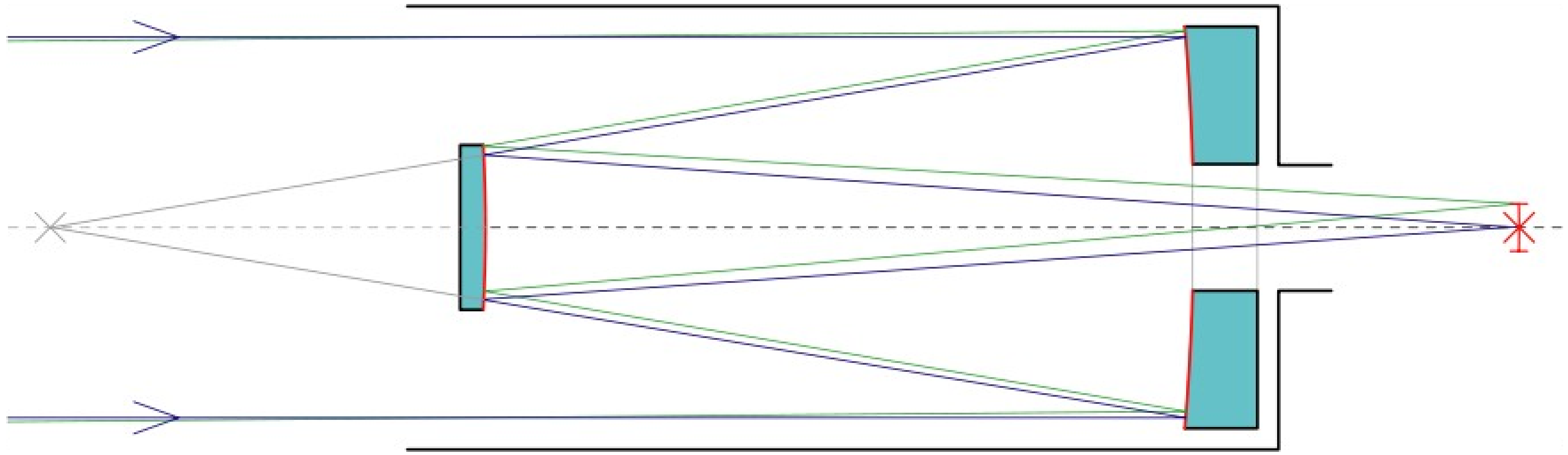
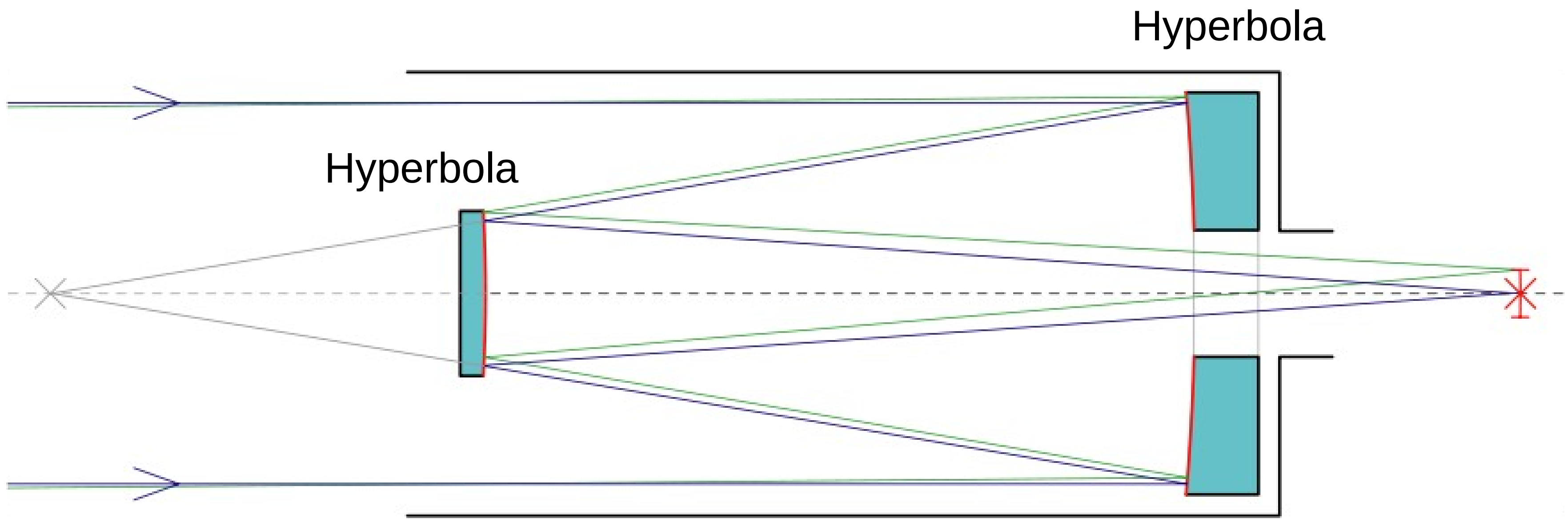
Solution to the field of view problem: >1 optical surface



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 → shape of one of the 2 mirrors becomes a free parameter that can be used to optimize image quality over the field of view.

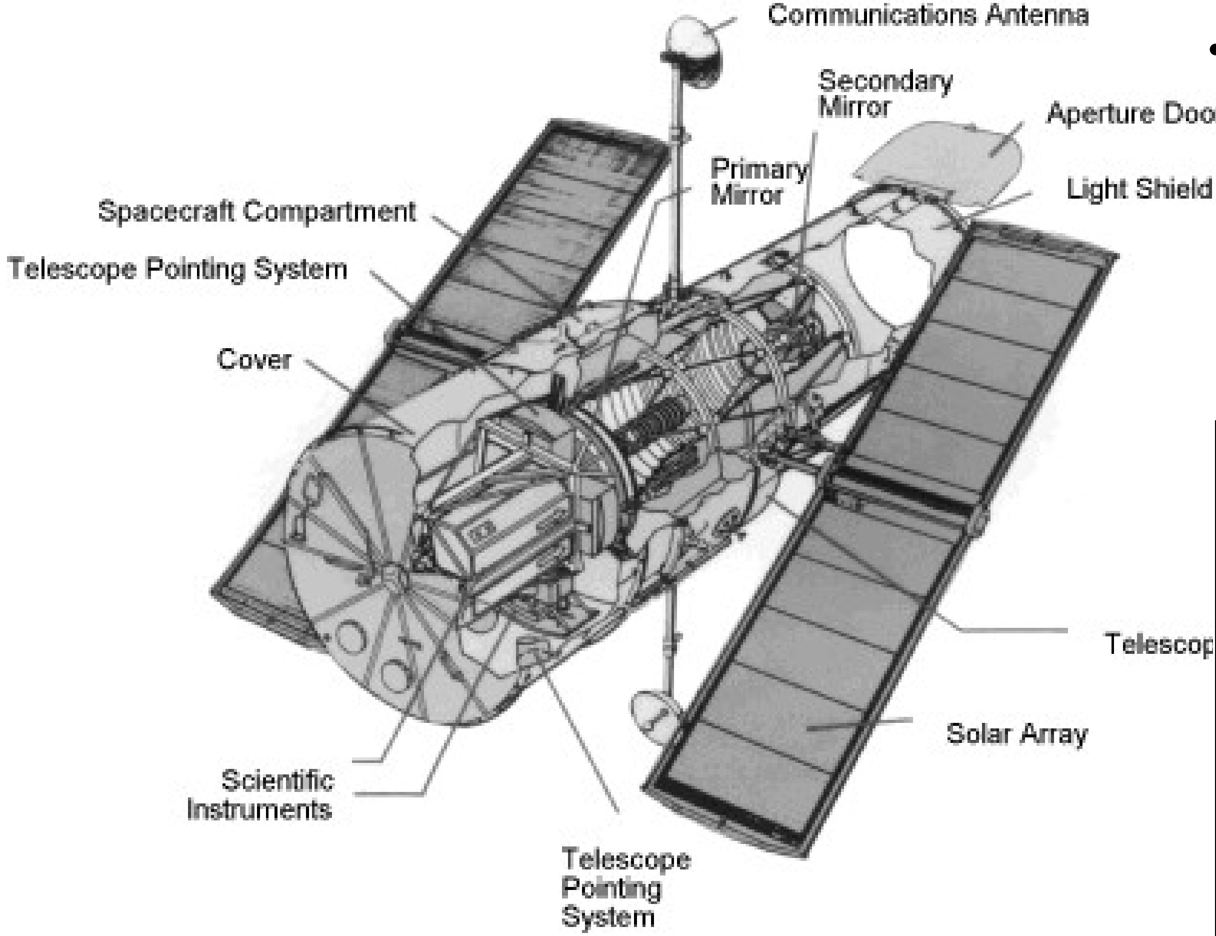
Ritchey Chretien Telescope



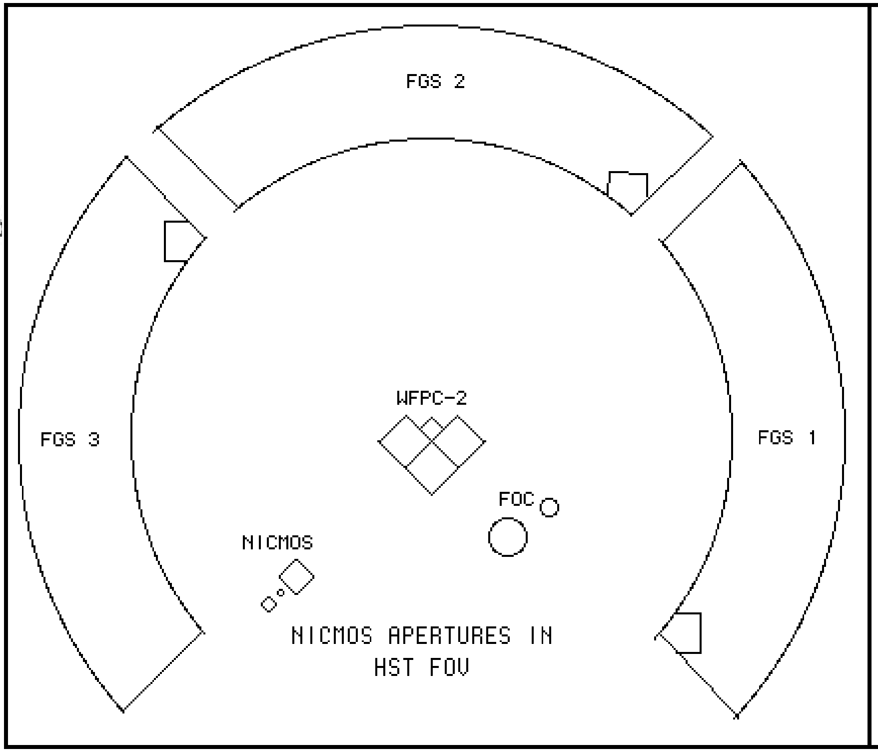
Primary and secondary mirror are hyperbola
Spherical and Coma can be removed by choice of conic constants for both mirrors
→ field of view is considerably larger than with single parabola
If PM and SM have same radius of curvature, field is flat

