Radio Astronomy

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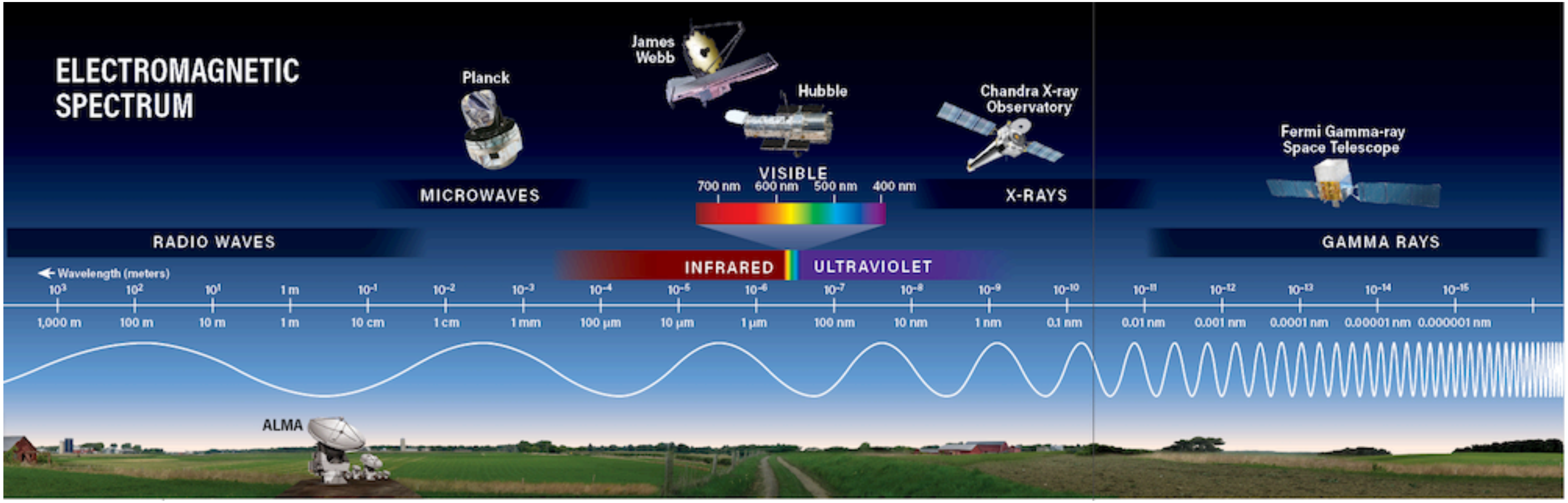
Electromagnetic radiation

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

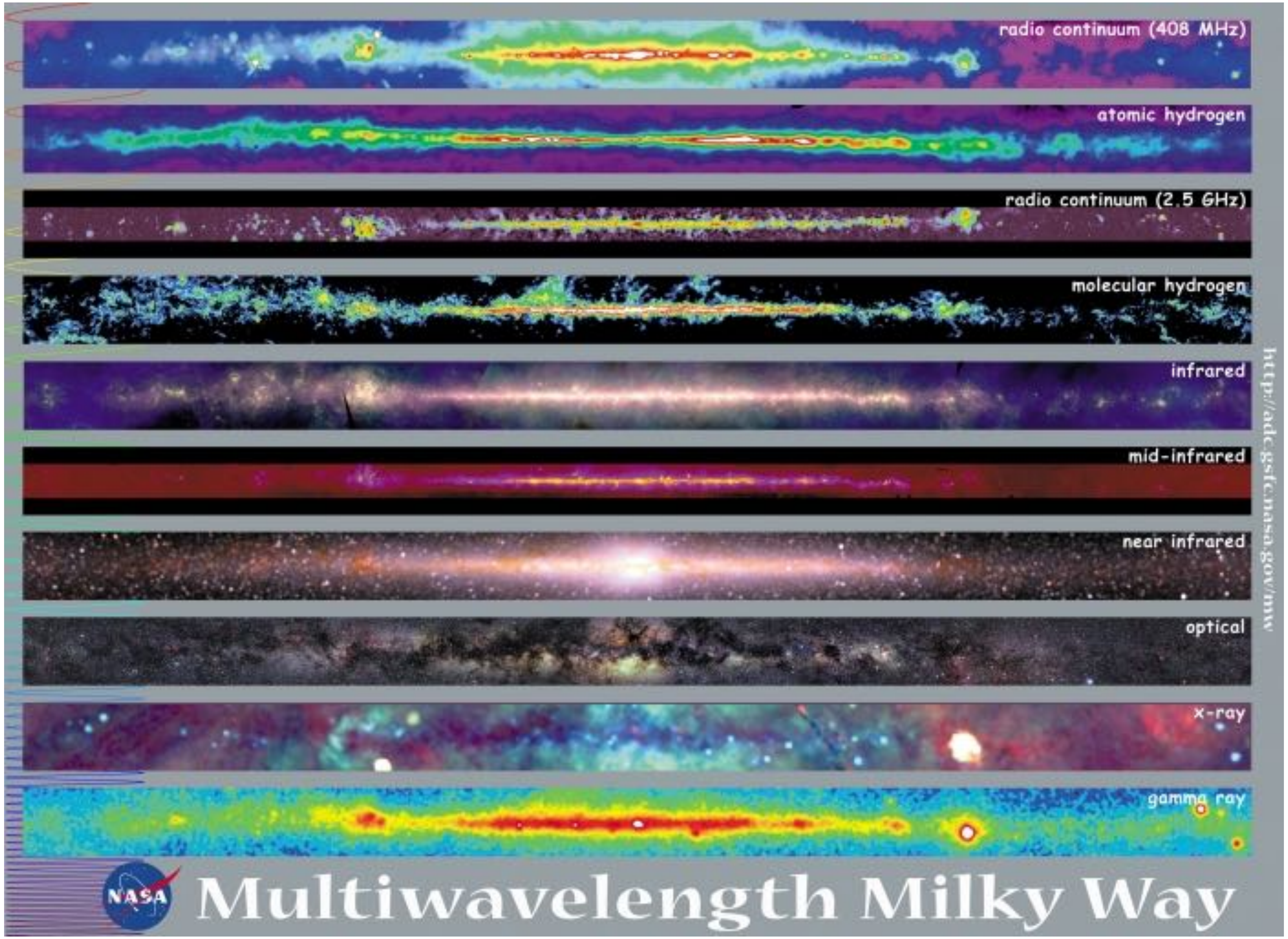
Spectral lines from gas clouds

Dust

Stars

Hot plasma

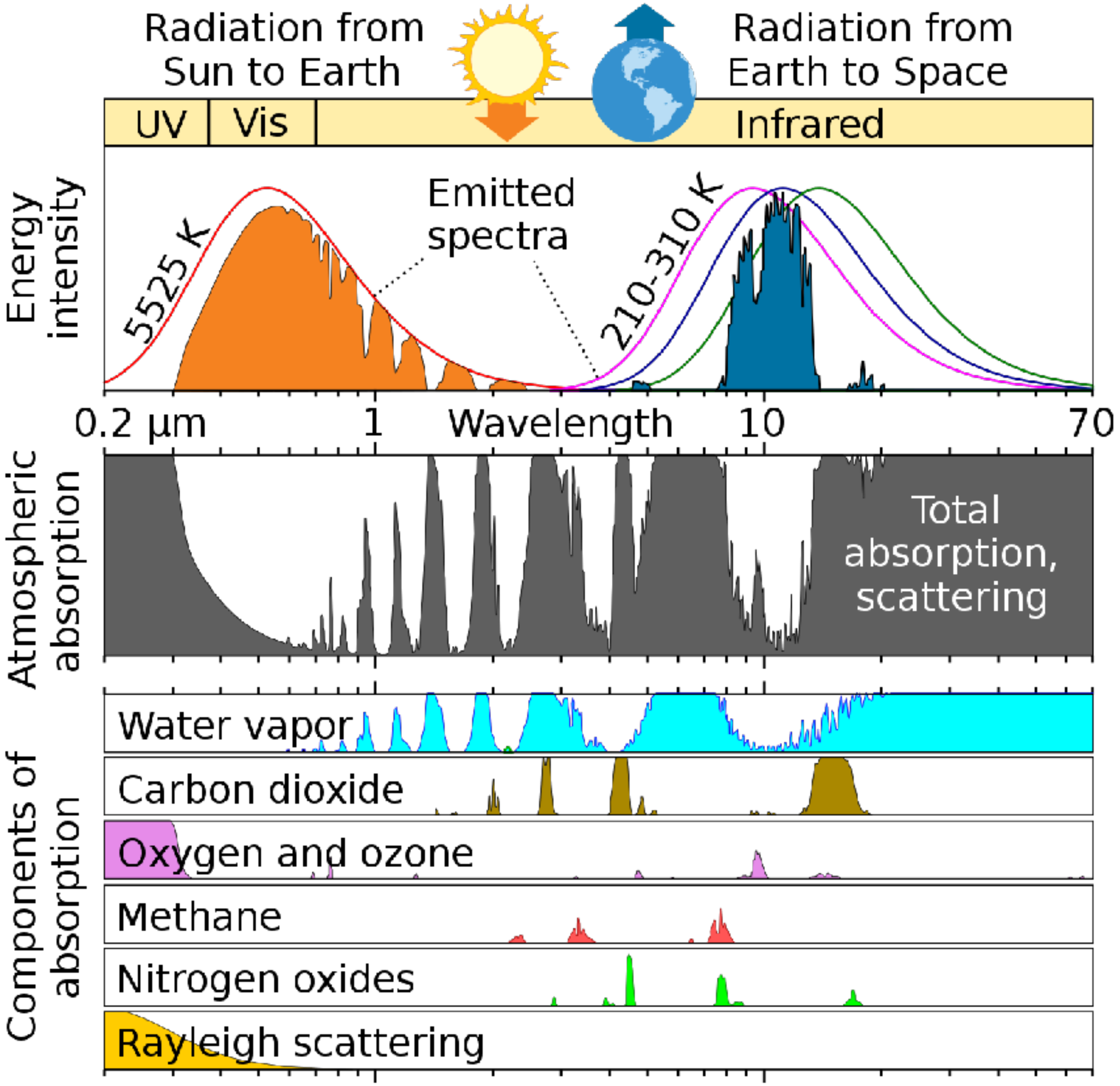
High energy sources



Electromagnetic radiation

Atmospheric transmission:

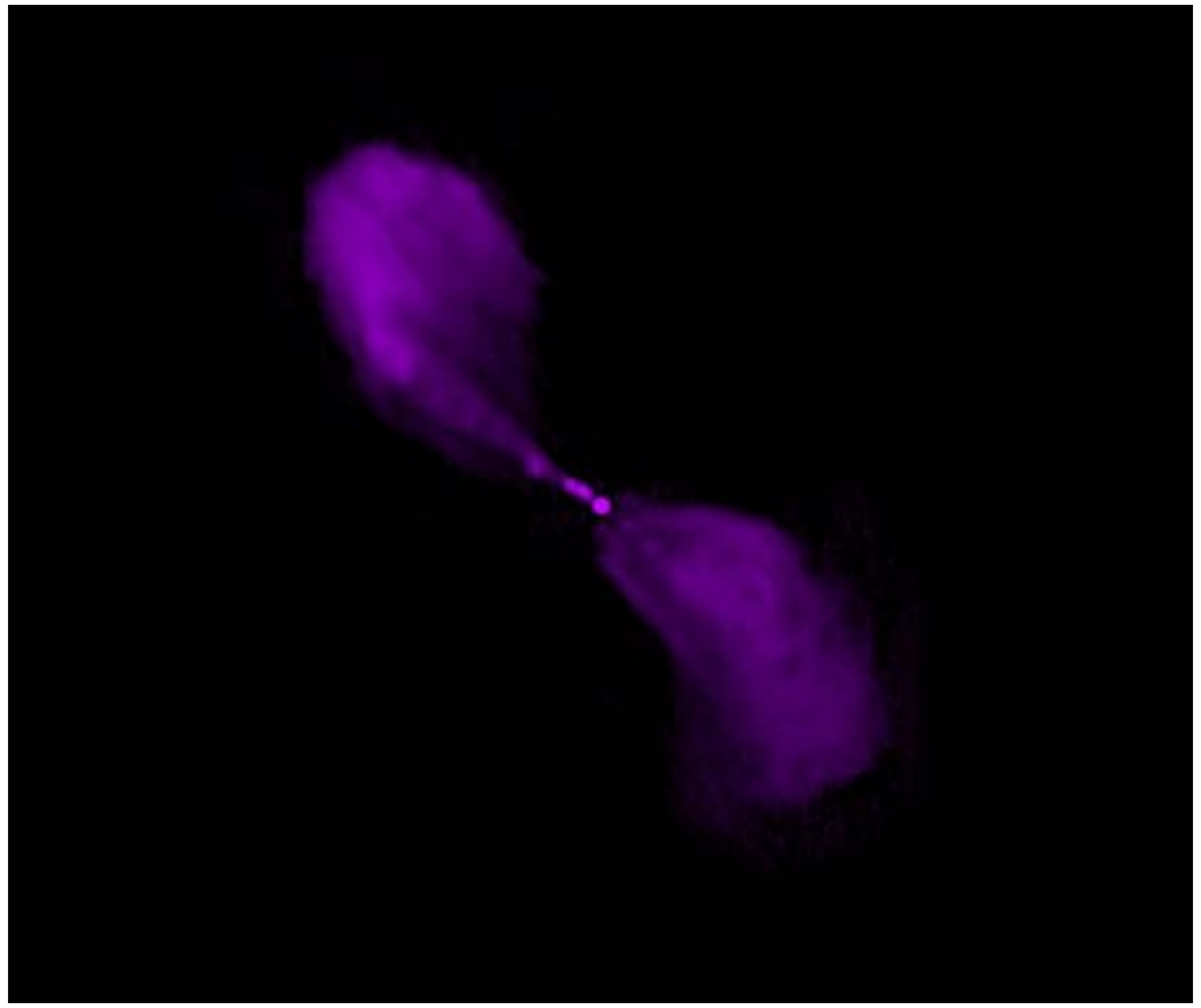
- The atmosphere is not see trough in all wavelengths
- Water vapour absorbs a large range of radiation
- The ionosphere reflects certain radiation
- **The atmospheric transmission characterises how much radiation can reach the surface of the Earth at different wavelengths.**

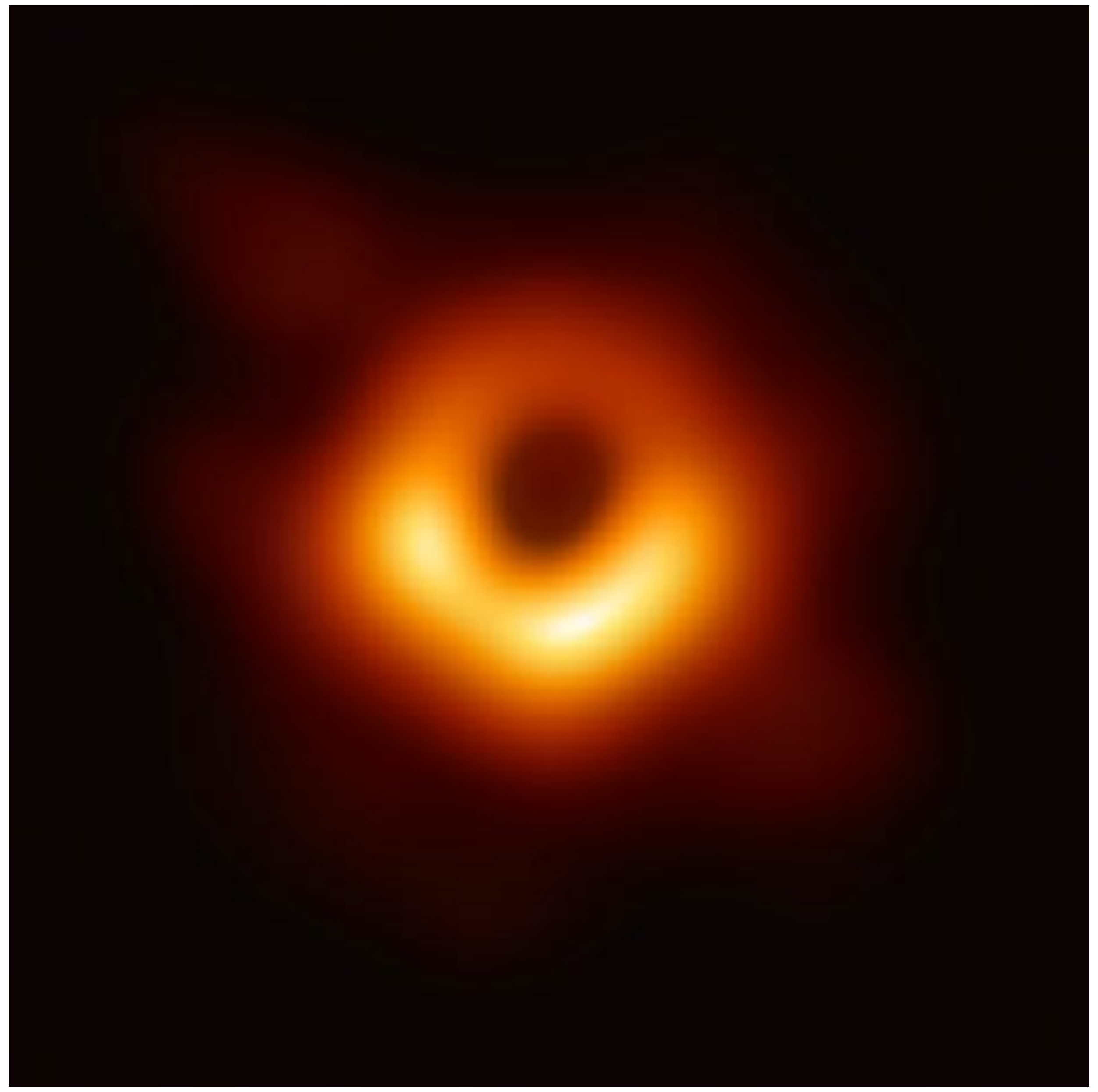


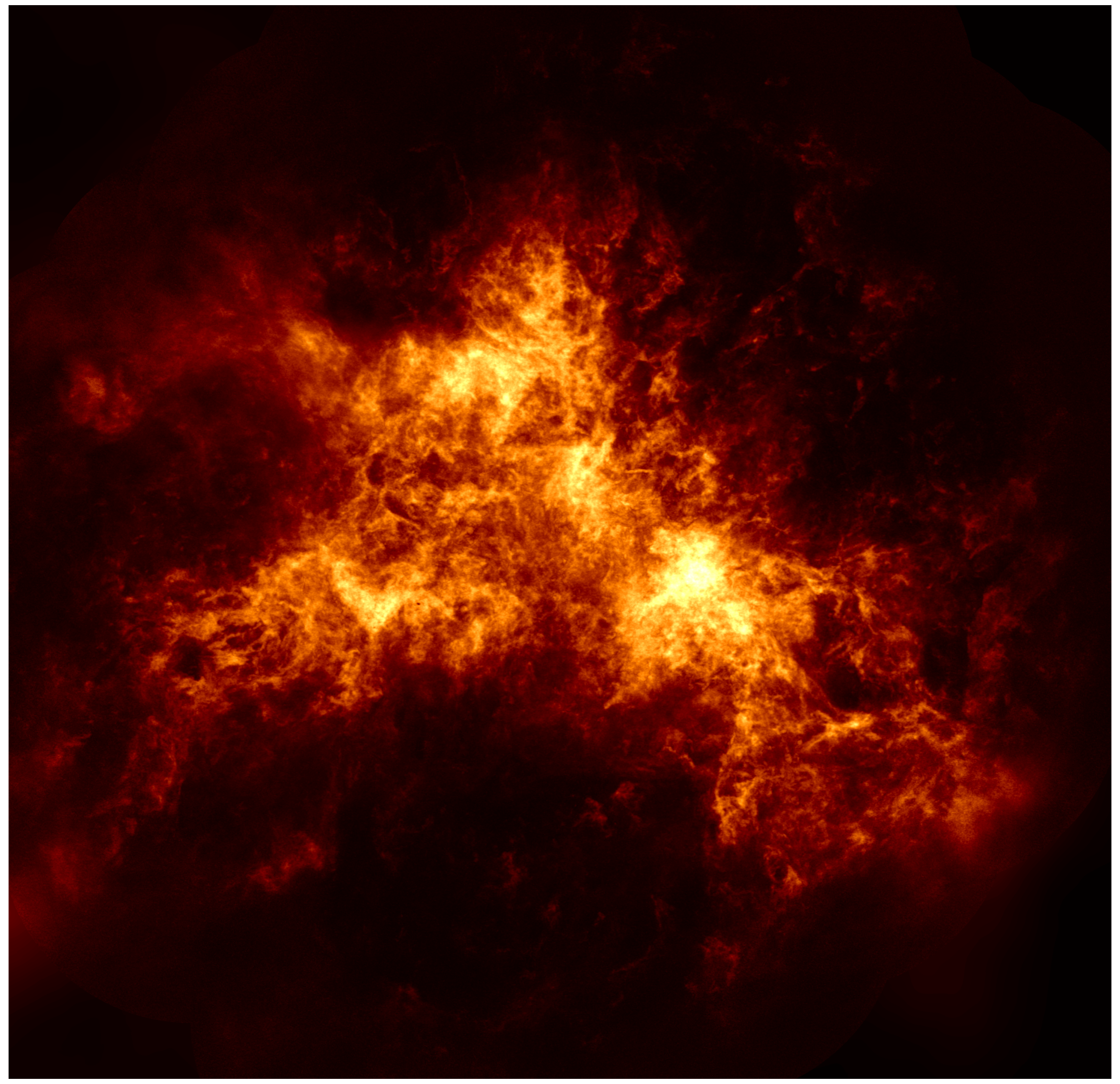
https://en.wikipedia.org/wiki/Atmospheric_window

Radio astronomy

- Radio astronomy is the study of natural radio emission from celestial sources.
- Between 10 MHz **(λ~30 m)** and 1 THz ($\lambda=c/\nu$~**0.3 mm**) at the low-frequency end of the electromagnetic spectrum.
  - The Earth's ionosphere reflects radio waves with frequencies below v~10 MHz **(λ~30 m).**
- **Nearly everything emits radio waves at some level**, via a wide variety of emission mechanisms.







