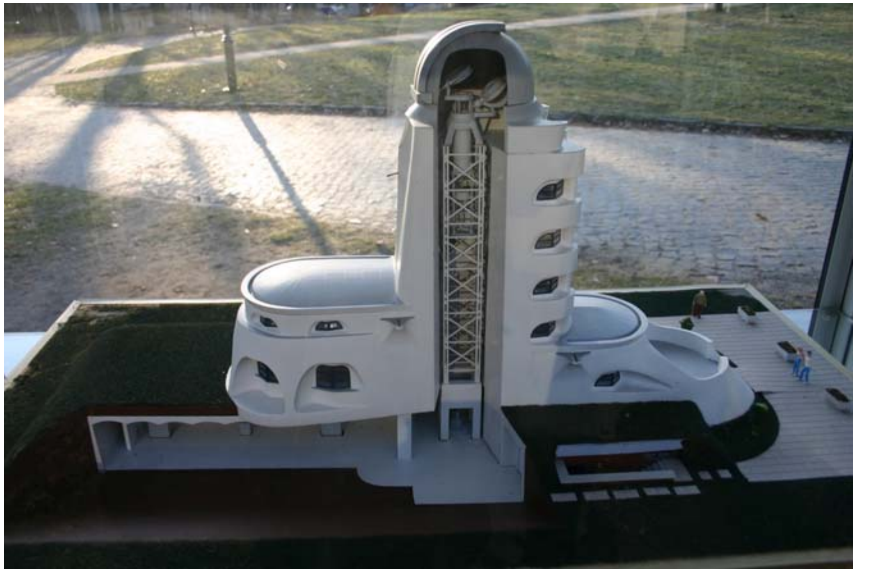
Solar Telescopes II

specific aspects of solar telescopes

In this lecture

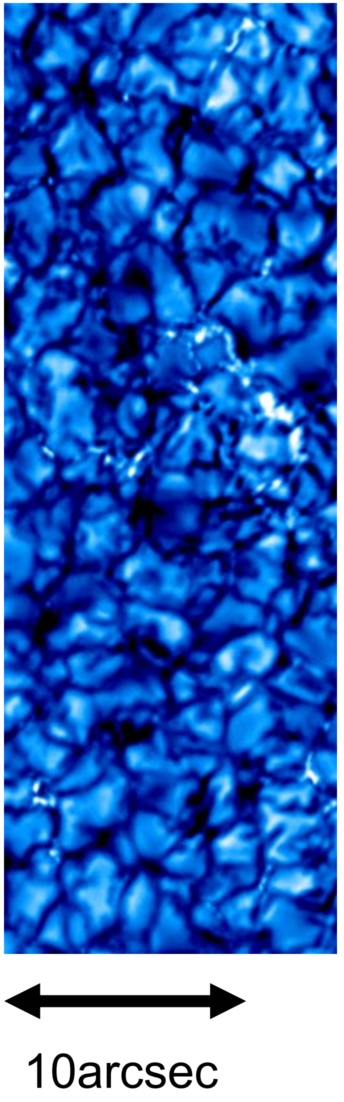
- we want to apply our knowledge obtained in the last lecture to understand the specific aspects of solar telescopes



science drivers in solar observing

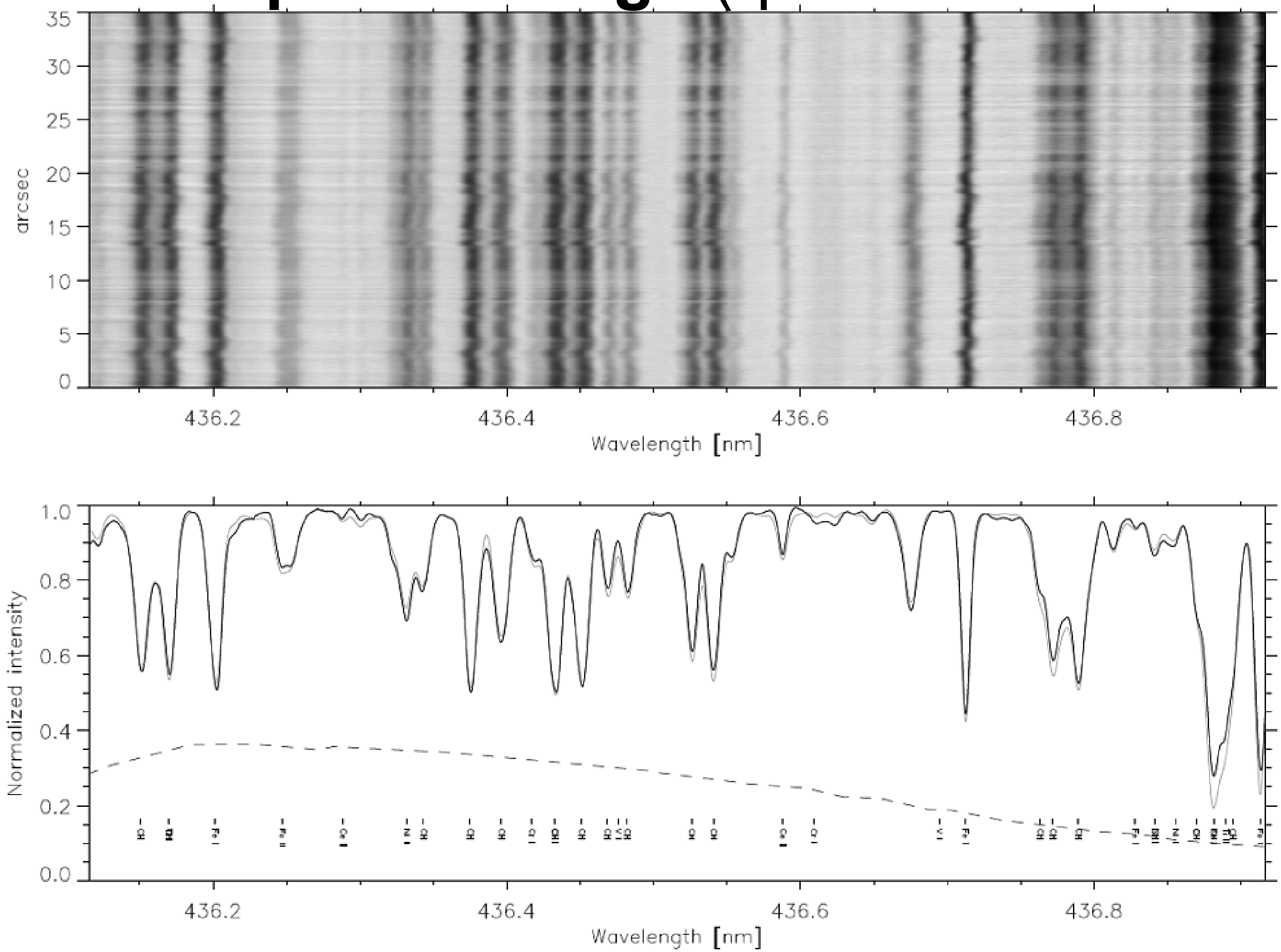
Sun is the only star that can be studied in detail

- → **highest spatial resolution** (angular resolution) in a relatively
- → **small FOV** (limited number of detector (=resolution) elements)



Physics encoded in shape of spectral lines

- → **highest spectral resolution** in
- → **narrow spectral range** (quasi-monochromatic)



Vasily Zakharov, PhD thesis

Optical parameters of solar telescopes: 1. Which focal length?

- typical scale of solar surface phenomena is on the order of 100km or smaller, which corresponds to an angular resolution of a fraction of arcsec !
- the typical size of a detector element (pixel) is 10µm

→ required plate scale is therefore ~ 4“/mm

→ **effective focal length ~ 50m!**

2. Which aperture is needed?

From wave optics: The ***angular resolution*** of an optical system is principally limited by ***diffraction at the entrance aperture***. The ***smallest resolvable angle*** on the sky is ~ ***ratio of wavelength to aperture***

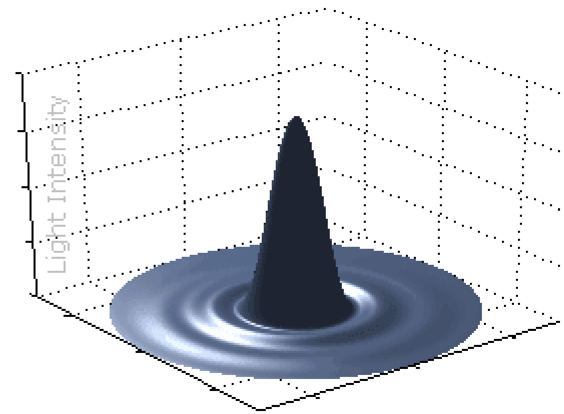
Special case: circular clear aperture D:

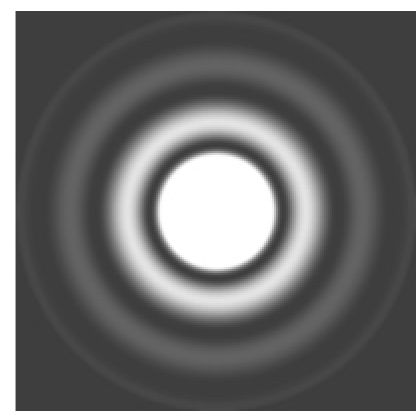
angular resolution is $1.22*\lambda/D$;

→ in the visible (λ=500nm) 0.1arcsec resolution needs D=1m!

