Astrophysical Objects

Multi-messenger astrophysics

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UNIVERSIDAD YACHAY TECH

SCHOOL OF PHYSICAL SCIENCES AND NANOTECHNOLOGY

Astrophysics

Observational astrophysics

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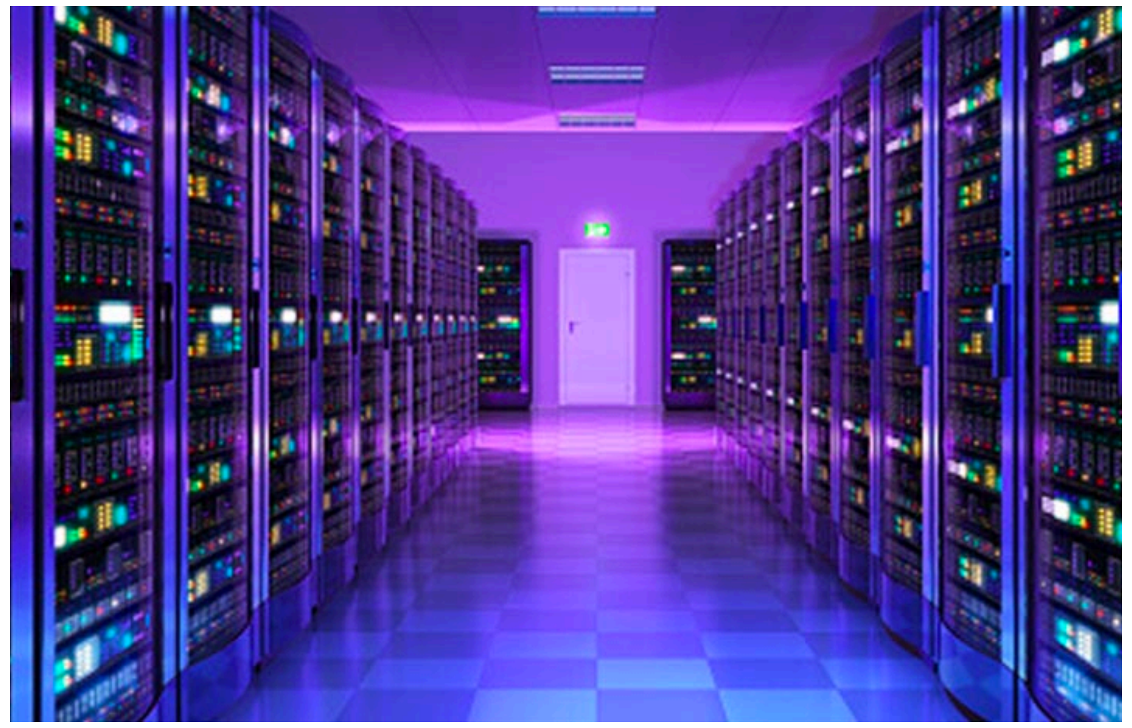

- Observations with telescopes
- Data analysis with computers
- Comparing results with theoretical predictions

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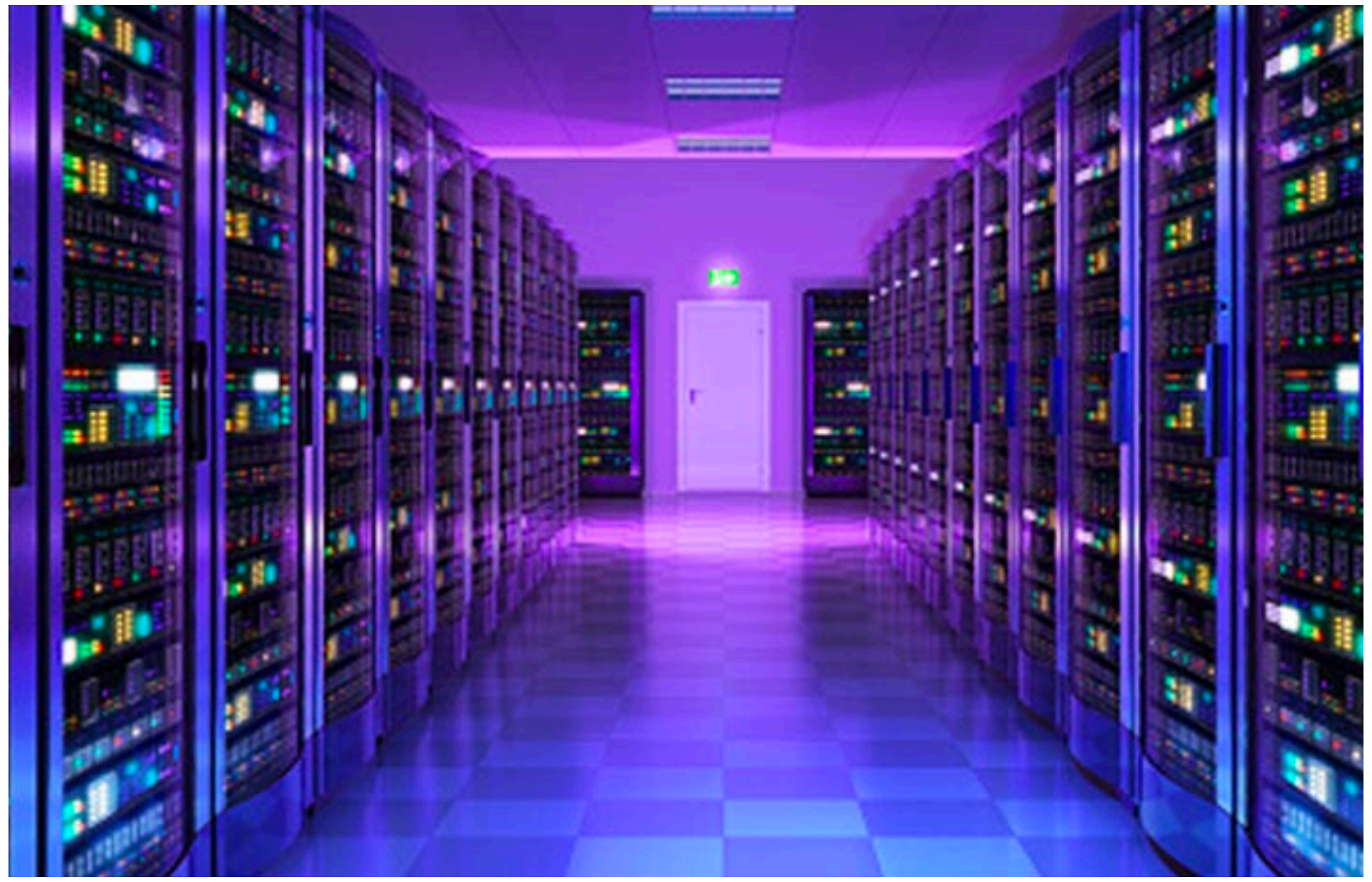
Theoretical astrophysics



- Analytical or numerical calculations/simulations
- Comparing results with observations

Multi-messenger astrophysics

What is multi-messenger astrophysics?

Multi-messenger astrophysics

Or sources of astrophysical 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 only interact trough the weak interactions, 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.

Detector types:

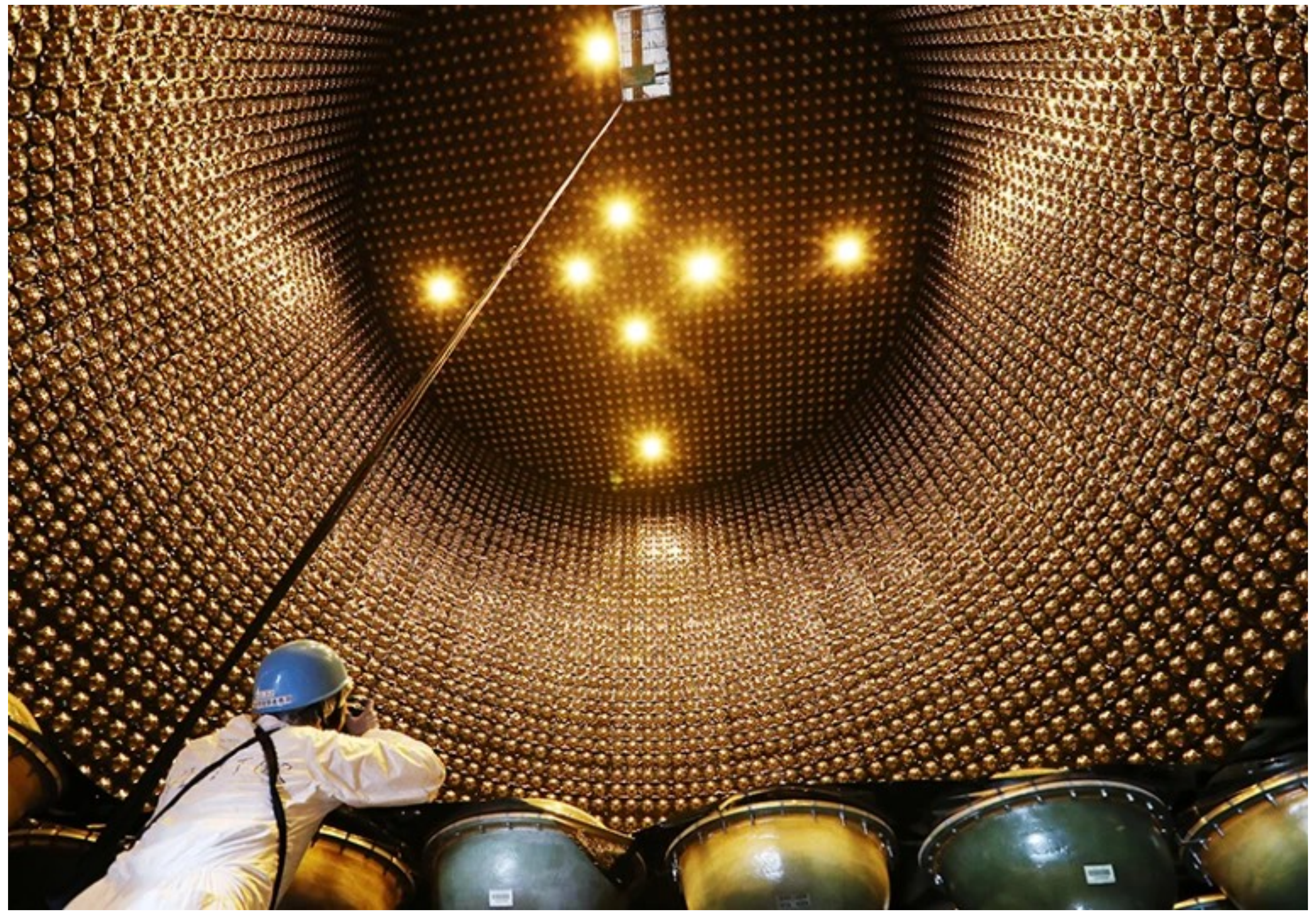
- **Radiochemical methods** (the neutrino triggers a chemical reaction, producing a radioactive element)
- **Cherenkov detectors** (the neutrino produces fast charged particles, if the speed of a charged particle is faster than the speed of light in the medium, then Cherenkov light gets emitted.)

Neutrinos

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. (Radiochemical method)
- In the late 1980s and the early 1990s, other neutrino detection experiments started, one of the most important being Kamiokande in Japan. (Cherenkov detector)
- 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!
- Current detectors are much more advanced. **We can detect more neutrinos, we can also detect neutrinos with different energies and we can measure their direction.**

SuperKamiokanda



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

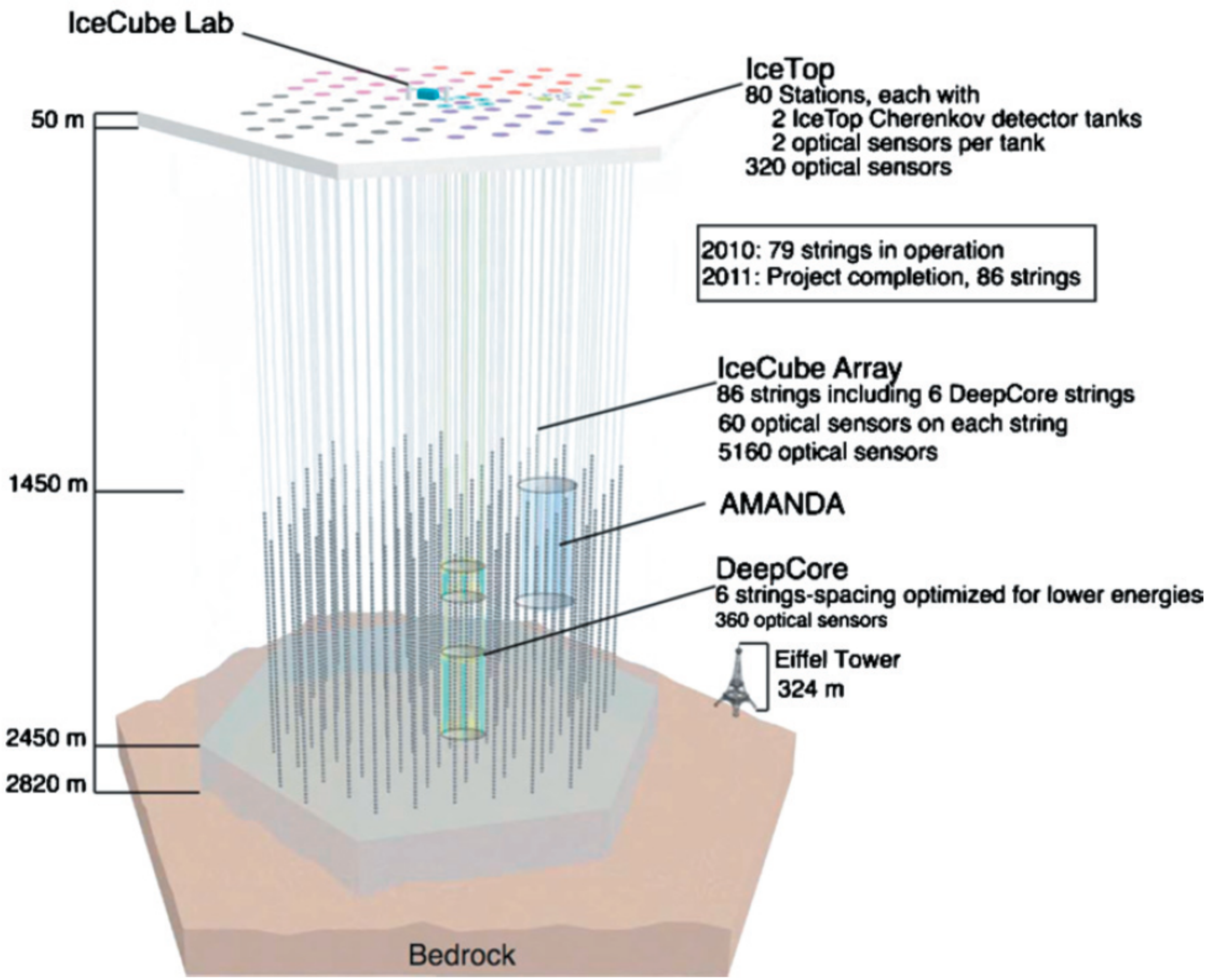
Neutrinos

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 -> notify other types of telescopes
- 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.

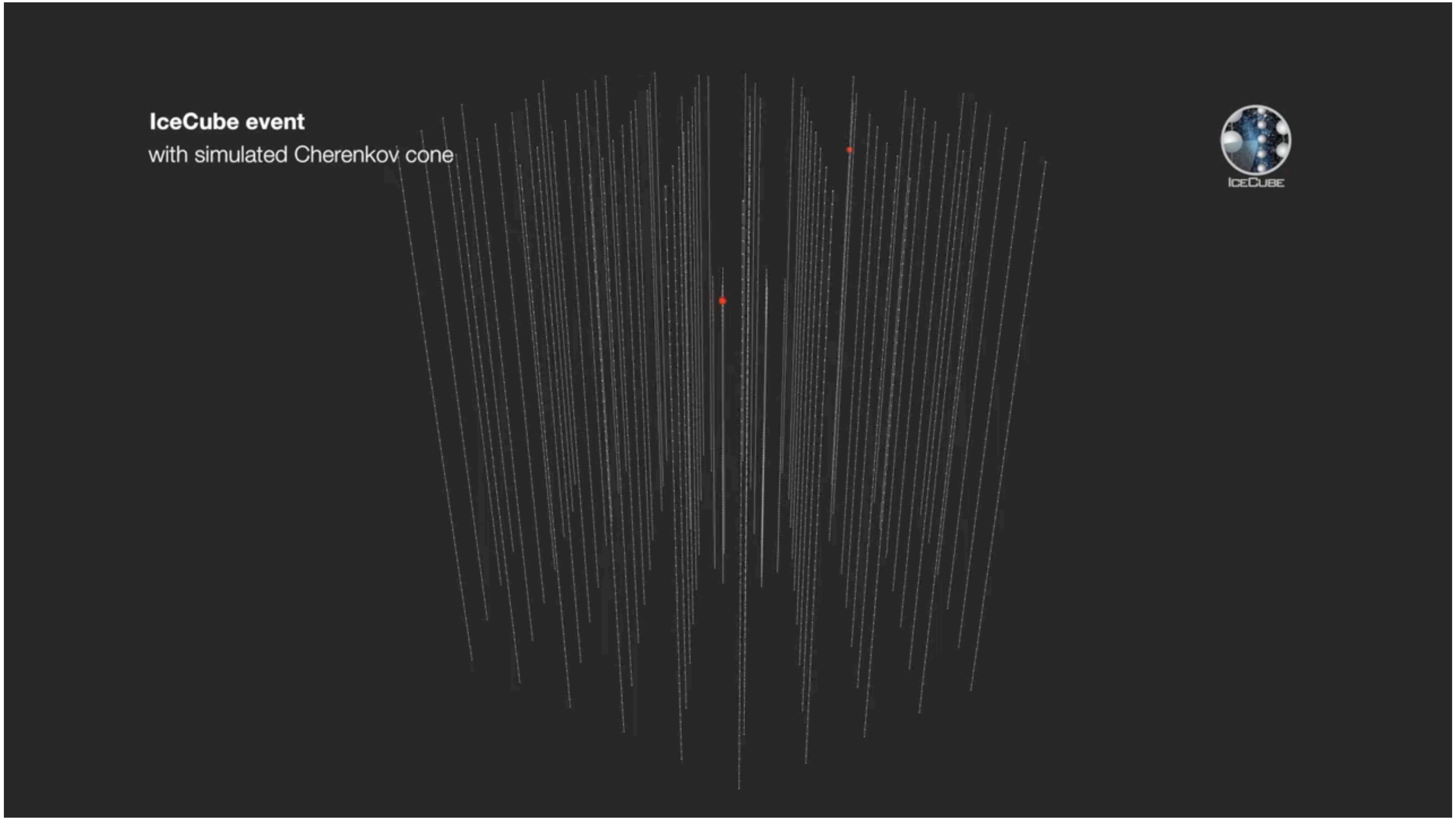
Citizen science project: Name that Neutrino!
https://www.zooniverse.org/projects/icecubeobservatory/name-that-neutrino

IceCube



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

Neutrinos



IceCube detects high-energy neutrinos using the Cherenkov light produced by relativistic charged particles that result from the interaction of these neutrinos with a nucleus of Antarctic ice. The highest energy neutrinos detected to date are included in this video, which also shows a simulated event and the blue Cherenkov cone.