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

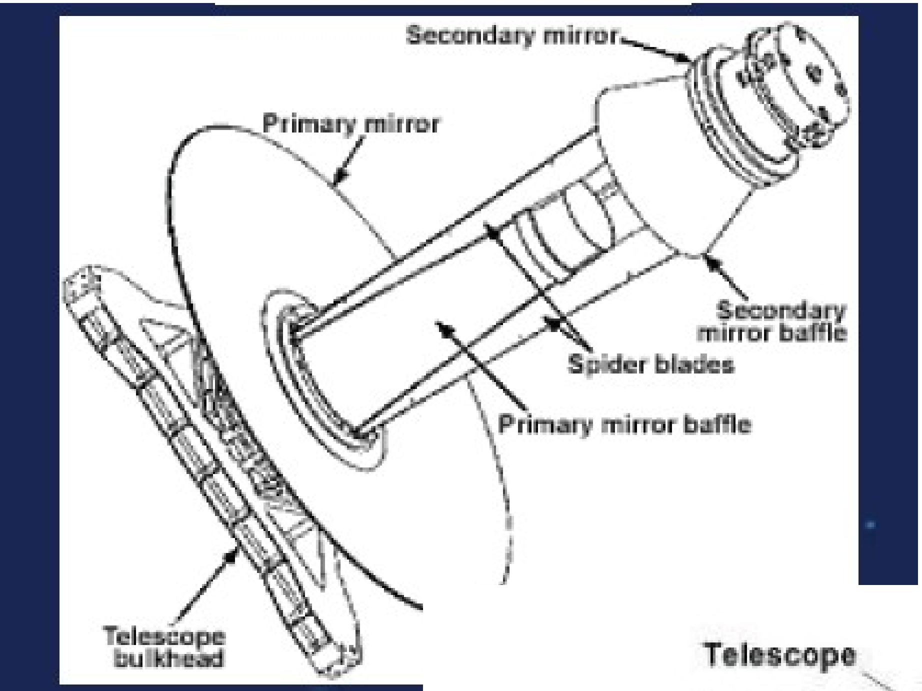
Hubble Space Telescope

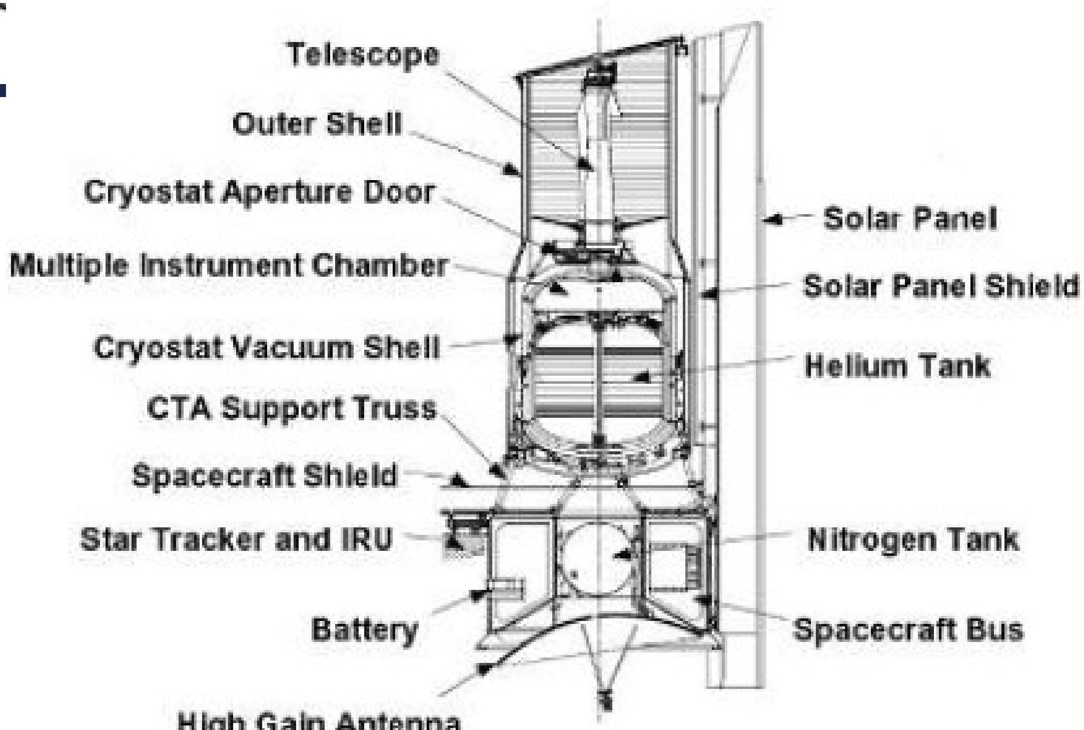


- Ritchey-Chretien design
- Aplanatic – coma is corrected by satisfying the sine condition
  - Primary mirror is not quite paraboloidal
  - Secondary is hyperboloid



Spitzer Telescope

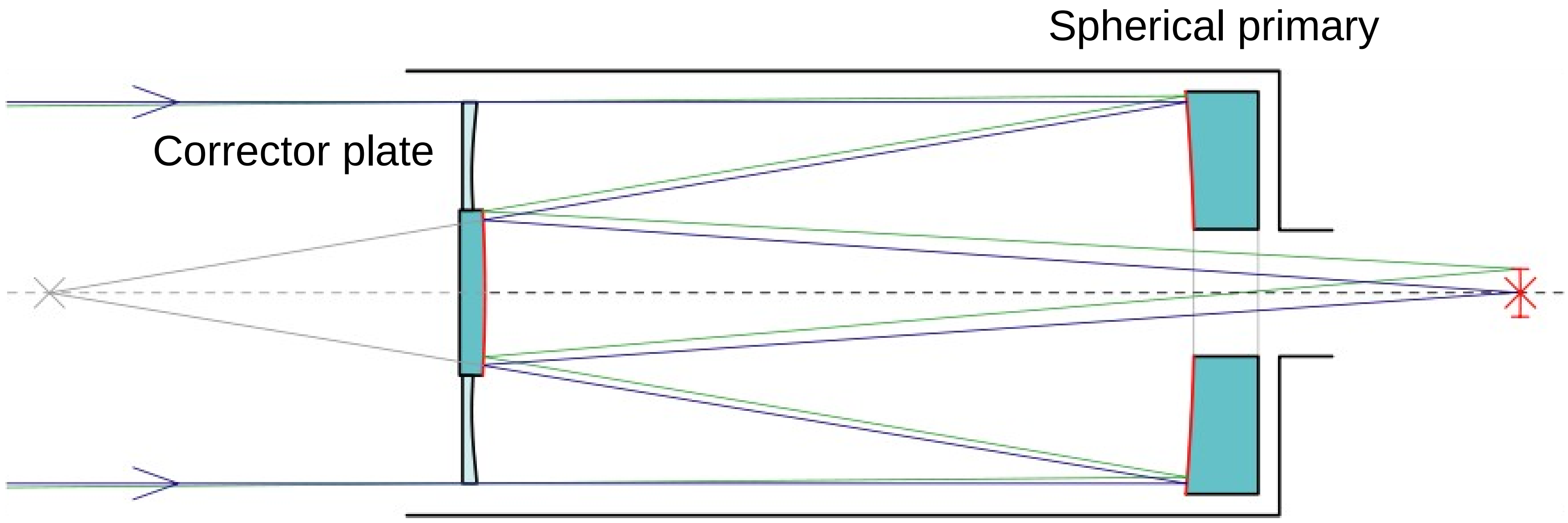




Ritchey-Chretien design
85 cm aperture
Cryogenic operation for low background

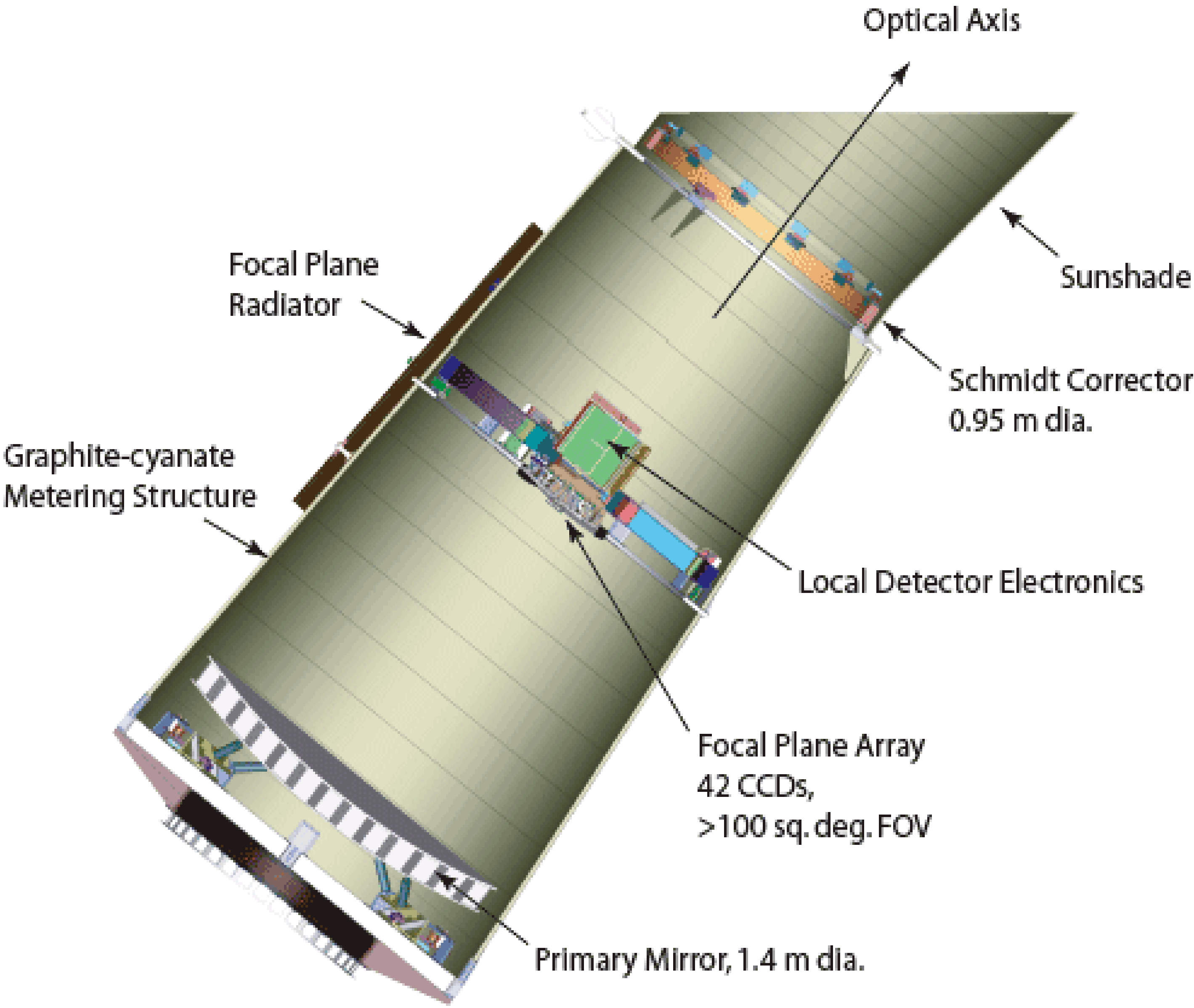
Schmidt-Cassegrain Telescope

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



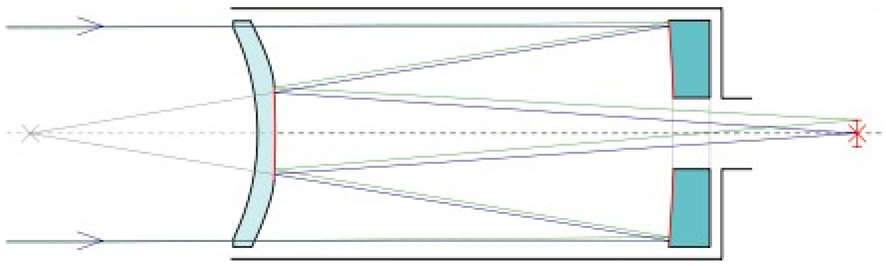
Corrector plate removes spherical aberration
Spherical aberration is field independent with a spherical mirror → correction is valid over a wide field of view
Secondary mirror can flatten the field with proper choice of radius of curvature

Schmidt Telescope:
Kepler optical design

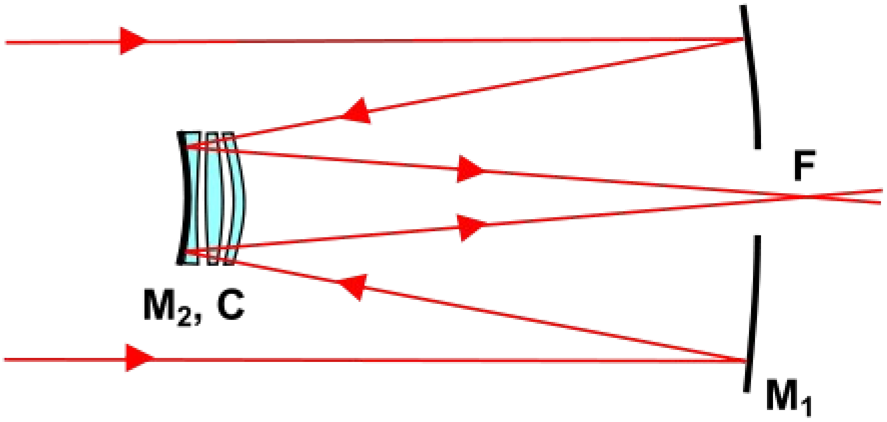


Kepler optical design: Schmidt camera for large field of view
detector at prime focus → no field flattening effect of secondary mirror
→ strong field curvature
Note that PM is larger than corrector plate !

