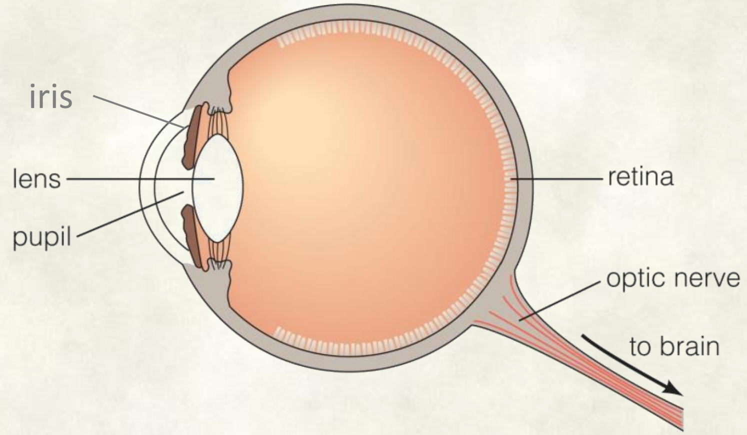
Astronomical Instruments

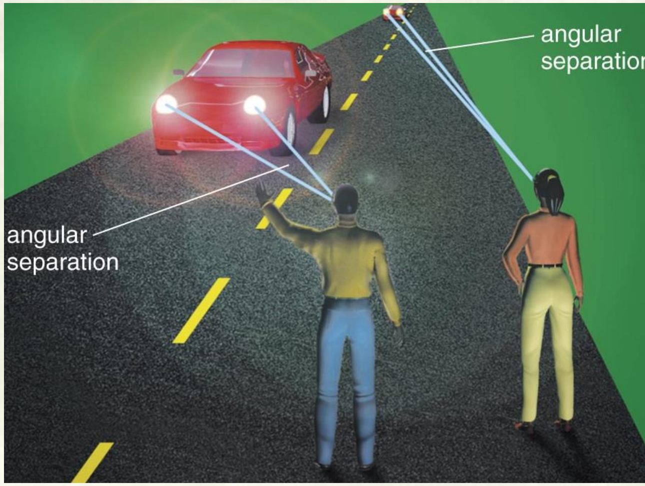
Human Eye



- Until 17th century all astronomical studies limited to naked eye observations. Equipment used were mainly to measure positions of celestial objects in the sky.
- Eye operates like a camera, with a *lens*, an *iris*, and a *retina*.
- The eye lens is filled with fluid, and its shape (and the focal length) can be adjusted by the surrounding muscles so that a sharp ("in focus") image is produced on the retina.
- The iris automatically adjusts the eye's input aperture "pupil" diameter according to the prevailing light level. The largest aperture size, under very dark conditions, is about 5-6mm.
- There are two kinds of photo-receptor cells in the retina:
  - Cones: less numerous and operate only at high light levels sense color and brightness
  - Rods: are more sensitive, operate best at low light levels, no color sensitivity

Eye

- **Resolution**: The maximum resolution of the human eye is typically one arc minute (1′). To see anything spaced less than that, an optical aid is needed to magnify it..
  - Example: Two stars separated by 1 arc second (1″) won't be visible to eye as separate stars. If we magnify them by a factor 60, separation would be 60″ = 1′, which is the limit of the resolution of eye and should be able to resolve.



- **Integration time:** The eye automatically adjusts the time interval during which it accumulates light before sending an image to the brain. It is typically 0.07-0.2s depending on the light level.

- **Dark Adaptation:** In the dark low light conditions, pupils dilate and the rods slowly become more sensitive. I t takes over 20 minutes to achieve highest sensitivity, or "full dark adaptation" .
  - White light will ruin the dark adaption in few seconds
  - Because the rods are less sensitive to red light, using a red flashlight helps preserve the dark adaptation.

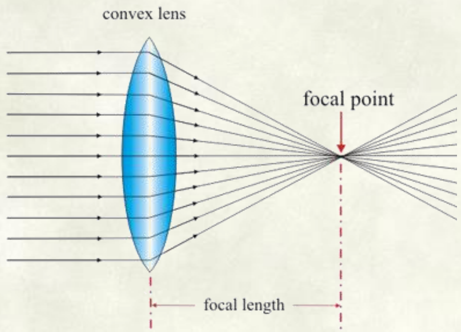
Optical Telescopes

- In 1609 Galileo (an few others) used a telescope to observe the sky and turned a new age of astronomy based on telescopes.

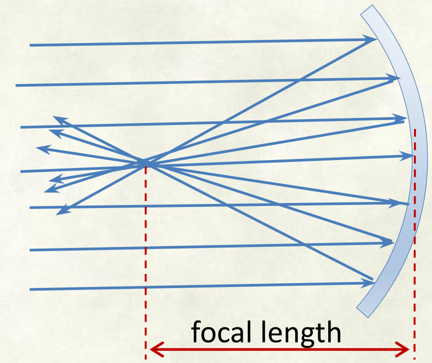
- Galileo wasn’t the inventor of the telescope, instead he heard about an optical device built by a Dutch spectacle-maker Hans Lippershey which can show things far away as they are closer.

- Galileo figured out how it would work and built his own device of better quality.

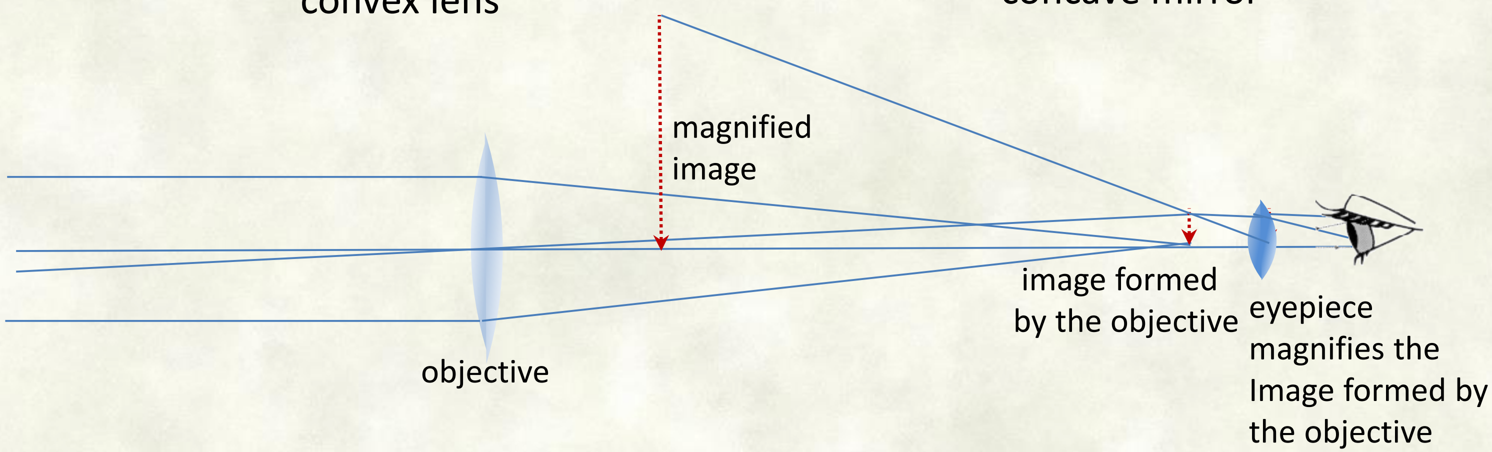
Telescopes



convex lens

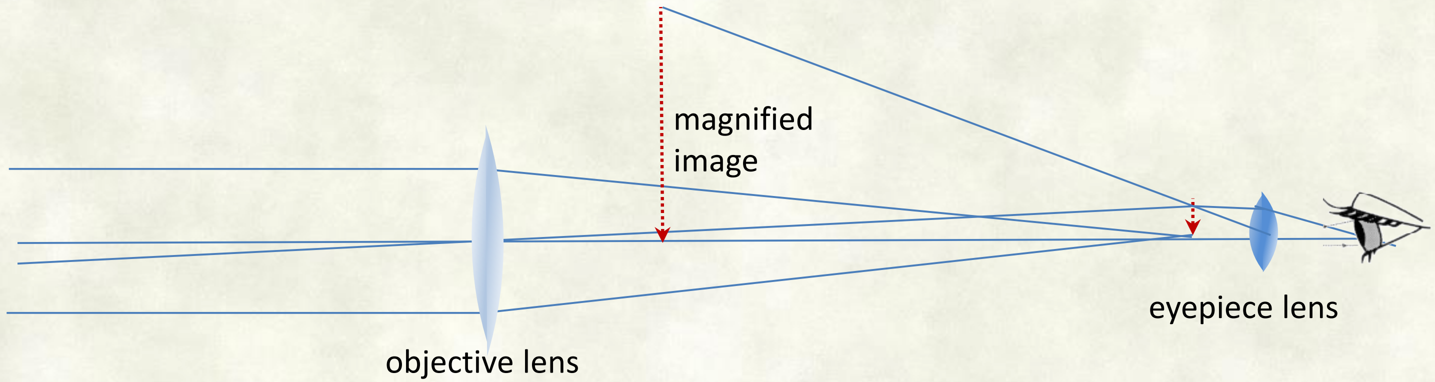


concave mirror



- A telescope consists of two optical parts
  - Objective: Collects light and forms a real image (convex lens or concave mirror)
  - Eyepiece: magnifies the image formed by the objective.

Refractive telescope



- Refractive telescope uses a lens as the objective,
  - Simplest and earliest type built
- Size of the image formed by the objective is proportional to its focal length. Longer focal length ⇒ larger image.
- Magnification by the eyepiece is inversely proportional to its focal length shorter focal length ⇒ larger image.

