
# Radio Astronomy
# Spectral lines

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# Radio telescopes

$\Theta = 1.22\ \lambda/D$

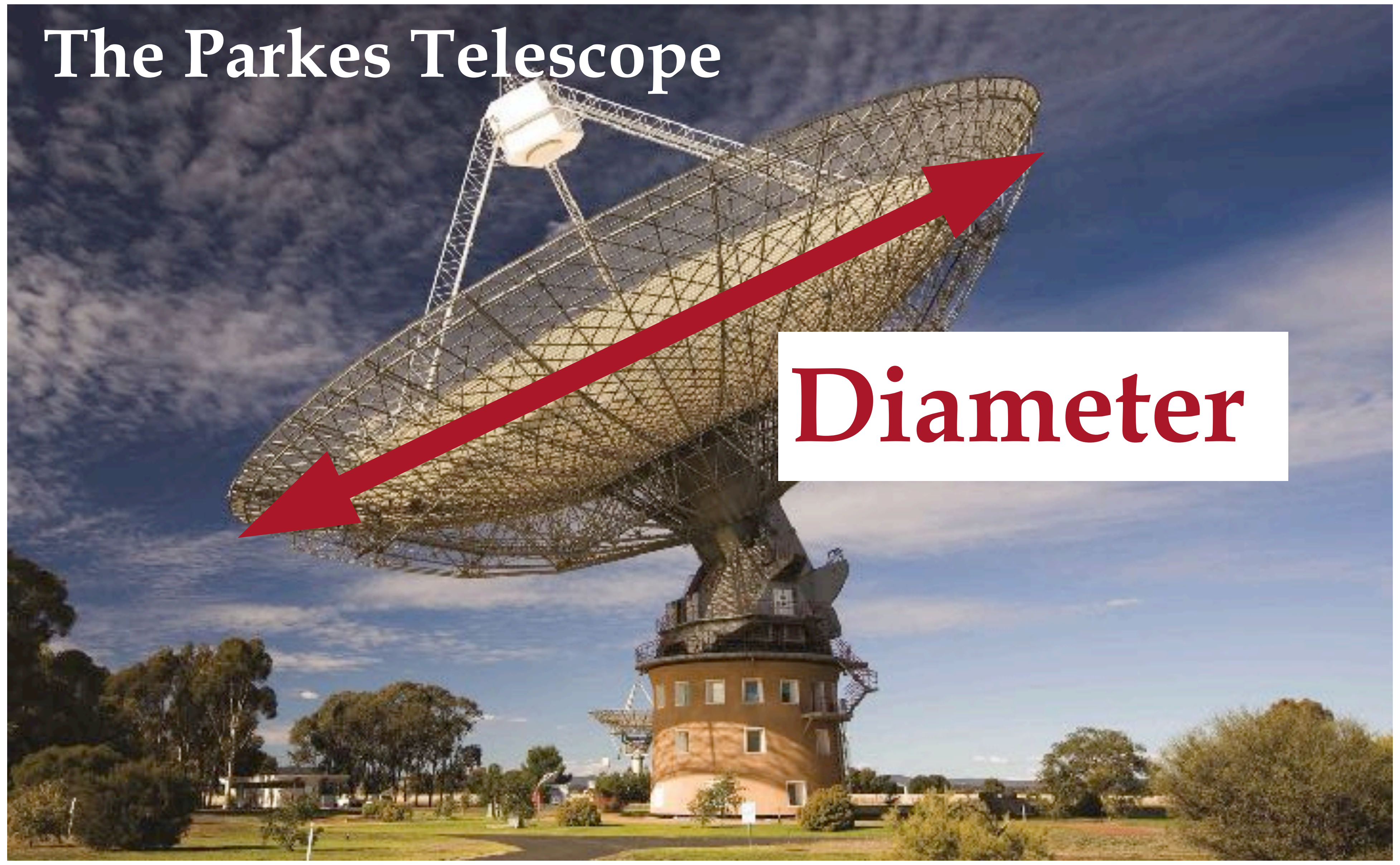
The **resolution of a telescope depends on its size and the wavelength** of light that is getting observed.

- 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:

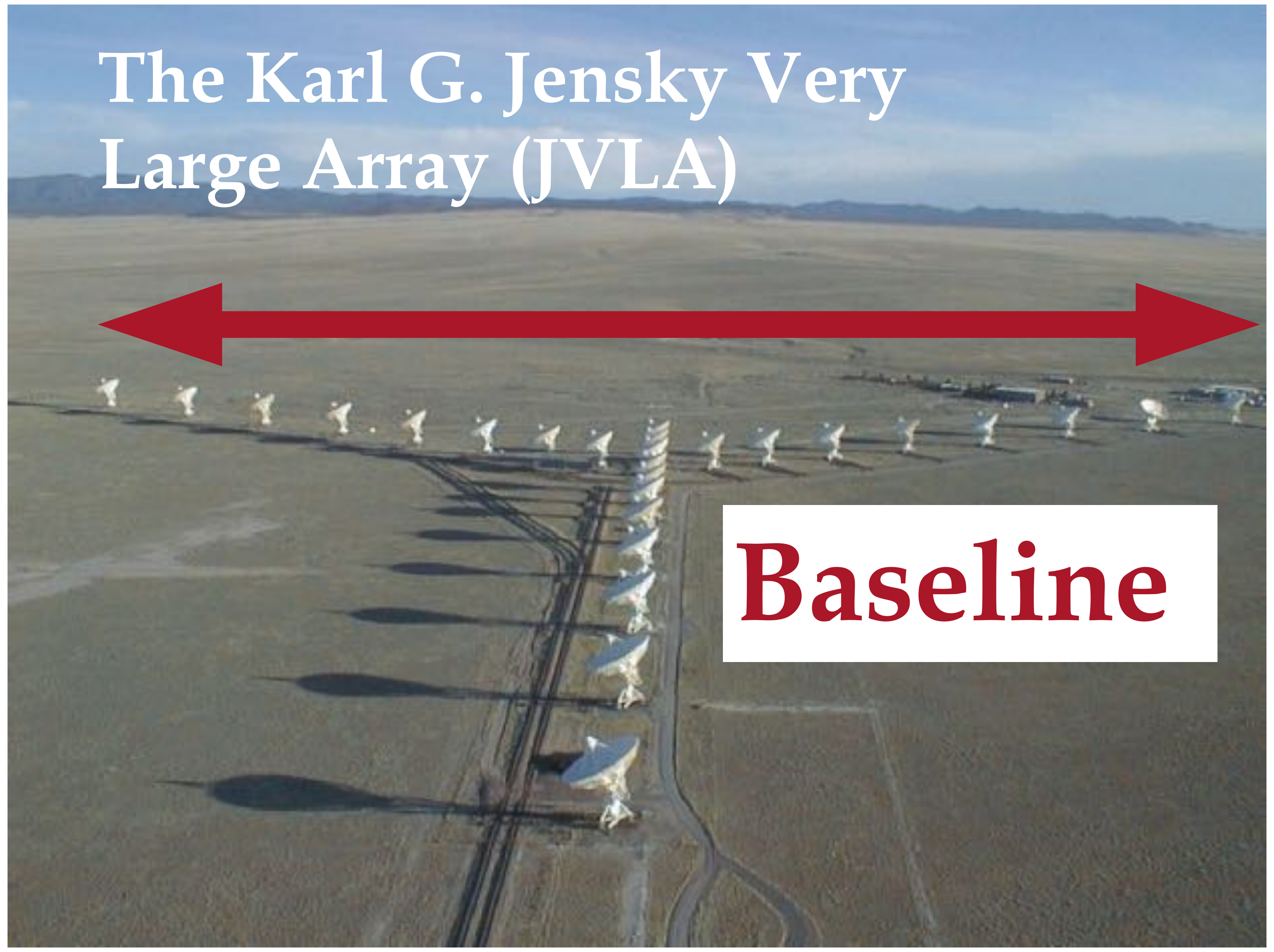
Resolution: ~ Diameter




www.csiro.au

## Interferometers:

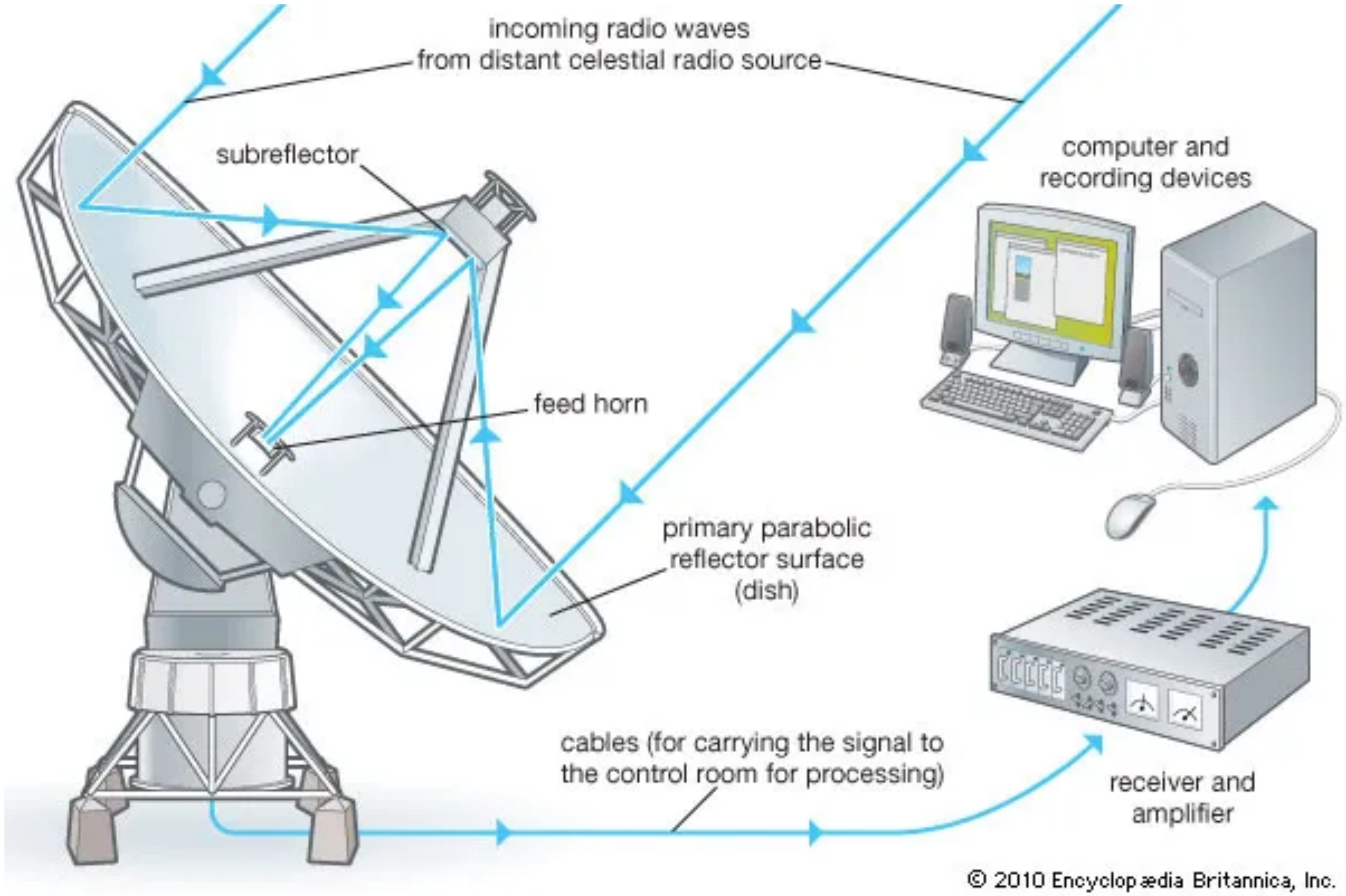
Resolution: ~ distance between telescopes



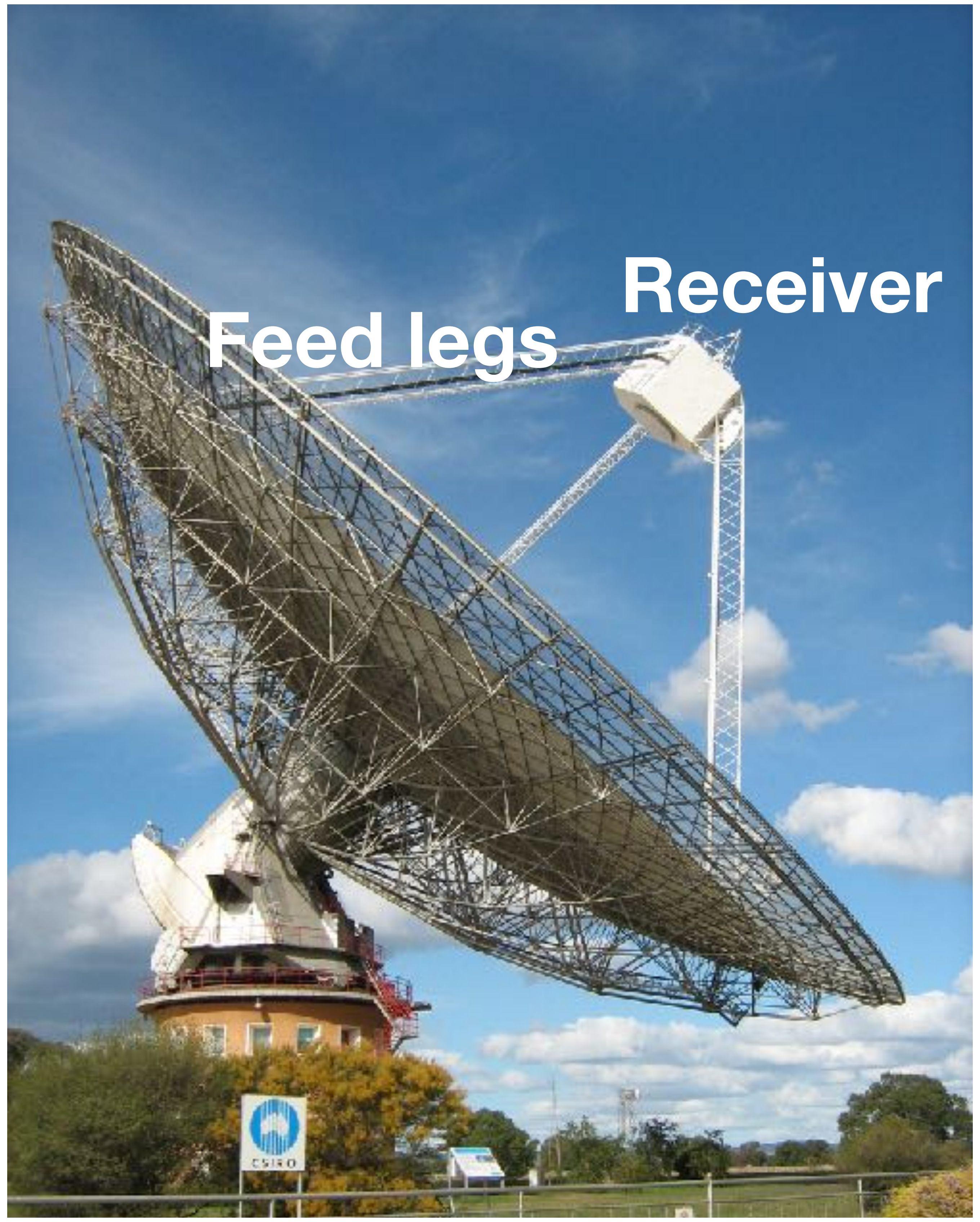

http://images.nrao.edu

# Radio telescopes

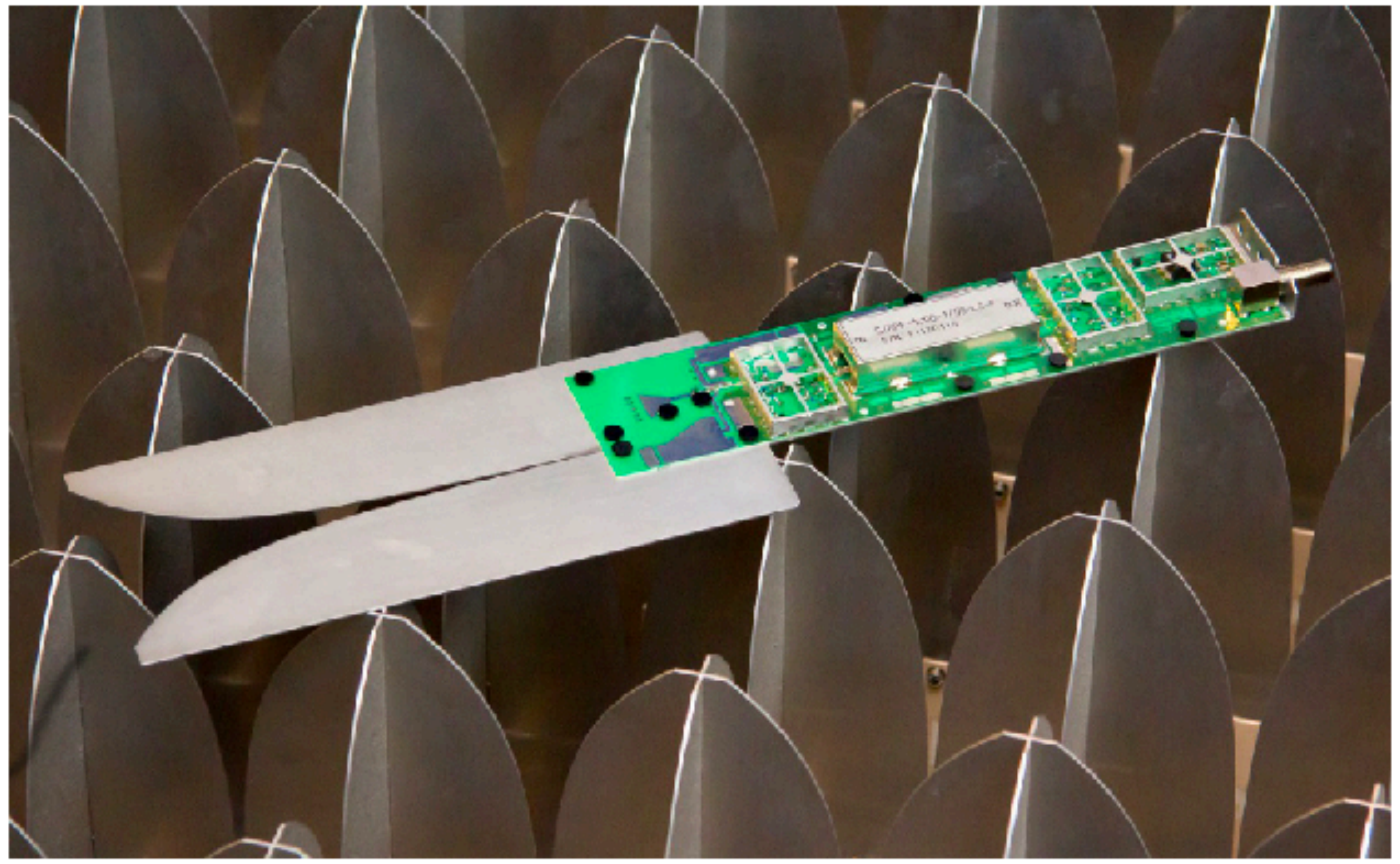
The antenna detects the signal → signal amplification and digitalisation
Recording and combining the signal in the computer.
Important: we record the phase information → interferometry




https://kids.britannica.com/students/assembly/view/145514

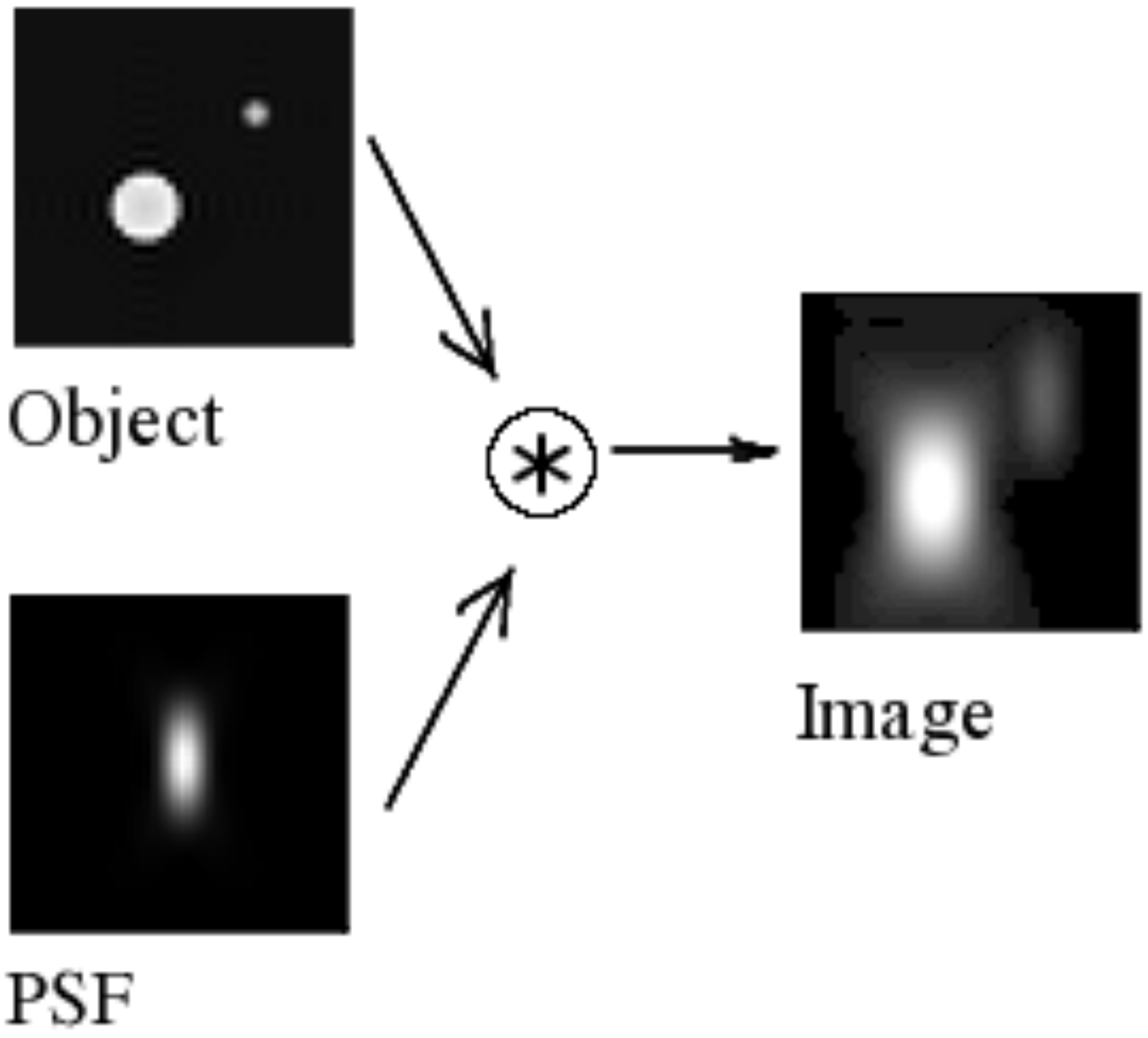



An individual antenna element



# Primary beam - sensitivity pattern

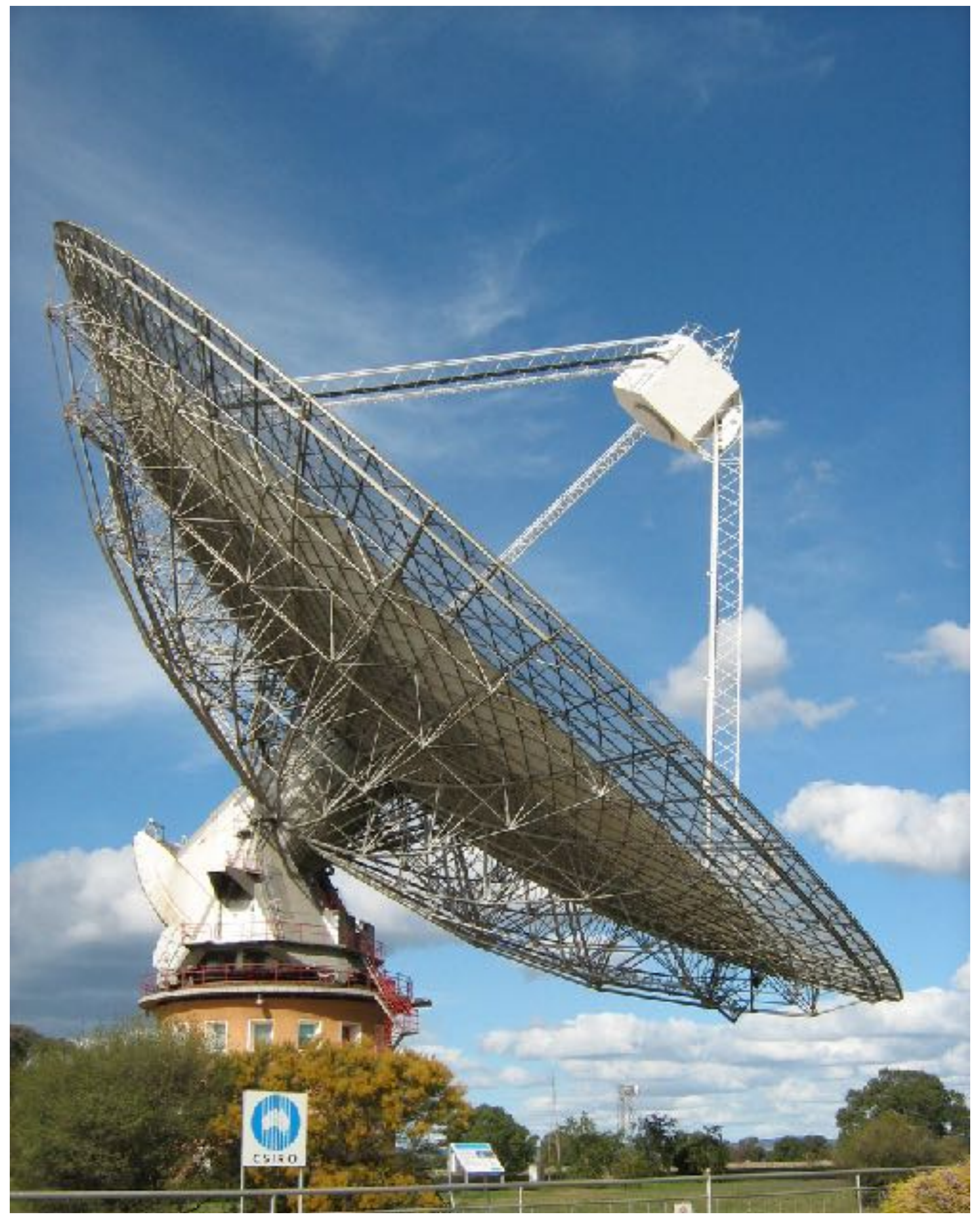
The **point spread function** (**PSF**) describes the response of a focused optical imaging system to a point source or point object.