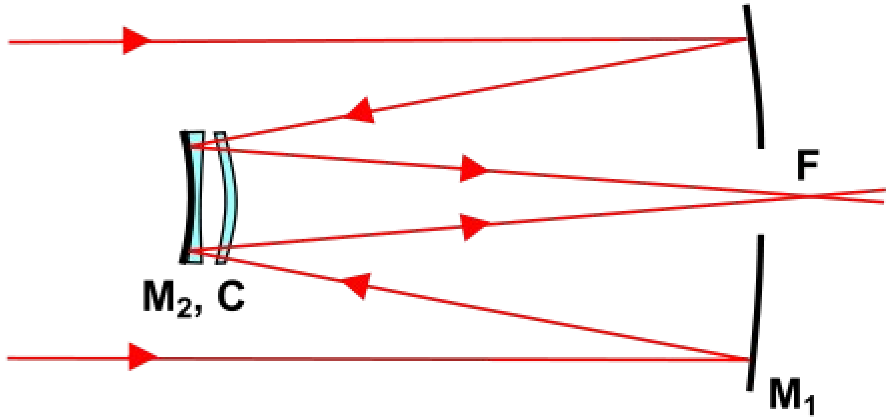
Other Catadioptric telescope designs



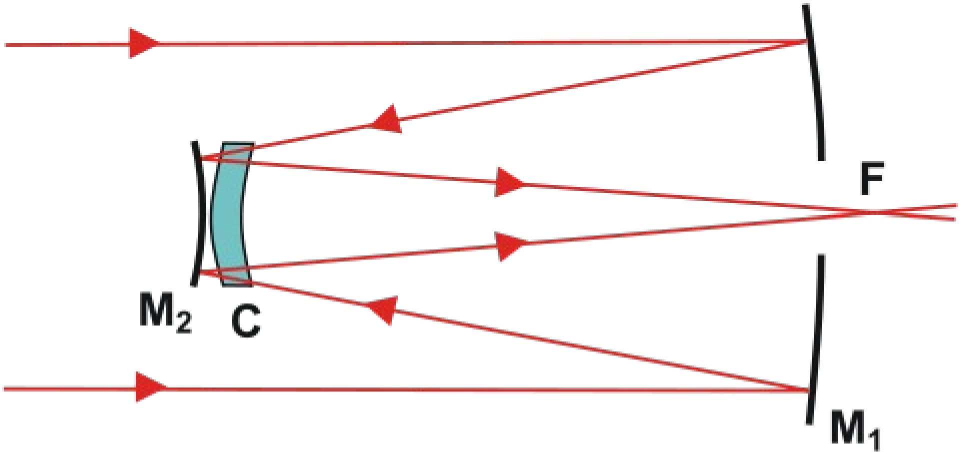
Maksutov-Cassegrain



Argunov-Cassegrain



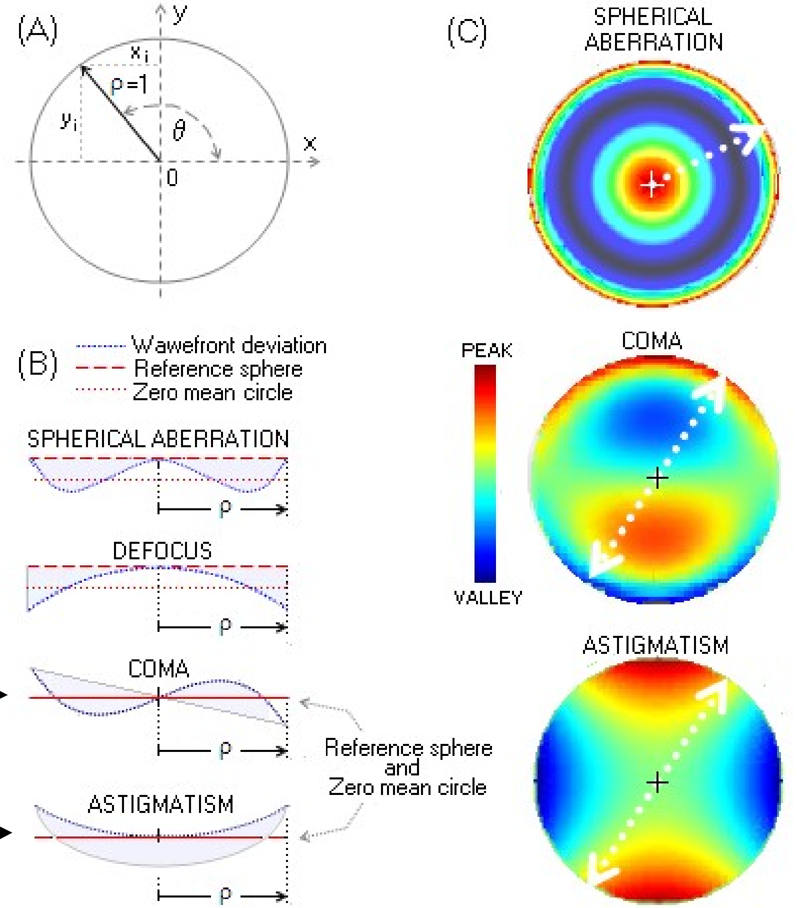
Klevtsov-Cassegrain



Sub-aperture Maksutov-Cassegrain

Maksutov-Cassegrain

Types of aberrations in optical systems



Wavefront errors

<u>Spherical aberration</u>

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

<u>Coma</u>

Off-axis aberration

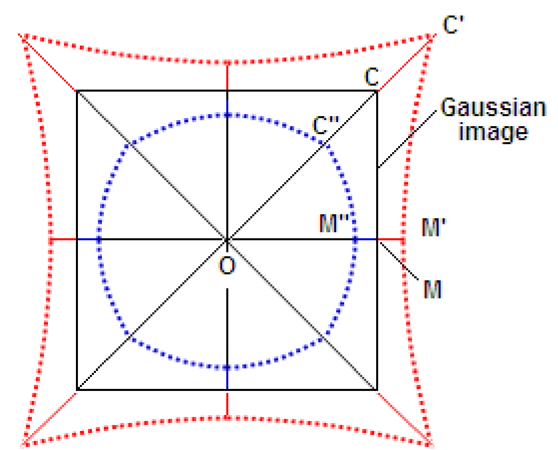
<u>Astigmatism</u>

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

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Types of aberrations in optical systems: Seidel aberrations

Seidel aberrations are the most common aberrations:

Spherical aberration

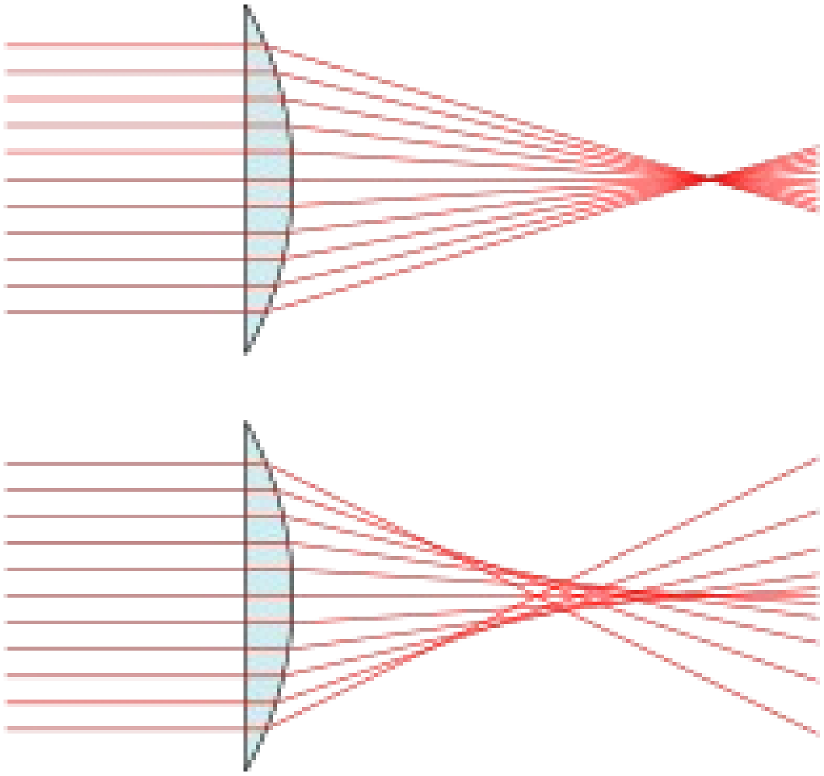
Coma

Astigmatism

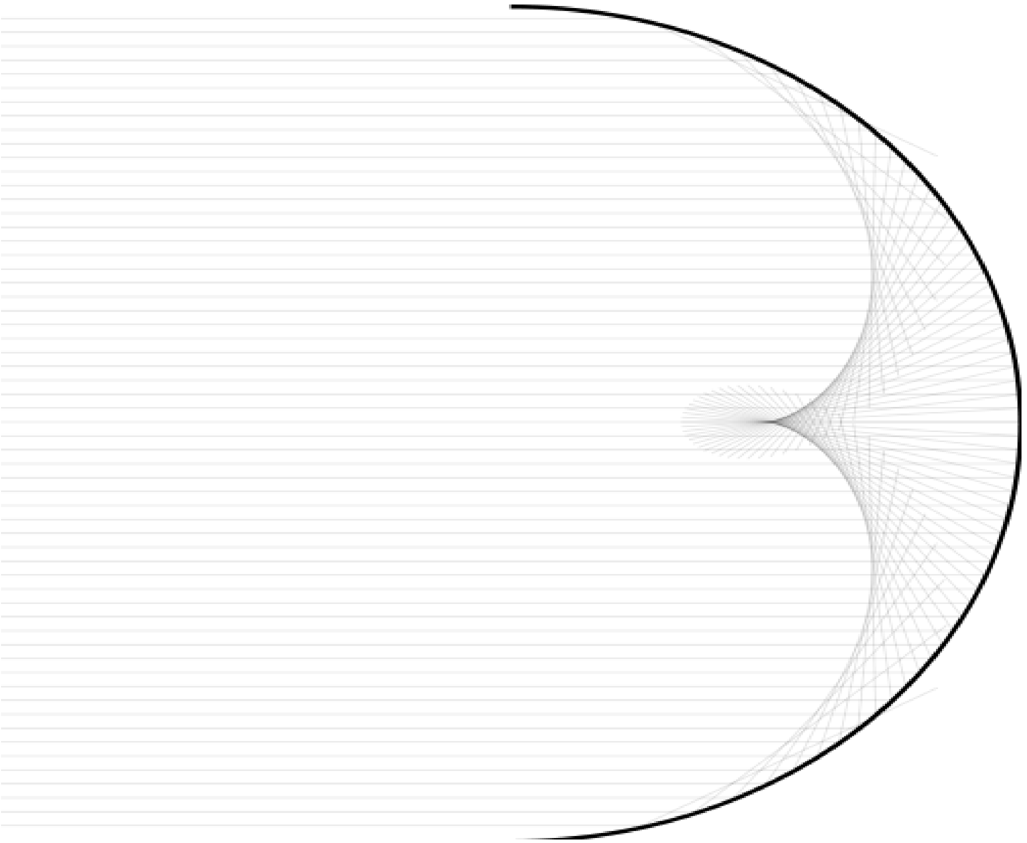
Field curvature

Field distortion

Spherical aberration (Geometric optics)

