xkcd.com

Another website recommendation...

xkcd.com

Optics and telescopes

We have seen that the electromagnetic radiation from astronomical objects gives us a lot of information about them.

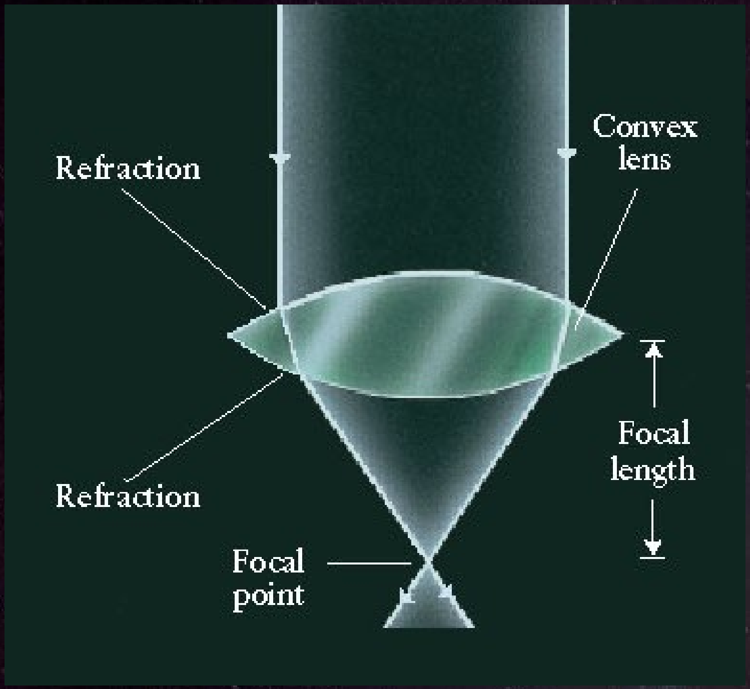
In the next few lectures, we'll be talking about how we actually detect the emission from objects at colossal distances from Earth.

The type of detector you need depends on the type of radiation you want to look at. We'll start by looking at optical radiation, and the telescope.

Telescopes - refractors

We learned earlier that EM radiation in a vacuum travels at *c*, the speed of light: 300,000 km/s. But it travels more slowly in a transparent substance like glass. This is called *refraction*.

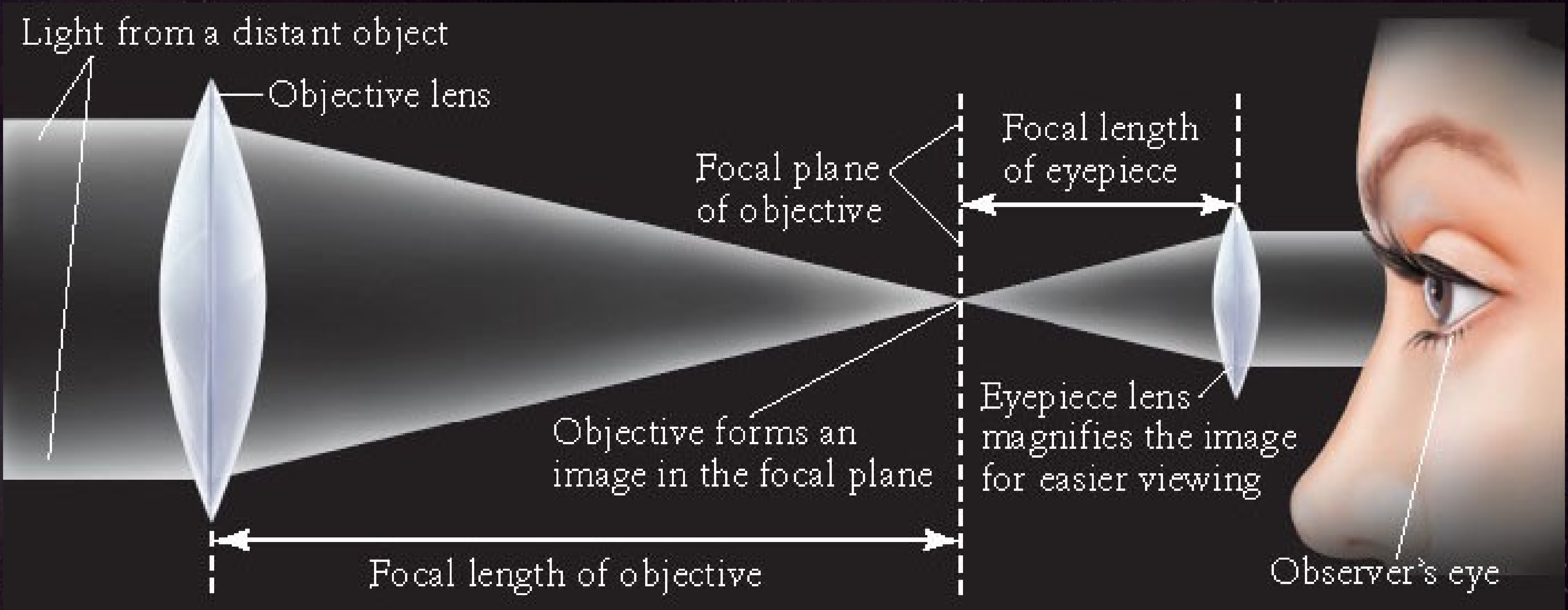
With the right shaped piece of glass, you can *focus* the light from a distant object, making it appear larger and brighter.



Telescopes - refractors

If you put a piece of film, or a CCD, at the *focal plane*, you could record an image.

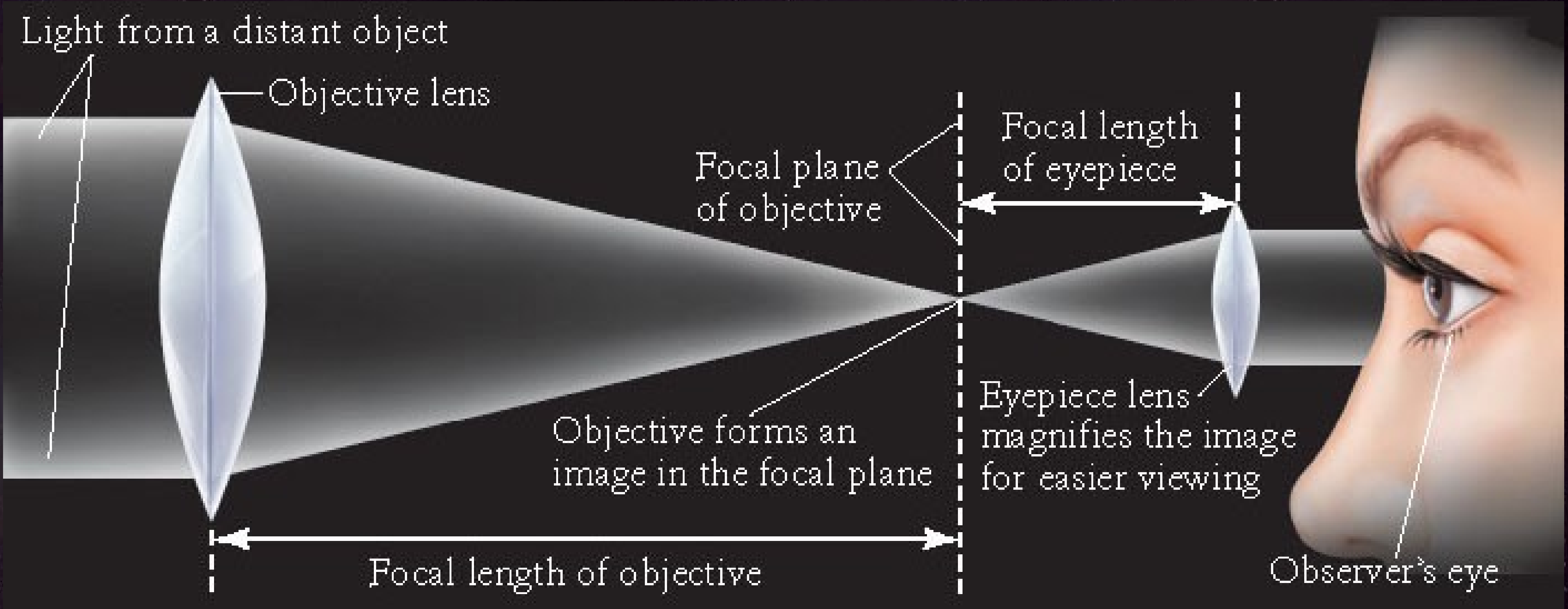
Alternatively, you could put a second lens behind the first, to magnify the image and make it easy to view with the human eye. That, basically, is the principle of a *refracting telescope*.



Telescopes - refractors

The first lens in the system is called the *objective* or *primary* lens. The magnifying lens is called the *secondary* or *eyepiece*.

The amount of magnification is given by the ratio of the two focal lengths. So a secondary lens with half the focal length of the primary would give an image twice as large as seen with naked eye.



Telescopes - refractors

The first telescopes, used in the early 1600s, were refractors. Galileo used a small refractor to stunning effect, discovering craters on the Moon, satellites around Jupiter, sunspots, and the phases of Venus and Mercury. Astronomy was revolutionised.

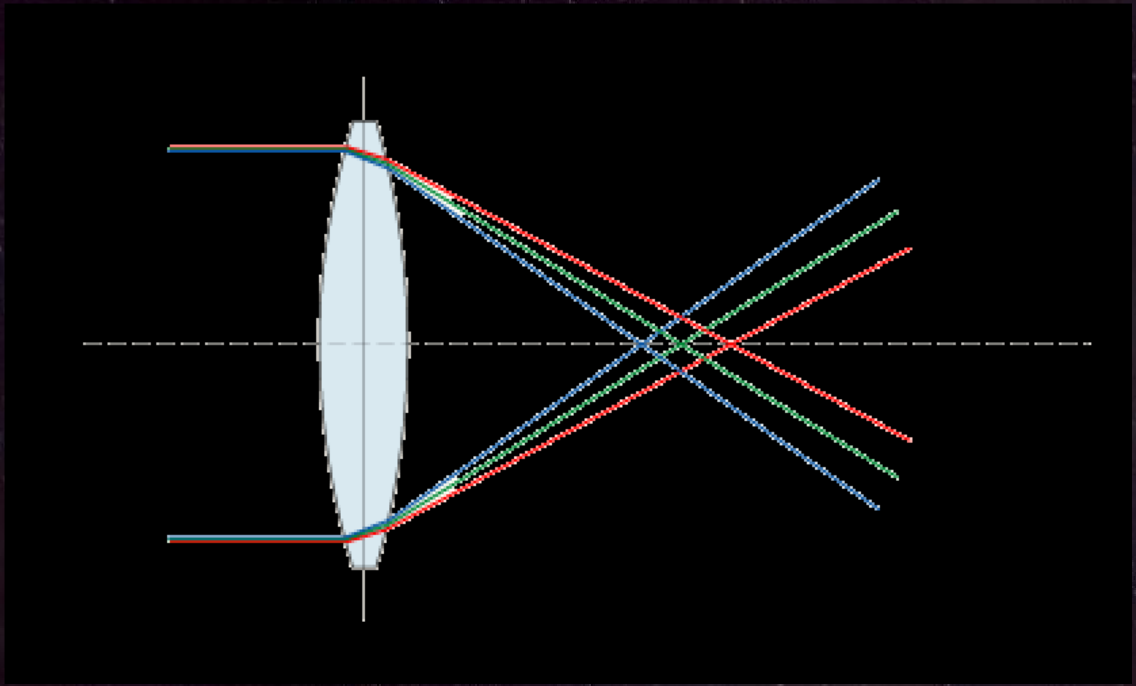
Galileo's telescope had a lens 3cm across. The human eye has a lens about 5mm across.

The *light-gathering power* of a telescope is proportional to the *area* of its lens, and therefore the *square* of the diameter. Galileo's telescope made things appear $(3/0.5)^2 = 36$ times brighter than the appear to the naked eye.

