Astronomical Instruments

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Outline

1) Telescopes: characteristics & designs

2) Ground vs space observations

3) Optical instruments (visible, infrared, ultraviolet)

4) Non-optical instruments (radio, X-ray, gamma)

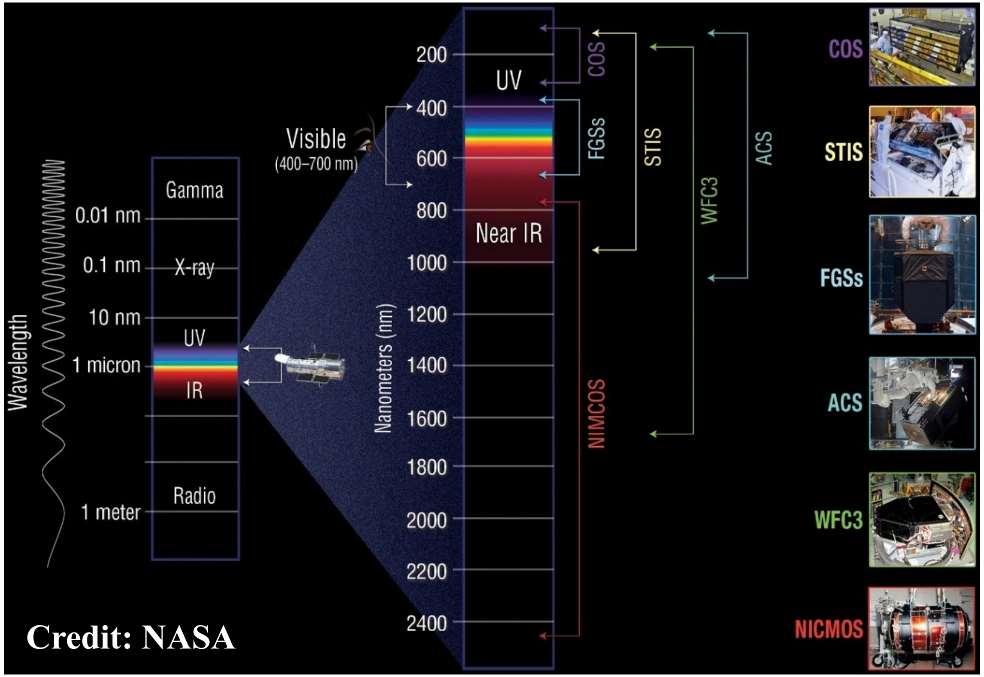
Telescopes are giant eyes that collect radiation

Three basic components of a modern system for measuring radiation from astronomical sources:

a telescope: a "bucket" for collecting visible light (or radiation at other wavelengths).

an instrument: sorts the incoming radiation by wavelength.

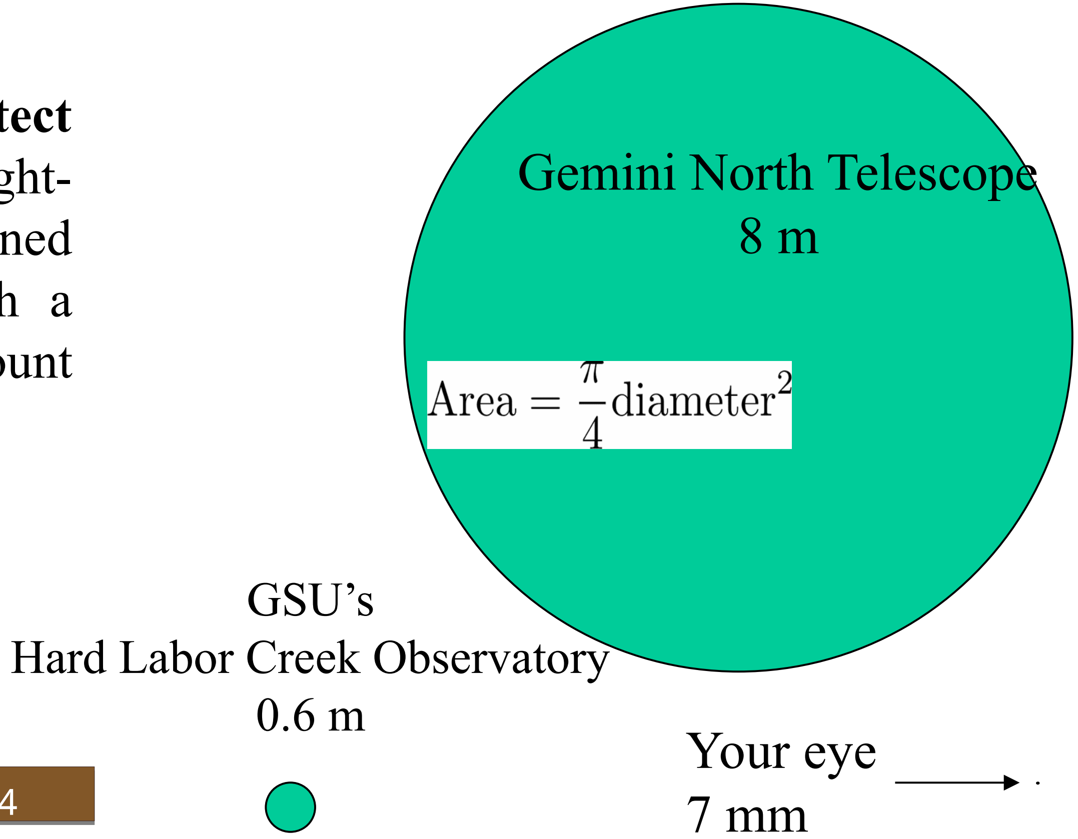
a detector: a device that senses the radiation in the wavelength regions we have chosen and permanently records the observations.



The Hubble Space Telescope carries multiple instruments, optimized for different wavelengths and tasks. Each instrument has its own detector.

Important properties of a telescope: Sensitivity

- **Sensitivity: how faint can the telescope detect objects?** This is determined by the light-collecting area of the telescope, itself determined by the telescope diameter. Telescopes with a larger collecting area can gather a greater amount of light in a shorter time.



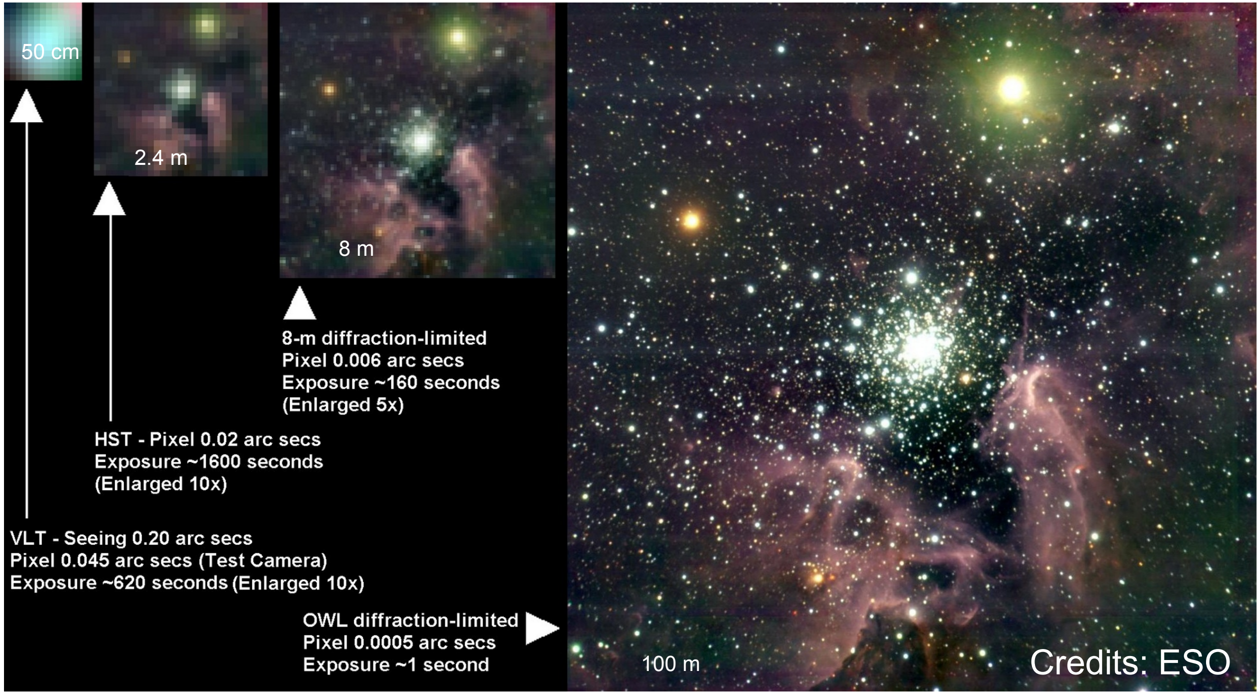
Important properties of a telescope: Angular resolution

Angular resolution: what are the smallest details the telescope can see?

Angular resolution is the capability of any image-forming device such as an optical or radio telescope to distinguish small details of an object.

A better angular resolution provides sharper images, while a lower one will have blurrier details. Angular resolution get better with larger telescope diameter and smaller wavelength of observation.

A large telescope observing objects in visible light will yield better resolution than a small telescope observing in infrared light.



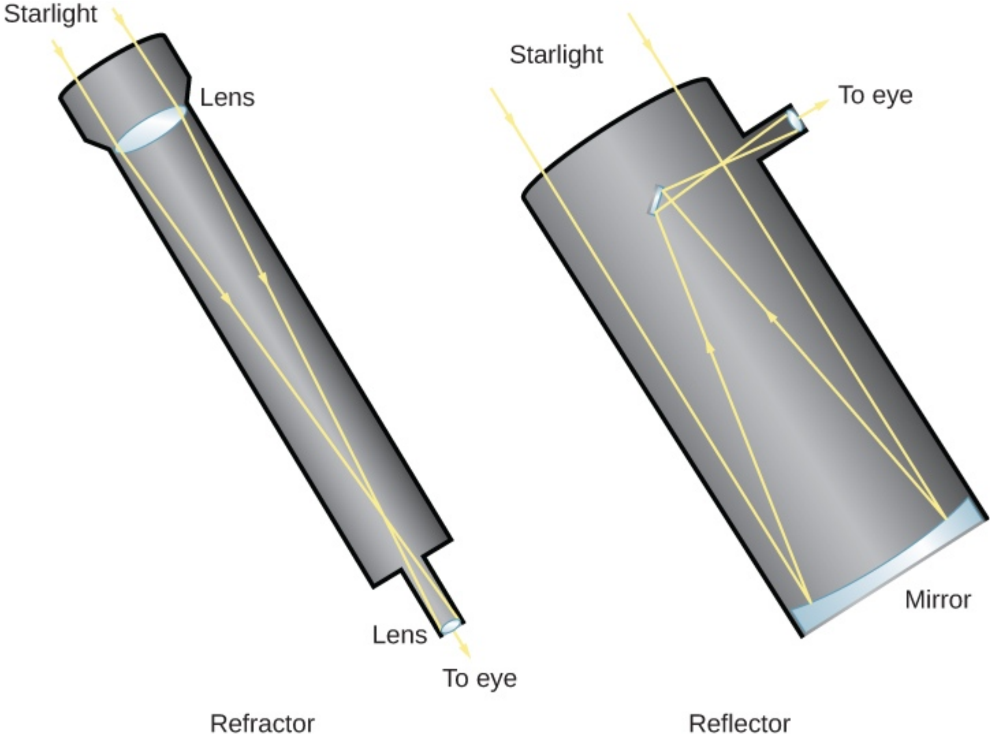
Simulated observations for different telescope sizes (equivalent diameters added by F. Baron)

Note: human eyes have an angular resolution of one arcminute (30cm at 1km distance, 8” at 1 mile)

Refracting vs reflecting telescopes

Refracting Telescopes focus light with lenses: Light enters a refracting telescope through a lens at the upper end, which focuses the light near the bottom of the telescope. An eyepiece then magnifies the image so that it can be viewed by the eye, or a detector like a photographic plate can be placed at the focus.