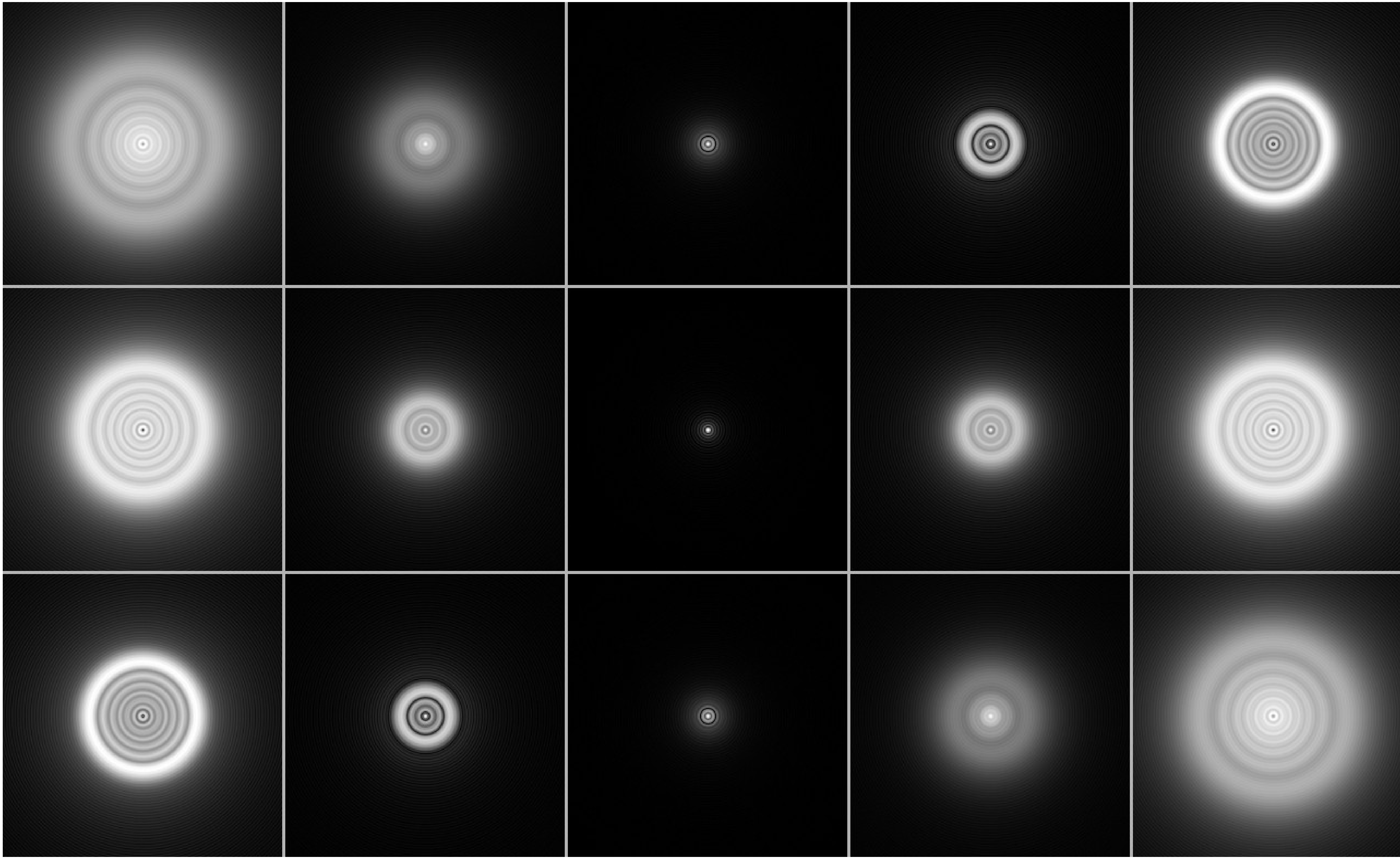


Lens: aspherical (top), spherical (bottom)

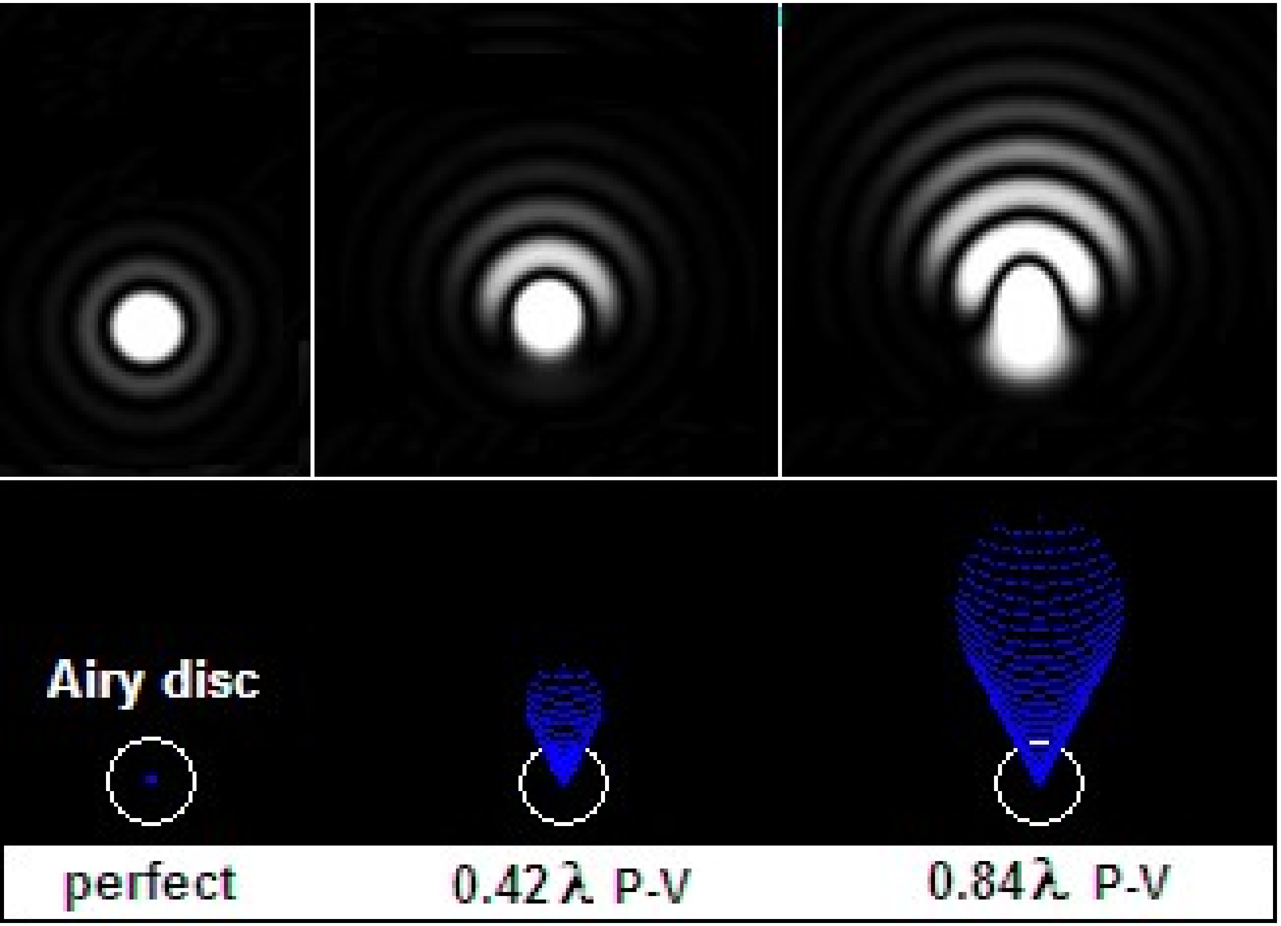


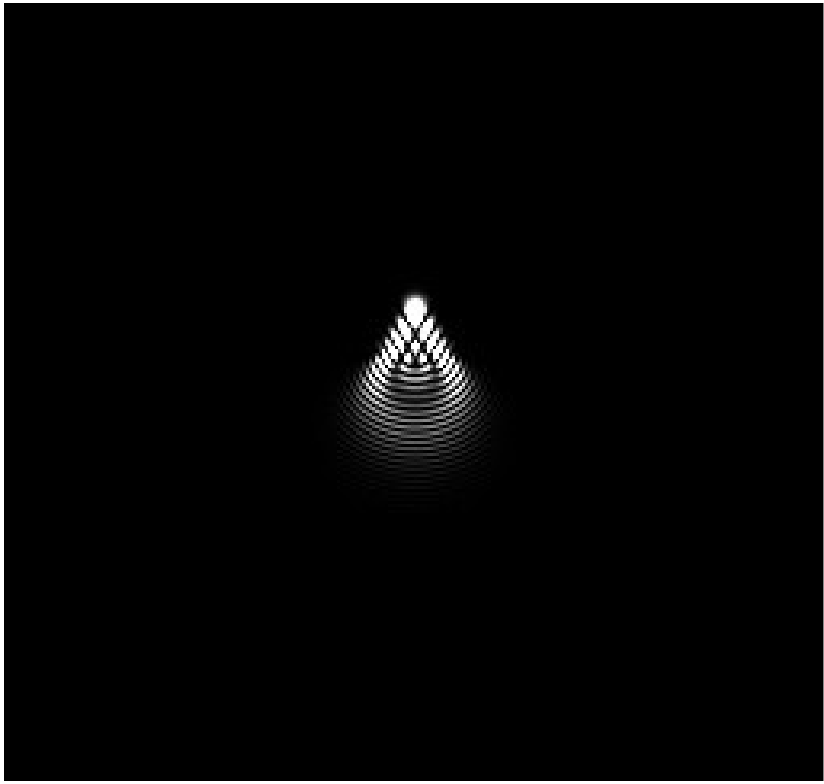
Spherical mirror

Spherical aberration (diffraction)