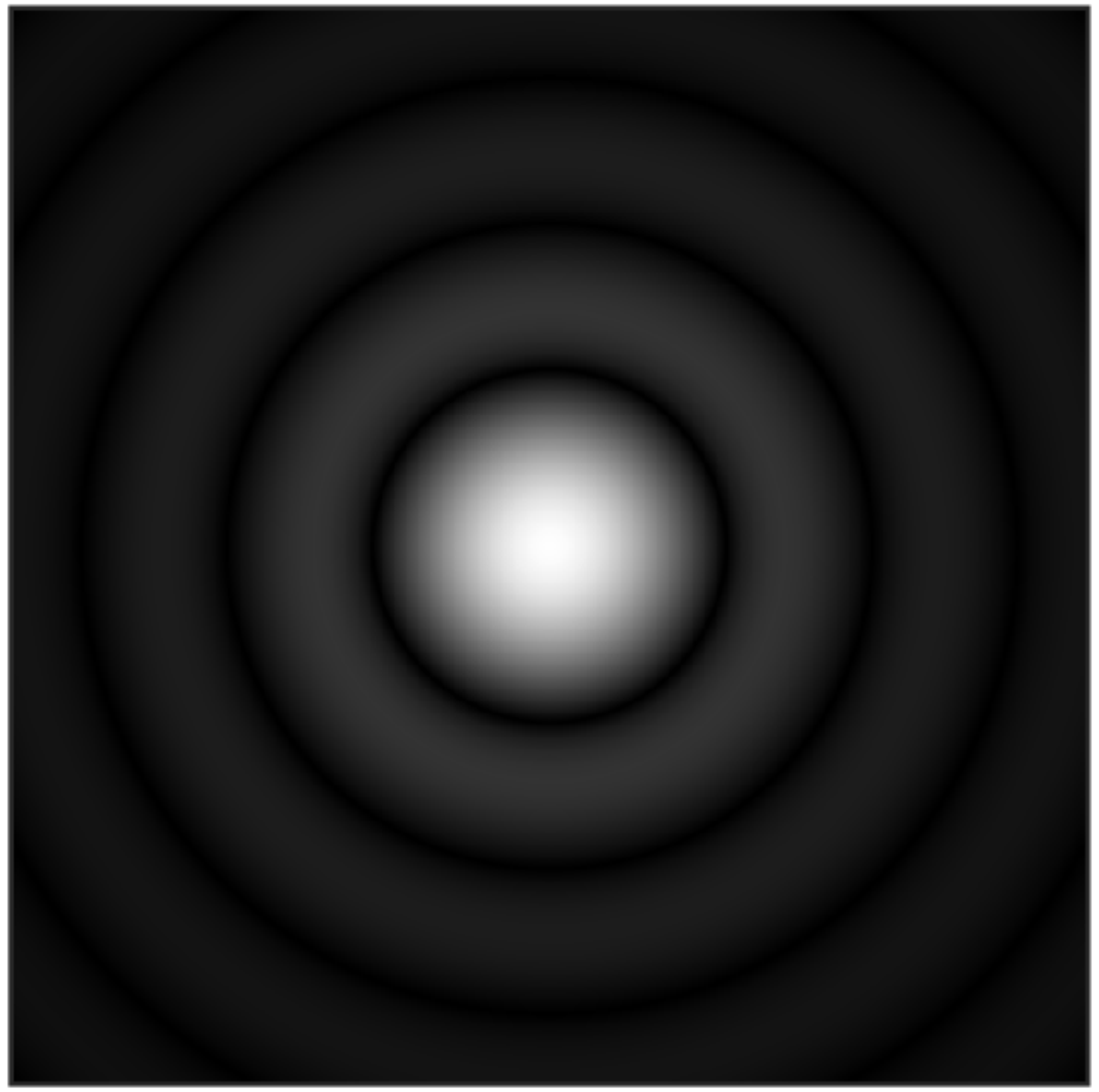


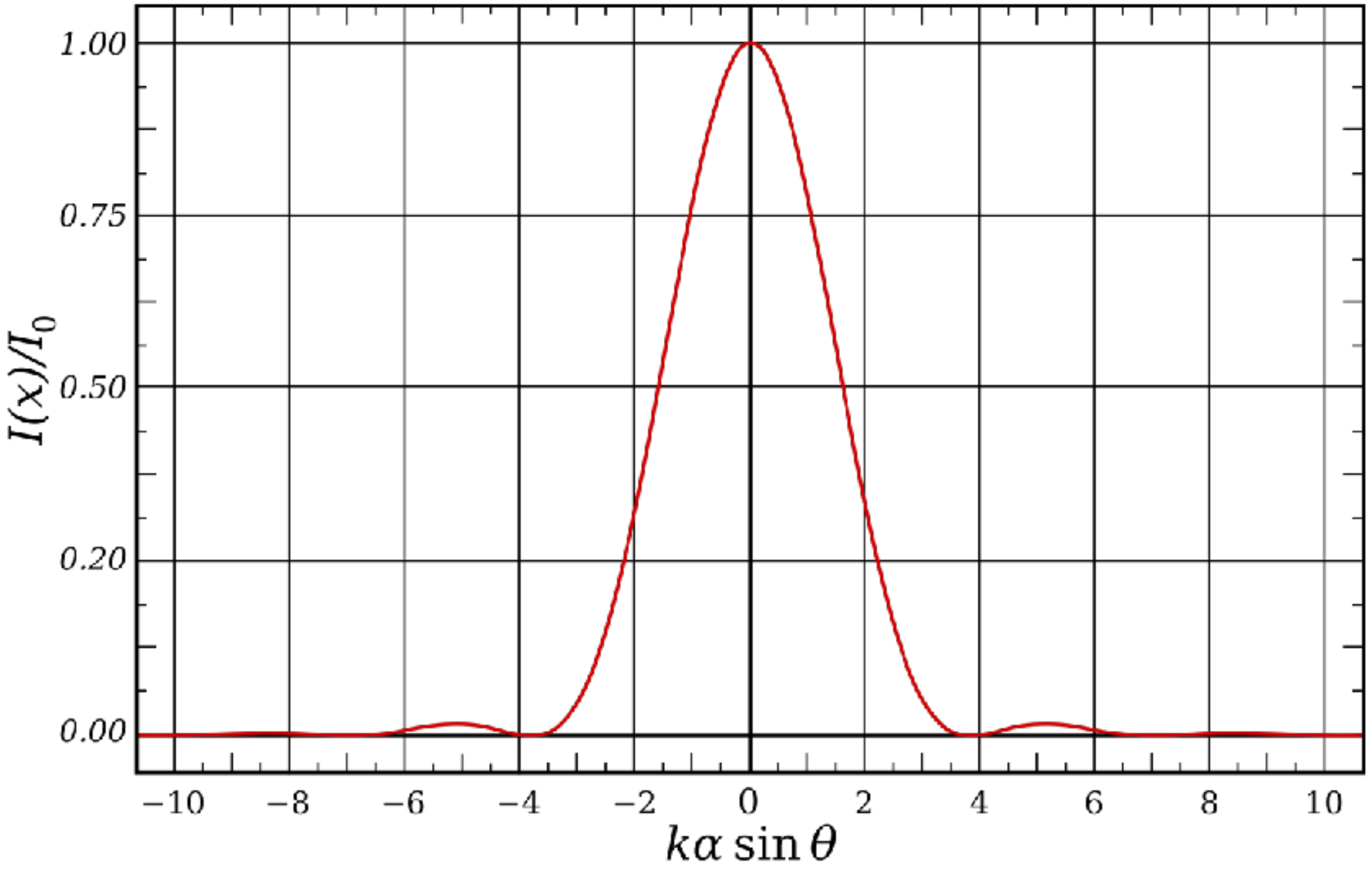

https://en.wikipedia.org/wiki/Point_spread_function

# Primary beam - sensitivity pattern

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





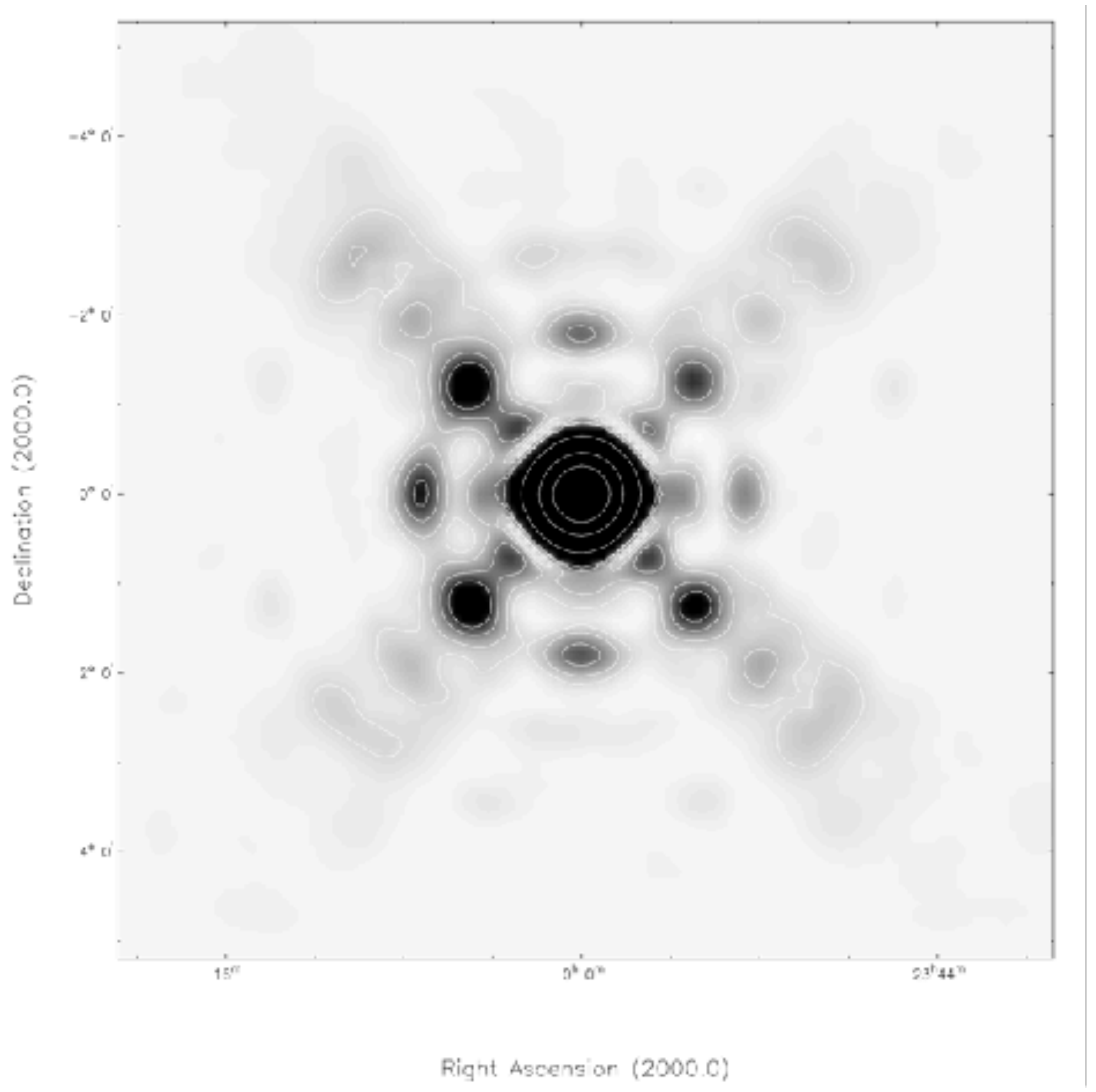



https://en.wikipedia.org/wiki/Airy_disk

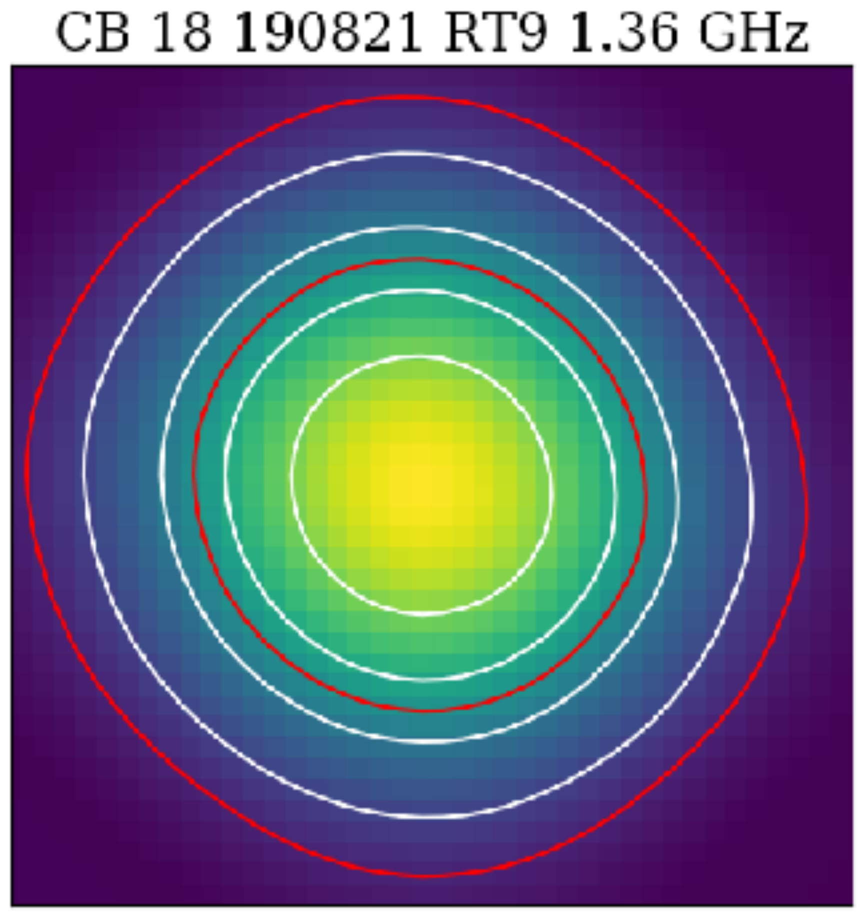
# Primary beam - sensitivity pattern

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

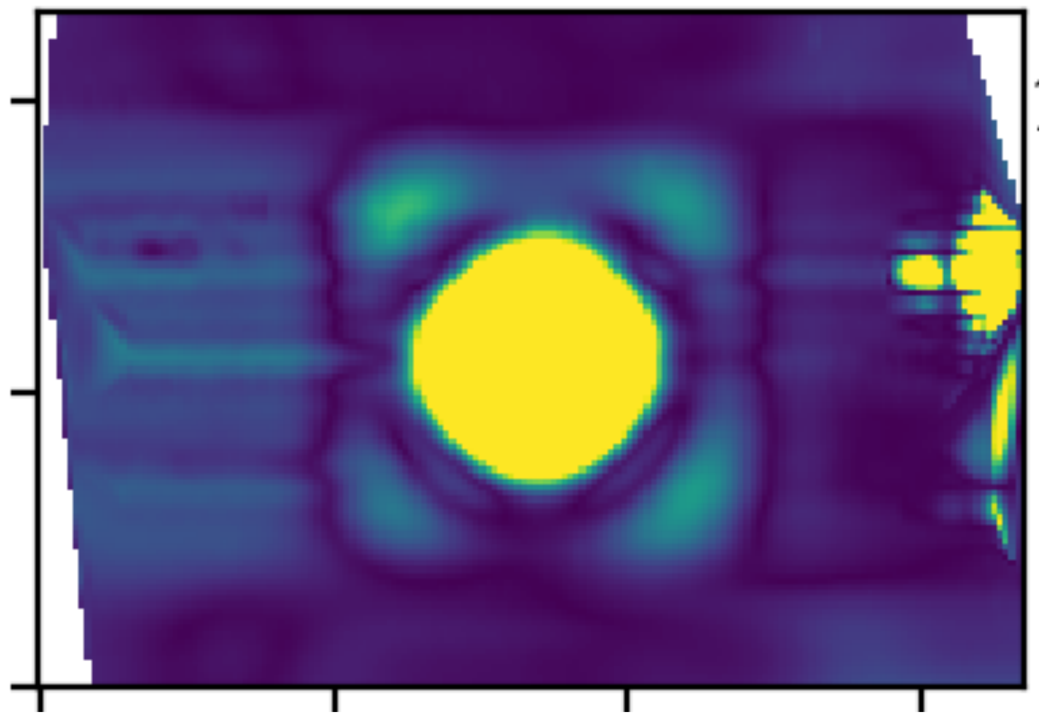
WSRT beam shape from Popping et al. 2008



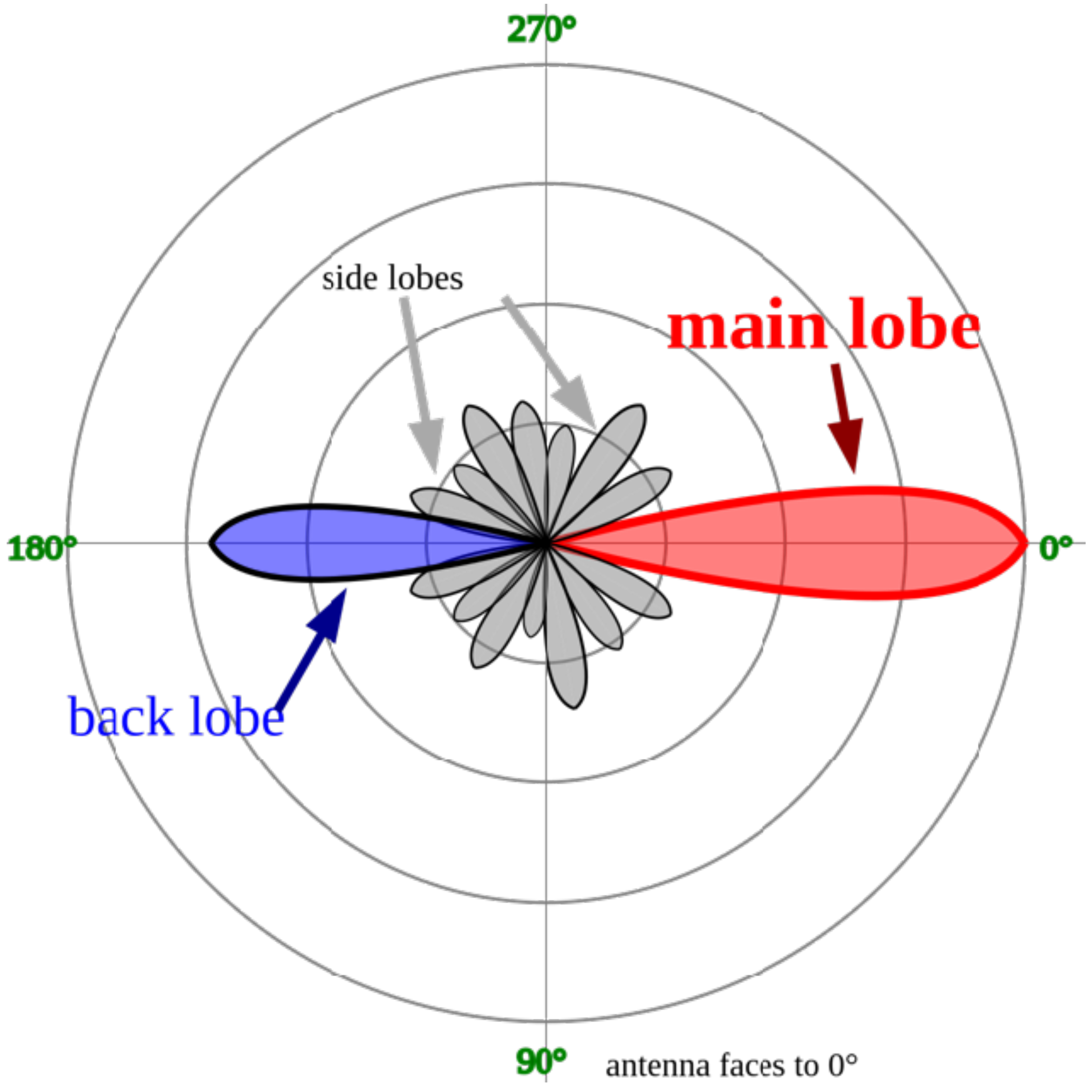

**Primary beam pattern**




**Faint side lobes**



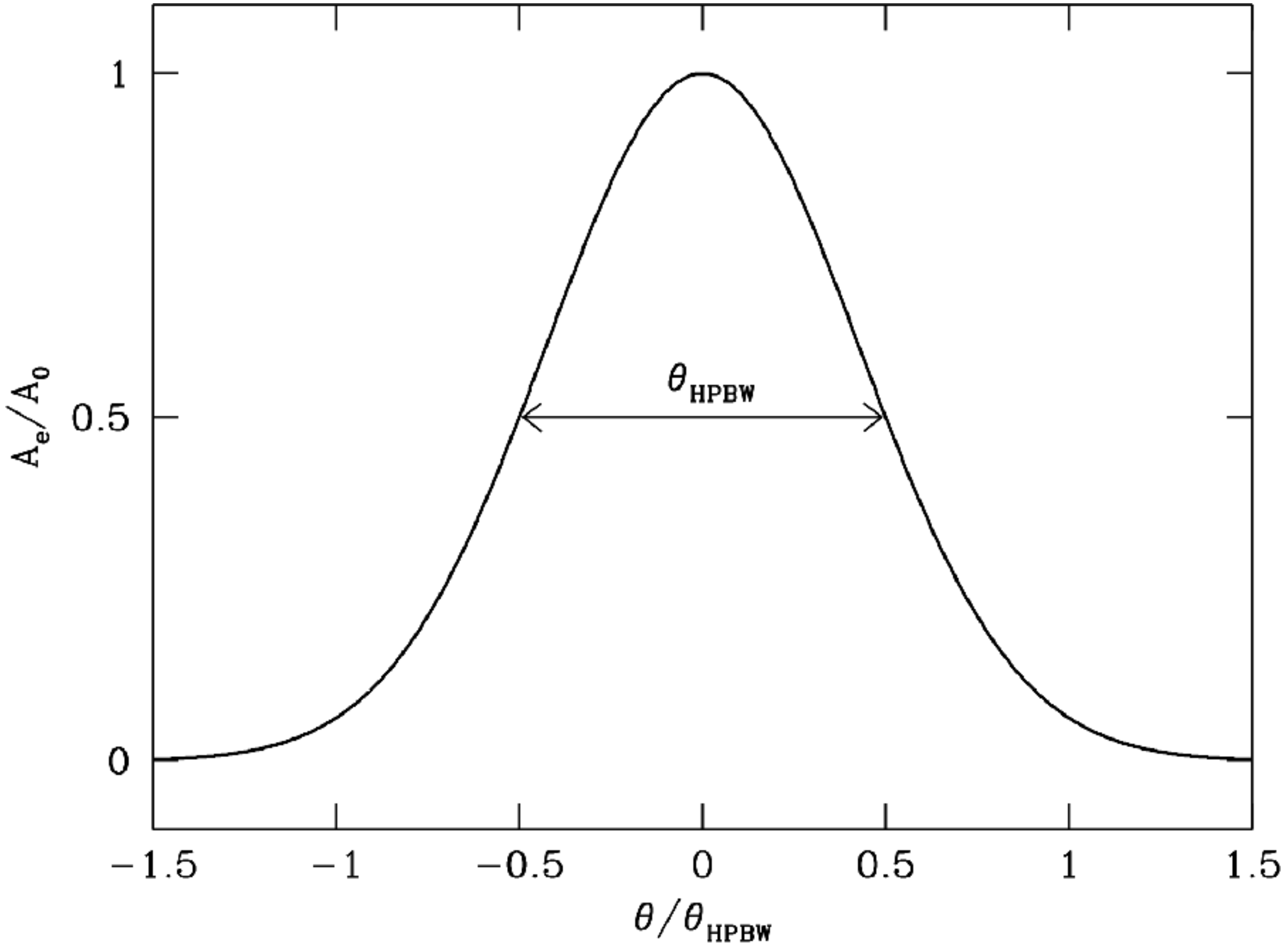
**Antenna radiation pattern**




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

# Primary beam - sensitivity pattern

The **beams of most radio telescopes are nearly Gaussian, and their beamwidths are usually specified by the angle $\Theta_{HPBW}$** between the half-power points.