Reflecting Telescopes focus light with mirrors: The upper end of a reflecting telescope is open, and the light passes through to the mirror located at the bottom of the telescope. A second mirror typically reflect the light to a position outside the telescope structure, where an observer can have easier access to it.

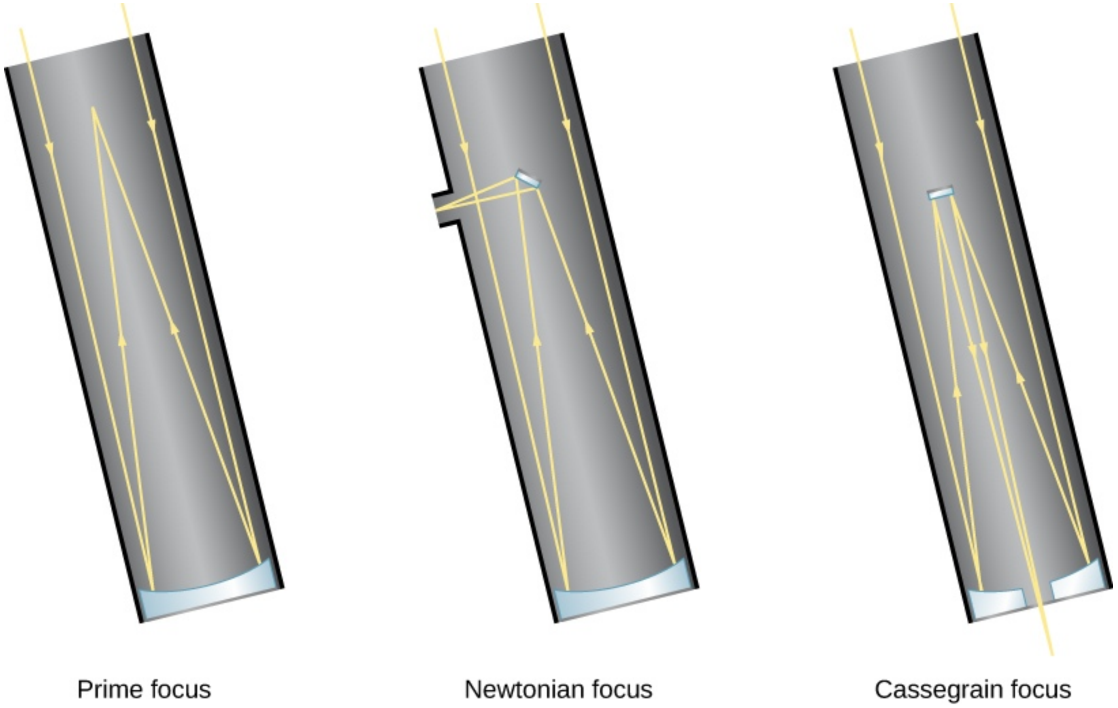


Refracting vs reflecting telescopes

Refracting telescope	*Reflecting telescope*
Two surfaces to polish per lens.	Only one large surface to grind and polish.
Glass is heavy and sags.	Mirror is supported in the back, so larger telescopes are possible.
Chromatic aberrations: glass absorbs some colors, plus different colors focus at different distances.	No chromatic aberration.
Largest one ever built was a 49-inch refractor built for the Paris 1900 Exposition, dismantled after the Exposition.	Largest single mirror is currently 8.4m (= 330 inches)
	Less expensive for any given aperture diameter, more compact designs, etc. → **All modern professional telescopes are reflective ones.**

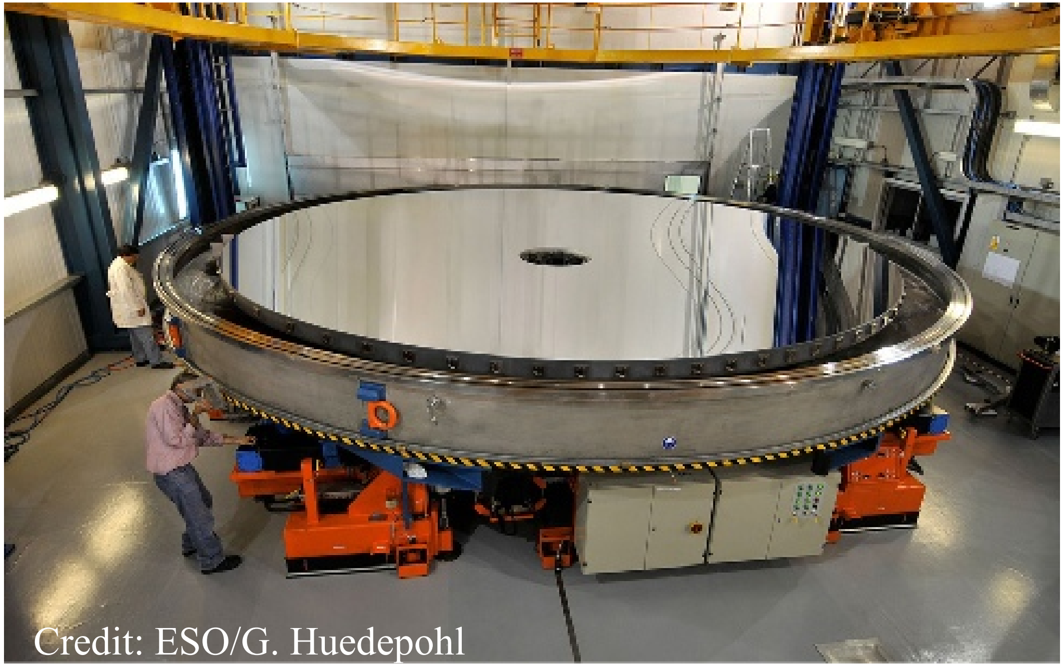
Focus arrangements for reflecting telescopes

Focus Arrangements for Reflecting Telescopes. Reflecting telescopes have different options for where the light is brought to a focus. With prime focus, light is detected where it comes to a focus after reflecting from the primary mirror. With Newtonian focus, light is reflected by a small secondary mirror off to one side, where it can be detected. Most large professional telescopes have a Cassegrain focus in which light is reflected by the secondary mirror down through a hole in the primary mirror to an observing station below the telescope.



Mirror surfaces

Large Telescope Mirror. This image shows one of the primary mirrors of the European Southern Observatory's Very Large Telescope, named Yepun, just after it was recoated with aluminum. The mirror is a little over 8 meters in diameter.



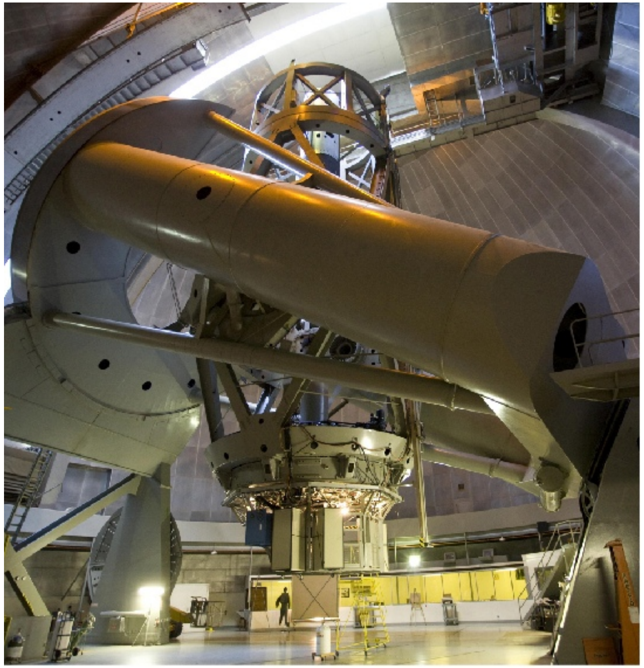
Credit: ESO/G. Huedepohl

Modern telescope mounts are lighter

Modern Reflecting Telescopes.

a) The Palomar 5-meter reflector: The Hale telescope on Palomar Mountain has a complex mounting structure that enables the telescope (in the open “tube” pointing upward in this photo) to swing easily into any position.

b) The Gemini North 8-meter telescope: The Gemini North mirror has a larger area than the Palomar mirror, but note how much less massive the whole instrument seems. (credit a: modification of work by Caltech/Palomar Observatory; credit b: modification of work by Gemini Observatory/AURA)



(a)

(b)

Early history of telescopes

1608: a patent for the telescope is submitted by Hans Lippershey in the Netherlands

Galileo improved on this design the following year and applied it to astronomy. In 1611, Johannes Kepler described how a far more useful telescope could be made with a convex objective lens and a convex eyepiece lens.

By 1655, astronomers such as Christian Huygens were building powerful but unwieldy Keplerian telescopes with compound eyepieces.

Early depiction of a "Dutch telescope" from 1624.

Early history of telescopes

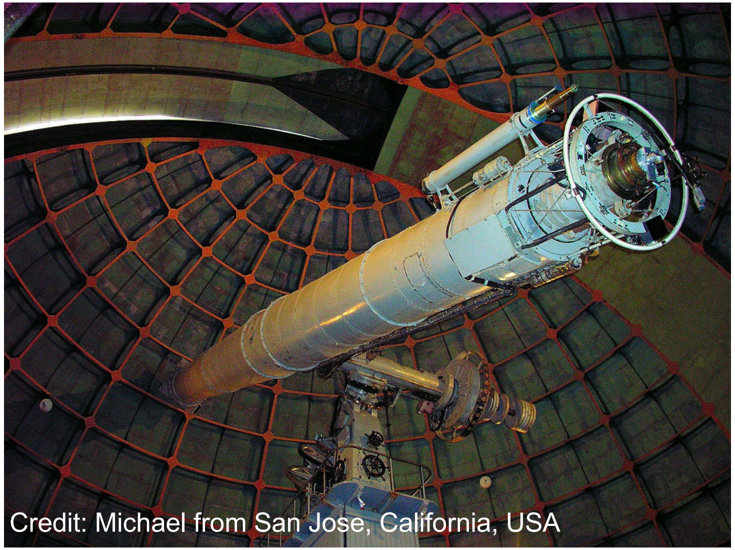
Isaac Newton is credited with building the first reflector in 1668 with a design that incorporated a small flat diagonal mirror to reflect the light to an eyepiece mounted on the side of the telescope.

Laurent Cassegrain in 1672 described the design of a reflector with a small convex secondary mirror to reflect light through a central hole in the main mirror.