Refractors - disadvantages

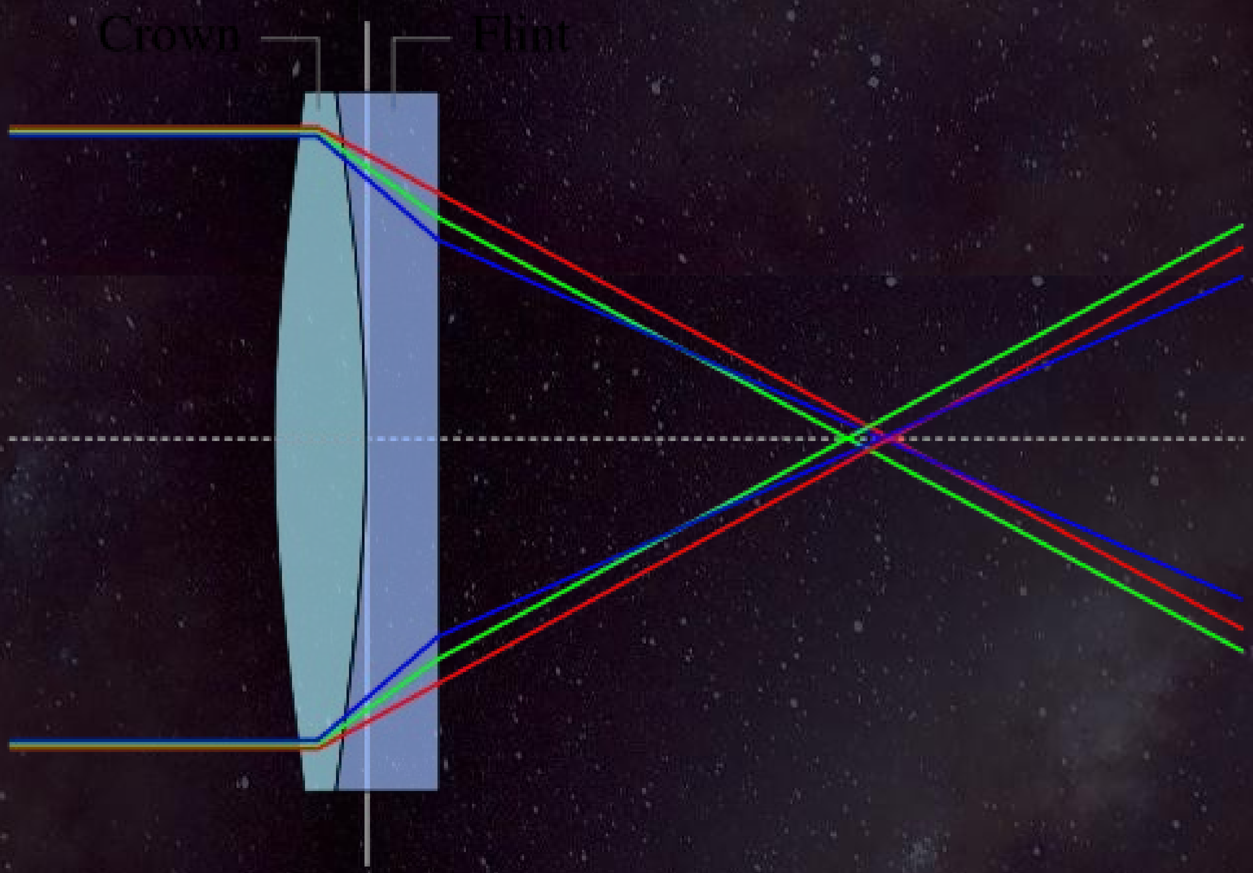
Refractors have a number of issues that ultimately limit their capabilties.

First is the problem of *chromatic aberration*: when light is refracted, the amount of refraction depends on the wavelength of the light: blue light is refracted more than red light, so the focal point is different for different colours.



Chromatic aberration

Chromatic aberration means that only one wavelength is in focus at a given position. With the addition of a second piece of glass with a slightly different refractive index, you can construct a lens which brings two wavelengths into focus at a given position:



Chromatic aberration

A lens which brings two wavelengths into focus at the same point is called an *achromatic lens*. You can improve things still further with a third piece of glass, bringing three wavelengths into focus at the same time. Such a lens is called *apochromatic*.

Better correction of chromatic aberration = more expensive.

Optical quality

Another problem with refracting telescopes is the quality of the glass. You want to lose as little light as possible when looking at astronomical objects, and this means you need very high quality glass, as free as possible from imperfections.

Higher quality glass = more expensive.

Weight distribution

Yet another problem with refractors is that the bigger the lens, the heavier it is. This means you need a very sturdy tube to hold it in place.

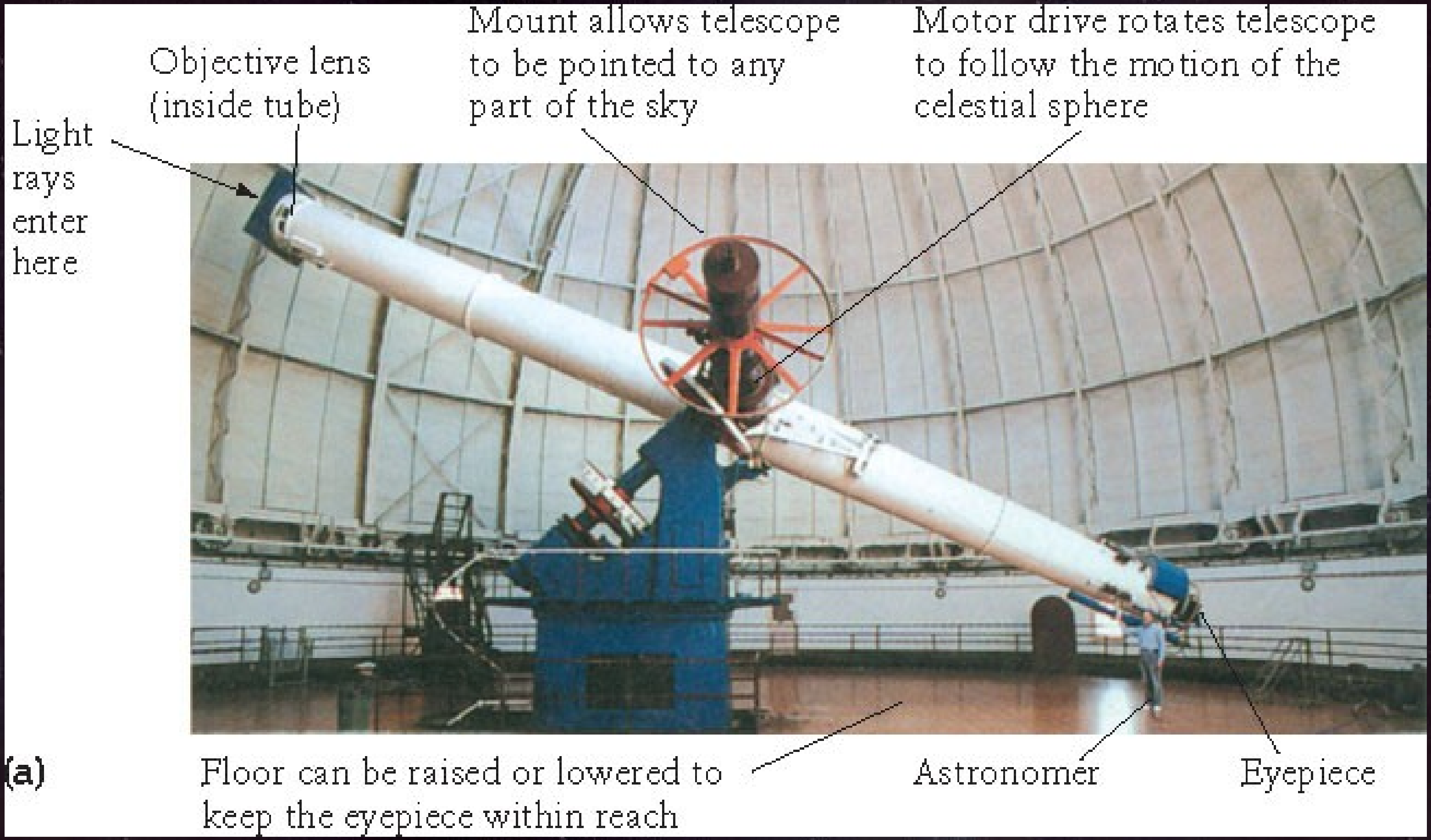
A large lens will also be distorted by its own weight as it is moved around, compromising the optical quality.

For this reason, the largest useful refractor ever built had a lens with a diameter of 40 inches / 1 metre. For comparison, the Radcliffe telescope at ULO has a diameter of 24 inches / 60 cm.

I think the Radcliffe might be the second largest refractor in the UK. Not totally sure though...

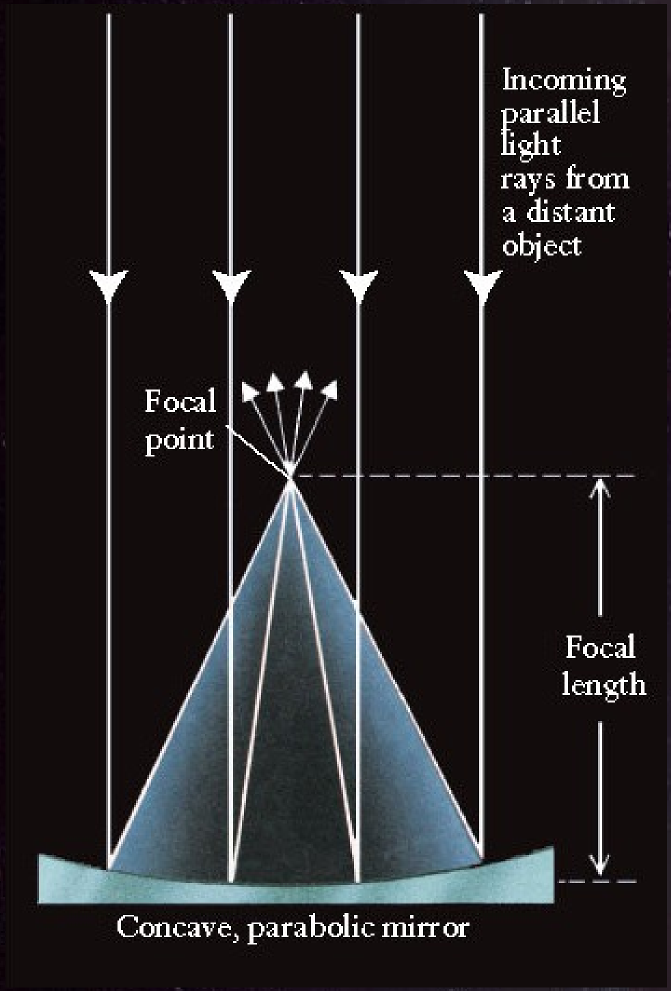
Weight distribution

The mirror of the Yerkes telescope weighs about two tonnes. The ~20m tube needs to be seriously strong to avoid terrible flexure problems.



Reflecting telescopes

Another way to bring light to a focus is with a curved mirror. This is the principle behind *reflecting telescopes*.

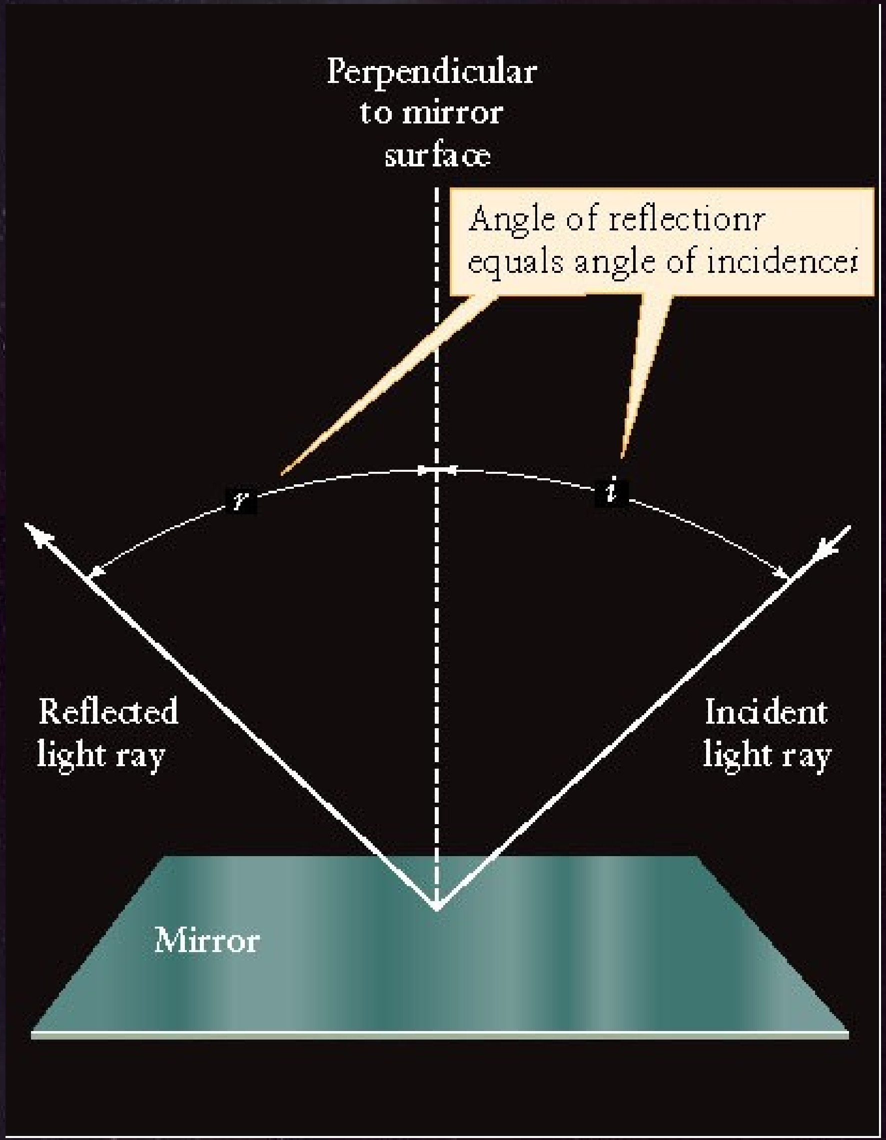


Reflectors - advantages

Reflecting instead of refracting light has many advantages:

1. Reflection is not wavelength-dependent. All light, no matter what its wavelength, is reflected at an angle which is the same as the *angle of incidence*.

This means there is no chromatic aberration.



Reflectors - advantages

2. While a refracting lens needs to be of extremely high quality throughout its volume, a reflecting mirror only needs to be of high quality on its surface.

What you put behind the mirror to support it makes no difference, so it's much cheaper to construct a large, very high quality mirror, than it is to construct a large very high quality lens.

Reflectors - advantages

3. Unlike a lens which has to sit at the end of a tube, far from the pivot, a mirror can be positioned close to the pivot.

Also, while internal flexure of a lens gets more and more difficult to avoid for larger lenses, mirrors do not suffer so much from this.

For these reasons, all the telescopes used today for professional astronomy, and most amateur telescopes as well, are reflectors.

