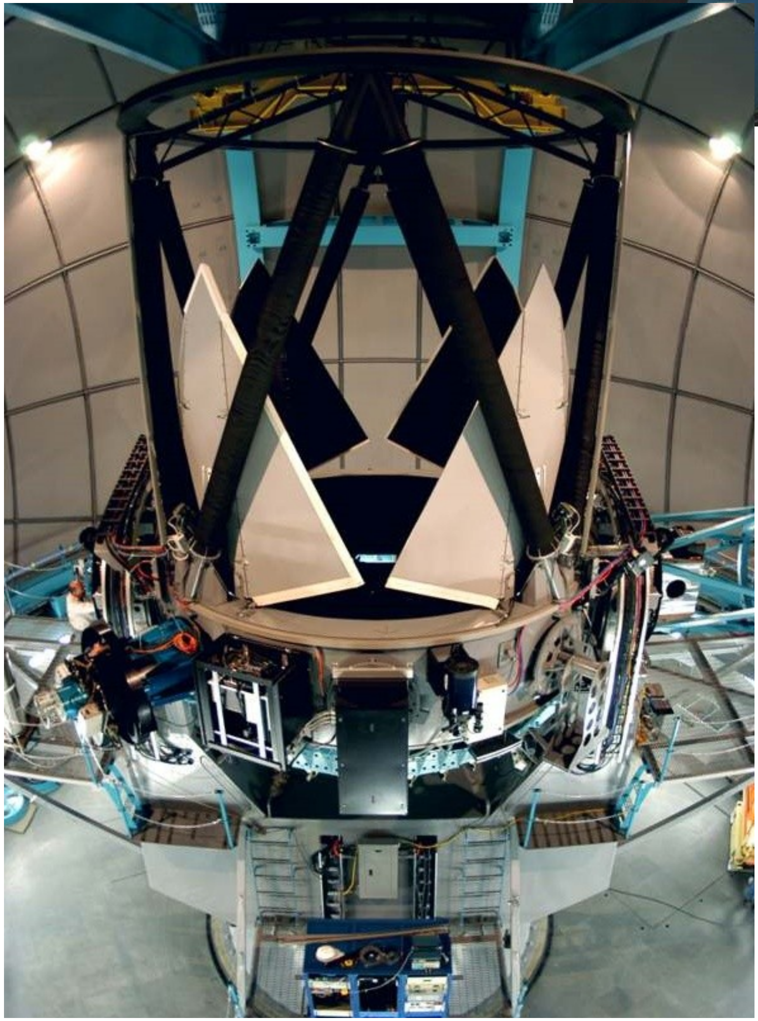
Optical-infrared telescopes

Light collectors



Atualização: 26/04/23

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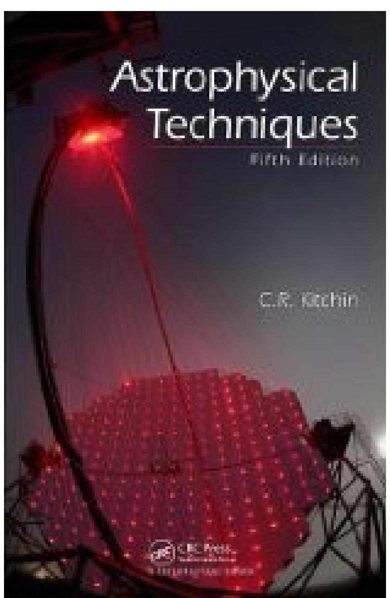

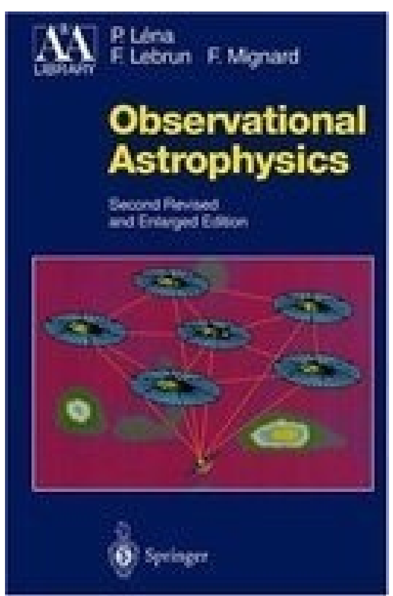

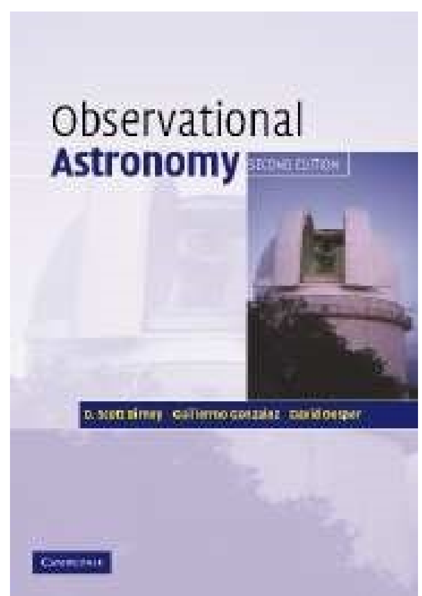

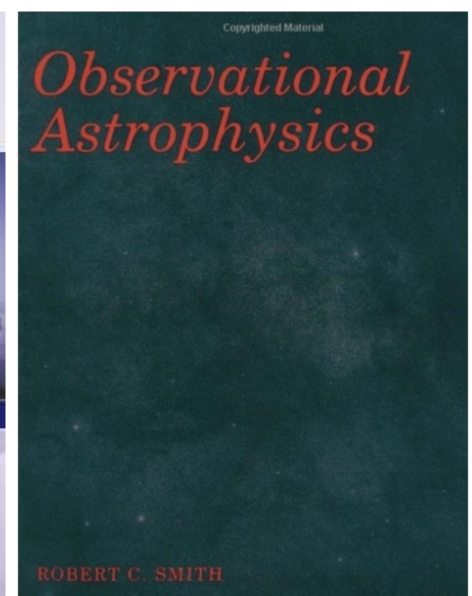

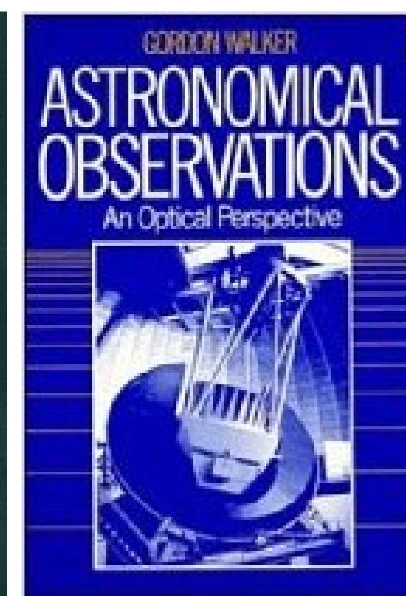

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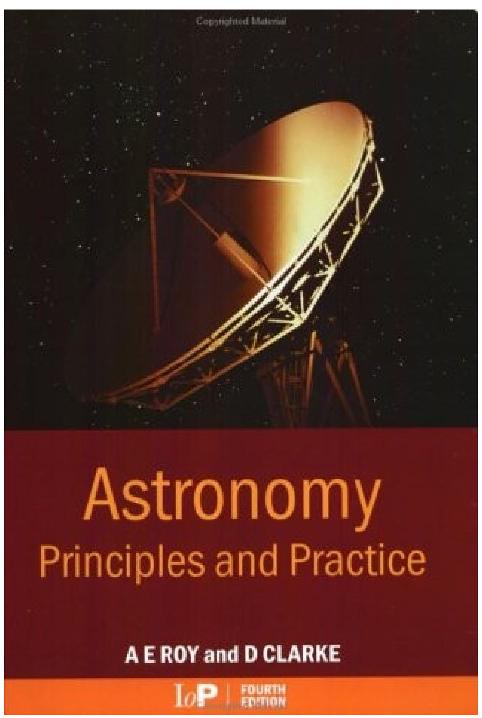
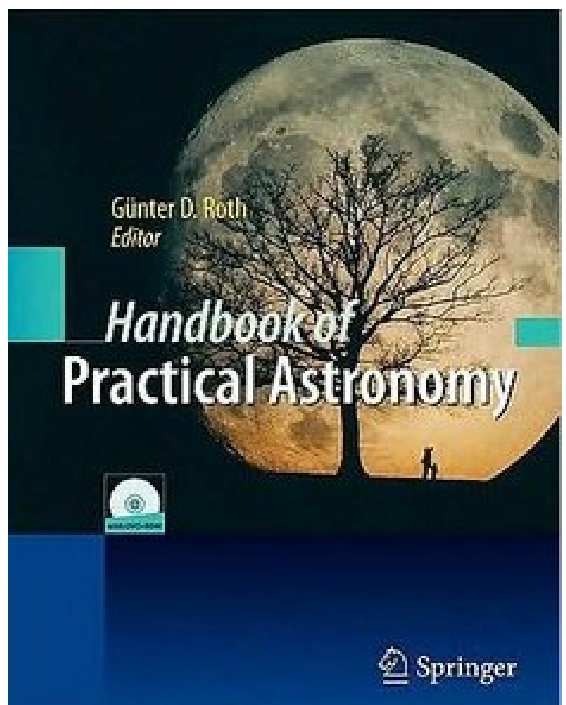
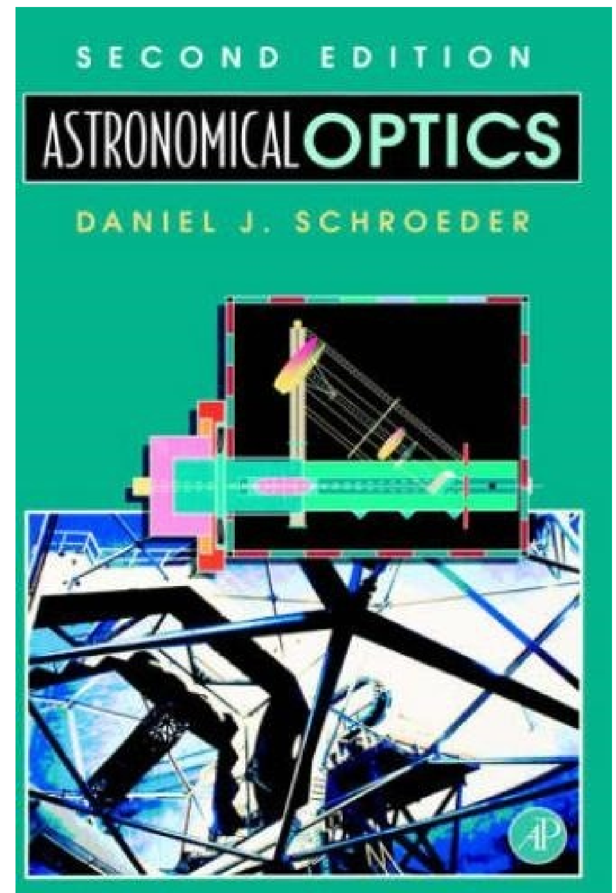




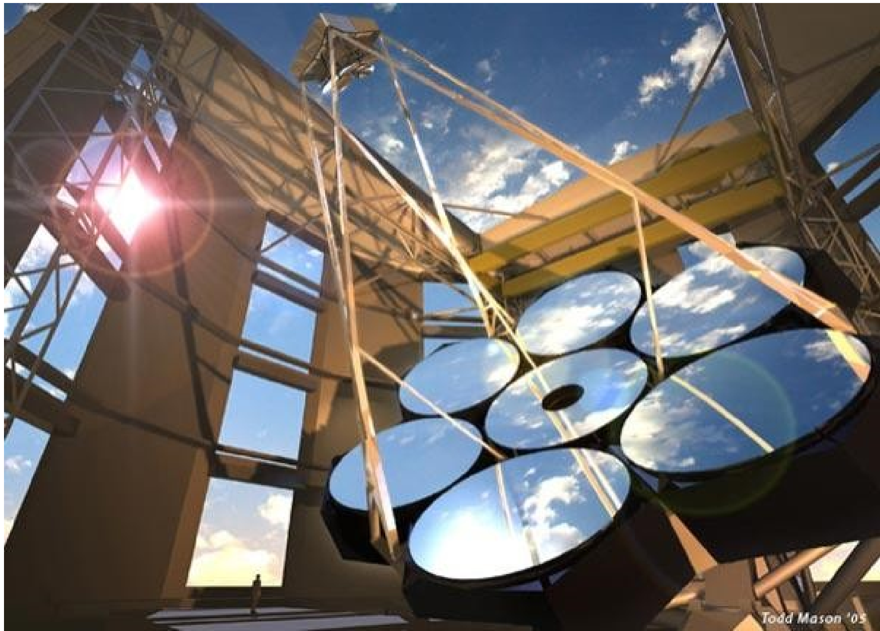


Main characteristics

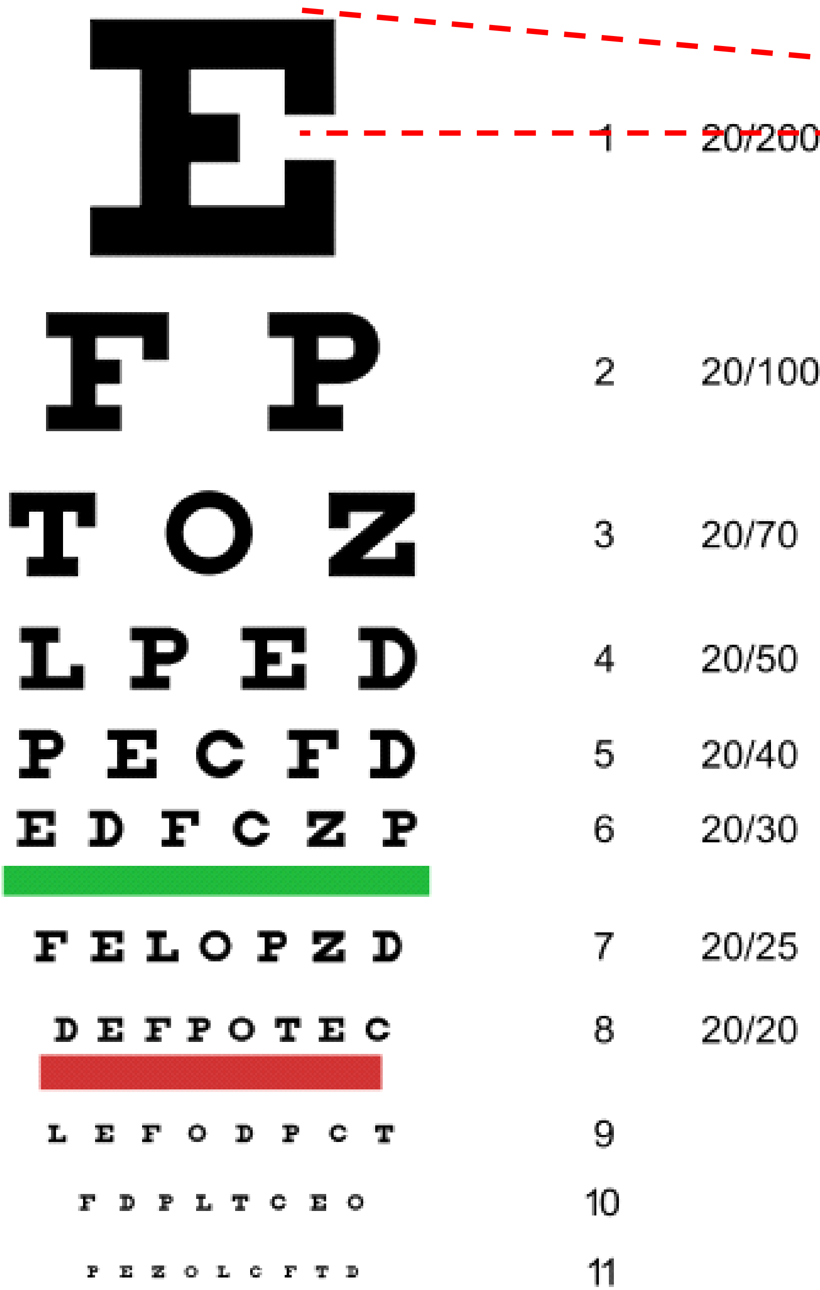
- collects energy ($\propto$ collector area)
- image formation: angular resolution

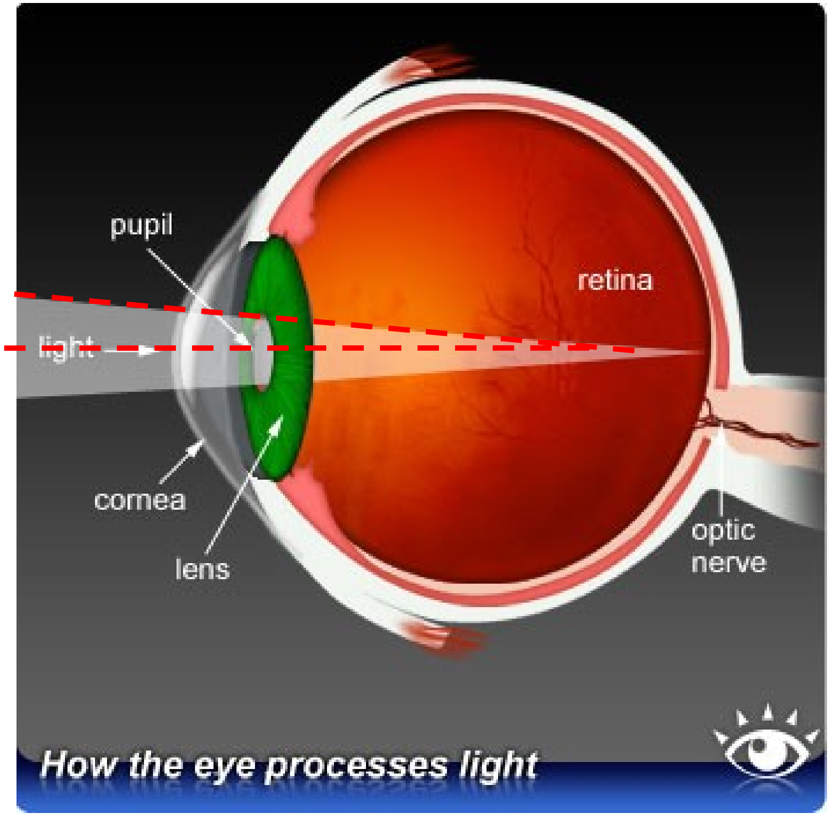
- Increase in collecting area →

- detection of fainter objects
- better angular resolution



Angular resolution





Is the capacity to resolve fine details.

The resolution is the smallest angle that could be discerned

Angular resolution: diffraction of a slit

- Light diffraction imposes a limit on angular resolution
- The diffraction pattern of a slit of width *d* is:

$$I_\theta = I_0 \frac{\sin^2(\pi d \sin\theta/\lambda)}{(\pi d \sin\theta/\lambda)^2}$$

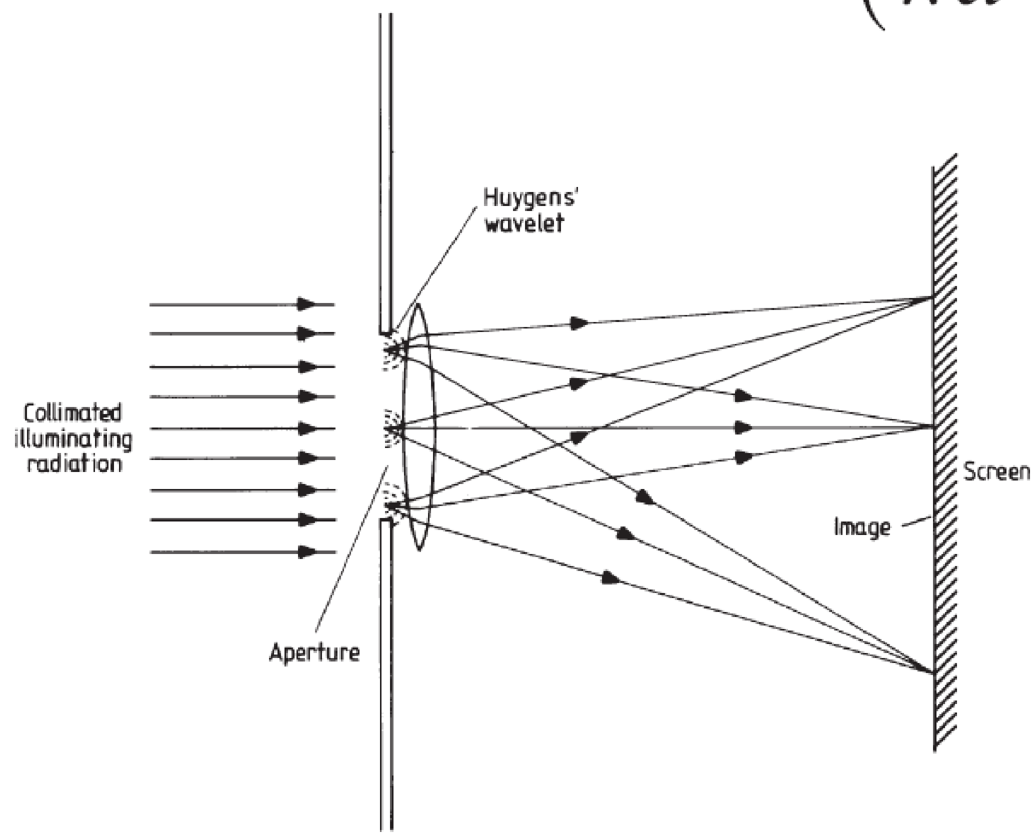


Figure 1.1.24. Fraunhofer diffraction at an aperture.

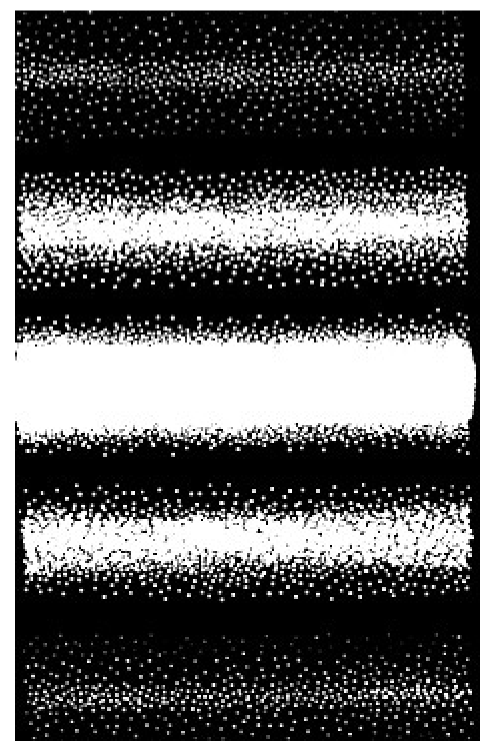
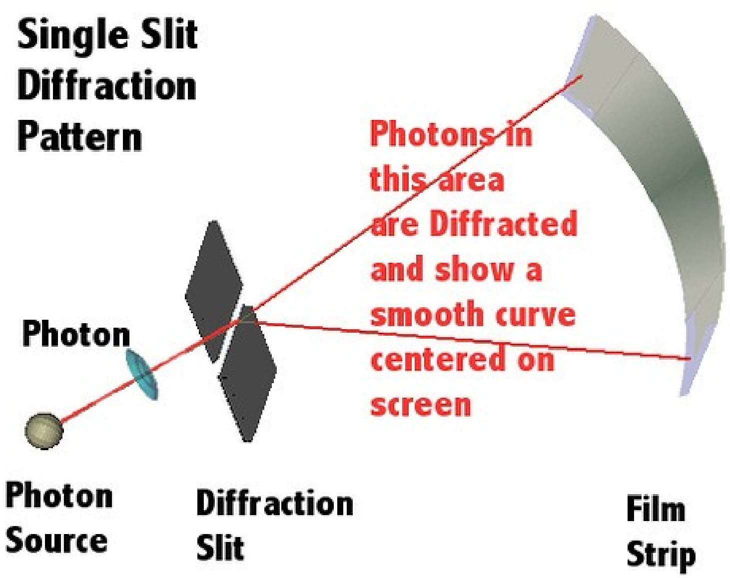
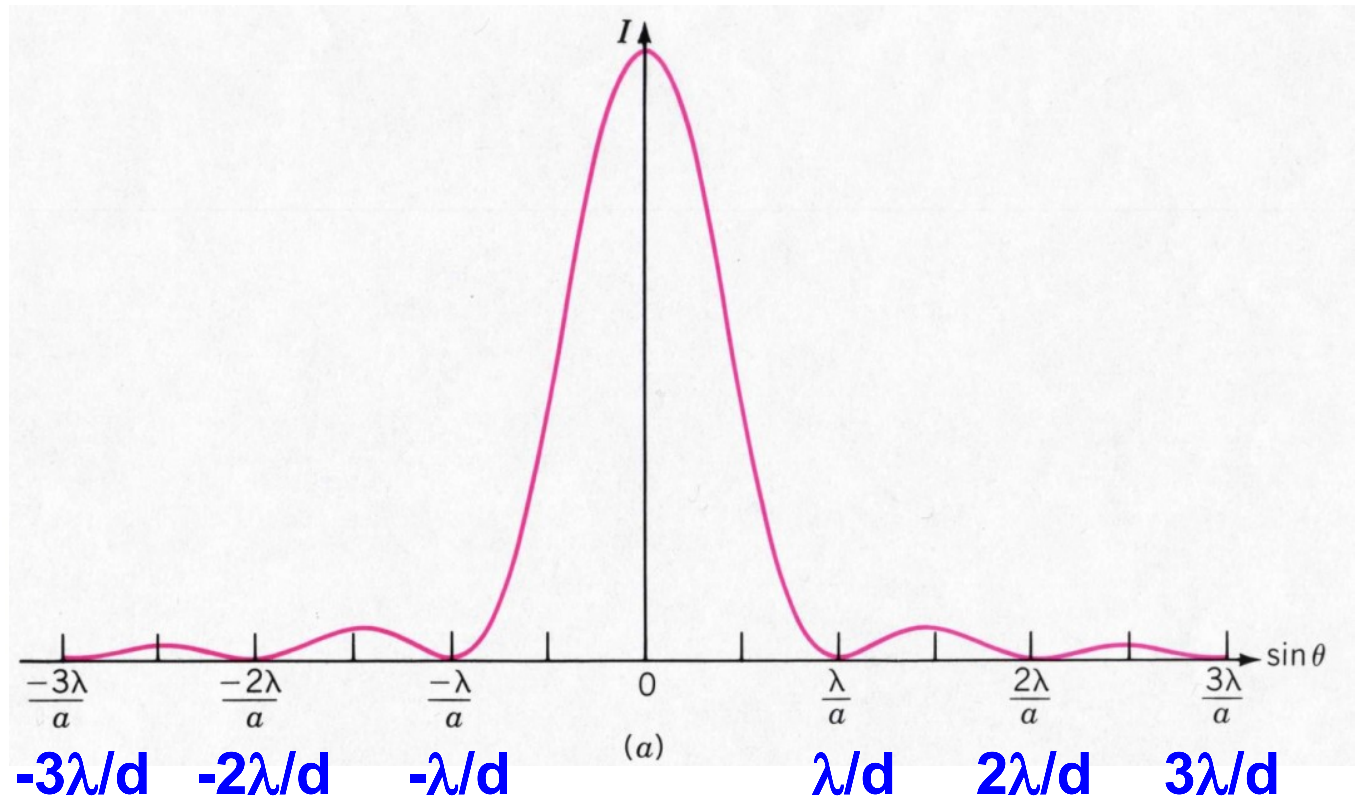


Figure 1.1.25. Image of a narrow slit

Angular resolution: diffraction of a slit

$$I_\theta = I_0 \frac{\sin^2(\pi d \sin\theta/\lambda)}{(\pi d \sin\theta/\lambda)^2}$$





Angular resolution: diffraction of a circular aperture

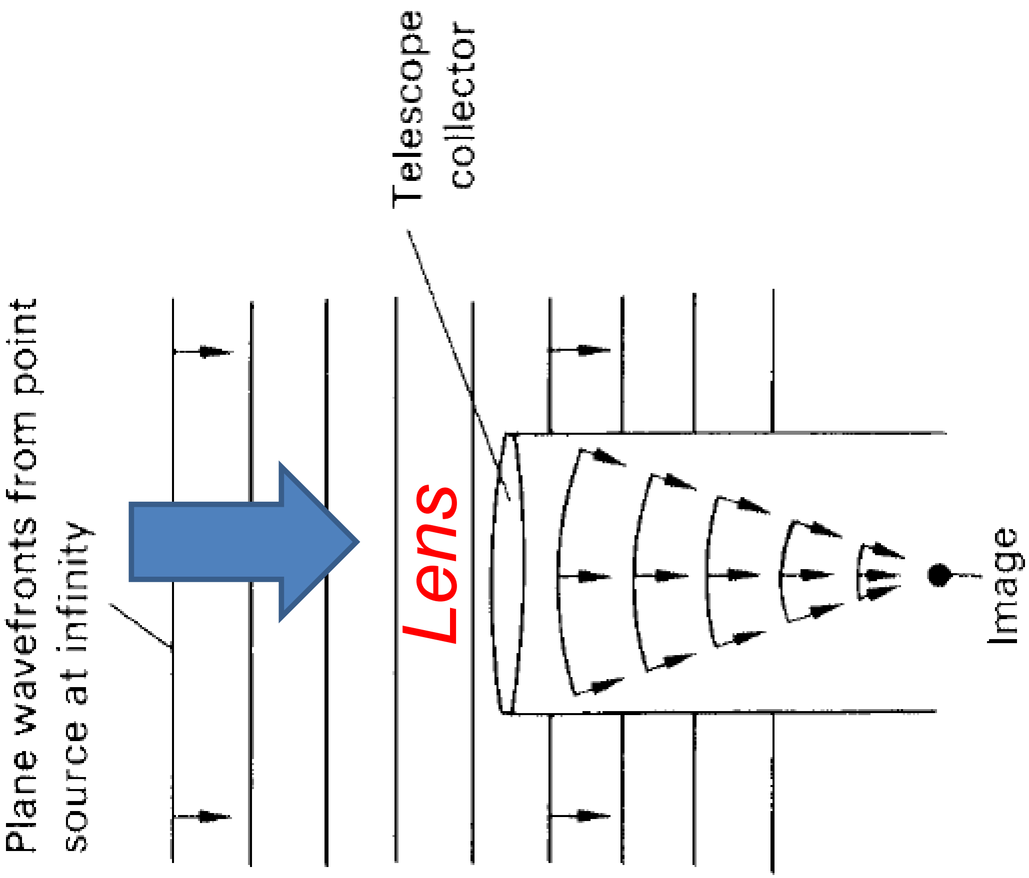
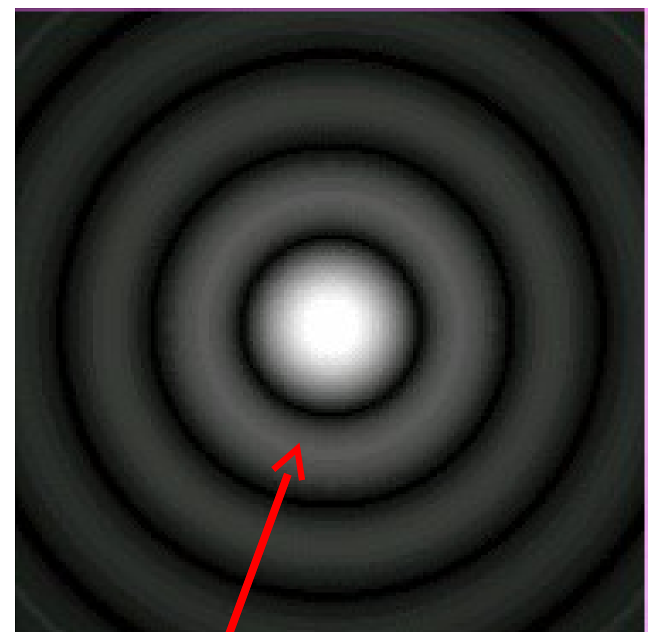


Figure 16.5. Wavefronts arriving at the telescope aperture

Roy & Clarke

Diffraction pattern

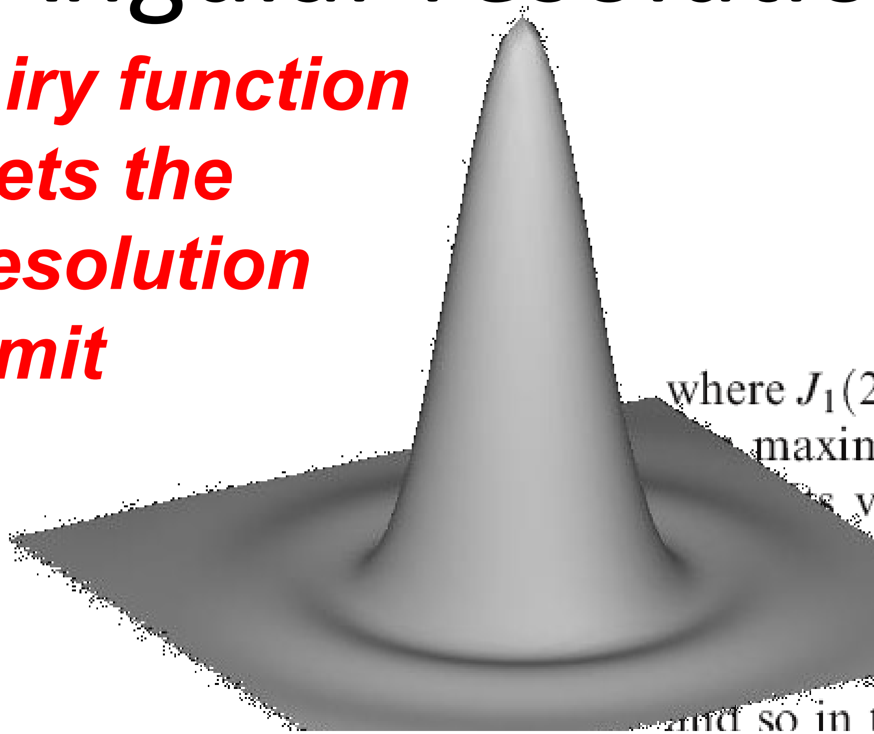


Airy disk: central disk defined by the first minimum

Angular resolution: circular aperture

(c) Kitchin

Airy function sets the resolution limit



$$I(\theta) \propto \pi^2 r^4 \left[\sum_0^\infty (-1)^n \frac{1}{n+1} \left(\frac{m^n}{n!} \right)^2 \right]^2$$

$$\propto \frac{\pi^2 r^4}{m^2} (J_1(2m))^2 \qquad m = \frac{\pi r \sin\theta}{\lambda}$$

where $J_1(2m)$ is the Bessel function of the first kind of order unity.
maximum or zero accordingly as $J_1(2m)/m$ reaches an extre
variation is shown in figure 1.1.28. The first few zeros
n of

$$m = 1.916, 3.508, 5.087, \ldots$$

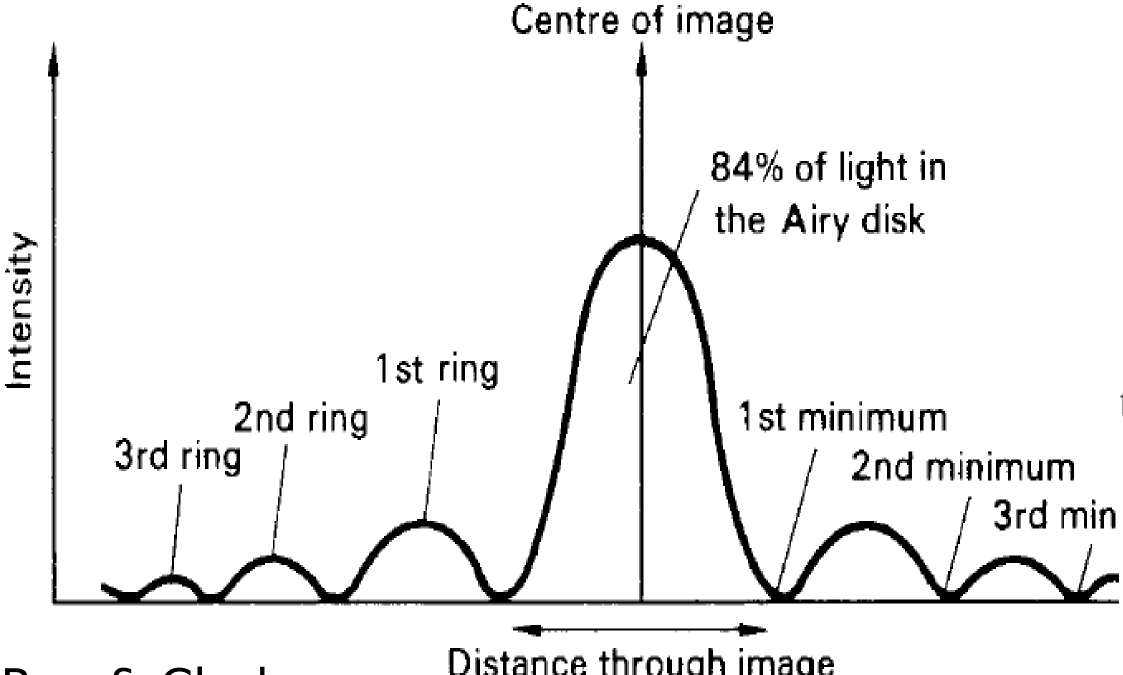
nd so in the image, the dark fringes occur at values of θ given b

$$\sin\theta = \frac{1.916\lambda}{\pi r}, \frac{3.508\lambda}{\pi r}, \frac{5.087\lambda}{\pi r}, \ldots$$

$$\theta \approx \frac{1.220\lambda}{d}, \frac{2.233\lambda}{d}, \frac{3.238\lambda}{d}, \ldots$$

the diameter of the aperture. The image structu

First zero of Bessel function



Roy & Clarke

Note: $r = d/2$

Angular resolution: Rayleigh criterium

The resolution limit is when the maximum of one Airy disk is over-imposed on the 1st minimum of the other image

