Fiat Lux II

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SSS 10 Nov 2022

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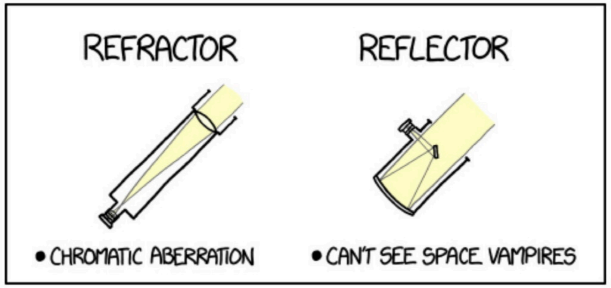

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Episode II

The Vampire Strikes Back

Unwanted Rainbows

In the talk

we saw that when light passes through glass different colours (wavelengths) are refracted through different angles.

This means that telescopes or microscopes made using a glass lens will suffer from **chromatic aberration**, or colour fringing.

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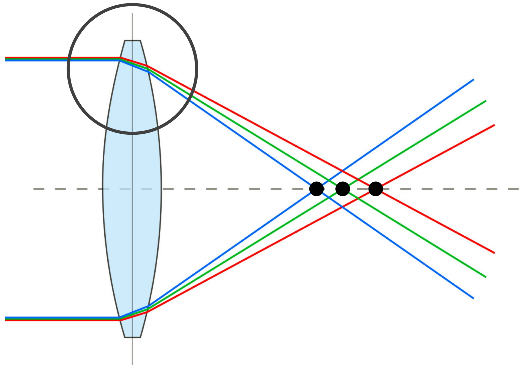
Chromatic Aberration



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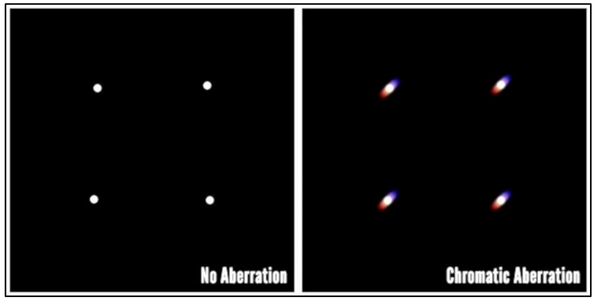
Chromatic Aberration



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Chromatic Aberration

There are two ways to approach chromatic aberration:

Fix the problem (figure out how to deal with it)

Avoid the problem (use mirrors instead)

The first approach was not taken very seriously for about a century as Newton said that CA is an inevitable side effect of focussing light through glass lenses – you can't have **refraction** (bending) without **dispersion** (separation of the colours).

The second approach was explored while astronomers using refracting telescopes just put up with unwanted colour fringing. This continued until the middle of the 18^{th} century.

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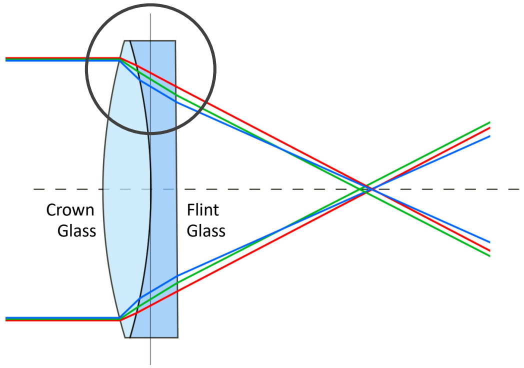
Fiat Lux II

Achromatic Lens



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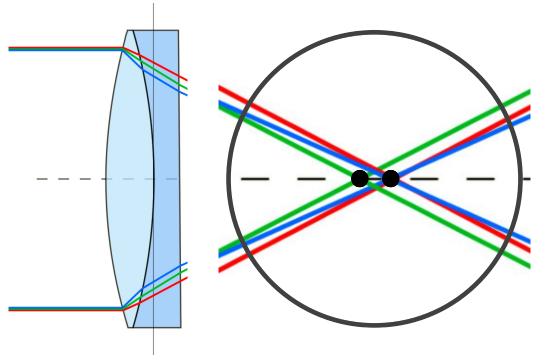
Achromatic Lens



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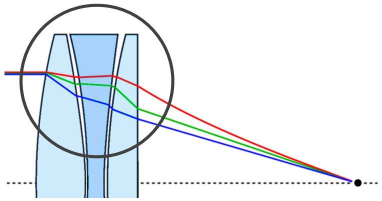
Apochromatic Lens



Apochromatic lenses have three elements whose surfaces have been carefully designed so that red, green and blue light waves are all brought to a focus at the same point, thus eliminating colour fringing.

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Apochromatic Lens

Fluorite is the mineral form of calcium fluoride and is a low-dispersion glass. This means that its refractive index changes very little with wavelength and so fluorite lenses have very low chromatic aberration.

[Aside – Camera manufacturers Canon use fluorite lenses whereas Nikon have adopted extra-low-dispersion (or **ED**) glass. Fluorite is a relatively fragile glass and so NASA do not use Canon lenses in space as they would suffer from the vibration that occurs during take-off.]