Combining those two: $\text{Magnification} = \dfrac{\text{focal length of the objective}}{\text{focal length of the eye piece}}$

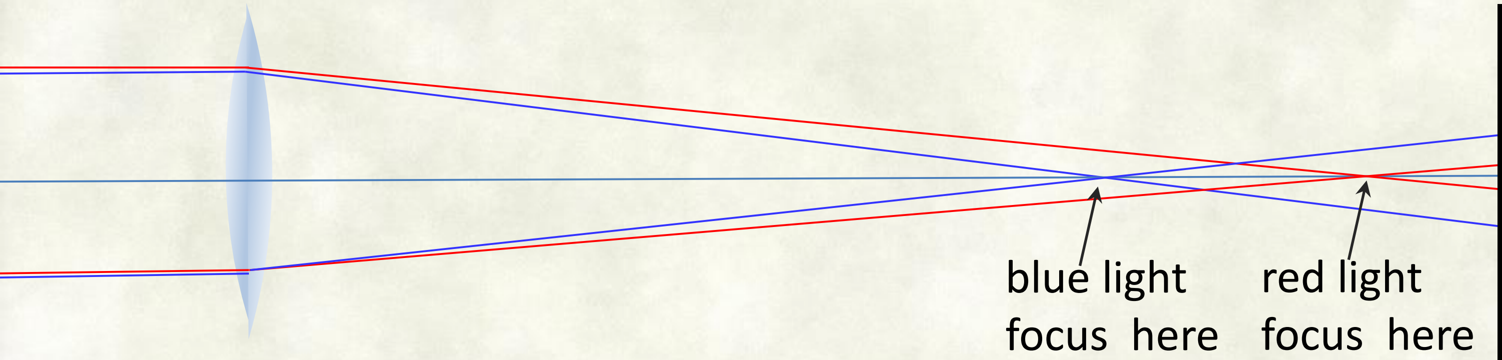
Amount of light collected = area of the objective

larger objective ⇒ brighter image

Since area $= \pi r^2$ light collected goes as the square of the diameter

To see fainter objects needs to collect more light ⇒ larger telescopes

Chromatic Aberration



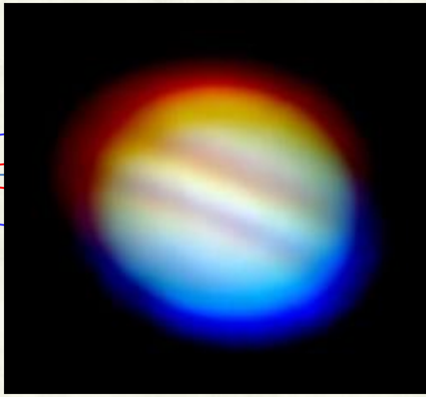
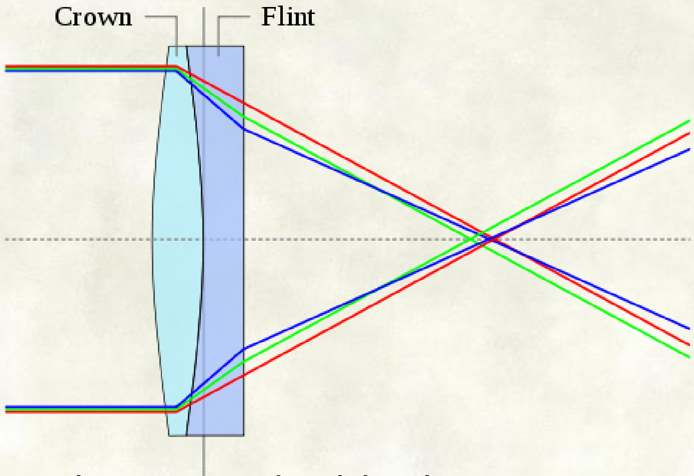


Image of Jupiter through a telescope with chromatic aberration

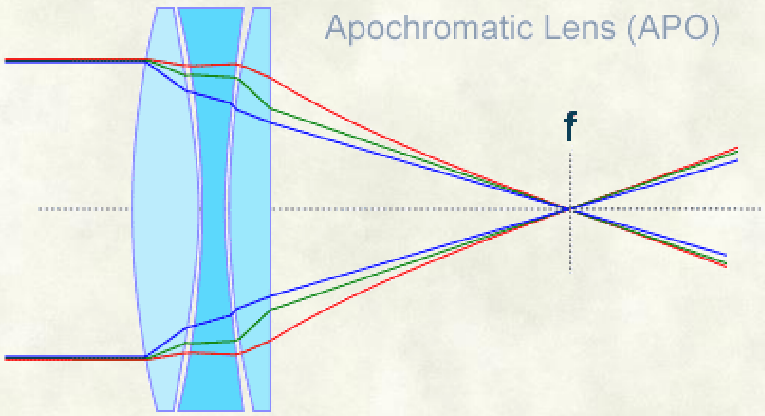
Limitations of the refracting telescopes:

- Chromatic aberration:
  - since blue light refracts more than red light , focal length of a lens is different for different colored light.
  - a simple objective lens cannot bring all colors of the image to a sharp focus

Correcting the Chromatic Aberration



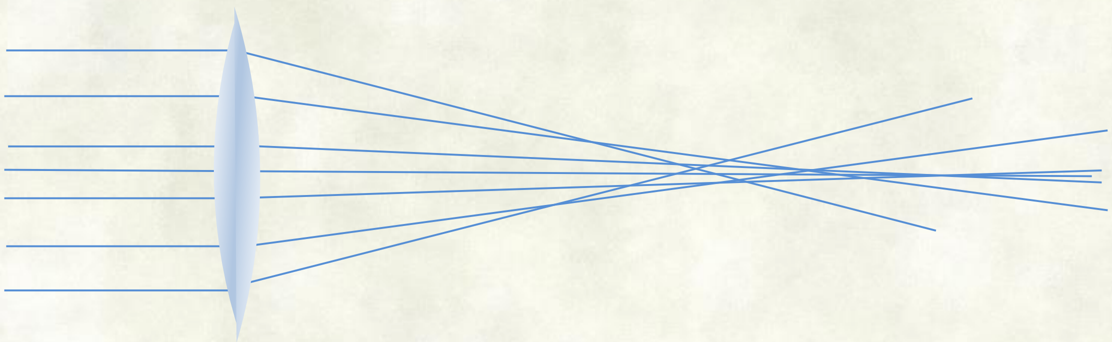
Achromatic doublet lens



Apochromatic triplet lens

- Combining lenses made of different types of glasses with different color dispersions, it is possible to reduce the chromatic aberration.
- First such color corrected lenses using crown and flit glass were made in mid 18th century, which had the same focal length for blue and red light, reducing most of detrimental effects of chromatic abrasion. Known as **achromatic** lenses they still show a little color aberration.
- Combining three types of lenses it is possible to have a lens color corrected for three colors. Known as **apochromatic** lenses, they have superior performance.

Spherical Aberration



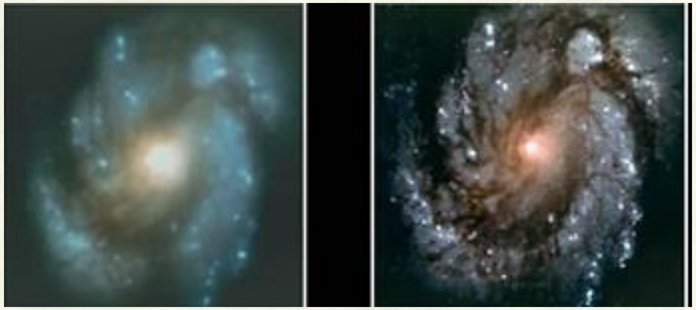
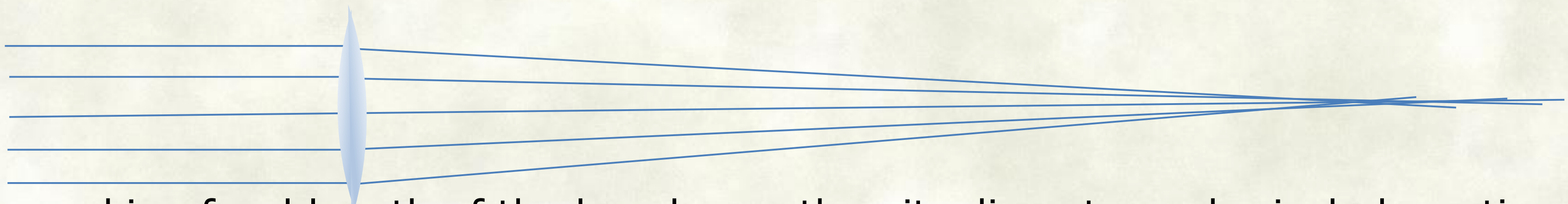


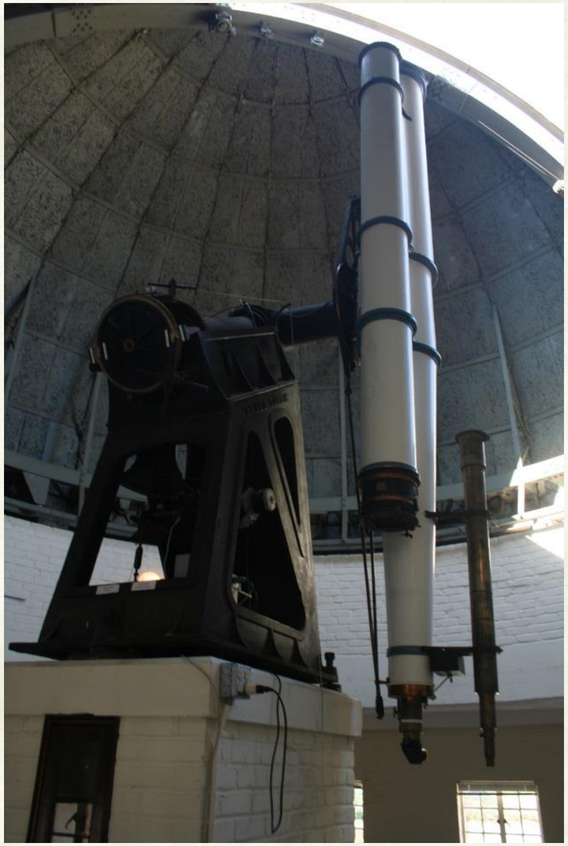
Image of a galaxy before and after correcting for spherical aberration of the Hubble space telescope

- Light that pass through the outer diameters of the lens will focus light at a point closer to the lens than the light that pass through near the center. This causes the resulting image to be blurred.