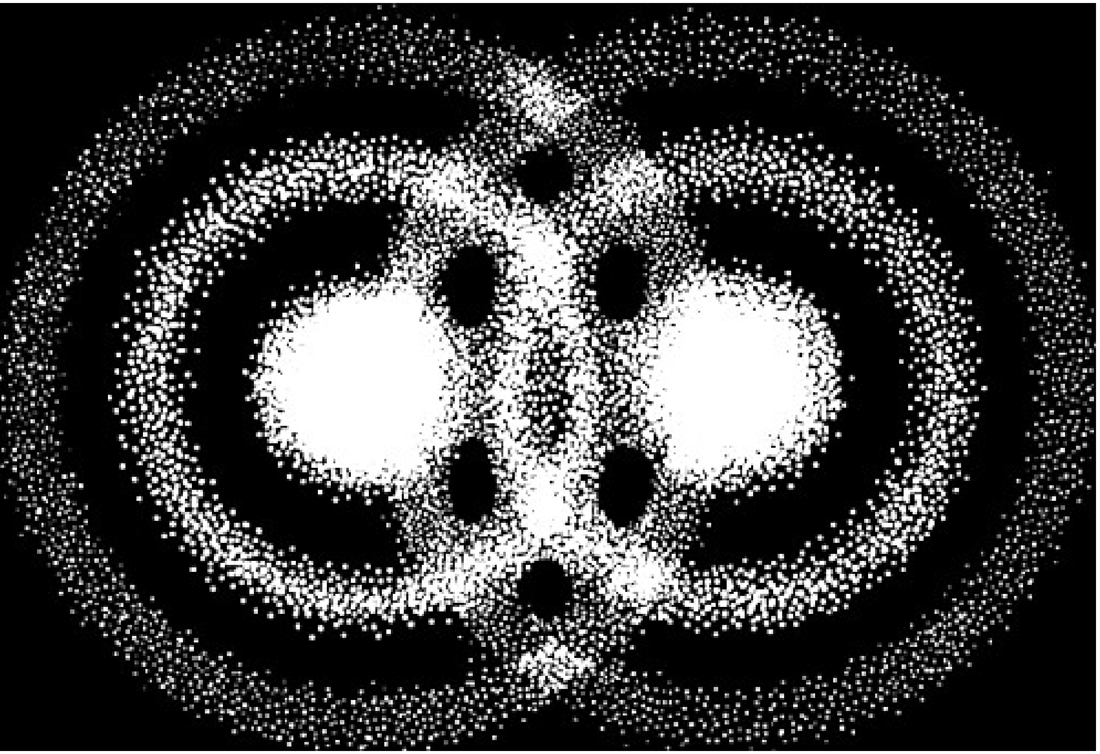
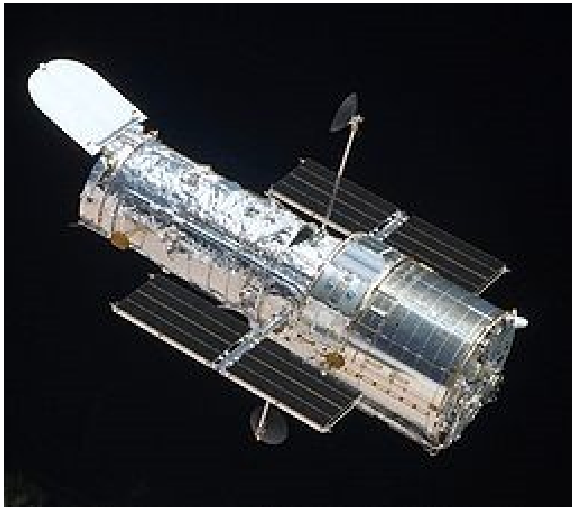


Figure 1.1.29. Image of two distant point sources through a circular aperture

(c) Kitchin

The first minimum occurs at a radius α [rad]:

$$\alpha = 1.22\, \lambda / d$$

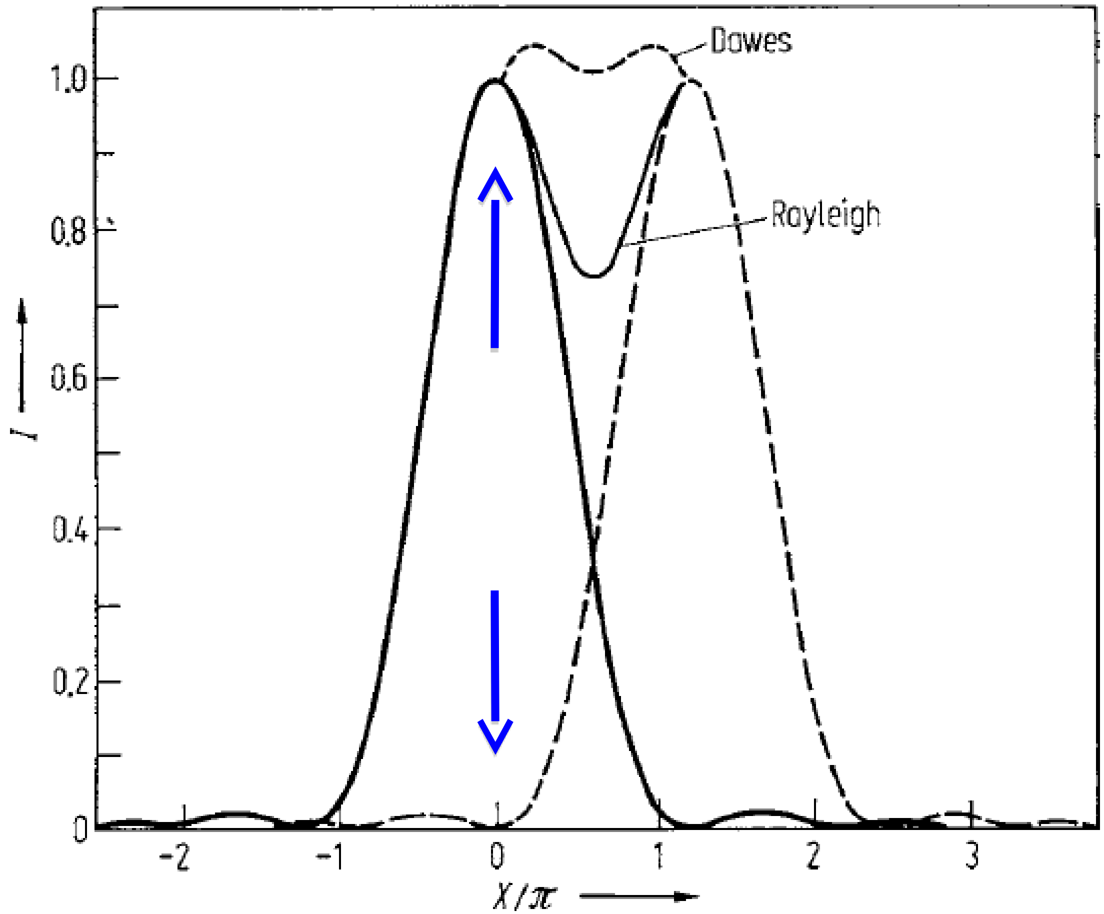


HST (2.4m)
~ 0,05"

Rayleigh vs. Dawes criteria

Rayleigh criterion: α **= 1.220** λ **/ d**

Empirical Dawes criterion ~10% lower



FWHM = 1.029 λ **/ d**

In practice both limits are difficult to reach due to imperfections of the instrument and the perturbations of the terrestrial atmosphere

Roth

Fig. 30. Intensity distribution in the diffraction disk of a star from a circular aperture. Shown superposed is a second star of the same brightness and the separation between the components (Rayleigh criterion); *dashed line* = intensity sum for the Dawes criterion

Angular resolution: Rayleigh criterium

$$\alpha \text{ [rad]} = \mathbf{1{,}22}\, \boldsymbol{\lambda} / \boldsymbol{d}$$

For V = 540nm:

$\alpha['']$ = **0,136 /*d*[m]**

A telescope with ***d* = 13,6 cm** reaches in the optical an **angular resolution of 1''**, about the same than the limit imposed by the ***seeing* (~ 1'')**

Angular resolution: Rayleigh criterium

$$\alpha\ [\mathrm{rad}] = \mathbf{1{,}22}\ \boldsymbol{\lambda} / \boldsymbol{d}$$

For V = 540nm:

$\alpha['']$ = **0,136** / d[m]

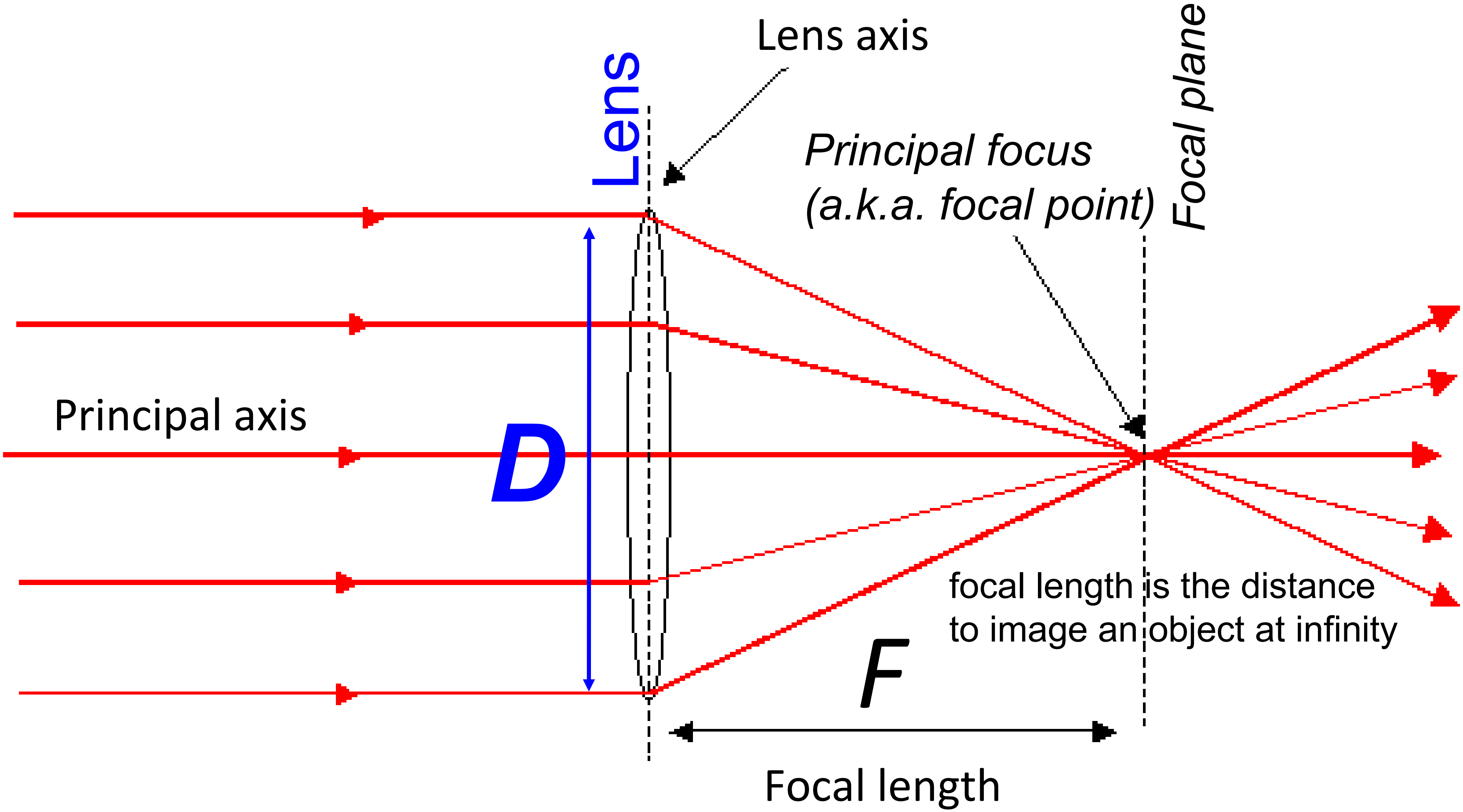
For K = 2,2µm:

$\alpha['']$ = **0,55** / d[m]

In the K band (infrared), a telescope with ***d*** **= 1 m** reaches an **angular resolution of 0,55”**

Focus, focal plane, focal distance

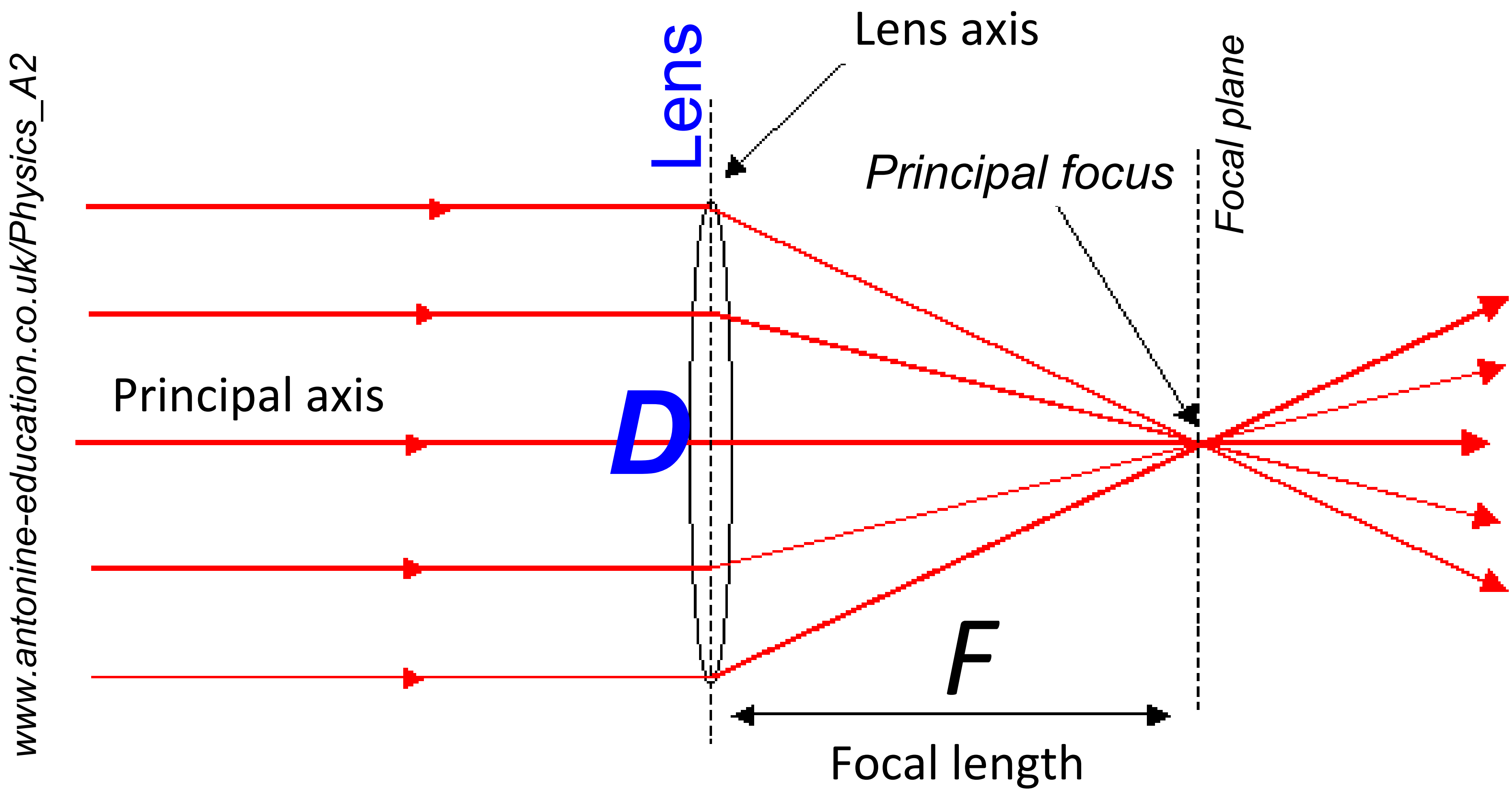
F: focal distance, D: aperture of the lens/mirror



www.antonine-education.co.uk/Physics_A2

Focal ratio *f/#* = *F* / *D*

F: focal distance, D: aperture, focal ratio *f/#*

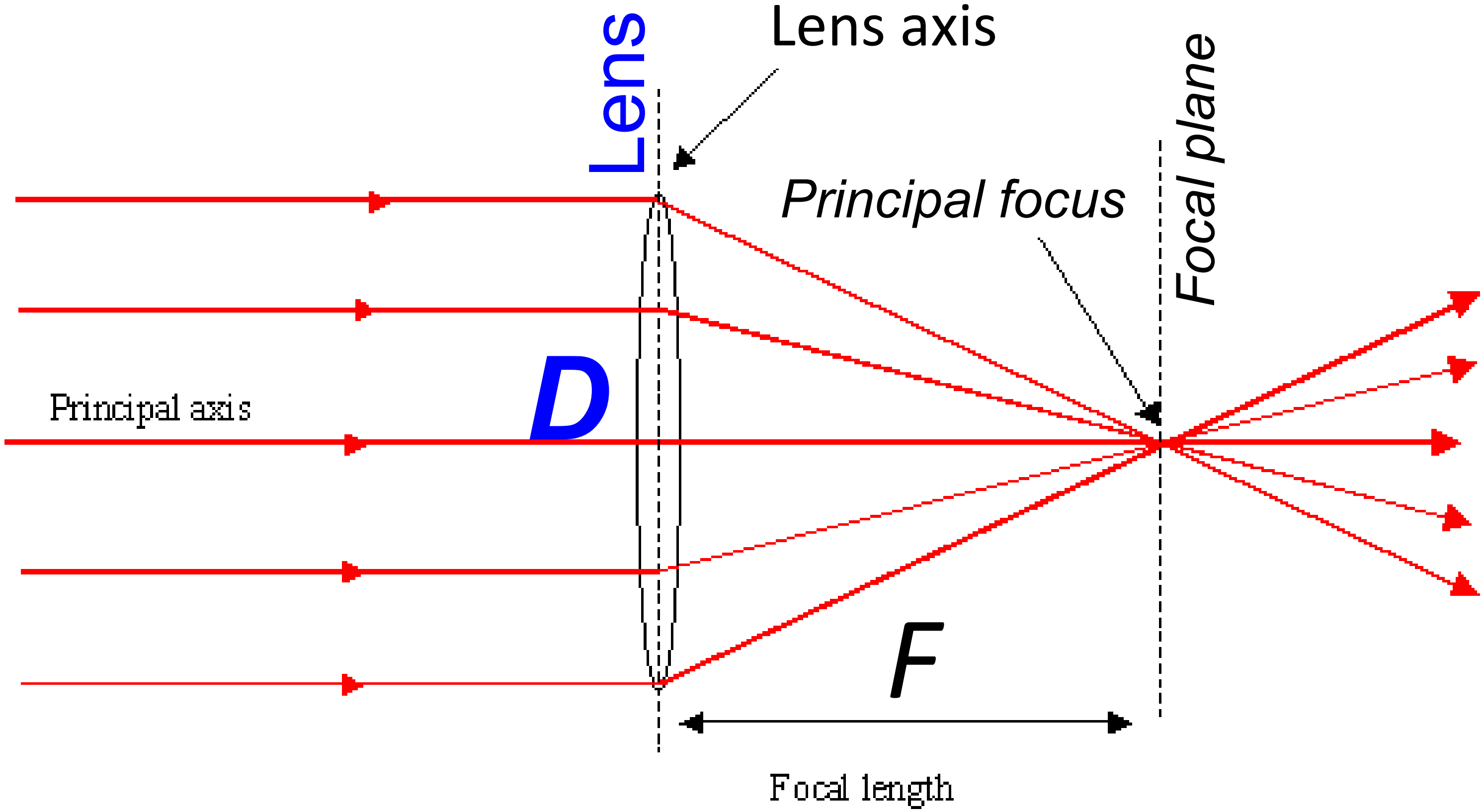


Focal ratio ≡ *f-ratio* ≡ *f-number* ≡ *f/#* = ***F/D***

Short (low) f/ (e.g. f/5): faster: brighter: wider field of view

Focal ratio *f/#* = *F* / *D*

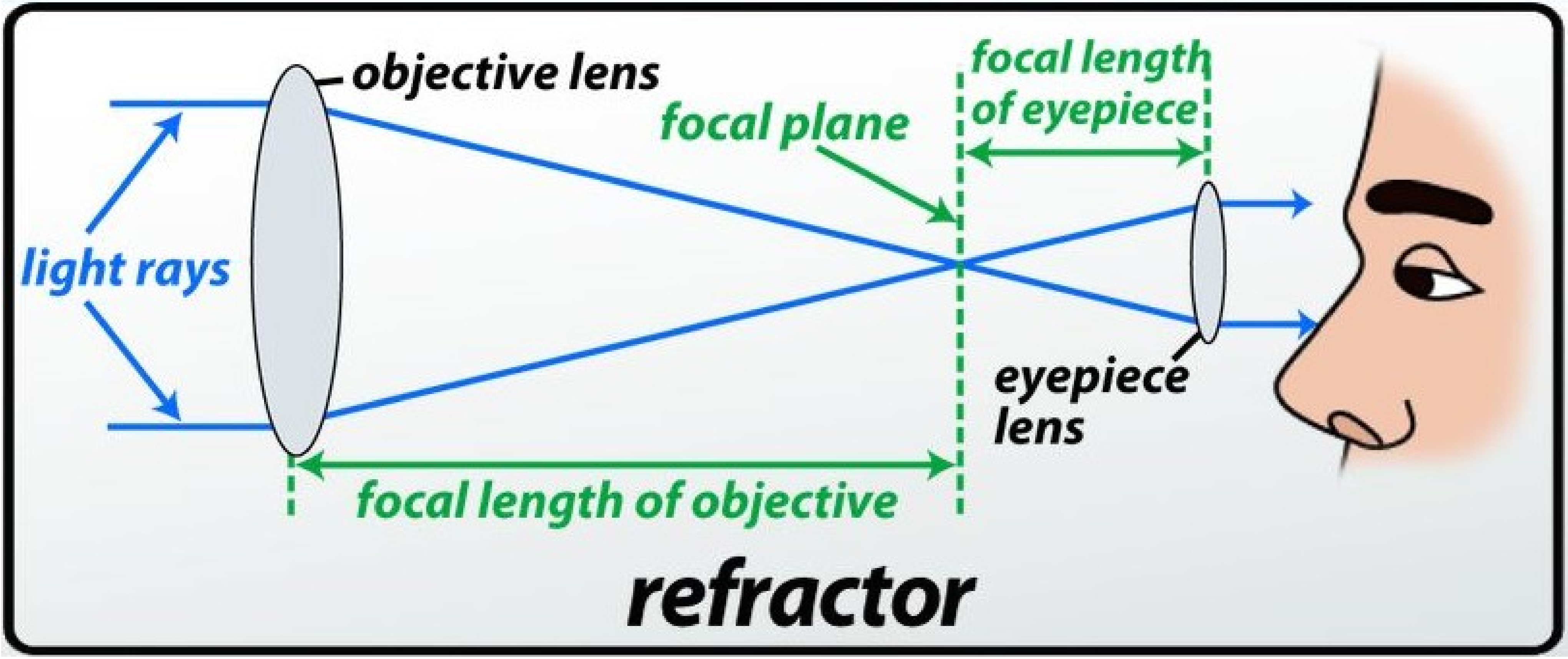
F: focal distance, D: aperture, focal ratio *f/#*



www.antonine-education.co.uk/Physics_A2

Example: the 1,6m telescope at OPD has f/10 at the Cassegrain focus. Find the focal distance F

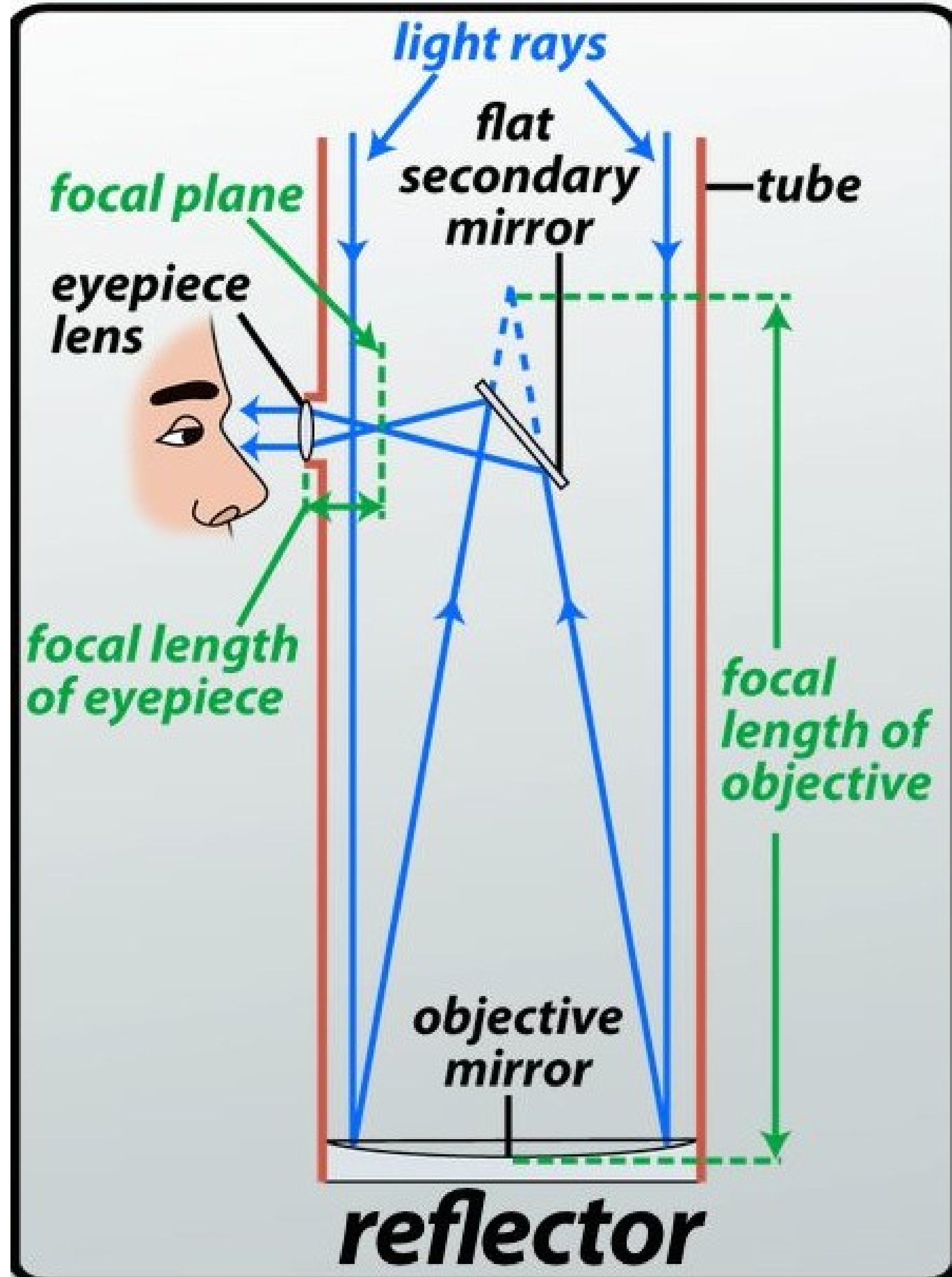
Response: F/D = 10, D=1,6m → F = 16m



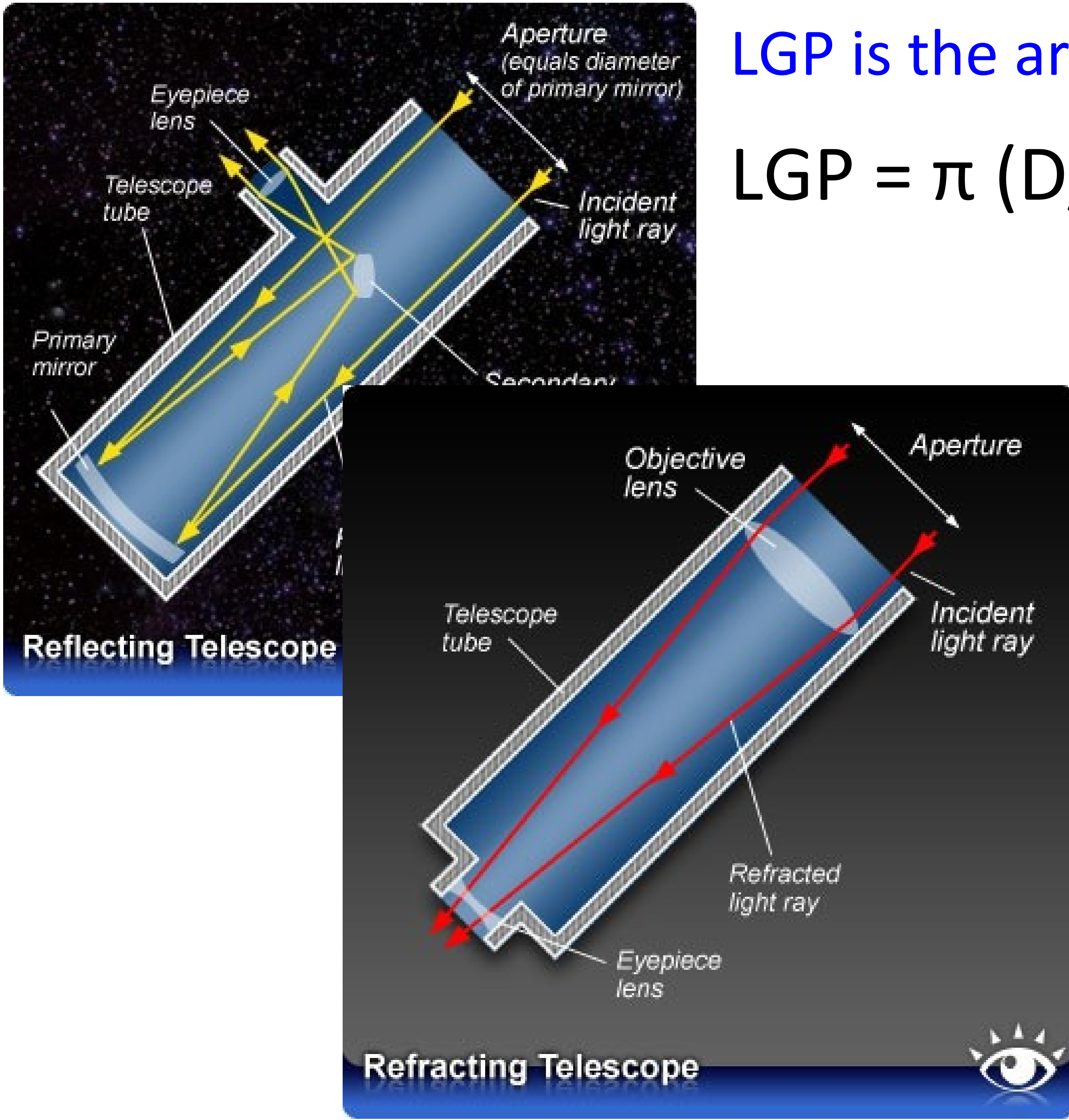
Focal plane & focal length (or focal distance)

study.com

Focal plane & focal length



Light gathering power (LGP)



LGP is the area of the objective

$$LGP = \pi\,(D/2)^2$$

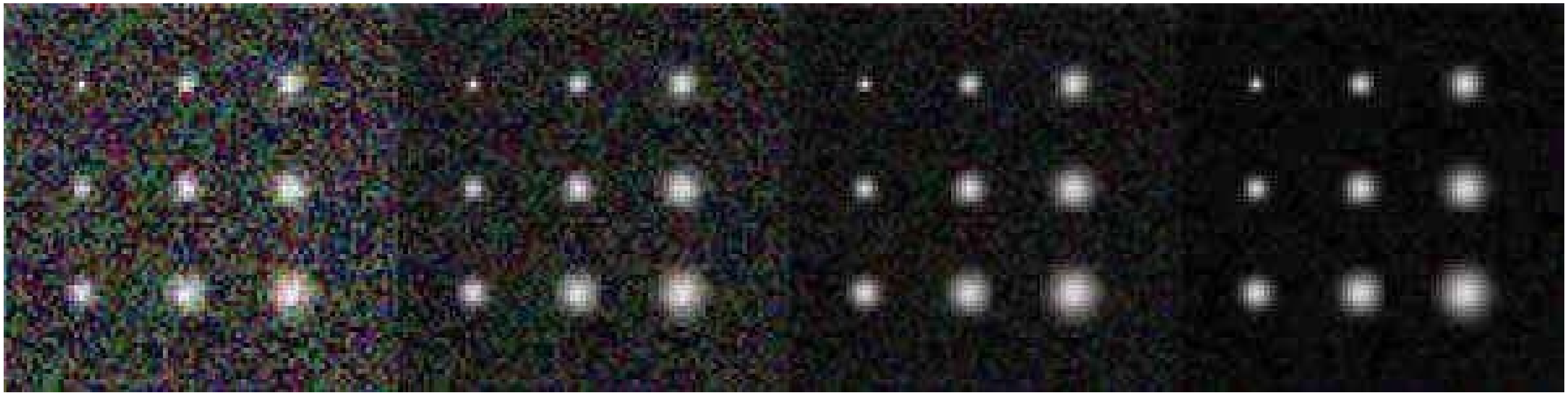
Young person in darkness: d_e ~7mm

Ex. Telescopes relative to the eye:

10 cm: 200 times !

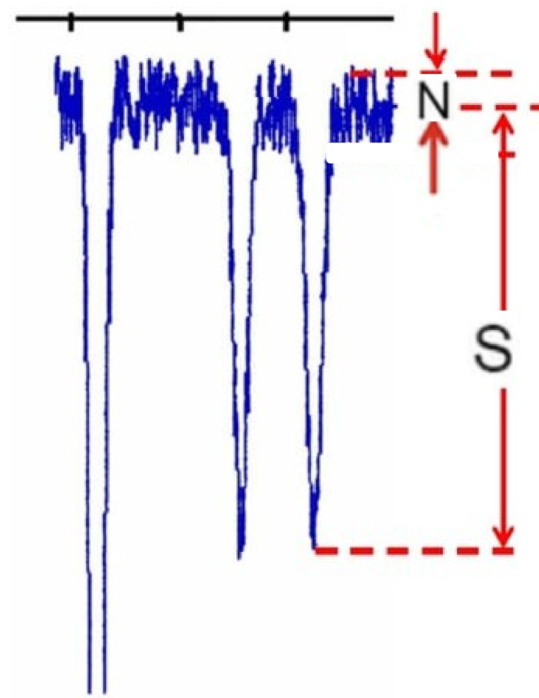
8m: 1.3×10^6 times !

Signal-to-noise (S/N) ratio, SNR



S/N = 2 S/N = 4 S/N = 8 S/N = 16

Photometric simulation of stars observed with a signal-to-noise ratio ranging from 2:1 to 16:1



Spectral lines detected with S/N ~ 10

Integration time

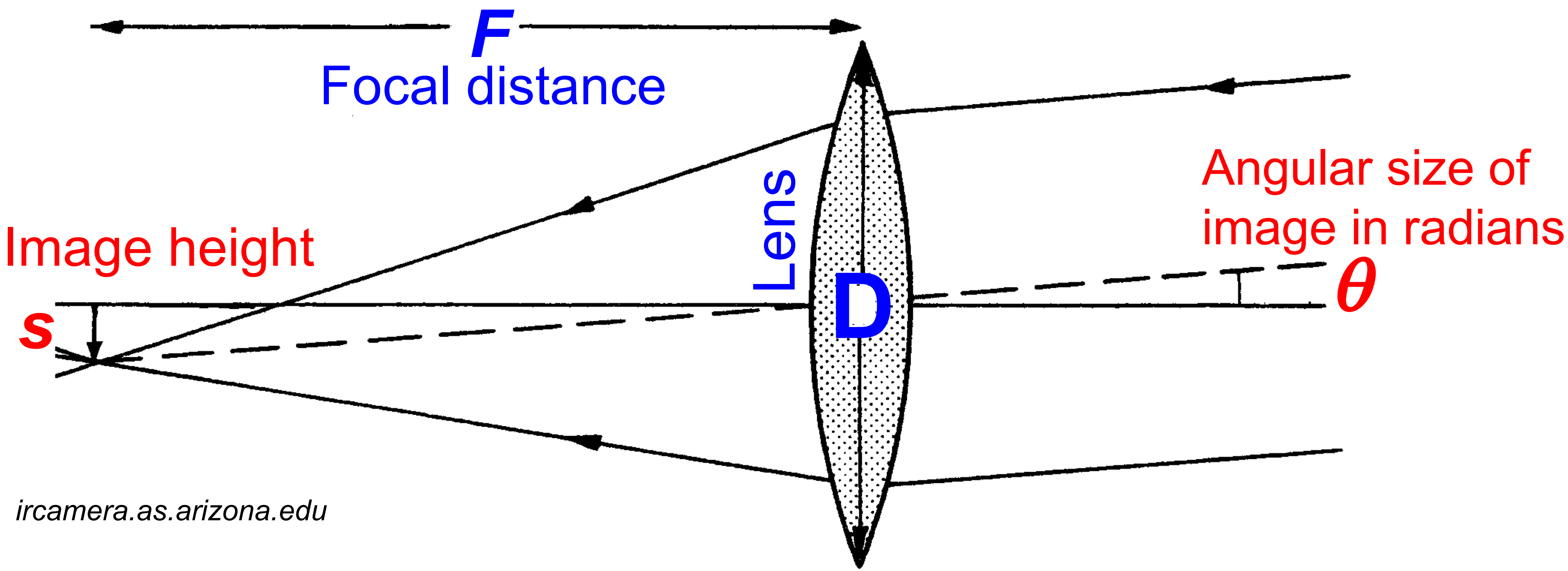
Joining the 4 ESO/VLT telescope (8m each) we can have a "super-VLT" with a diameter equivalent to 16m. If we can observe a galaxy in 1h with the super-VLT, how long would it take to achieve the same S/N if the observation is done with the 1,6m telescope at OPD?