In addition to using lenses with intrinsically low levels of chromatic aberration, manufacturers compensate for aberrations by using lenses that do not have spherical surfaces – **aspheric** lenses.

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Apochromatic Lens

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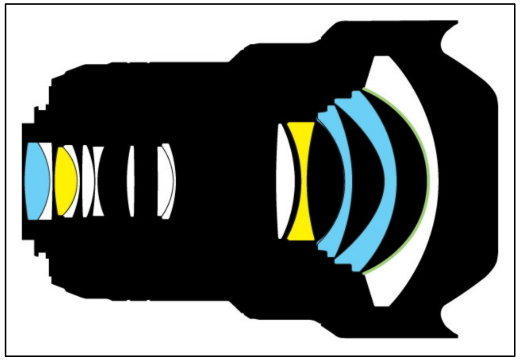
Camera Lens



Nikon use ED (yellow) and aspheric (blue) lenses

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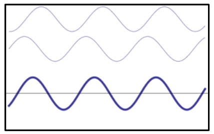
Wave Interference

In the talk

we saw that when light waves meet they can interfere with each other and either reinforce each other or cancel each other out.



Animation courtesy of Dr Dan Russell, Pennsylvania State University

This means that when a glass lens or metal mirror reflect light waves to a focus, the light waves must arrive **in phase** if the image is to be as clear and bright as possible.

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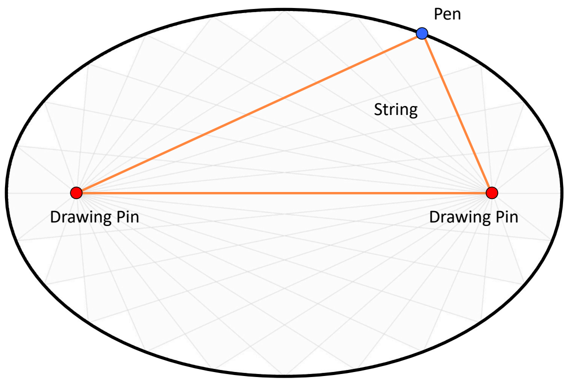
Making an Ellipse



