Introduction to Astrophysics and Cosmology

Introduction to astrophysics

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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.

Detector types:

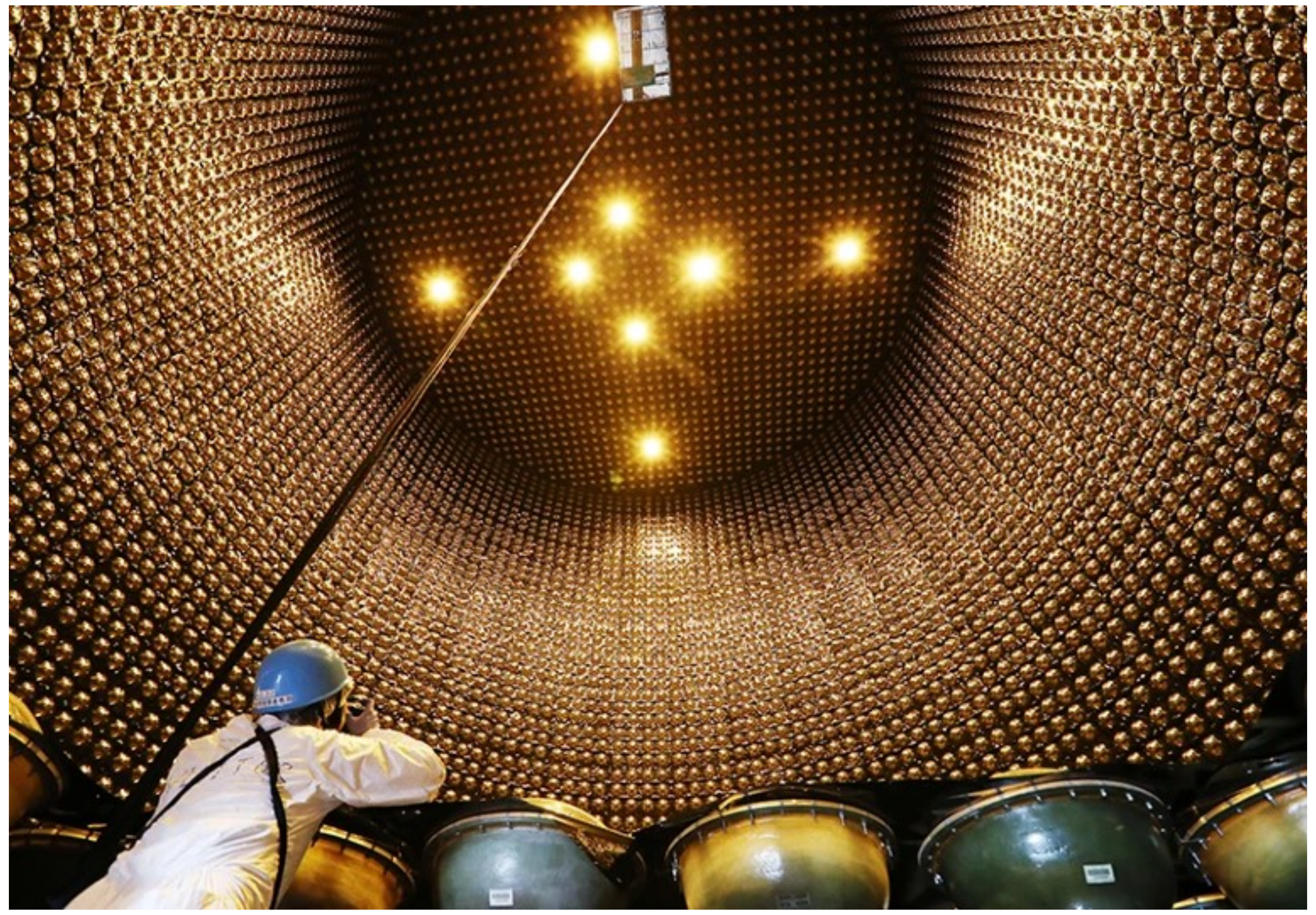
- Radiochemical methods (the neutrino triggers a chemical reaction, producing a radioactive element)
- Cherenkov detectors (the neutrino produces fast charged particles, if the speed of a charged particle is faster than the speed of light in the medium, then Cherenkov light gets emitted.)

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 C2Cl4 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!
- 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

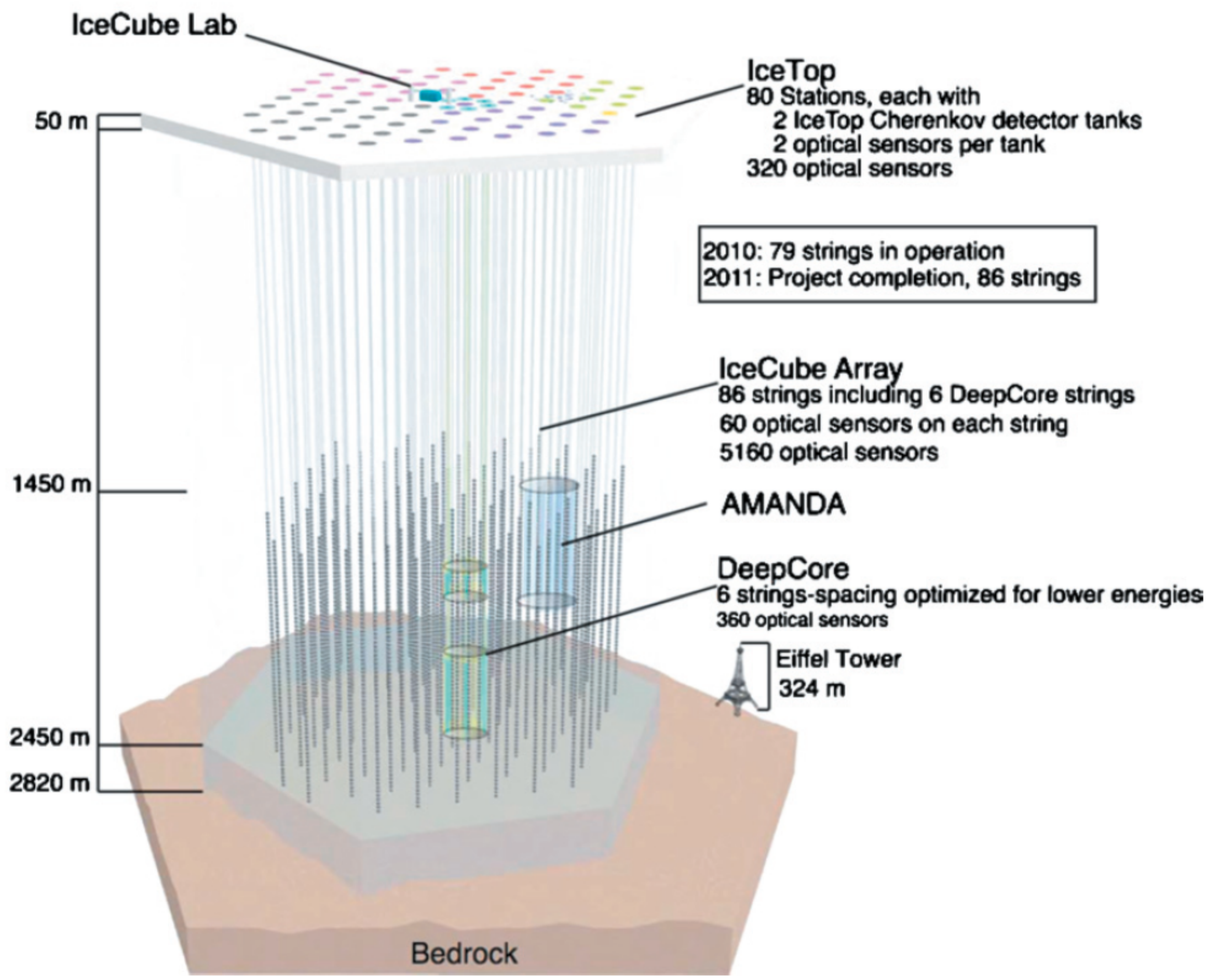
Neutrinos

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.

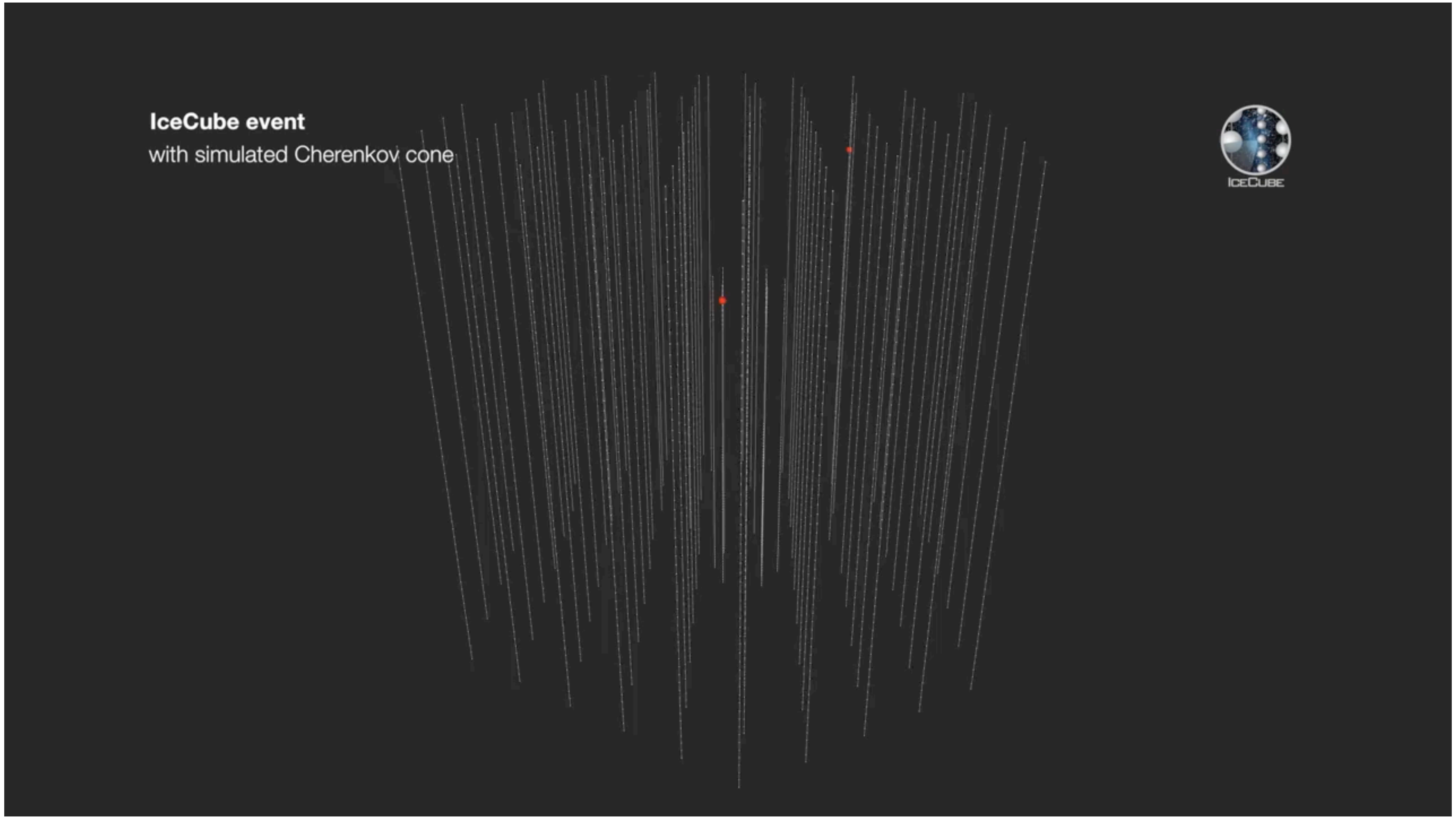
Citizen science project: Name that Neutrino!
https://www.zooniverse.org/projects/icecubeobservatory/name-that-neutrino

IceCube



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

Neutrinos



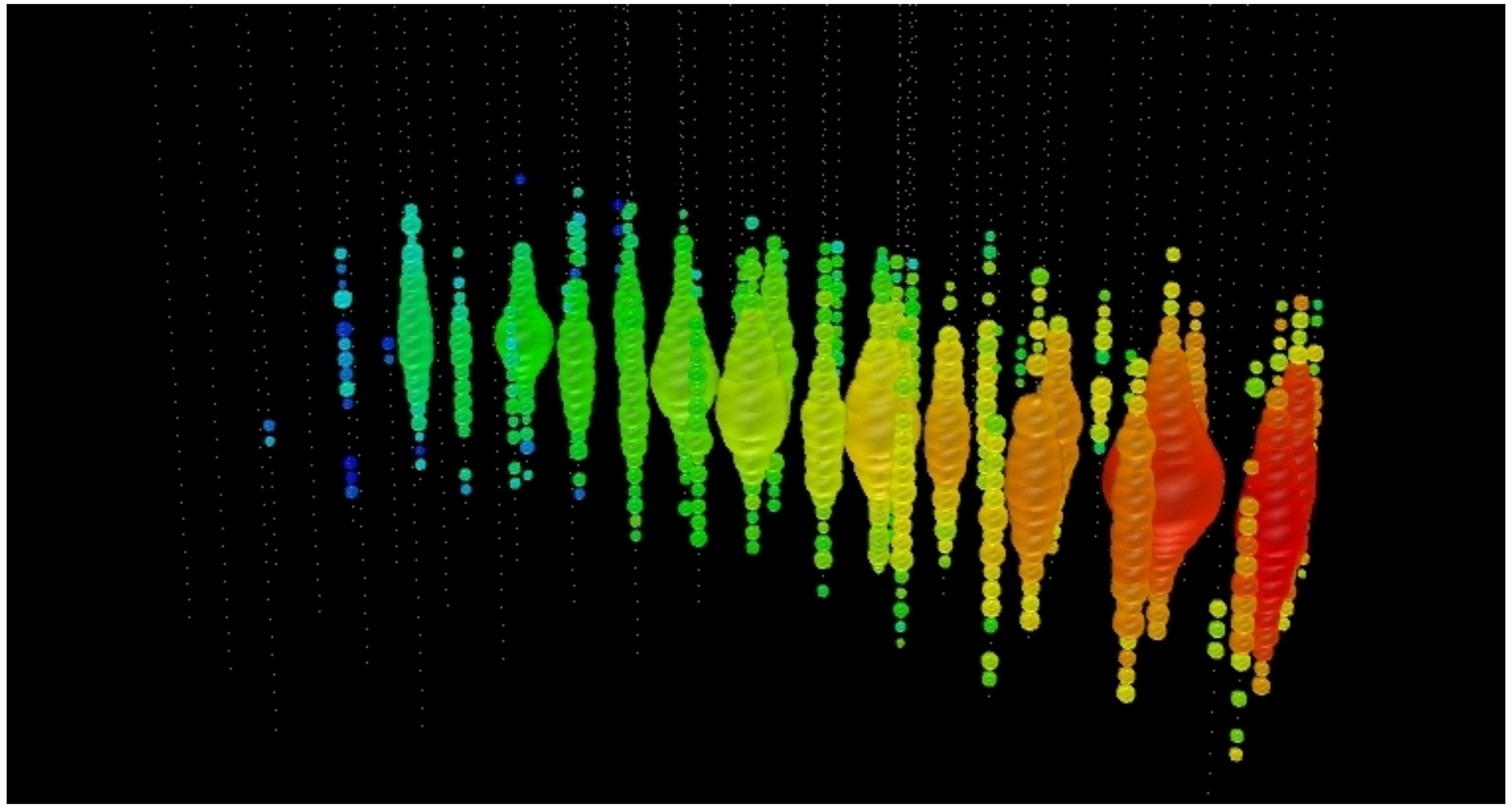
IceCube detects high-energy neutrinos using the Cherenkov light produced by relativistic charged particles that result from the interaction of these neutrinos with a nucleus of Antarctic ice. The highest energy neutrinos detected to date are included in this video, which also shows a simulated event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

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

Neutrinos

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

Located at the South Pole, the IceCube Neutrino Observatory is the largest particle detector in the world, using thousands of light sensors buried in the Antarctic ice.



A signal within IceCube is represented by a series of "bubbles" that show which sensors have detected light. These bubbles are color-coded, with red bubbles indicating the earliest light detected and bluer bubbles for the last detected light.

Gravitational waves

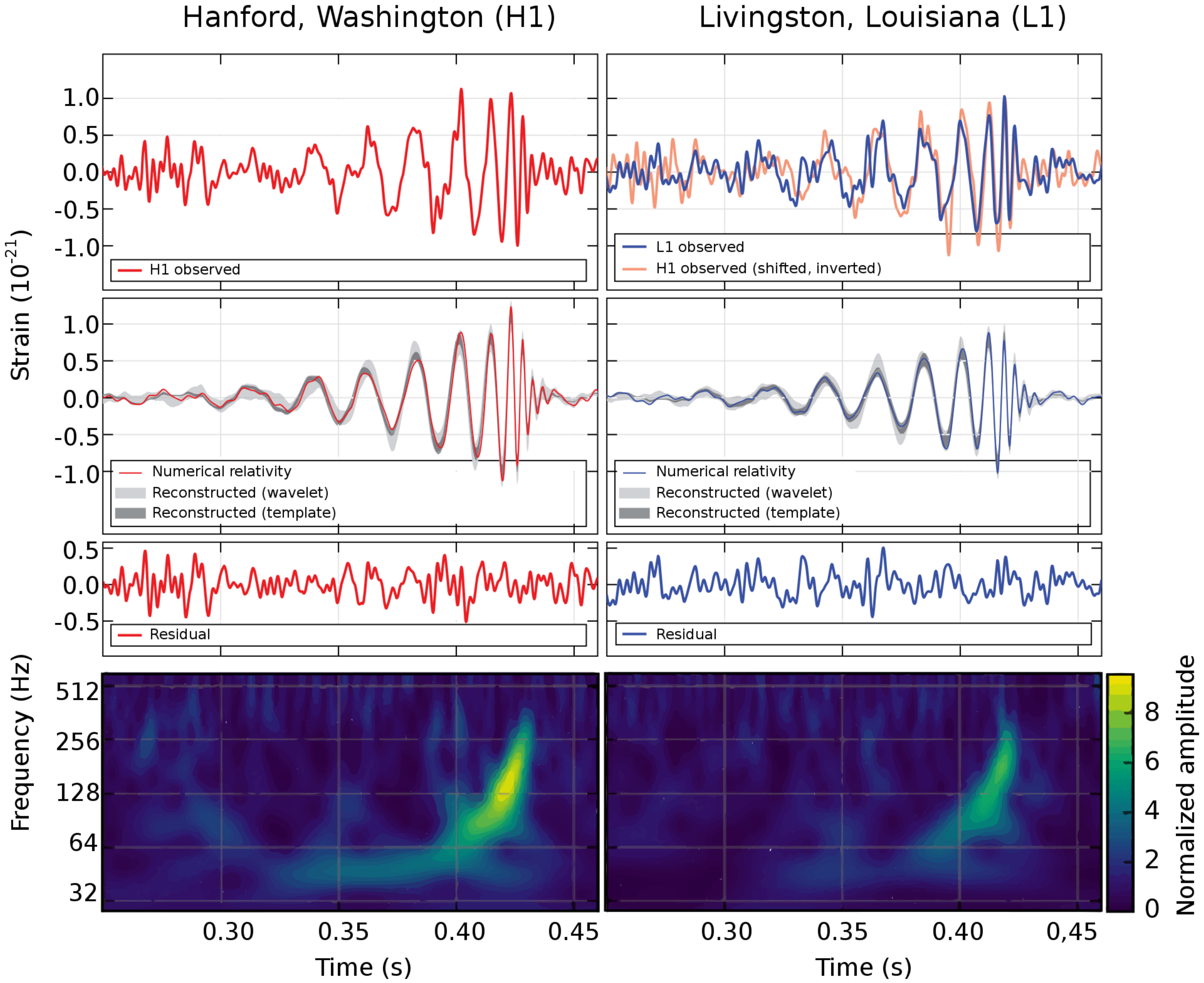
How are they detected?
What are the astronomical sources?
Where would the observatories be?