Diffraction limit

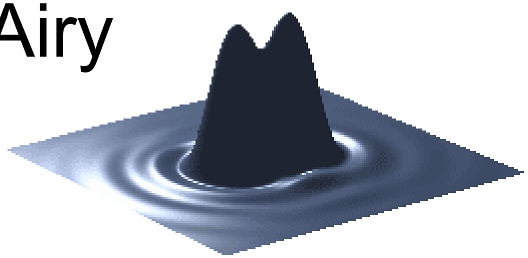
- diffraction sets upper value of image „sharpness“
- classical view: diffraction at entrance aperture creates intensity pattern in focal plane (Airy disc); angular radius 1.22λ/D (for circular unobscured aperture)
- Airy pattern: „point spread function“ PSF

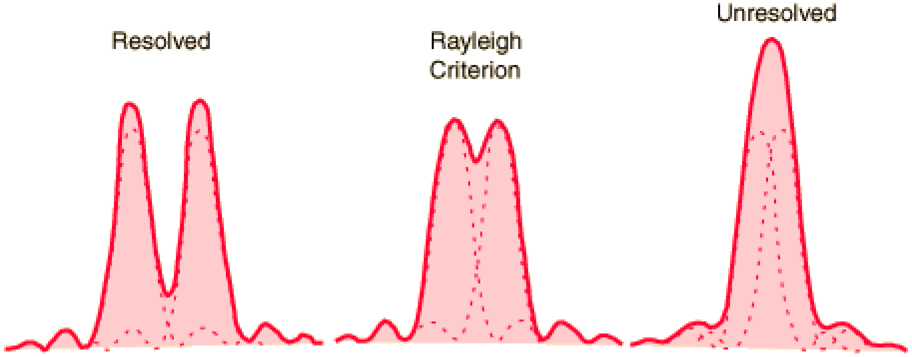


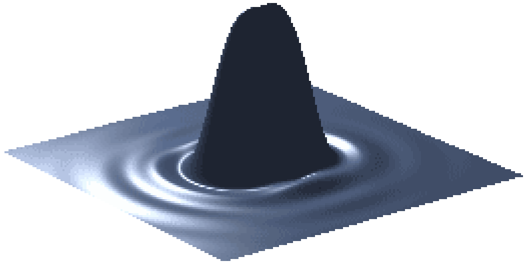


Resolving two point sources (double star in front of black sky)

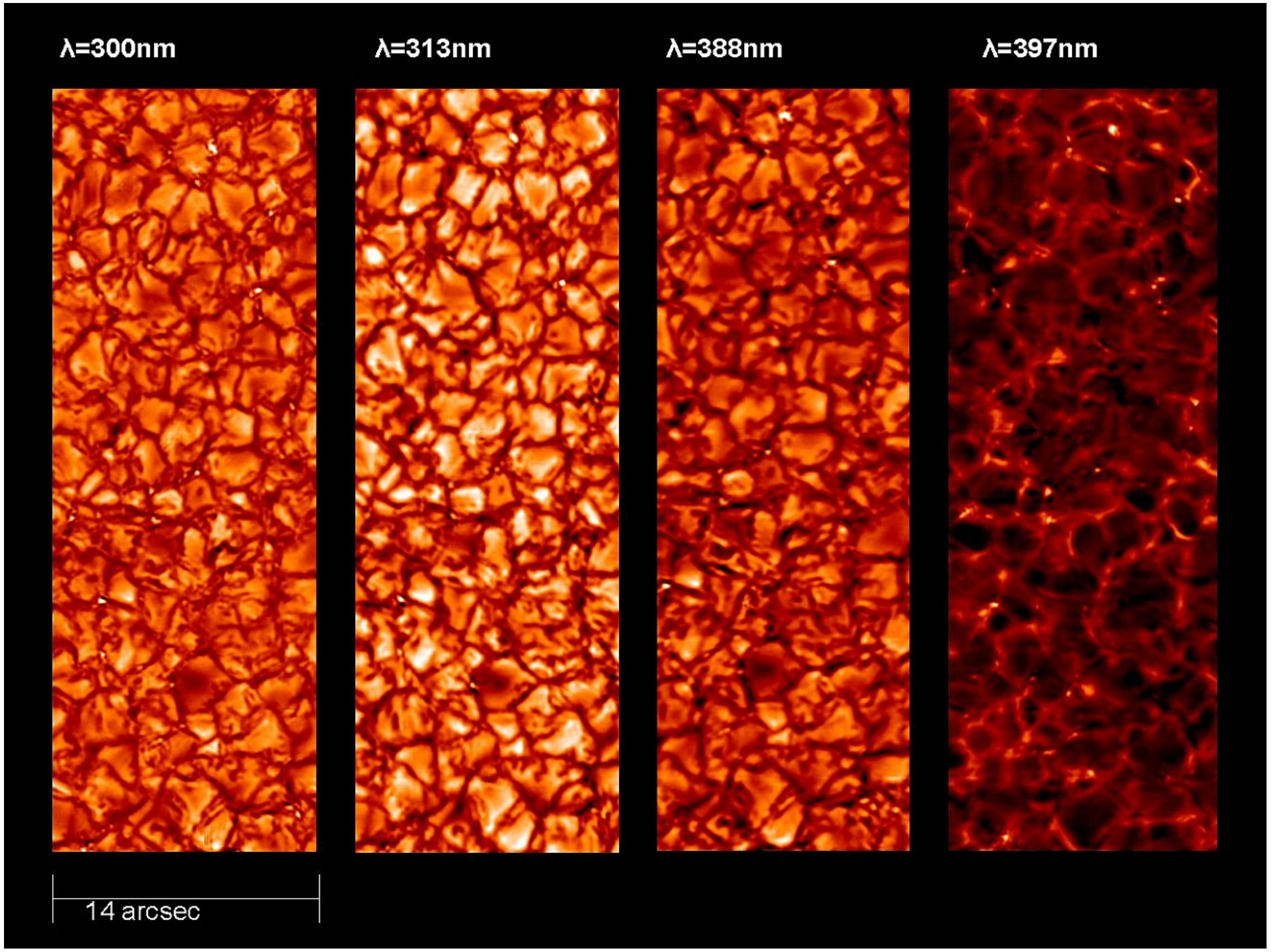
- *Rayleigh criterion*: two point sources can be *just barely distinguished* if the peak of (Airy Star 1) is imaged at the first minimum of (Airy Star 2)







How to deal with extended objects?



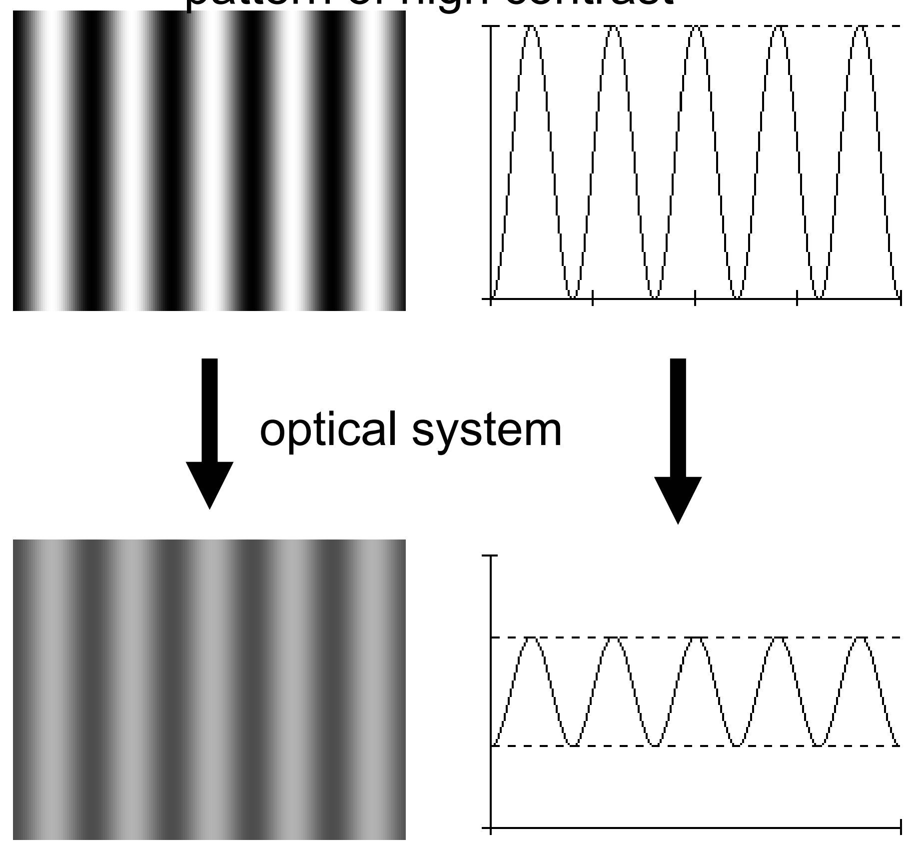
Sunrise / SuFI images

Resolution of a solar telescope

- Rayleigh criterion not adequate for Sun: extended object, there might be no point sources!
- We define resolution via the ability to image intensity contrast