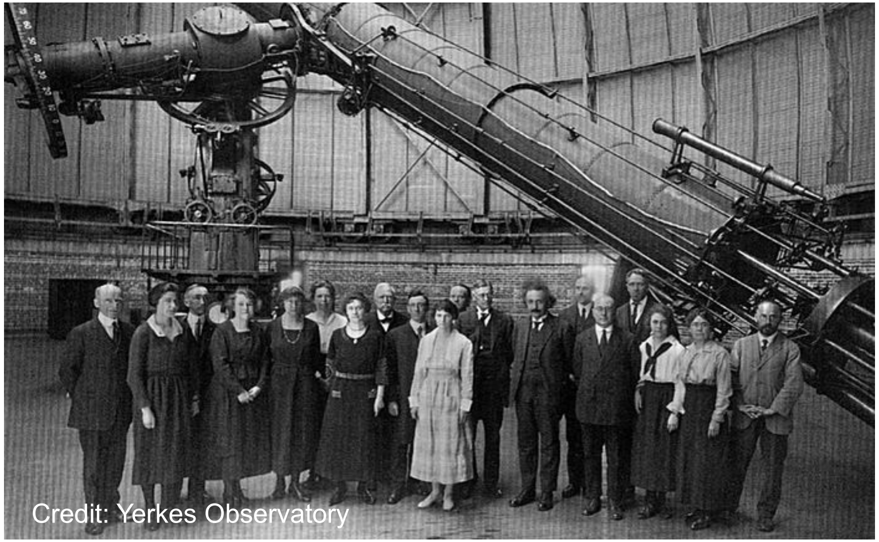
A replica of Newton's second reflecting telescope, which he presented to the Royal Society in 1672. The focus is reflected off the secondary.

Large Refracting Telescopes

The eyepieces on the Greenwich 28 inch refractor.



The Lick Refractor was the largest refracting telescope in the world when built in 1888, and today is second in size only to the 40-inch Yerkes refractor.



The 40-inch refractor at the Yerkes Observatory is the largest refractor ever successfully used for astronomy. In this picture taken in 1921, Albert Einstein and the staff of the Observatory pose in front of the refractor.

Large Reflecting Telescopes: Gemini Observatory

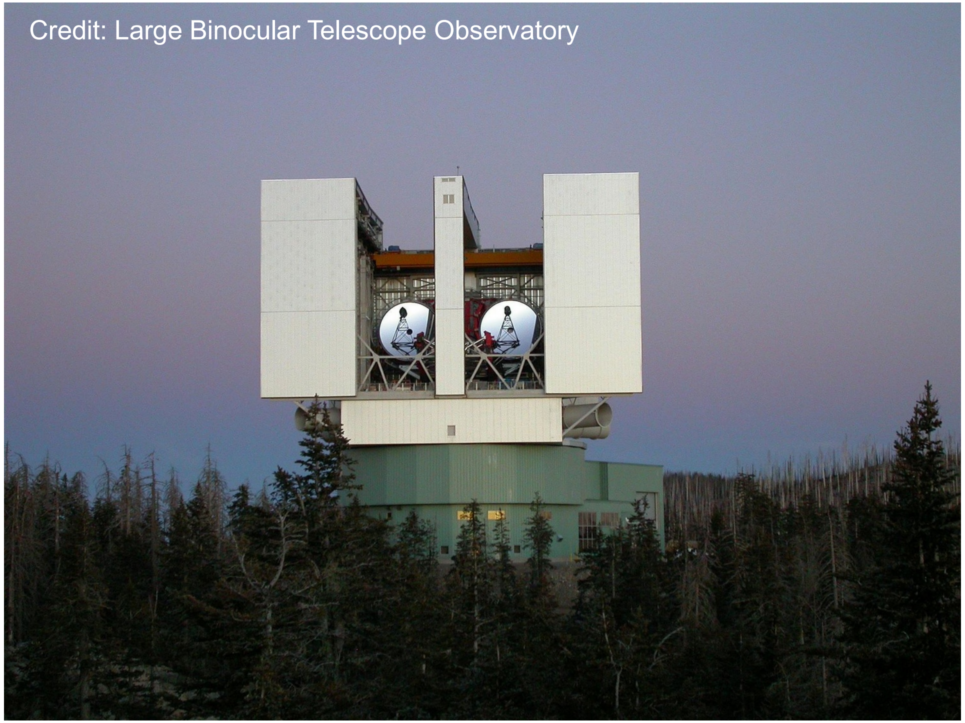
Gemini North at sunset on top of Mauna Kea, Hawai.

Gemini South at Cerro Pachon in Chili

Gemini Observatory is an astronomical observatory consisting of two 8.1-metre telescopes, Gemini North and Gemini South, which are located at two separate sites in Hawaii and Chile, providing coverage of both the Northern and Southern skies.

Large Reflecting Telescopes: The Large Binocular Telescope (2x8.4 m)

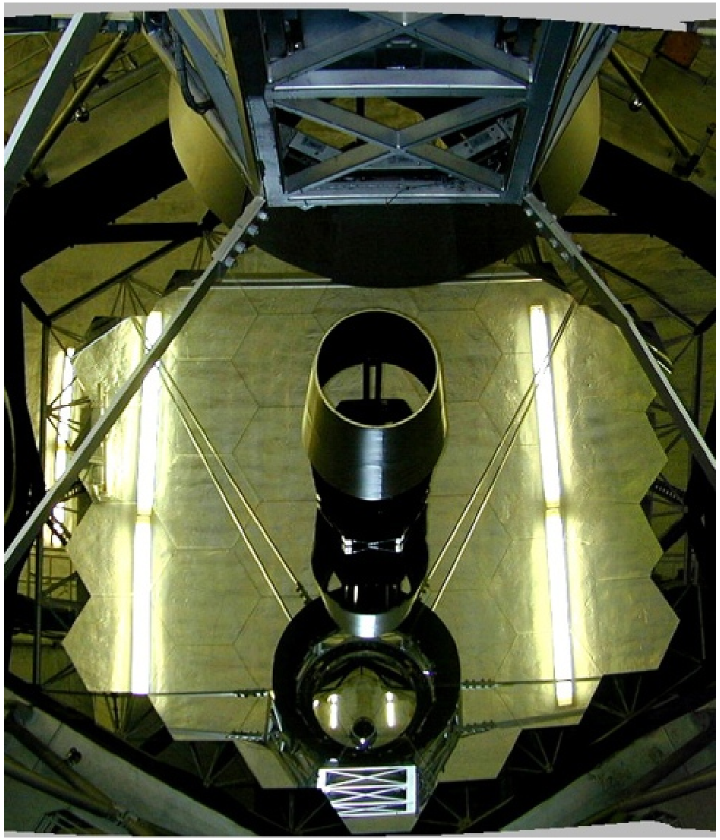
The two mirrors at the LBT are currently the largest of monolithic telescopes.



The Large Binocular Telescope at Mt. Graham, Arizona.

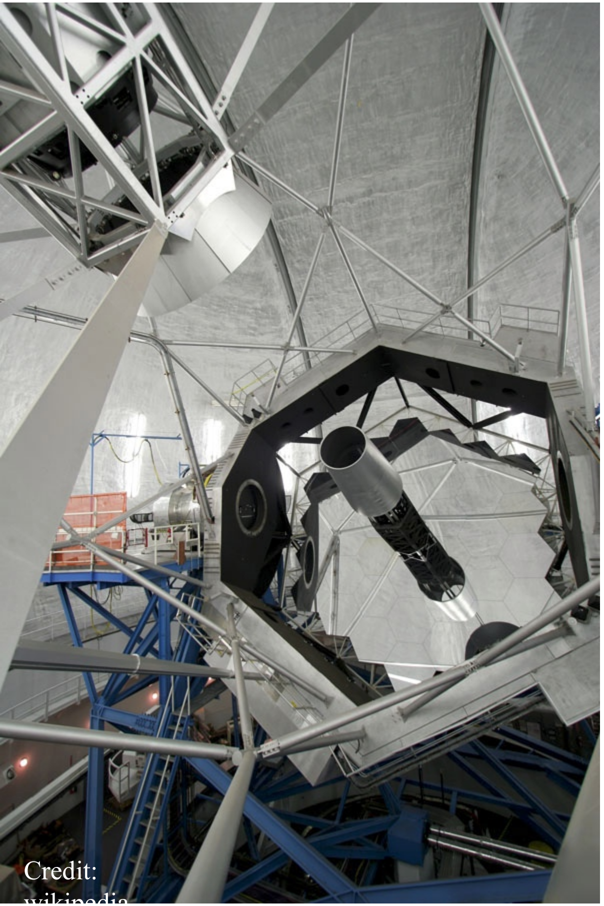
Beyond monolithic telescopes: segmented mirrors

A **segmented mirror** is an array of smaller mirrors designed to act as segments of a single large curved mirror.



Thirty-Six Eyes Are Better Than One. The mirrors of the 10-meter Keck I and II telescopes are composed of 36 hexagonal sections. (credit: NASA)

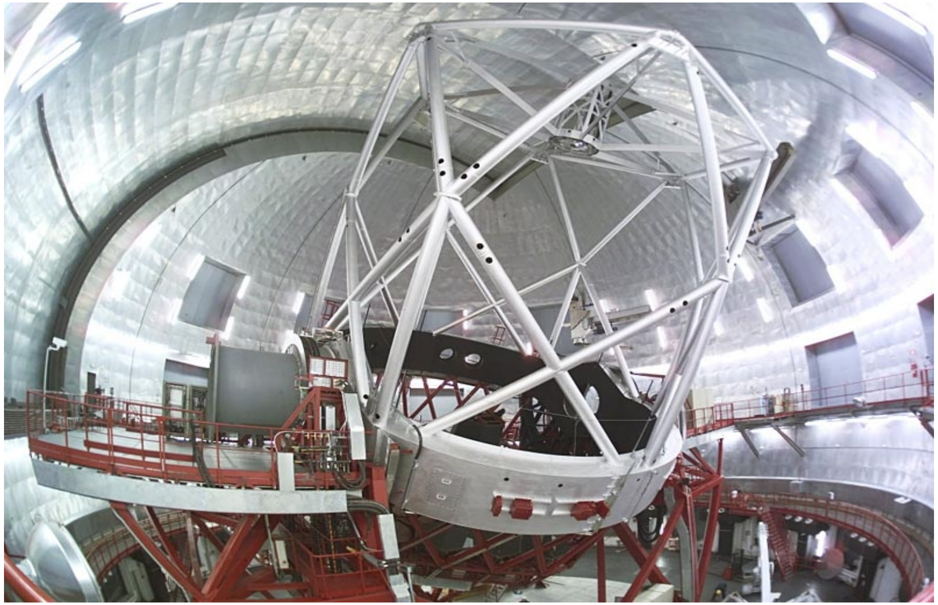
Large Segmented Telescopes: the Keck telescopes

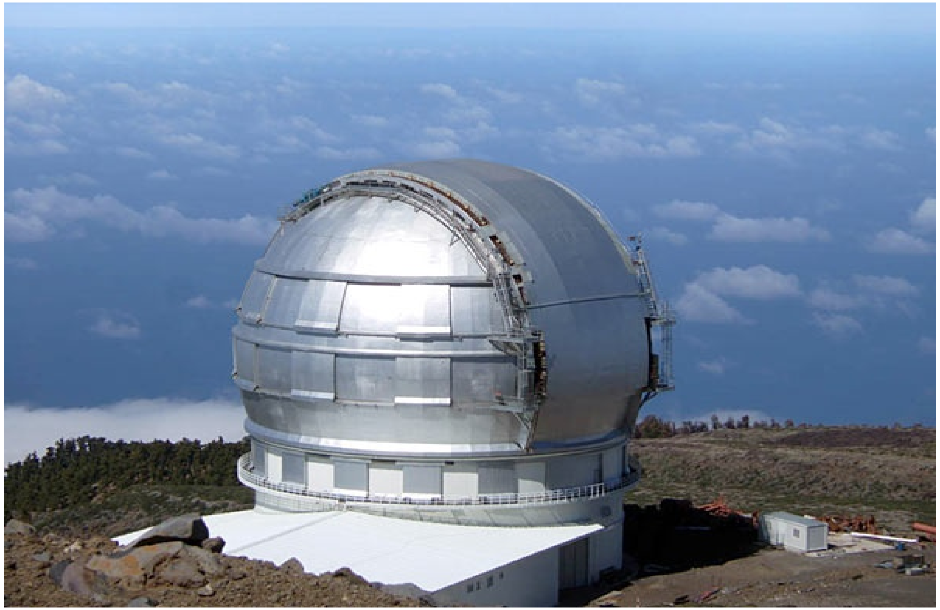


Another view of the Keck II telescope showing the segmented primary mirror.