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

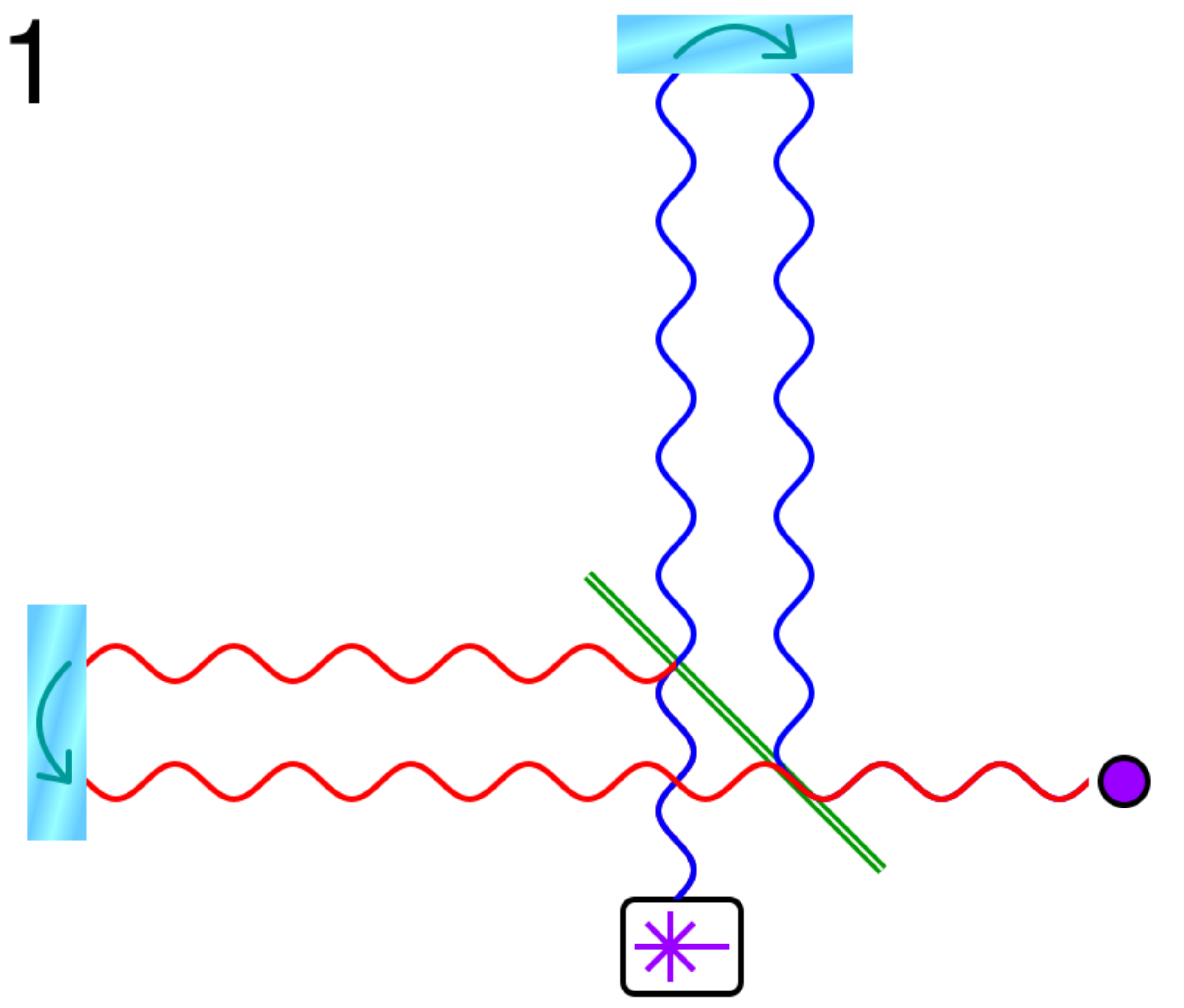
Gravitational waves

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.

1



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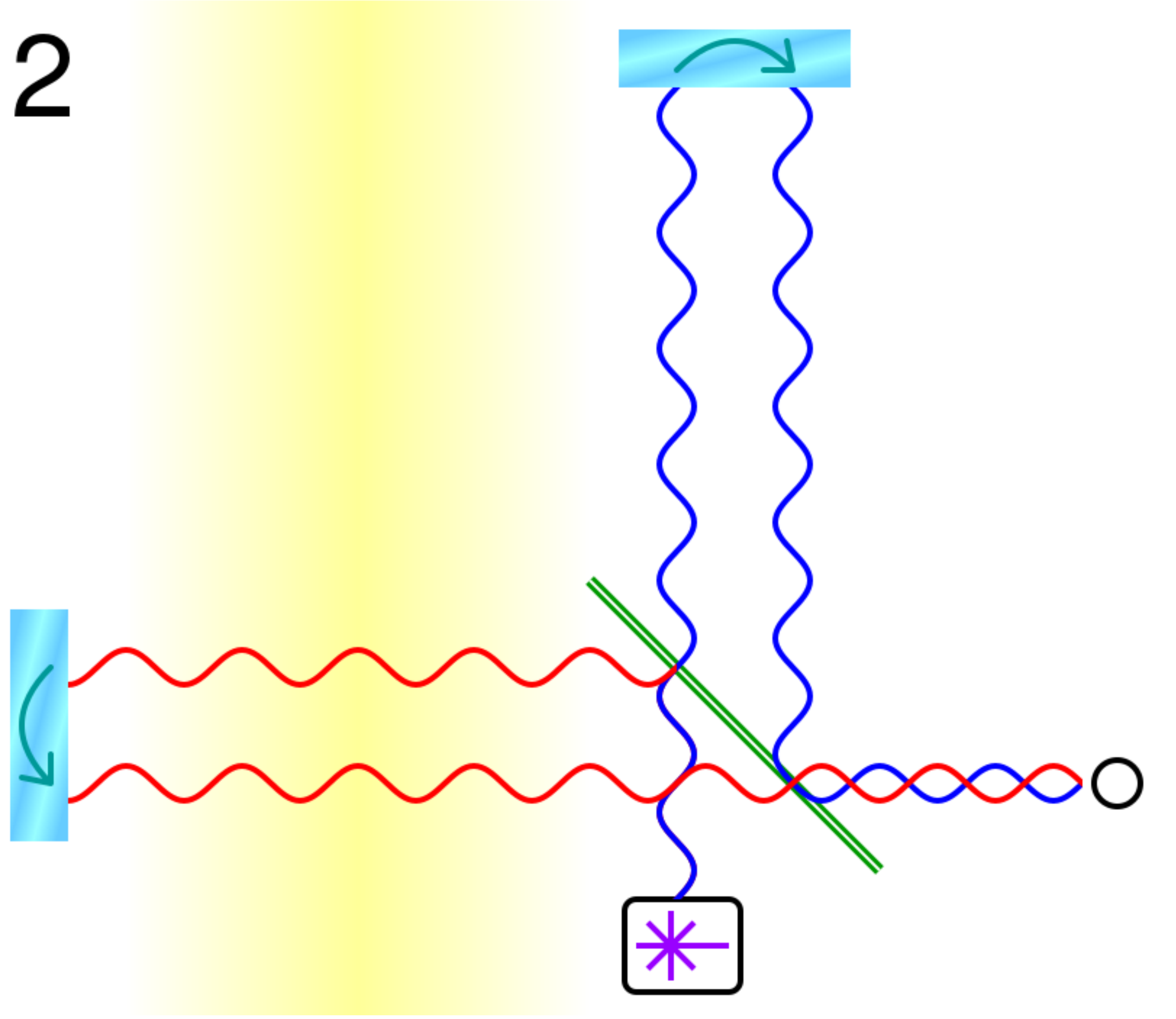
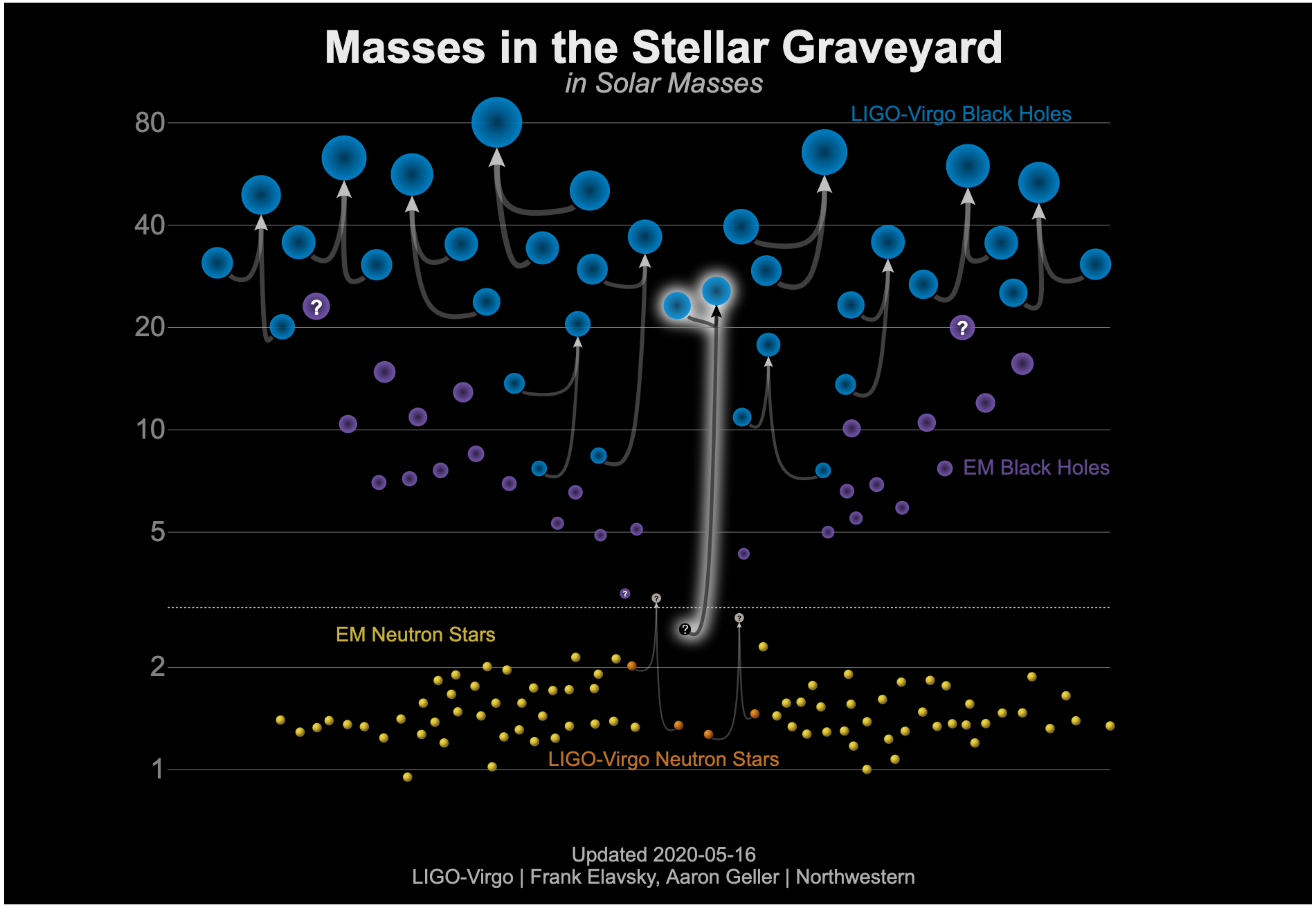


Gravitational waves

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.

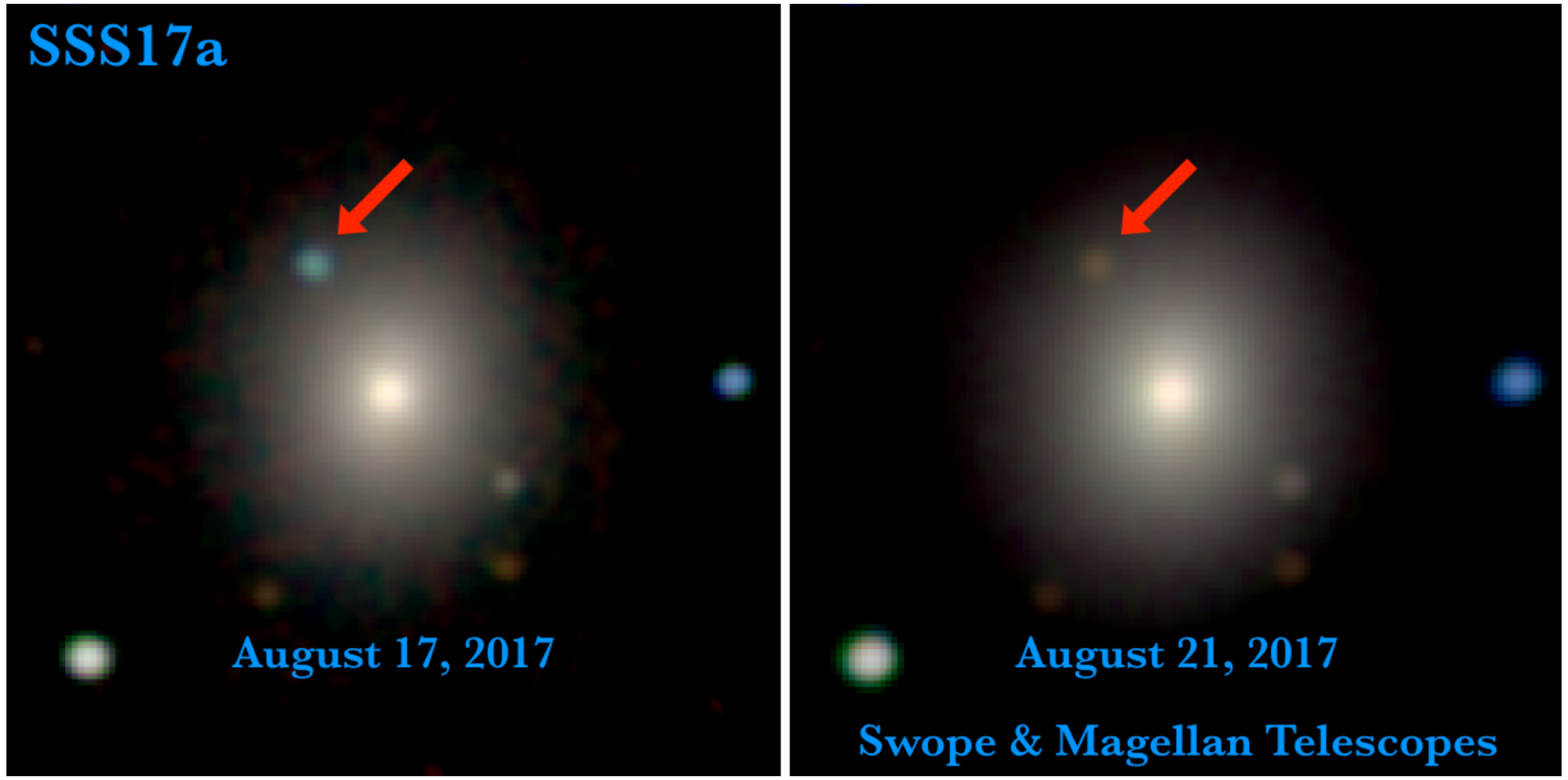


https://www.ligo.org/detections.php

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)

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



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)

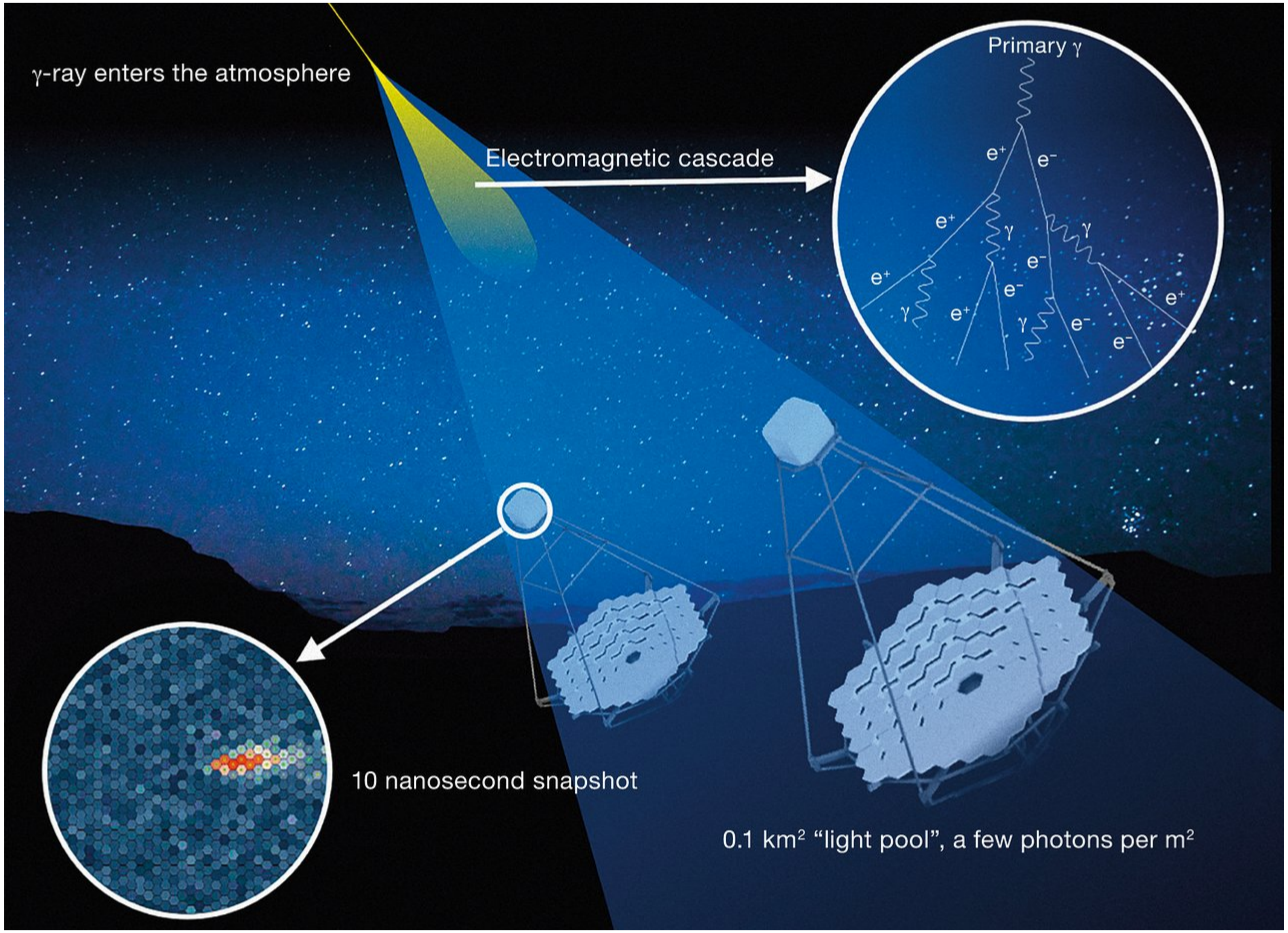
https://www.cta-observatory.org/about/how-cta-works/

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.