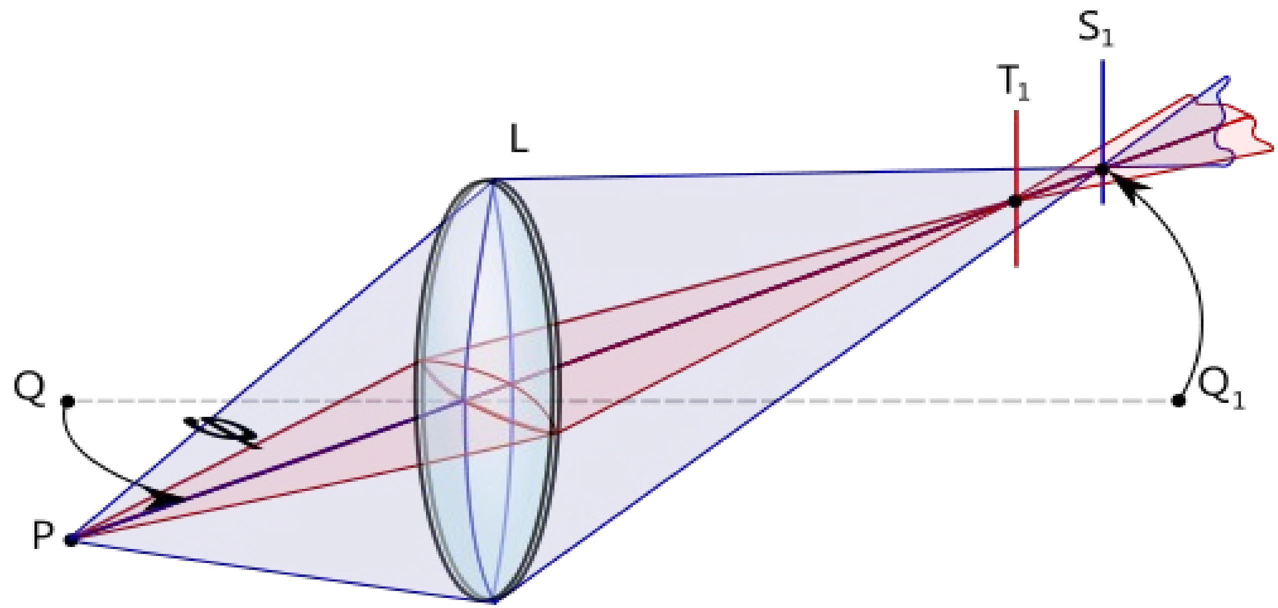


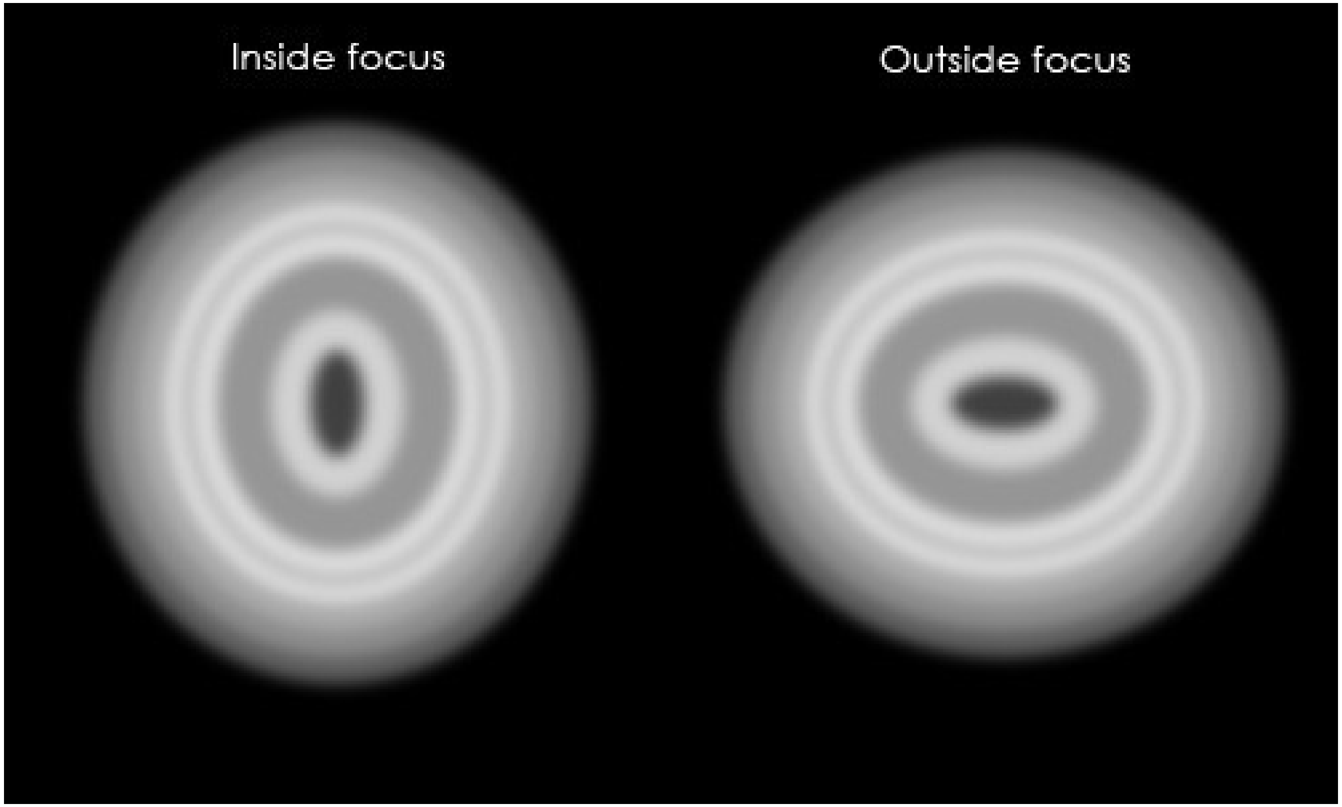
Coma





Astigmatism





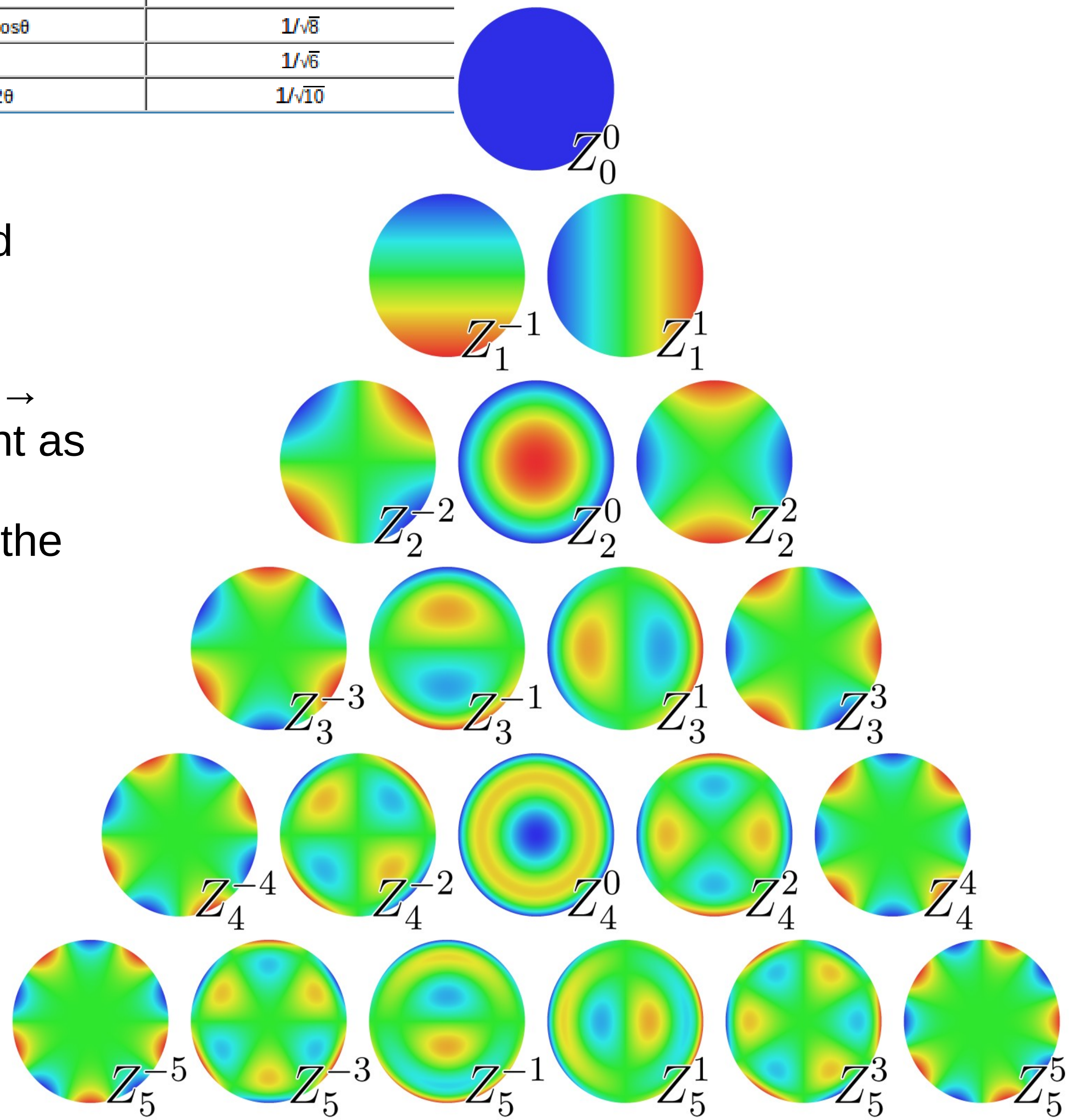
stararizona.com

Wavefront errors: Zernike Polynomials

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	$\rho^2\cos2\theta$	$\sqrt{6}\rho^2\cos2\theta$	$1/\sqrt{6}$
Secondary astigmatism	4	2	$(4\rho^4-3\rho^2)\cos2\theta$	$\sqrt{10}(4\rho^4-3\rho^2)\cos2\theta$	$1/\sqrt{10}$

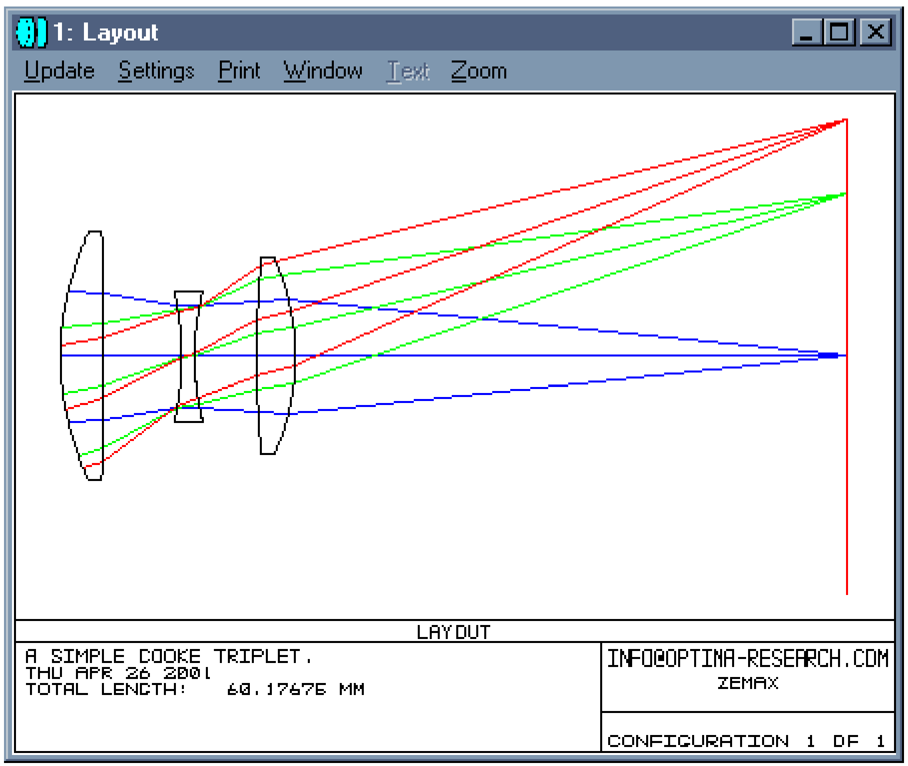
Zernike polynomials are the most standard basis for quantifying aberrations:
- analytical expressions
- orthonormal basis on a circular aperture → makes it easy to decompose any wavefront as a sum of Zernike polynomials
- the first Zernike polynomials correspond the the most common optical aberrations

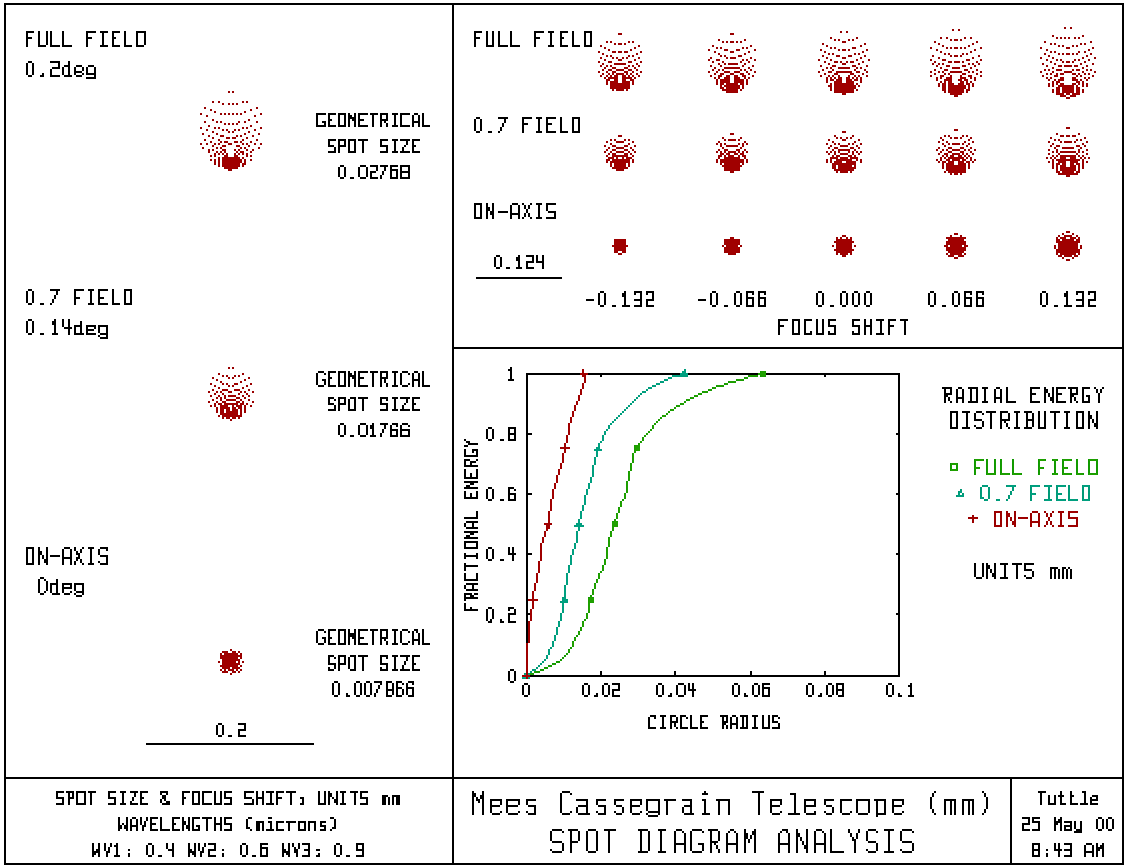
For example:
pointing → tip and tilt
telescope focus, field curv → focus
tilt a lens → astigmatism
parabolic mirror used off-axis → coma



