Introduction to Astrophysics and Cosmology

Introduction to astrophysics

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Unit of mass

What do you think?

Unit of mass

Astrophysics deals with objects that are generally very much larger or further than everyday objects.

For mass measurements **Solar mas** is used most often: $M_\odot$

$M_\odot = 1.99 \times 10^{30}$ kg.

Examples:

- The masses of most stars lie within a relatively narrow range from $0.1M_\odot$ to $20_\odot$
- The mass of a typical galaxy can be $10^{11}M_\odot$.
- Globular clusters, which are dense clusters of stars having nearly spherical shapes, typically have masses around $10^5M_\odot$

Unit of length

What do you think?

Unit of length

The average distance of the Earth from the Sun is called the ***Astronomical Unit*** (AU). Its value is:
AU = 1.50×10^{11} m.

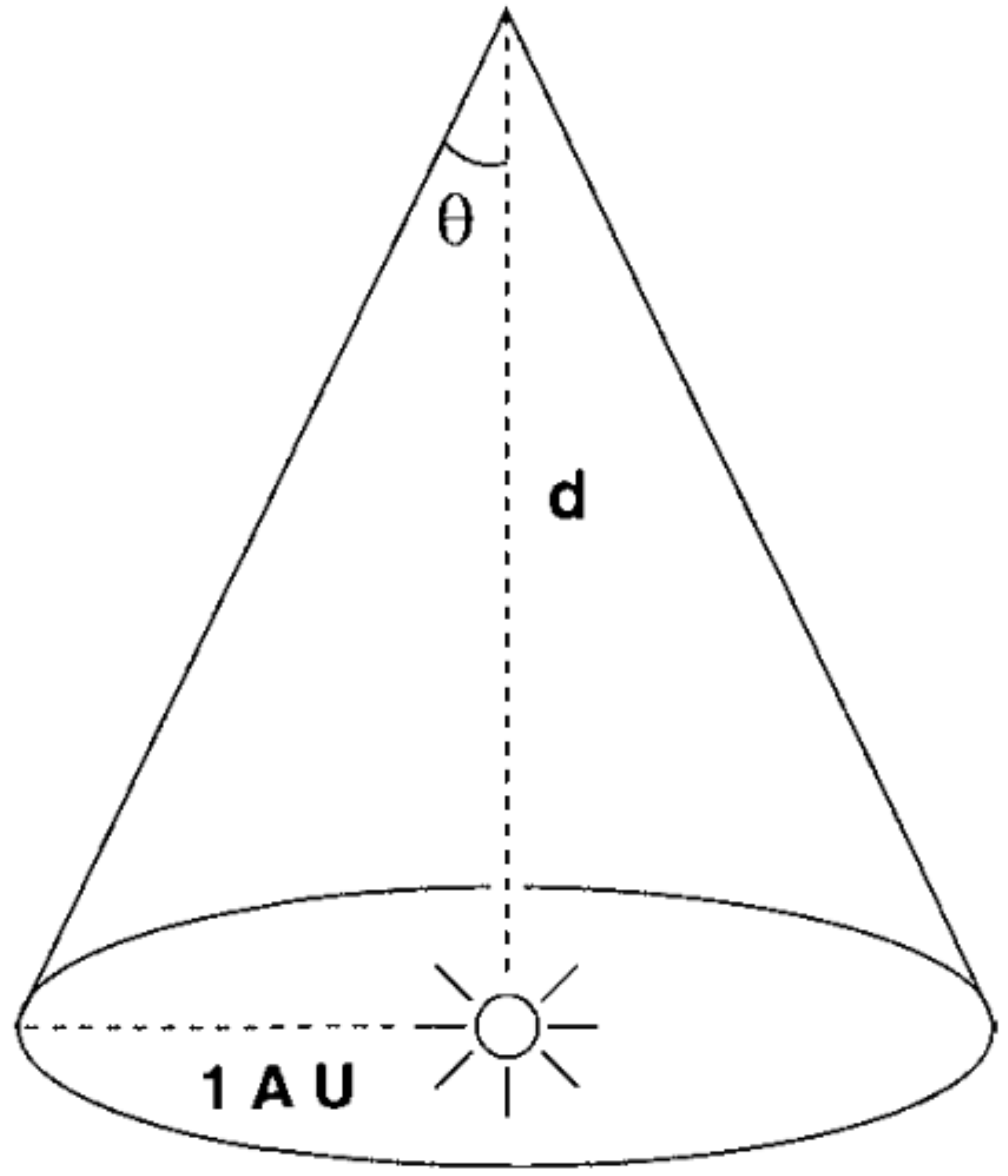
As the Earth goes around the Sun, the nearby stars seem to change their positions very slightly with respect to the faraway stars. This phenomenon is known as ***parallax*.**

Let us consider a star on the polar axis of the Earth's orbit at a distance *d* away, as shown in the figure. The angle θ is half of the angle by which this star appears to shift with the annual motion of the Earth and is defined to be the parallax. It is given by

$$\theta = \frac{1\ \mathrm{AU}}{d}$$

The *parsec* (pc) is the distance where the star has to be so that its parallax turns out to be 1". (1" is equal to π/(180 × 60 × 60) radians)

pc = 3.09×10^{16} m.



Definition of a parsec (d)

Unit of length

It may be noted that 1 pc is equal to 3.26 light years (not used much in astronomy)

For even larger distances, the standard units are **kiloparsec** (10^3 pc, kpc), **megaparsec** (10^6 pc, Mpc) and **gigaparsec** (10^9 pc, Gpc).

Examples:

- The nearest star, Proxima Centauri, is at about a distance of 1.31 pc.
- Our Galaxy and many other galaxies like ours are shaped like disks with thickness of order 100 pc and radius of order 10 kpc. The geometric mean between these two distances, which is 1 kpc, may be taken as a measure of the galactic size.
- The Andromeda Galaxy, one of the nearby bright galaxies, is at a distance of about 0.74 Mpc.
- The distances to very faraway galaxies are of order Gpc

Unit of time

What do you think?

Unit of time

Astrophysics uses many timescales from the age of the Universe is of the order of a few billion years to the same of pulsars which emit pulses periodically after intervals of fractions of a second.

Astrophysicists use **years** for large time scales and **seconds** for small time scales, the conversion factor being

yr = 3.16×10^7 s.

gigayear (10^9 yr, Gyr) is often used

The stars typically live for millions to billions of years. The age of the Sun is believed to be about 4.5 Gyr.

Table 1.1 Approximate conversion factors to be memorized.

$M_\odot$	$\approx$	2×10^{30} kg
pc	$\approx$	3×10^{16} m
yr	$\approx$	3×10^{7} s

Celestial Coordinates

The sky appears as a spherical surface above our heads. We call it the *celestial sphere*.

These coordinates are defined in such a way that faraway stars which appear immovable with respect to each other have fixed coordinates.

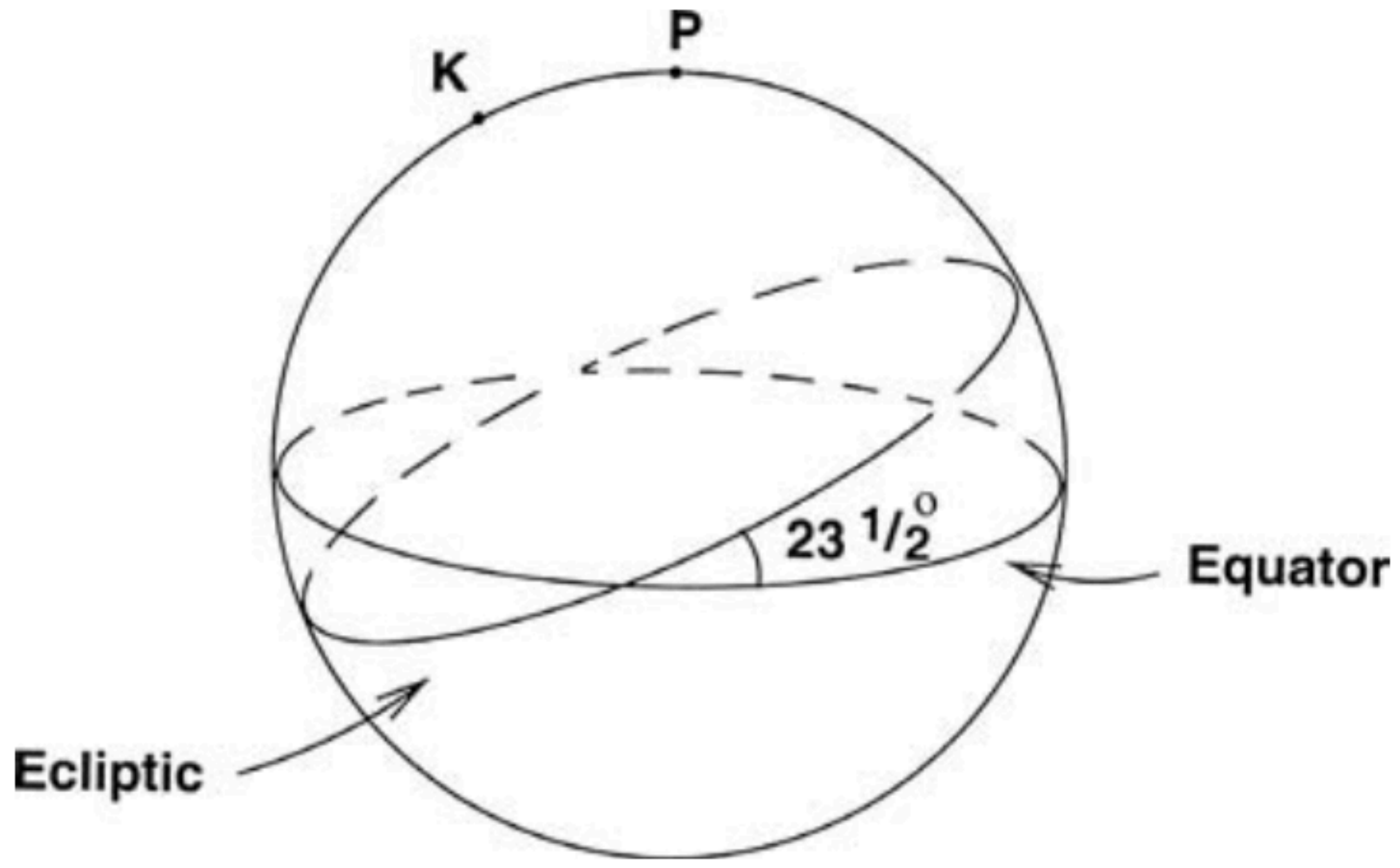
Position can be defined similarly to the latitude and longitude on Earth's surface.

Declination (δ) ~ latitude

Right ascension (R.A.) ~ longitude

The points where the Earth's rotation axis would pierce the celestial sphere are called ***celestial poles***

The great circle on the celestial sphere vertically above the Earth's equator is called the ***celestial equator***

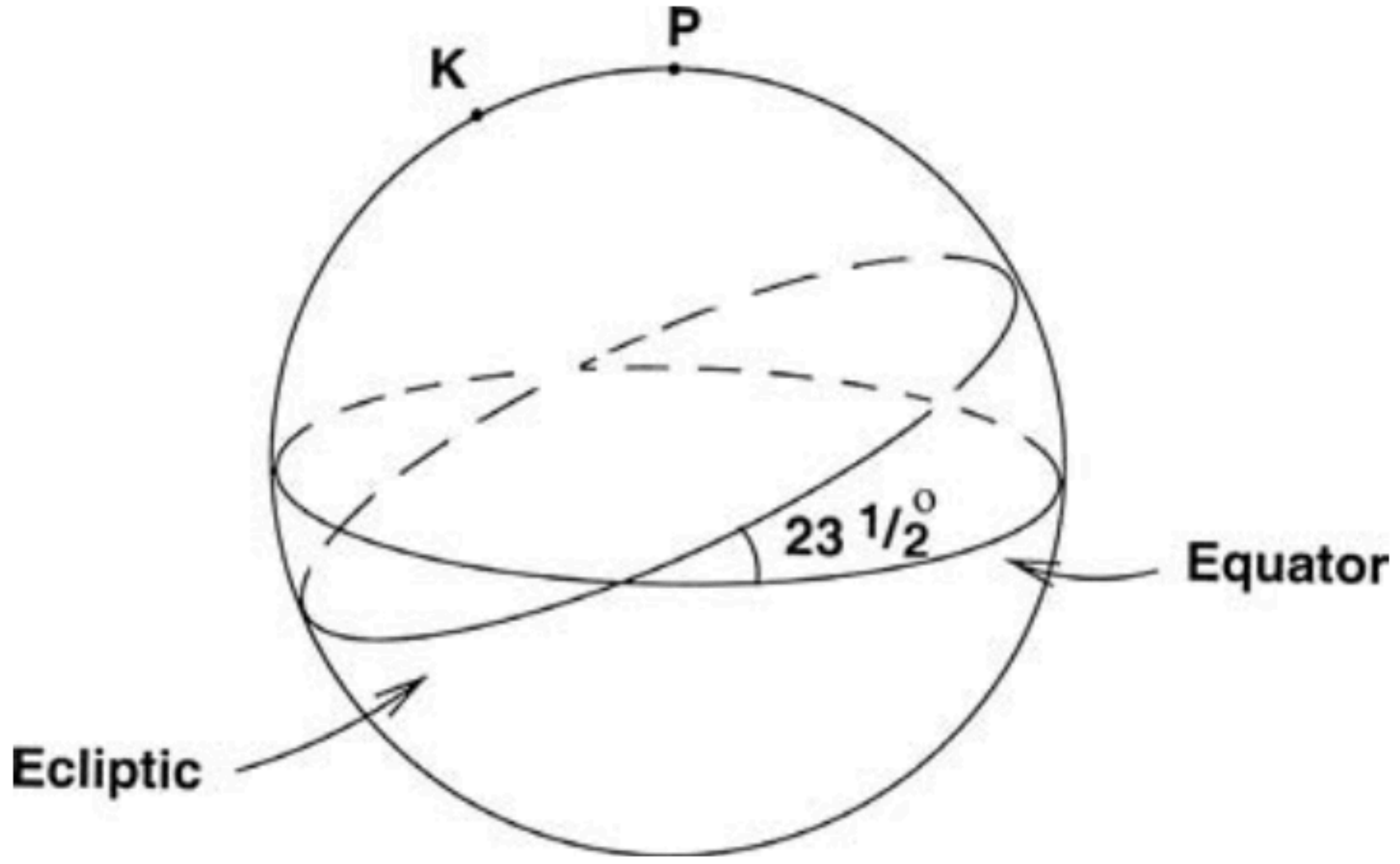


P is the celestial pole and K is the pole of the ecliptic.

Celestial Coordinates

Just as the zero of longitude is fixed by taking the longitude of Greenwich as zero, we need to fix the zero of R.A. for defining it.

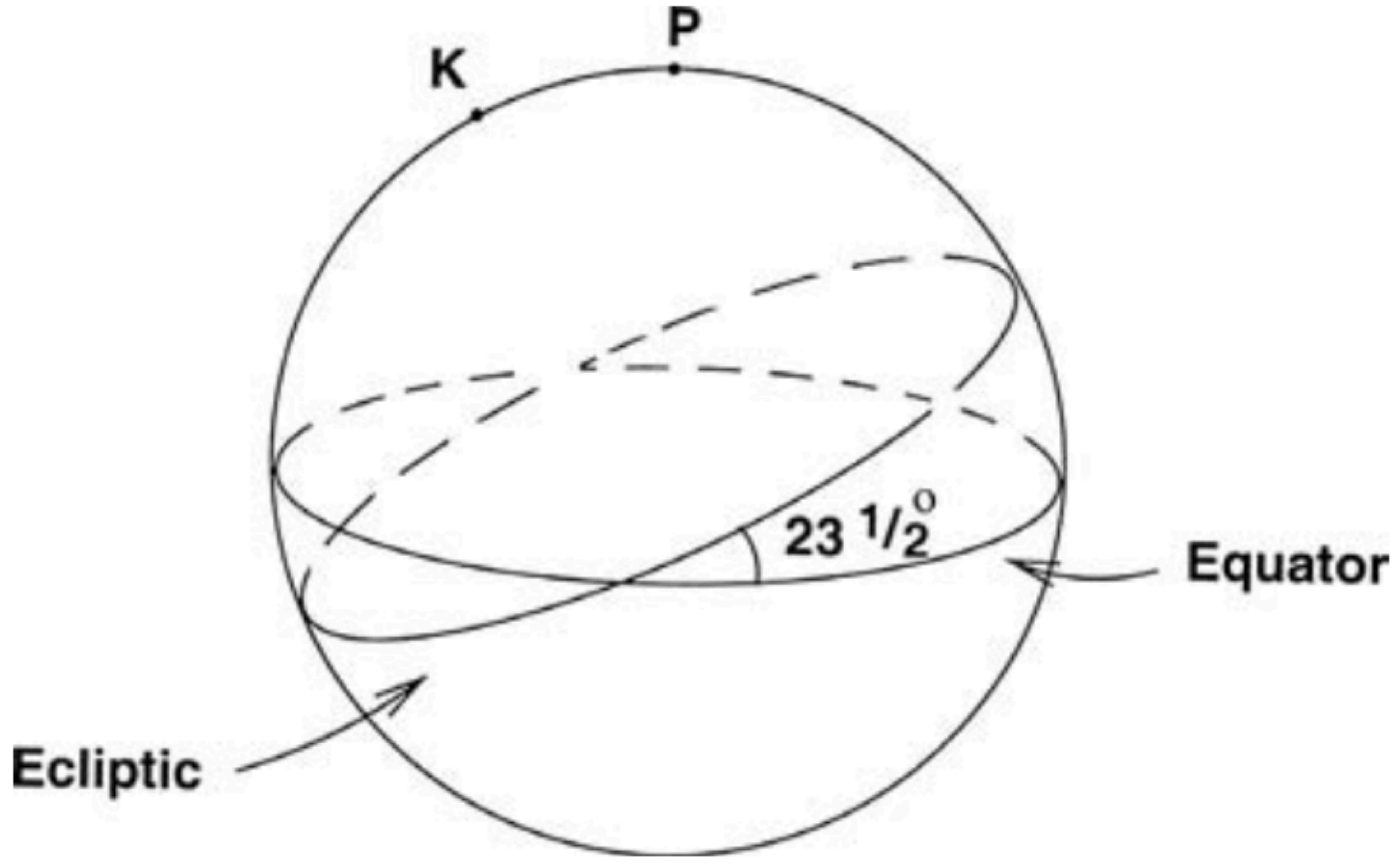
- This is done with the help of a great circle called the ***ecliptic***.
- Since the Earth goes around the Sun in a year, the Sun's position with respect to the distant stars, as seen by us, keeps changing and traces out a great circle in the sky. The ecliptic is this great circle.
- Twelve famous constellations (known as the *signs of the zodiac*) appear on the ecliptic. It was noted from almost prehistoric times that the Sun happens to be in different constellations in different times of the year.