Radio quite zones

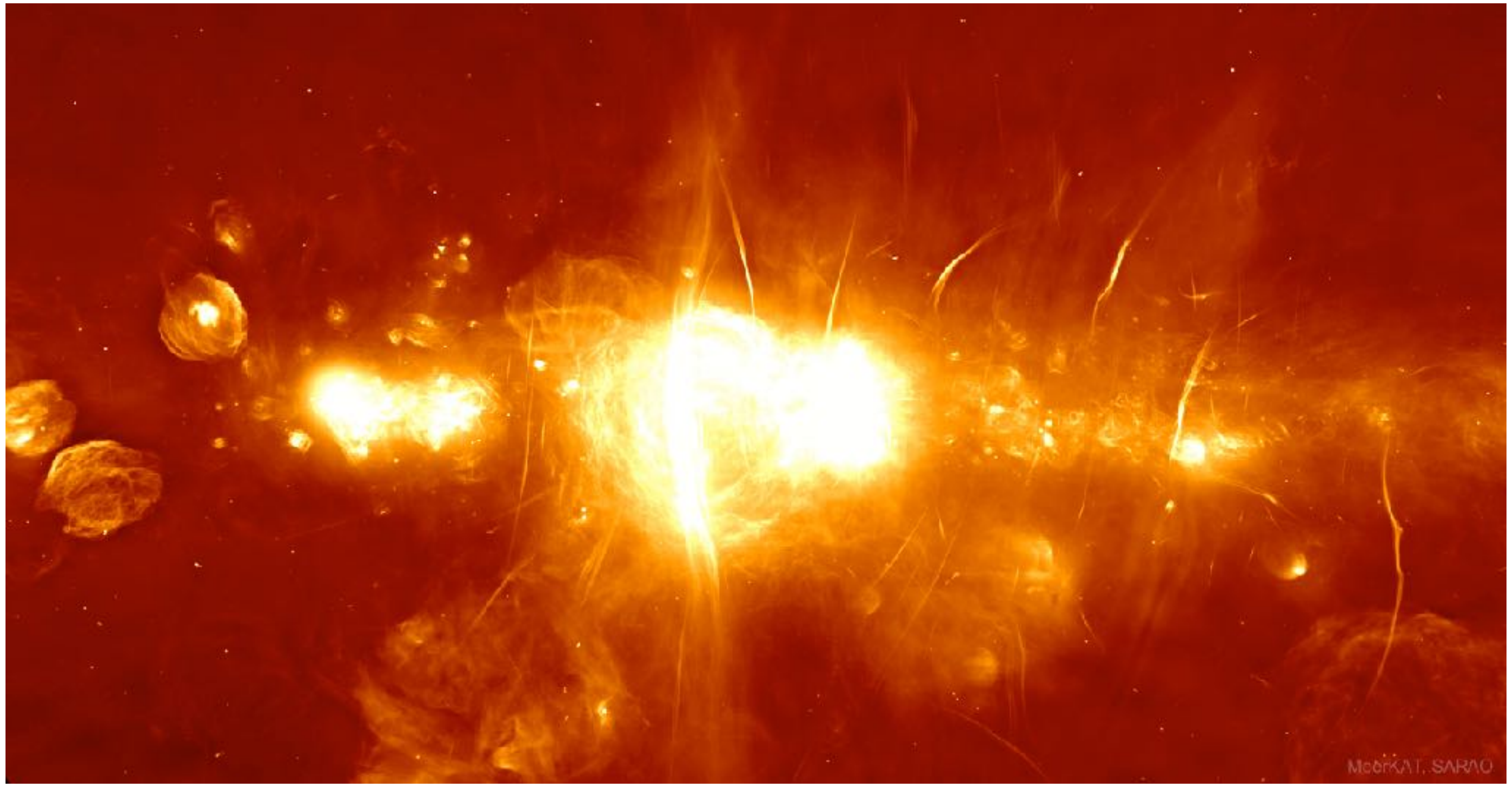
- Most radio telescopes are located in radio quiet zones
- Any transmitting device (e.g. **mobile phones, tablets, laptop wifi**) needs to be turned off in these zones to prevent interference with the observations
- Other forbidden devices are: **microwave ovens, BBQ lighters, very old TVs**
- Every 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

Major discoveries of radio astronomy

1. **nonthermal radiation (synchrotron radiation, bremsstrahlung)** from our Galaxy and many other astronomical sources;
2. radio galaxies and quasars (quasi-stellar radio sources) powered by **supermassive black holes** (SMBHs);
3. **spectral-line emission** from cold interstellar gas atoms, ions, and molecules;
4. **maser** (microwave amplification by stimulated emission of radiation) emission from interstellar molecules;
5. **cosmic microwave background** radiation from the hot big bang;
6. pulsars and **neutron stars**;
7. indirect evidence for **gravitational radiation**;
8. **evidence for dark matter in galaxies**, deduced from their HI (neutral hydrogen) rotation curves;
9. **extrasolar planets**;
10. **Wifi**

Radio astronomy

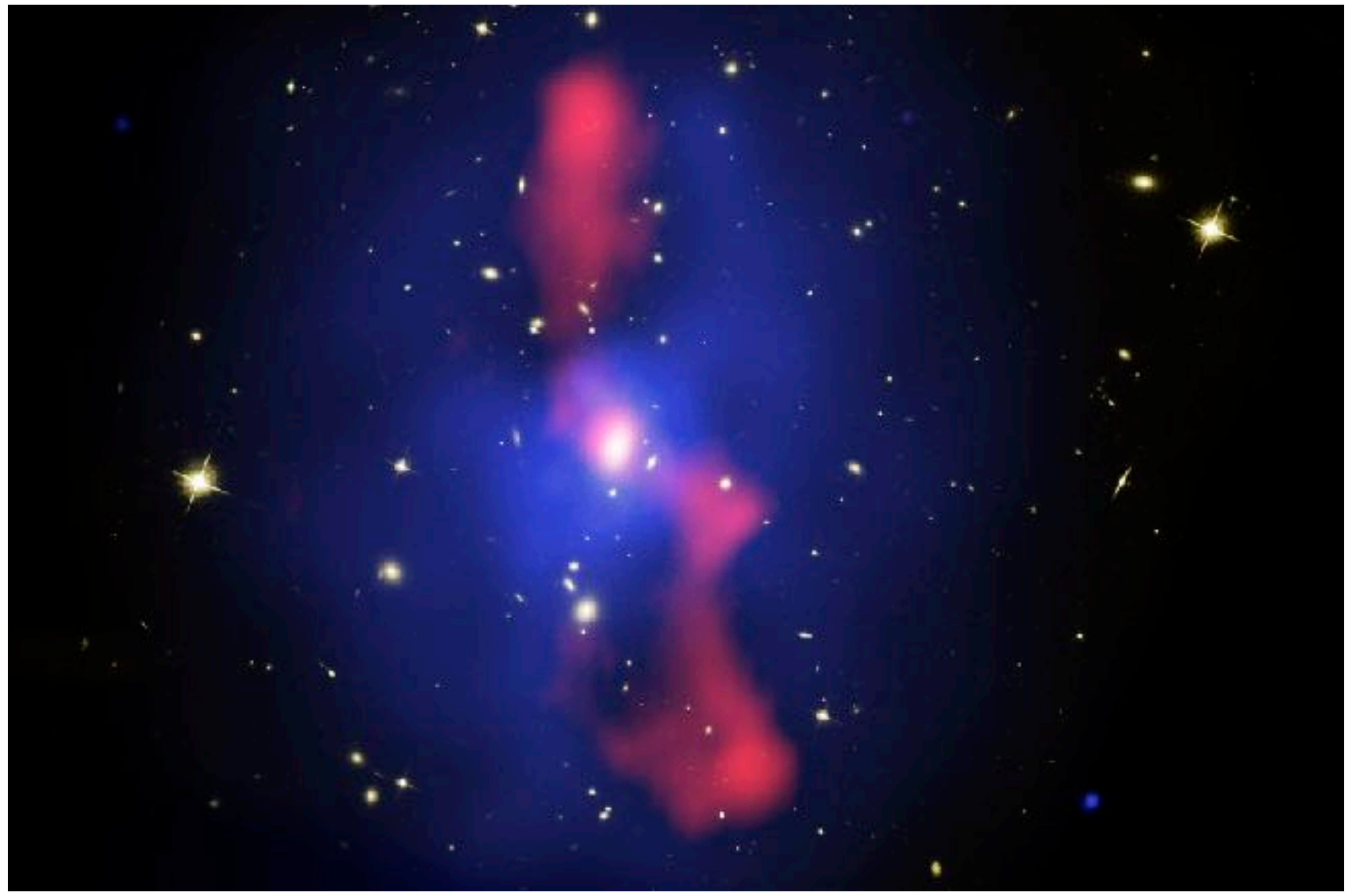


Dust scattering is negligible because **interstellar dust grains are much smaller than radio wavelengths**, so the **dusty interstellar medium (ISM) is nearly transparent**. This allowed radio astronomers to see through the dusty disk of our Galaxy and discover the compact radio source Sgr A_* powered by the supermassive black hole at its center.

Radio spectral lines trace extremely low-energy transitions produced by atomic hyperfine splitting (the 21-cm line of neutral hydrogen), the quantized rotation rates of polar molecules such as carbon monoxide in interstellar space, and high-level recombination lines from interstellar atoms.

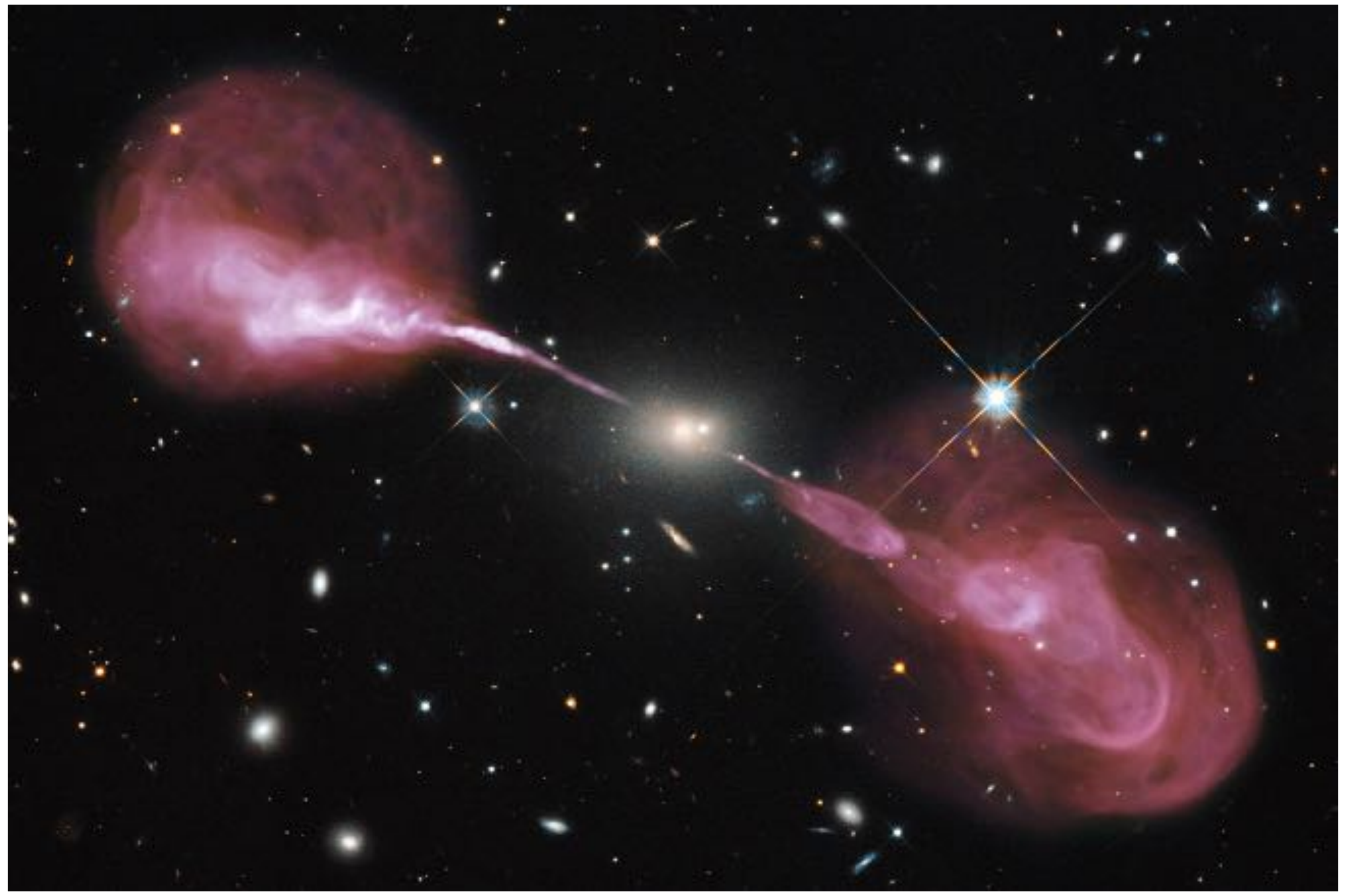
Radio astronomy

The radio source (red) in the galaxy cluster MS0735.6+7421 has displaced the X-ray emitting gas (blue)



Radio **synchrotron sources live long** after their emitting electrons were accelerated to relativistic energies, so they can provide long-lasting emission of past energetic phenomena.

The radio galaxy Hercules A (3C 348).



Most **plasma effects** (scattering, dispersion, Faraday rotation, etc.) are strong enough at low radio frequencies to **trace interstellar electron densities and magnetic field strengths.**

Radio astronomy

- A **wide variety of radio telescopes and observing techniques** are needed to cover the radio window effectively.
- With radio detectors **we can record the phase information,** allow the construction of **multielement aperture-synthesis interferometers** with possible angular resolution approaching **10^{-4} arcsec.**
- **Spectrometers with extremely high spectral resolution and frequency accuracy.**

Radio telescopes

$$\Theta=1.22\,\lambda/D$$

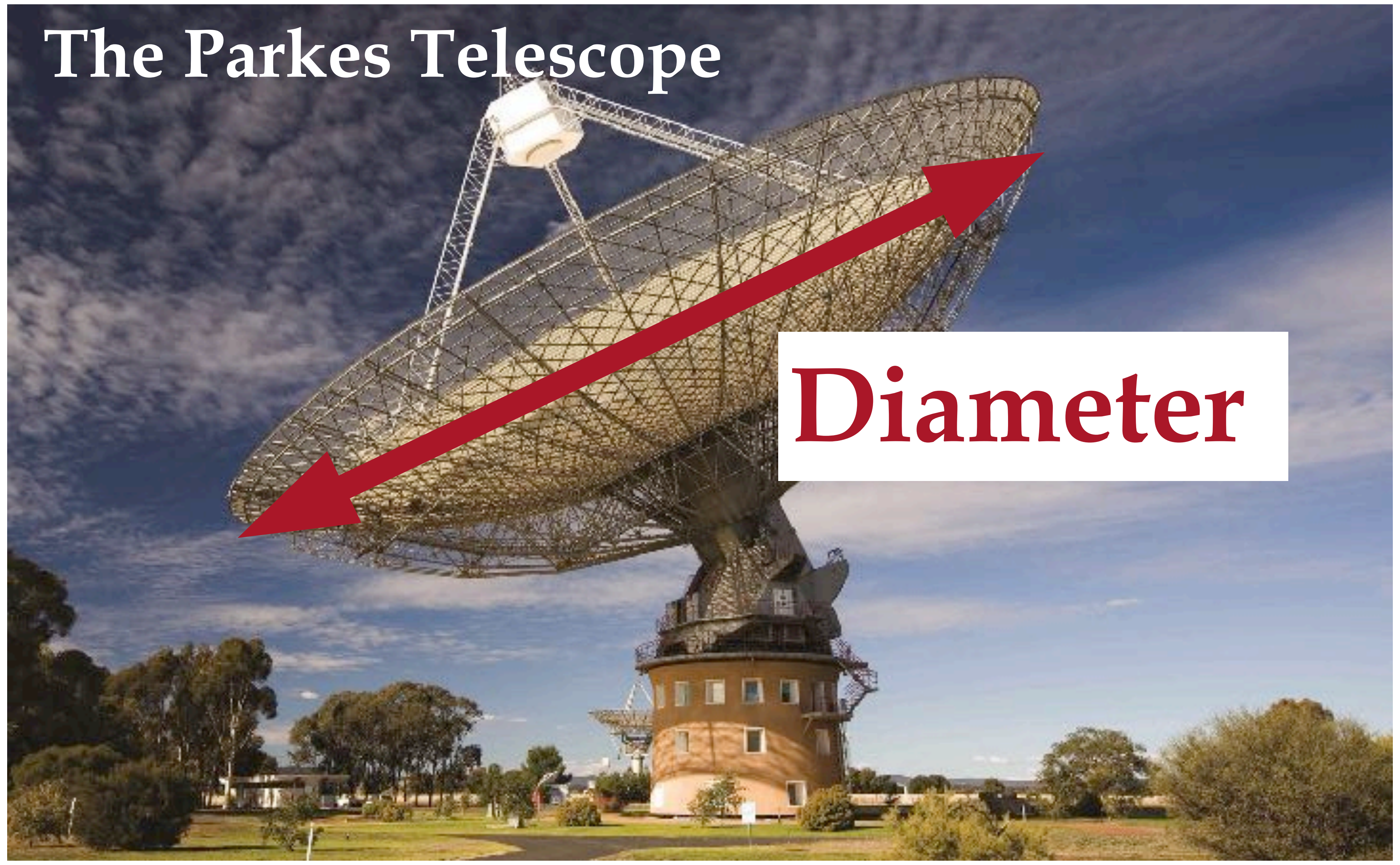
The **resolution of a telescope depends on its size and the wavelength** of light that is getting observed.