https://icecube.wisc.edu/science/research/

Gravitational waves

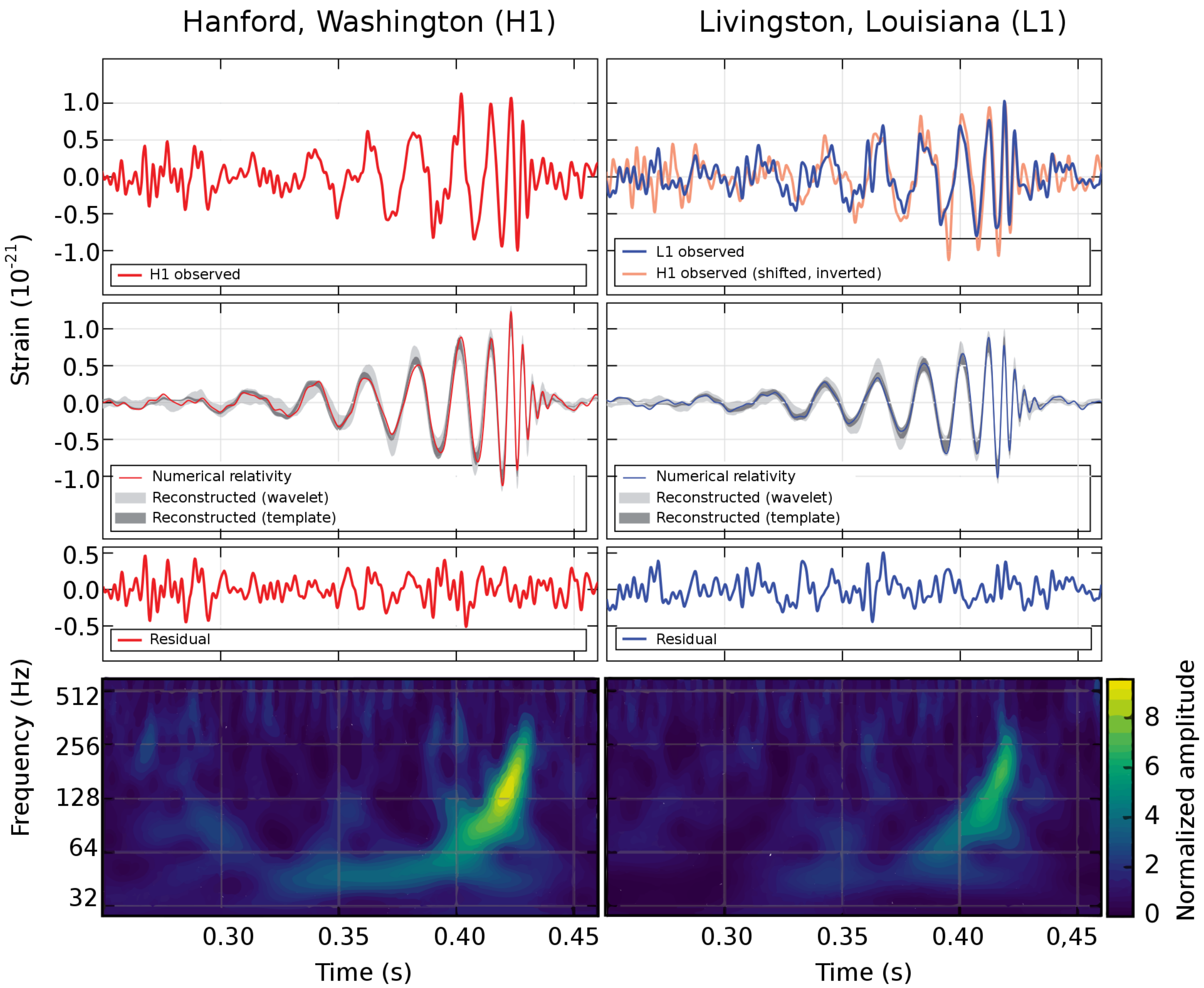
How are they detected?
What are the astronomical sources?
Where would the observatories be?

Gravitational waves

- **Indirect detection with binary pulsars spiralling towards each other,** because they are loosing energy due to gravitational radiation.
- **Direct detection by laser interferometry, e.g. LIGO and Virgo**

Virgo Collaboration: Virgo gravitational wave detector near Pisa, Italy

The first detection of merging black holes in 2015



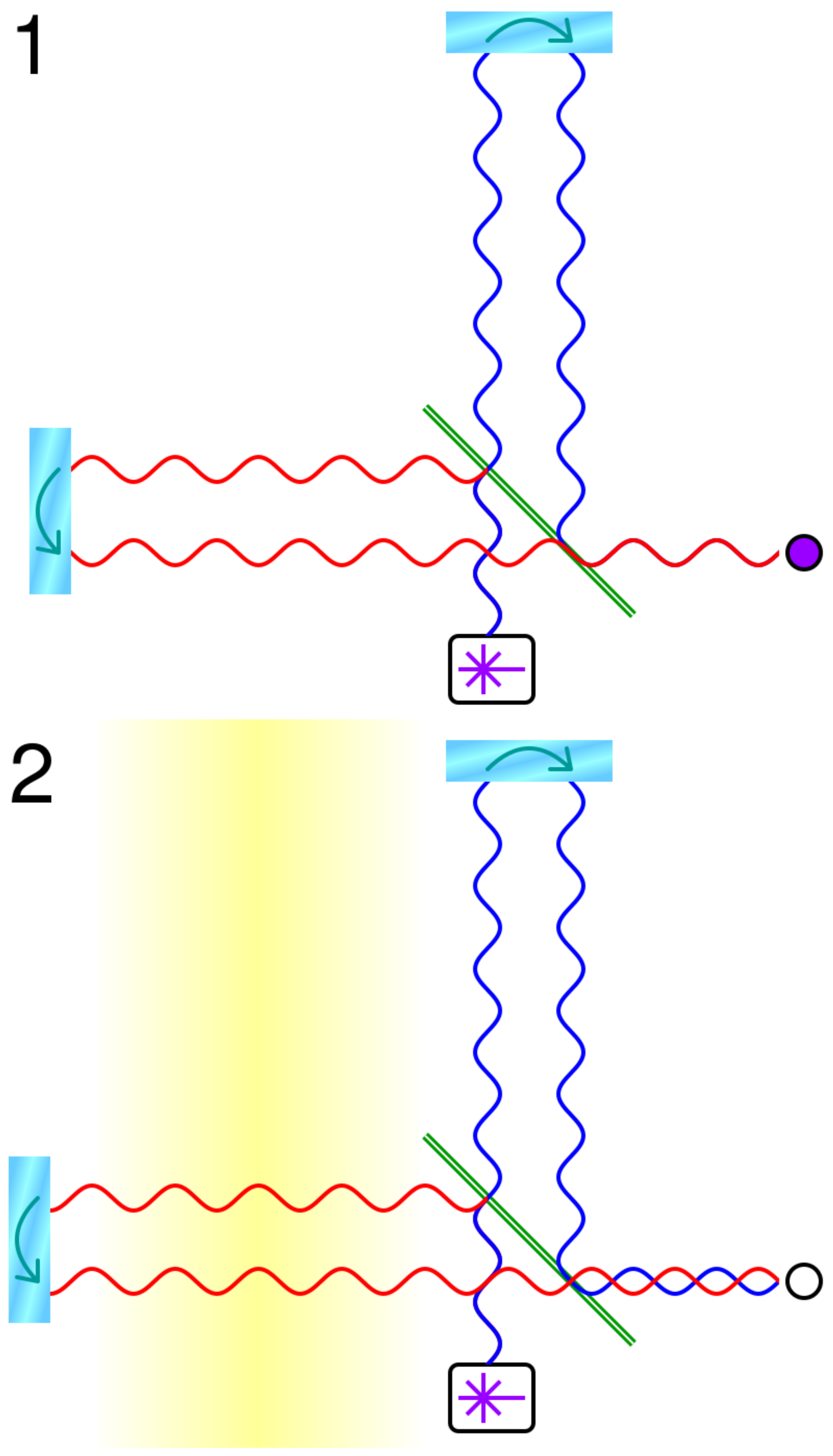
https://en.wikipedia.org/wiki/List_of_gravitational_wave_observations

Gravitational waves

LIGO is essentially a Michelson interferometer with two 4km long arms

Simplified operation of a gravitational wave observatory
Figure 1: A beamsplitter (green line) splits coherent light (from the white box) into two beams which reflect off the mirrors (cyan oblongs); only one outgoing and reflected beam in each arm is shown, and separated for clarity. The reflected beams recombine and an interference pattern is detected (purple circle).
Figure 2: A gravitational wave passing over the left arm (yellow) changes its length and thus the interference pattern.

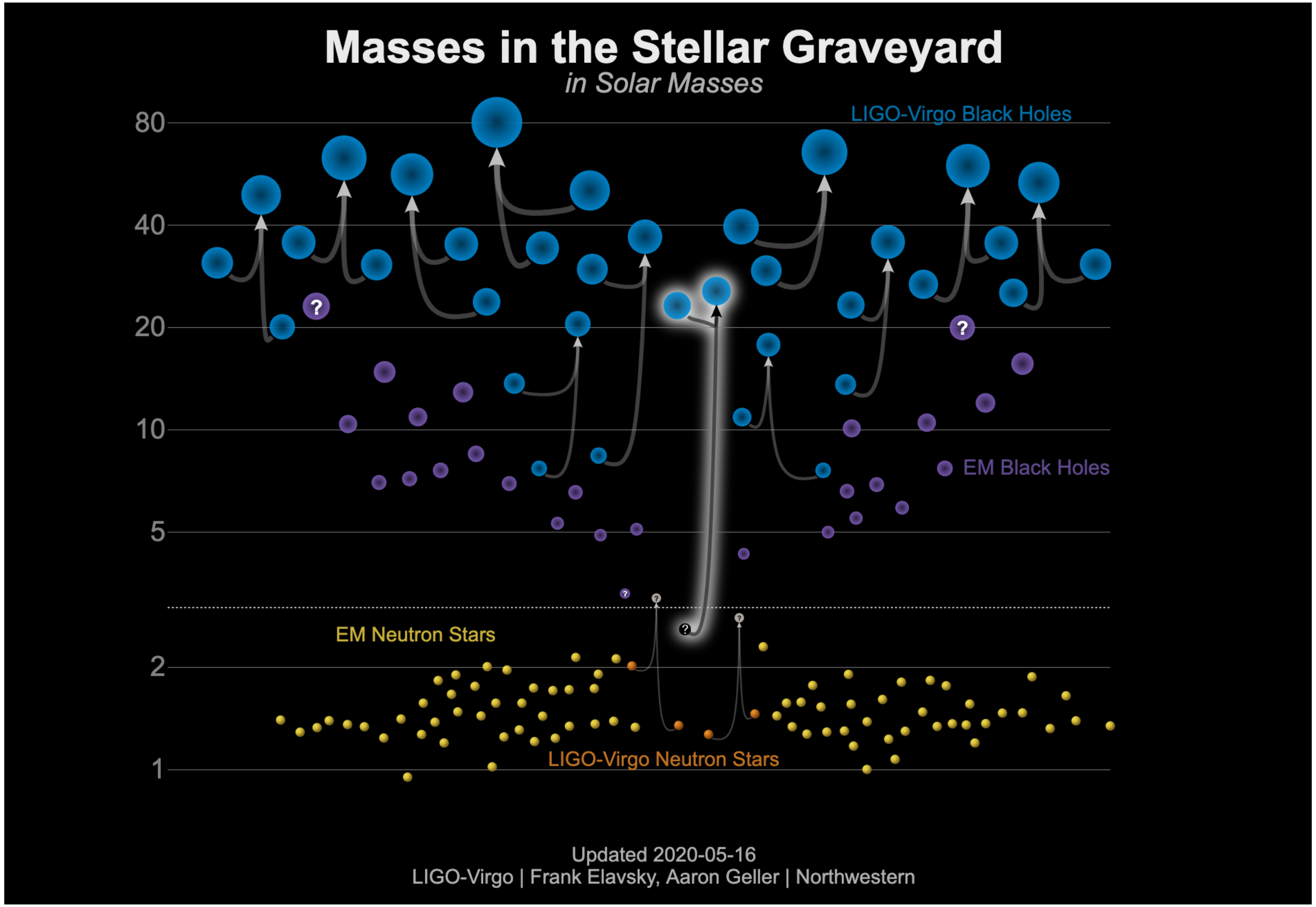
This is an incredibly high precision experiment, where the most challenging part is to reduce the noise.



Gravitational waves

Masses of LIGO/Virgo detections.

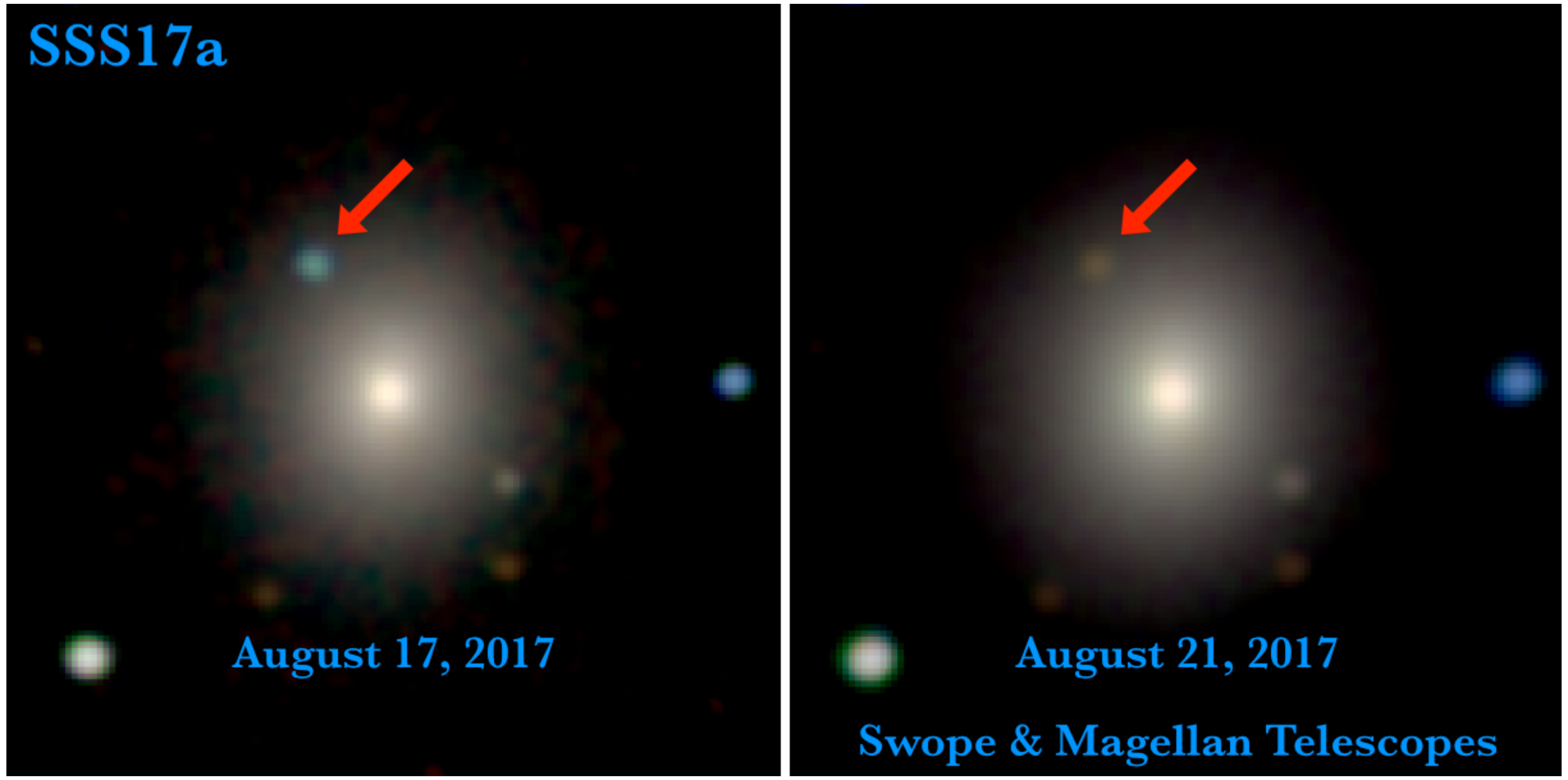
- LIGO and Virgo have observed the merger of several compact object binaries.
- The black holes represent a new population with masses that are larger than what had been seen previously with X-ray studies alone (X-ray binary systems).
- This plot shows the masses of the binary components before merger,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

- Neutron star: a degenerate (dead) star consisting of neutrons
- Gamma-ray burst: a flash of gamma rays from an astronomical object

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)

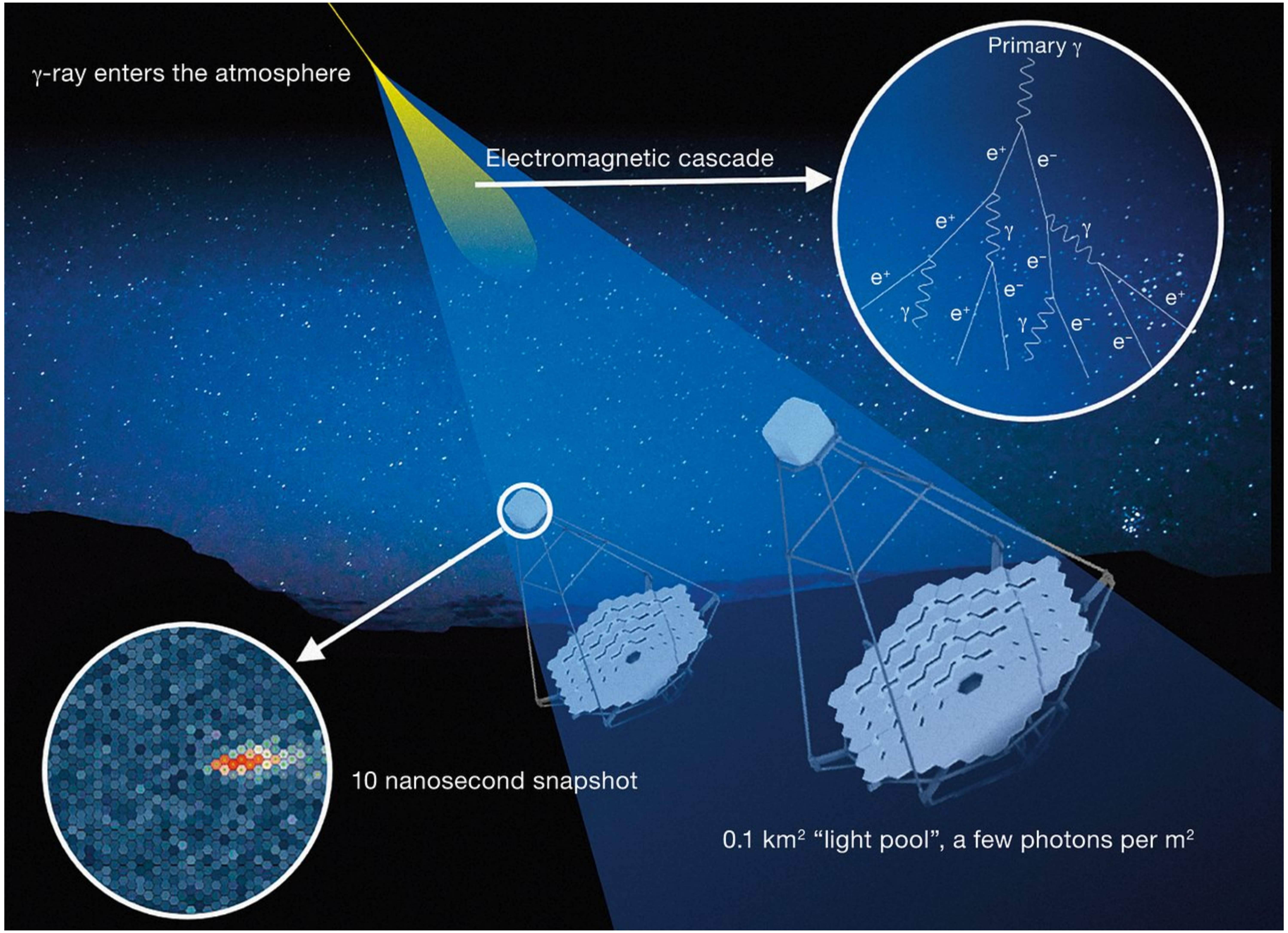
https://www.cta-observatory.org/about/how-cta-works/

Cosmic rays

Illustration on how CTAO (Cherenkov Telescope Array Observatory) will work:

- γ-rays hit the atmosphere and generate particle showers
- the ultra-high energy charged particles produce Cherenkov light
- The faint Cherenkov light gets detected by an array of telescopes

CTAO has two telescope arrays in La Palma, Spain and in Paranal, Chile.



