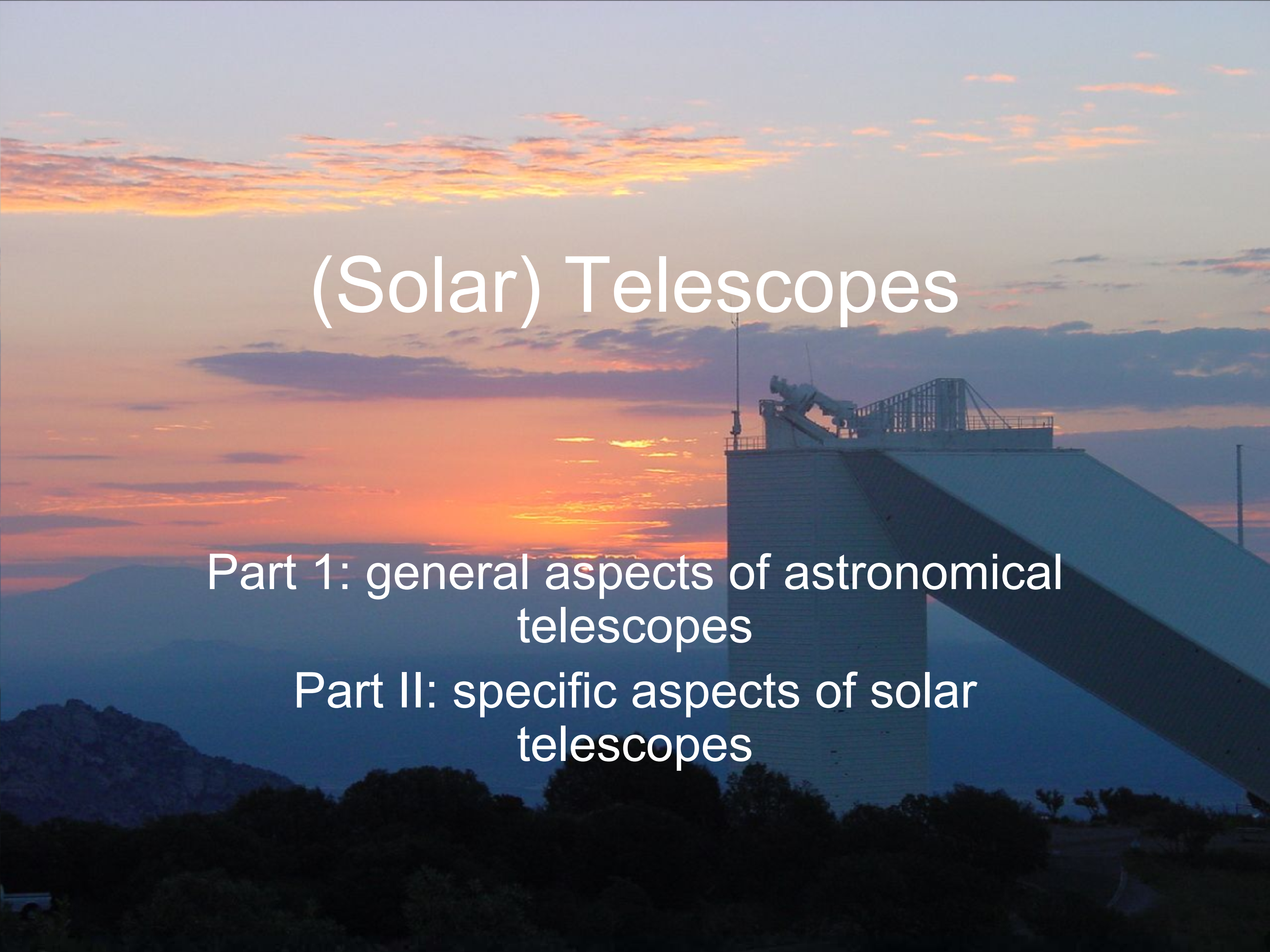


(Solar) Telescopes

Part 1: general aspects of astronomical telescopes

Part II: specific aspects of solar telescopes

Contents of Part I

- What are telescopes good for?
- some historical aspects
- the paraxial telescope
- real optical systems
- a simple (solar) telescope
- the telescope Zoo

Contents of Part II

- science drivers in solar observations
- optical parameters of solar telescopes
- performance criteria of (solar) telescopes
- specific problems in solar observations
  - stray light
  - thermal aspects 1: „mirror seeing“
  - thermal aspects 2: athermalisation of optics

Contents of Part II contd.

- Examples of solar telescopes: a personal retrospective
  - McMath Pierce facility Kitt Peak
  - Solar Tower telescopes
  - Gregory telescopes
  - SUNRISE telescope
  - Polarimetric and Helioseismic Imager (PHI) onboard Solar Orbiter

Telescopes I

General aspects of astronomical telescopes

What is a telescope?

A telescope

- is historically a direct viewing system (telescope means „far distance viewing“ → needs eye as part of the optical train!)
- is today an instrument to map an angular pattern on the sky (the object is at „infinite“ distance!) onto a detector → in this sense all modern „telescopes“ are cameras!
- collects (hopefully lots of) photons and concentrates them on detector element

History of solar telescopic viewing

- first telescope pointed to the sky by Galileo; also the Sun is target: Sunspots seen
- Scheiner uses telescope to project an image of the Sun (safe (indirect) solar viewing)
- first dedicated solar telescopes from beginning of 20th century on, first peak in the 40ies (military interest in flare forecast; very actual, still good argument to get funding ☺)

optical basics of telescopes

- understanding a telescope is easiest using the concept of geometrical optics („light rays“; the *paraxial* approximation is the paradise: you can build everything and don´t have to bother with real optics and its limitations → typical „proposal optics“

The paraxial telescope

- in the following, optical elements are represented by ideal „operators“ acting on direction of geometric light rays (this is also sometimes called „matrix optics“)
- paraxial approximation: in Snell´s law replace sin x ~ x

NOTA BENE!

- each „paraxial lens“ can represent a complex optical system:
  - a real lens
  - a combination of lenses
  - a mirror
  - a combination of mirrors
  - a combination of mirrors and lenses

in this case the telescope is called a :

- a real lens / a combination of lenses → refractor
- a mirror / a combination of mirrors → reflector
- a combination of mirrors and lenses → catadioptric system

basic parts of an optical system

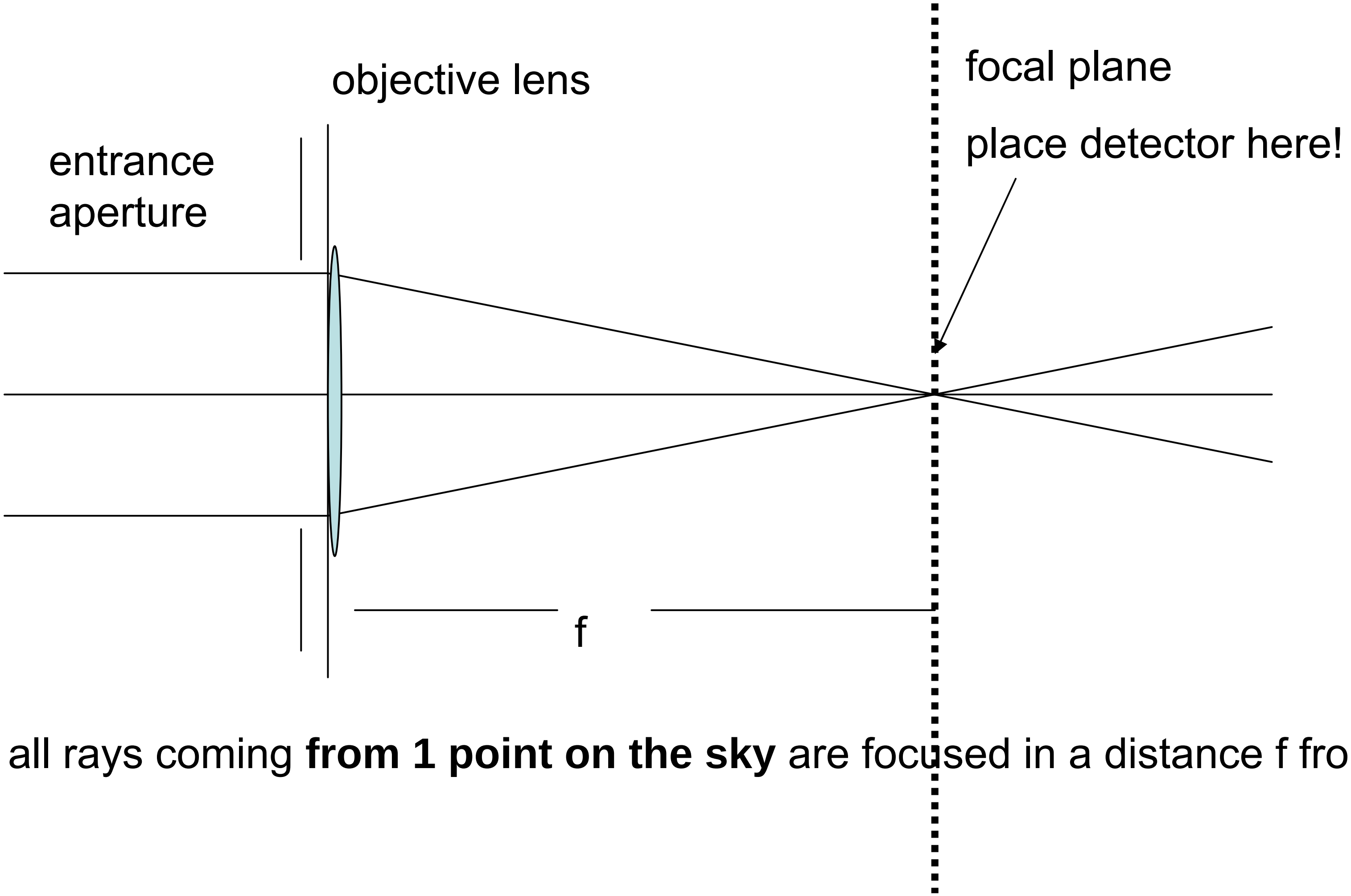
You need:

- entrance aperture
- objective lens
- focal plane (detector)   that´s it!