- By making focal length of the lens larger than its diameter, spherical aberration can be reduced.

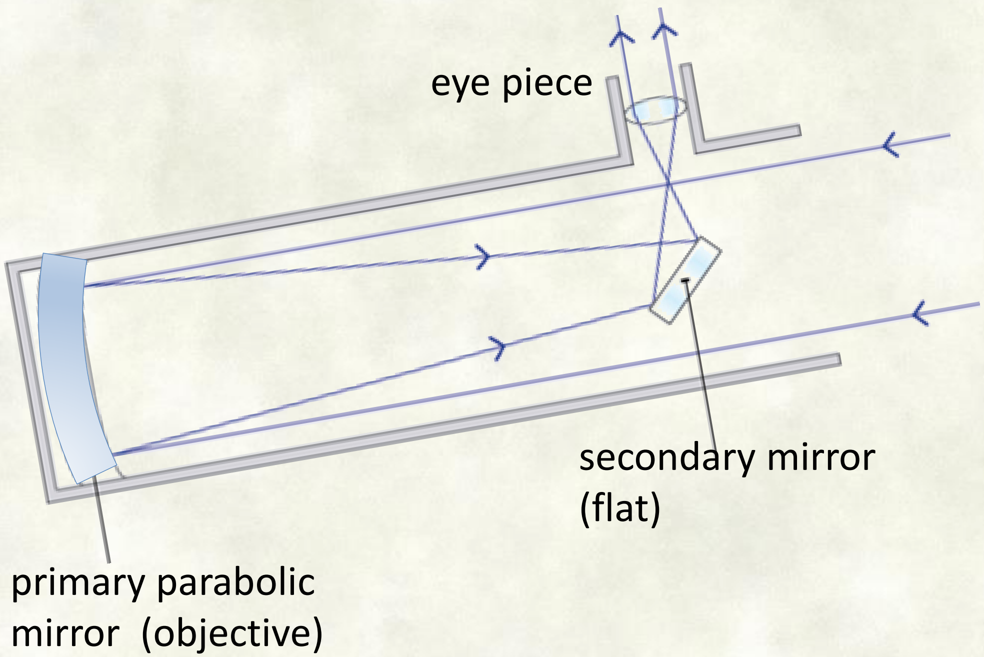
$$\text{f ratio} = \frac{\text{focal length}}{\text{diameter}}$$; refractor telescopes usually have $f > 8$ to reduce spherical aberration

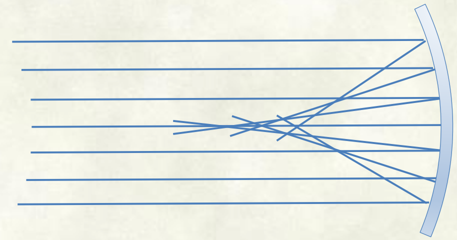


15 in refractor at the Kennon observatory

- A Modern refractor telescopes

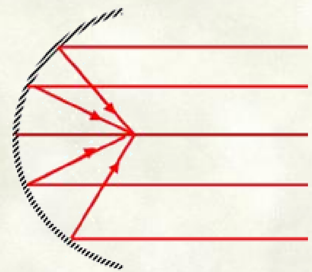
Reflecting telescope





Spherical mirror has spherical aberration, won't focus all light to a same point

Caustic curve from the light reflected from circular surface of a tea cup



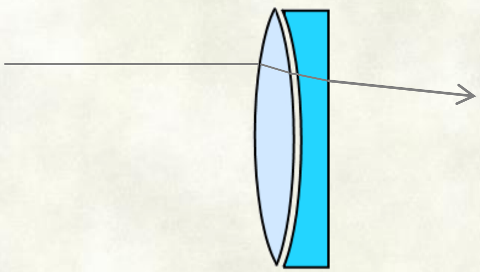
A parabolic mirror focus a beam of parallel light to a single point. same point

reflector of a headlight parabolic to produce a parallel beam of light

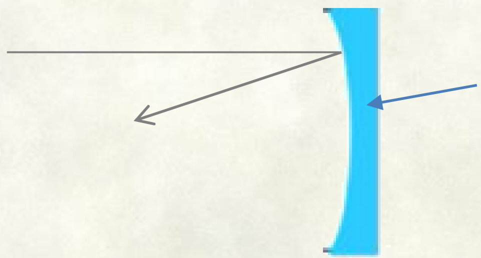
- Reflecting telescope uses a concave mirror as the objective.
- Since reflection does not depend on the color of the light, image formed by a concave mirror is free from chromatic aberration.
- Spherical concave mirrors still have spherical aberration, but making it can be eliminated by making the mirror parabolic.
- Isaac Newton built the fist reflecting telescope in 1668.

Reflecting telescope

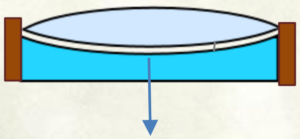
- Reflecting telescope has many advantages over refractors:
  - Free of chromatic aberrations
  - Making the mirror parabolic gets rid of spherical aberration(it introduce other aberrations, but less severe), can make the telescope shorter.
  - Cheaper to make
    - Since lights reflects from the surface of the mirror, internal defects of the glass won't affect the performance of the telescope.



light go through four surfaces



light reflects from one surface

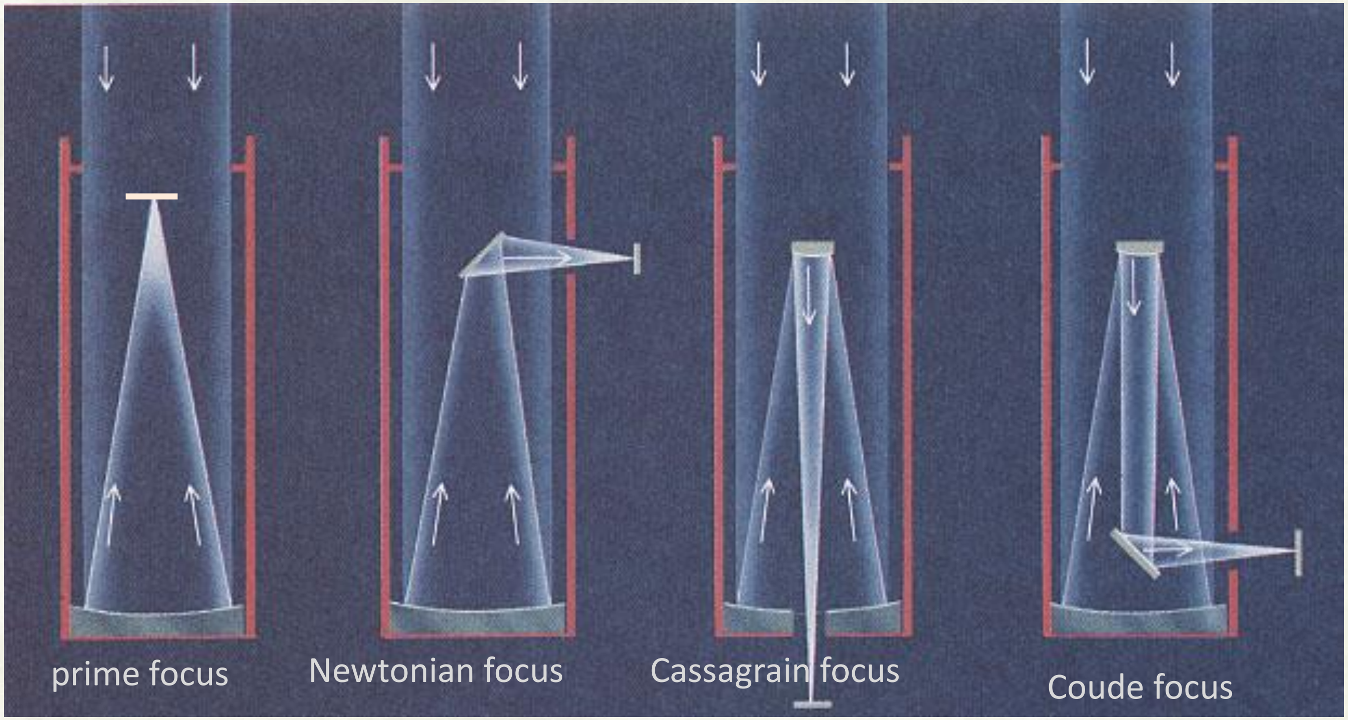


weight can cause the lens to sag

extra mechanical support to reduce flexing

    - Only one surface need to be ground and polished, whereas for a refractor with an achromatic there are four surfaces, and any internal defects (air bubbles, impurities etc) will degrade the performance.
  - Lens can only be supported from edges, large lenses sag under their own weight and deform causing shape of the lens to alter and degrade performance (shape of the surfaces has to accurate to $\lambda/8 \sim 600/8 = 75$nm for visible light). So it is not possible to make very large lenses.
  - Mirrors can be supported from the back to make it more rigid and reduce flex. So large mirrors can be made. They are usually made of glass and coated with aluminum or other high reflective material.