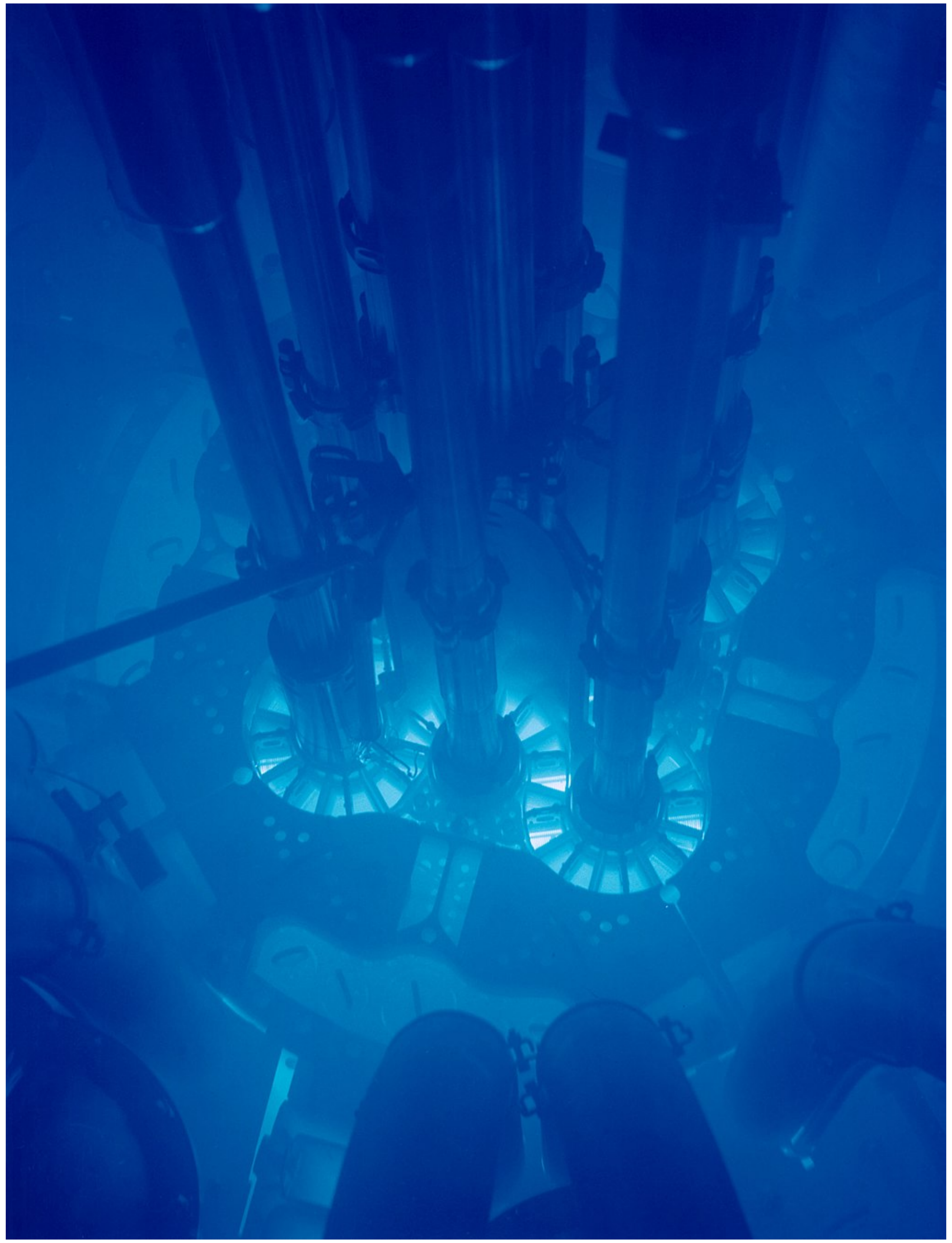
https://www.eso.org/public/images/eso1841x/

Cherenkov radiation

Cherenkov radiation is electromagnetic radiation emitted when a charged particle (such as an electron) passes through a dielectric medium at a speed greater than the speed of propagation of light in that medium.

A classic example of Cherenkov radiation is the characteristic blue glow of an underwater nuclear reactor. Its cause is similar to the cause of a sonic boom, the sharp sound heard when faster-than-sound movement occurs.

Astrophysics examples: cosmic rays hitting the atmosphere of Earth, neutrino detectors.



Cherenkov radiation glowing in the core of the Advanced Test Reactor.

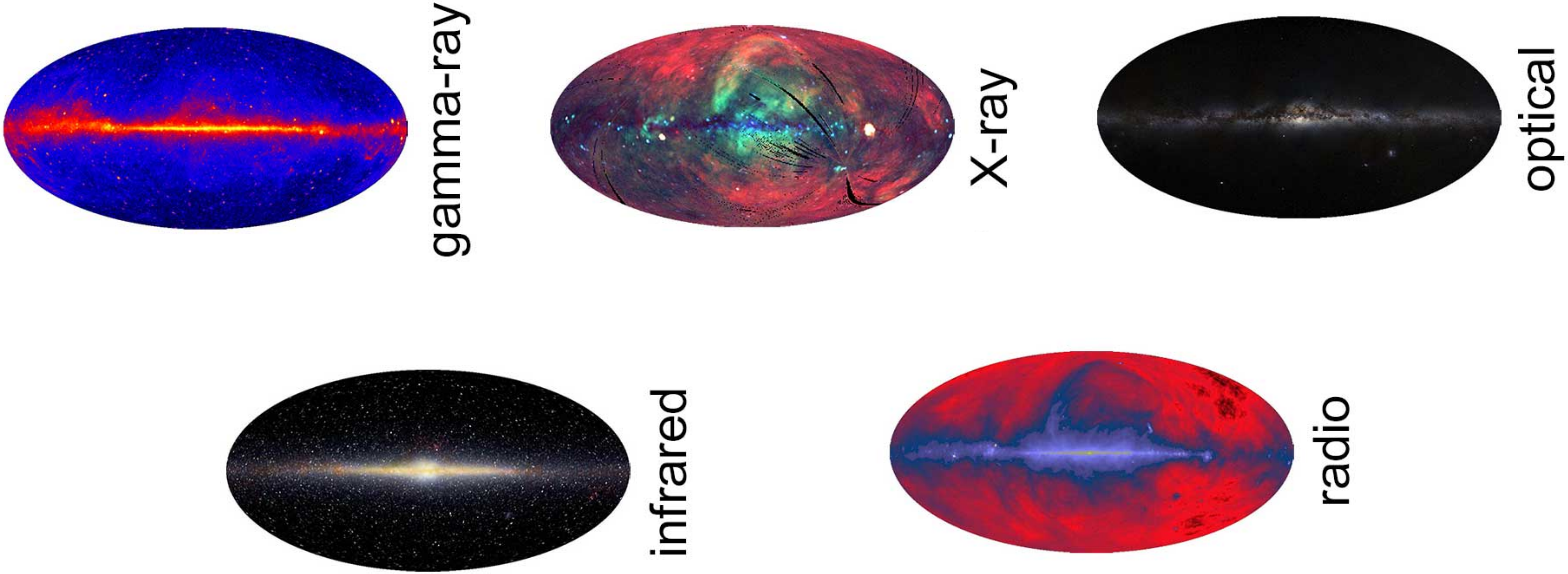
https://en.wikipedia.org/wiki/Cherenkov_radiation

Electromagnetic radiation

Multi-wavelength astrophysics

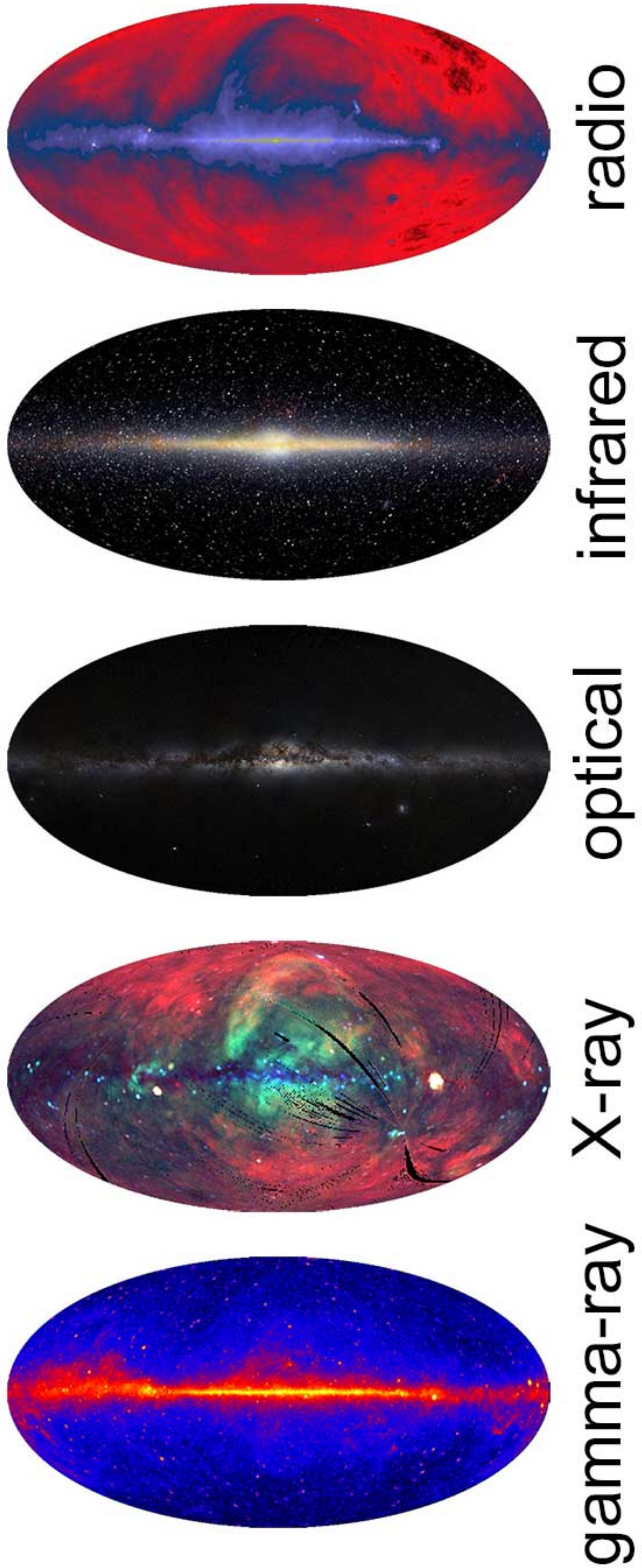
What is multi-wavelength astrophysics?

Multi-wavelength astrophysics



Multi-wavelength astrophysics

Type Of Radiation	Radiated by Objects at this Temperature	Typical Sources
Gamma-rays	$> 10^8$ K	accretion disks around black holes
X-rays	10^6-10^8 K	gas in clusters of galaxies; supernova remnants; stellar corona
Ultraviolet	10^4-10^6 K	supernova remnants; very hot stars
Visible	10^3-10^4 K	planets, stars
Infrared	10-10^3 K	cool clouds of dust and gas; planets
Microwave	1-10 K	cool clouds of gas, including those around newly formed stars; the cosmic microwave background
Radio	< 1 K	radio emission produced by electrons moving in magnetic fields