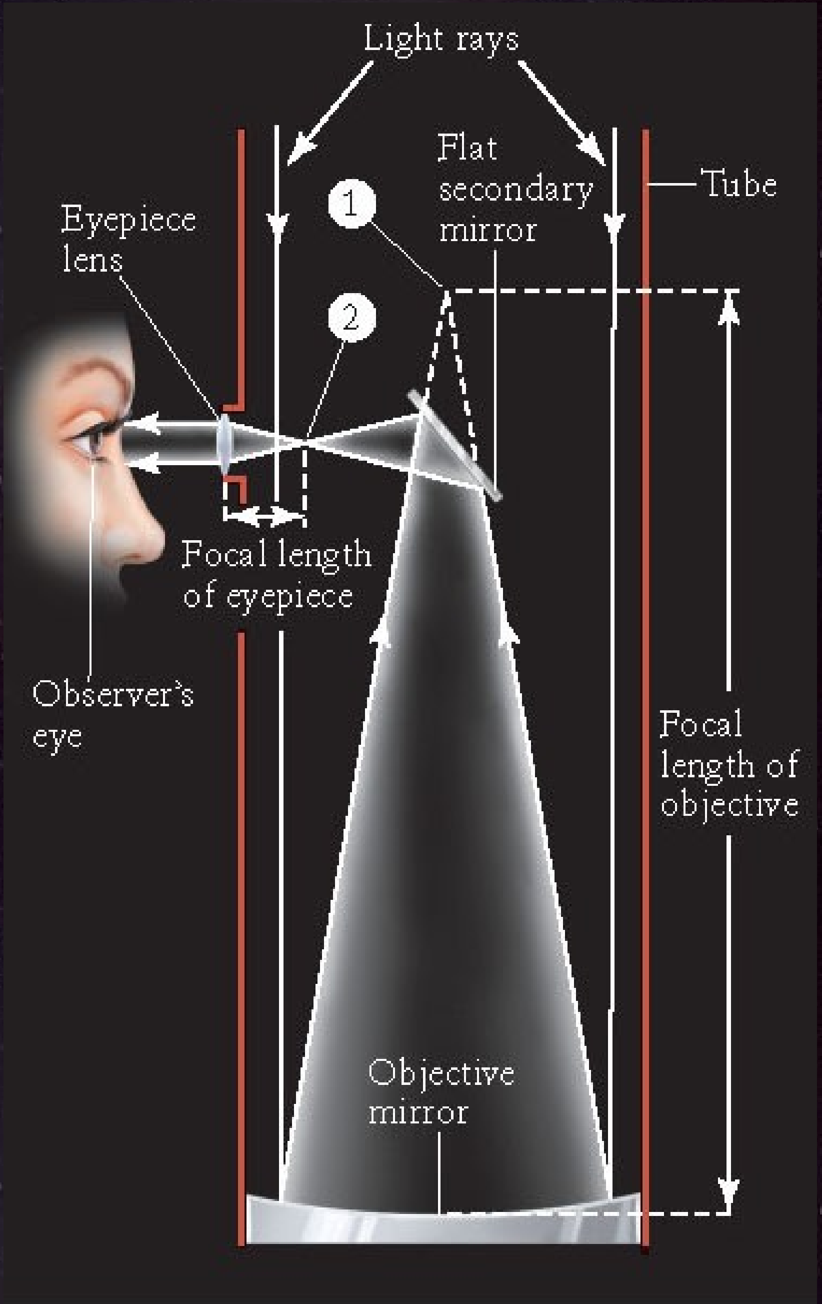
The largest optical telescopes in the world are the twin Keck telescopes on Hawaii, with 10m mirrors. At about 10 times the diameter of the largest refractor, they have 100 times the light-gathering capability.

Reflectors - disadvantages

But it's not all good. From the diagram earlier, you can see that the focus point of a mirror is in front of it, not behind it as with a lens.

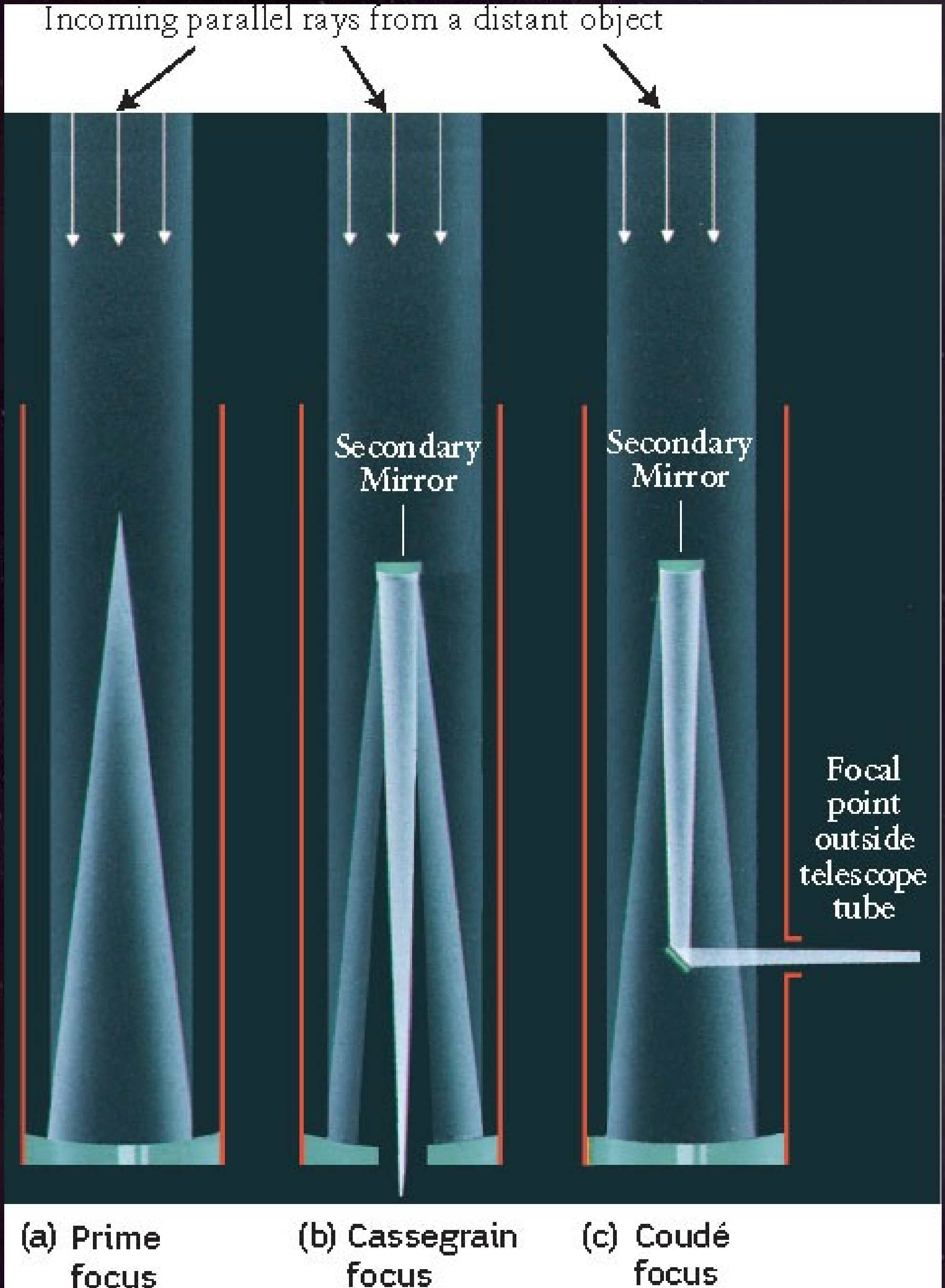
To get your image into a useful position, you have to place either a detector or another mirror at the prime focus. This means you will lose some of the incoming light.

There are many different ways of bringing the light to a focus in a useful position.



(a)

Reflectors - disadvantages



Reflectors - disadvantages

Perhaps counterintuitively, the secondary mirror does not cause a hole in the image. It just reduces the effective light collecting area.

It will not even noticeably affect the image quality unless its area is more than ~25% of that of the primary.

So, if you had a 2 metre primary mirror, you could have a secondary 1 metre across without degrading the image quality. The effective diameter of the telescope would be 1.73m

(Area of primary – area of secondary $= 4\pi \times 2^2 - 4\pi \times 1^2$

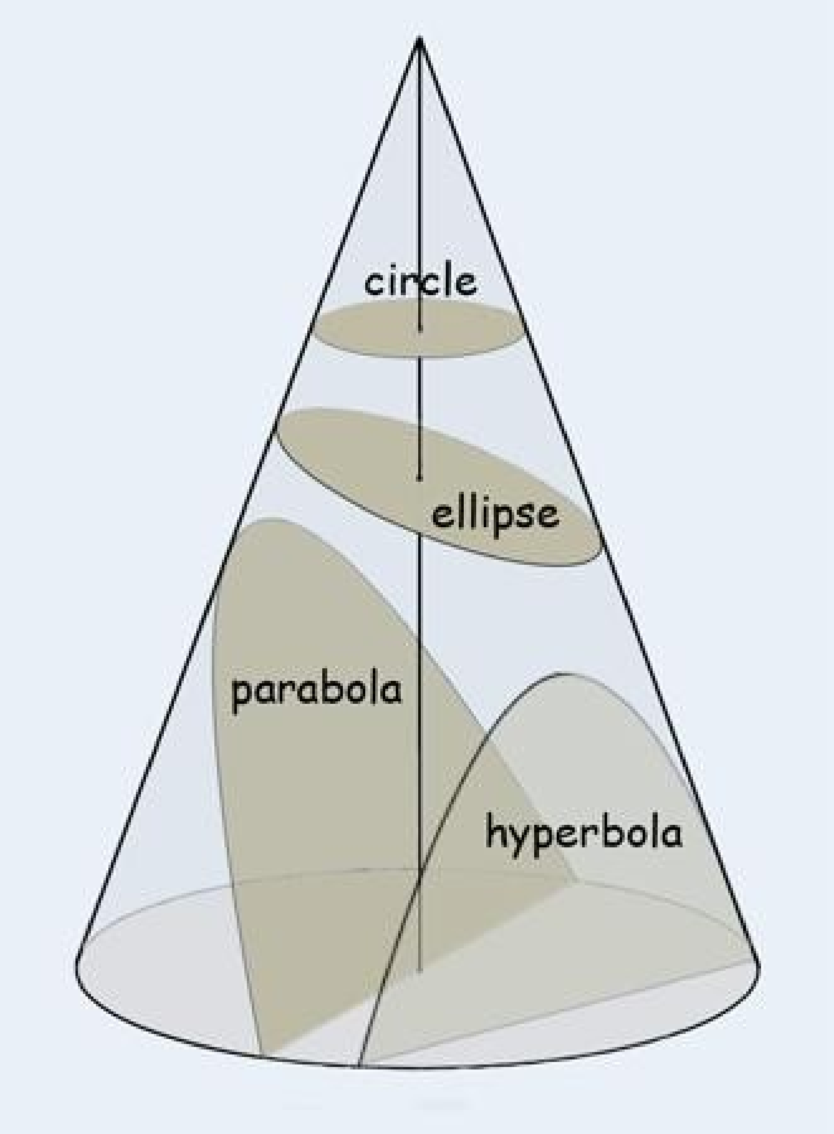
$= 37.7$ square metres

effective diameter $= (37.7/4\pi)^{1/2}$

$= 1.73$)

Conic sections

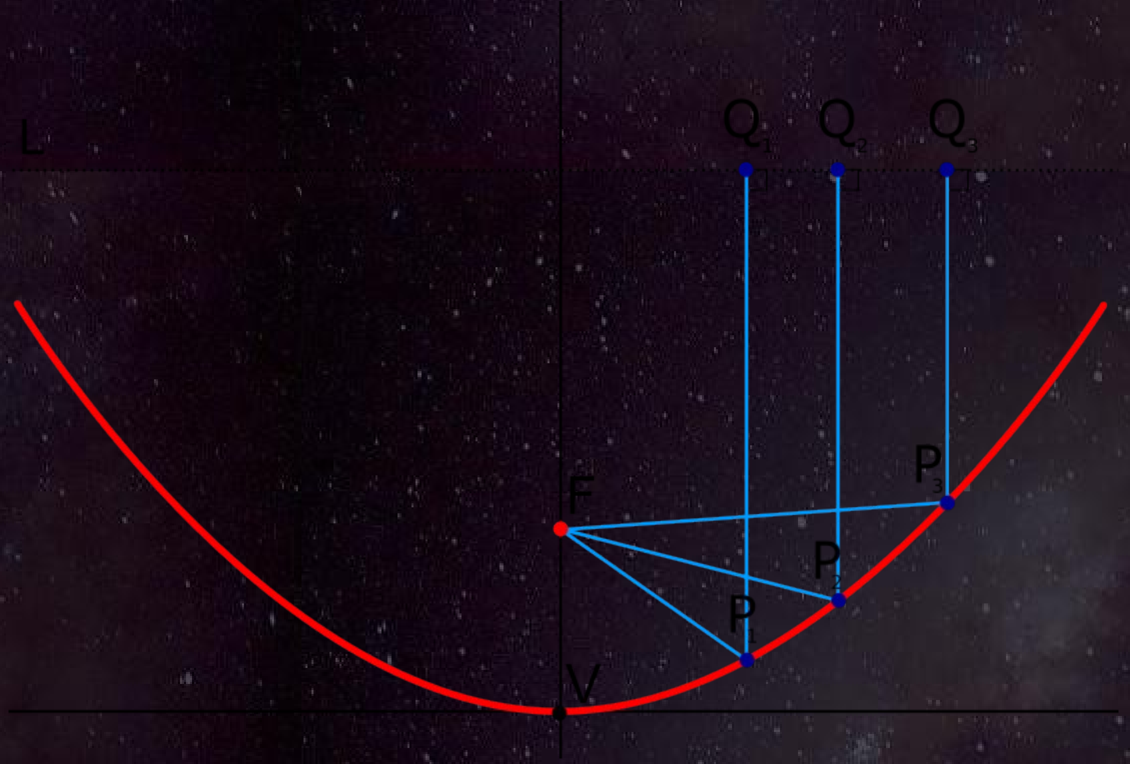
Mirrors in reflecting telescopes are shaped like a meniscus. Their exact shape can be spherical, parabolic or hyperbolic.