Types of reflector tetescopes



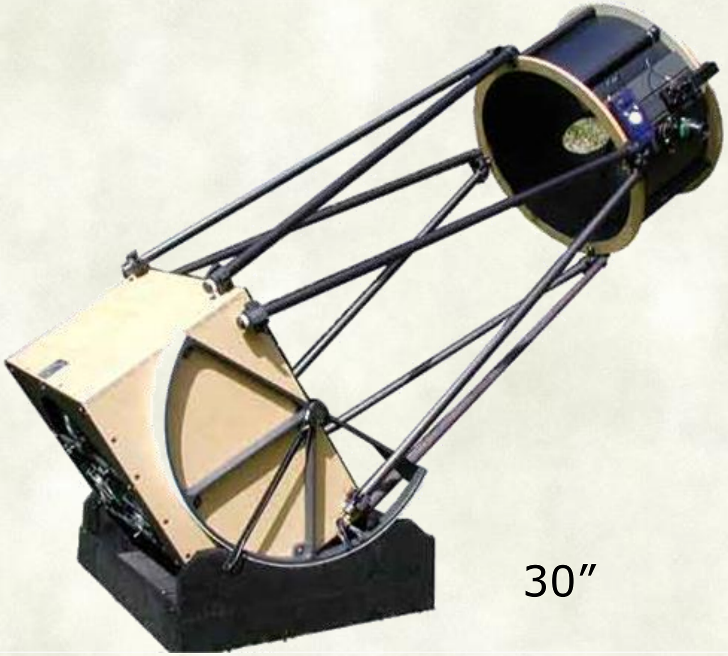
- Only amateurs look through telescopes (since early 20th century)!
- All large telescopes use photographic plates or electronic imaging devices (CCD) to record images or analyze light spectroscopically.
- This allows prolong exposures time to record faint object, which could last minutes, hours or days,

(exposure time of the human eye is about $\frac{1}{15}$ s.)

Newson's first reflecting telescope

Commercially made reflecting telescopes

8″

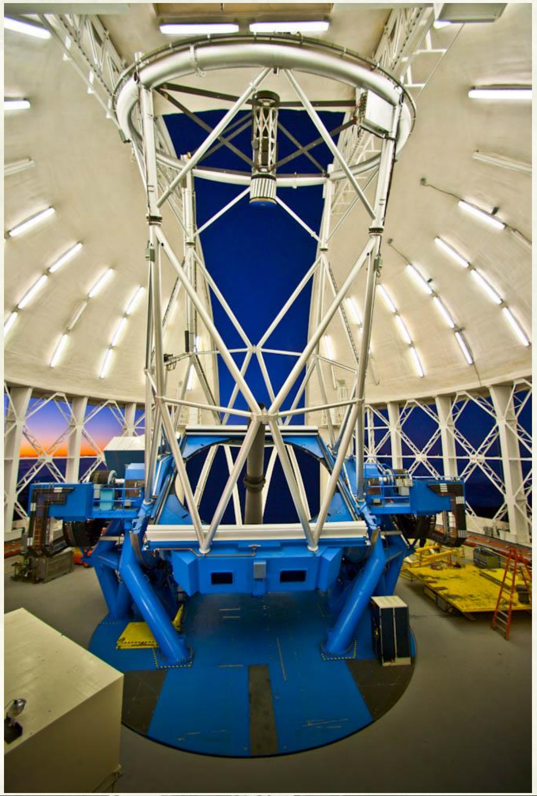


30″

Armature built reflecting telescopes

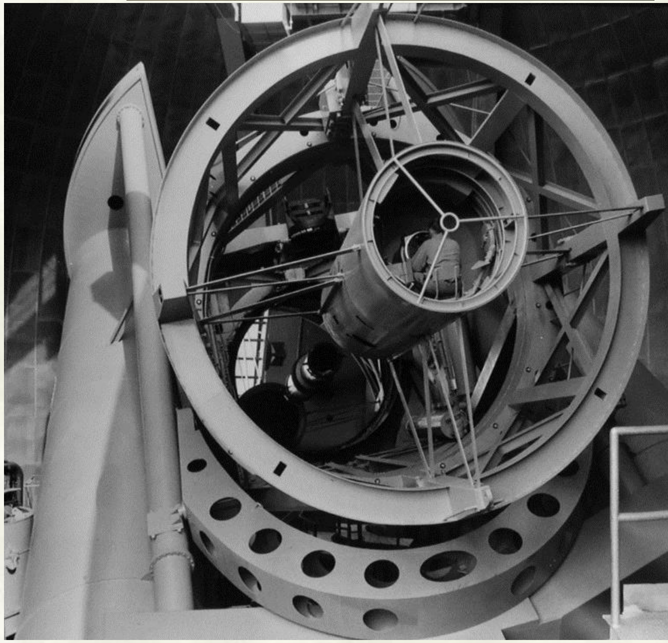
Largest refractor is the 40" (1m) telescope at the Yerkes observatory, WI built in 1897. All larger telescopes since then were reflectors

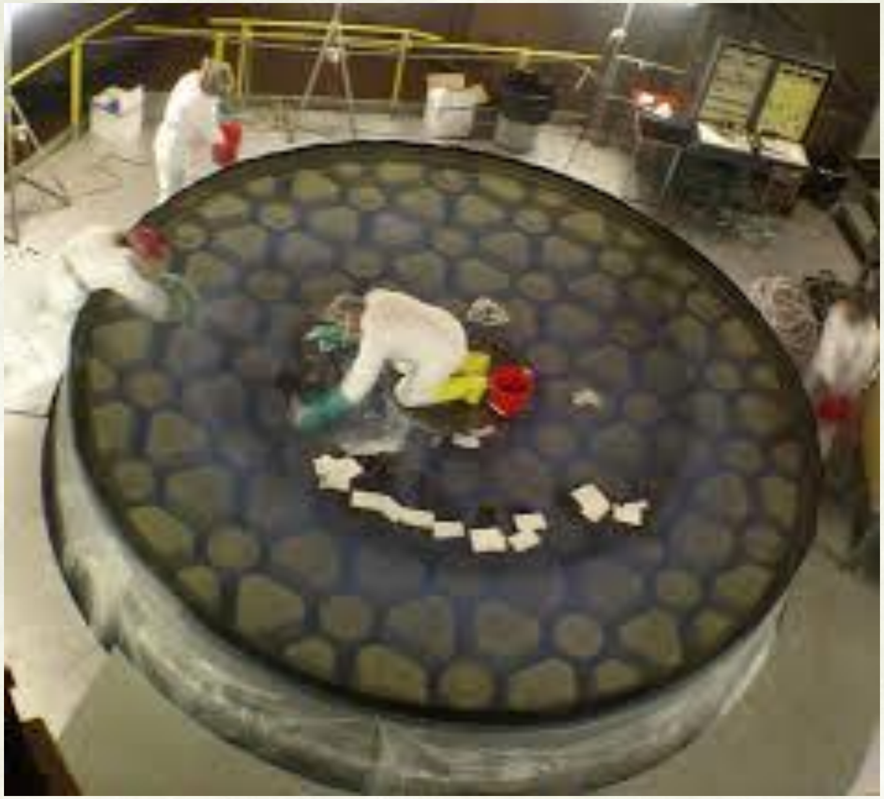
8.1m Gemini telescope Mauna Kea Observatory, Hawaii built in 1999 (right)

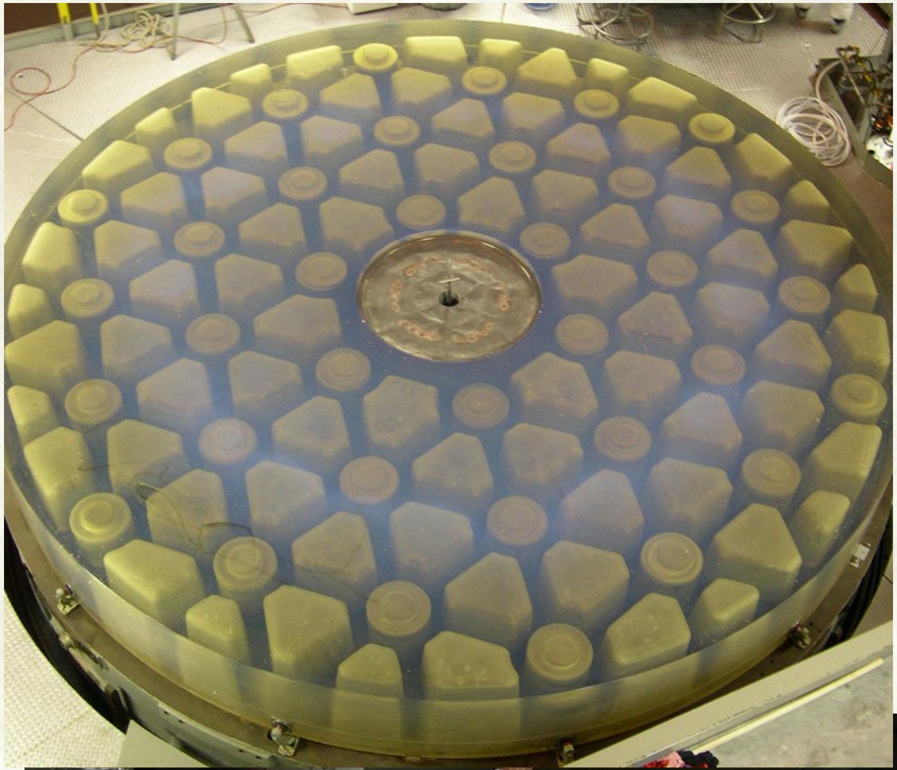


200" (5.1m) Hale reflector at the Mount Palomar Observatory CA, built in 1948. (lower left)
prime focus of the Hale (lower right)