https://imagine.gsfc.nasa.gov/science/toolbox/multiwavelength1.html

Electromagnetic radiation

Non thermal radiation

Spectral lines from gas clouds

Non thermal radiation

Spectral lines from gas clouds

Dust

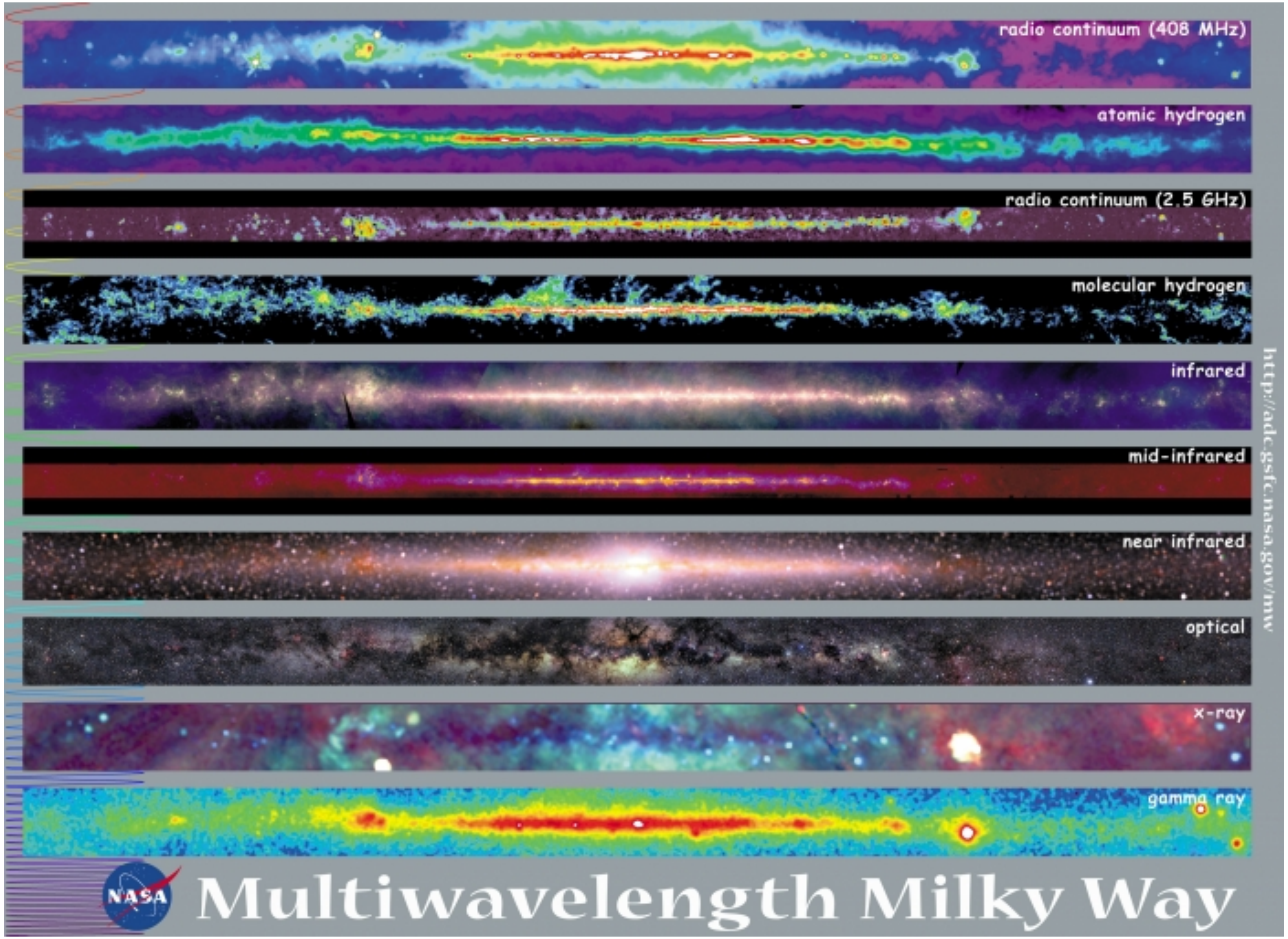
Dust

Old Stars

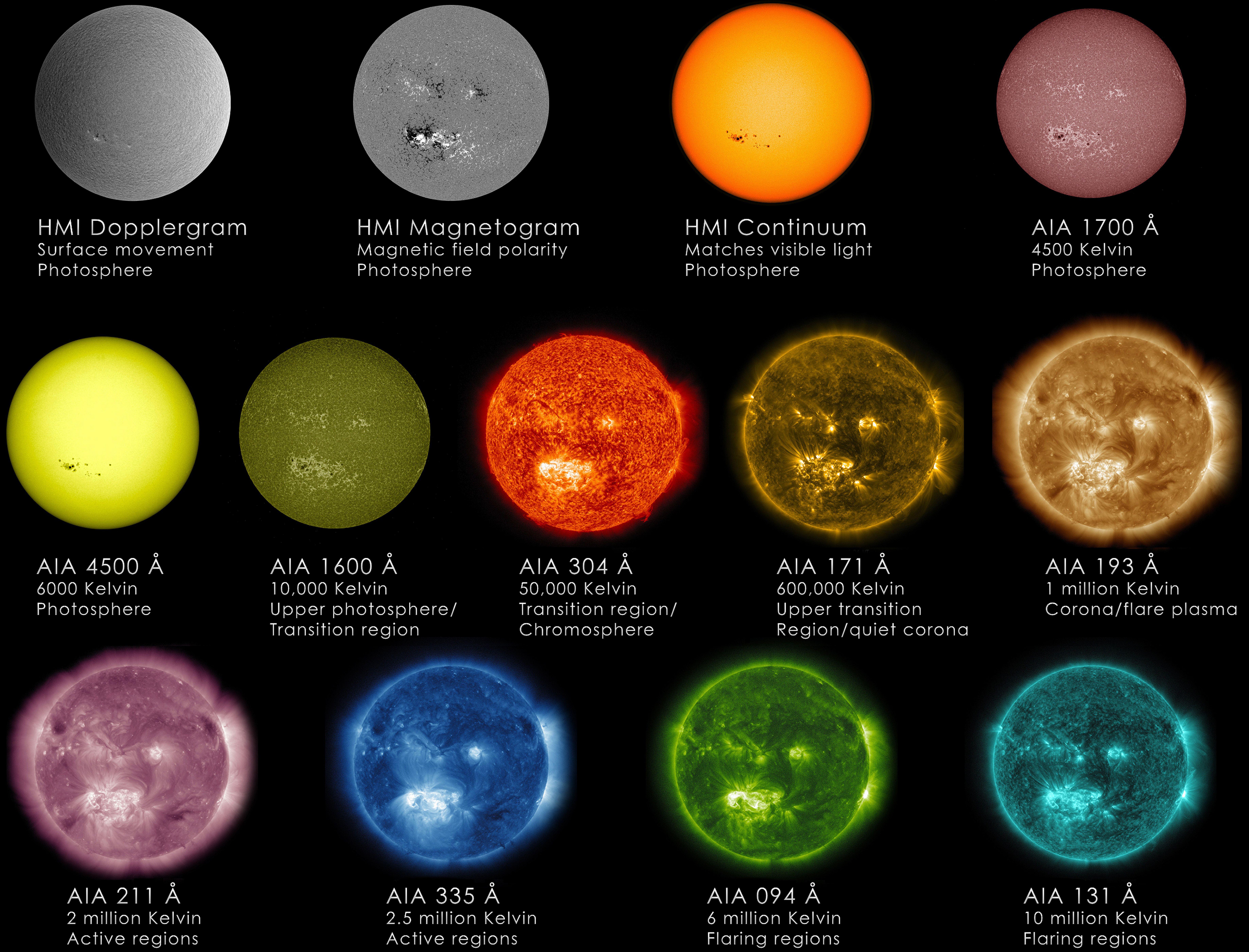
Stars

Hot plasma

High energy sources



The Sun



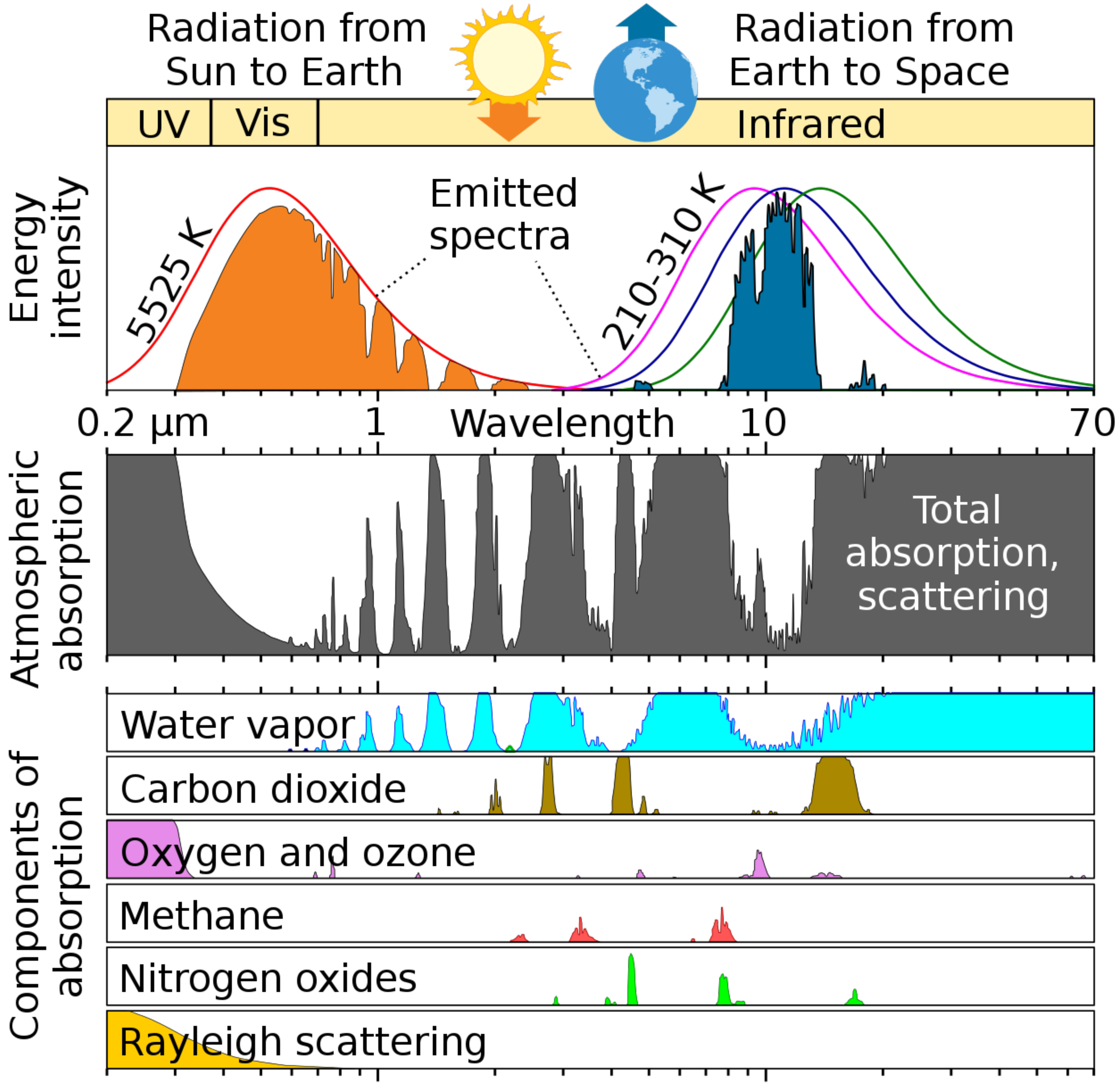
NASA's Solar Dynamics Observatory (SDO) shows how observations of the sun in different wavelengths helps highlight different aspects of the sun's surface and atmosphere

https://www.nasa.gov/mission_pages/sunearth/news/light-wavelengths.html

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
- **The atmospheric transmission characterises how much radiation can reach the surface of the Earth at different wavelengths.**
- The parts of the atmosphere were radiation gets through are also called **atmospheric windows.**

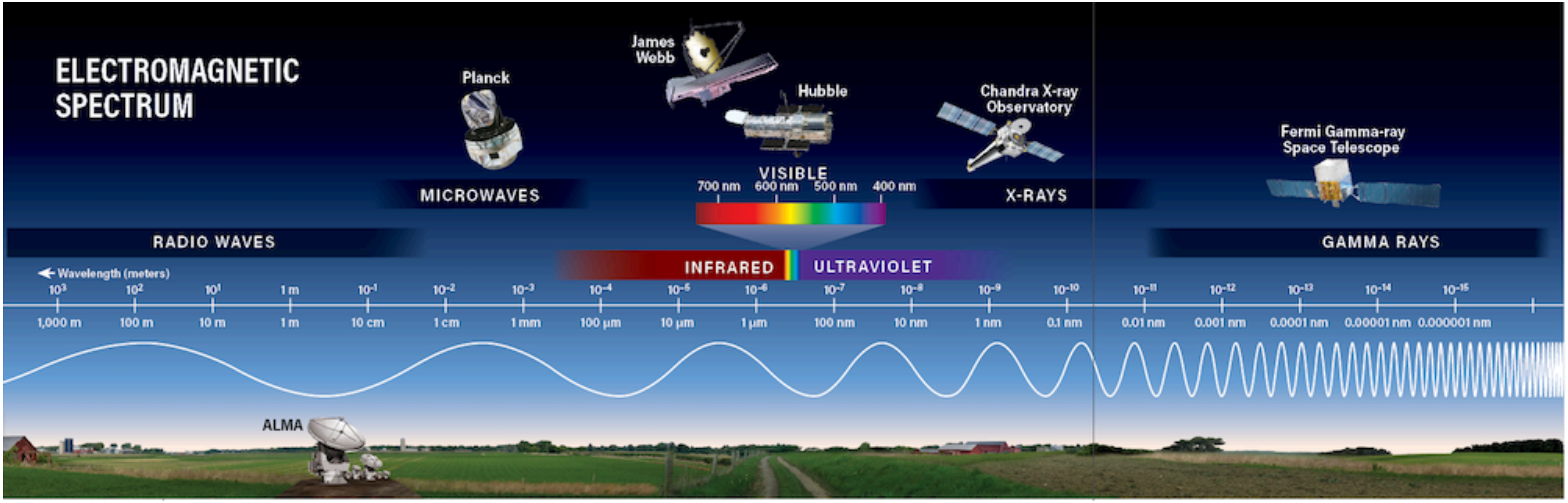


https://en.wikipedia.org/wiki/Atmospheric_window

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

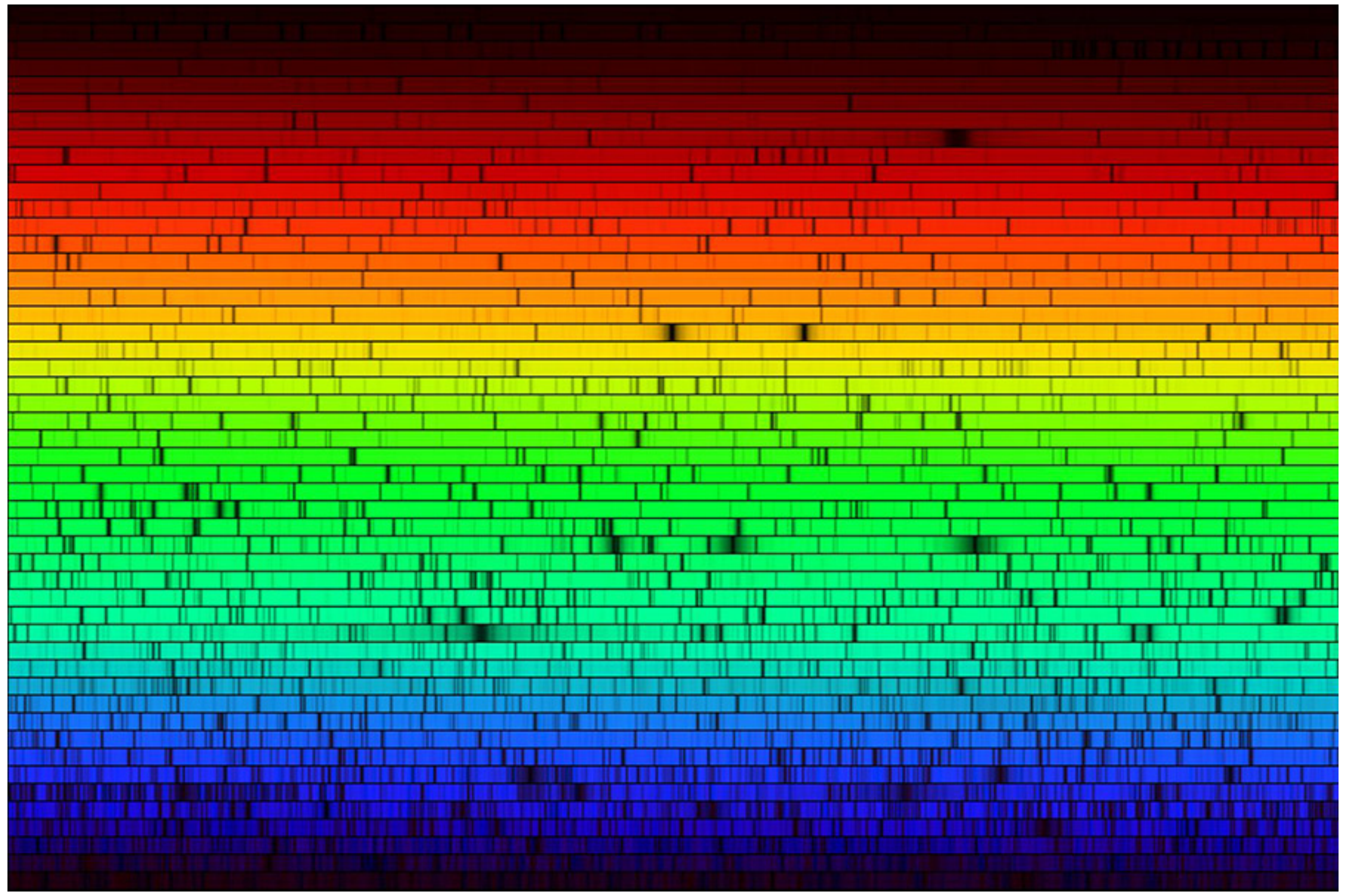
Two types of measurements:

Imaging

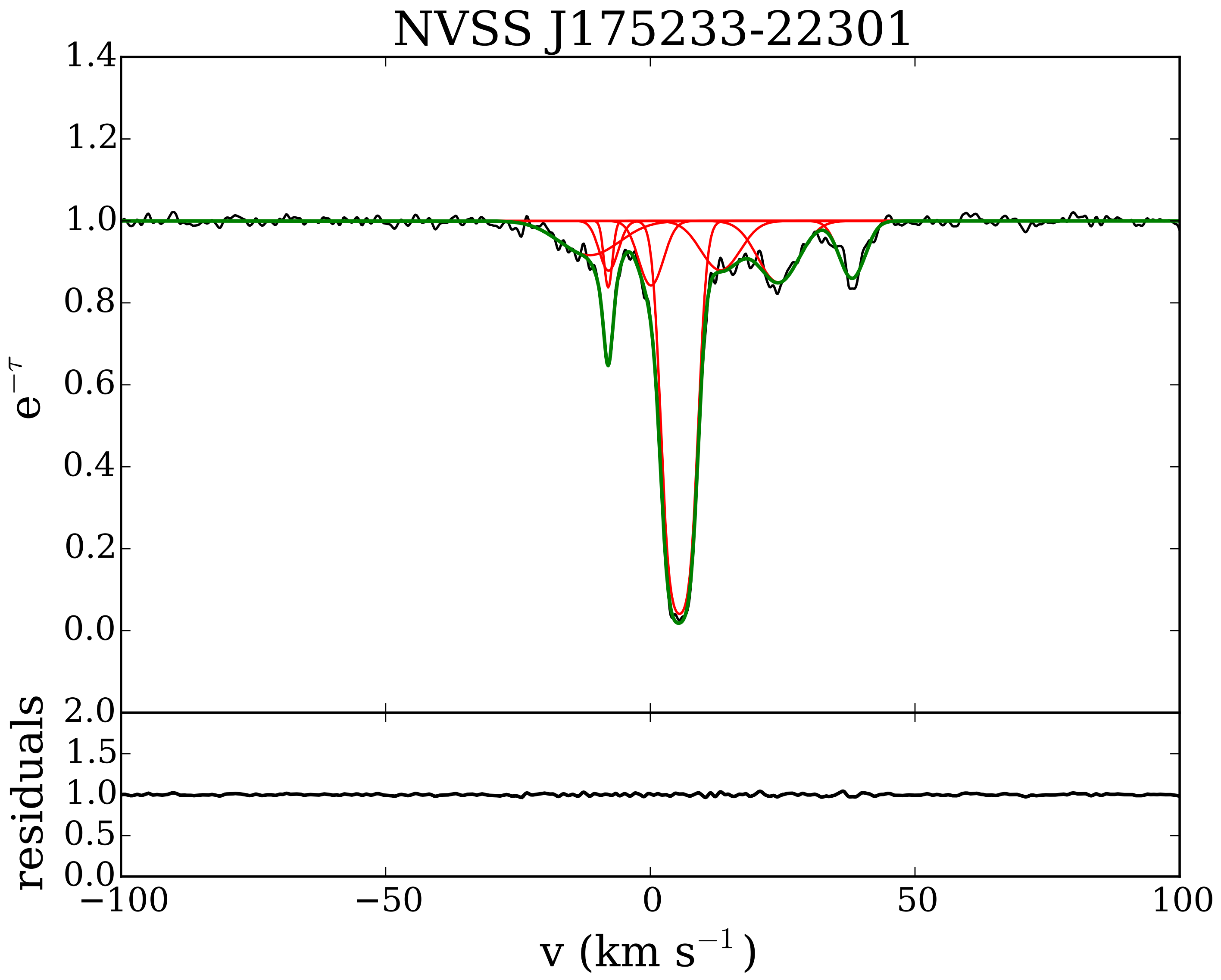
Spectroscopy

M101 galaxy

Spectrum of the Sun



Neutral Hydrogen absorption spectra



Gamma-ray astronomy

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

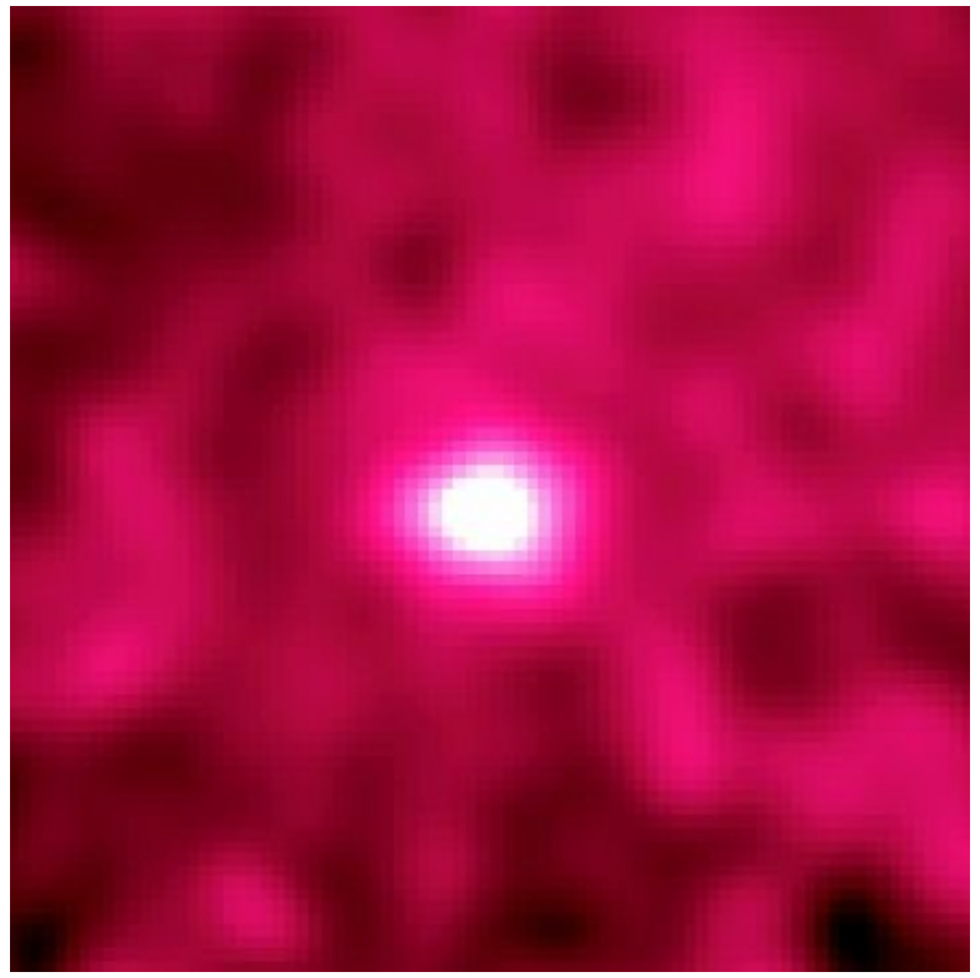
Gamma-ray astronomy

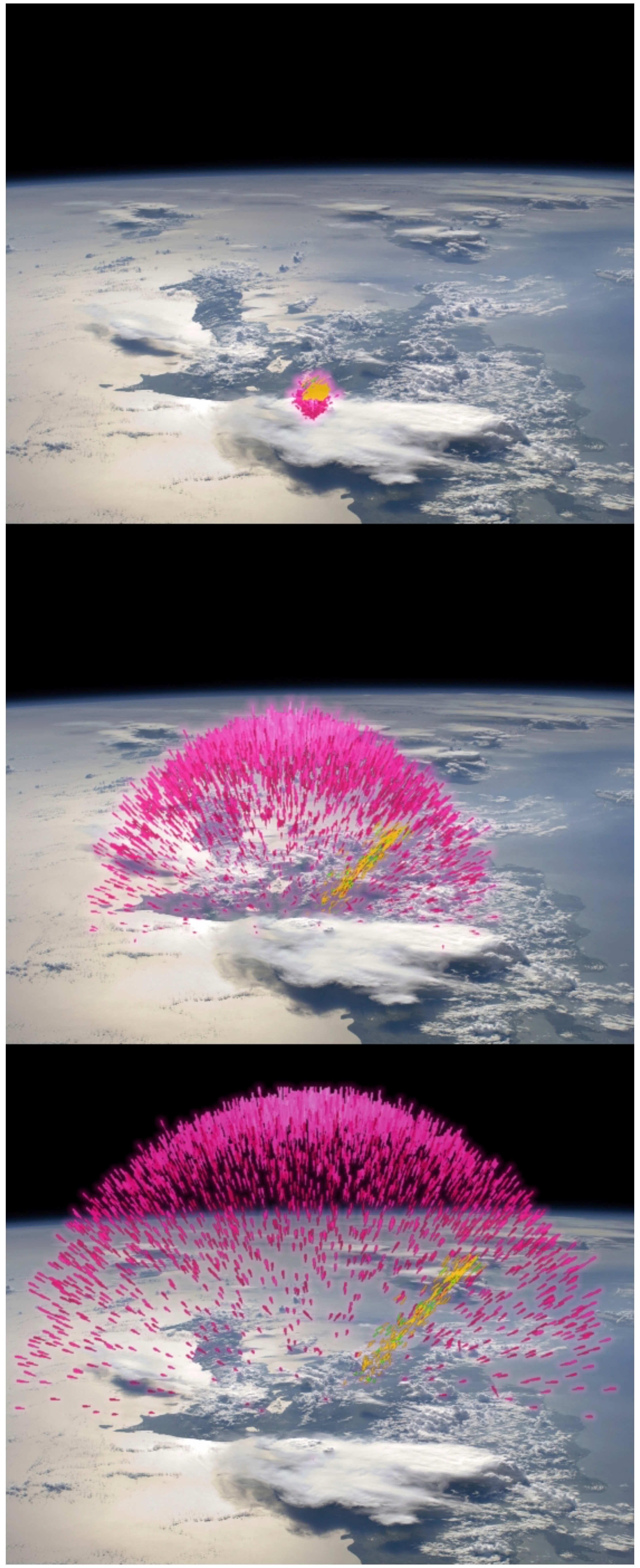
- Radiation above a 100 keV (from high energy sources)
- Sources: solar flares, supernovae, hypernovae, pulsars, blazars (AGN with the jet pointing towards Earth), thunderstorms on Earth, etc.
- Gamma-ray telescopes (satellites): INTEGRAL, Fermi, Egret, AGILE, etc.
- Indirect detection trough particle showers in the atmosphere (see cosmic ray section)