- 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:

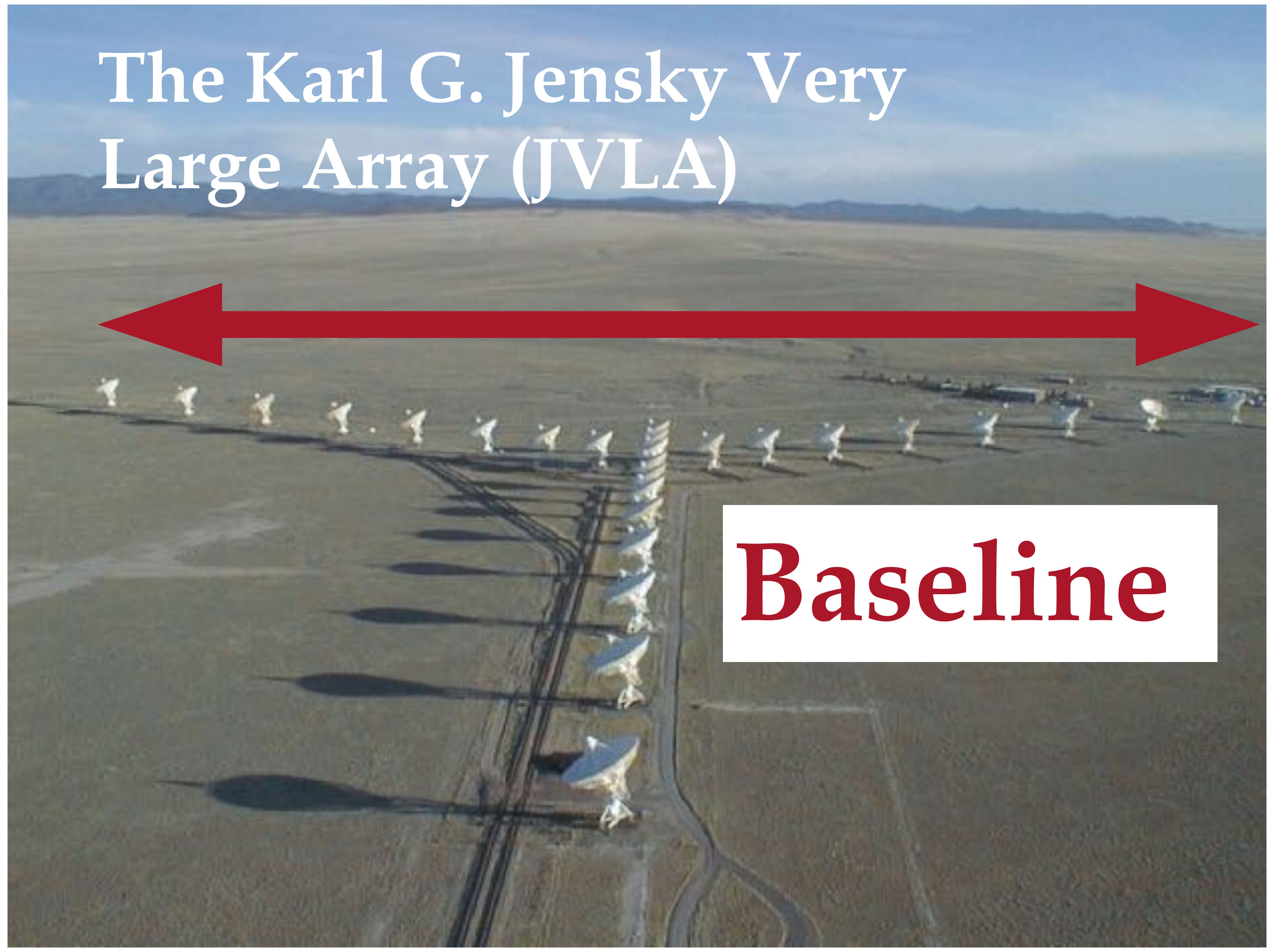
Resolution: ~ Diameter



www.csiro.au

Interferometers:

Resolution: ~ distance between telescopes



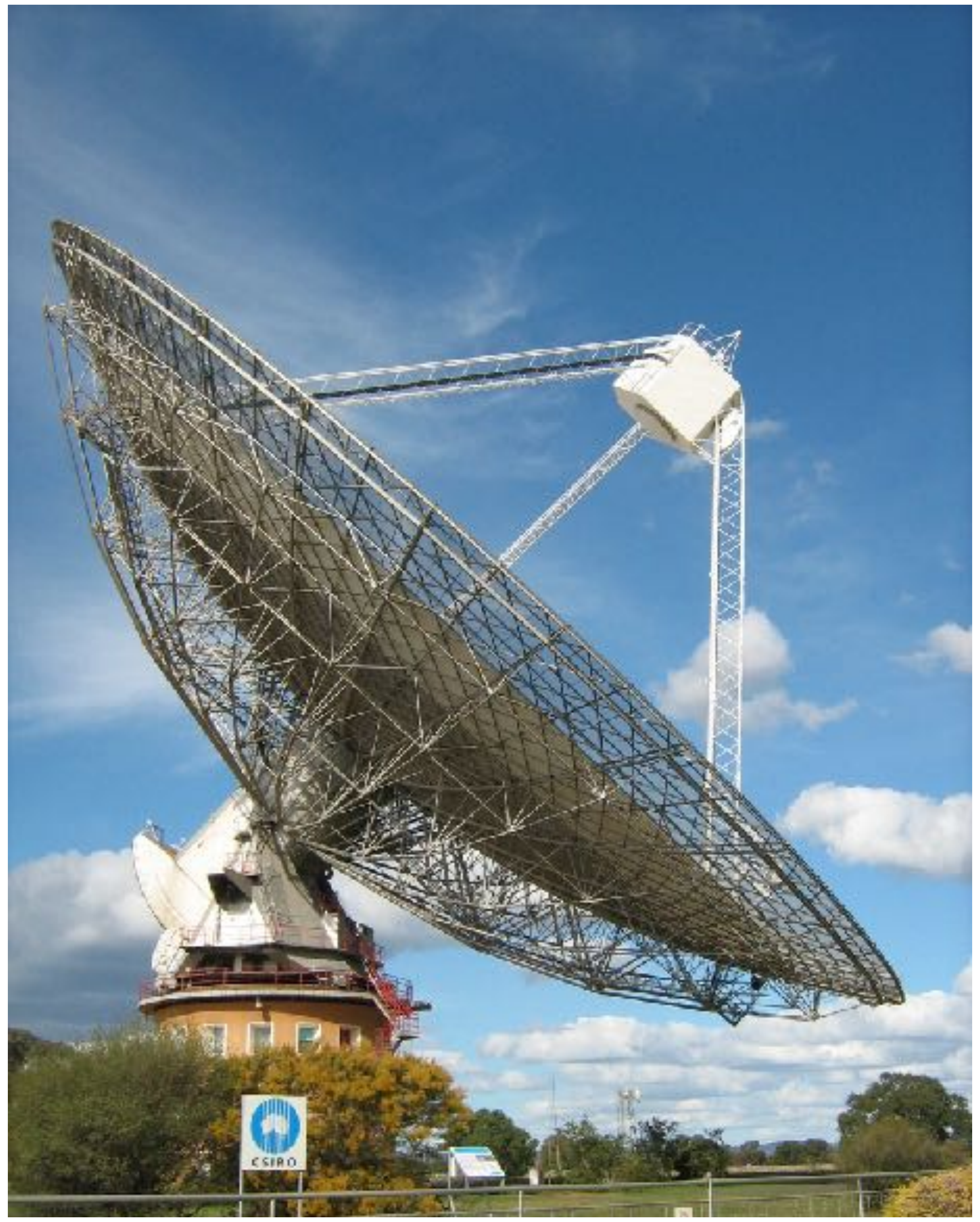
http://images.nrao.edu

Telescopes - single dishes

Dish shaped telescopes are typically used for cm and mm waves.
Great for detecting faint sources.

Effelsberg (Germany)

Parkes Telescope (Australia)



FAST: The Five Hundred Meter Aperture Telescope (China)

Telescopes - Interferometers

Great for high resolution, but does not work well for faint sources.

Very Large Array (VLA)

The Australia Telescope Compact Array (ATCA)

Telescopes - Interferometers

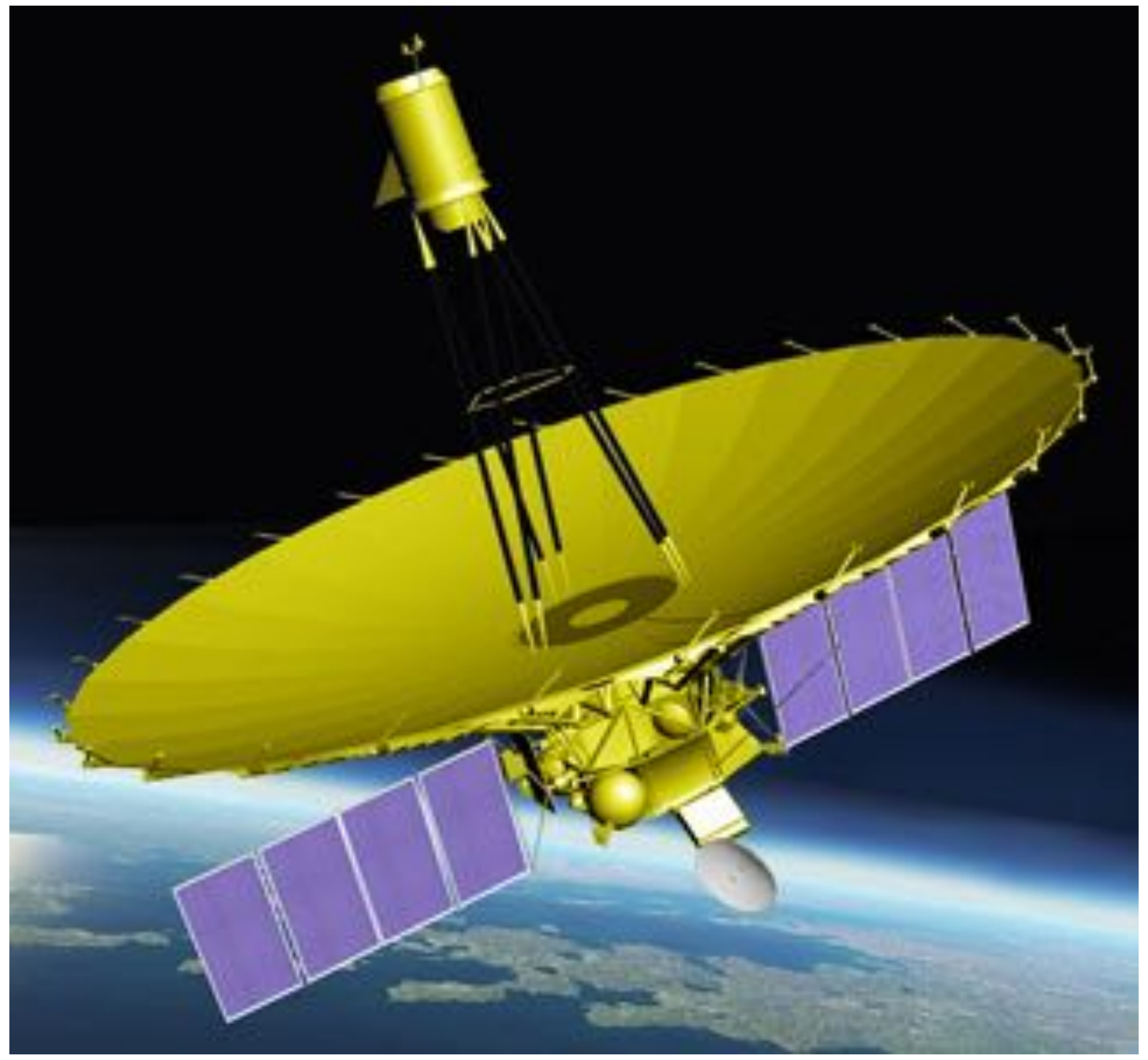
What is the maximum distance between antennas for an interferometer?

Telescopes - Interferometers

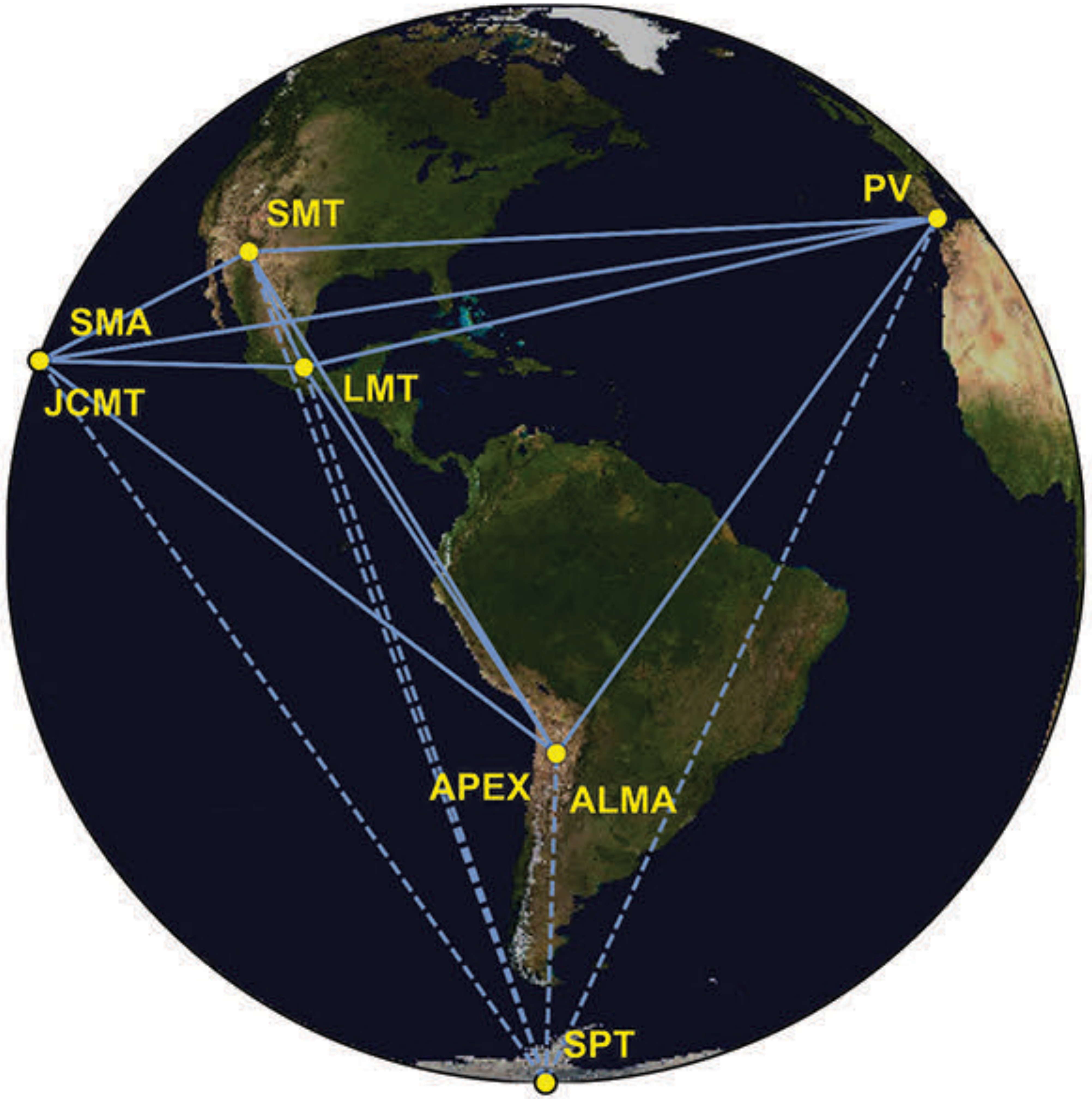
Very Long Baseline Interferometry (VLBI)