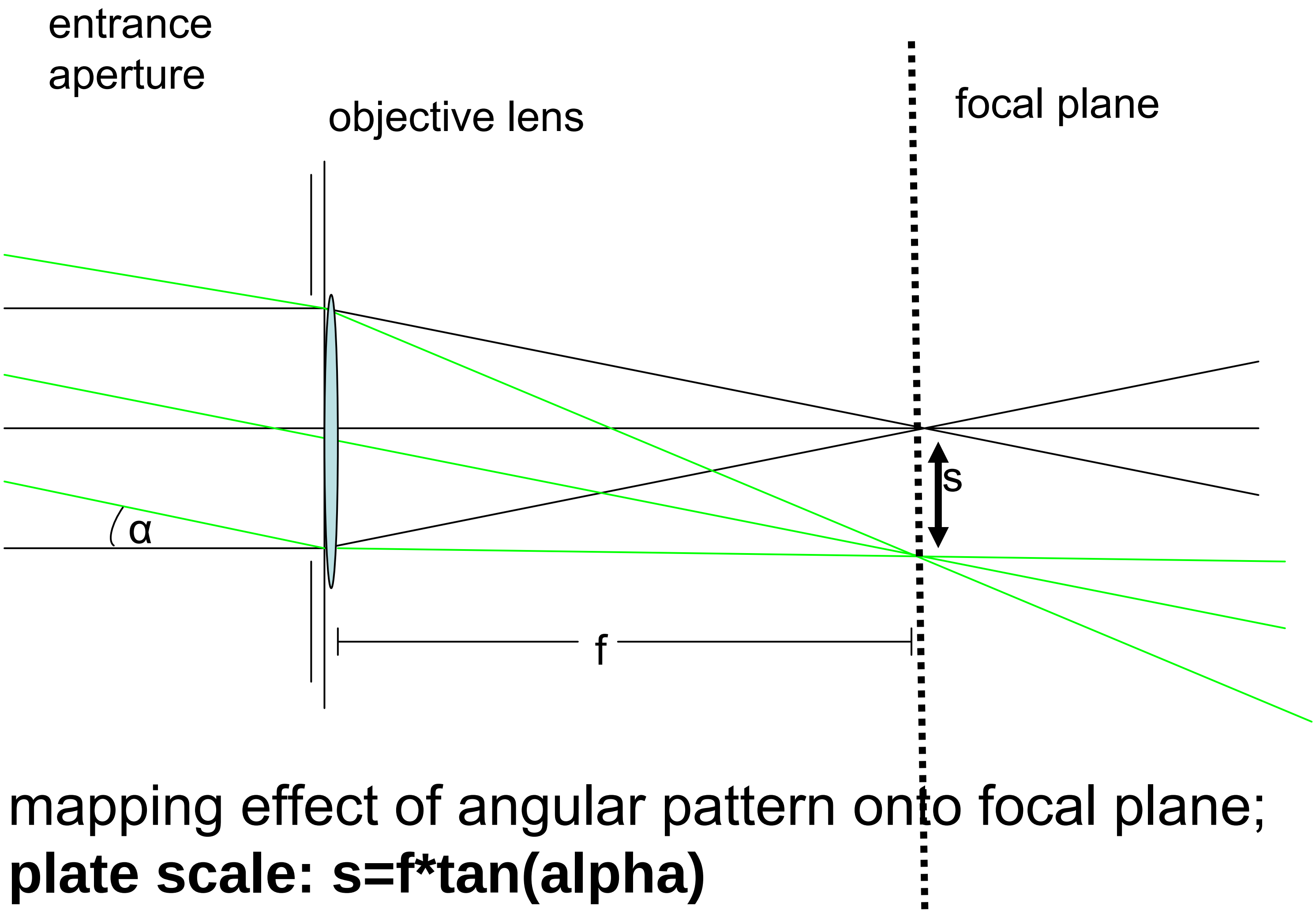
You can further add:

- „eyepiece“ optics (can also be a complex instrument, c.f. a spectrograph, spectropolarimeter, magnetograph, Fabry-Pérot interferometer....)

our first telescope



all rays coming **from 1 point on the sky** are focused in a distance f from lens



mapping effect of angular pattern onto focal plane;
plate scale: s=f*tan(alpha)

given in arcsec/mm or arcsec/px

f can be defined via plate scale: „effective focal length“

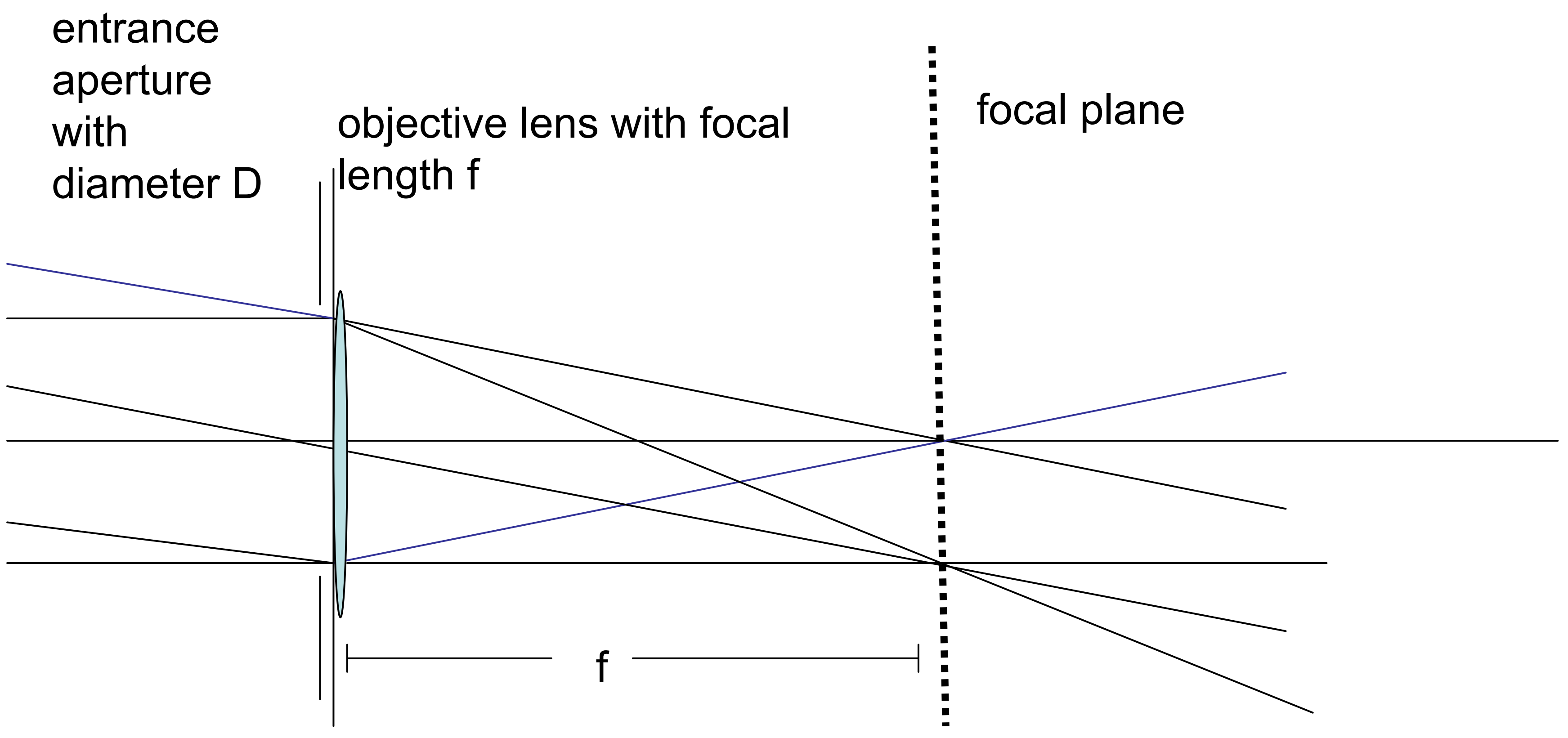
basic parameters of an optical system

- angular magnification
- plate scale
- field of view
- entrance pupil diameter

} this is what you want

- focal length
- f-ratio
- exit pupil diameter

} this is what you need



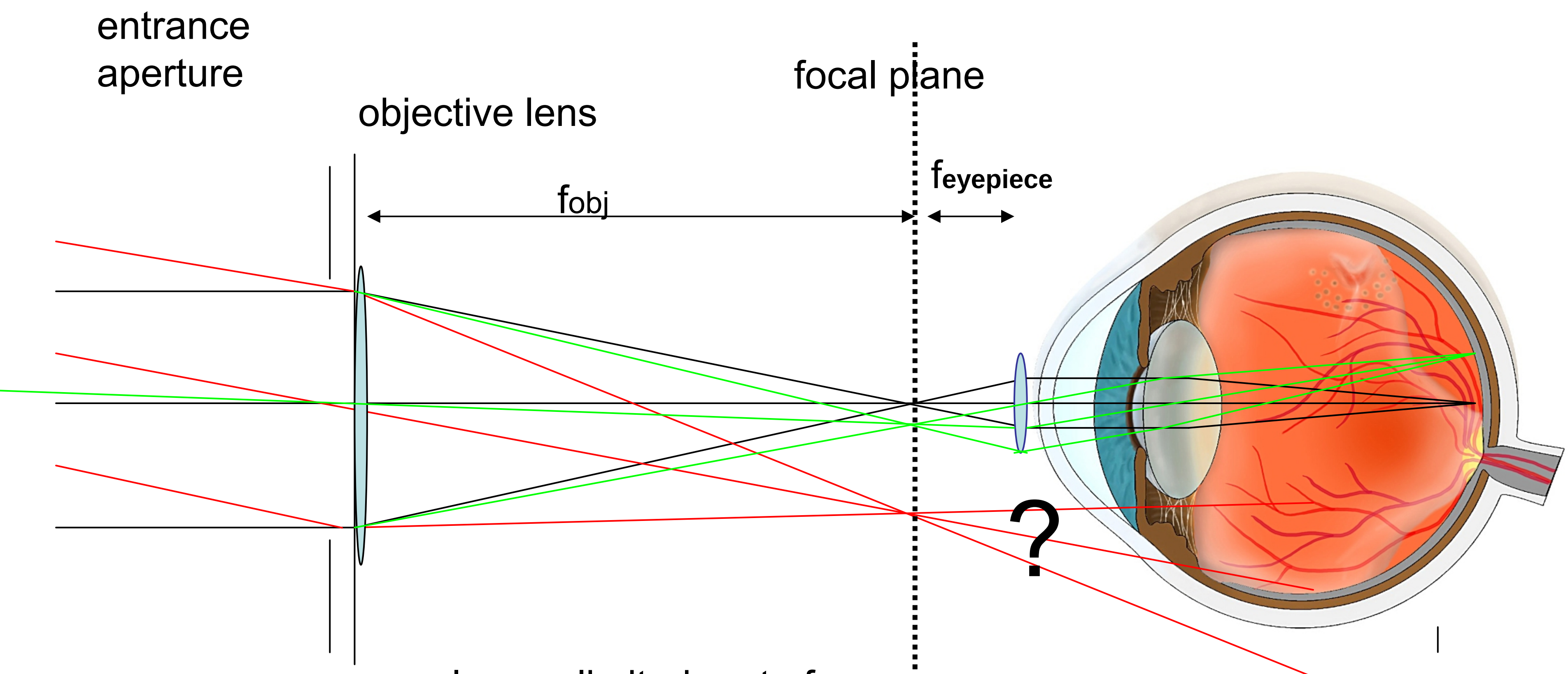
light from one point (direction) on the sky falling onto aperture area is concentrated in one „point“ on the detector

photon collecting power

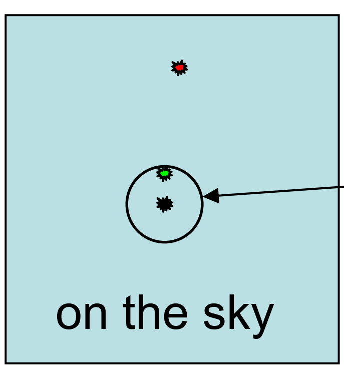
- **stellar image (point) brightness proportional to $\sim D^2$**
- **area brightness of an extended object given by ratio $D^2/F^2 = (D/f)^2$ (since size of the image scales with f!)**
- **in photography D/f is called the *„aperture“* (c.f. 1/2.8, 1/5.6, ...1/32)**
- **in astronomy f/D is called *f-ratio or F#***
- **high F#: *slow system*: needs long exposure**
- **low F#: *fast system*: allows fast exposures**

visual observations: the eyepiece

- eyepiece re-collimates the image rays („parallel light“) in order to allow „reimaging“ by the observers eye
- „the intermediate image in the telescope is seen trough a magnifying lens“
- angular magnification given by f_{obj}/f_{okular}