Fermi satellite

https://fermi.gsfc.nasa.gov/

The Moon in gamma rays, the gamma rays are produced by cosmic ray particle bombardment of the surface

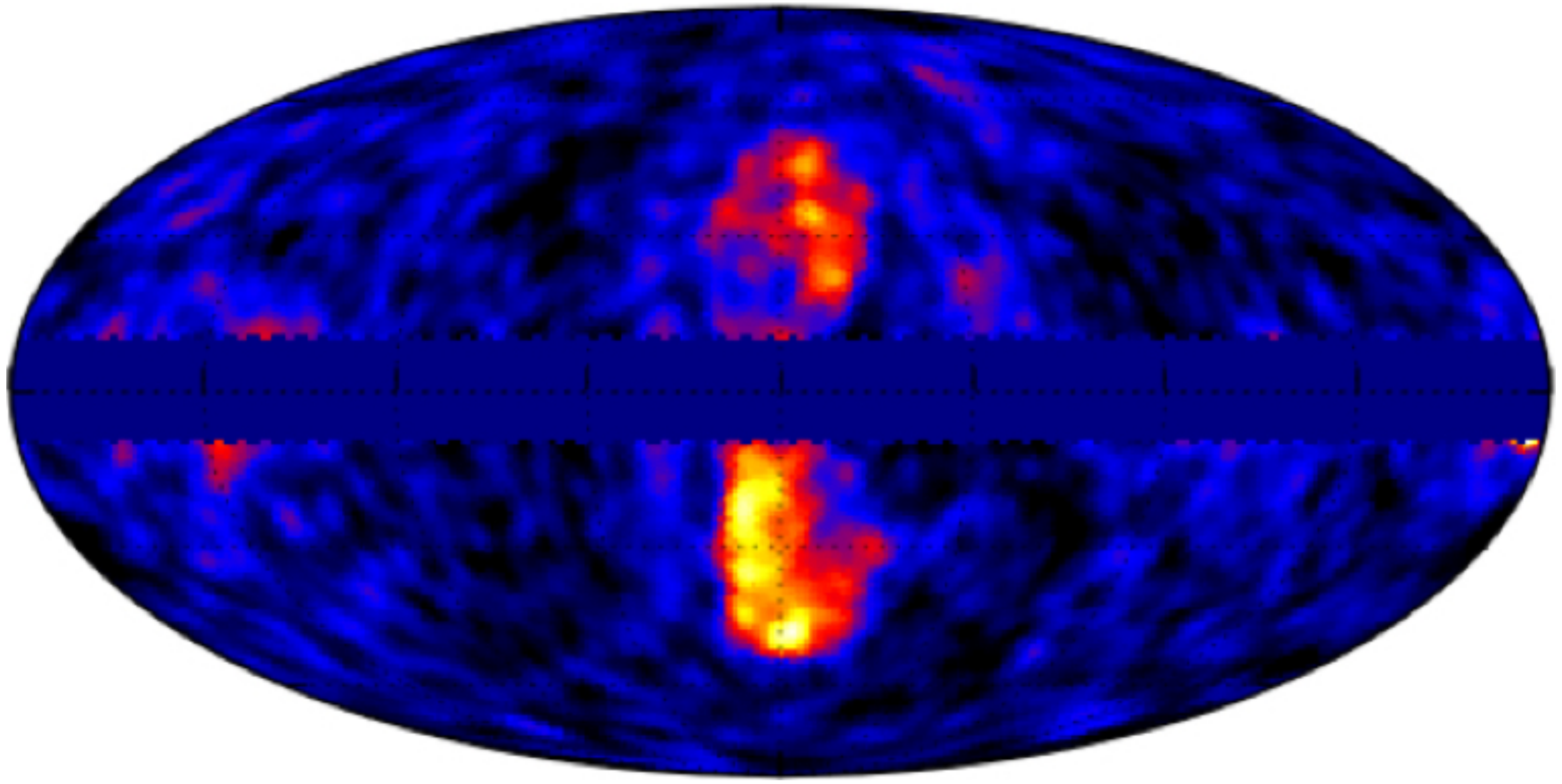


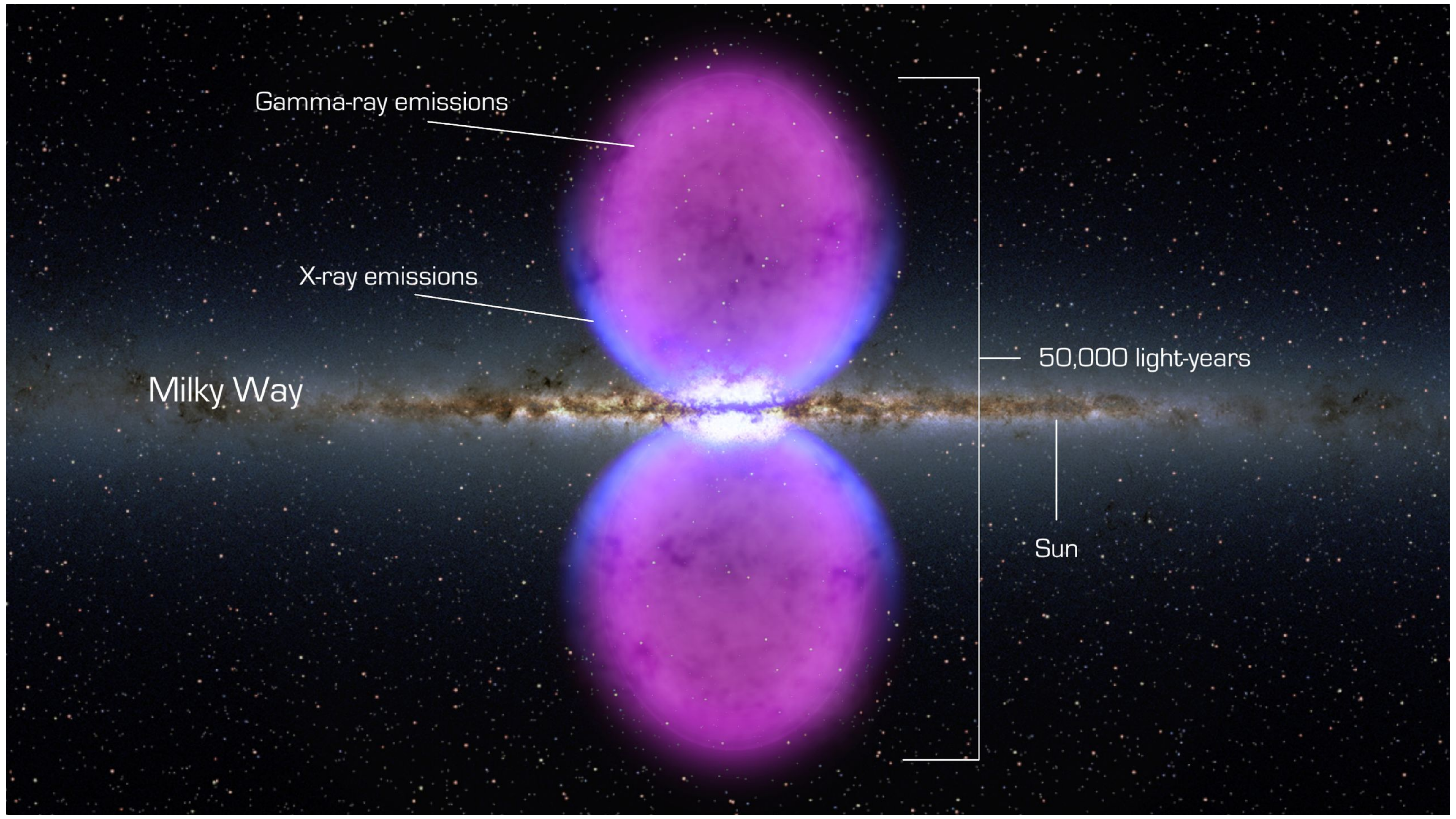


https://en.wikipedia.org/wiki/Gamma-ray_astronomy

Gamma-ray astronomy

- **Fermi bubbles:** large scale diffuse gamma ray emission attributed to the activity in the centre of the Galaxy. Current theory is that they are either produced **by the supermassive black hole or by intense star formation activity.**





https://en.wikipedia.org/wiki/Gamma-ray_astronomy

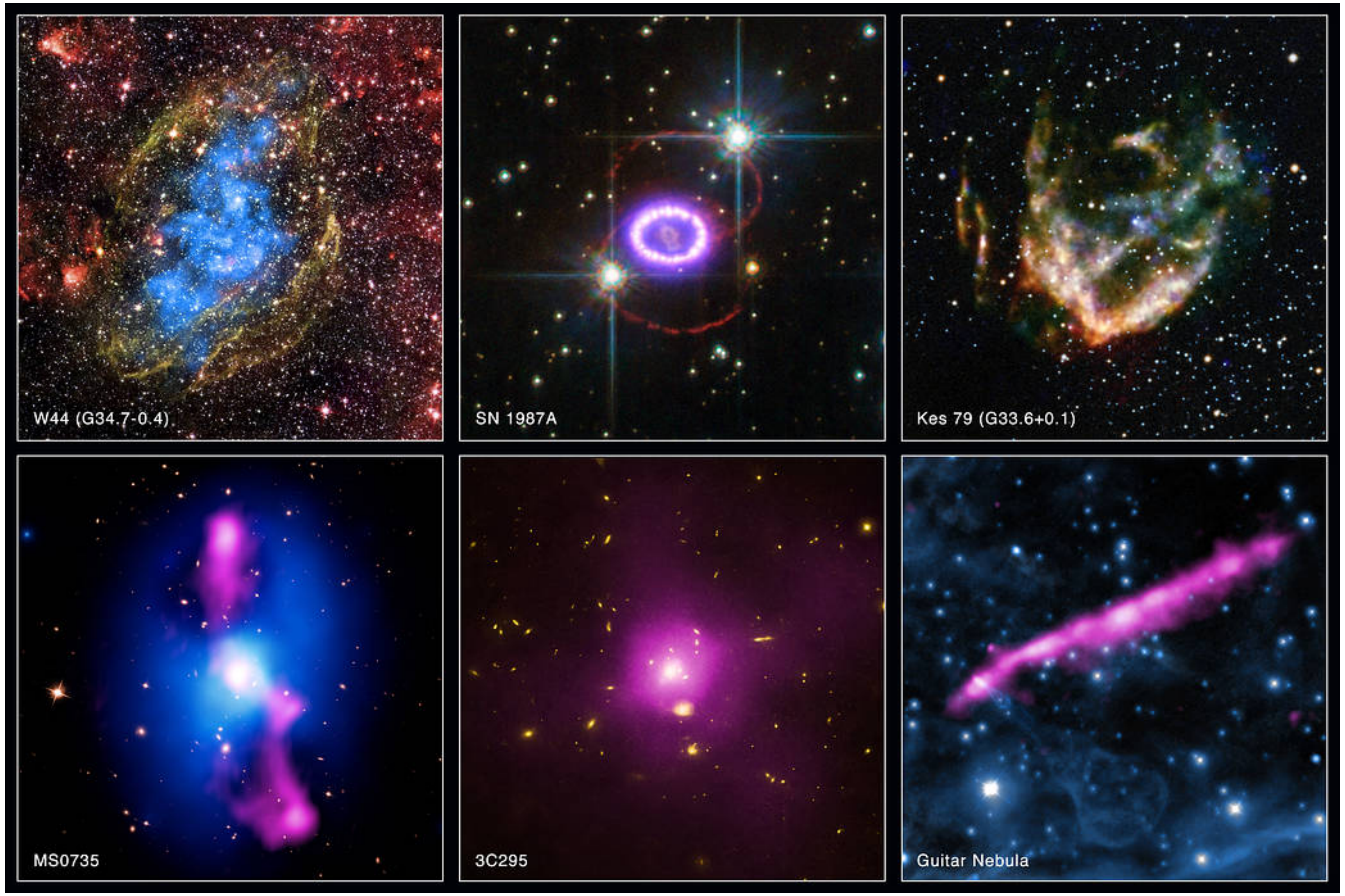
https://fermi.gsfc.nasa.gov/

X - ray astronomy

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

X - ray astronomy

- **Only detectable above the atmosphere:** balloon experiments and satellites
  - Example telescopes: ROSAT, Chandra, XMM-Newton
  - Sources: hot plasma (millions of K)
  - Examples: the Sun, Supernova remnants, intra cluster matter in galaxy clusters, AGN, accreting binary systems, neutron star or black hole binaries.

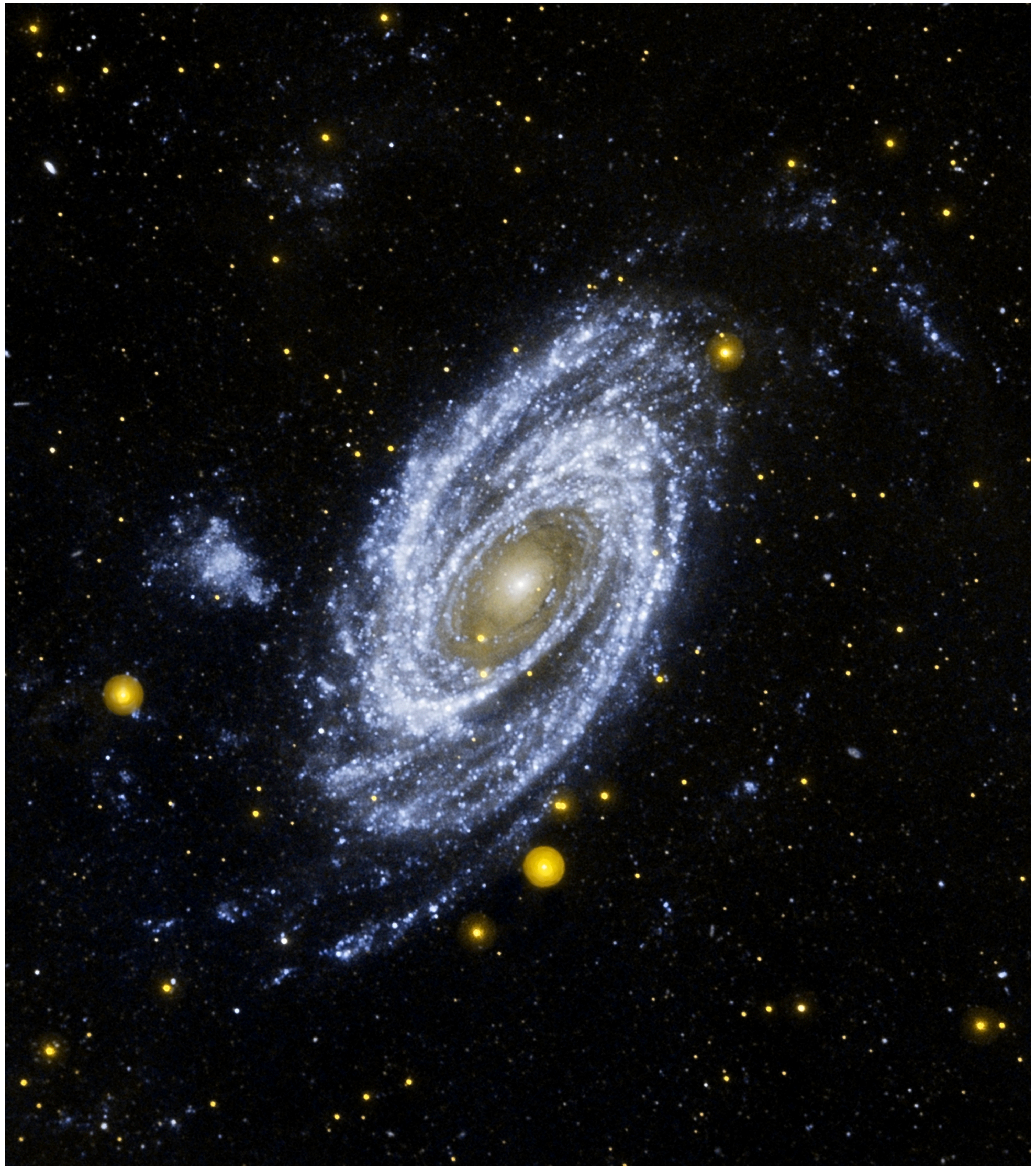


Ultraviolet (UV) astronomy

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

Ultraviolet (UV) astronomy

- **Mostly only detectable above the atmosphere:** satellites
- Used to measure: the chemical composition, densities, and temperatures of the **interstellar medium** (spectral lines in UV), and the temperature and composition of **hot young stars** and **white dwarfs.**
- Example telescopes: Hubble Space Telescope, GALEX space telescope



The Galaxy M81 in UV light
What is visible in this galaxy are the hot young stars in the spiral arms

Optical astronomy

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

Optical astronomy

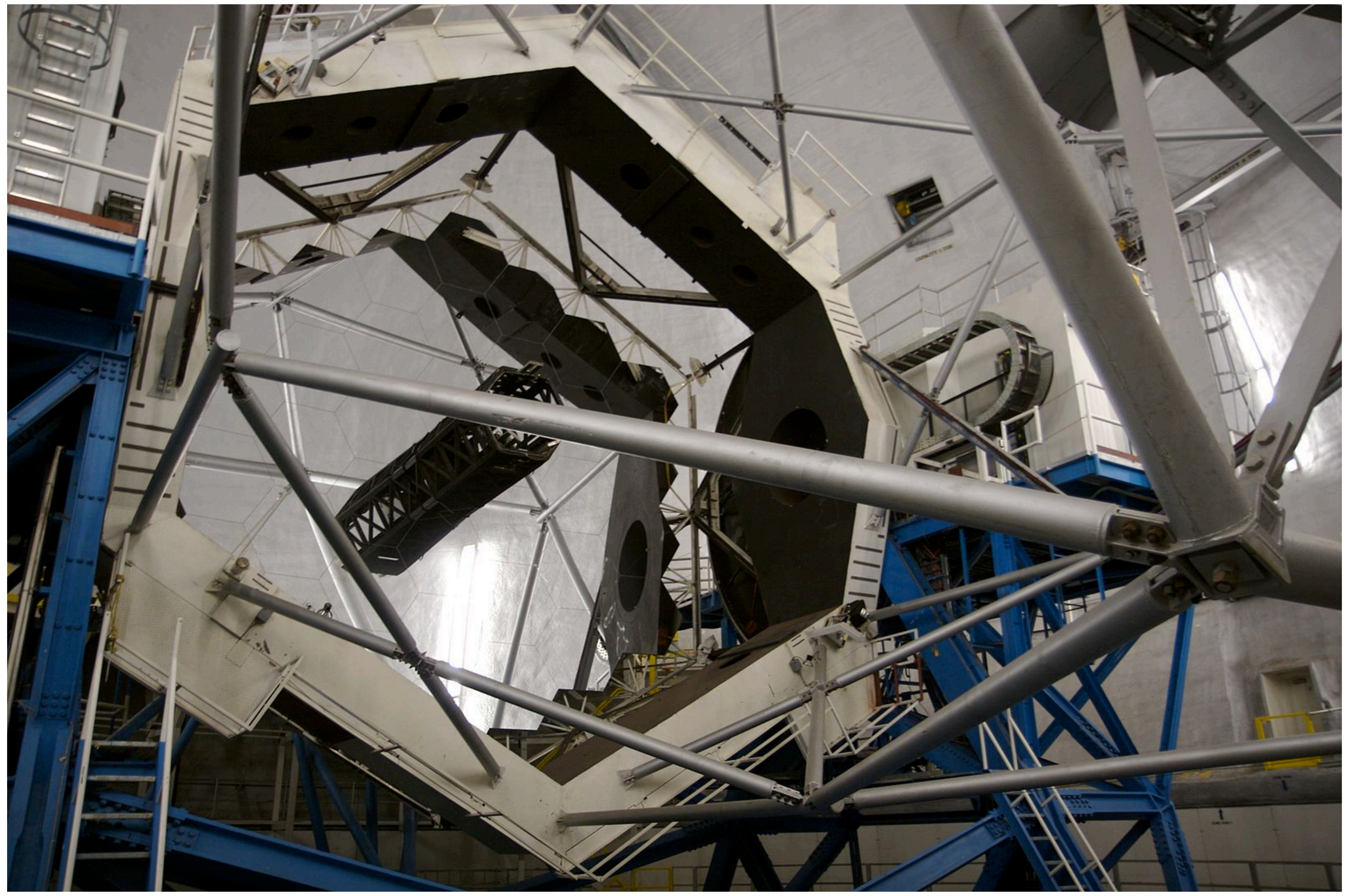
Early telescopes with lenses.