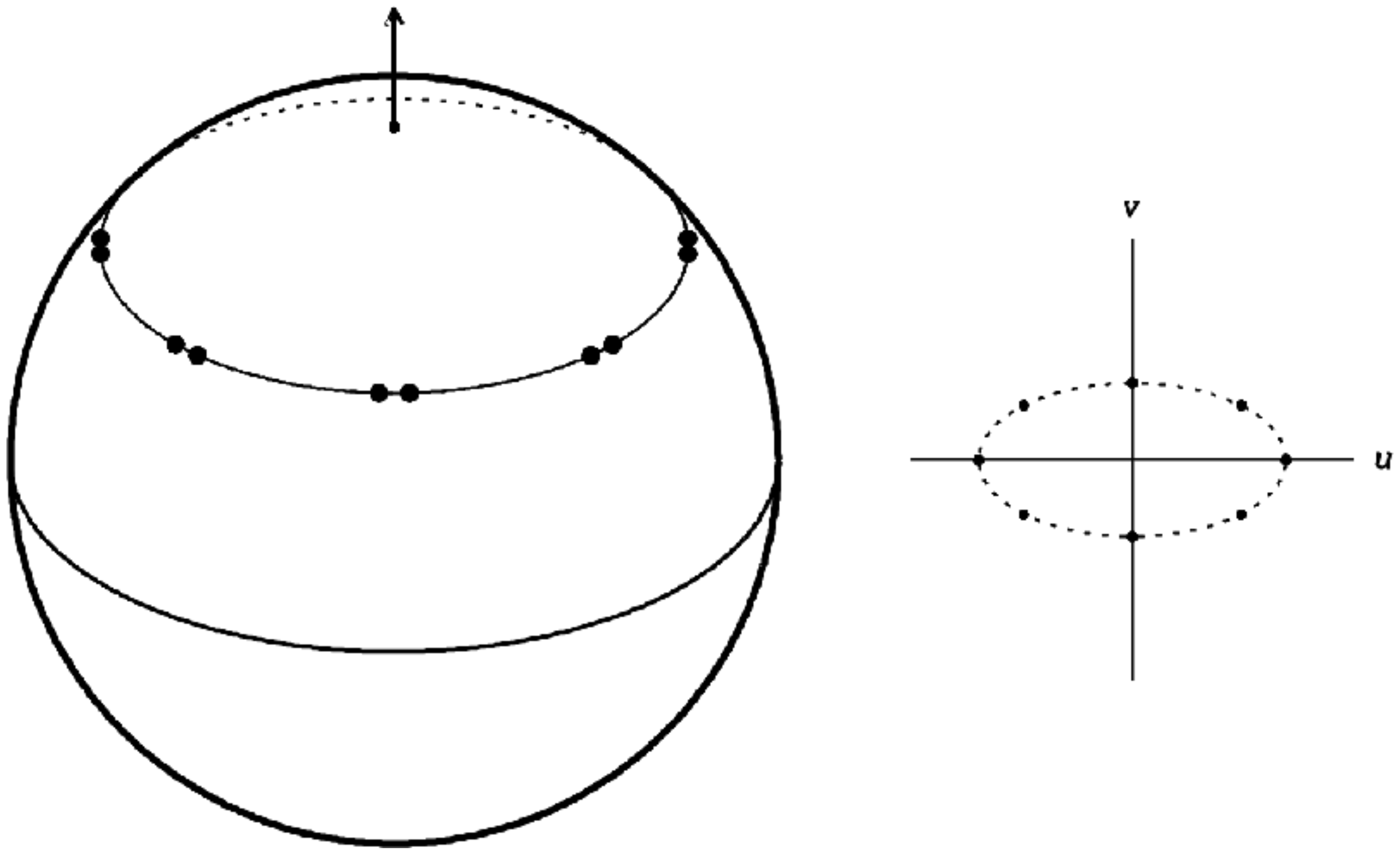



Abscissa: offset θ from the beam center in units of the HPBW. Ordinate: Effective aperture $A_e$ normalized by the peak effective aperture $A_0$

the beam solid angle of a Gaussian beam is:

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

# Interferometry - Earth rotation aperture synthesis




- **The Earth's rotation varies the projected baseline coverage of an interferometer.**
- All **baselines of an east–west line will remain in a single plane perpendicular to the Earth's north–south rotation axis** as the Earth turns daily.
- **Visibility: the intensity observed by the telescope**
- The **brightness distribution of a source is simply the two-dimensional Fourier transform of the measured visibilities.**

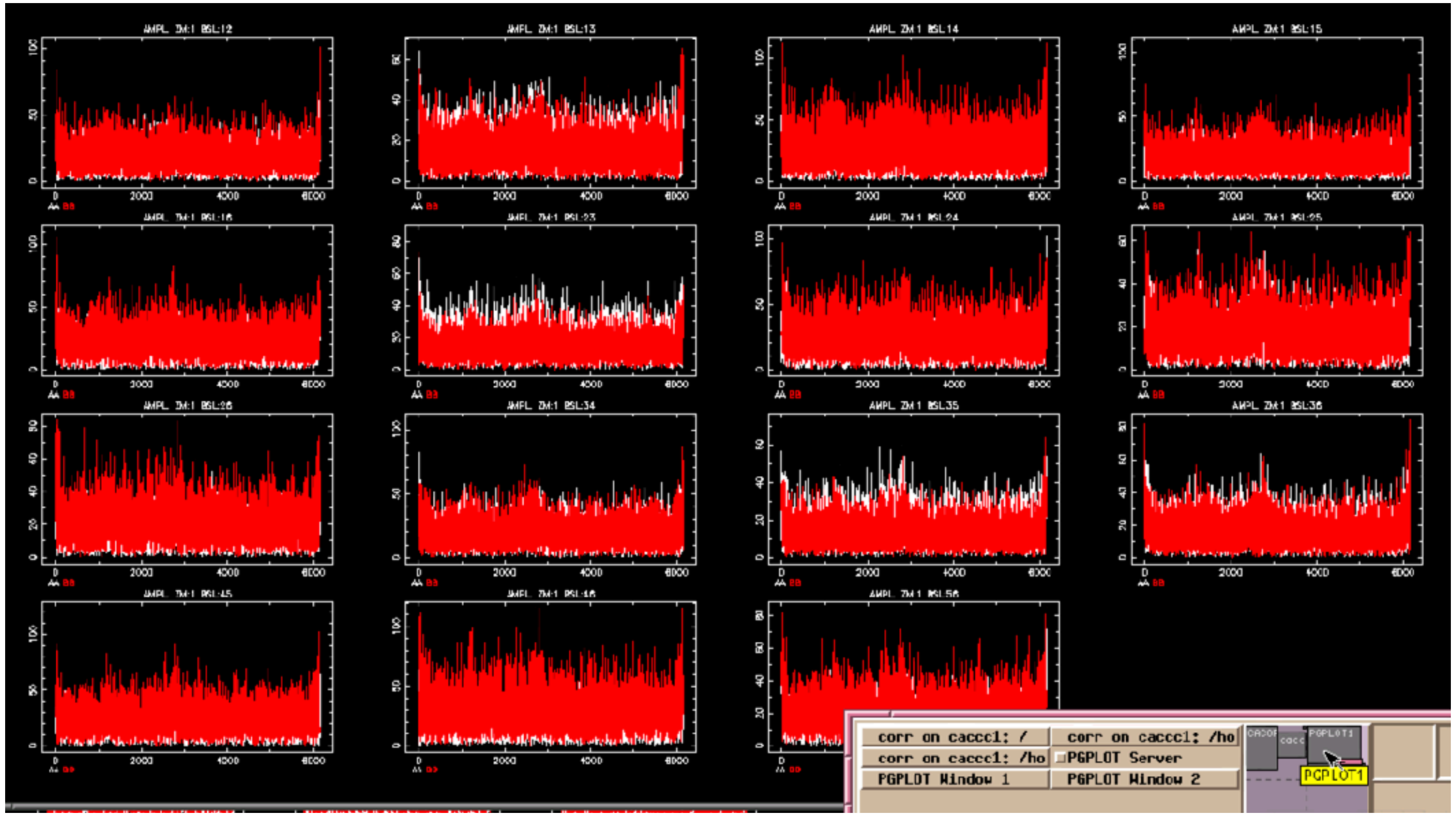
- The Figure illustrates Earth-rotation aperture synthesis by an east–west two-element interferometer at latitude +40° as viewed from a source at declination $\delta$=+30°.

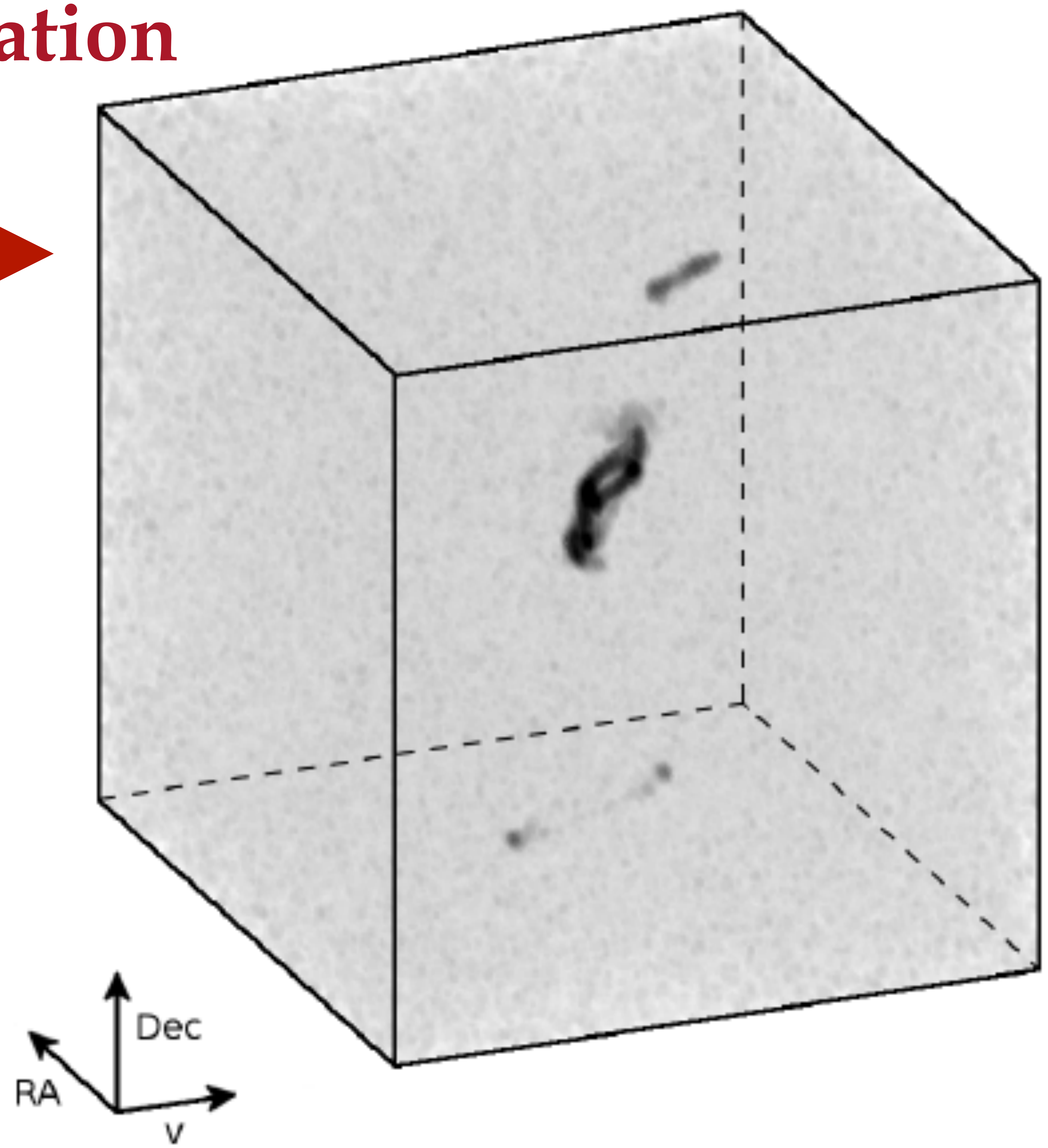
# Interferometry - Earth rotation aperture synthesis

What the telescope measures: **intensity as a function of**

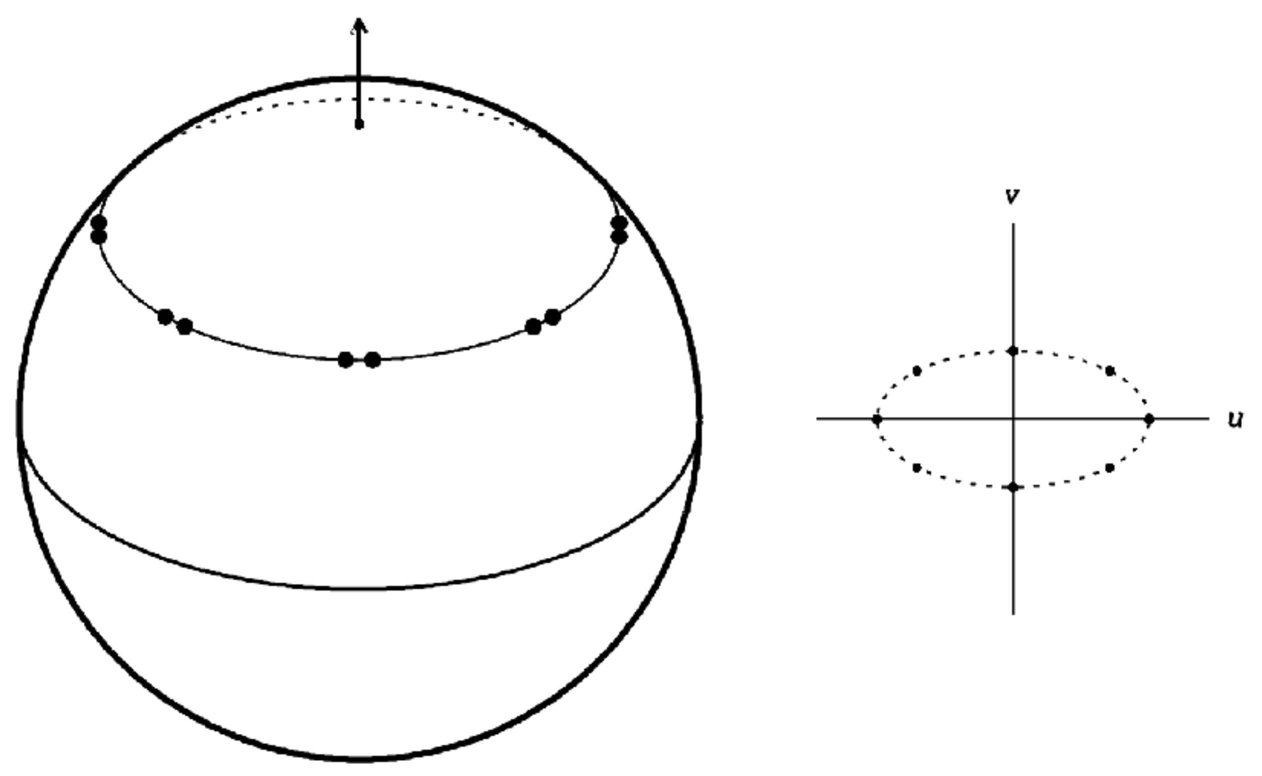
- Frequency
- Time
- Baseline
- Polarisation

Calibration and inverse Fourier transformation



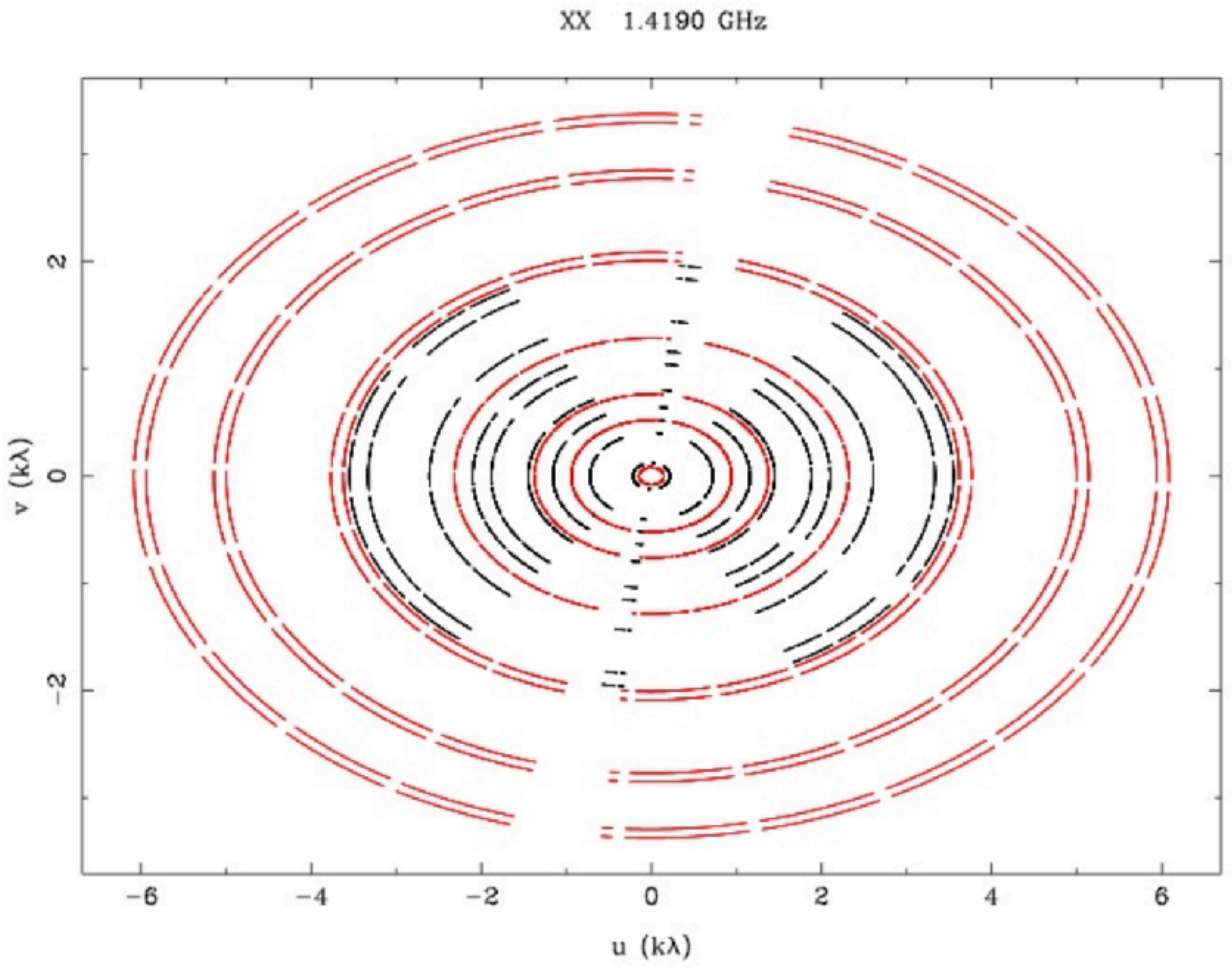


# Earth rotation aperture synthesis




- 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, 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 **the (u,v) coverage will become a number of concentric ellipses having the same shape.**

Example uv coverage of ATCA observations

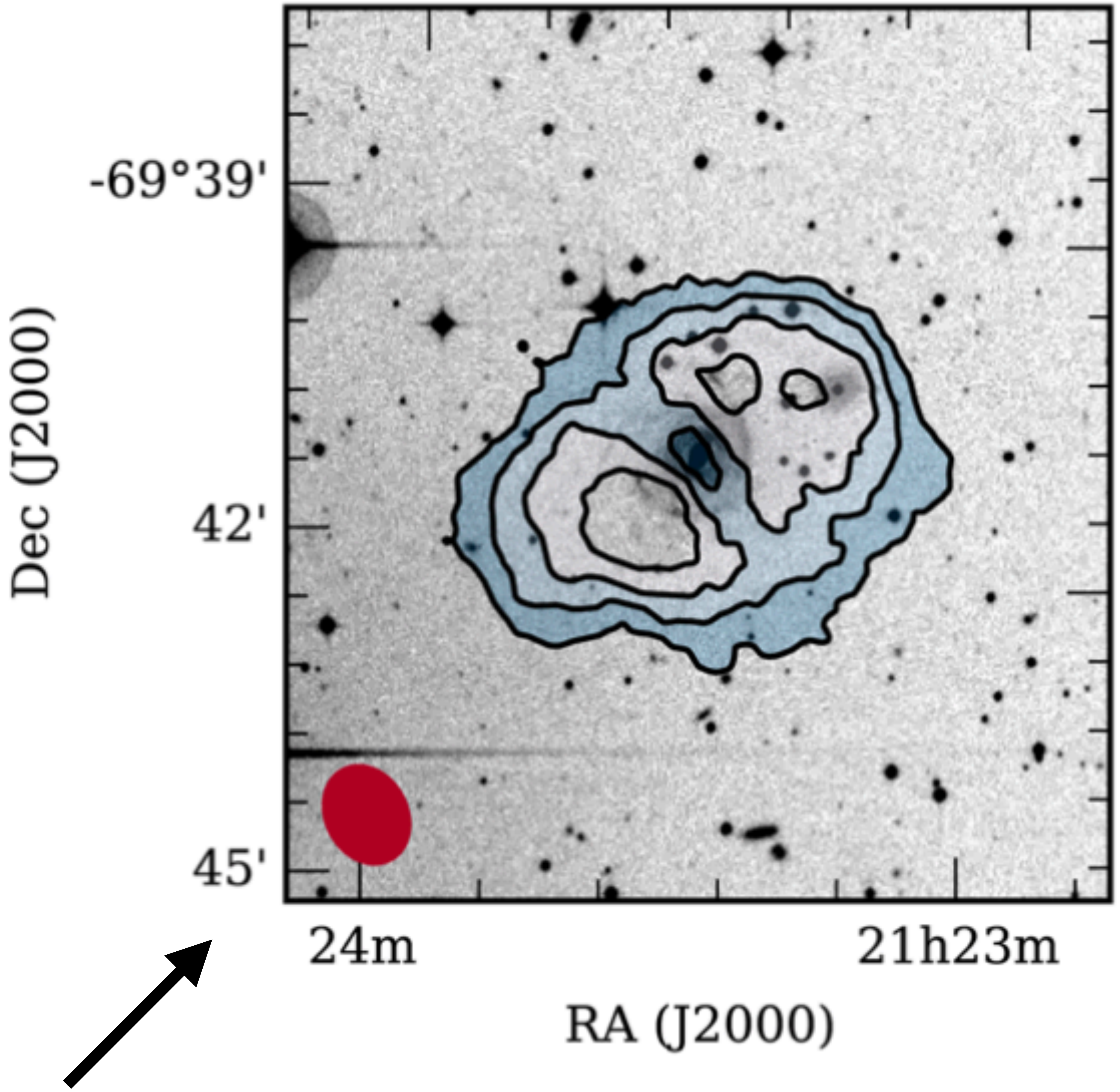



**A radio interferometer observes the Fourier plane and works like a Fourier filter.**

# Earth rotation aperture synthesis

- Thus the **synthesized beam** obtained by east–west Earth-rotation aperture synthesis can approach an elliptical Gaussian.