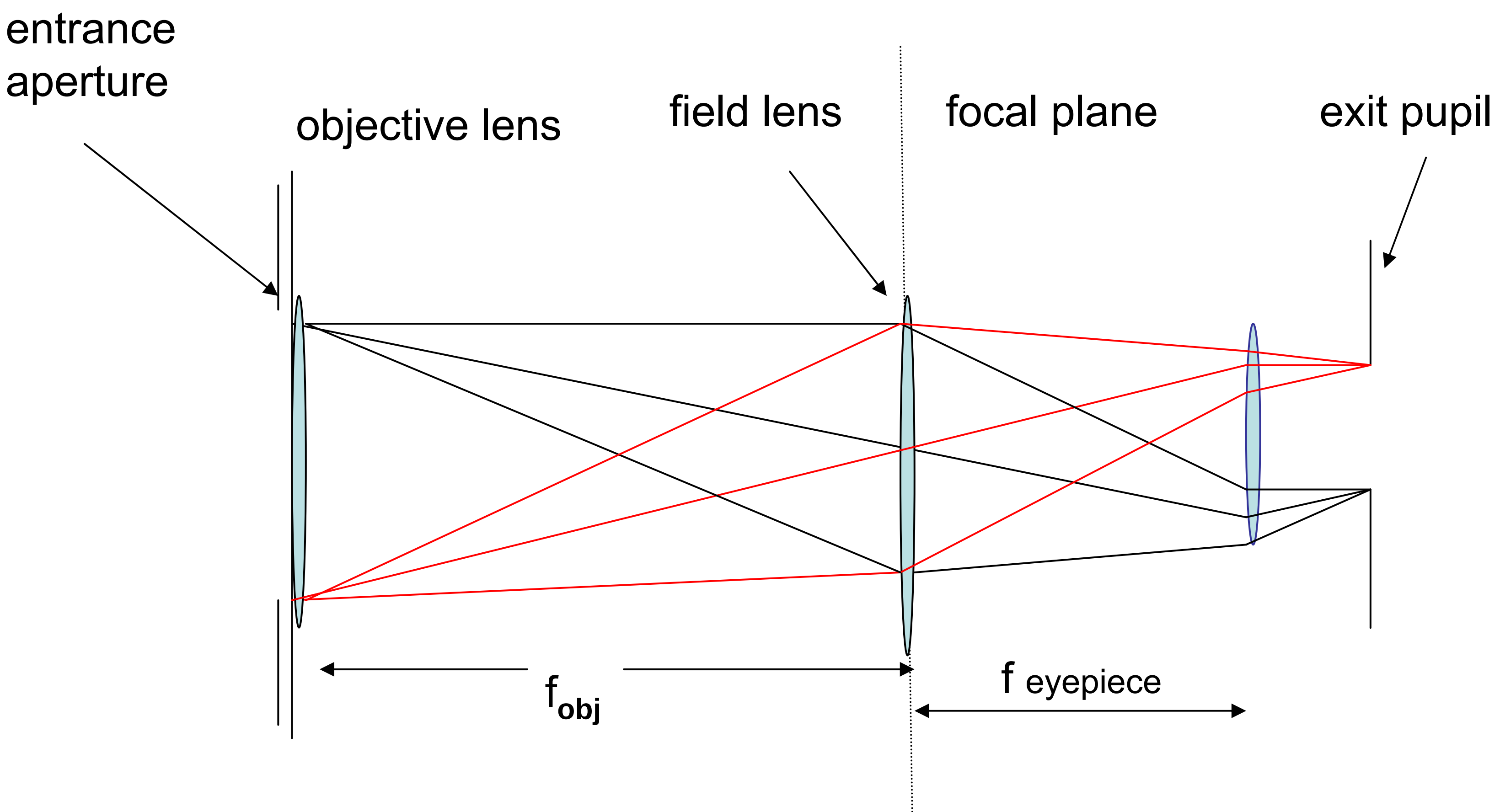


only very limited part of the intermediate image can be seen (limited *field of view* FOV)



FOV and field lens

- how is it achieved that the light that enters the telescope can exit again???
- small size of eyepiece restricts the angular coverage in observations (FOV)
- Solution: place lens in focal plane to image the entrance pupil onto eyepiece lens
- diameter of this lens determines the useable field→ *„field lens“*



field lens images the entrance aperture onto the so-called ***exit pupil*** of the system; the size of the exit pupil is D*feye/fobj; it should match the size of the entrance pupil of the following optical system (for visual observations: 5-7mm for dark adapted eye); therefore the size of the human eye limits the maximum and minimum useful magnification for a telescope with given aperture D !

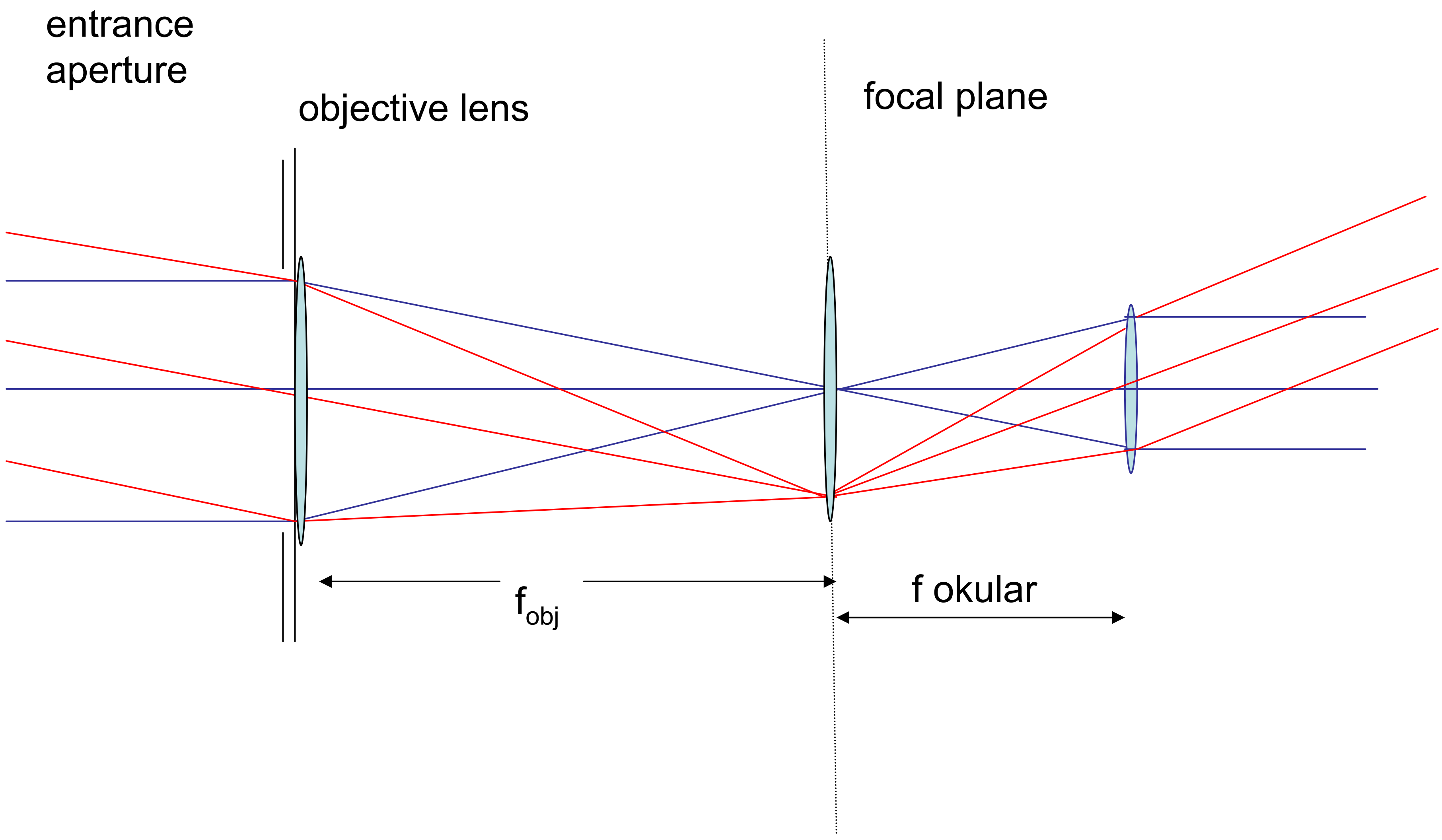
interlaced optical paths

- in every optical instrument:

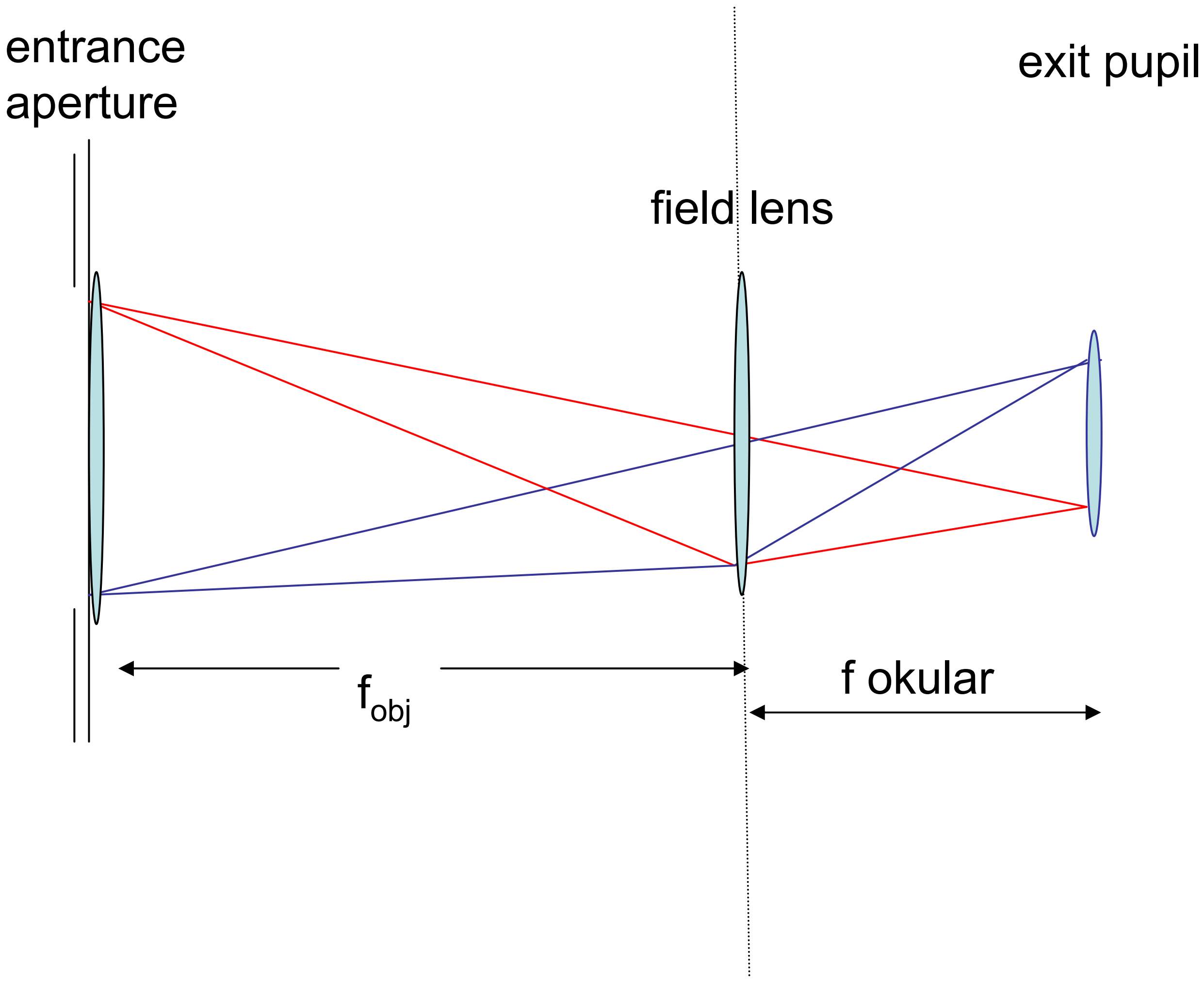
  image path ←→ pupil path are nested in each other !!!