The Keck I and II telescopes atop Mauna Kea, Hawaii

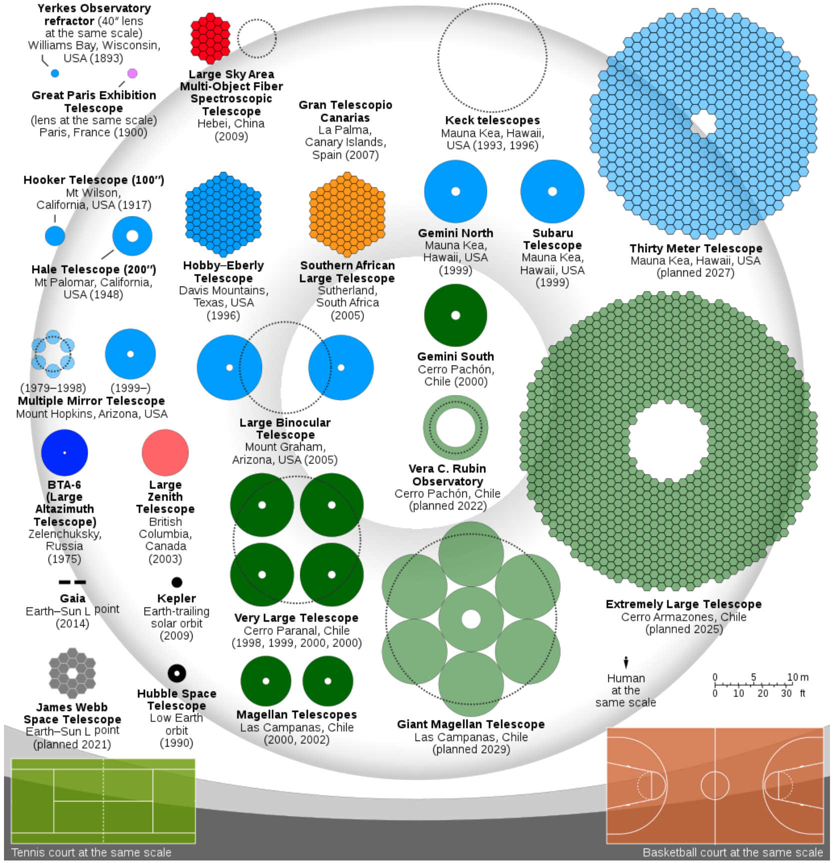
Large Segmented Telescopes: the Gran Telescopio Canarias (10.4 m)



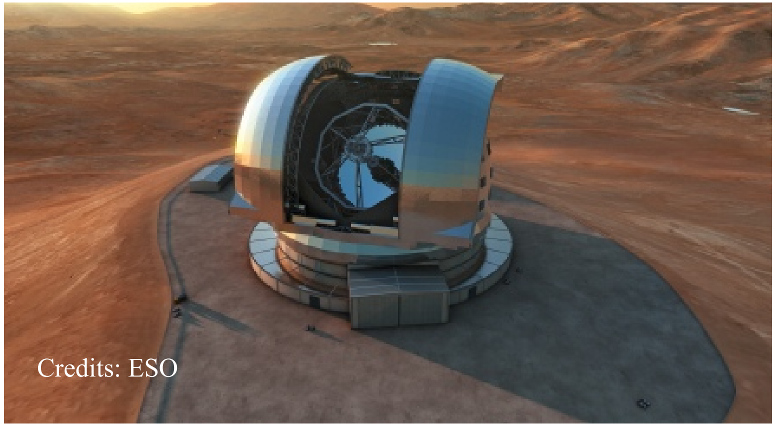


The GTC current offers the largest segmented mirror of any observatory.

Large segmented Telescopes: the future Extremely Large Telescopes



Artist's Conception of the European Extremely Large Telescope. The primary mirror in this telescope is 39.3 meters across. The telescope is under construction in the Atacama Desert in Northern Chile.

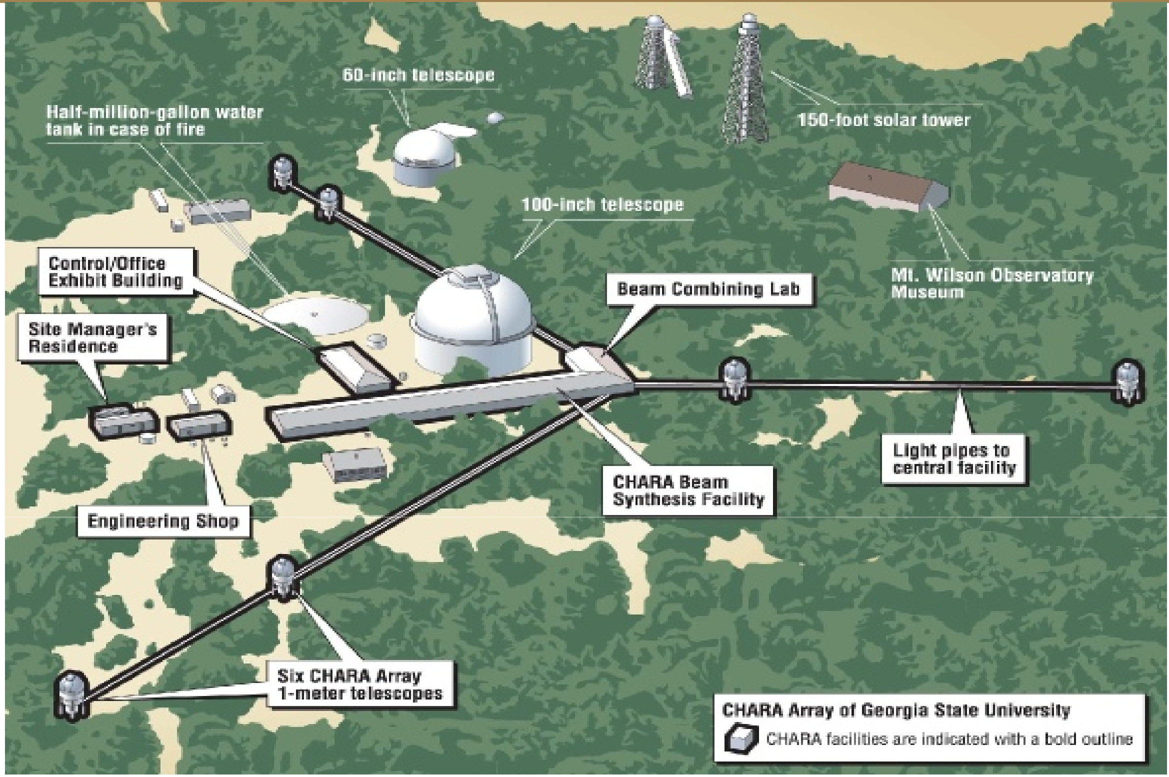


Computer rendering of the Thirty Meter Telescope, a planned 30 m telescope (2029).

Beyond monolithic telescopes: optical interferometry

An interferometric array is composed of multiple telescopes linked together. All the telescopes observe the same target simultaneously, so that their lights can be combined to form an interference pattern. From the patterns, images can be reconstructed.

Contrary to monolithic or segmented mirror, the angular resolution will depends on the distance between telescopes, not on the diameter of the telescopes.



GSU's Center for High Angular Resolution Astronomy (CHARA) - 6 x 1m telescopes, 330m maximum distance between telescopes

Beyond monolithic telescopes: GSU’s optical interferometer CHARA

The angular resolution achieved by current the CHARA array is equivalent to that of a 300m diameter telescope (milli-arcsecond scale).

The sensitivity is of course not equivalent to a telescope of that size, since the collecting surface of an interferometric array is that of the individual telescopes.

Modern optical interferometers have been in routine operation for 20-30 years and can now actually image the surface of stars.

Beyond monolithic telescopes: GSU’s optical interferometer CHARA

GSU astronomers working at the CHARA array

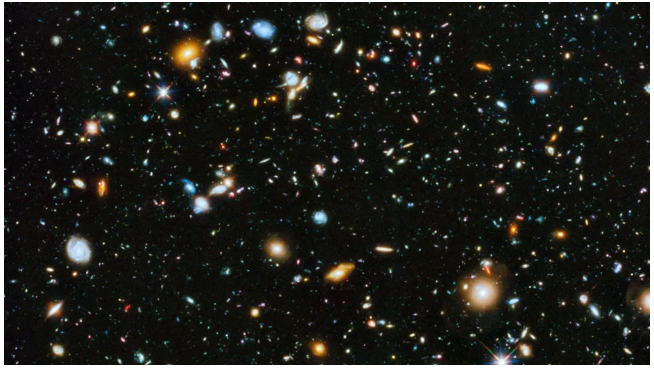
Beyond monolithic telescopes: the Very Large Telescope Interferometer

4 x 8.2m + 4 x 1.8m

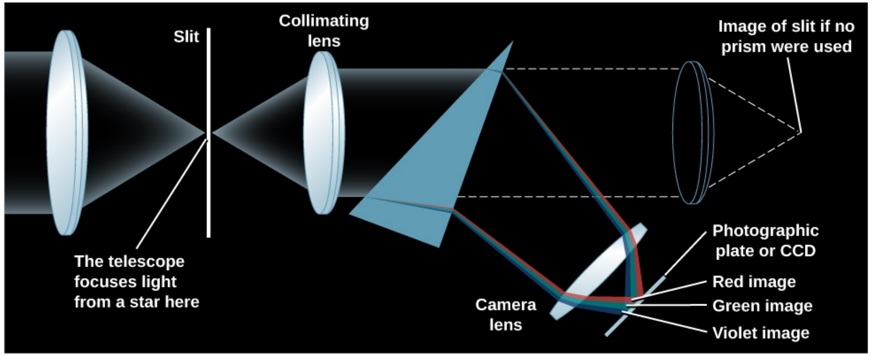
maximum distance between telescopes ~ 200m

What do astronomers do with telescopes?

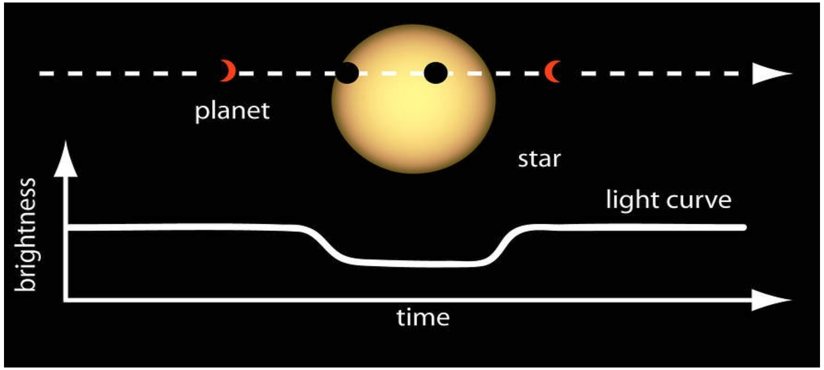
- Imaging: taking pictures of the sky



- Spectroscopy: breaking light into color components



- Photometry: a technique concerned with measuring the flux, or intensity of an astronomical object's light



Why take data at different wavelengths?

The same part of the sky looks different when observed with instruments that are sensitive to different bands of the spectrum. Gathering data at different wavelengths often provides complementary information on the studied objects.

Orion Region at Different Wavelengths:

a) a) Visible light: this shows part of the Orion region as the human eye sees it, with dotted lines added to show the figure of the mythical hunter, Orion.