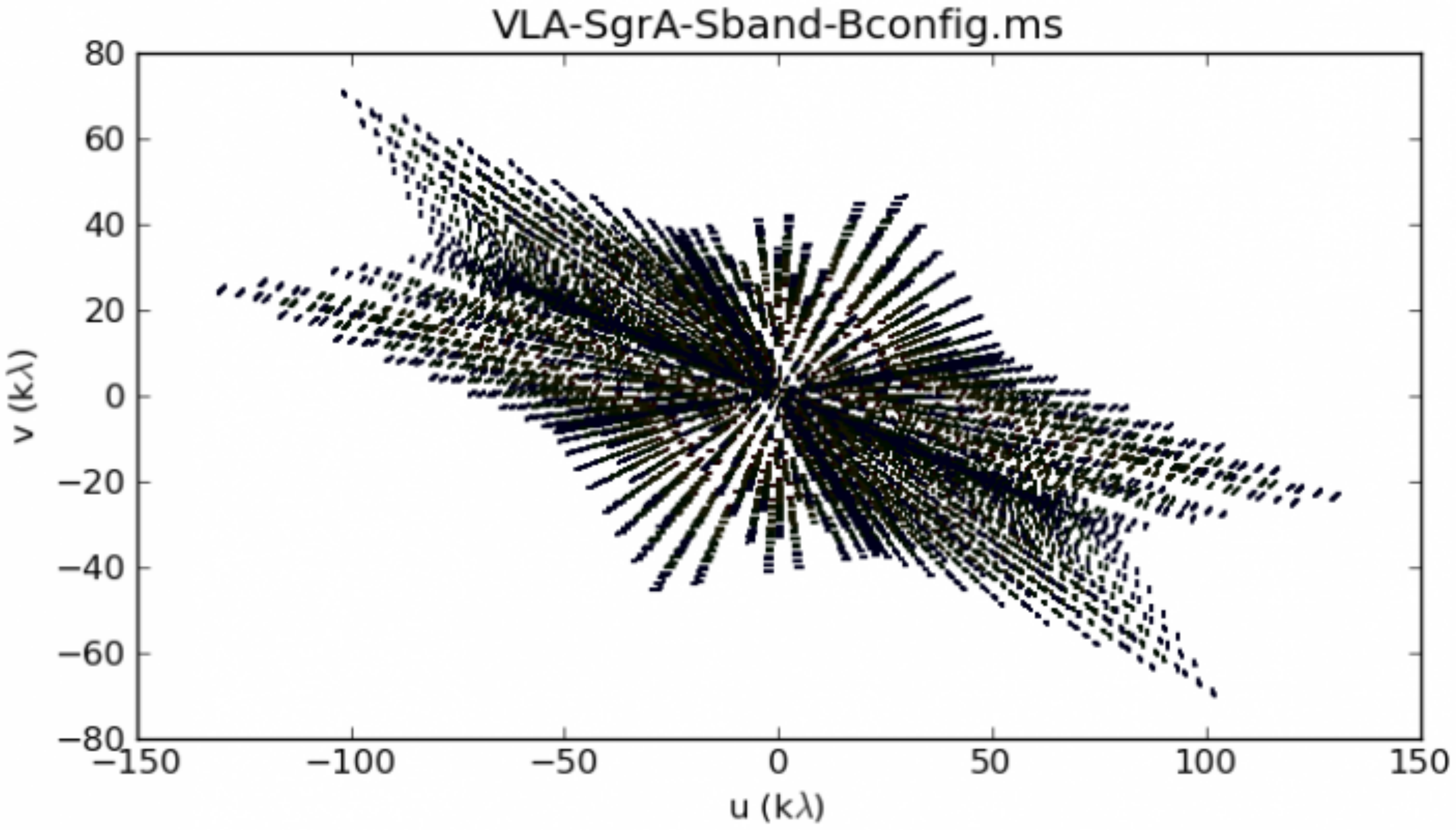
- The **synthesized beam depends on:**
  - **the antenna configuration,**
  - **the length of the observation and**
  - **the declination of the source**




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.



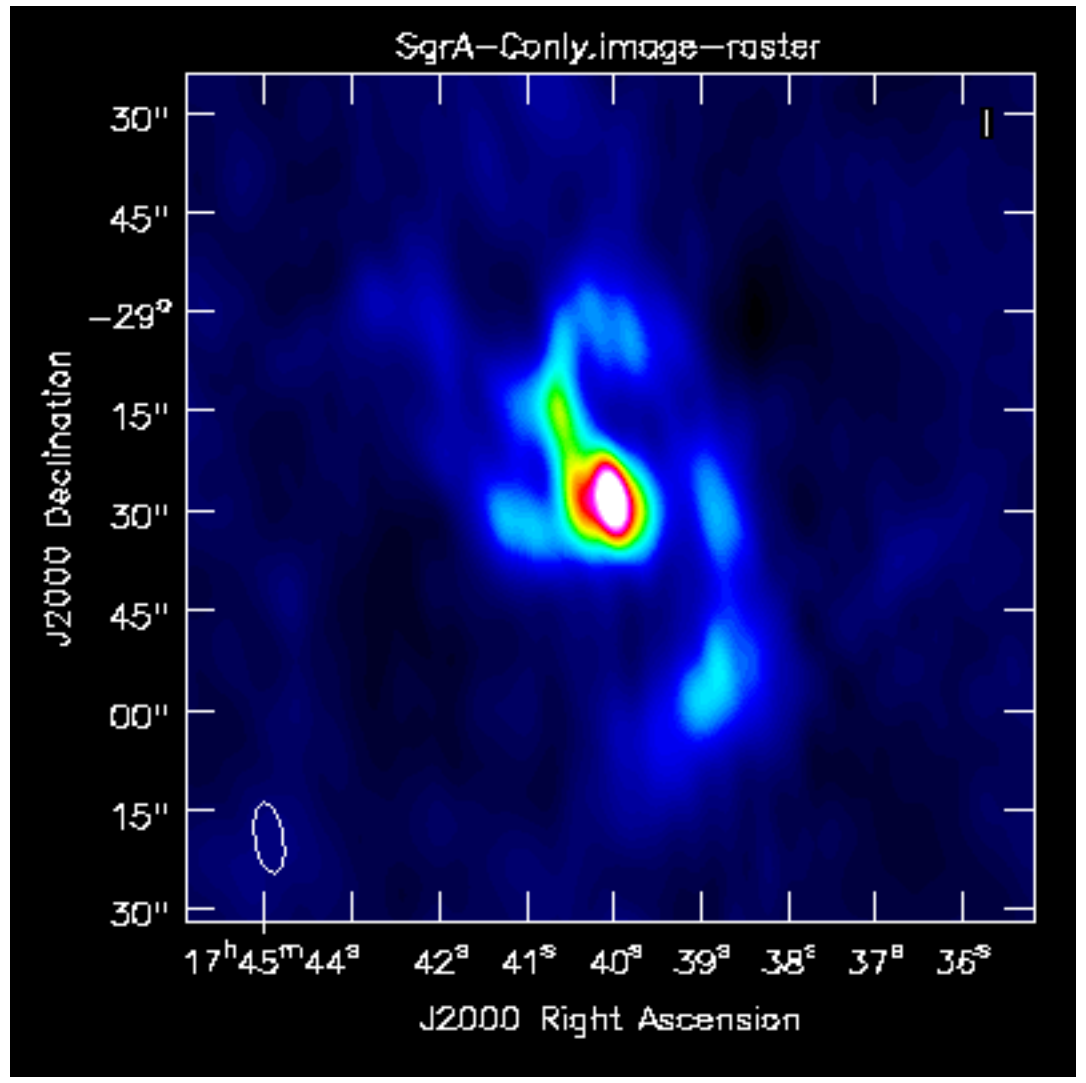

https://casaguides.nrao.edu/index.php/VLA_Data_Combination-CASA5.0.0

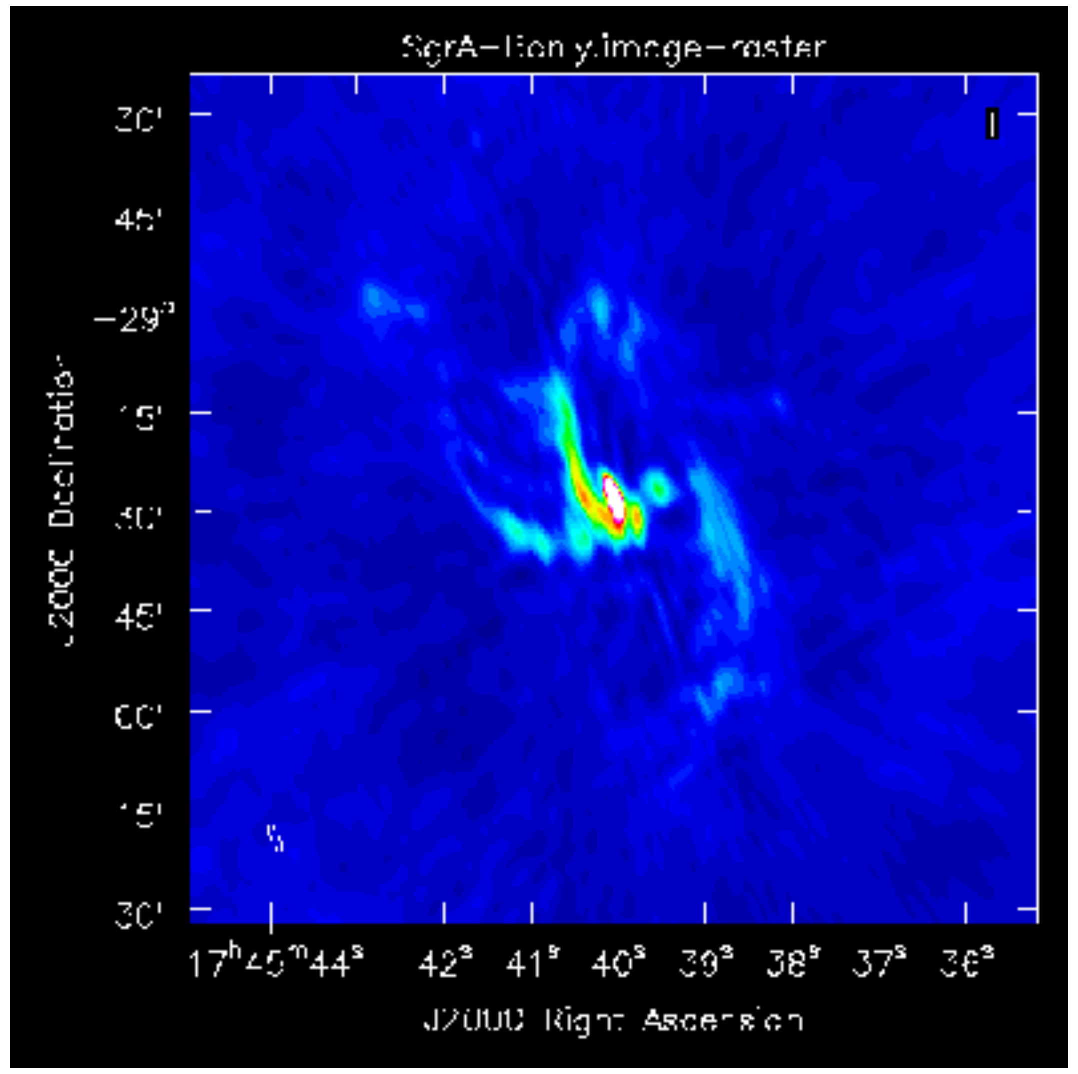
Example uv coverage for VLA observations

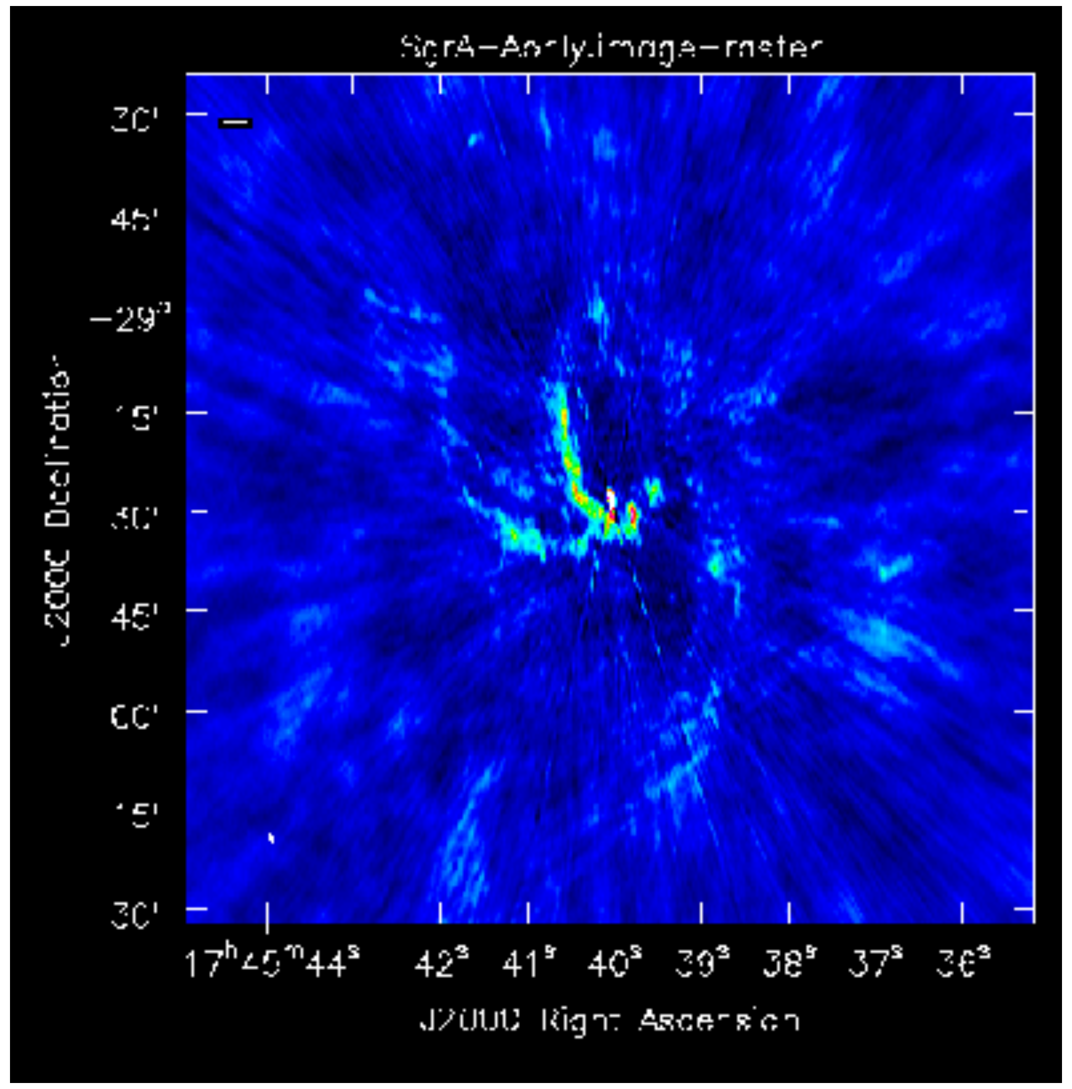
# Earth rotation aperture synthesis

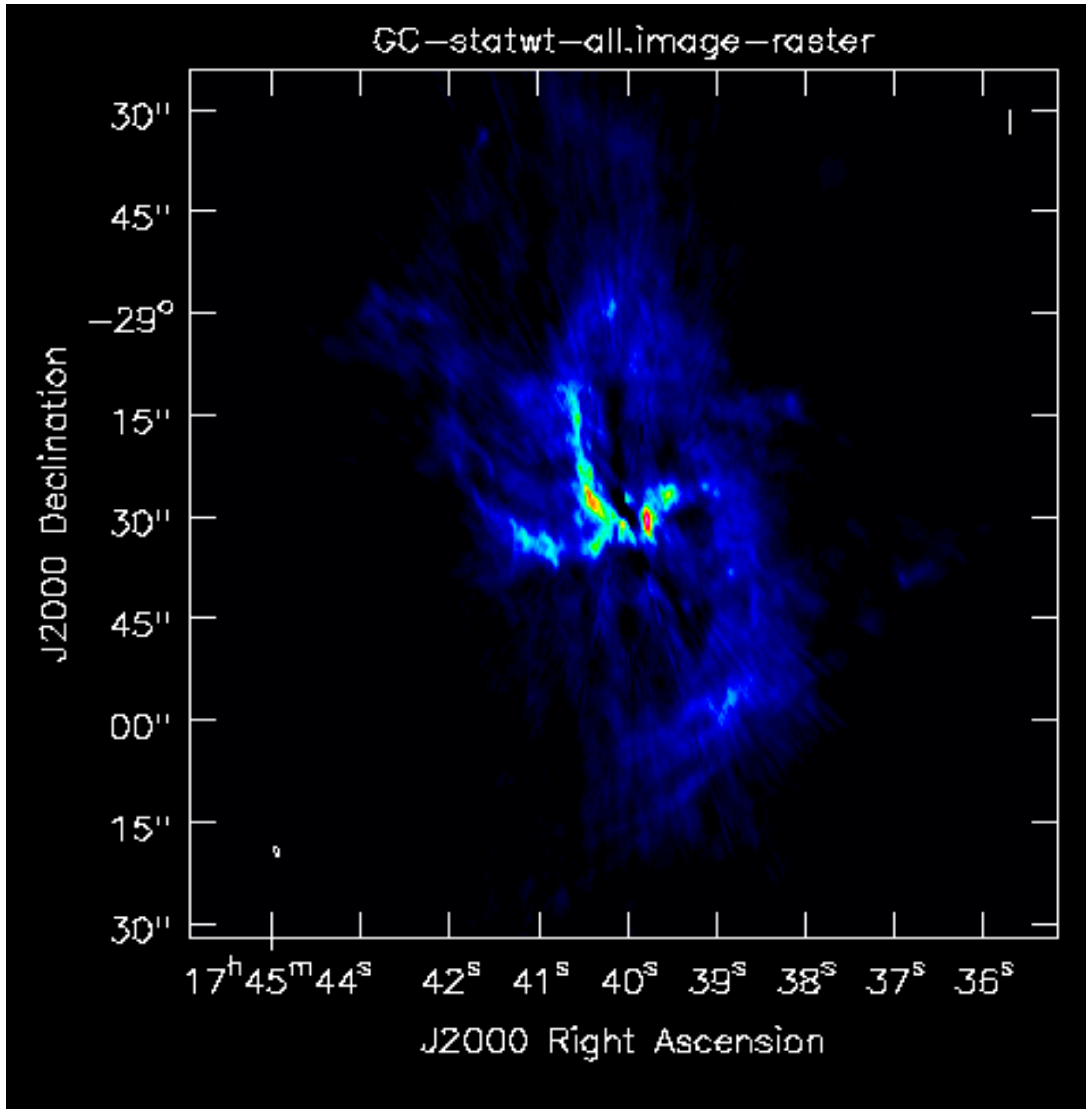
- The Y shaped JVLA **antennas can be moved along railway tracks.**
- The different configurations can achieve **different spatial resolutions.**
- The data from the different arrays can be combined to yield a better image.

The combined image.



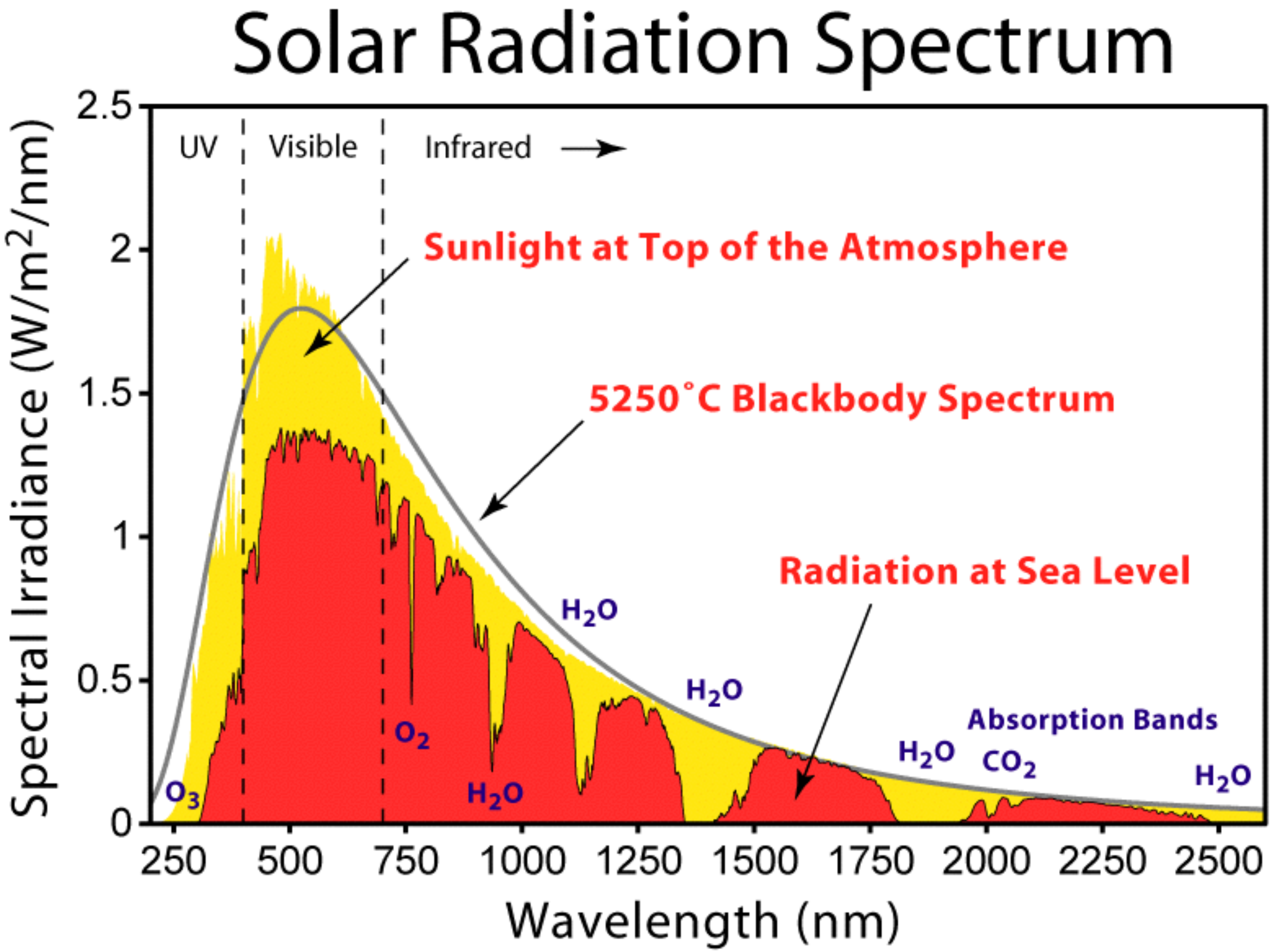





3 different array configurations of the JVLA, yield images with different spacial resolution.