40 inch refractor at the Yerkes observatory







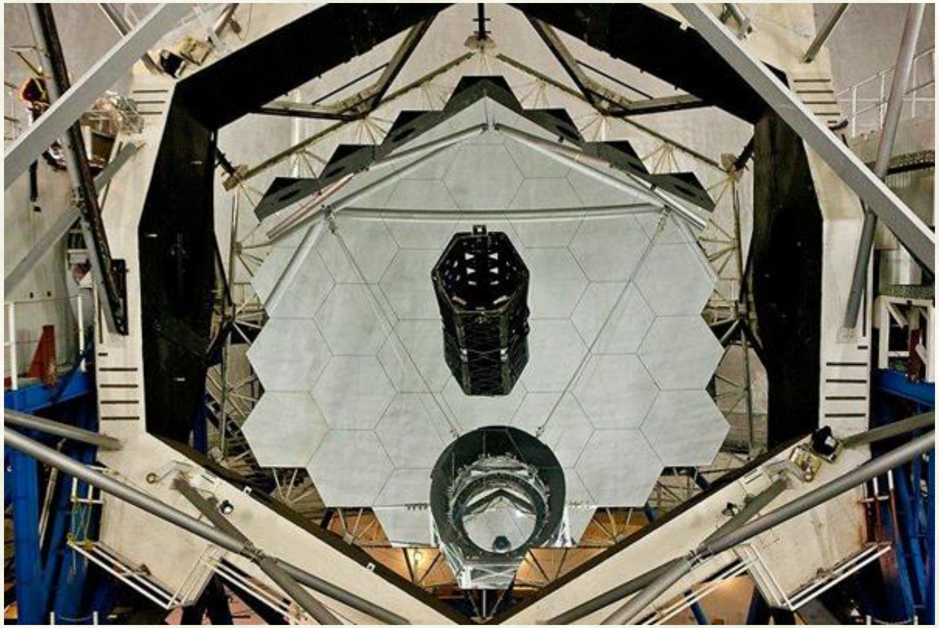
5m mirror of the Mt. Palomar telescope, aluminum layer stripped. Cleaning for recoating

(weight 14.5 tons; thick to make them rigid and won't deform under own weight)

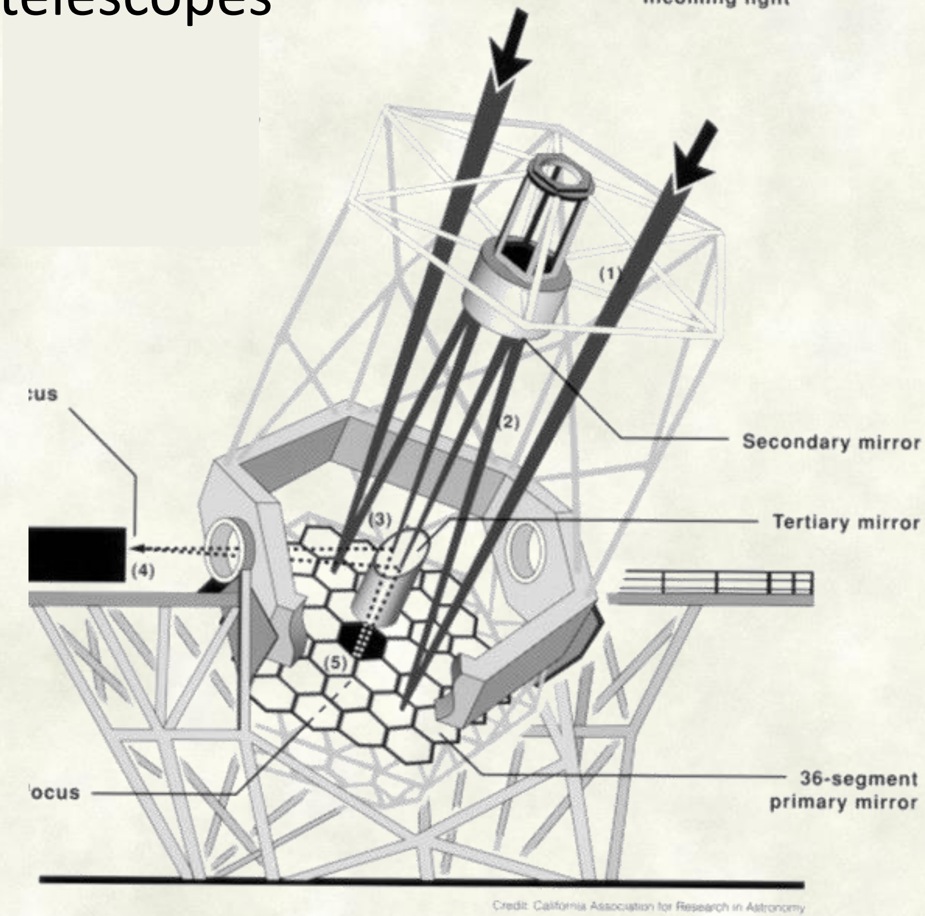
It was the largest telescope in the world for over 4 decades (1948 to 1990s)

After recoating

Segmented mirror telescopes



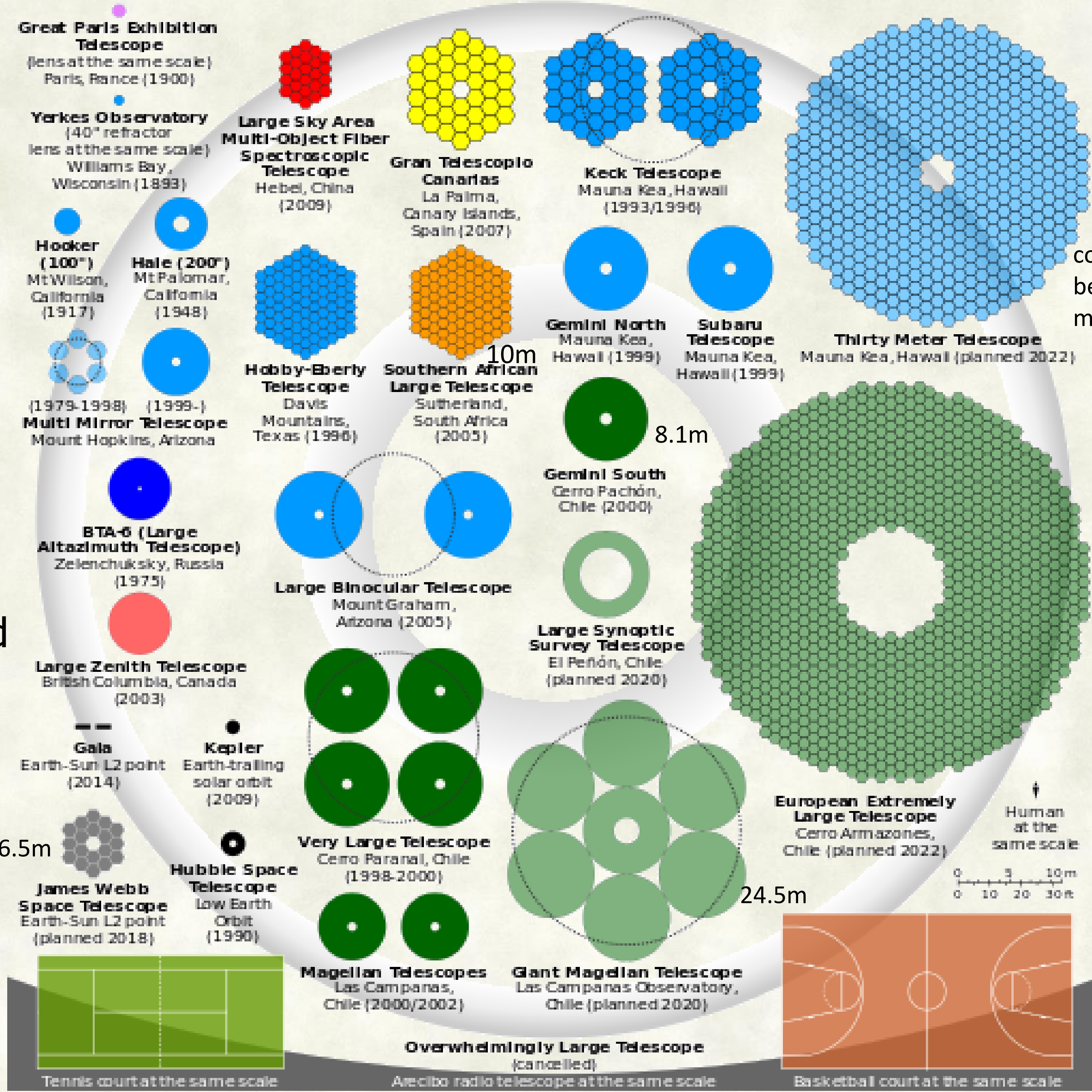
Segmented mirror of the 10m Keck telescope, consist of 36 mirror segments



- Even with elaborate support systems it is difficult and expensive to make mirrors larger than 8m.
- Modern larger telescopes use segmented mirrors
  - Primary mirror is build by combining large number of small mirror segments, which are kept properly aligned by mechanical actuators and electronics to form a single large mirror.