Rpta: 100 hours. Considering 2h of observation at OPD (near the meridian) by night, the observation may take 50 nights …

$$t_1 = (D_2/D_1)^2 \, t_2$$

t_1 , t_2 : observing time with telescopes of diameters D_1 , D_2

Physical size of the image



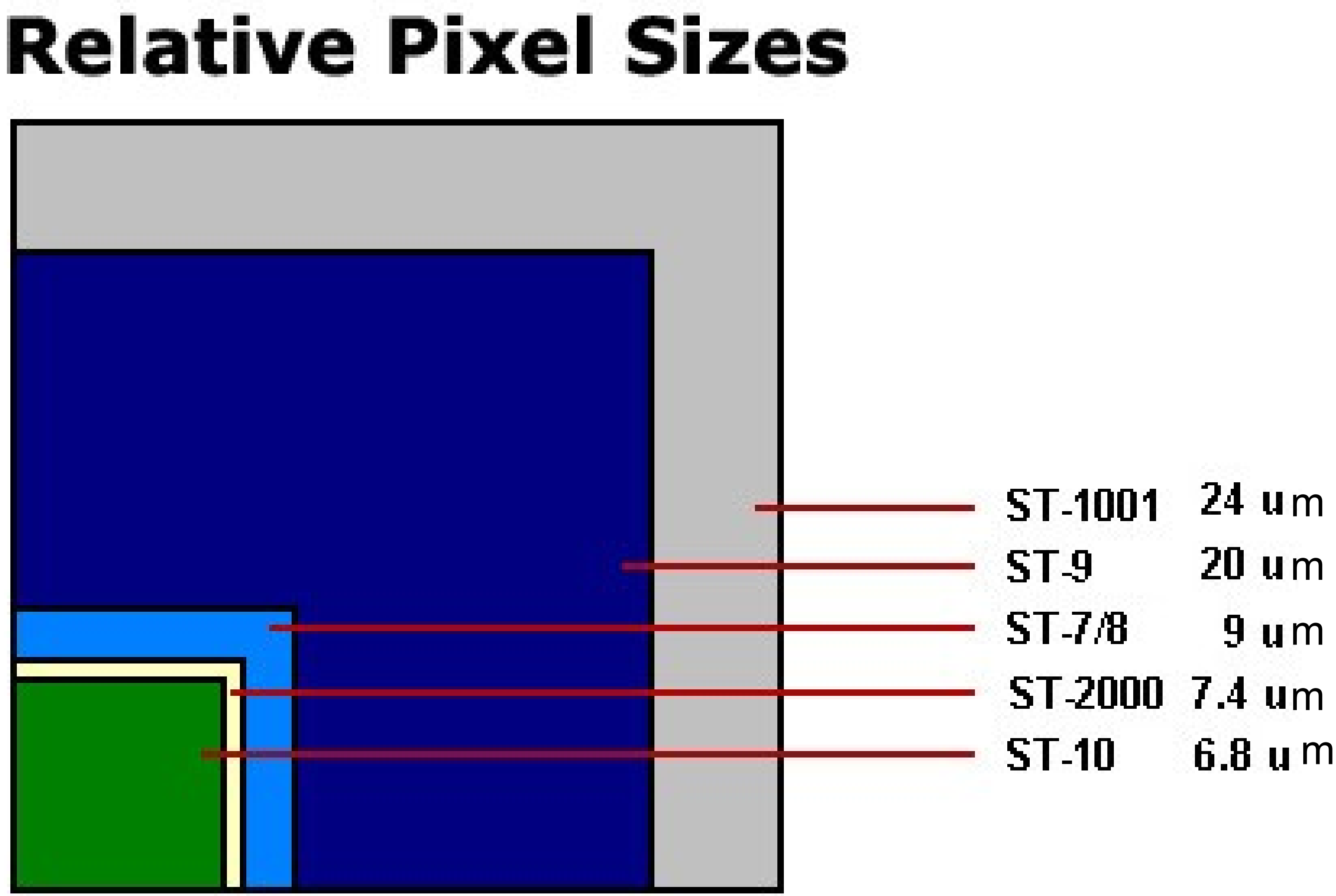
Physical size *s* of image *θ* on the detector:

$$s = F\,tan\theta \sim F\,\theta$$

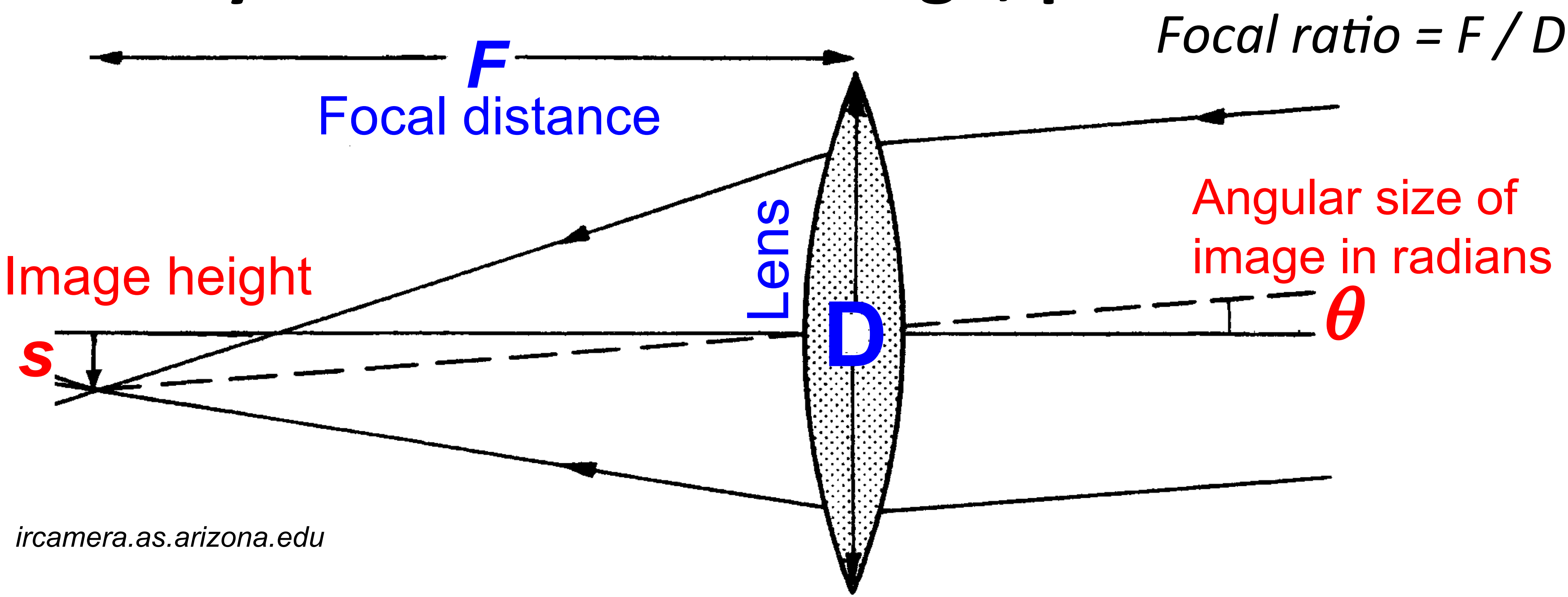
Example: if F = 8m, estimate **s** for θ = 1”

1 rad = 206265” → s = 8m*1/206265 = 3,9 x 10^{-5} m = 39 µm

How large is the pixel of a CCD?



Physical size of the image, plate scale



Physical size *s* of image *θ* : $s = F \tan\theta \sim F\,\theta$

Plate scale $p = d\theta / ds = 1/F = 206265'' / F$

IAG: f/13.5; D = 61cm. What is the plate scale?

F = 13.5 x 61cm = 8235 mm

p = 206265”/8235mm = 25”/mm = 0.5”/20μm (1mm=10^3 μm)

Field of view

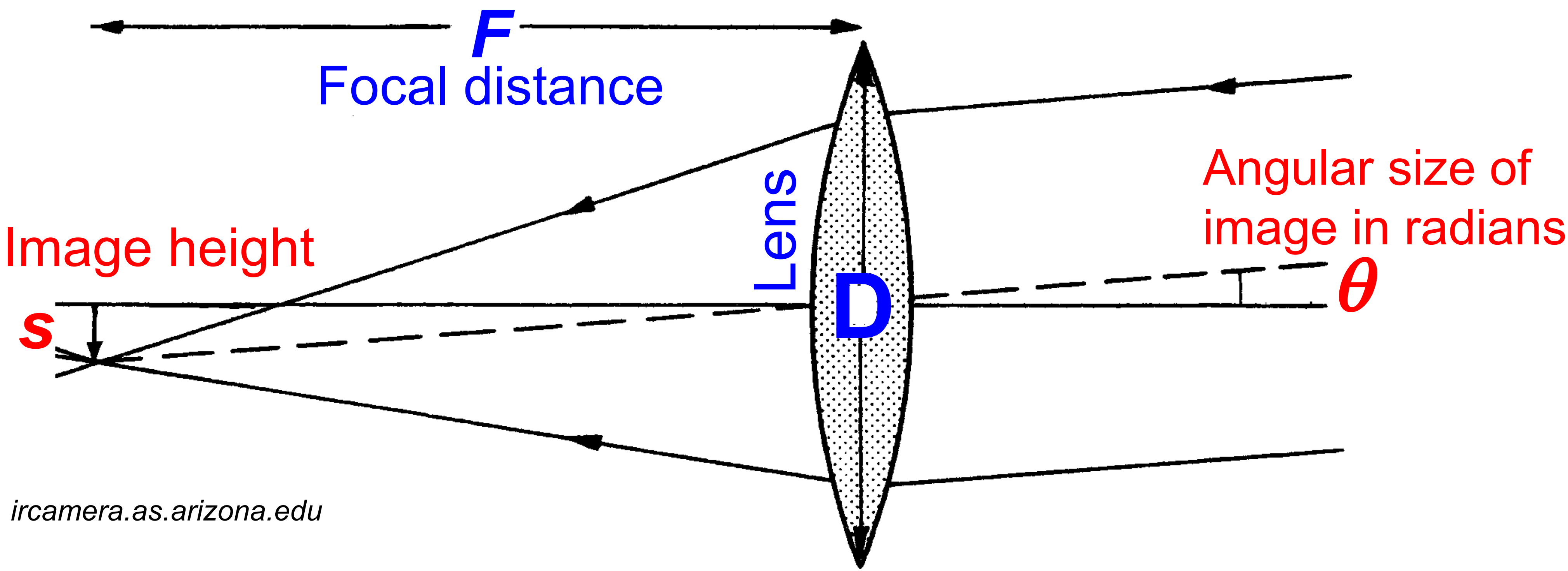


Plate scale $p = d\theta\,/\,ds\ = 1/\,F = 206265''\,/\,F$

Field of view $\theta = s\ /\ F$

s: size of the CCD

F: focal distance

Refractor telescopes: disadvantages

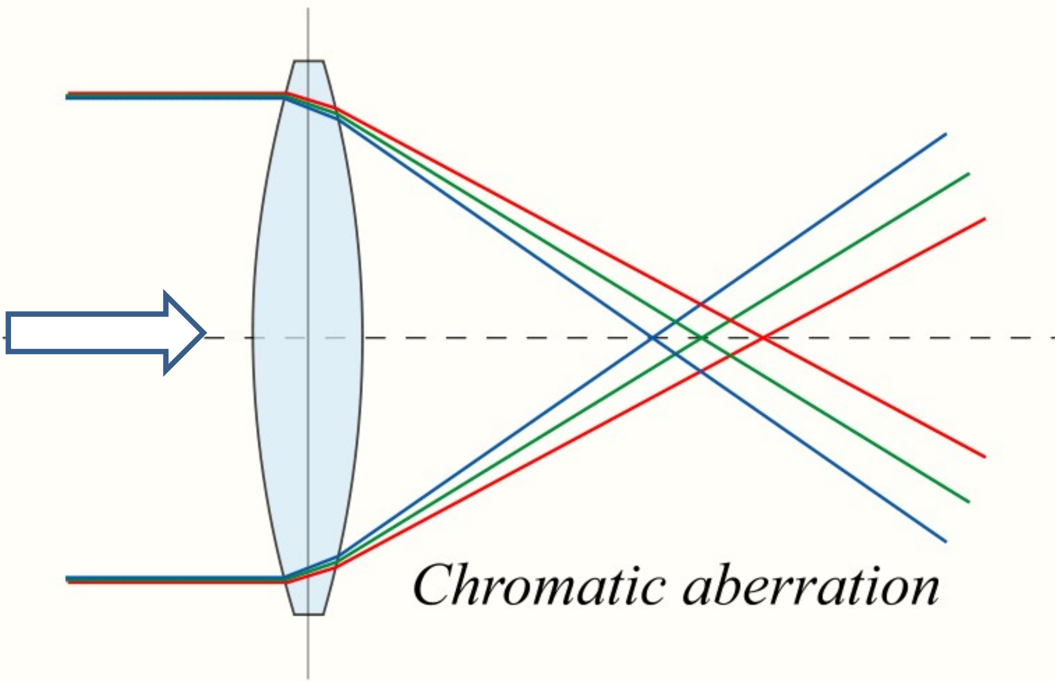
Longest refractor (1m) at Yerkes observatory

- Mechanical
  - ⇨ Lens must be supported on the edges. As there is no central support, it may get distorted
- Size of the tube

To diminish chromatic/spherical distortions, the focal distance must be large, increasing the cost. Example: huge domes

- Absorption by the lens
  - ⇨ Absorption of UV light
- Lens imperfections, air bubbles

Refractor telescopes: chromatic aberration



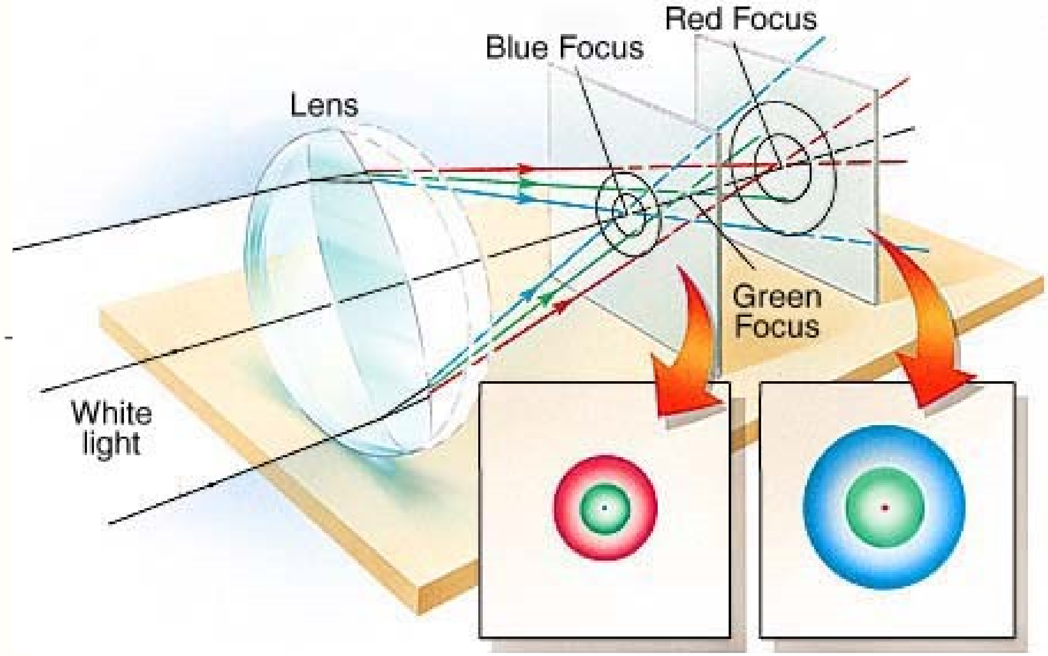
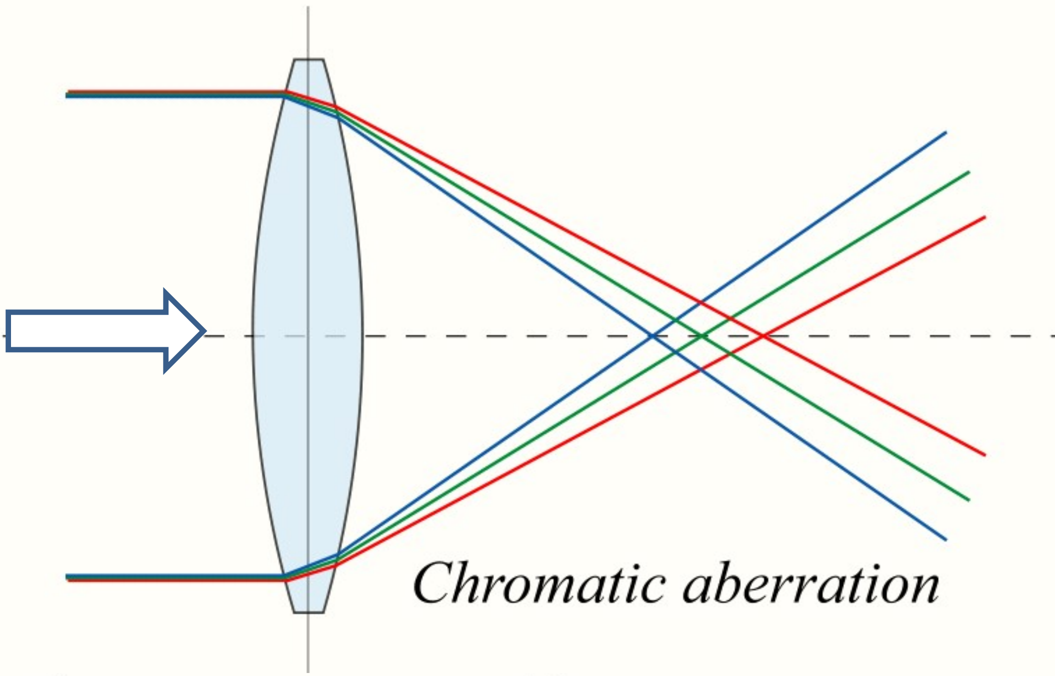
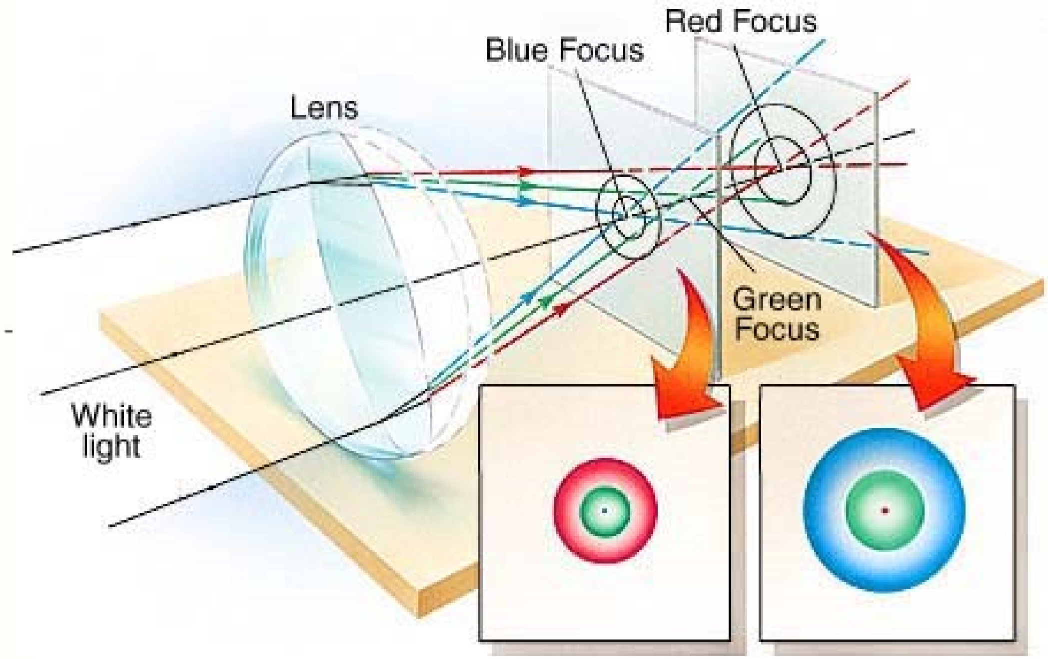


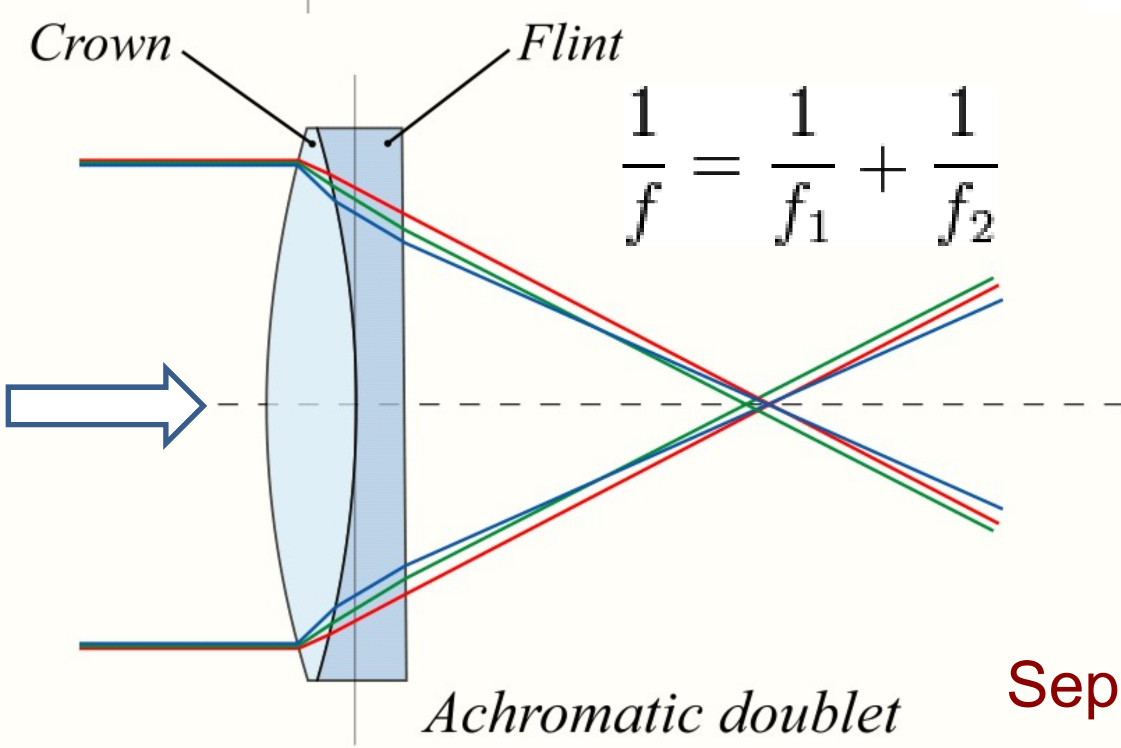
Table 1.1.5. Refraction index $n(\lambda)$ → focal distance $f(\lambda)$

	Refractive index at the specified wavelengths (nm)				
Glass type	361	486	589	656	768
Crown	1.539	1.523	1.517	1.514	1.511
High dispersion crown	1.546	1.527	1.520	1.517	1.514
Light flint	1.614	1.585	1.575	1.571	1.567
Dense flint	1.705	1.664	1.650	1.644	1.638

Refractor telescopes: chromatic aberration



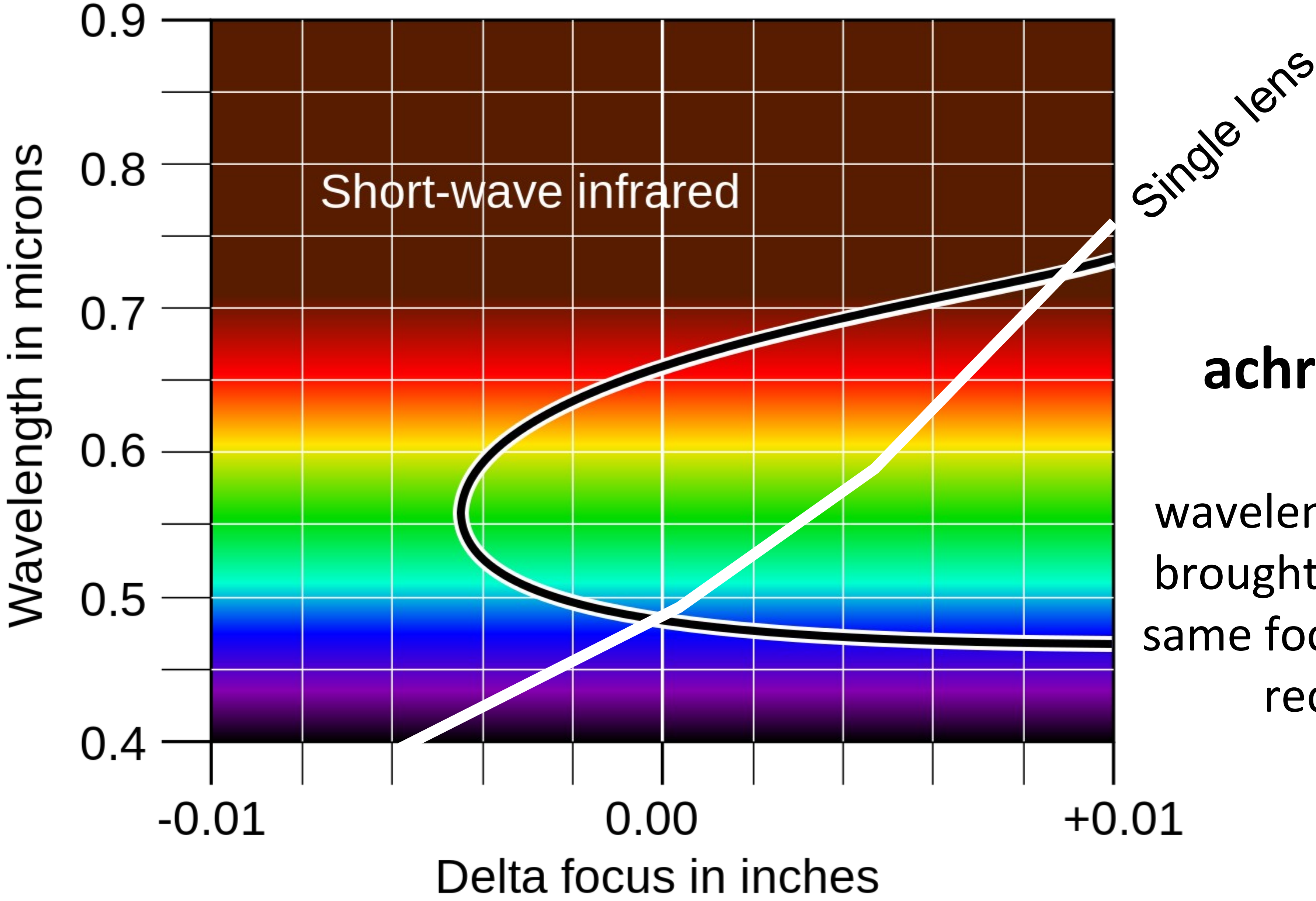




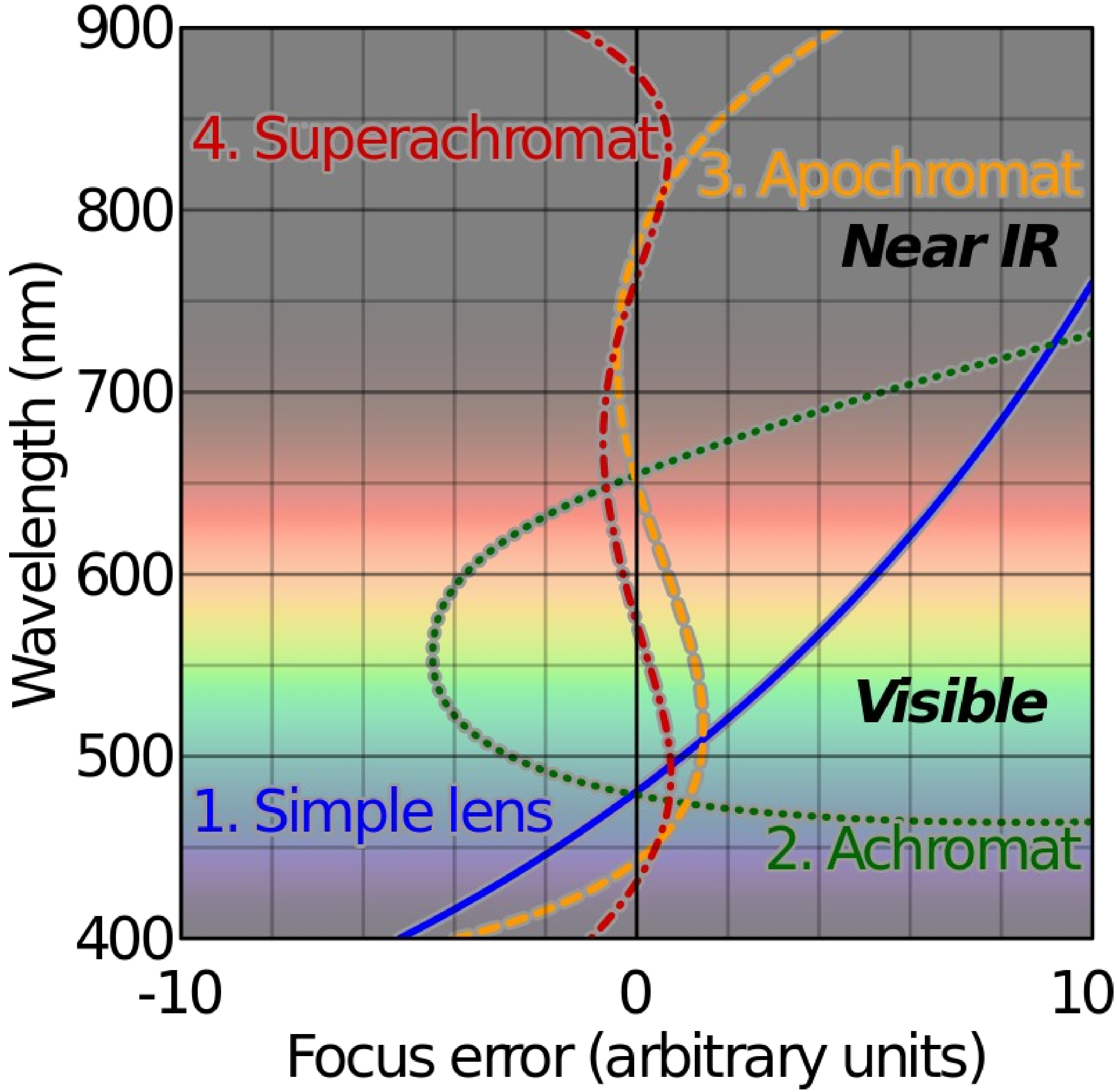
$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2}$$

- Refraction index $n(\lambda)$ → focal distance $f(\lambda)$
- Correction with "achromatic lens" by fusing lenses (doublets, triplets, etc): but correction is not perfect

Separation d → add term: – d/(f1 . f2)



In an **achromatic lens**, 2 wavelengths are brought into the same focus, here red & blue.



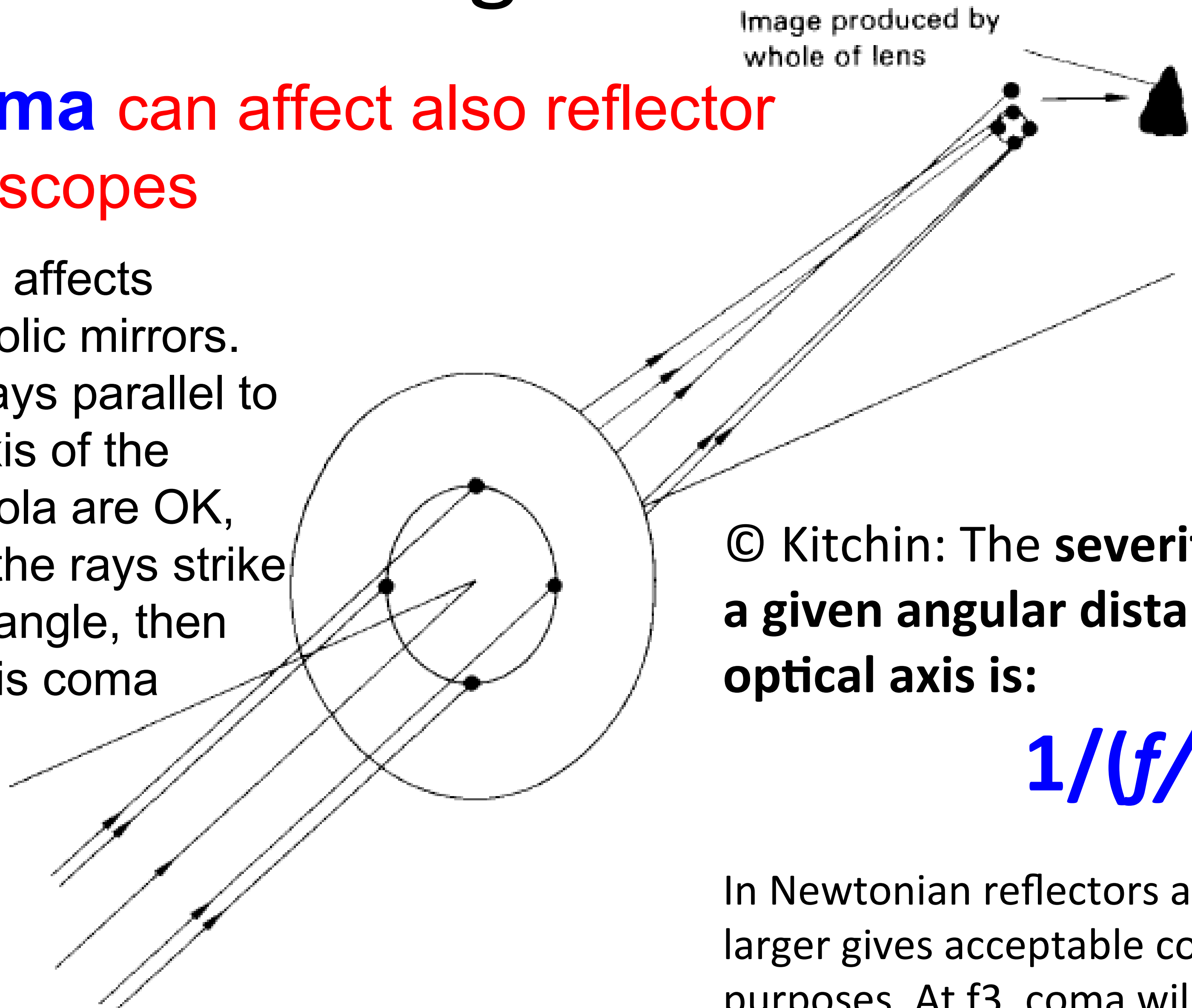
Focus error for 4 types of lens, over the visible & near infrared spectrum.

(c) https://en.wikipedia.org/wiki/Achromatic_lens#/media/File:Comparison_chromatic_focus_shift_plots.svg

Disadvantages of refractors: coma

Coma can affect also reflector telescopes

Coma affects parabolic mirrors. The rays parallel to the axis of the parabola are OK, but if the rays strike at an angle, then there is coma



© Kitchin: The **severity of the coma at a given angular distance from the optical axis is:**

$$1/(f/\#)^2$$

In Newtonian reflectors a focal ratio of f8 or larger gives acceptable coma for most purposes. At f3, coma will limit the useful field of view to about 1’ of arc

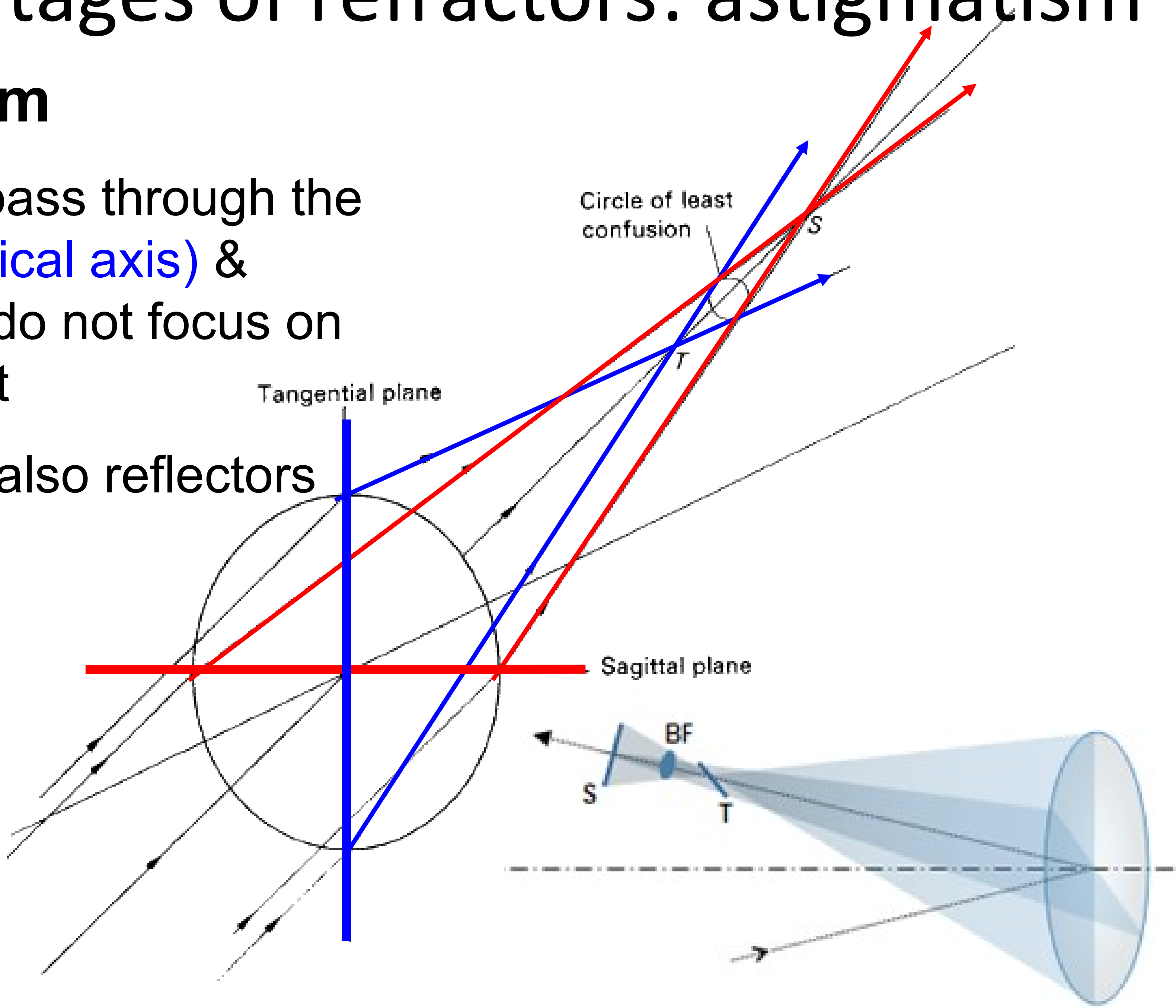
Roy & Clarke

Figure 16.19. When coma is present, any annulus of the lens produces an annular image; the total aberrated image can be thought of as being made up of a series of such annular images, the sizes increasing as the outer zones of the lens are considered.