- 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

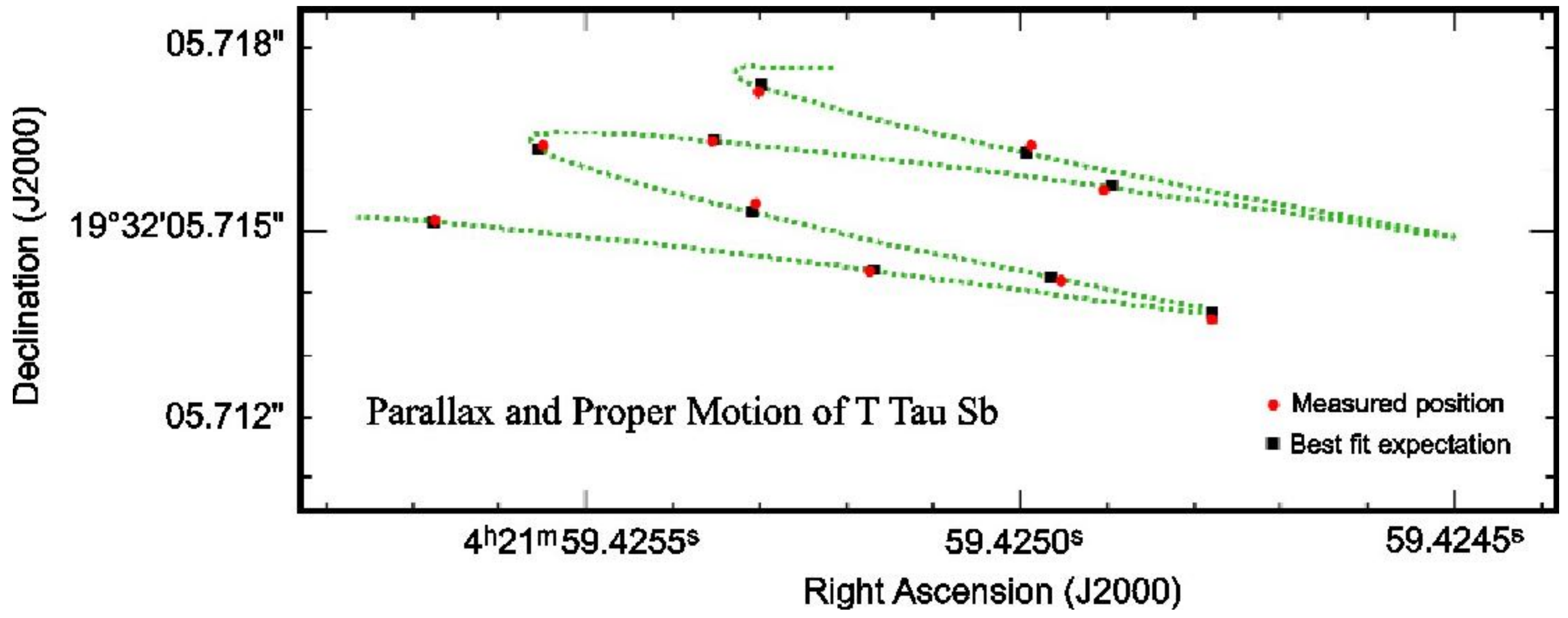


Event Horizon Telescope



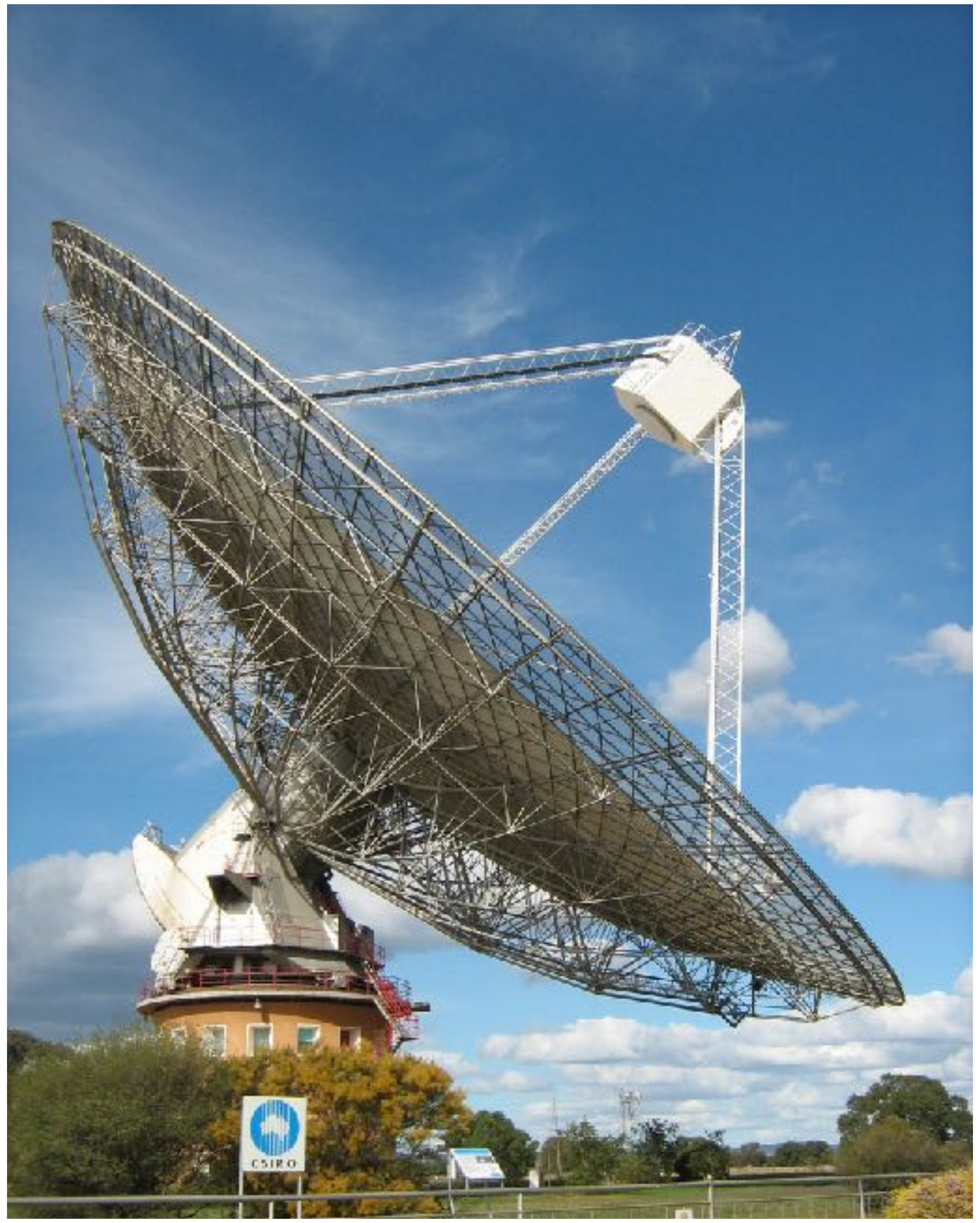
Radio astronomy

The **finest angular resolution** for imaging faint and complex sources is **obtainable at the long-wavelength (radio)** end of the electromagnetic spectrum. Interferometers also yield **extremely accurate astrometry** because interferometric positions depend on measuring time delays which can be done extremely accurately.



Multiepoch VLBA position measurements of T Tau Sb, young stellar object, allowed to determine its **parallax distance** with unprecedented accuracy: d=146.7±0.6 pc, and even to **detect accelerated proper motion.**

The best of both



Single-dish for short spacing
-> large angular scales

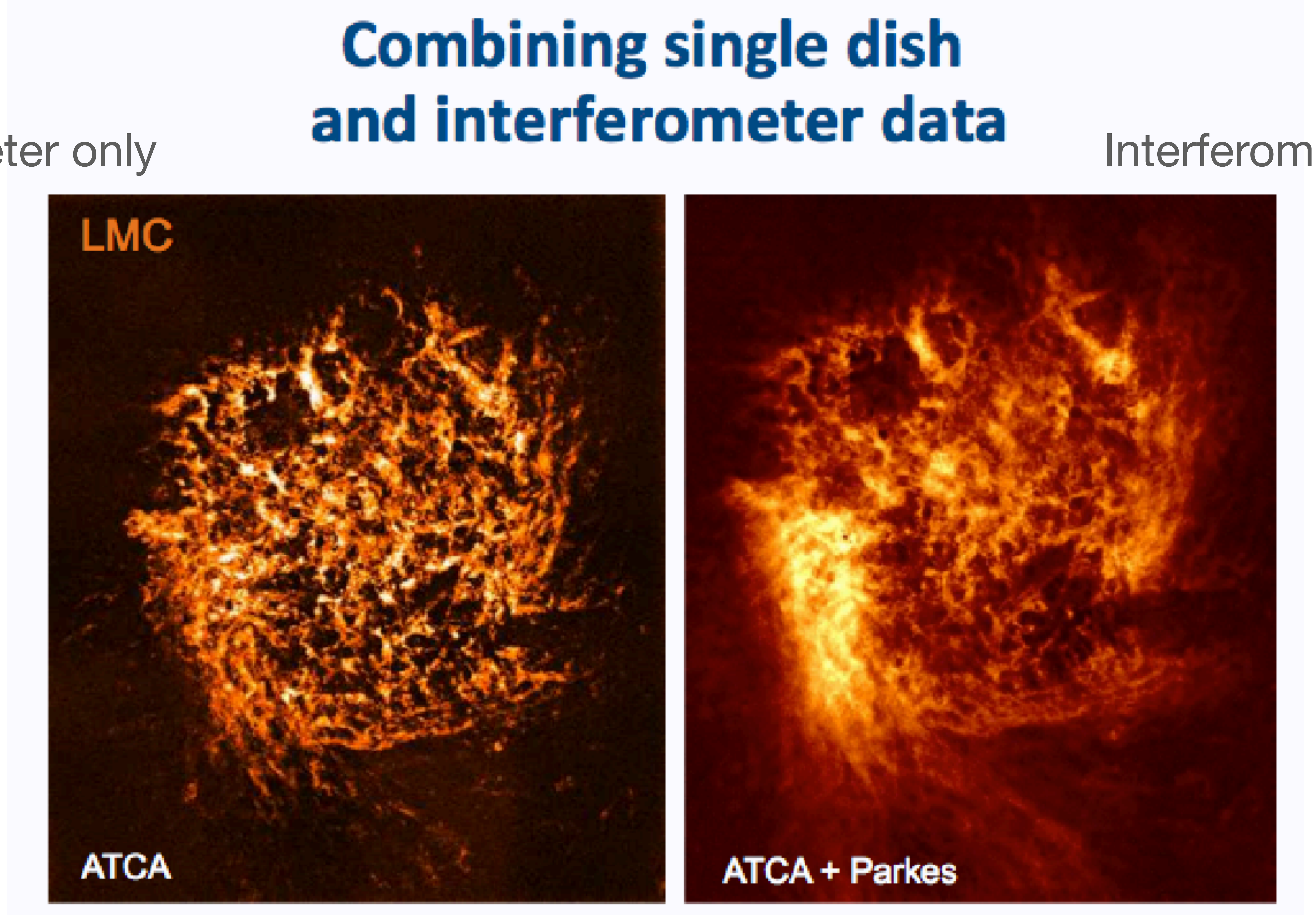
+

Interferometer for longer spacing
-> small angular scales

The best of both

Interferometer only

Interferometer + single dish



HI mosaic (1344 pointings) of the Large Magellanic Cloud by Kim et al. (1998, 2003).

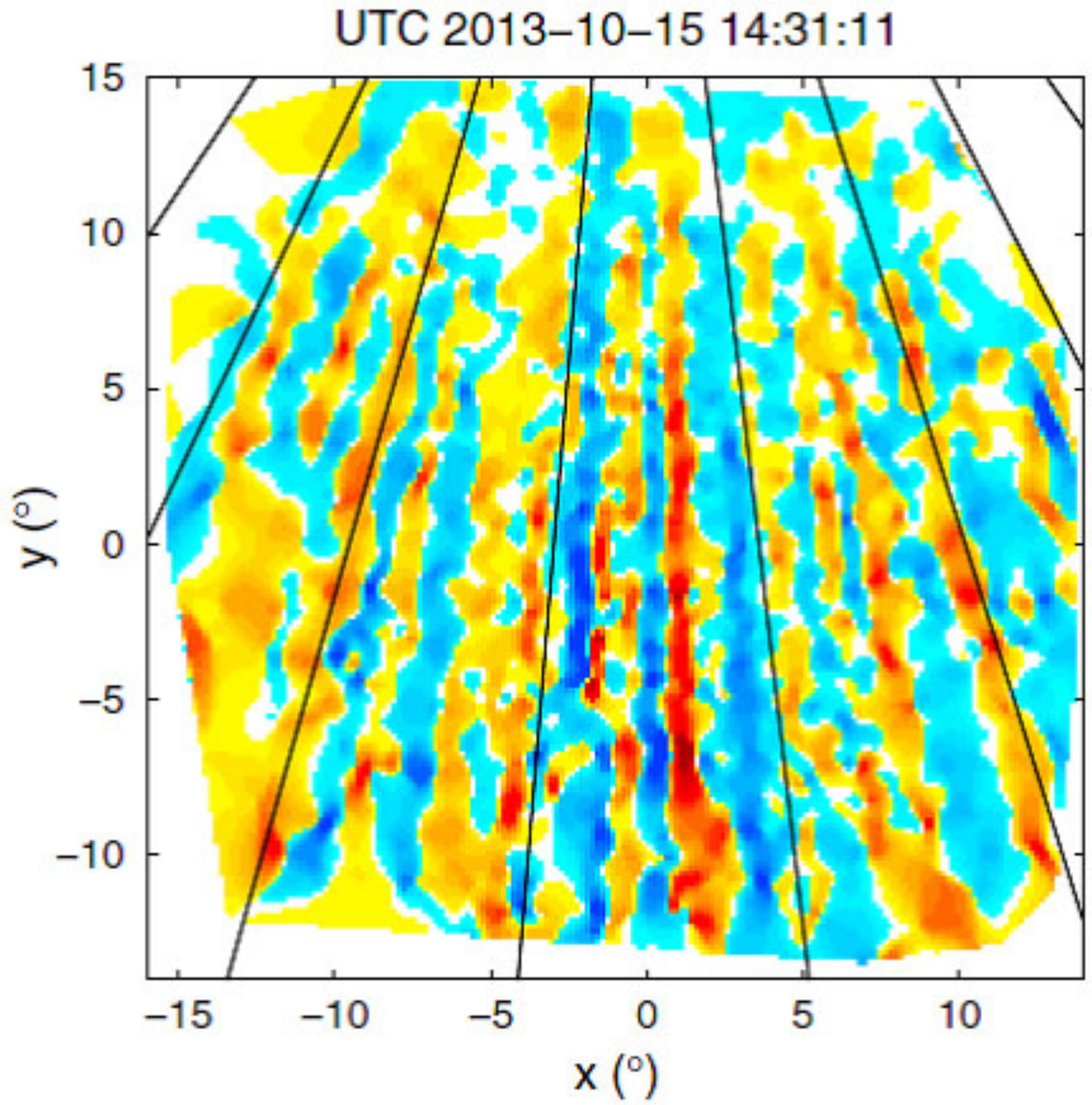
Telescopes - Interferometers

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.

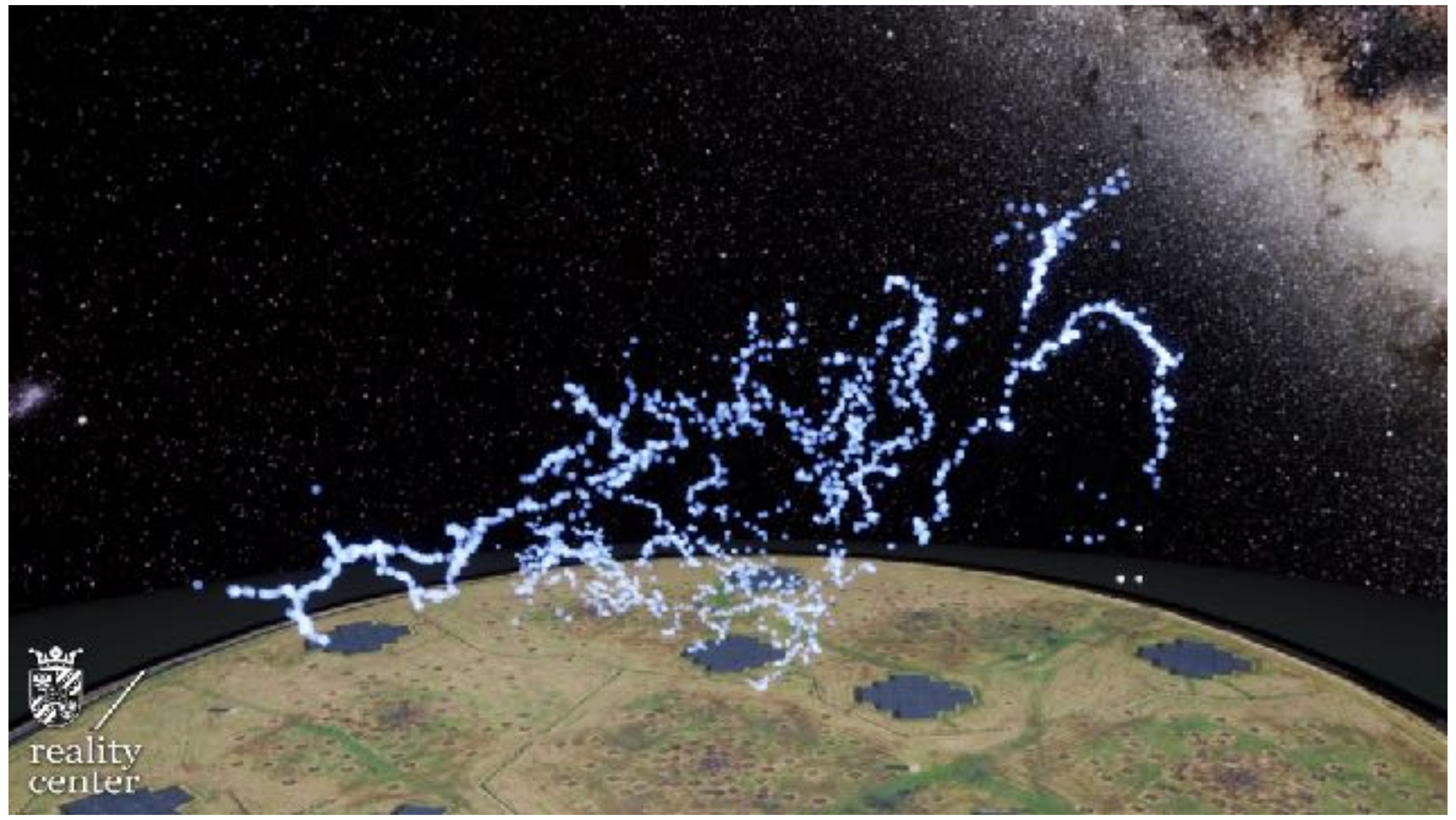
The Murchison Widefield Array (MWA)



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

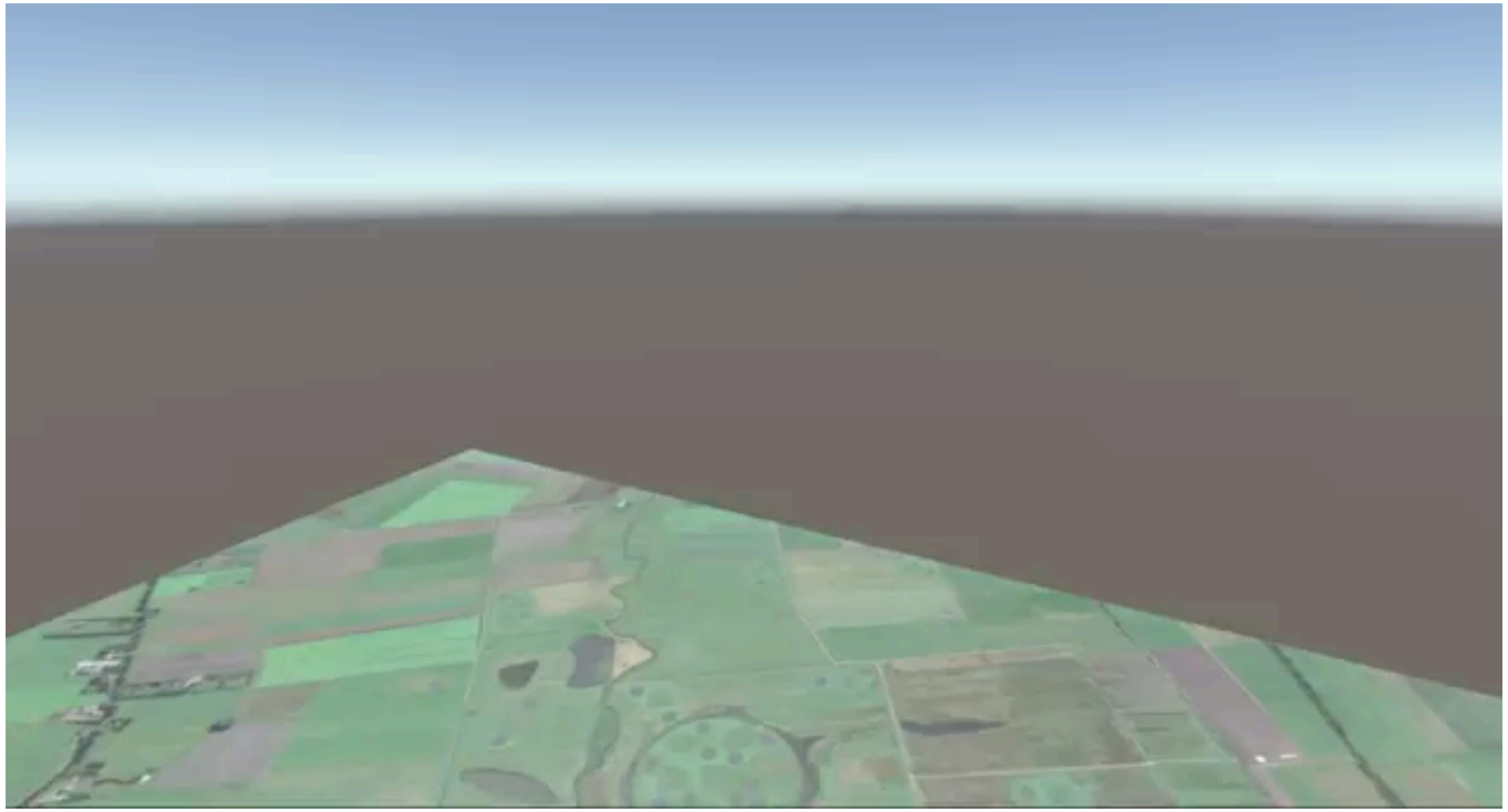
Telescopes - Interferometers

Metal sticks or wires are used for m waves.