→ „Modulation transfer function“ MTF

object with intensity pattern of high contrast

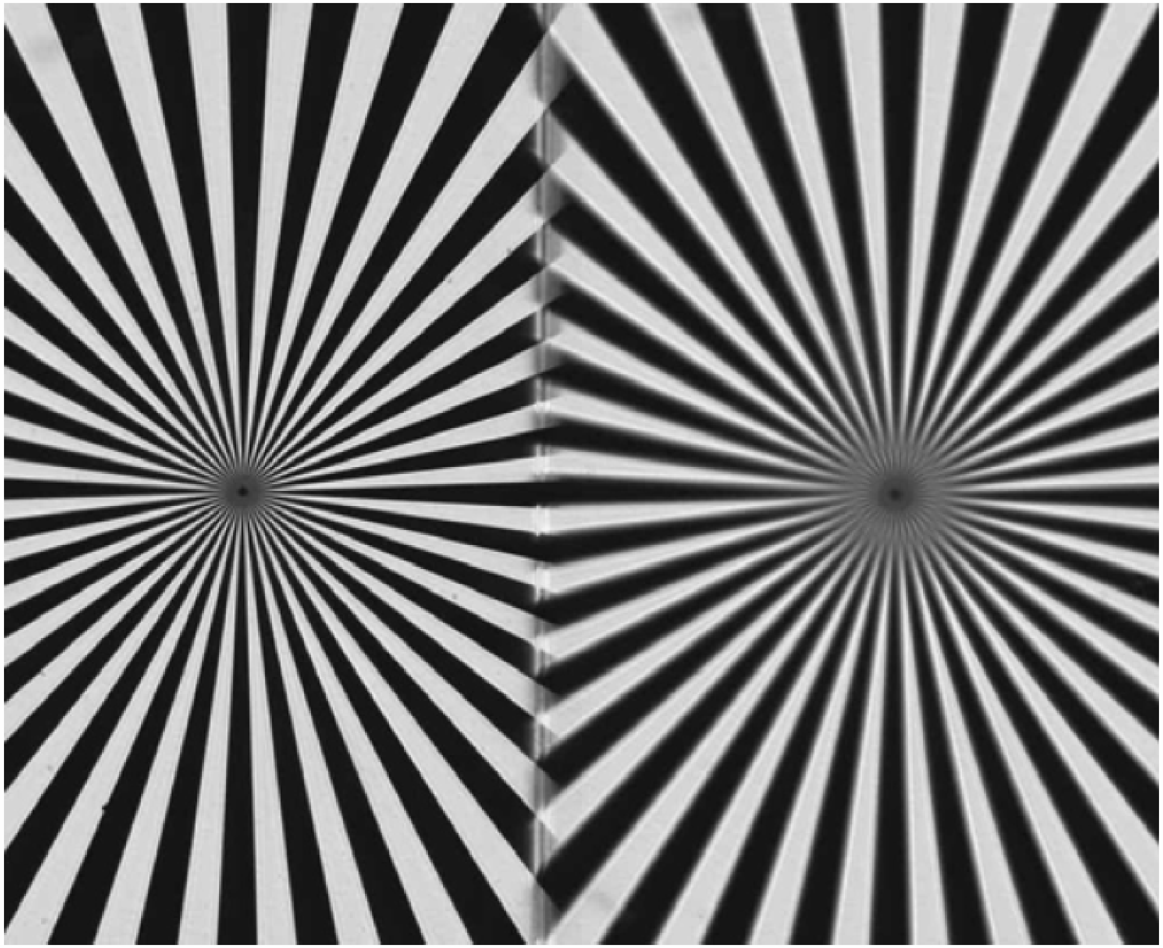


measured intensity distribution with significantly reduced contrast

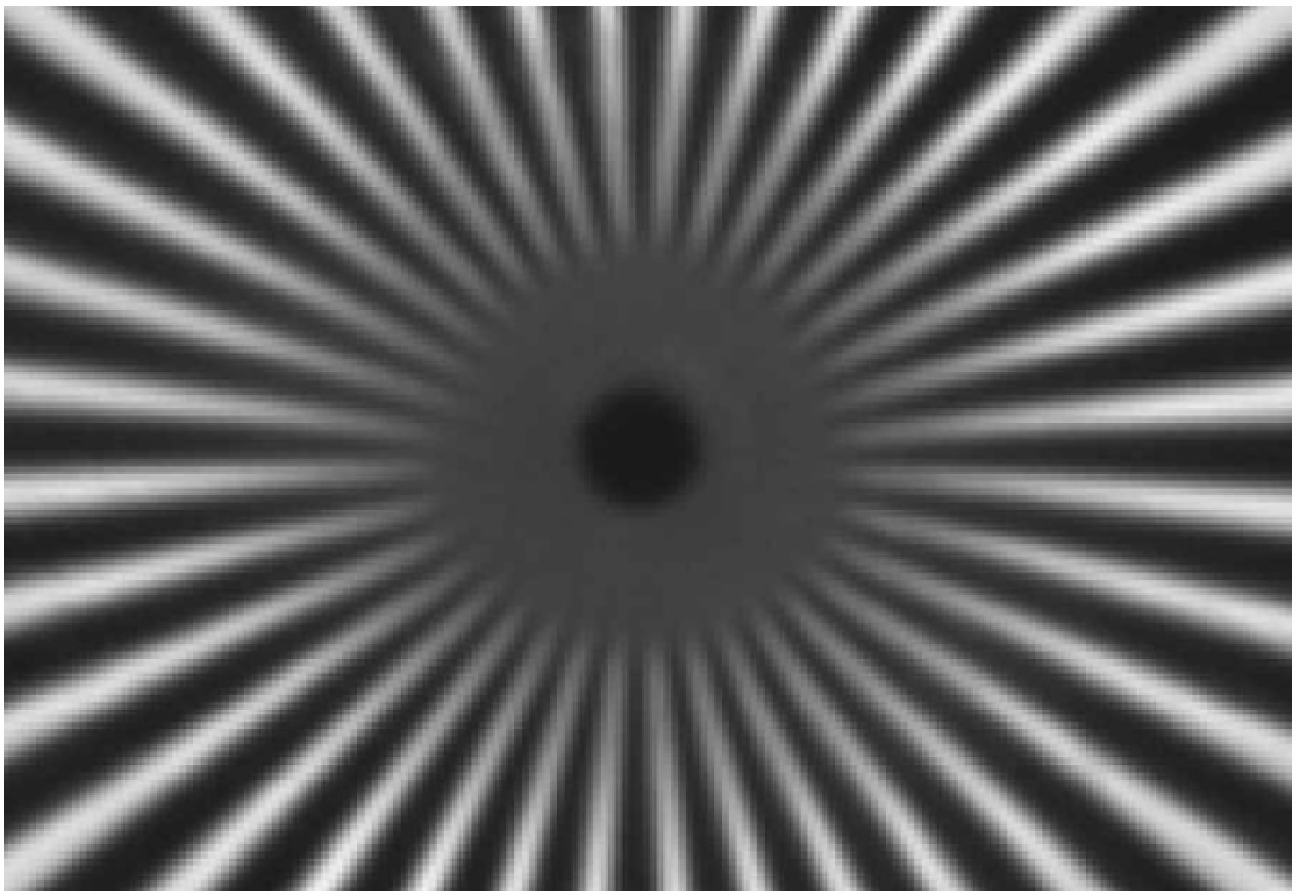
physical meaning of the MTF

- extended objects show contrast pattern that can be Fourier analysed in spatial frequencies
- low frequencies (=large scale structures) will be imaged through system without problem
- high frequencies will be more and more „damped“ by diffraction (and aberrations)
- ***cut-off frequency***: It is the frequency of a sin-pattern, which is completely smeared by the optics to a uniform grey (amplitude of sin variation = 0) image.
- $\mathbf{f_{limit} = D/\lambda}$

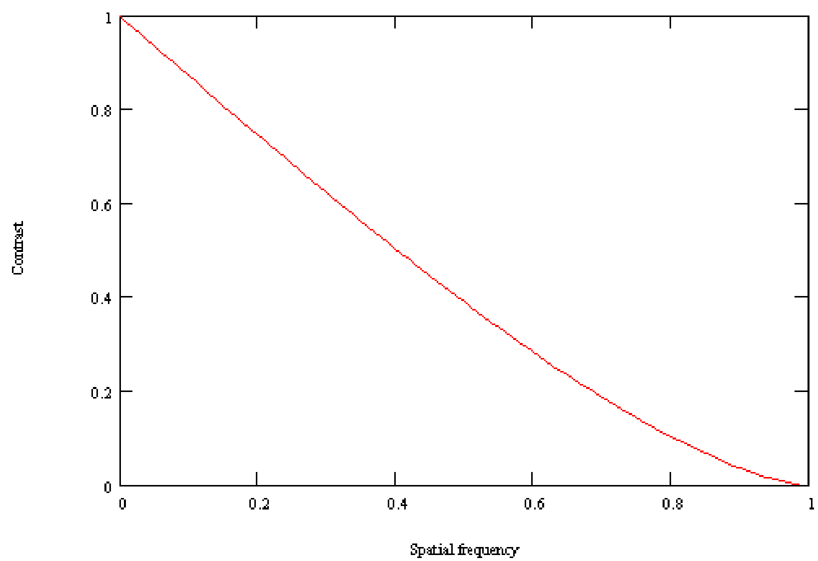
How to see effect of MTF?

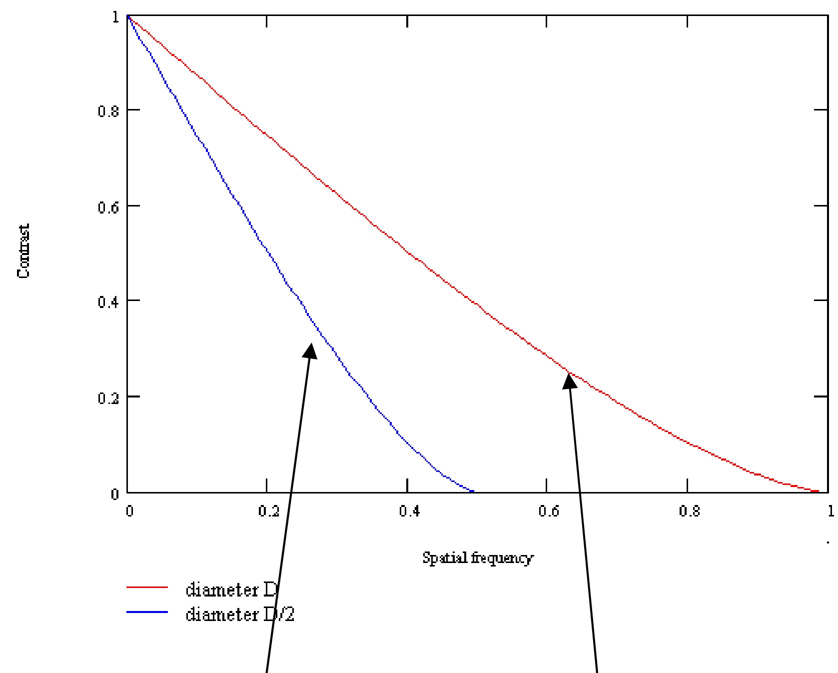


Siemens star (Sunrise SuFI)



MTF curves (circular, unobscured entrance apertures of different sizes)





Hinode-size (D=50cm); Sunrise-size (D=1m)

if both telescopes are perfect, the larger telescope will provide higher contrast images AT ALL SPATIAL FREQUENCIES!

advantages of the MTF representation

- MTFs can be multiplied! The optical performance of the system can be regarded as the **product** of the individual contributions:

  (seeing)*Telescope*instrument*detector

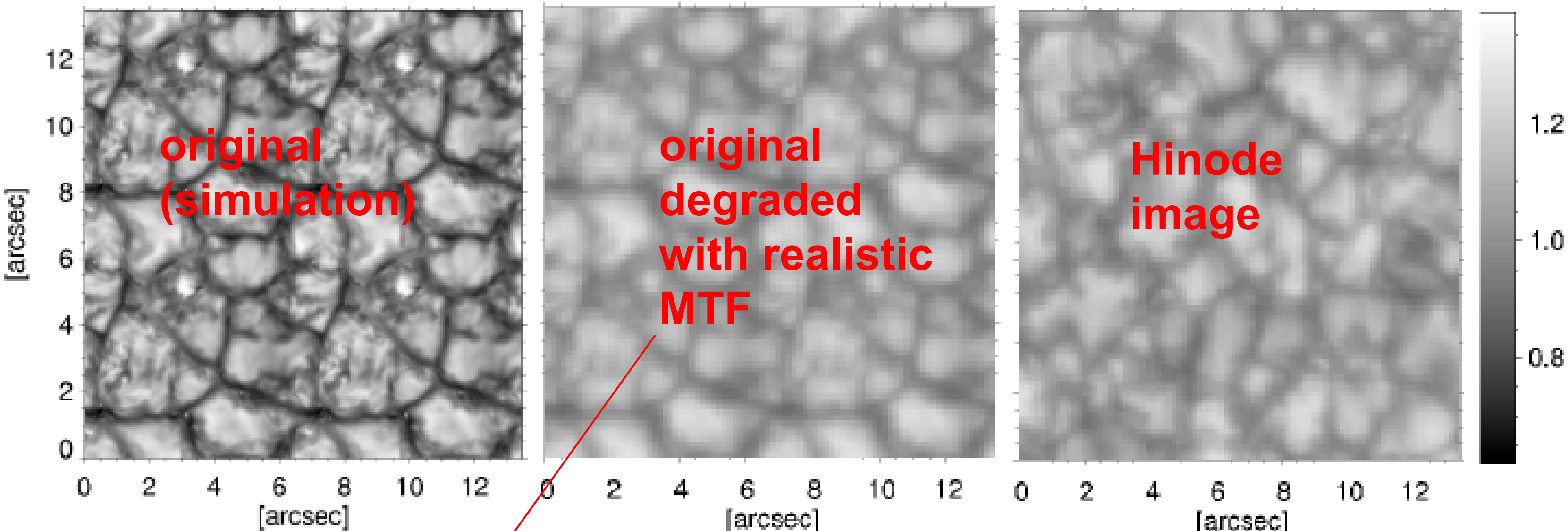
- at a frequency corresponding to 1.22λ/D (Rayleigh diffraction limit for circular aperture) a perfect telescope transmits only ~10% of the original contrast! A CCD has an MTF of ~50% near the sampling frequency. The solar photosphere has typical rms contrasts of 15%.........