P is the celestial pole and K is the pole of the ecliptic.

Celestial Coordinates

- The celestial equator and the ecliptic are inclined at an angle of about 23.5 deg and intersect at two points.
- One of these points, lying in the constellation Aries, is taken as the zero of R.A. When the Sun is at this point, we have the vernal equinox.
- It is a standard convention to express the R.A. in hours rather than in degrees.
- The celestial sphere rotates around the polar axis by 15 deg in one hour. Hence one hour of R.A. corresponds to 15 deg.



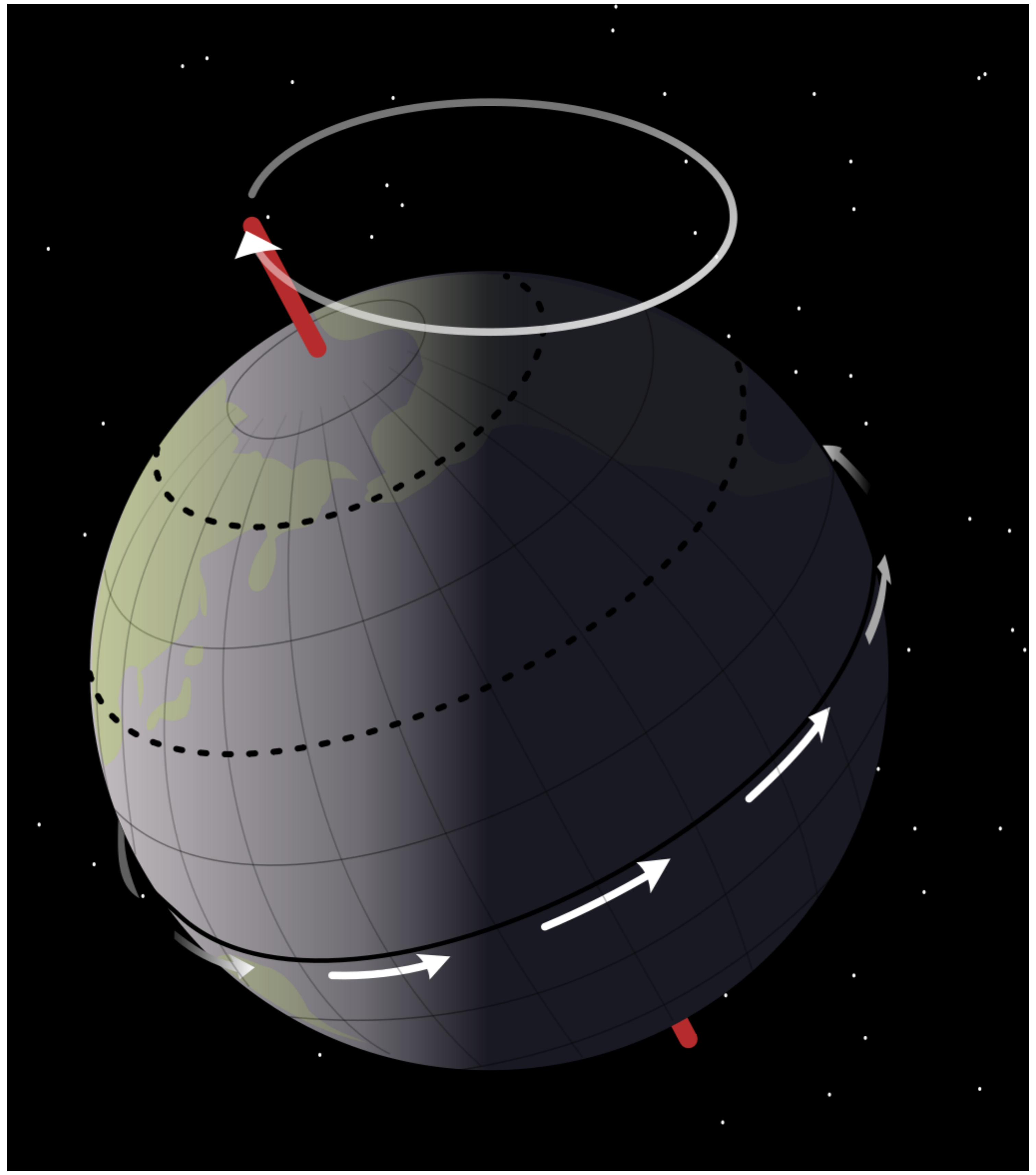
P is the celestial pole and K is the pole of the ecliptic.

Celestial Coordinates

The declination and R.A. are basically defined with respect to the rotation axis of the Earth, which fixes the celestial poles and equator.

One problematic aspect of introducing coordinates in this way is that the **Earth's rotation axis is not fixed**, but precesses around an axis perpendicular to the plane of the Earth's orbit around the Sun. This means that the point P celestial pole in traces out an approximate circle in the celestial sphere slowly in about 25,800 years, around the pole K of the ecliptic.

This phenomenon is called ***precession*** and was discovered by Hipparchus (second century BC) by comparing his observations with the observations made by earlier astronomers about 150 years previously.



https://en.wikipedia.org/wiki/Axial_precession

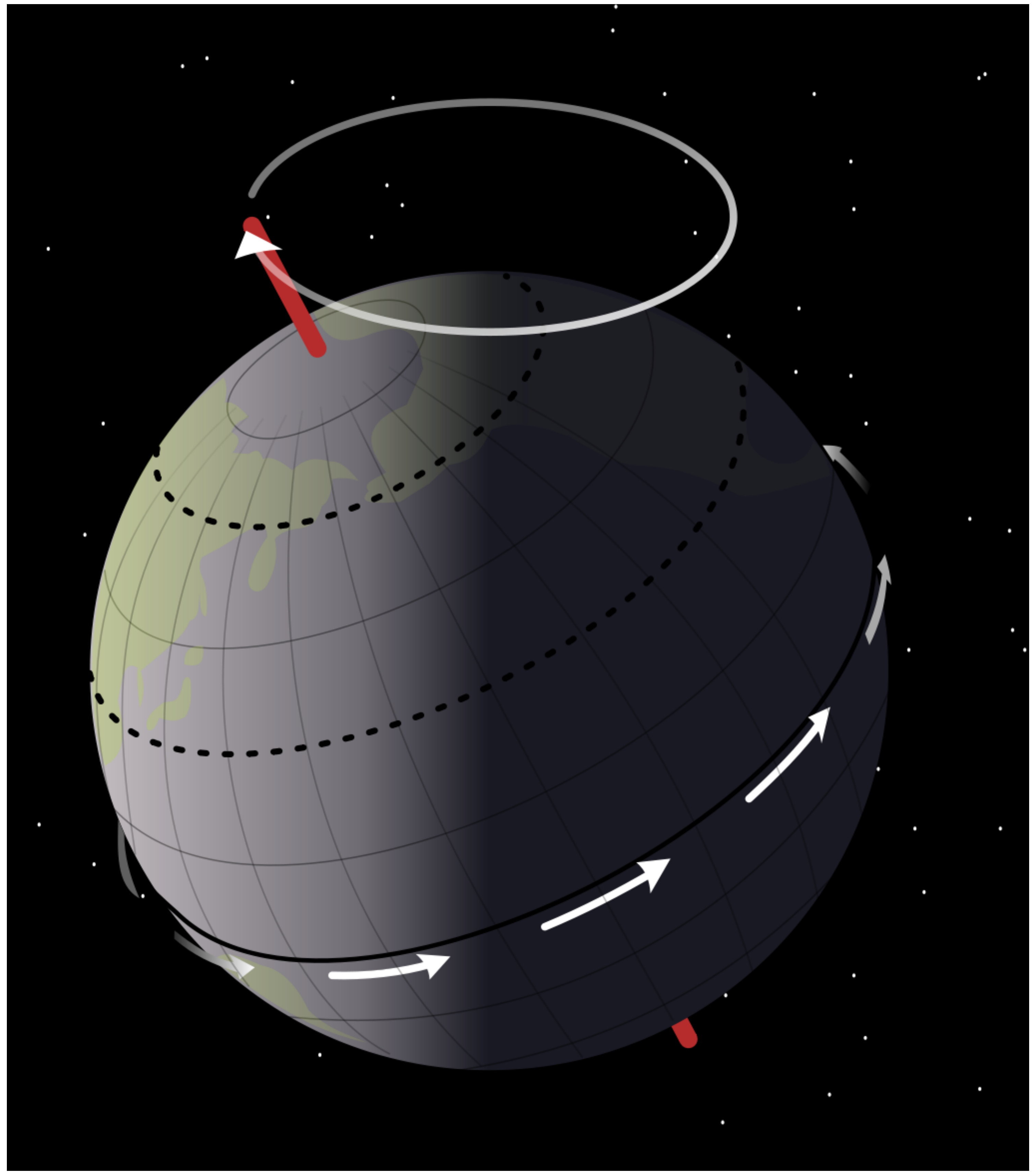
Celestial Coordinates

The precession is caused by the gravitational torque due to the Sun acting on the Earth and can be explained from the dynamics of rigid bodies.

Due to precession, the positions of the celestial poles and the celestial equator keep changing slowly with respect to fixed stars. Hence, **if the declination and the R.A. of an astronomical object at a time are defined with respect to the poles and the equator at that time, then certainly the values of these coordinates will keep changing with time.**

The current **convention** is to use the coordinates defined with respect to the positions of the poles and the equator in the year 2000.

This equatorial coordinate system is actually very practical for telescopes for observing.



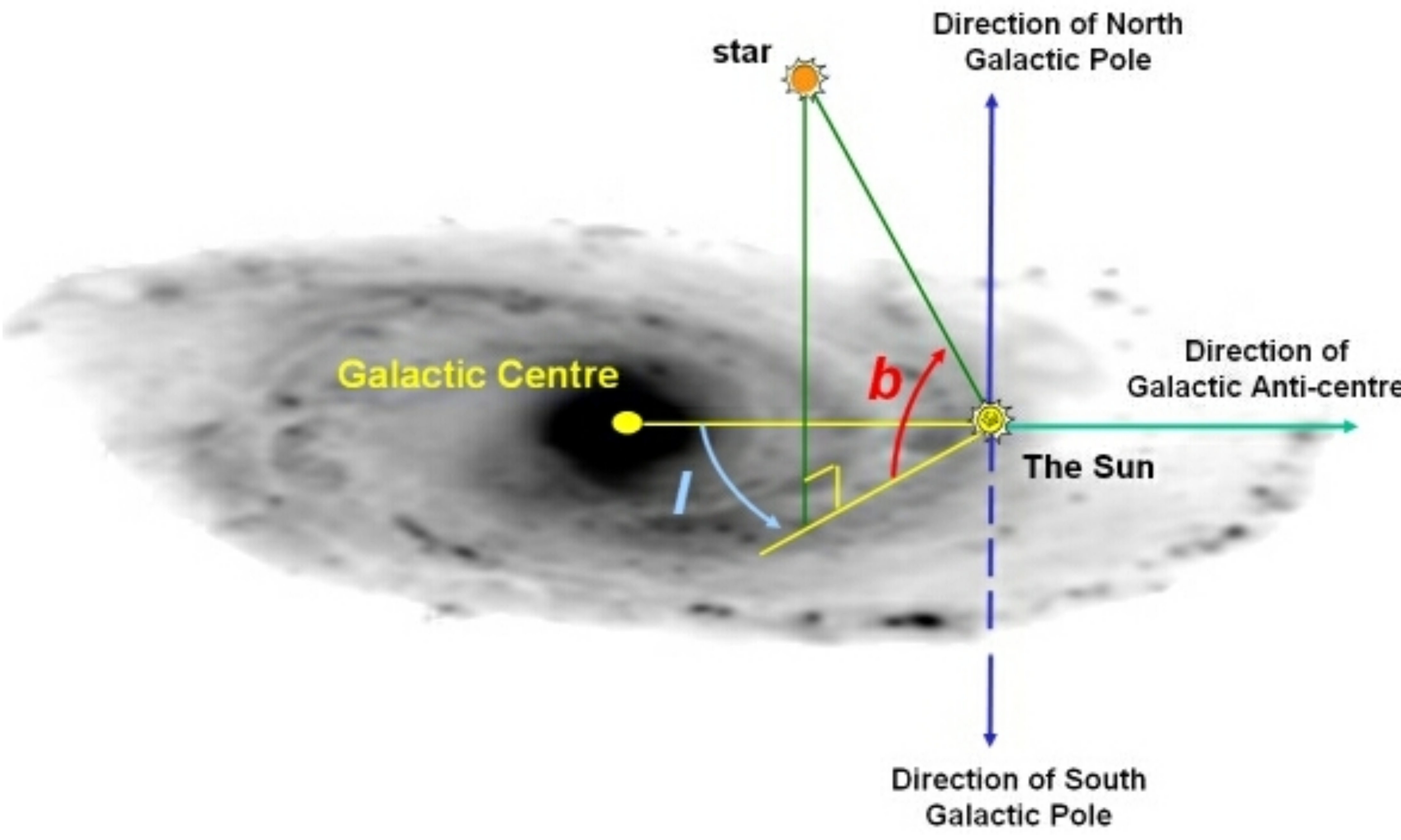
https://en.wikipedia.org/wiki/Axial_precession

Other coordinate systems

Which other coordinate systems are used?

Other coordinate systems

- There is another coordinate system, called ***galactic coordinates*,** widely used in galactic studies. In this system, the plane of our Galaxy is taken as the equator and the direction of the galactic centre as seen by us (in the constellation Sagittarius) is used to define the zero of longitude. (Coordinates: l, b)
- The **supergalactic coordinate system** corresponds to a fundamental plane that contains a higher than average number of local galaxies in the sky as seen from Earth.



https://astronomy.swin.edu.au/cosmos/G/Galactic+Coordinate+System

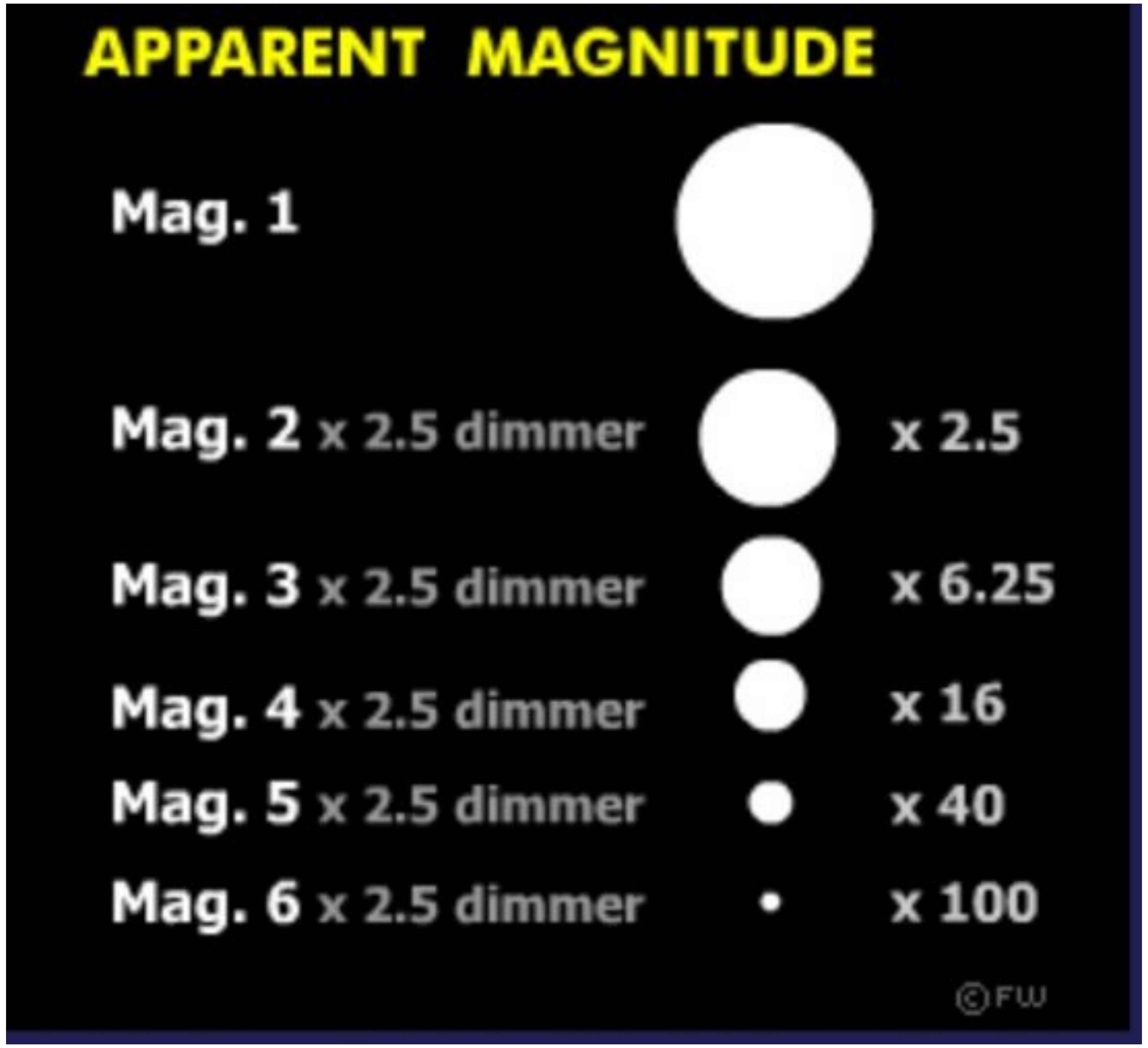
What do we use to quantify the brightness of objects?