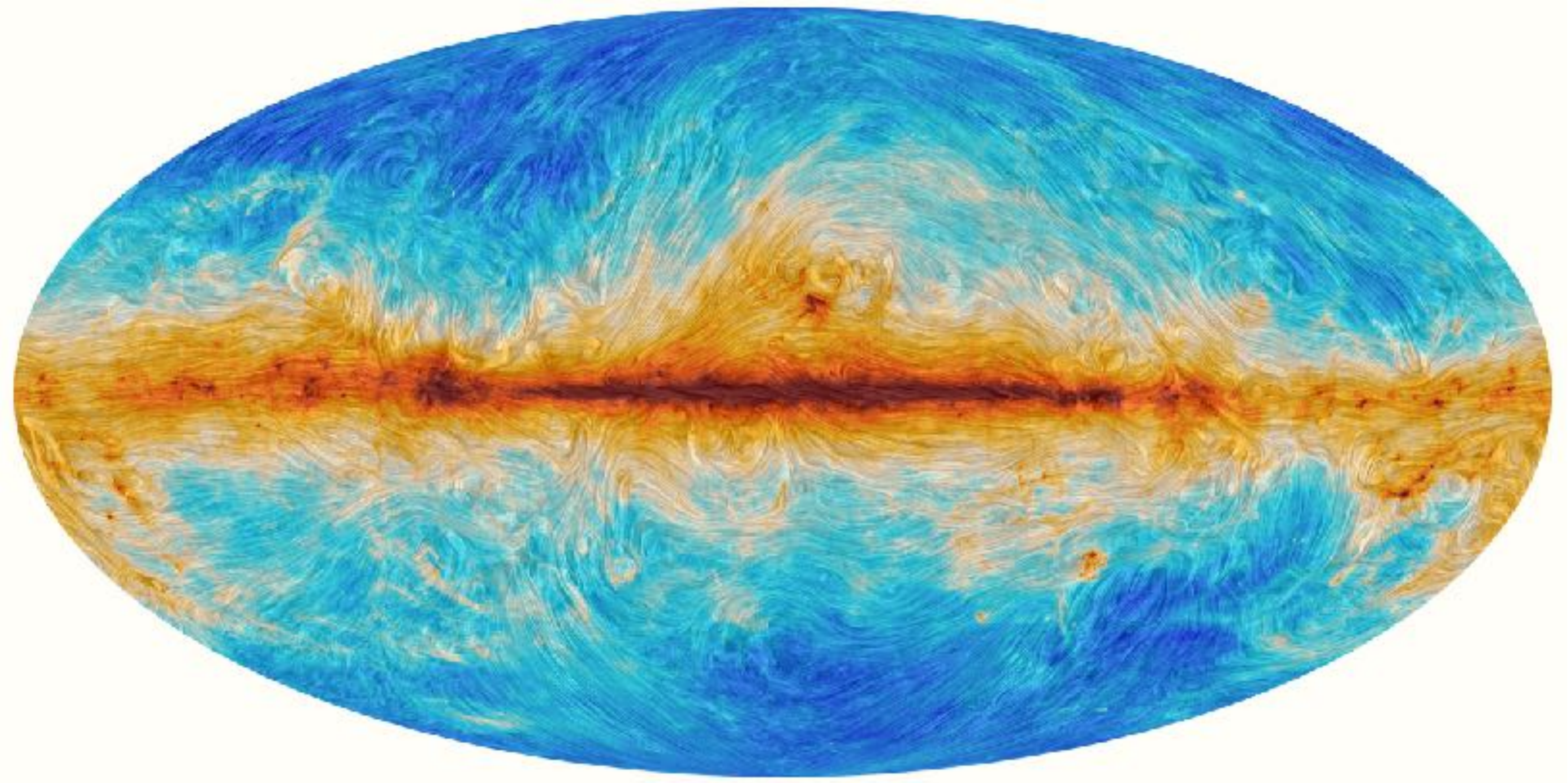
https://casaguides.nrao.edu/index.php/VLA_Data_Combination-CASA5.0.0

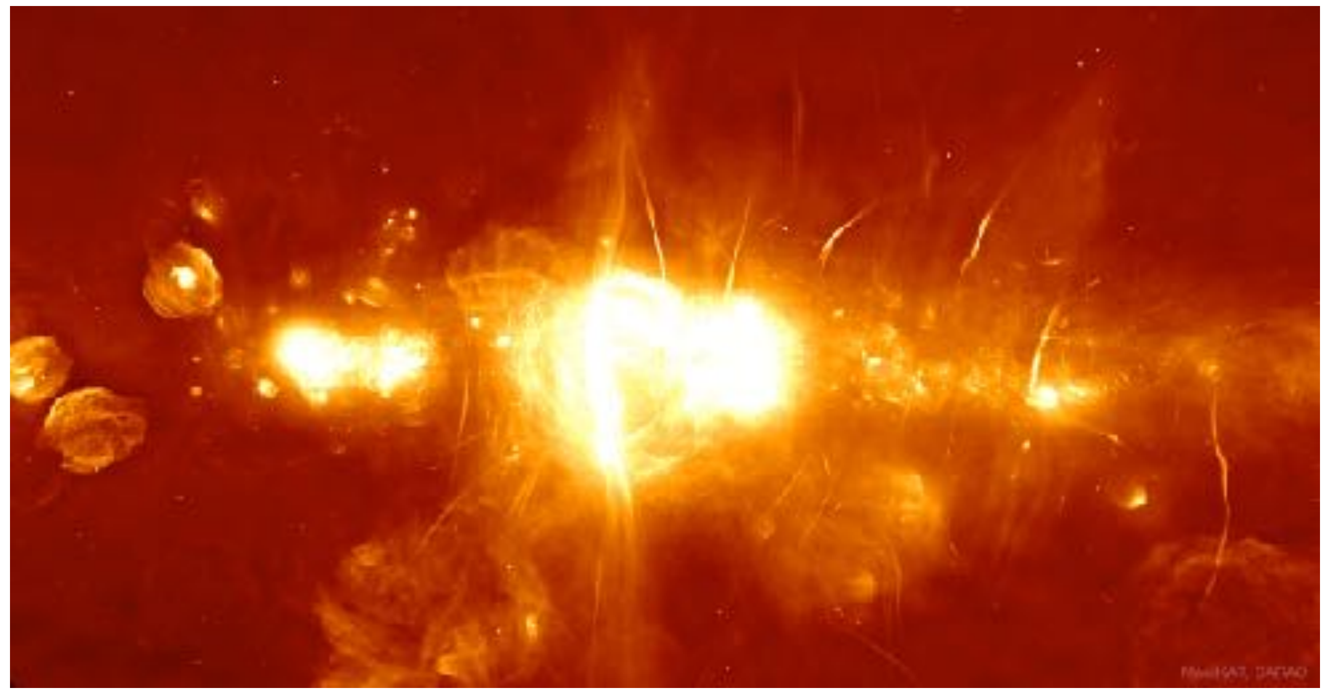
# Continuum and spectral lines

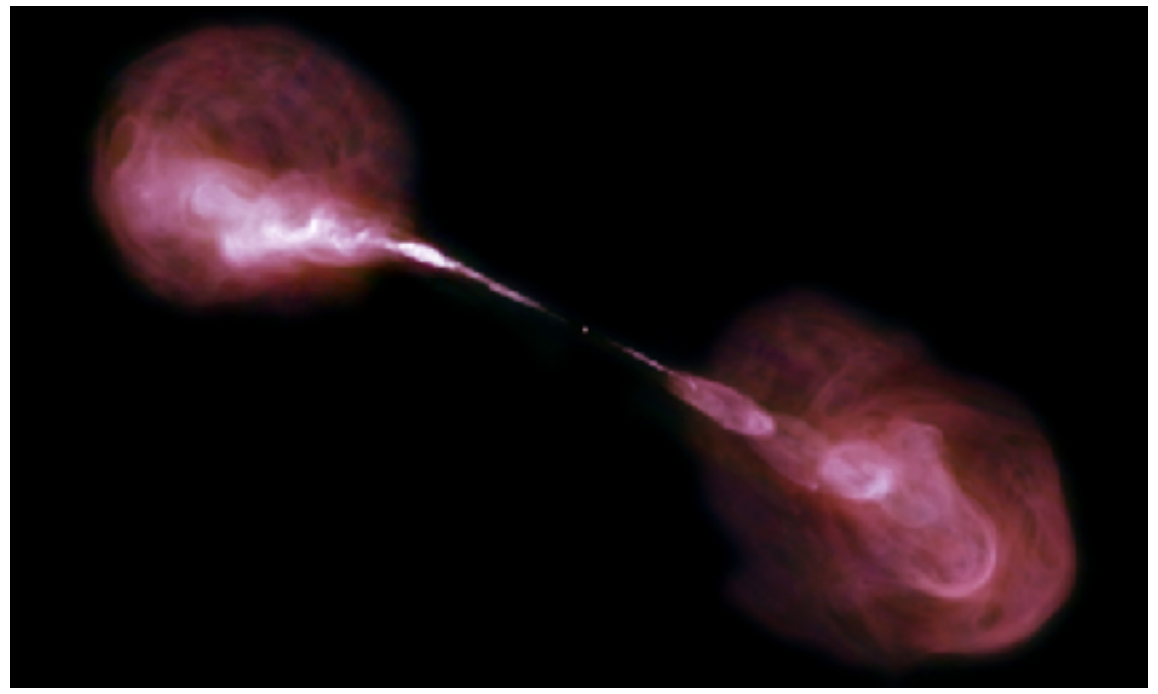


# Continuum and spectral lines

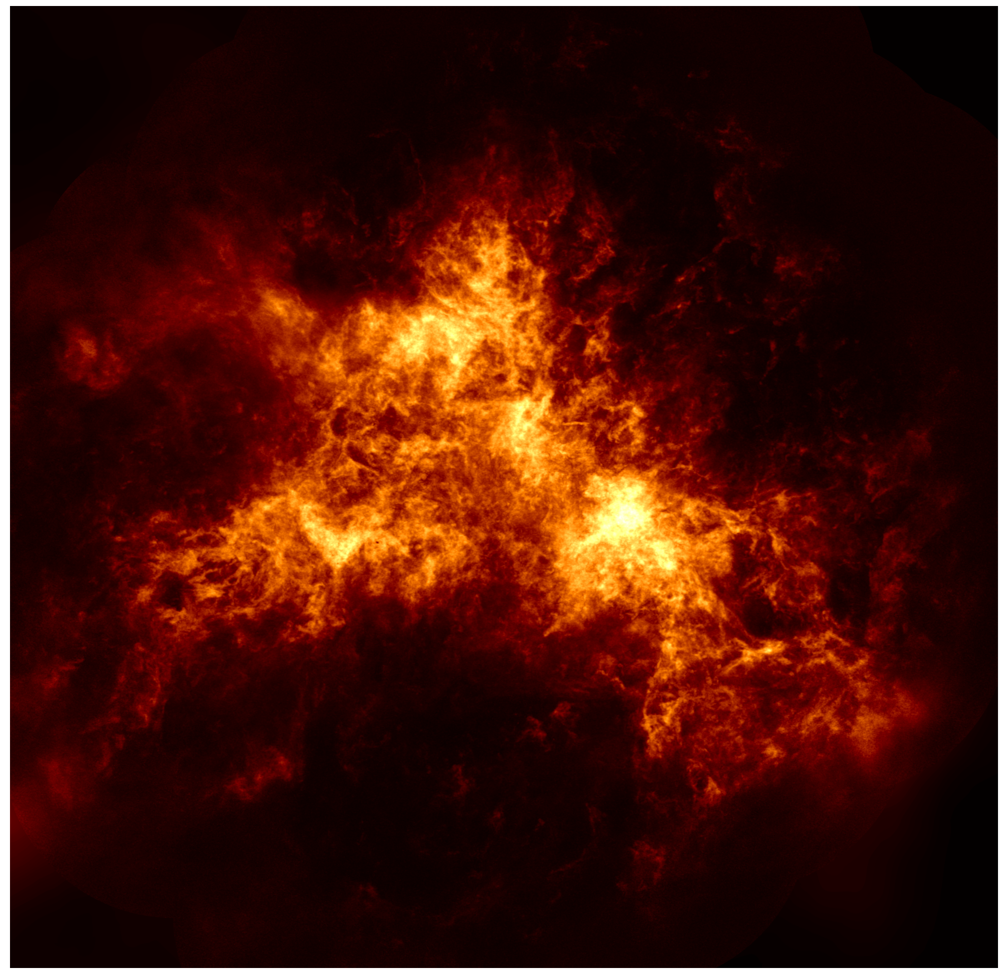
## Continuum sources:

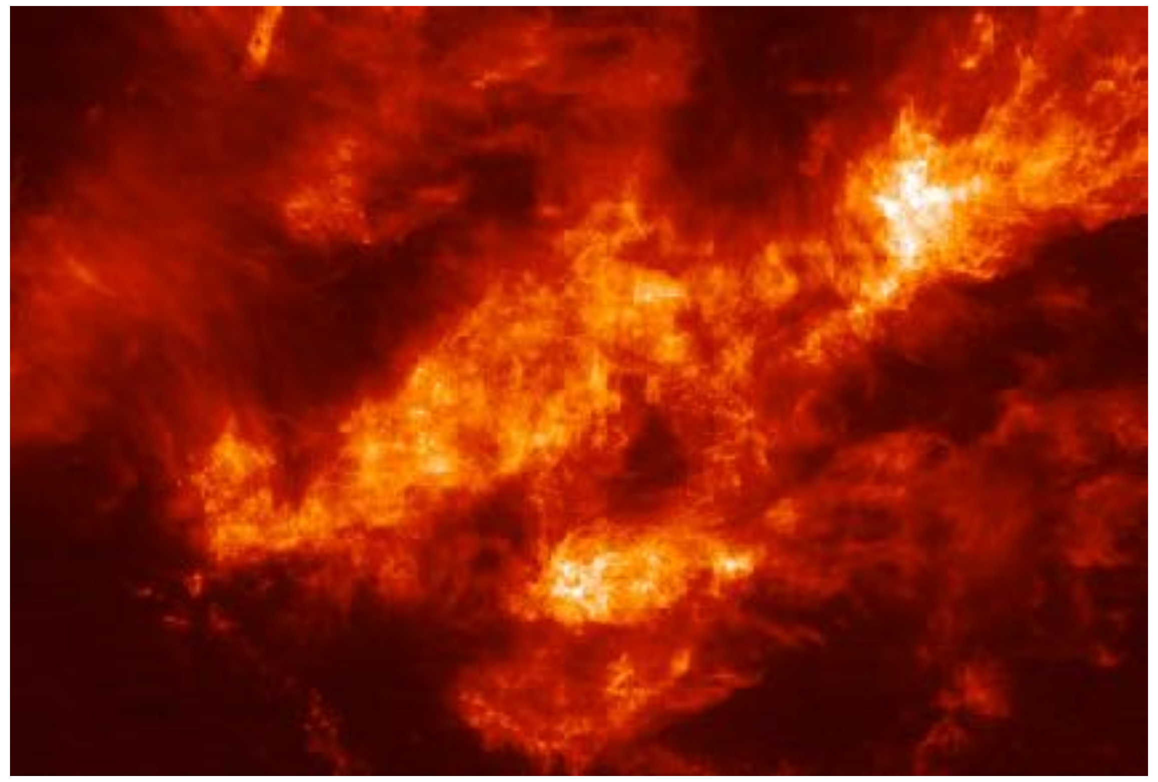


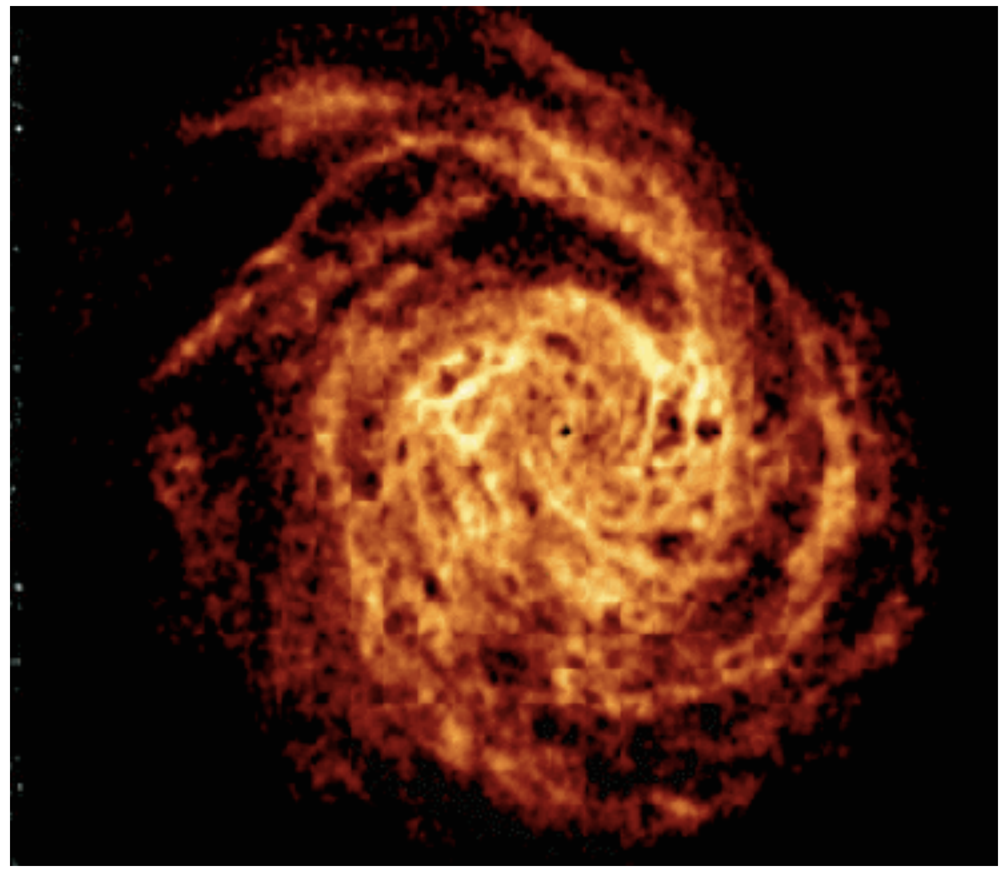


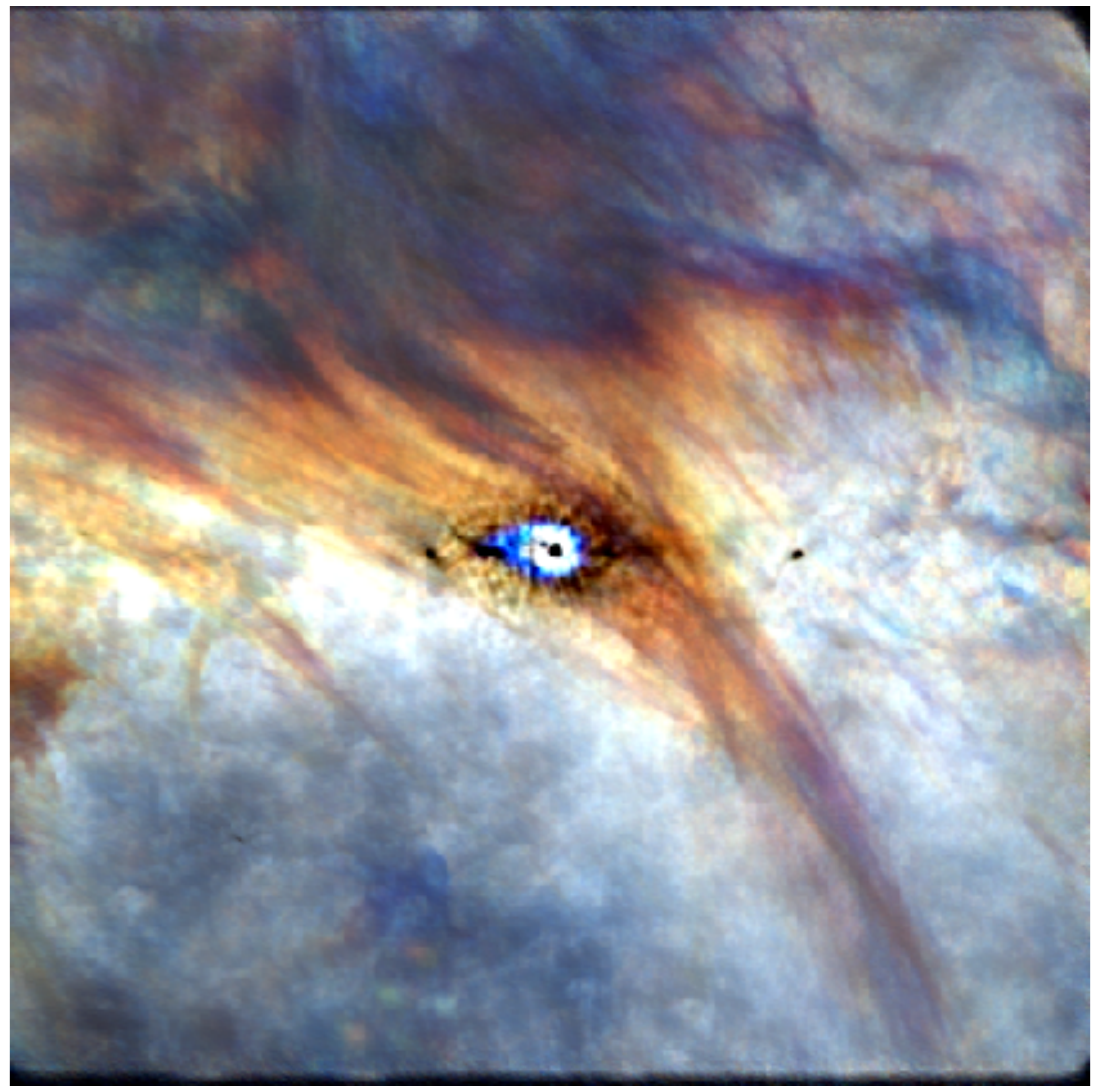


## Spectral line sources:









# Spectral lines

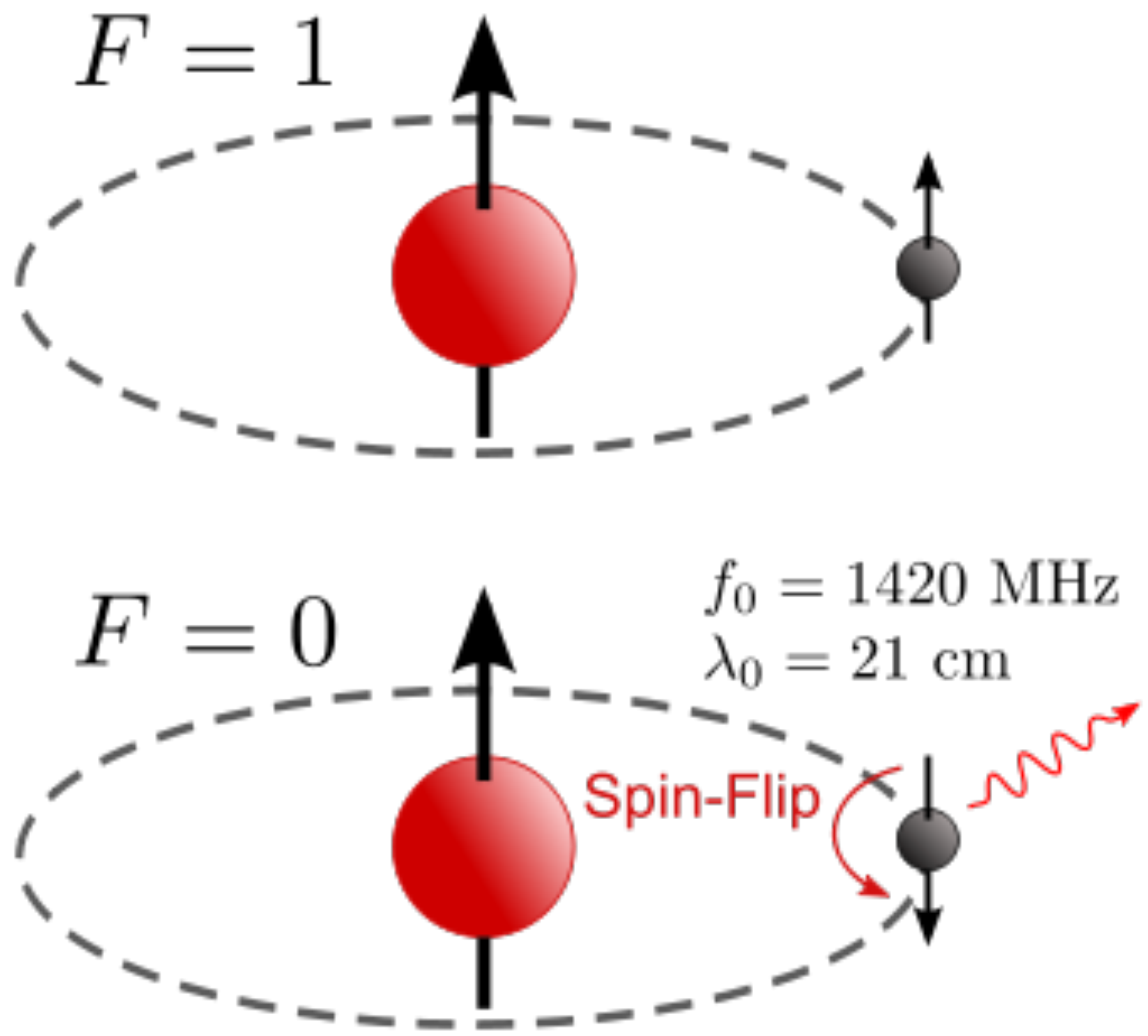
What are the mechanisms for spectral line emission?

What information can we learn from spectral line transition?