(a) (b) (c)

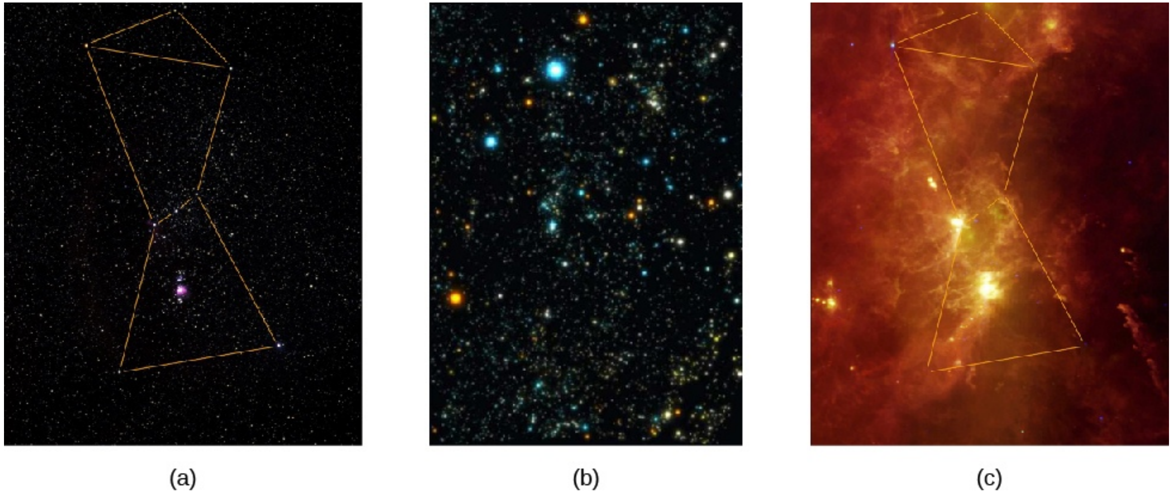
Credit
a: modification of work by Howard McCallon/NASA/IRAS
b: modification of work by Howard McCallon/NASA/IRAS;
c: modification of work by Michael F. Corcoran

Why take data at different wavelengths?

Orion Region at Different Wavelengths:

a) b) X-rays: here, the view emphasizes the point-like X-ray sources nearby. The colors are artificial, changing from yellow to white to blue with increasing energy of the X-rays. The bright, hot stars in Orion are still seen in this image, but so are many other objects located at very different distances, including other stars, star corpses, and galaxies at the edge of the observable universe.

b) c) Mid-infrared radiation: here, we mainly see the glowing dust in this region.



Credit
a: modification of work by Howard McCallon/NASA/IRAS
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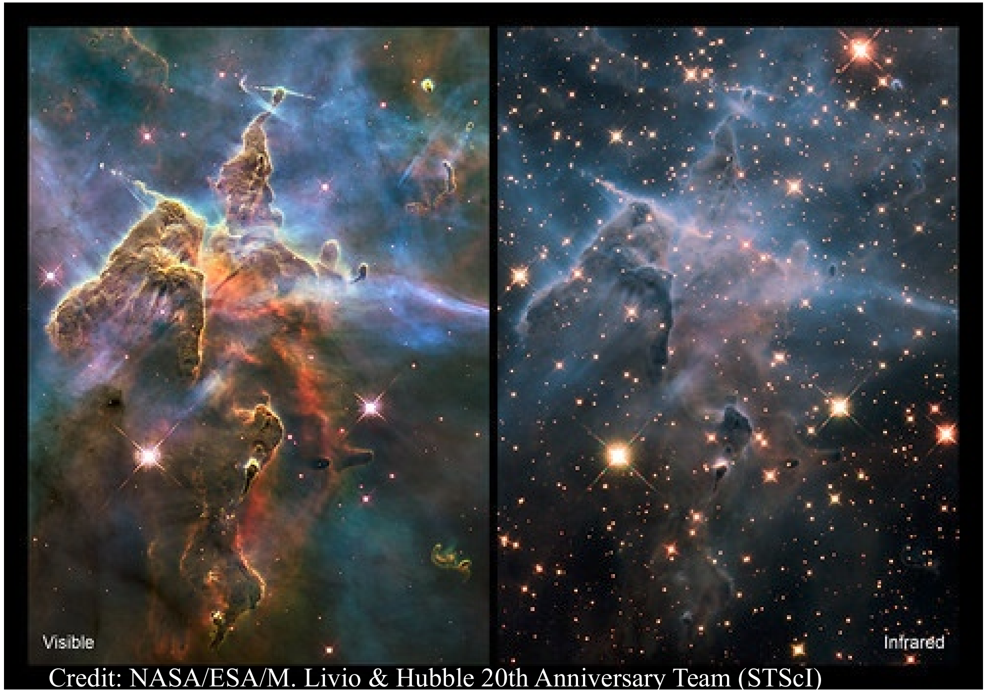
Visible vs infrared wavelengths

Infrared waves can penetrate places in the universe from which light is blocked, as shown in this infrared image where the plastic bag blocks visible light but not infrared.



Comparison of the Carina Nebula in visible light (left) and infrared (right), both images by Hubble. Infrared light can propagate more easily through dust, hence more stars can be seen in the infrared here.

Ground-based observations: ideal conditions

Best conditions for ideal observing:

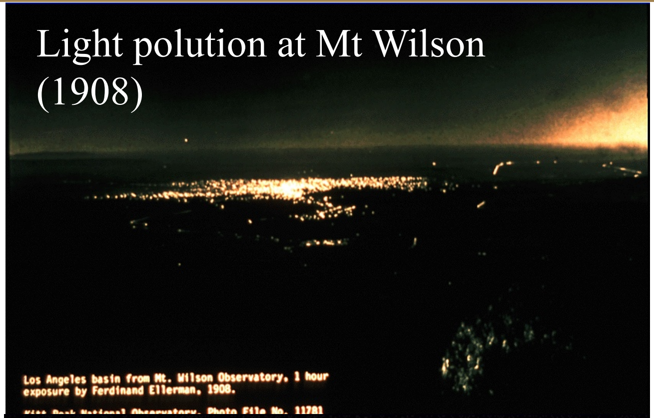
Calm (not too windy)

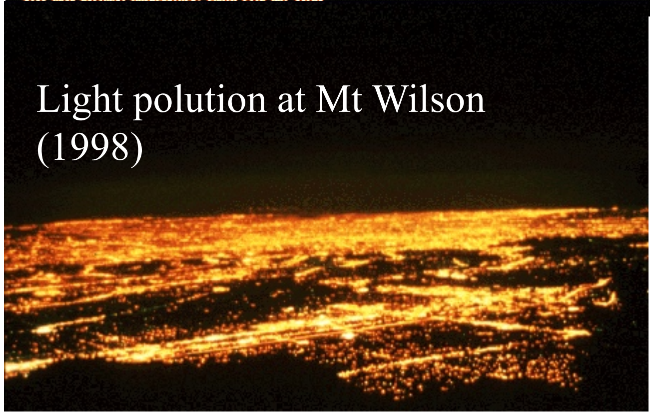
At high altitudes (less atmosphere to see through)

Dark (far from city lights)

Dry (few cloudy nights)

Hence modern observatories are often located atop remote mountains and/or in desertic areas.





Scattering of human-made light in the atmosphere is a growing problem for astronomy

Ground-based observations: ideal conditions

High and Dry Site. Cerro Paranal, a mountain summit 2.7 kilometers above sea level in Chile's Atacama Desert, is the site of the European Southern Observatory's Very Large Telescope. This photograph shows the four 8-meter telescope buildings on the site and vividly illustrates that astronomers prefer high, dry sites for their instruments. The 4.1-meter Visible and Infrared Survey Telescope for Astronomy (VISTA) can be seen in the distance on the next mountain peak.

Credit:

Ground-based observations: adaptive optics

Due to temperature inhomegeneities in the atmosphere ("turbulence"), stars **scintillate** and appear as twinkling dots. The typical size of a dot is of the order of the arcsecond.

In pratice, the angular resolution of a telescope is limited to the equivalent of that of a 10-cm telescope!

Professional astronomers can use **adaptive optics** systems to measure the atmospheric corruption of the images and compensate for them in real time using deformable mirrors.

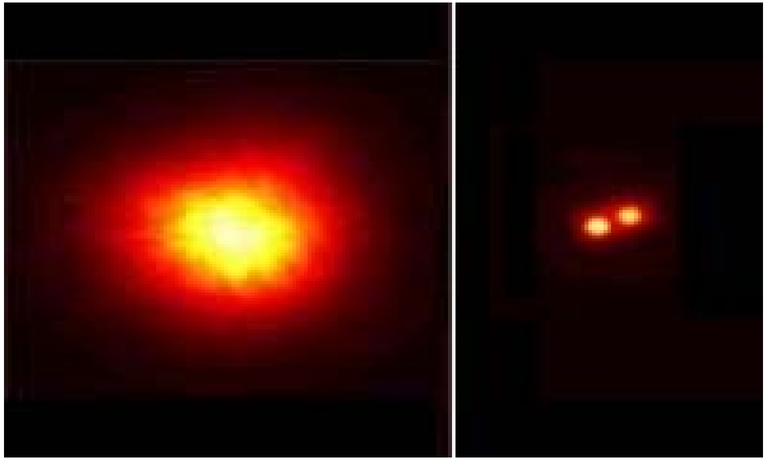


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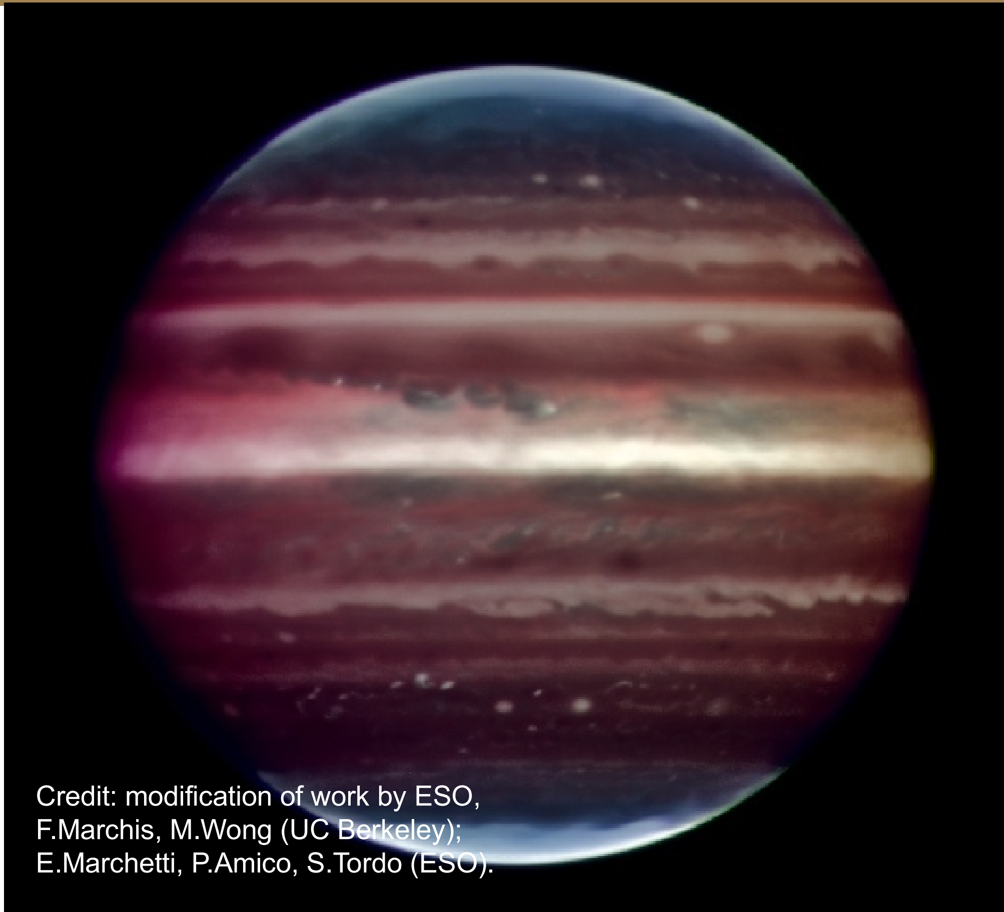
Image of a binary star taken with and without adaptive optics correction.