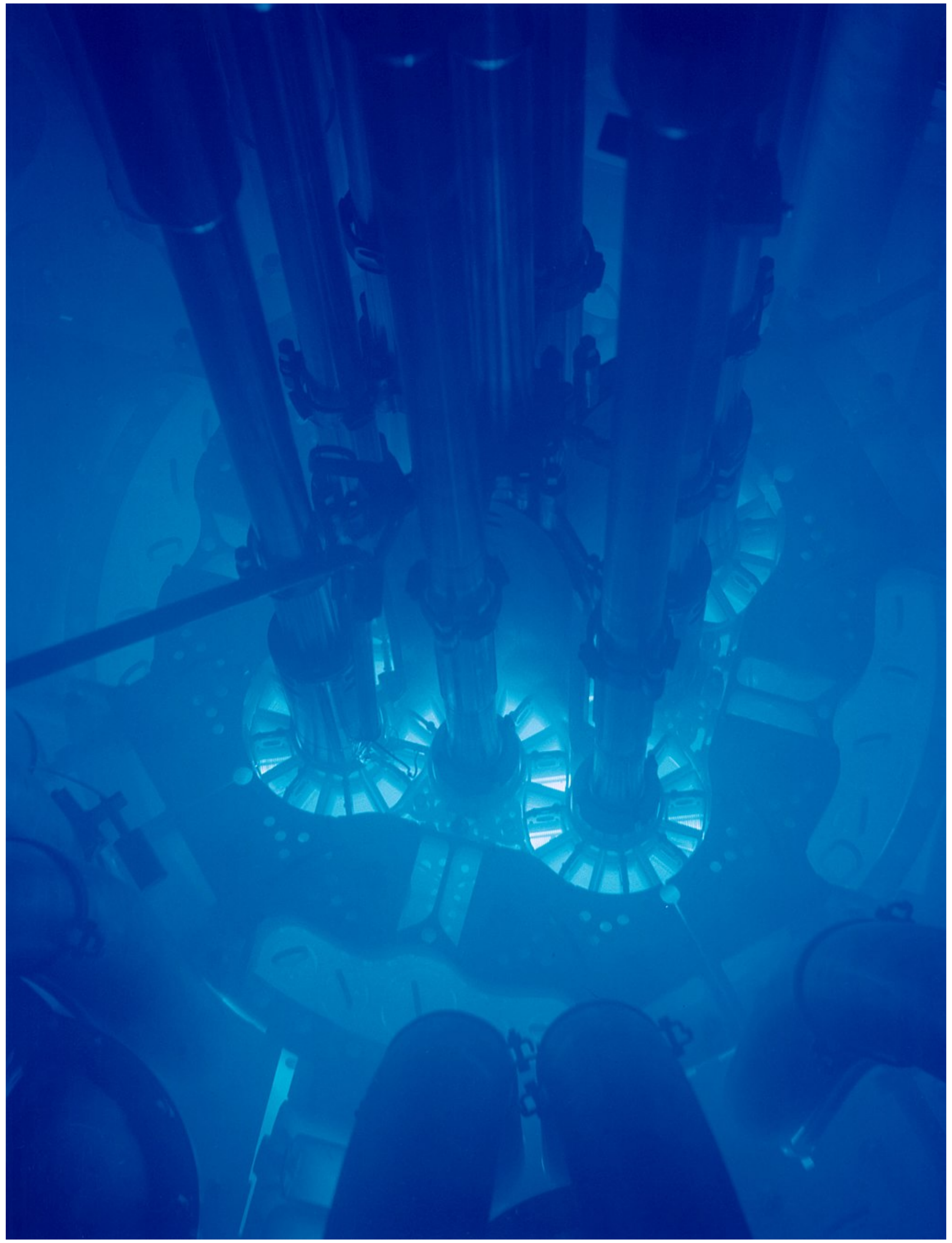
https://www.eso.org/public/images/eso1841x/

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.

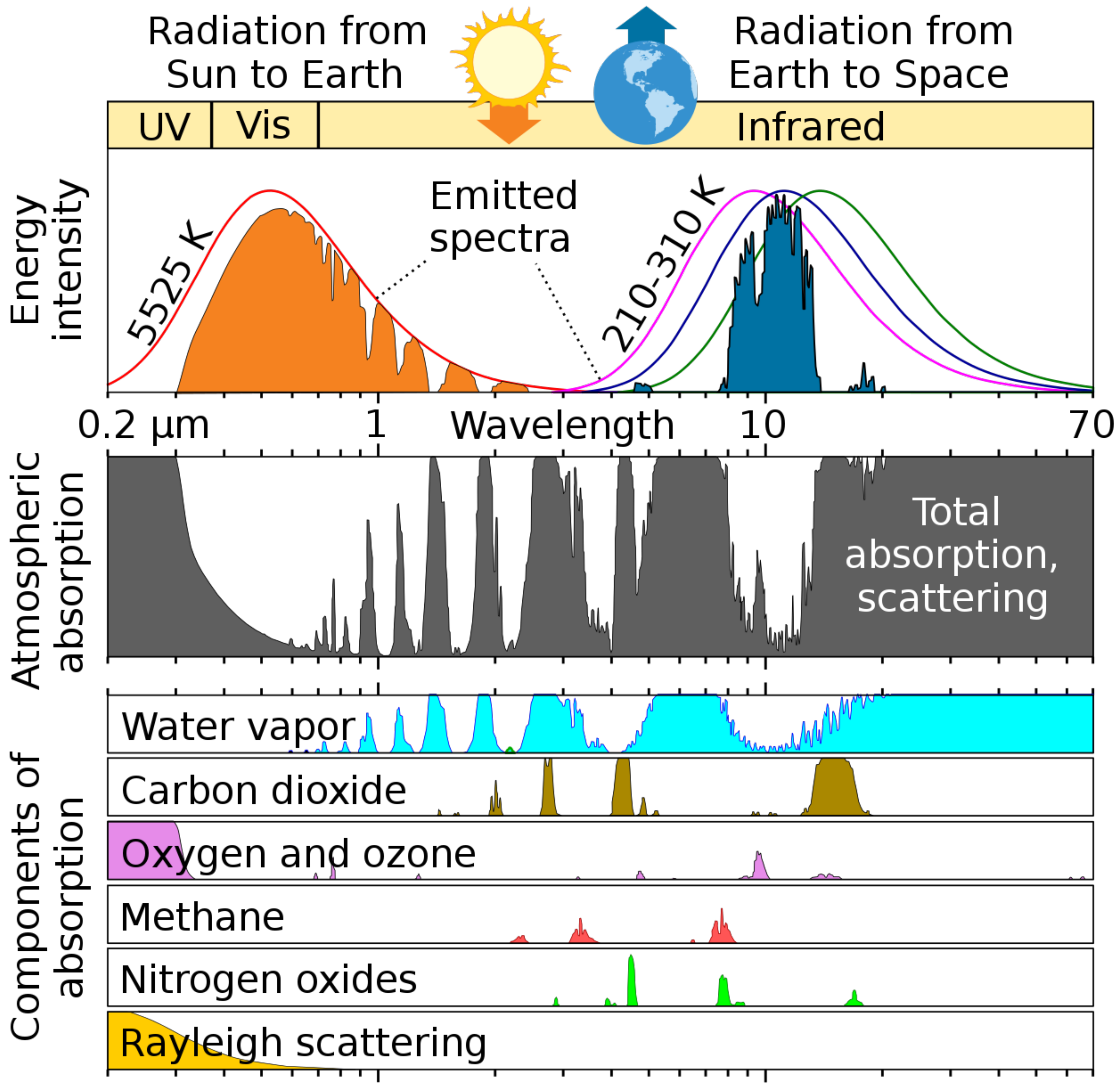
https://en.wikipedia.org/wiki/Cherenkov_radiation

Electromagnetic radiation

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.**

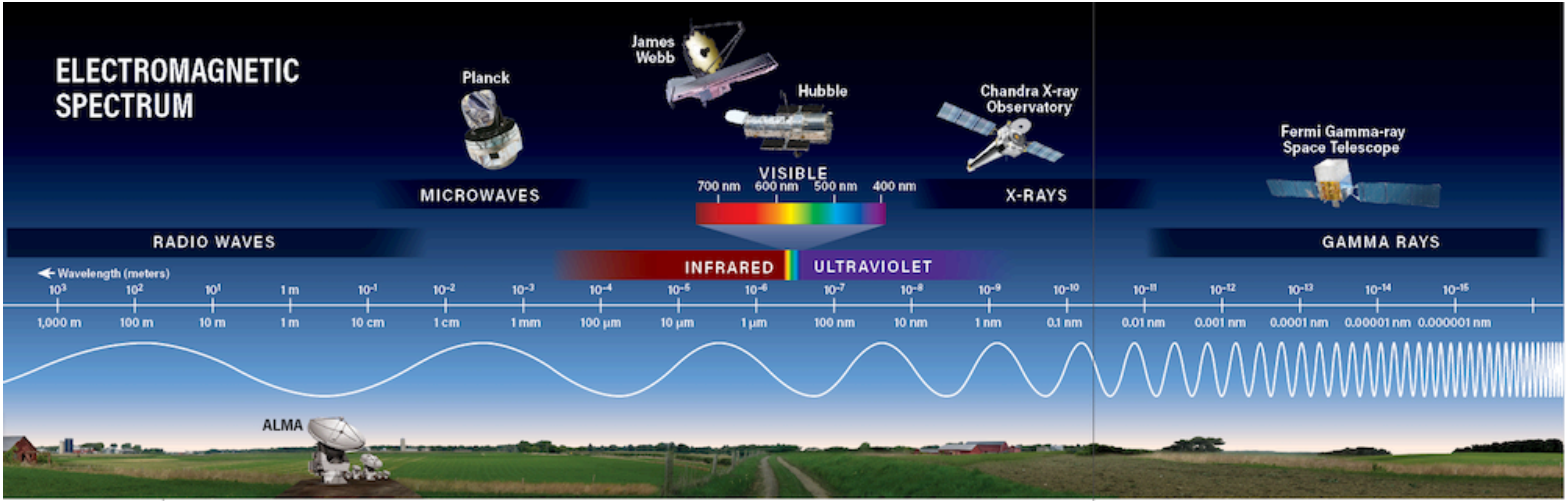


https://en.wikipedia.org/wiki/Atmospheric_window

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

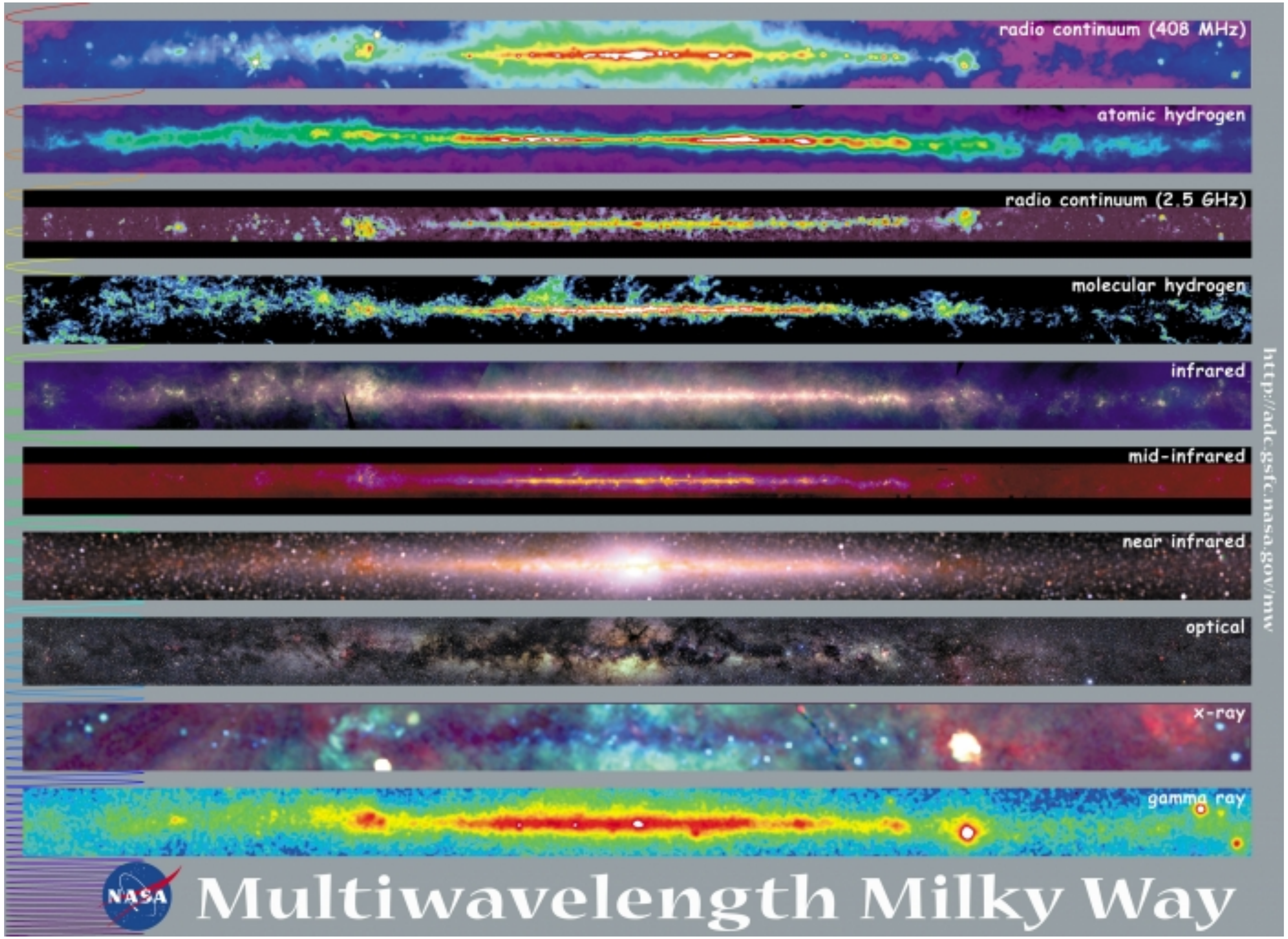
Spectral lines from gas clouds

Dust

Stars

Hot plasma

High energy sources



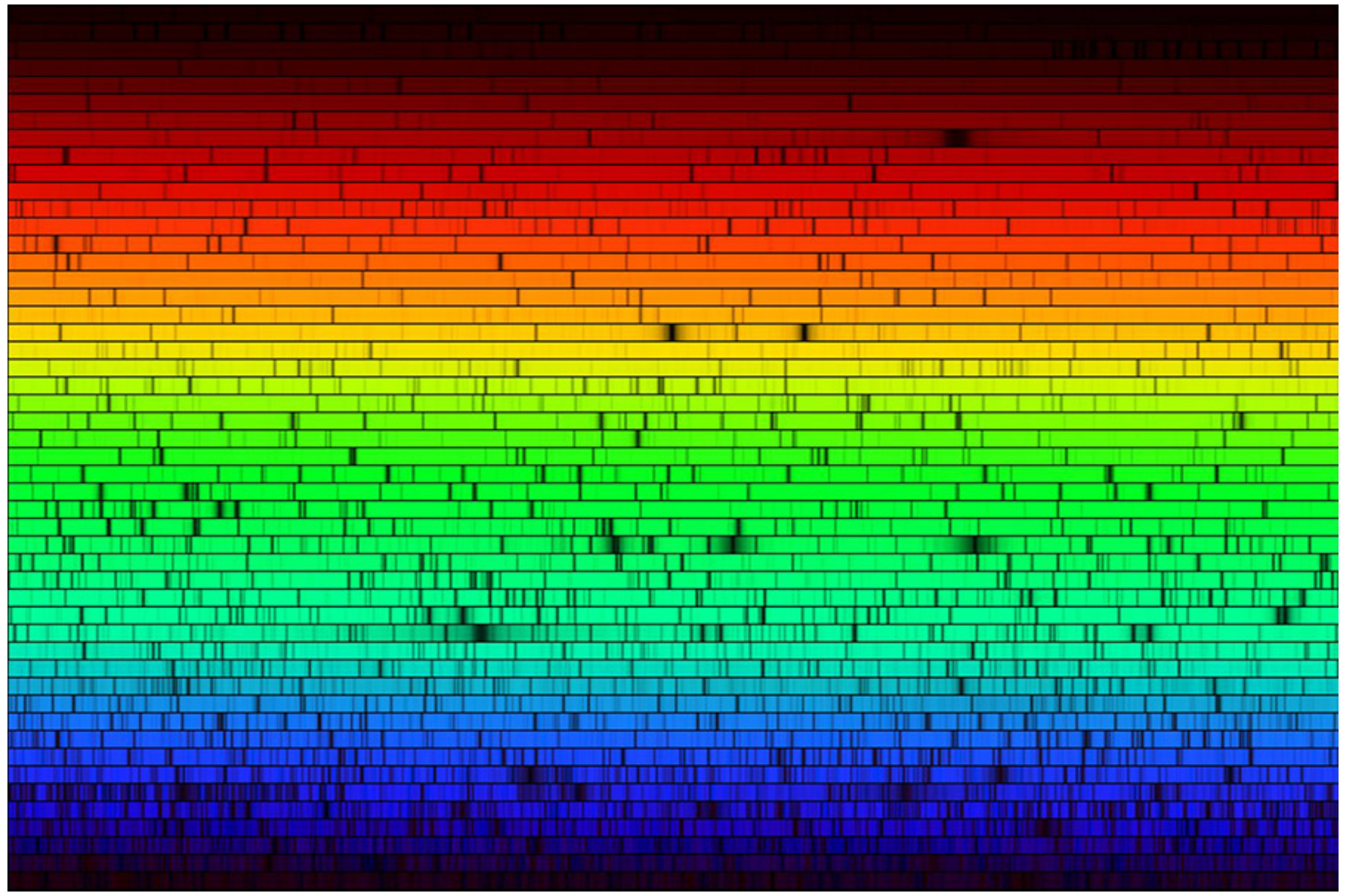
Electromagnetic radiation

Two types of measurements:

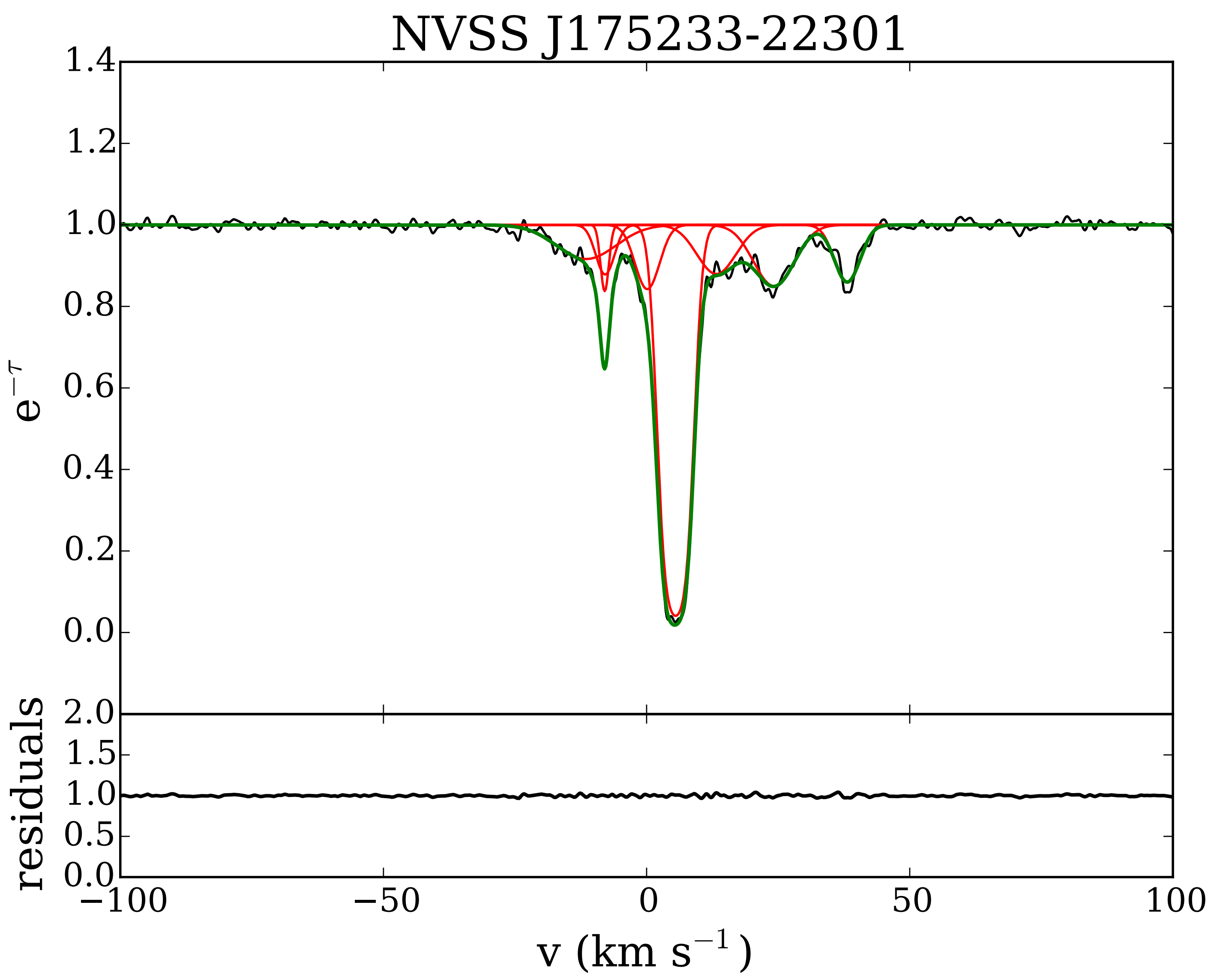
- Imaging
- Spectroscopy

M101 galaxy

Spectrum of the Sun



Neutral Hydrogen absorption spectra



Optical astronomy

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

Optical astronomy

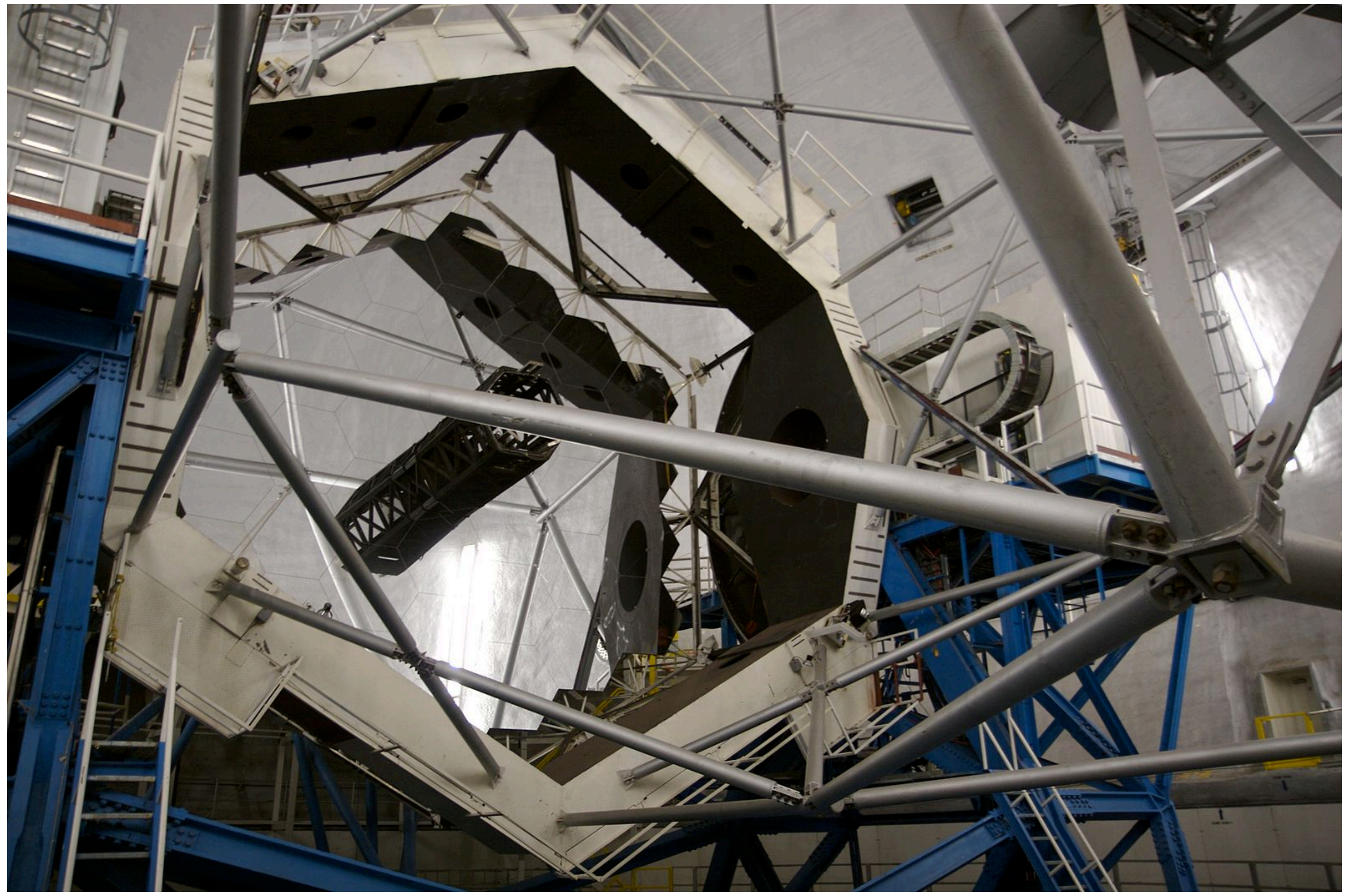
Early telescopes with lenses

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.

Optical astronomy

Hubble Deep field - lots of galaxies

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

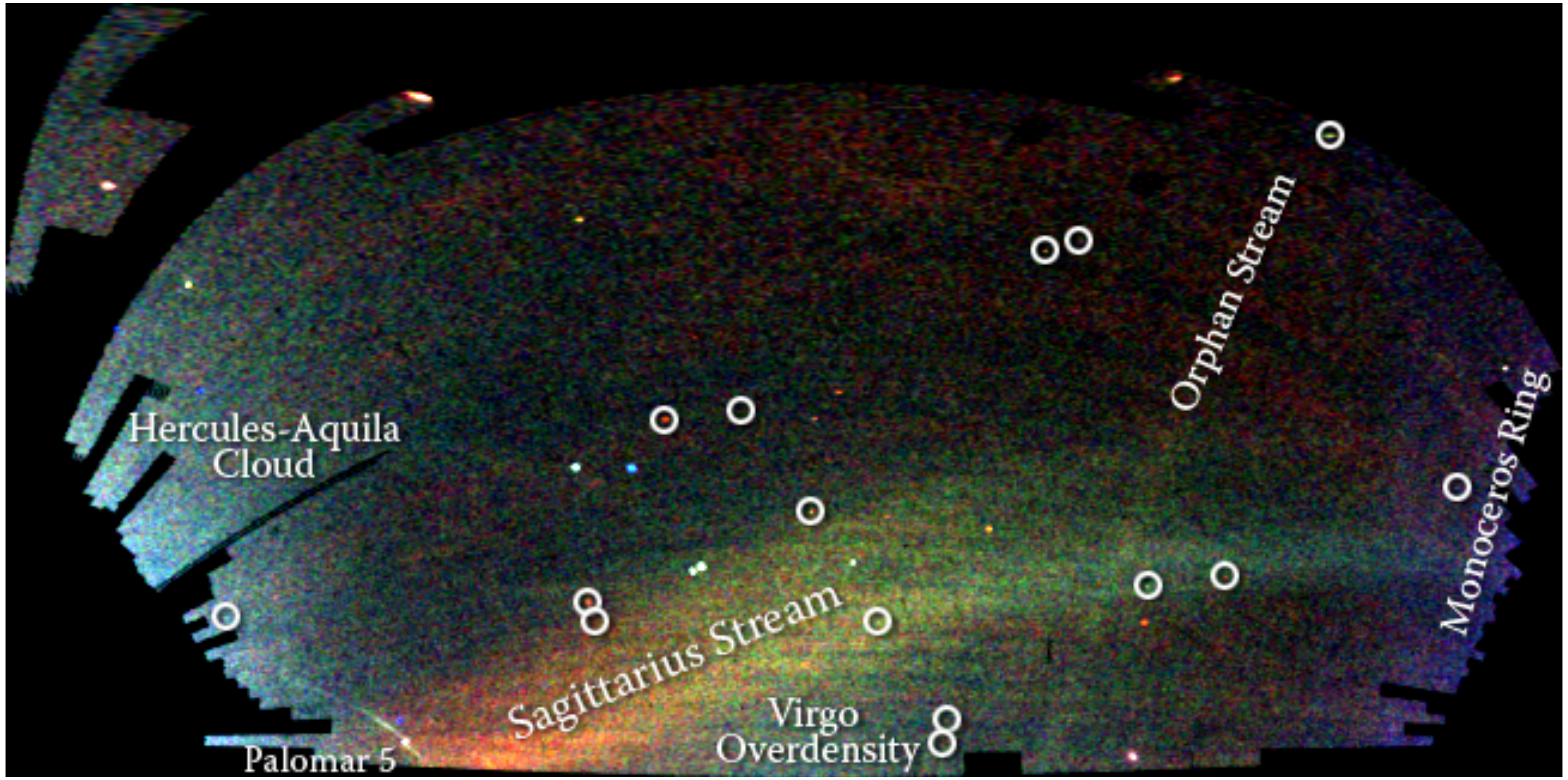
Milky Way with VLT telescope

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

Optical astronomy

Globular cluster M80

A map of stars in the outer regions of the Milky Way Galaxy, derived from the SDSS images of the northern sky. Structures visible in this map include streams of stars torn from small dwarf galaxies and globular clusters. Circles enclose new Milky Way companion galaxies and globular clusters.



https://www.sdss3.org/science/gallery_fos_dr6_marked.php

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

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

$$\Theta=\lambda/D$$

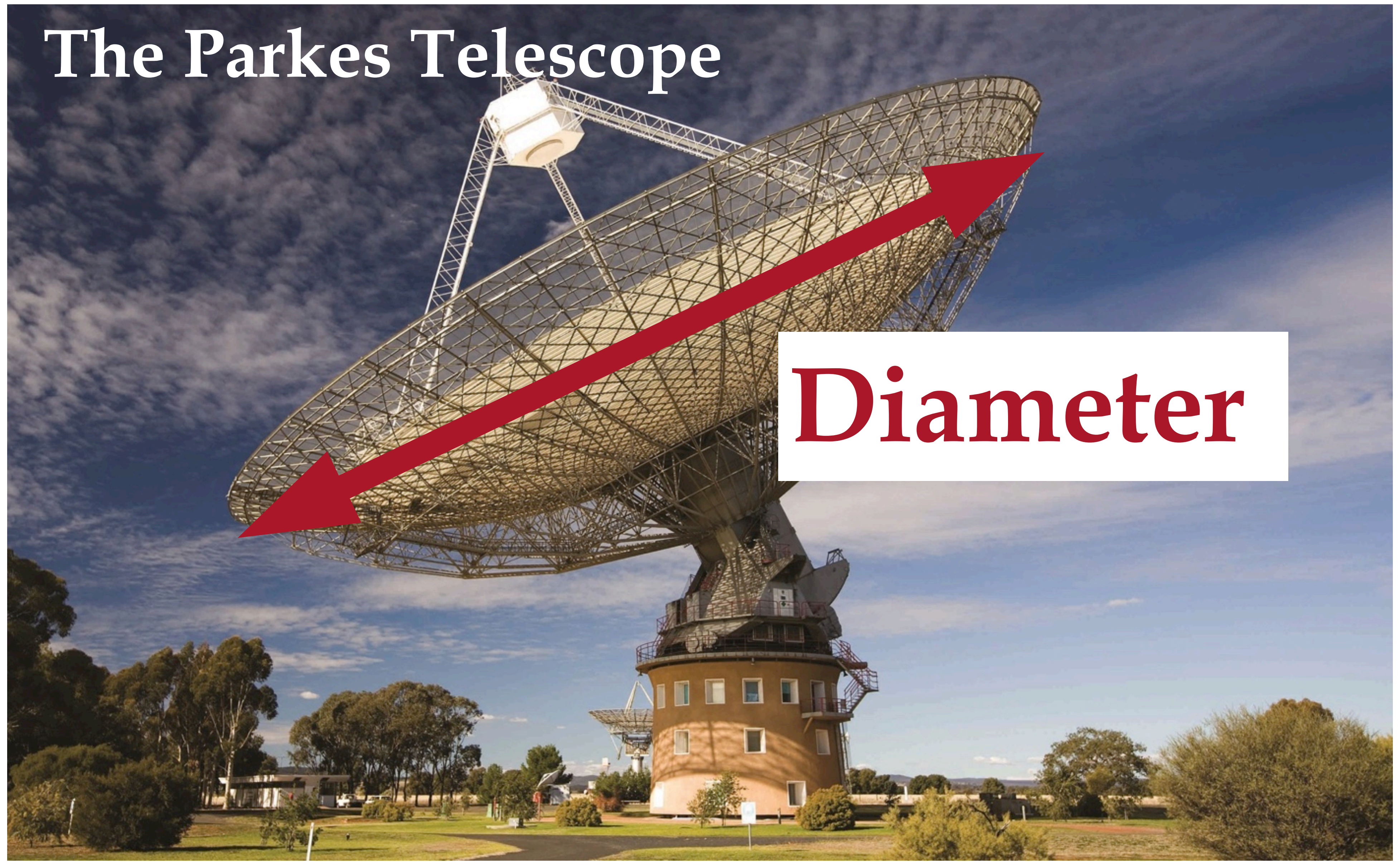
The resolution of a telescope depends on its size and the wavelength of light that is getting observed.