# Spectral lines

**What are the mechanisms for spectral line emission?**

- Atomic transitions
- Spin flip transition
- Rotational transition of molecules
- Recombination lines



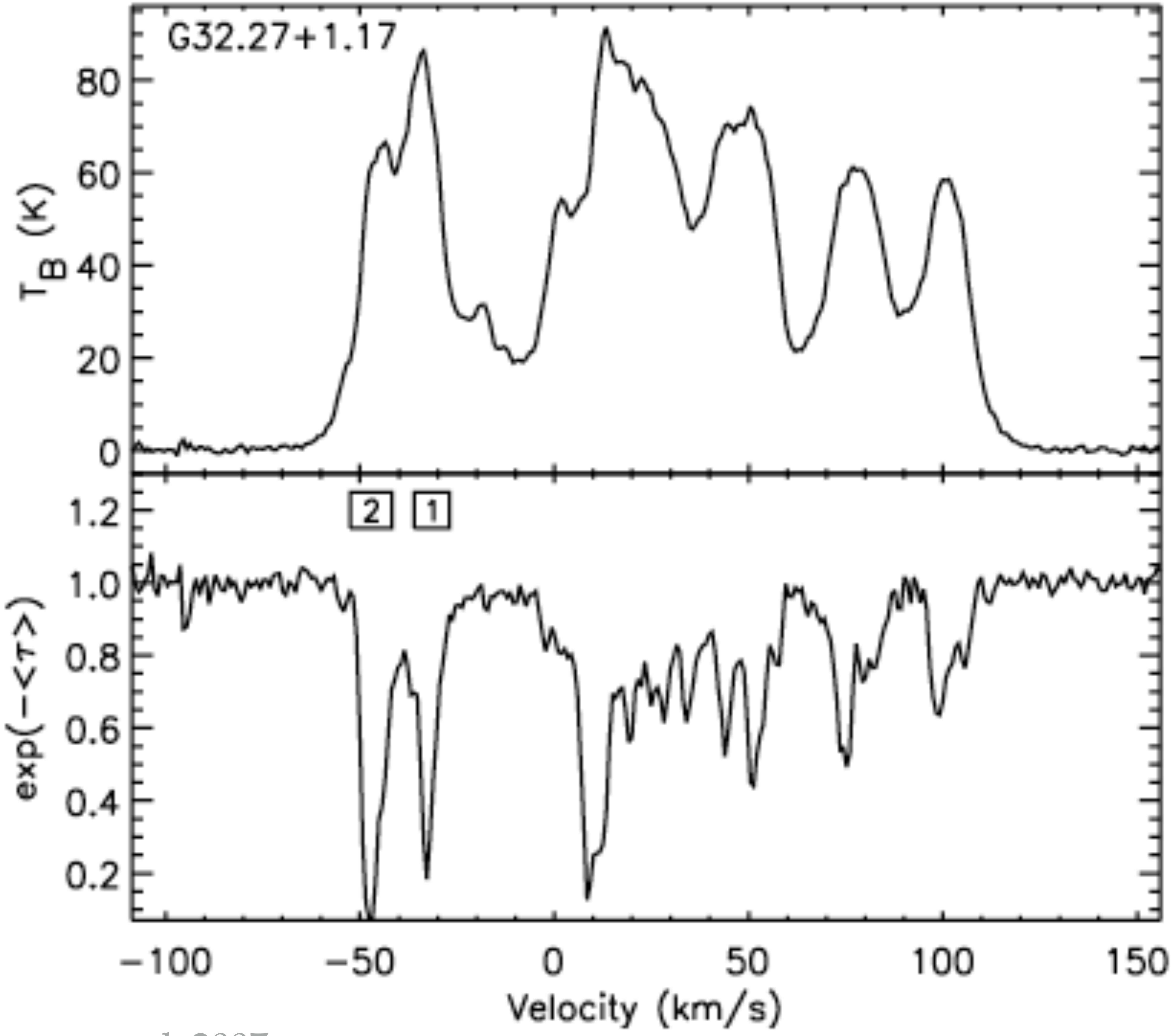

**What information can we learn from spectral line transition?**

- Chemistry
- Mass
- Dynamics
- Physical conditions (e.g. temperature, shocks)
- Turbulence

# Emission and Absorption

**Each Gaussian component corresponds to a gas cloud in the Milky Way.**

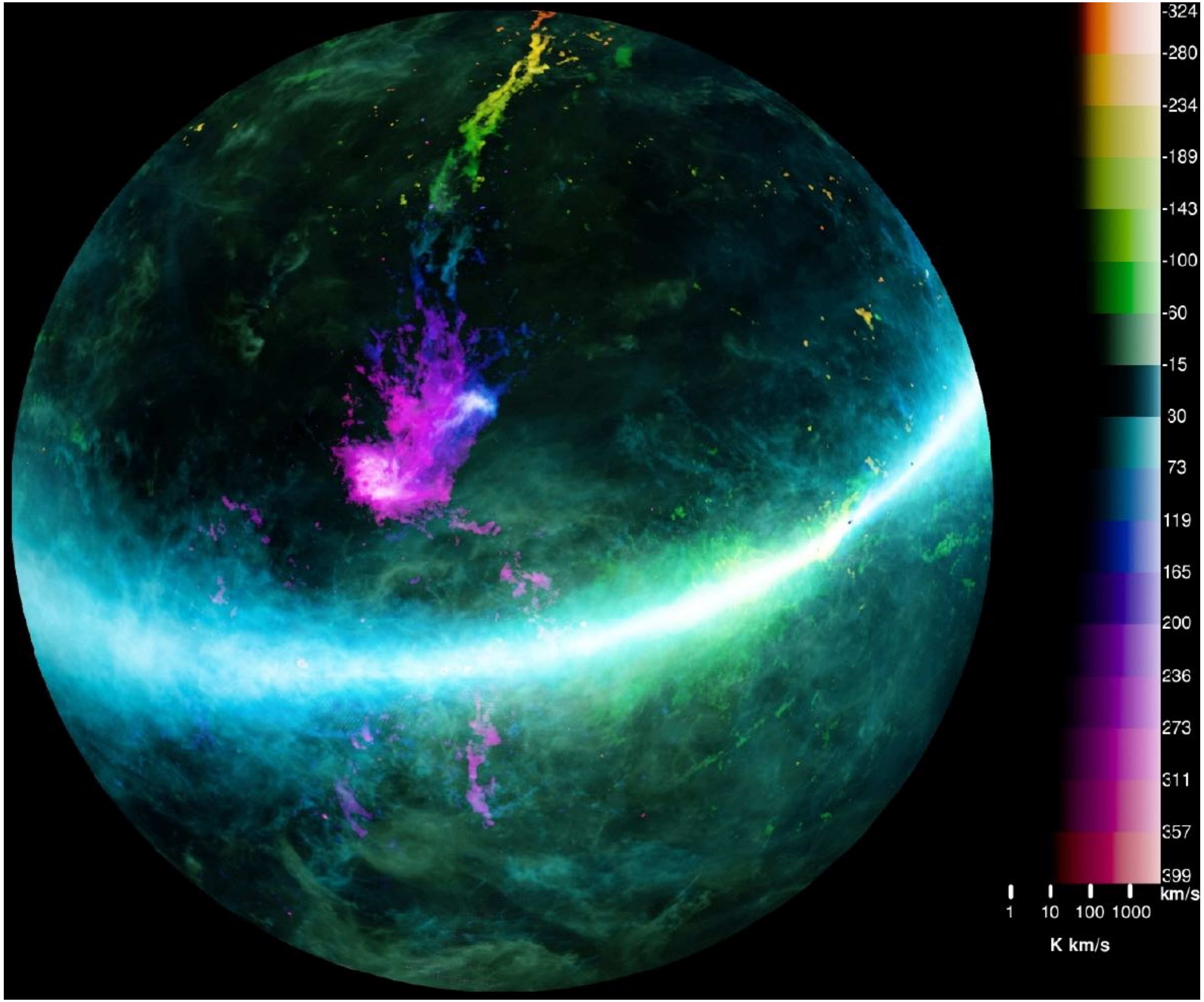
- Emission → generally warm gas
- Absorption lines → generally cold gas




Strasser et al. 2007

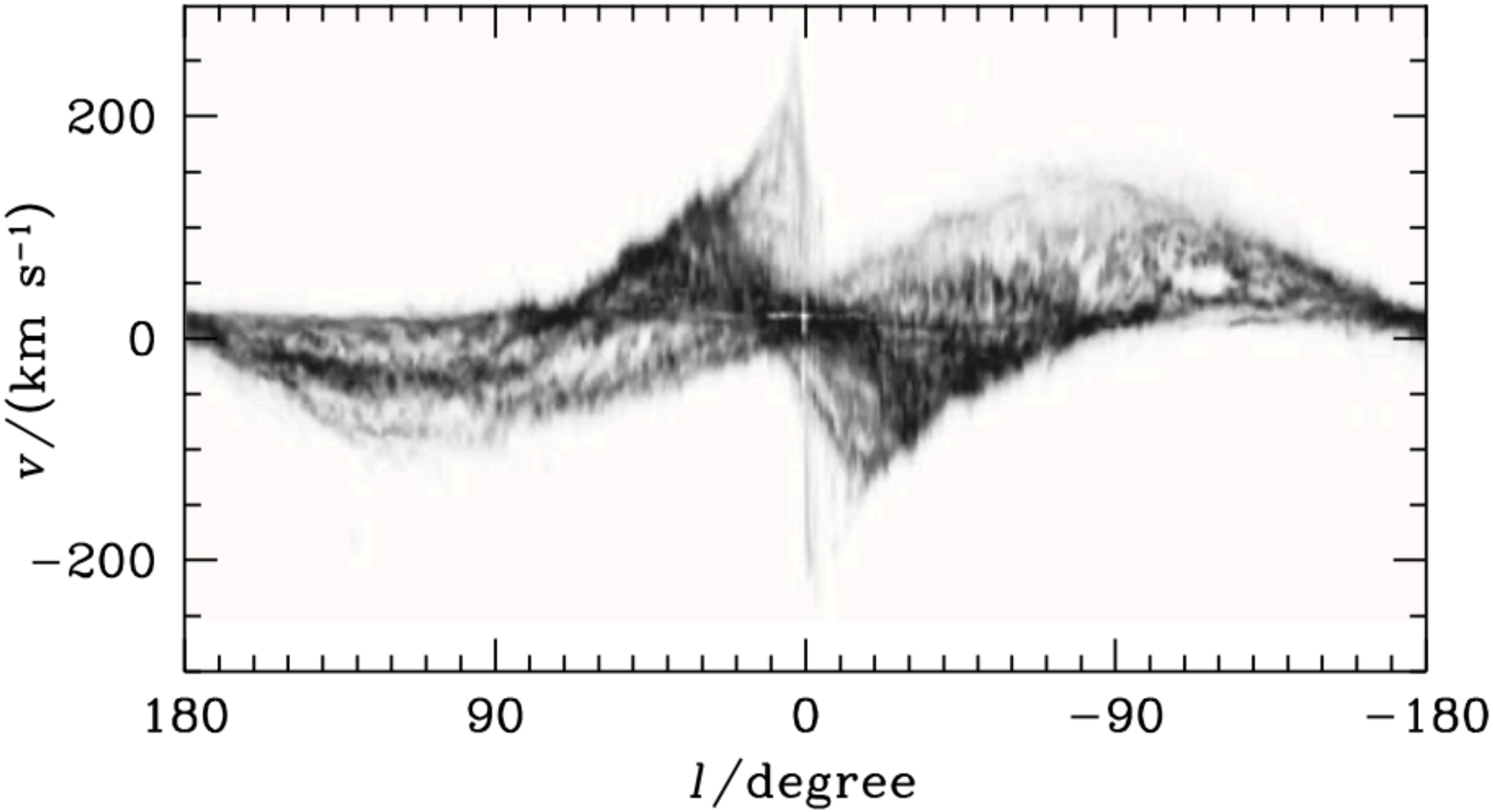
# HI

HI in the Milky Way + the Magellanic system
Warm HI (~4000 K) in emission



# Motion of the gas

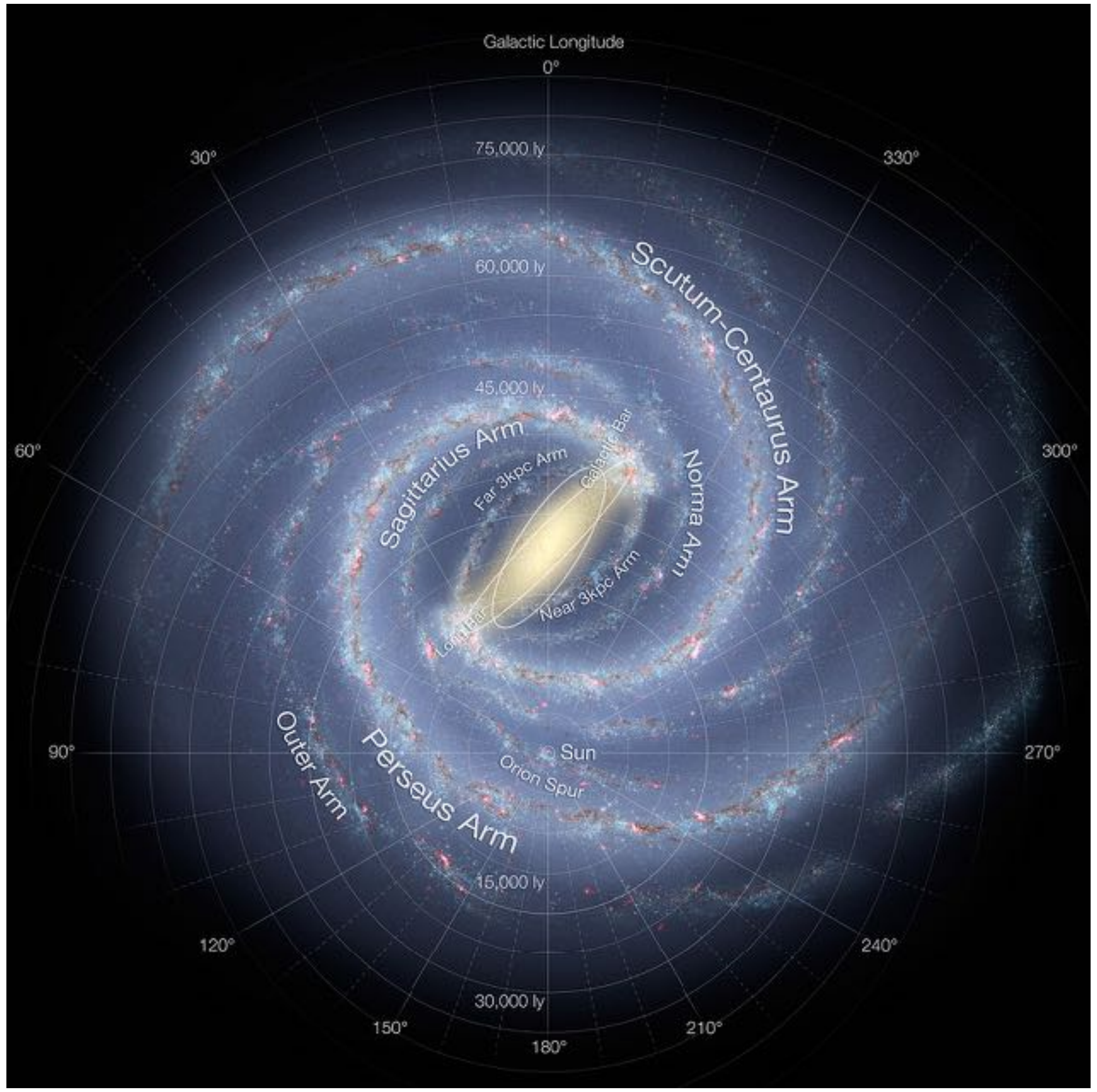
- Figure shows $I\,(l, b = 0°, v_R)$ plotted in the $l$–$v_R$ plane. The distribution of the interstellar gas has to be found out from plots like this.



# Motion of the gas

**Reconstructed gas distribution in the galactic plane.**

Note the presence of spiral structures -> spiral arms



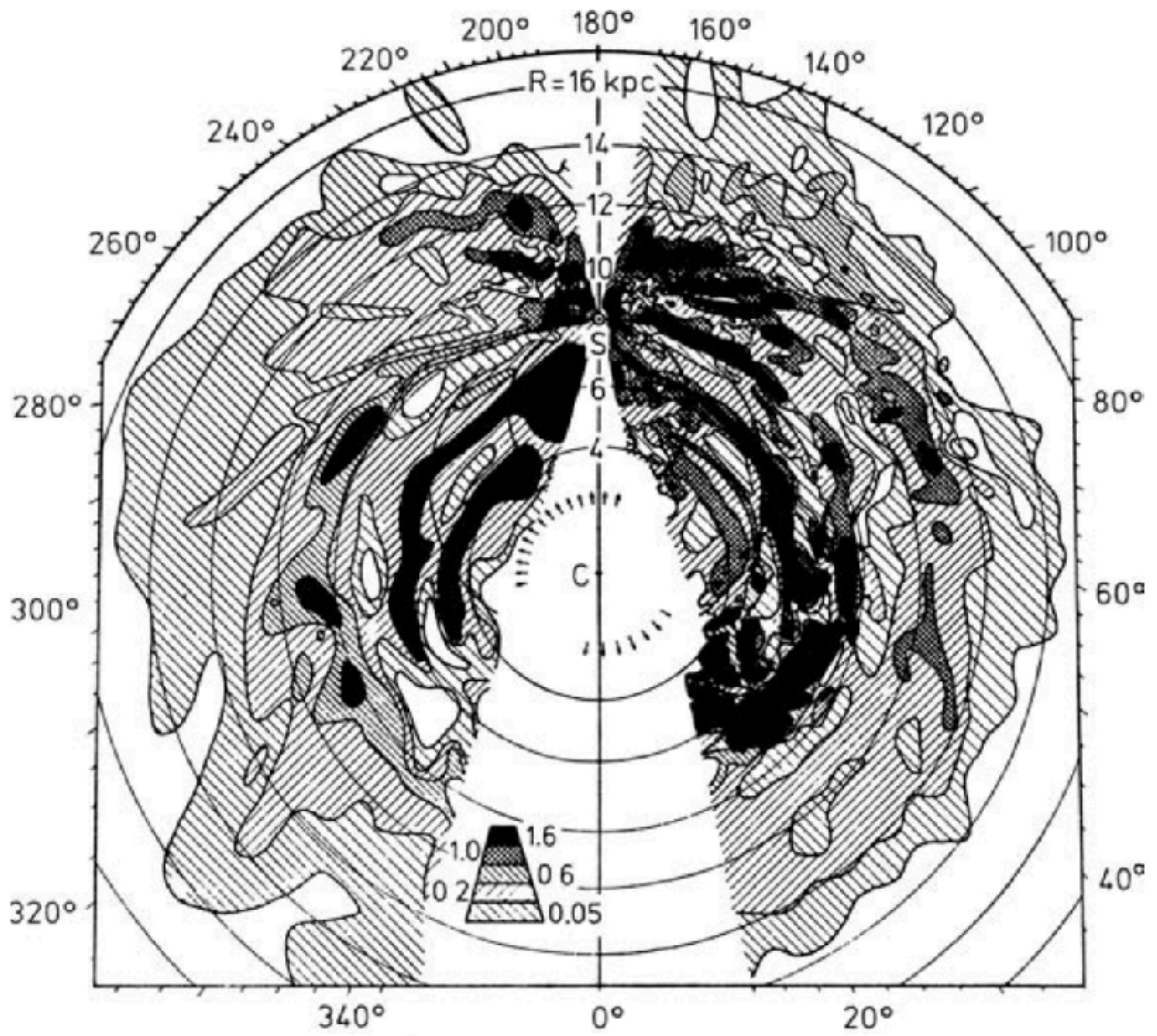
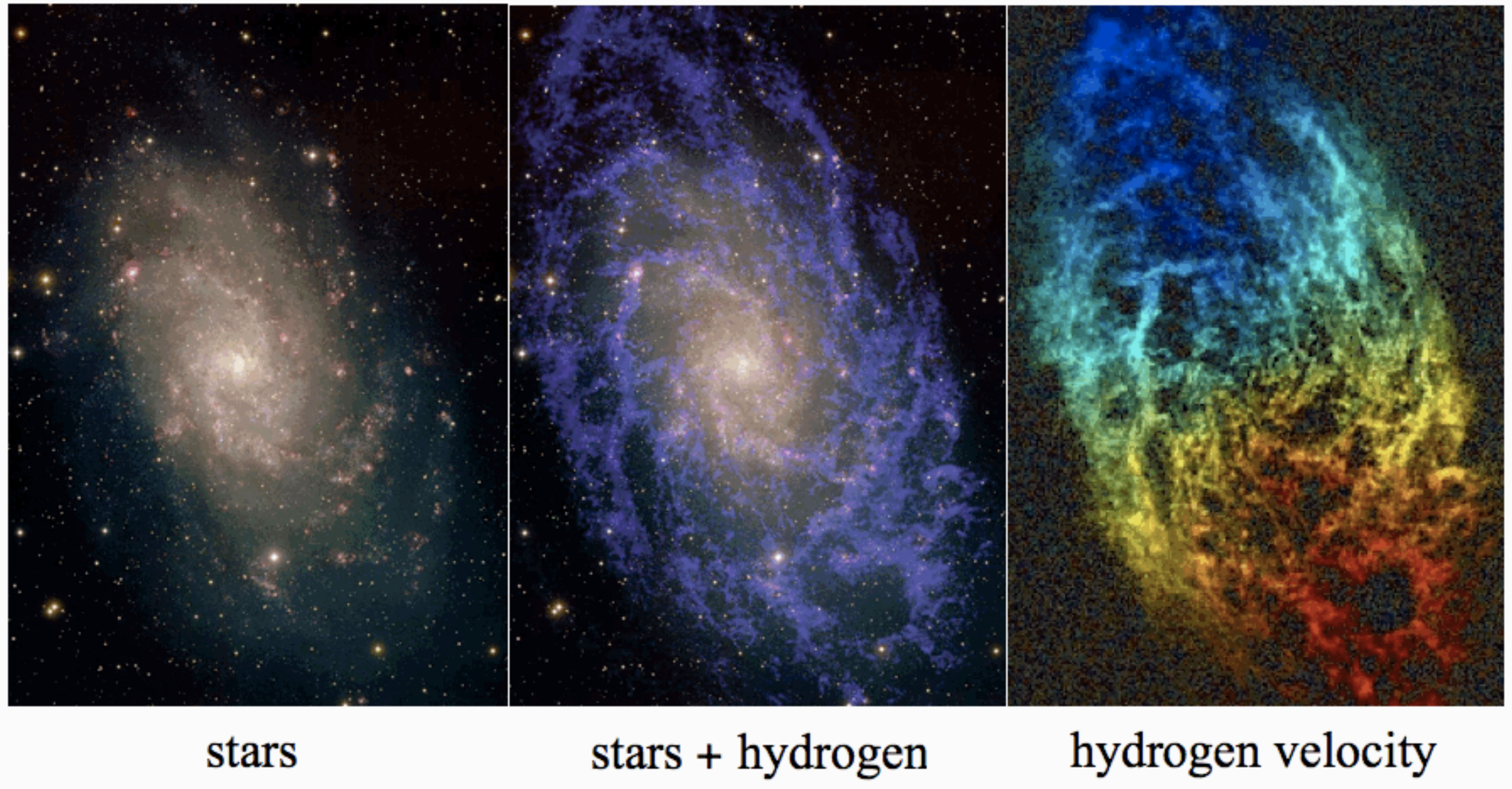



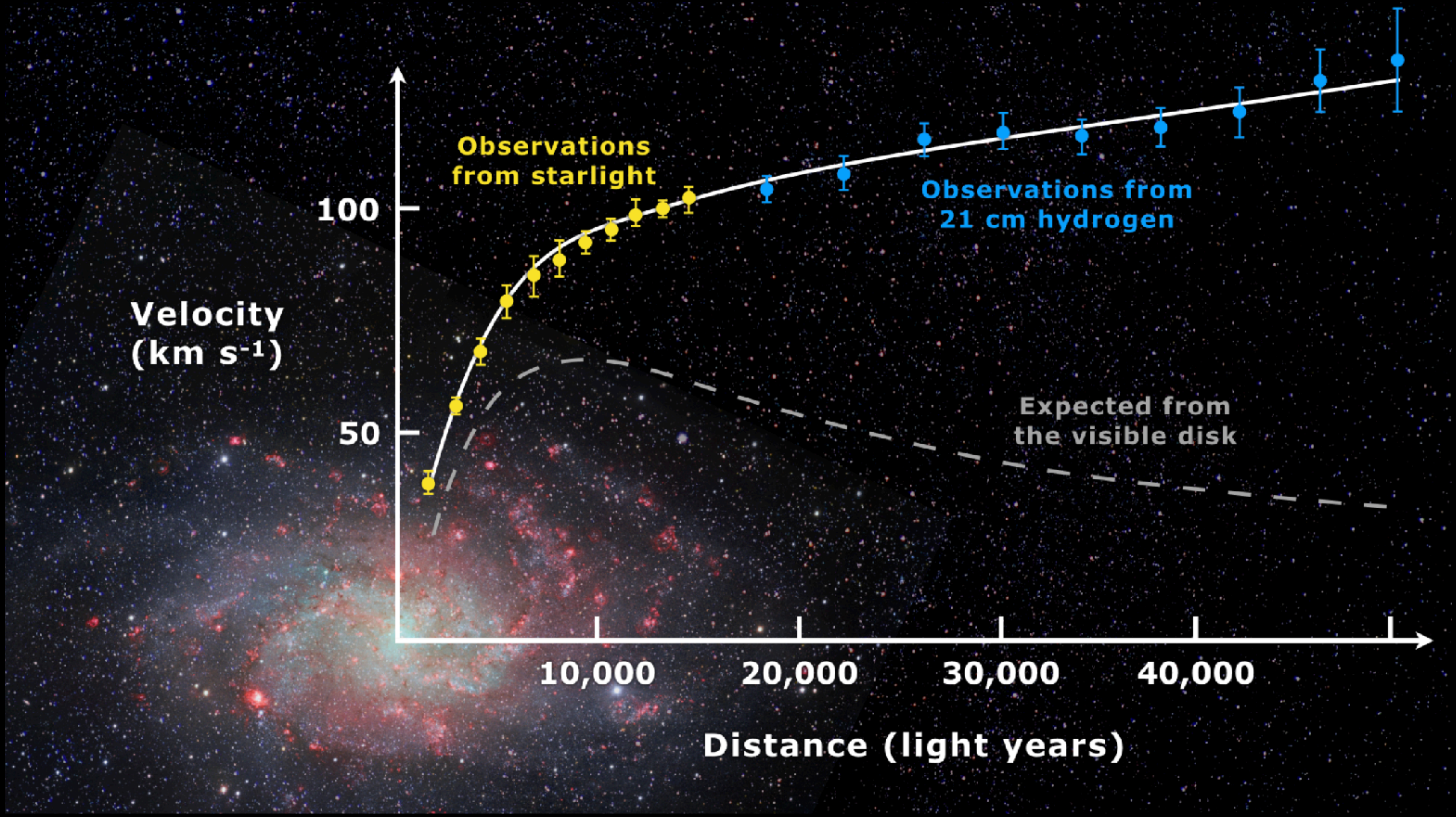

**Fig. 6.10** The distribution of neutral hydrogen in the galactic plane, as found by Oort, Kerr and Westerhout (1958) from 21-cm observations. (©Royal Astronomical Society. Reproduced with permission from *Monthly Notices of Royal Astronomical Society*.)

