Hale COLLAGE (NJIT Phys-780)

Topics in Solar Observation Techniques

# Lecture 02: Astronomical Optical Telescopes


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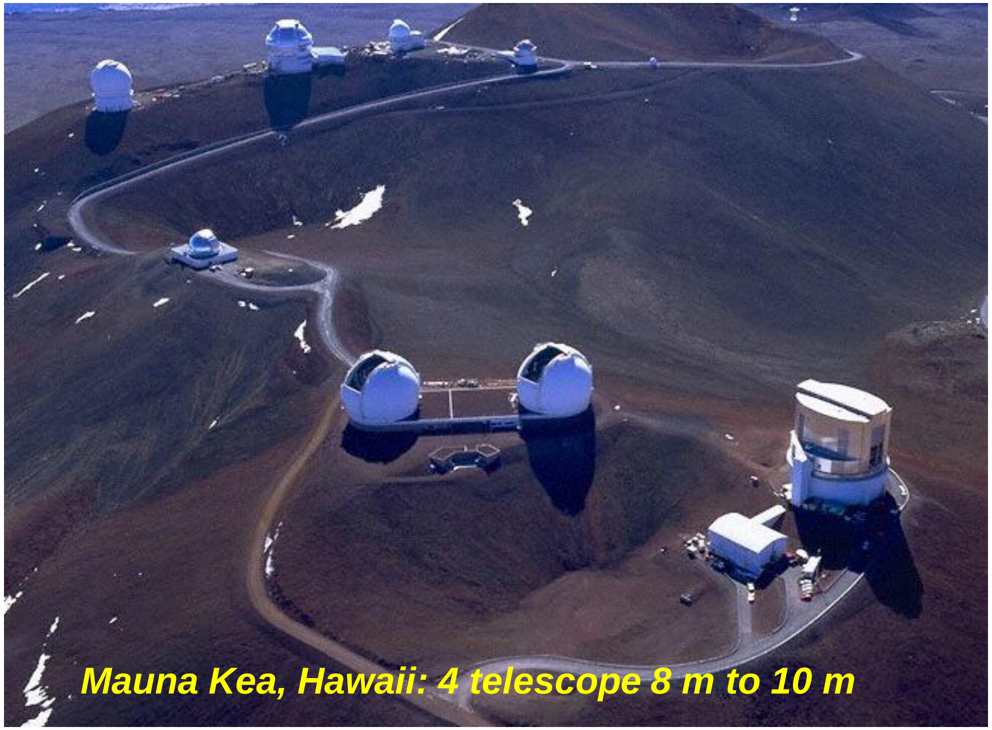


# 1. Telescope Functions

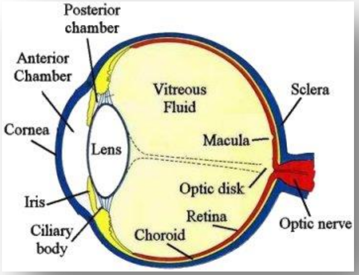
- *Astronomical telescopes make objects from space appear as **bright**, **contrasty** **(or** **sharp)** and **large** as possible.*
- *An optical telescope is an instrument that gathers and focuses light, mainly from the visible/IR part of the electromagnetic spectrum, to create a magnified image for direct view, or to make a photograph, or to collect data through electronic image sensors.*

- *Light gathering power*
- *Resolving power*
- *Magnification*

# Light Gathering Power

- *Aperture of telescope objective (the primary lens or mirror) determines how many photon a telescope receives.*
- *High cadence, high resolution solar spectro-polarimetry measurement are always photon-starved.*

| eye | SDO | Hinode | NST | DKIST | KECK |
|---|---|---|---|---|---|
| 6mm | 14cm | 50cm | 1.6m | 4m | 10m |
| 1 | $5.4\times10^2$ | $6.9\times10^3$ | $7.1\times10^4$ | $4.4\times10^5$ | $2.7\times10^6$ |



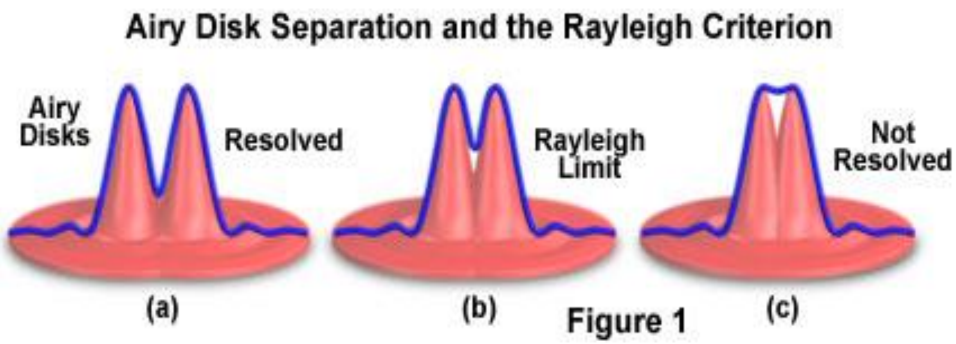

# Resolving Power

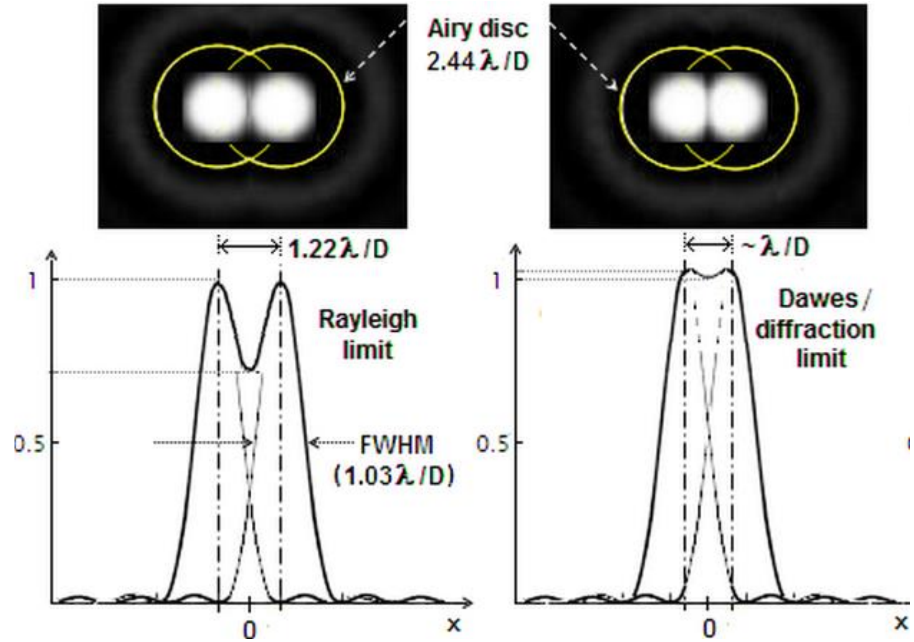
- ***Rayleigh criterion:*** *angle defined as that for which the central peak of one PSF falls upon the first minimum of the other*

$$\theta\ (rad) = 1.22\frac{\lambda}{D} \qquad \theta\ ('') = 0.25\frac{\lambda\,(\mu m)}{D\,(m)}$$

- ***Sparrow criterion:*** *angular separation when the combined pattern of the two sources has no minimum between the two centers*

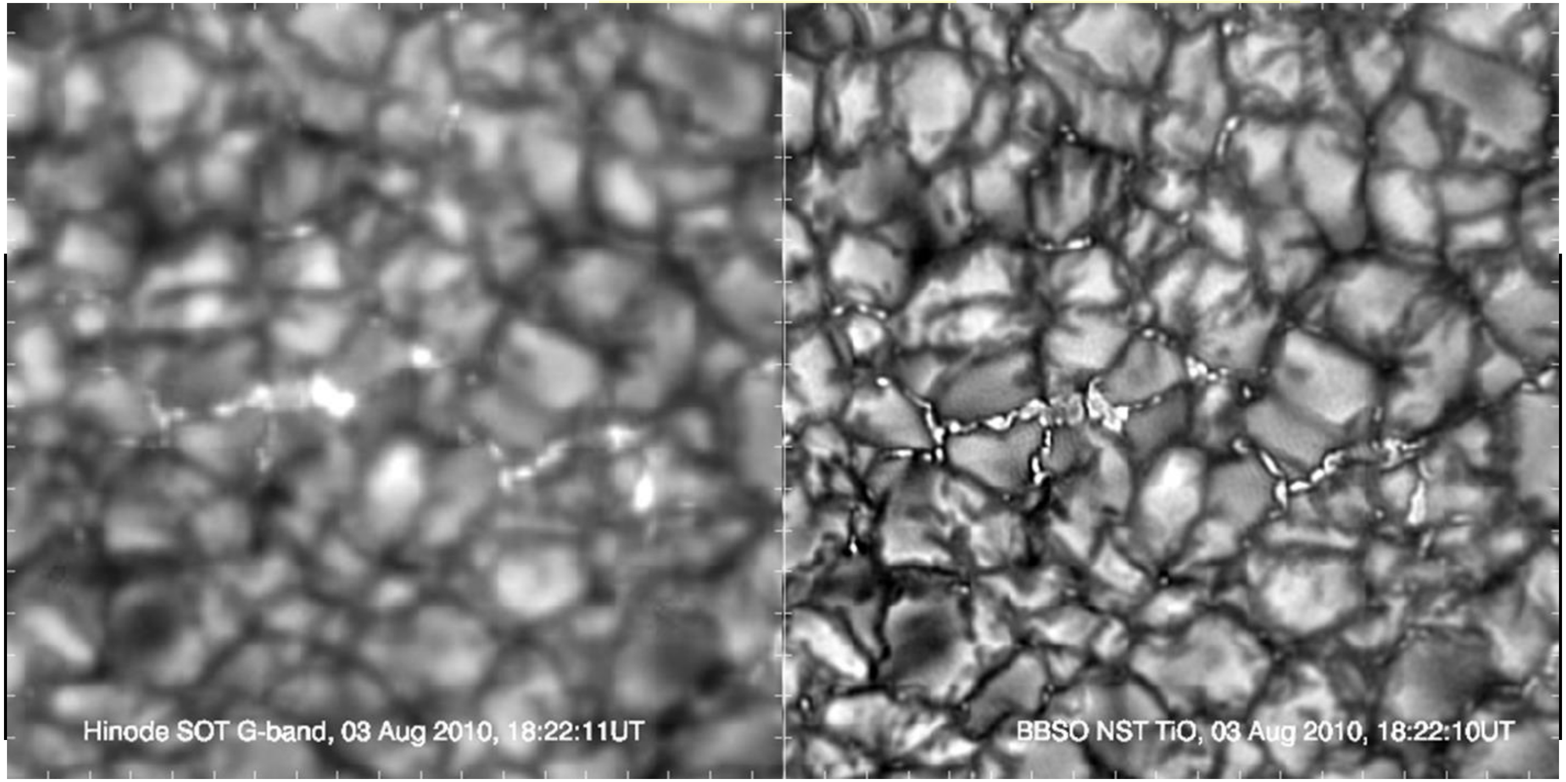
$$\theta\ (rad) = \frac{\lambda}{D}$$



# Telescope Resolution

- ***Angular resolution:*** *can be quantified as the smallest angle between two point sources for which separate recognizable images are produced*