The magnitude scale

The magnitude scale for describing apparent brightnesses of celestial objects is a logarithmic scale, because the human eye is more sensitive to a geometric progression of intensity rather than an arithmetic progression.

On the basis of naked eye observations, the Greek astronomer Hipparchus (second century BC) classified all the stars into **six classes** according to their apparent brightnesses.

A quantitative basis of the magnitude scale was given by Pogson (1856) by noting that the faintest stars visible to the naked eye are about 100 times fainter compared to the brightest stars. Since the brightest and faintest stars differ by five magnitude classes, **stars in two successive classes should differ in apparent brightness by a factor $(100)^{1/5}$.**



https://earthsky.org/astronomy-essentials/what-is-stellar-magnitude/

The magnitude scale

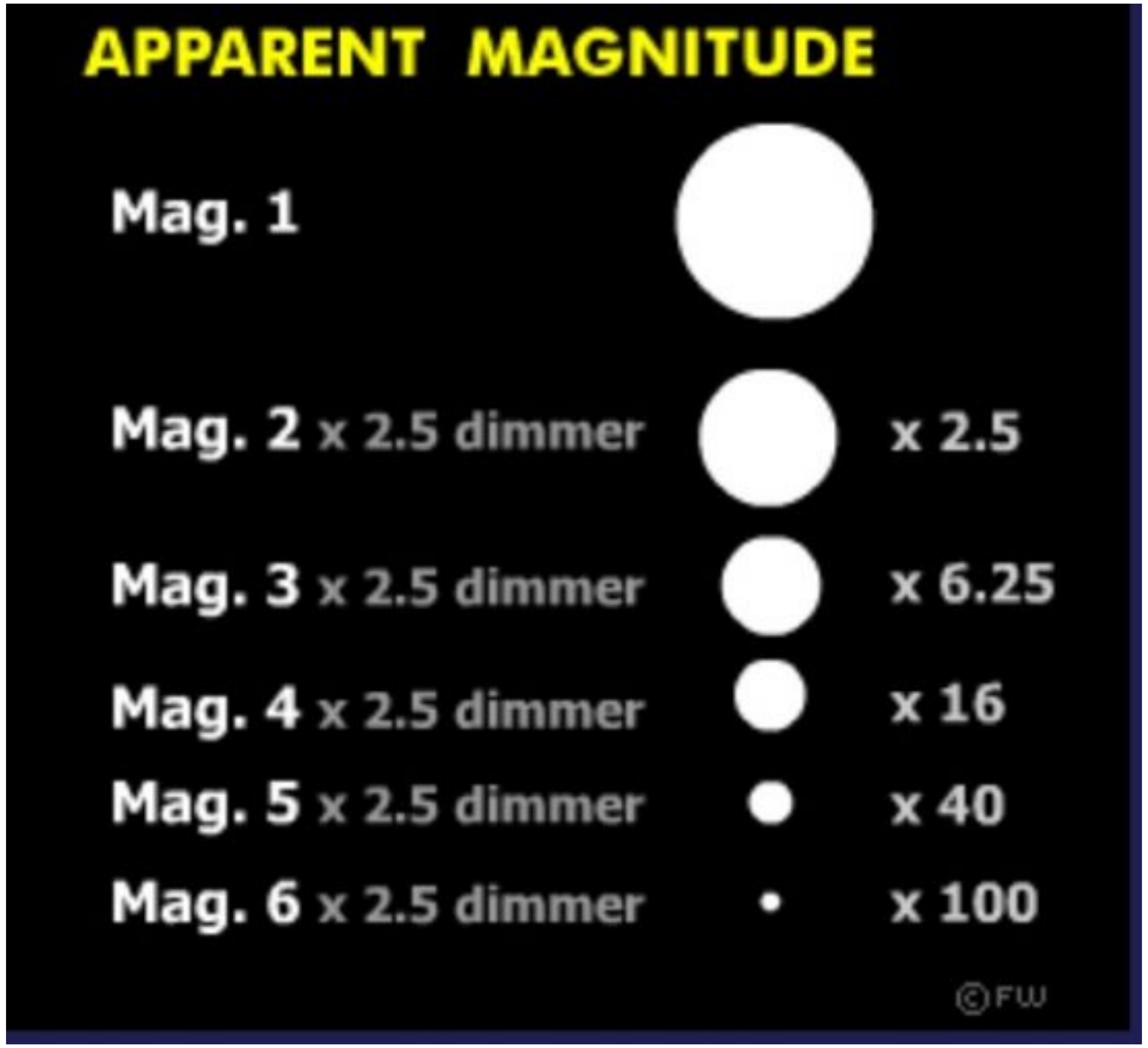
Suppose two stars have apparent brightnesses l_1 and l_2, whereas their magnitude classes are m_1 and m_2. It is clear that

$$\frac{l_2}{l_1} = (100)^{\frac{1}{5}(m_1 - m_2)}.$$

$$\boxed{m_1 - m_2 = 2.5 \log_{10} \frac{l_2}{l_1}.}$$

the definition of ***apparent magnitude* denoted m**, which is a measure of the apparent brightness of an object in the sky.

Note that the magnitude scale is defined in such a fashion that a fainter object has a higher value of magnitude.



https://earthsky.org/astronomy-essentials/what-is-stellar-magnitude/

The magnitude scale

Since a star emits electromagnetic radiation in different wavelengths: what is the wavelength range over which we consider to measure its apparent brightness quantitatively?

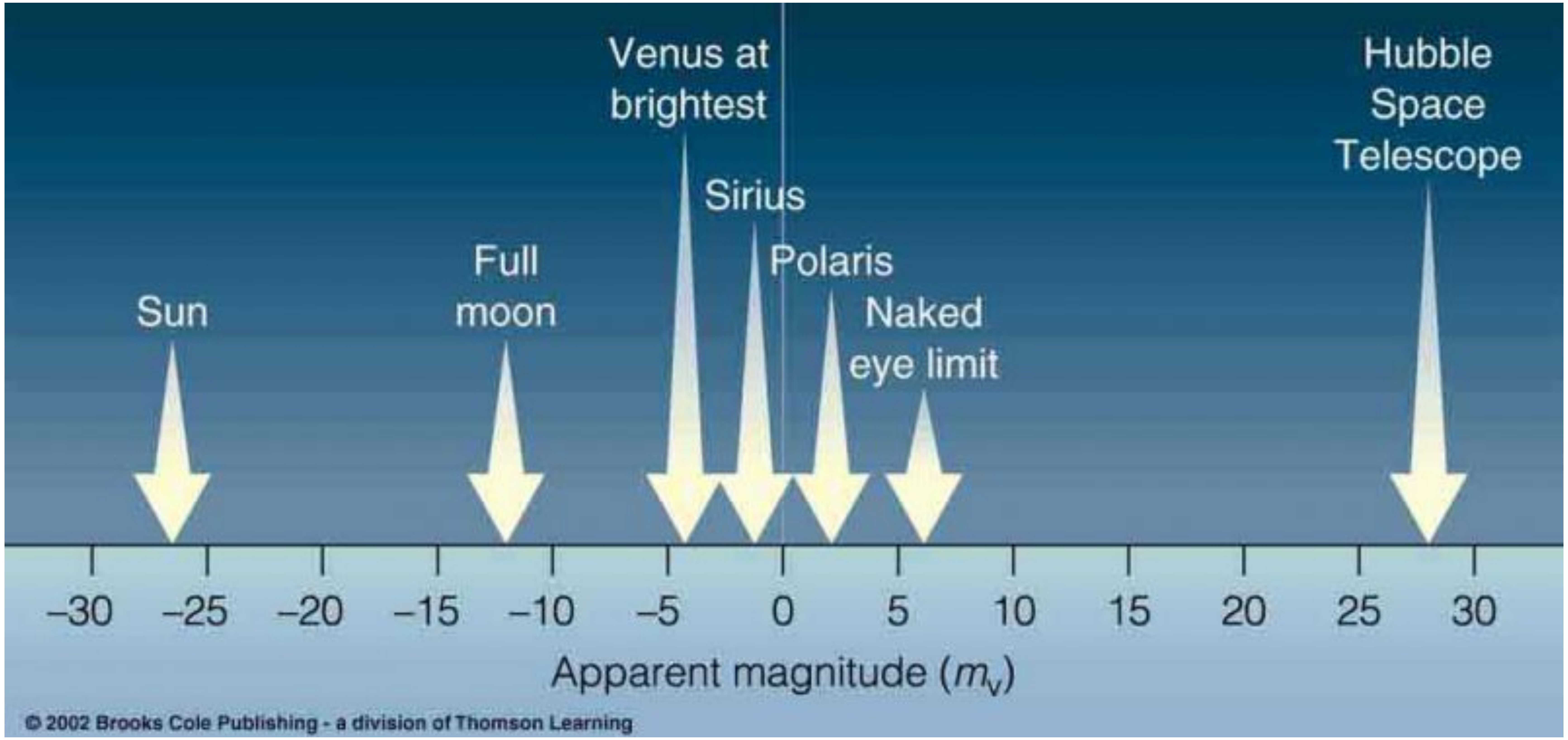
If we use apparent brightnesses based on the radiation in all wavelengths, then the magnitude defined from it is called the ***bolometric magnitude***. But this is not very practical to measure in practice.

A much more convenient system, called the Ultraviolet–Blue–Visual system or the **UBV system**, was introduced by Johnson and Morgan (1953) and is now universally used

- In this system, the light from a star is made to pass through filters which allow only light in narrow wavelength bands around the three wavelengths: 3650Å, 4400Å and 5500Å. From the measurements of the intensity of light that has passed through these filters, we get magnitudes in ultraviolet, blue and visual, usually denoted by U, B and V .
- 1Å = 10^{-10} m

Typical examples of V magnitudes are: the Sun, $V = -26.74$; Sirius, the brightest star, $V = -1.45$; faintest stars measured, $V \approx 27$.

The magnitude scale



https://earthsky.org/astronomy-essentials/what-is-stellar-magnitude/

The magnitude scale

Suppose we consider a reddish star. It will have less brightness in B band compared to V band. Hence its B magnitude should have a larger numerical value than its V magnitude. So we can use **(B – V) as an indication of a star's colour.** The more reddish a star, the larger will be the value of (B – V).

The a**bsolute magnitude** of a celestial object is defined as the magnitude it would have **if it were placed at a distance of 10 pc**. This is often used to denote the intrinsic brightness of objects.

The relation between relative magnitude m and absolute magnitude M can easily be found. If the object is at a distance d pc, then $(10/d)^2$ is the ratio of its apparent brightness and the brightness it would have if it were at a distance of 10 pc.

$$m - M = 2.5 \log_{10} \frac{d^2}{10^2}$$

$$\boxed{m - M = 5 \log_{10} \frac{d}{10}.}$$

Calculate the absolute magnitude

A star at a distance of 4 pc has an apparent magnitude 2. What is its absolute magnitude?

Given the fact that the Sun has a luminosity 3.9×10^{26} W and has an absolute magnitude of about 5, find the luminosity of the star.

Sources of astronomical information

How do we get astronomical information?

Sources of astronomical information

How do we get astronomical information?

- Electromagnetic radiation
- Neutrinos
- Gravitational radiation
- Cosmic rays
- + more for planetary and solar system science (plasma probes, magnetometers, rock samples from the Moon and from asteroids, etc.)

Neutrinos

How are they detected?
What are the astronomical sources?
Where would the observatories be?

Neutrinos

A Nuclear reactions inside stars produce neutrinos.

Since neutrinos take part in weak interactions alone, most of the neutrinos **created at the centre of a star** can come out without interacting with the stellar matter. Unlike photons which come from the outer layers of a star and cannot tell us anything directly about the stellar core, neutrinos come out of the core unmodified.

However, **the very small crossection of interaction between matter and neutrinos also makes it difficult to detect neutrinos**. Because of this difficulty of detecting neutrinos, we expect to detect neutrinos only either from very nearby sources or from sources which emit exceptionally large fluxes of neutrinos (like a supernova explosion) if the source is not too nearby.

For detecting neutrinos, we need a huge amount of some substance with atoms having nuclei with which neutrinos interact. In the 1960s Davis started a famous experiment to detect neutrinos from the Sun by using a huge underground tank of cleaning liquid C_2Cl_4 as the detector.

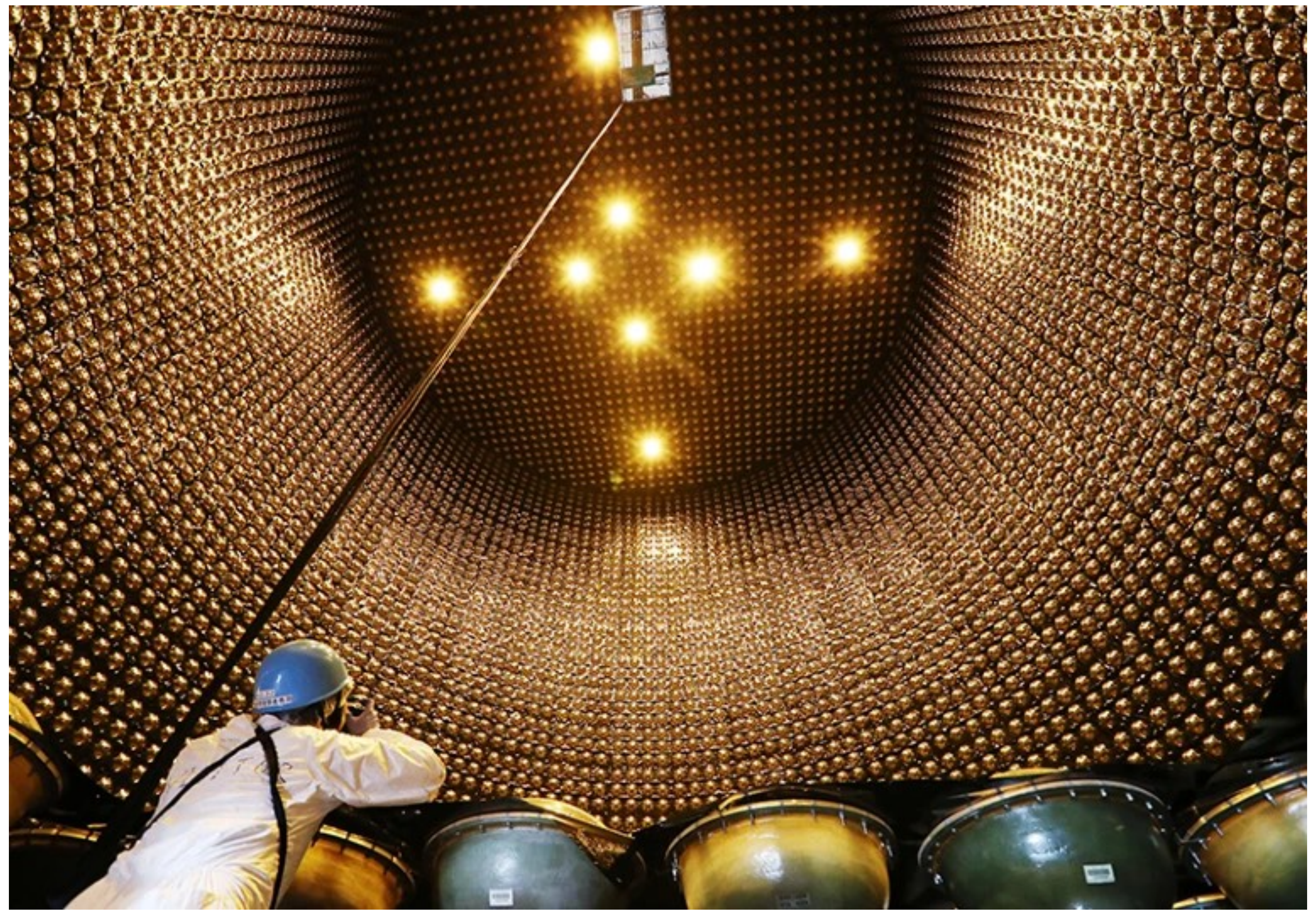
In the late 1980s and the early 1990s, other neutrino detection experiments started, one of the most important being Kamiokande in Japan. Apart from the Sun, the only other astronomical source from which it has so far been possible to detect neutrinos is the **Supernova 1987A**. Only about 20 neutrinos detected in two terrestrial experiments could be ascribed to this supernova!