Ground-based observations: adaptive optics

One of the clearest pictures of Jupiter ever taken from the ground, this image was produced with adaptive optics using an 8-meter-diameter telescope at the Very Large Telescope in Chile. In this case, adaptive optics uses infrared wavelengths to remove atmospheric blurring, resulting in a much clearer image.



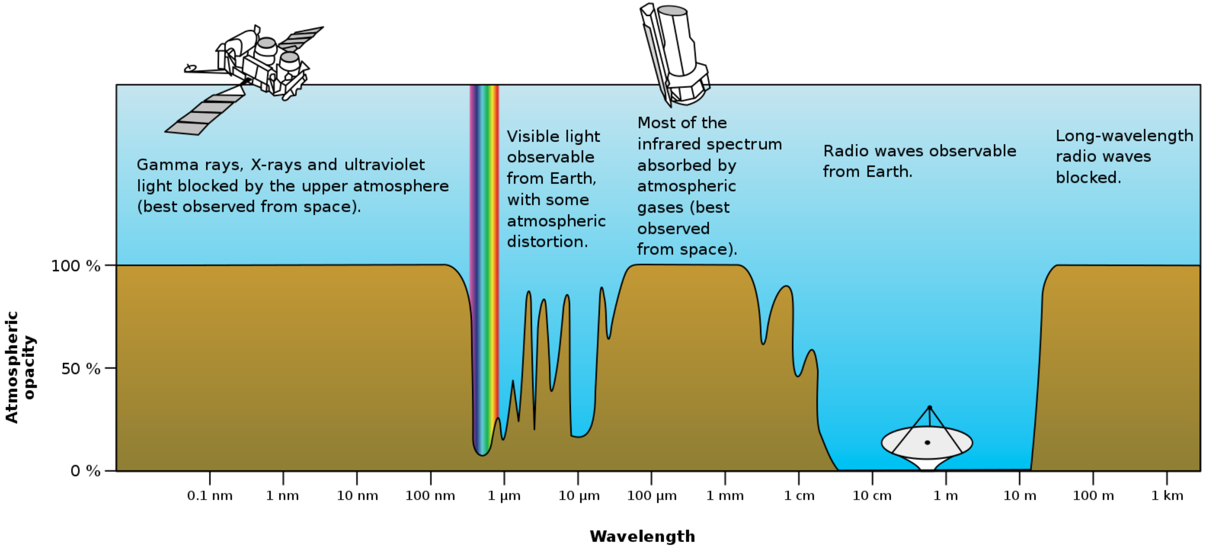
Credit: modification of work by ESO, F.Marchis, M.Wong (UC Berkeley); E.Marchetti, P.Amico, S.Tordo (ESO).

Ground vs space observations

Only visible, and near-infrared, and some radio light pass easily through Earth's atmosphere.

Even then they are subject to blurring and background light pollution.

Telescopes in space can observe other wavelengths with a pure sky.



Atmospheric transmission of Earth's atmosphere

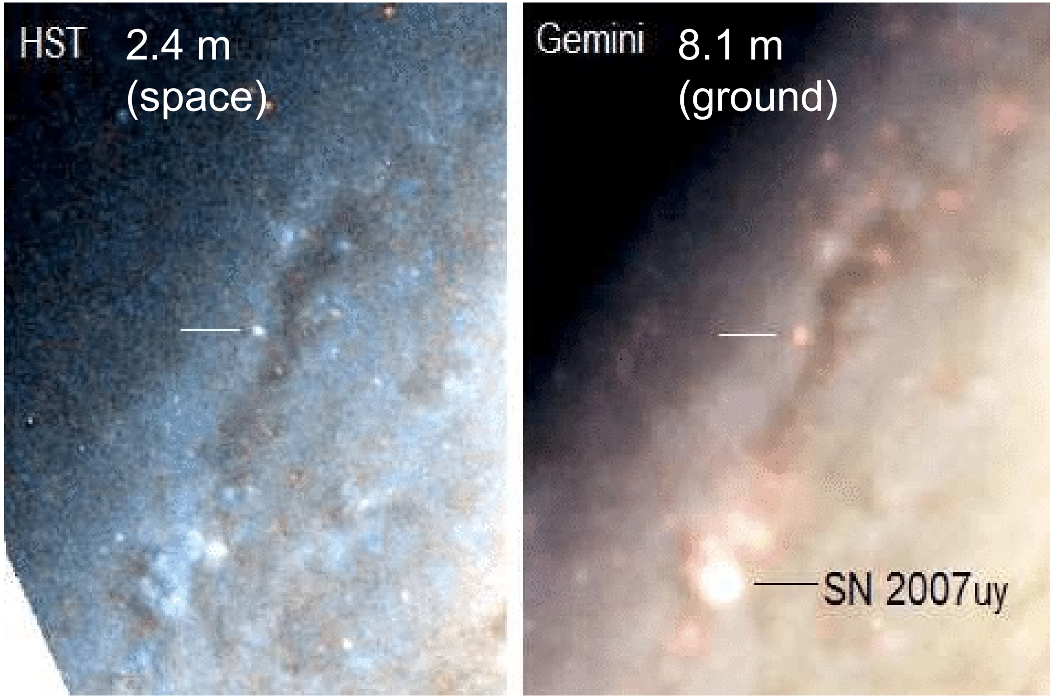
Ground vs space observations

Since space observations do not suffer from atmospheric perturbation, adaptive optics is not needed and the telescope resolution is only limited by its diameter.

However space is expensive!

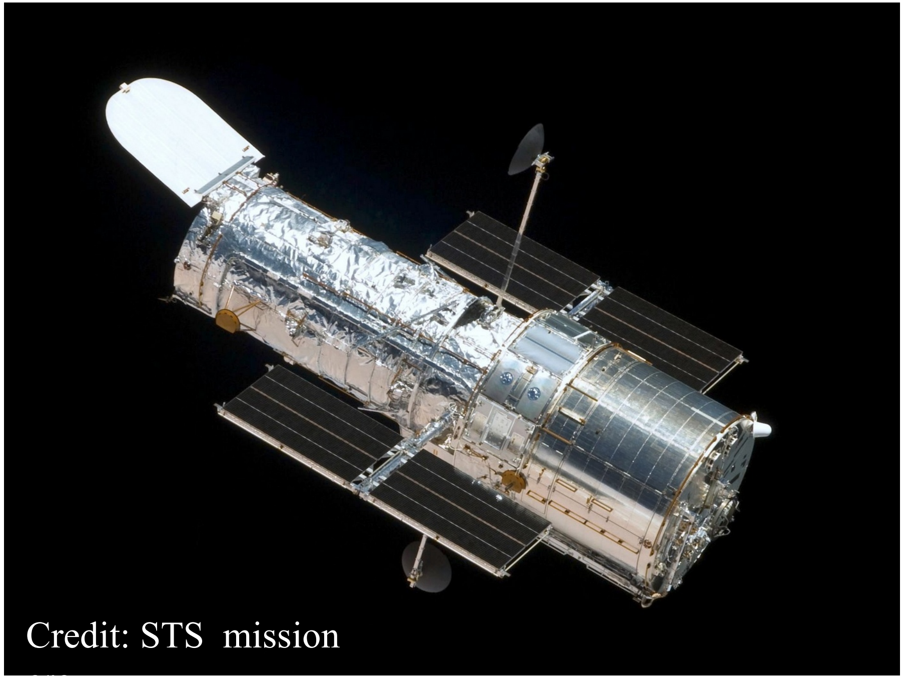
Hubble Space Telescope cost at launch: $4.7 billion.

Construction cost of both Gemini telescopes: $184 million.



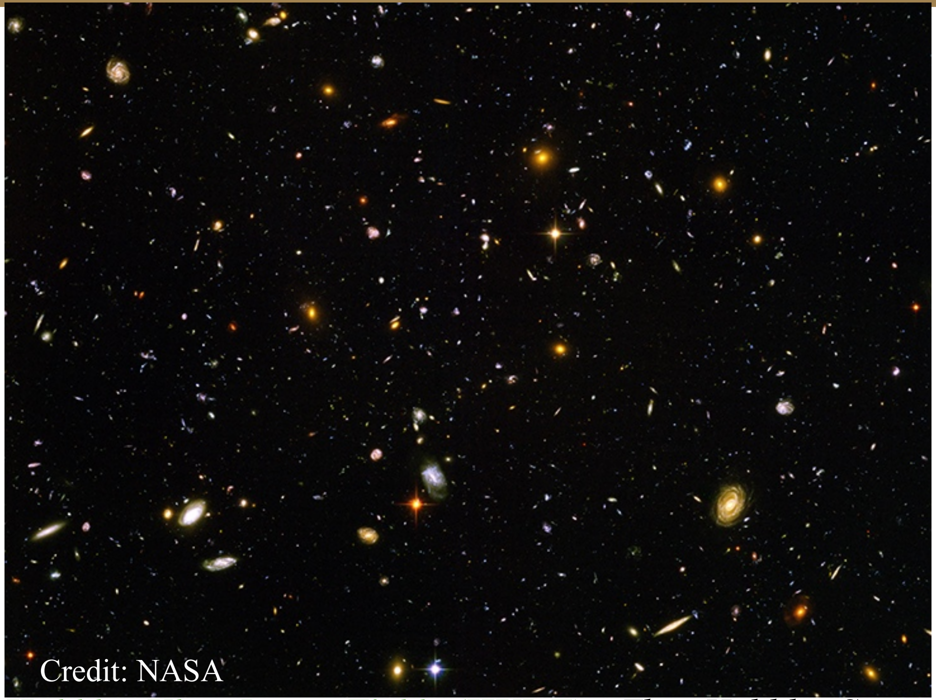
Images of the region 40 '' ×60 '' around SN 2015bh the galaxy NGC 2770.

The Hubble Space Telescope



Credit: STS mission

Launched in 1990 and still in operation, the HST is a 2.4m telescope carrying near-infrared, visible and ultraviolet instruments.



Credit: NASA

Hubble Ultra-Deep Field (HUDF). *The Hubble Space Telescope has provided an image of a specific region of space built from data collected between September 24, 2003, and January 16, 2004. These data allow us to search for galaxies that existed approximately 13 billion years ago.*

Future space telescope: James Webb Space Telescope (JWST)

The JWST launch is planned for Fall 2021. 6.5 m segmented mirror, and instruments from visible to mid-infrared.

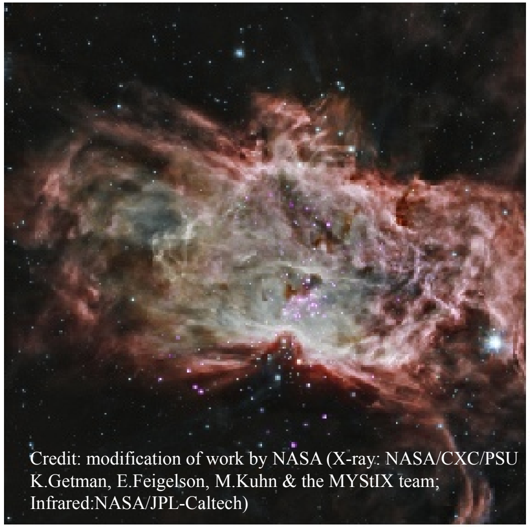
Early full-scale model on display at NASA Goddard (2005).