Wavefront errors

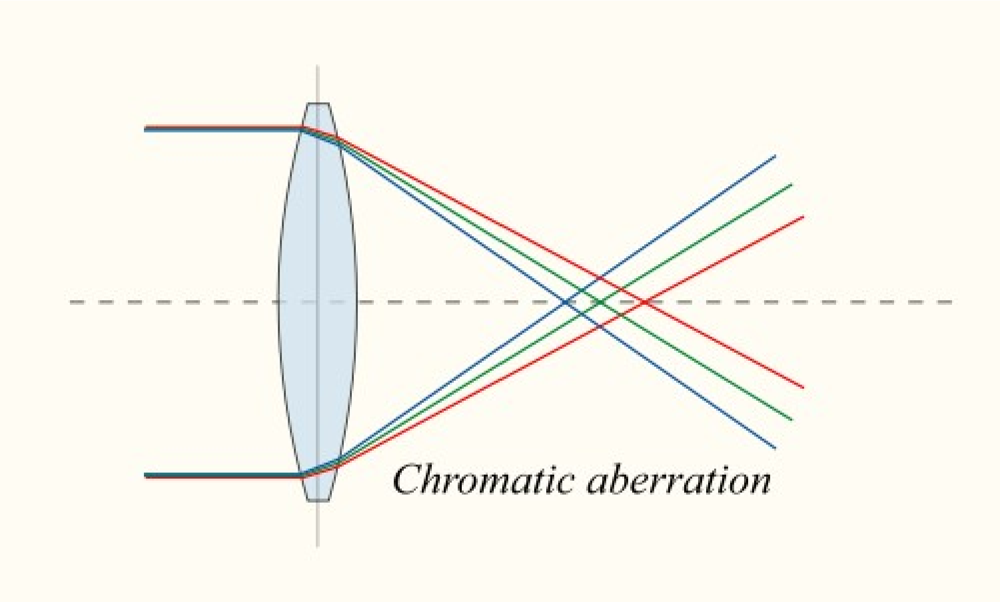
Wavefront errors are usually computed by raytracing through the optical system. Optical design softwares do this (Zemax, Code V, Oslo, etc...). Optical design software is used to minimize aberrations if given a well defined set of parameters to optimize.

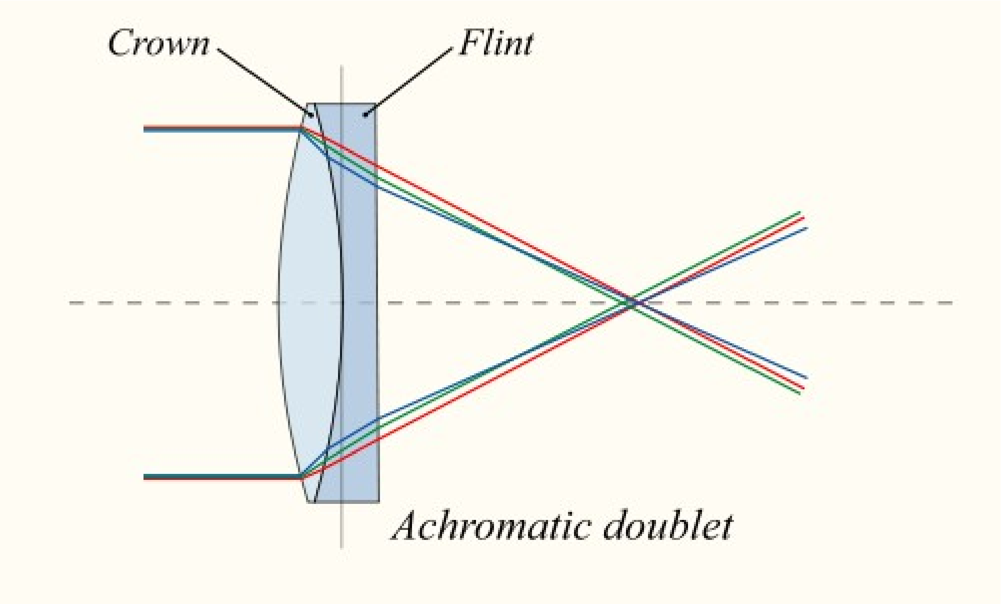




Chromatic aberrations

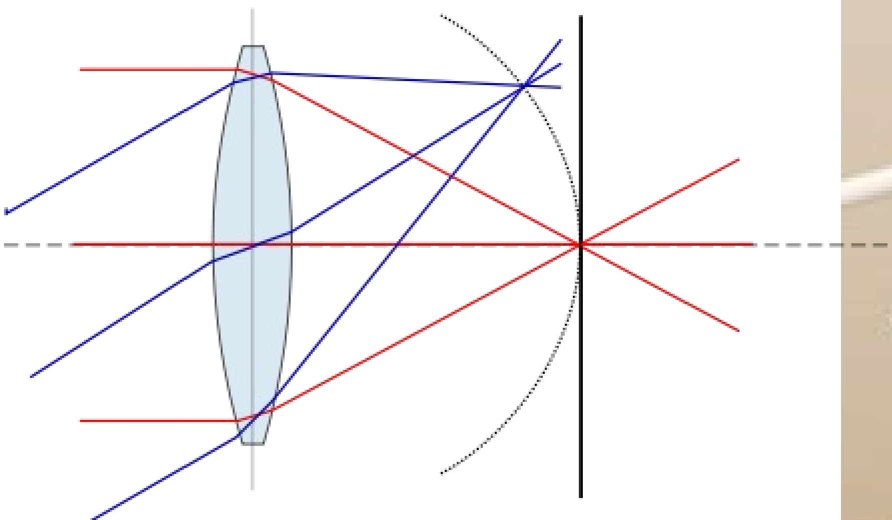
Chromatic aberrations only affect lenses (not mirrors)





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

Field curvature

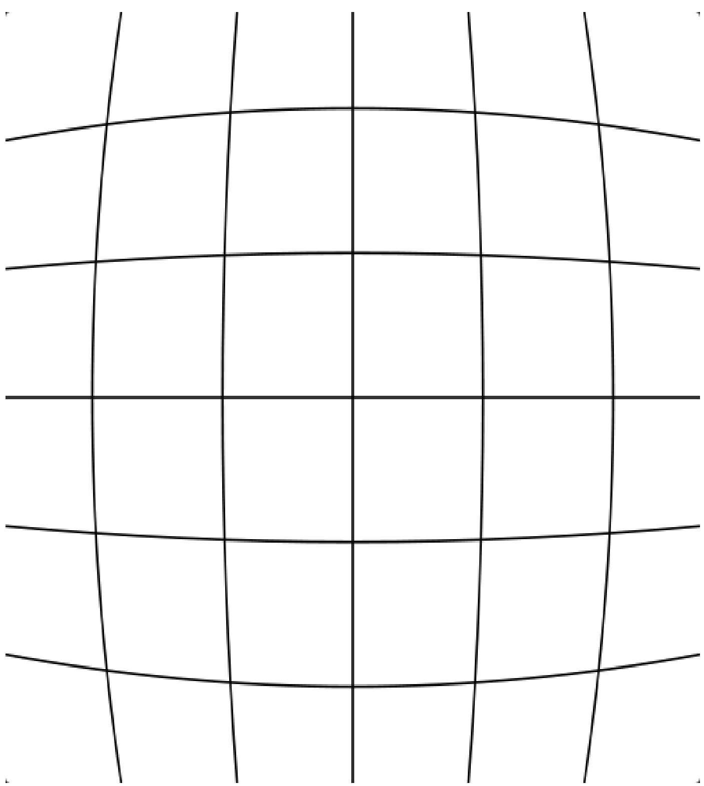


Most detectors are flat:
field curvature produces focus error across the detector

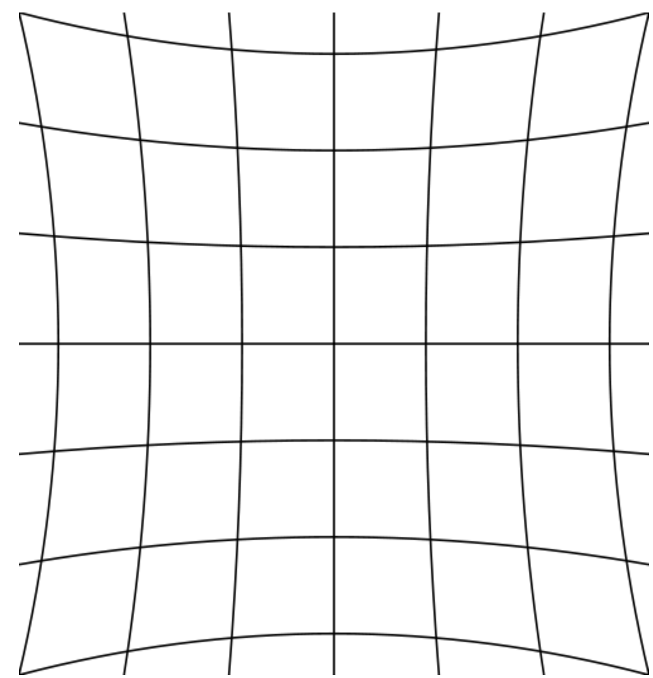
Focal plane array for Kepler mission
The detectors are mounted to match the strong field curvature

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.

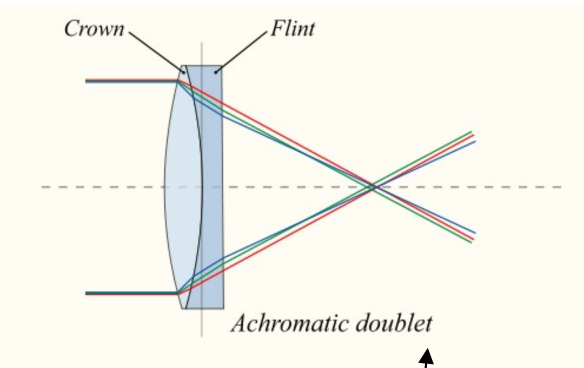
Field curvature can be minimized by a refractive corrector. Sometimes, it is simpler to build a curved focal plane detector than optically correct field curvature (see example on the right)

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

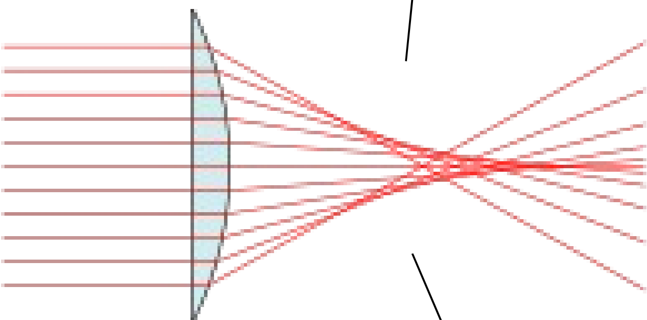
Chromatic aberration is not an issue with reflecting telescopes, but is a design contraint for refractive wide field correctors.

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.