Reflectors - mirrors

The shape of the mirror in a reflecting telescope has to balance two problems that affect reflecting telescopes.

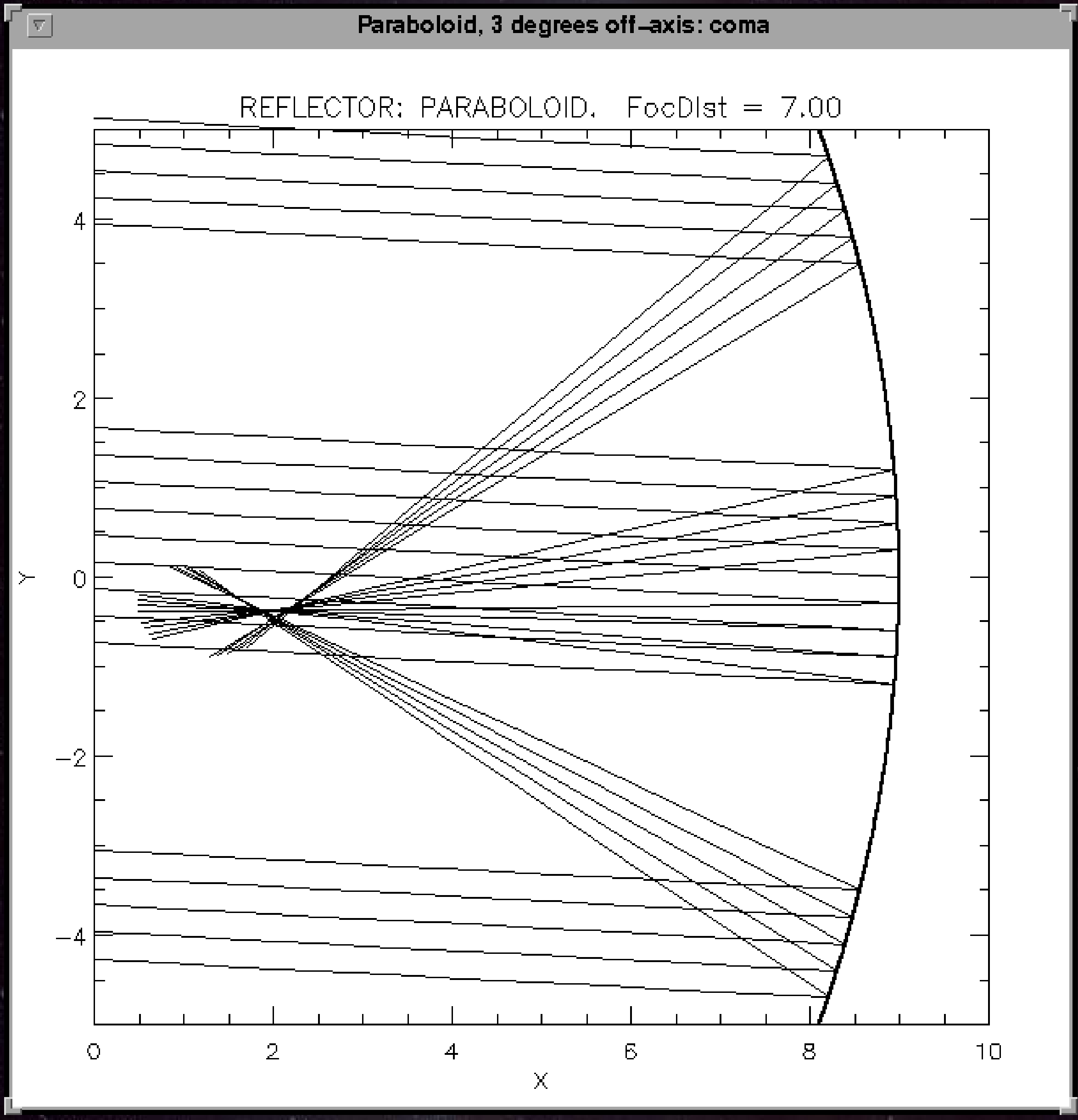
For parallel light rays travelling along the *axis* of the mirror, a parabolic mirror is the best shape – it will bring all the light rays to a single focus.



Reflectors - mirrors

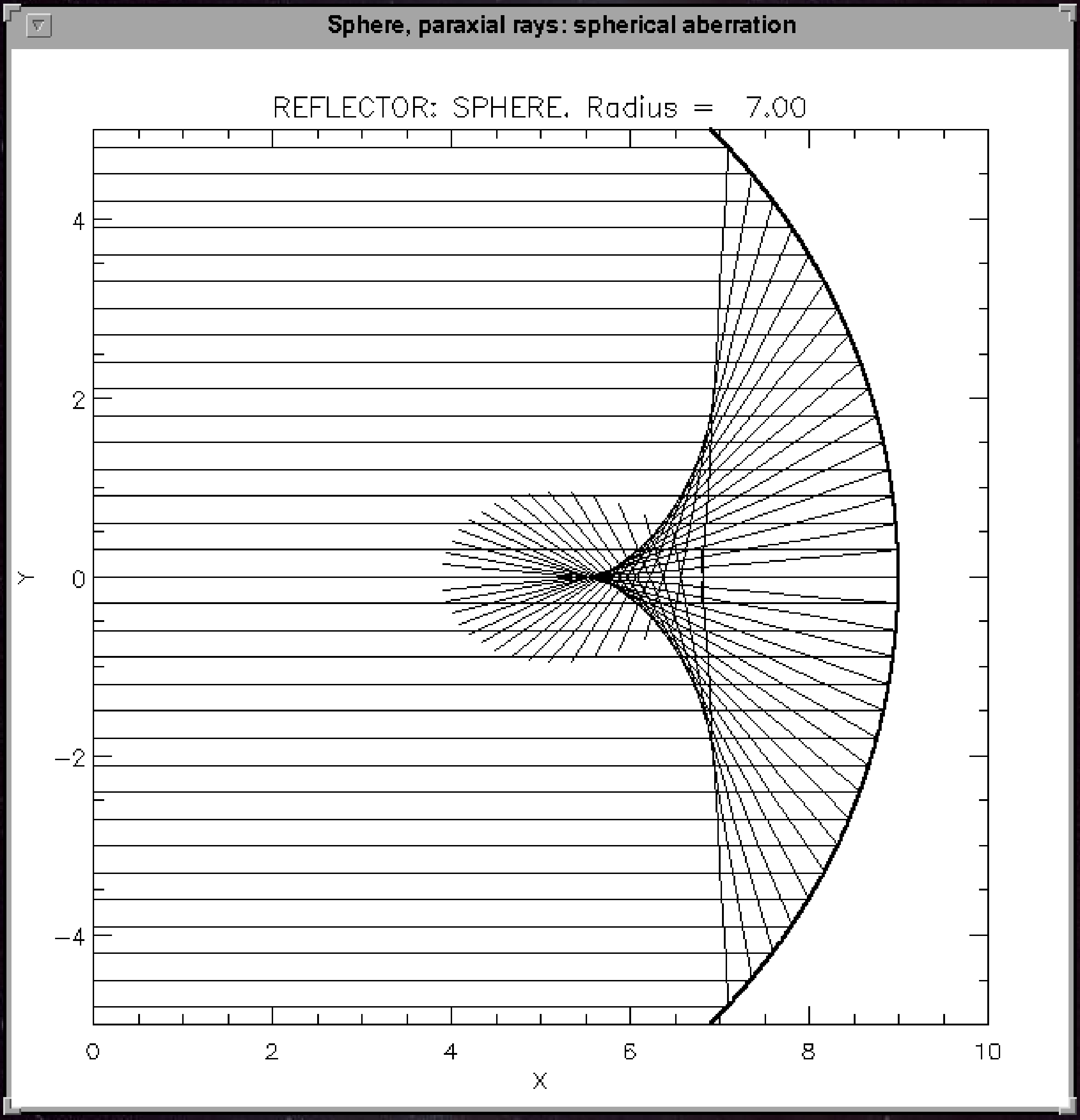
But not all of the light is travelling parallel to the axis of the mirror. Light that is *off-axis* is brought to a slightly different focus, and so the image is distorted.

The problem is called coma. It is worst for objects further from the centre of the field of view.



Reflectors - mirrors

A spherical mirror is easy to make and does not suffer from coma, but it does suffer from *spherical aberration*: light falling on the outer part of the mirror is brought to a different focus to light falling on the inner part of the lens.



Reflectors - mirrors

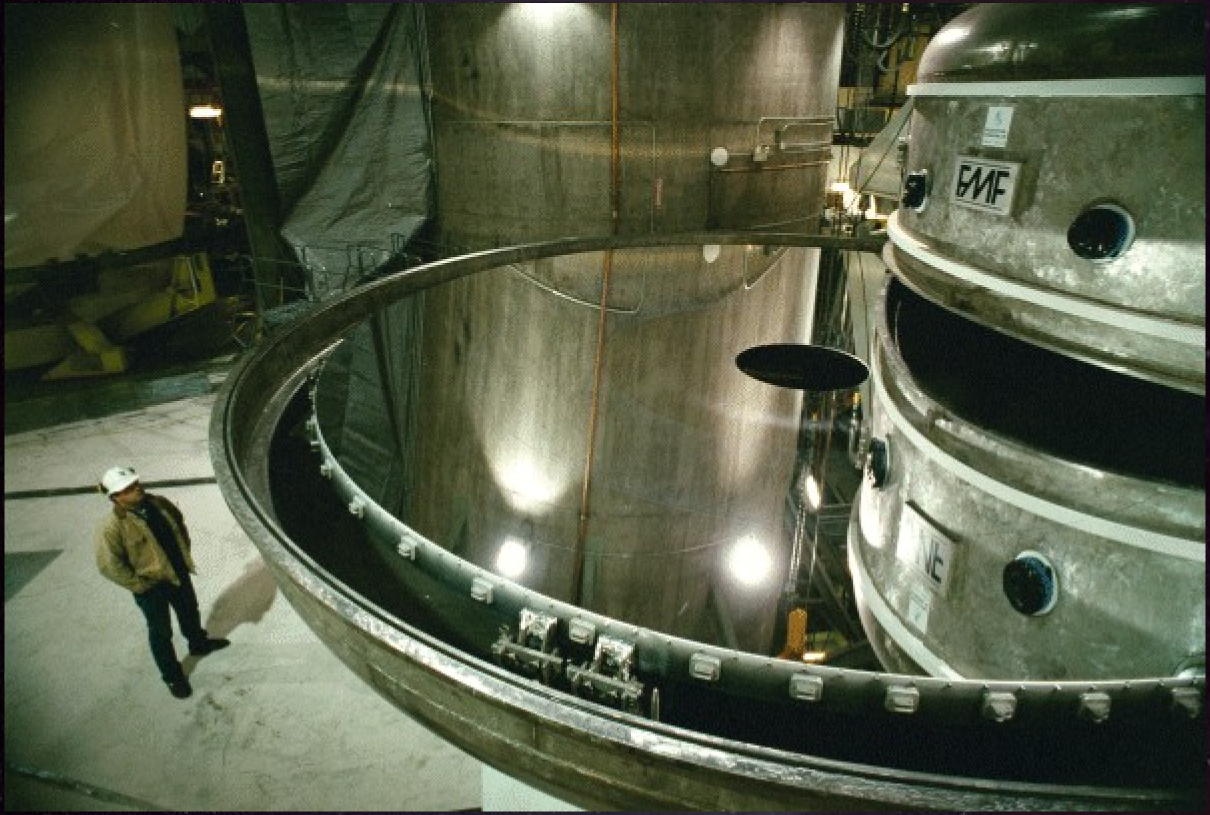
One solution for small telescopes is to use a spherical mirror to avoid coma, and a correcting lens in front of the mirror to reduce the spherical aberration.

Many variants of this design exist. A telescope which uses lenses and mirrors is called *catadioptric*.

Catadioptric telescopes suffer from the same disadvantages as refractors and so are limited to relatively small sizes.

Reflectors - mirrors

A better solution is a *Ritchey-Chrétien* telescope: this uses *hyperbolic* primary and secondaries, to eliminate the off-axis aberrations.



The disadvantage is the cost of making hyperbolic surfaces. Ritchey-Chrétien telescopes are the favoured design for very large professional telescopes, such as the two Keck 10m telescopes in Hawaii, the two Gemini 8m telescopes in Hawaii and Chile, and the four telescopes at the VLT in Chile.

Making mirrors

The construction of mirrors for large telescopes is very complex. A common method of constructing the base is with a spinning furnace. By spinning the furnace a few times a minute as the glass inside it cools, you 'pre-figure' the mirror into a roughly spherical shape.

Then, the mirror grinding and polishing takes place. For the highest image quality, you need a mirror surface that is accurate to within about 1/20 of the wavelength of the light you are looking at.

So, for visible light with a wavelength of ~500nm, you need a mirror polished to an accuracy of ~25nm.

The width of a human hair is ~100,000nm!

Making mirrors

The final step is to coat the mirror with a highly reflective substance.