Mirrors of the JWST as they underwent cryogenic testing. The mirrors were exposed to extreme temperatures in order to gather accurate measurements on changes in their shape as they heated and cooled.

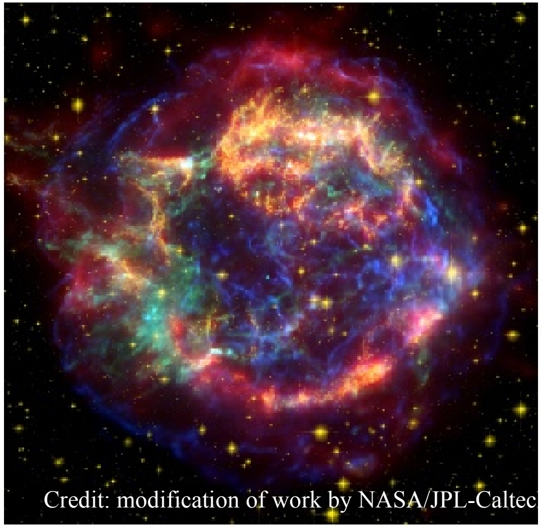
Stratospheric Observatory for Infrared Astronomy (SOFIA)

Not quite in space, SOFIA is onboard a plane and allows observations to be made above most of Earth's atmospheric water vapor, where 85% of the full infrared range is available.

The Spitzer Space Telescope (SST)



Flame nebula

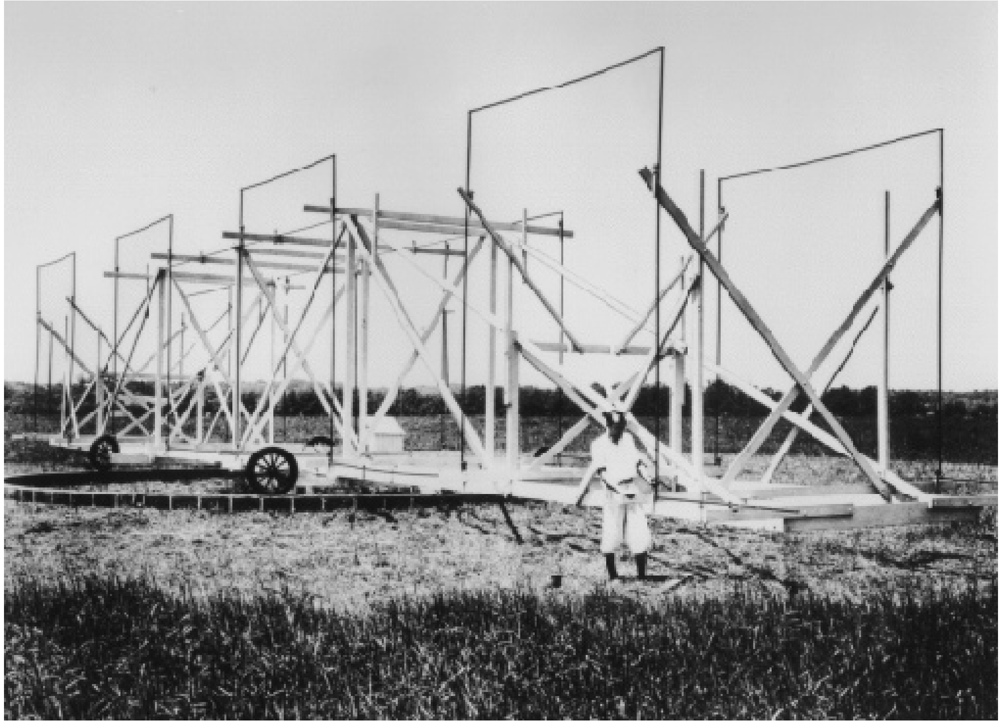


Cassiopeia A

Helix nebula

These SST was a telescope (2003-2020) with instruments in the infrared. Here images show a region of star formation, the remnant of an exploded star, and a region where an old star is losing its outer shell. The colors in these images have been selected by astronomers to highlight details like the composition or temperature in these regions.

Beyond optics: radio astronomy

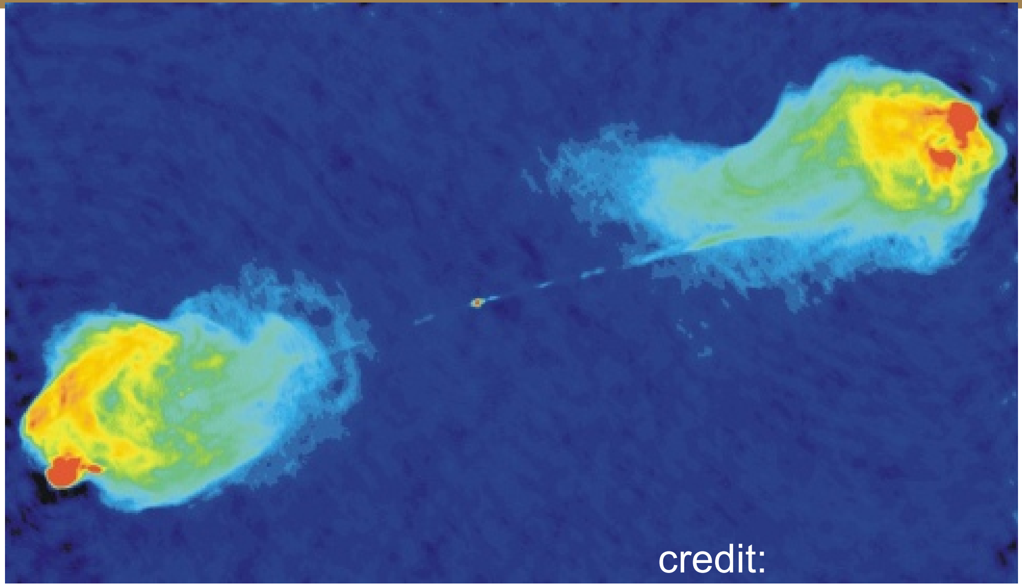


First Radio Telescope: *This rotating radio antenna was used by Jansky in his serendipitous discovery of radio radiation from the Milky Way.*

The Robert C. Byrd Green Bank Telescope is a *fully steerable radio telescope in West Virginia that went into operation in August 2000 and about 100 meters across.*

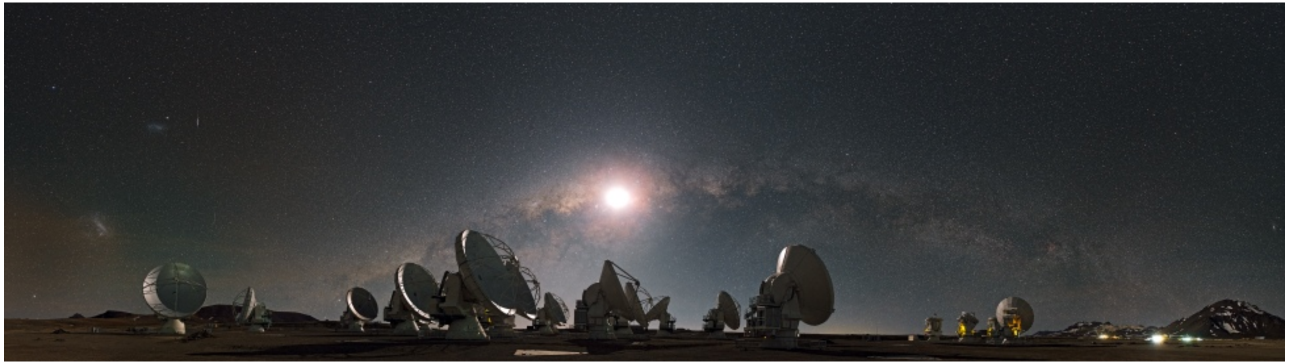
Beyond optics: radio interferometry

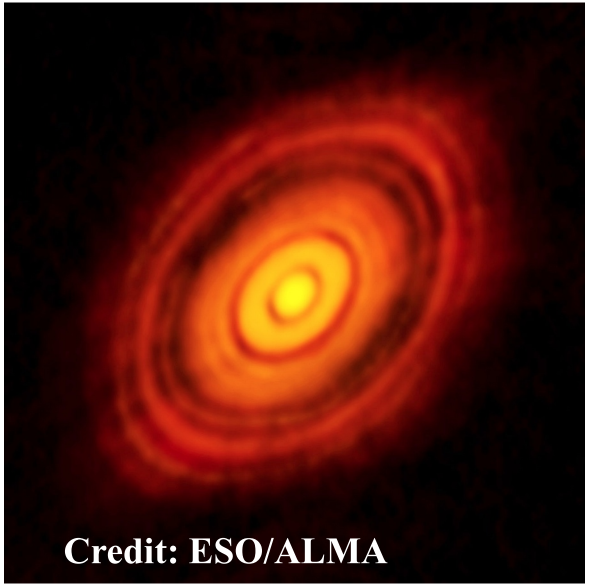
The Very Large Array (VLA) radio interferometric observatory, New Mexico.



Reconstruction from radio observations at the VLA of the galaxy Cygnus A. Colors have been added to help the eye sort out regions of different radio intensities. Red regions are the most intense, blue the least. The visible galaxy would be a small dot in the center of the image. The radio image reveals jets of expelled material on either side of the galaxy.

Beyond optics: radio interferometry

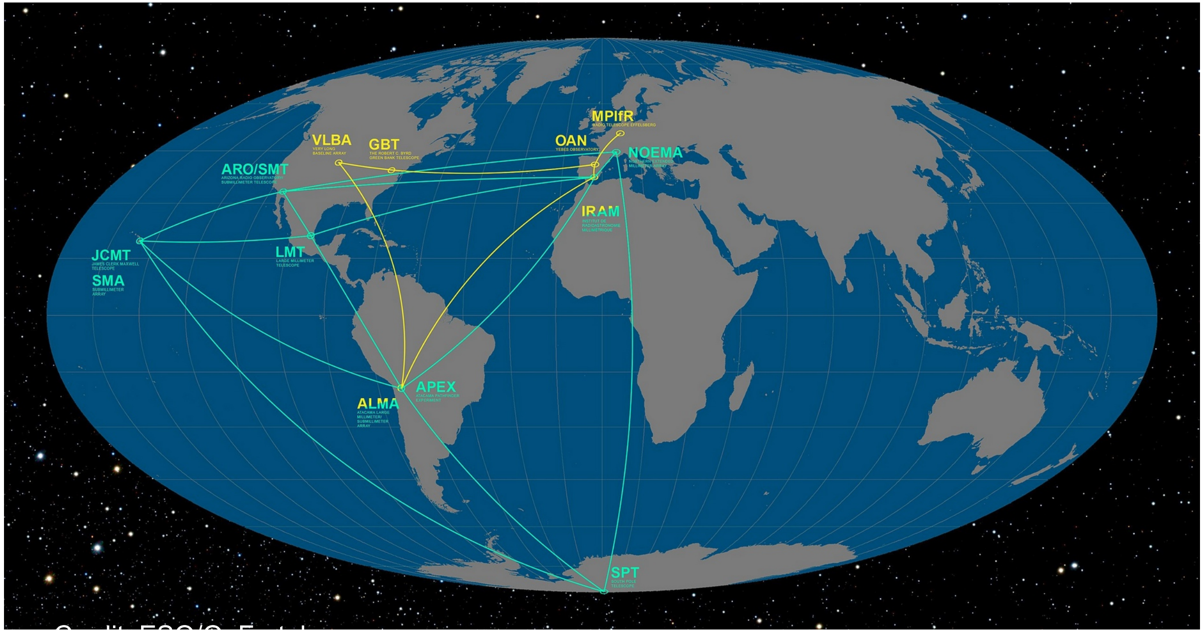




Atacama Large Millimeter/Submillimeter Array (ALMA). *Located in the Atacama Desert of Northern Chile, ALMA is the interferometric facility that currently provides the highest resolution for radio observations by observing at millimiter wavelengths.*

ALMA image of the protoplanetary disc around HL Tauri - This is the sharpest image ever taken by ALMA — sharper than is routinely achieved in visible light with the NASA/ESA Hubble Space Telescope. It shows the protoplanetary disc surrounding the young star HL Tauri.