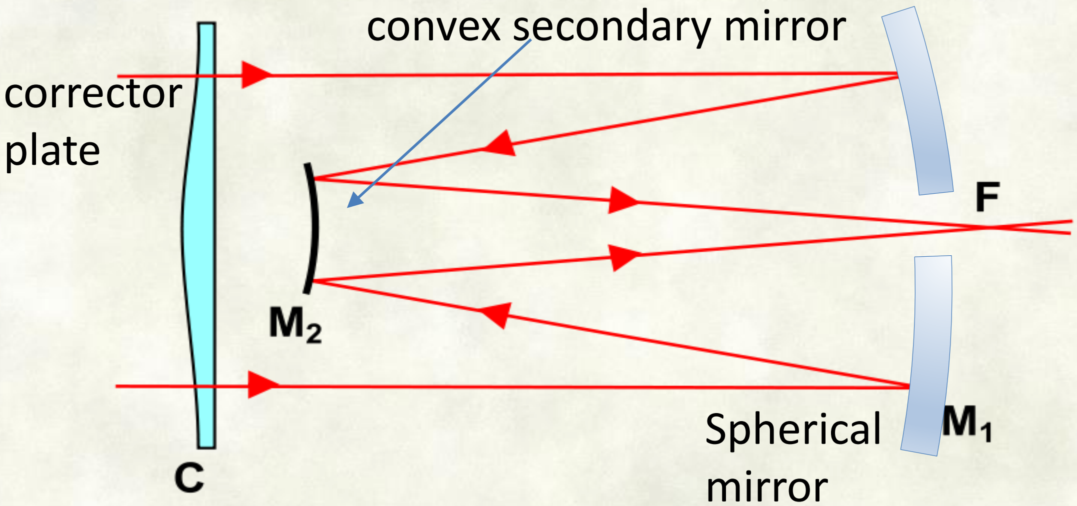
Large telescopes:

past, present and future



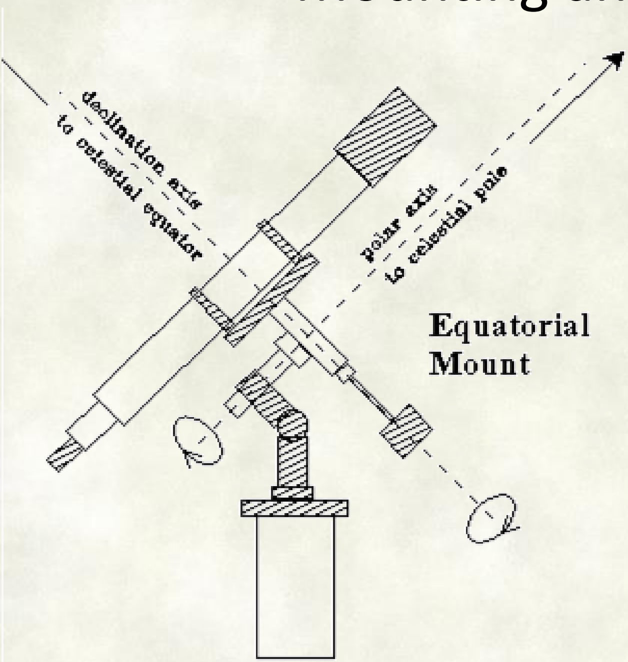
construction began this month

Schmidt Cassegrain telescope



- Spherical mirrors are easier to make than parabolic primary mirrors.
- In the Schmidt Cassegrain design, a spherical concave mirror is used as the primary mirror, a corrector is placed in the front to correct the spherical abreaction of the spherical mirror
- This way it is possible to have a short focal length primary objective mirror free of spherical aberration.
- Secondary mirror is a concave mirror which reflect light through a hole in the primary.
- Effective focal length of the telescope is much larger than its length, a compact design.

Mounting and Tracking telescopes.



Since object in the sky move East to West due to rotation of the Earth, to keep a telescope pointed at an object over time it has to be moved or tracked.

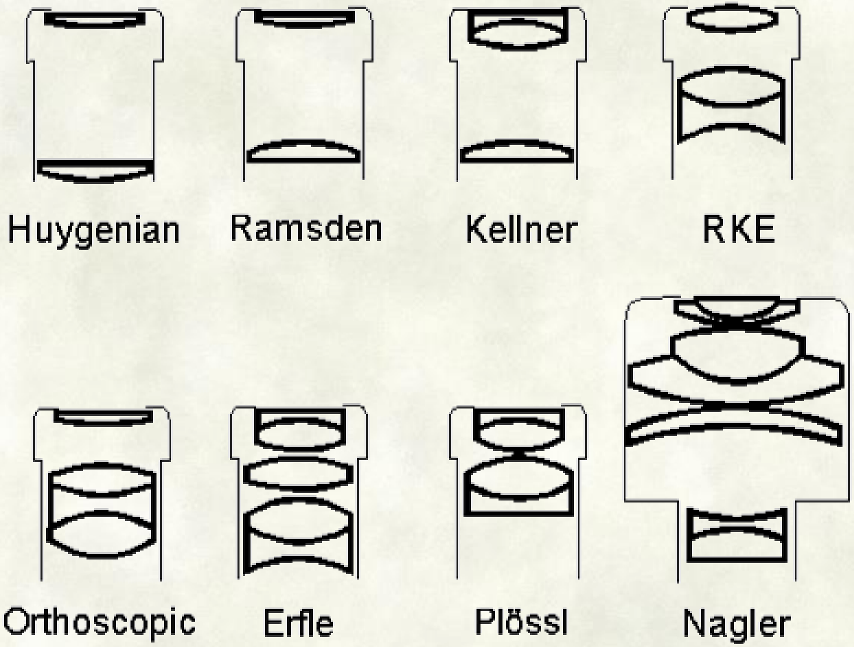
This is done with an equatorial mount, which has two axis:

- one axis (called polar axis) is in the celestial north south direction, parallel to the earth axis.

  To compensate for the Earth's rotation, the telescope is moved in this axis in   the opposite direction of the Earth's rotation at the same rate.

- The other axis on an equatorial mount (called the *declination axis)* allows movement of the scope at right angles to the polar axis.

Eyepieces



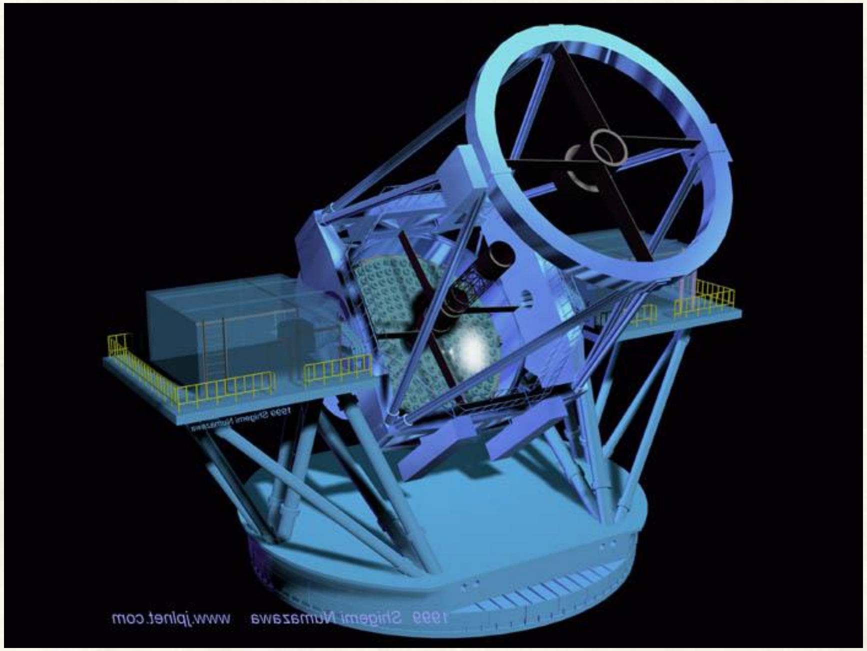
Arrangement of lenses in some commonly used eyepiece types.

Eyepieces come in many different designs

To correct for various aberrations and improve performance, it is necessary to combine many lenses of different types in an eyepiece.

Mounting/Tracking of telescopes

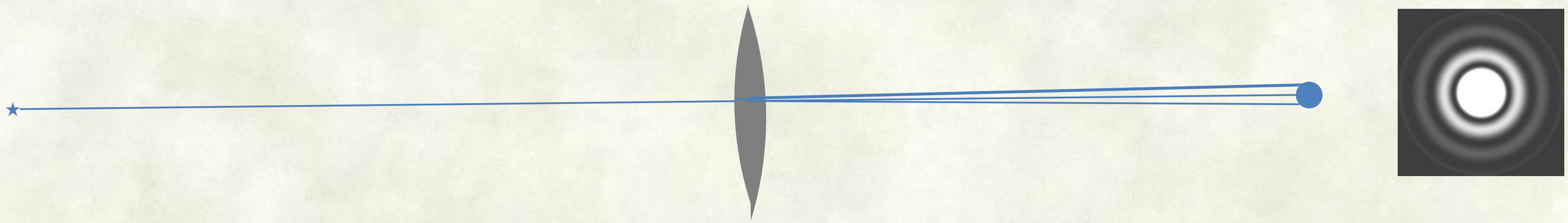
4m Blanco telescope on an Equatorial mount



Subaru 8.2m telescope on an alt-azimuth mount

- Equatorial mounts are too expensive for the modern large telescopes, instead they are mounted in Alt- Azimuth mounts tracked using servo mechanisms controlled by computers

Resolution power of a telescope



- Due to wave nature of light image of a point source (like a star) is not a point but a set of bright rings around a central bright spot (called Airy disk)