Modern telescopes with mirrors, for better resolution and sensitivity. There are many different optical designs.

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

Adaptive optics:

- Artificial star generated with a laser
- The properties of the atmosphere can be measured based on this “star”
- Flexible mirrors are used to correct for the measured atmospheric turbulence

Optical astronomy

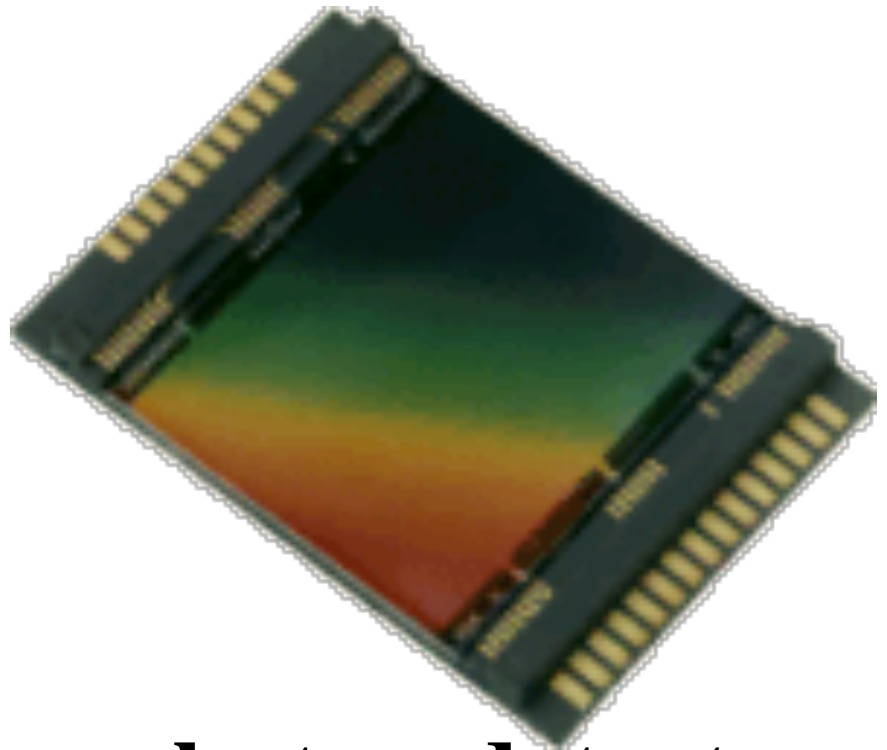
Other important effects:

- Optics of the telescope (What happens with the light once it gets into the telescope)
- Calibration of the data (To get the correct scale for the measurements)
- What are we actually observing? E.g. extinction effects

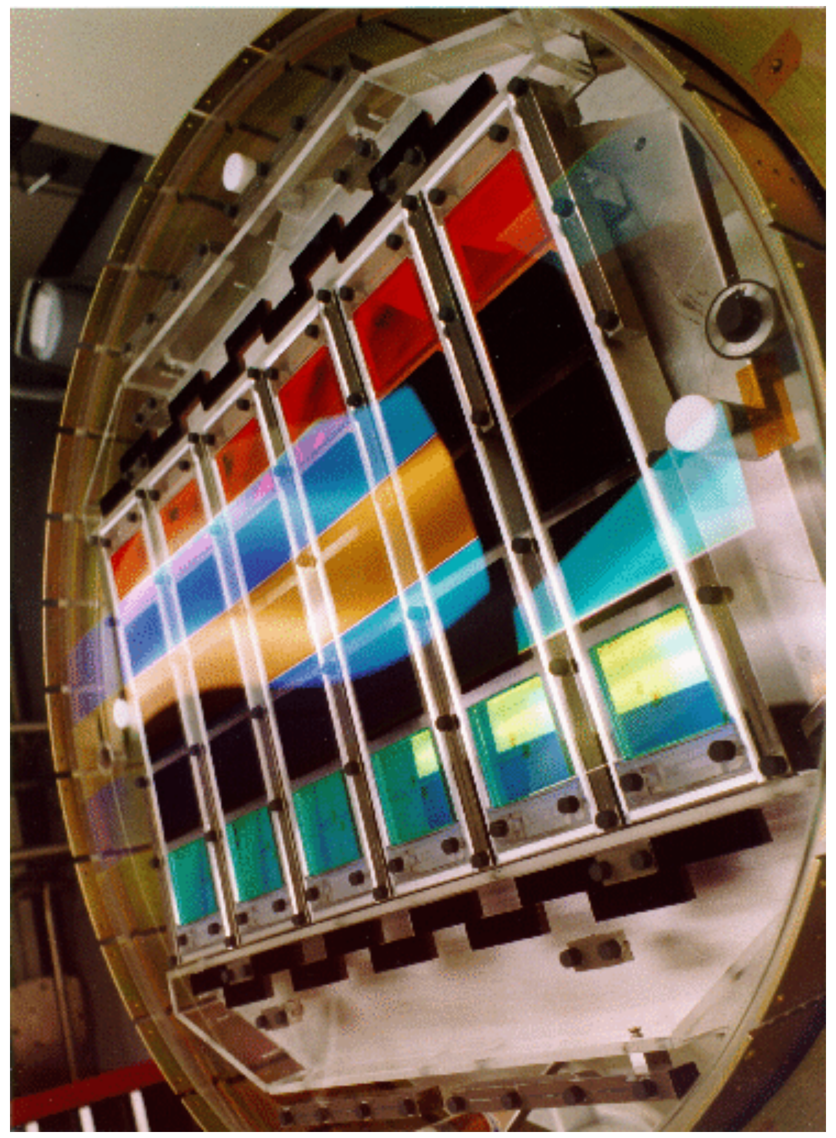
Calibration image **Raw image** **Calibrated image**

https://skyandtelescope.org/astronomy-blogs/imaging-foundations-richard-wright/dark-frames-and-bias-frames-demystified/

Optical astronomy

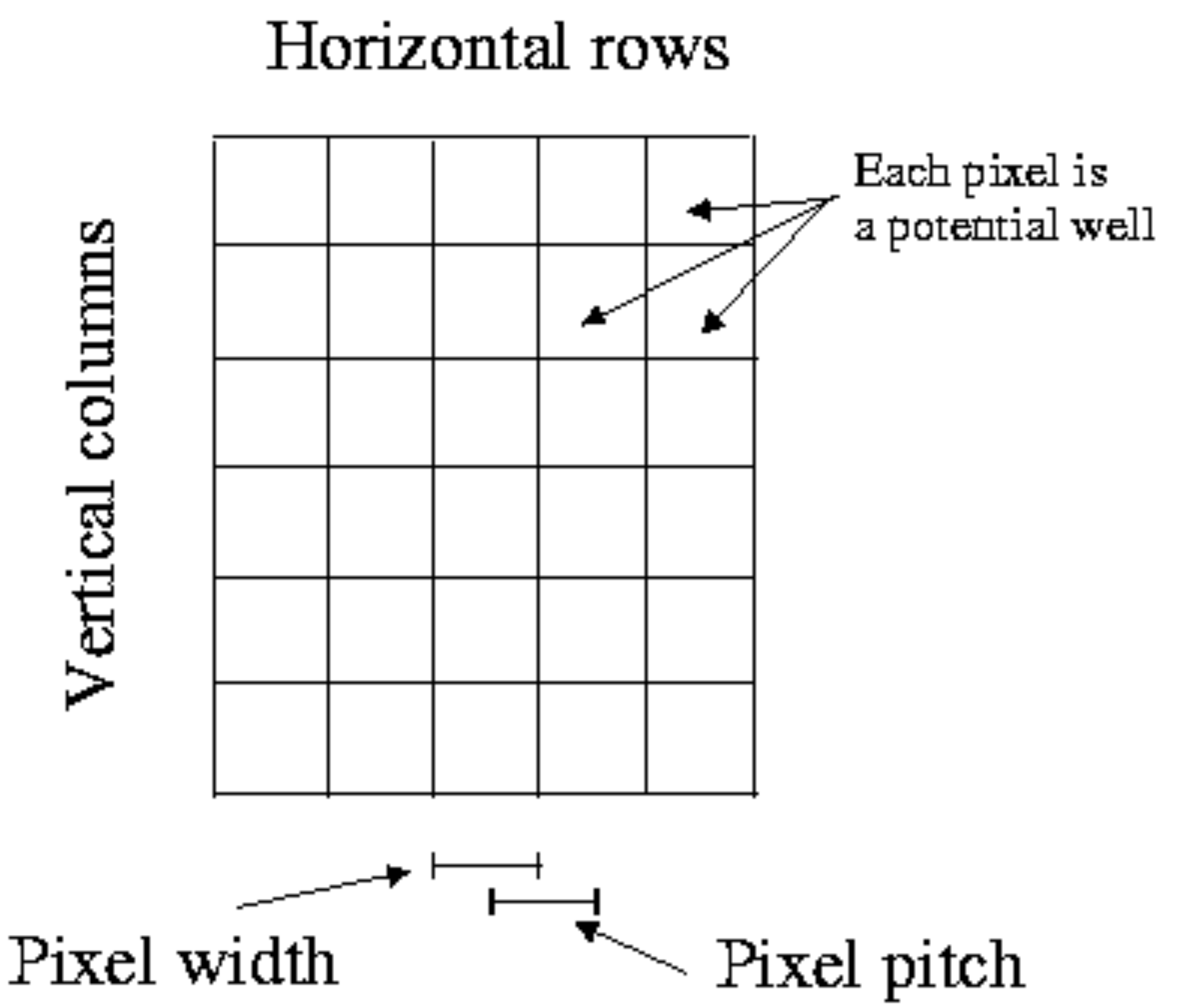


An array of 30 CDD chips from the Sloan Digital Sky Survey



CCD detectors:

- A Charge Coupled Device (**CCD**) is a highly sensitive **photon detector.** The CCD is divided up into a large number of light-sensitive small areas (known as pixels) which can be used to build up an image.
- **A photon of light which falls within the area defined by one of the pixels will be converted into one (or more) electrons and the number of electrons collected will be directly proportional to the intensity of the light at each pixel.**
- When the CCD is clocked out, the number of electrons in each pixel are measured and the image can be reconstructed.
- A CCD will consist of a large number of pixels, arranged horizontally in rows and vertically in columns.
- A CCD treats light as "particles" - only the intensity of the radiation is measured.
- Used for nearly all UV, optical and infrared telescopes, also used for X-rays.



https://www.mssl.ucl.ac.uk/www_detector/ccdgroup/optheory/ccdoperation.html

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 largest observatories (best location) are in:

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

High mountains close to the sea with stable airflow.

Optical astronomy

Hubble Deep field - lots of galaxies

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

Milky Way with VLT telescope

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

Infrared astronomy

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

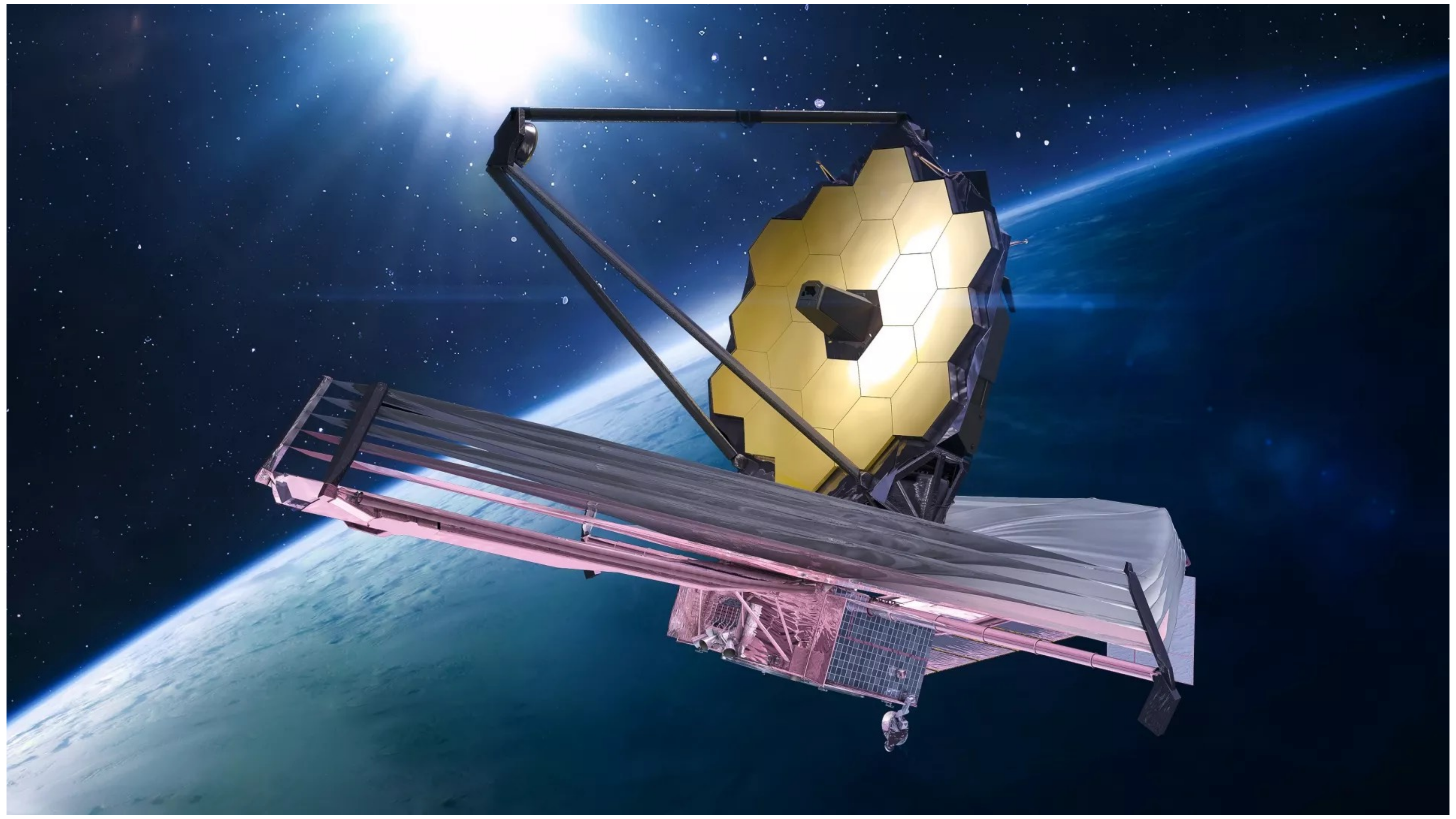
Infrared astronomy

- Telescopes on **high mountains** can observe in the near-infrared, e.g. VISTA, UKIRT etc.
- Observatories on **airplanes**: e.g. SOFIA, Galileo Observatory, Kuiper Airborne observatory
- **Space observatories**: Spitzer, AKARI, Herschel observatory, James Webb Space Telescope (JWST), WISE
- Difficulty: requires cryostatic cooling (e.g. liquid nitrogen cooling)

SOFIA observatory

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

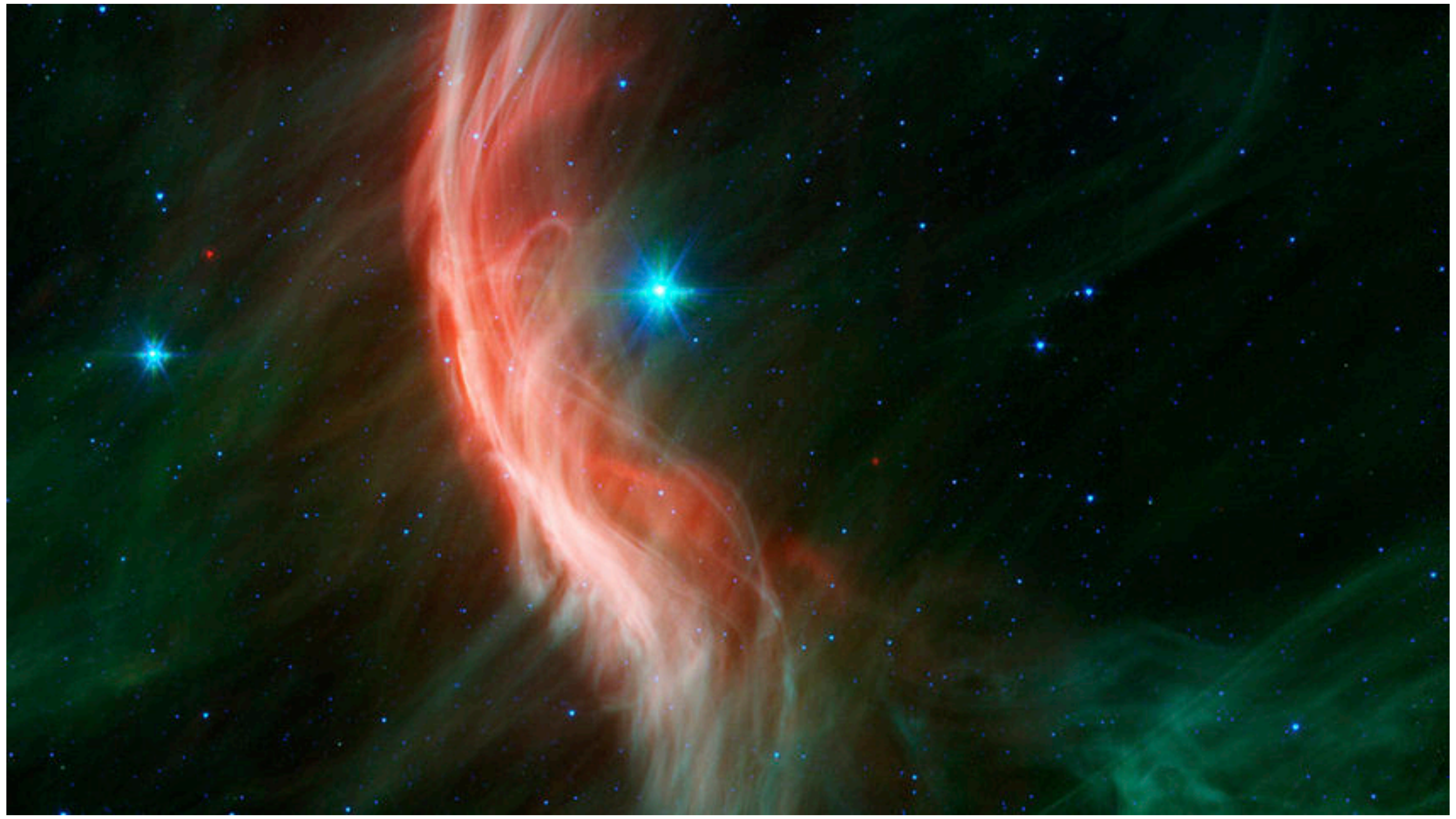
James Webb Space Telescope (JWST)