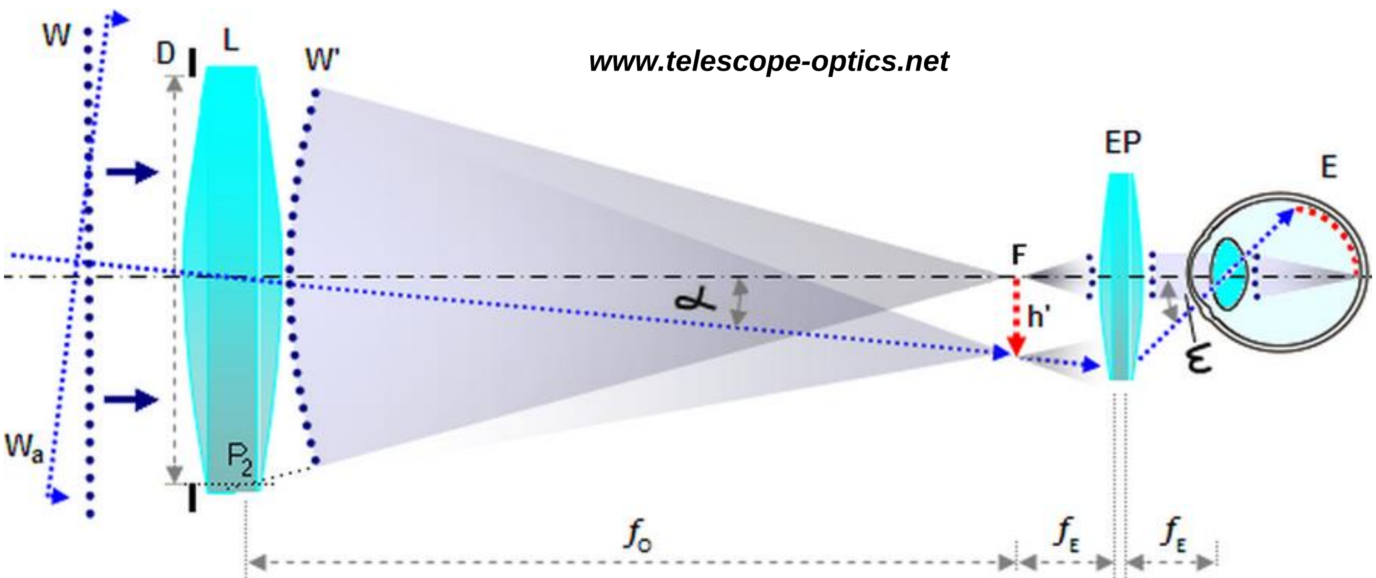


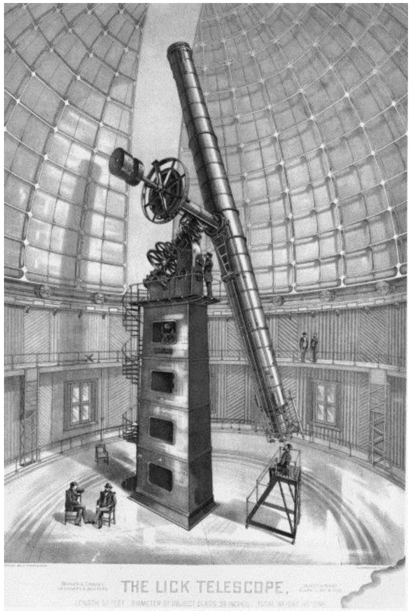
# Magnification

- ***Magnification:*** *is given by a ratio of the image size produced on the retina when looking through a telescope, versus retinal image size with the naked eye.*

$$M_T = \frac{\varepsilon}{\alpha} = \frac{\tan\varepsilon}{\tan\alpha} = \frac{h^{'}/f_e}{h^{'}/f_o} = \frac{f_o}{f_e}$$

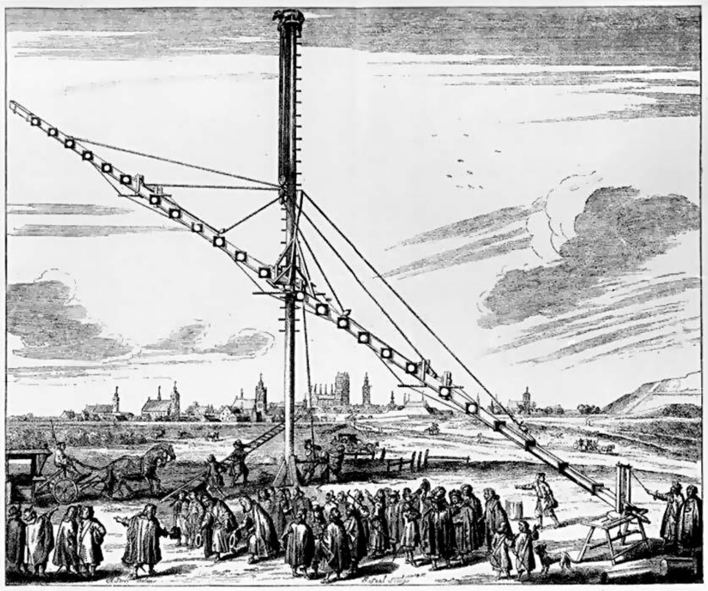
$$M_T = \frac{f_o}{f_e} = \frac{D}{d} = \frac{D}{d_{eye}}$$



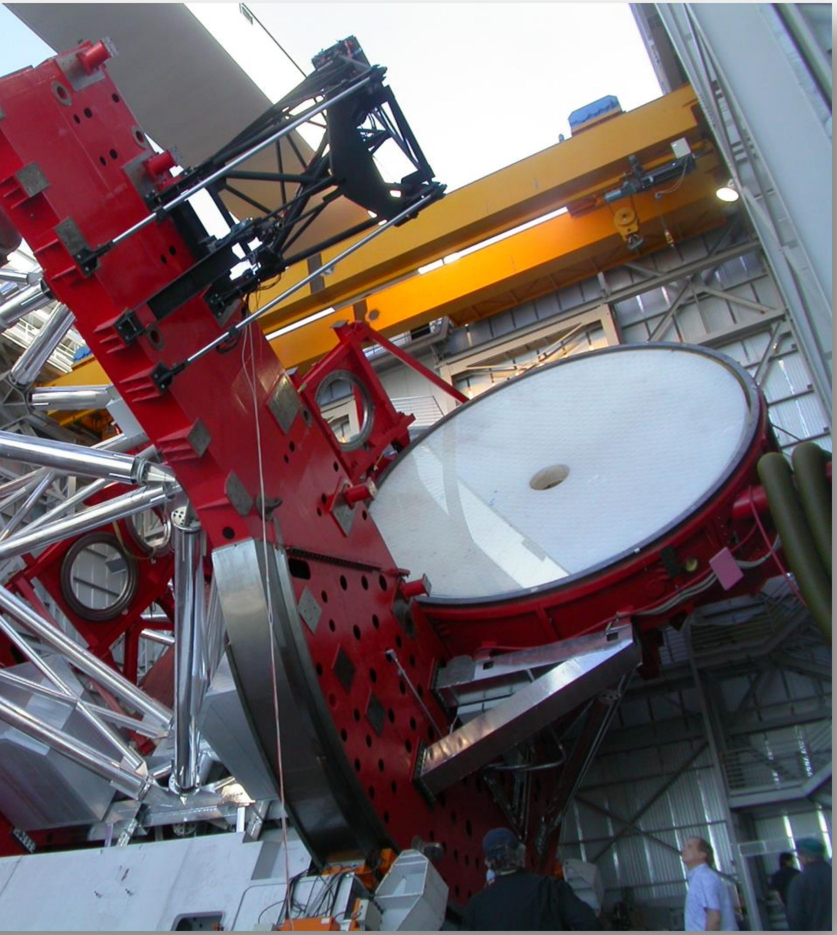
# Refracting Telescopes - Lenses

- *Lenses are easy to manufacture when small – Galileo telescope*
- *Difficult to implement for large telescopes*
  - *Lens thickness increases with diameter, and needs to be held at its edges*
  - *Lens is located in the front of the telescope. Center of mass is close to the top of the telescope (top-heavy)*
- *Refracting telescopes suffer from chromaticity problem*
  - *Refraction index is chromatic: a simple lens has a focal length which changes with wavelength*
  - *Refracting telescopes used to be very long and narrow field of view*



***Johann Hevelius 45-m long telescope (1673)***

# Reflecting Telescopes - Mirrors

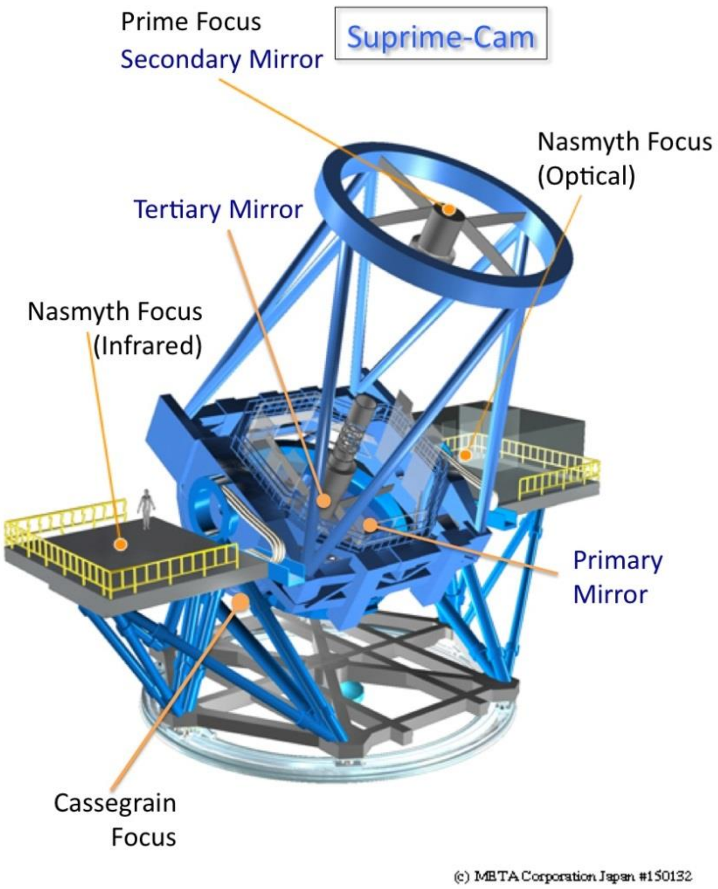


Large Binocular Telescope (LBT): 8.4 m

- *Reflection is achromatic*
- *Ideally suited for large telescopes*
  - *Mirror is supported from the bottom, and can be thin with active control*
  - *Mirror is located at the back of the telescope: center of mass is low*
  - *Telescope tube can be relatively short (F ratio of modern large telescopes is ~ 1 to 2)*
  - *Lower cost per inch of aperture*
  - *Mirror  can cover wide spectral range from EUV to NIR*