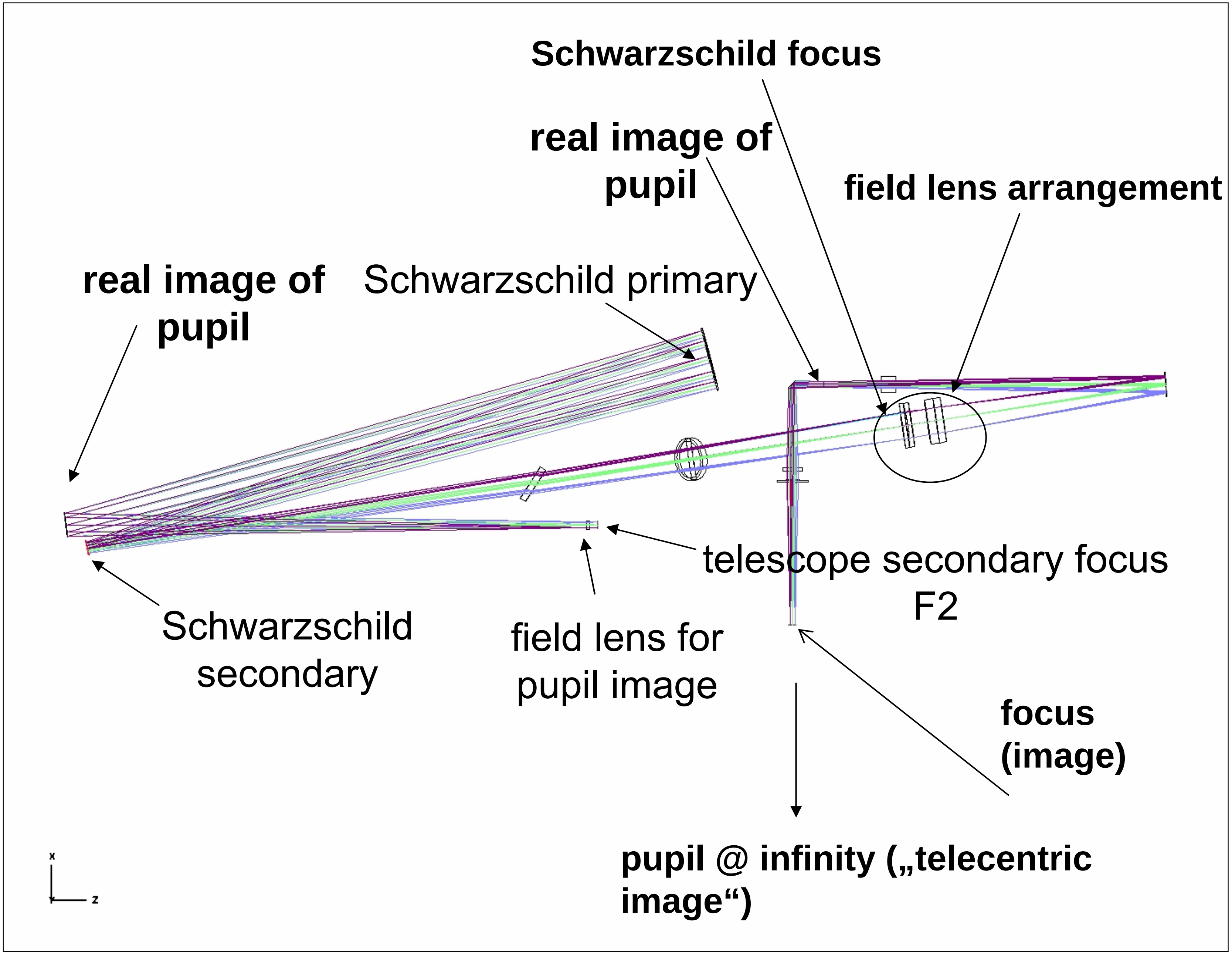
Example: SUNRISE ISLID reimager:

image path of our example telescope



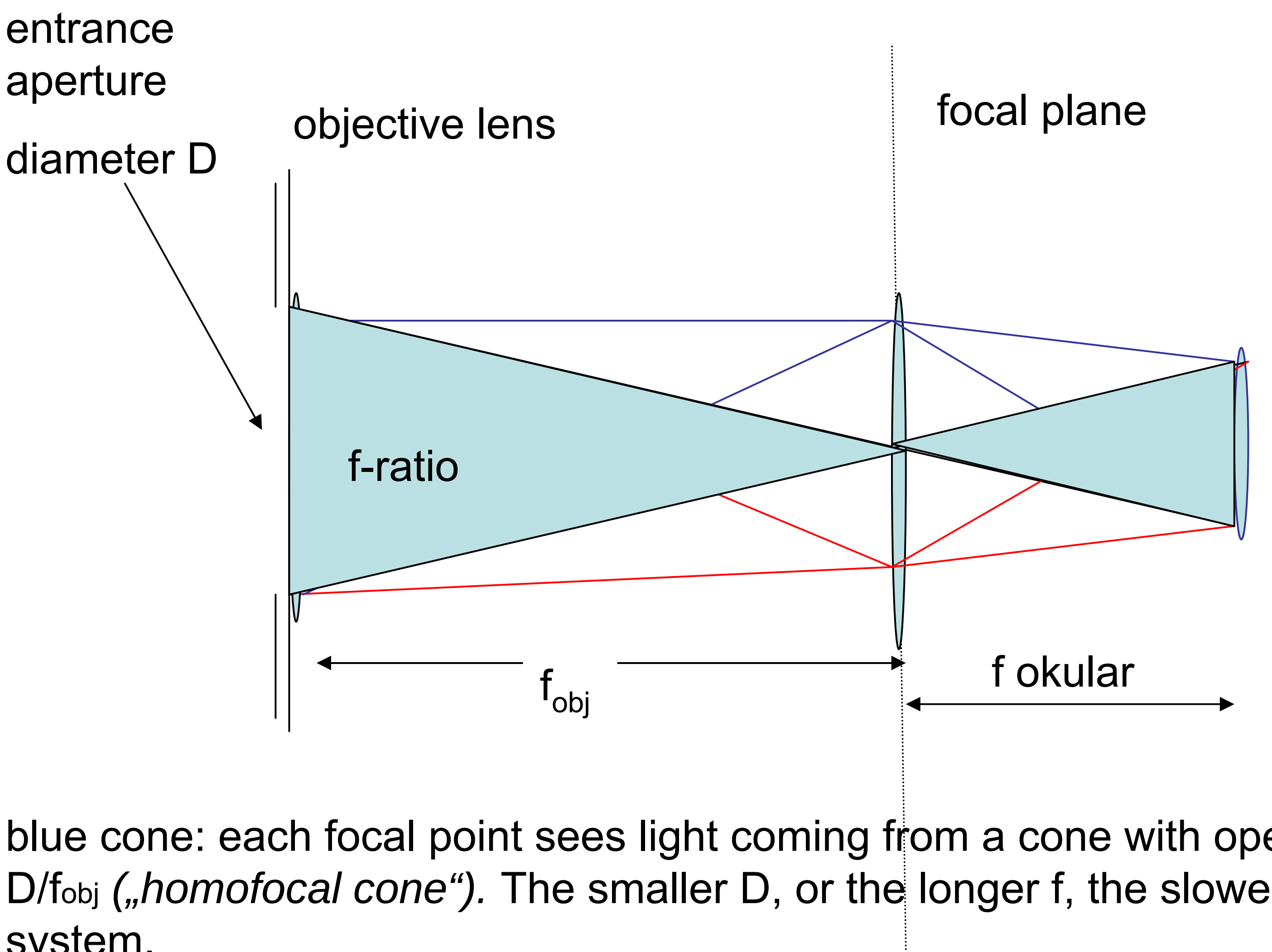
pupil path of our example telescope





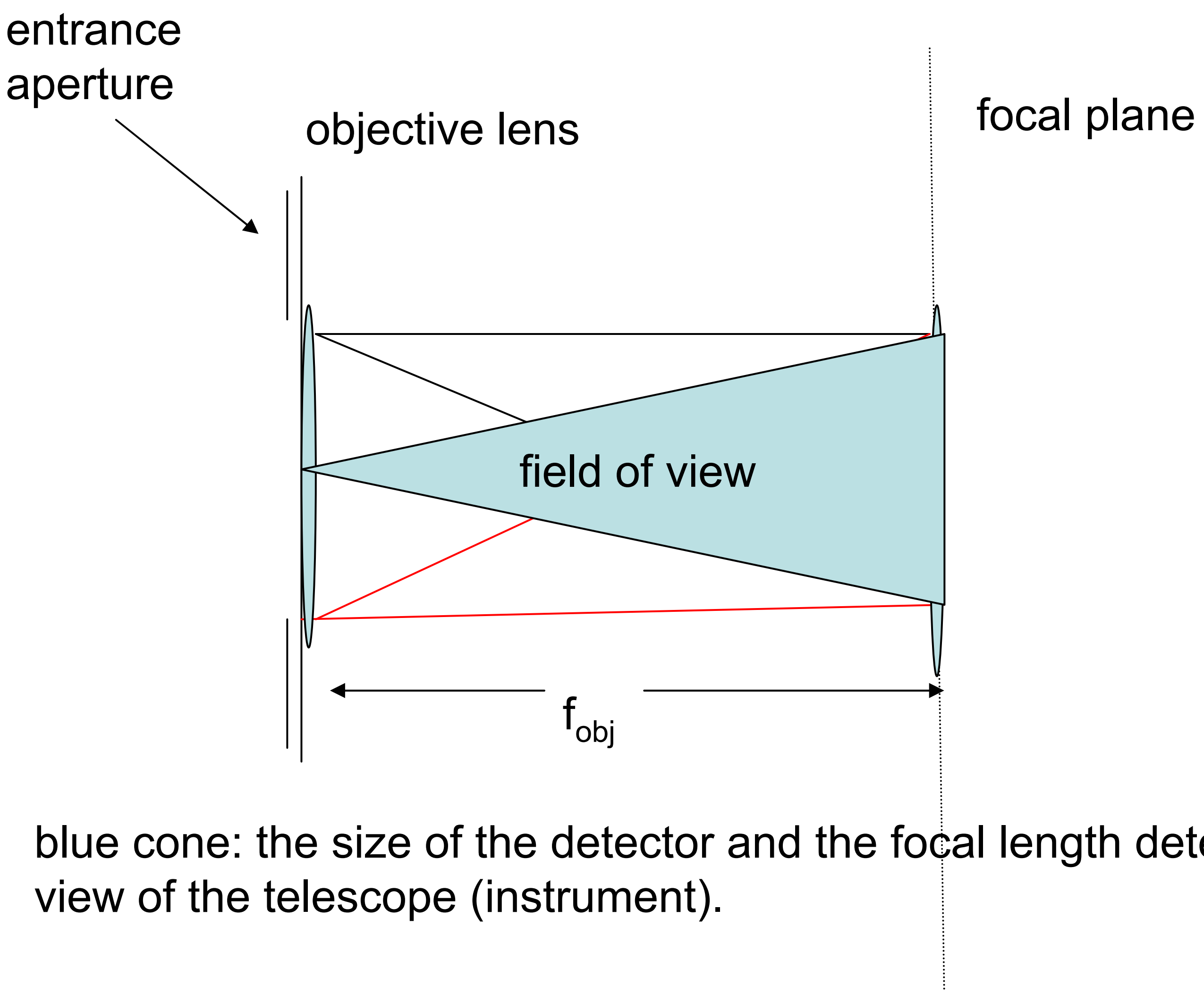
Schwarzschild focus
real image of pupil
field lens arrangement
real image of pupil
Schwarzschild primary
telescope secondary focus F2
Schwarzschild secondary
field lens for pupil image
focus (image)
pupil @ infinity („telecentric image“)
x
z

the two relevant angles in optical systems: F# and FOV



blue cone: each focal point sees light coming from a cone with opening angle D/f_{obj} *(„homofocal cone“).* The smaller D, or the longer f, the slower is the system.