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

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

Singel dish telescopes:

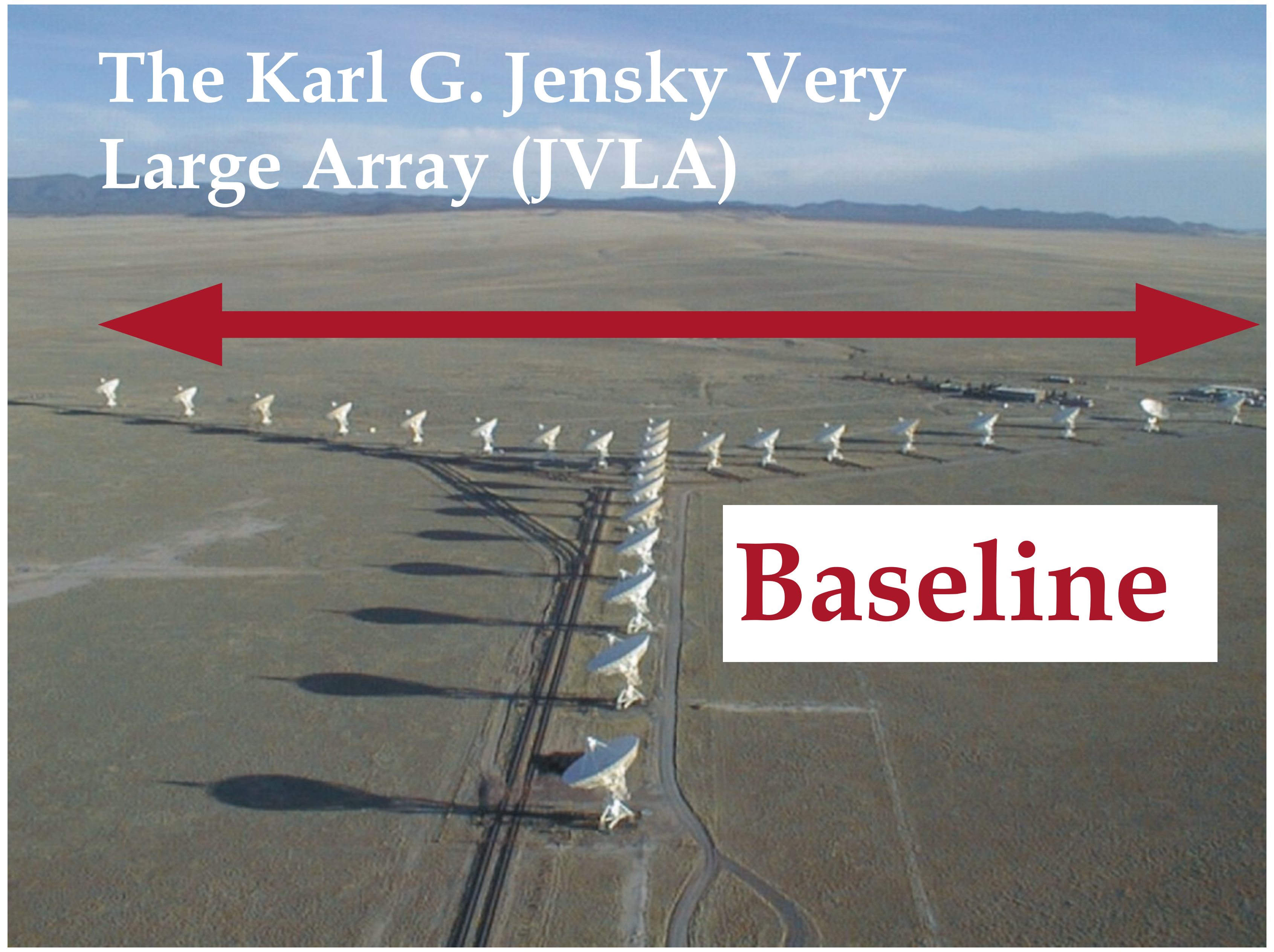
Resolution: ~ Diameter



www.csiro.au

Interferometers:

Resolution: ~ distance between telescopes



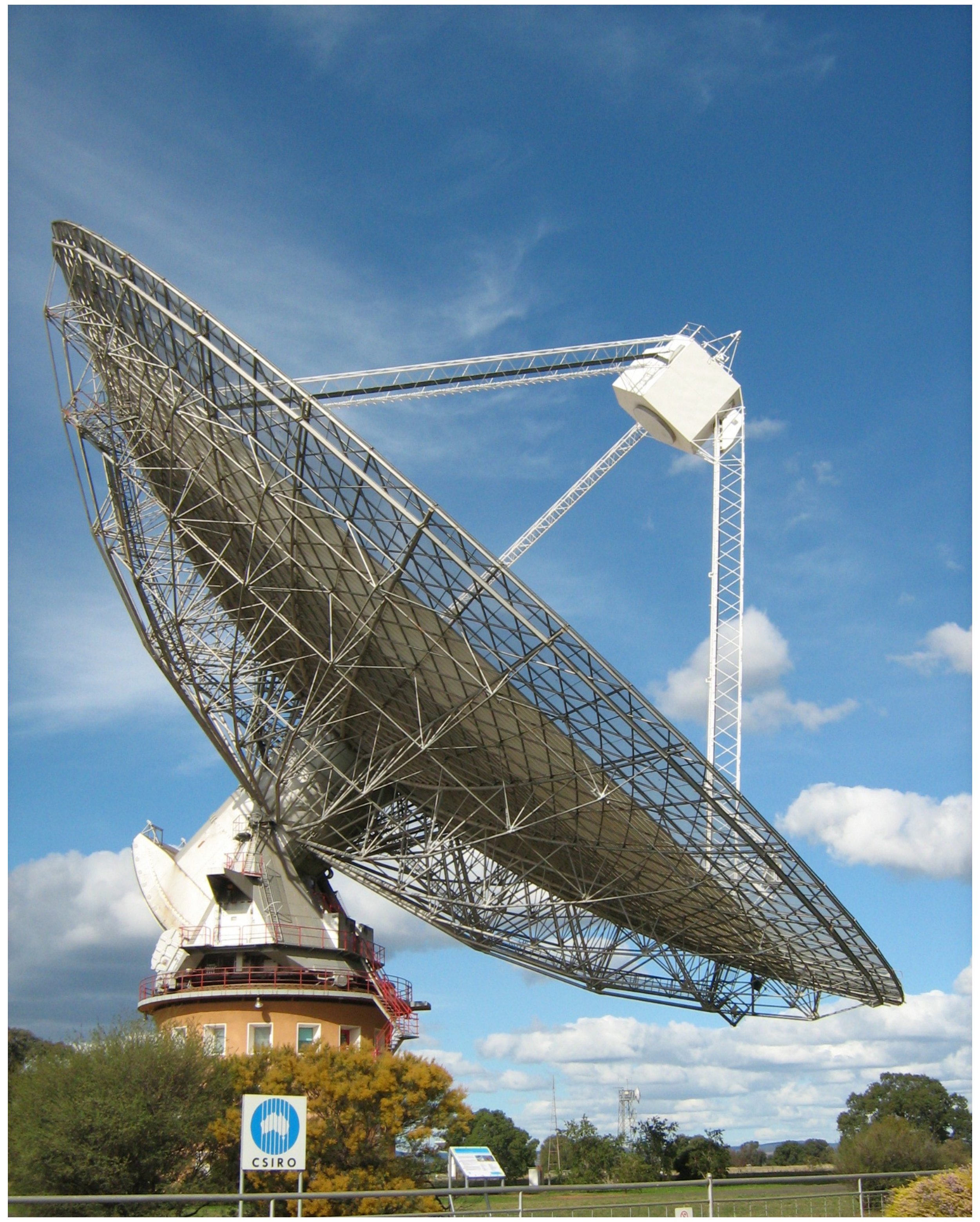
http://images.nrao.edu

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)

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/

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

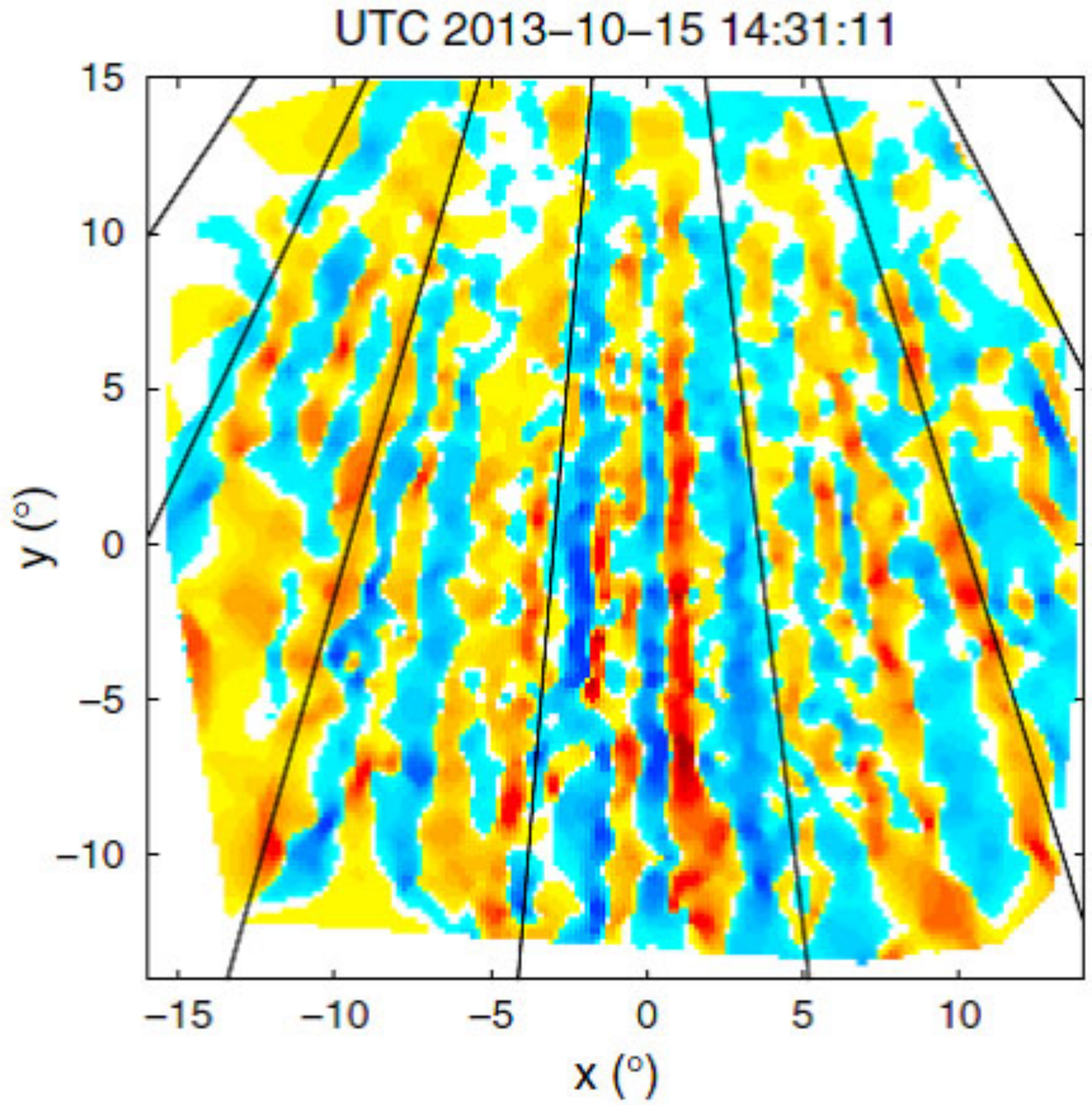
Telescopes - Interferometers

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)

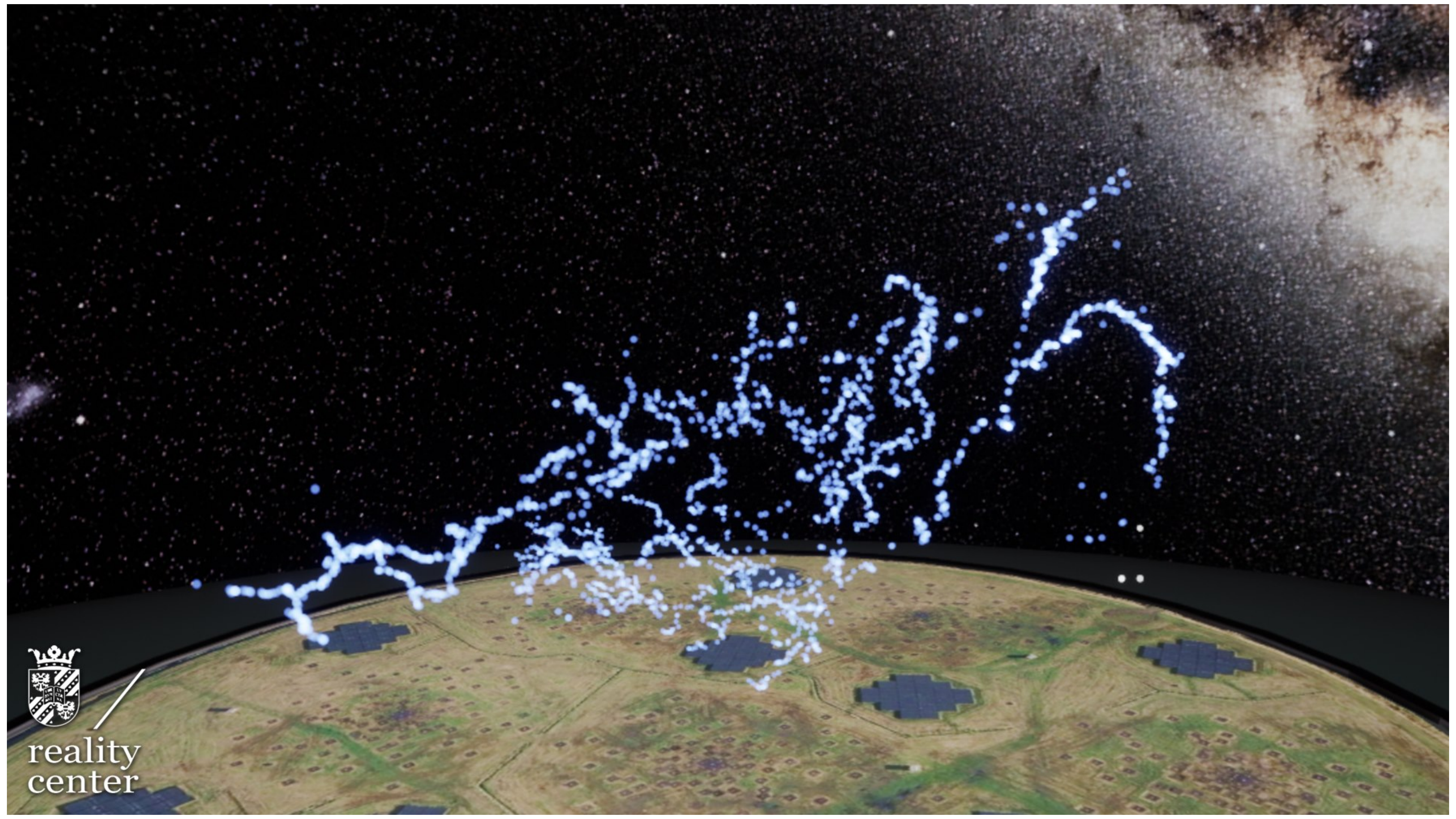


Imaging **plasma tubes in the earth's ionosphere!** (Cleo Loi)

Telescopes - Interferometers

Metal sticks or wires are used for m waves.

LOFAR (Low Frequency ARray)



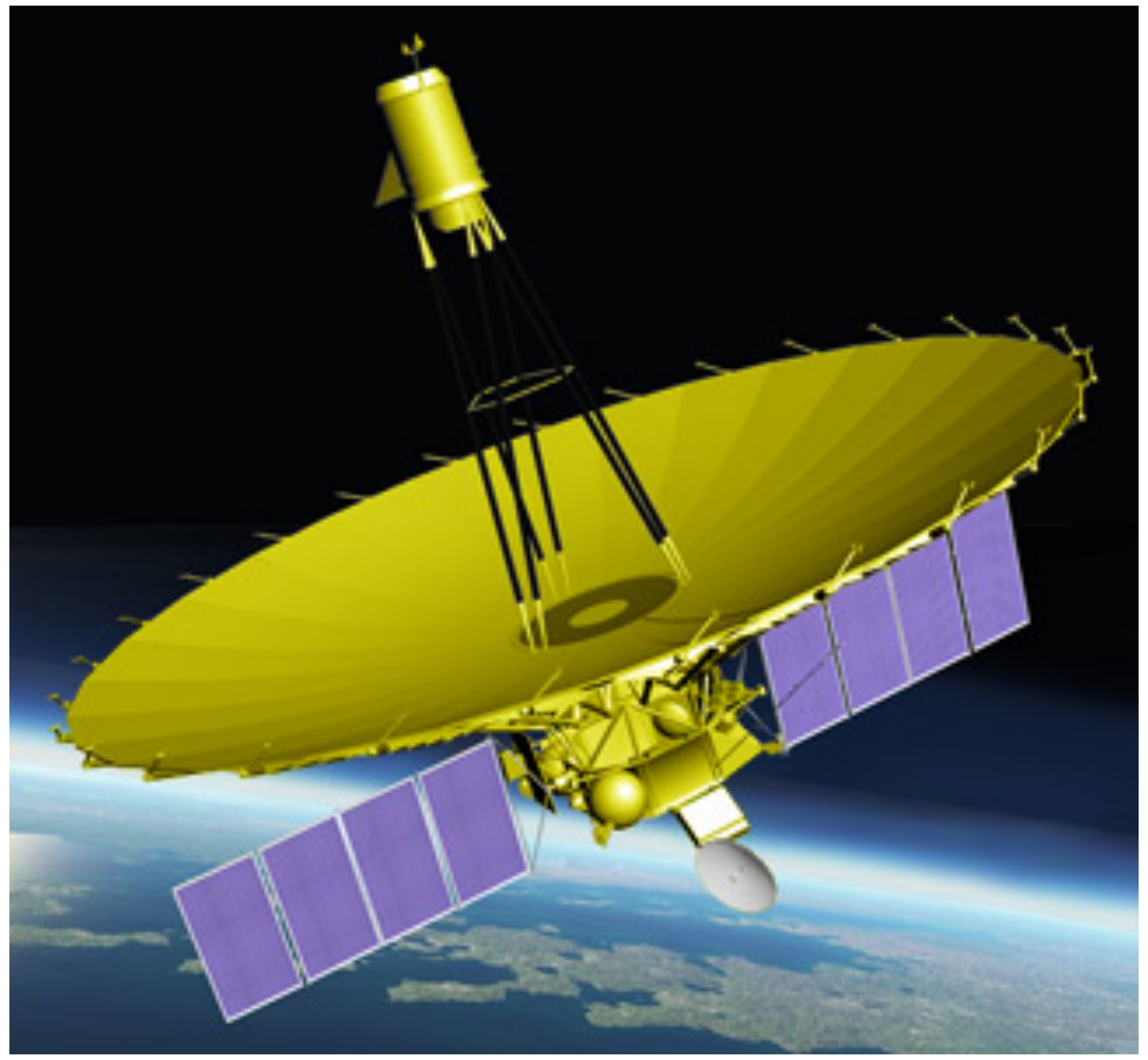
Imaging **the path of lightning.**

Telescopes - Interferometers

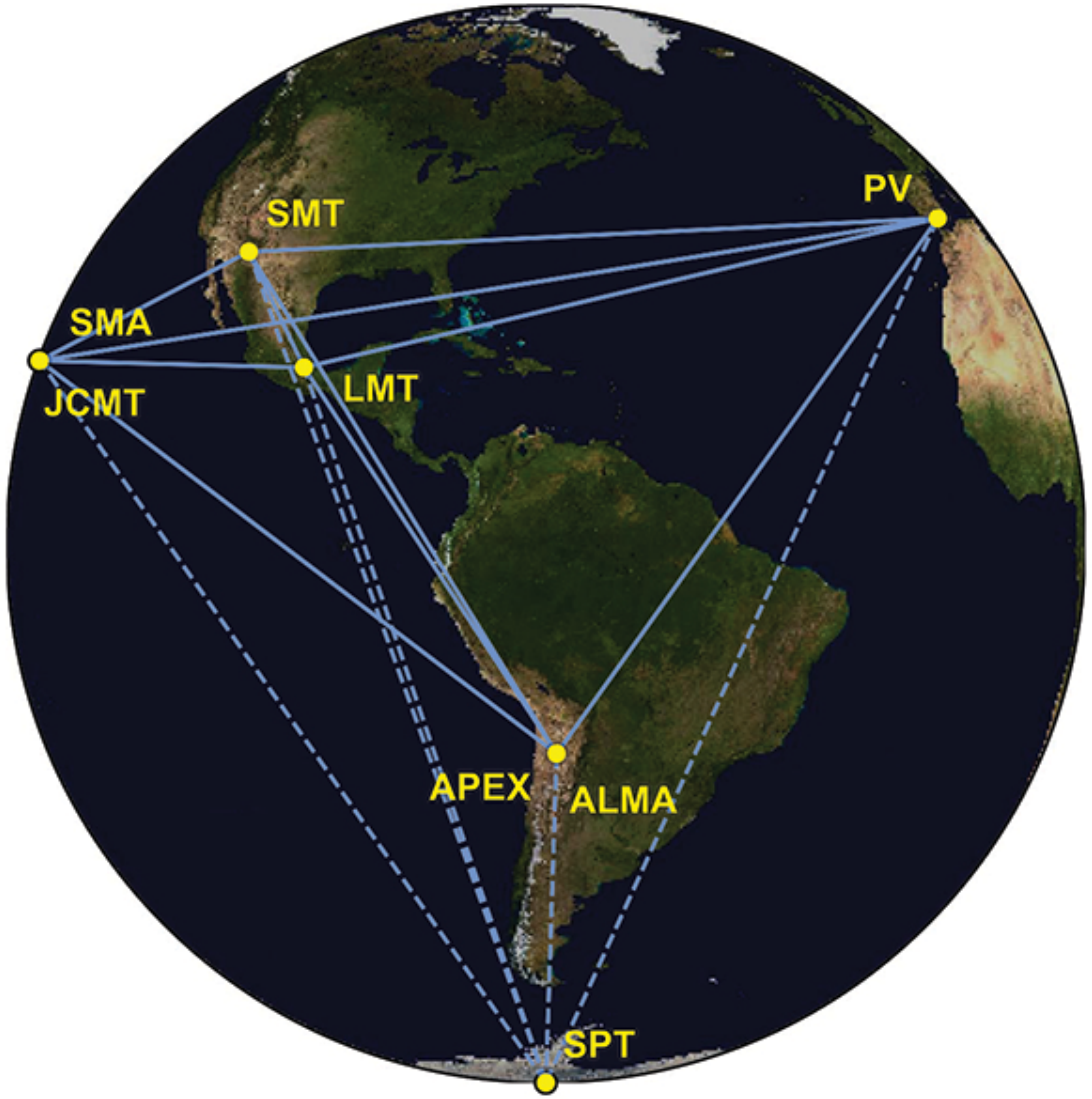
Very Long Baseline Interferometry (VLBI)