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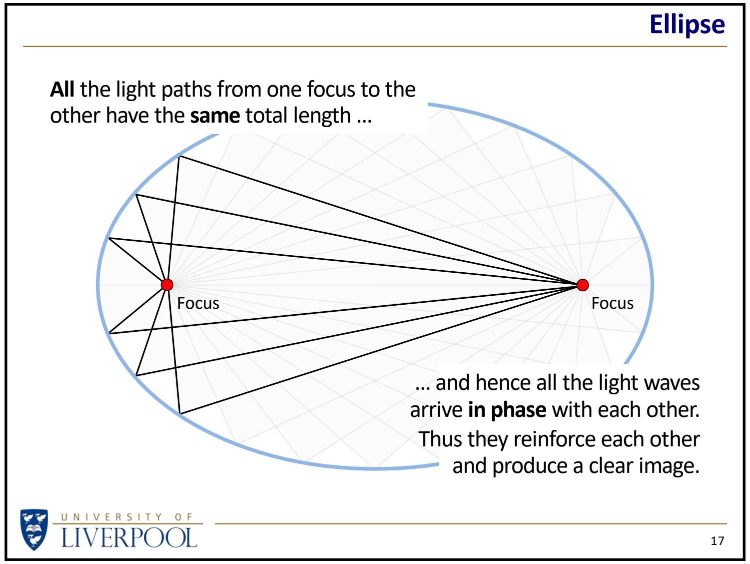
Ellipse
All the light paths from one focus to the other have the **same** total length …
Focus
Focus
… and hence all the light waves arrive **in phase** with each other.
Thus they reinforce each other and produce a clear image.
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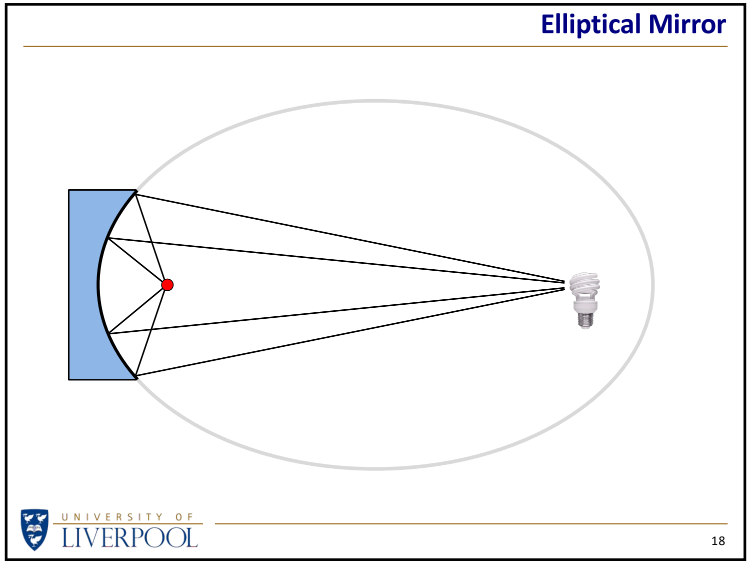
Elliptical Mirror
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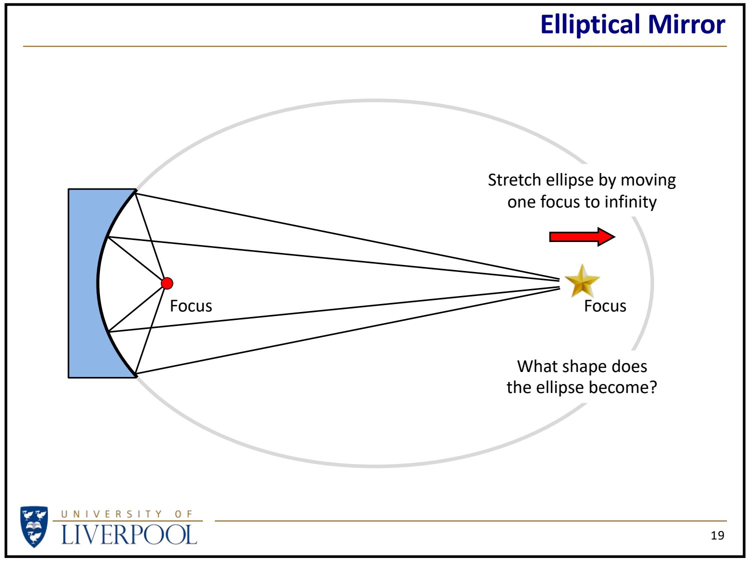
Elliptical Mirror
Stretch ellipse by moving one focus to infinity
Focus
Focus
What shape does the ellipse become?
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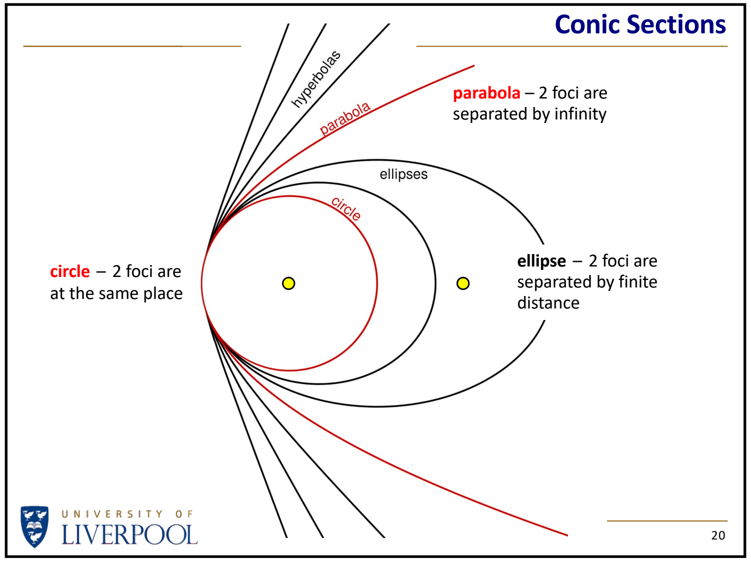
Conic Sections
hyperbolas
parabola
parabola – 2 foci are separated by infinity
ellipses
circle
circle – 2 foci are at the same place
ellipse – 2 foci are separated by finite distance
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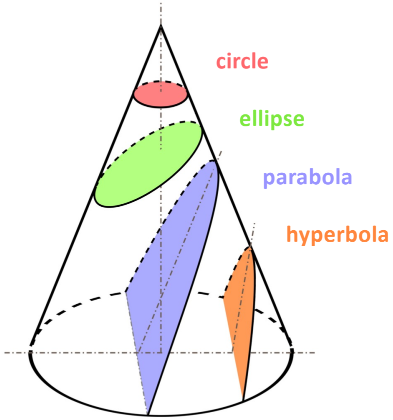
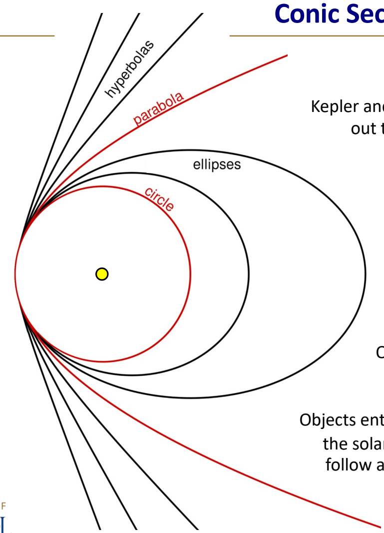
Conic Sections



Conic Sections – Aside

These curves that define the shapes of mirrors that are suitable for focusing light are also the curves that describe orbits around the Sun.

This is because the maths is basically the same for both.