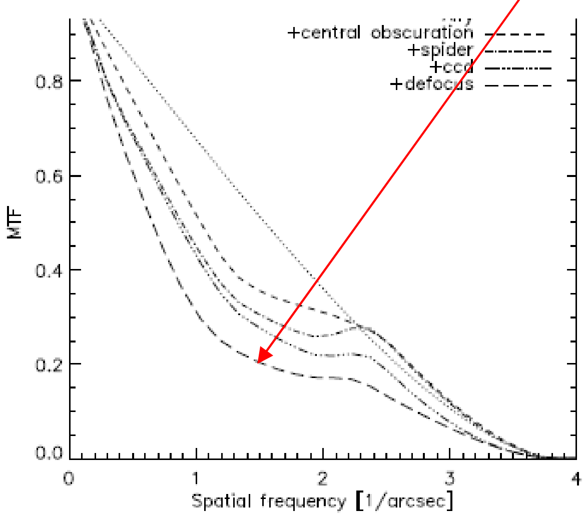
→ measured contrast at high frequencies very low ! Compare to photon noise!!!

A „diffraction limited“ optical system

- diffraction sets theoretical limit to image contrast
- geometrical optical aberrations also significantly reduce contrast!!
- optical systems are usally considered „diffraction limited“ as long as the contributions of geometrical aberrations do not exceed the ones due to diffraction

Example: granulation contrast as seen by Hinode





Effects taken into account	rms [%]
none	14.4
Airy	10.9
+ central obscuration	9.6
+ spider	8.7
+ CCD	8.5
+ defocus (1.5 mm)	7.5

Danilovic et al., A&A 484, L17–L20 (2008)

Contrast killers

- Aberrations
- stray light
  - not necessarily „scattered“ light!!
  - usually used term for every photon, which should not be in a detector pixel...regardless of the mechanism that brings it there!
  - most severe: medium order aberrations, (seeing; only on ground), spectral leakage in high spectral resolution instruments)

Specific problems in solar observations

Stray light

- stray light decreases contrast (the minima of the Airy pattern are not zero anymore!)
- not a real problem for low-res observations in white light in quiet solar regions (bright target)
- serious problem in observations in a spectral line in a sunspot umbra (5% continuum intensity times 5% residual intensity in the line core!) → see lecture on magnetographs
- **dominating problem in coronographs (**see lecture on magnetographs)

Stray light in solar telescopes

- In contrast to any non-solar telescope, the only light contamination source in solar physics is the object itself!!!!! You cannot avoid that all photons of all wavelengths from the whole solar disk enter the telescope!!

Straylight severeness

- How many parasitic photons can you afford in a pixel? Typically 1%, that´s the typical photon noise anyway..
- Now it depends on the following ratio:

Number of photons that you expect in the pixel (**target** brightness * **efficiency** of your optical system)

as compared to

Number of photons that could potentially take a wrong route and end up in the pixel (**total Sun** brightness * straylight suppression capability of your system)

Example: Sunrise SuFI 313nm

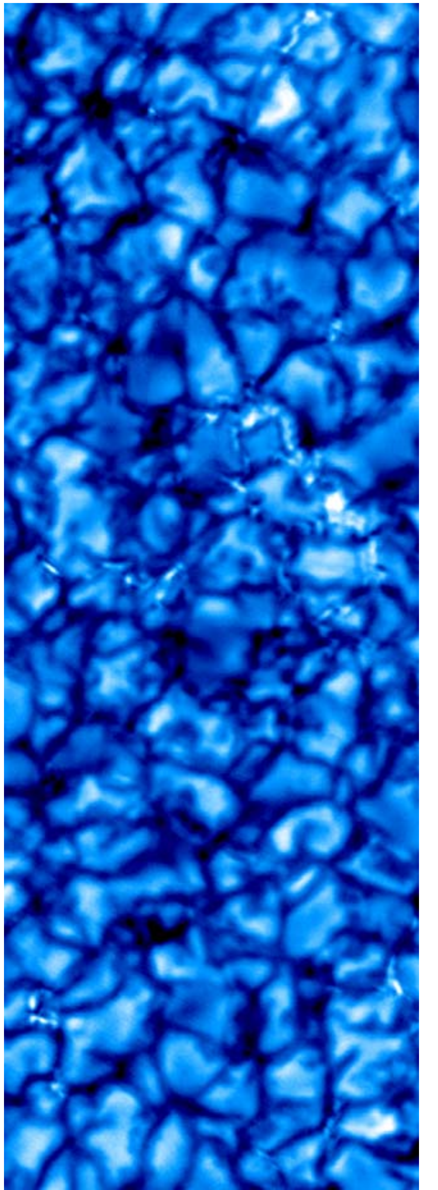
- FoV 20“x40“ : ~1xE-4 of solar disk
- 1px: ~1E-6 of FoV
- spectral band 1nm in UV: ~1xE-4 of full spectrum
- throughput ~1E-2

→ only 1 photon out of 1E16 in the system is a good one!!!!

- goal: parasitic photons < 1xE-2 relative

→ straylight suppression factor of 1E-18 needed

and „local“ (near angle) smearing due to wave front aberrations NOT yet taken into account!!!!