The Gemini telescopes are coated with silver. Just 50 grammes of silver coats each of the 8m mirrors, and this coating reflects 98.75% of the light that falls on it.

Coatings are very thin – typically about 0.1μm thick. Silver and aluminium both react with the atmosphere and so slowly degrade over time, becoming less reflective. Mirrors need to be recoated every 1-2 years.

Telescope mounts

Telescope mounts form one of the crucial components of the system. For very high quality observations, you need a very steady mount.

Mounts are isolated from the ground surrounding them to minimise the transferrence of vibrations (you may have noticed this at ULO).

Telescope mounts

The most common mount for small telescopes is an *equatorial mount*. With this kind of mount, the telescope is able to rotate around an axis which points to the celestial poles.

Then, to track an object, you only need to rotate the telescope in one direction at a constant rate.

This makes guiding relatively easy – but autoguiding systems are ubiquitous at large telescopes.

Telescope mounts

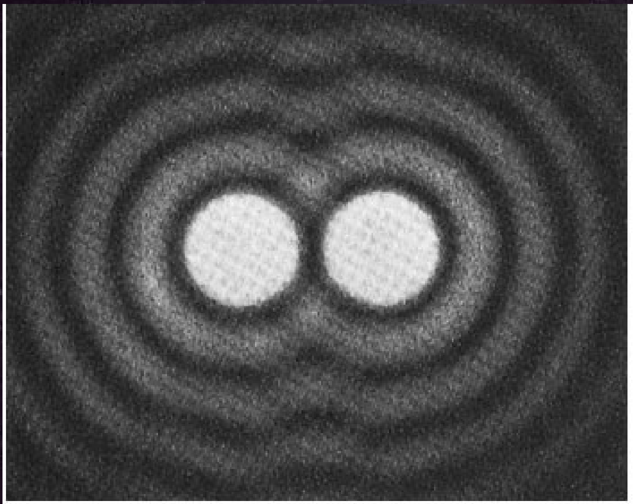
For very large telescopes, equatorial mounts become too expensive. Instead, the simpler *altazimuth* mount is used. The telescope is not tilted onto the polar axis.

Altazimuth mounts are cheaper to build, but suffer from *field rotation*. This is corrected by rotating the detector at the same rate as the sky appears to be rotating.

Limits to observations

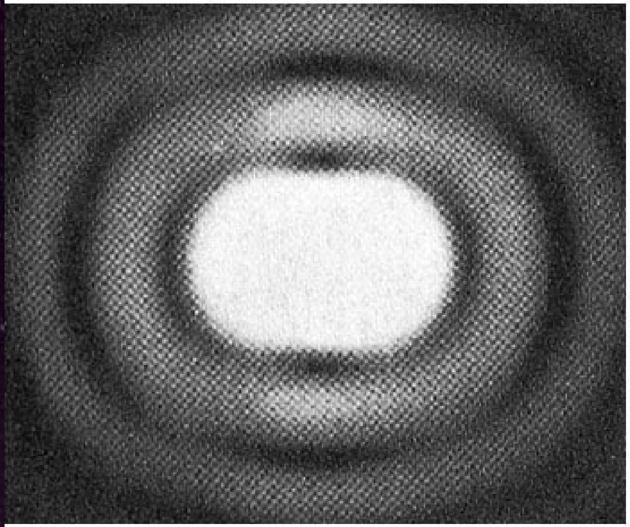
Why make big telescopes? First of all, you can gather more light. The 10m Keck telescope can see things 10 million times fainter than Galileo's 3cm telescope could.

The second reason is that a larger lens or mirror can *resolve* smaller objects. There is a fundamental limit to how small an object any telescope can resolve, caused by *diffraction*. The smaller a telescope aperture, the more it diffracts light, so larger telescopes suffer from less diffraction.



(a)

Two light sources with angular separation greater than angular resolution of telescope: Two sources easily distinguished



(b)

Light sources moved closer so that angular separation equals angular resolution of telescope: Just barely possible to tell that there are two sources

Limits to observations

For a perfectly constructed and polished mirror or lens, the *diffraction limit* is given by

$$\theta = 2.5 \times 10^{-4}\ \lambda/D$$

where is the resolution limit, is the wavelength in nanometres, and D is the diameter of the mirror or lens.

So, for visible light (500nm), the human eye's diffraction limit is $2.5 \times 10^{-4} \times 500 / 0.005 = 25$ arcseconds

For the Hubble Space Telescope, with a 2.4m mirror, the diffraction limit is $2.5 \times 10^{-4} \times 500 / 2.4 = 0.05$ arcseconds

For the 10m Keck telescope, the limit is $2.5 \times 10^{-4} \times 500 / 10 = 0.0125$ arcseconds

Limits to observations

In practice, the Hubble Space Telescope can achieve its diffraction-limited resolution, but the Keck could not, originally.

This is because the Keck is on the surface of the Earth, underneath the atmosphere. The atmosphere is in constant motion, and this 'smears' images out a bit. It is the reason stars 'twinkle'.

The resolution limit imposed by the atmosphere is called the *seeing*. At the very best sites, the seeing might typically be ~0.6 arcseconds. At Mill Hill, it is normally 3-4 arcseconds.

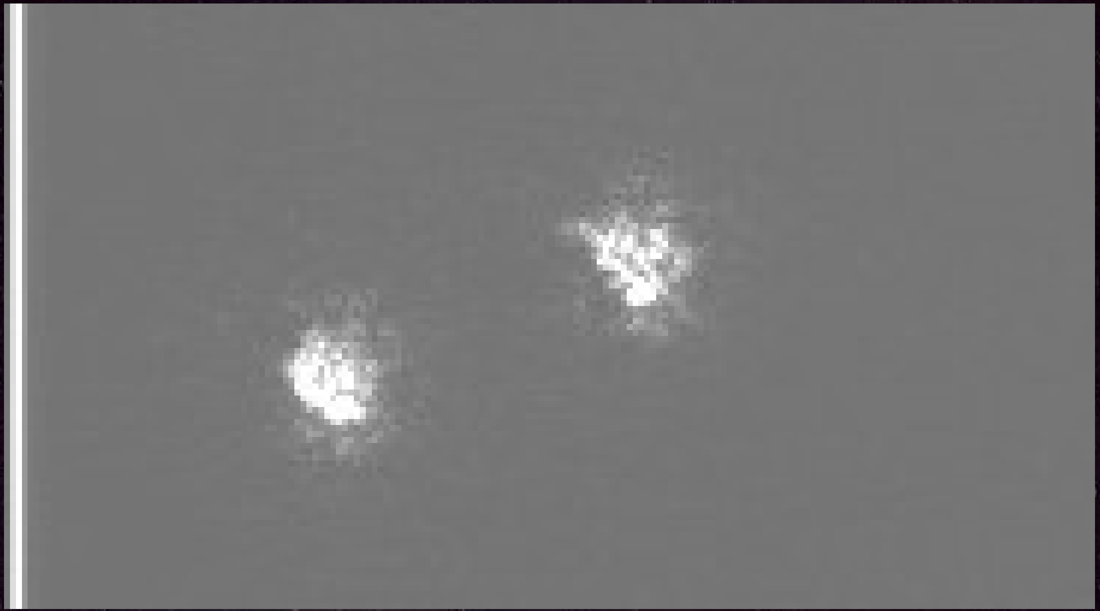
I have seen ~10 arcsecond seeing on La Palma...!

Overcoming seeing

The Hubble Space Telescope overcame the limits of seeing by going into space. In recent years, it has become possible to achieve diffraction-limited imaging from the ground.

One way of doing this is called *lucky imaging*. You simply take a huge number of images with very short exposures. In some of them, you'll be lucky and the column of atmosphere you are looking through will hardly have moved at all during the exposure.

Then, you can throw away all the duff exposures and keep the few good ones.



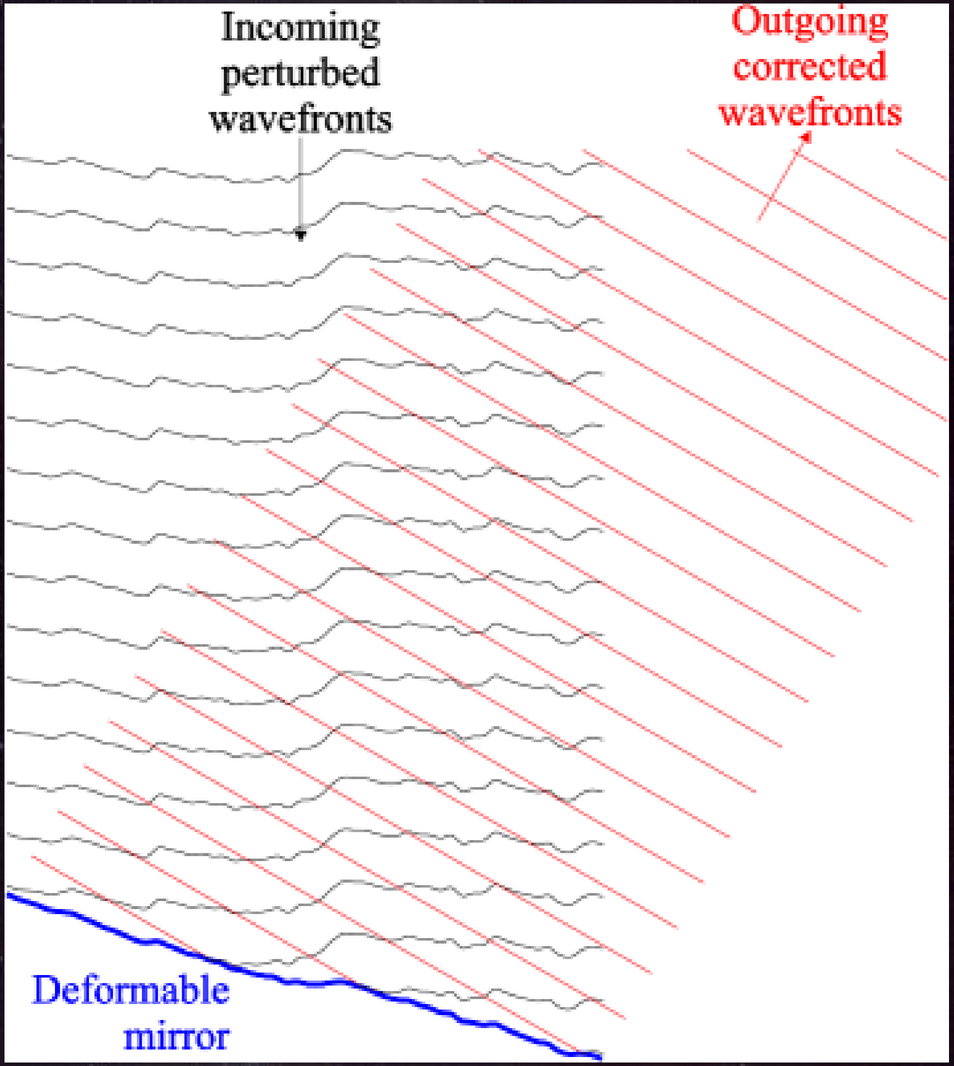
This works pretty well – but it's horribly inefficient.

Overcoming seeing

A more efficient method is with a technique called *adaptive optics*.

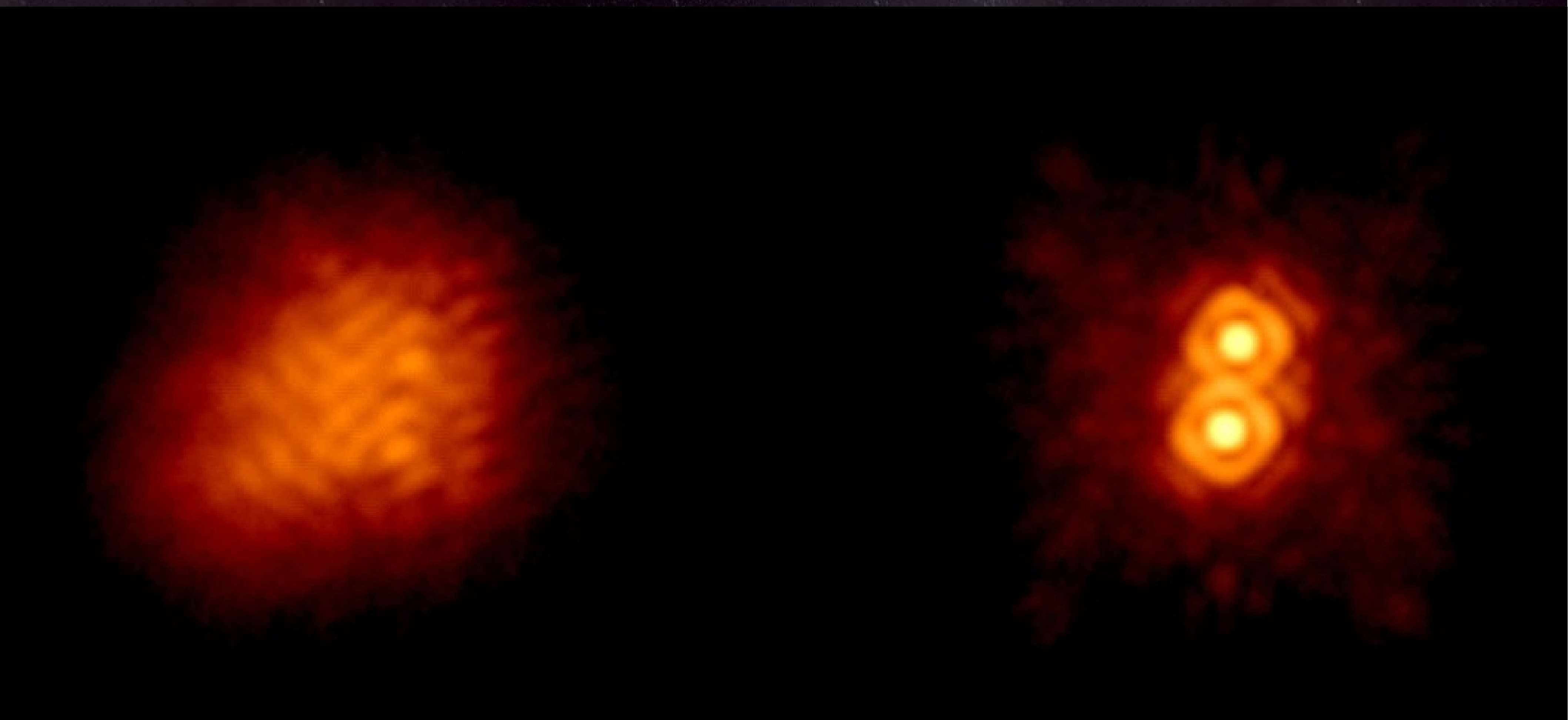
By looking at the light from a star, and watching how it changes as the atmosphere distorts it, extremely fast computers can control *actuators* which distort the mirror of a telescope by the tiny amounts needed to correct for the atmospheric distortion.