LOFAR (Low Frequency ARray)

Imaging **the path of lightning.**



https://www.youtube.com/watch?v=UcKQSG_3MUk

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?

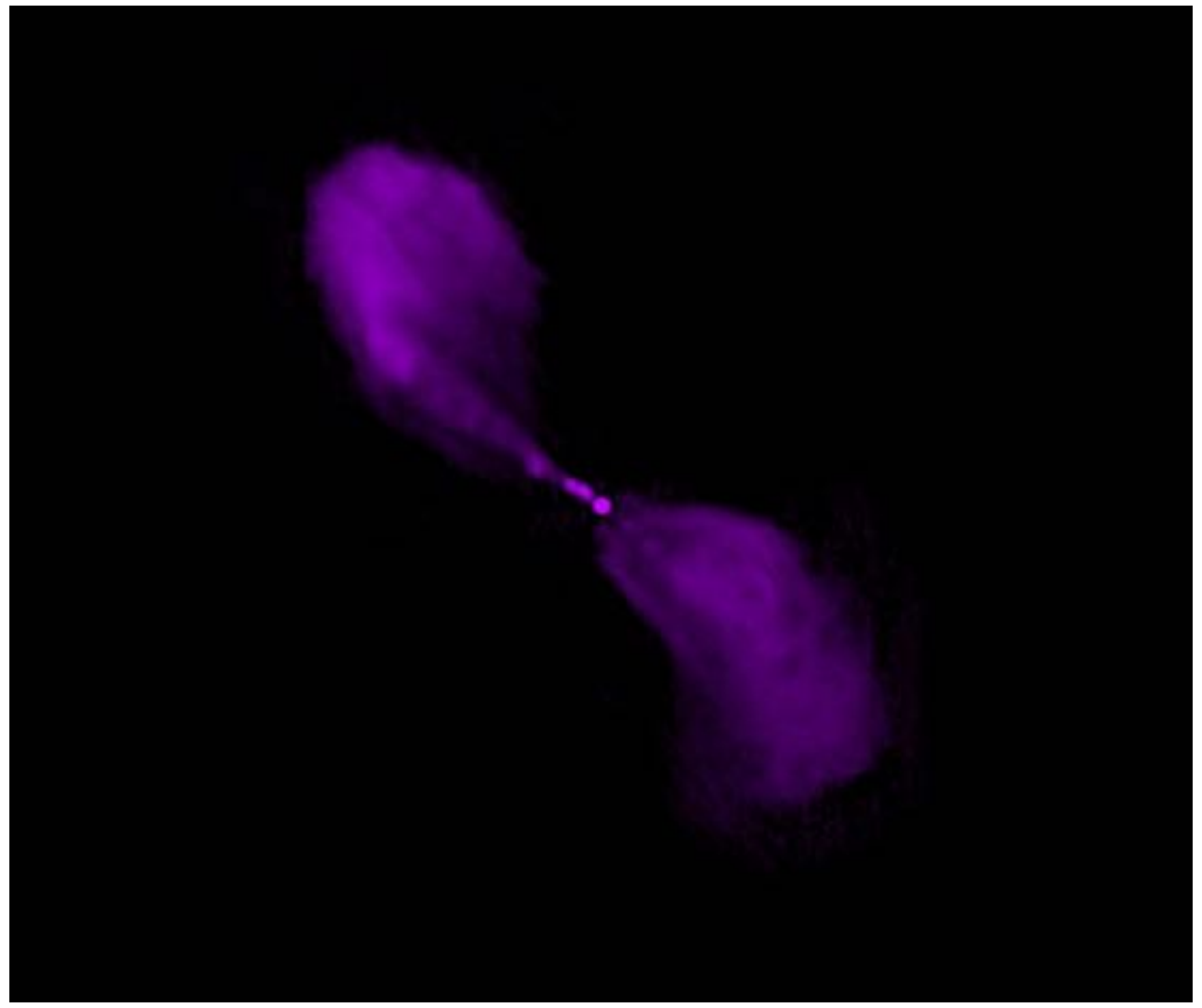
Note: you need to convert radians to arcseconds

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

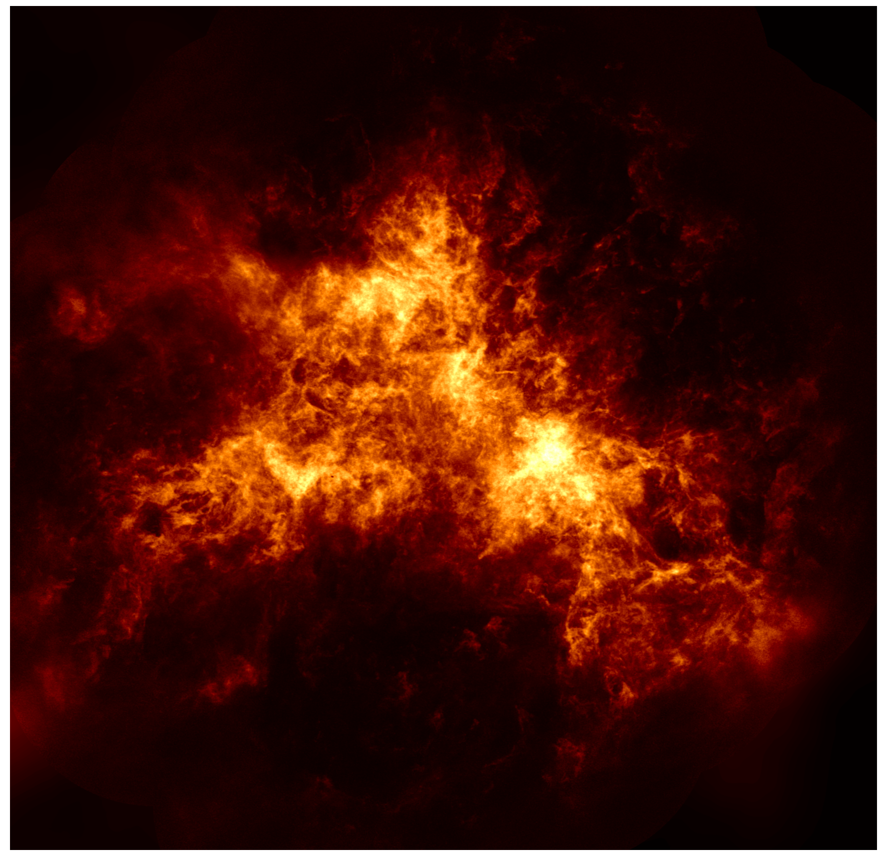
$$\theta = 1.22\frac{\lambda}{D}$$

Telescopes - Interferometers

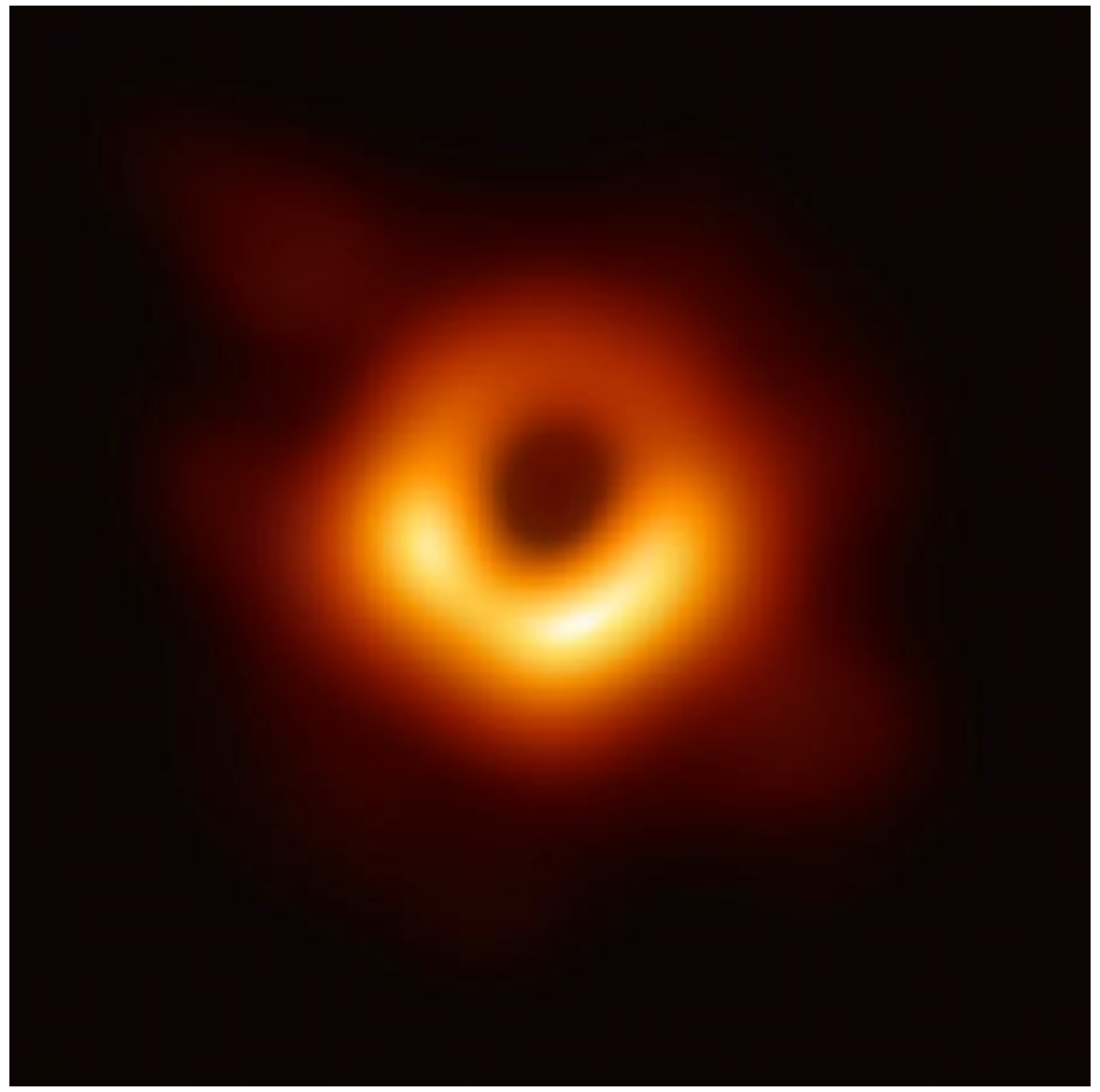
AGN



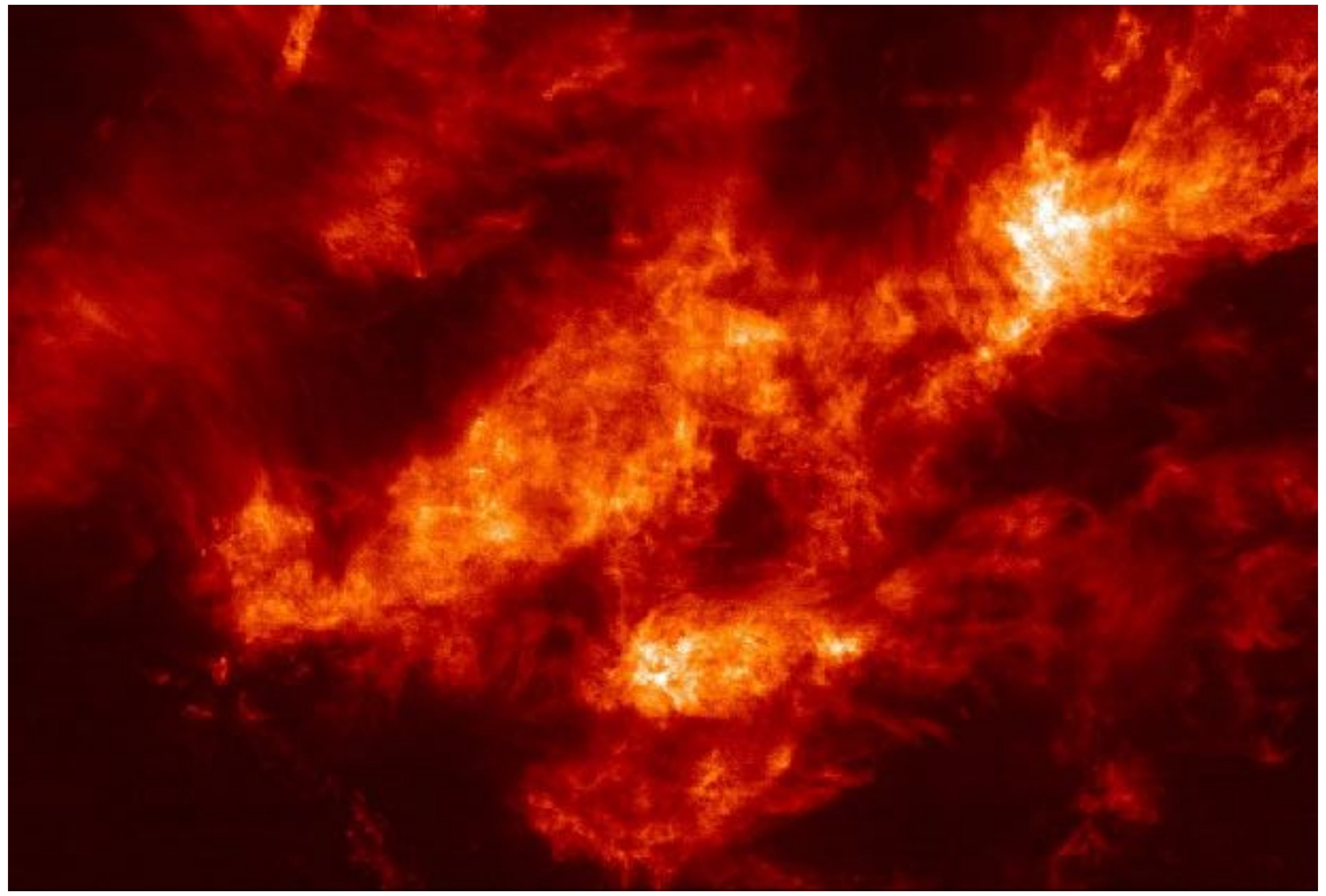
HI in galaxies (SMC)