Neutrinos

Current day experiments: Super-K, LVD, IceCube, KamLAND, Borexino, Daya Bay, and HALO

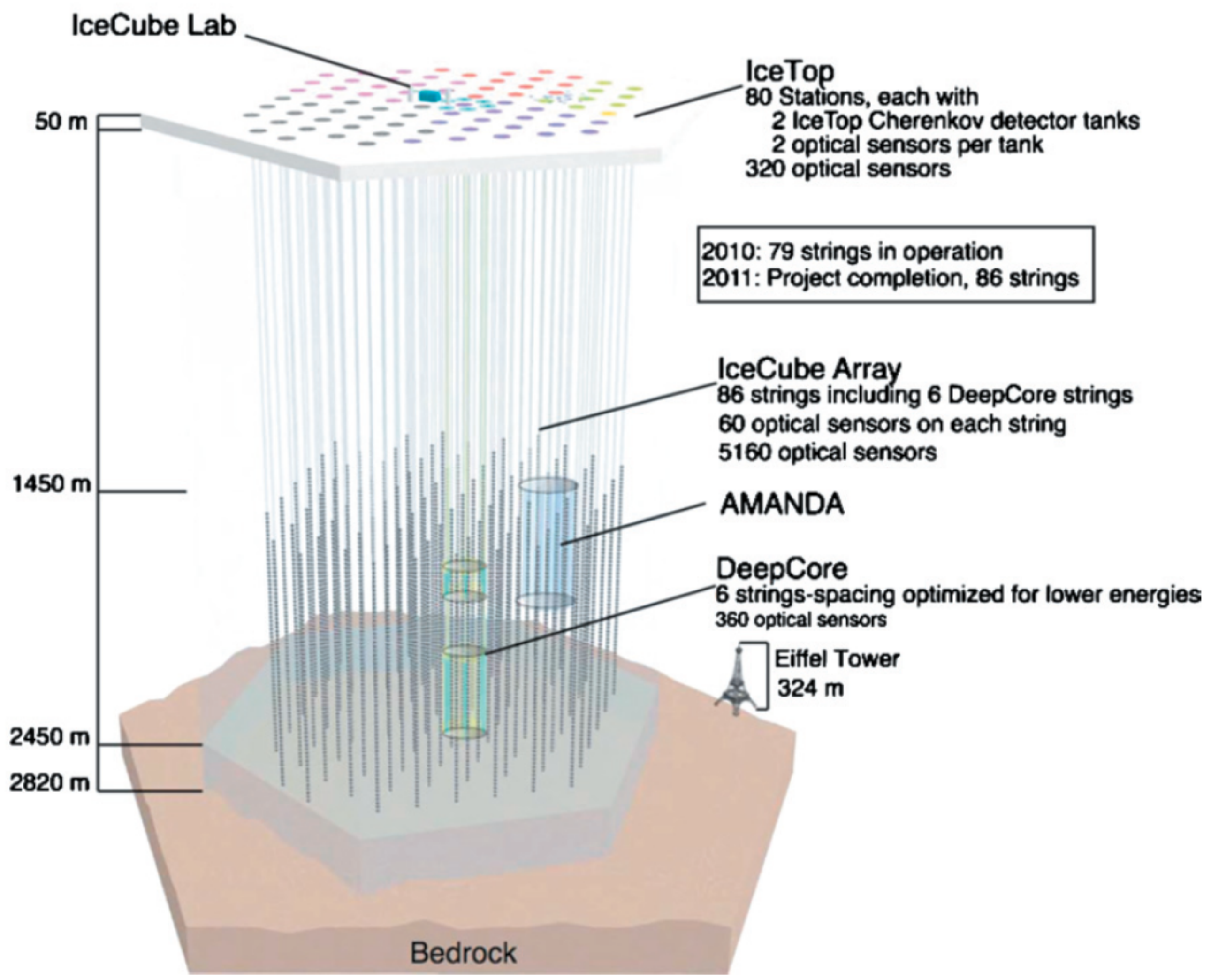
- Supernova Early Warning System (SNEWS) - since neutrinos can escape the supernova much faster than photons
- In July 2018, IceCube, gamma-ray telescopes Fermi and MAGIC, and several other experiments announced the detection of **neutrinos and photons from blazar** TXS 0506+056 (black hole with a jet pointing towards Earth). These results constitute the first-ever identification of a likely source of extragalactic neutrinos and of high-energy cosmic rays.

SuperKamiokanda



https://www.nature.com/articles/d41586-019-00598-9

IceCube



https://en.wikipedia.org/wiki/Neutrino_astronomy

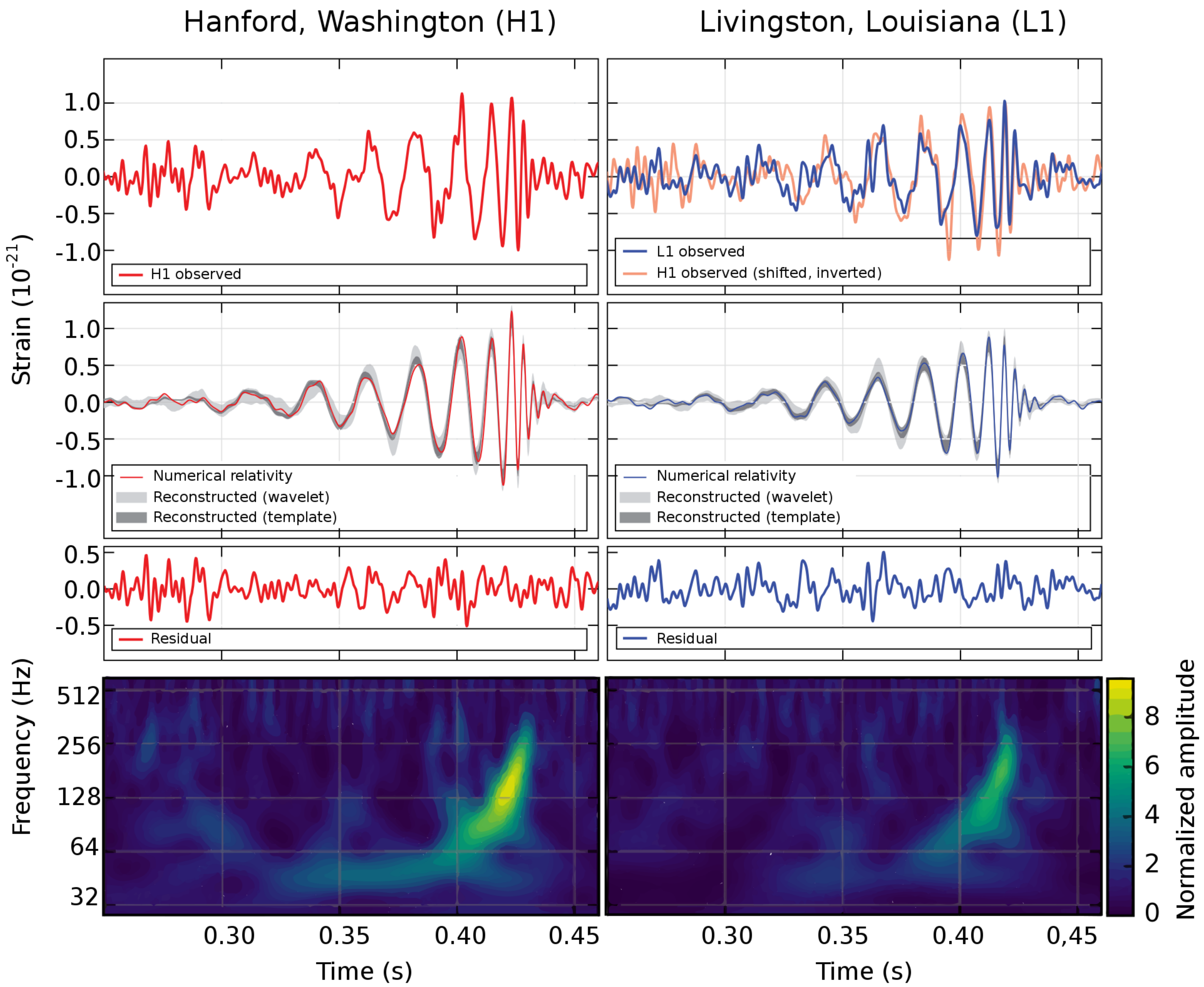
Gravitational waves

How are they detected?
What are the astronomical sources?
Where would the observatories be?

Gravitational waves

- Indirect detection with binary pulsars spiralling towards each other, because they are loosing energy due to gravitational radiation.
- Direct detection by LIGO

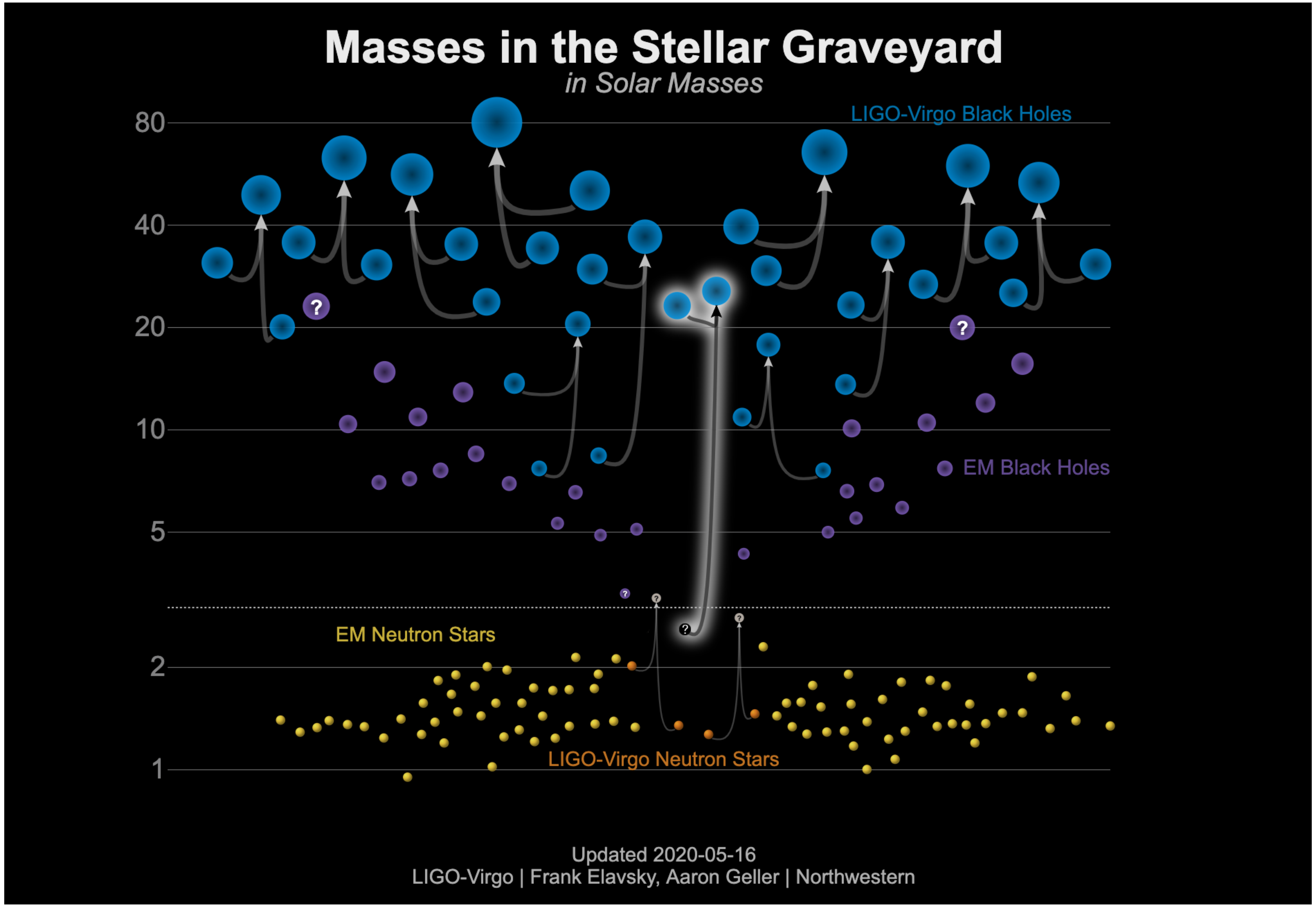
The first detection of merging black holes in 2015



https://en.wikipedia.org/wiki/List_of_gravitational_wave_observations

Gravitational waves

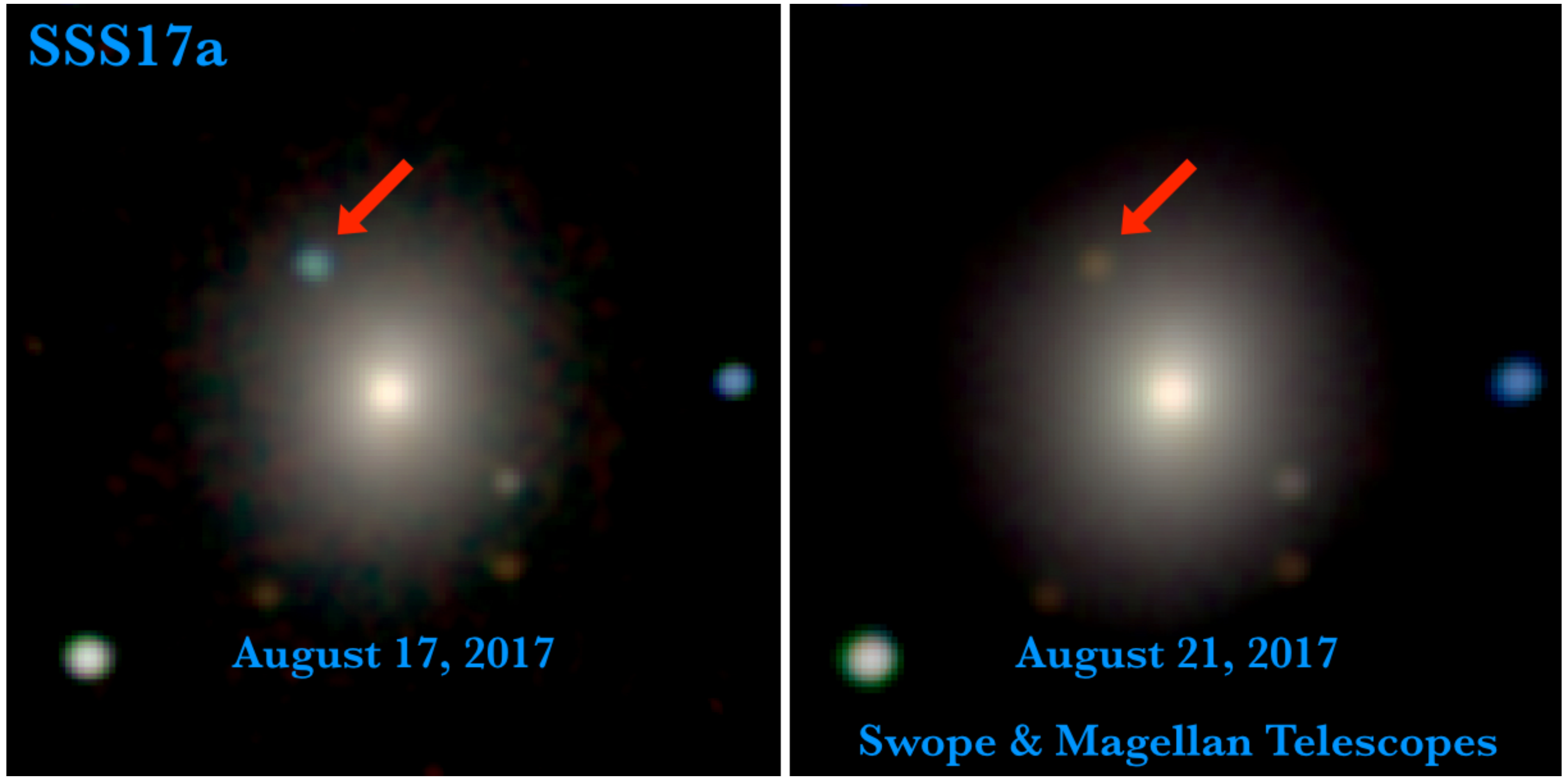
Masses of LIGO/Virgo detections. LIGO and Virgo have observed the merger of several compact object binaries. The black holes represent a new population with masses that are larger than what had been seen previously with X-ray studies alone. This plot shows the masses of the binary components before merger, as well as the mass of the merger remnant.



https://www.ligo.org/detections.php

Gravitational waves

- 2017 - the observation of the GW170817 transient - **double neutron star merger**
- In contrast to the case of binary black hole mergers, binary neutron star mergers were expected to yield an electromagnetic counterpart, that is, a light signal associated with the event.
- A gamma-ray burst (GRB 170817A) was detected by the Fermi Gamma-ray Space Telescope, occurring 1.7 seconds after the gravitational wave transient.
- The signal, originating near the galaxy NGC 4993, was associated with the neutron star merger.
- These events are also called **kilonova**s (similar to a very bright supernova)



https://www.ligo.org/detections/GW170817.php

Cosmic rays

How are they detected?
What are the astronomical sources?
Where would the observatories be?