- 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

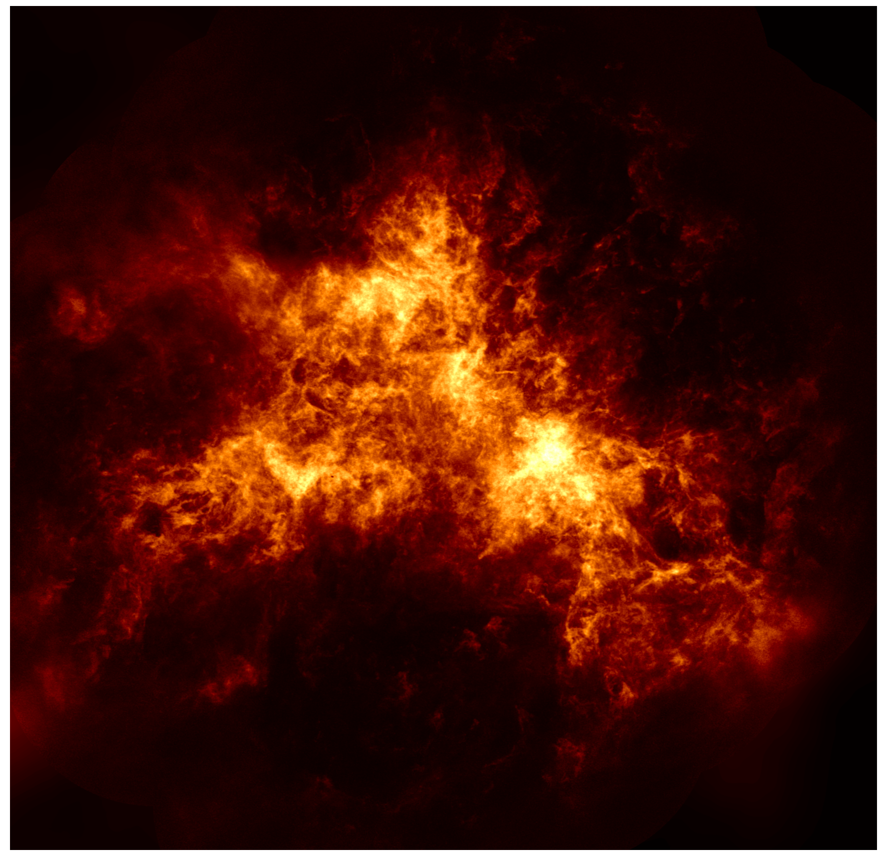


Event Horizon Telescope

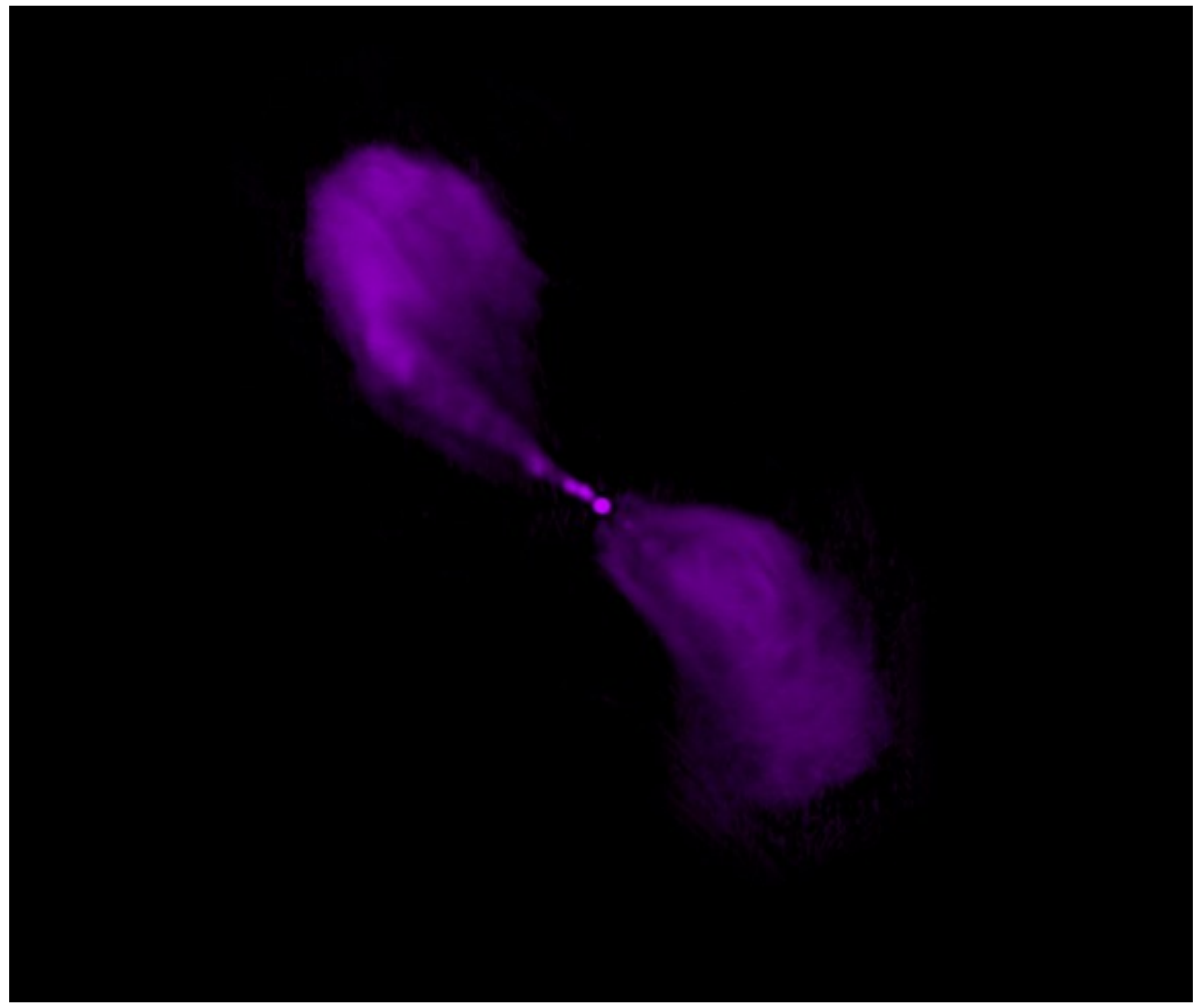


Telescopes - Interferometers

HI in galaxies (SMC)