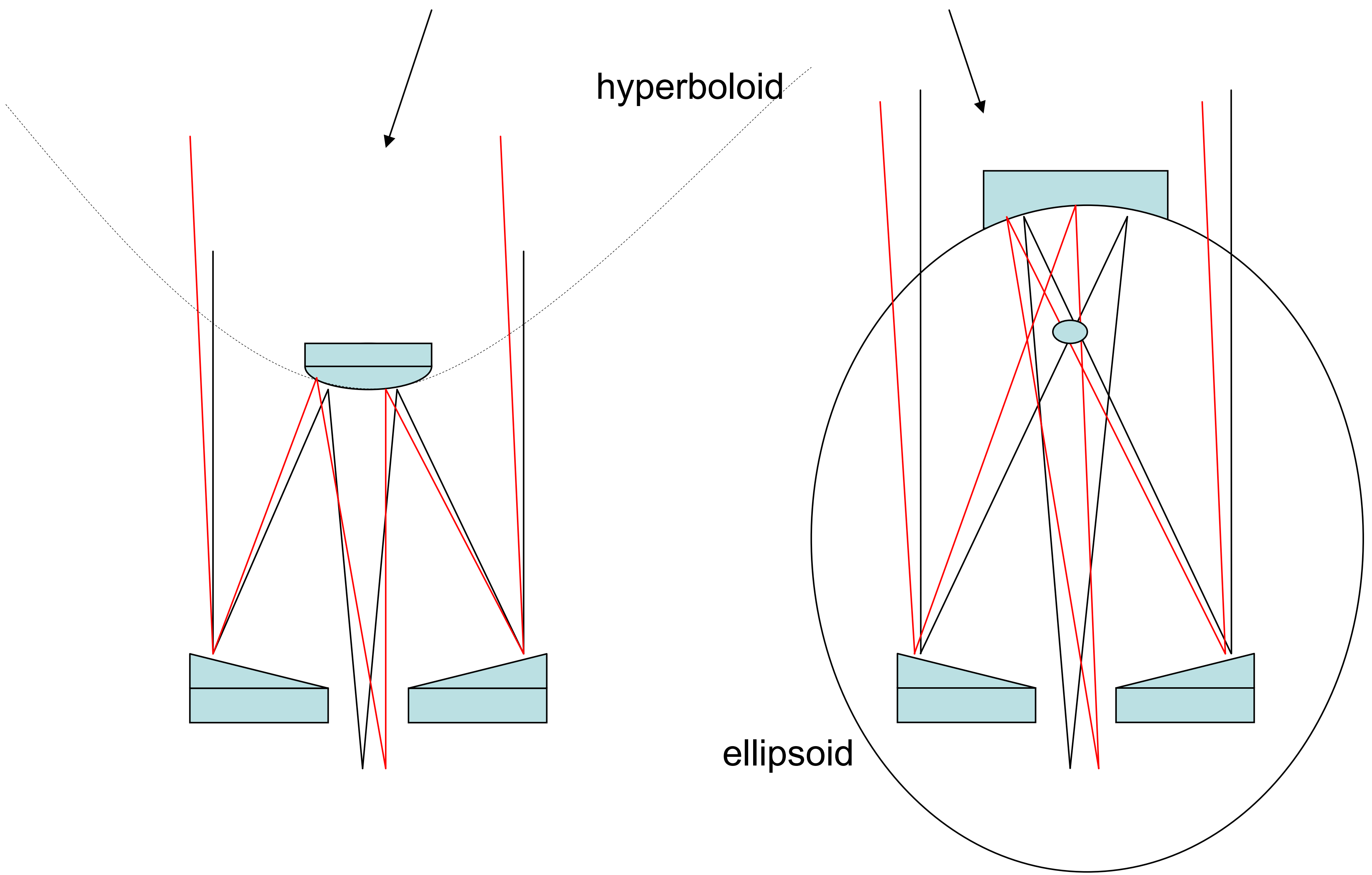


How to do stray-light killing: the Gregory telescope with primary field stop

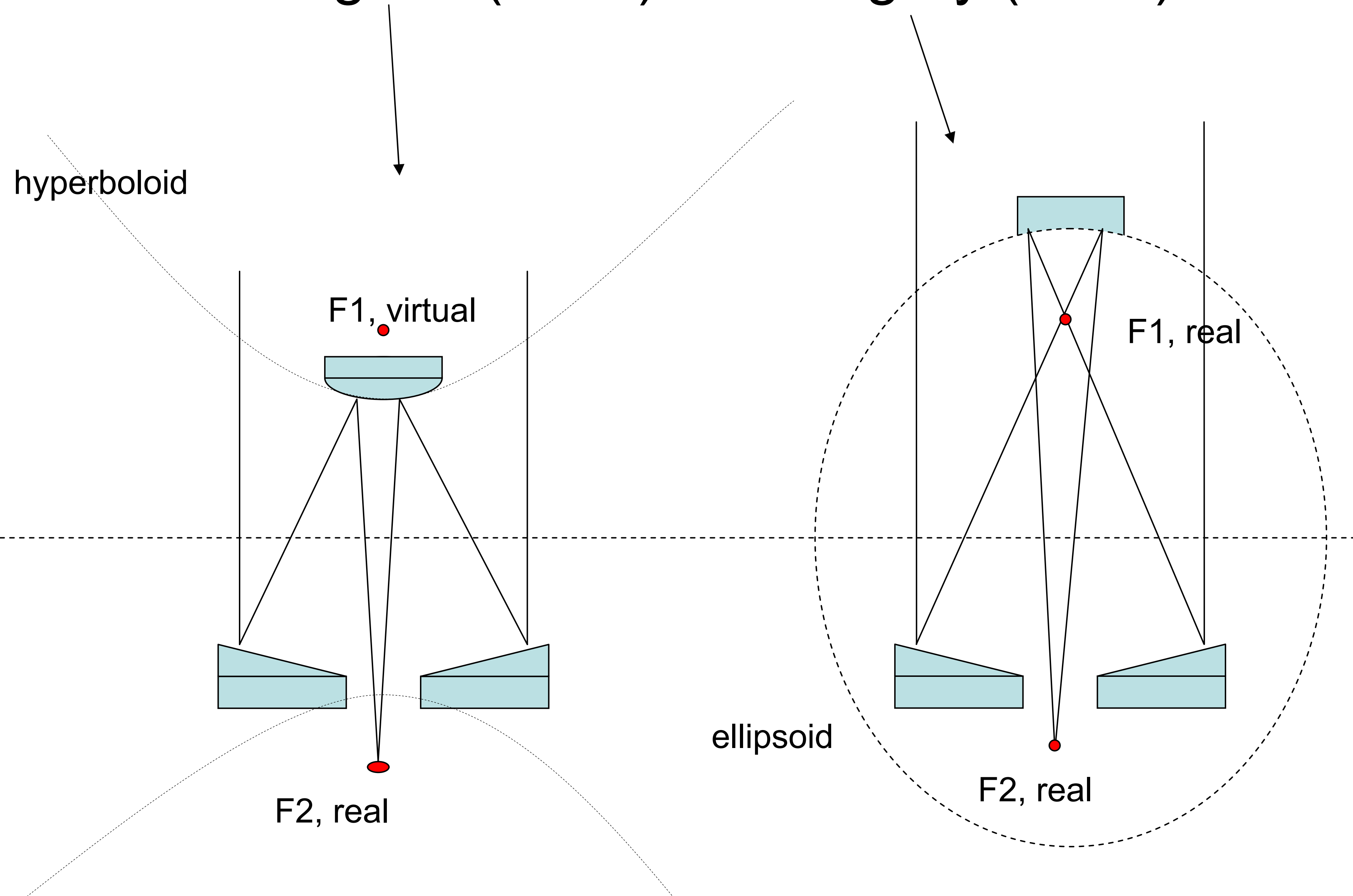
- first used in Hainberg observatory Göttingen, then GCT Locarno

- today: GREGOR, SUNRISE

Cassegrain vs. Gregory:



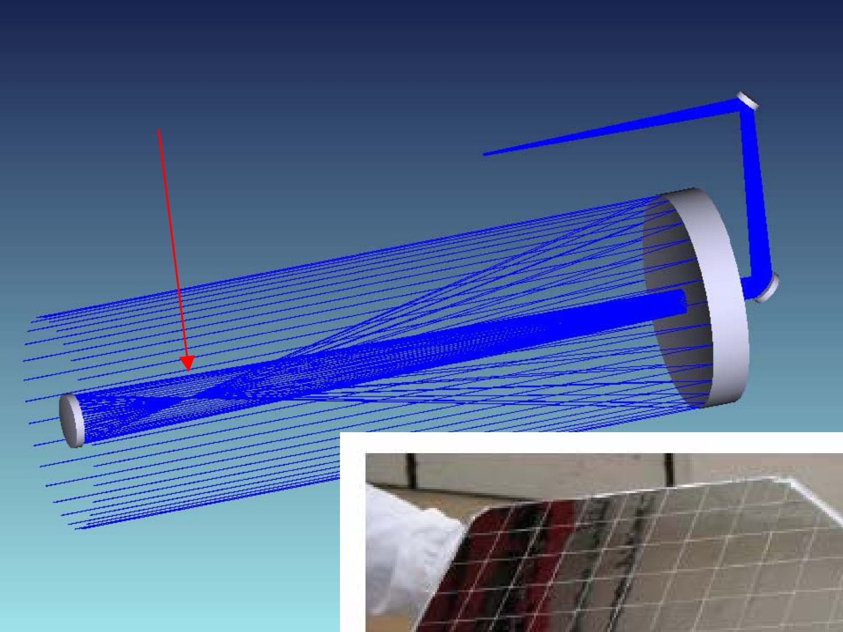
Cassegrain (1668) vs. Gregory (1663):



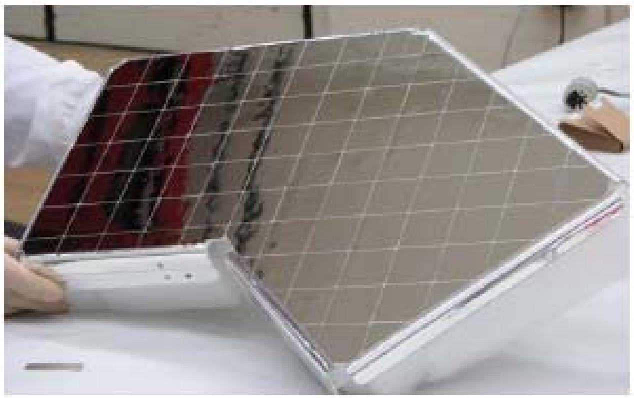
Advantage of the Gregory

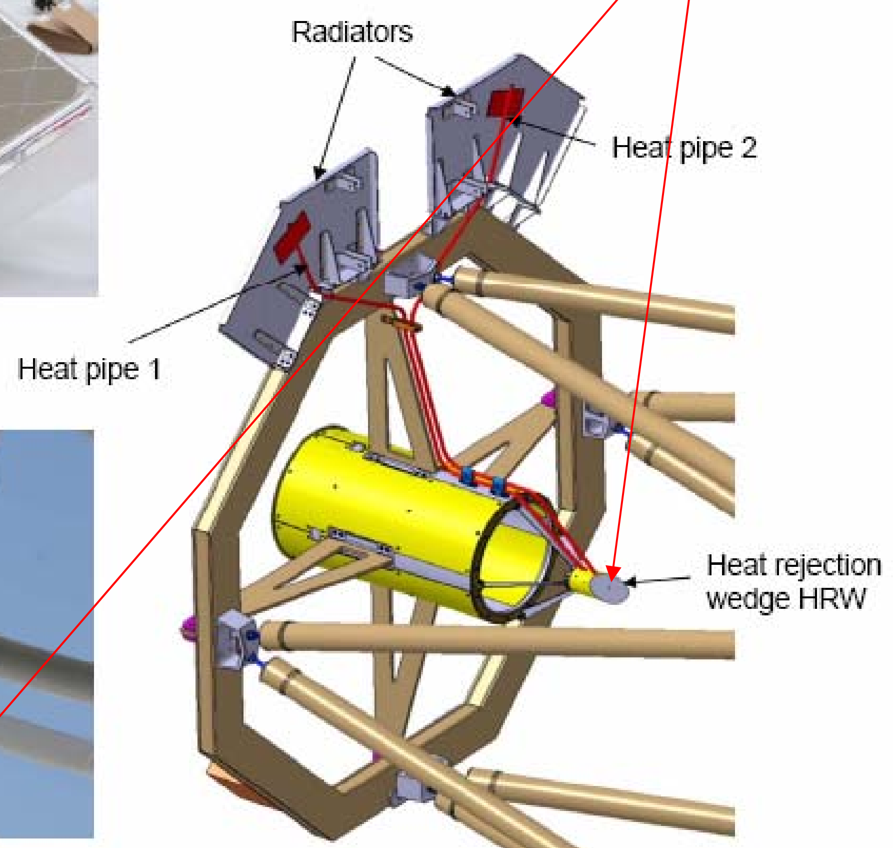
- in the Gregory telescope the prime focus (primary solar image) is *real*
- here a first field stop (mirror with small hole) can be placed that takes out all photons coming from unused parts of the solar disk (typ. 99%)!
- *side effect: takes also most of the energy away!*