The actuators work at frequencies of typically ~100Hz. AO systems are now in place at most ground-based professional observatories.



Overcoming seeing

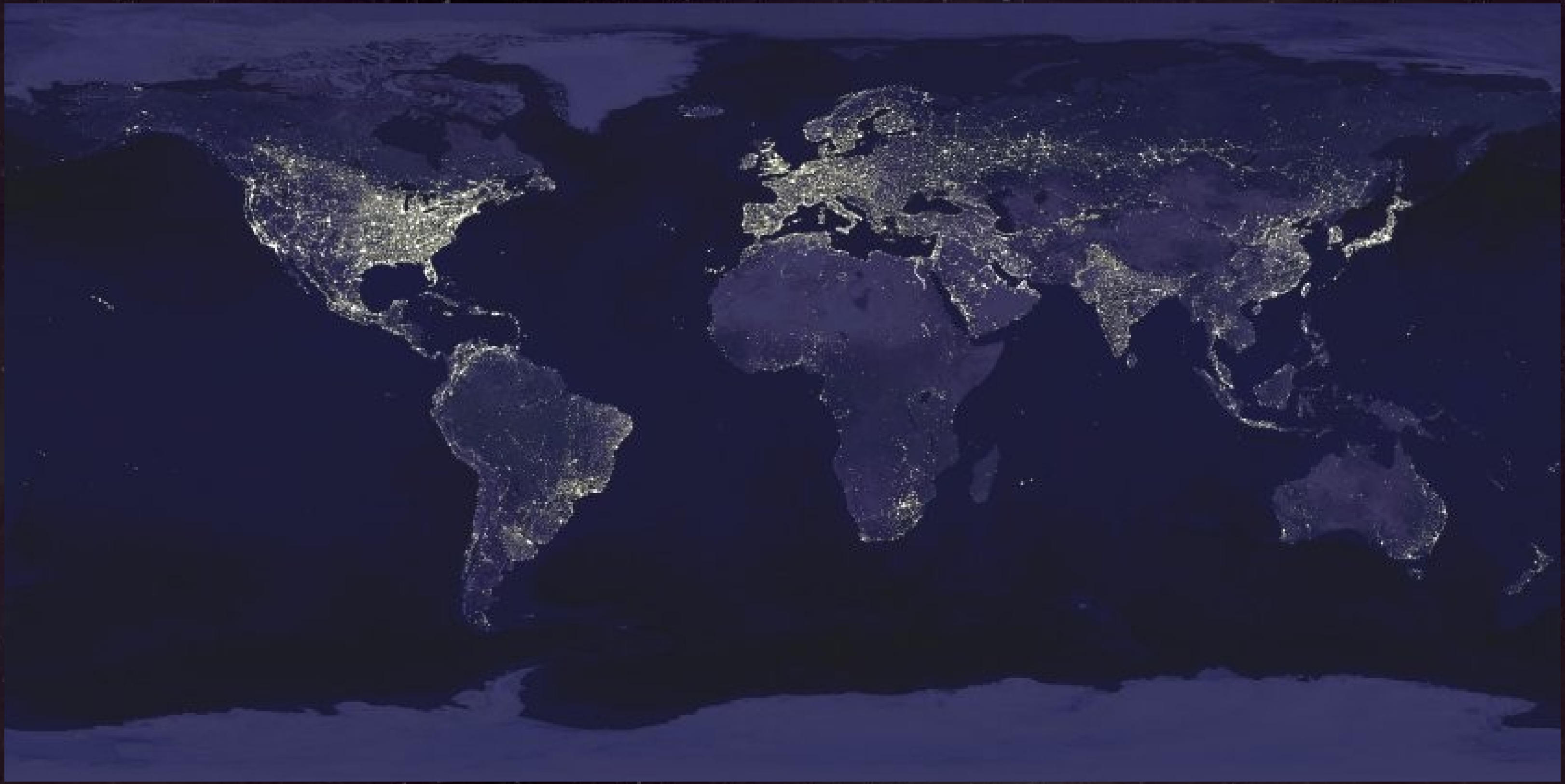
With AO, you can get close to the diffraction limit at the largest ground-based telescopes.



Other ground-based problems

But although you can overcome seeing limits, other problems remain.

Most large telescopes are in remote places, to avoid light pollution. But it is impossible to avoid it completely.



Other ground-based problems

And even if every light on the planet was switched off at night, there would still be some background light. The atmosphere glows, very very faintly, because of cosmic rays hitting it, ions recombining, and chemical reactions.

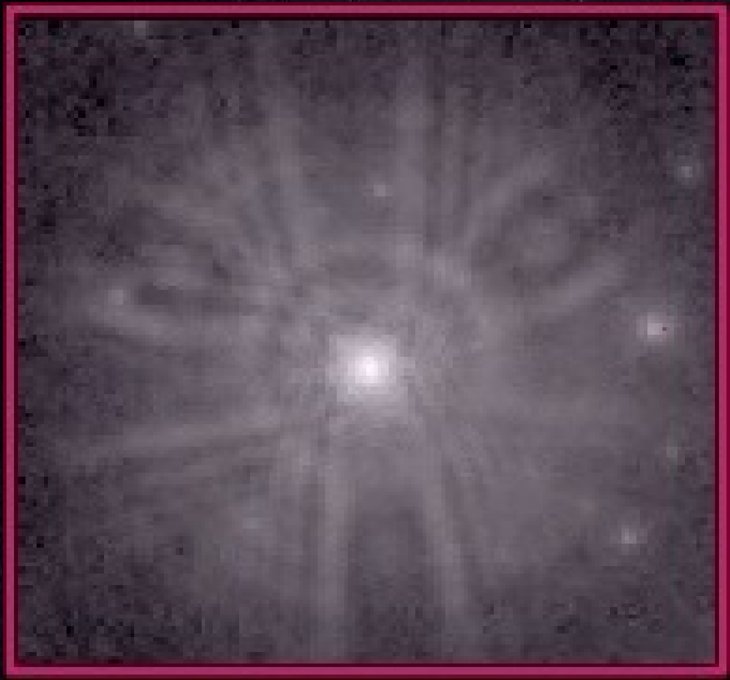
And, when the moon is around, the sky is very bright, because moonlight gets scattered around.

So, ground-based observations are ultimately limited by the background. Solution – go to space!

Hubble Space Telescope

Even with its fairly modest 2.4m mirror, Hubble made stunning advances in astronomy, because it avoided all the problems that the atmosphere causes.

It wasn't all plain sailing though. Immediately after launch, it was realised that there had been a problem...



Hubble Space Telescope

I mentioned earlier that telescope mirrors need to be accurate to ~1/20 of the wavelength of light. Hubble's mirror was as perfectly figured as any mirror ever has been... but to slightly the wrong shape.

This came about because of incompetence and mismanagement at Perkin-Elmer, the company contracted to do the polishing.

They tested the shape of the mirror with three machines, one of which had been wrongly calibrated. Inexplicably, although two machines said the mirror was wrong, they trusted the one that said it was right, and Hubble's early years were a bit of a disaster.

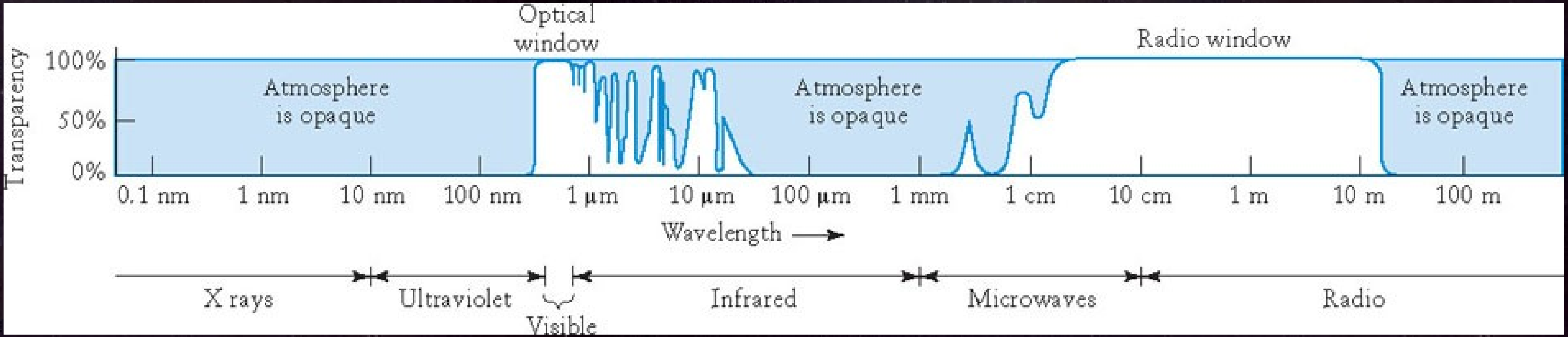
Hubble Space Telescope

The problem was solved when Hubble was serviced in 1993. New optical components were put in, which had exactly the same error as the mirror, but in the opposite sense.

The improvements were dramatic:

More advantages of space

Another problem with the atmosphere is that it absorbs very strongly at many wavelengths:



If you want to observe gamma rays, x-rays, UV or sub-mm radiation, you need a space observatory.

Detectors

So, we've discussed a lot about how telescopes are made, and how they produce images, and what affects the quality of those images. Now, we'll discuss how to record those images.

The ability to record astronomical images came about in the mid-19th century with the advent of photography. This was quite a revolution. Long photographic exposures reveal detail which cannot be seen with the naked eye.

Film

Photographic film consists of silver halide crystals. Light falling on the film breaks up these crystals, resulting in a build up of silver atoms called a *latent image*.

The latent image is invisible. To get a final image, you need to remove all the remaining silver halides to make film light-insensitive, then react the silver with something else to produce a visible image. This is the process of *developing*.

It is not hard to get the developing very wrong – as many who have had photos developed at cheap places will know...

Film - disadvantages

The main disadvantages of film as an astronomical detector are

1. very low *quantum efficiency (QE)*. This is the fraction of photons falling on the detector which are recorded. For film, it's typically about 0.02, which means that 98% of the light falling on the film is not recorded.

2. Non-linear response. This means that there is not a simple direct relation between the brightness of an object and its brightness on the film. When imaging very faint objects with film, to record an object half as bright as another often requires much more than twice the exposure.

This is called *reciprocity failure*, because it breaks the simple brightness of source = brightness on film / exposure time relation.

Film - disadvantages

Over the years, people came up with very innovative ways of (partially) overcoming these problems.

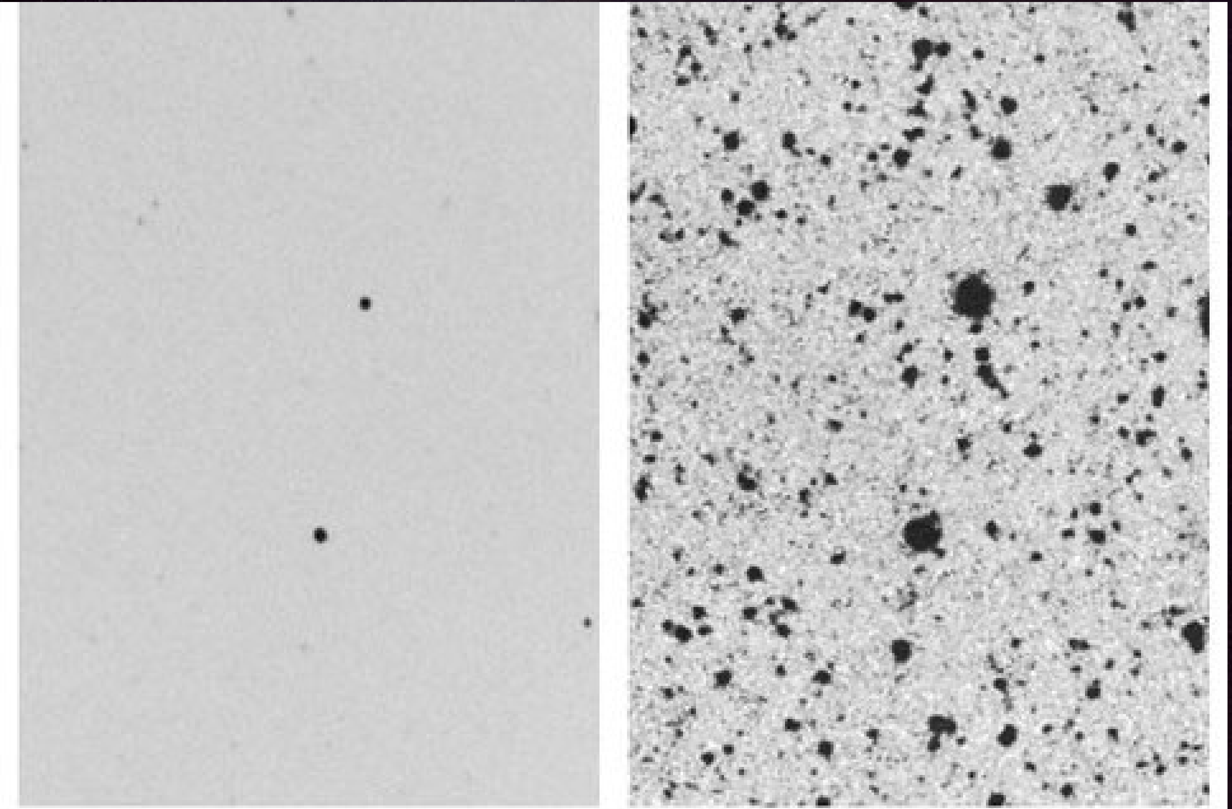
One way was called *hypersensitising* or *hypering*: this involved baking film in pure nitrogen for many hours. This made its quantum efficiency much higher, but this kind of approach is quite inconvenient.