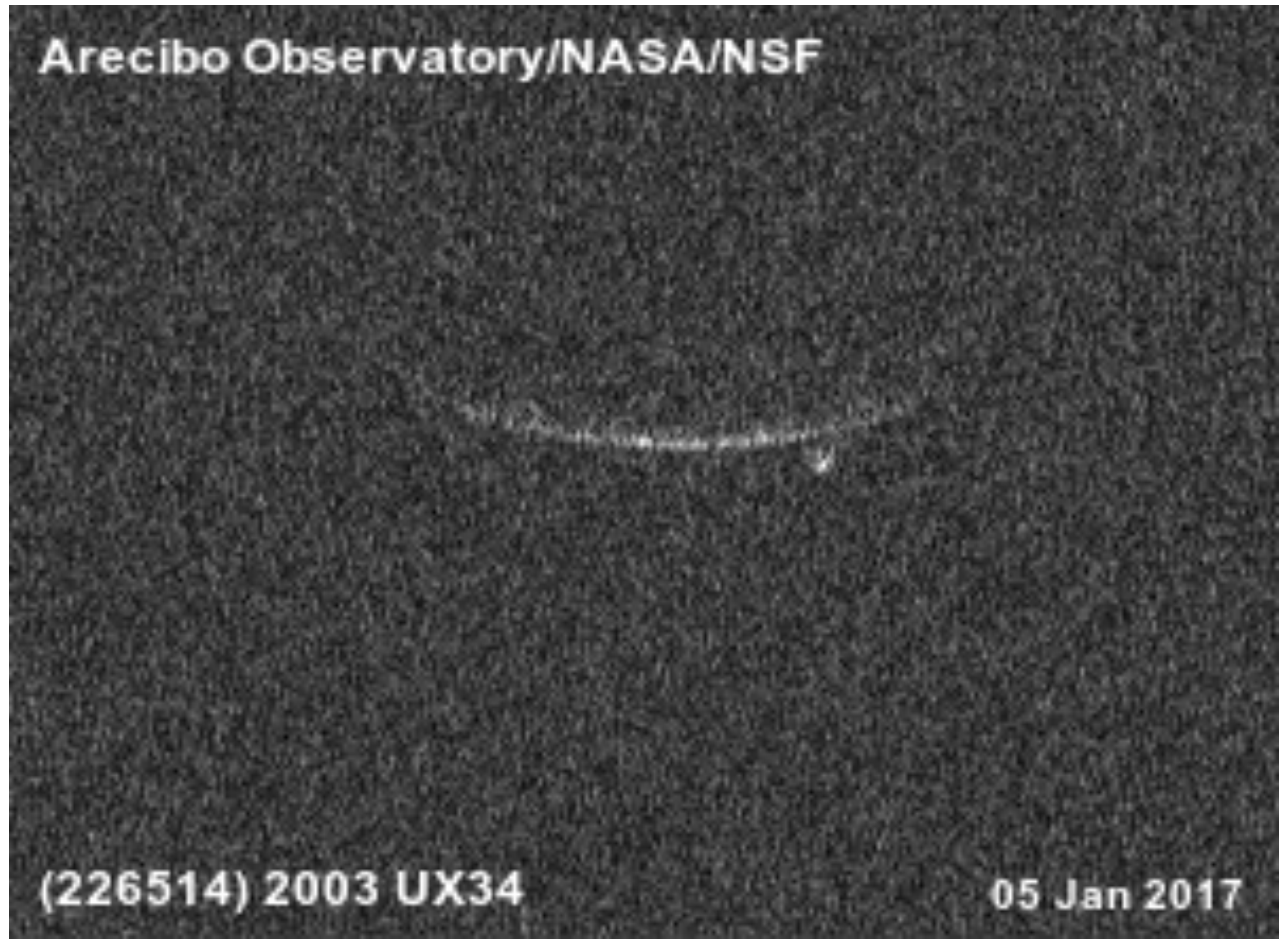
Accretion disk of a black hole



CO gas in the Taurus molecular cloud

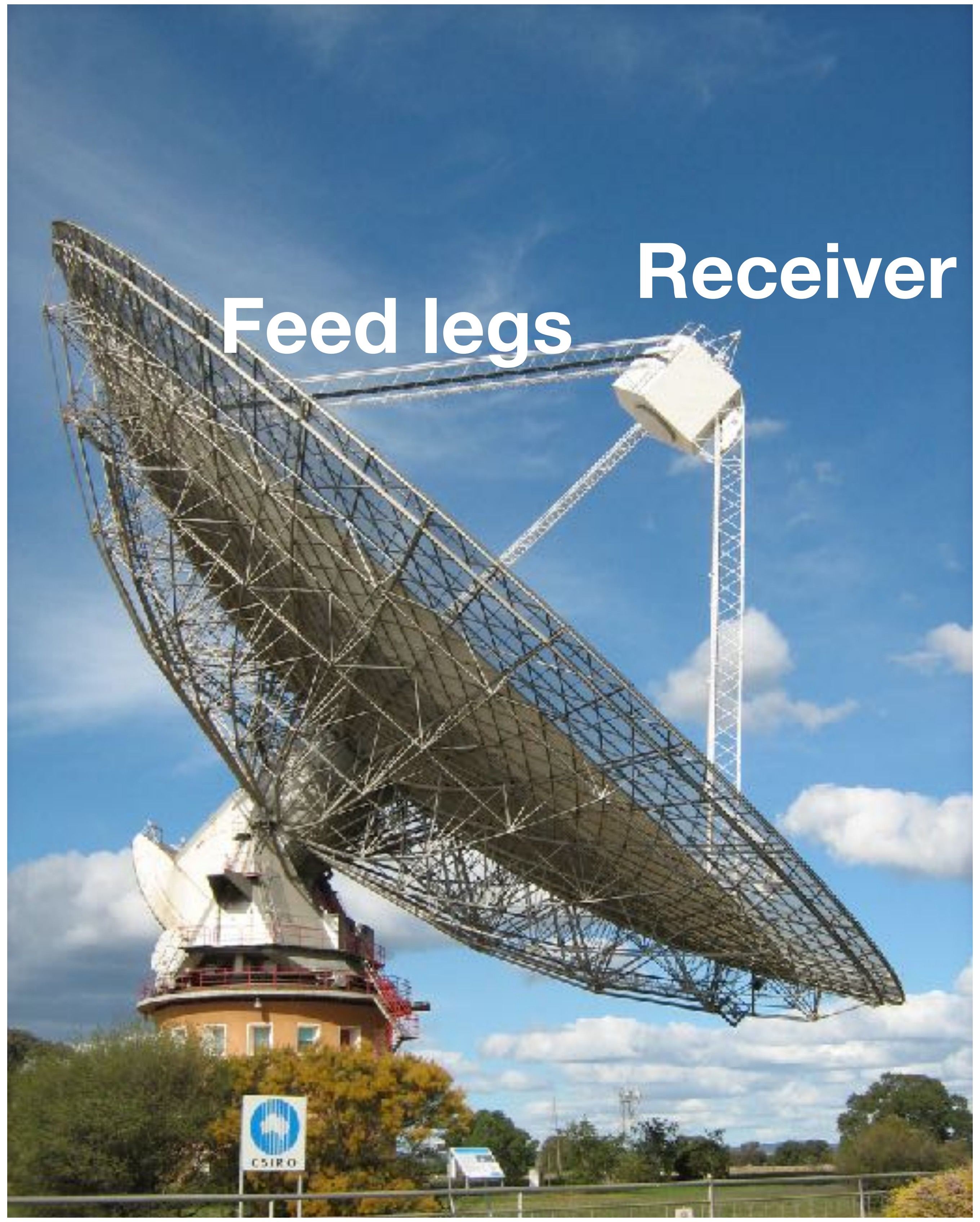


Double asteroid



Radio telescopes

Most radio telescopes use circular paraboloidal reflectors to obtain large collecting areas and high angular resolution over a wide frequency range.

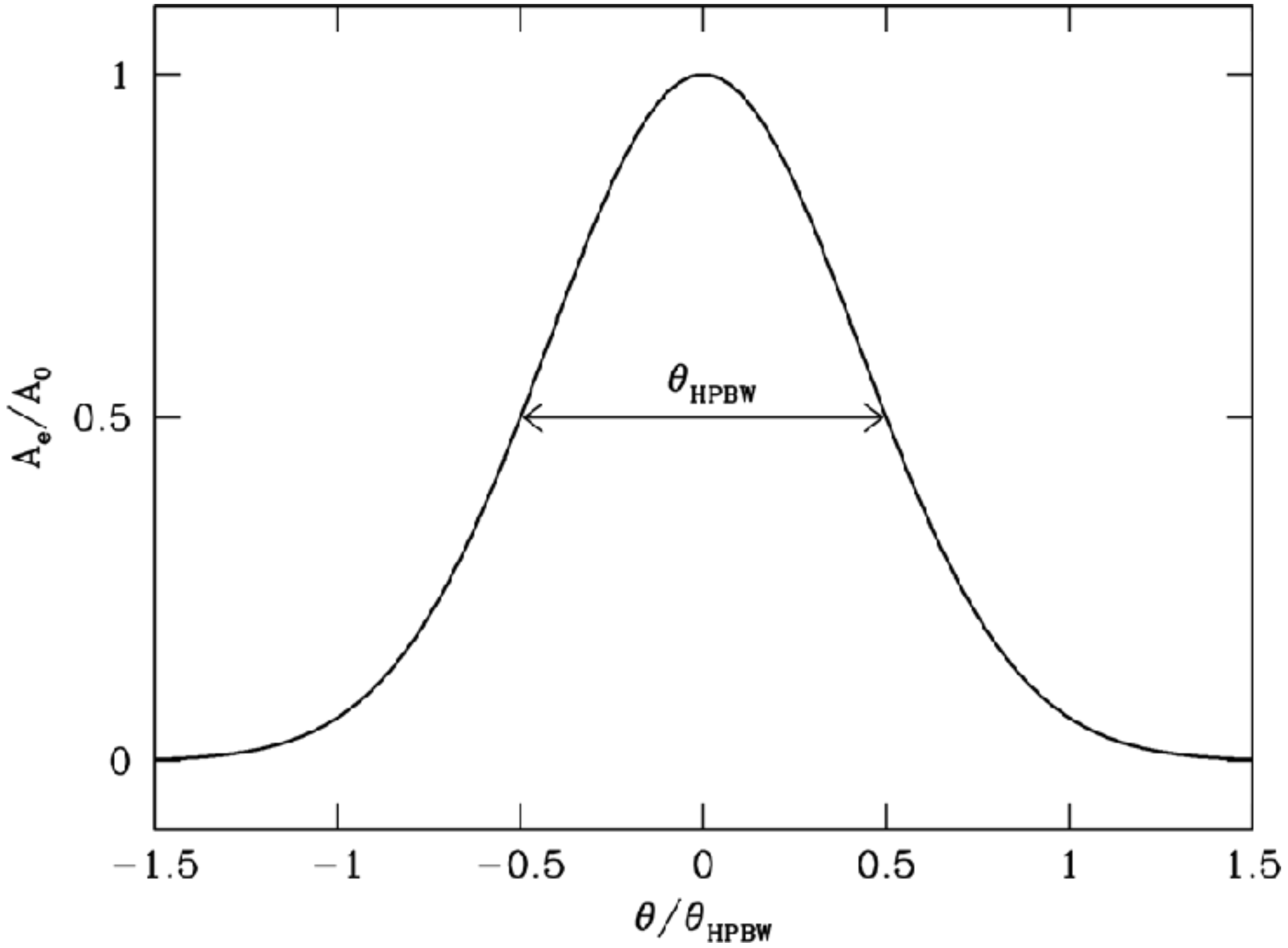


Gaussian Beam Solid Angle and Beamwidth

Most apertures associated with reflectors and lenses are circular. The power pattern of a uniformly illuminated circular aperture is known as the **Airy pattern**.

Figure 3.15: The beams of most radio telescopes are nearly Gaussian, and their beamwidths are usually specified by the angle Θ_{HPBW} between the half-power points.

Abscissa: offset θ from the beam center in units of the HPBW. Ordinate: Effective aperture A_e normalized by the peak effective aperture A_0



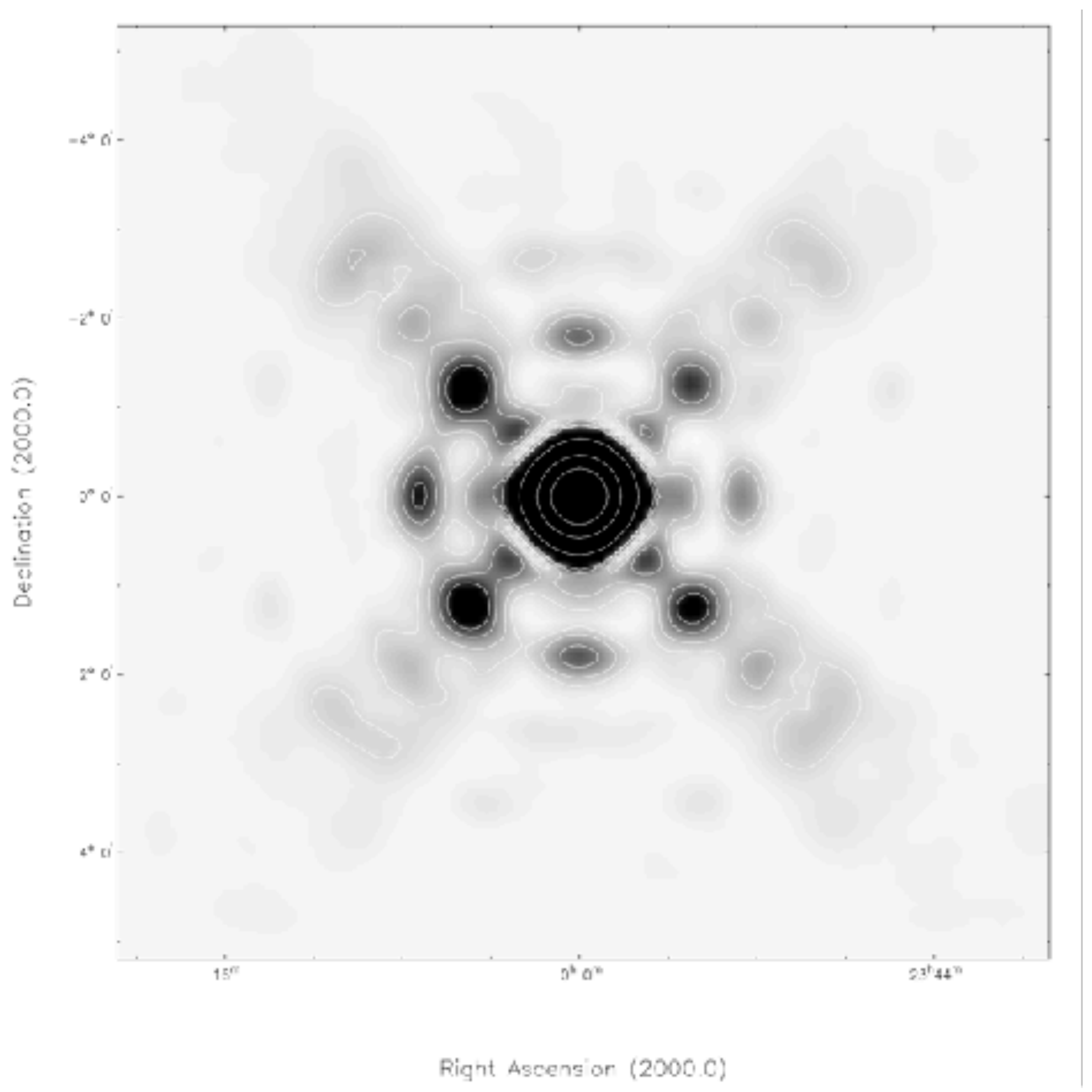
the beam solid angle of a Gaussian beam is:

$$\Omega_A = \left(\frac{\pi}{4\ln 2}\right)\theta_{\mathrm{HPBW}}^2 \approx 1.133\,\theta_{\mathrm{HPBW}}^2$$

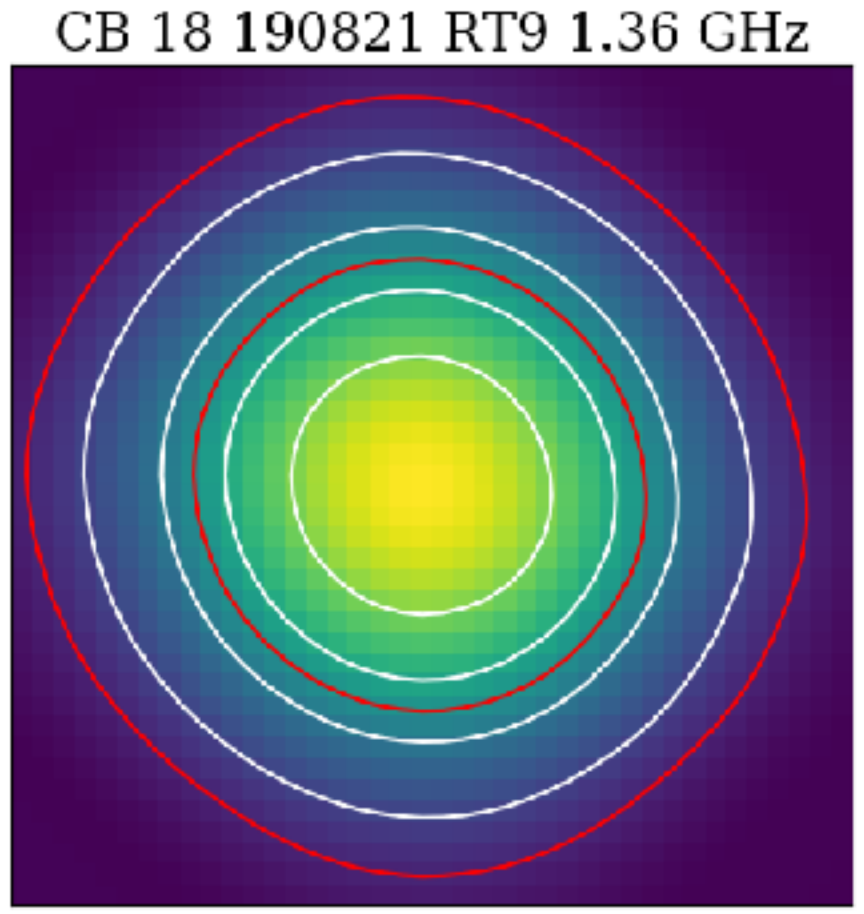
Gaussian Beam

- The primary beam response is important for
  - Correct deconvolution of the images
  - **Correct flux scale**
  - Mosaicking

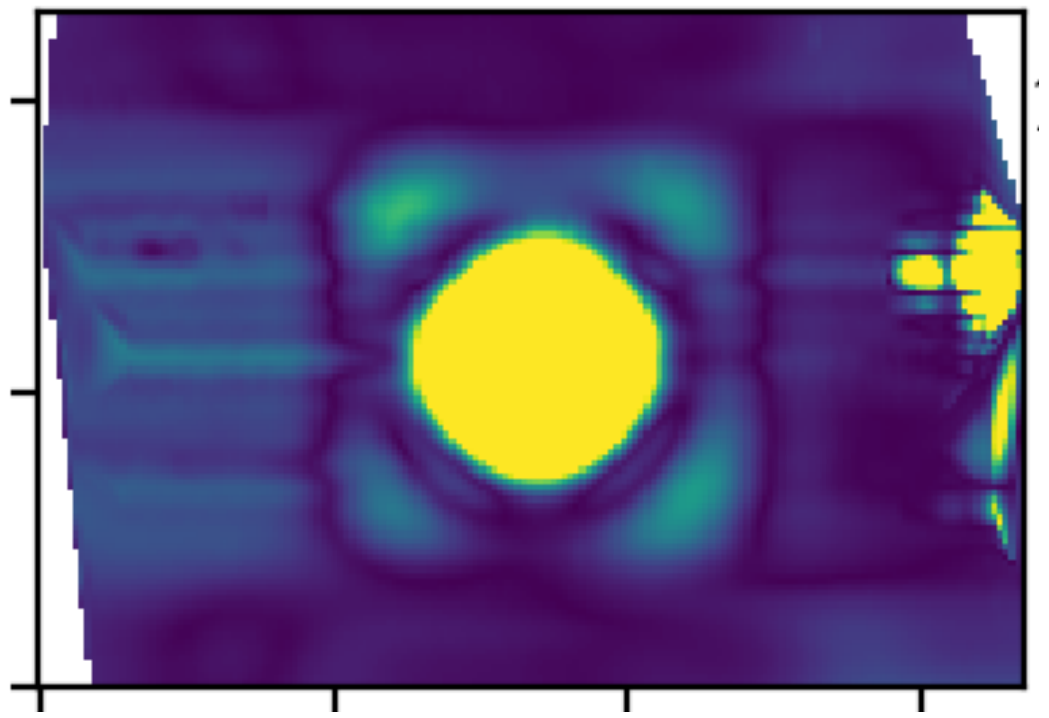
WSRT beam shape from Popping et al. 2008