Cosmic rays

Most common way of detection is vis **Cherenkov radiation.**

When gamma rays reach the earth's atmosphere they interact with it, producing particle showers. Nothing can travel faster than the speed of light in a vacuum, but light travels 0.03 percent slower in air. Thus, these ultra-high energy particles can travel faster than light in air, excite the air molecules and create a blue flash of "Cherenkov light" similar to the sonic boom created by an aircraft exceeding the speed of sound. This is the light that the telescopes detect.

Telescopes: H.E.S.S., MAGIC and VERITAS), CTAO (Cherenkov Telescope Array Observatory)

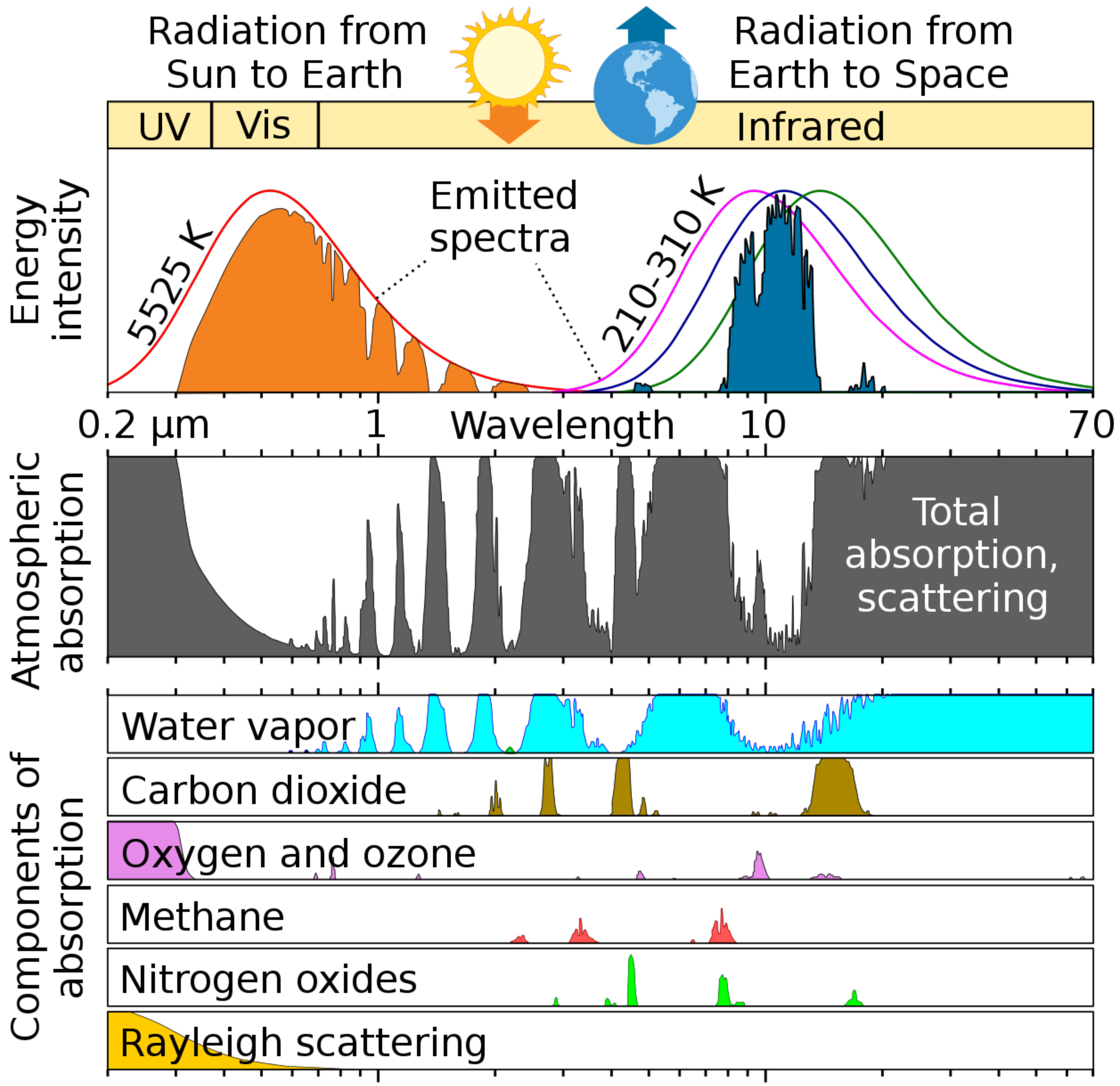
https://www.cta-observatory.org/about/how-cta-works/

Electromagnetic radiation

Electromagnetic radiation

Atmospheric transmission:

- The atmosphere is not see trough in all wavelengths
- Water vapour absorbs a large range of radiation
- The ionosphere reflects certain radiation

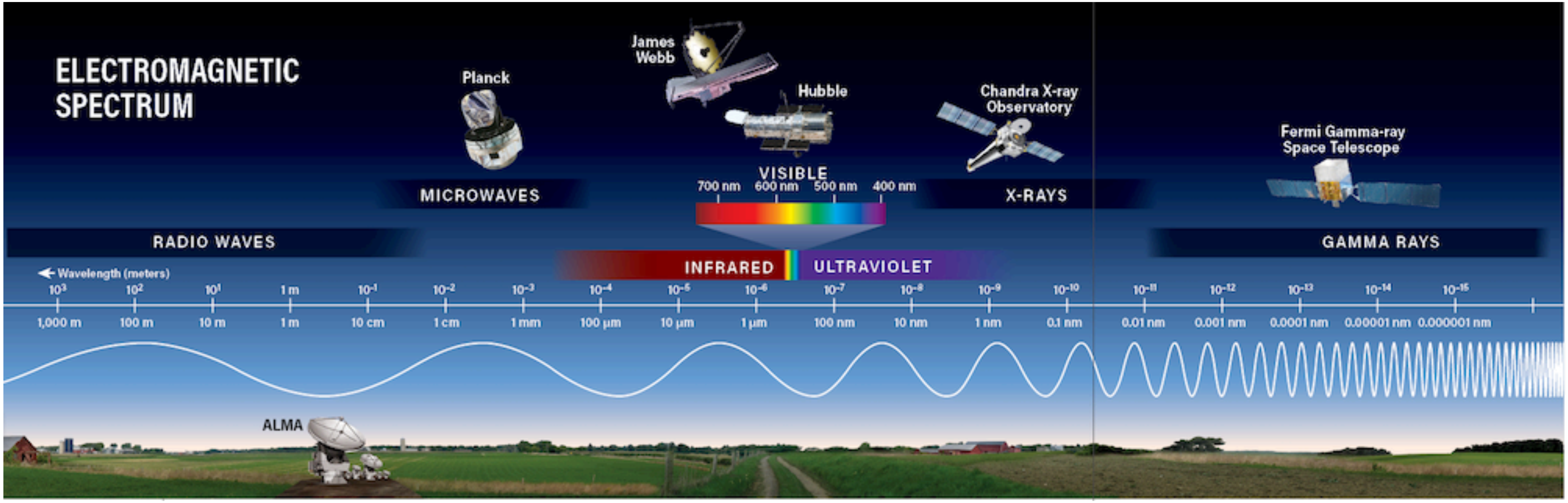


https://en.wikipedia.org/wiki/Atmospheric_window

Electromagnetic radiation

Telescopes observing at different wavelengths have different requirements:

- High mountains in dry places, to minimise water vapour
- Remote sights with no light or radio contamination
- In space



https://astronomy.com/magazine/ask-astro/2022/09/ask-astro-how-do-telescopes-see-different-parts-of-the-electromagnetic-spectrum

Electromagnetic radiation

Non thermal radiation

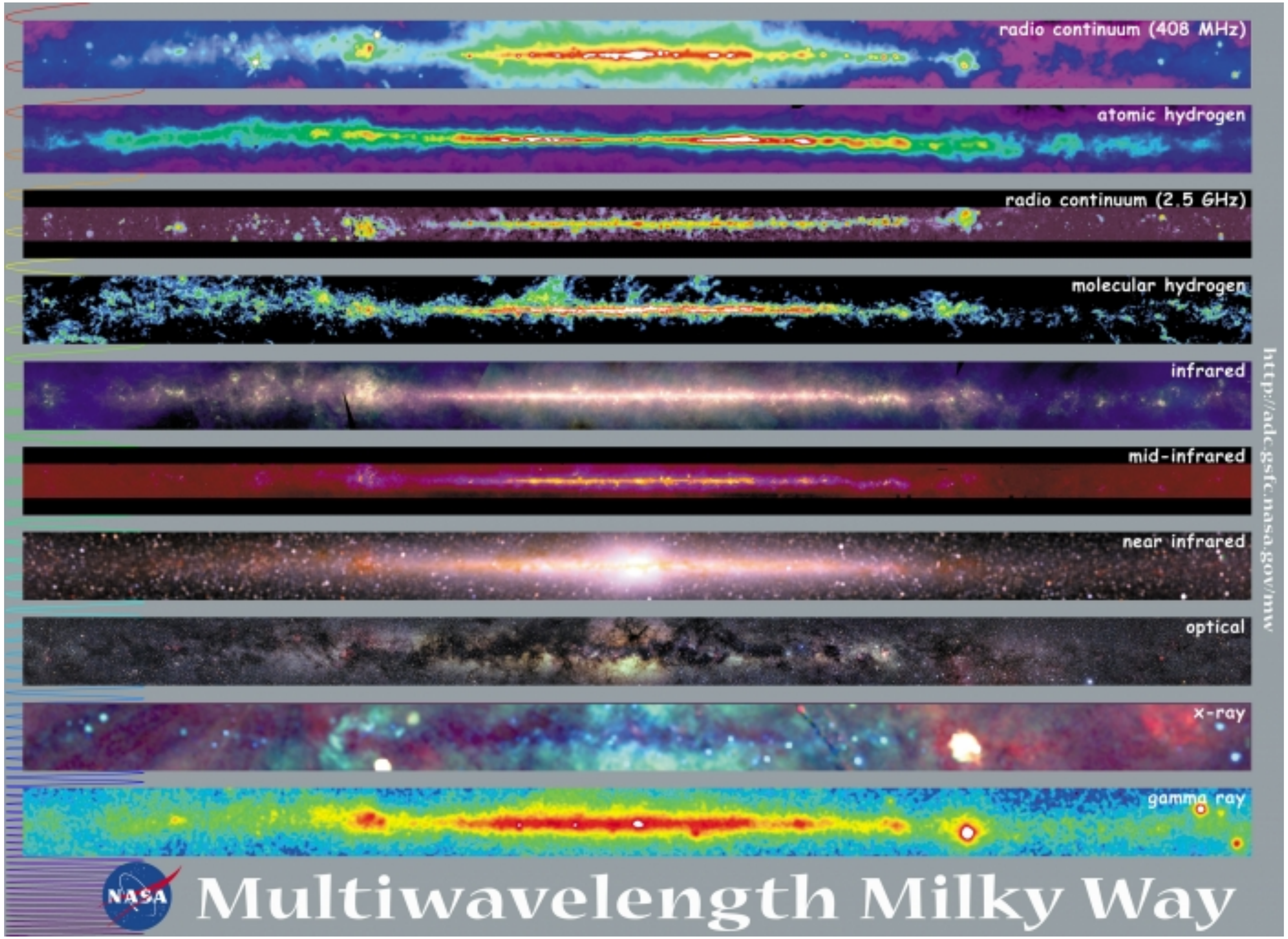
Spectral lines from gas clouds

Dust

Stars

Hot plasma

High energy sources



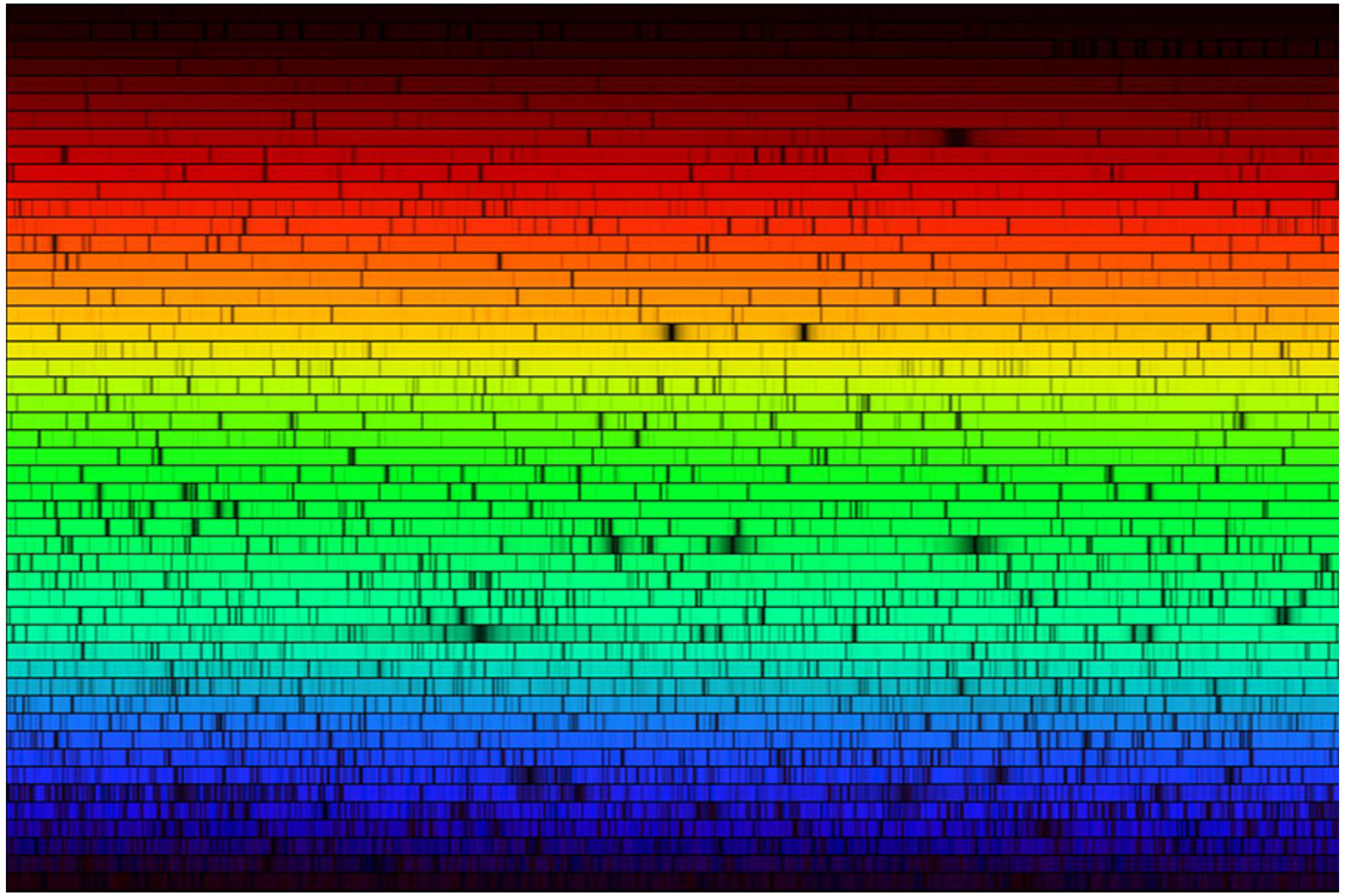
Electromagnetic radiation

Two types of measurements:

- Imaging
- Spectroscopy

M101 galaxy

Spectrum of the Sun

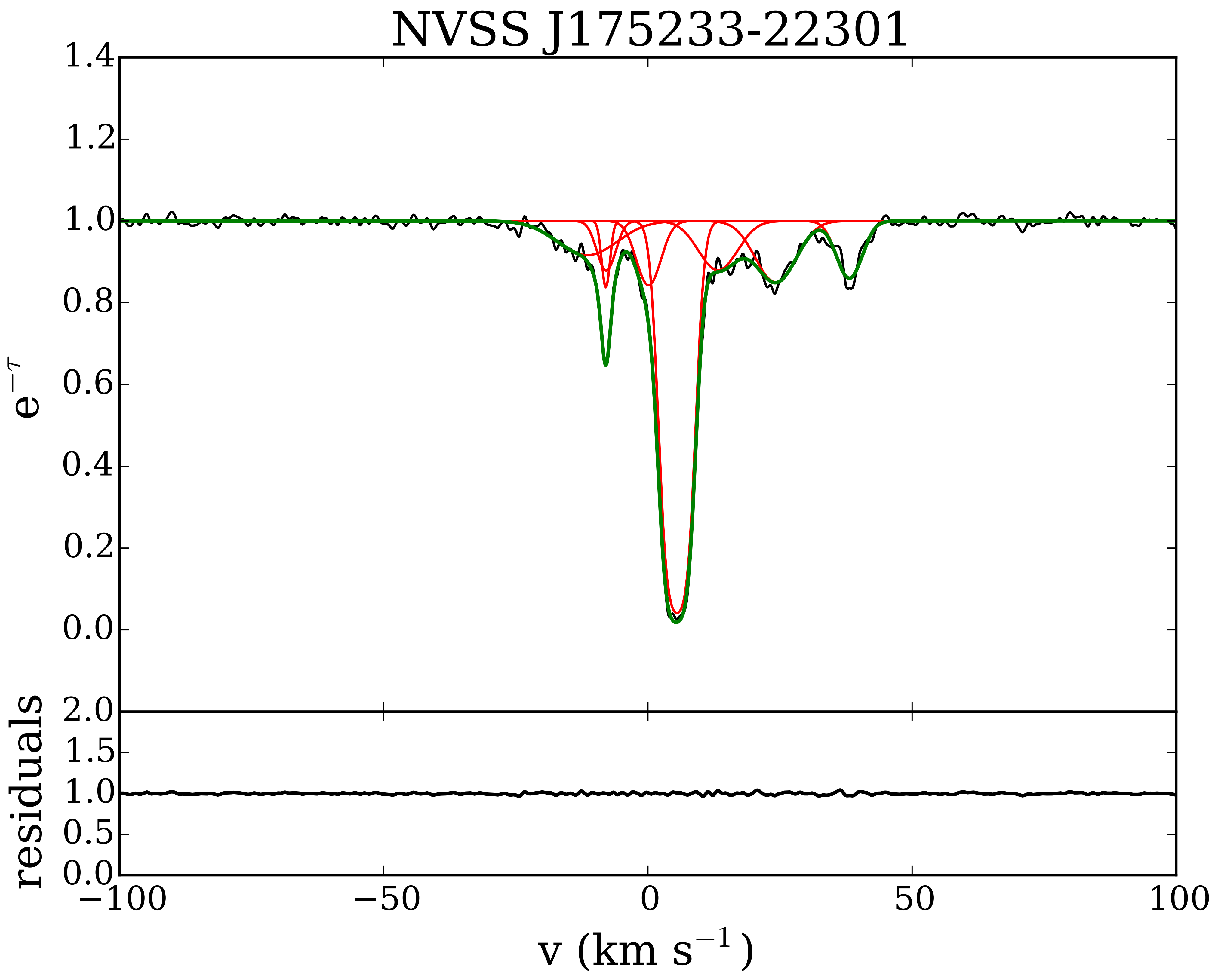


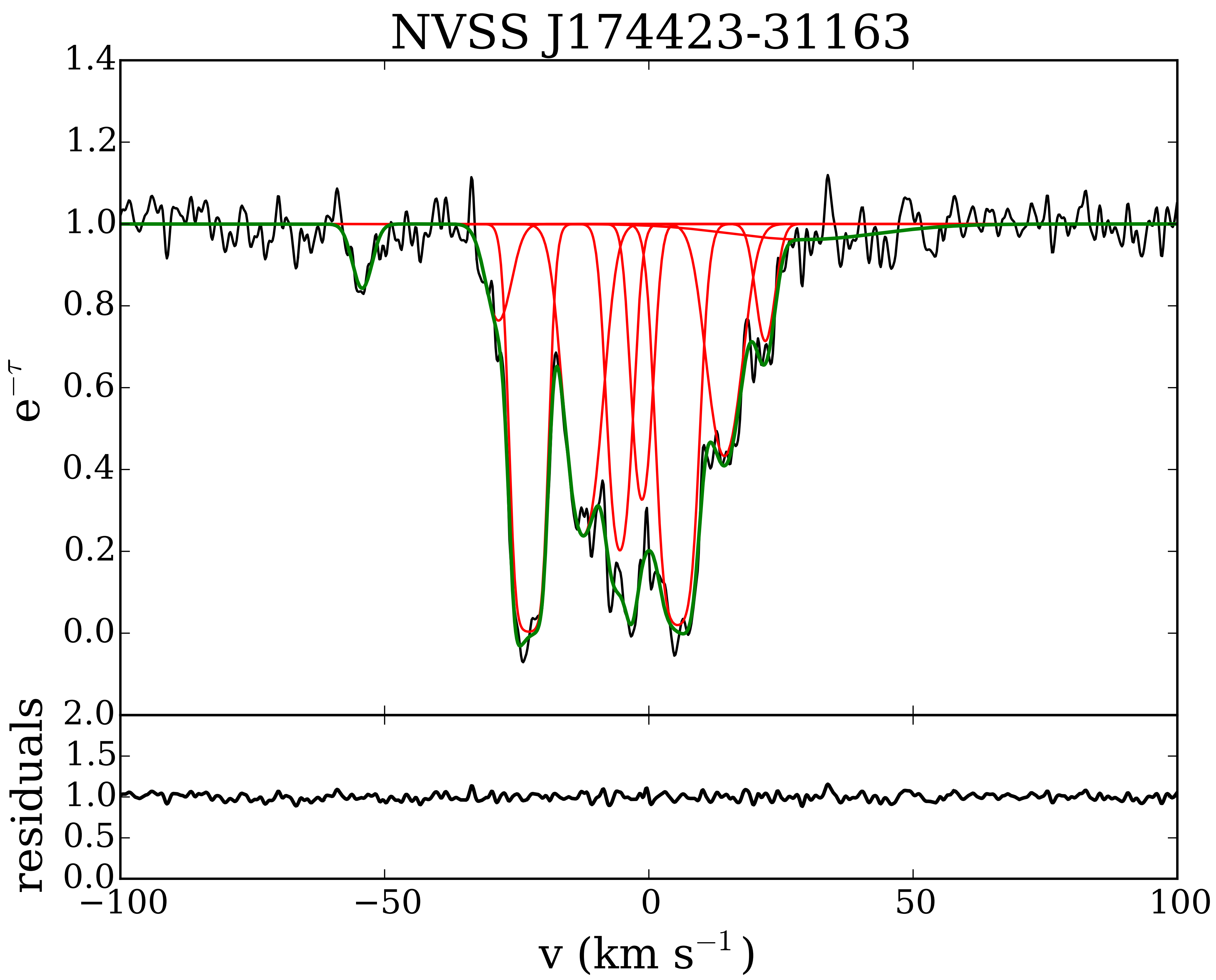
Electromagnetic radiation

Two types of measurements:

- Imaging
- Spectroscopy

Neutral Hydrogen absorption spectra





Optical astronomy

What are the astronomical sources?
Where would the observatories be?

Optical astronomy

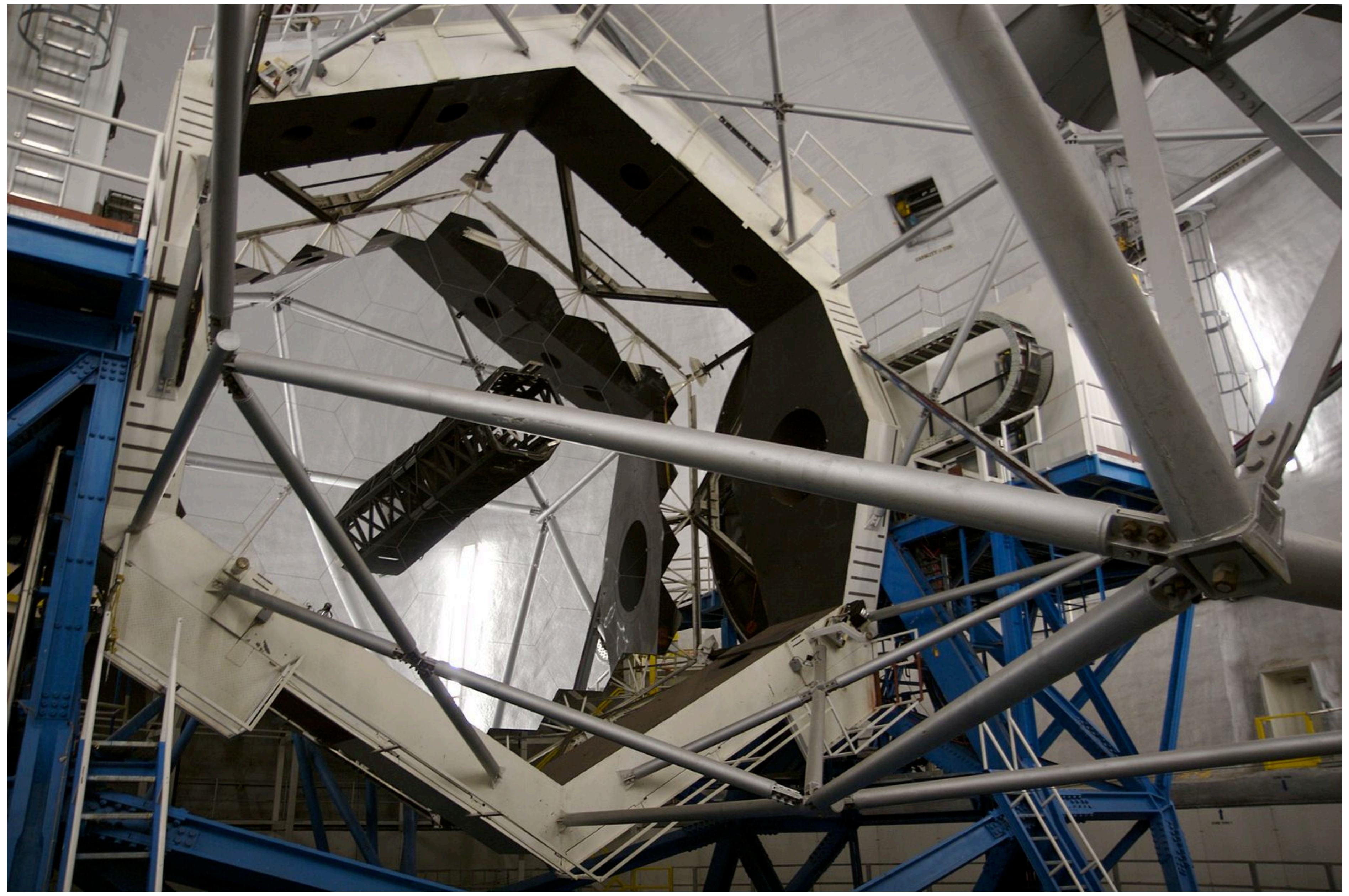
Early telescopes with lenses

Modern telescopes with mirrors, for better resolution and sensitivity

Angular resolution of a telescope: $$\theta = 1.22\frac{\lambda}{D}$$

D is the diameter of the mirror or the lens, λ is the wavelength

The Keck Telescope, with a 10m mirror, made out of hexagonal segments



Optical astronomy

For a 1m telescope, the resolving power at a wavelength of 5000 Å should be of order $0.12''$.

Telescopes which are of this size and larger, however, produce images much less sharp than what is theoretically expected. This is because the air through which the light rays pass before reaching the telescope is always in **turbulent motion**. As a result, the paths of light rays become slightly deflected, giving rise to blurred images. Astronomers use the term ***seeing*** to indicate the quality of image under a given **atmospheric conditions**. Seeing is rarely good enough to allow images which are sharp enough to resolve more than 0.5".

Solutions:

- sending the telescope to space
- **Speckle imaging** (taking very short exposure images and adding them together)
- **Adaptive optics** (using an extra, deformable mirror that corrects for atmospheric turbulence)

It is clear that a bigger ground-based telescope cannot achieve higher resolutions beyond a certain limit. However, the light-gathering ability of a telescope depends on D^2 -> larger telescopes can detect fainter objects.

Optical astronomy

The largest optical telescopes to date have mirrors ~ 10m

- GTC (Gran Canaria Telescope (Spain, Canary Islands))
- Subaru (USA, Hawai)
- Keck (USA, Hawai)
- HET (Hobby-Eberly Telescope (USA))
- LBT (Large Binocular Telescope (USA))
- VLT (Very Large Telescope (Chile))
- SALT (Southern African Large Telescope)
- Gemini (USA, Hawai + Chile)

The biggest observatories (best location) are:

- The Canary Islands (Spain)
- Hawaii (USA)
- Atacama Desert (Chile)

High mountains close to the sea with stable airflow.

Radio astronomy

What are the astronomical sources?
Where would the observatories be?

Radio quite zones

- Most radio telescopes are located in radio quiet zones
- Any transmitting device (e.g. **mobile phones, tablets, laptop wifi**) needs to be turned off in these zones to prevent interference with the observations
- Other forbidden devices are: **microwave ovens, BBQ lighters, very old TVs**
- Every electronic device causes radio frequency interference (**RFI**)
- Signal coming from space is very weak, terrestrial devices can easily wipe out observations
- RFI sources that we can not control: **Satellites, GPS, airplane communication**
- Theses zones are usually a few to tens of km extended

The radio quiet zone around in Western Australia

Radio telescopes

$$\Theta = \lambda / D$$

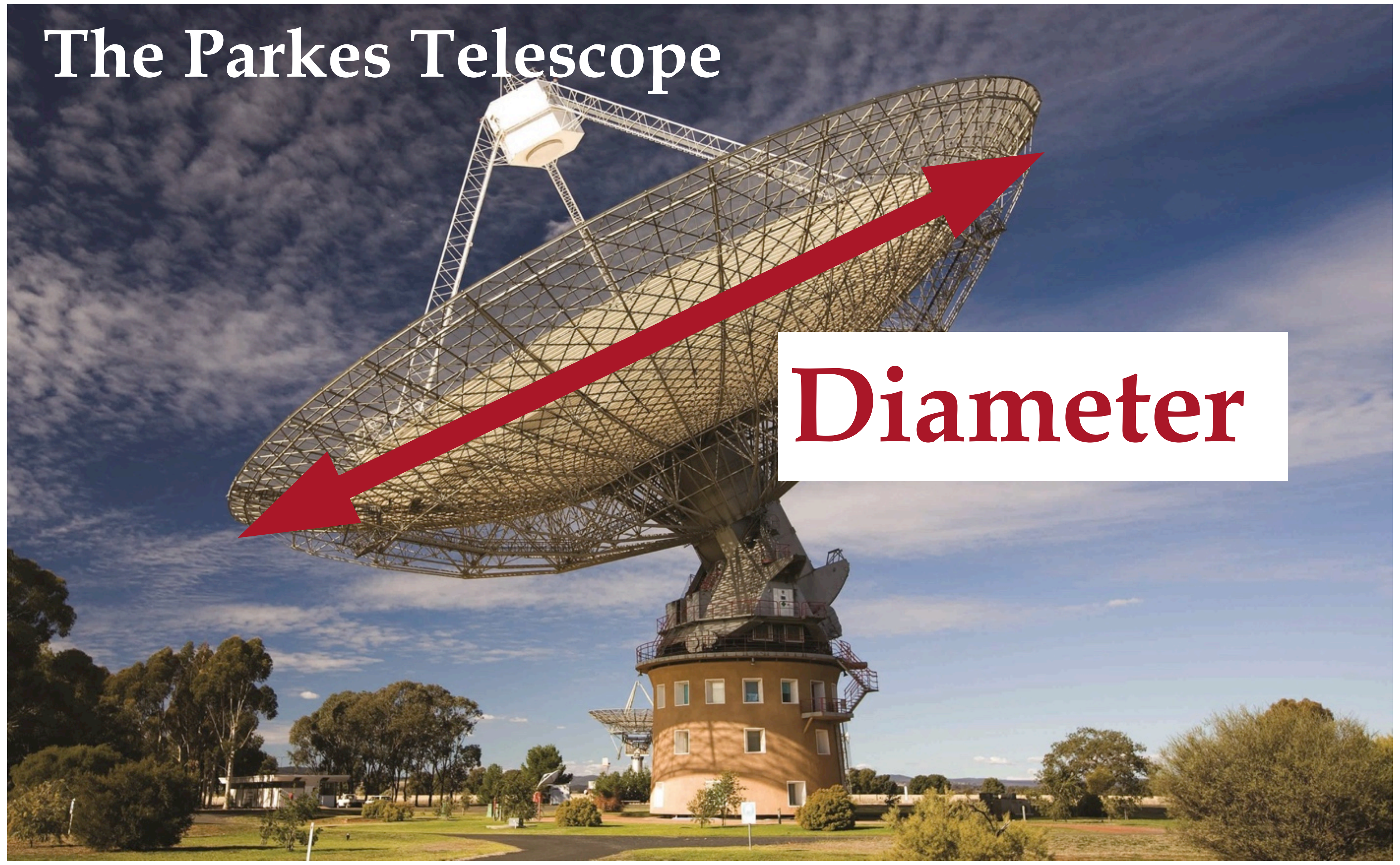
The resolution of a telescope depends on its size and the wavelength of light that is getting observed.