Film also becomes more sensitive when cooled to well below freezing. Again, not very convenient.

Charge-Coupled Devices (CCDs)

In the early 1970s, *charge-coupled devices* were invented and developed. These involve semiconductors which give off an electron when struck by a photon (the photoelectric effect).

A well-designed CCD can have a QE of nearly 100% in some parts of the EM spectrum. Typically, their QE is ~70%, so they are 35 times more efficient than film.



(b) An image made with photographic film

(c) An image of the same region of the sky made with a CCD

Charge-Coupled Devices (CCDs)

The main disadvantage used to be that their size was extremely limited, and was much smaller than film plates could be. This is less of a restriction nowadays as the cost of components has dropped, and larger format CCDs can be made.

Charge-Coupled Devices (CCDs)

A typical CCD in a commercial digital compact camera is very small – my old Canon Powershot has a sensor 5.5mm wide and 4mm high (cf 36x24 mm for 35mm film). It has 3 million pixels.

In comparison, the largest astronomical CCD detector that I know of is at Llano del Hato in Venezuela. It is 18.2cm wide and 12.6cm high, and has 67 million pixels.

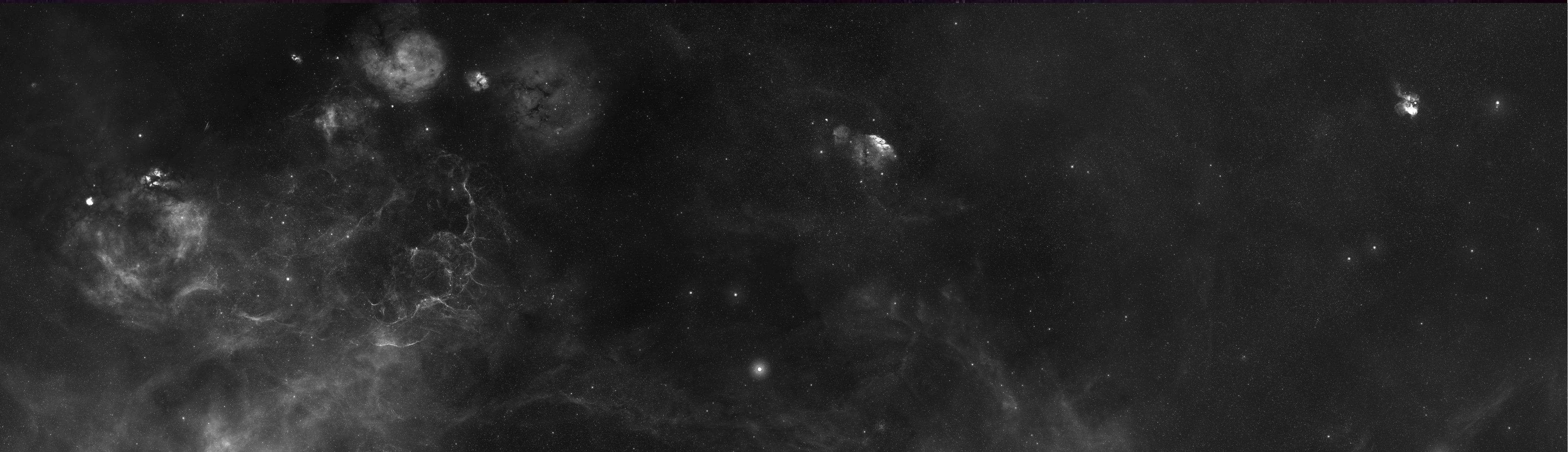
The Palomar Observatory Sky Survey used photographic plates 36cm x 36cm.

Larger CCDs are very expensive, and astronomical CCDs must be as free from defects as possible.

Charge-Coupled Devices (CCDs)

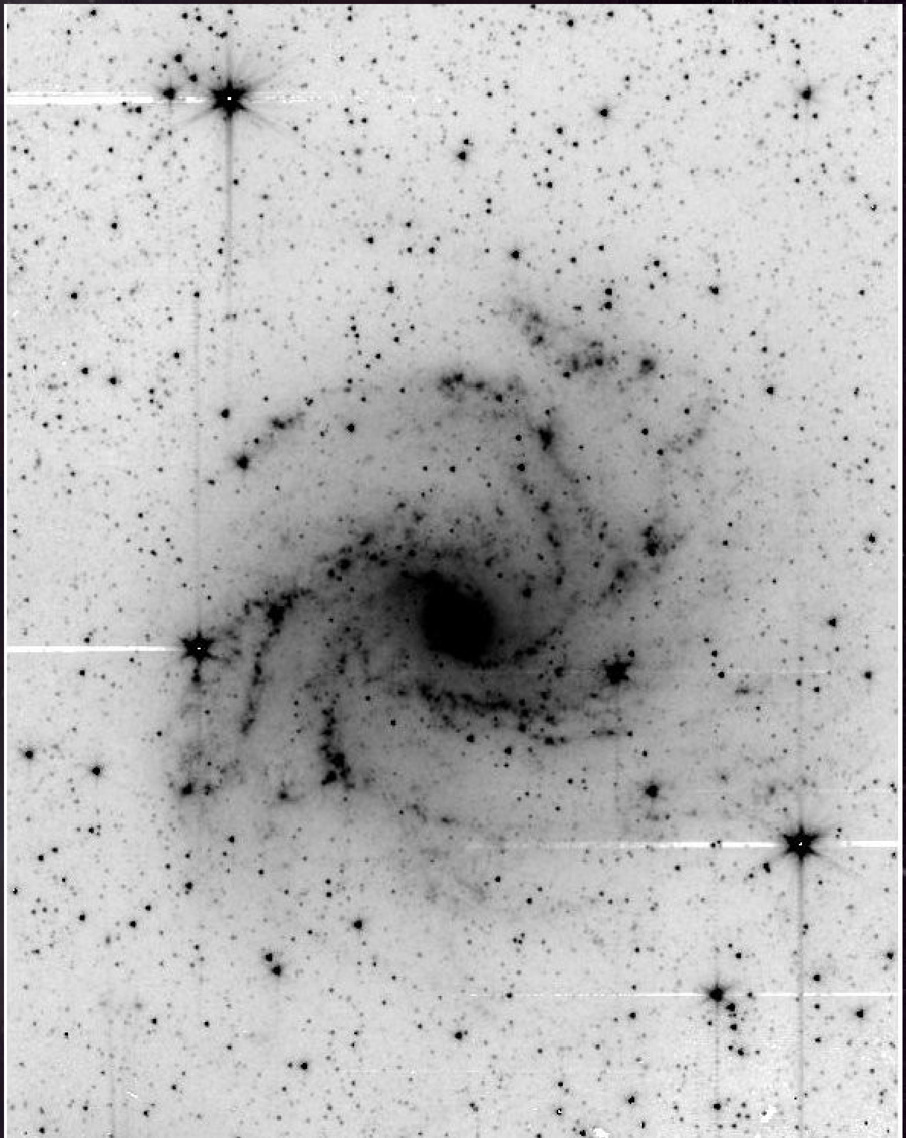
The most recent major film-based astronomical survey that I know of was completed in 2003. The Macquarie/AAO/Strasbourg H-alpha (MASH) survey imaged the southern Galactic plane using tech-pan film, which is extremely fine-grained and sensitive to red light.

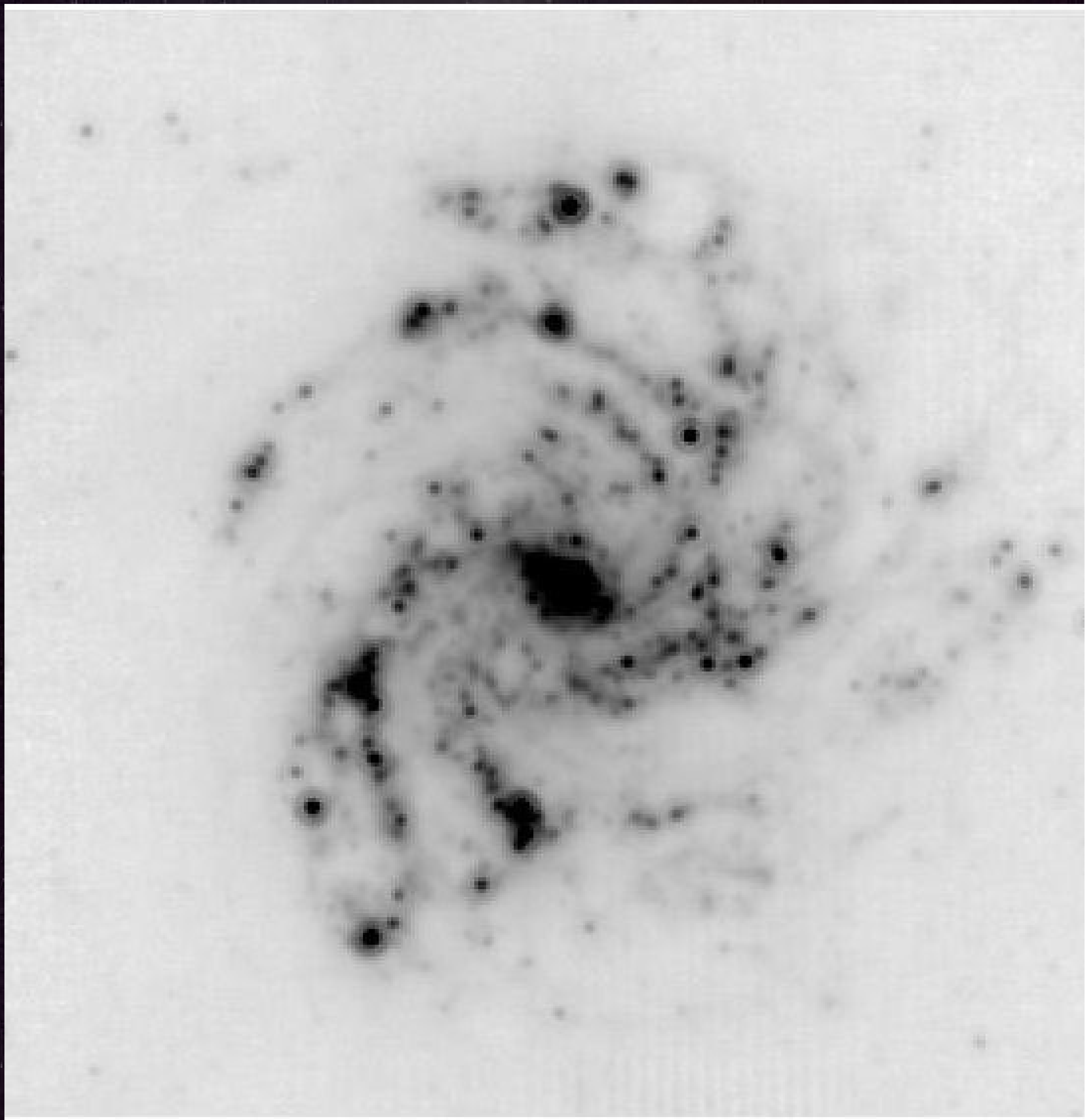
The large area of film compared to CCDs led MASH to go with film. But this was probably the last film-based survey.



Mirrors at other wavelengths

For a given mirror size, optical performance gets worse at longer wavelengths.