# Reflecting Telescopes - Mirrors

- Light bounces back toward the object
  - Focal plane in front of the telescope, or secondary mirror needs to be used to send light to instrument
  - Slight light loss due to 2nd obstruction
  - On-axis telescopes have more stray lights
- Mirrors have ~ 4x tighter optical surface tolerances than lenses
  - For surface defect h, wavefront error is 2h in reflection, h(n-1) in refraction
  - Mirror often need to be made non-spherical with <100 nm surface accuracy
- Mirrors need to be reflective



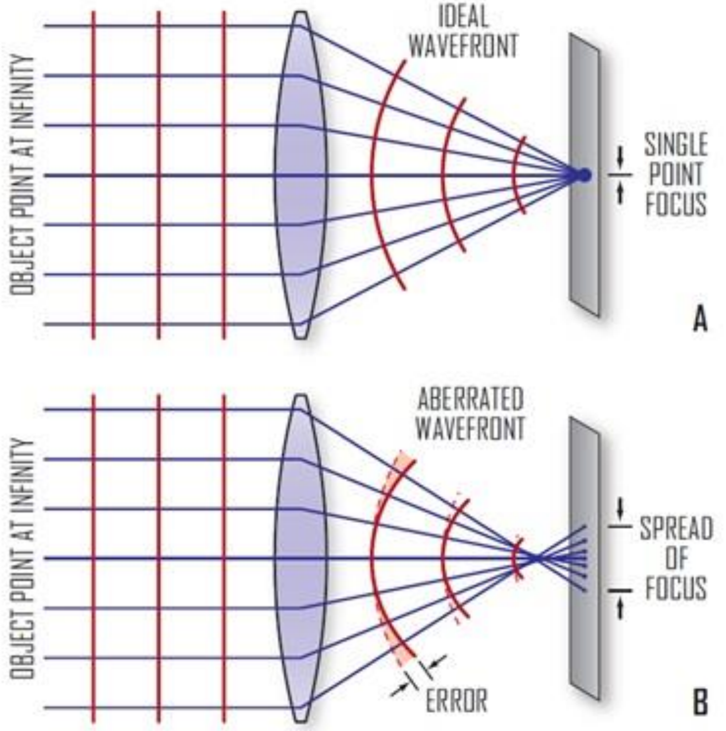

*8.2 m Subaru Telescope*

# 2. Optical Aberrations

- *It is very challenging to keep the image sharp on large telescopes. Image quality is limited by telescope optical quality, actually, by telescope optical aberrations.*
- *Ideal optics (Gaussian optics) produces an exact point-to-point conjugated correspondence between the source and its image.*
- *In real optical system, aberrations occur when light from one point of an object do not converge into a single point after transmission through the system.*

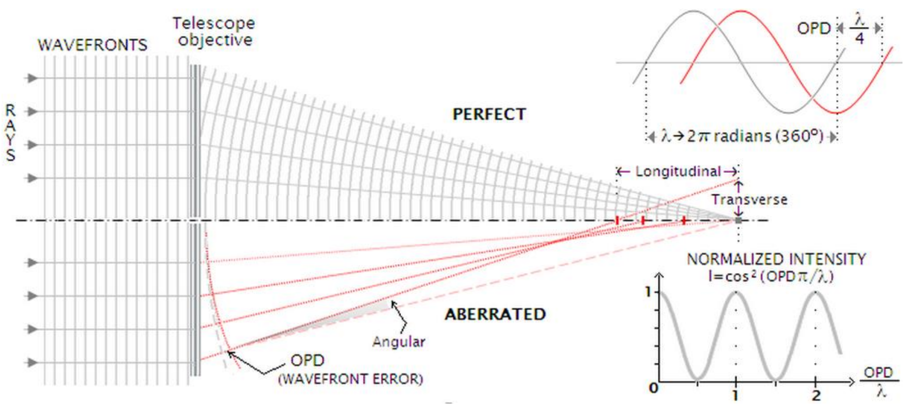
# Telescope Aberrations

- *Perfect optics and aberrated optics*
- ***Aberrations:** any deviation of the wavefront formed by an optical system from perfect spherical (or from perfect flat).*
- ***Aberrations** disturb optimum convergence of the energy to a point-image, with the result being degradation of image quality.*

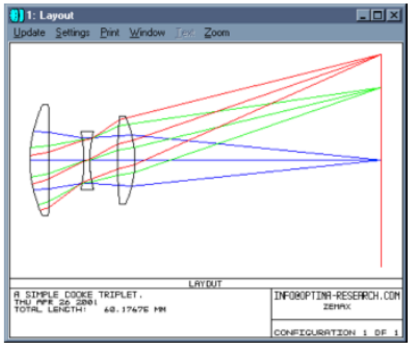


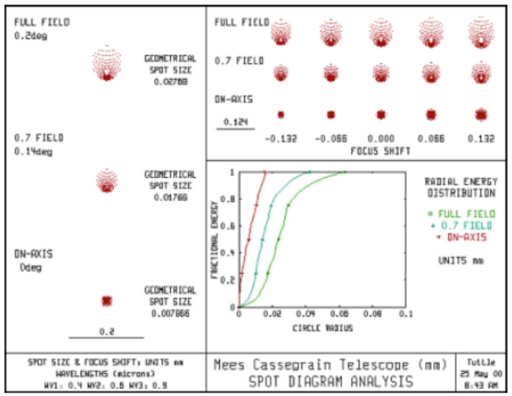
# Aberration Measure

- ❑ ***Wavefront aberrations:*** *measured at the wavefront itself, as a deviation from the perfect reference sphere.*
  - ❑ *Wavefront error (P-V or RMS), phase error*




**www.telescope-optics.net**



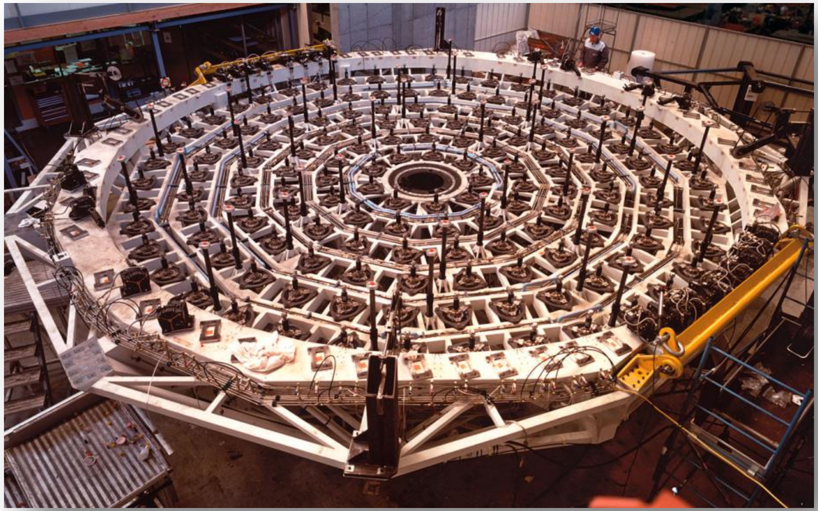




***Courtesy:*** *Olivier Guyon*

- ❑ *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*

# Aberrations: causes

- ***Intrinsic telescope aberration:*** *are those inherent to conical surface, to glass medium, and those resulting from fabrication errors*
  - *Chromatic aberrations*
  - *Monochromatic aberrations:*
    - *Spherical aberration*
    - *Coma*
    - *Astigmatism*
    - *Field curvature*
    - *Image distortion*
    - *Fabrication error*

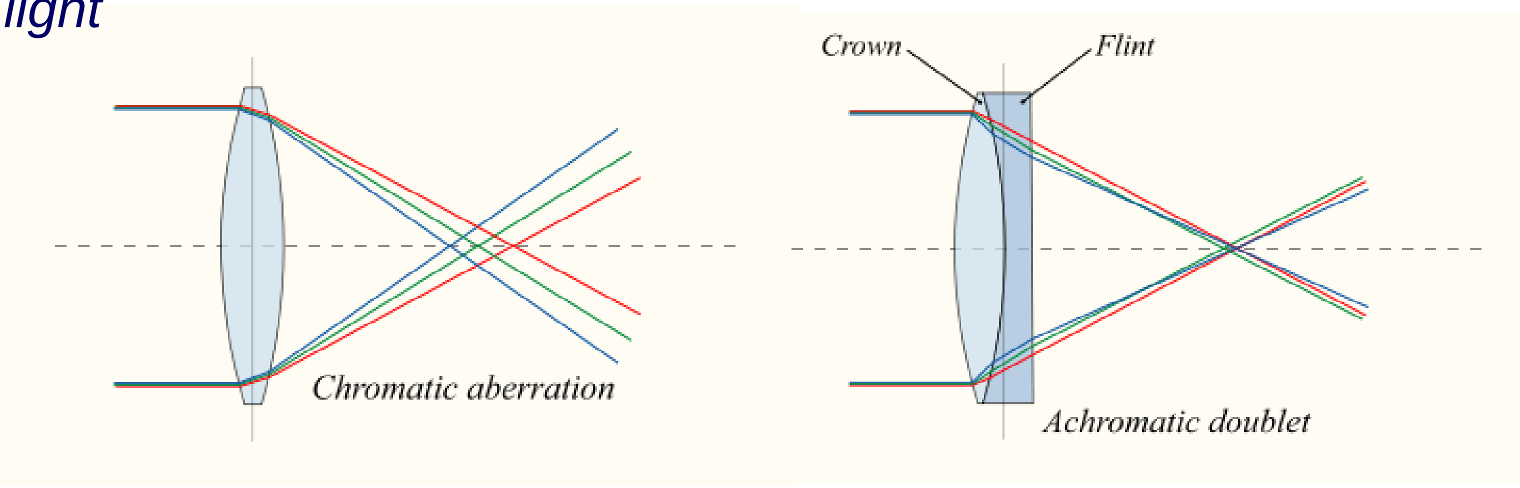


***active optics for 8 m VLT mirror cell***

- ***Induced telescope aberrations:*** *caused by (1) alignment errors, (2) forced surface deformations due to thermal variations, gravity and improper mounting, and (3) atmosphere turbulence.*