Infrared astronomy

- Sources: interstellar dust, old stars, supernova remnants

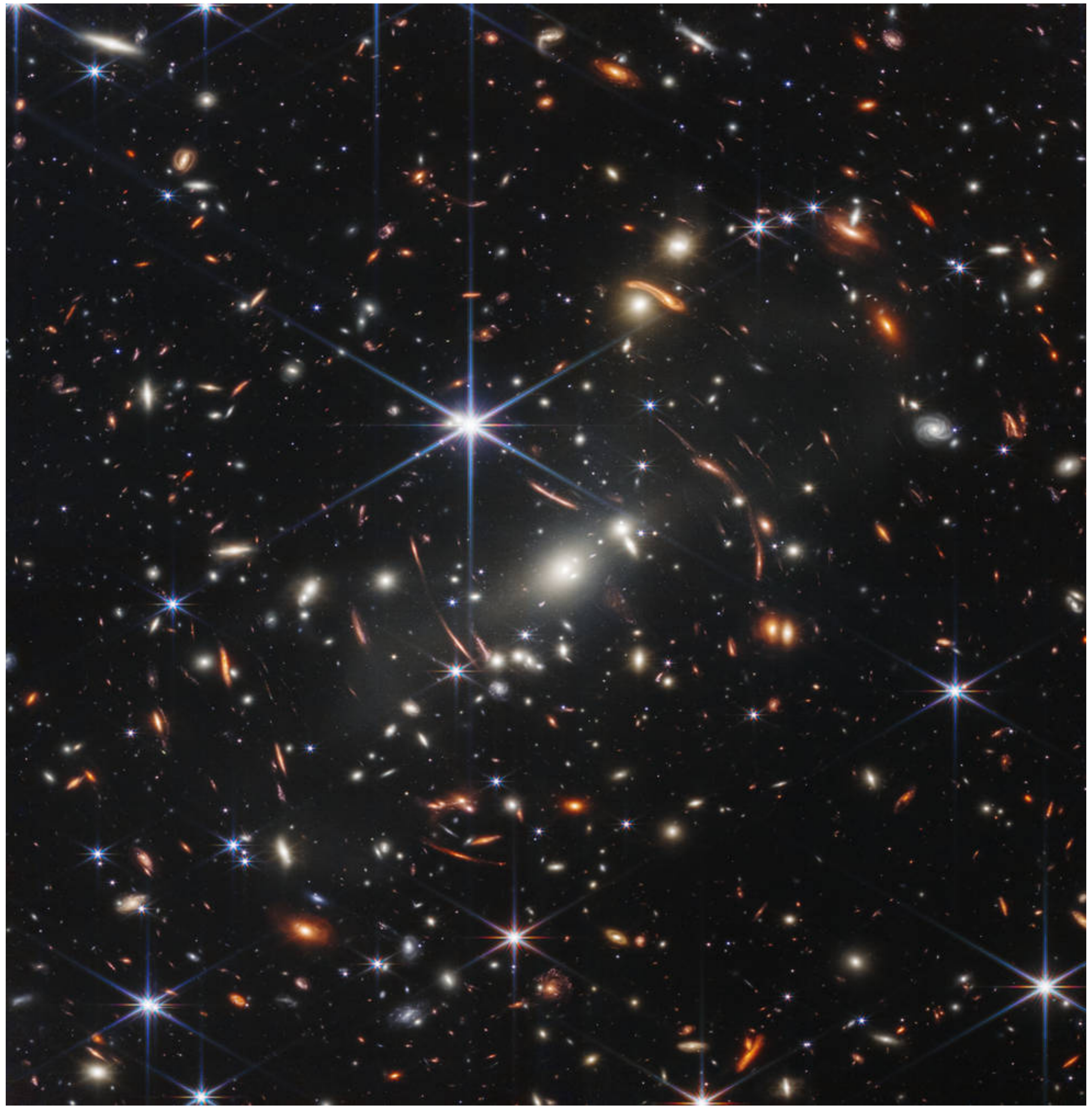
SPITZER image of stellar winds creating bow shocks around a giant star



Herschel image of the Andromeda galaxy - emission from cold dust

Infrared astronomy

- Images from the new JWST telescope



High redshift galaxies

Dust in galaxies

Interstellar medium, dust

https://www.nasa.gov/webbfirstimages

Radio astronomy

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

Radio quite zones

- Most radio telescopes are located in radio quiet zones. Theses zones are usually a few to tens of km extended and in regions of low population densities.
- Every electronic device causes radio frequency interference (**RFI**) (e.g. **mobile phones, tablets, laptop wifi, microwave ovens, BBQ lighters, very old TVs**
- RFI sources that we can not control: **Satellites, GPS, airplane communication**
- Signal coming from space is very weak, terrestrial devices can easily wipe out observations

The radio quiet zone around in Western Australia

Radio telescopes

Radio telescopes are essentially metal antennas.
The resolution of a telescope depends on its size and the wavelength of light that is getting observed:

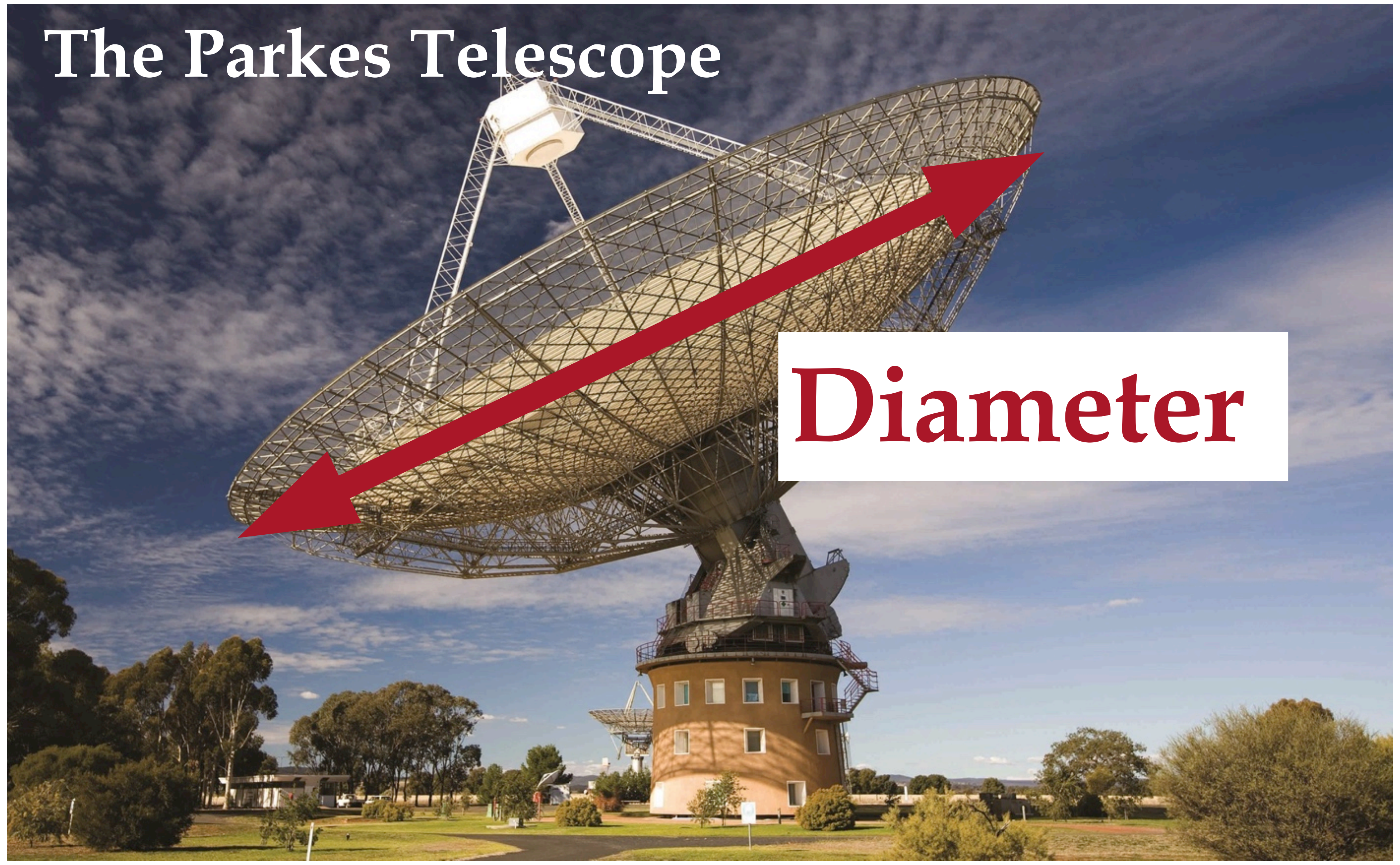
- This is good for short wavelengths, like UV or optical telescopes
- But unfortunate for radio telescopes

Singel dish telescopes:
Resolution: ~ Diameter

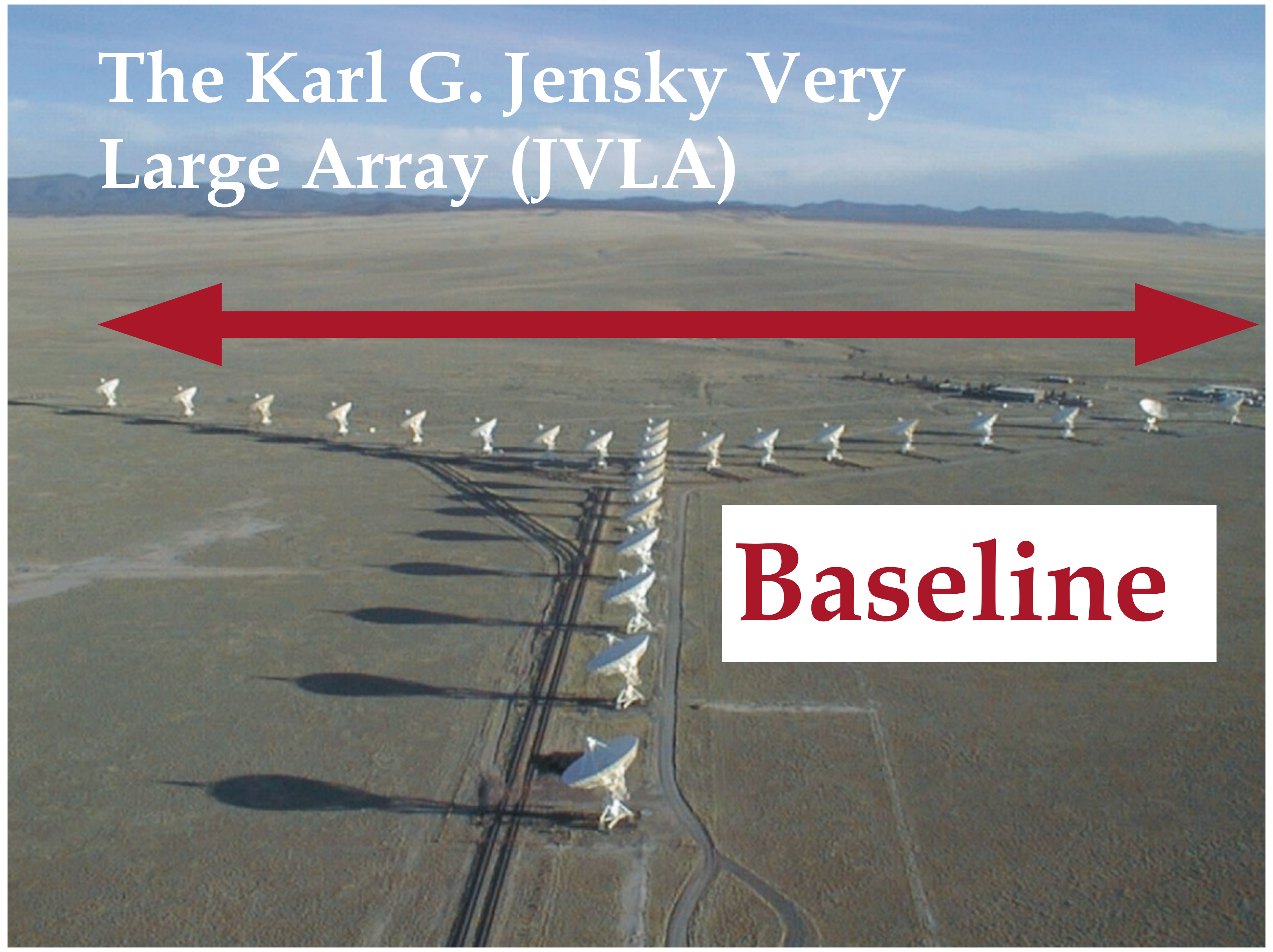
Interferometers:
Resolution: ~ distance between telescopes

Θ=1.22 λ/D

Θ – resolution
(in radians)
λ – wavelength
D – diameter/baseline



www.csiro.au



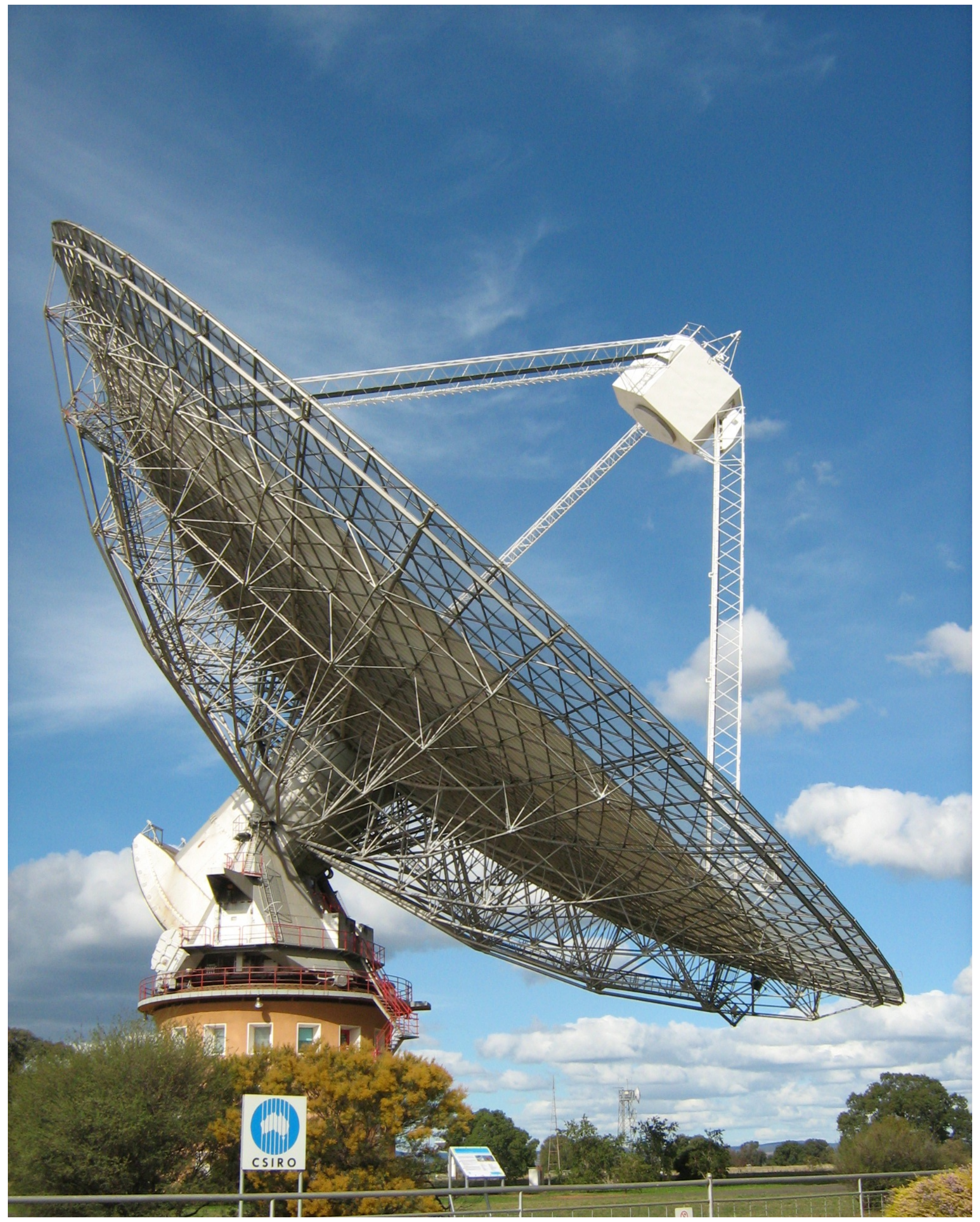
http://images.nrao.edu

Telescopes - single dishes

- Dish shaped telescopes are typically used for cm and mm waves.
- The dish acts like a mirror and collects the radiation, which results in greater sensitivity. -> Fainter objects can be detected.

Effelsberg (Germany)

Parkes Telescope (Australia)



FAST: The Five Hundred Meter Aperture Telescope (China)

Telescopes - Interferometers

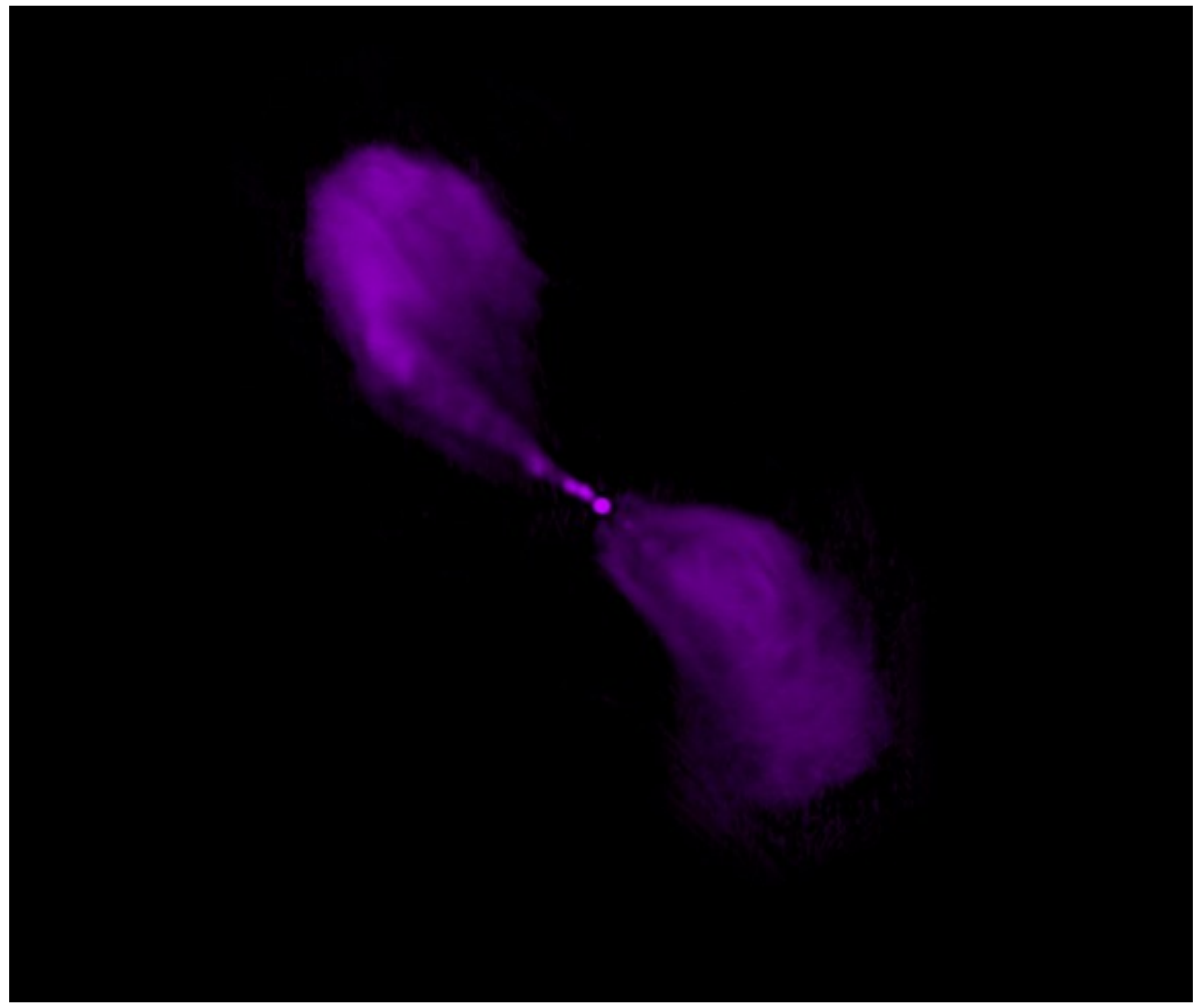
- Many antennas, but they act as one telescope.