Post-focus instruments must match the F# of the feeding telescope!



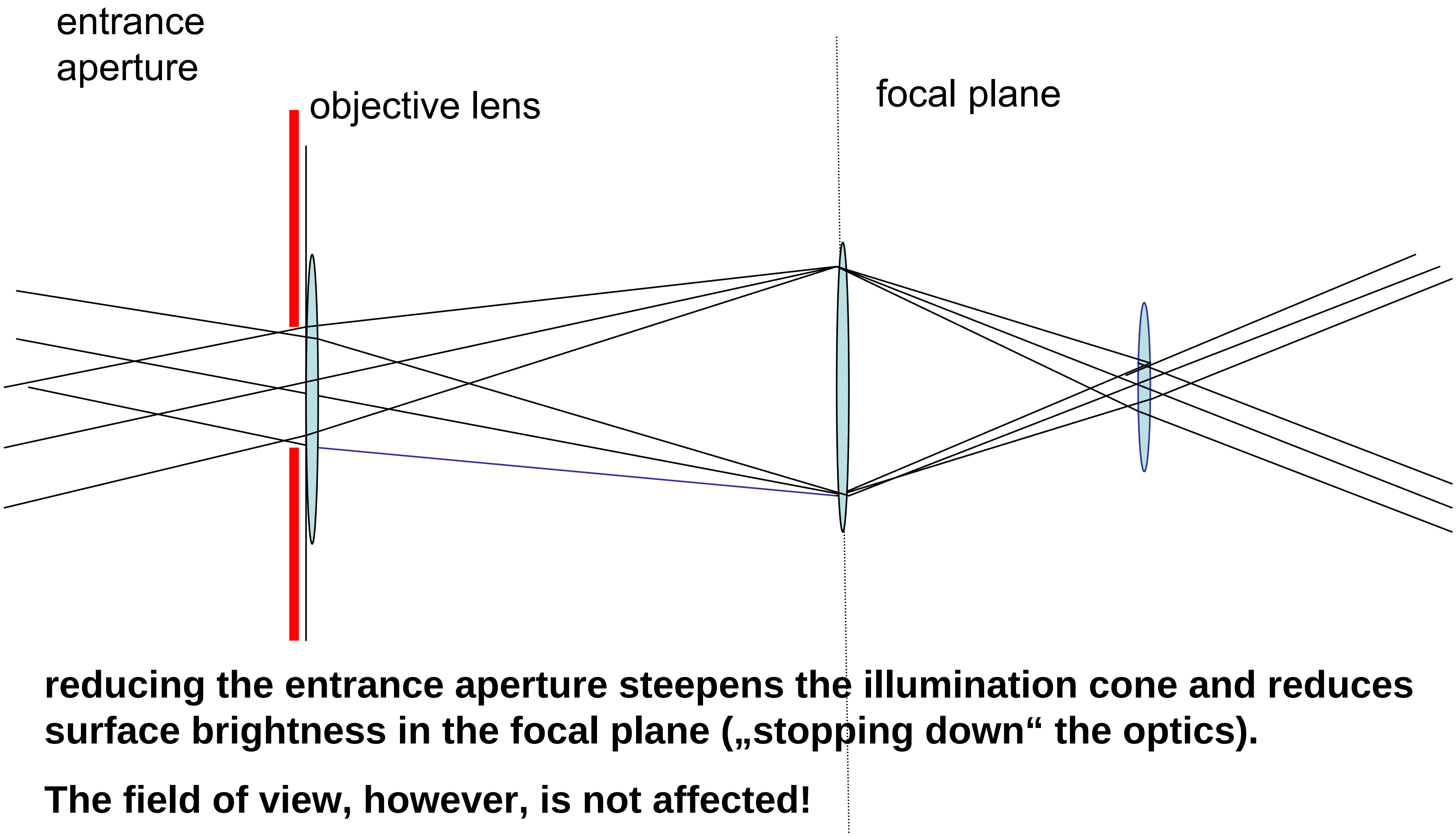
blue cone: the size of the detector and the focal length determine the field of view of the telescope (instrument).

Field stops, apertures, obscurations, spiders, vignetting..

Let´s talk about obstacles of all kinds...

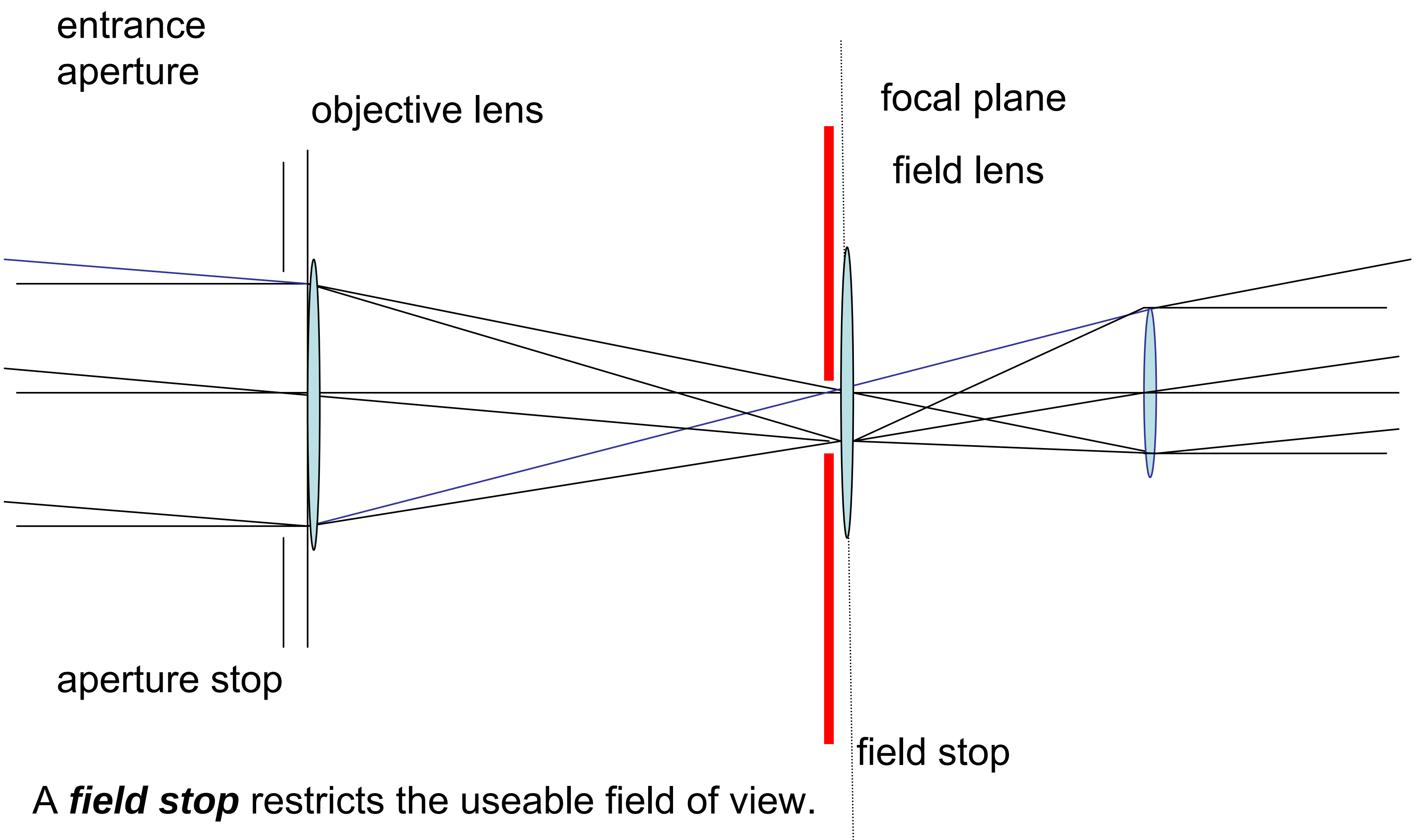
- light rays propagate until they hit an optical surface or a wall....

the effect of an obstacle depends on its location in the optical system



reducing the entrance aperture steepens the illumination cone and reduces surface brightness in the focal plane („stopping down“ the optics).

The field of view, however, is not affected!

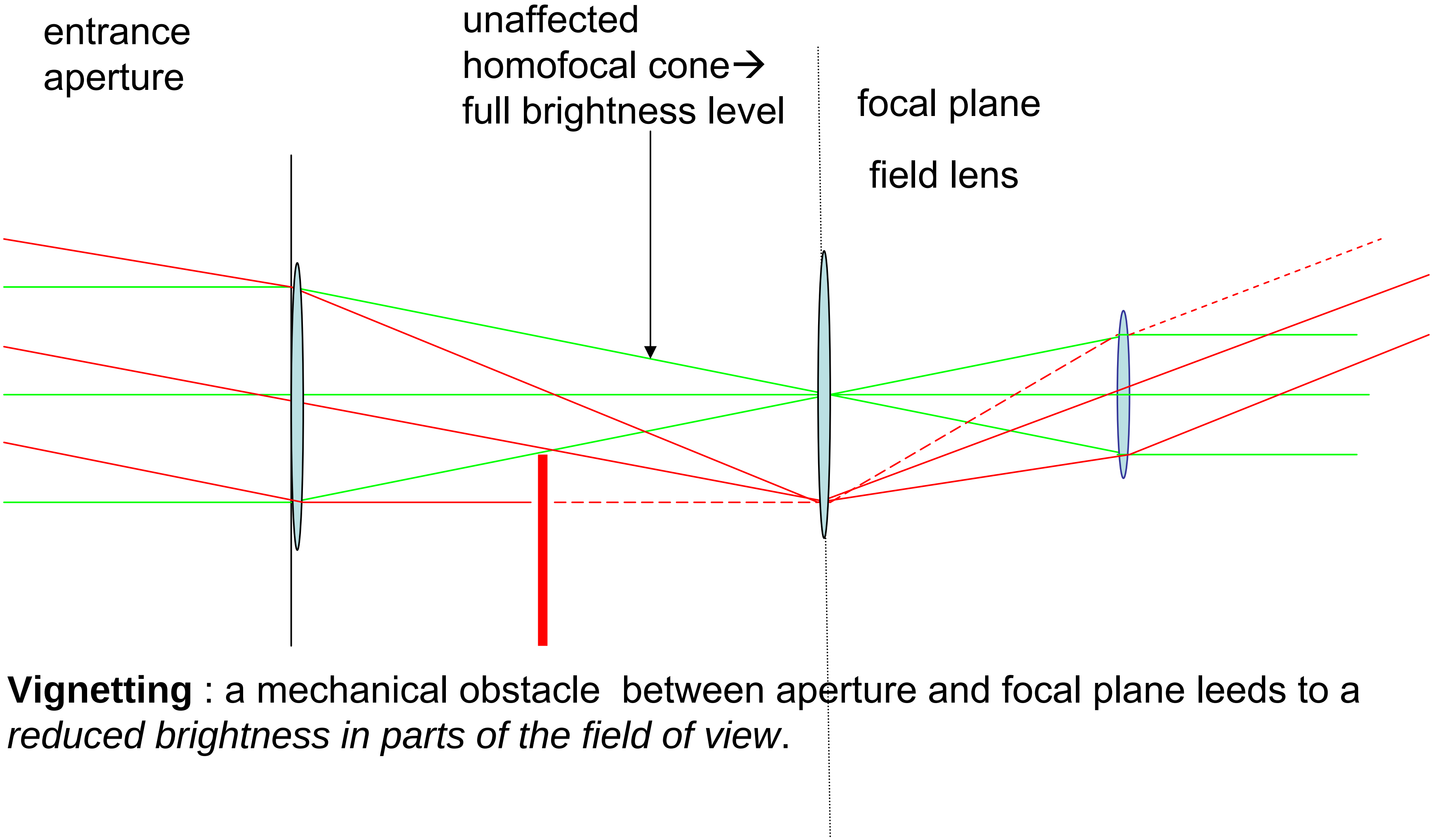


A ***field stop*** restricts the useable field of view.