# Chromatic Aberration

- ***Chromatic aberration:*** *is present only in refractive systems*
- ***Chromatic aberration*** *occurs because lenses have a different refractive index for different wavelengths of light*
- *Refractive index decreases with increasing wavelength*
- *Red light is refracted to the greatest extent followed by blue and green light*




- ***Solution to CA:*** *(1) achromatic doublet, (2) reflecting system*

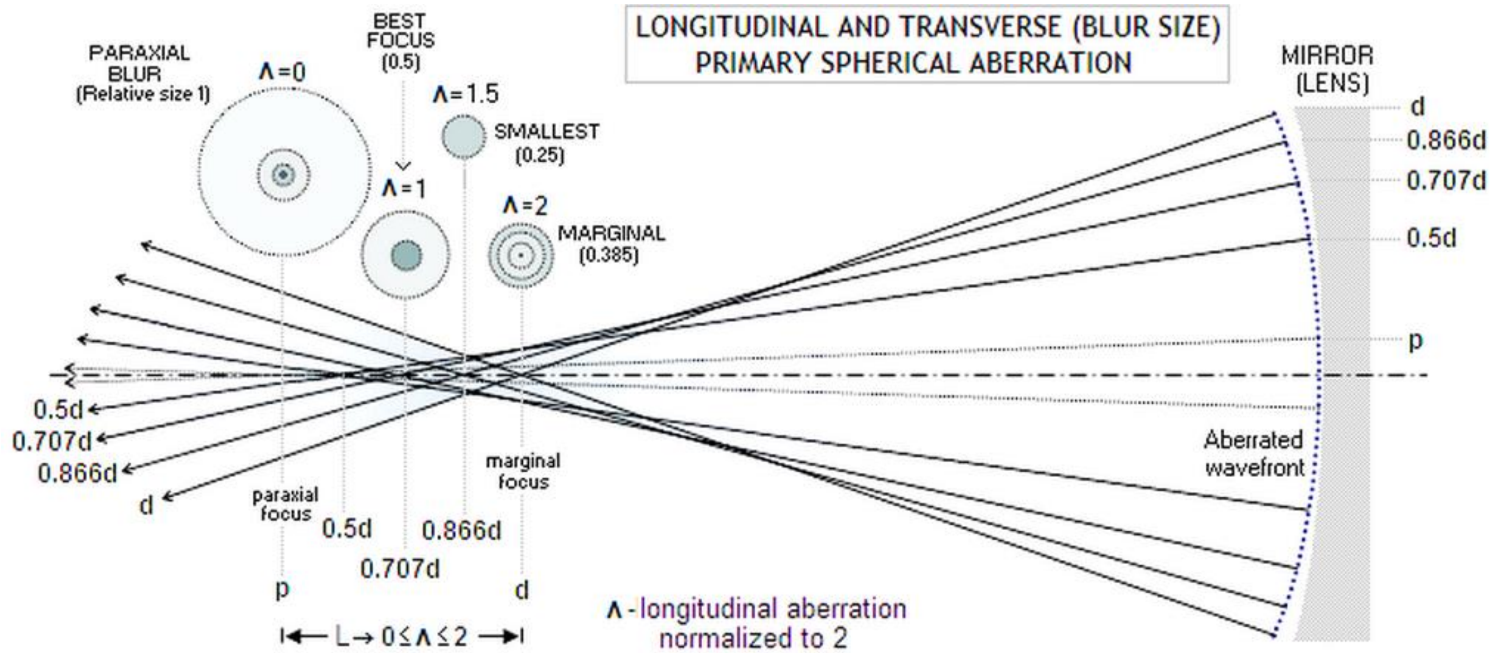
# Spherical Aberration

- ***Spherical aberration (SA):*** *rays issuing from a source at infinity on axis do not all converge at the same point*
- *The peripheral ray have a shorter focus*
- *The paraxial rays have a longer focus*
- *Only form of monochromatic axial aberration*

$$\sin\varphi = \varphi - \frac{\varphi^3}{3!} + \frac{\varphi^5}{5!} - \frac{\varphi^7}{7!} + \ldots$$

# Spherical Aberration

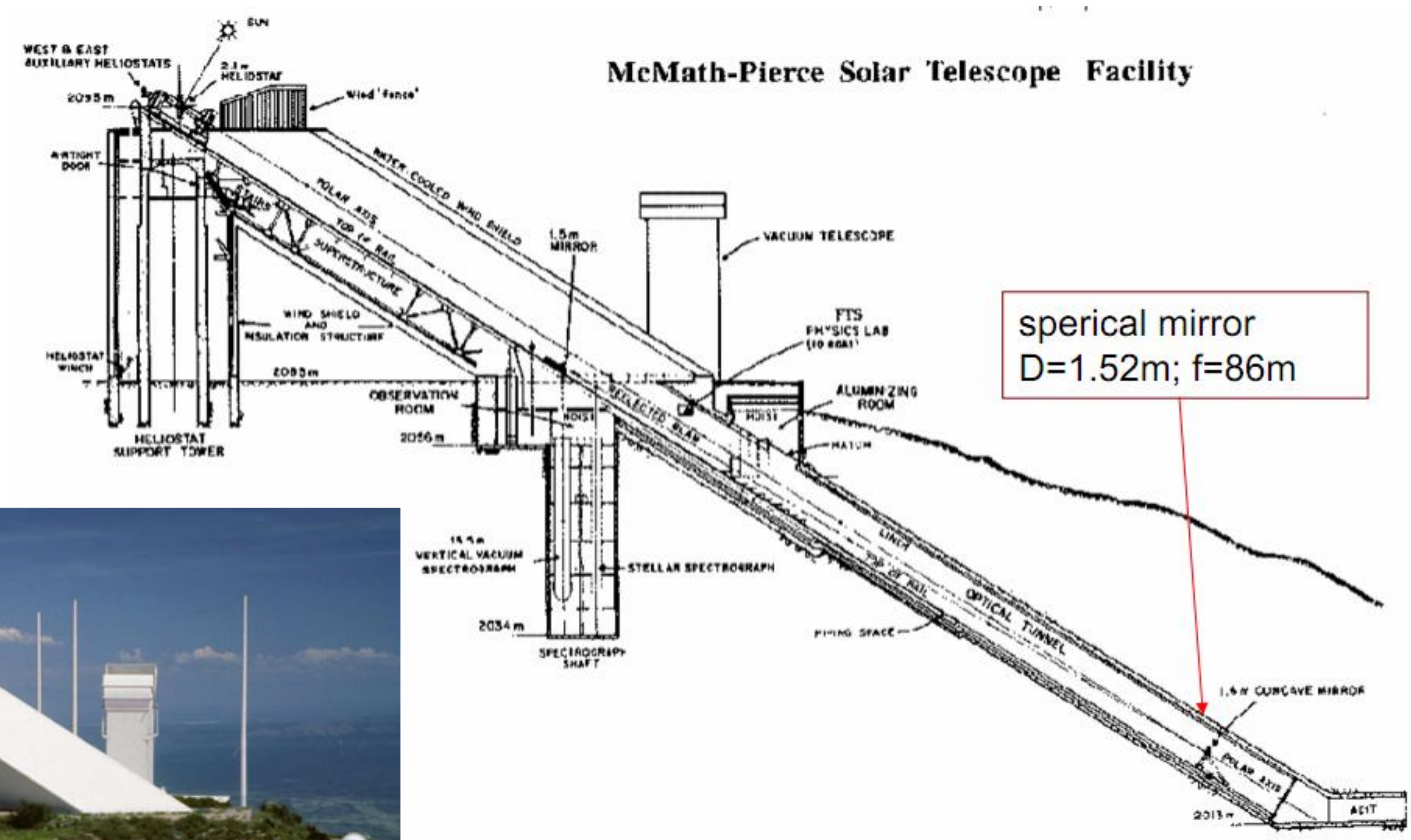
- Spherical and paraboloidal mirrors




- Solutions
  - Spherical PM: Large F#
  - Parabolic PM

$$SA \propto (F\#)^{-3} = \left(\frac{D}{f}\right)^3$$

# McMath-Piece Telescope




# Coma

- ***Coma:*** *rays issuing from an off-axis source do not all converge at the same point in the focal plane*
- ***This creates a blur which resembles a comet***
- ***Off-axis aberration:*** *it occurs either due to the incident wavefront being tilted, or decentered with respect to the optical surface*