Disadvantages of refractors: astigmatism

Astigmatism

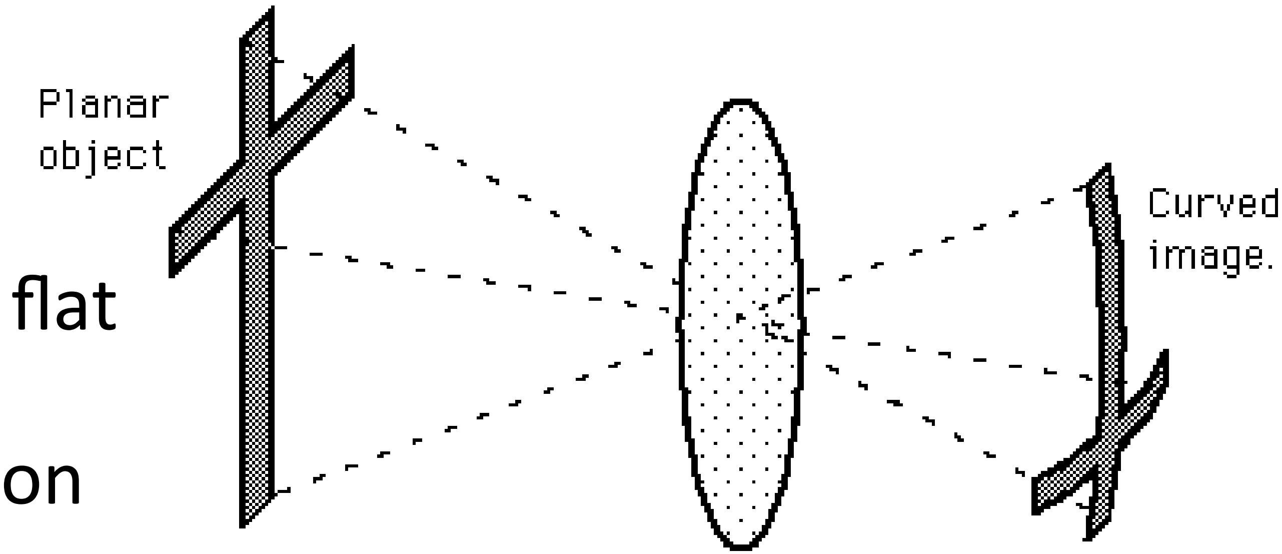
- Rays that pass through the tangential (optical axis) & sagittal plane do not focus on the same point
- Can affect also reflectors



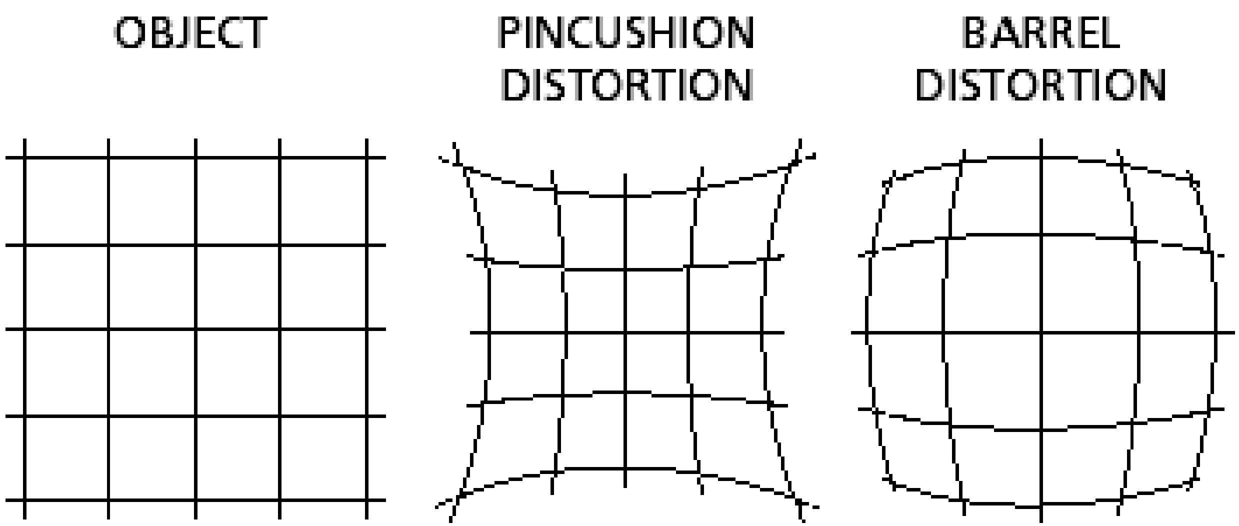
Roy & Clarke

Figure 16.20. Points T and S represent the foci of rays passing through the tangential and sagittal planes of a lens; the spread of the astigmatic image lies between the points T and S.

Other aberrations



- Image curvature: flat object shows distorted image, i.e. focus is not on a plane

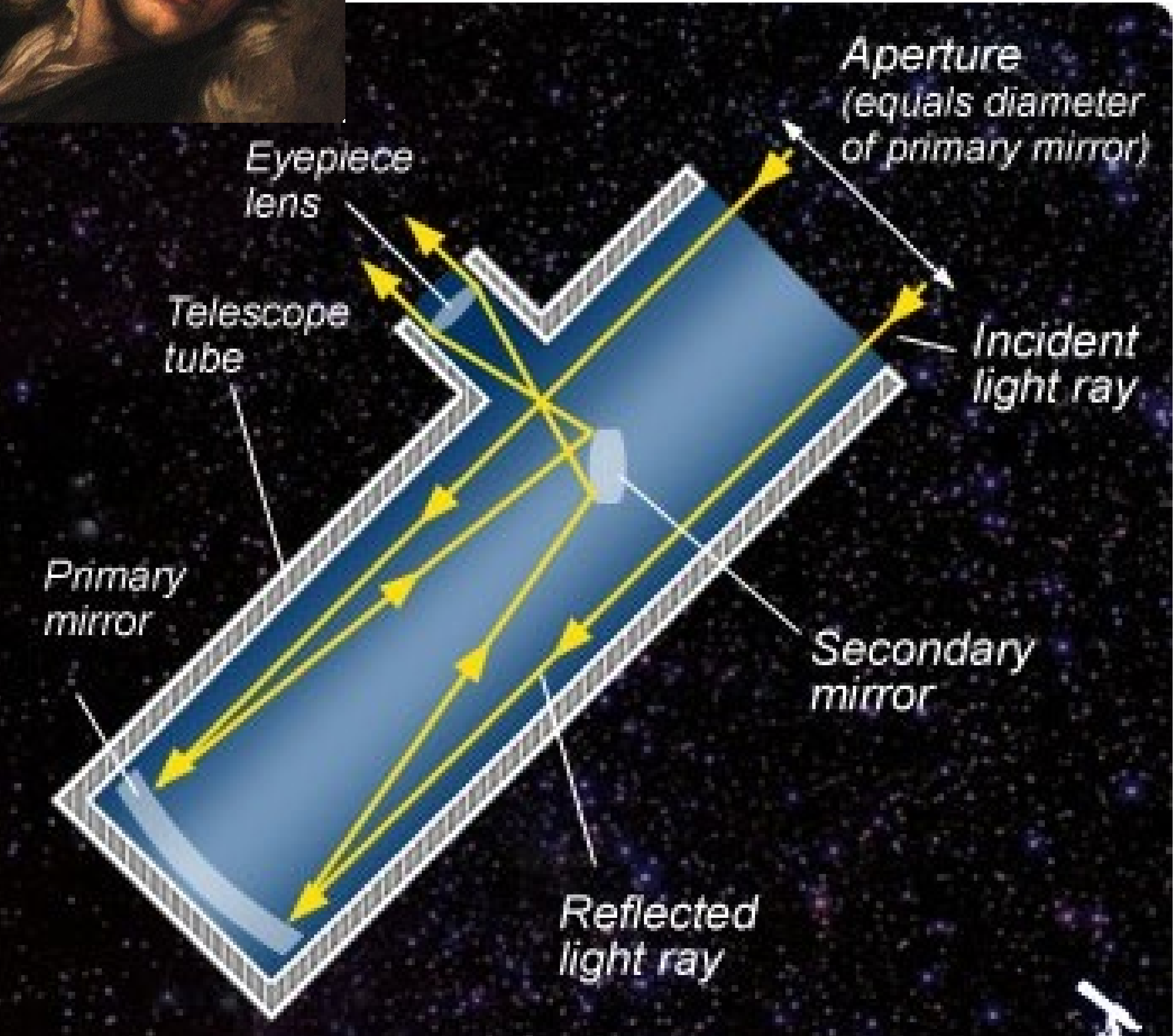


- Distortion: variation of the magnification on the image plane

Reflector telescopes I

“Invented” by Newton (1668)

At least the first working reflector



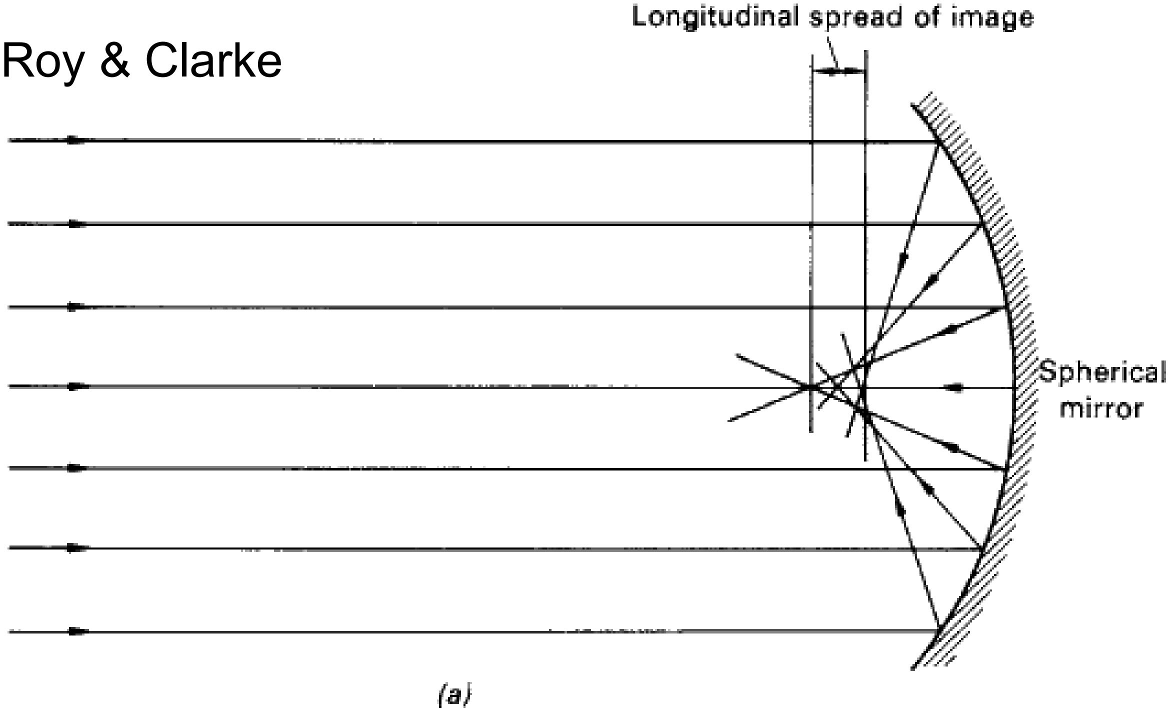
- Objective: mirror

  - Does not suffer chromatic aberration

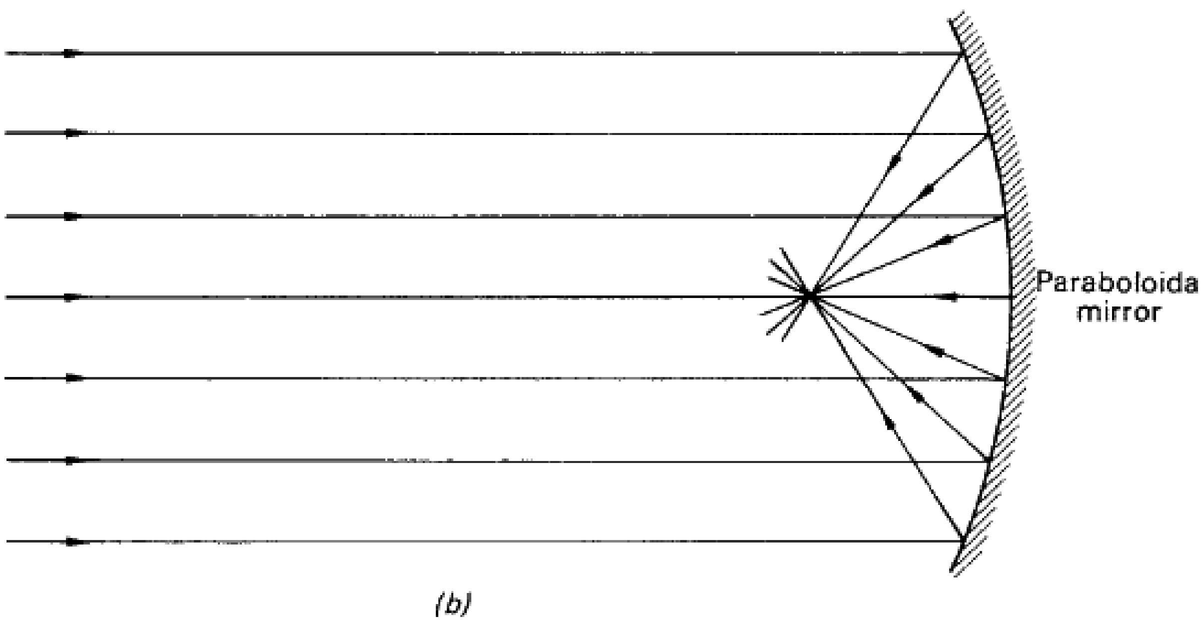
  - Newton’s mirror was spherical, but a parabola is preferred, because it focuses at a single point

Spherical aberration

Roy & Clarke

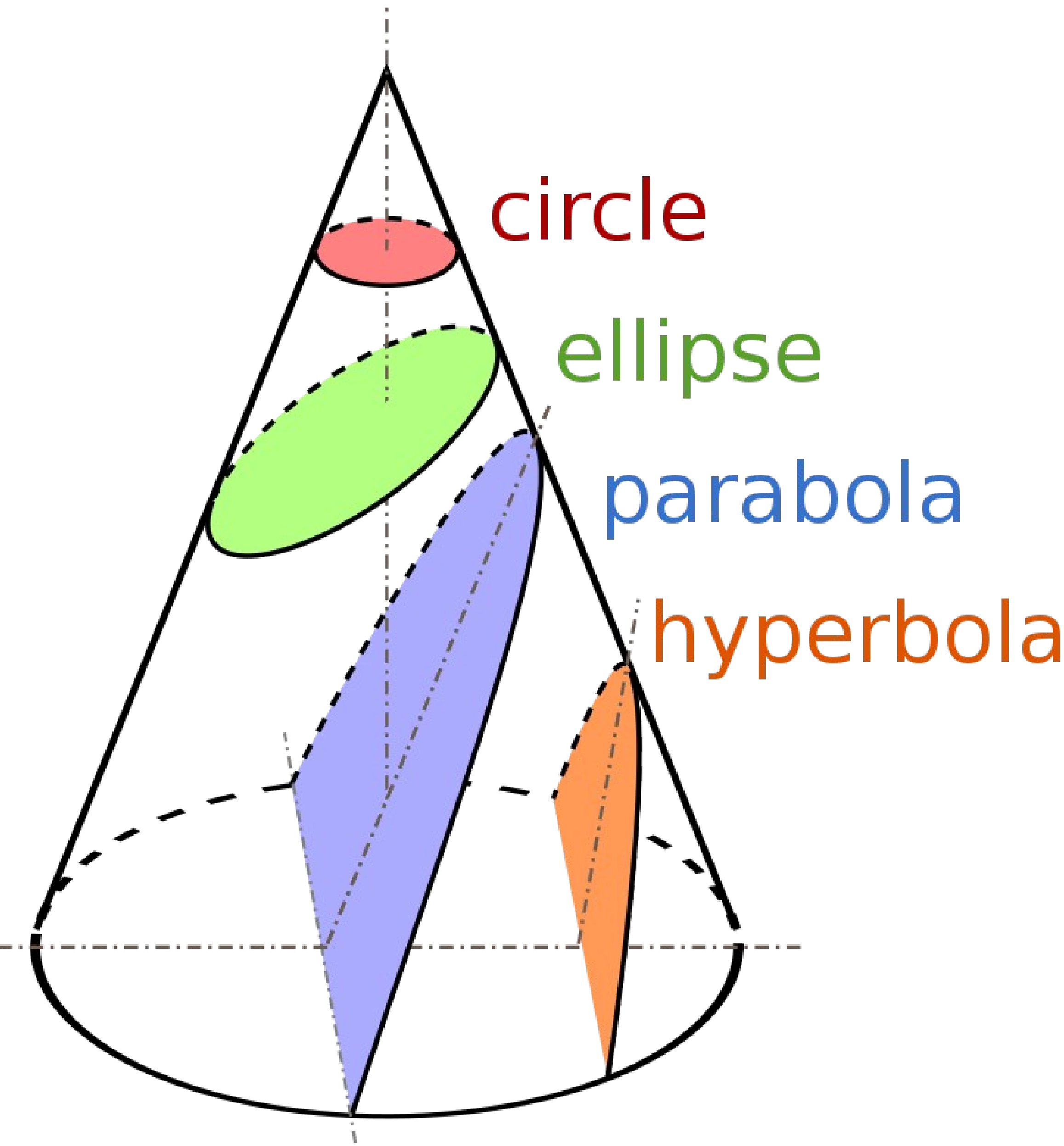


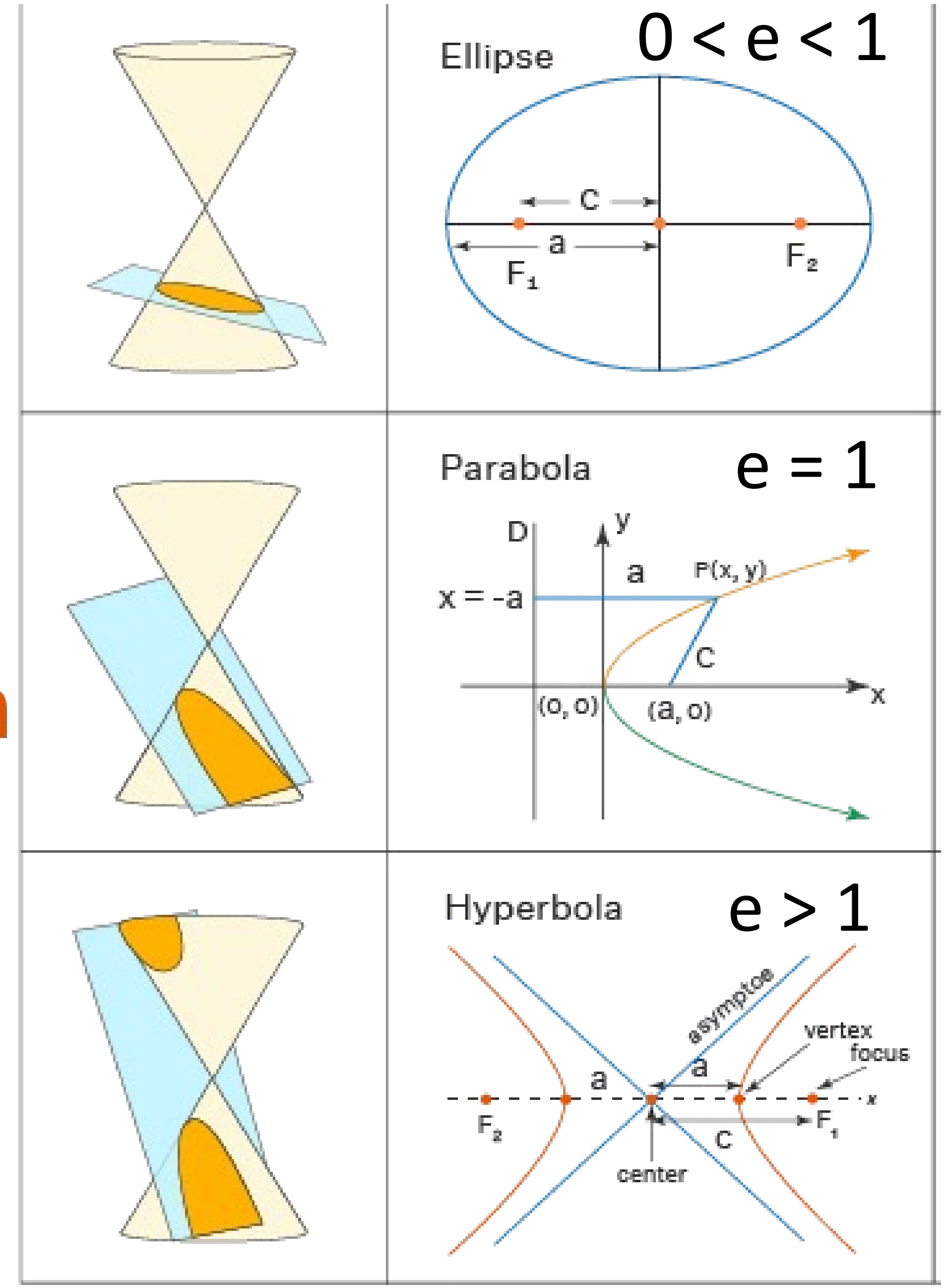
Spherical mirror (spherical aberration)



Parabolic mirror

Figure 16.23. (*a*) Spherical mirror exhibiting the effect of spherical aberration. (*b*) Paraboloidal mirror removes spherical aberration; incident rays parallel to the optic axis are brought to the same focus, independent of their distance from the axis.

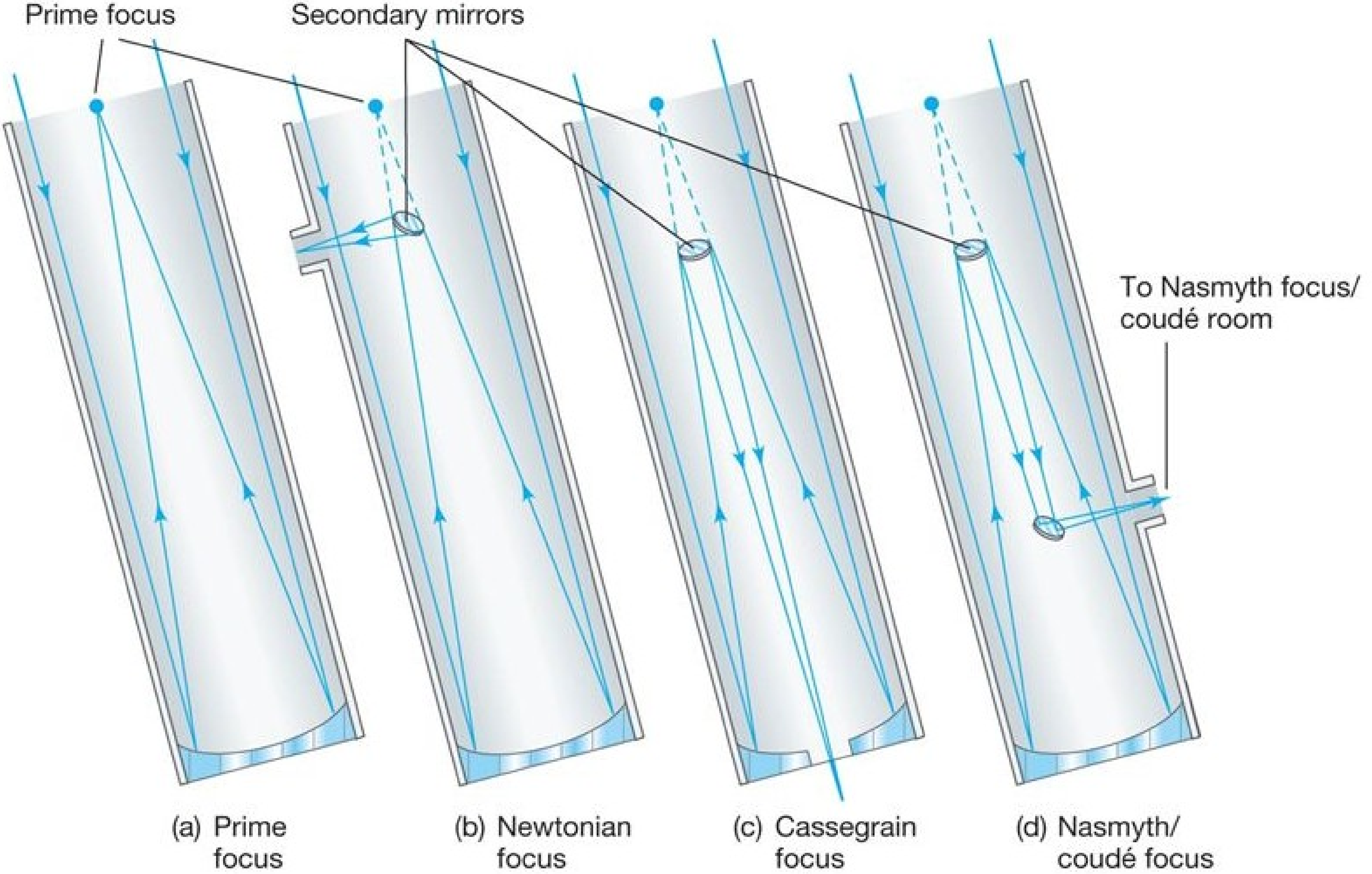




e = eccentricity

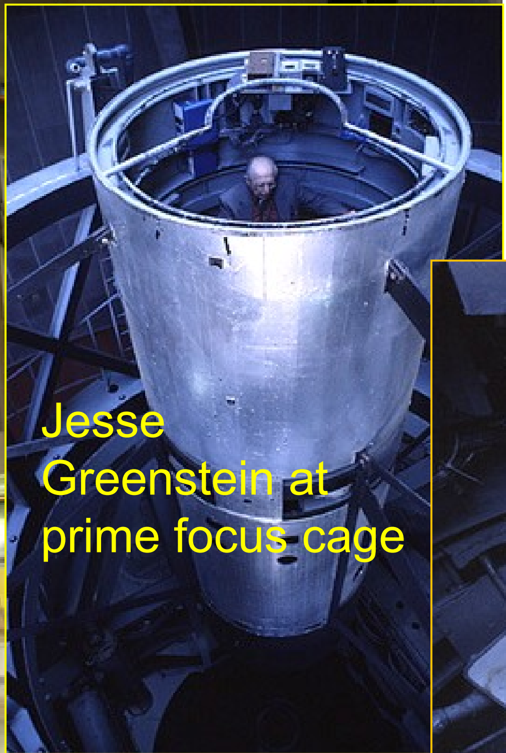
c = distance from any point on the conic section to its focus

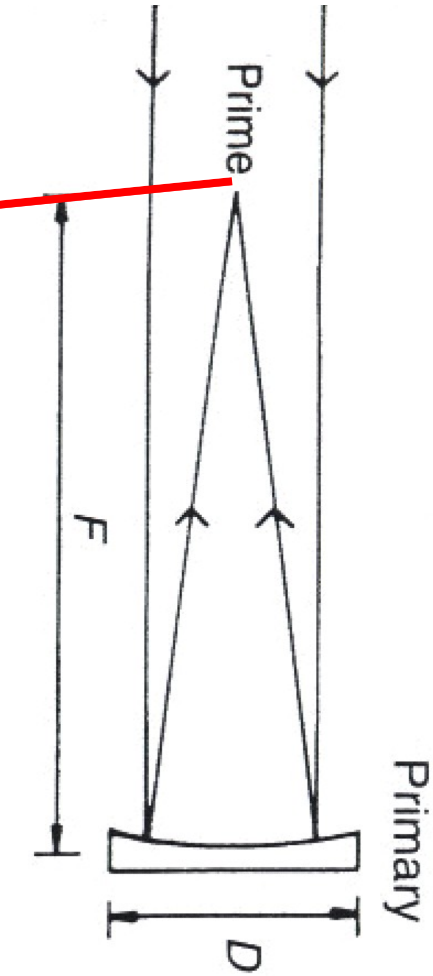
Types of reflecting telescopes



Types of focus: *prime focus*

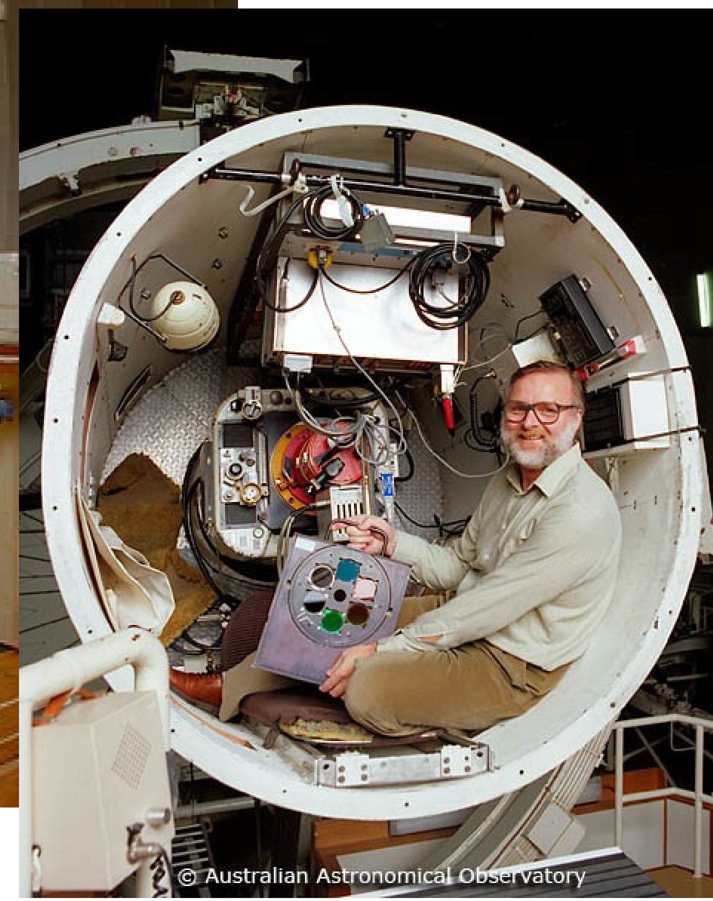
Smith





Anglo Australian Telescope

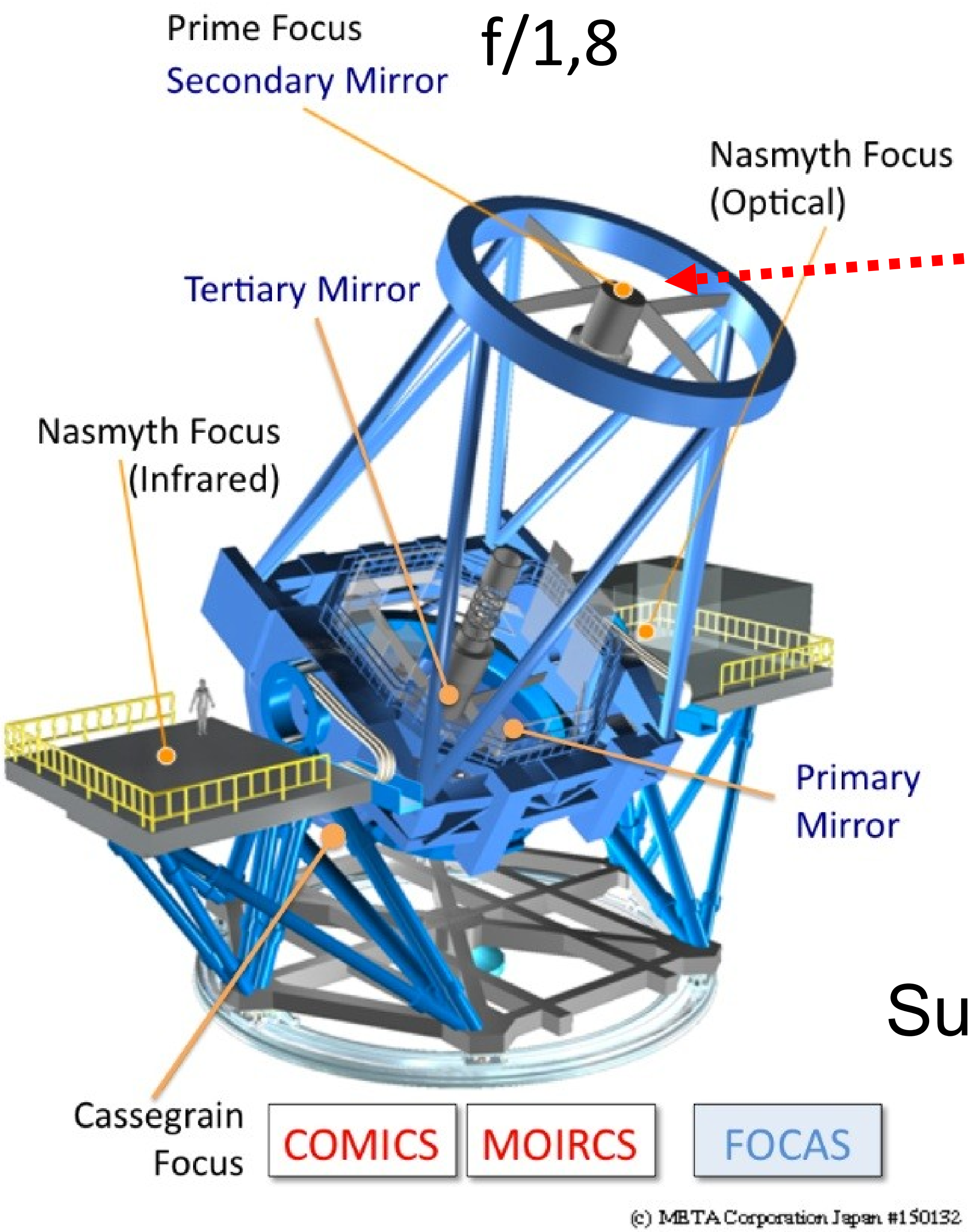

© Australian Astronomical Observatory


© Australian Astronomical Observatory

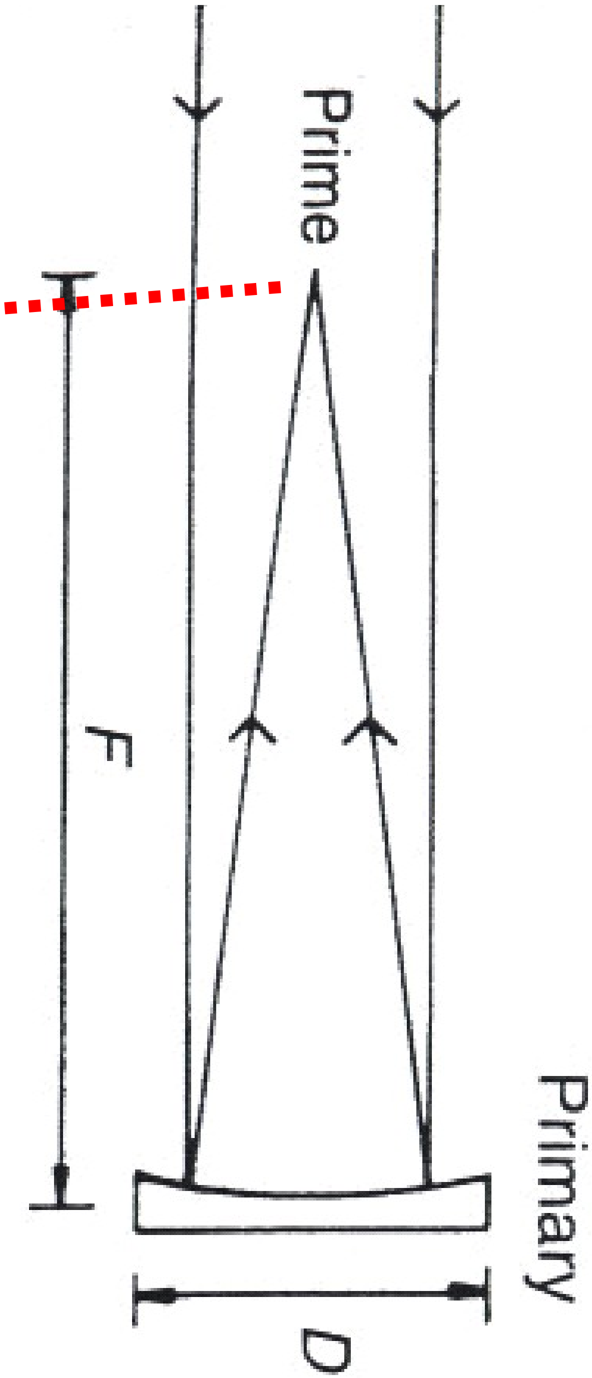
Prime focus of Subaru (8m)

Smith

f/1,8

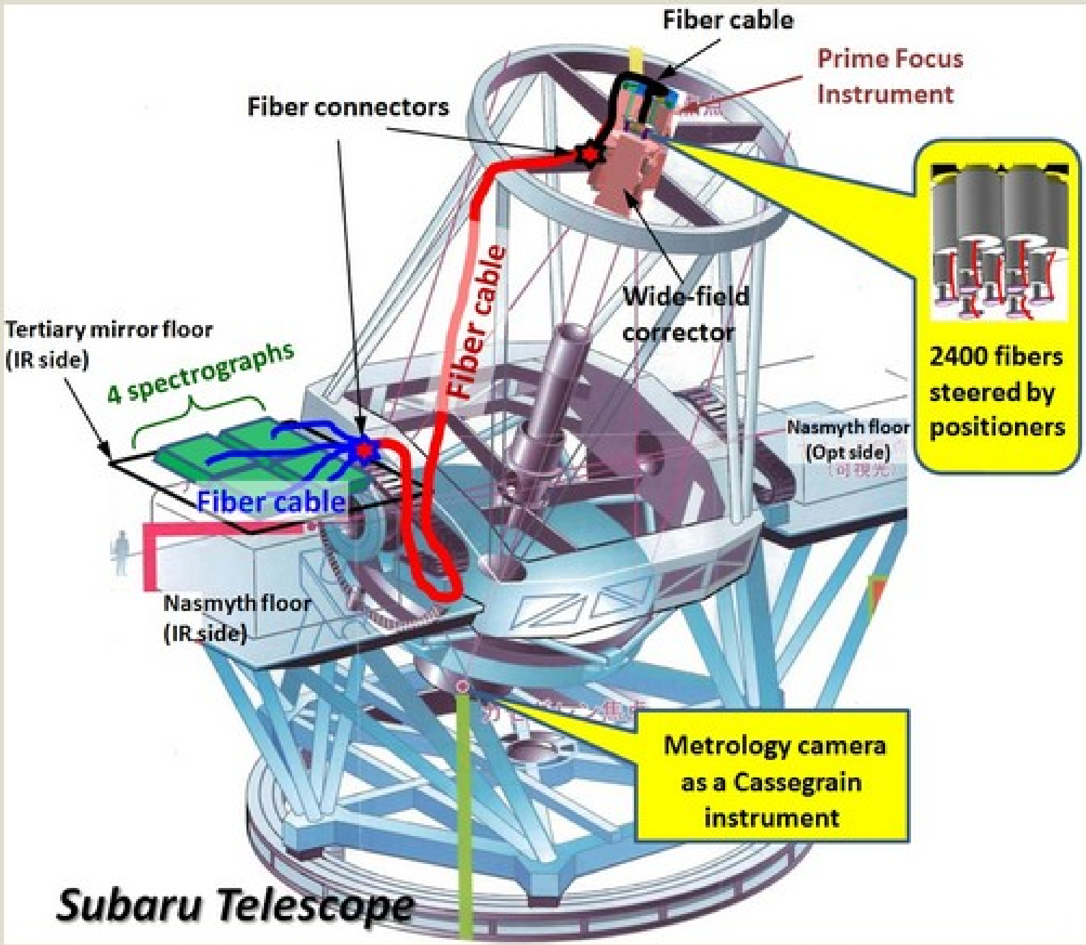


Subaru



http://oir.asiaa.sinica.edu.tw/subaru/pfs.php

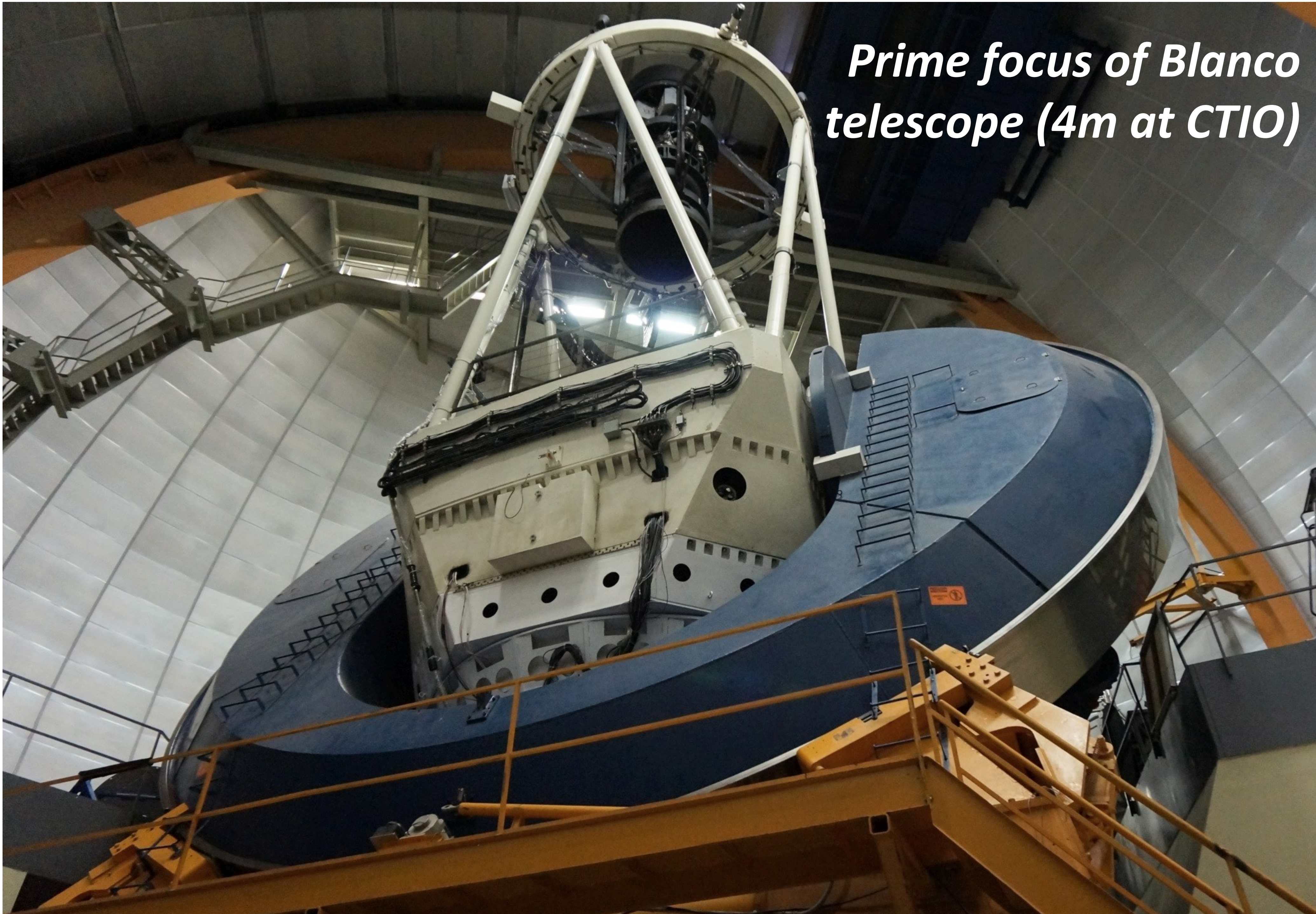
Prime Focus Spectrograph (PFS) for Subaru Telescope



PFS is a fiber fed spectrograph system with a fiber positioner system designed to be mounted at the prime focus of the Subaru 8.2m telescope on Mauna Kea, and feeding 4 fixed spectrographs mounted near the Nasmyth focus. With 2400 fibers & fiber positioners, PFS allows simultaneous spectral observations of up to 2400 astronomical targets. Allocation for the PFS components on the Subaru telescope is shown left. This optical/near-infrared multi-fiber spectrograph targets cosmology with galaxy surveys, Galactic archaeology, and studies of galaxy/AGN evolution.