It has no influence on the brightness of the image! Note: During a solar eclipse the moon acts as a field stop! Extreme danger for the retina, since the surface brightness on retina remains unchanged!

Vignetting

- What happens, if a mechanical obstacle is placed somewhere in between a pupil and an image?



Vignetting : a mechanical obstacle between aperture and focal plane leeds to a *reduced brightness in parts of the field of view*.

:

unvignetted and vignetted image

fond at: leicabirding.blogspot.com

founf at: http://www.marchlords.com/pics/05-0410/100_0371.jpg

sharp field stop

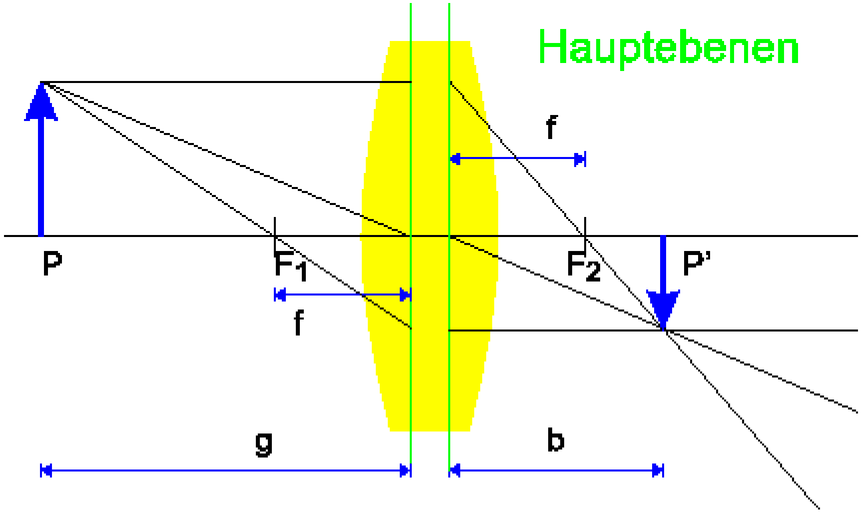
unsharp field stop with decreasing intensity towards edge of field

from dream to reality: real optics

real optical systems

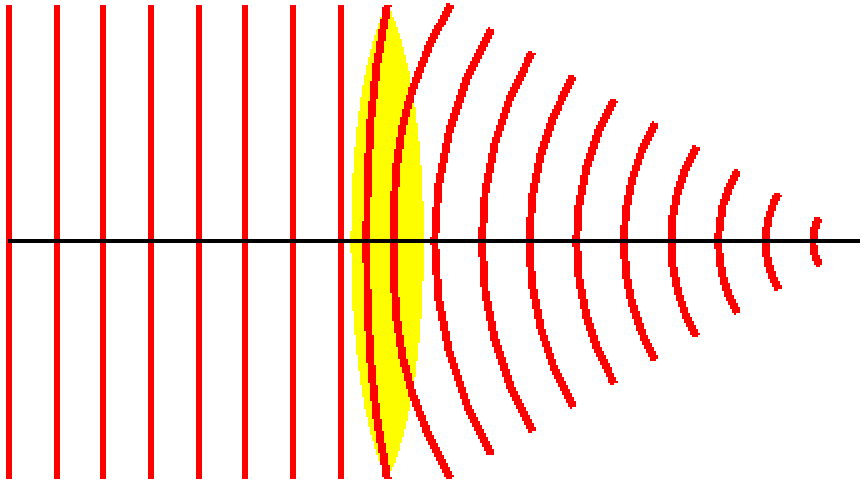
We abandon the paraxial approximation, but remain in the concept of geometrical optics

- geometric optics: light represented by rays; rays obey Snell´s law of refraction



alternatively: wave optics

- wave optics: concept of wave fronts; optical elements deform wave fronts by influencing optical path lenght → next lecture



Reality: optical aberrations

- paraxial approximation not fullfilled for real optical elements → one has to fight with *optical aberrations*
- *aberrations* can make your life difficult!
- several types of aberrations:

1. purely geometric aberrations: no impact on quality of point image, but on its location
   - image curvature
   - image tilt
   - distortion
2. wavefront relevent aberrations: detoriate image quality

only wavefront aberrations regarded here!

chromatic aberrations

- come always into play when using **refractive** elements
- *refractive index* (optical path length in glass) depends on frequency (wavelength); called „*dispersion*“
- effects: *lateral* and *axial colour*
- inherent to refractive optics (Refractors)
- can be disregarded for mirror optics (Reflectors)

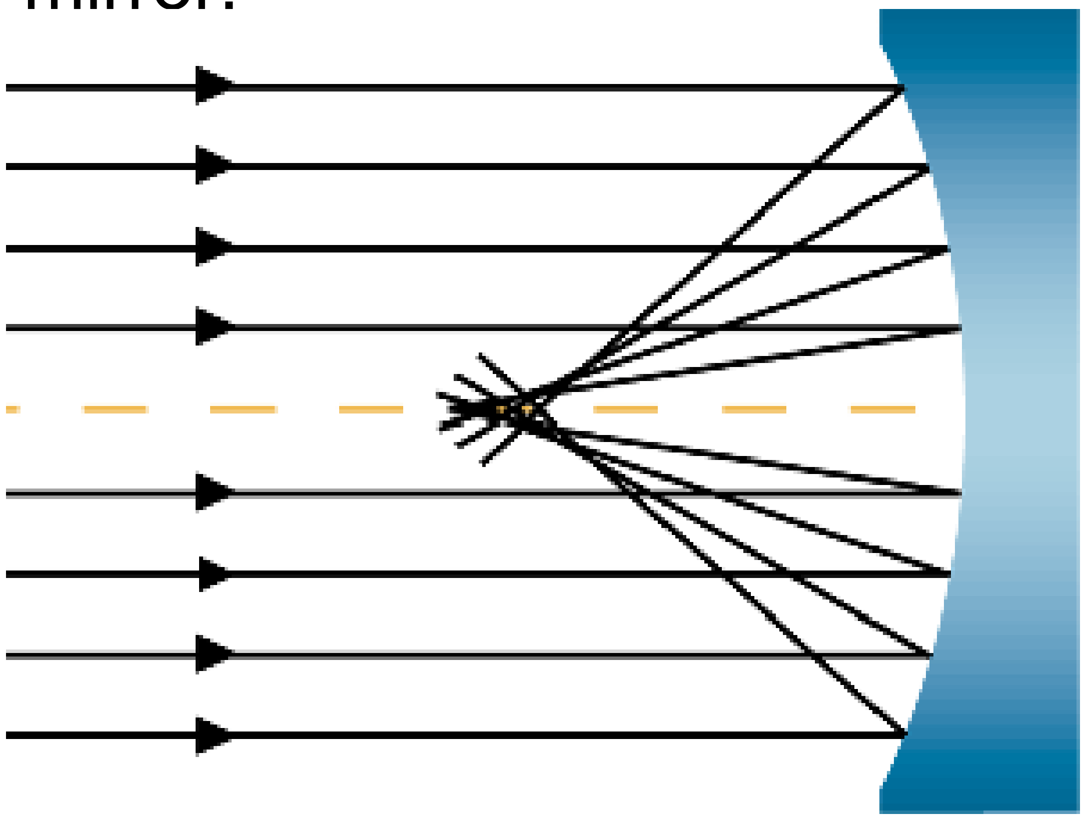
shape aberrations

- wavefront deformation by optical surfaces
- relevant for both, reflecting and refractive surfaces!

In the following, we will demonstrate the problem using the example of a simple telescope:

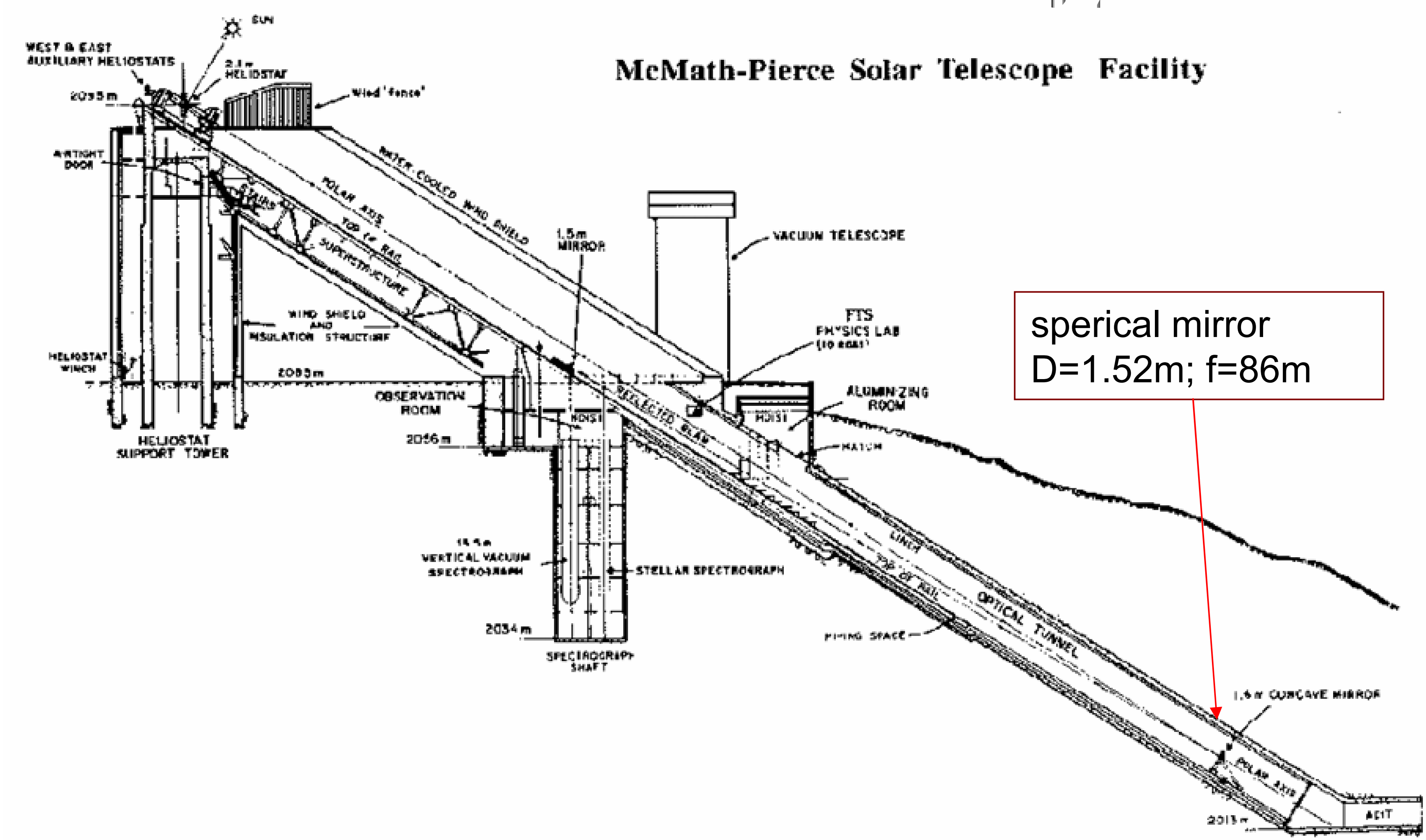
a simple (solar) telescope

- Our example telescope uses nothing else then a spherical mirror:



The Mc Math Pierce facility, Kitt Peak, Az

McMath-Pierce facility (Kitt Peak National Observatory)



spherical aberration

- spherical aberration limits the useful aperture of a spherical mirror (lens), and hence the f-ratio (german name: „Öffnungsfehler“)
- for f# >40 spherical aberration becomes negligeable as compared to the inevitable effect of diffraction (see next lecture)→ spherical mirrors work very well for slow systems!!
- remark: spherical aberration is independent on field angle → spherical mirrors are ideal for wide angle systems → Schmidt camera

excurs: The classical Schmidt camera

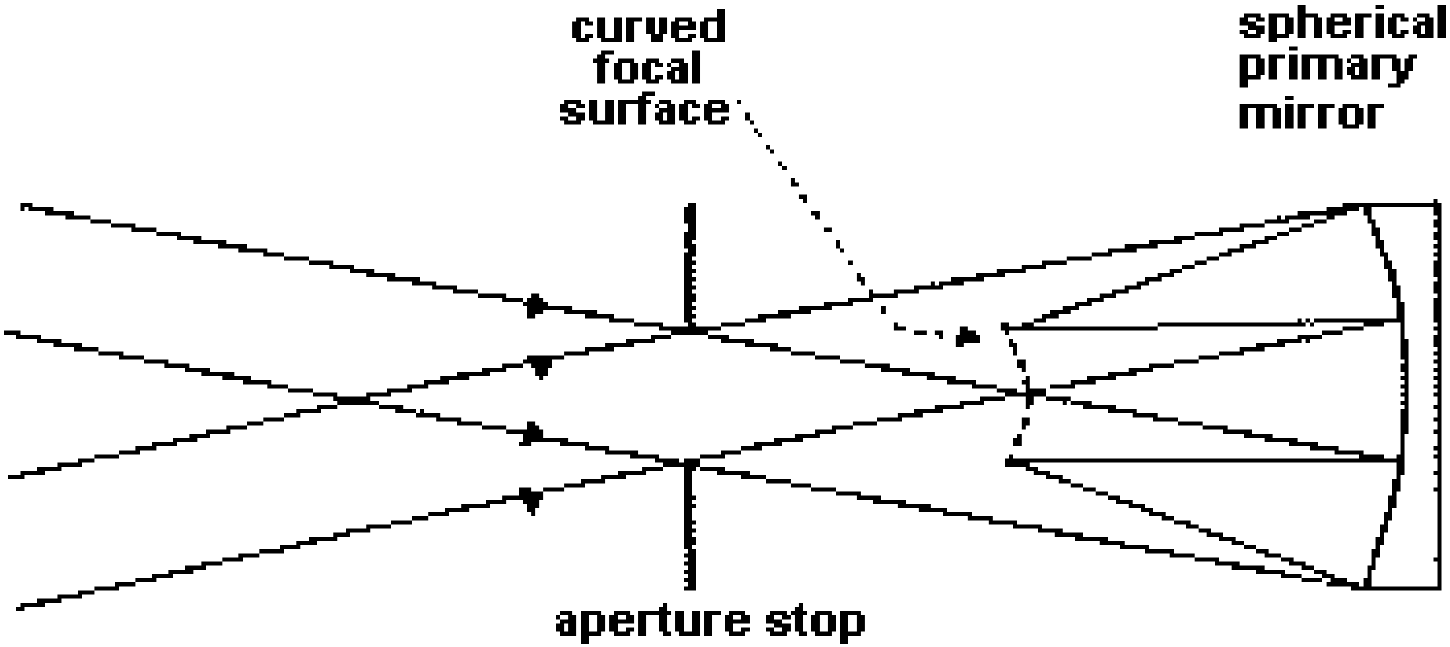


Figure 1. The optical layout of the lensless Schmidt camera.

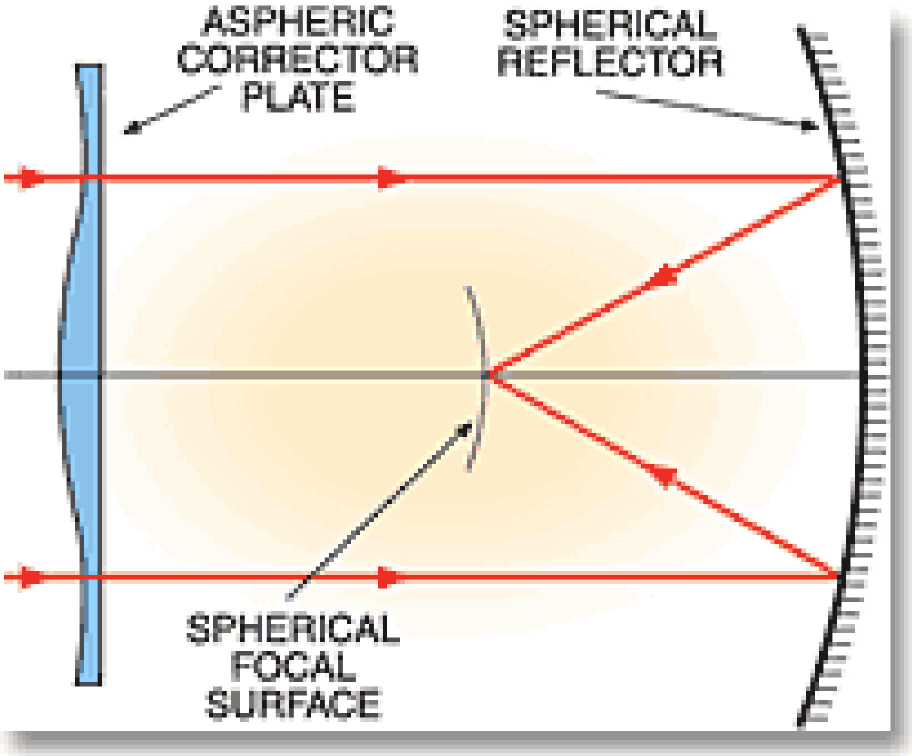
The classical Schmidt camera

- entrance aperture in center of curvature of the mirror limits the f-number to tolerable values of spherical aberration-→ slow system
- since the entrance aperture is placed in the center of the sphere, it works equally well for all directions on sky→ wide field camera!
- sharp image lies on a curved image plane
- the size of this image limits the useful field, since it forms an obstacle for the entering light.....

How to make a Schmidt camera faster?

- a corrector plate *(„Schmidt plate“)* in the enlarged entrance aperture (still in center of the spherical mirror) corrects for the now strong spherical aberration
- in order to correct for the spherical aberration, it must deform the wavefront to an aspheric shape

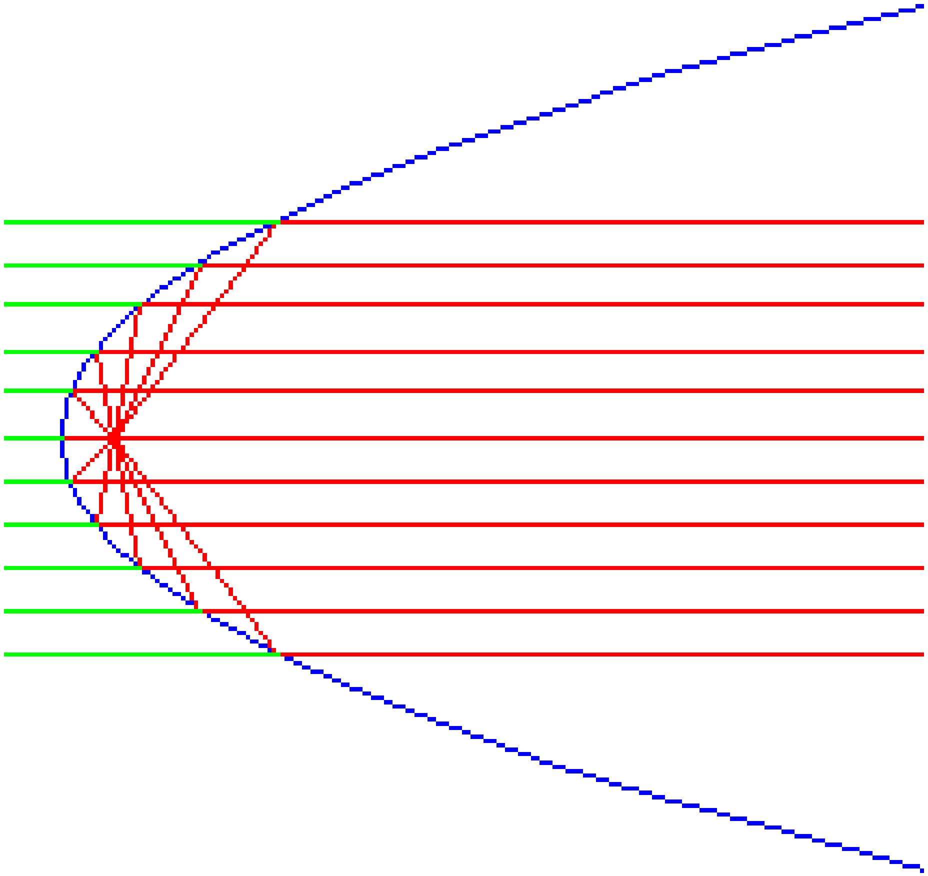
→ aspherisation („*aspheric optics*“, aspheric lens; hard to manufacture!!!)



aspherical surfaces

- A sphere is not the best shape to focus parallel rays into one point; but there is a shape that does it:

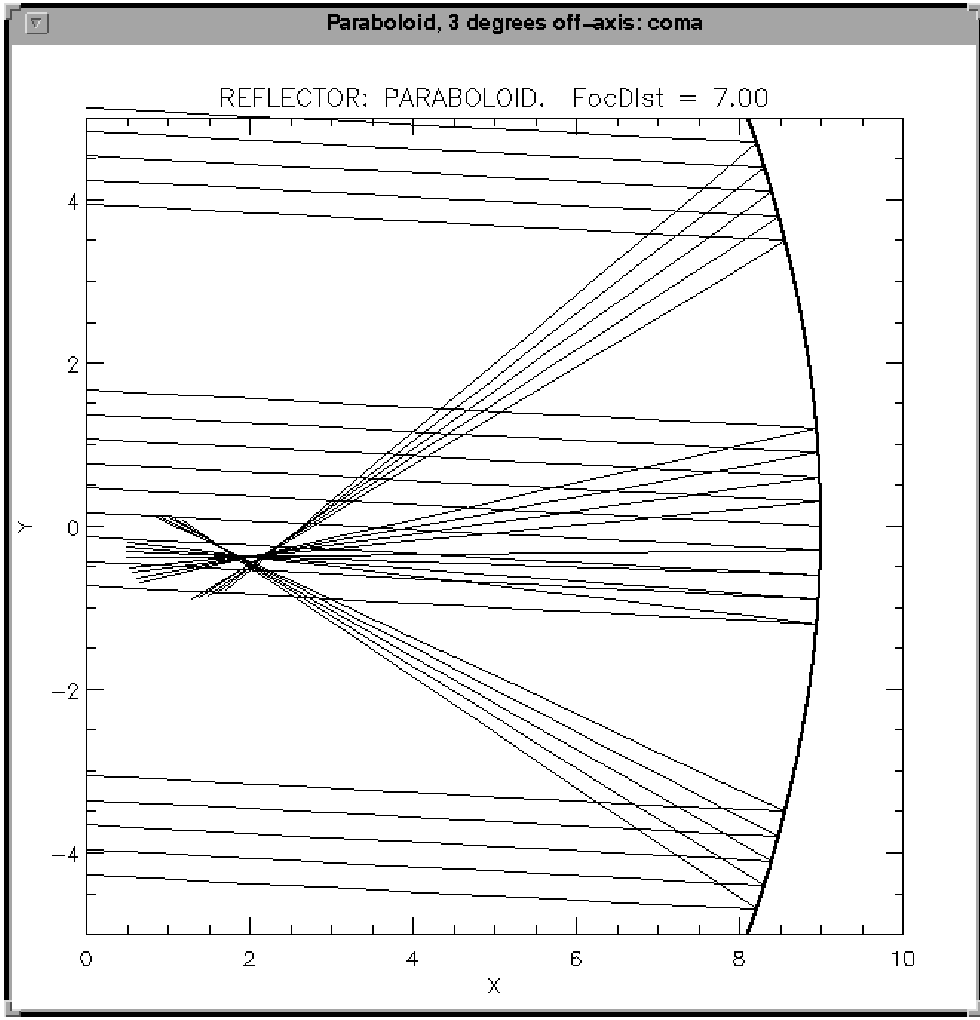
aspheric optics: parabola



A parabolic shape is perfect for all apertures! But only for light rays entering along the symmetry axis! EXTREMELY LIMITED FIELD OF VIEW!

aberrations of aspheres

- aberration free focus only „on axis“; deviation from rotational symmetry (edges of FOV) causes aberrations:
- (astigmatism)
- Coma



selecting a mirror

- for large f# a spherical mirror is the best choice (easy to manufacture, very insensitive to alignment errors: shift compensates tilt!)
- prime focus (solar) telescopes with f# > 40 use spherical mirrors
- example: McMath-Pierce facility on Kitt Peak (f# 54, 1.5m diameter, 86m (!) focal length, observation in prime focus)

arguments against prime focus telescopes

- high angular resolution requires large effective focal length (non-vanishing pixel size!)
- in prime focus:

effective focal length = focal length = length!