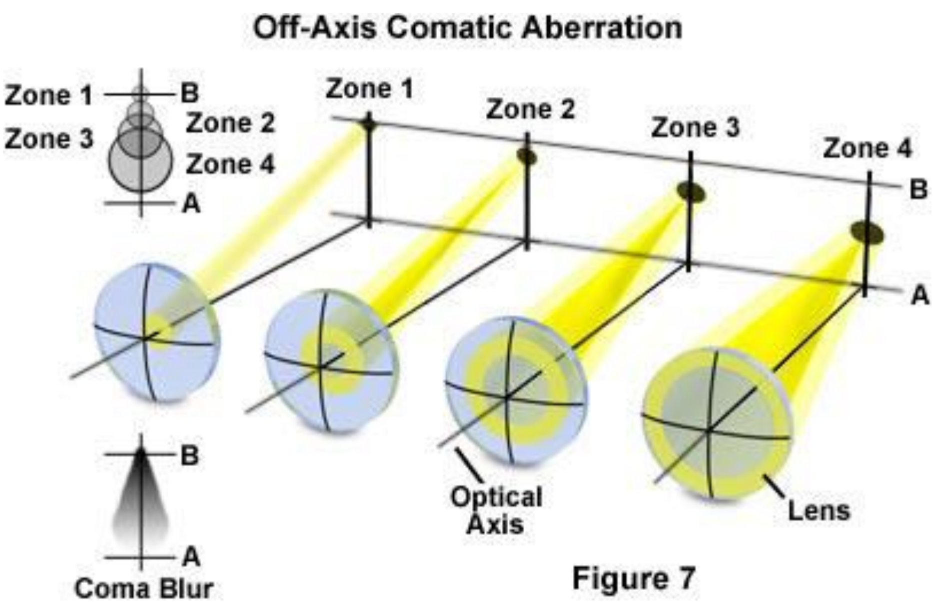
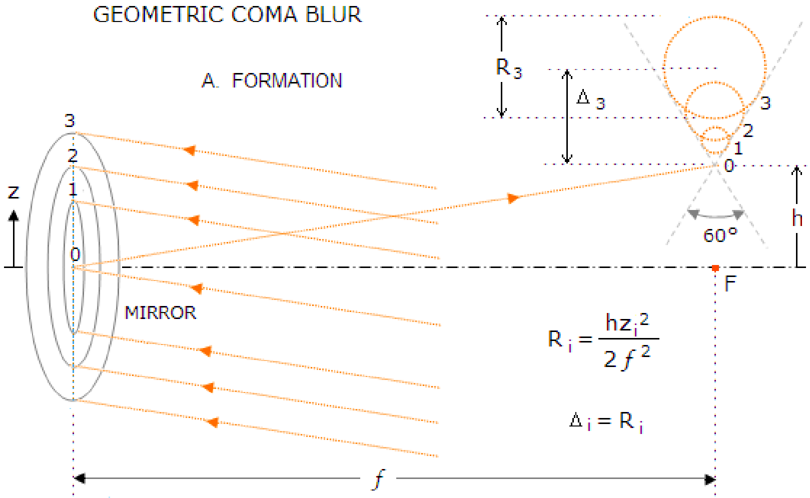
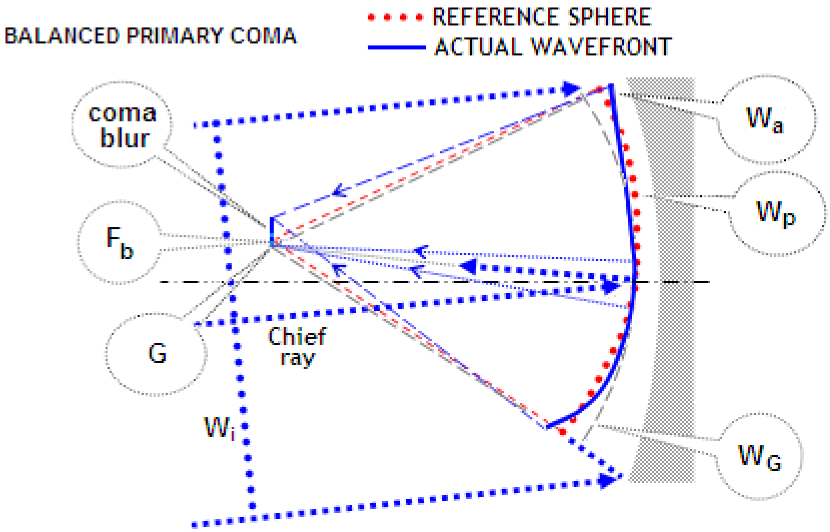


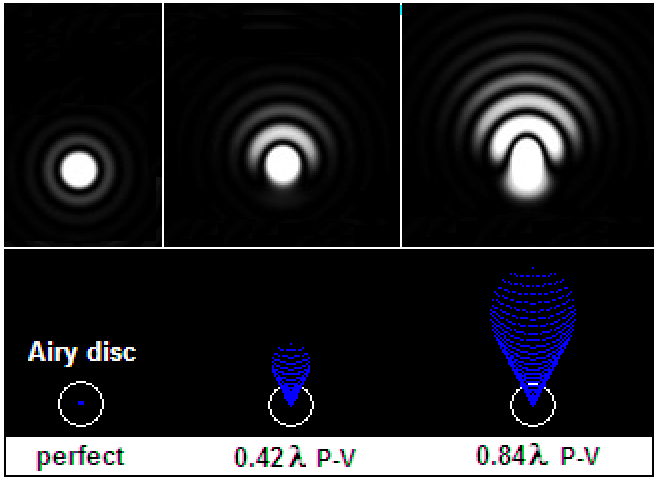

Figure 7



# Coma

- **Coma:** *either affects off-axis image points or the result of axial misalignment of optical surface*
- *It is the dominant aberration in off-axis telescope: NST, DKIST*

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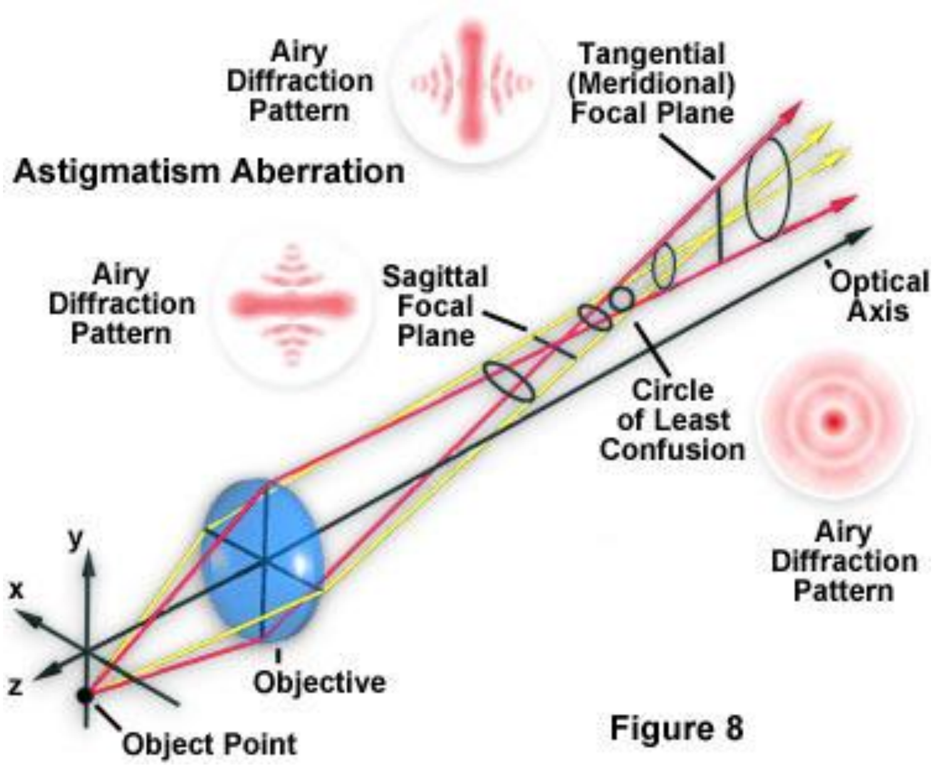
- ***Solutions***
  - *Limit field of view*
  - *Use large F#*

$$Coma \propto \alpha(F\#)^{-2} = \alpha(\frac{D}{f})^2$$

# Astigmatism Aberration

- ***Astigmatism:*** *off-axis point aberration caused by the inclination of incident wavefronts relative to the optical surface*
- ***Astigmatism:*** *results from the projectional asymmetry onto surface*
- ***Astigmatism:*** *the focus of rays in the plane containing the axis of the system and off-axis source (the tangential plane) is different from the focus of rays in the perpendicular plane (sagittal plane)*



# Astigmatism Aberration

- Either affects off-axis image points or the result of axial misalignment of optical surface
- It is the dominant aberration in off-axis telescope: NST, DKIST
- **Solutions**
  - Limit field of view
  - Use large F#

$$AA \propto \alpha^2 (F\#)^{-1} = \alpha^2 (\frac{D}{f})$$

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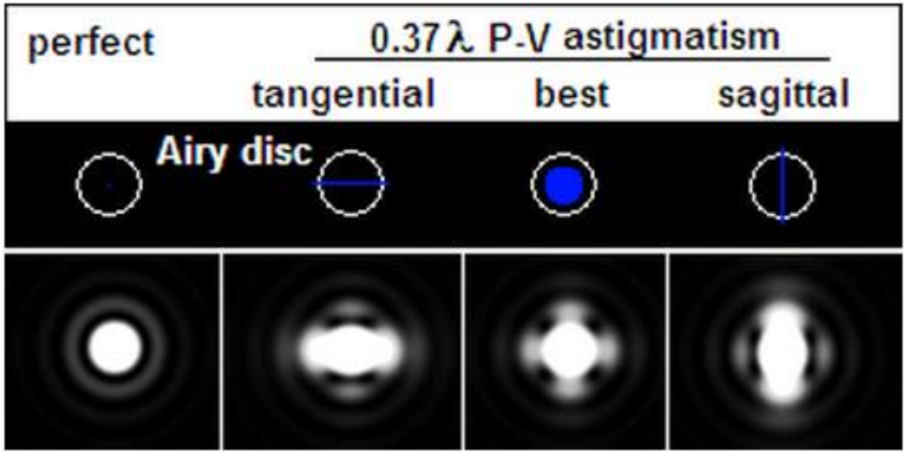
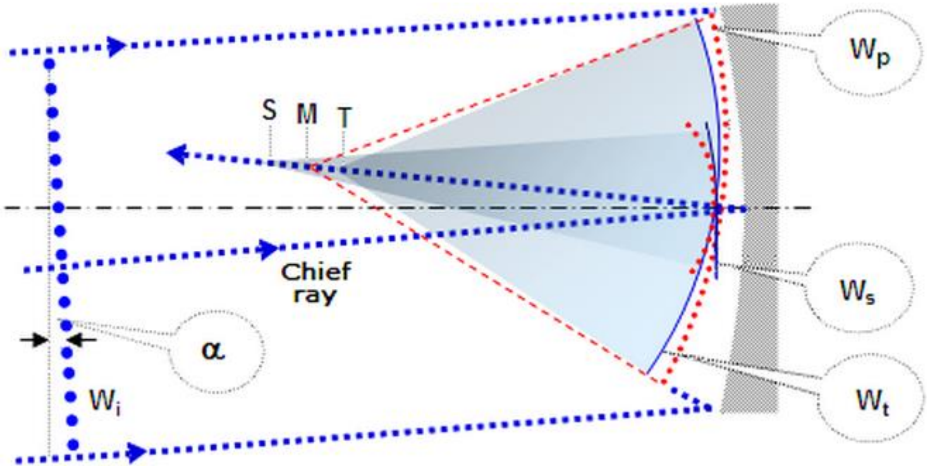
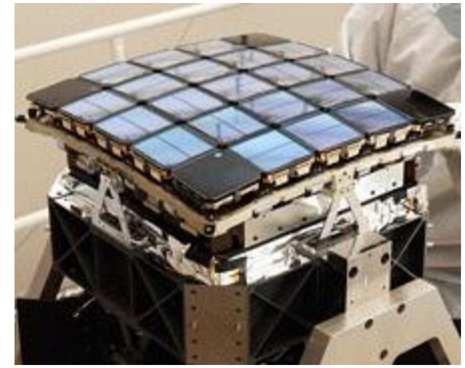