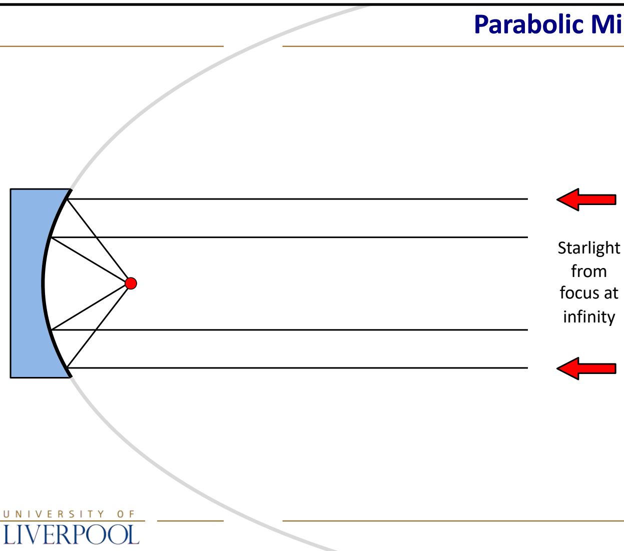


Kepler and Newton figured out the maths behind planetary orbits.

Planets follow closed elliptical orbits, but a comet falling into the solar system from way out in the Oort cloud follows a parabolic path.

Objects entering and leaving the solar system at speed follow a hyperbolic orbit.

Parabolic Mirror

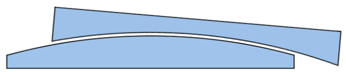


Why Spherical Mirrors?

If a parabola is the 'correct' shape to use for a telescope mirror, then why are some telescope mirrors spherical?

The answer is simple – they are easier and cheaper to make!

For amateur telescope makers grinding a spherical mirror is relatively straightforward.



A concave sphere and a convex sphere, each with the same radius, are the **only** shapes that will stay in contact with each other when moved. Making any other shape is much more tricky.

500m Aperture Spherical Telescope

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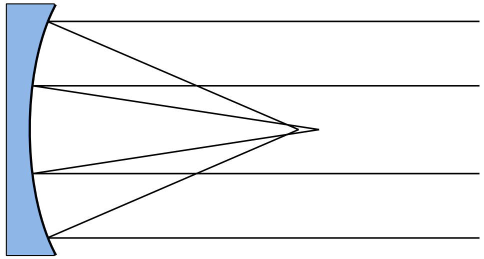
Spherical Aberration



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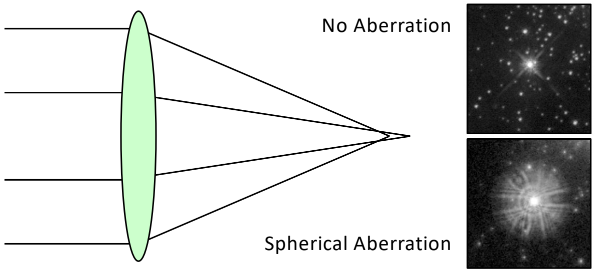
Spherical Aberration



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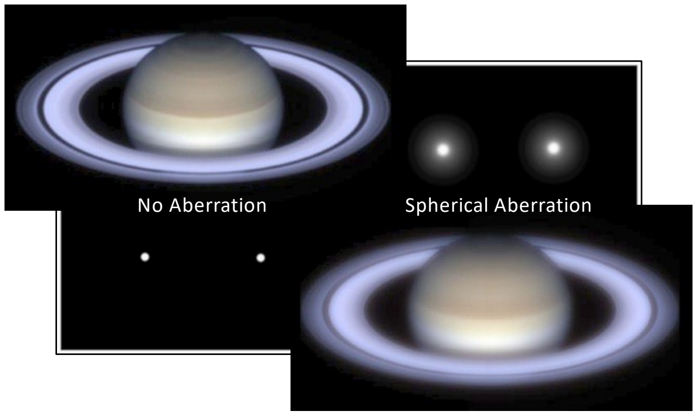
Spherical Aberration



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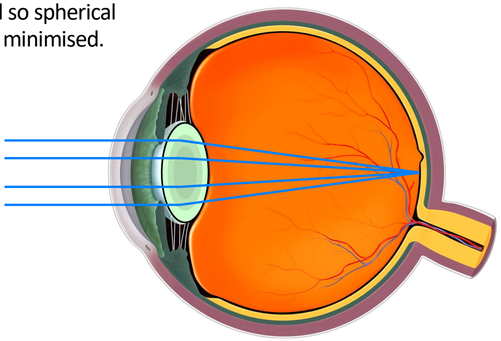
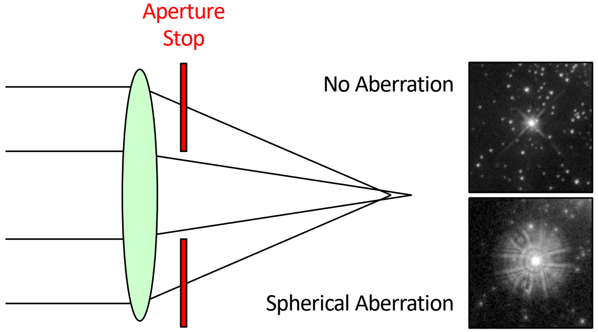
Spherical Aberration