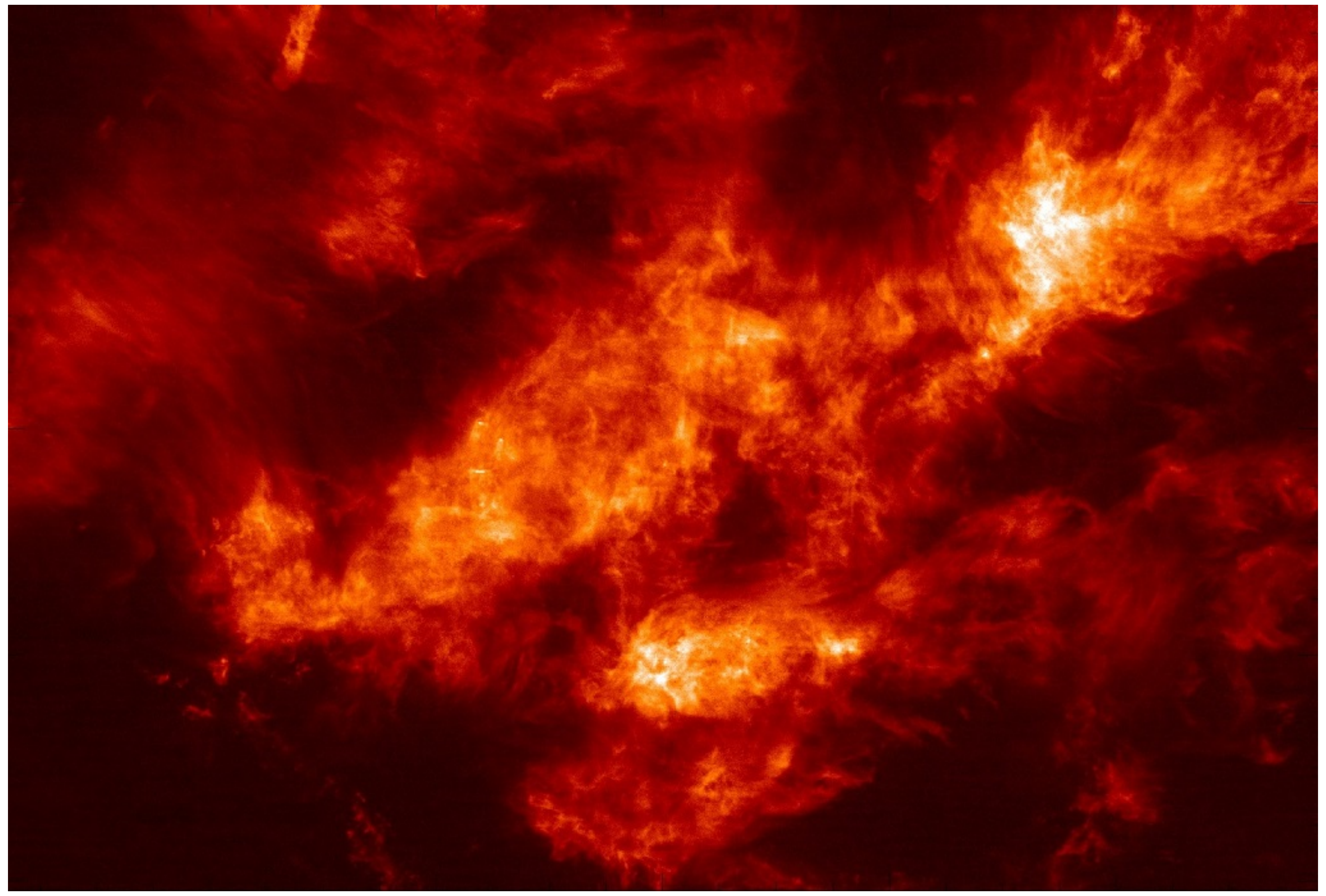


AGN

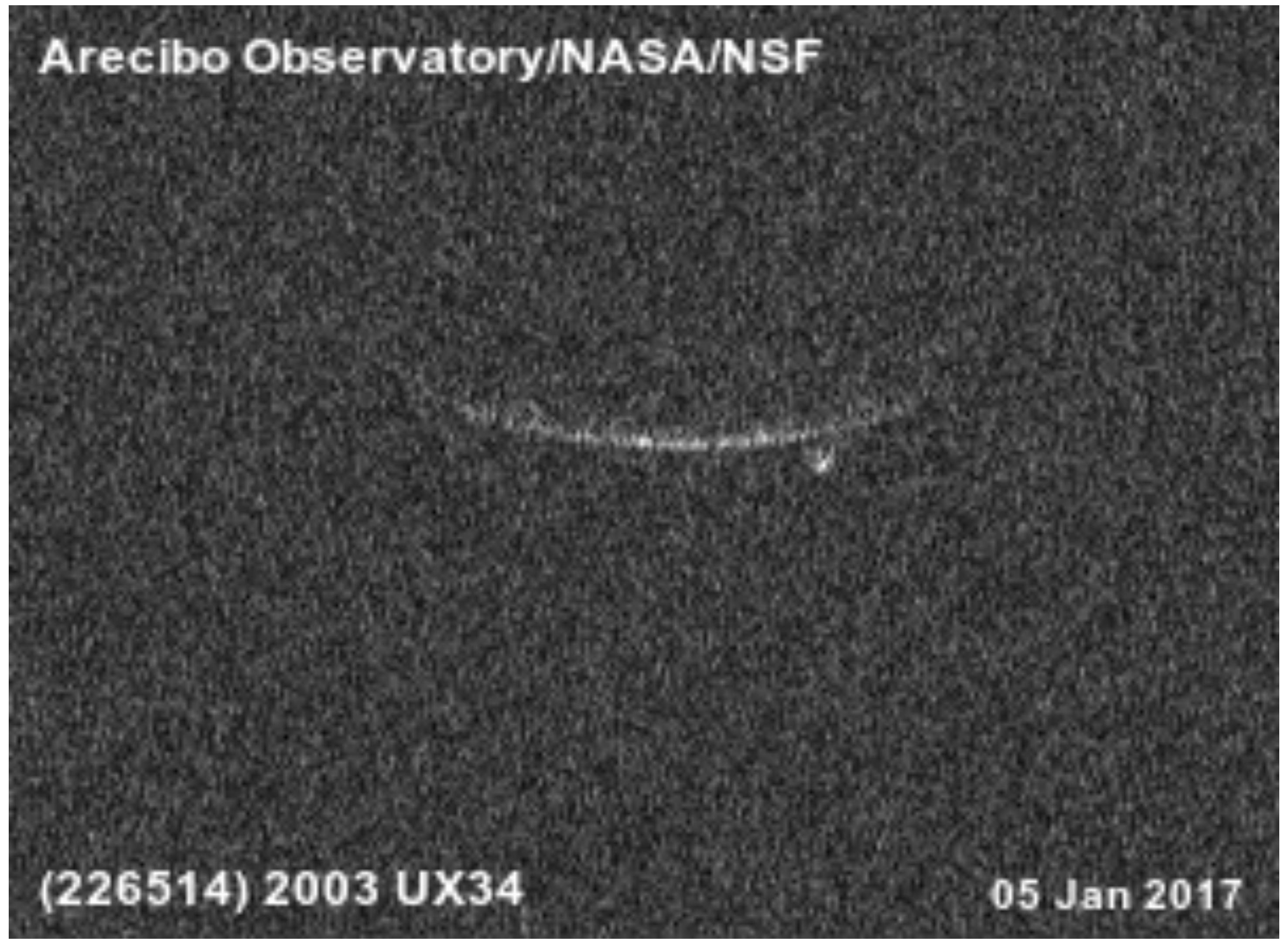


Accretion disk of a black hole

CO gas in the Taurus molecular cloud



Double asteroid



Infrared astronomy

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

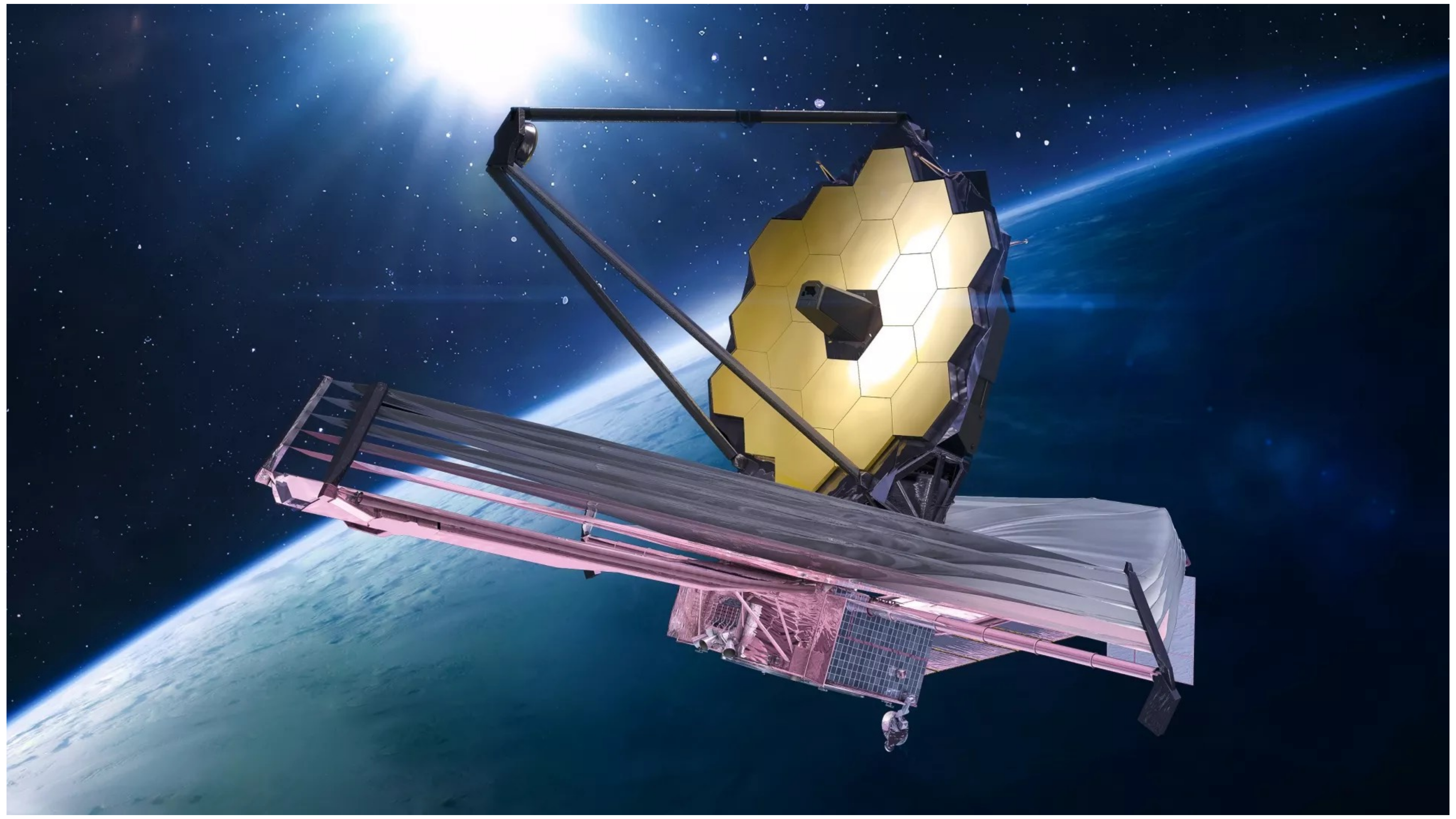
Infrared astronomy

- 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

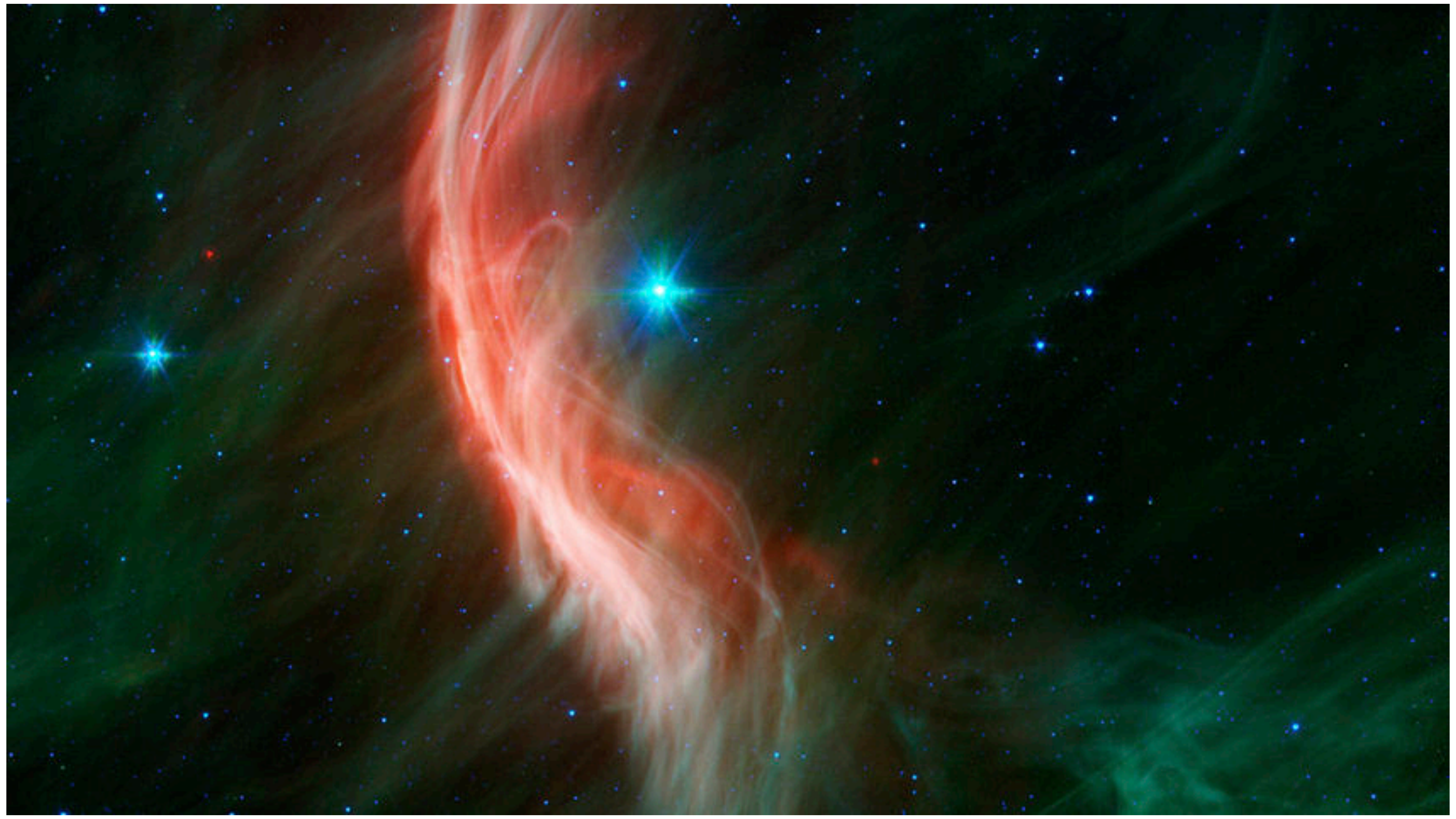
James Webb Space Telescope (JWST)



Infrared astronomy

- Sources: interstellar dust, old stars, supernova remnants

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



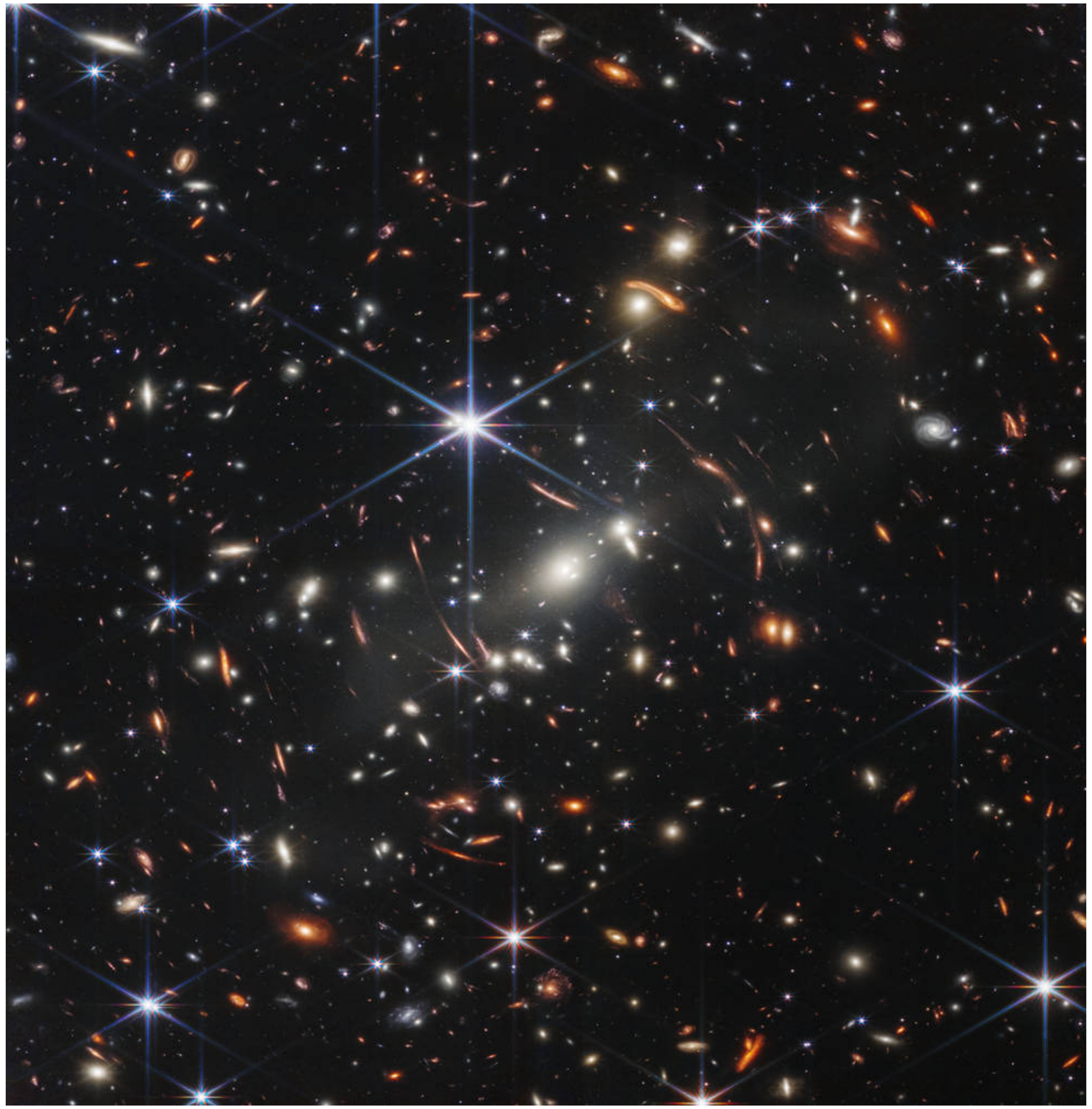
Herschel image of the Andromeda galaxy - emission from cold dust

Infrared astronomy

- Images from the new JWST telescope

Dust in galaxies

High redshift galaxies



Interstellar medium, dust

https://www.nasa.gov/webbfirstimages

X - ray astronomy

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

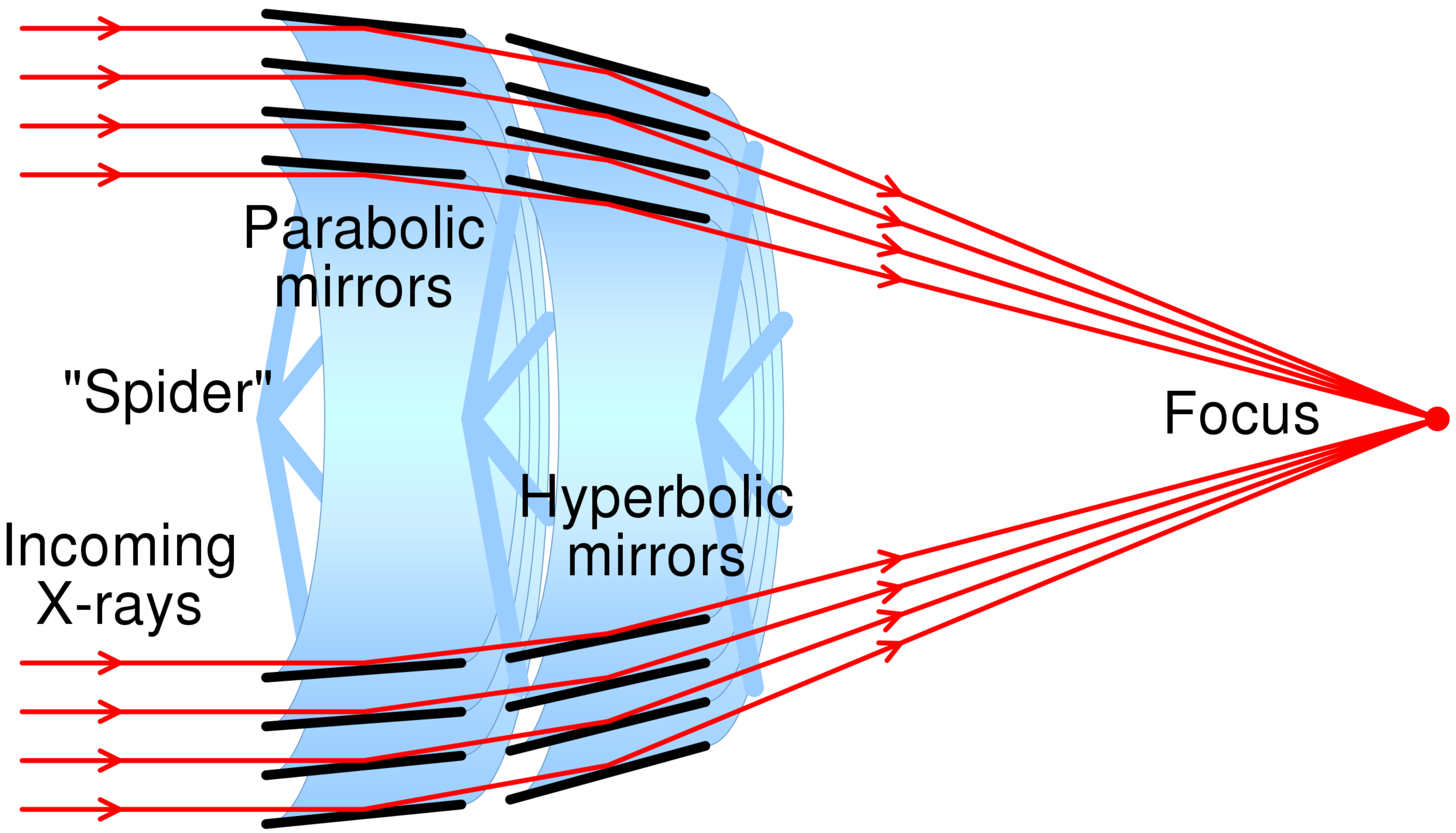
X - ray astronomy

- Only detectable above the atmosphere: balloon experiments and satellites

- X-rays are reflected from metal surfaces only when they are incident at grazing angles (otherwise, they pass through metals). Hence X-ray telescopes are designed very differently from optical telescopes.
- Also, mirrors in X-ray telescopes have to be much smoother than mirrors in optical telescopes because of the small wavelength of X-rays.
- Examples: ROSAT, Chandra, XMM-Newton

Chandra X-ray telescope

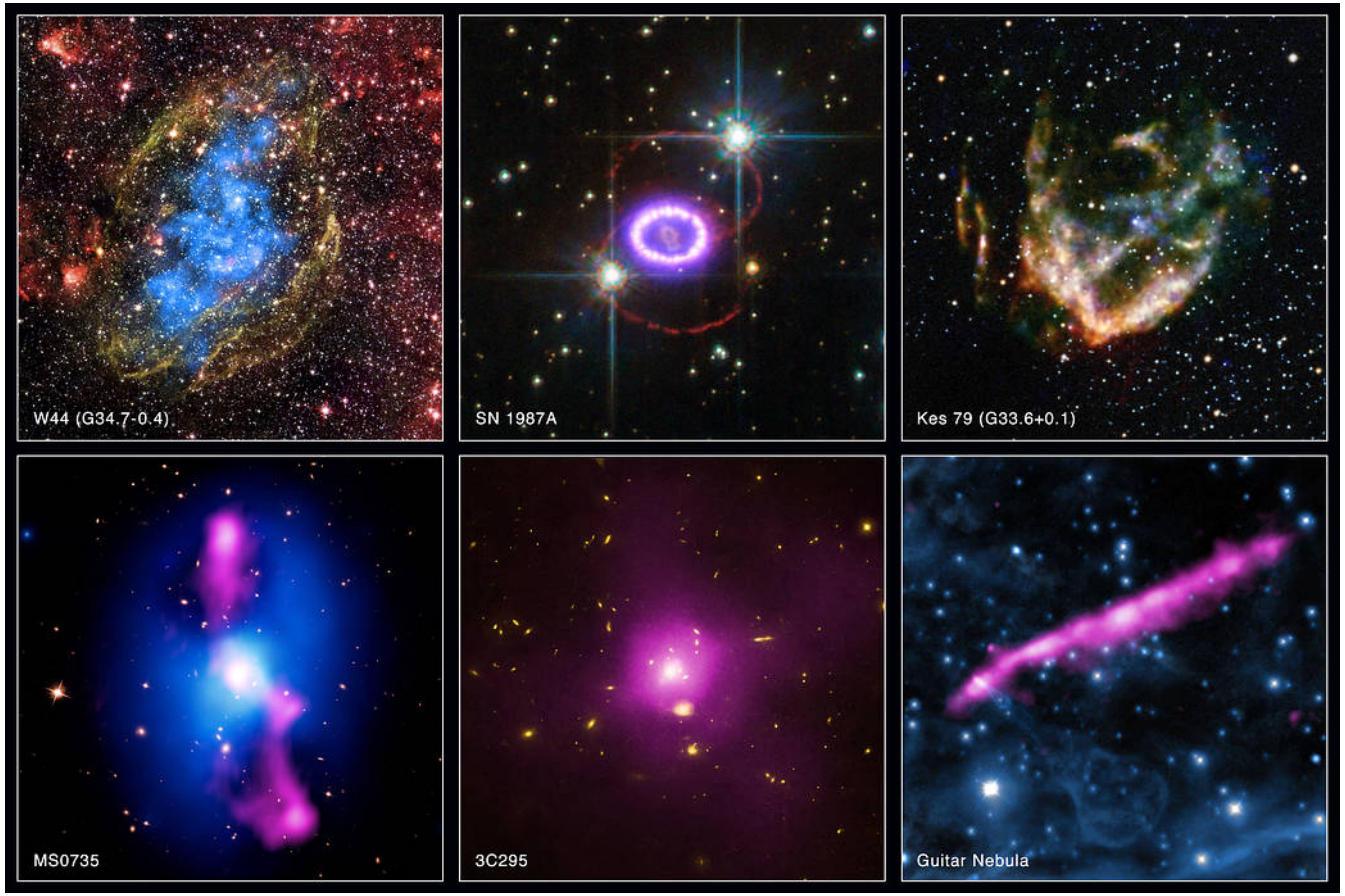
Schematics of X-ray telescope optics



X - ray astronomy

Composit images with Chandra X-ray data

- Sources: hot plasma (millions of K)
- Examples: the Sun, Supernova remnants, intra cluster matter in galaxy clusters, AGN, accreting binary stars, neutron star or black hole binaries.