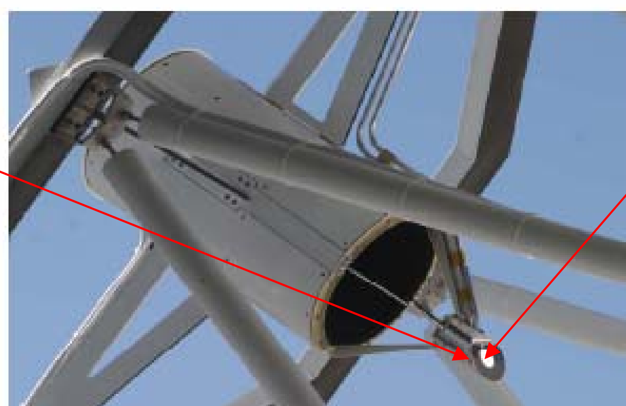
Sunrise prime field stop



small hole, d=2.8mm







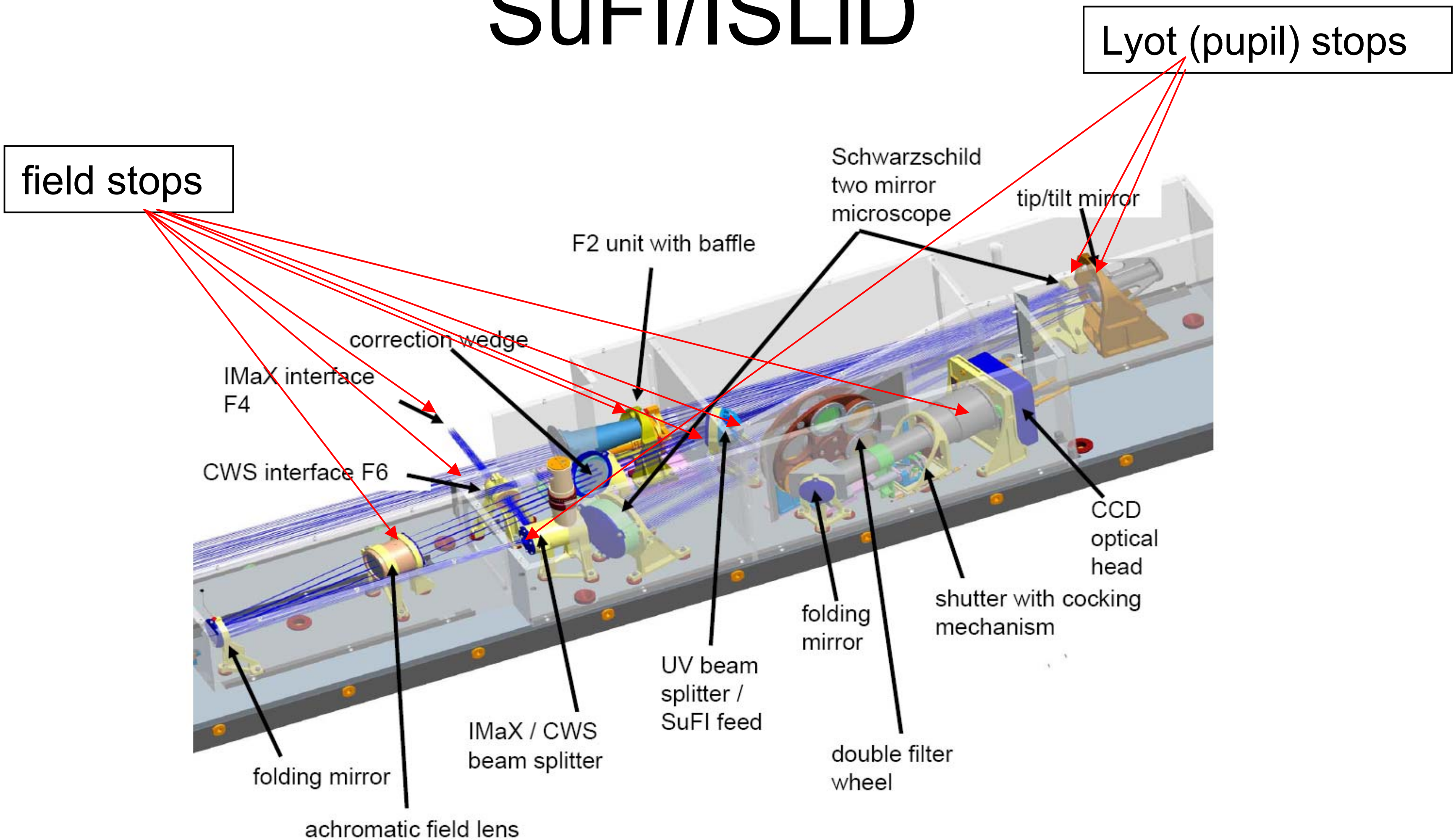
solar image

(d=2.5cm, P=1kW)

further measures

- place stops in every intermediate image and pupil, wherever possible!
- most famous example: Lyot Coronograph!
  - telescope with field stop (occulter for disk) + reimager with real internal pupil image. Without further trick this thing does not work; Lyot placed a pupil stop in the internal pupil to get rid of the bright diffraction pattern occuring at the fully illuminated entrance aperture!

Straylight suppression in Sunrise SuFI/ISLiD



SuFI ctd.

- after wavelength selection light path must be light tight!

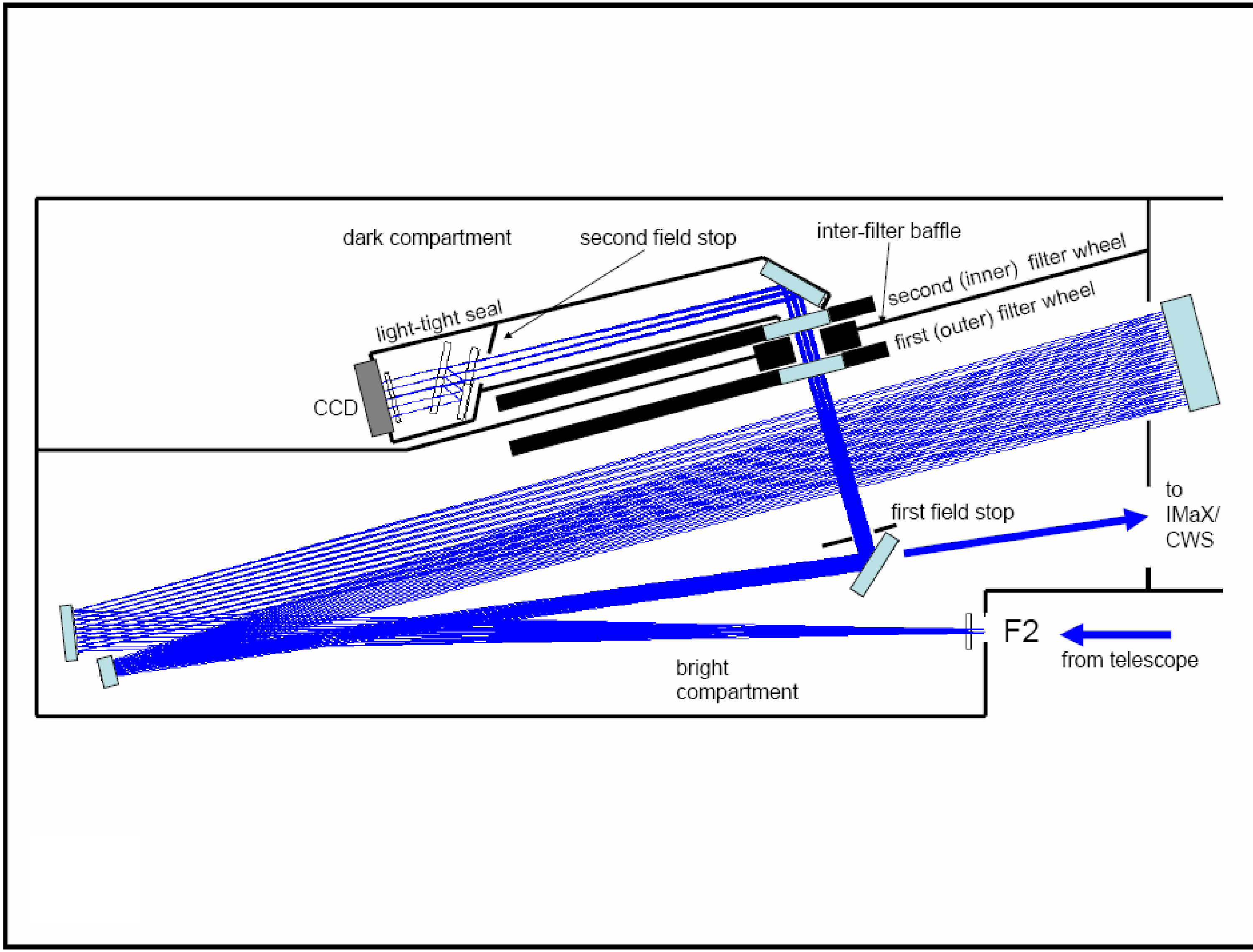


Fig. 12. Scheme of the baffling system of SUFI. The light tight innermost seal covers the light path after the second filtering, which is severly vulnerable to parasitic illumination. The double filter wheel seperates the dark compartment from the bright compartment. Two consecutive field stops narrow the field which is propagated to the detector.

Some thermal considerations

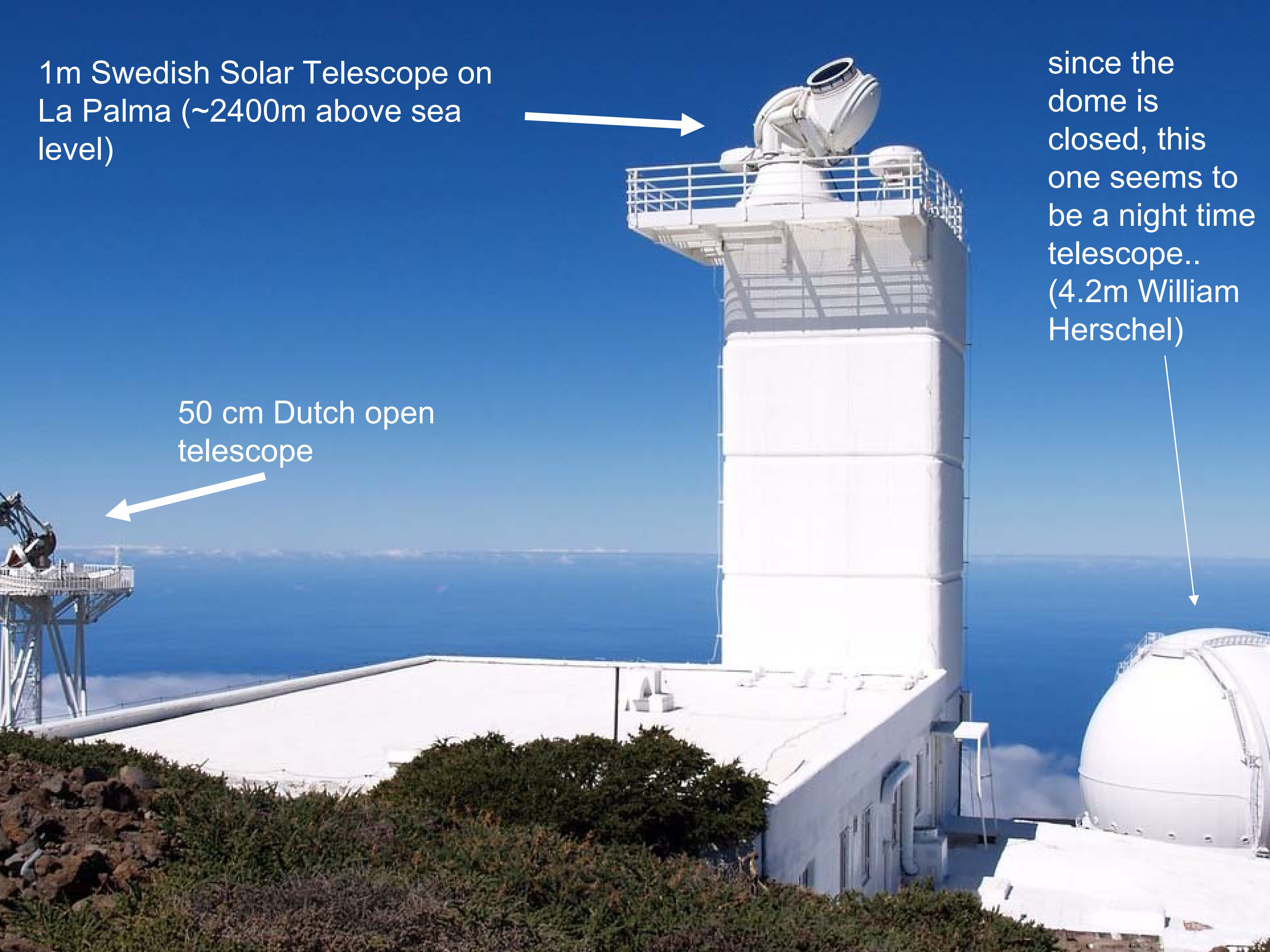
WIEDER HABEN SCHRÖDERS KOLLEGEN DAS TELESKOP HEIMLICH AUF DIE SONNE AUSGERICHTET.