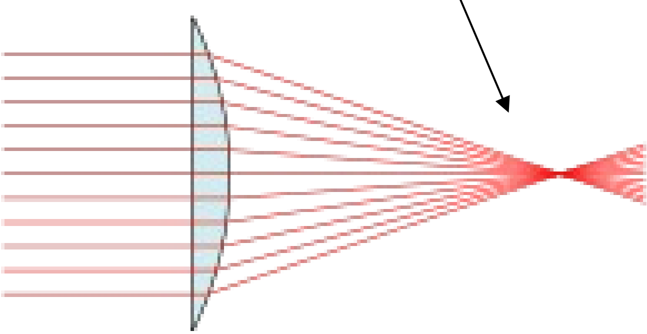
Example: lens design



solve chromatic aberration

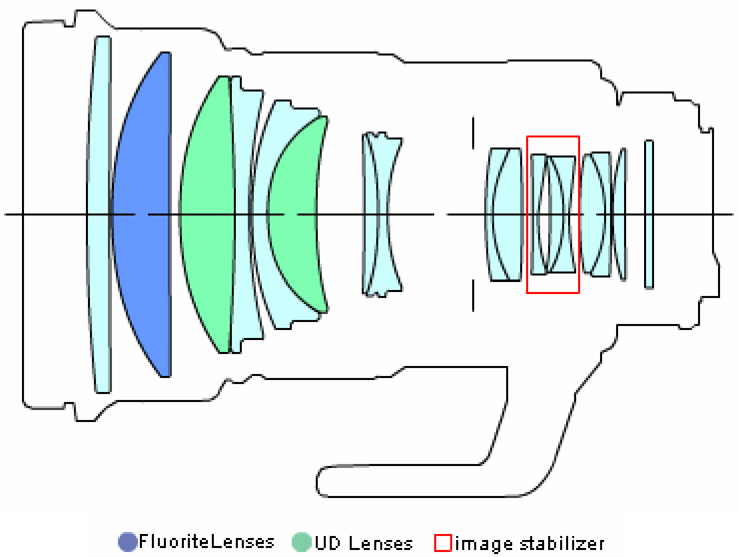


solve spherical aberration



aspheric lens

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



Canon 200mm F2 lens

Example: SuprimeCAM corrector (Subaru Telescope)

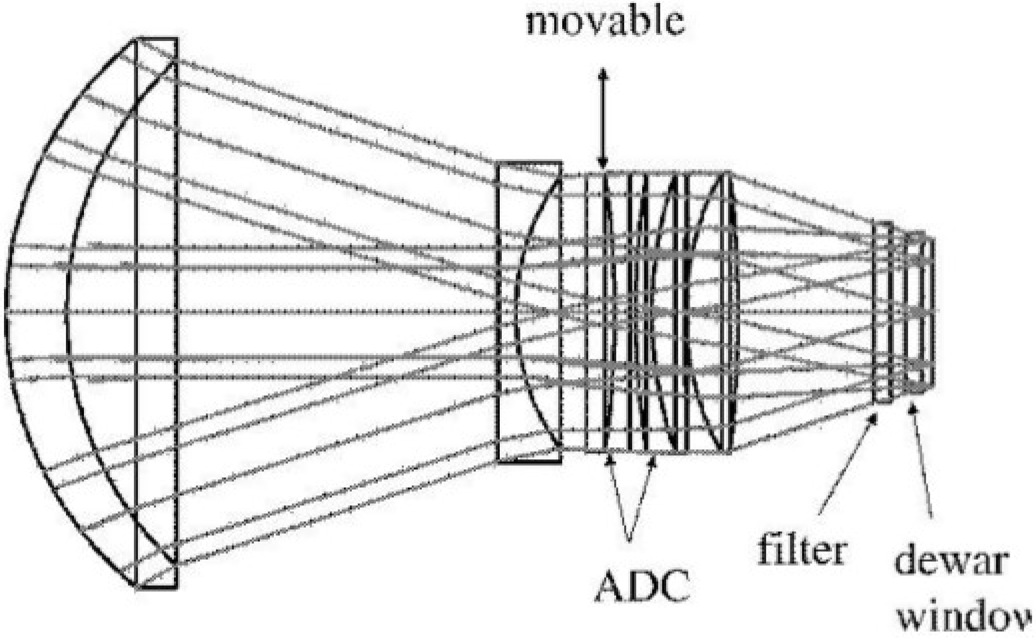


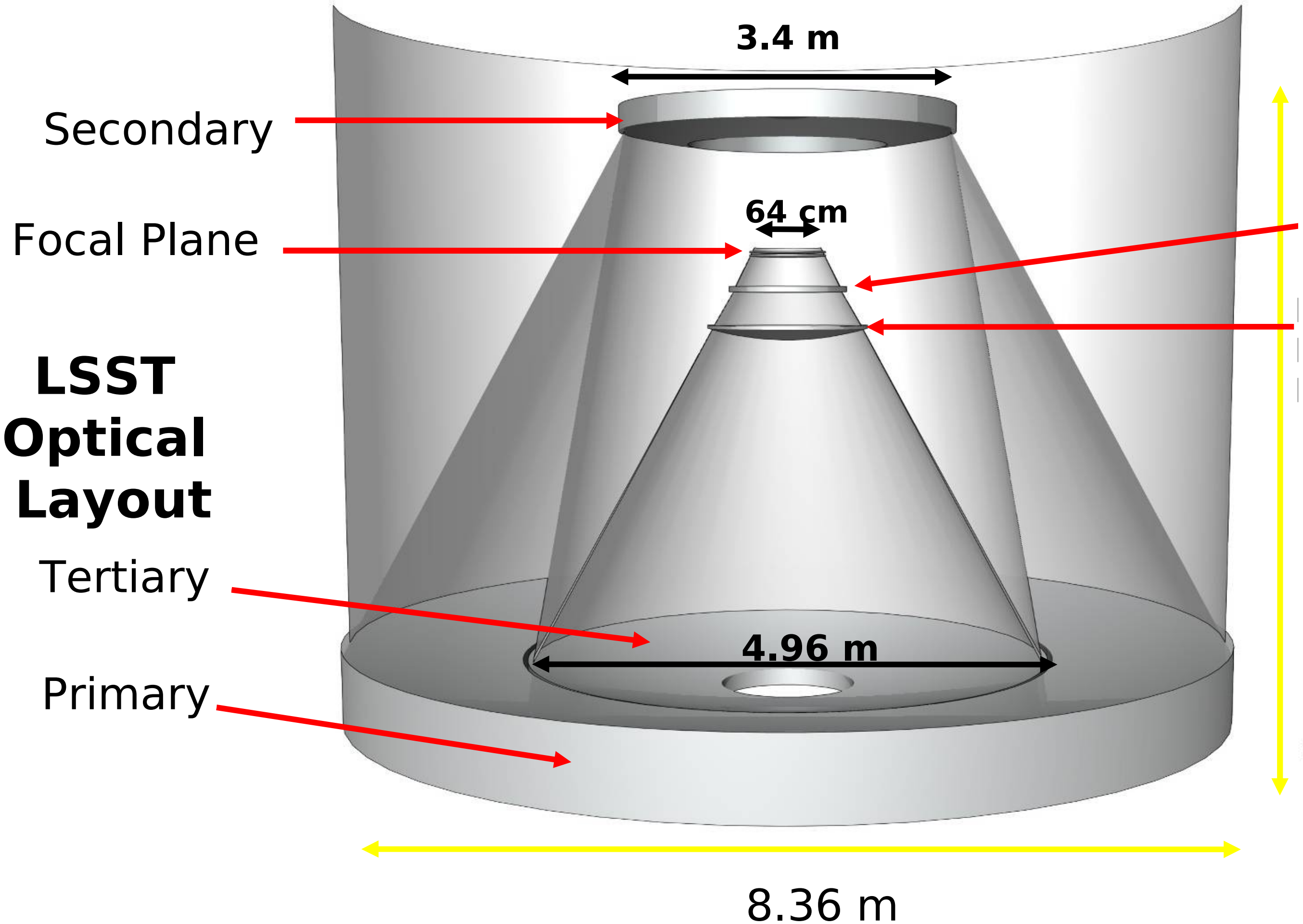
Fig. 14. Prime-focus corrector for Suprime-Cam based on a three-lens corrector design (Wynne 1965), but optimized with additional optical components for ADC.

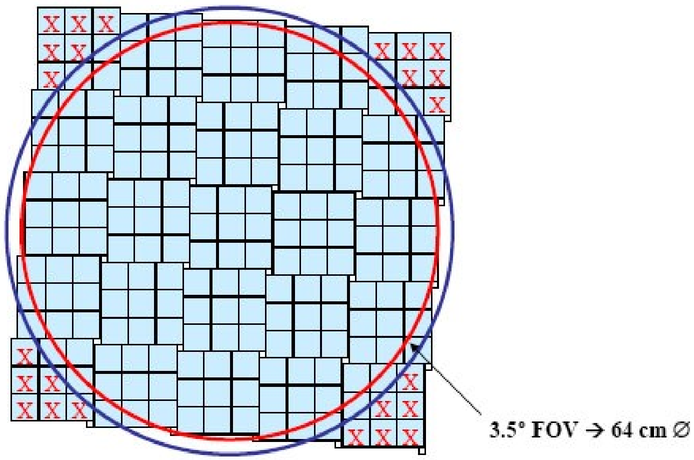
LSST

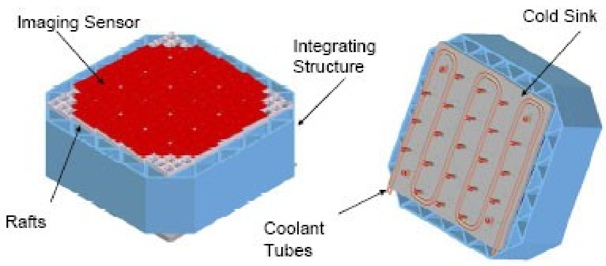
3.5° field of view for all-sky survey

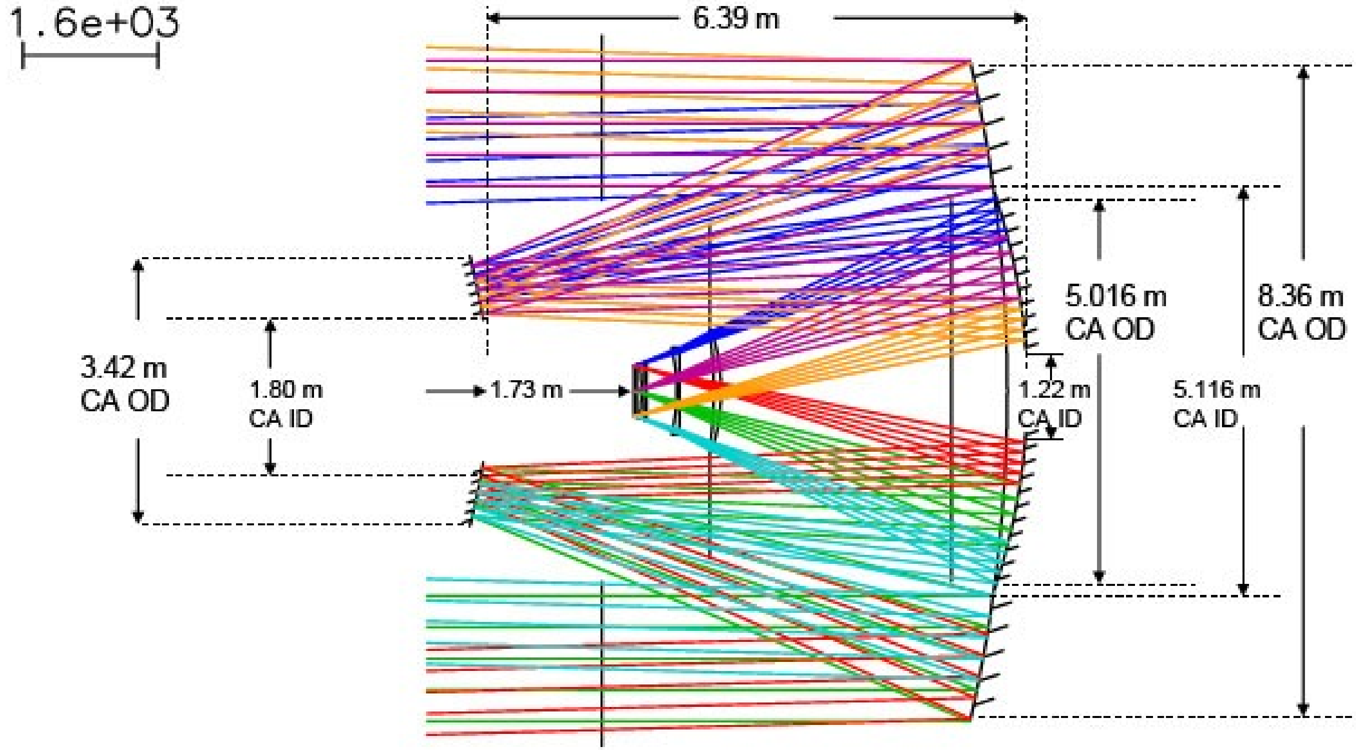
Primary and Tertiary mirrors to be made at UA *on the same substrate*