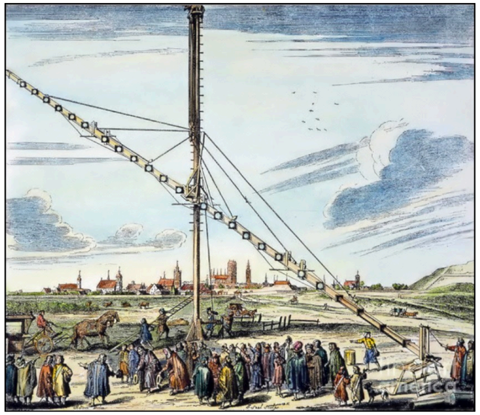
The human eye has a lens whose density varies from the centre to the edge and so spherical aberration is minimised.



Spherical Aberration



Hevelius' Telescopes



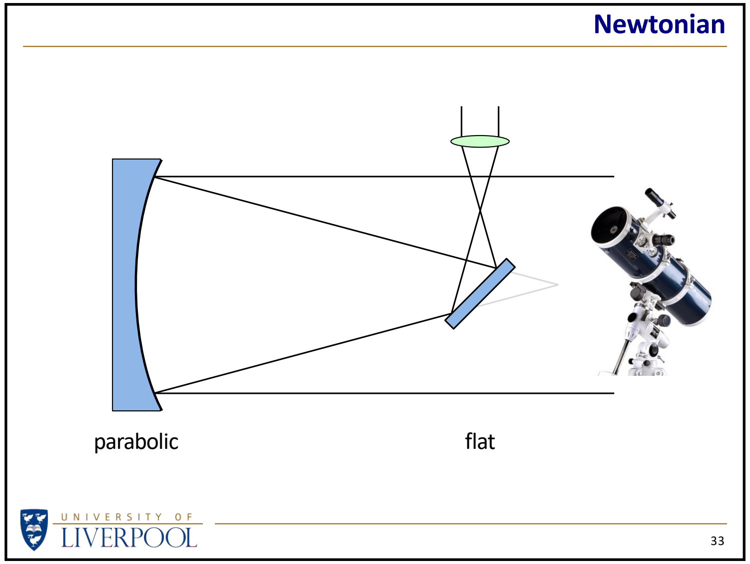
Hevelius said it was "*Easy to use*"

Halley said it was "*Useless*"

Reflecting Telescopes

So we have decided to use mirrors to make a telescope with as few aberrations as possible.

What combinations of mirrors, and of what shape, allow us to construct a reflecting telescope?