- This is good for short wavelengths, like UV or optical telescopes
- But unfortunate for radio telescopes

Θ – resolution
λ – wavelength
D – diameter/baseline

Singel dish telescopes:

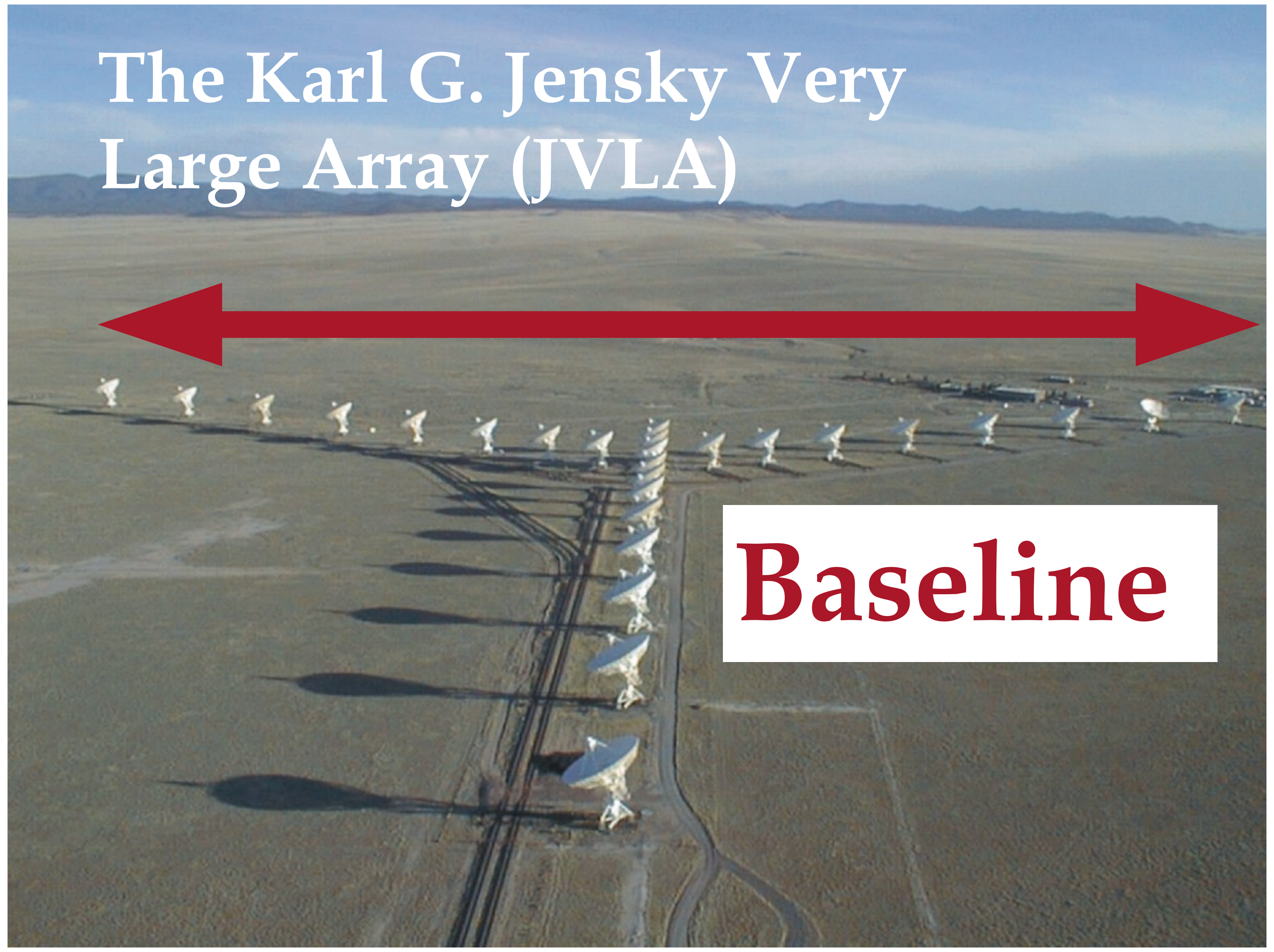
Resolution: ~ Diameter



www.csiro.au

Interferometers:

Resolution: ~ distance between telescopes



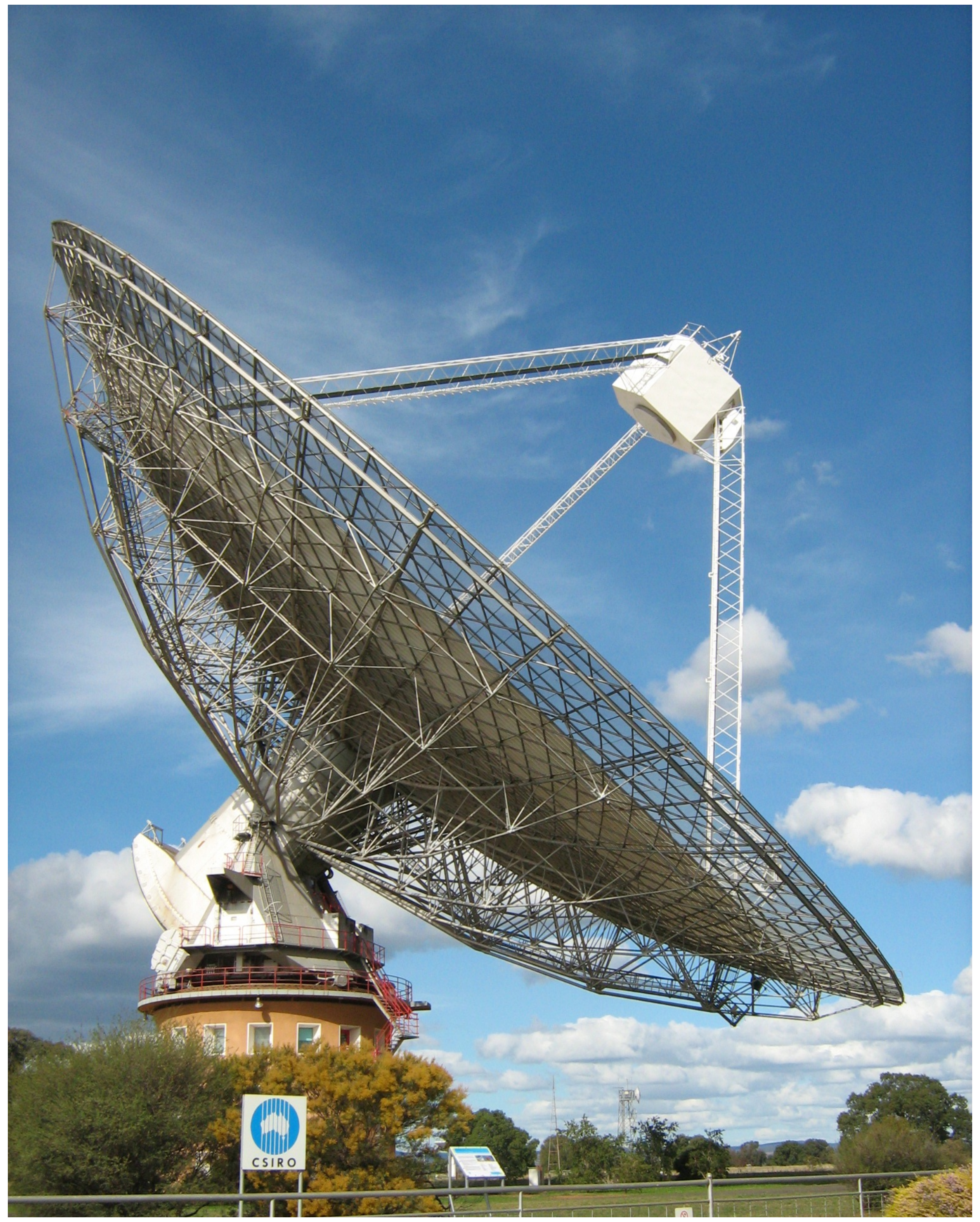
http://images.nrao.edu

Telescopes - single dishes

Dish shaped telescopes are typically used for cm and mm waves.

Effelsberg (Germany)

Parkes Telescope (Australia)



FAST: The Five Hundred Meter Aperture Telescope (China)

Telescopes - Interferometers

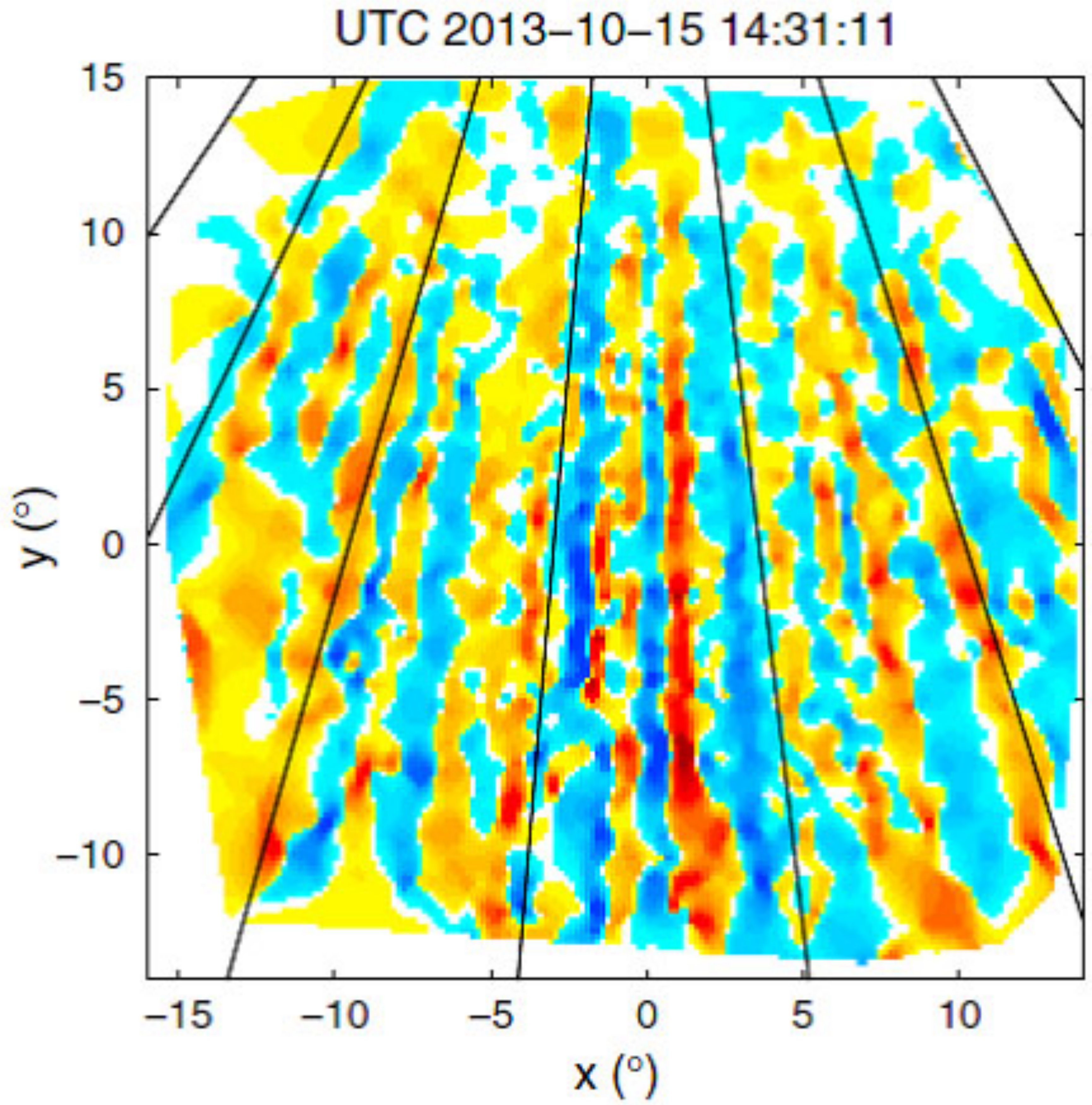
Very Large Array (VLA)

The Australia Telescope Compact Array (ATCA)

Telescopes - Interferometers

"Metal Sticks" are used for m waves.

The Murchison Widefield Array (MWA)

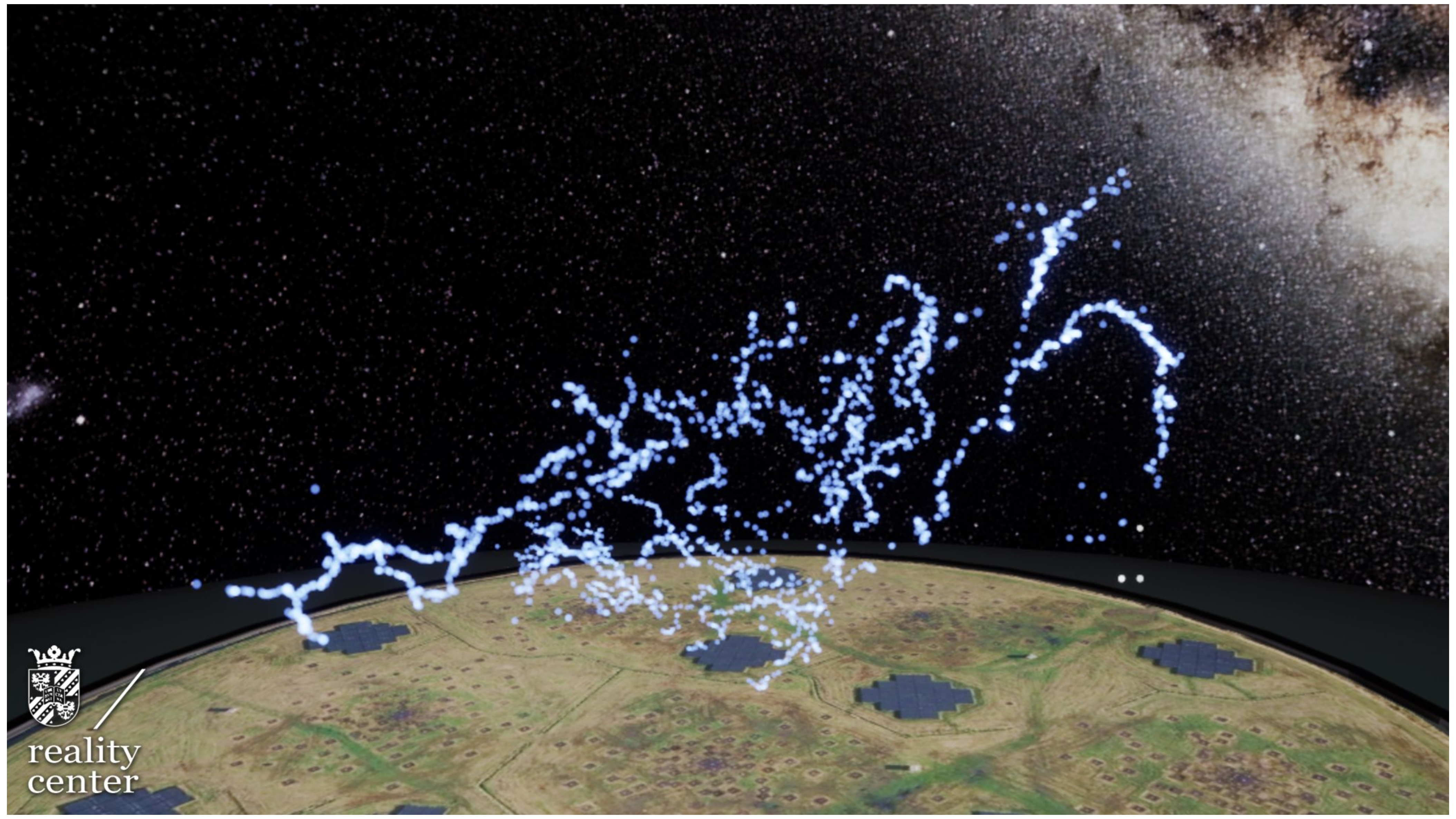


Imaging **plasma tubes in the earth's ionosphere!**
(Cleo Loi)

Telescopes - Interferometers

"Metal Sticks" are used for m waves.