Taking advantage of Subaru's wide field of view, which is further extended with the recently completed **Wide Field Corrector (WFC)**, PFS will enable us to carry out multi-fiber spectroscopy of **2400 targets** within **1.3 degree** diameter. A microlens is attached at each fiber entrance for F-ratio transformation into a fainter (on slower) one so that difficulties of spectrograph design are eased. Fibers are accurately placed onto target positions by positioners, each of which consists of two stages of piezo-electric rotary motors, through iterations by using back-illuminated fiber position measurements with a wide-field metrology camera. Fibers then carry light to a set of four identical fast-Schmidt spectrographs with three color arms each: the wavelength ranges from **0.38 um to 1.3 um** will be simultaneously observed with an average resolving power of 3000. Before and during the era of extremely large telescopes, PFS will provide the unique capability of obtaining spectra of 2400 cosmological/astrophysical targets simultaneously with an 8-10 meter class telescope.

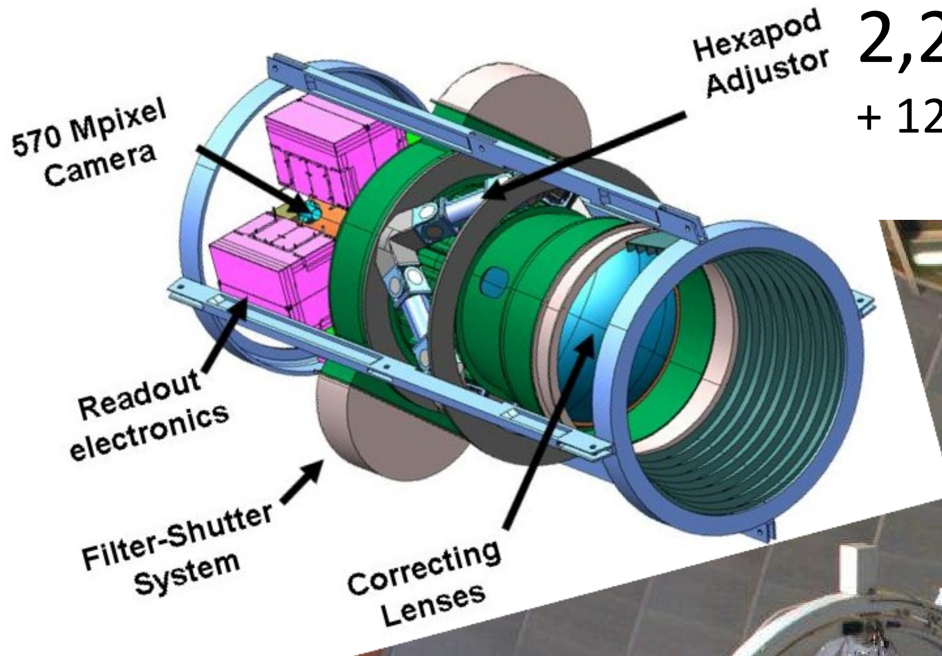
DECAM installed (September 2013)

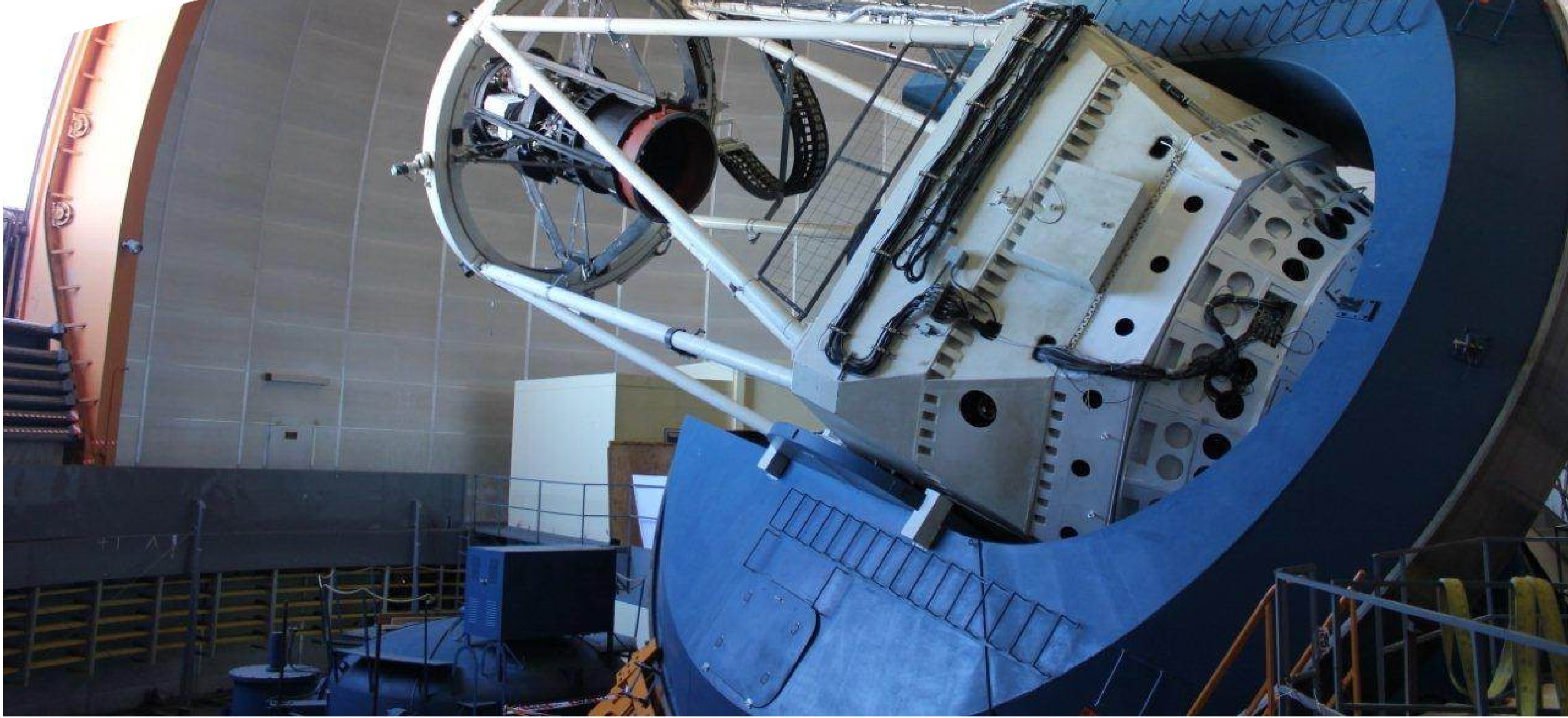


DECAM
(Dark Energy Camera)

2,2° FOV (62 CCDs)

+ 12 CCDs (guiagem e foco)





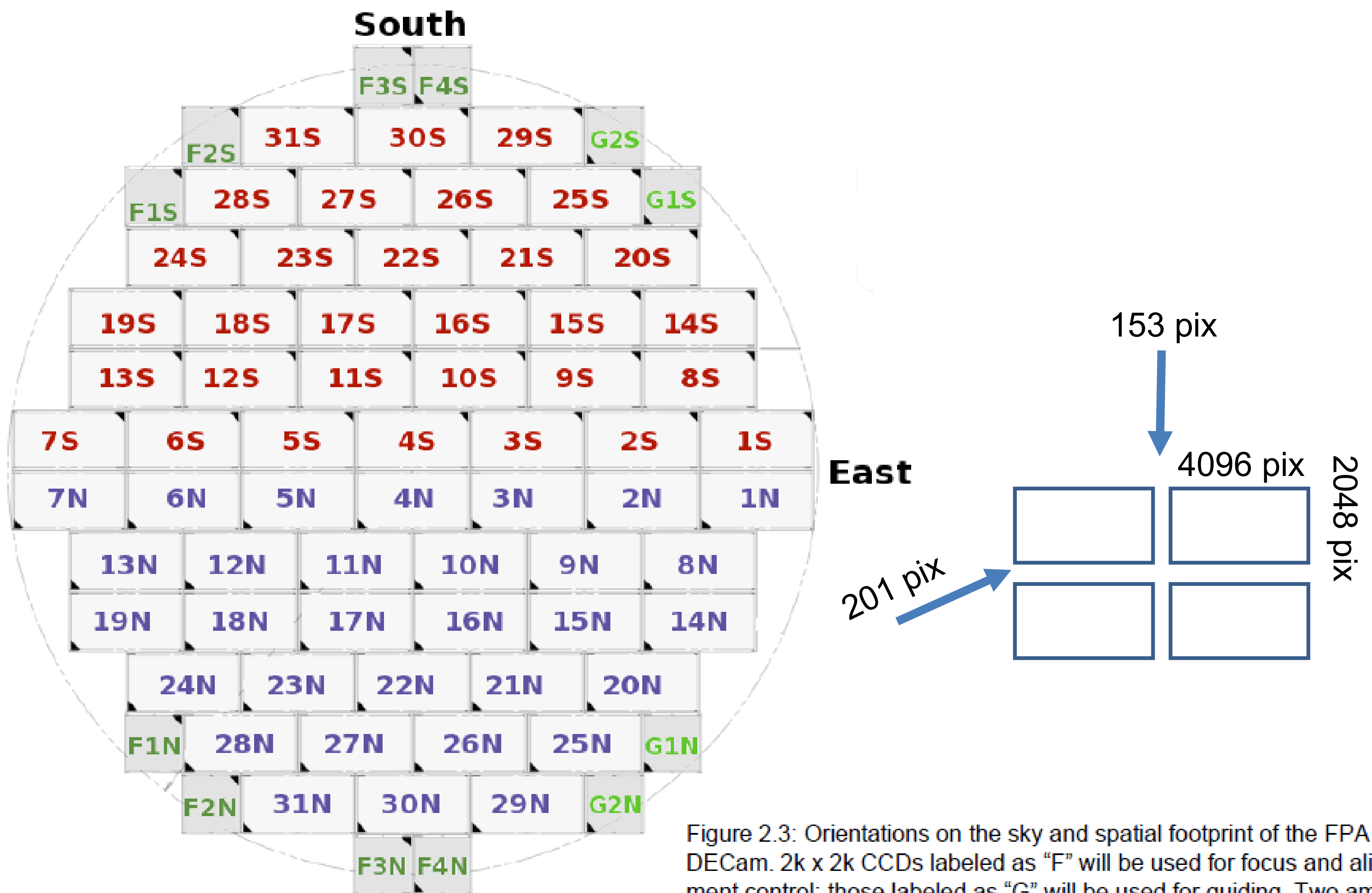
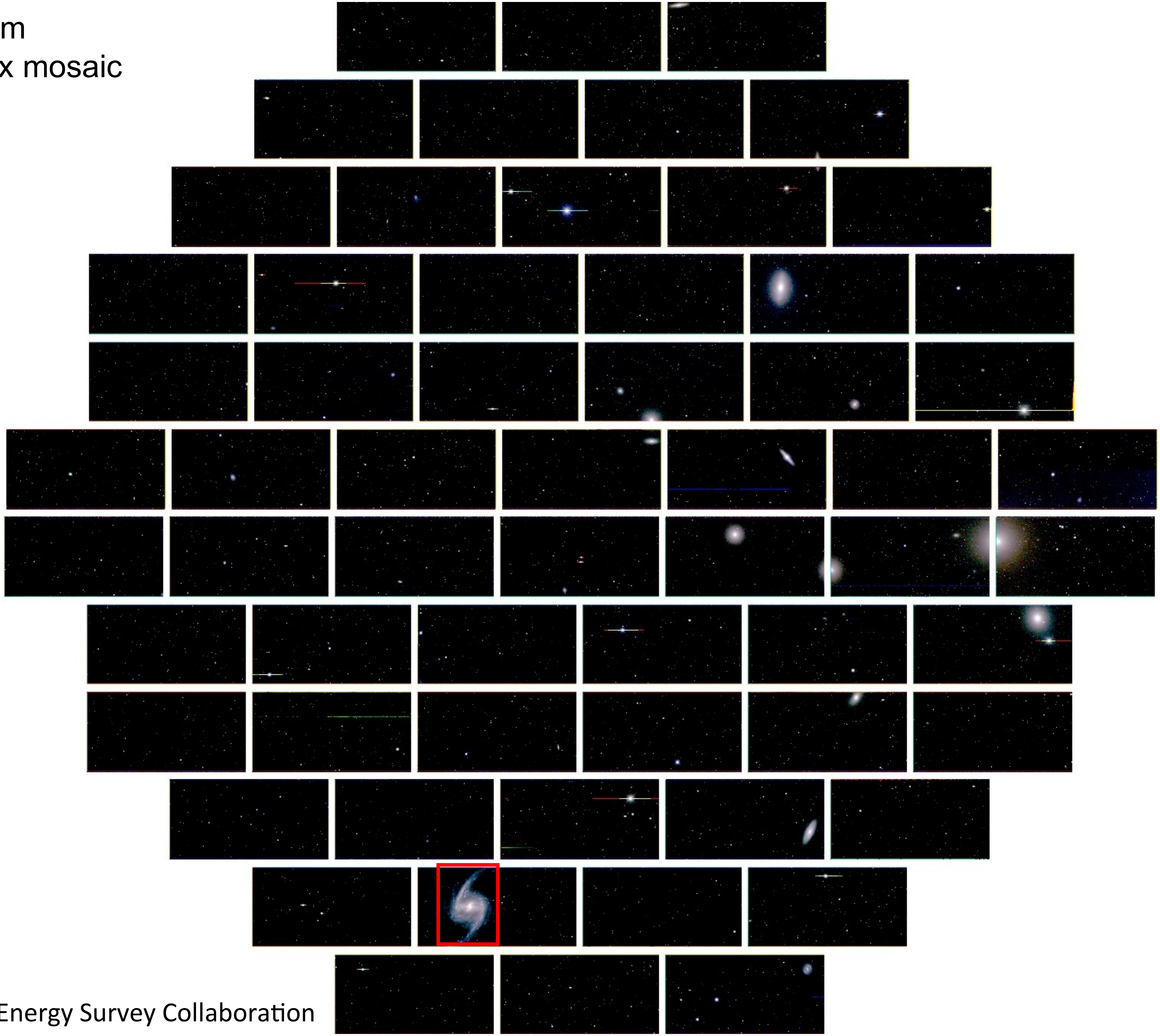


Figure 2.3: Orientations on the sky and spatial footprint of the FPA for DECam. 2k x 2k CCDs labeled as "F" will be used for focus and alignment control; those labeled as "G" will be used for guiding. Two amplifiers on each chip may be used for parallel read-out. The pixel coordinate origin is in the lower-left corner of each detector array.

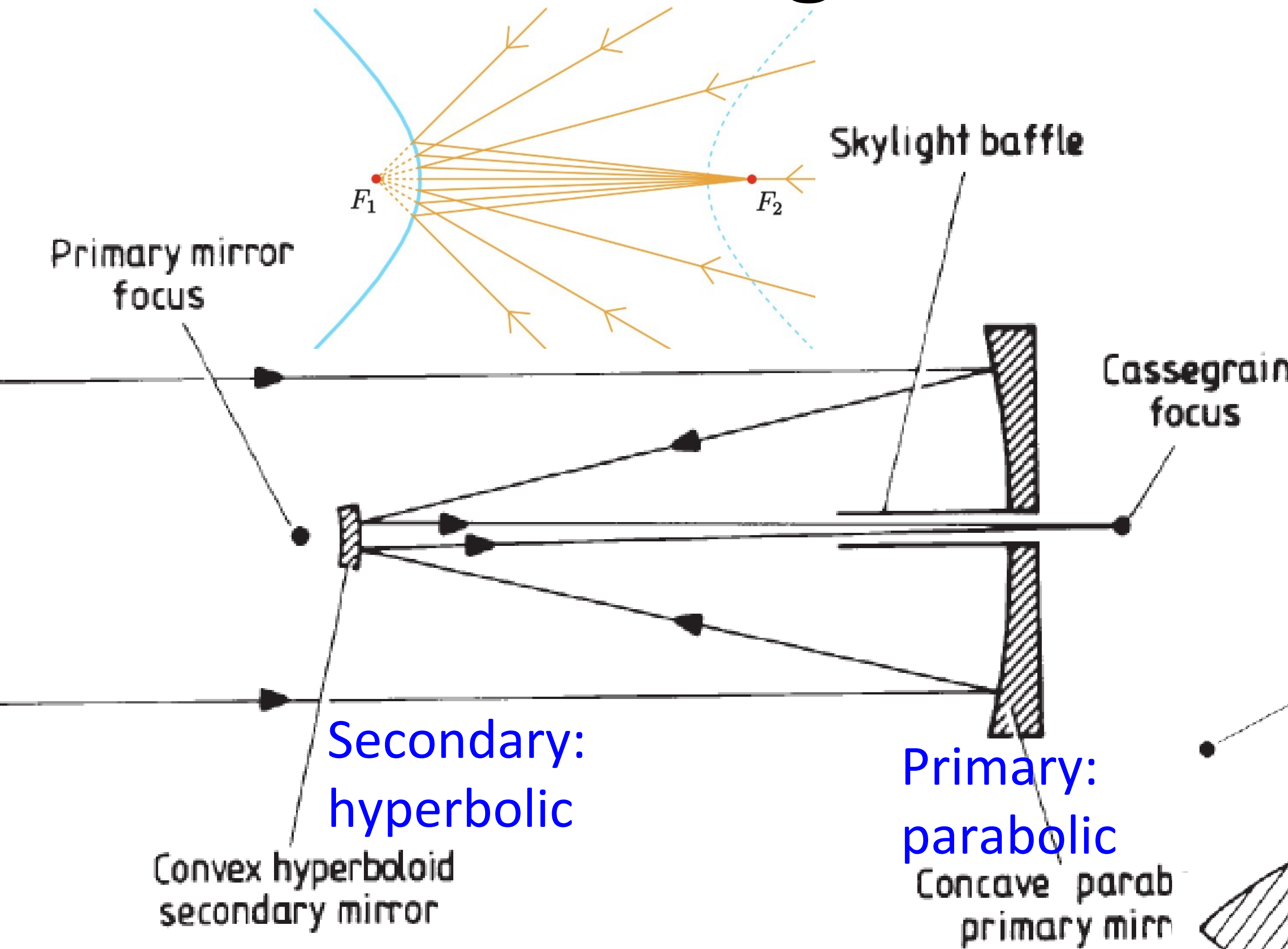
http://www.noao.edu/meetings/decam/media/DECam_Data_Handbook.pdf

DECam
Fornax mosaic



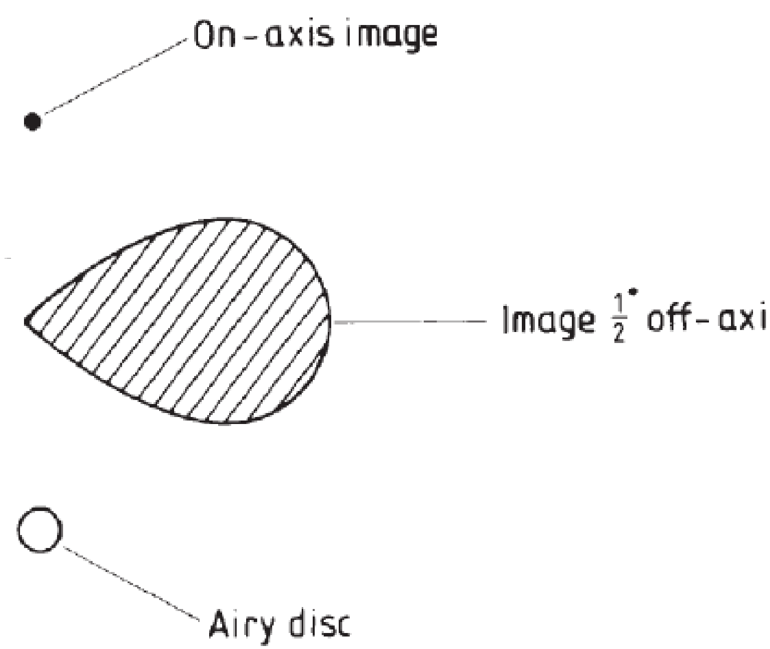
NGC 1365 is a barred spiral galaxy around 60 million light years from Earth, located in the Fornax galactic cluster.

Reflectors: Cassegrain focus



Cassegrain telescope optical system.

- adequate position to put instruments
- compact telescope: secondary increases the focal distance of the telescope

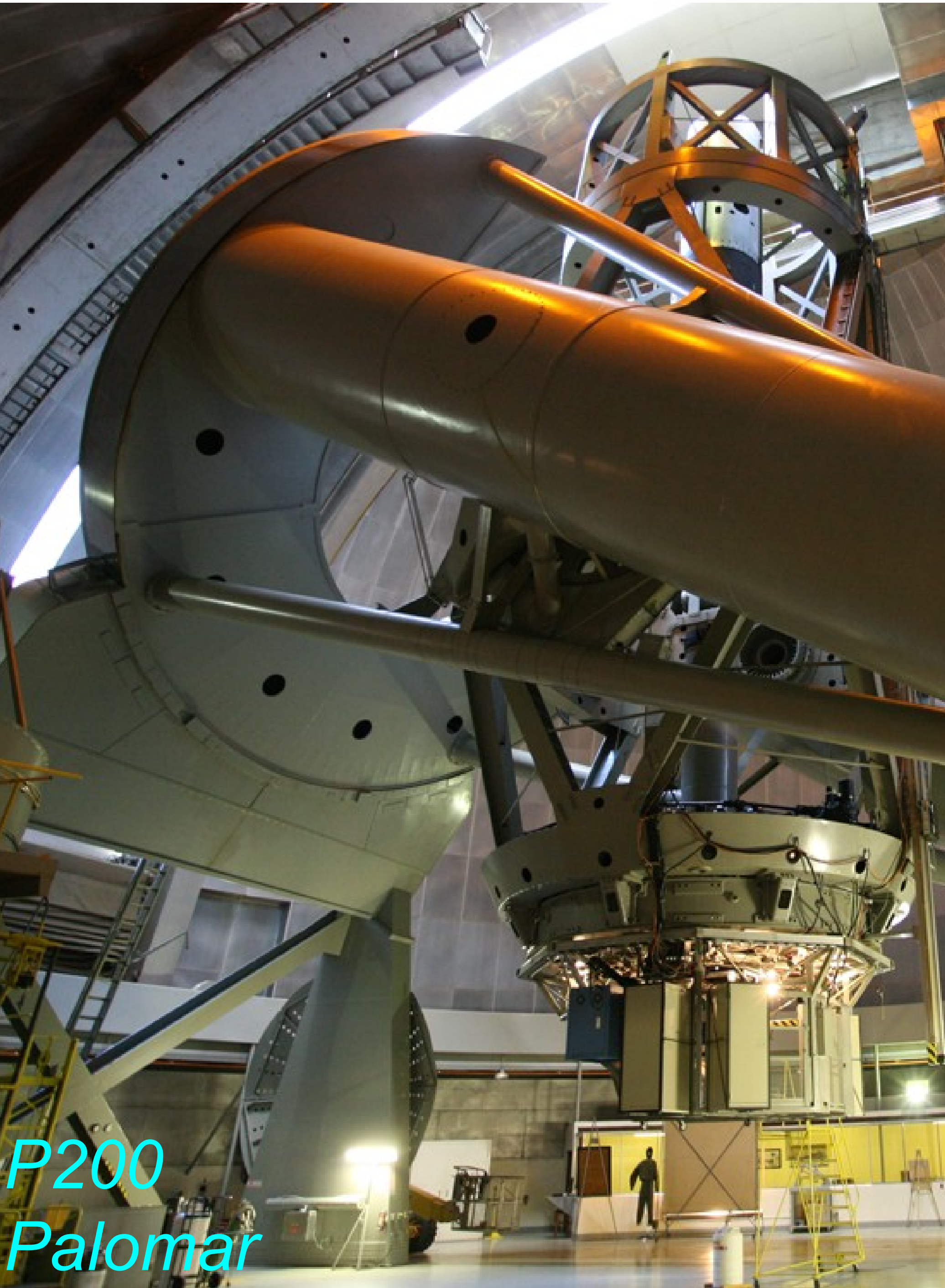


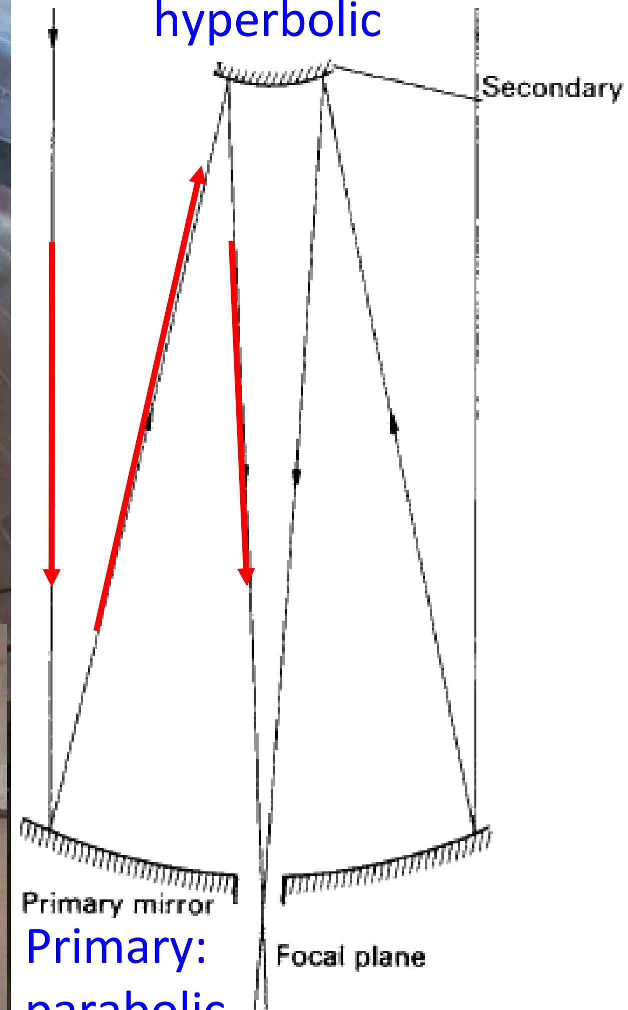
Kitchin

Images in a 0.25 m f4/f16 Cassegrain telescope

5″

Reflectors: Cassegrain focus



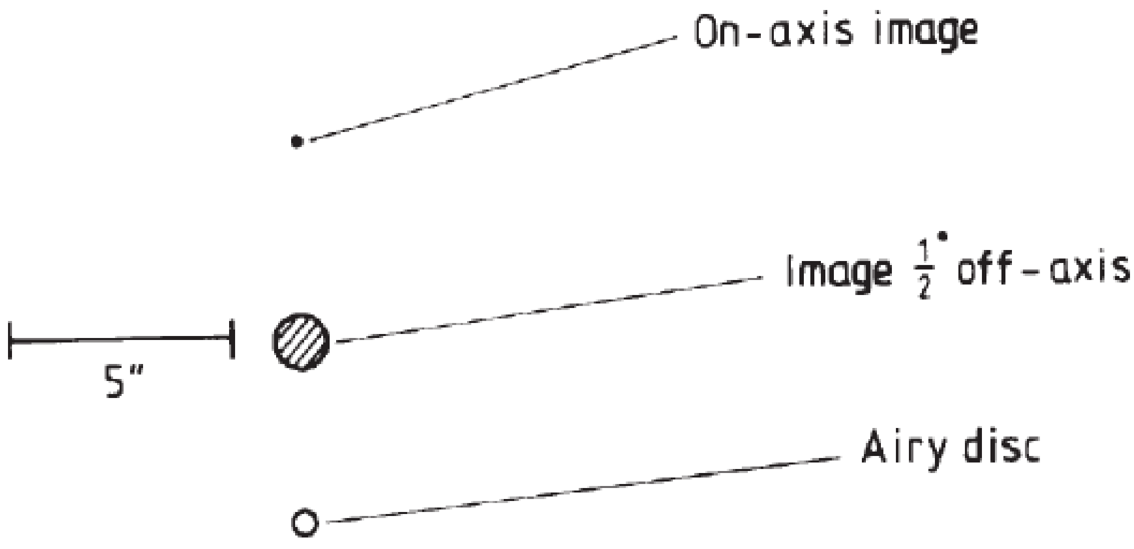


Palomar 5m: Last big telescope of Cassegrain type

Zeiss, OPD.
Primary: parabolic, secondary: hyperbolic
A razão focal no foco Cassegrain é f/12,5

Reflectors: Ritchey-Chrétien telescope

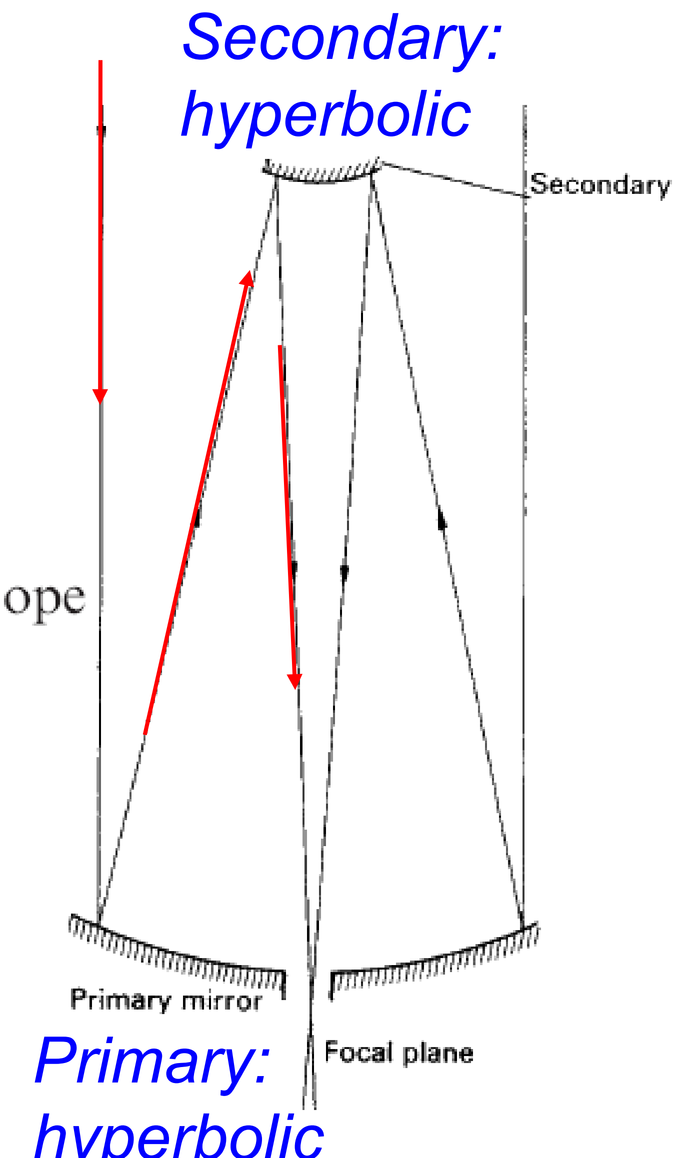
Variation of Cassegrain with hyperbolic primary: better image quality



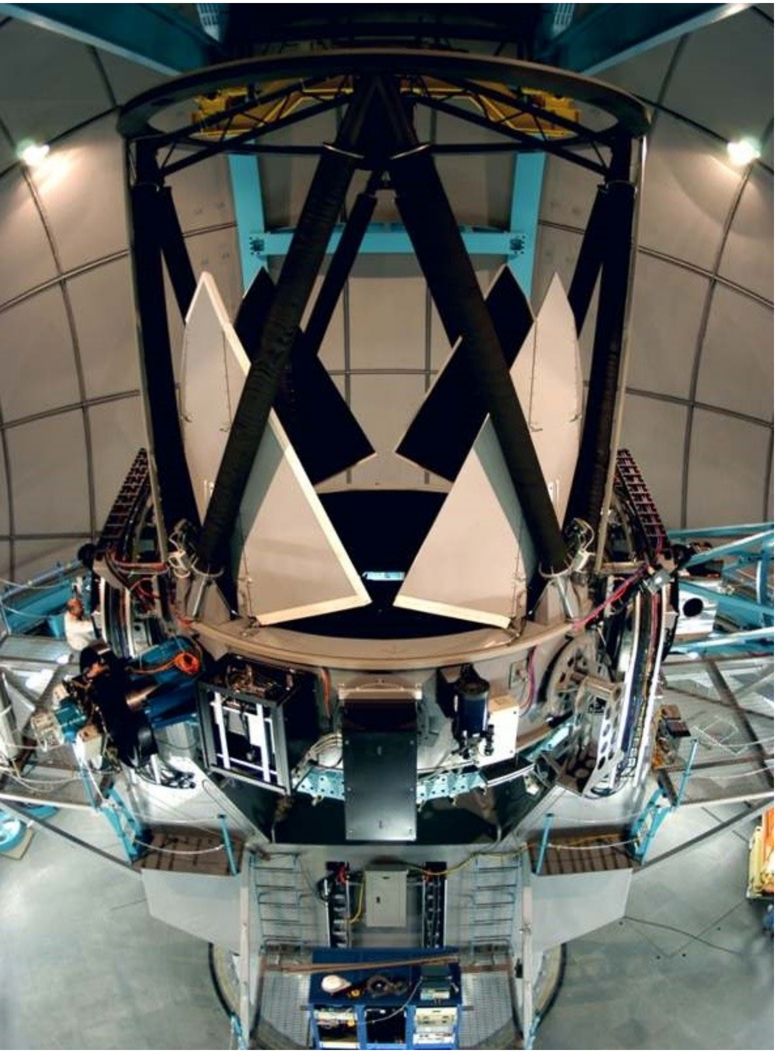
Ray tracing images in a 0.5 m f3/f8 Ritchey–Chrétien telescope

Kitchin

George Ritchey's 24-inch (60cm) reflecting telescope, first RCT constructed in 1927