Newtonian
parabolic
flat
UNIVERSITY OF LIVERPOOL
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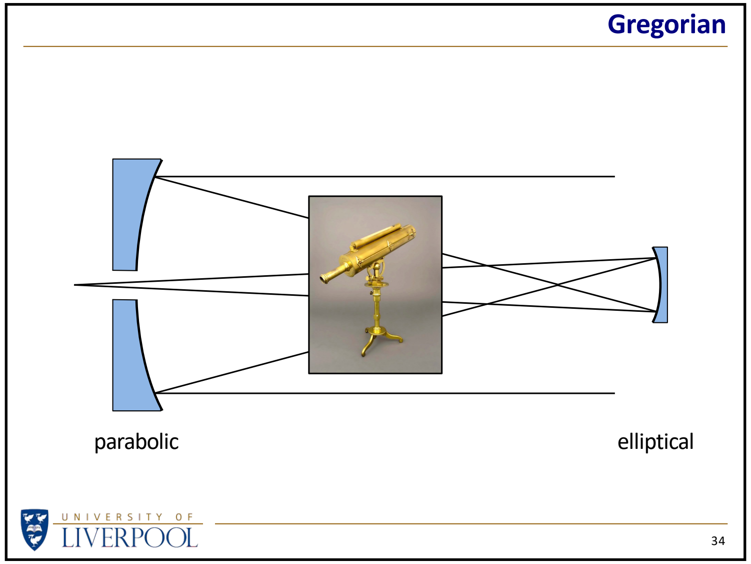
Gregorian
parabolic
elliptical
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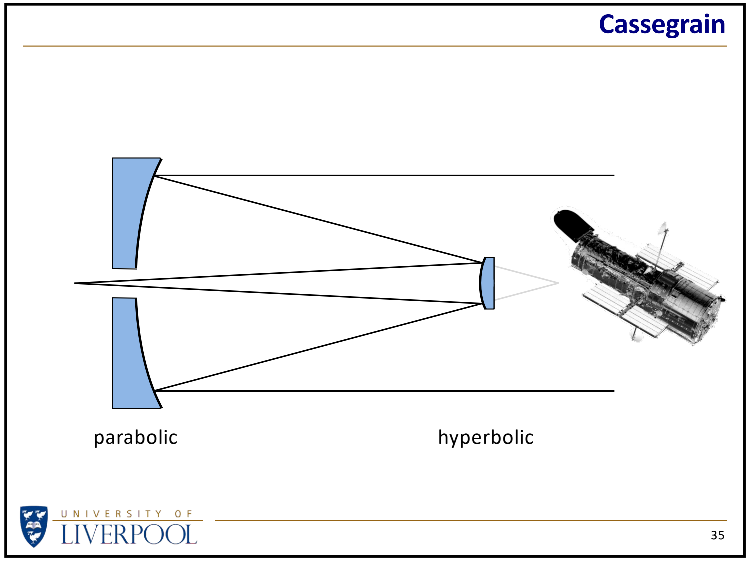
Cassegrain
parabolic
hyperbolic
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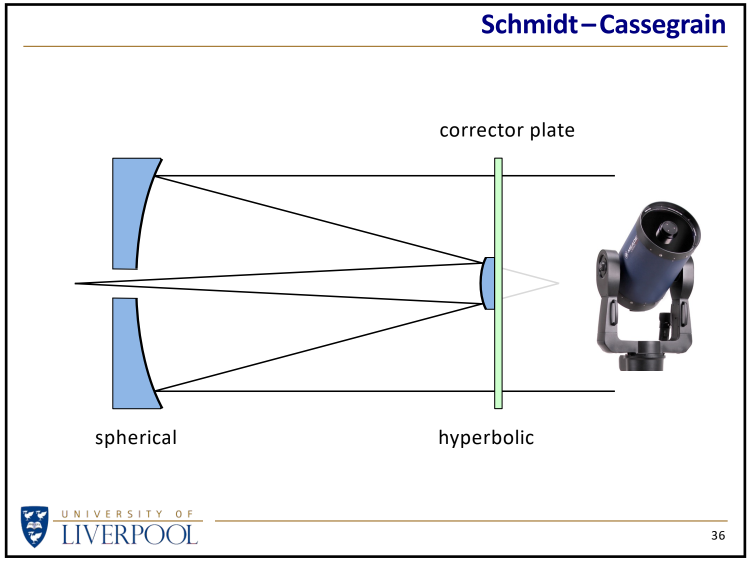
Schmidt–Cassegrain
corrector plate
spherical
hyperbolic
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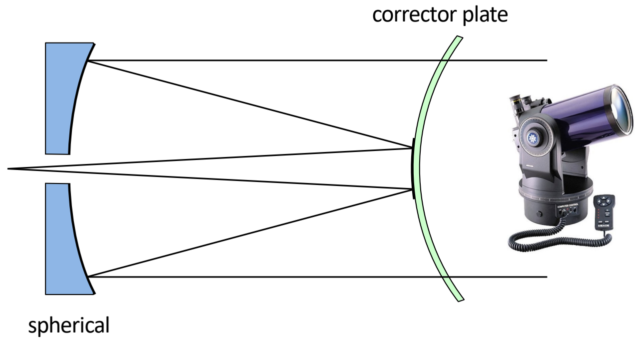
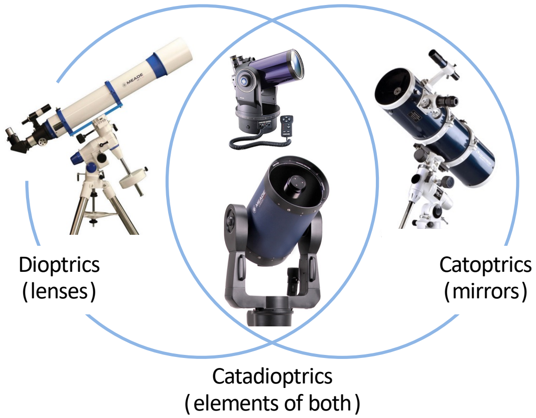
Maksutov



Telescope Types

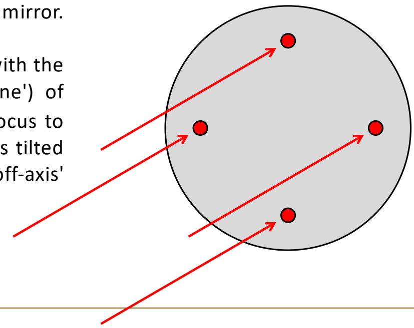


Parabolic Problems

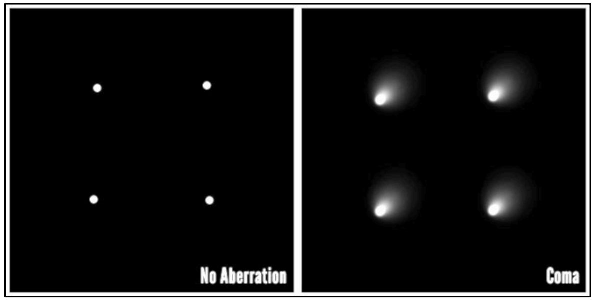
Although a parabolic mirror will focus light entering the telescope along the optical axis, any light hitting the mirror at an angle will not come to a perfect focus. This type of aberration is called **coma**.

This can be demonstrated by firing four parallel laser beams at a parabolic mirror.