LOFAR (Low Frequency ARray)



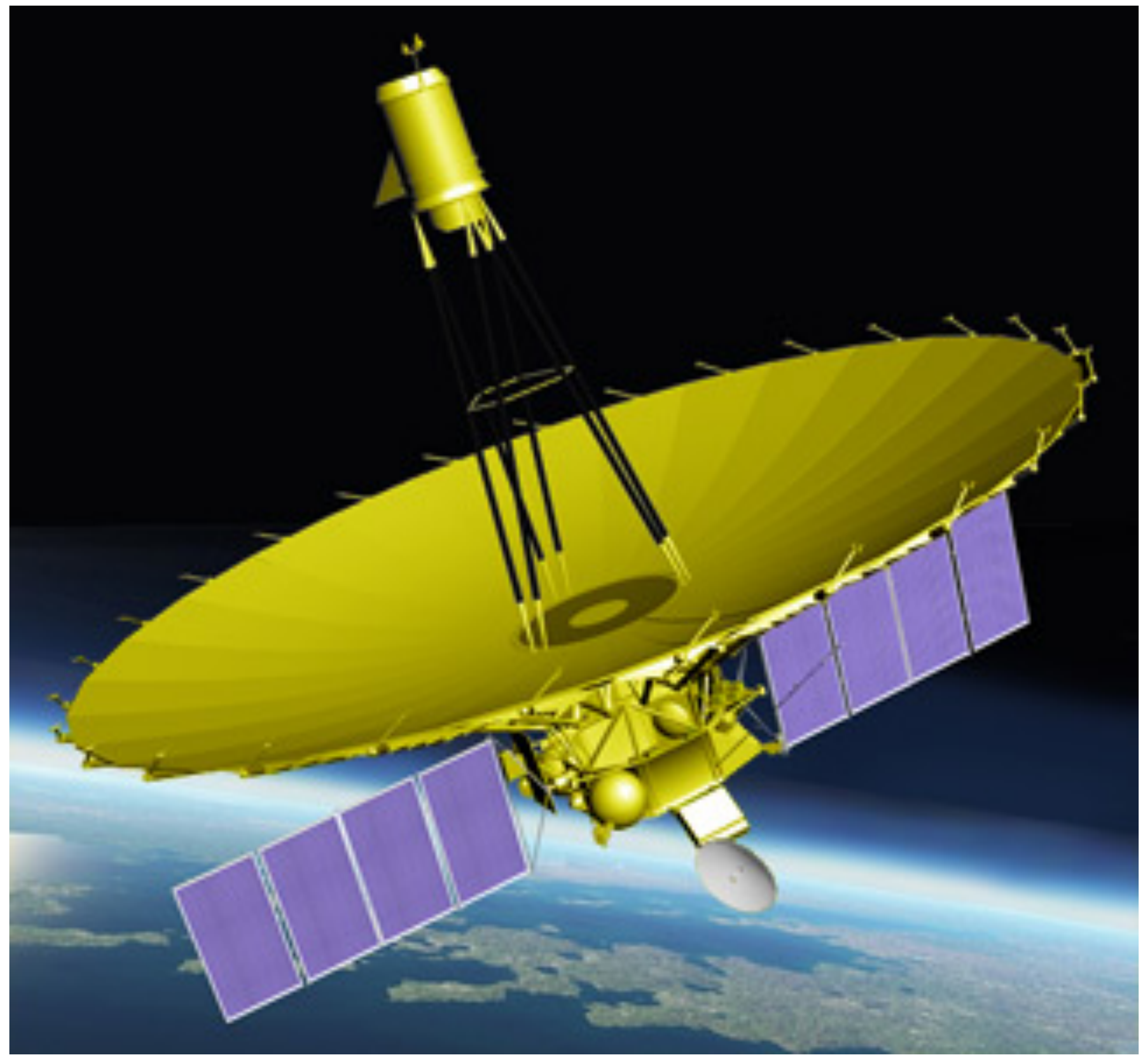
Imaging **the path of lightning.**

Telescopes - Interferometers

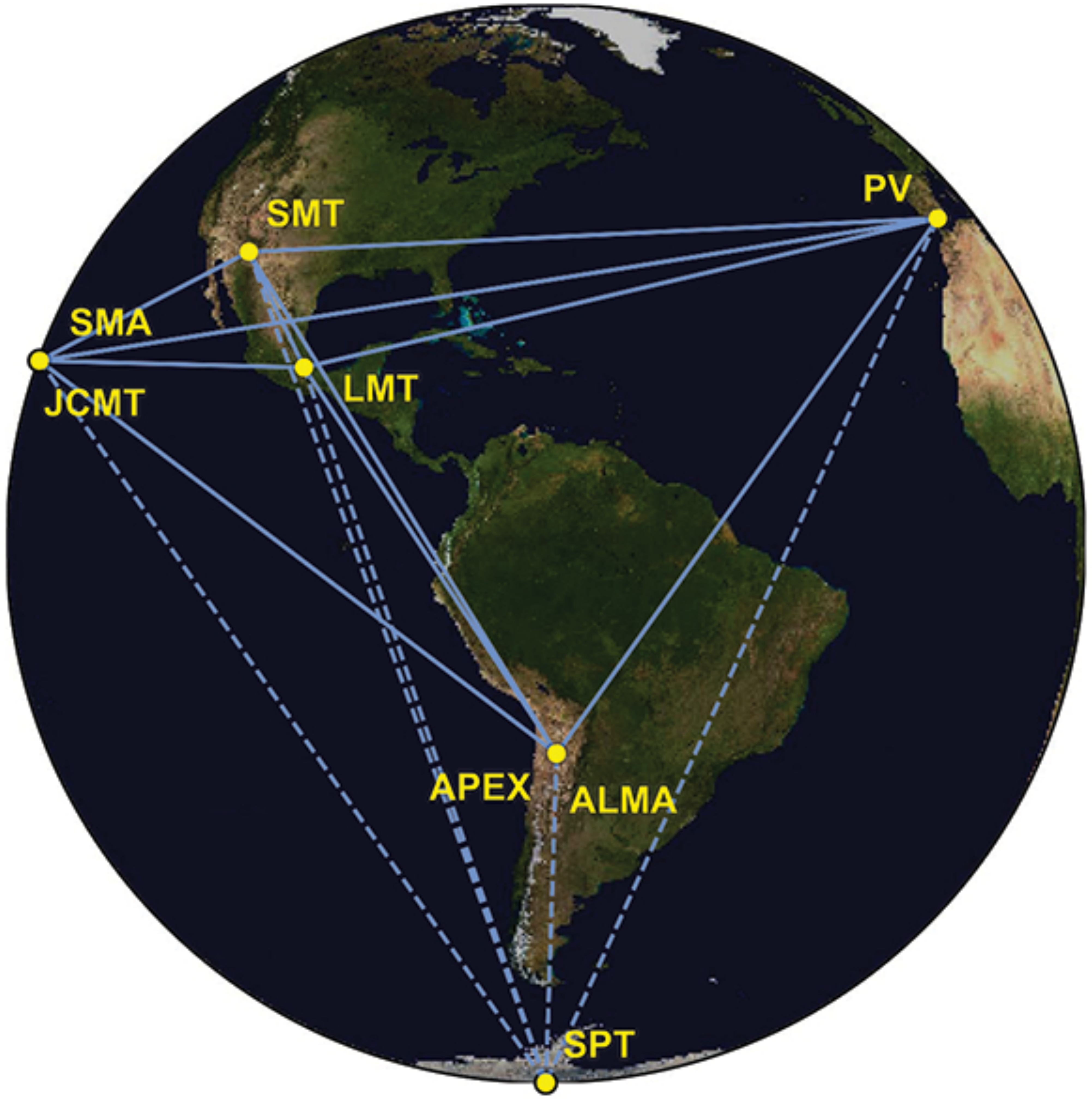
Very Long Baseline Interferometry (VLBI)

- radio interferometry with telescopes on different continents
- Space VLBI - including a telescope on a satellite
  - Can reach baselines of the Earth - Moon distance

Radio-Astron satellite

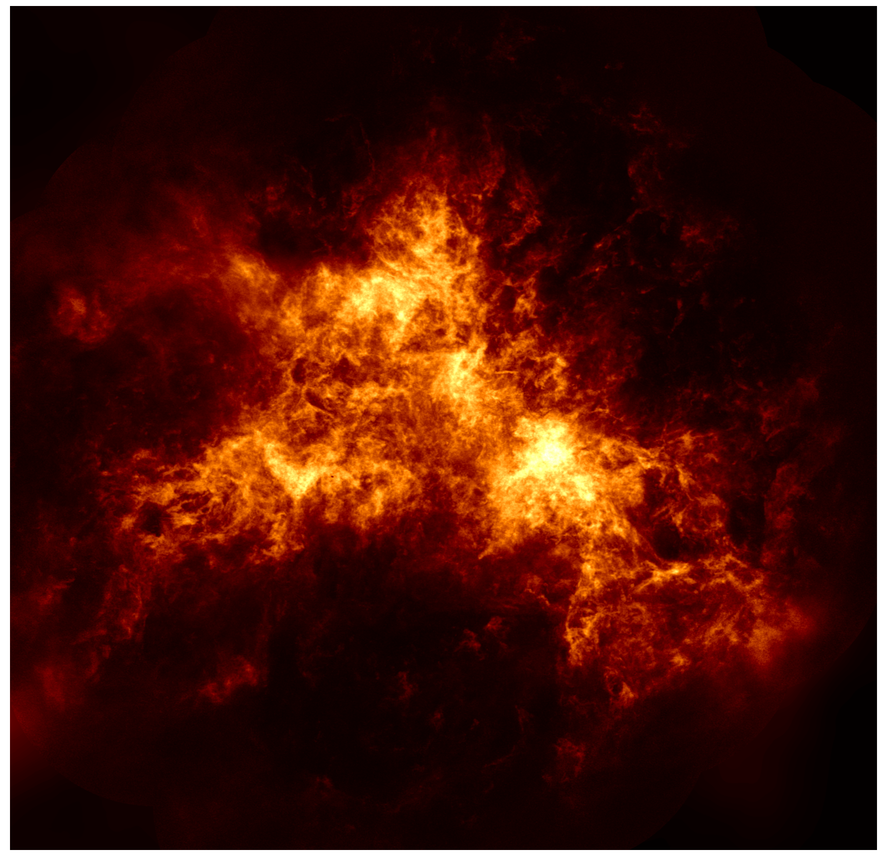


Event Horizon Telescope

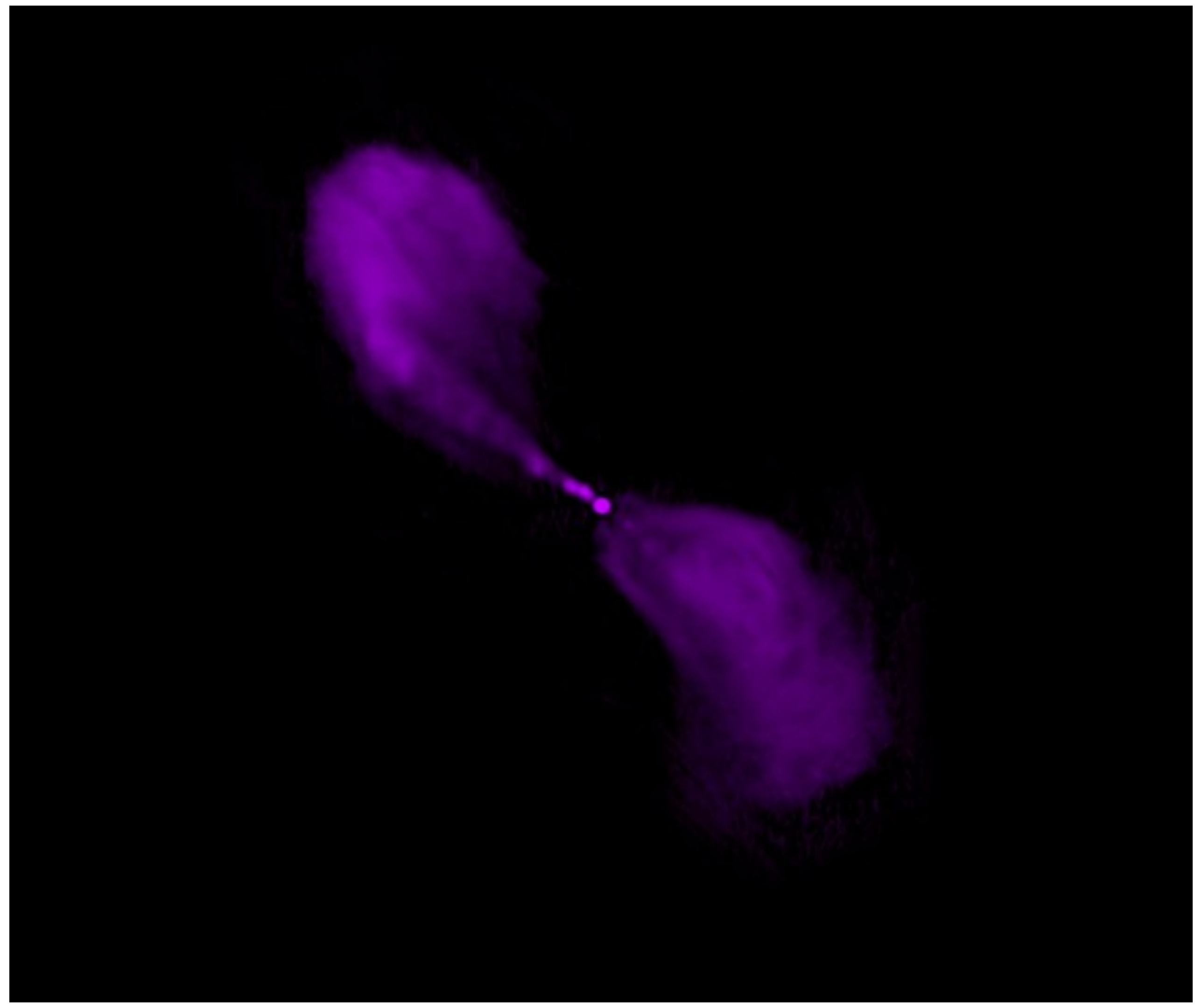


Telescopes - Interferometers

HI in galaxies (SMC)

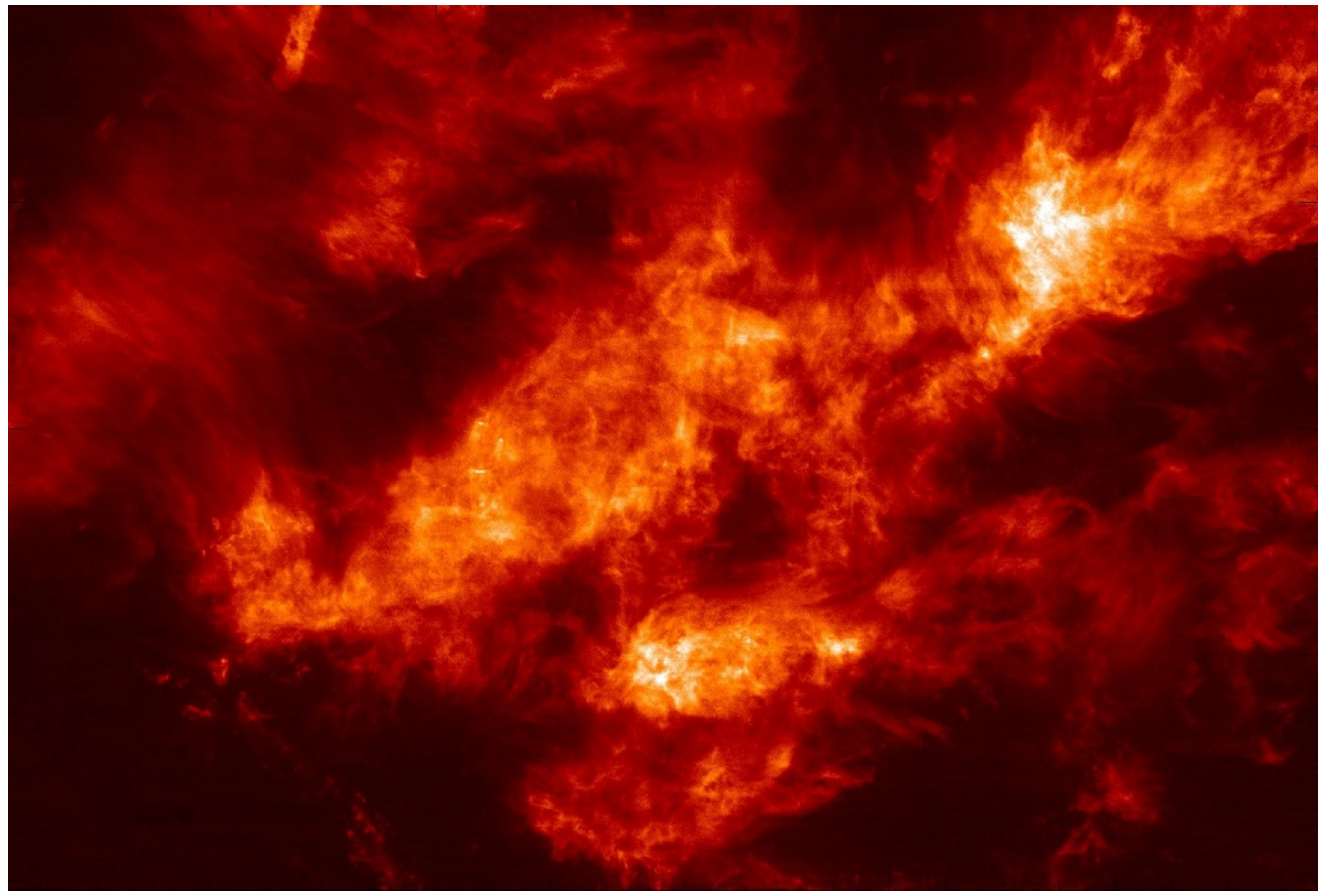


AGN



Accretion disk of a black hole

CO gas in the Taurus molecular cloud



Double asteroid