Putting a McMath on a satellite might cause problems with the funding agencies....

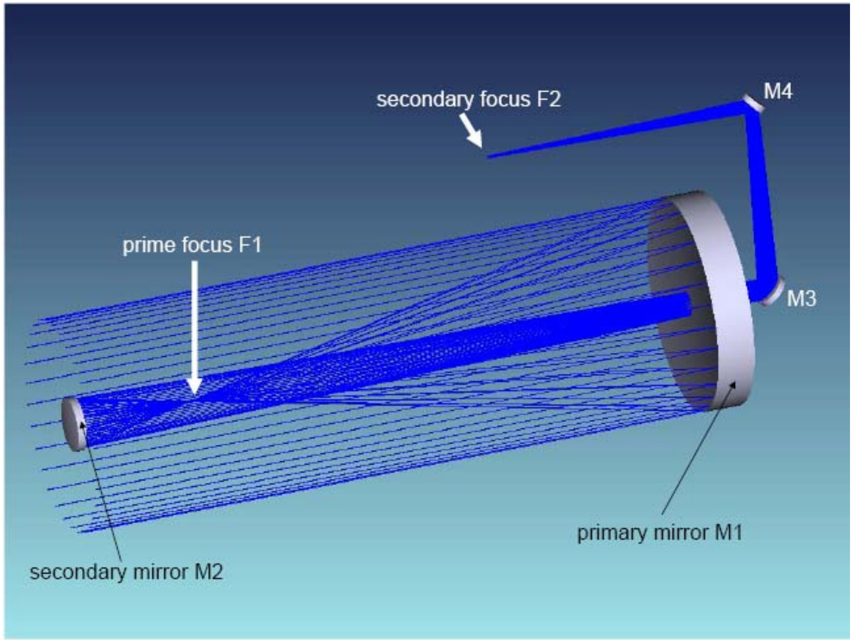
So, how to make a telescope compact??

Telescopes with short primary focal length

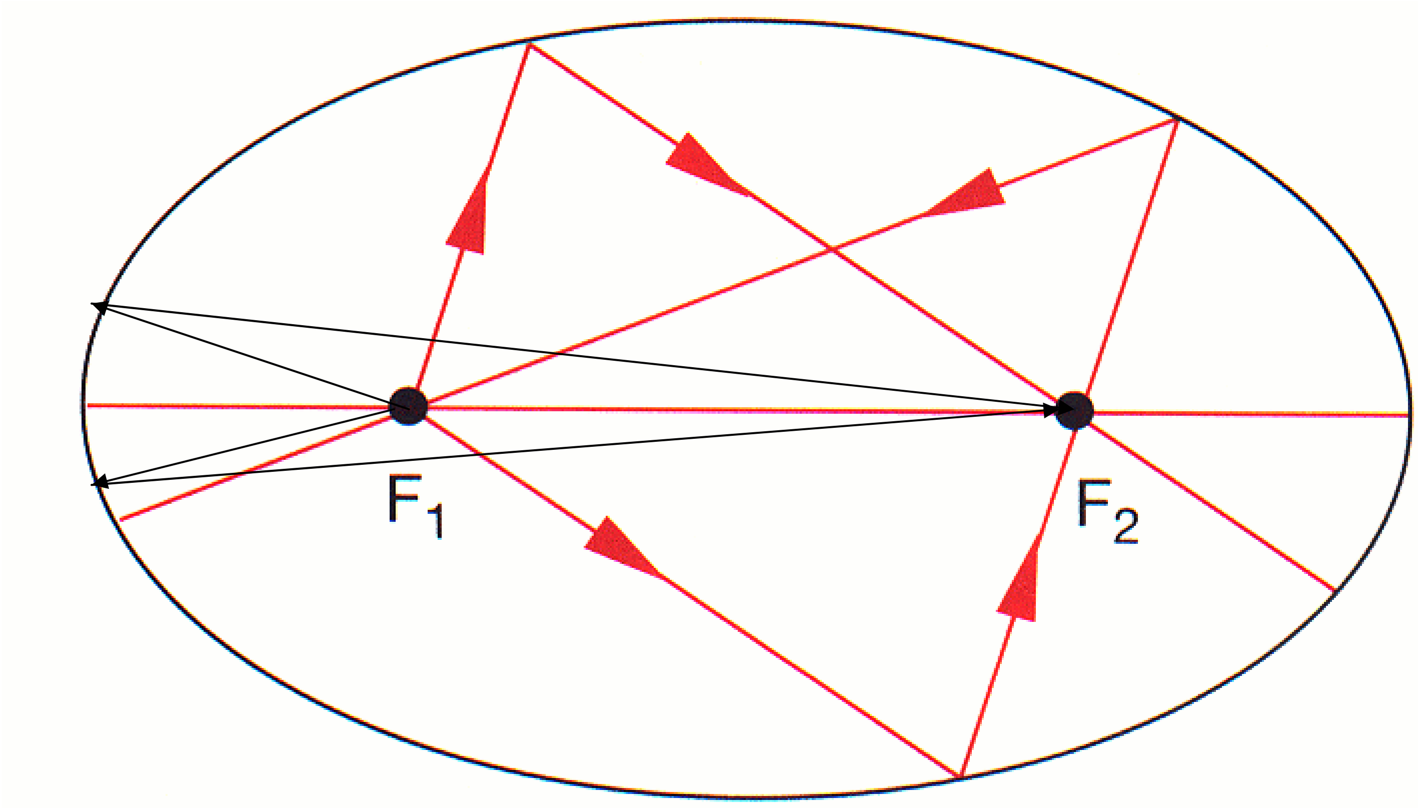
- compact telescopes consist of a short primary focal length + internal magnification
- observation in secondary (tertiary) focus
- folded designs
- 2nd mirror can be used to compensate for primary aberrations („optical systems“)

Example: the Gregory telescope

- fast primary focus F1 is provided by parabolic mirror
- then the primary image in F1 is magnified by another asphere: the ellipsoid!



aspheric optics: ellipsoid



Sunrise telescope

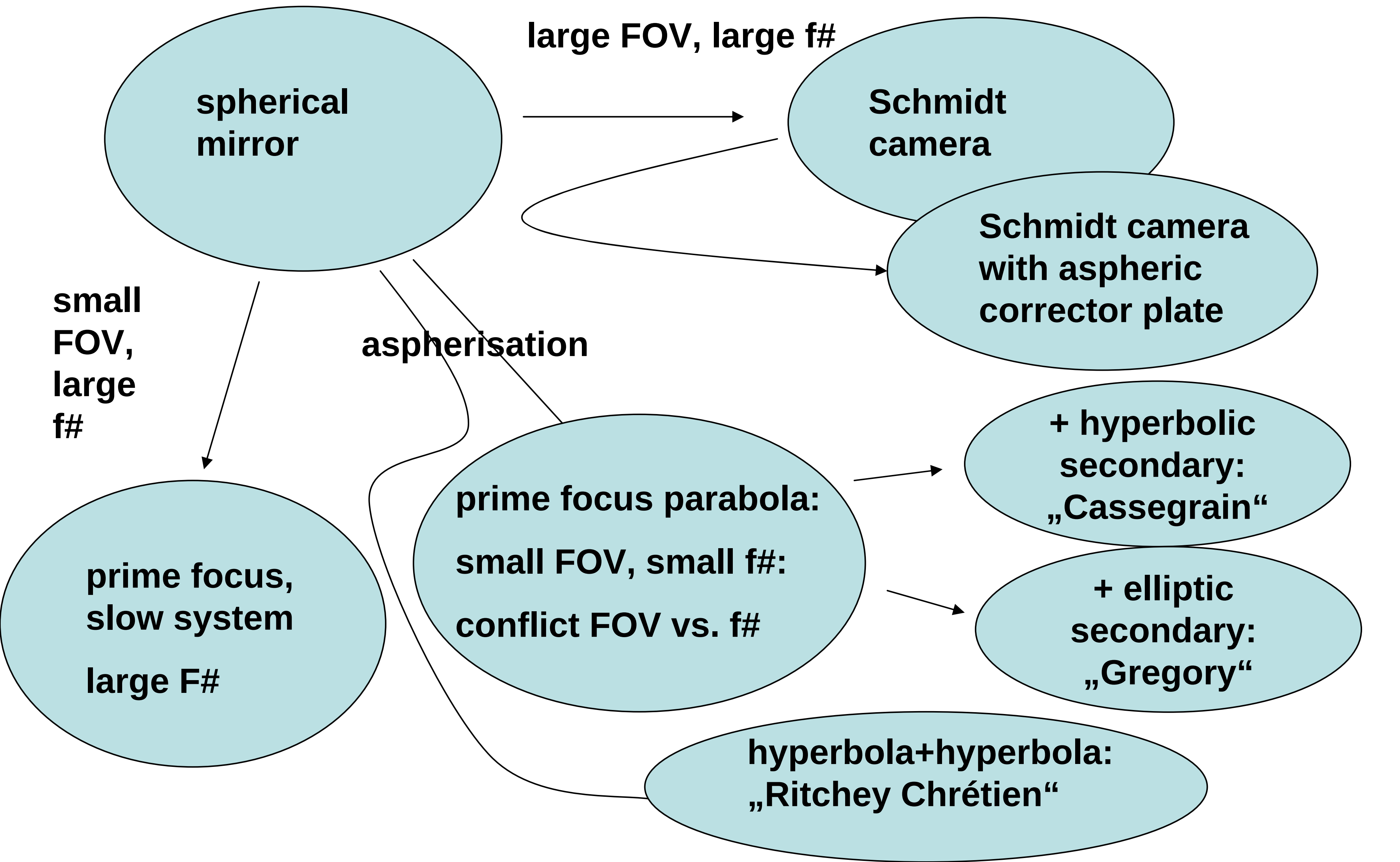
parabolic primary
D=1m, f=2.42m

elliptic secondary
mirror for 10times
magnification (f=55cm,
490cm)

other telescope types

- there is an endless number of telescope types
- the choice strongly depends on the specific needs
- one always has to find a compromise between field-of-view and f#
- in addition: your life gets tougher when going to shorter wavelengths → next lecture

the telescope Zoo



NOTA BENE!

- compensating optical aberrations of non-ideal surfaces by adding more surfaces must be done extremely carefully, otherwise you risk to fight fire with gas..
- **keep it as simple as you can**
- **an optical design that gives you perfect results on the computer might not work in reality: somebody has to build it, and you have to align it!!**