Thermal problems of solar telescopes

- solar energy input not negligible (~1kw/m^2)
- is absorbed near telescope or in telescope:
  - near telescope: local turbulence: ground *seeing*
  - in telescope: „mirror“ *seeing*
- can heat up optical system: performance decrease (→„athermal optics“), destruction

Seeing: the enemy

- *seeing* is the dominant problem in ground based solar observations
- solutions:
  - site selection: mountains on islands
  - air knife: laminar flow along mirror
  - evacuation: no air – no problem?
  - helium filling


1m Swedish Solar Telescope on La Palma (~2400m above sea level)
since the dome is closed, this one seems to be a night time telescope.. (4.2m William Herschel)
50 cm Dutch open telescope

What is *mirror seeing*

- Excurs: Mirrors
  - mirrors are coated with Al or „protected silver“
  - residual absorption ~4-10% (of total Sunlight!)
  - substrate: typ. ZERODUR, has high thermal resistance; deposited energy cannot be drained away from the mirror surface
  - mirror surface will heat up, air becomes convectionally unstable → turbulence
  - refractive index of air depends on density

→„air lenses“ in pupil plane

Seeing: the enemy

- *seeing* is the dominant problem in ground based solar observations
- solutions:
  - site selection: mountains on islands
  - air knife: laminar flow along mirror
  - evacuation: no air – no problem?
  - helium filling

open telescopes

- DOT (Dutch Open Telescope)
  - Experimental telescope
  - open construction: wind avoids internal seeing
  - Site: Observatorio de los Roque de los Muchachos, La Palma

Seeing: the enemy

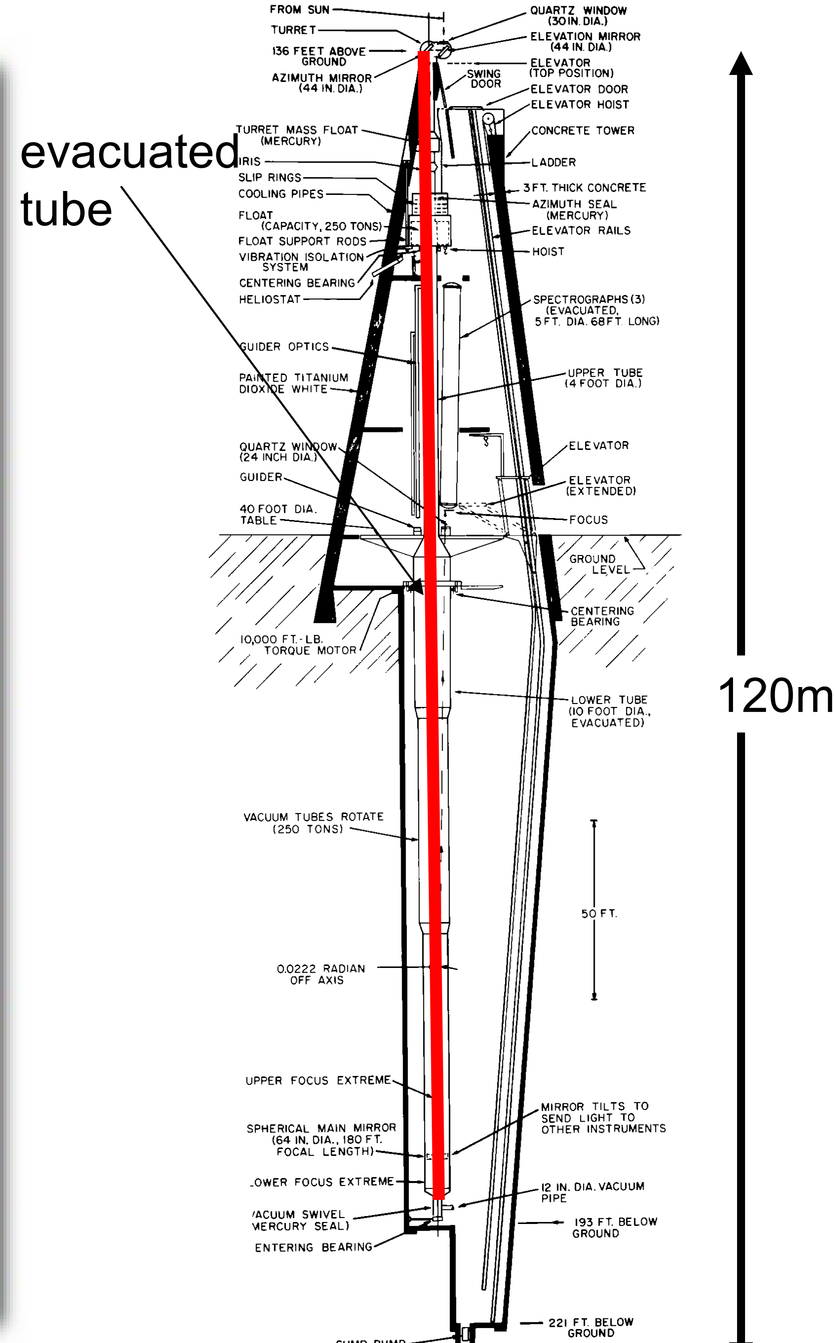
- *seeing* is the dominant problem in ground based solar observations
- solutions:
  - site selection: mountains on islands
  - air knife: laminar flow along mirror
  - evacuation: no air – no problem?
  - helium filling

evacuated telescopes

- SST (swedish solar telescope on La Palma) is an evacuated refractor
- objective lens serves as vacuum window
- internal optical path is seeing free

64.000$ question: WHY DOESN´T THE ABSORPTION IN THE LENS (also a few %) POSE THE SAME PROBLEM AS IN A MIRROR TELESCOPE?

Dunn Solar Telescope, Sacramento Peak, New Mexico



Seeing: the enemy

- *seeing* is the dominant problem in ground based solar observations
- solutions:
  - careful site selection: mountains on islands
  - tower telescopes to avoid ground turbulence
  - air knife: laminar flow along mirror
  - evacuation: no air – no problem?
  - helium filling

50cm SOLIS VSM

helium filled telescopes

- large vacuum windows must withstand enormous forces
- stress detoriates image quality and polarization properties („stress induced birefringence“, see lecture on magnetometry)
- solution: pressurize telescope with helium
- examples: THEMIS, SOLIS VSM

effects of helium

- very high thermal conductivity

→ instantaneous equilibration of local temperature (density) inhomogeneities

- very low refractive index

→ no „(air) lenses“

In contrast to vacuum telescopes, the window is not subject to pressure difference → reduced stress

Thermal effects on optical performance

What can happen?

Temperature variations (esp. gradients) can have different effects on an optical component:

- change in position (thermal expansion/deformation of mechanical mounts, tube length)
- change in shape (thermal expansion of glass)
- change in refractive index („thermal lensing“, worst offender!)

What you can do

- minimize thermal effects by careful material choice and/or thermal stabilisation of your system
- design instrument as „athermal“ system, which automatically compensates optical effects by careful combination of materials with different response to temperature
- counteract by (active) realignment/refocussing

In most cases you need to do all of them!!

methods in building „athermal“ optical systems

- material choice: Mirrors can be made from ZERODUR (Astrositall, ULE) with negligeable thermal expansion; refractive components cannot!

→lenses must change their position to compensate for the change in refractive power!

→ lens mount must be made of a material with a well selected thermal expansion coefficient (CTE)

Athermal design using ZERODUR mirrors: Caveat

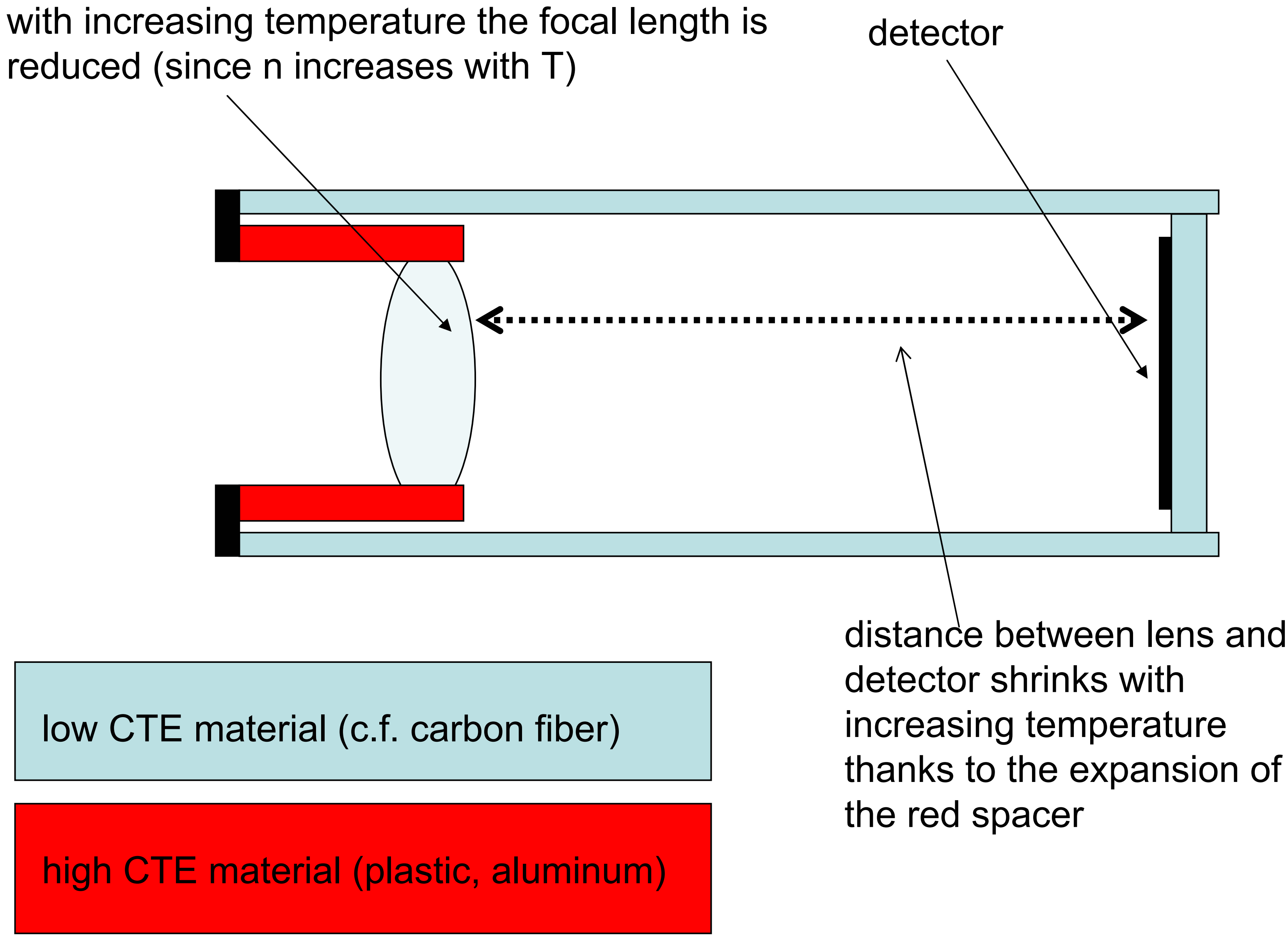
- since the mirrors will not change their properties, also the rest of the system must not change! DON´T MAKE THE (COMMON) MISTAKE OF BUYING (MAKING) EXPENSIVE ZERODUR MIRRORS AND USING ALUMINUM AS THE TELESCOPE TUBE/OPTICAL BENCH! The expansion of the tube/bench will spoil your focus (or more)!