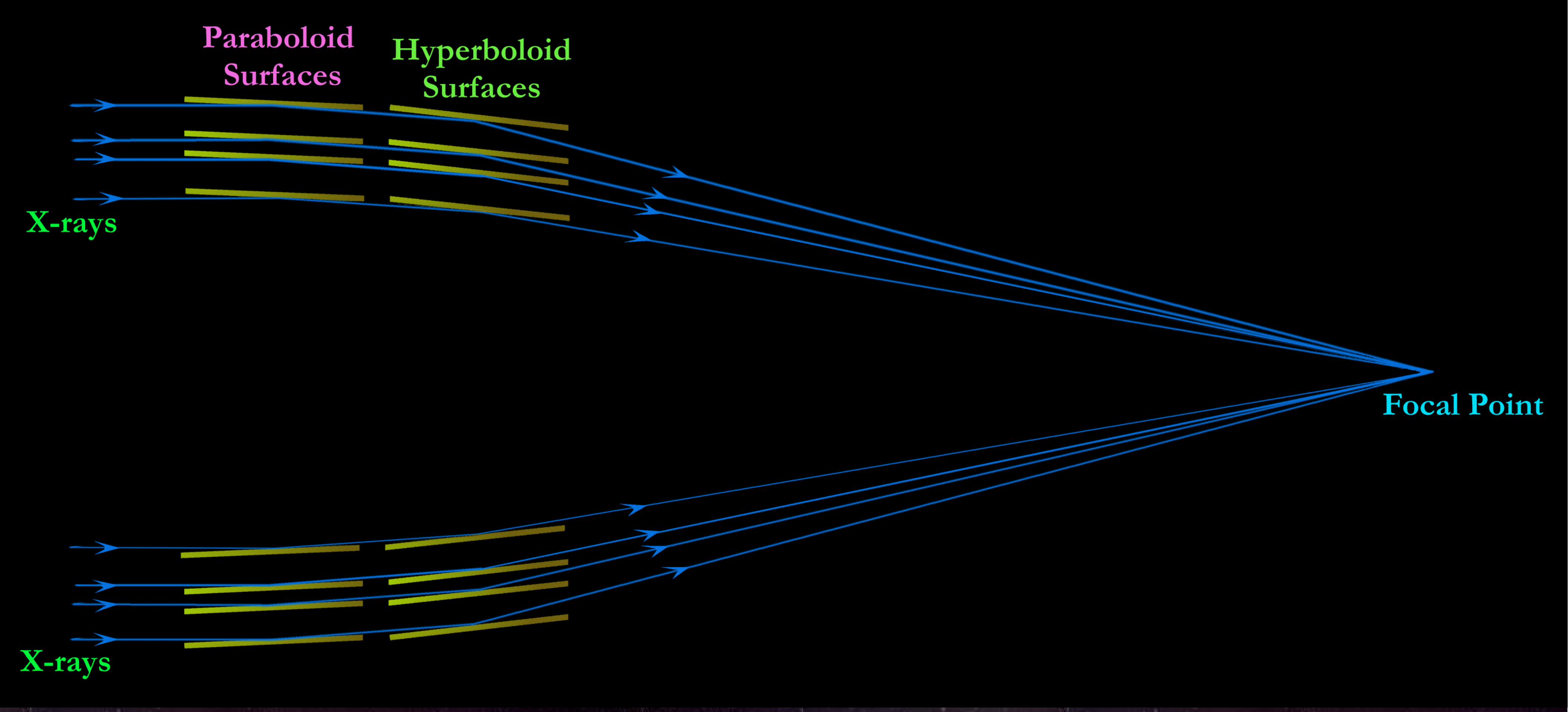


Mirrors at other wavelengths

But, although you need a larger mirror at longer wavelengths, the mirror does not have to be so finely made. The 1/20th-wavelength accuracy criterion becomes easier to achieve at longer wavelengths. Radio telescopes are much easier to make than optical telescopes.

Mirrors at other wavelengths

Mirrors at very short wavelengths are tricky, because X-rays and gamma rays can penetrate the mirror, if they fall directly on it. Instead, *grazing incidence mirrors* are used:



Radio telescopes

We saw earlier that the resolution limit of a telescope is given by

$$\theta = 2.5 \times 10^{-4}\ \lambda/D$$

Radio wavelengths are about 100,000 - 1,000,000 times longer than optical wavelengths, so to achieve the same resolution, you would need a telescope at least a hundred thousand times larger.

The largest radio telescope is Arecibo, with a dish 305m across. This is pretty huge, but it's only 30 times as large as the largest optical telescope. You really need a telescope tens of kilometres across.

Interferometry

Resolution is thus a major problem in radio astronomy. To overcome this, the technique of *interferometry* was developed.

By observing an object with two or more very widely spaced telescopes, you are effectively observing them with a mirror with a diameter equal to the separation of the telescopes.

Combining the signals is very complex, and you have to know the distance between the telescopes very precisely, but the technique is very refined, and in fact, the resolution that is possible with interferometry is much better than optical telescopes can do.

Interferometry

The Very Large Array is a single-site interferometric array, in New Mexico. 27 dishes in a Y configuration can cover an area 27km across, and can achieve a resolution of 0.05 arcseconds.

Very Long Baseline Interferometry

Still better resolution is possible with Very Long Baseline Interferometry (VLBI).

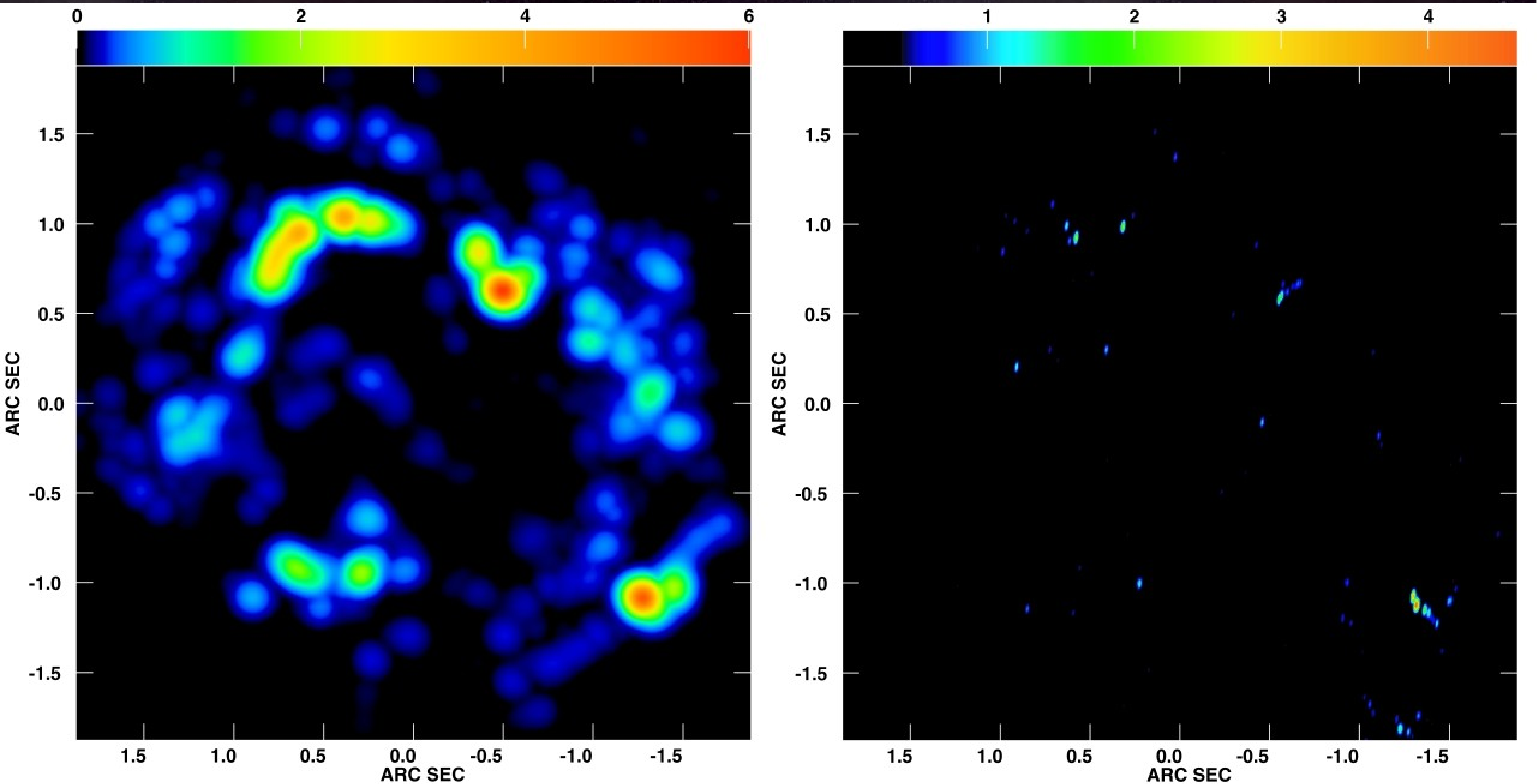
In the UK, the Multi-Element Radio Linked Interferometer Network (MERLIN) consists of 7 radio telescopes across the UK (including Jodrell Bank), separated by up to 217km. Its resolution is significantly better than the VLA.

MERLIN can also act as part of the European Very Long Baseline Network (EVN), and the EVN can also observe at the same time as the Very Long Baseline Array (VLBA) in the US.

And... the EVN + VLBA can also operate with space-based radio telescopes, giving an effective aperture of ~20,000km! This gives resolutions of just micro-arcseconds.

Very Long Baseline Interferometry

A shell of gas around a supergiant star, imaged with Merlin (left) and the EVN (right)



Infrared astronomy

The atmosphere absorbs strongly at many infrared wavelengths (this is what gives rise to the greenhouse effect). This makes observing infrared radiation from the ground quite difficult.

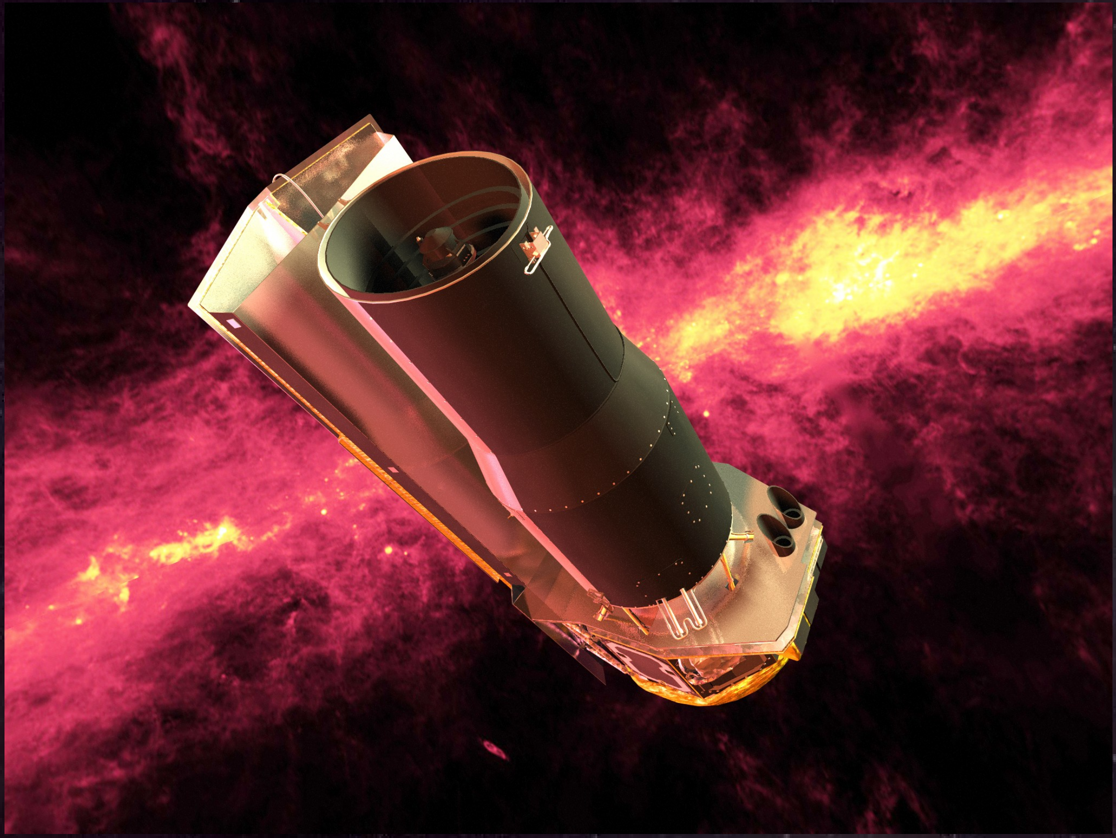
Water vapour accounts for about 75% of the absorption, so observing is possible, if you go somewhere dry enough, or high enough (because water vapour is strongly concentrated in the lower parts of the atmosphere).

Mauna Kea, at 4200m above sea level, is a good place to observe from, as is the Atacama desert in South America, and Antarctica.

Infrared astronomy

Observing in Antarctica would also go some way towards solving the other problem with IR astronomy – the equipment itself radiates strongly at IR wavelengths.

So, telescopes and detectors need to be cooled to reduce their IR emission.



Infrared space observatories

Infrared space telescopes have included the Infra-Red Astronomical Satellite (IRAS) in the 1980s, Infrared Space Observatory (ISO) in the 1990s, and Spitzer in the 2000s. Herschel will be launched soon... maybe... and will have a much larger mirror than these ones (3.5m v. 60-80cm).

All of these have been cooled to ~4K (-269°C) by tanks of liquid helium. The helium evaporating cools down the telescope. This limits the lifetime of the instrument – no more helium = no more IR observations.

The James Webb Space Telescope, successor to Hubble, will have a large sun shield to allow it to reach very cold temperatures without the need for liquid helium.

Spectrographs

We've talked a lot about spectra, but not said anything yet about how they are obtained.

Newton did a little bit of early spectroscopy, using prisms. But in the same way as refractors are not as good as reflectors, prisms are not as good for producing spectra as *gratings*.

You can see how gratings work if you hold a CD or DVD at an angle to a source of light. The fine rulings on the surface *diffract* the light, and different wavelengths are diffracted by different amounts.

Gratings can disperse the light much much more than prisms can, so you can study objects in much more fine detail.

Spectrographs

There is always a trade-off with spectrographs. The more you disperse the light, the longer your exposure needs to be to detect it.

Ultra-high resolution spectroscopy can detect motions equivalent to walking pace from the Doppler effect.

But if you were studying stellar motions in galaxies, where the stars are moving at ~10-100km/s, you only need a spectral resolution that is enough to measure these speeds accurately.