- Size of the Airy disk is $\sim 250000\,\frac{\lambda}{D}$ arc seconds

  D: diameter of the objective λ : wave length of light

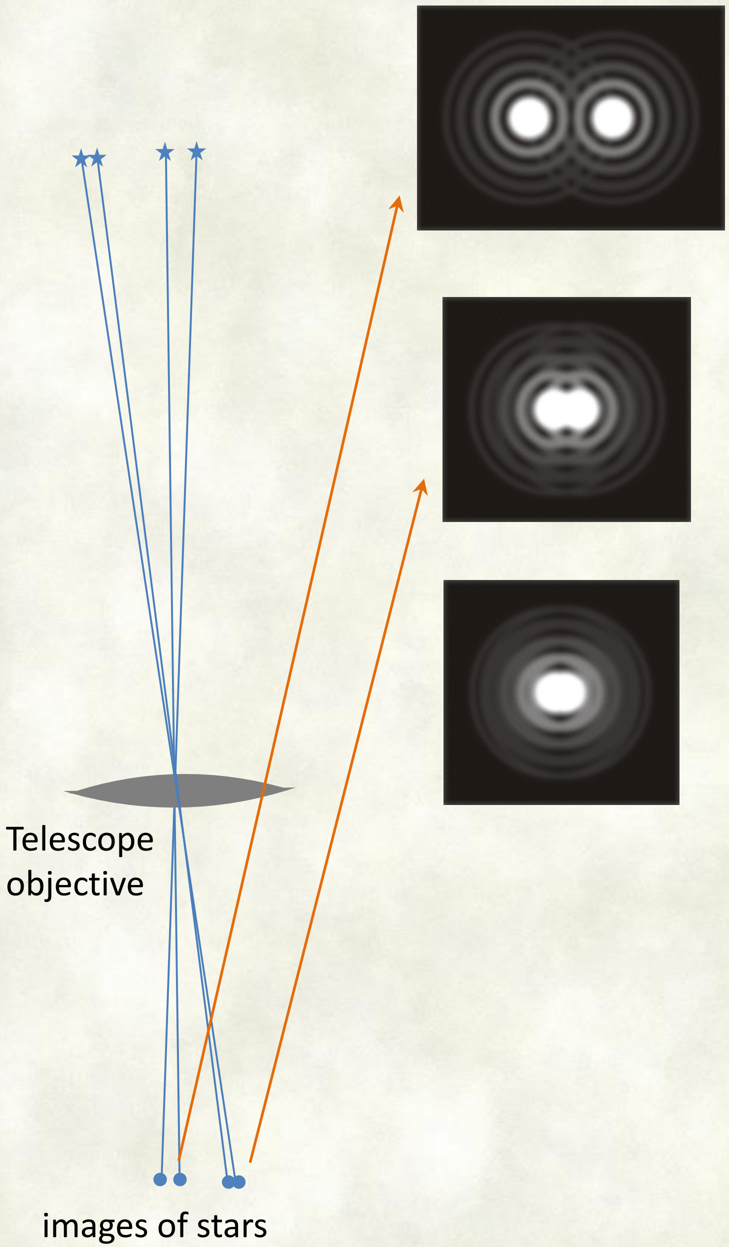
  – Larger the diameter of the telescope smaller the Airy disk

- Even though object we are looking at has small angular size, due to this effect image we see through the telescope has a larger angular diameter.
  – star angular diameter < 0.05”   size of the Airy disk for a 10 cm objective 1.3”

- So regardless of the size of the object, image formed by the telescope has a finite minimum size determined by the diameter of the objective.

- This become problematic when we try to see objects very close, or features very small.

Resolution power of a telescope



Two close stars appear as two Airy disks. Well resolved

When stars ae closer Airy disks starts to overlap and making difficult to distinguish individual stars

When the two stars are even closer,   Airy disks of the two stars are totally merged together and no longer able to tell them apart.

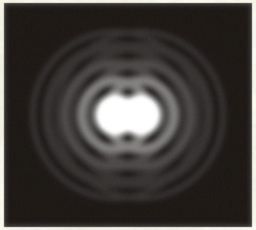
Regardless how much we magnify (using higher power eye piece) they won’t separate

Telescope is the limit of its resolution power.

Resolution power

Nearest objects of a telescope can resolve is is when two images touch each other , ie when they are separated by the size of Airy disk:

Maximum resolution of the telescope: $2.5\times10^{5}\frac{\lambda}{D}$ arc seconds



for wave length 550nm it is $\frac{13.4}{D}$ (D in centimeters)

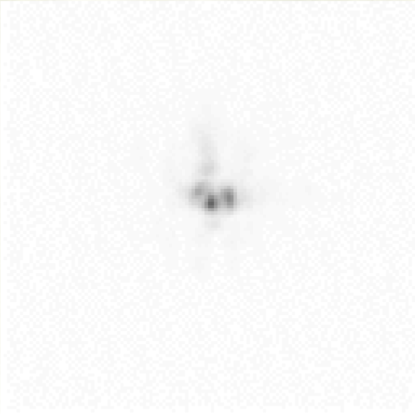
(middle of the visible spectrum)

So a telescope of 13.4cm diameter will have a resolution of 1”

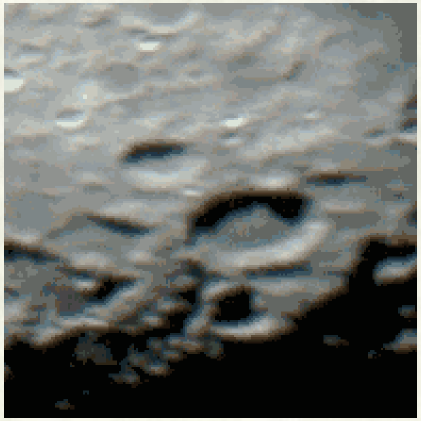
- To resolve any two stars separated by 1” one needs at least a telescope of diameter 13.4cm. Regardless how much the magnification, any smaller telescope won’t able to resolve them.

- This is the theoretical value, assuming perfect optics and seeing conditions.
  - If the telescope optics is not good, we won’t achieve this resolution
  - Even with good optics due to atmospheric turbulences it is hard to achieve resolution below 1”

Viewing and Seeing



star



moon

Views through a telescope under poor seeing conditions

double star Zeta Aquarii being messed up by atmospheric seeing (separation of 2", through an 8" telescope).

from : www.skyandtelescope.com/astronomy-equipment/beating-the-seeing

- Atmospheric conditions are described in terms of "seeing" and "transparency"
- **Transparency:** how much light reach the telescope thorough the atmosphere, translates to the faintest star that can be seen.
  - higher humidity ⇒ more absorption in air ⇒ low transparency
- **Seeing** indicates the resolution that the atmosphere allows due to turbulence. Steady, less turbulence air ⇒ better seeing
- Typical is 2"-3", a good night is 1" at sea level
- Remedy: avoid as much atmosphere and water vapor as possible
  - ⇒ Go to deserts and Mountain tops!

few good observing sites on Earth (~0.1” resolution)

Mauna Kea, Hawaii

La Silla, Atacama desert, Chile

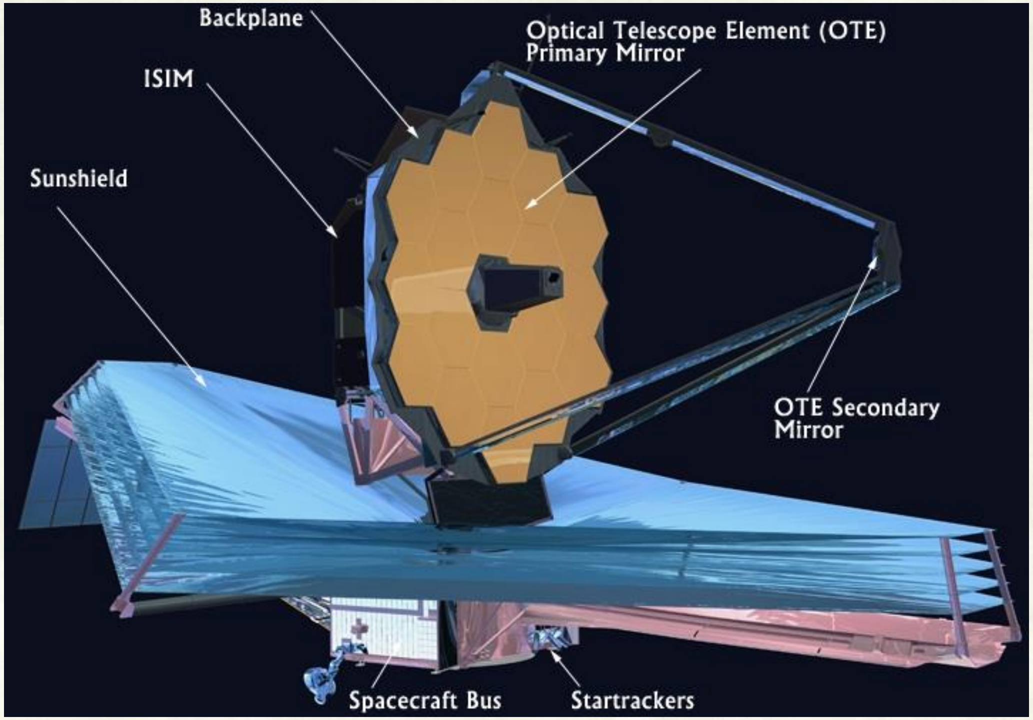
Kitt peak Arizona

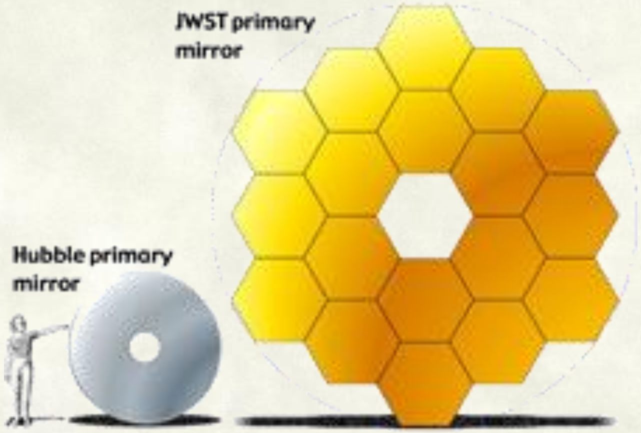
Hubble space telescope

Whirlpool galaxy from a 4m ground based telescope (lefts) and from the Hubble space telescope (right)