# Field Curvature and Distortion

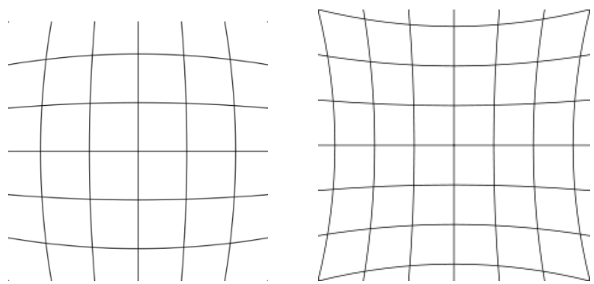
- ***Field curvature:*** *occurs when the images does not form on a "plane", but on a curved surface*

$$FC \propto \alpha^2 (F\#)^{-1} = \alpha^2 (\frac{D}{f})$$



- ***Distortion:*** *plate scale is not perfectly constant but varies both with the field angle and the direction*

$$OD \propto \alpha^3$$



- ***Fabrication Errors:*** *deviations of an actual optical surface from the perfect reference surface due to fabrication process*

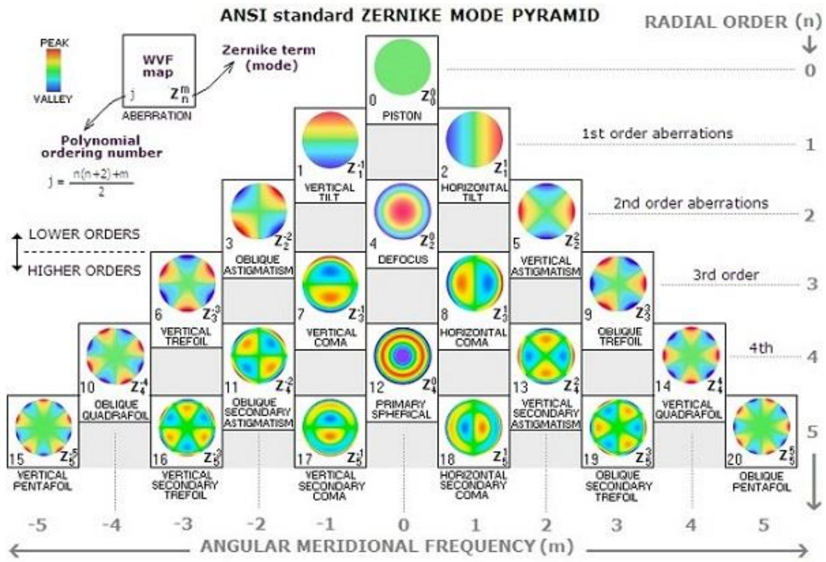
# Zernike Polynominals

- Zernike polynomials are the most standard basis for quantifying aberrations
  - Analytical expressions
  - Orthonormal basis on a circular aperture
  - The first Zernike polynominals correspond the most common optical aberrations

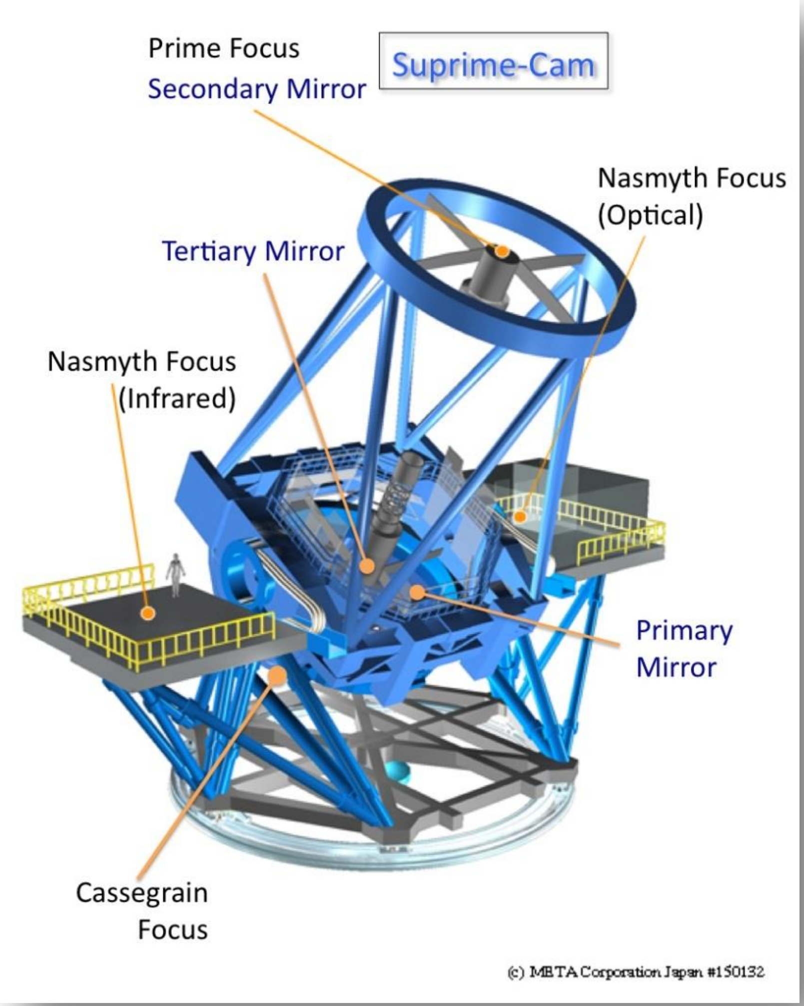
$$w(x,y) = \sum_{k=0}^{M} a_k z_k(x,y)$$

**Table 1. Zernike polynomials up to the forth order**

| Term | Polar representation | Monomial representation | Meaning |
|---|---|---|---|
| $Z_0(x,y)$ | $1$ | $1$ | Constant term |
| $Z_1(x,y)$ | $rsenq$ | $x$ | Tilt on x direction |
| $Z_2(x,y)$ | $rconsq$ | $y$ | Tilt on y direction |
| $Z_3(x,y)$ | $r^2sen(2q)$ | $2xy$ | Astigmatism with axis at ± 45° |
| $Z_4(x,y)$ | $2r^2 -1$ | $-1+2y^2+2x^2$ | Focal aberration (myopia or hyperopia) |
| $Z_5(x,y)$ | $r^2cos(2q)$ | $y^2-x^2$ | Astigmatism with axis at ± 90° |
| $Z_6(x,y)$ | $r^3sen(3q)$ | $3xy^2-x^3$ | |
| $Z_7(x,y)$ | $(3r^3-2p)senq$ | $-2x+3xy^2+3x^3$ | Coma of 3rd order at x axis |
| $Z_8(x,y)$ | $(3r^3-2p)cosq$ | $-2y+3y^3+3x^2y$ | Coma of 3rd order at y axis |
| $Z_9(x,y)$ | $r^3cos(3q)$ | $y^3-3x^2y$ | |
| $Z_{10}(x,y)$ | $r^4sen(4q)$ | $4y^3x-4x^3y$ | |
| $Z_{11}(x,y)$ | $(4r^4-3r^2)sen(2q)$ | $-6xy+8y^3x+8x^3y$ | |
| $Z_{12}(x,y)$ | $6r^4-6r^2+1$ | $1-6y^2-6x^2+6y^4+12x^2y^2-6x^4$ | Spherical aberration of 3rd order |
| $Z_{13}(x,y)$ | $(4r^4-3r^2)+cos(2q)$ | $-3y^2+3x^2+4y^4-4x^2y^2-4x^4$ | |
| $Z_{14}(x,y)$ | $r^4cos(4q)$ | $y^4-6x^2y^2+x^4$ | |



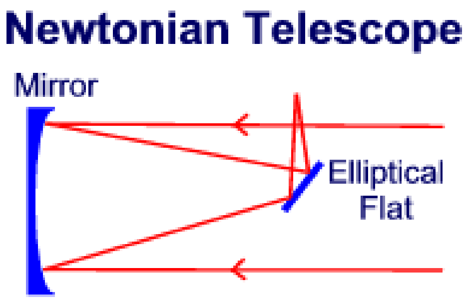
# 3. Modern Large Telescopes

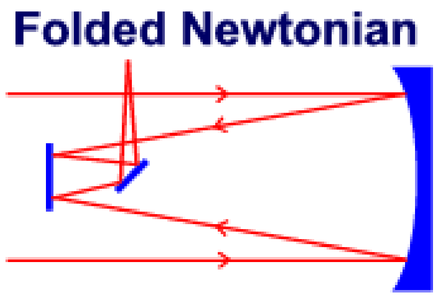


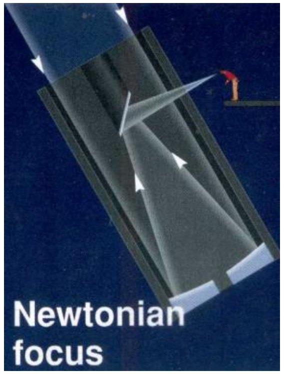

***8.2 m Subaru Telescope***

# Newtonian Telescope Optics

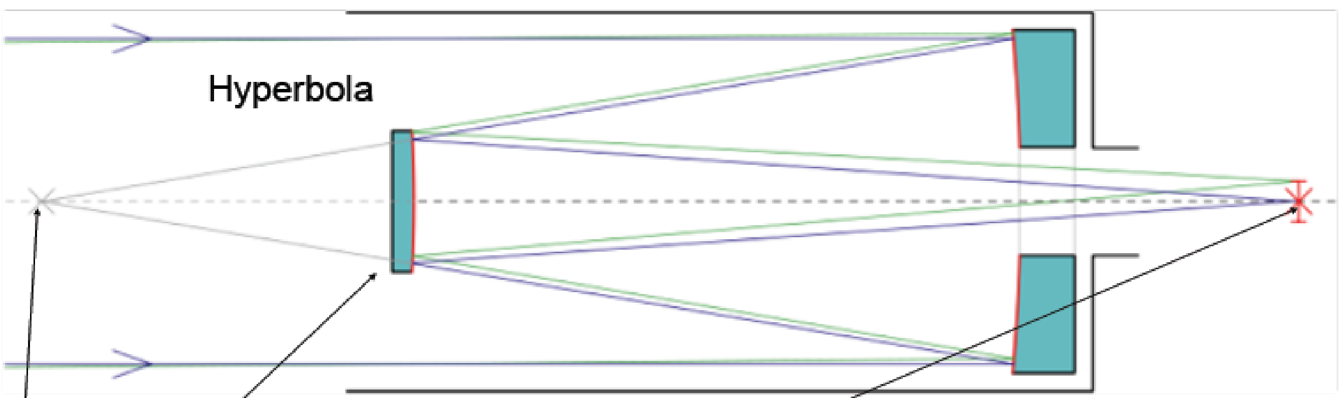
- *Most commonly used of the amateur telescopes*
- *Ease of construction, portability, insensitivity to alignment and cheap*
- *Primary mirror placed at the bottom of telescope tube*
- *Secondary mirror: small elliptically shaped flat mirror*
- *An alternative: "Folded Newtonian" provides high magnification with a long focal length*
- *Main drawback: coma aberration at the edge of the field of view*
- *A disadvantage is the extra obscuration caused by the circular flat*