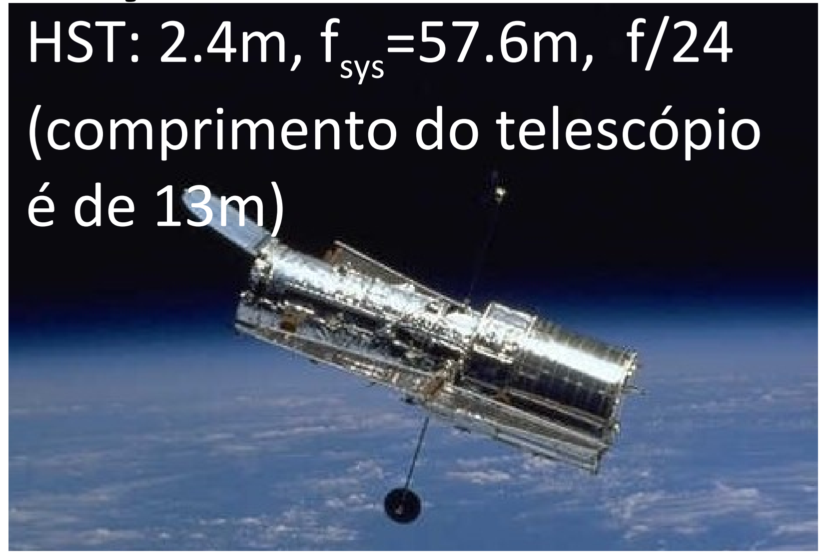


Reflectors: Ritchey-Chrétien telescope



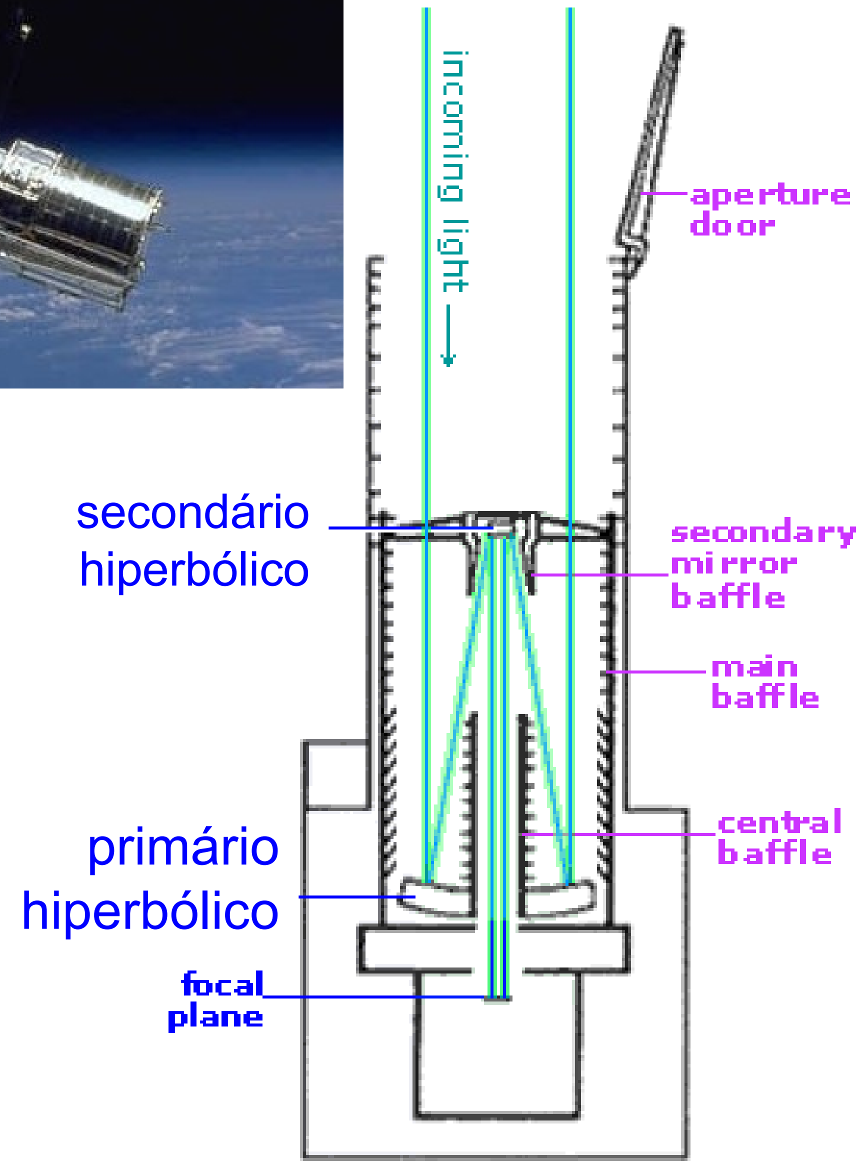
SOAR: 4.1m, f/16

HST: 2.4m, f_{sys}=57.6m, f/24
(comprimento do telescópio é de 13m)



LNA: 1.6m, f/10

Cut through HST

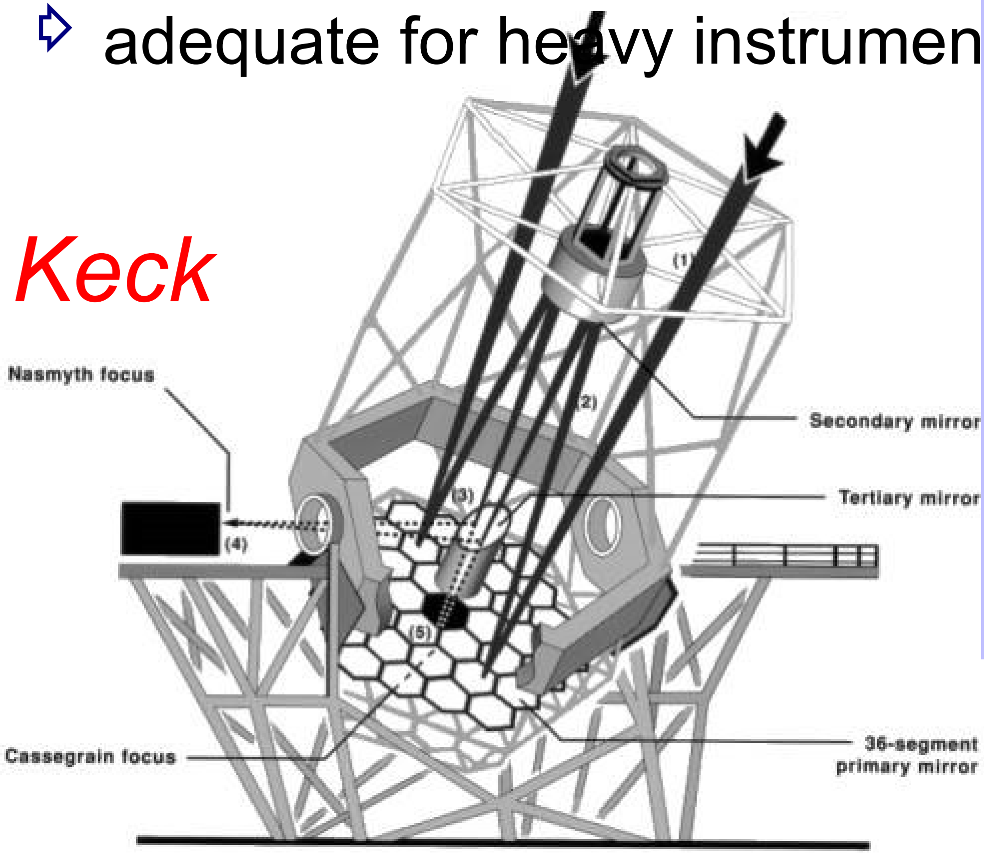


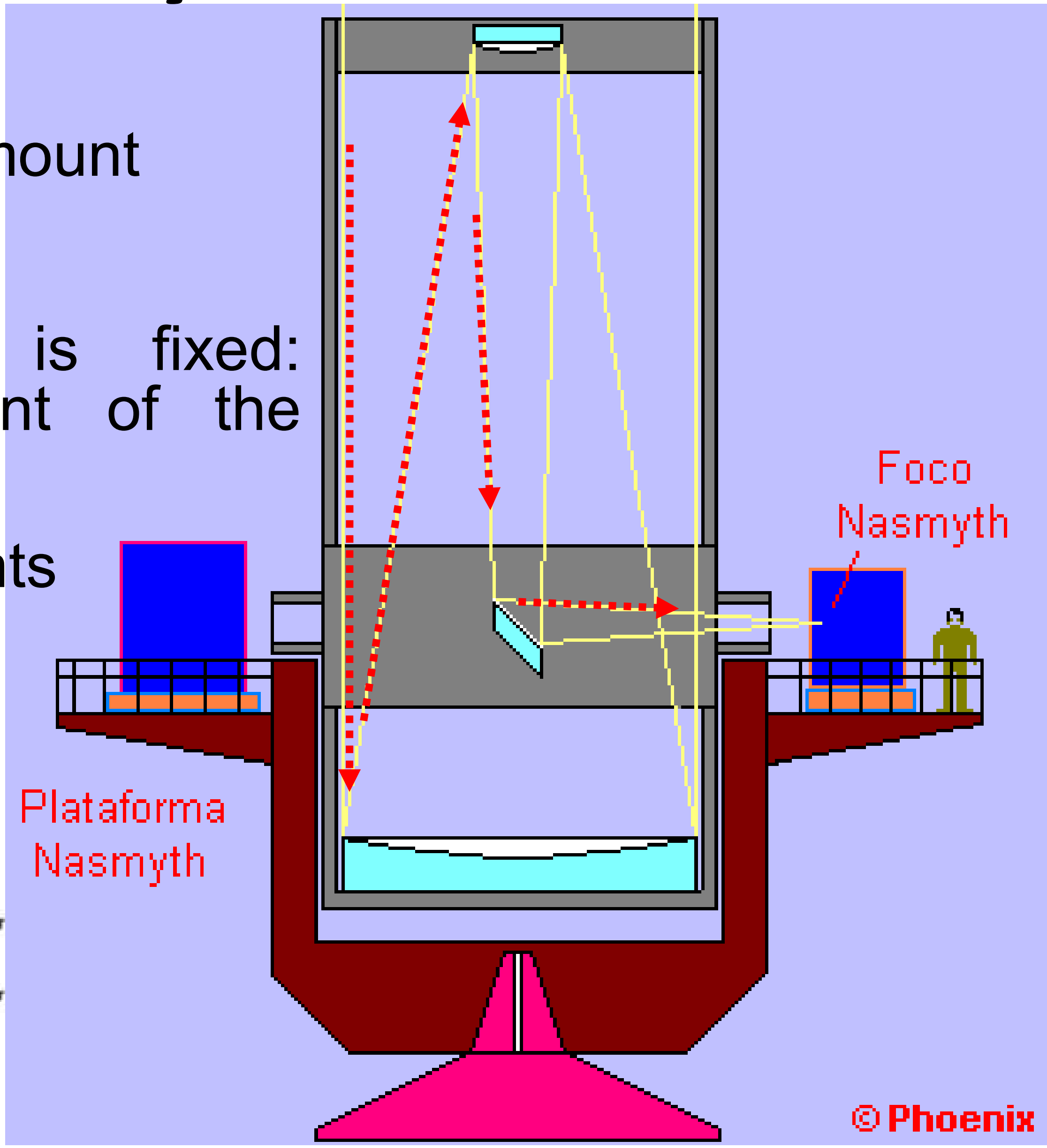
Nasa

Refletors: focos Nasmyth & Coudé

Nasmyth

- telescope with alta-azimutal mount
- flat mirror at the altitude axis
- position of the focus is fixed: independent of the movement of the telescope
- adequate for heavy instruments





Big telescopes have Nasmyth focus for big instruments, except Gemini …

Reflectors: Coudé focus

Coudé: similar to Nasmyth but for equatorial mount

Example: Coudé spectrograph at OPD

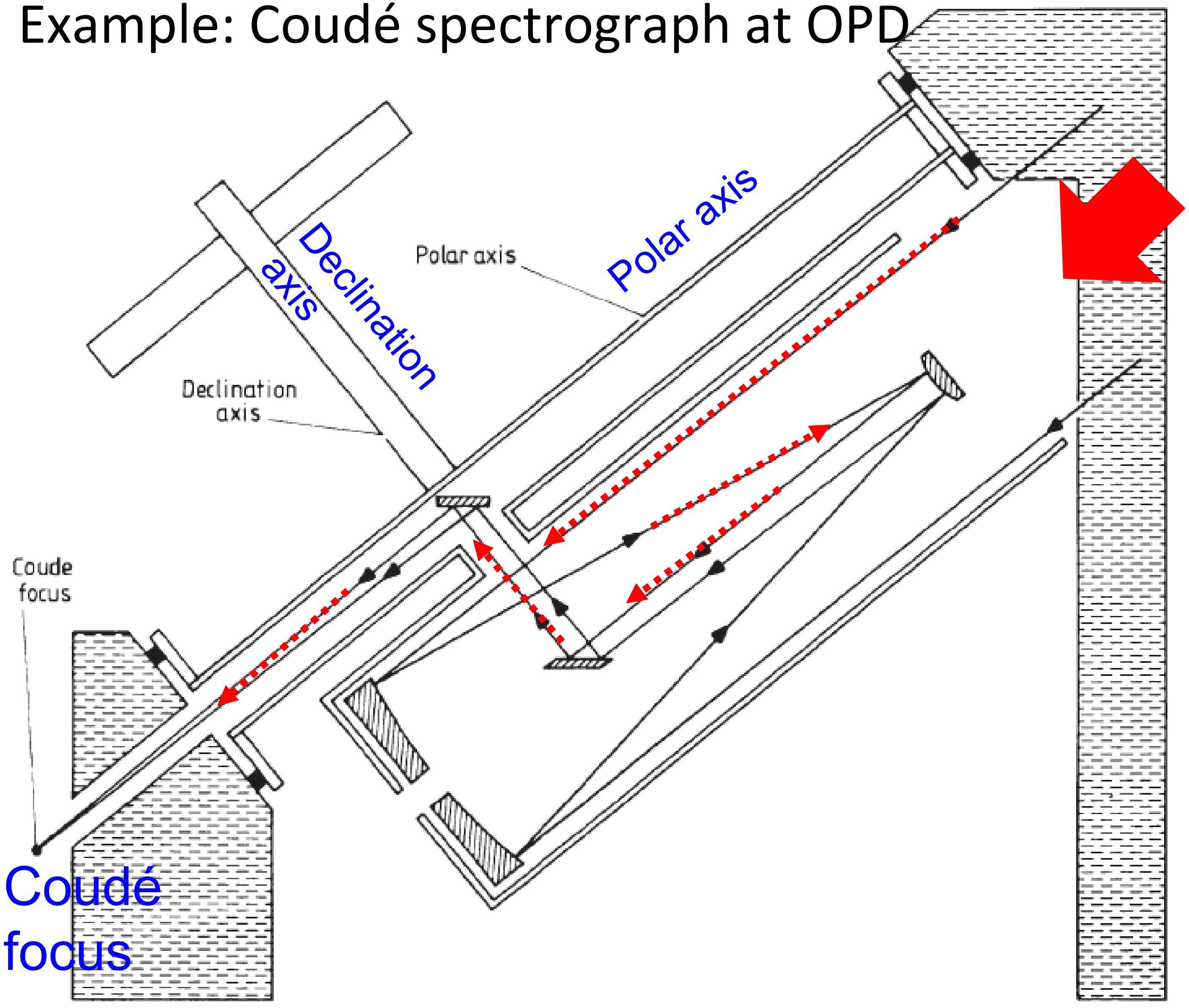
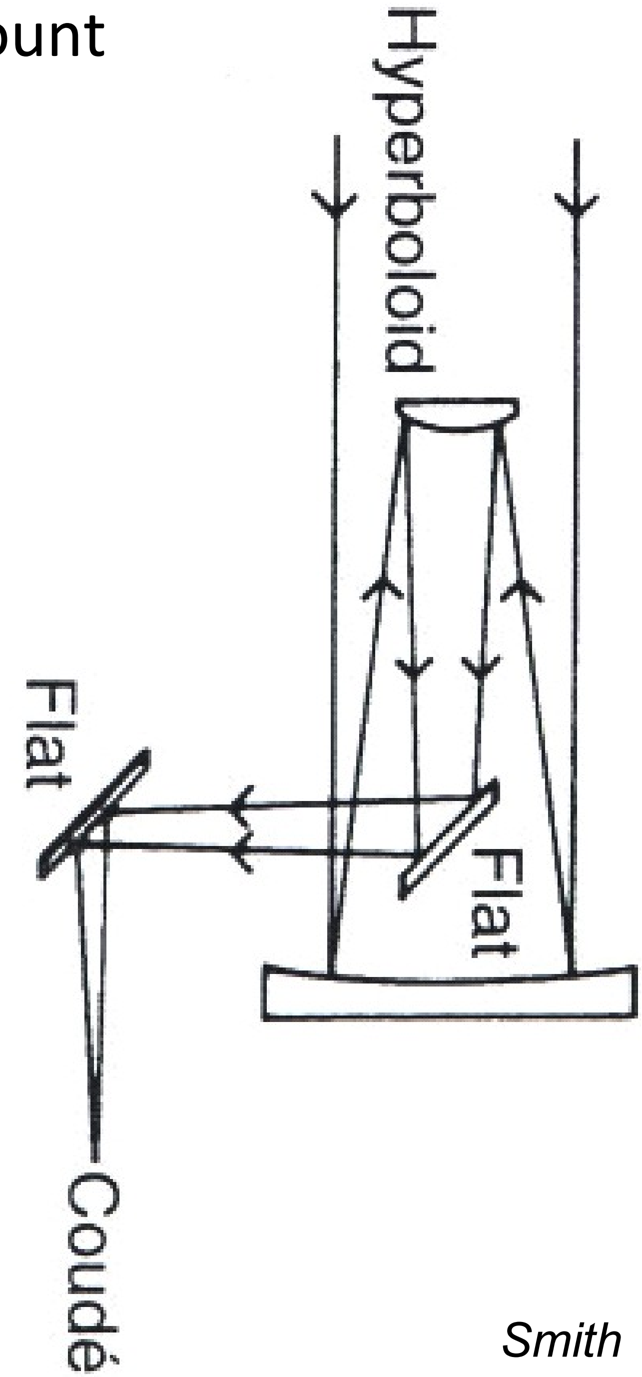


Figure 1.1.44. Coudé system for a modified English mounting.

Kitchin

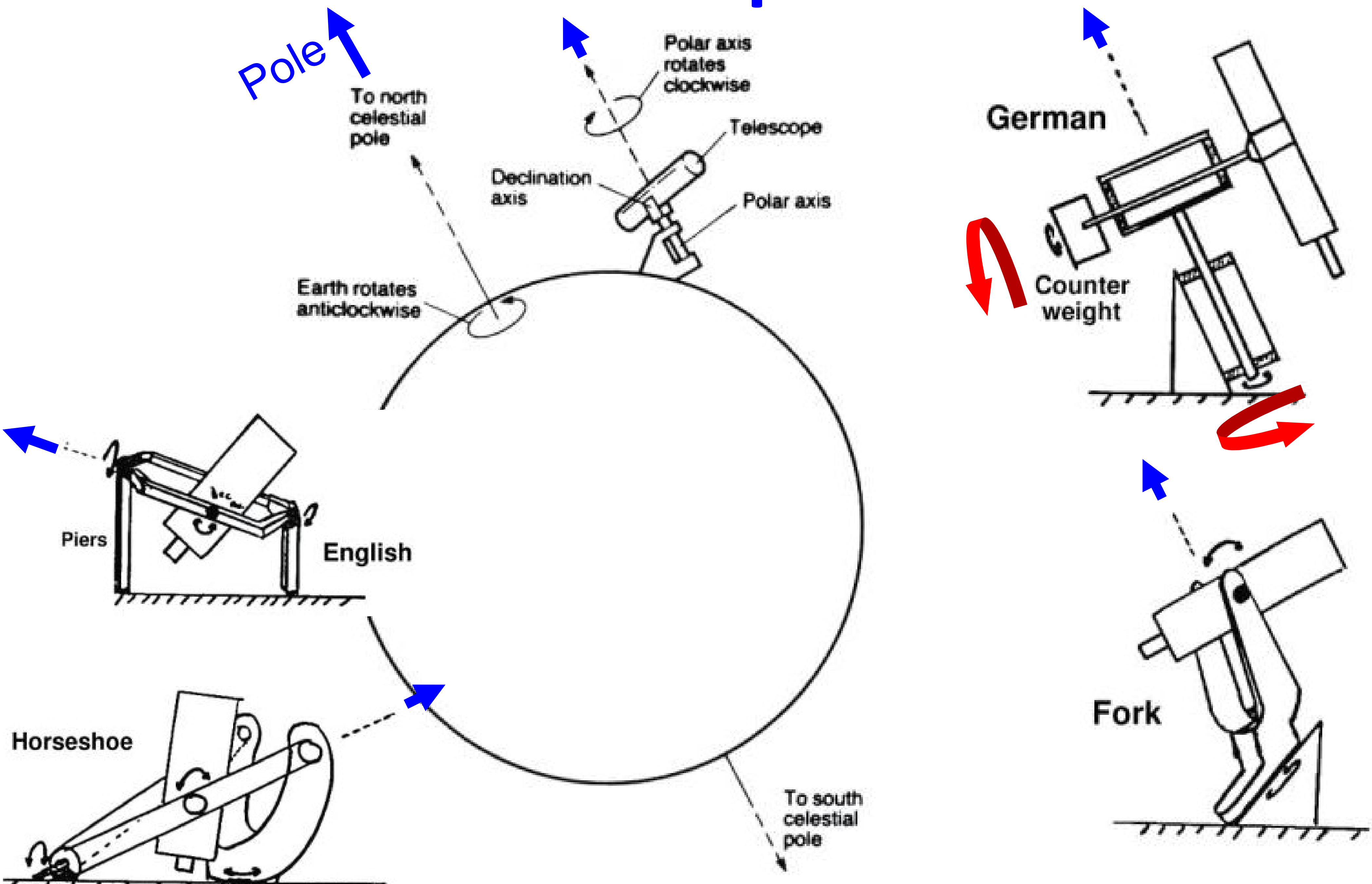


Smith

Reflectors: problems similar to those of refractor telescopes

- Spherical
- Coma
- Astigmatism
- Image curvature
- Distortion
- Vignetting (is not a fault of mirror or lens. It arises because of uneven illumination on the image plane (obstruction of the light path by parts of the instrument)

Mounts: Equatorial



Birney

Mounts: Equatorial / German

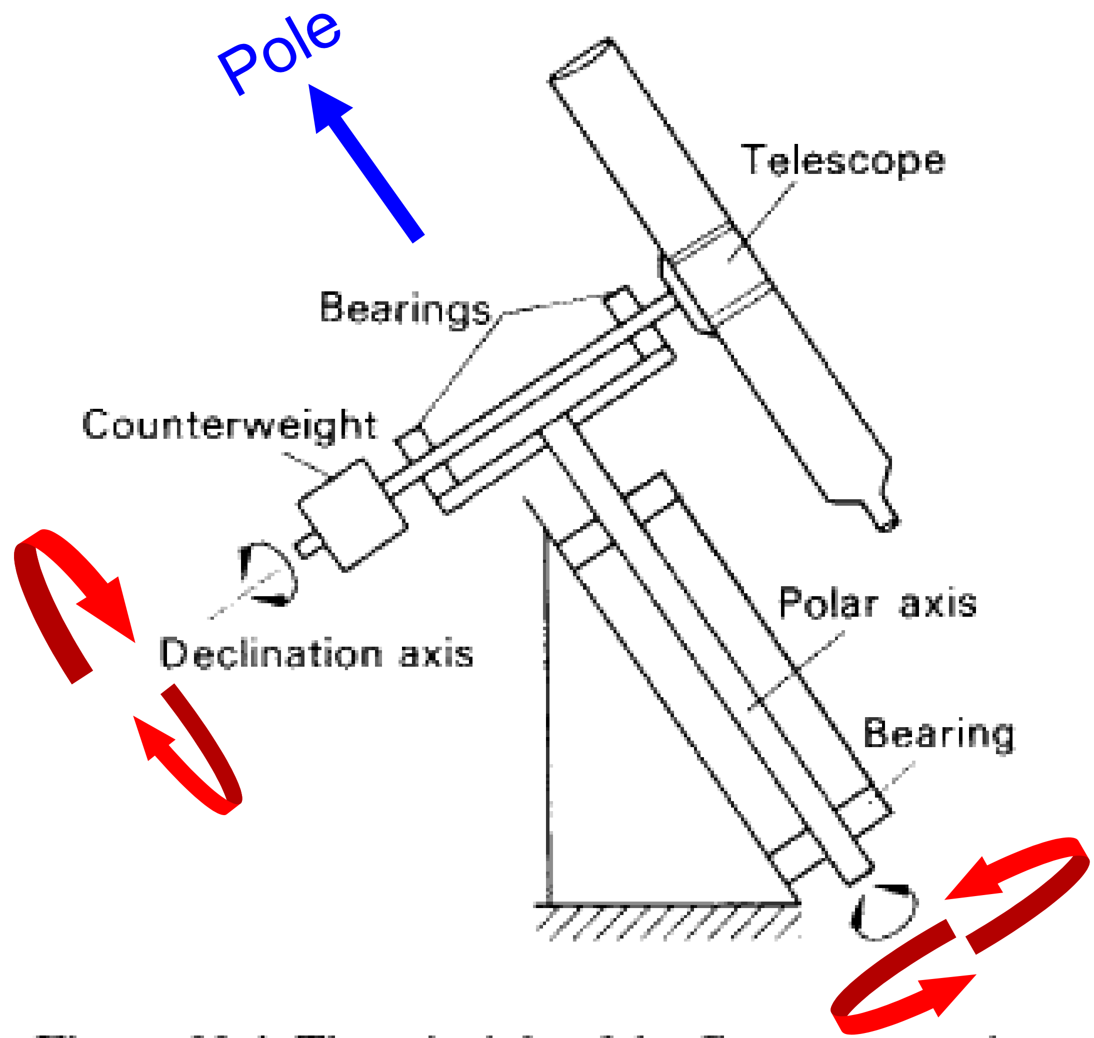
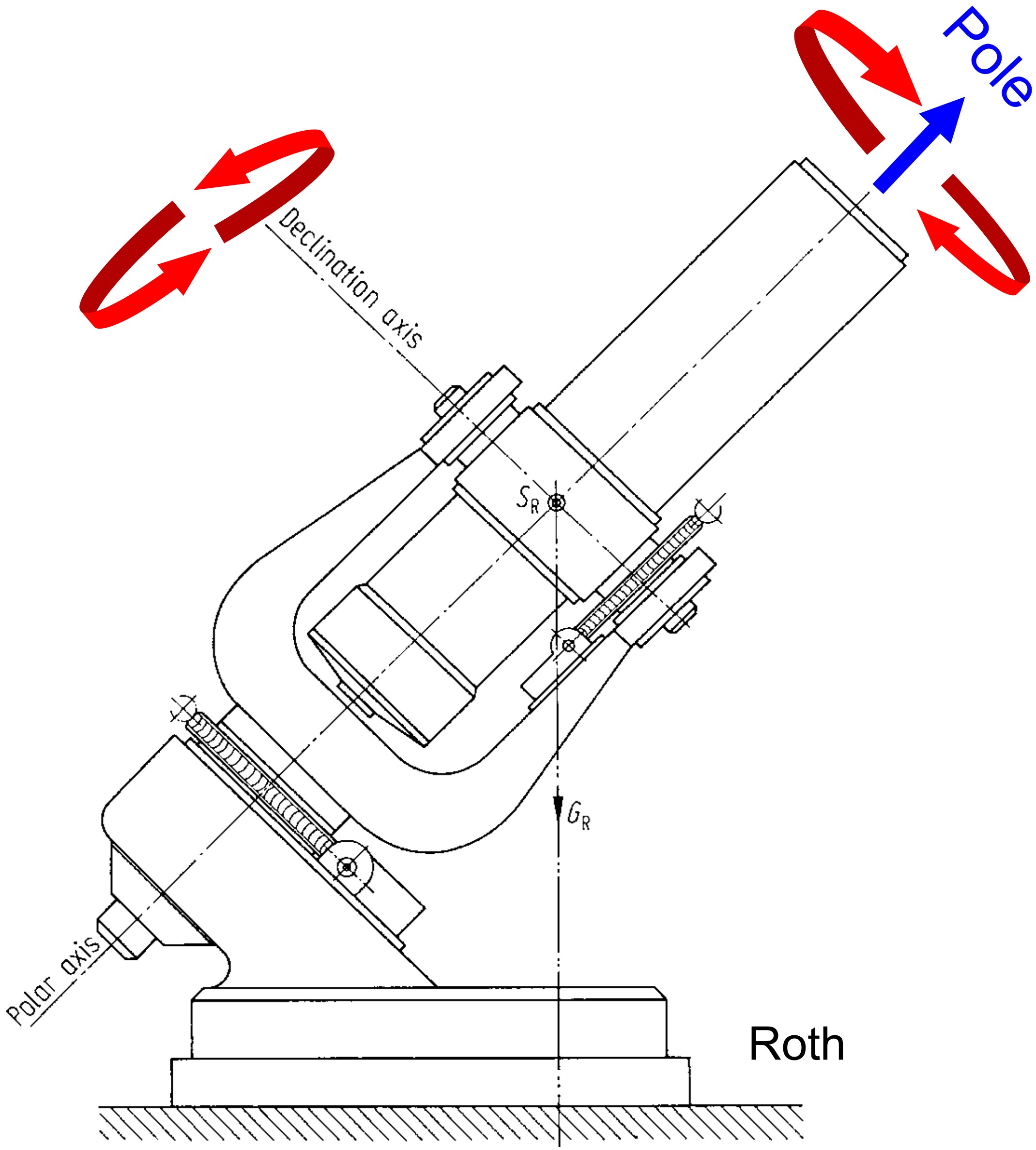


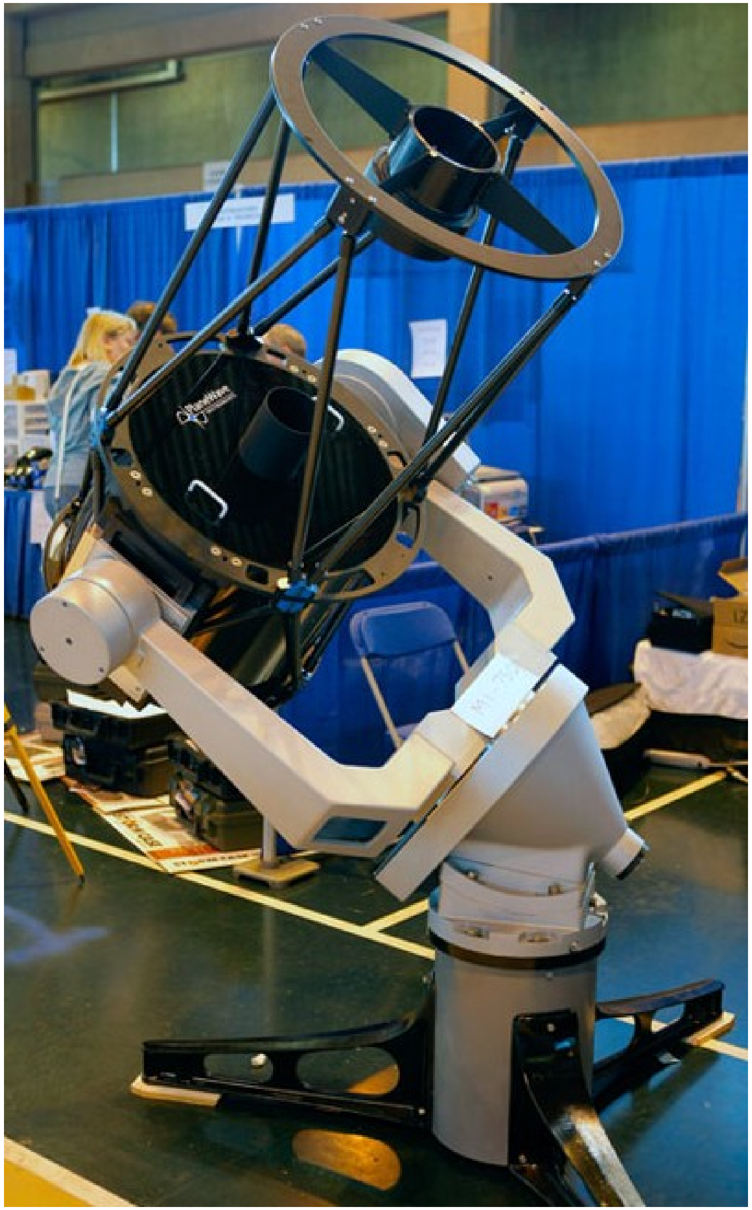
Figure 22.4. The principle of the German mounting.

Roy & Clarke

Mounts: Equatorial / *Fork* (Garfo)



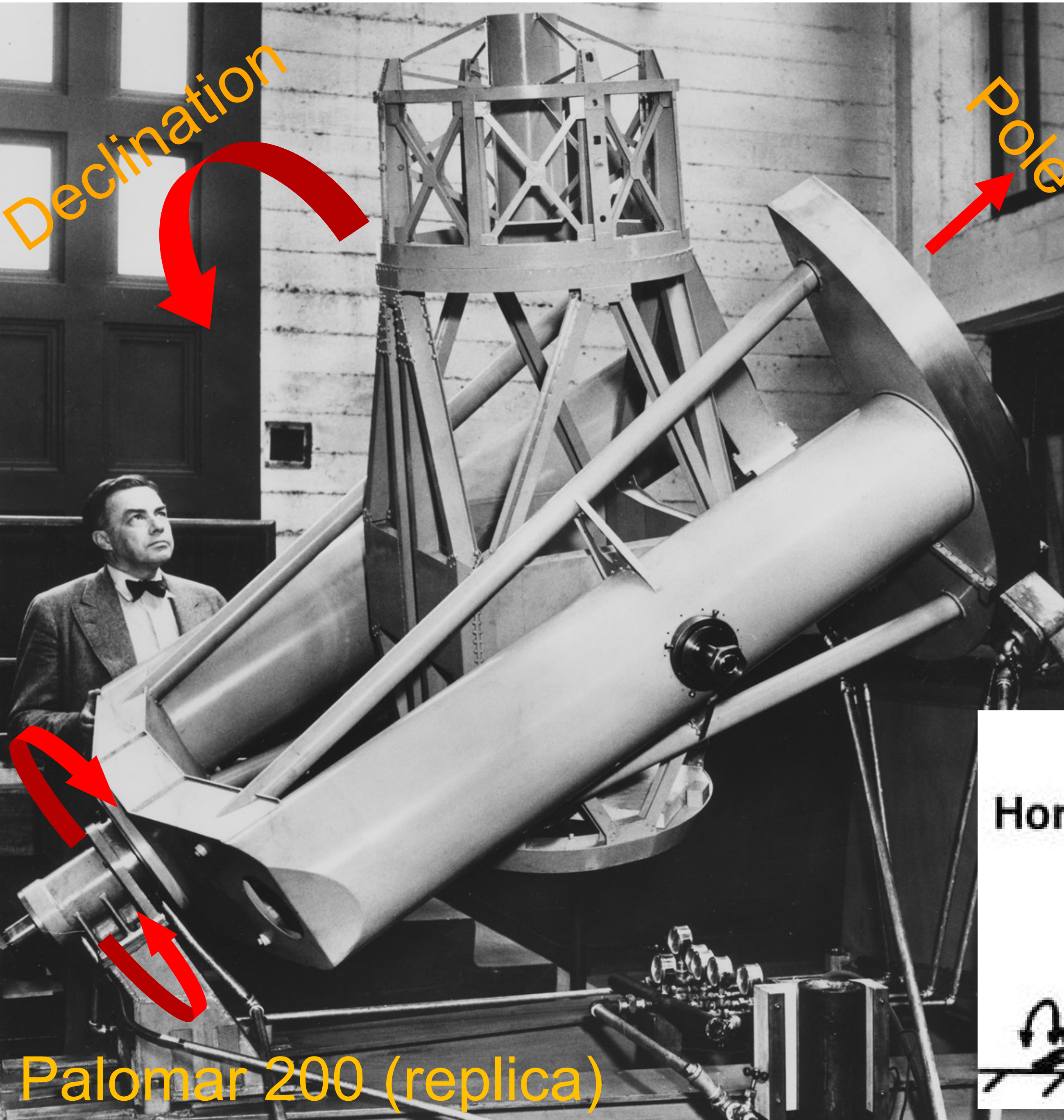
Roth

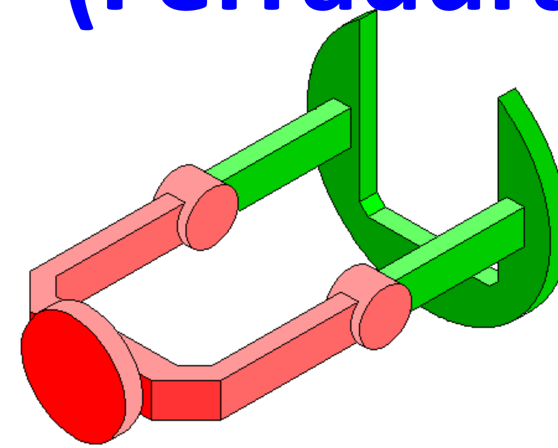


Fork equatorial

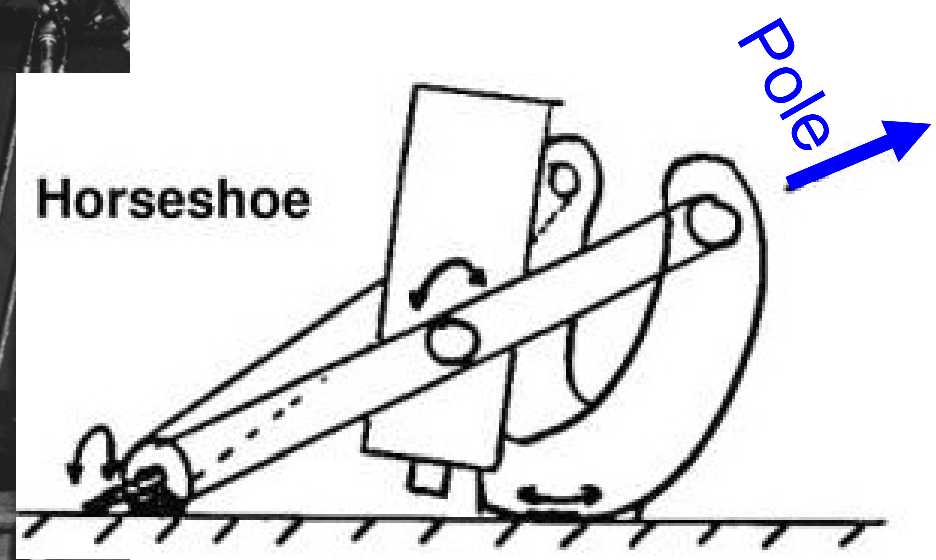
2,2 m telescope at La Silla
Fork mount

Mounts: Equatorial / *Horseshoe* (Ferradura)