- Or avoid the atmosphere altogether. Go to space!
- Hubble space telescope (2.5m primary) is in operation since 1990.
- Its successor James Webb space telescope is under construction

James Webb space telescope

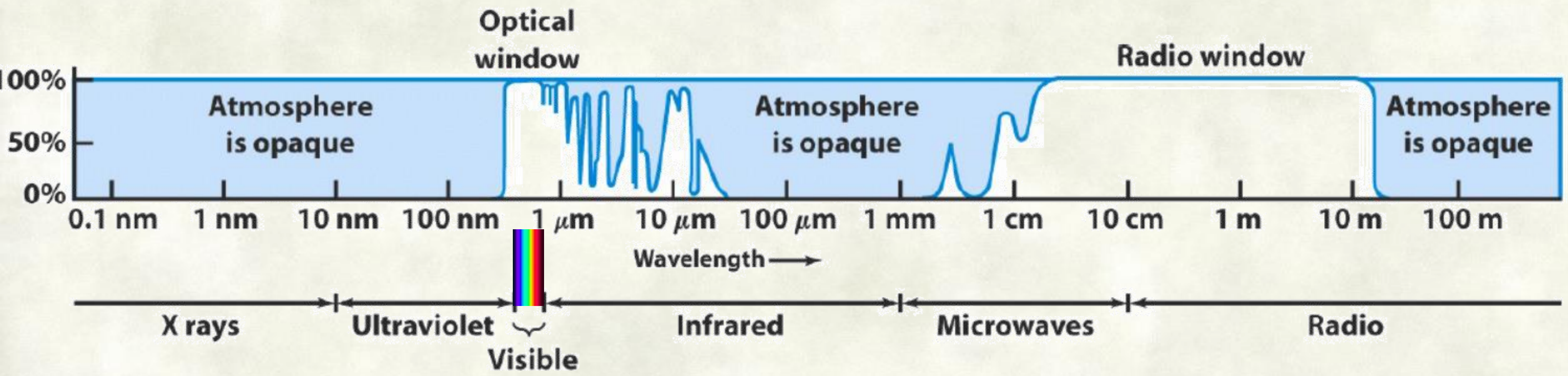




- 6.5 m primary mirror made of 18 segments
- Optimized to work in infrared wave lengths
- with a planned launch in 2018.
- Costs over $8 billion

Exploring with other EM radiations and particles

Radiation from whole electromagnetic spectrum, and other types of radiations are now used to study the universe.



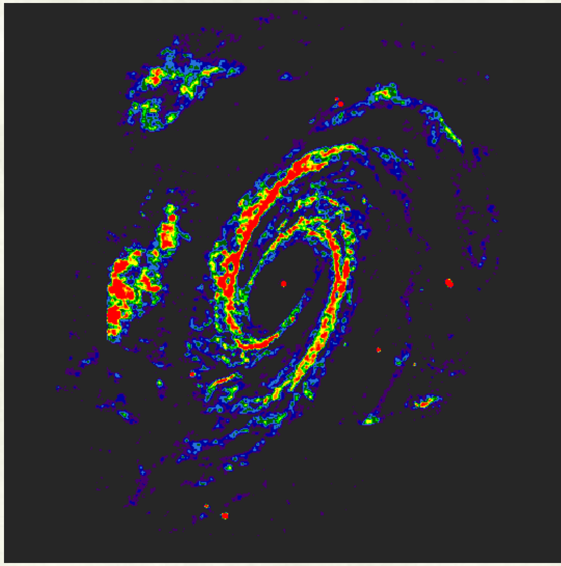
- Atmosphere absorbs much of the radiation that arrives from space
- There are two wavelength regions atmosphere is transparent, called the optical window and the radio window
- To study objects with radiation in other wave lengths, has to go above the atmosphere (high flying balloons, air planes, satellites)

Radio telescopes

- Radio telescopes use large reflecting antennas to collect and focus radio waves
- They are then amplified and analyzed by radio receivers, witch scan the object and produce results in the form of color coded images, contour maps, graphs etc.
- Radio waves have longer wavelengths. Very large dishes are required to obtain a reasonable resolution.

100 m Green Bank Telescope, NRAO, VA

76m radio telescope at Jodrell Bank, UK



Radio image of the galaxy M81 by the VLA, (at 21cm Hydrogen line color represents the brightness – false color)

Very Large Array (VLA), NM consists of 27 radio telescopes each 25m in diameter. Signals from them can be combined to synthesis a telescope 36km in diameter, giving an angular resolution of 0.05 arc seconds.

M81 in visible light

Number of radio telescopes can be combined to work together as a telescope with a larger aperture.

Infrared telescopes

SOFIA (stratospheric Observatory for Infrared Astronomy) infrared observatory.

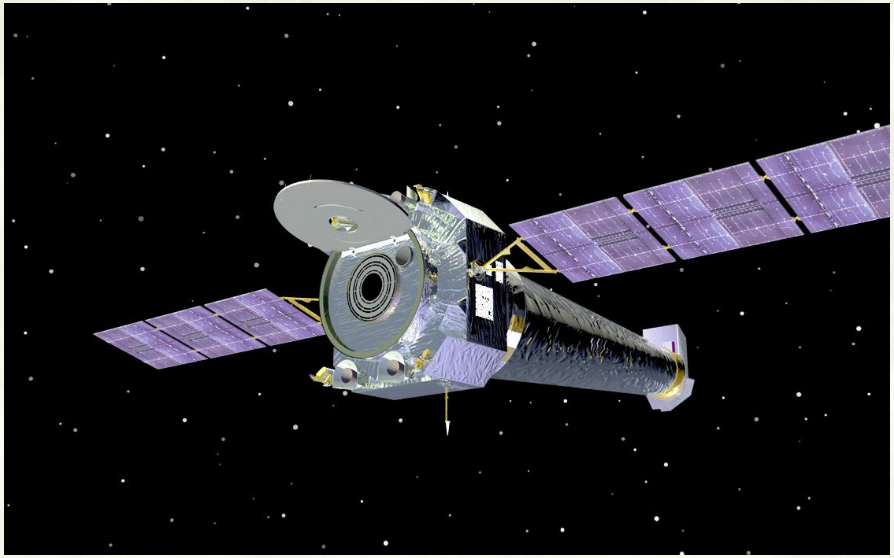
Has the capability to observe in 1–655 micrometer wavelength range using a 2.5 m apature reflecting telescope

Spitzer Space Telescope IR observatory

IR image of the nebula NGC 2264 from the Spitzer,

Region where new stars are in the process of forming, no visible light yet, but visible in IR.

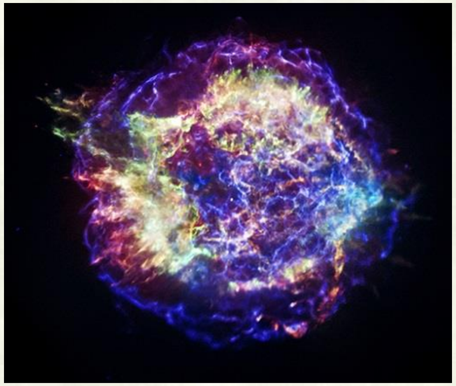
X-ray Telescopes



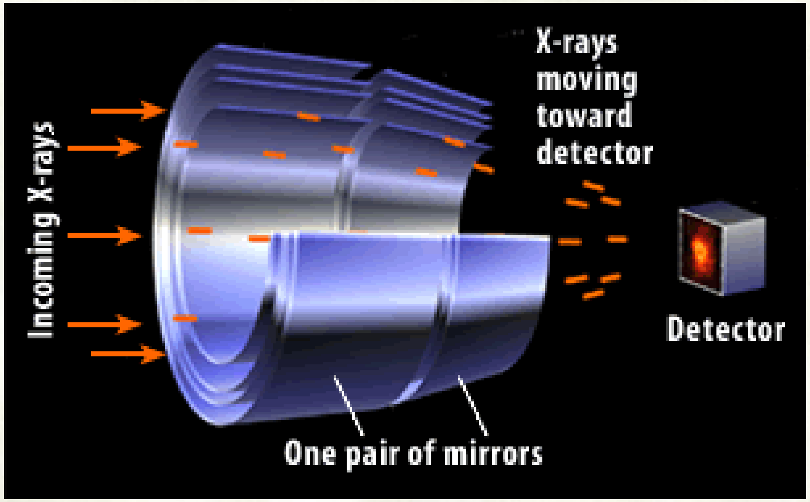
Chandra X-ray Observatory (resolution < 1”)

Atmosphere is opaque to X-rays, so has to be in space to detect X-rays

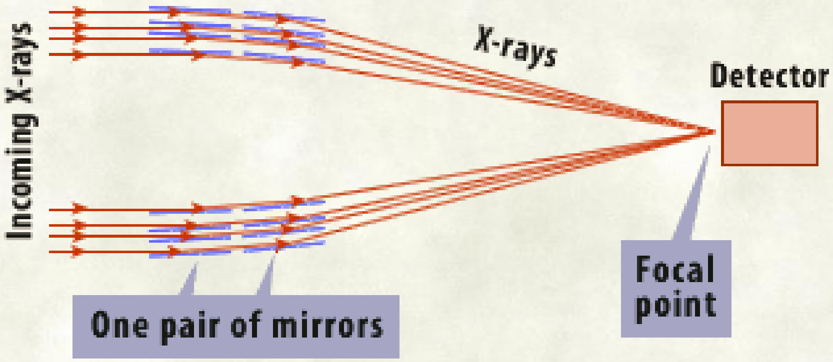
Crab nebula X ray image by Chandra



Cassiopeia A supernova remnant X-ray image



grazing incidence optics to focus X-rays.



Chandra’s mirrors are positioned so they’re almost parallel to the entering X-rays. The mirrors look like open cylinders, or barrels. The X-rays skip across the mirrors much like stones skip across the surface of a pond.