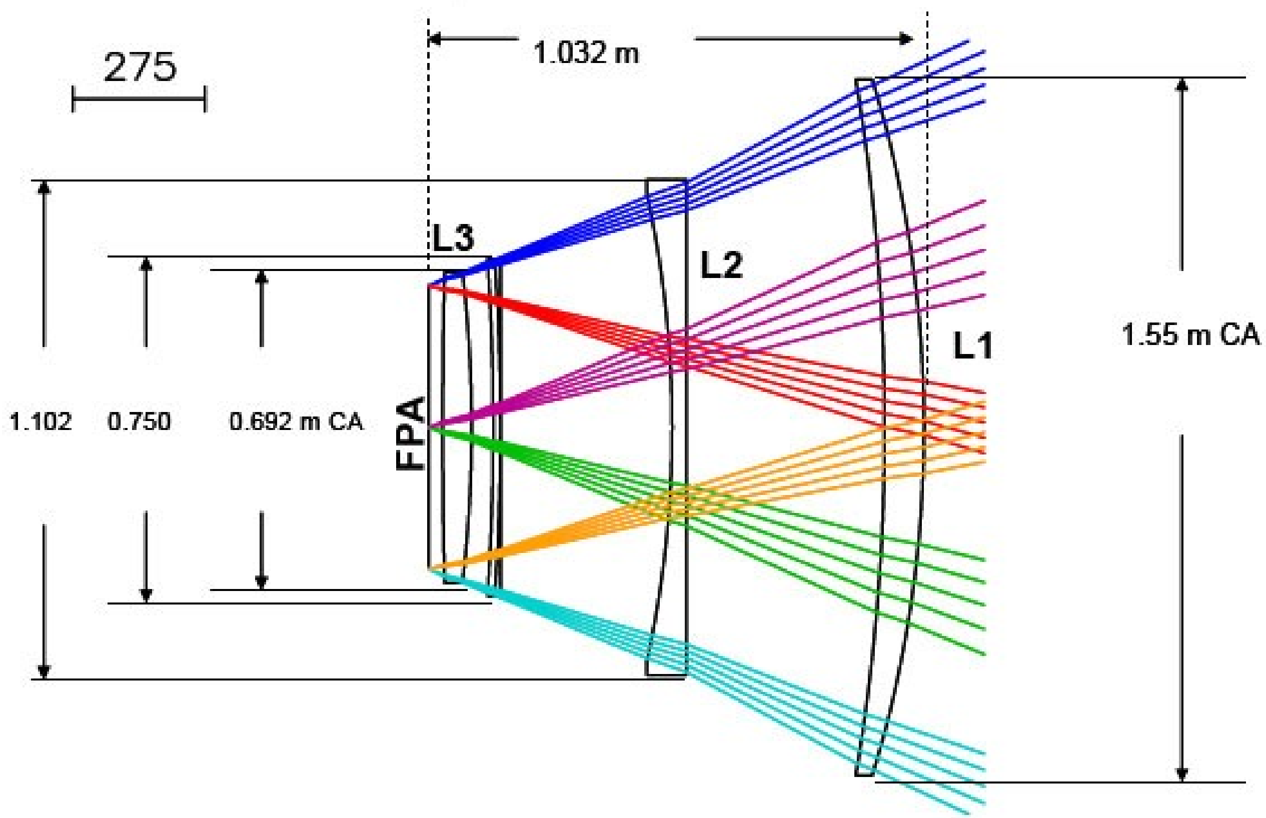
200 4k x 4k detectors







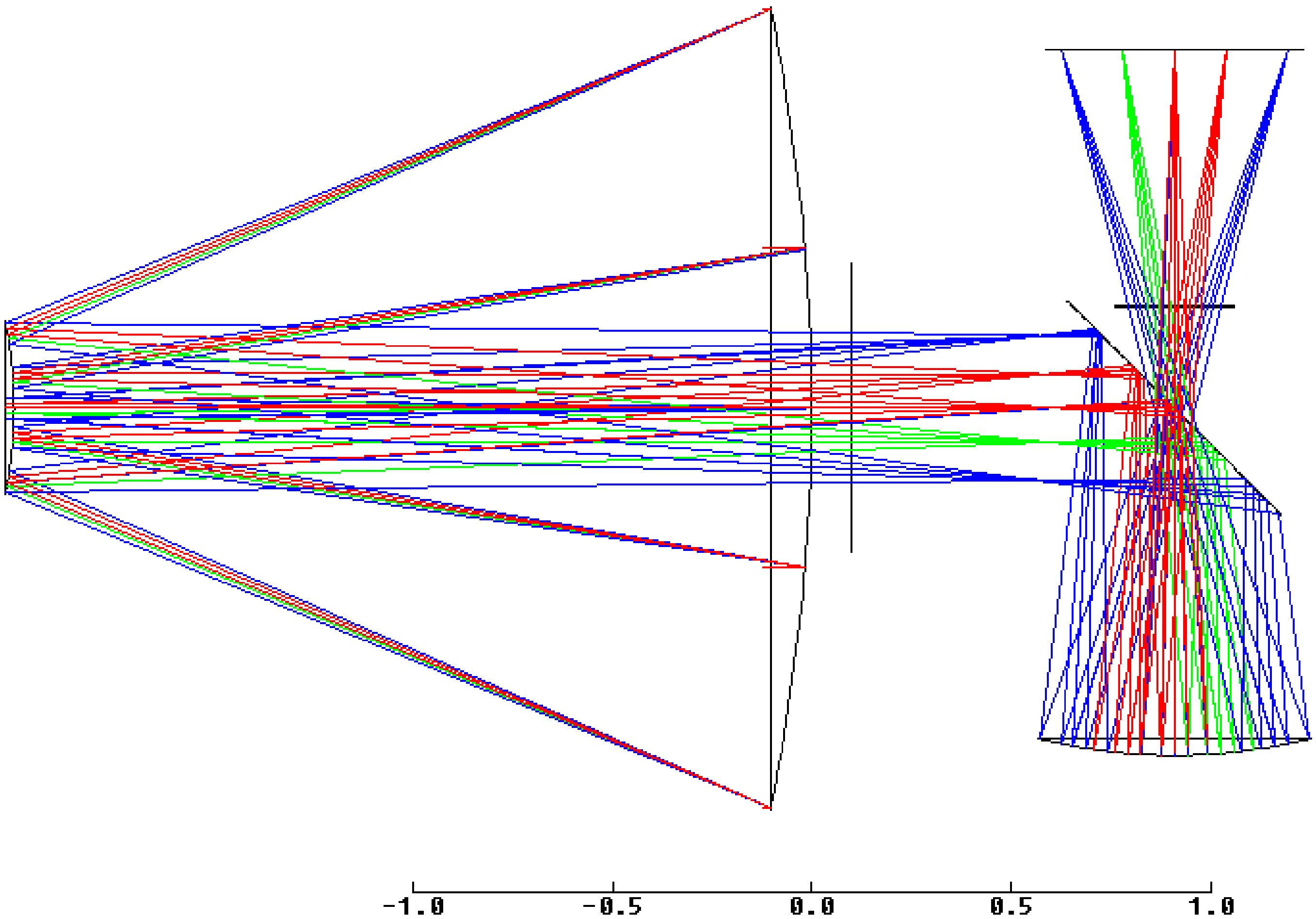

1.6e+03
6.39 m
5.016 m
CA OD
8.36 m
CA OD
3.42 m
CA OD
1.80 m
CA ID
1.73 m
1.22 m
CA ID
5.116 m
CA ID

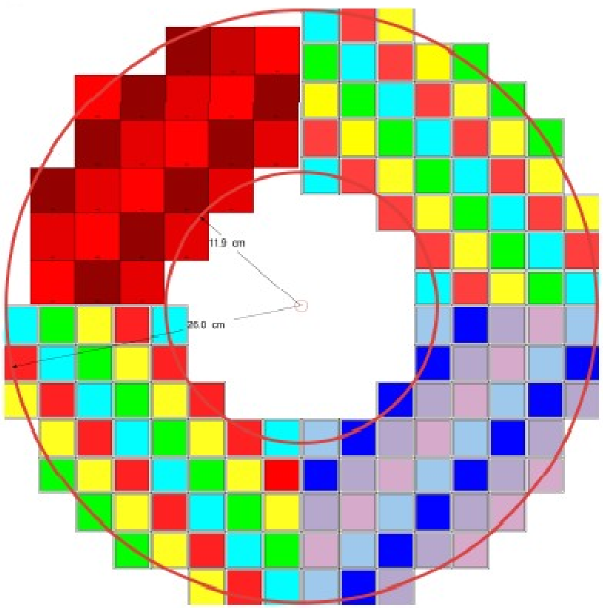

275
1.032 m
L3
L2
L1
1.55 m CA
1.102
0.750
0.692 m CA
FPA

TMA (Three Mirror Anastigmat)

SNAP, annular FOV, 1.4 sq degrees,
2 m aperture, diffraction limited for > 1 um

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

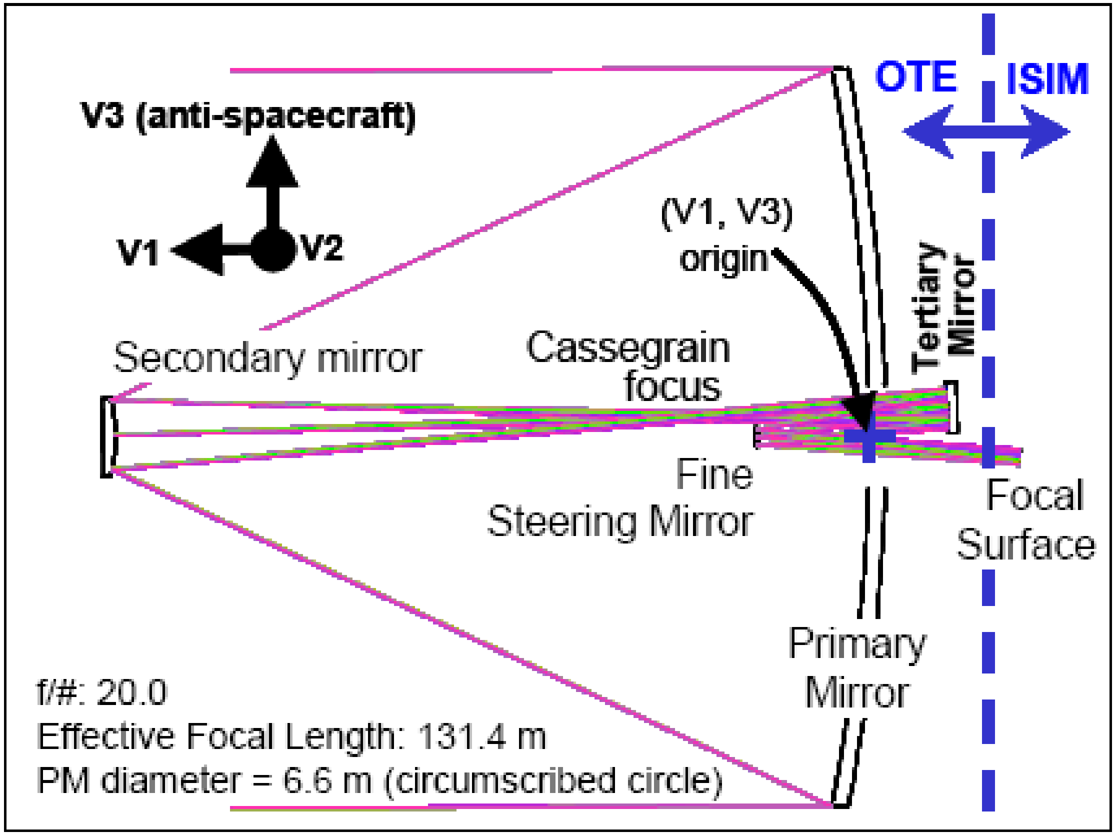


Figure 11 JWST Observatory Telescope Optical Layout