ZERODUR ctd.

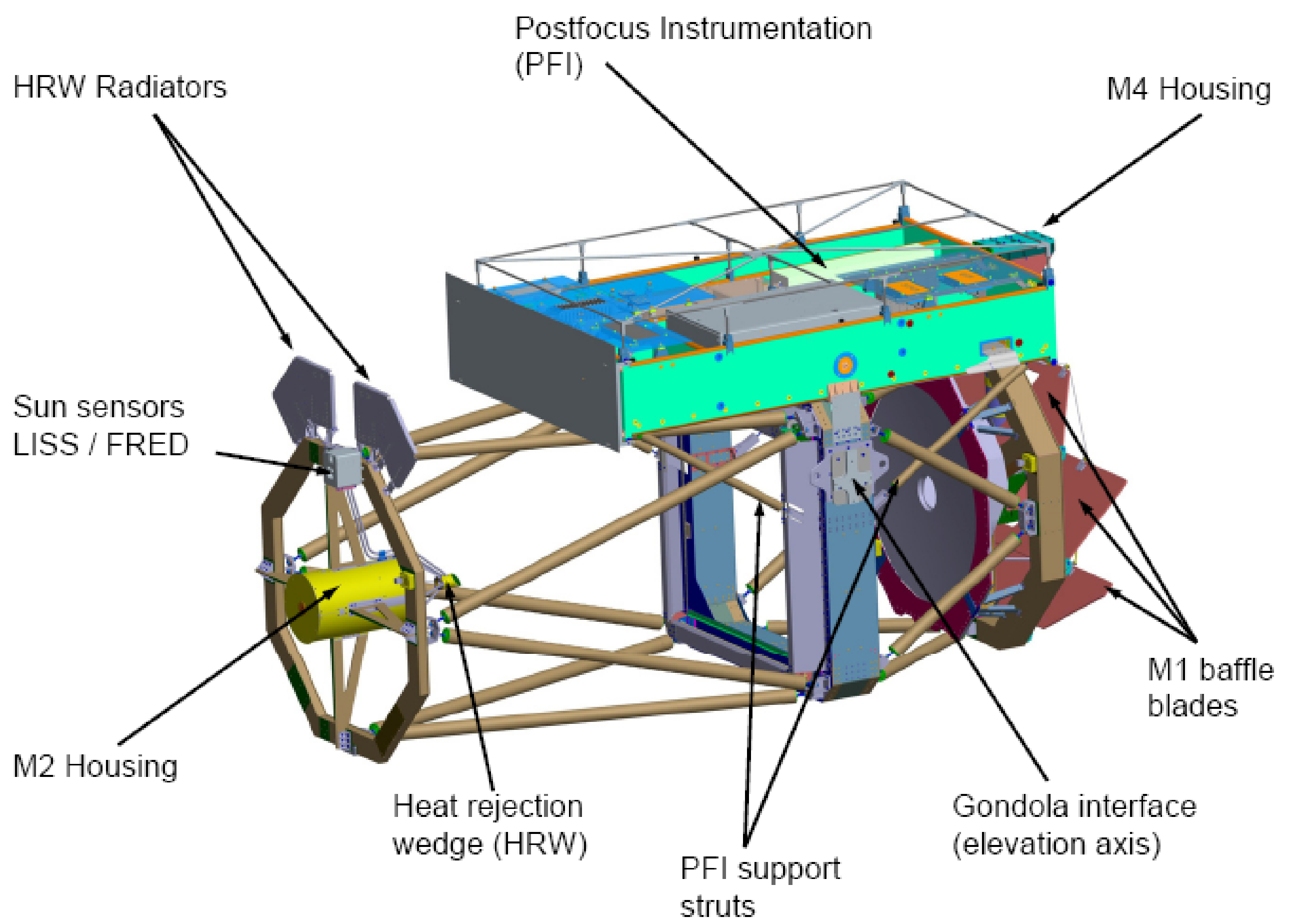
- ZERODUR must be used in combination with low (ideally zero) CTE structures: carbon fiber (attention, anisotropic expansion coefficient!), or INVAR (steel, difficult to machine, extremely heavy!)
- If you cannot avoid materials with non-vanishing thermal expansion, choose a mirror material with a similar CTE; then the whole system will keep its shape factor! Example: OSIRIS on Rosetta: Mirrors and Structure from SiC!

athermal lens design

- lenses will change their refractive index and their shape!
- to keep the focus at right position the tube length must shrink.....that would mean a negative CTE
- trick: Mount lens (or detector!) on thickness compensator:


with increasing temperature the focal length is reduced (since n increases with T)
detector
distance between lens and detector shrinks with increasing temperature thanks to the expansion of the red spacer
low CTE material (c.f. carbon fiber)
high CTE material (plastic, aluminum)

Example: SUNRISE



Sunrise telescope

- Grade 0 ZERODUR for main mirror (parabola, D=1m, f=2.42m) and secondary ellipsoid

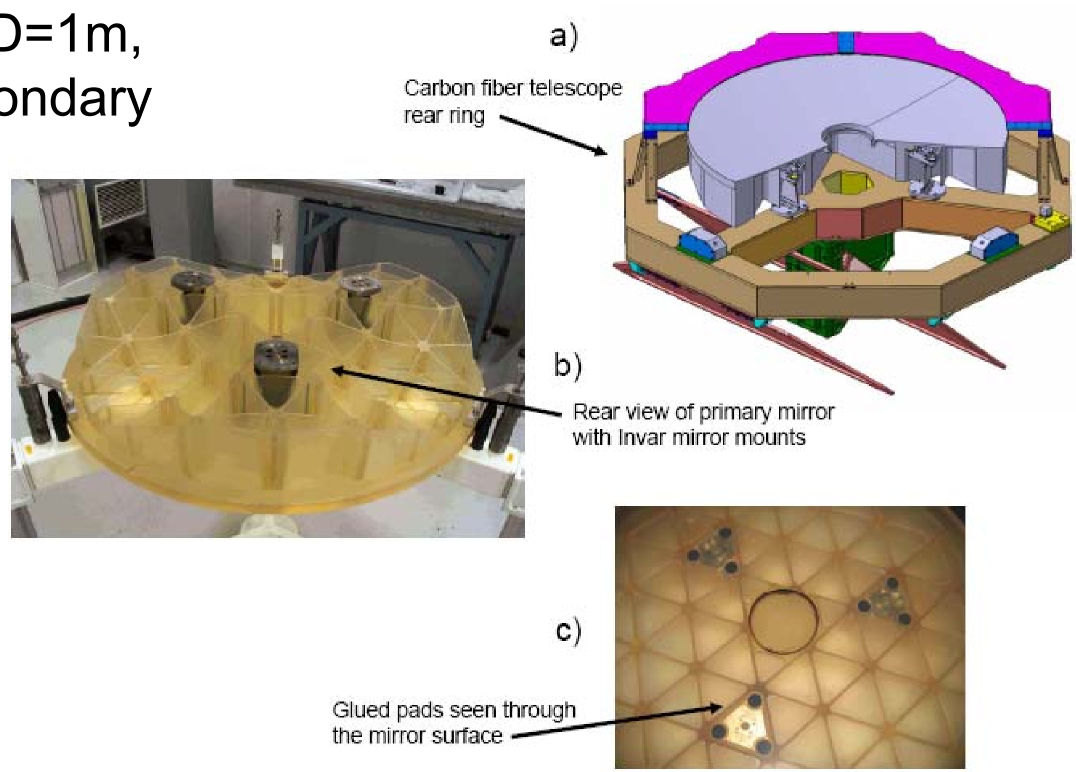


Figure 4. a) CAD model of the main mirror cell with the lightweighted ZERODUR mirror. The mirror is mounted with three flex blade fixation points to the carbon fiber structure, which forms the rear ring of the telescope. b) Backside view of main mirror after integration of the three flex blade fixation points. c) Glass/metal junction formed by glued Invar pads

Sunrise ctd.

- distance and parallelism of M1 and M2 are secured by athermal Serrurier structure composed of carbon fiber struts with almost zero CTE; expansion of central frame (made from steel) is compensated by aluminum adapters between steel frame and carbon fiber struts; the length of the aluminum piece is exactly calculated for optimum compensation!

Sunrise ctd.

- still, distance of M1 and M2 varies with elevation of telescope (which influences the overall temperature of the system)
- to compensate for this, M2 is mounted on a pecision translation stage for in-flight focus compensation
- between the coldest (-10^{o}C) and the warmest (-10^{o}C) situation M2 was moved by 0.1mm with a step size of 1 µm!

Sunrise telescope at MPS

Outlook

- currently design of the Polarimetric and Helioseismic Imager onboard Solar Orbiter
- due to strongly elliptical orbit around Sun (distance changes between 0.28 and 0.8 Au), temperature of instrument (telescope + interferometer) will change between $-30^{o}C$ to $+70^{o}C$......
- clever thermo-mechano-optical system design needed