# HI in other galaxies



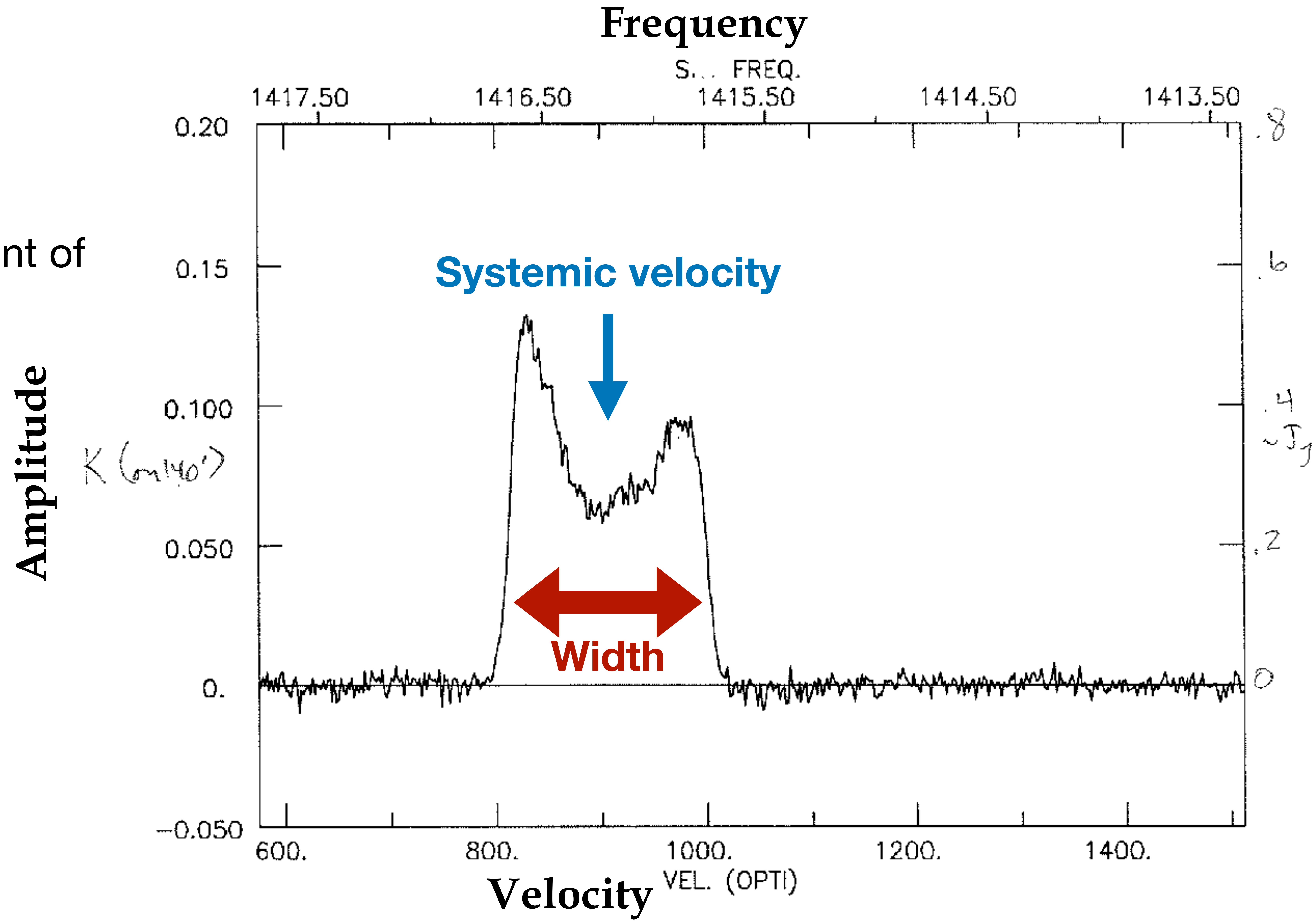

Optical and HI images of M33 (left and center) On the right is illustrated the Doppler velocities of the HI, color coded for redshift and blueshift.

# Rotation curve



# HI in spiral galaxies

UGC 11707 is a very blue spiral galaxy, indicative of a large amount of HI in the galaxy

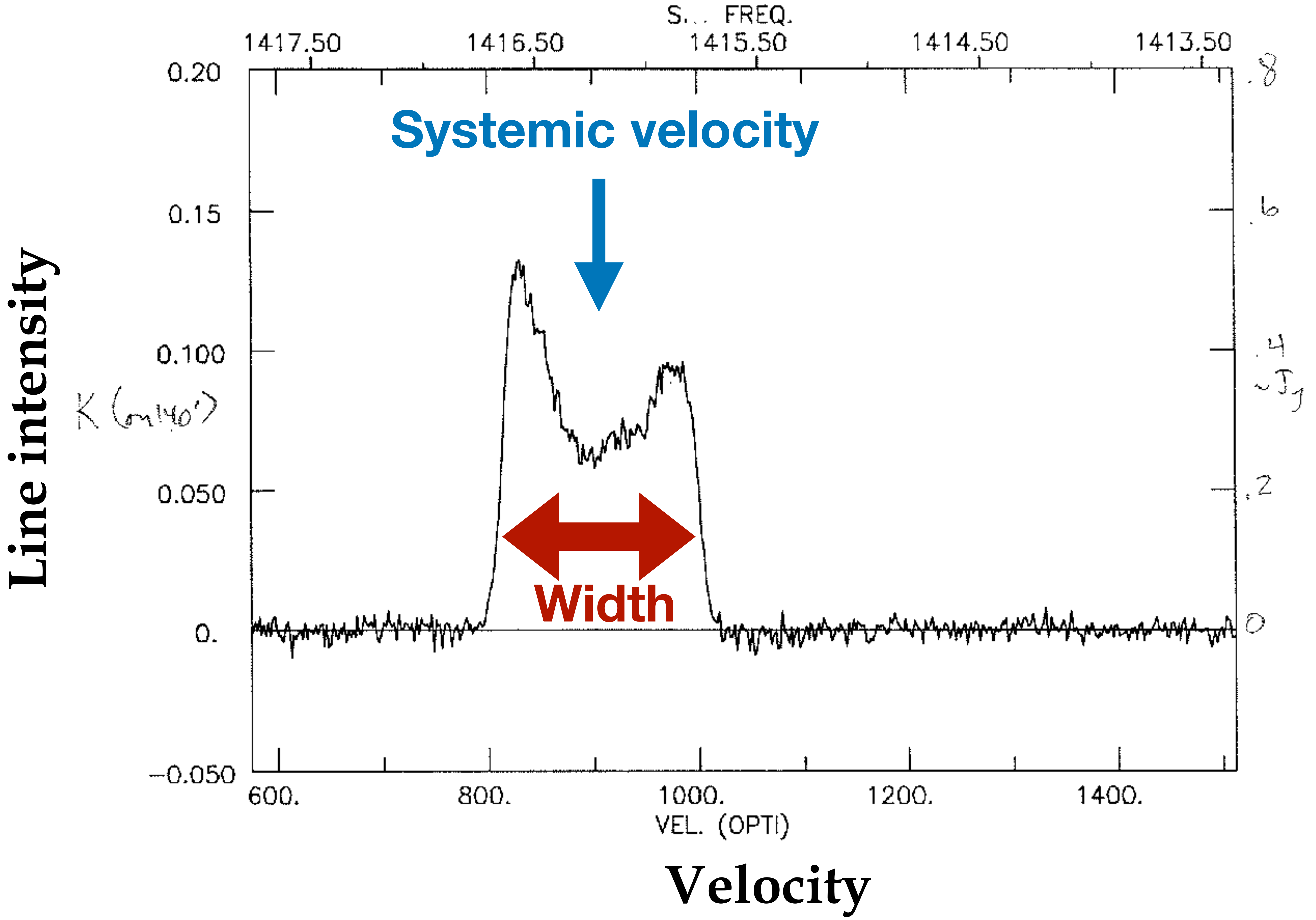



HI profile of UGC 11707
https://www.cv.nrao.edu/~sransom/web/Ch7.html

# HI in spiral galaxies

We use the HI profiles of galaxies to calculate the following parameters:

1. The midpoint of the emission profile in km/s, yields the **systemic velocity** of the galaxy. This can be used to make an estimate of the redshift-**distance** using Hubble's law.
2. The **total HI line flux**, can be used to derive the total **HI mass**, using the estimated distance.
3. The observed width of the HI line profile, in km/s, gives the **observed Doppler broadening** due to the galaxy's **rotation**. In combination with an estimate of the galaxy's size and inclination on the plane of the sky, the width parameter can be used to make an estimate of the galaxy's total **dynamical mass**.



# HI in spiral galaxies

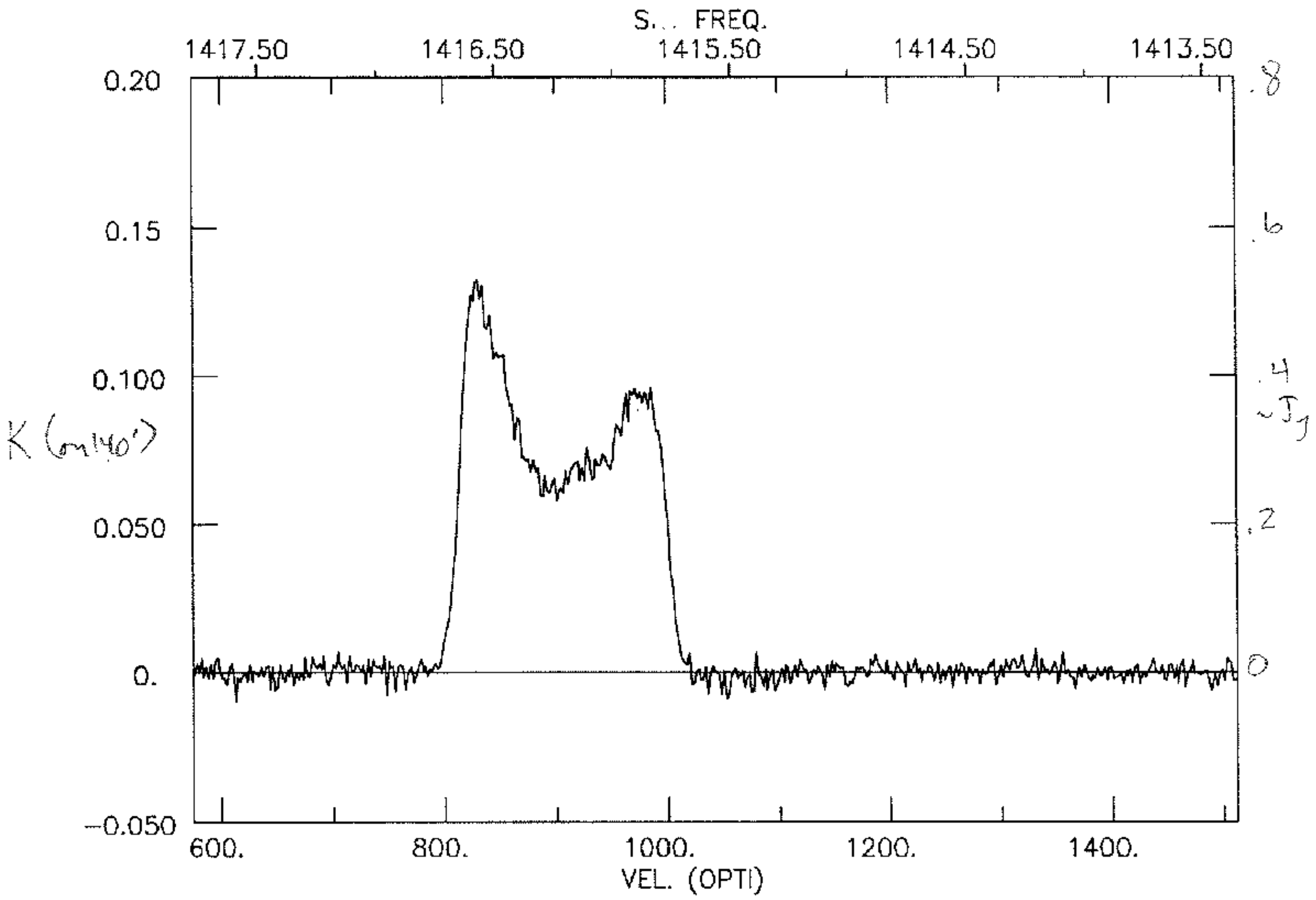
**Line intensity is proportional to HI mass, if the gas is optically thin $\tau << 1$**

$$\left(\frac{M_{\mathrm{H}}}{M_{\odot}}\right) \approx 2.36 \times 10^{5} \left(\frac{D}{\mathrm{Mpc}}\right)^{2} \int \left[\frac{S(v)}{\mathrm{Jy}}\right] \left(\frac{dv}{\mathrm{km\ s^{-1}}}\right)$$

HI mass of a galaxy    Distance    Integrated intensity

**Hubble flow distance** to the galaxy, based on the redshift of the line: $D = v/H_0$

Where $v$ is the velocity of the line centre (recession velocity) and $H_0$ is the Hubble constant.

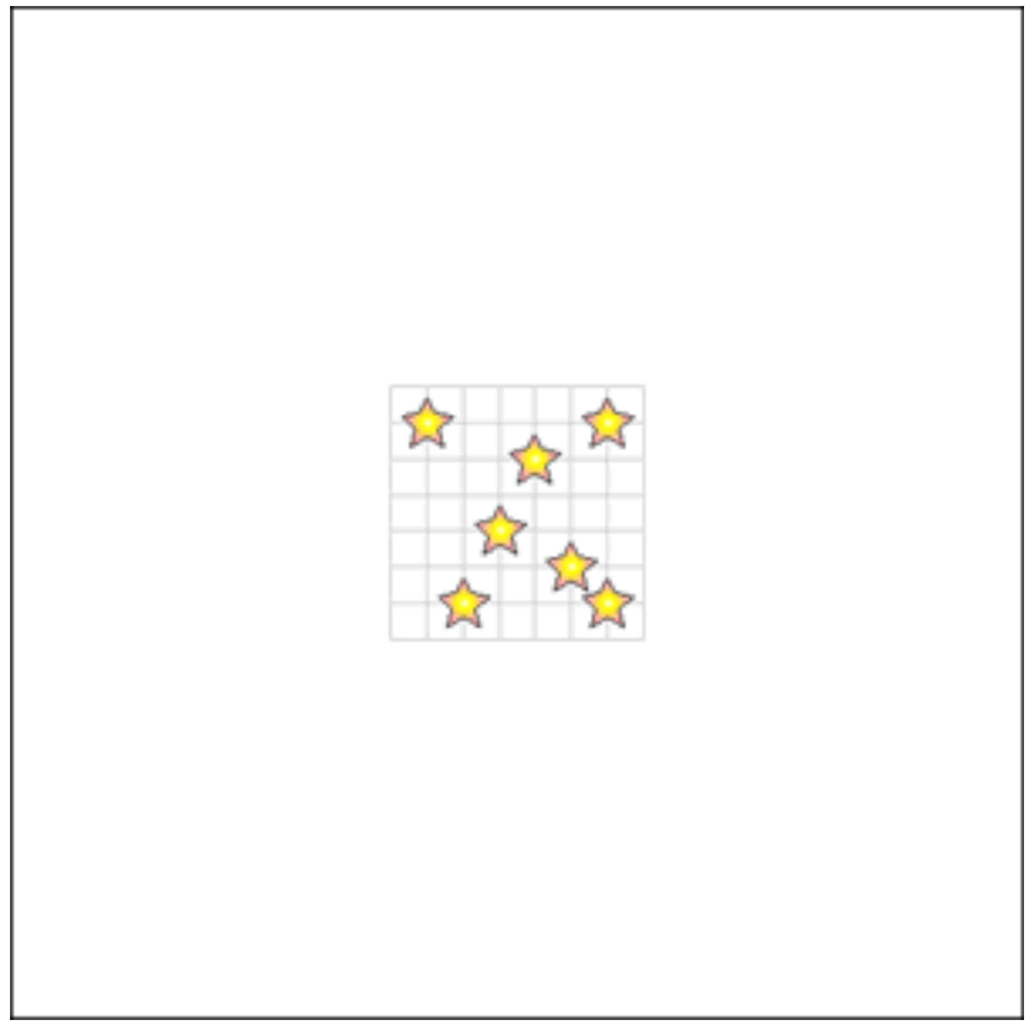


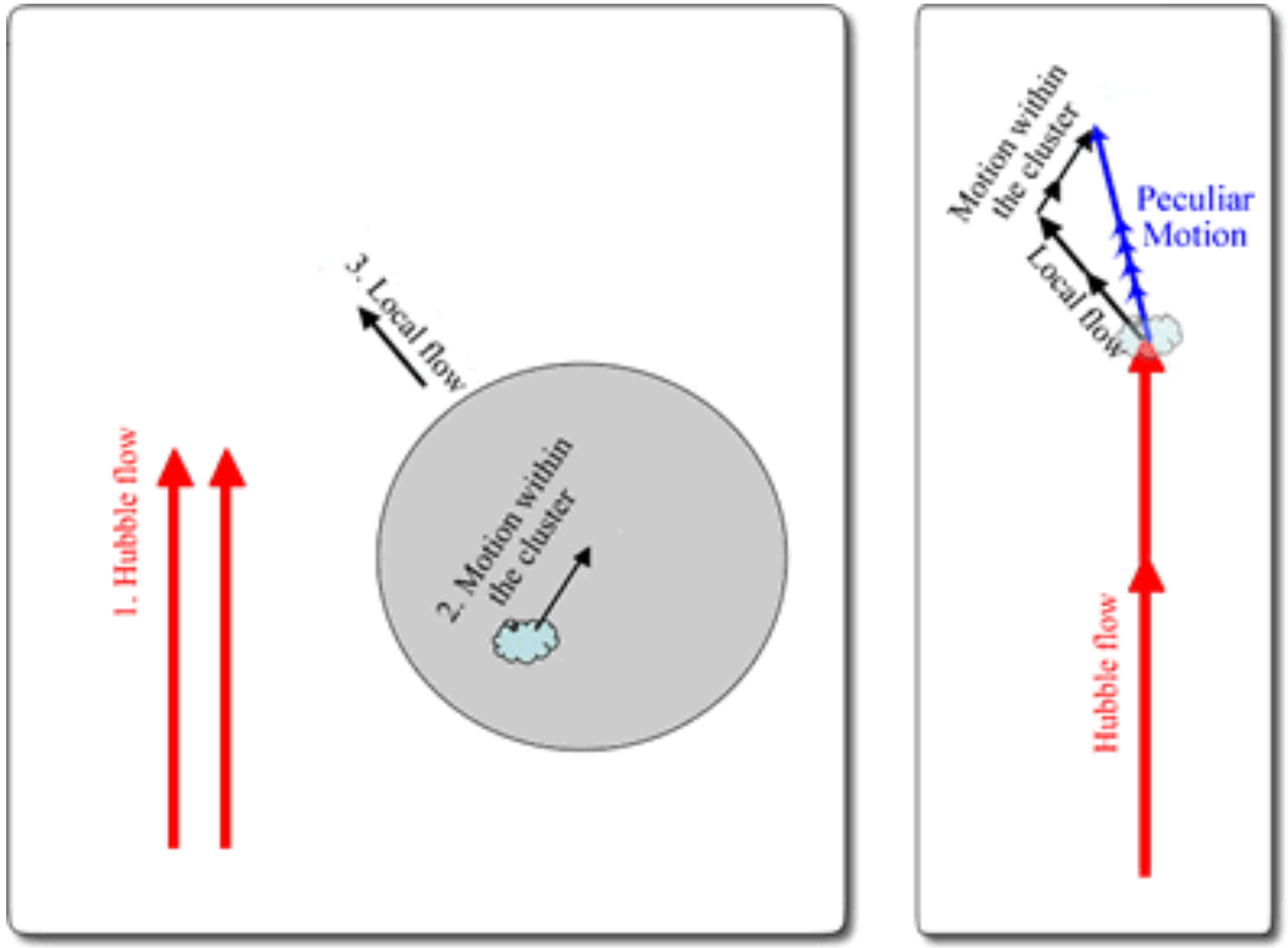

HI profile of UGC 11707
https://www.cv.nrao.edu/~sransom/web/Ch7.html

# Hubble flow

The **'Hubble flow' describes the motion of galaxies due solely to the expansion of the Universe.** The idea of the expanding Universe was first put forward by Edwin Hubble in 1929, after observing a **correlation between the redshifts of galaxies and their distances measured** using the period-luminosity relationship for Cepheid variable stars. Hubble found that all galaxies were moving away from us, and that the velocity of their recession was proportional to their distance from us, this is called the **Hubble Law:**
$v = H_0 \times D$

The motions of galaxies are influenced by more than just the Hubble flow. The net motions of galaxies are comprised of the Hubble flow, the local flow, and the motion of the galaxy within its cluster and/or group environment. These deviations from the pure Hubble flow are referred to as **peculiar motions**.