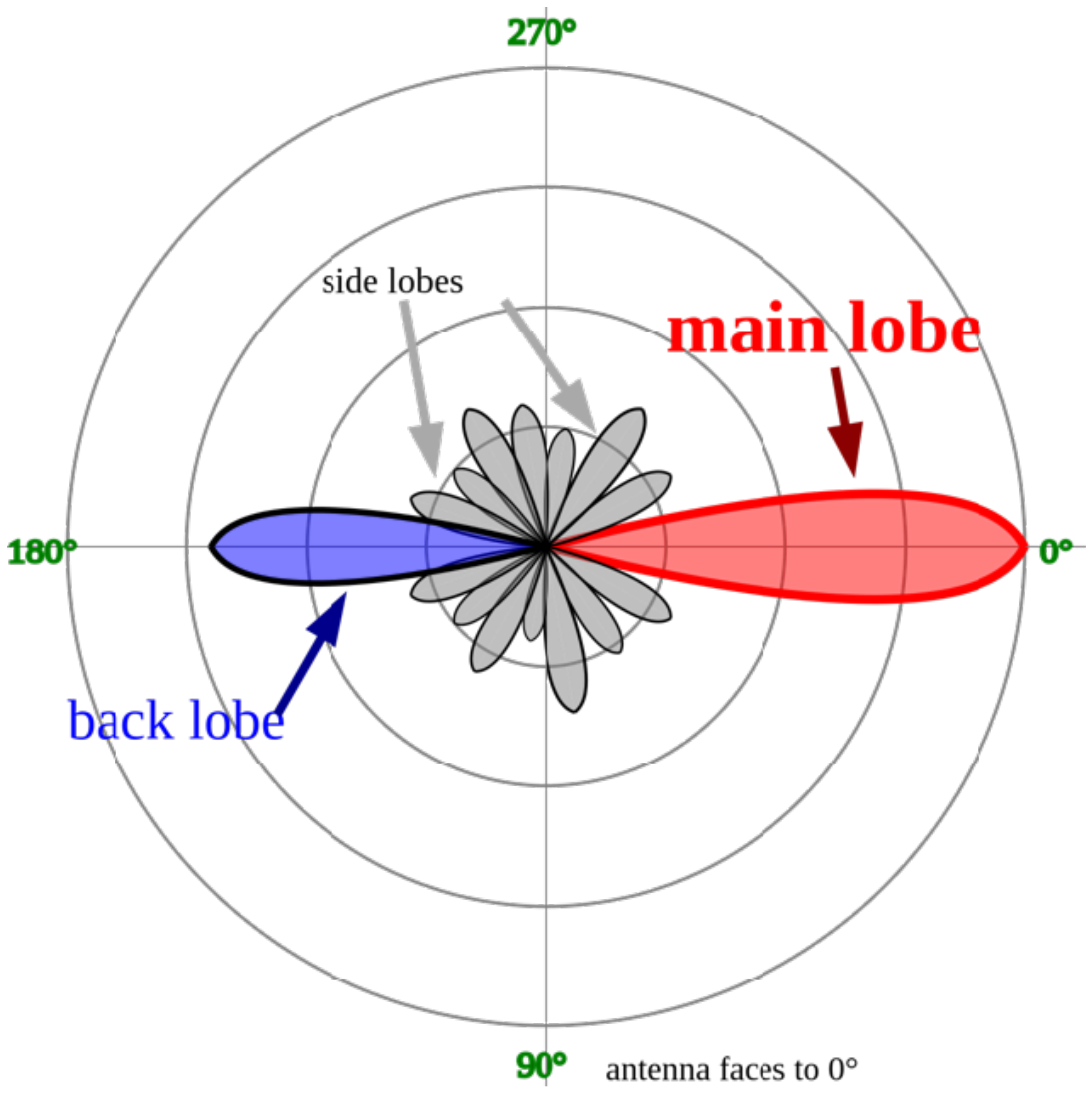
Primary beam pattern



Faint side lobes



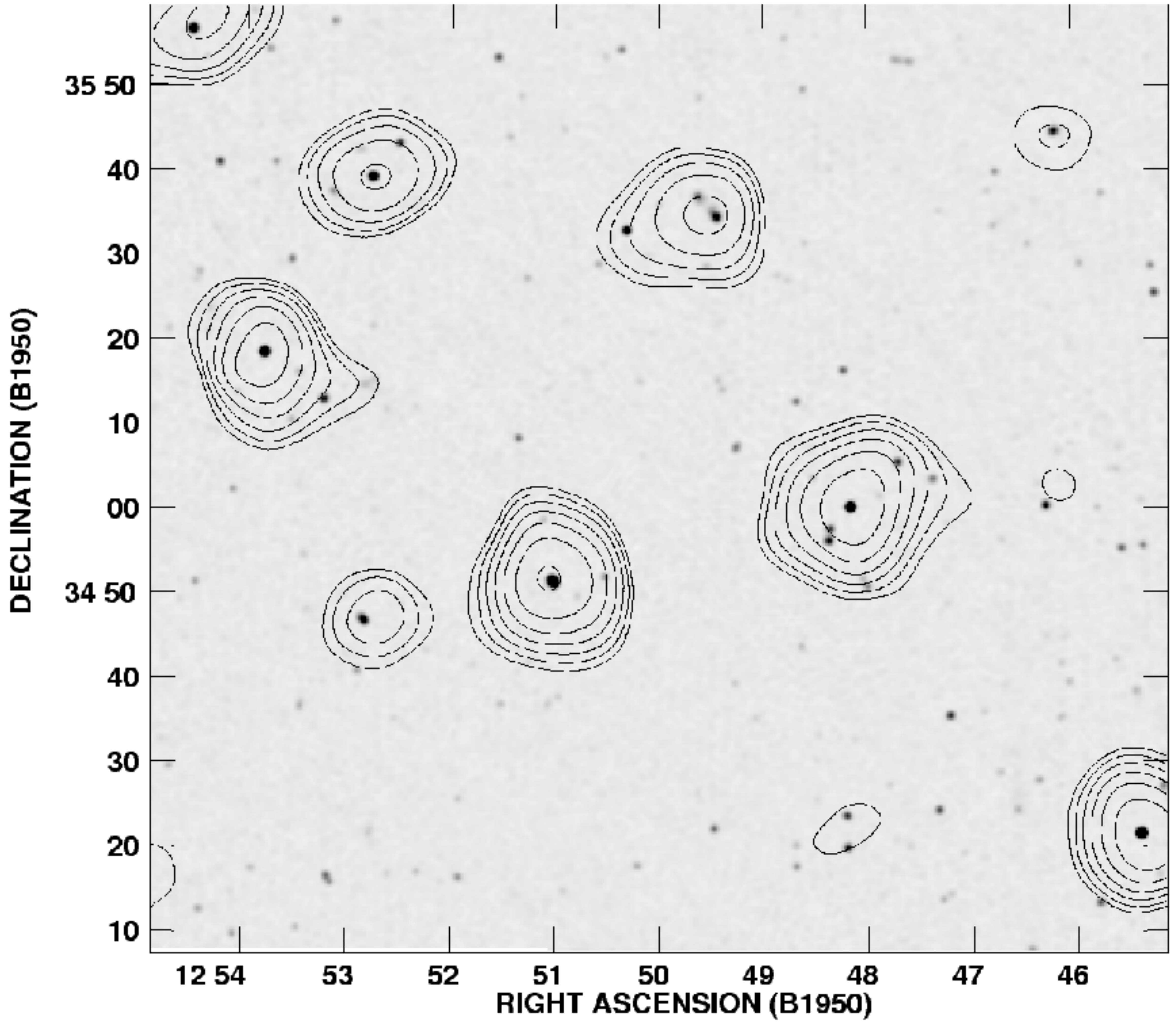
Antenna radiation pattern



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

Confusion

Contours: 300-foot telescope, image: VLA 1.4 GHz image at a substantially better resolution.

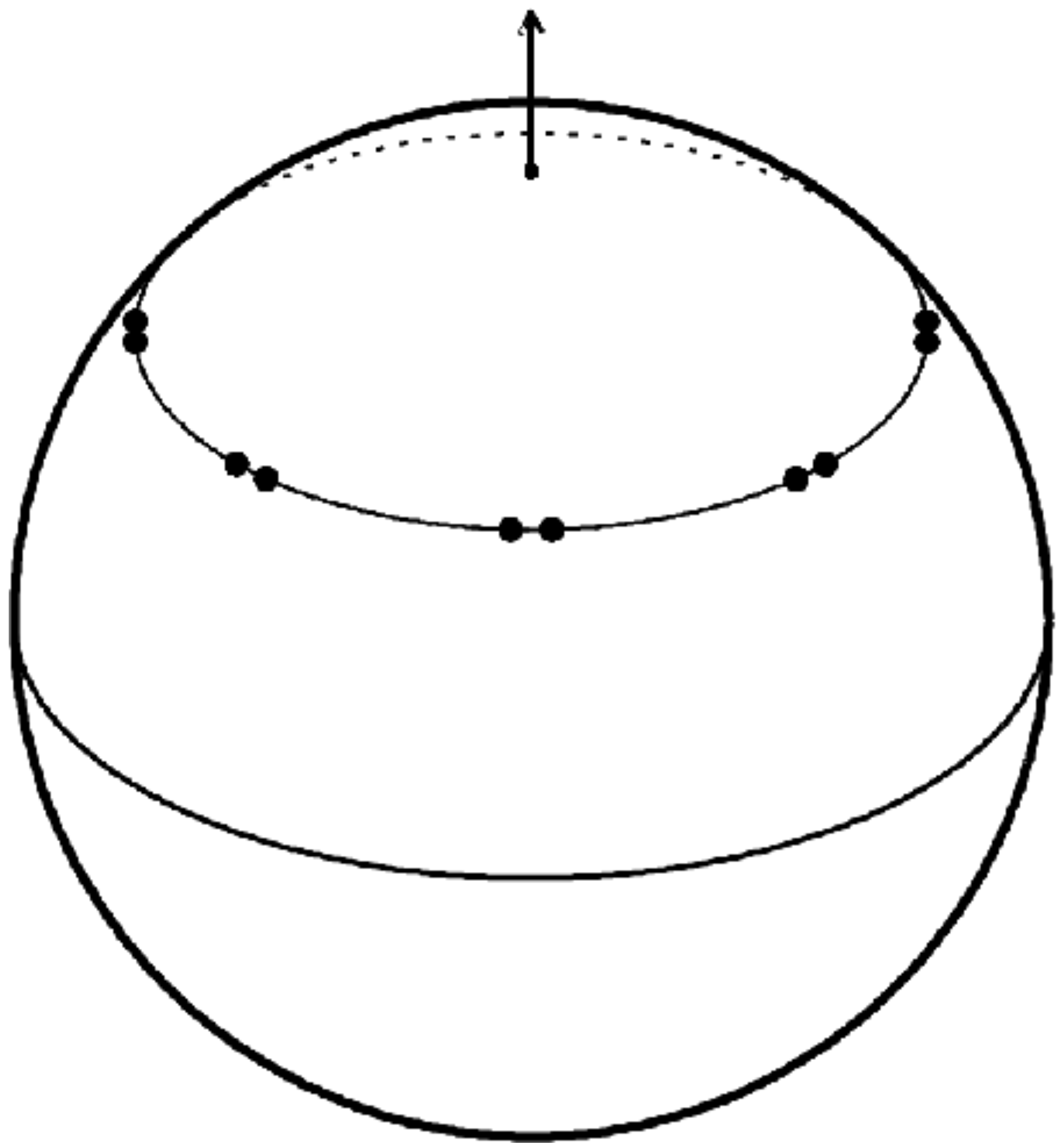


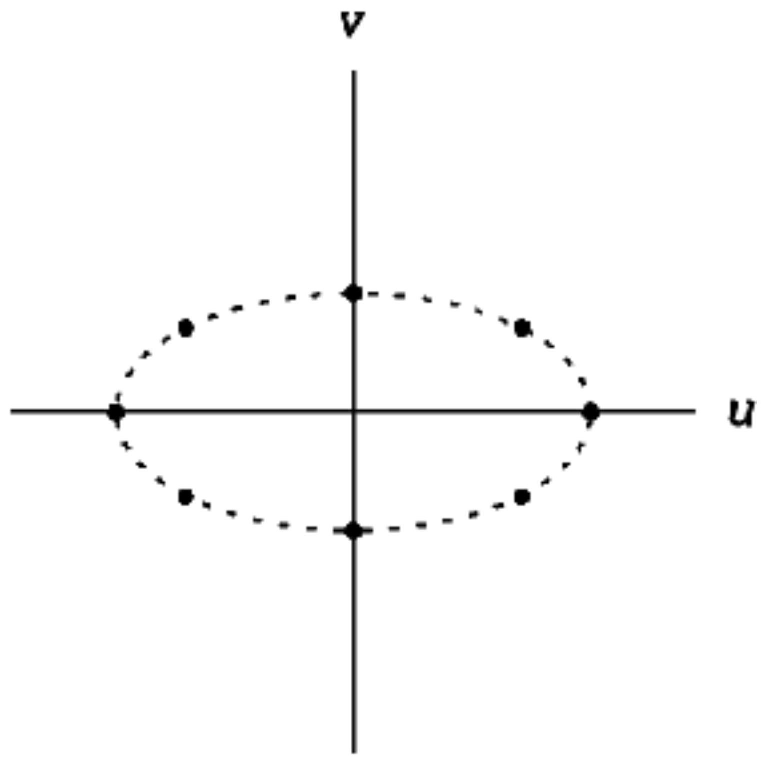
Resolution is important!

- Single-dish telescopes: large collecting areas and broad beams at long wavelengths.
- Nearly all discrete continuum sources are extragalactic and extremely distant, so they are distributed randomly and isotropically on the sky.
- The **sky-brightness fluctuations caused by numerous faint sources** in every telescope beam are called **confusion**, this limits the sensitivity of single-dish continuum observations at frequencies below ν~10 GHz.

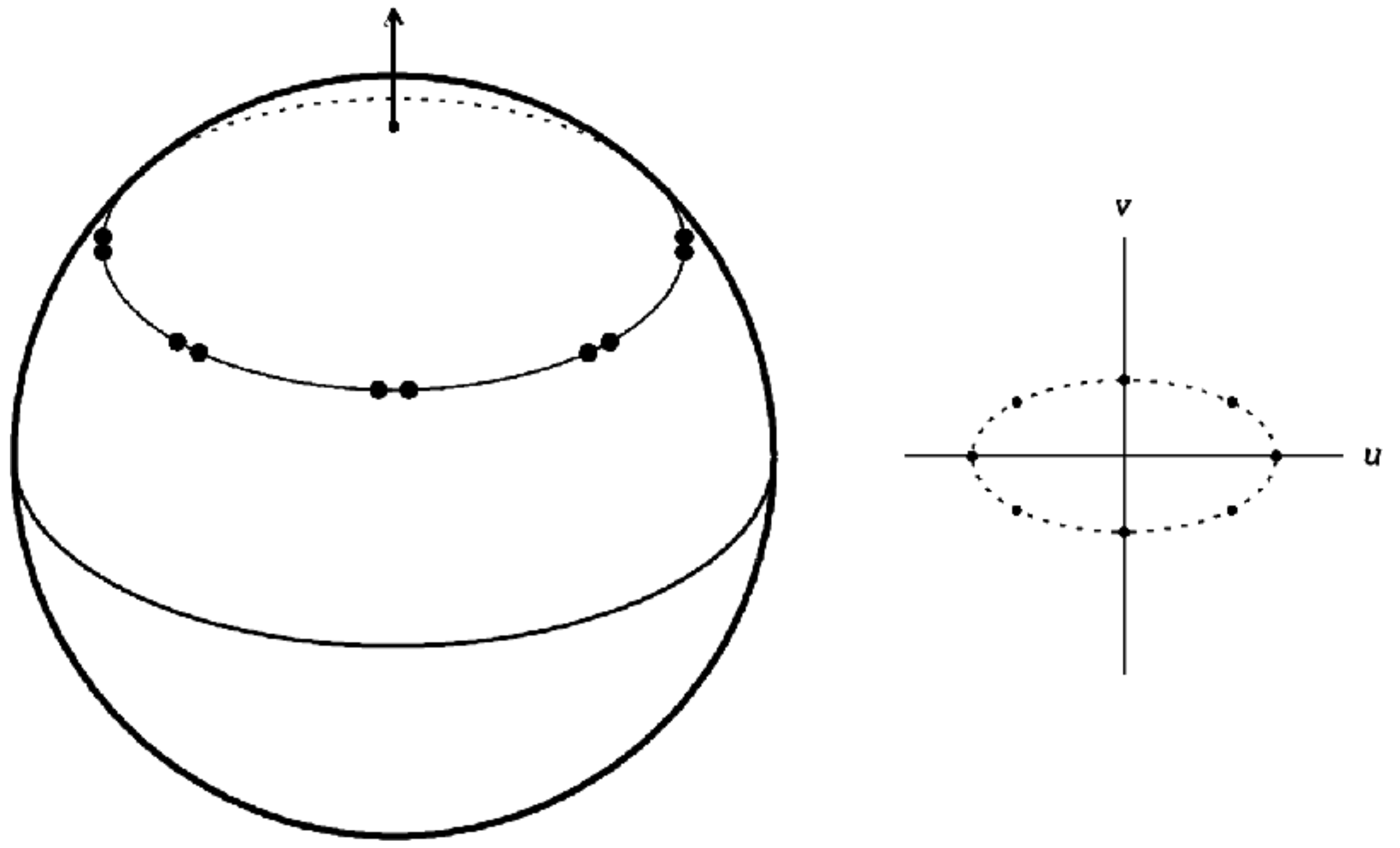
Earth rotation aperture synthesis

- **The Earth's rotation varies the projected baseline coverage of an interferometer whose elements are fixed on the ground.**
- In particular, all baselines of an interferometer whose baselines are confined to an east–west line will remain in a single plane perpendicular to the Earth's north–south rotation axis as the Earth turns daily.
- Confining all baselines to two dimensions has the computational advantage that the **brightness distribution of a source is simply the two-dimensional Fourier transform of the measured visibilities.**
- The Figure illustrates Earth-rotation aperture synthesis by an east–west two-element interferometer at latitude +40° as viewed from a source at declination δ=+30°.