Beyond optics:
very long baseline radio interferometry



Longer distances between telescopes lead to better resolution. This infographic details the locations of the participating arrays of the Event Horizon Telescope (EHT) and the Global mm-VLBI Array (GMVA).

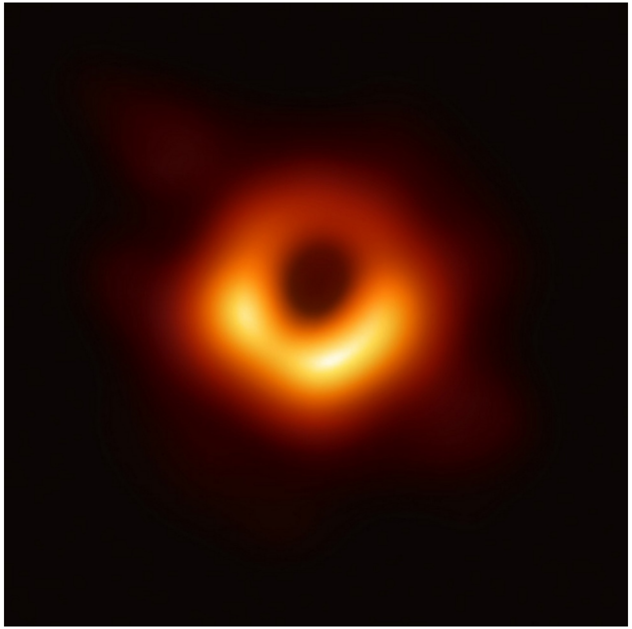
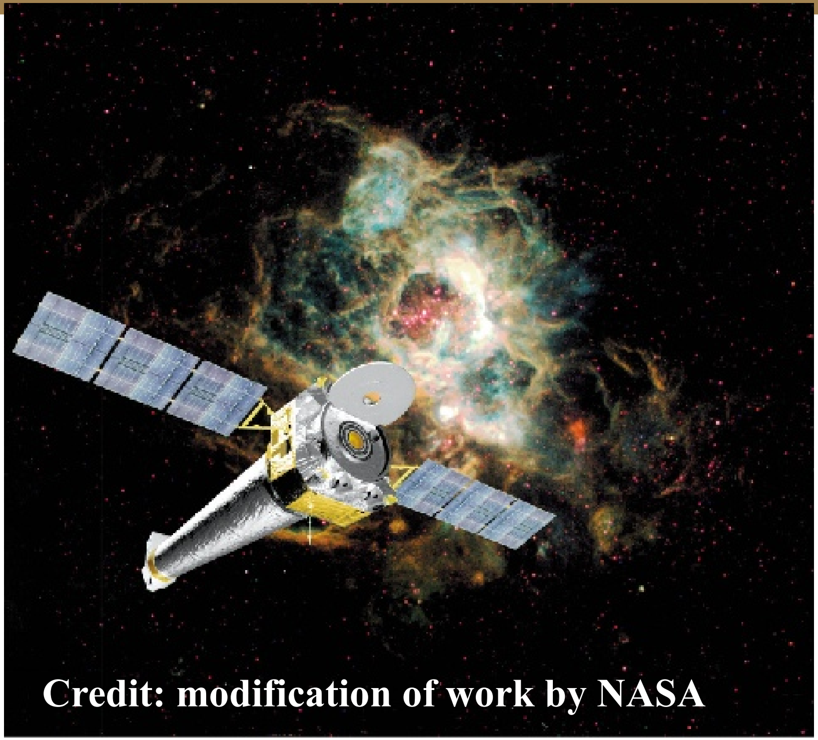


Image of M87 generated from data gathered by the Event Horizon Telescope in 2017.*

Beyond optical: X-ray astronomy


Credit: modification of work by NASA

Chandra X-Ray Satellite. Chandra, the world’s most powerful X-ray telescope, was developed by NASA and launched in July 1999.

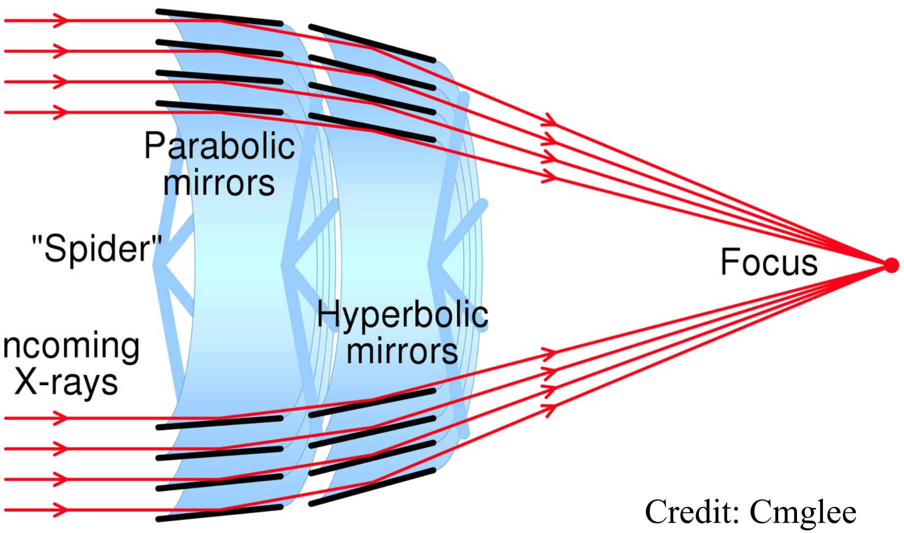
XMM-Newton developped by ESA and lauched in December 1999**.** Here a mock-up at Cité de l'Espace in Toulouse (France).


Credit: Poppy/wikipedia

Beyond optical: X-ray astronomy

X-ray traces very hot gas (millions of degrees)

X-ray astronomers can use high altitude balloons. Here, the High Energy Focusing Telescope balloon.

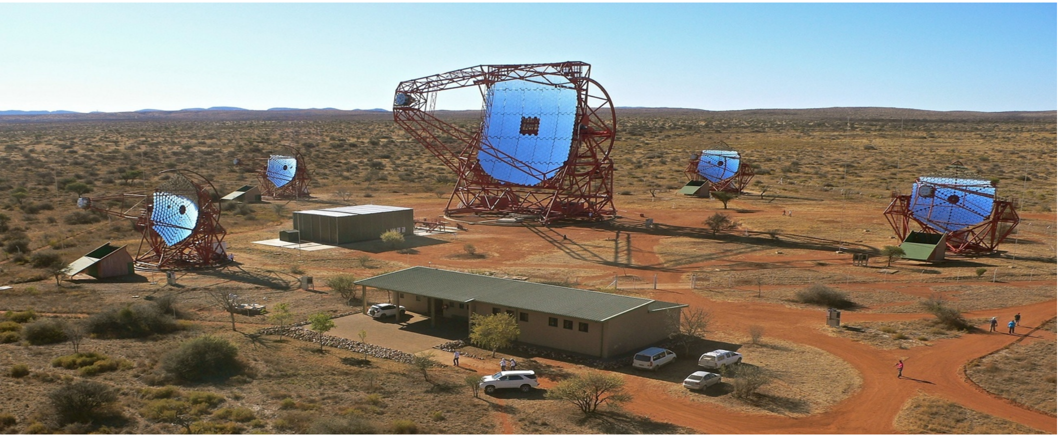


Credit: Cmglee

Focusing of X-rays requires special mirrors to focus X-ray photons through grazing bounces off the mirror surfaces.

Beyond optical: gamma ray astronomy

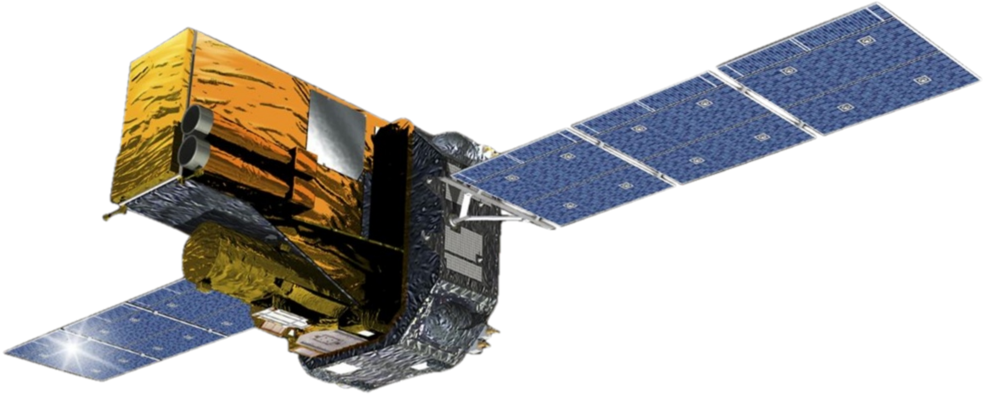
Gamma rays come from stellar corpses, explosions, energetic and distant galaxies



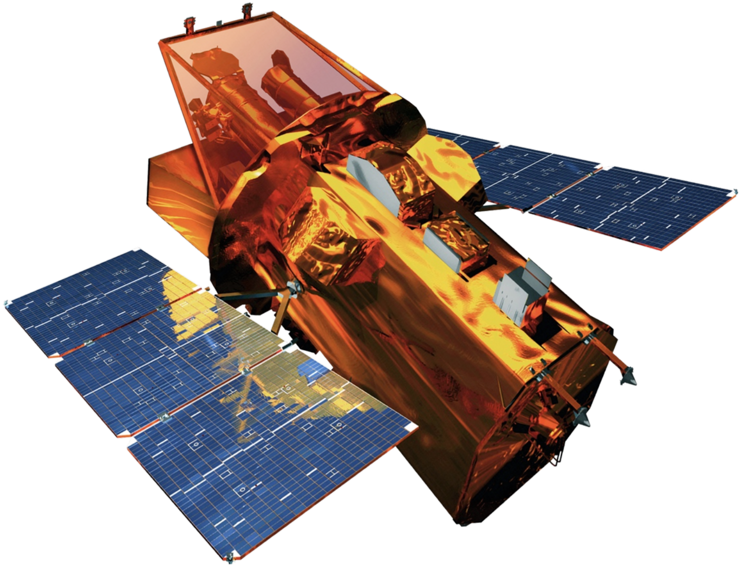
Most ground-based gamma ray telescopes are giant light buckets (low optical quality mirrors) called Cherenkov telescopes. Here the H.E.S.S. II five-telescope gamma-ray experiment in Namibia.

Detecting gamma rays can be done with any optical elements. Here a closeup of the HAWC gamma ray detector tanks. Each tank contains circa 188,000 liters of water and four photomulitplier tubes.

Beyond optical: gamma ray astronomy



ESA's INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL)



NASA's Swift Gamma Ray Burst Detecting Satellite

Credits