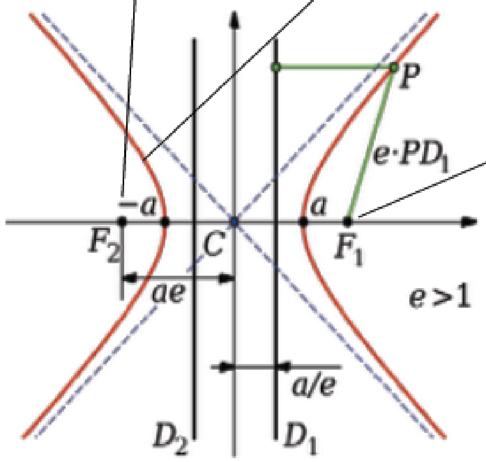


# Cassegrain Telescope Optics




***Courtesy:*** *Olivier Guyon*

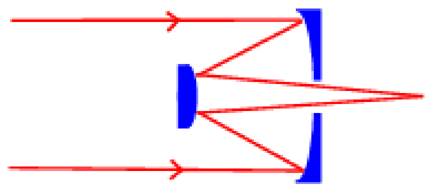
If secondary mirror is flat, then focus is inside telescope (not practical)

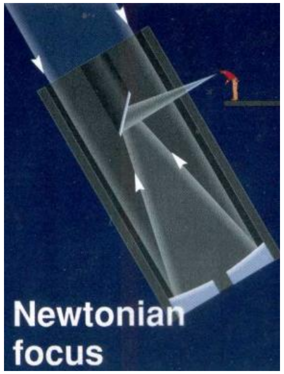
Hyperbola is curve/surface for which difference between distances to two focii (F1 and F2) is constant (=2a). Fermat's principle → hyperbola

# Cassegrain Telescope Optics

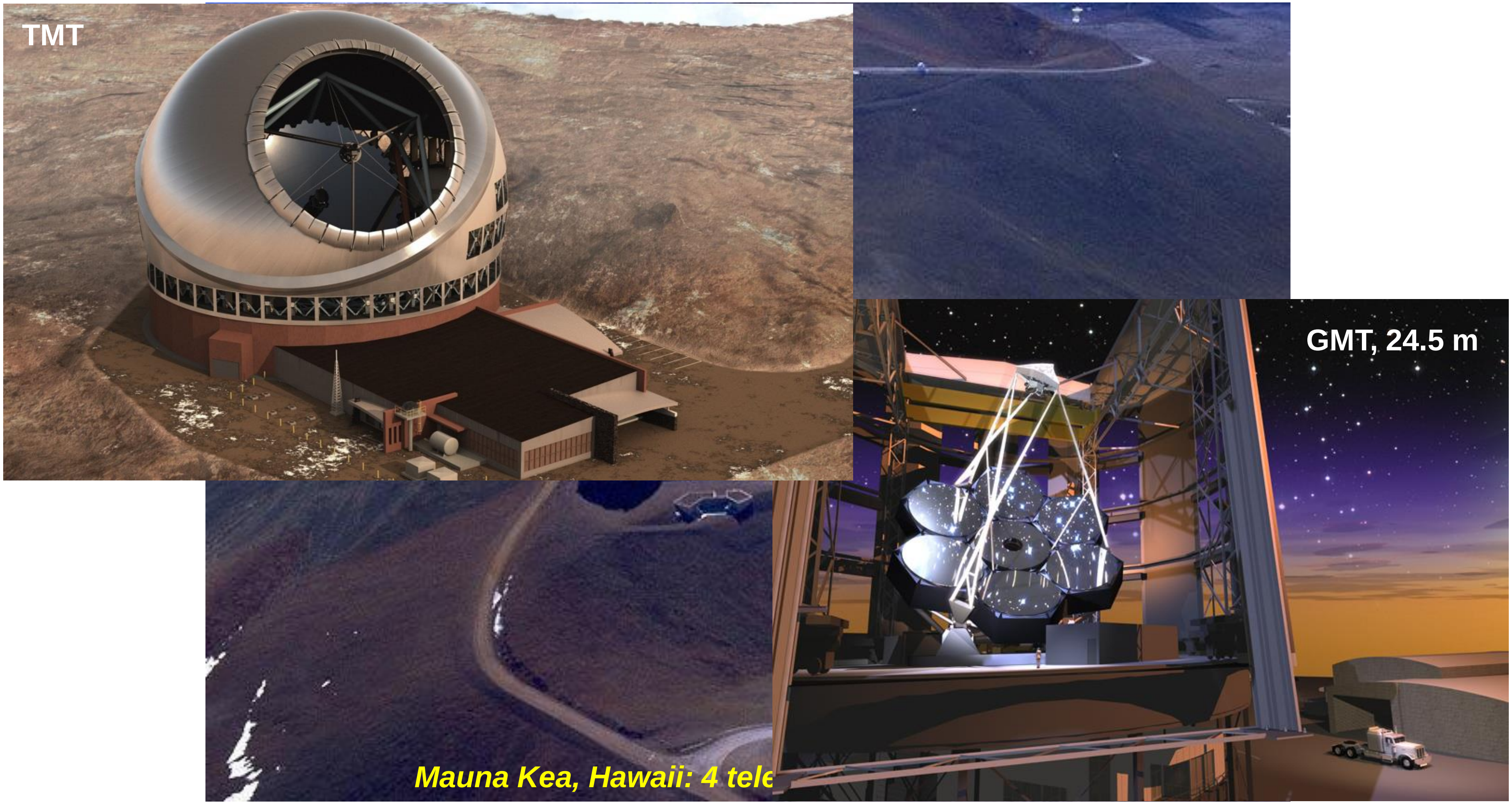
- *Most commonly used of the astronomical night-time telescopes*
- *Longer effective focal length and higher magnification*
- *Concave PM with a hole at its center: placed at the bottom of tube*
- *Convex SM with a small aperture: placed near the top of telescope*
- ***Classical Cassegrain:** a parabolic PM with a hyperbolic SM*
- ***Dall-Kirkham system:** an under-corrected parabolic PM with a spherical SM for direct viewing with small field of view*
- ***Ritchey-Chretien (RC) system:** overcorrected hyperbolic PM and SM for a wide field with a coma free*

**Cassegrain Telescope**

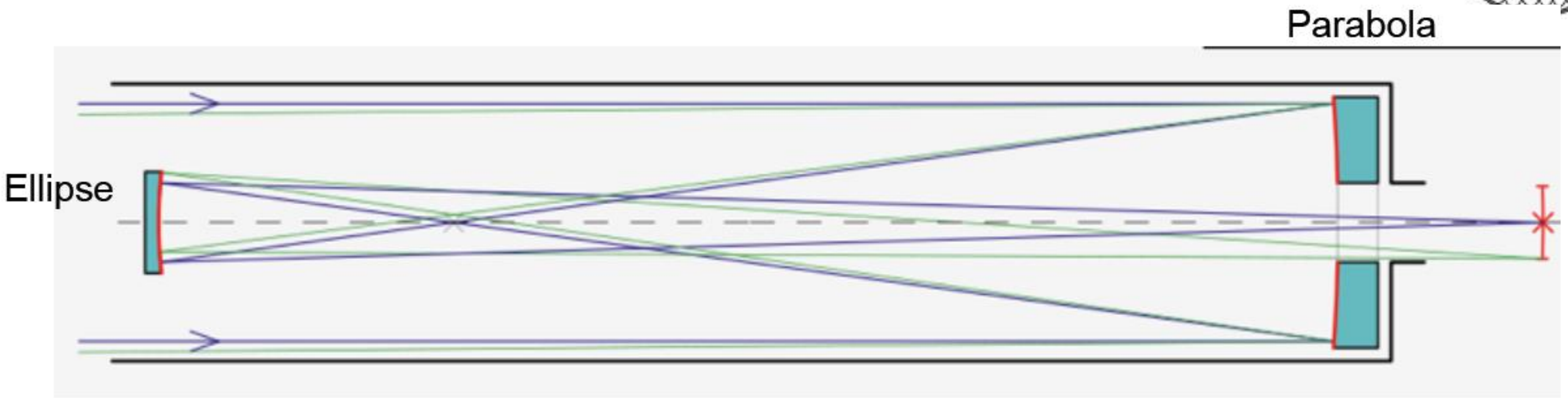


# 3. Modern Large Telescopes

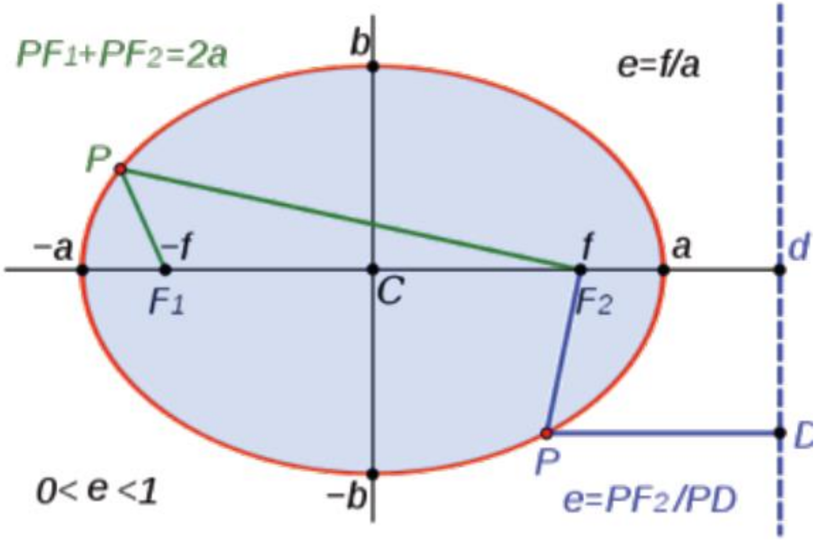


# Gregorian Telescope Optics




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

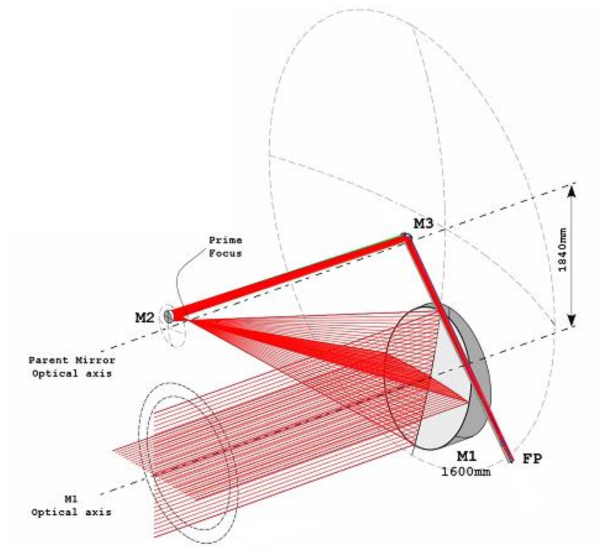
Ellipse is curve/surface for which sum of distances to two focii (F1 and F2) is constant (=2a).
Fermat's principle → Ellipse