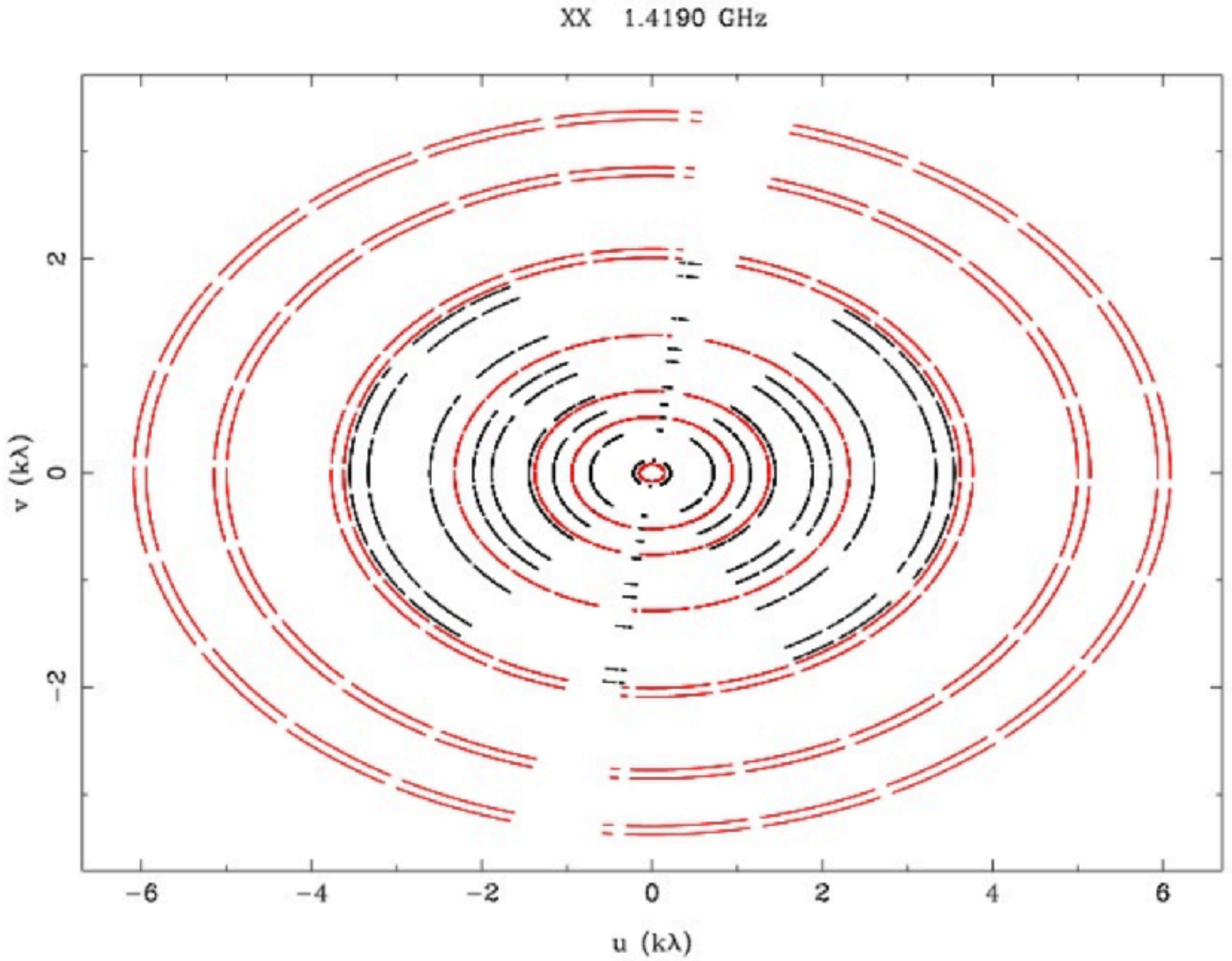


Earth rotation aperture synthesis



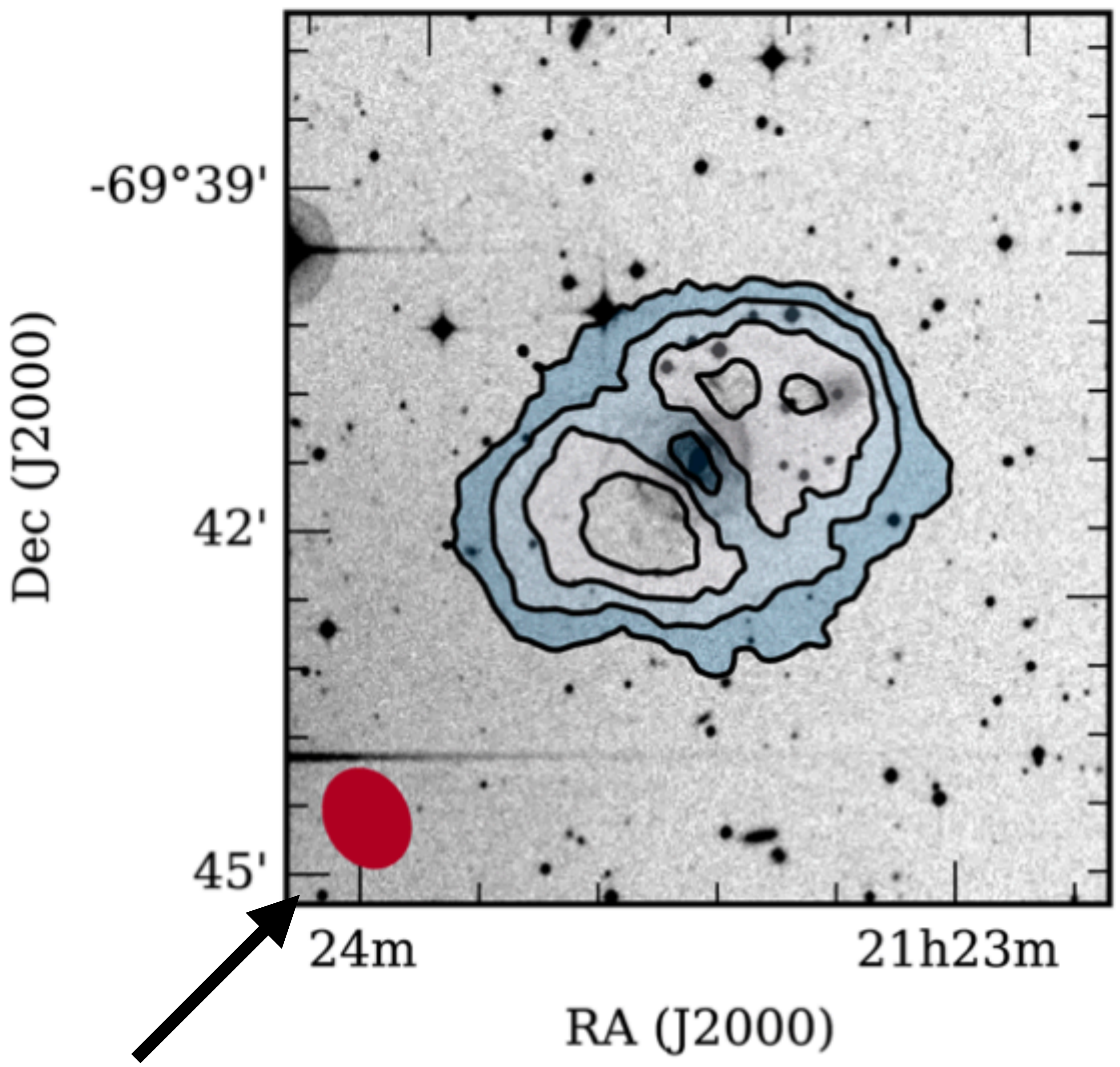
- Let **u** be **the east–west component of the projected baseline in wavelengths** and **v be the north–south component of the projected baseline** in wavelengths.
- During the 12-hour period centered on source transit, the interferometer traces out a complete ellipse on the (u,v) plane.
- The maximum value of u equals the actual antenna separation in wavelengths, and the maximum value of v is smaller by the projection factor sinδ, where δ is the source declination.
- If the interferometer has more than two elements, or if the spacing of the two elements is changed, **the (u,v) coverage will become a number of concentric ellipses having the same shape.**

Example uv coverage of ATCA observations



Earth rotation aperture synthesis

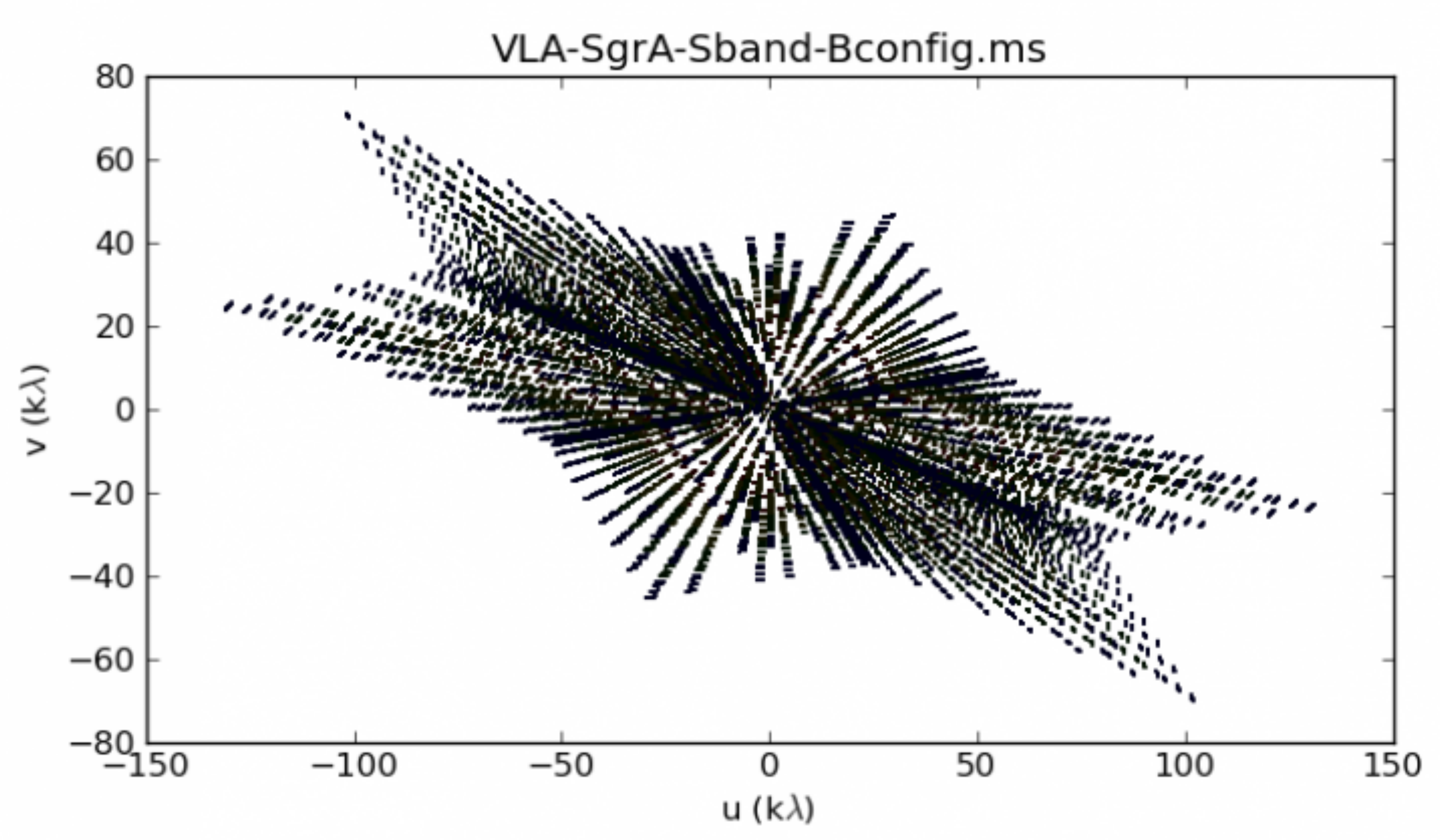
- Thus the **synthesized beam** obtained by east–west Earth-rotation aperture synthesis can approach an elliptical Gaussian.
- The synthesized beamwidth is $\approx u^{-1}$ radians east–west and $\approx u^{-1}\csc\delta$ radians in the north–south direction.
- The synthesized beam is circular for a source near the celestial pole, but the north–south beamwidth is very large for a source near the celestial equator.



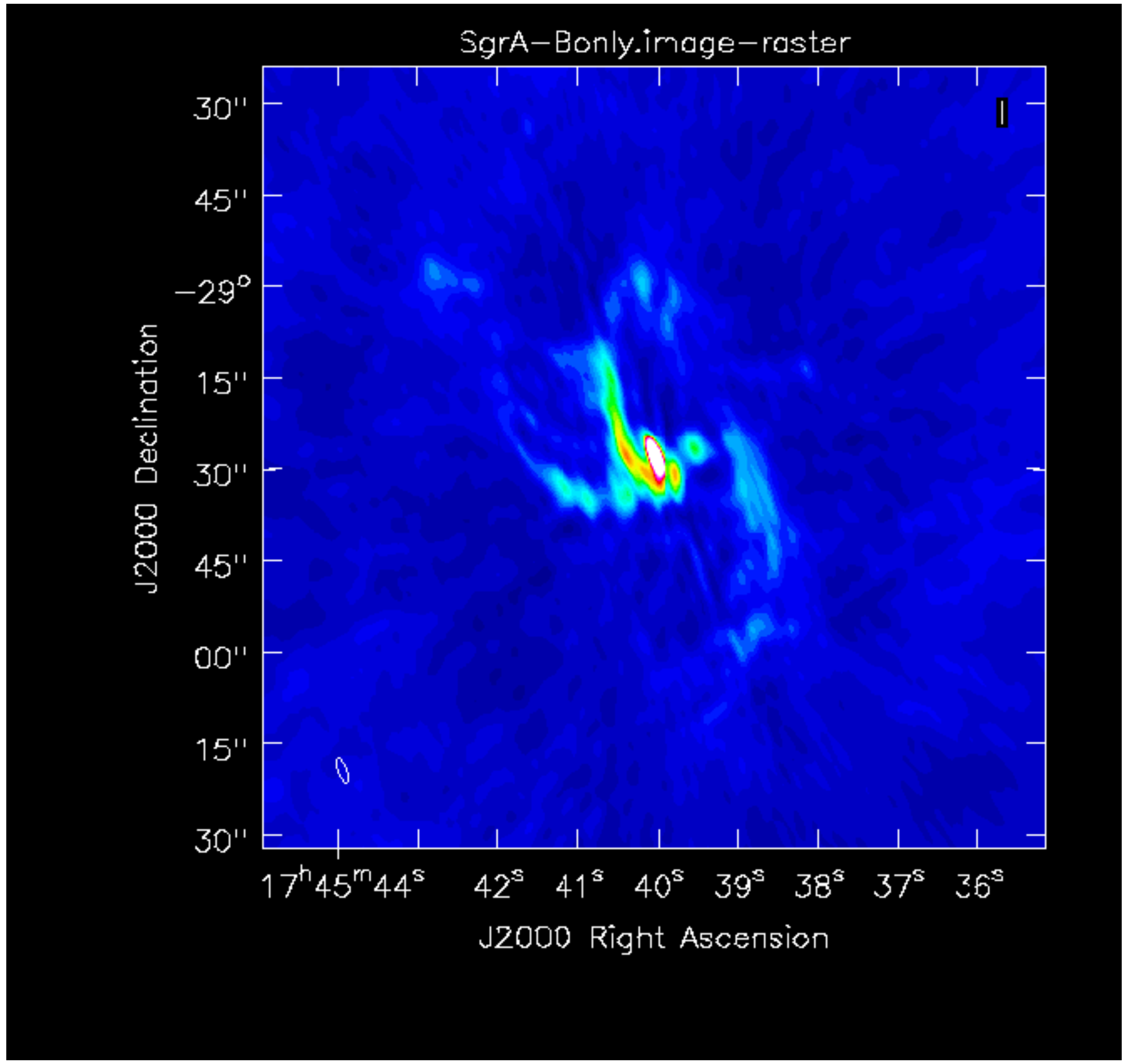
Synthesised beam for neutral hydrogen data of a galaxy

Earth rotation aperture synthesis

- Non linear arrays, e.g. the Y shaped JVLA fill a 3 dimensional projected volume (u, v, w). Which makes imaging a bit more complicated, but with much better spacial sampling.



Example uv coverage for VLA observations

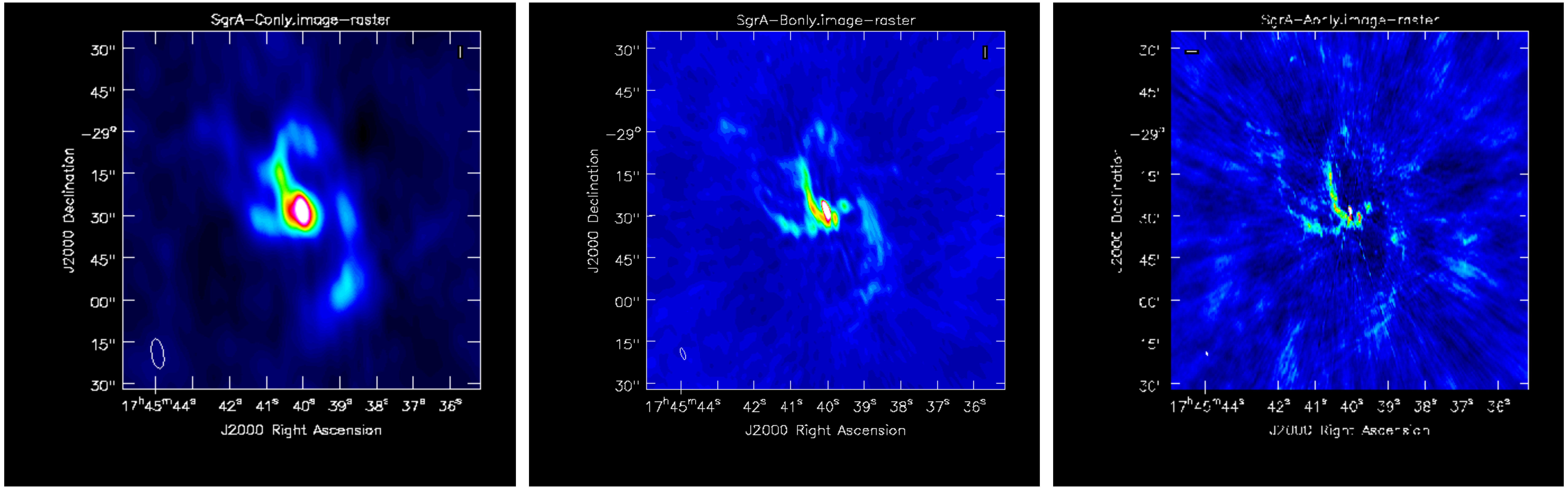


The corresponding image of a region in the Galactic Centre.

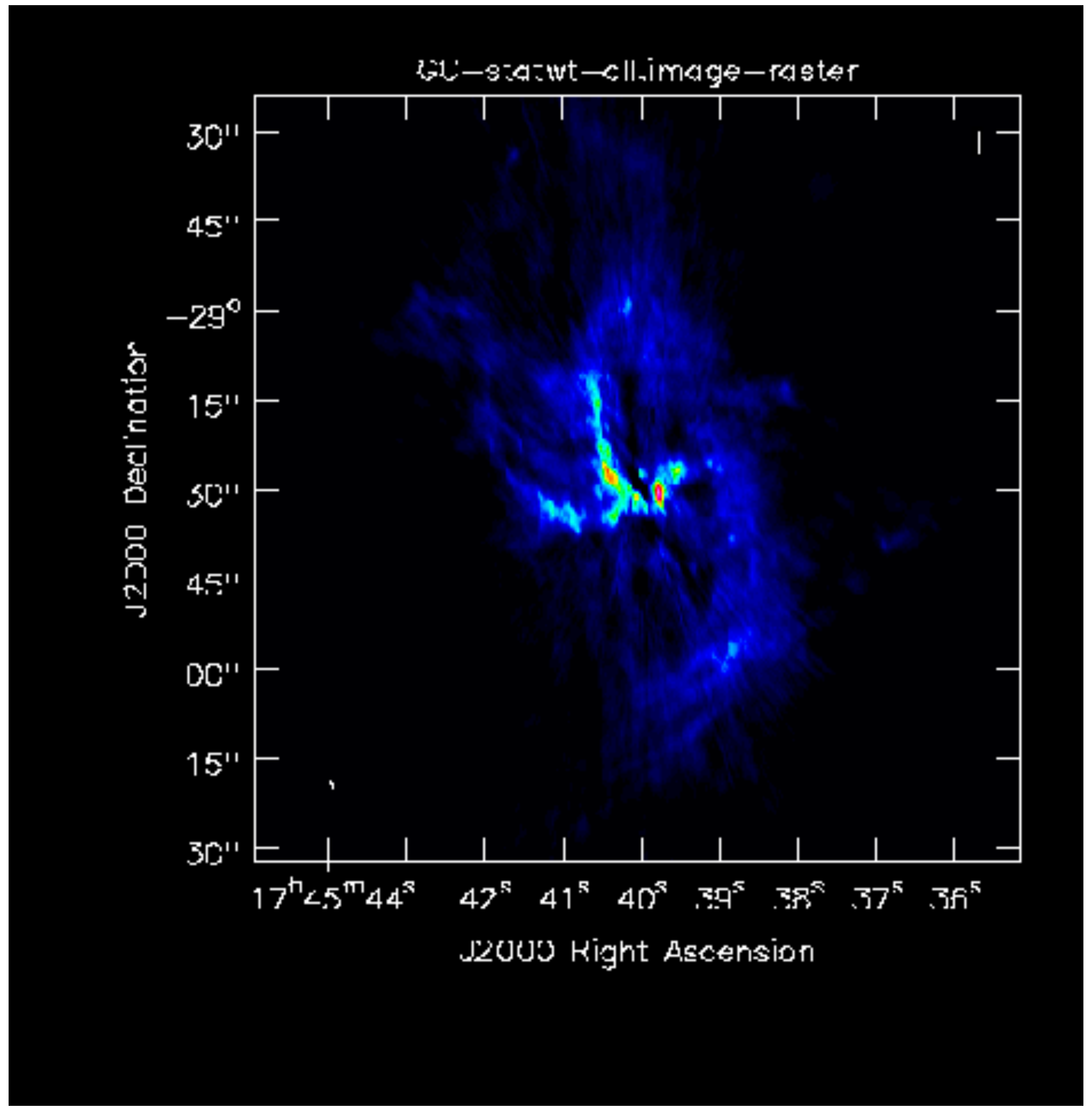
https://casaguides.nrao.edu/index.php/VLA_Data_Combination-CASA5.0.0

Earth rotation aperture synthesis

- The Y shaped JVLA antennas can be moved along railway tracks.
- The different configurations can achieve different spatial resolutions.
- The data from the different arrays can be combined to yield a better image.



3 different array configurations of the JVLA, yield images with different spacial resolution.



The combined image.

https://casaguides.nrao.edu/index.php/VLA_Data_Combination-CASA5.0.0