Gamma-ray astronomy

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

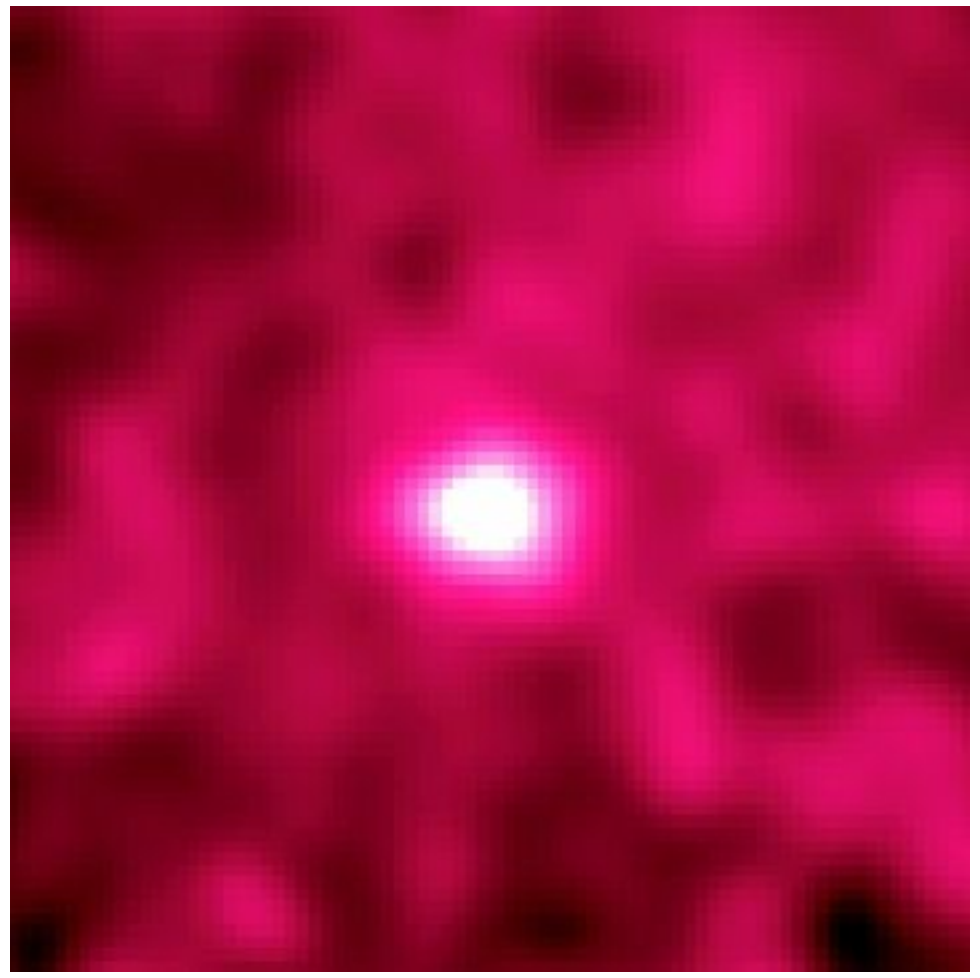
Gamma-ray astronomy

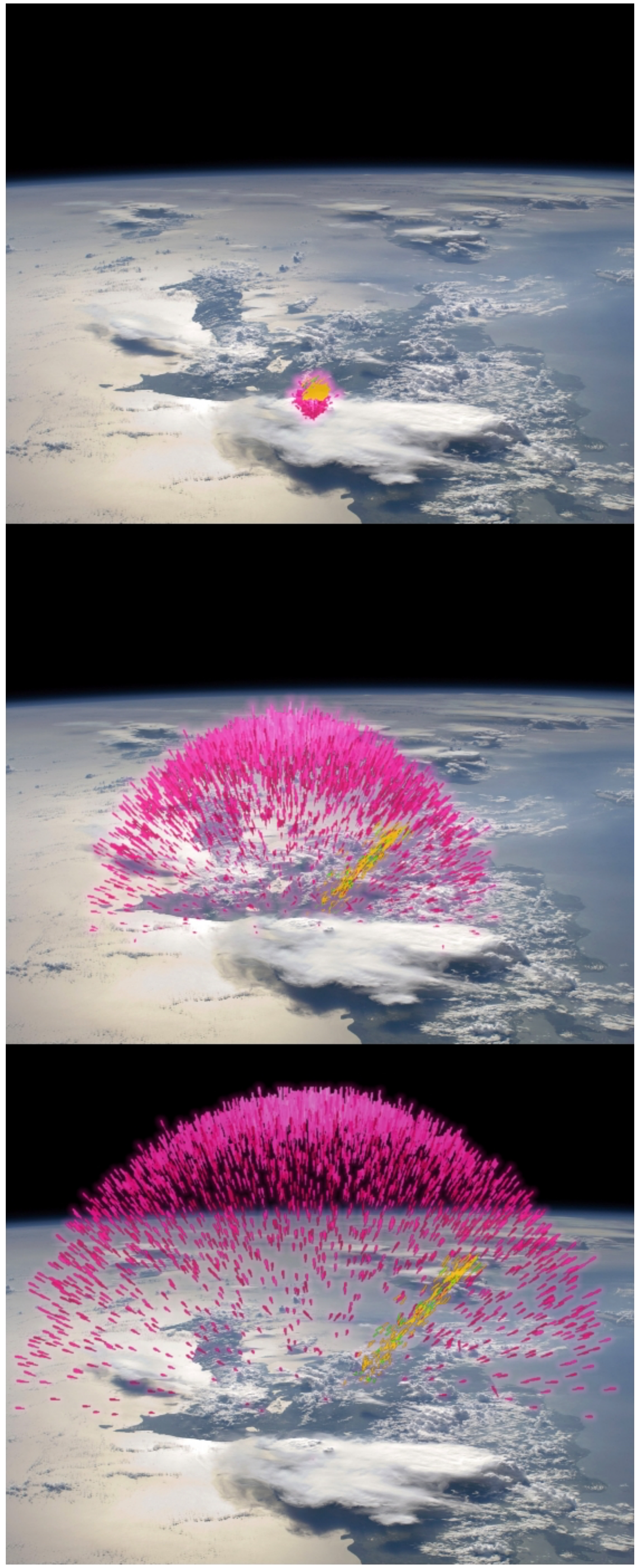
- Radiation above a 100 keV (from high energy sources)
- Sources: solar flares, supernovae, hypernovae, pulsars, blazars (AGN with the jet pointing towards Earth), thunderstorms on Earth, etc.
- Gamma-ray telescopes (satellites): INTEGRAL, Fermi, Egret, AGILE, etc.
- Indirect detection trough particle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

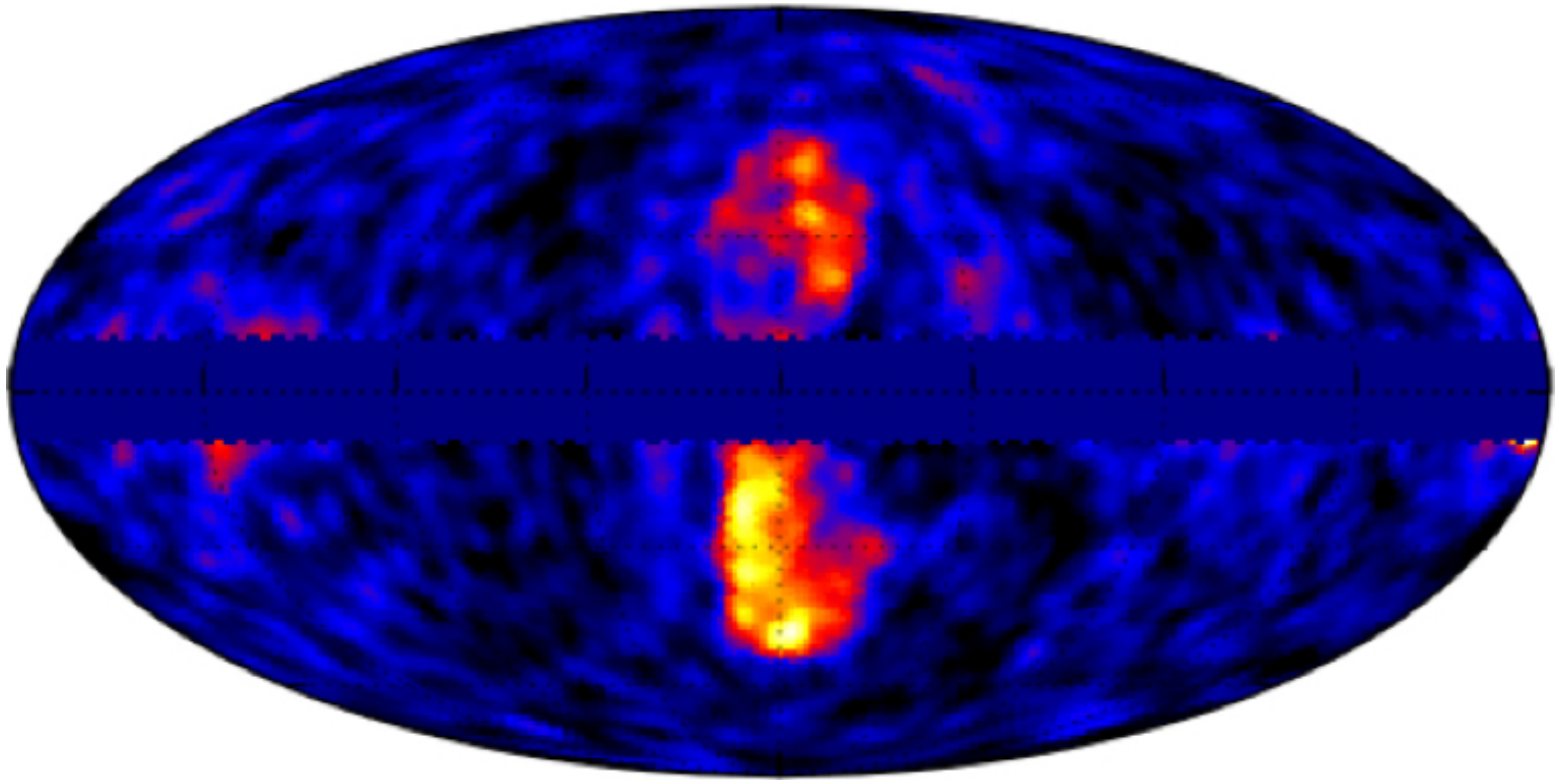


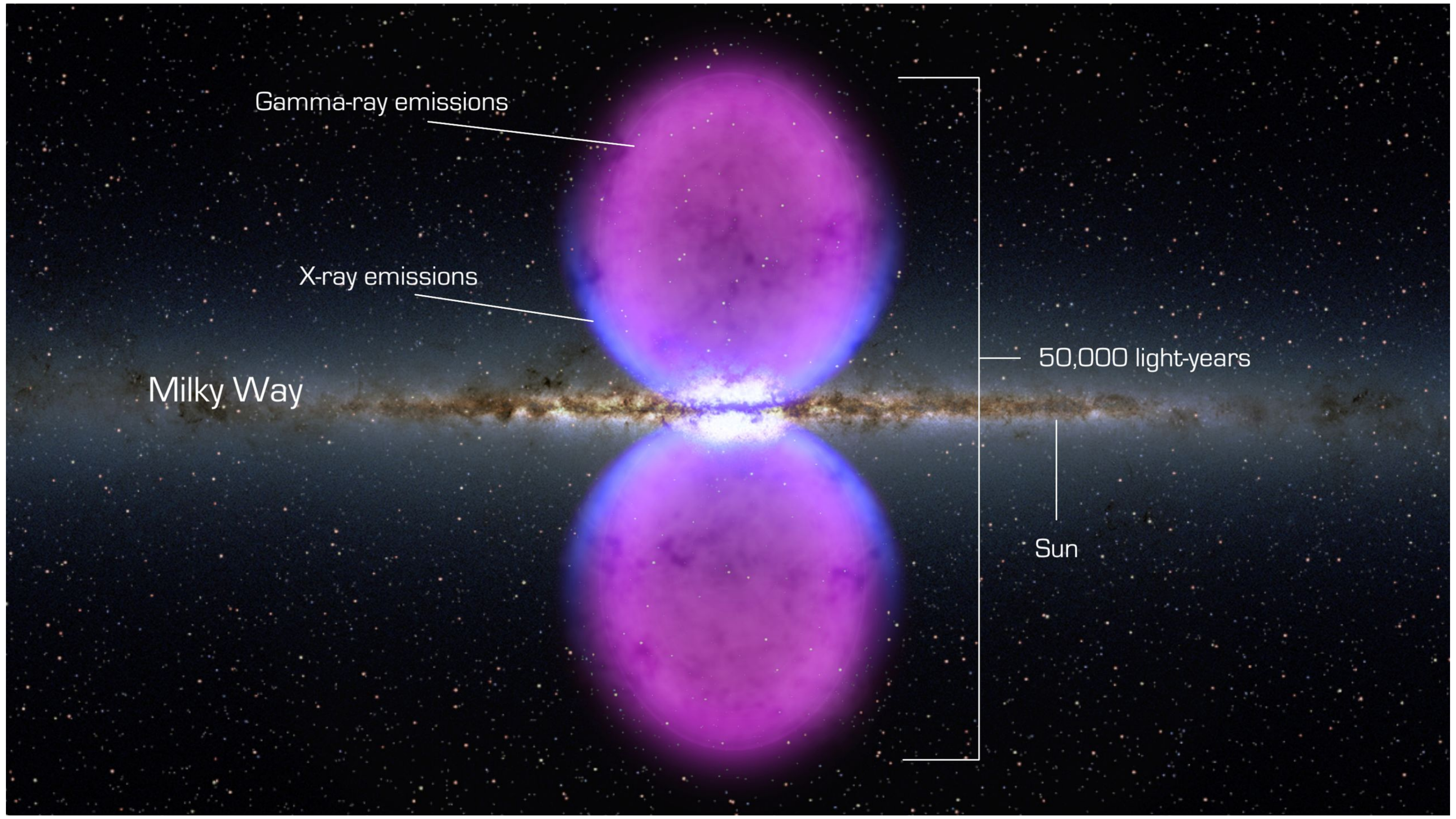


https://en.wikipedia.org/wiki/Gamma-ray_astronomy

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 black hole or by intense star formation activity.



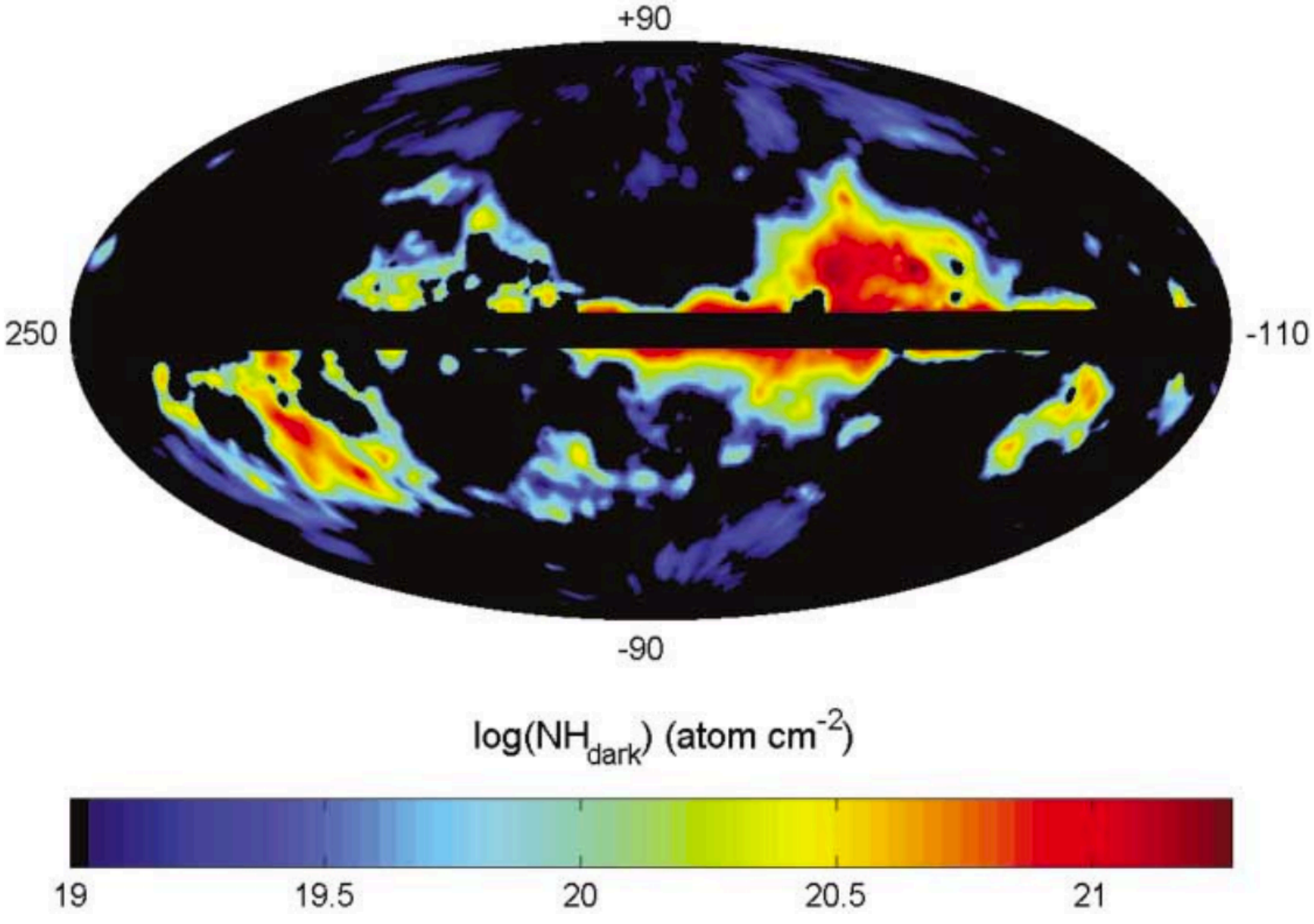


https://en.wikipedia.org/wiki/Gamma-ray_astronomy

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

Gamma-ray astronomy

- Dark gas in the Galaxy
- Using the diffuse gamma ray radiation, we can calculate the number of particles in the Inter Stellar Medium (ISM) and compare that with observations of neutral hydrogen (HI) and CO. Turns out, there is some extra material that we are not sure what it is. More neutral HI or more molecular gas not traced by CO.



Grenier et al (2005)

Naming conventions

Astronomical objects have various naming conventions

- historical catalogs
  - Henry Draper Catalog (HD …) for stars
  - Messier for galaxies and nebulas e.g. M101
  - New General Catalogue (NGC …) for galaxies
  - Third Cambridge Catalogue of Radio Sources (3C 273, …) for bright radio sources
  - Constellation name + number e.g. Cygnus A, Sgr A*
- Survey or telescope name + coordinates e.g. PKS … (PKS stands for the Parkes telescope)
- dates (for transient events) e.g. SN1987A

Guidlines are provided by the International Astronomical Union (IAU)

Useful websites

Some websites that astronomers use regularly:

To find publications:

Astrophysics Data System (ADS) - https://ui.adsabs.harvard.edu/# (this is like a library for papers)

ArXiv - https://arxiv.org/ (preprint publications, free access)

Any sort of data catalogue + information on objects:

Centre de Données astronomiques de Strasbourg (CDS) Strasbourg astronomical Data Center
http://cds.u-strasbg.fr/

Information on extragalactic objects:

NASA/IPAC Extragalactic Database (NED) https://ned.ipac.caltech.edu/

Science quality images from various surveys:

Skyview: https://skyview.gsfc.nasa.gov/current/cgi/titlepage.pl

+ there are many more free to access data bases

To look at pretty images of the sky, not directly for science:

Wikisky: http://www.wikisky.org/

GLEAMoscope: https://gleamoscope.icrar.org/gleamoscope/trunk/src/