Very Large Array (VLA)

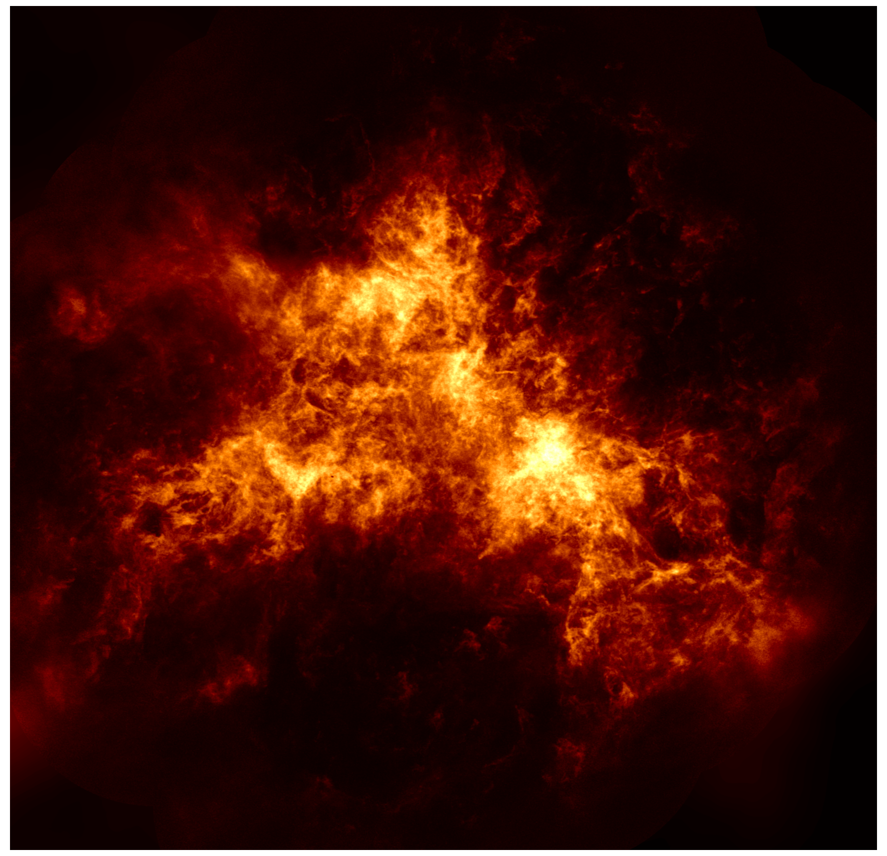
The Australia Telescope Compact Array (ATCA)

Telescopes - Interferometers

AGN

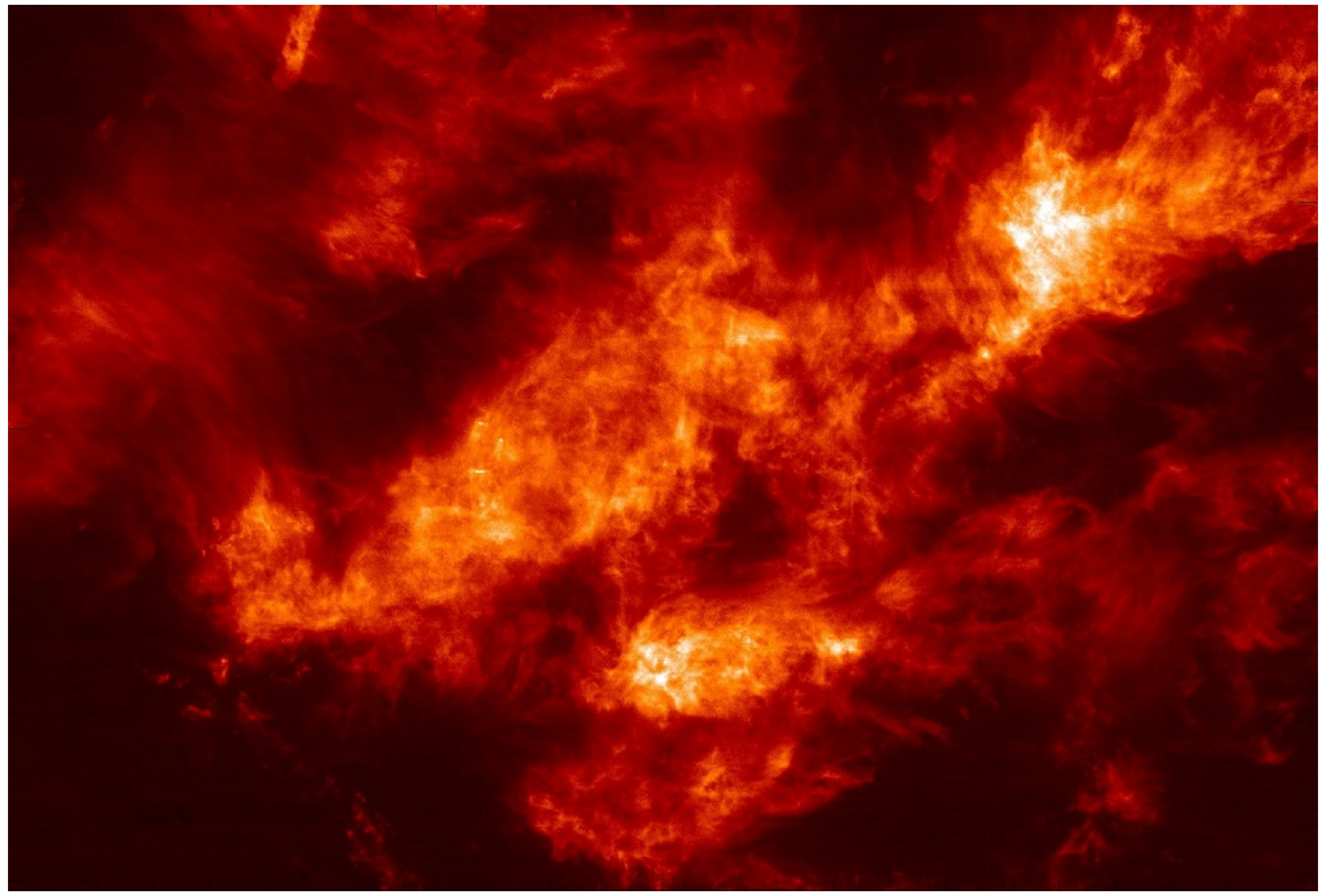


HI in galaxies (SMC)

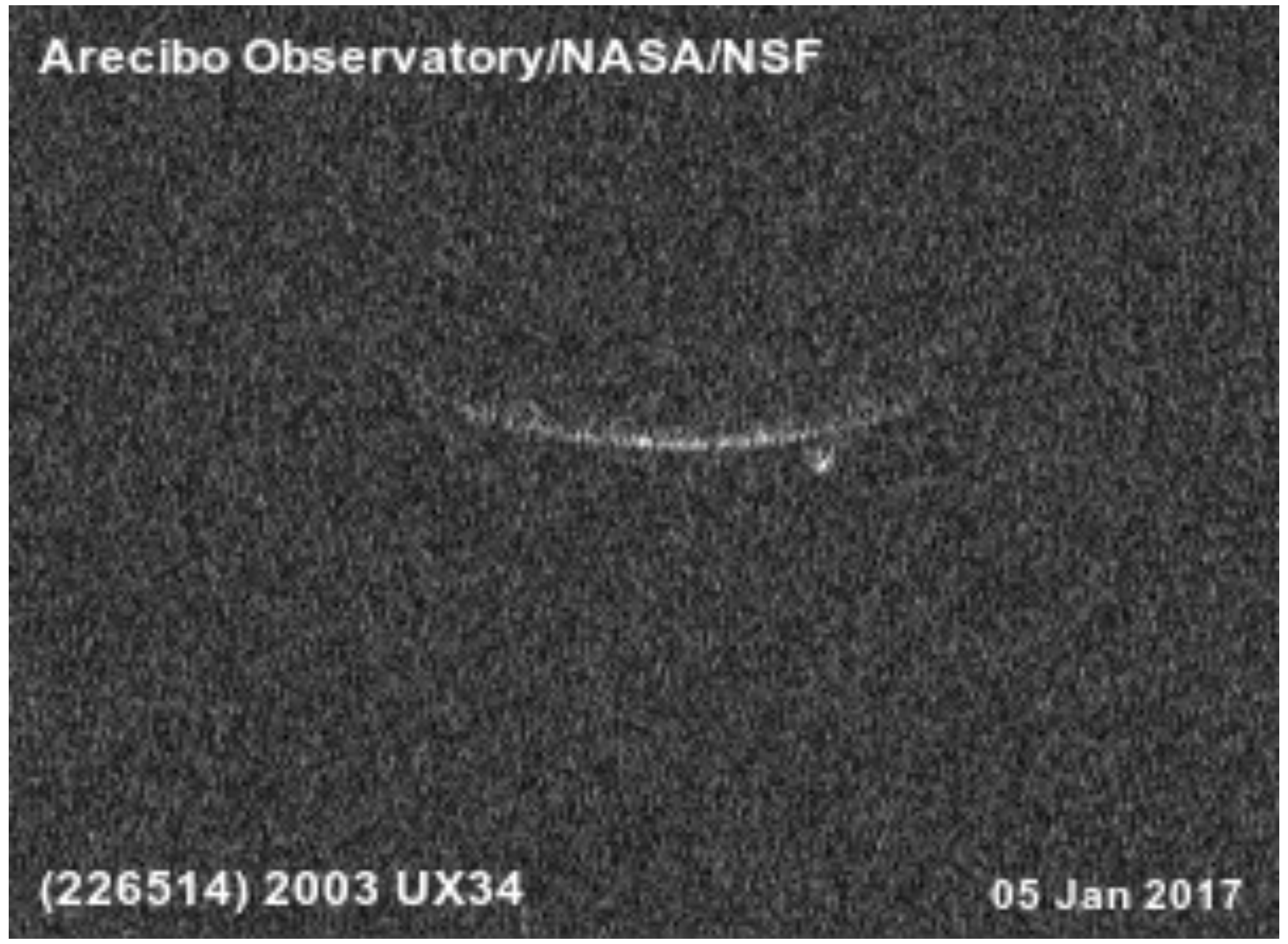


Accretion disk of a black hole

CO gas in the Taurus molecular cloud



Double asteroid



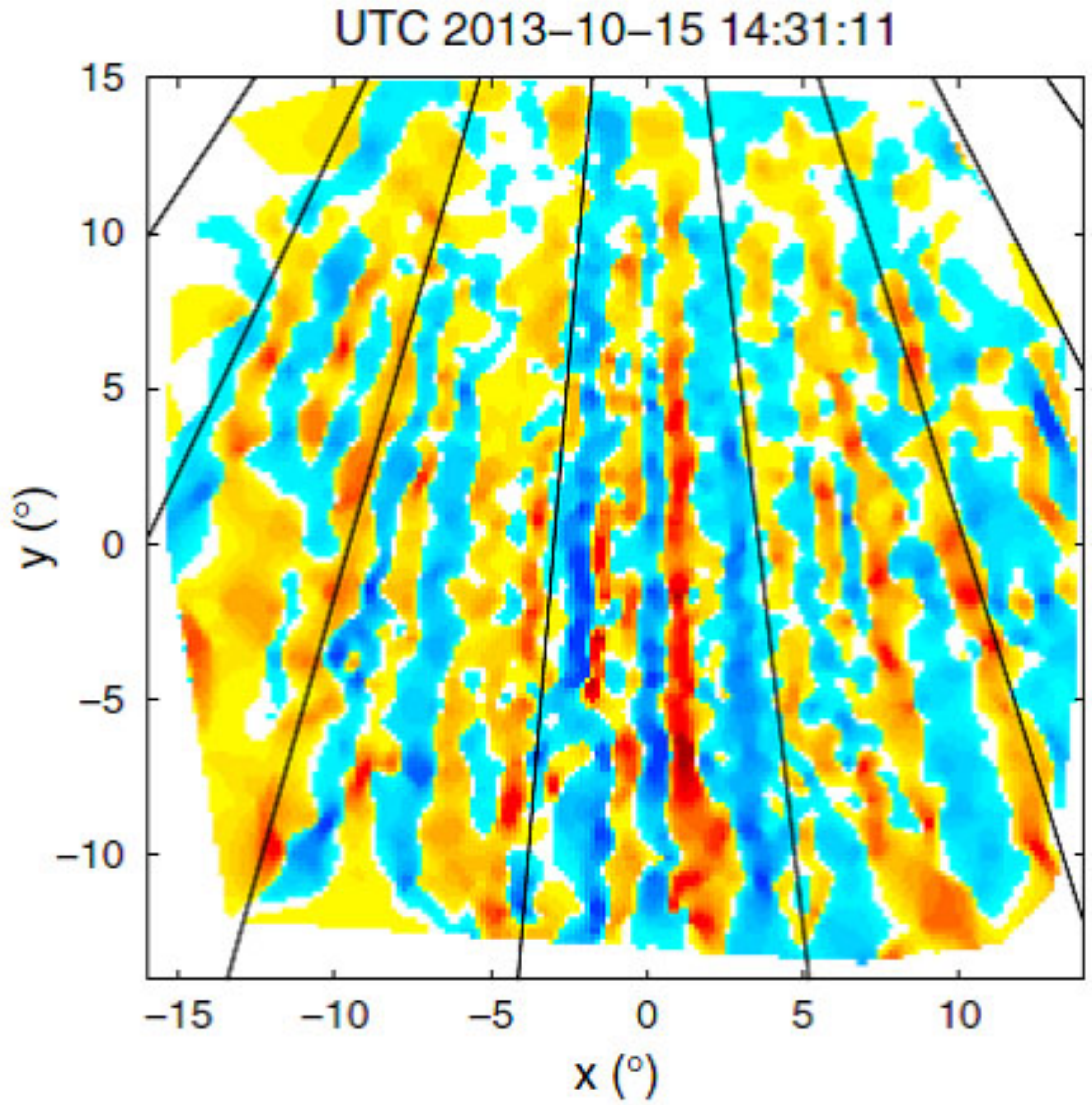
Telescopes - Interferometers

Are there radio telescopes that are not dishes?
What else can they be used for besides astronomy?

Telescopes - Interferometers

Metal sticks or wires are used for m waves.

The Murchison Widefield Array (MWA)

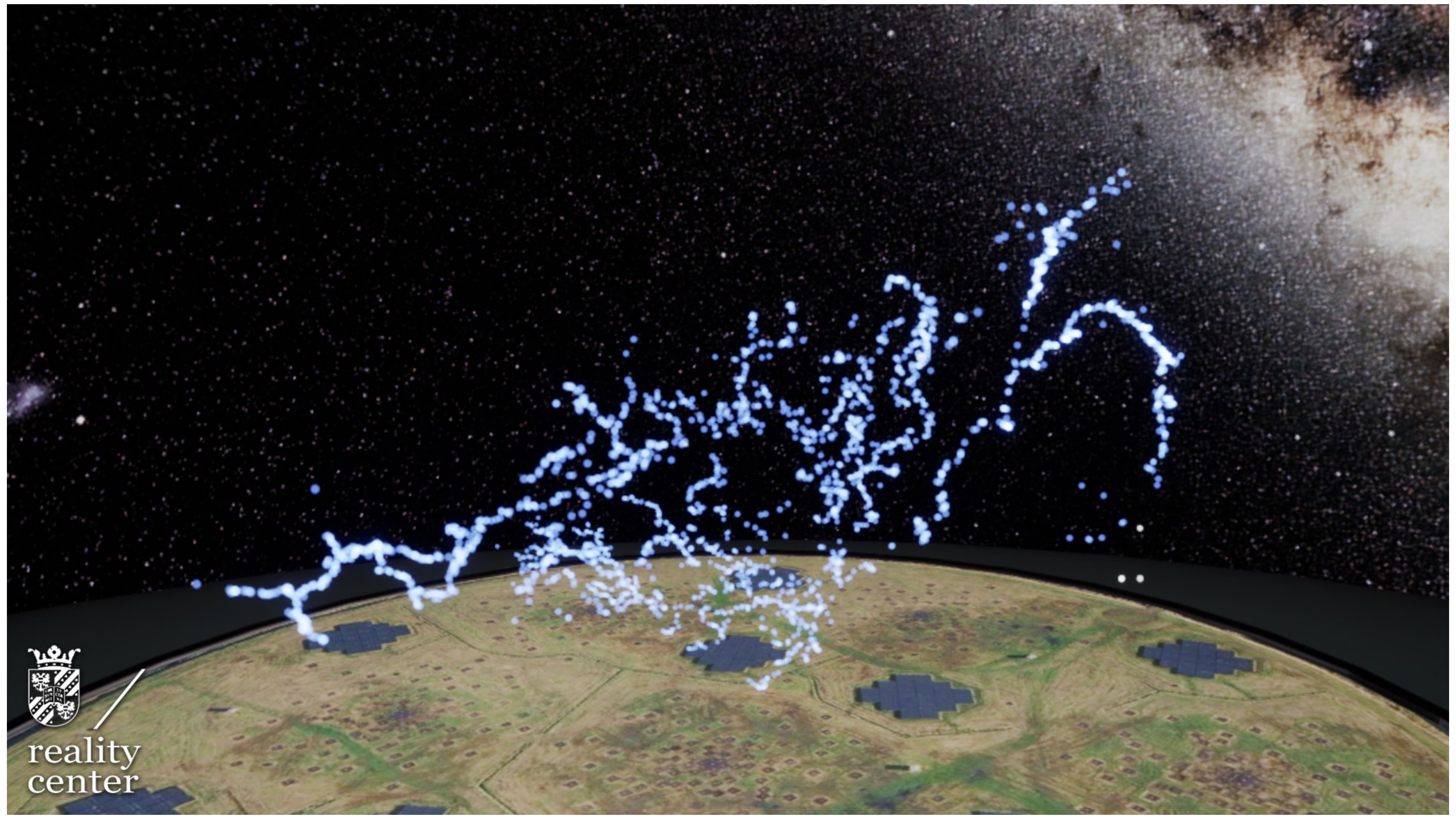


Imaging **plasma tubes in the earth's ionosphere!**
(Cleo Loi)

Telescopes - Interferometers

Metal sticks or wires are used for m waves.

LOFAR (Low Frequency ARray)



Imaging **the path of lightning.**

Calculate the resolution for a few telescopes

The Giant Metrewave Radio Telescope (GMRT) near Pune has several antennas spread over a region of size about 10 km.

Make an estimate of the resolution (in arcseconds) which this telescope is expected to have. How large will an optical telescope have to be to achieve similar resolution in visible light?

http://www.gmrt.ncra.tifr.res.in/

$$\theta = 1.22\frac{\lambda}{D}$$