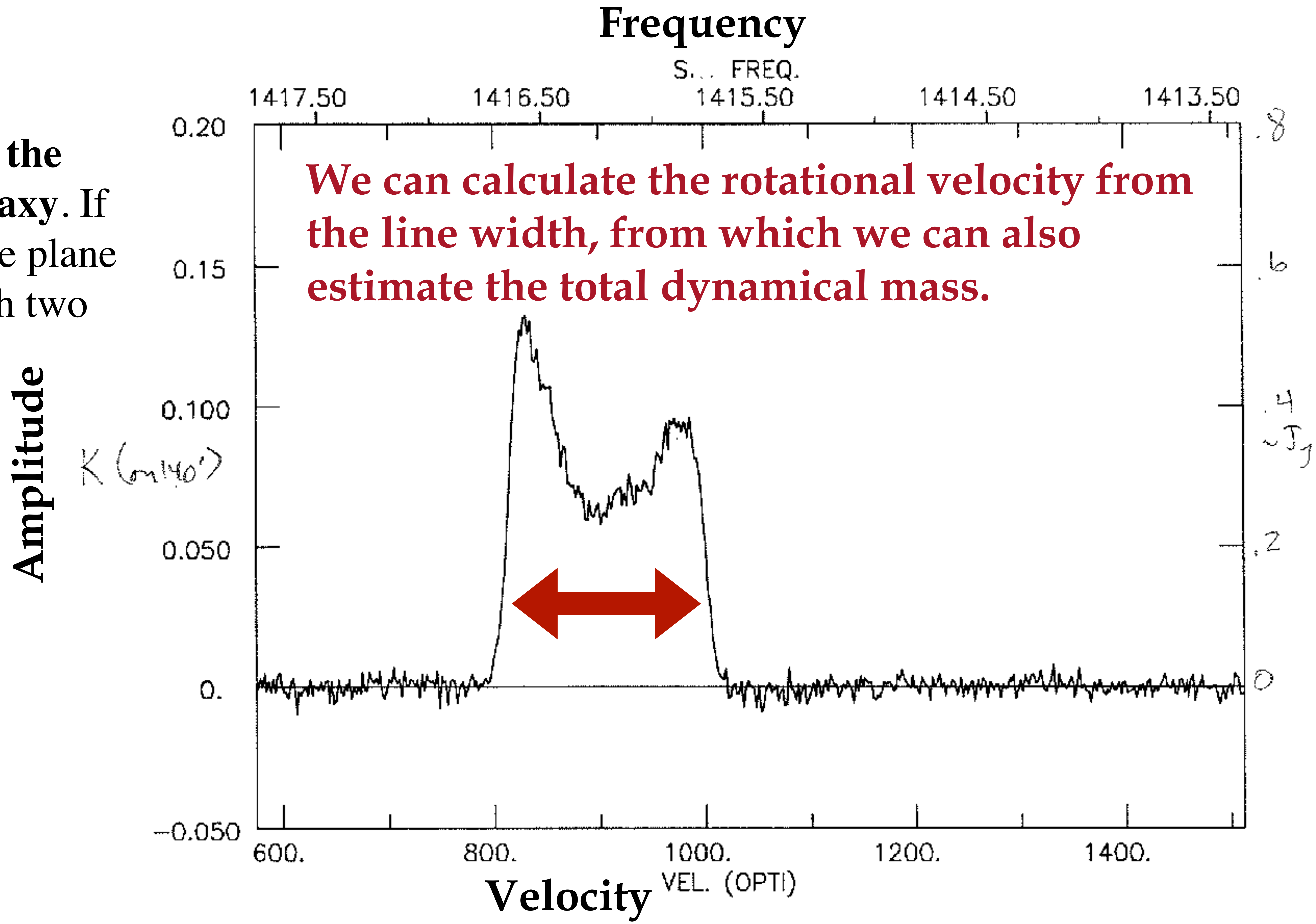





https://astronomy.swin.edu.au/cosmos/h/hubble+flow

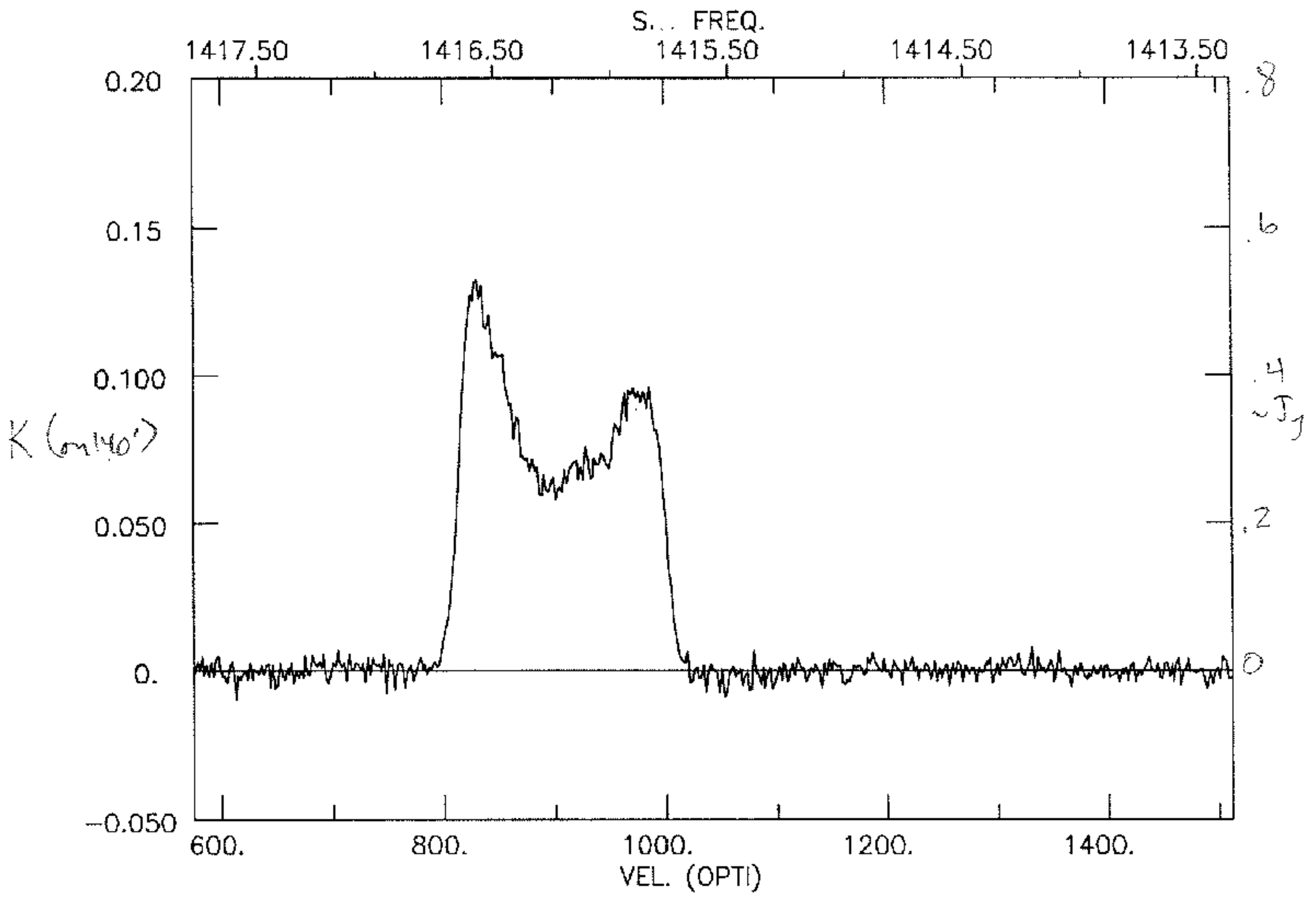
# HI in spiral galaxies

The **shape of the HI line is due to the gas rotating in the disk of the galaxy**. If a galaxy is inclined compared to the plane of the sky, we see a line profile with two peaks.




HI profile of UGC 11707
https://www.cv.nrao.edu/~sransom/web/Ch7.html

# HI in spiral galaxies




$$v(r) = \frac{v_{\rm r}(r)}{\sin i}$$

- Where $v(r)$ is the rotational velocity at radius r,
- $v_r(r)$ is the tangential component of the rotational velocity, contributing to the width of the line profile,
- And $i$ is the inclination of the galaxy compared to the plane of the sky. The inclination is proportional to the axis ratio of the galaxy.

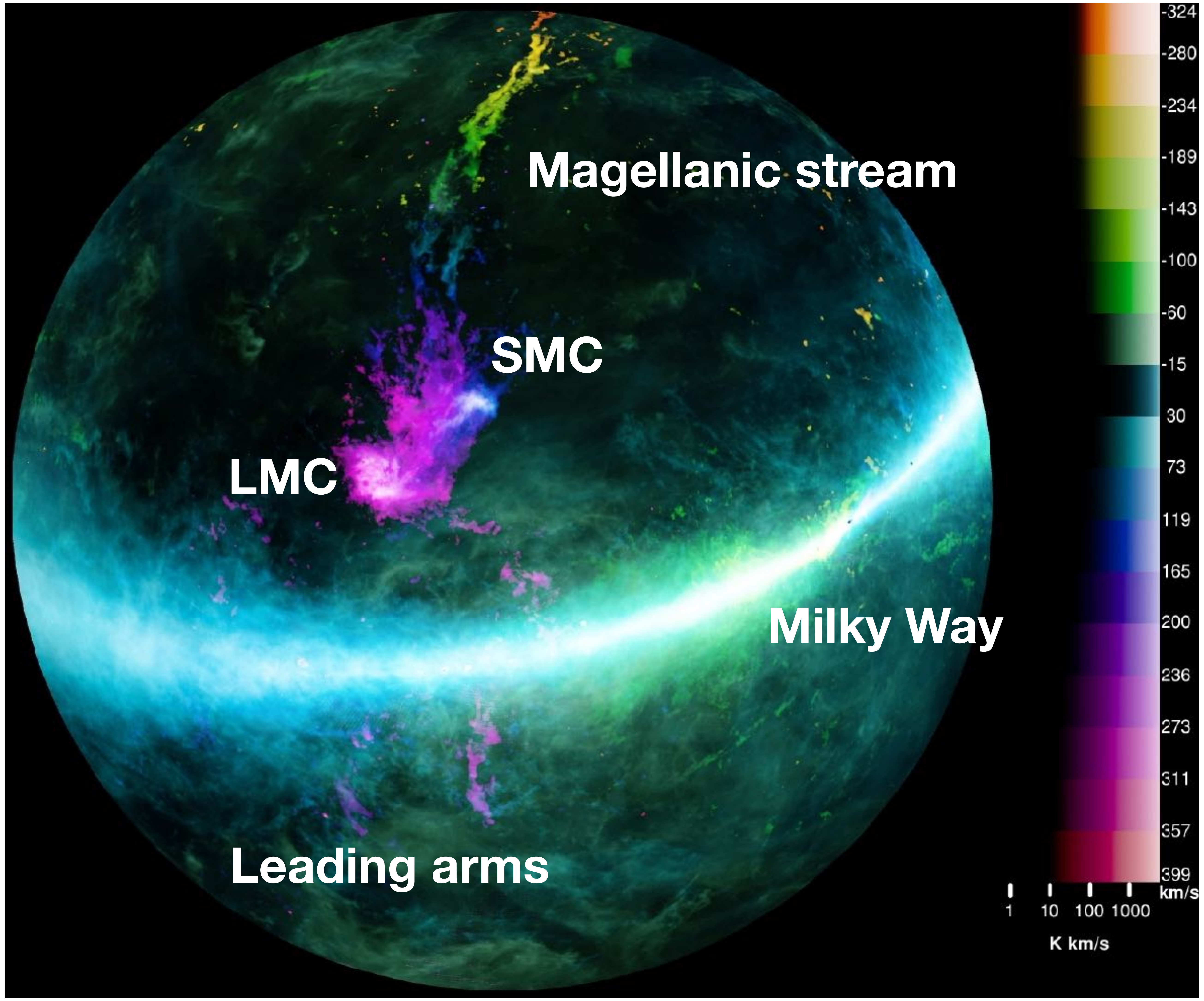
The galaxies **dynamical mass inside a radius r** is:

$$\left(\frac{M}{M_\odot}\right) \approx 2.3 \times 10^5 \left(\frac{v}{\rm km\ s^{-1}}\right)^2 \left(\frac{r}{\rm kpc}\right)$$

Here $v$ is the rotational velocity at radius r.

# Tidal interactions

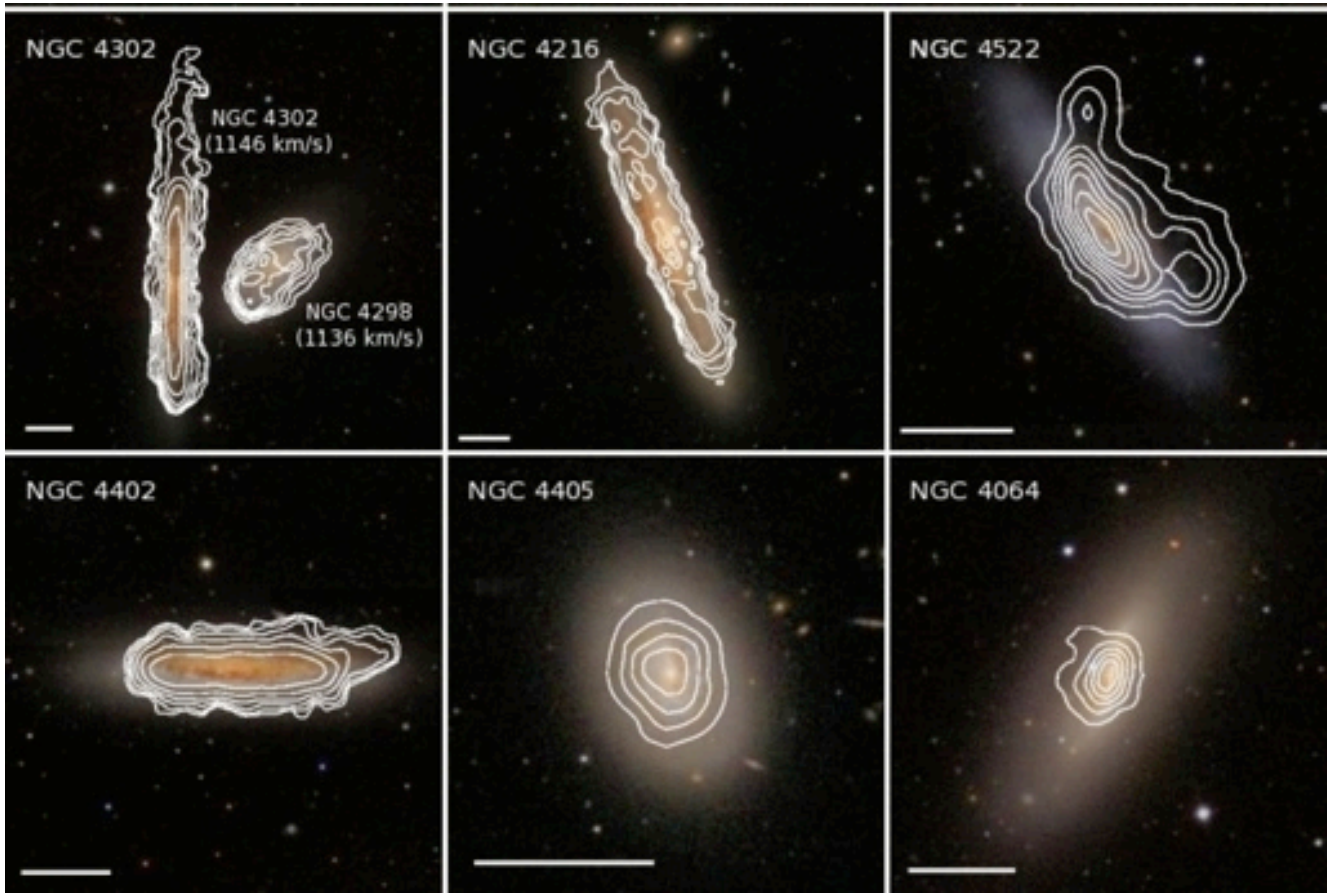
HI image




Optical image

# Gas removal in galaxy clusters

**Galaxies in the Virgo cluster**, optical image + HI contours.
They have significantly smaller HI disks compared to galaxies not in clusters.

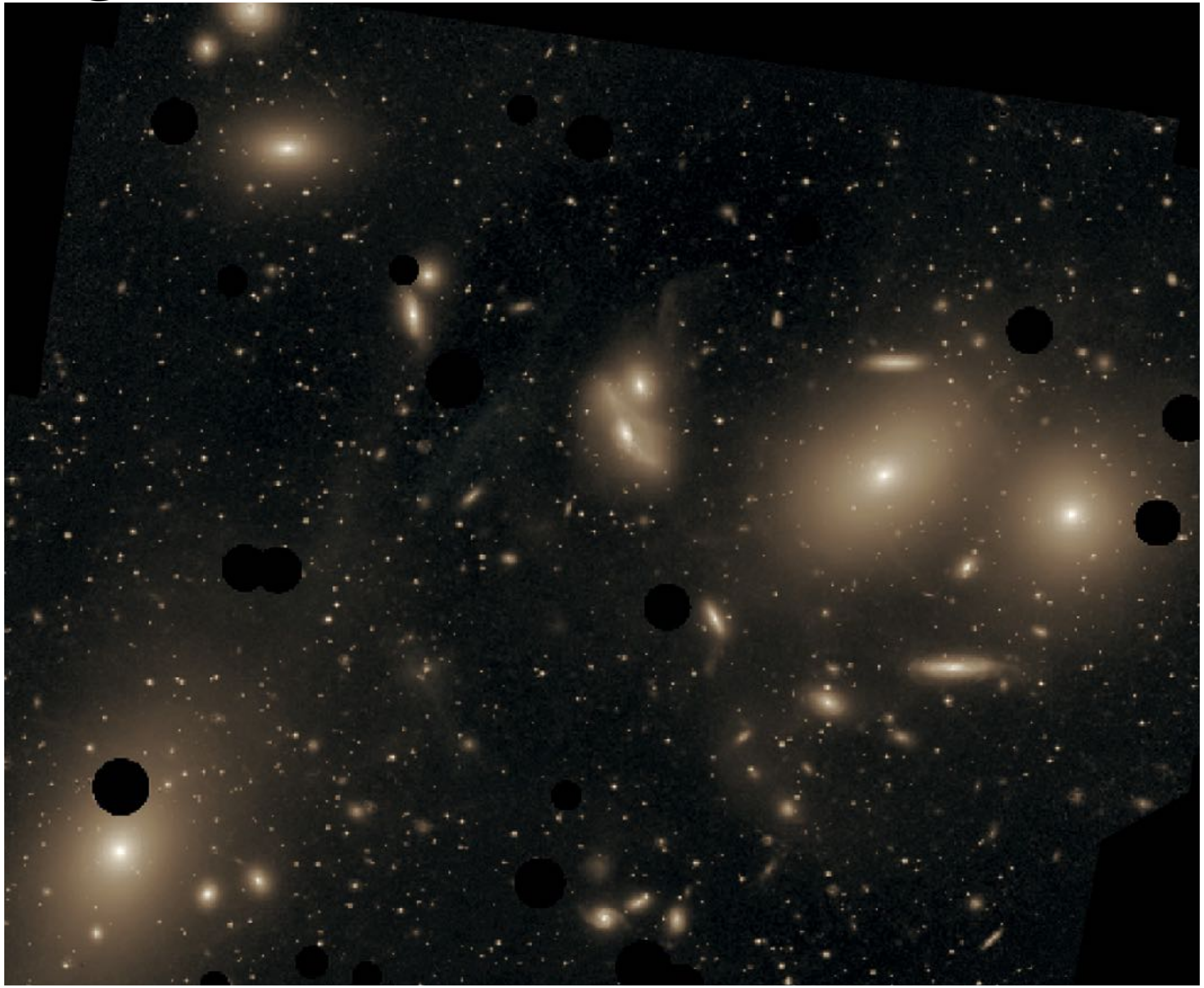



Gas removal processes in galaxy clusters:

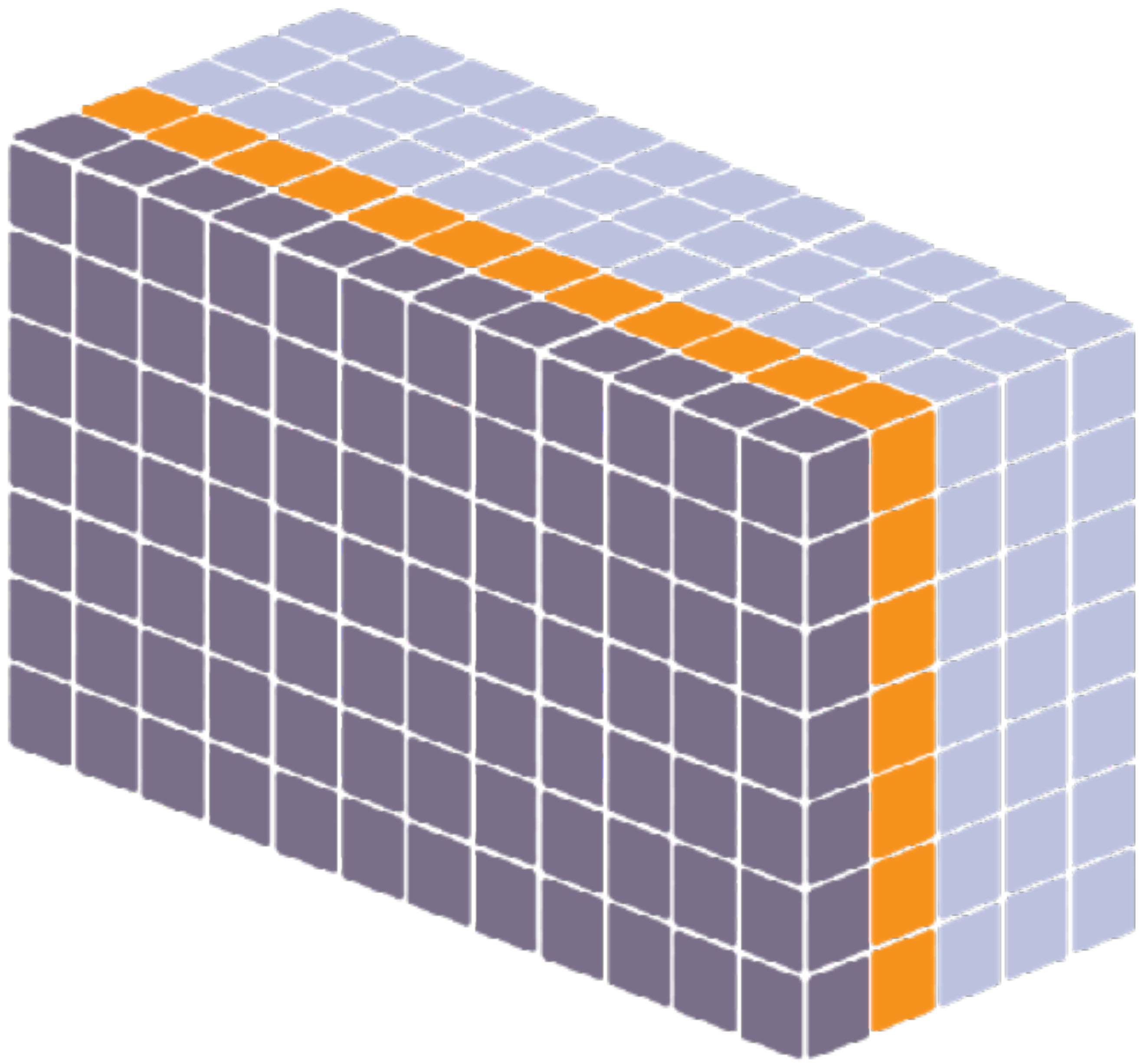
- Tidal interactions
- Ram pressure stripping
- Starvation

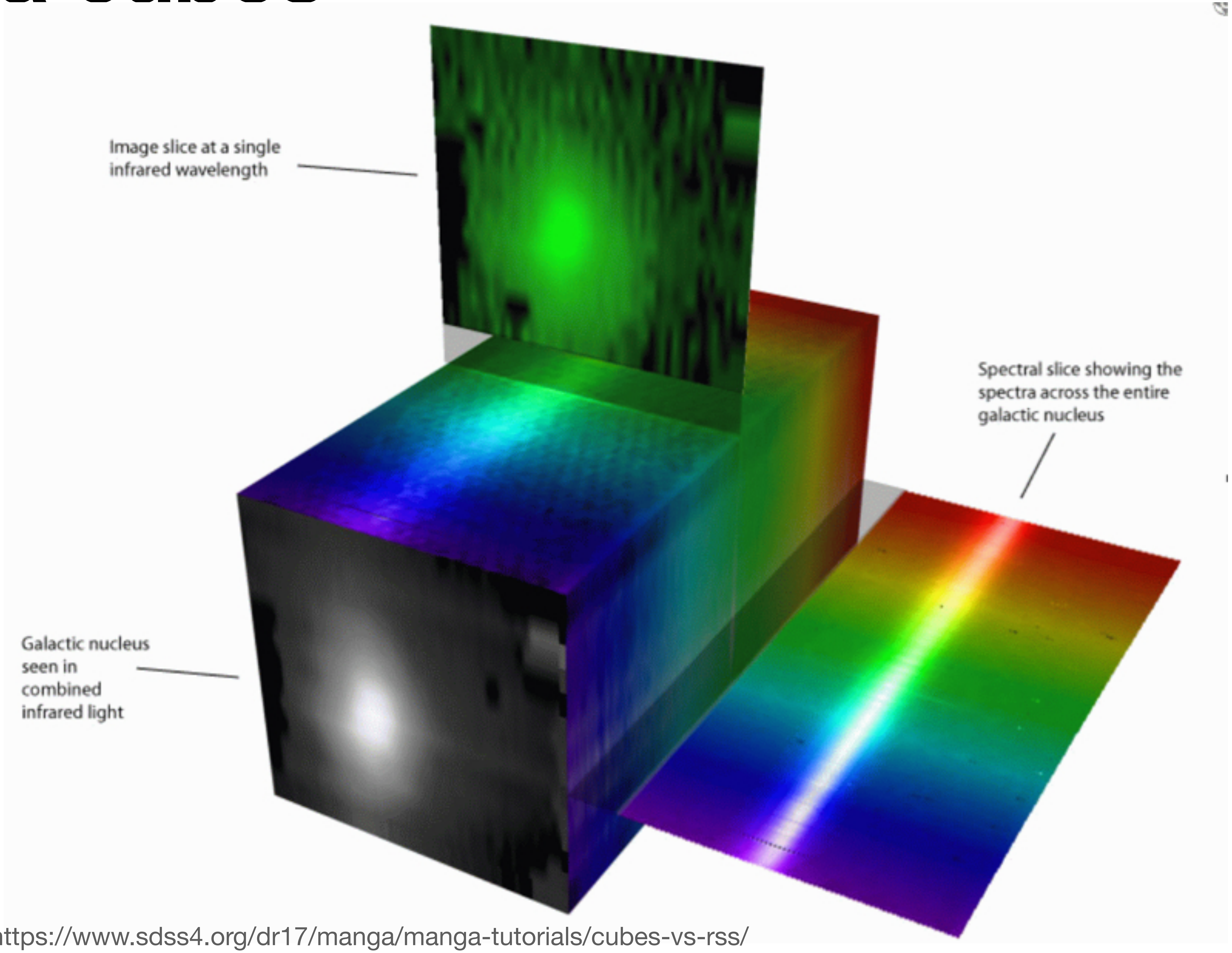
**Extreme gas removal can eventually transform a spiral galaxy into an elliptical galaxy.**

# The Virgo galaxy cluster



# Tutorial - 3D data cubes



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