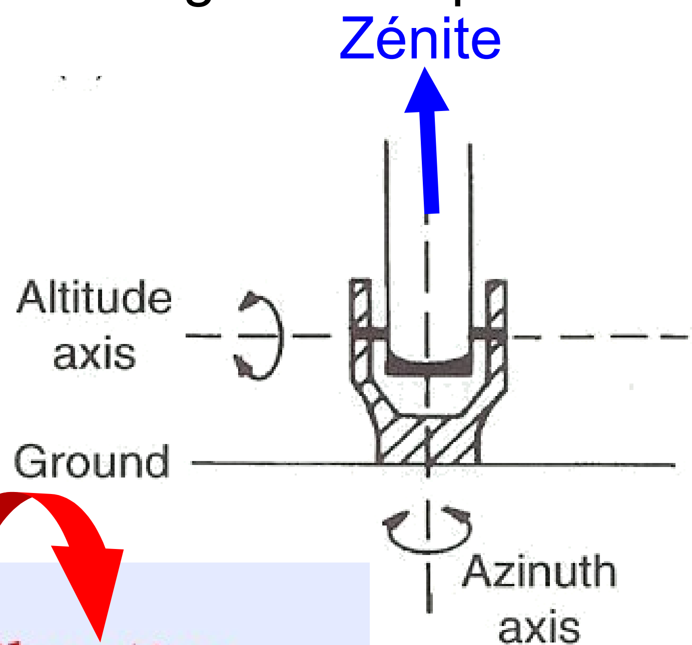


Old large telescopes (<=5m) have *horseshoe* mount

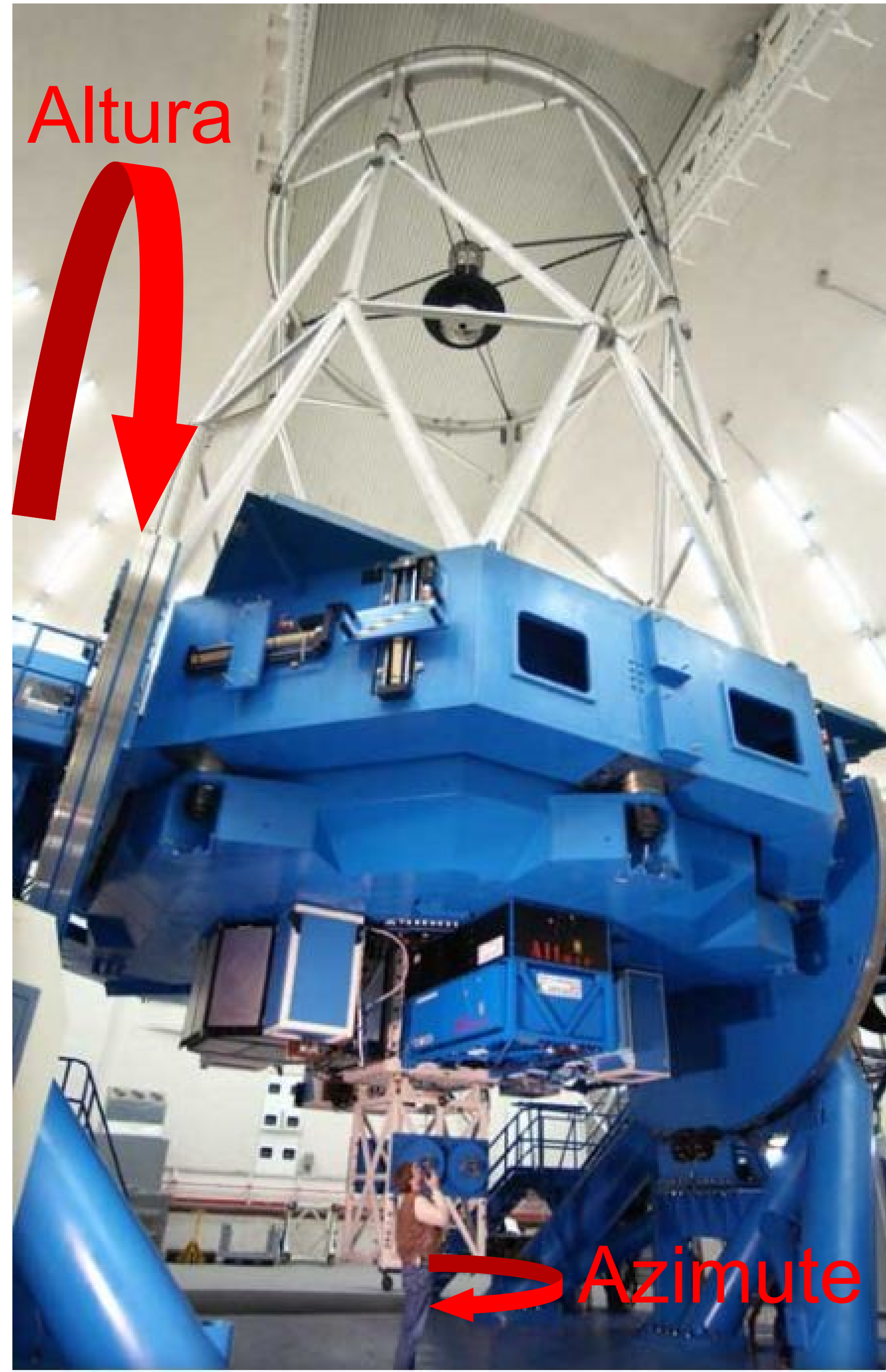


Mounts: Alta-azimutal

- common at all large telescopes

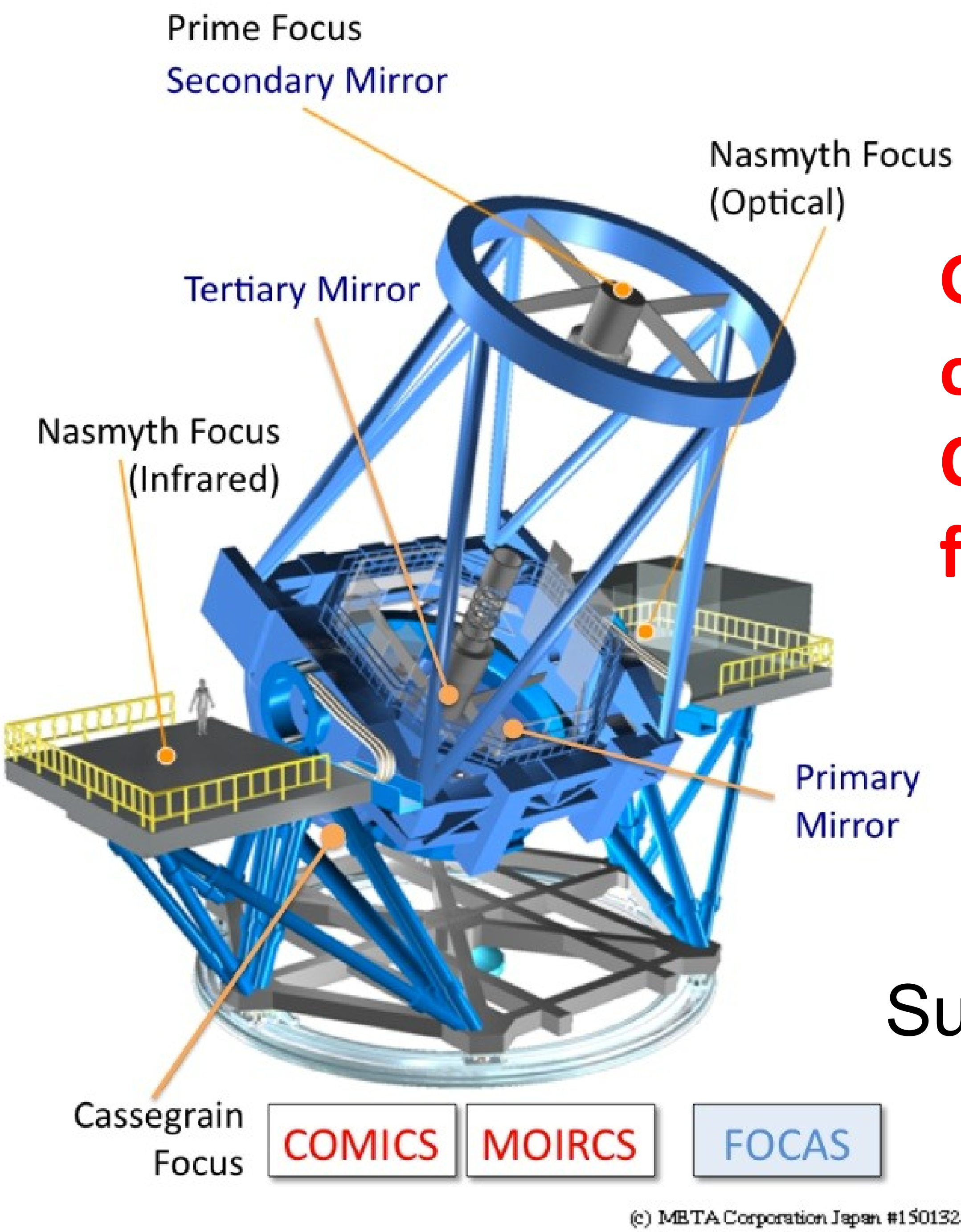


Gemini North



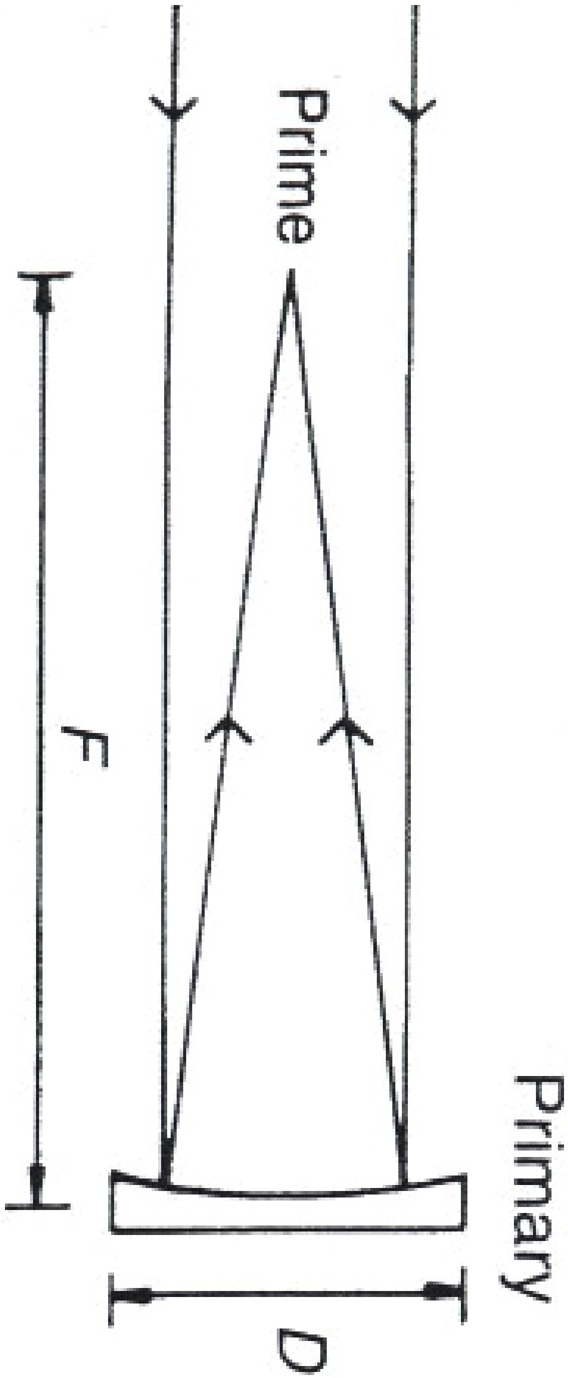
Subaru has Prime + Nasmyth + Cassegrain focus

Smith



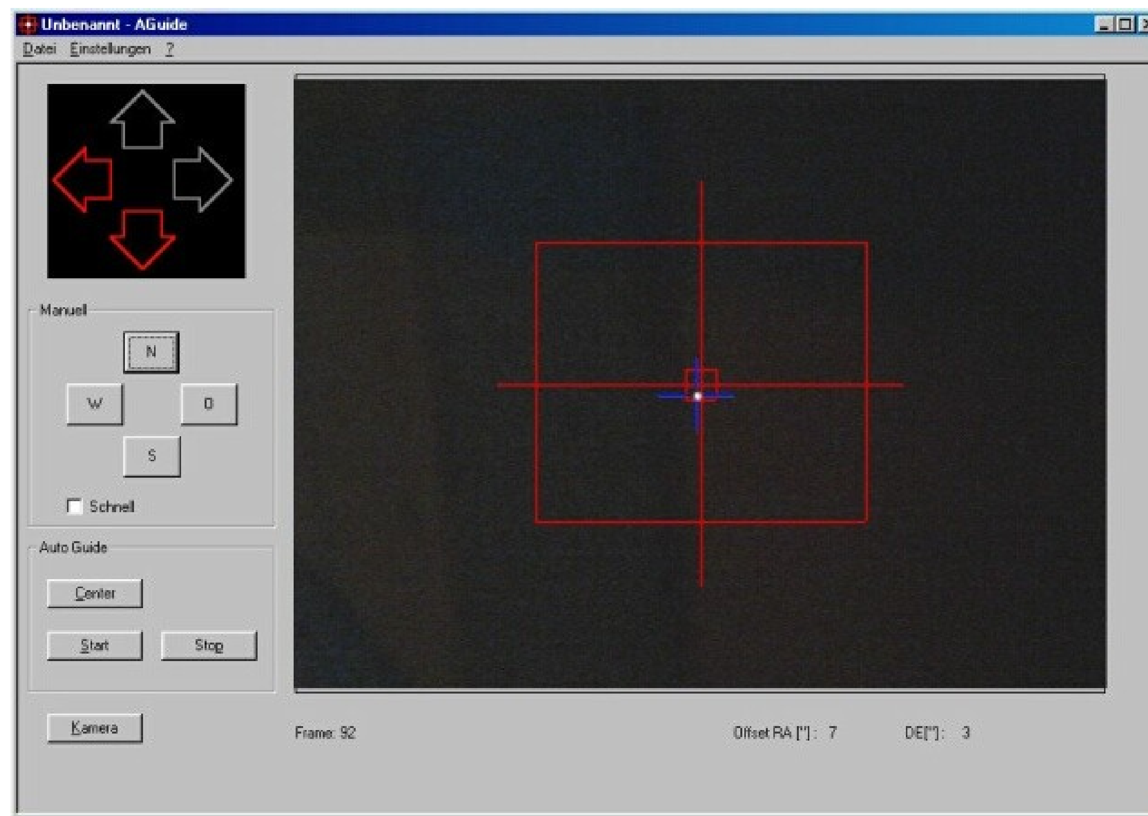
Gemini has only Cassegrain focus

Subaru

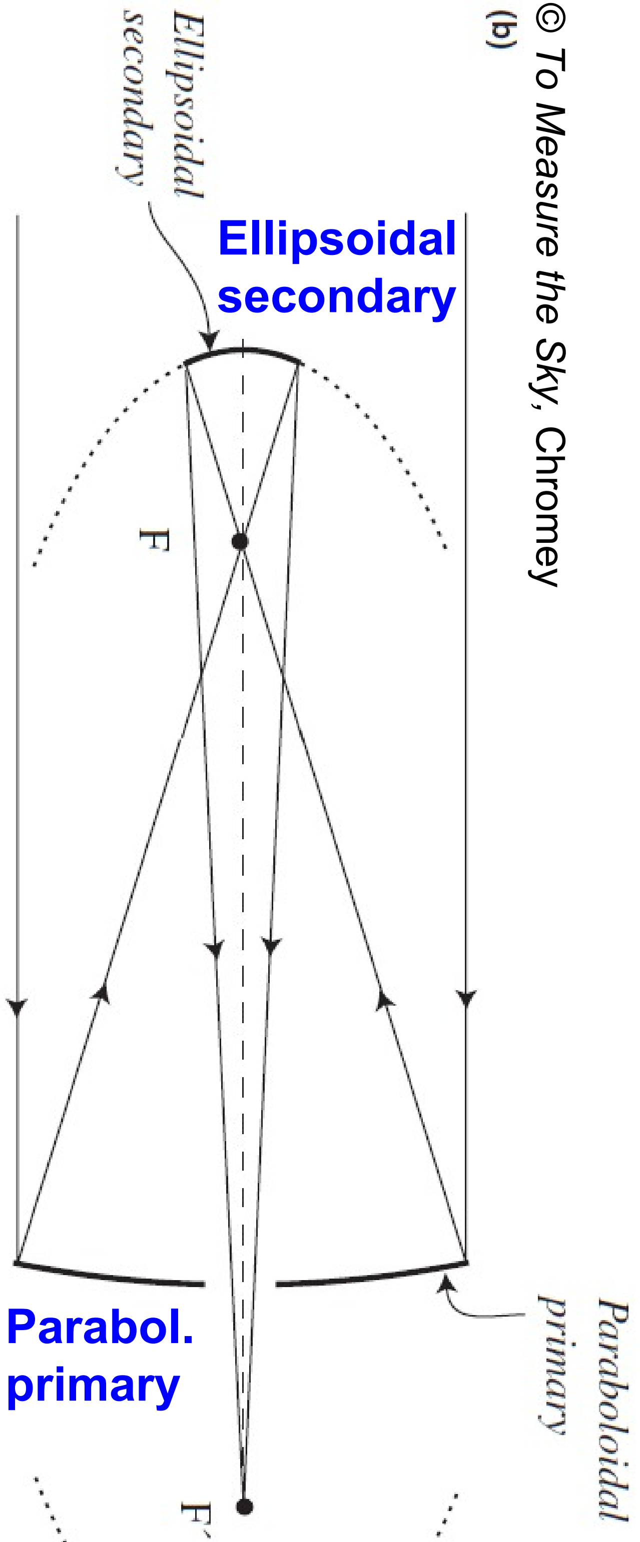


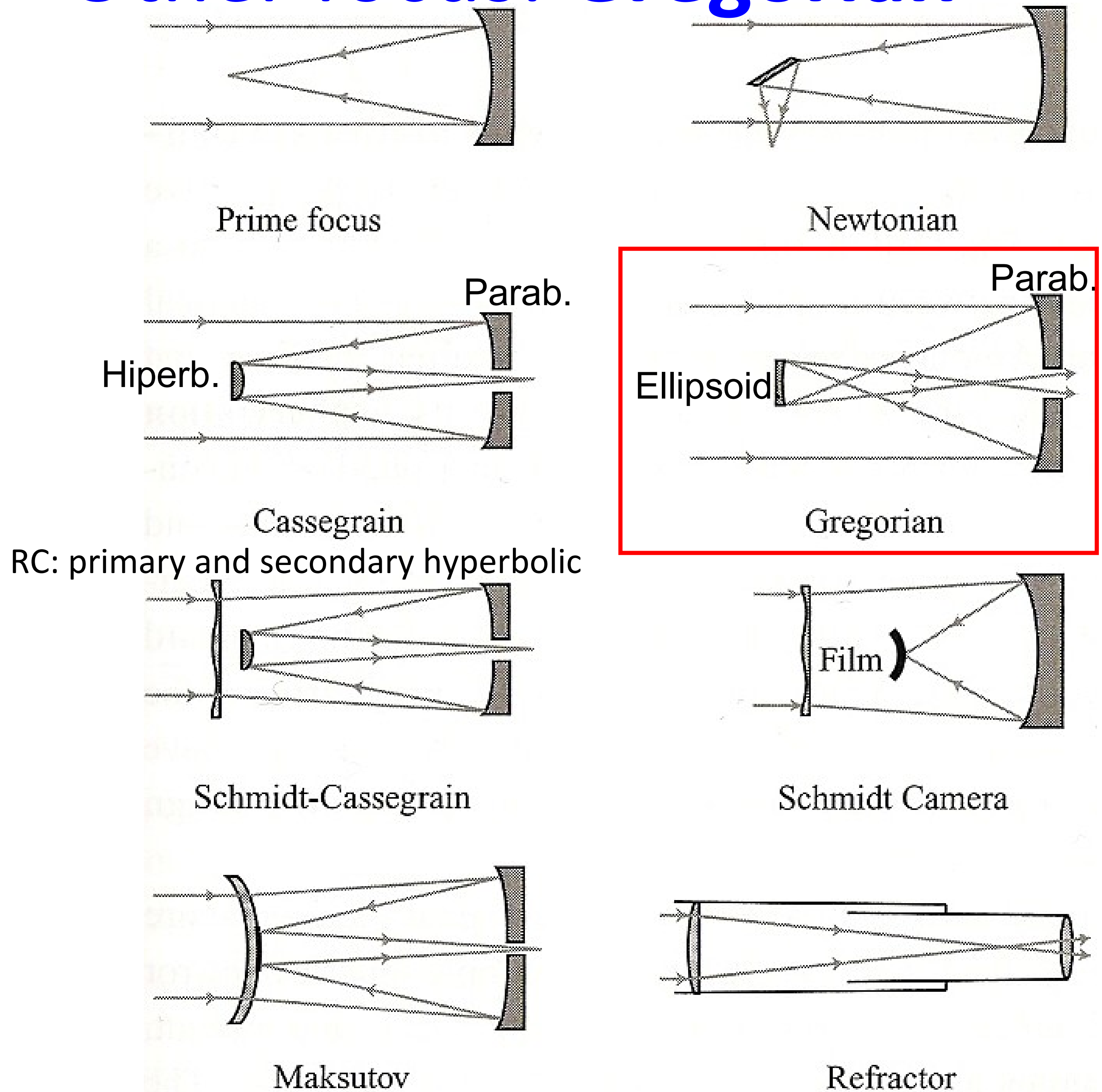
The pointing and guiding are not perfect (in any mount)

- mechanical flexure
- errors in the gears ("engrenagens")
- Atmospheric refraction
- Correction of the guiding is made by *guiders* & *auto-guiders* → needed for long integrations

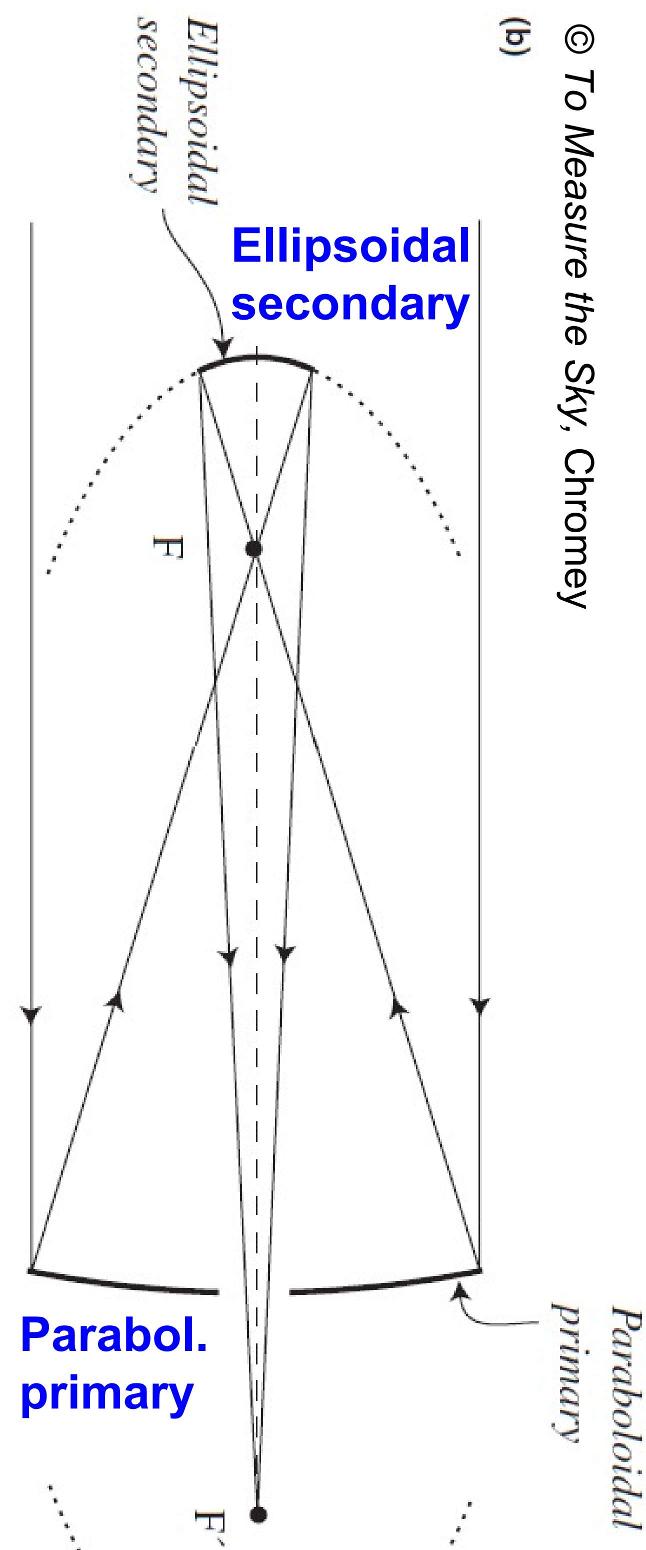


Other focus: **Gregorian**



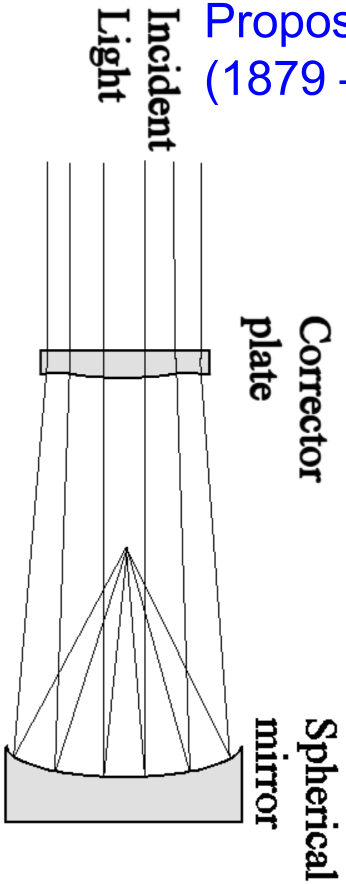


Other focus: **Gregorian**



Magellan 6.5m telescopes

Schmidt Camera (catadioptric telescope)



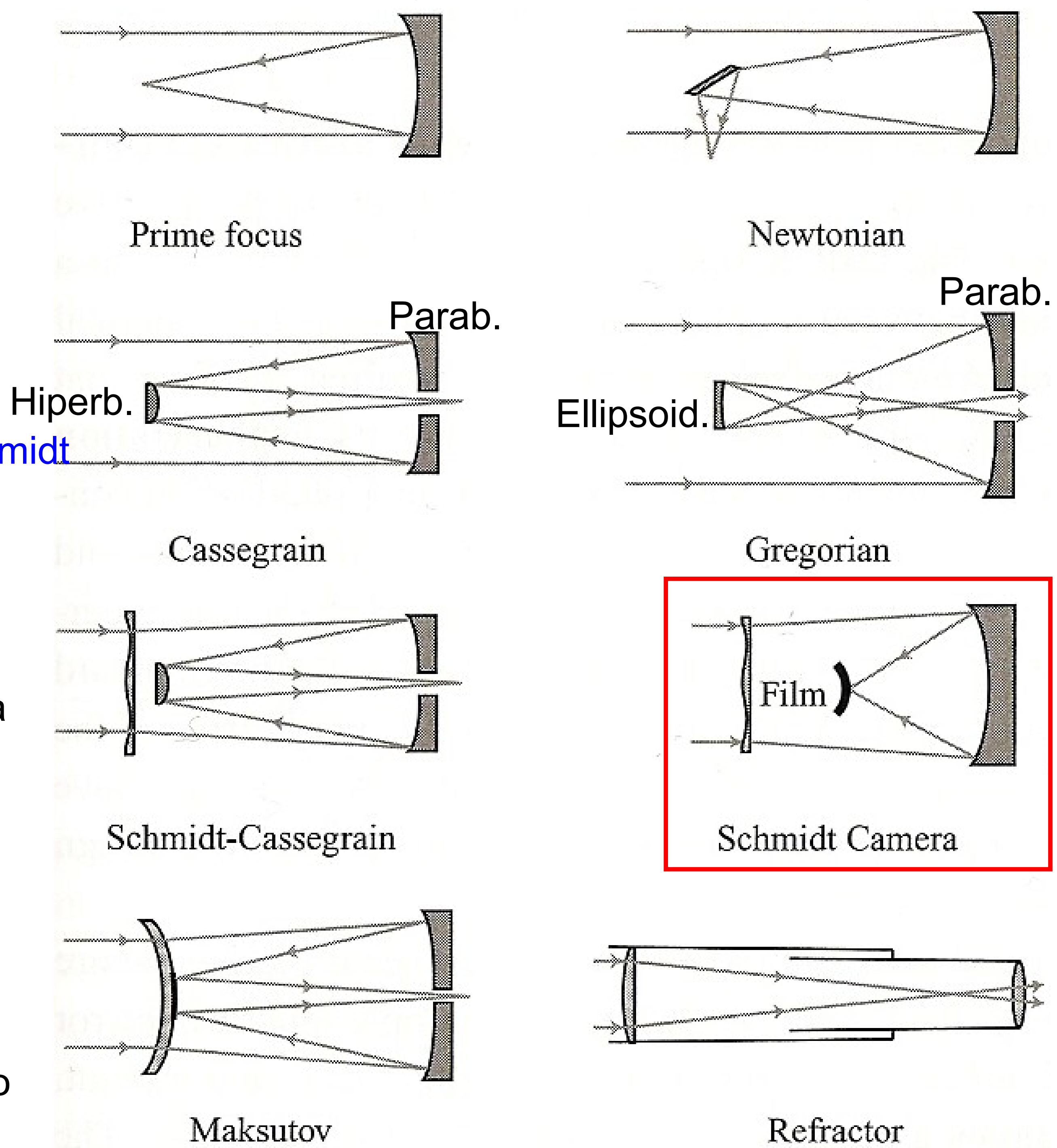
Proposed by Bernhard Schmidt (1879 – 1935) in 1929

telescópio híbrido: lens+mirror

- espelho primário esférico (sem coma do parabólico)

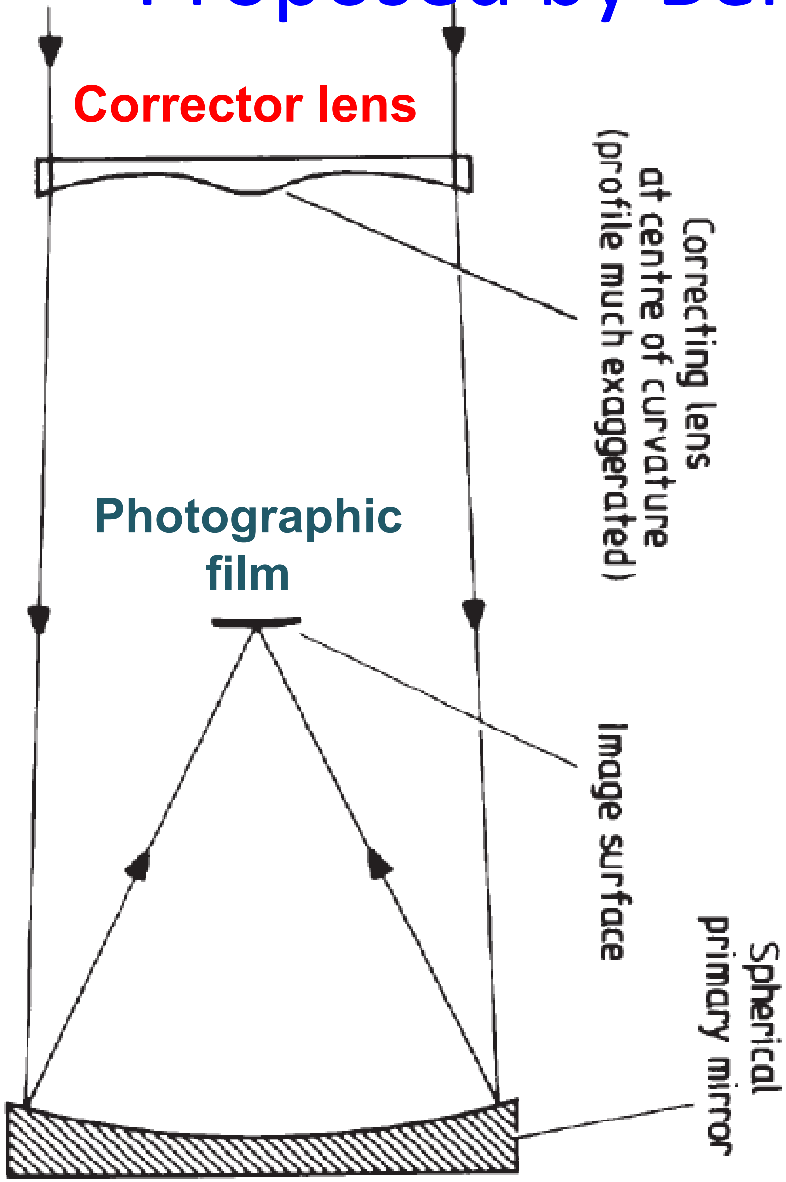
- lente antes do primário corrige aberração esférica

- única aberração: curvatura de campo

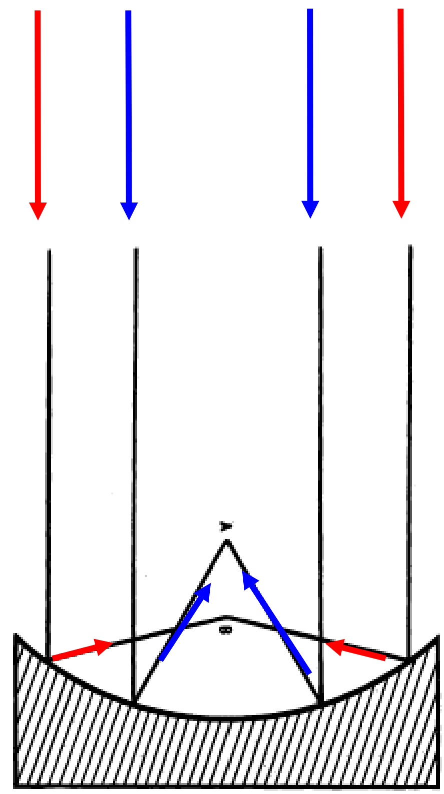


Schmidt Camera (catadioptric telescope)

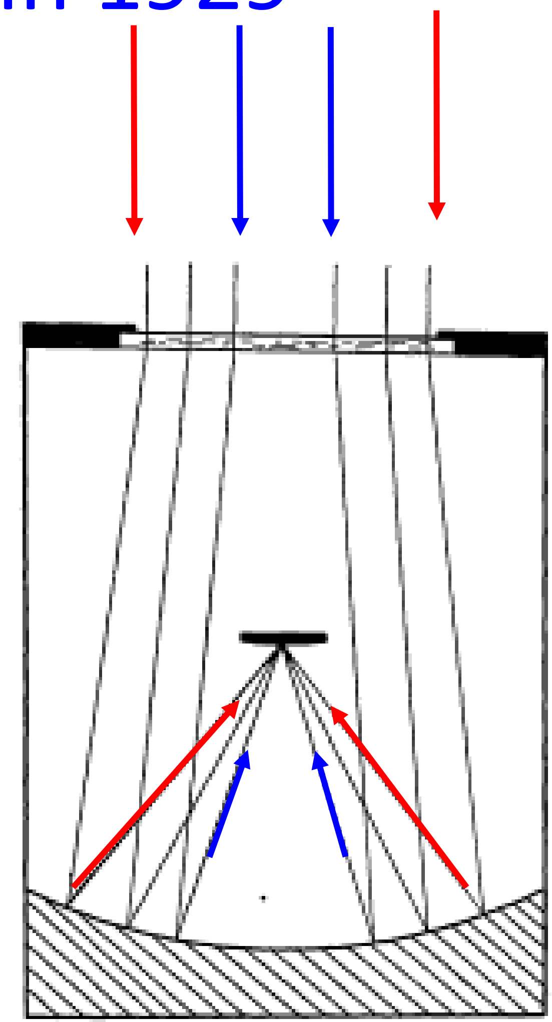
Proposed by Bernhard Schmidt in 1929



Spherical primary

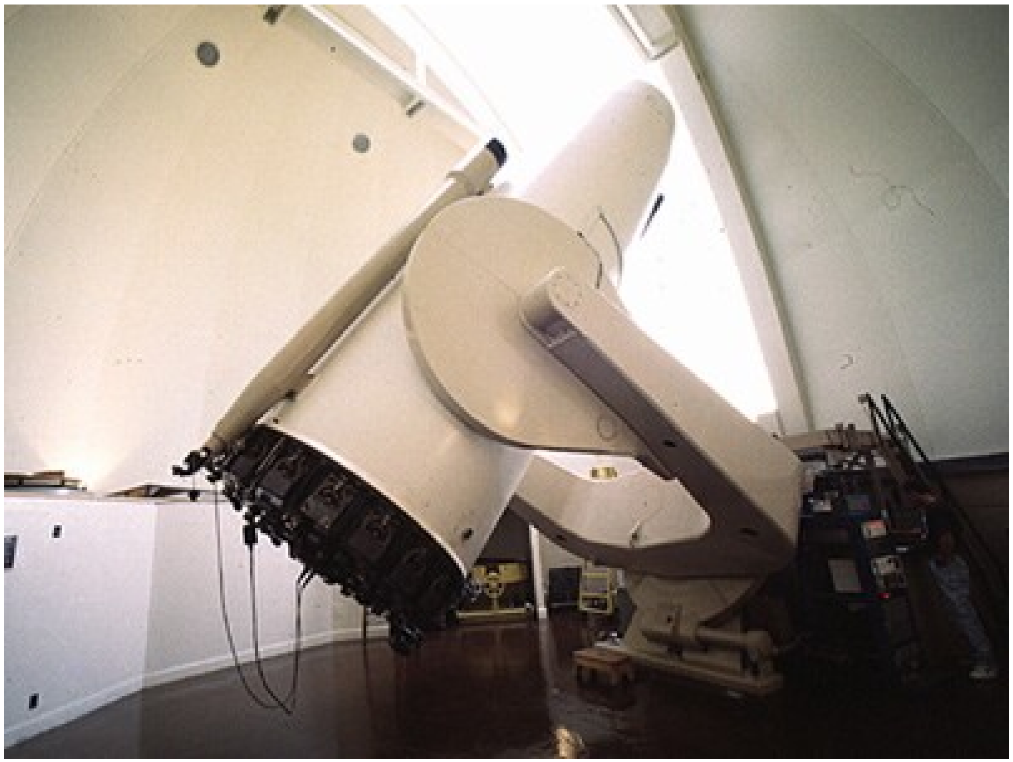


Spherical primary (spherical aberration)

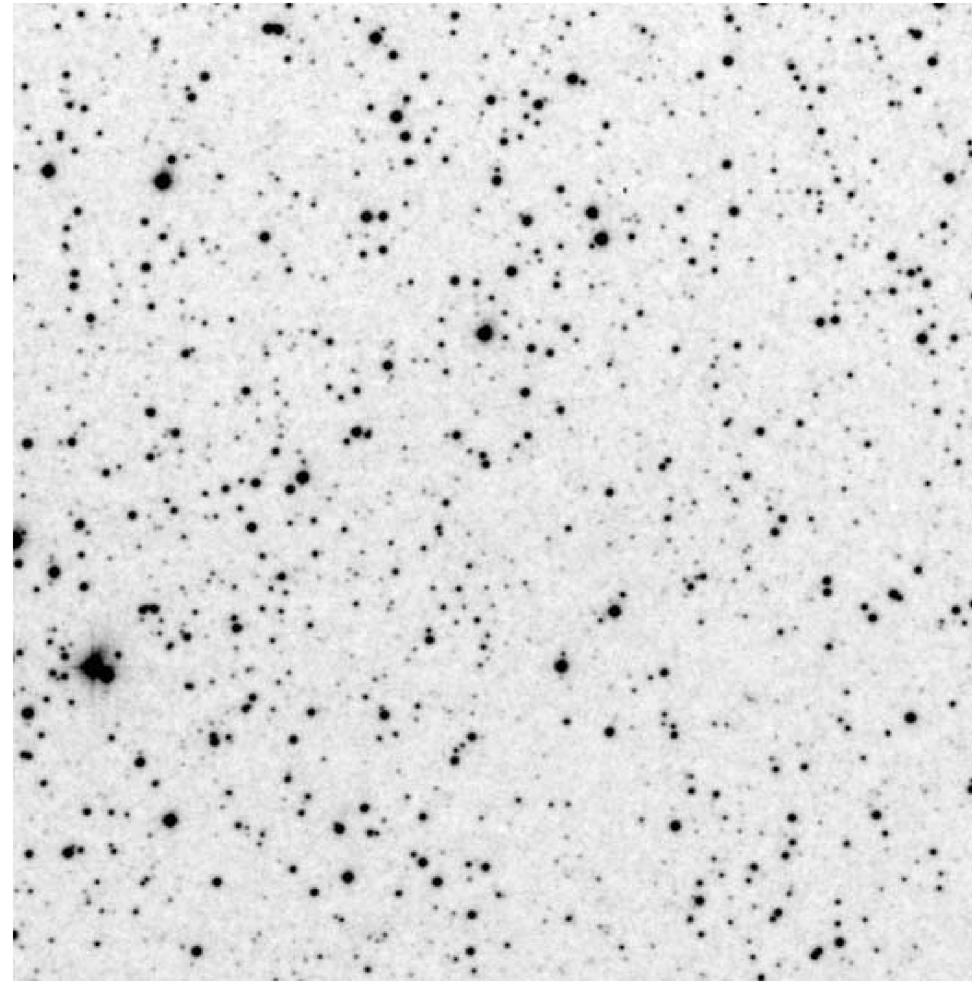


Spherical primary + lens eliminates aberration

Figures from Smiley et al. 1936, PA 44, 415



*The 48 inch (1,22m) Oschin **Schmidt Telescope** at the Palomar Observatory*



Palomar Observatory Sky Survey: POSS

The Survey utilized 14-inch square photographic plates, covering about 6° of sky per side (approximately 36 square degrees per plate). November 11, 1949 to December 10, 1958.