If the beams are aligned with the optical axis (the 'centreline') of the mirror then they all focus to a point, but if the mirror is tilted so that the beams are 'off-axis' then they do not.



Coma



Parabolic Problems

Coma can be corrected by adding a 'coma corrector' lens to the telescope optics, but it would be better if the mirror did not have this aberration in the first place.

Changing the **parabolic** mirror to a **hyperbolic** mirror, and choosing its shape very carefully, allows this aberration to be eliminated.

This is the Ritchey–Chrétien design that was introduced in the early 20th century.

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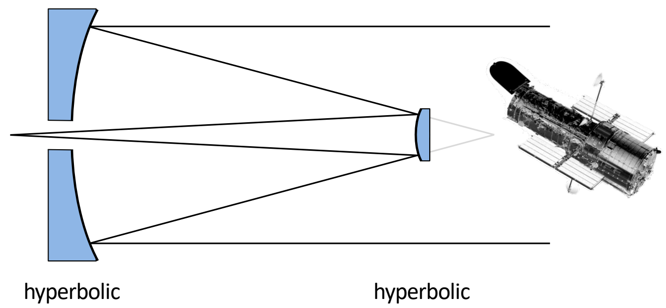
Ritchey–Chrétien



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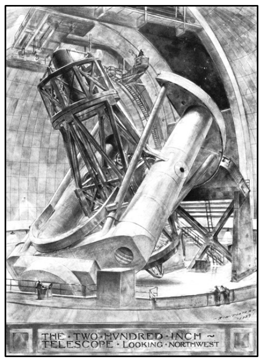
Parabolic Problems

The last big research telescope that used a parabolic mirror was the Hale 200" telescope on Mount Palomar.

When it was built the Ritchey–Chrétien design was already well established but Hale and Ritchey never saw eye-to-eye and as a result Hale adopted the more traditional parabolic mirror design.

This limitation did not prevent the Hale telescope making significant advances and astronomical discoveries during the many decades that it held the title of the world's largest telescope.



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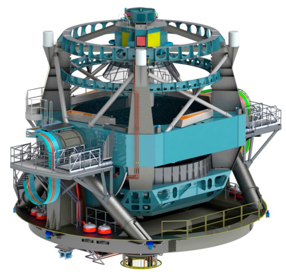
State of the Art

Many research telescopes use the Ritchey–Chrétien design, but the very latest telescopes have adopted a customised three–mirror approach.

A third mirror allows the designers to correct for aberrations present in the other two mirrors, in much the same way that adding lens elements in an apochromatic lens can remove the chromatic aberration created by other elements.



The telescope shown here is the Large Synoptic Survey Telescope (LSST) due for completion in 2023. More about this in Fiat Lux III.

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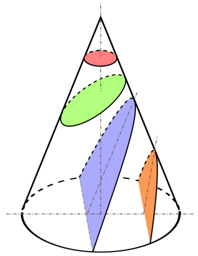
State of the Art

Not all telescope use mirrors that have shapes that are conic sections.

Until recently the mathematics that determines the optimum shape for telescope mirrors has produced equations that can be solved by scientists or engineers or mathematicians (i.e., by *people*). The results are the conic sections that we have seen.



However, for the Cerenkov Telescope Array (CTA) being constructed in the high Andes the mirrors have been designed by solving the relevant equations numerically (i.e., by *computers*). There is no easy way to describe or visualise the shape of the mirrors – we just have to trust the computers to get it right.

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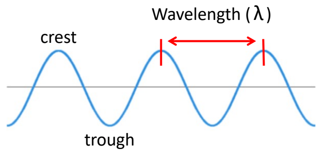
Wavelength of Light

In the talk

we saw that the wavelength of visible light is in the range 400–700 nm (blue–red).

For best performance, a mirror surface should be accurate to a fraction of the wavelength, or about 100 nm.



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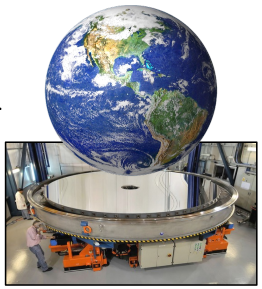
Wavelength of Light

Computer-controlled fabrication of telescope optics is so precise that large mirrors many metres in diameter can be figured and polished to the desired shape (usually hyperbolic or elliptical) with microscopic surface deviations of no more than 20 nm.

To visualise that degree of smoothness, imagine the mirror scaled up by a factor of a million until it is the size of the Earth …



… then the deviations from the desired smooth shape would be no more than about 2 cm in height!

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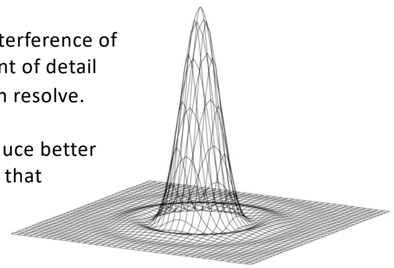
Diffraction

In the talk

we saw that diffraction (the interference of lots of waves) limits the amount of detail that any optical instrument can resolve.