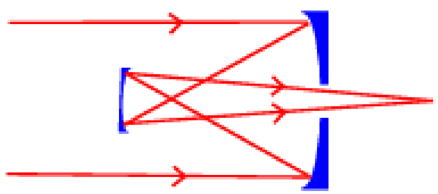

***Courtesy:** Olivier Guyon*

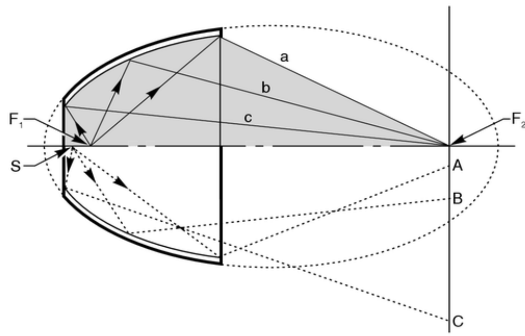
# Gregorian Telescope Optics

- *Most commonly used of the solar telescopes*
- *Prime focus for installation of solar heat stop*
- *Concave PM: placed at the bottom of the telescope structure*
- *Concave SM with a small aperture: placed near the top of telescope*
- *Optics: a parabolic PM with a elliptical SM*
- *A disadvantage for on-axis Gregorian telescope is the extra obscuration caused by the SM and support structure*




**Gregorian Telescope**






NJIT
New Jersey's Science & Technology University

*Big Bear Solar Observatory*

THE EDGE IN KNOWLEDGE

# 1.5 meter GREGOR

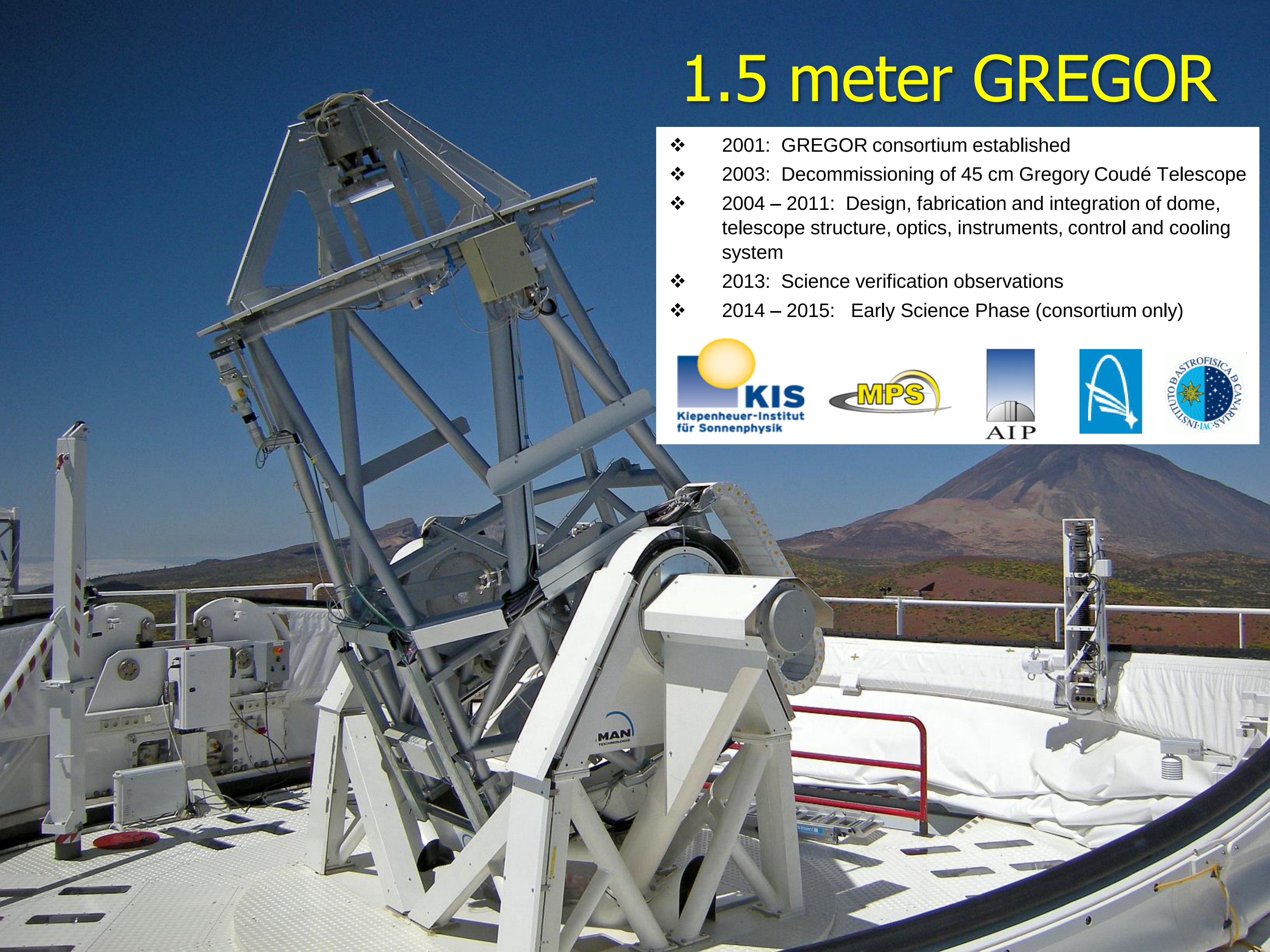
- 2001: GREGOR consortium established
- 2003: Decommissioning of 45 cm Gregory Coudé Telescope
- 2004 – 2011: Design, fabrication and integration of dome, telescope structure, optics, instruments, control and cooling system
- 2013: Science verification observations
- 2014 – 2015: Early Science Phase (consortium only)

KIS Kiepenheuer-Institut für Sonnenphysik

MPS

AIP

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC

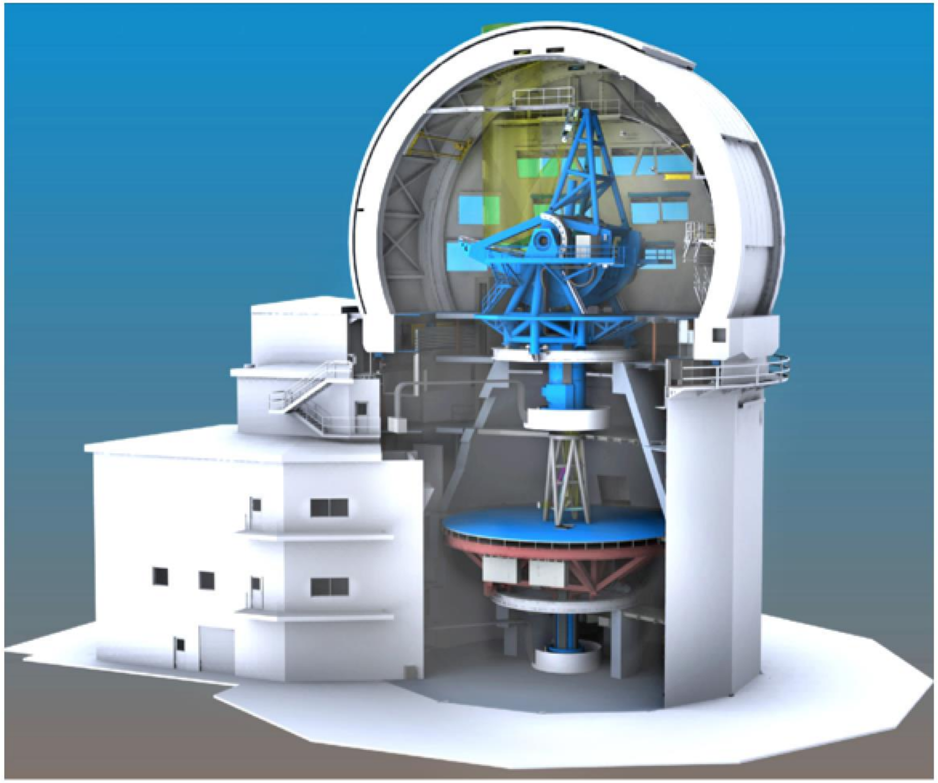


# NST Features

- All reflecting, off-axis Gregory optical configuration
- PM: off-axis 1.6 m clear aperture (1.7 m blank) with f/2.4
- Figuring PM to 16 nm rms
- Effective focal length: 83.2 m (*F*/52 at Gregorian focus and *F*/28 at Coudé focus)
- FOV: 2' in prime focus
- Wavelength range from 400 nm to NIR in Coudé lab with AO
- Integrated active optics (ao) and adaptive optics (AO)
- Quasi-static telescope alignment
- Diffraction limited: 0.06″@ 500 nm and 0.2″@ 1.56 μm with AO
- Polarization calibration optics immediately before M3
- Facility-class instruments

# DKIST Main Features

- Four-meter aperture
- All reflecting, Off axis optical design
- Integrated high-order adaptive optics (MCAO)
- Low-scattered light - coronal in NIR
- Integrated high-precision polarimetry
- Facility-class instruments



**High Spatial (25km@500nm), Spectral & Temporal Resolution**

**High Precision Polarimetry (accuracy $5 \times 10^{-4}$Ic)**

**High Photon Flux, Low Scattered Light**

**Simultaneous UV, VIS, NIR & Far Infrared (new diagnostics)**