Going Wider, Going Deeper

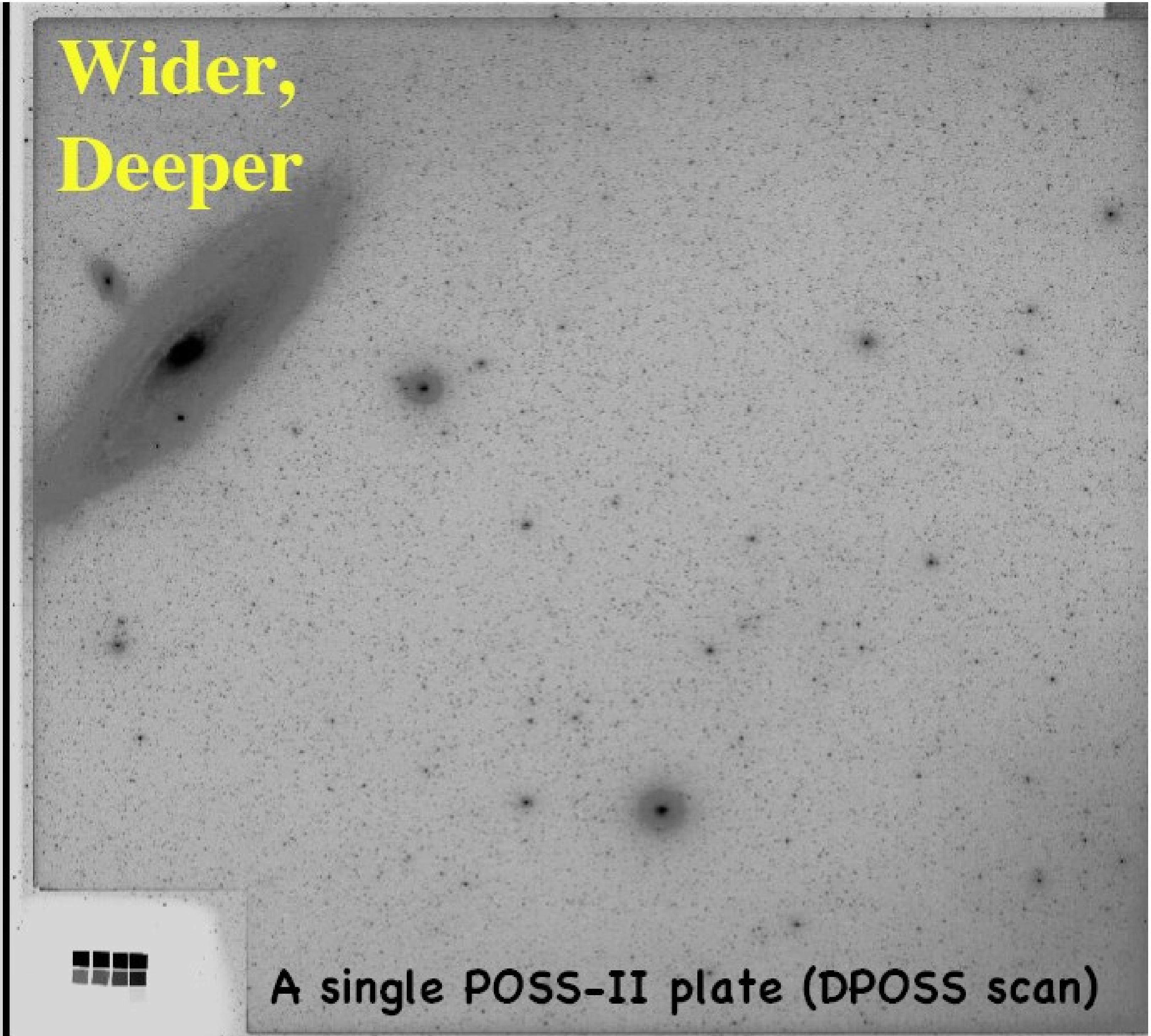
Moon:

Fields of view of:

P200:

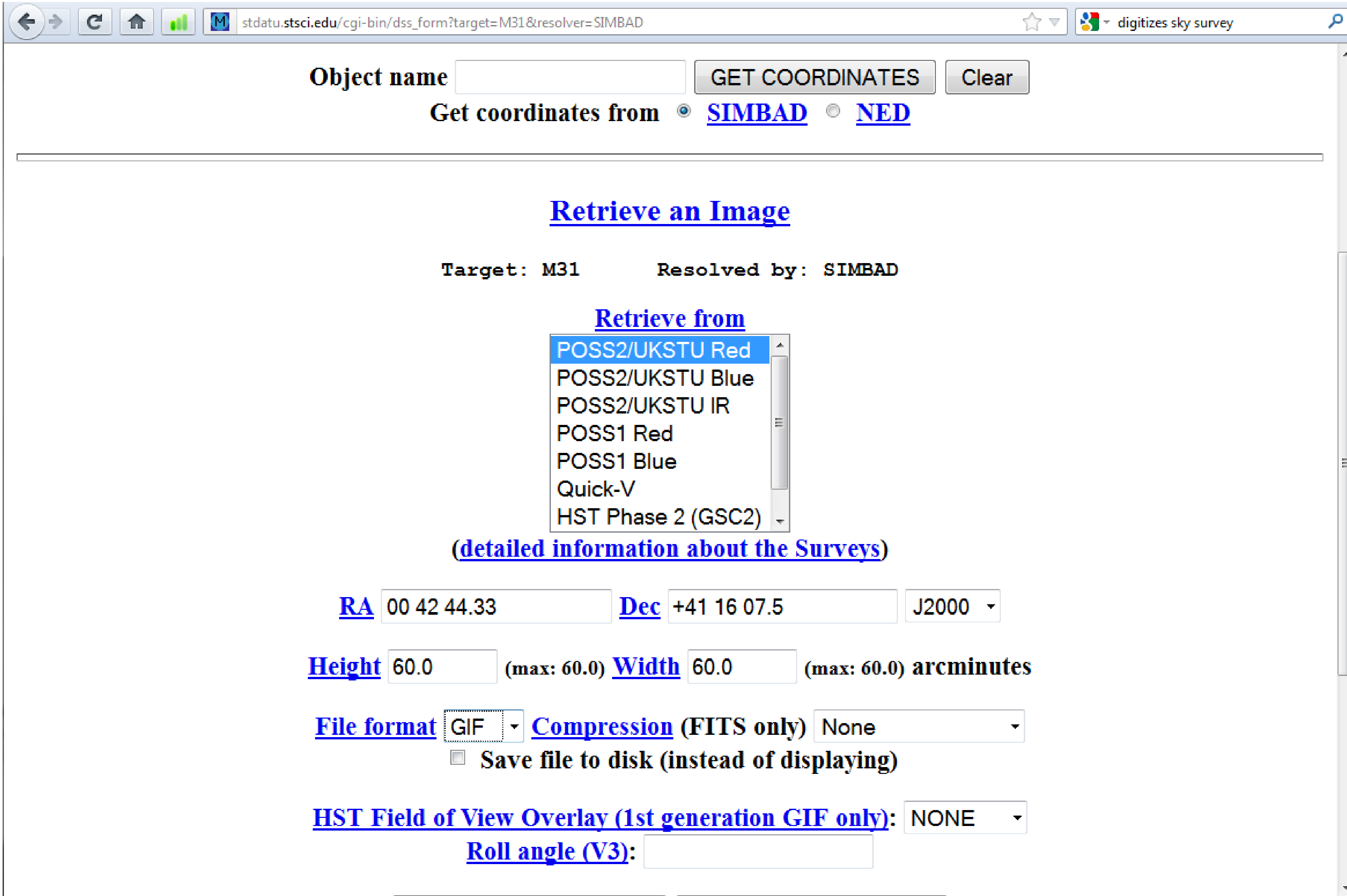
Keck:

HST:



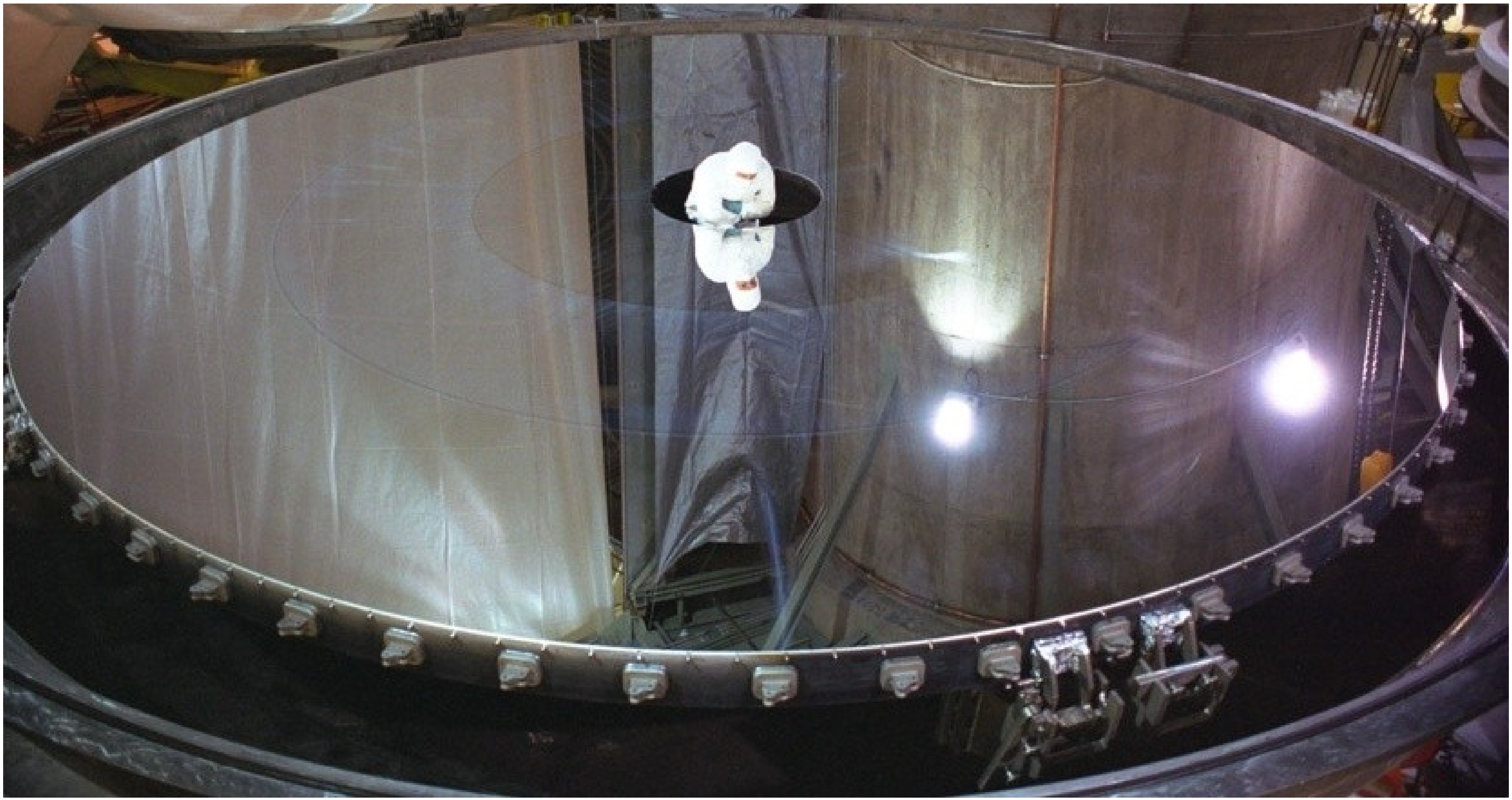
The STScI Digitized Sky Survey

http://stdatu.stsci.edu/cgi-bin/dss_form



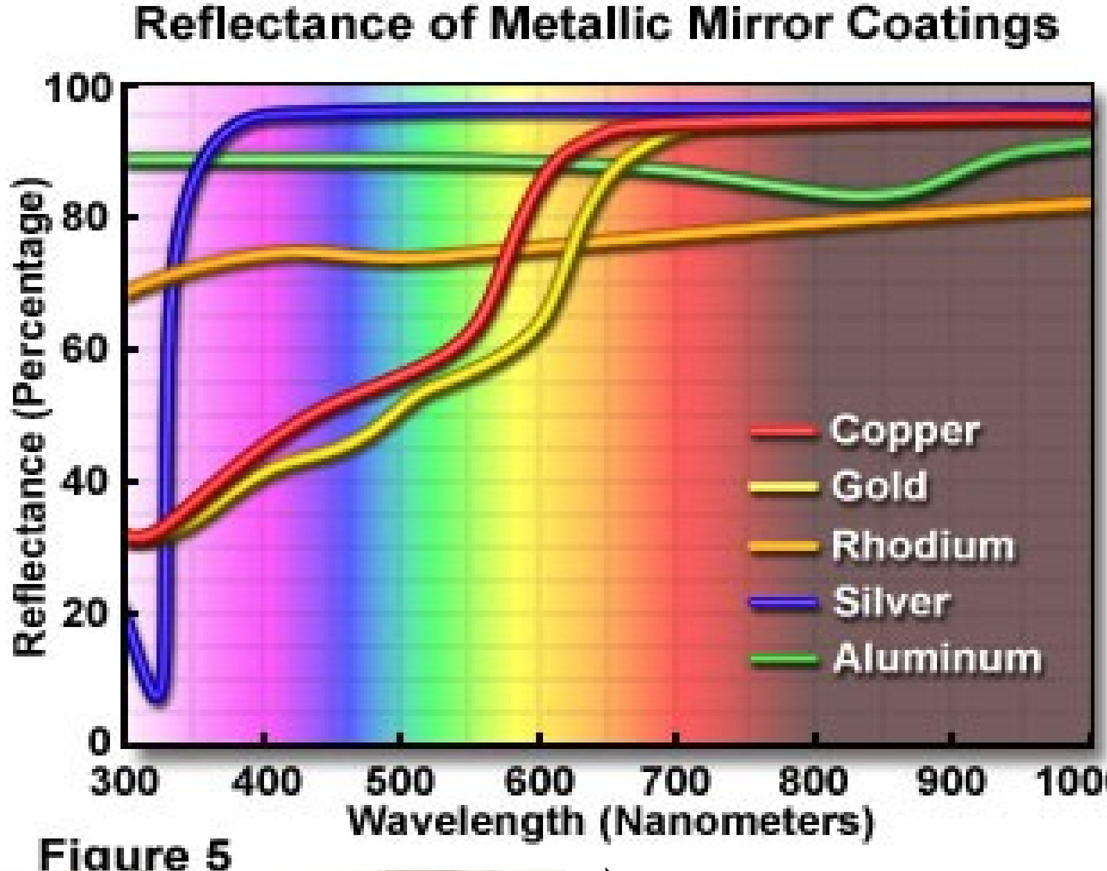
M31 from the
Digitized Sky Survey,
60 x 60 arcmin

Reflectors : *mirror coating*



Refletores: mirror coating

- Coating in the optical-UV: aluminum; infrared: silver

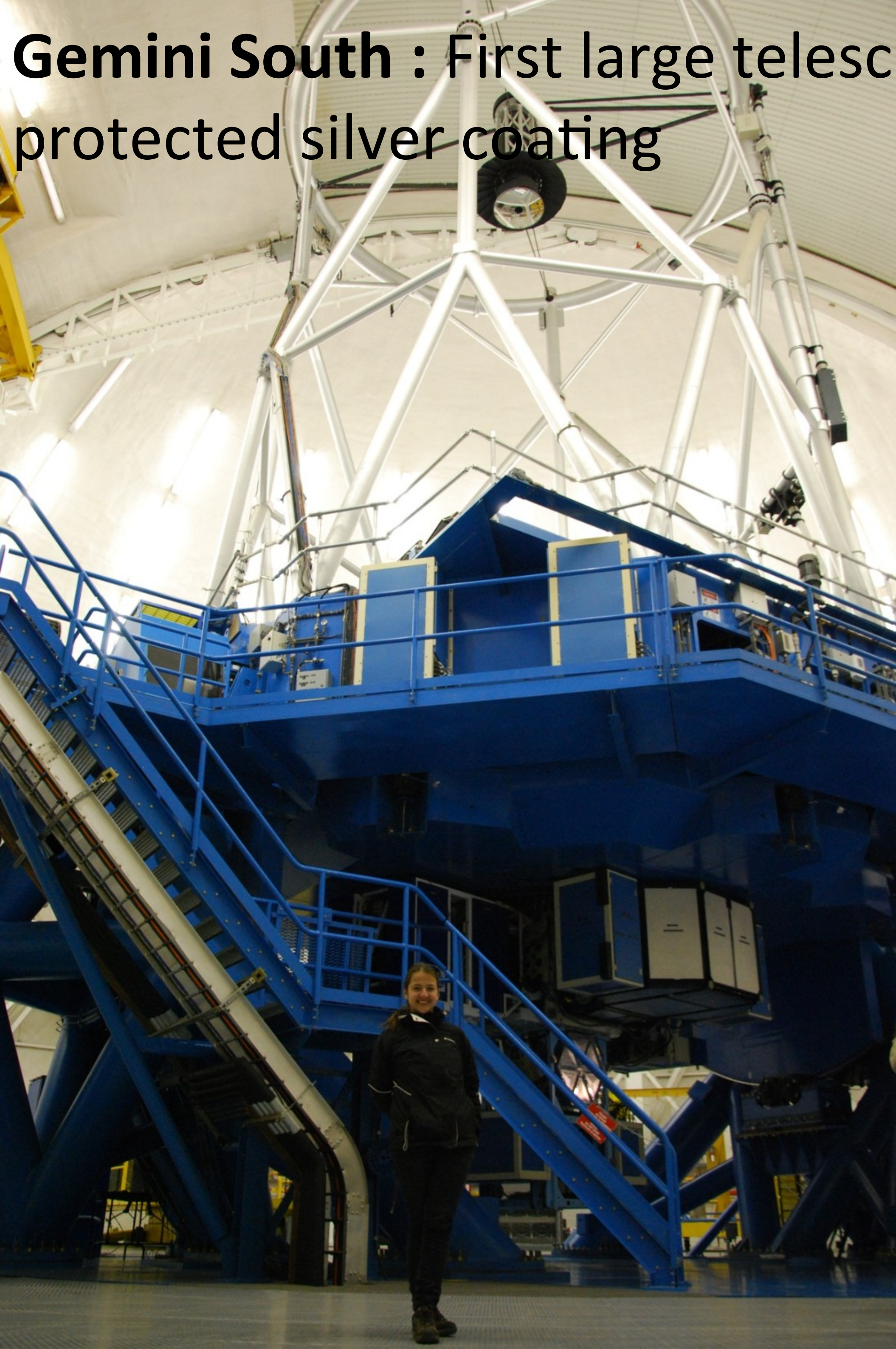


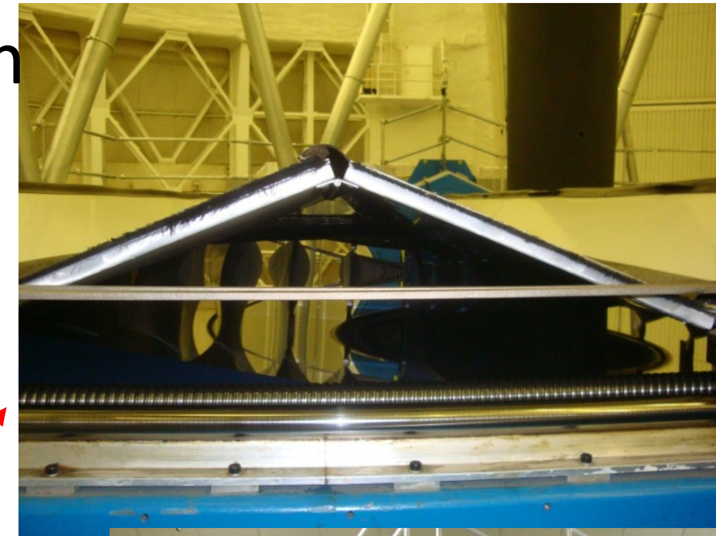
micro.magnet.fsu.edu/primer/lightandcolor/

Coating of the 0.6m telescope of Serra da Piedade at LNA

⇨ Silver was not much used in big telescopes, because the coating degrades quickly (months). Since 2004 Gemini introduced “protected” silver

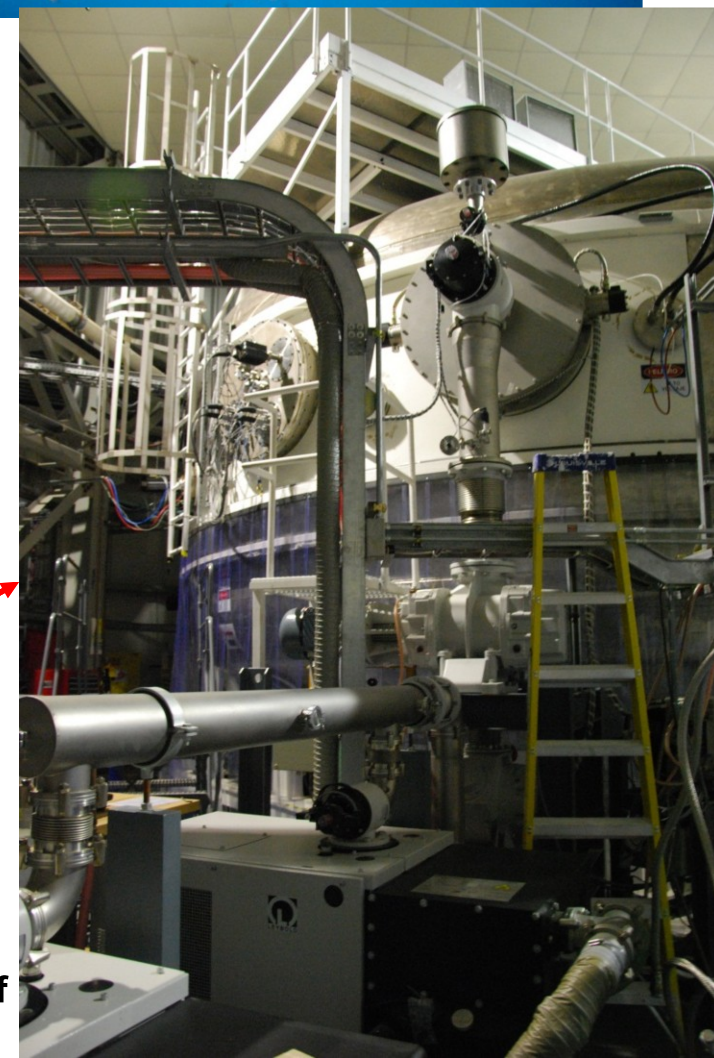
Gemini South : First large telescope with protected silver coating





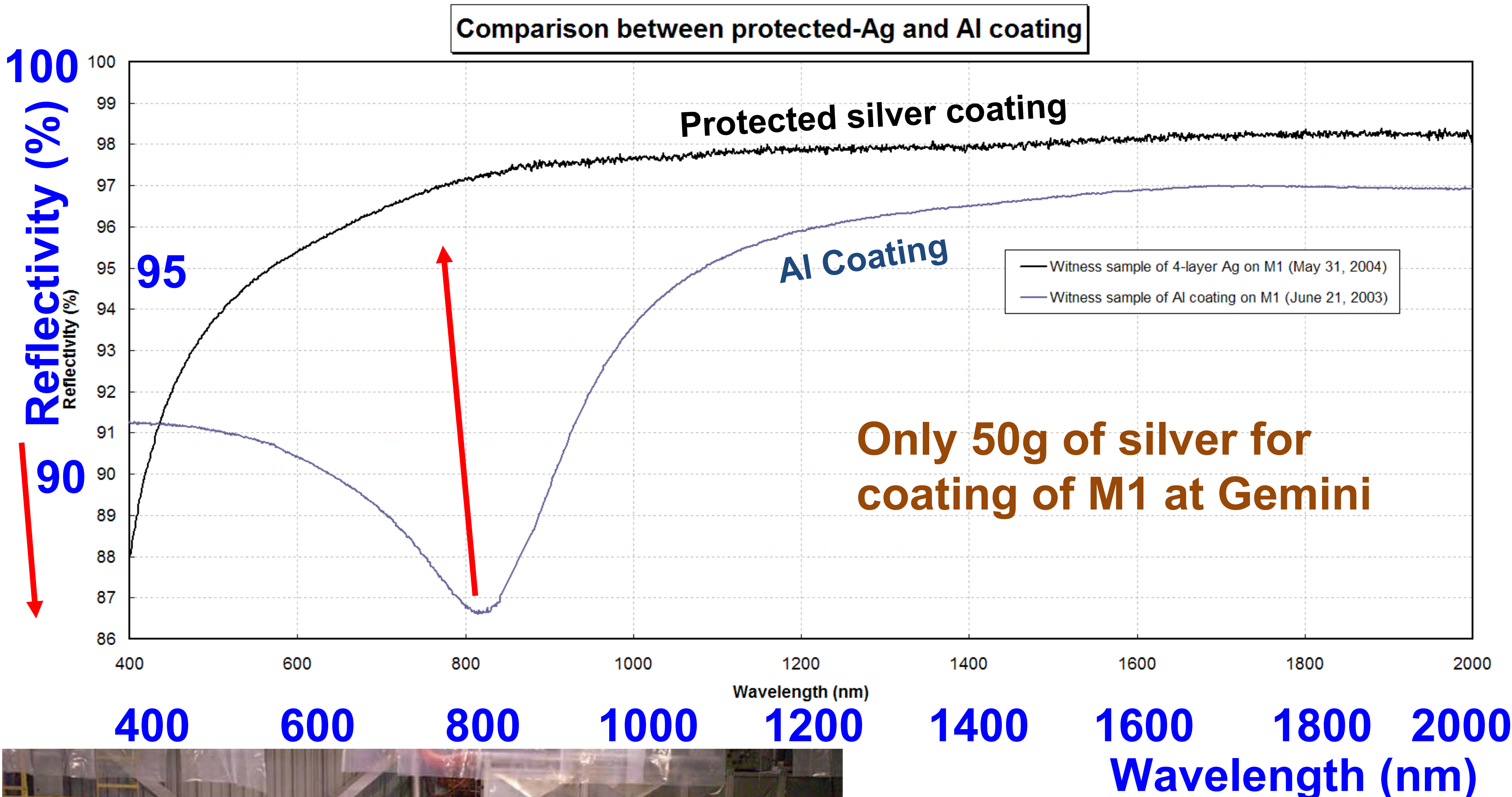
Gemini S. primary

Instruments



Coating chamber

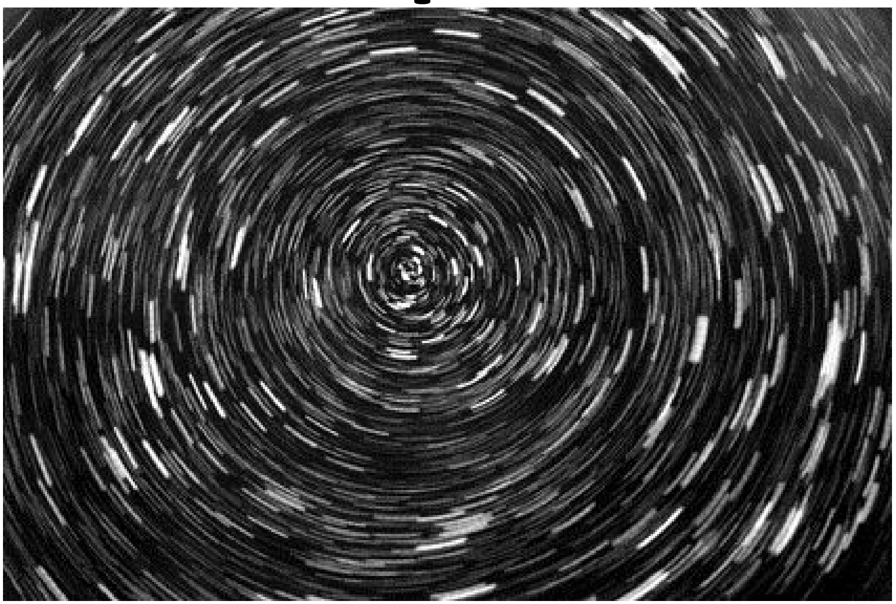
Ana (AGA5802 student) in front of Gemini South



Ag: better reflectivity and less emissivity in the IR

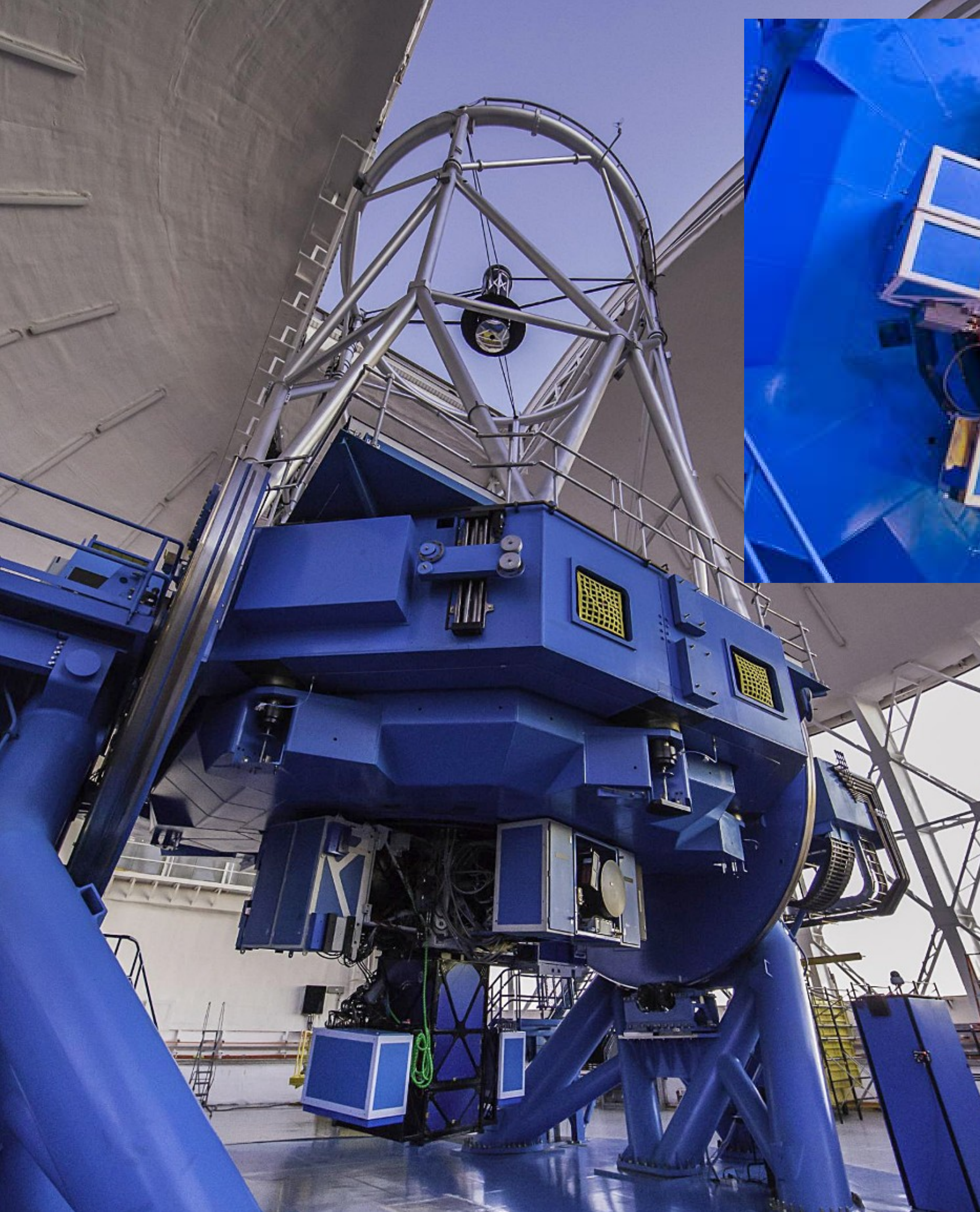
http://www.gemini.edu/node/16

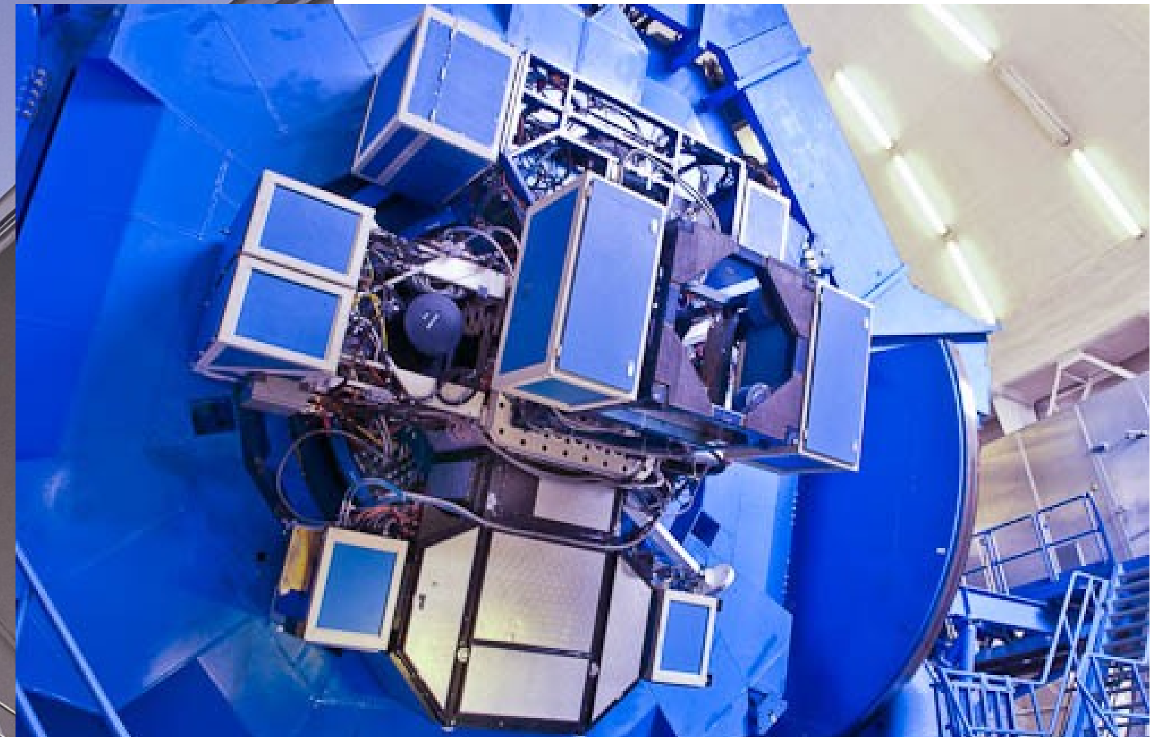
Field rotation in AltAzimutal telescopes



NTT 3,6m telescope (La Silla, ESO). One of the first large telescopes with altAzimutal mount

One of the NTT field de-rotators at a Nasmyth focus





The **ISS** (Instrument Support Structure) of the 8m Gemini South is attached to the telescope via the **Cassegrain rotator** (de-rotator at Cassegrain focus)

(c) Images: Gemini Obs.