Larger lenses and mirrors produce better images with diffraction effects that are less noticeable.



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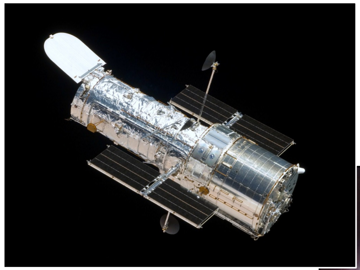
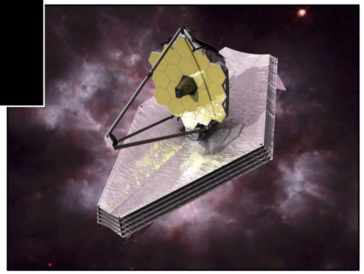
HST and JWST



Hubble Space Telescope

James Webb Space Telescope



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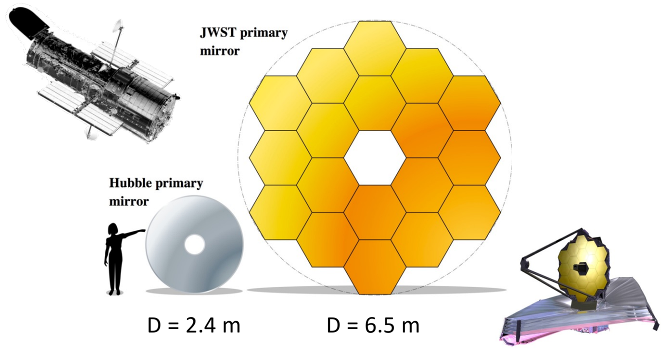
HST and JWST Mirrors



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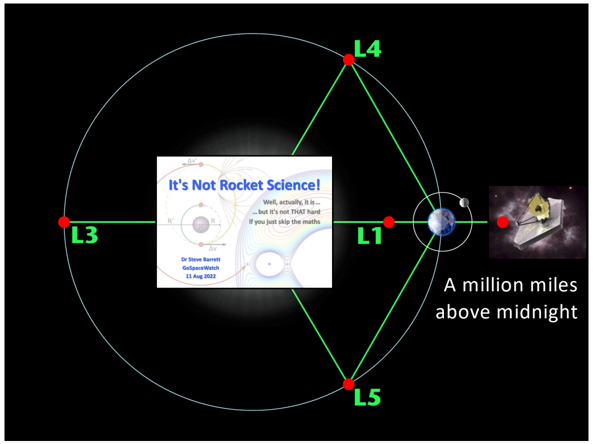
Lagrange Point 2



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JWST

By working in the **infrared** region of the spectrum, the JWST is able to see more than if it was sensitive to only visible light.

This means it will be able to study star and exoplanet formation and also the evolution of the first galaxies.

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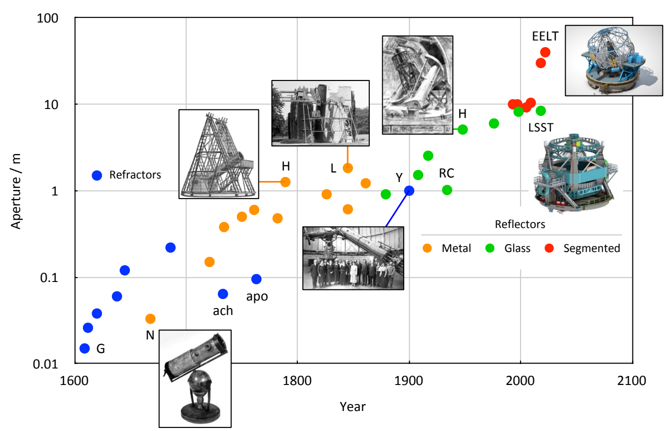
Fiat Lux II

Telescopes 1600–2020



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Telescopes 1600–2020

On the previous slide the following abbreviations are used:

G	Galileo's refracting telescope	< 1" lens
N	Newton's reflecting telescope	> 1" mirror
ach	First achromatic lens	2" lens
apo	First apochromatic lens	4" lens
H	Herchel's 40 foot telescope	47" mirror
L	Leviathan of Parsonstown	72" mirror
Y	Yerkes 40" refractor	40" lens
RC	Ritchey-Chrétien telescope	24" mirror
H	Hale 200" reflector	5 m mirror
LSST	Large Synoptic Survey Telescope	8 m mirror
EELT	European Extremely Large Telescope	40 m mirror

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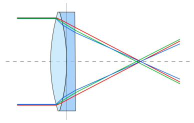
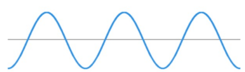
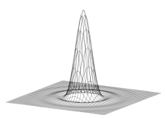
Summary

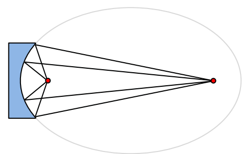
Chromatic aberration and achromatic lenses





Interference of light and elliptical, parabolic and hyperbolic mirrors





Diffraction of light determines the resolution of a telescope

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