ASTRON

university of groningen / faculty of science and engineering / kapteyn astronomical institute

Active galactic nuclei at radio wavelengths: properties, life and impact

Raffaella Morganti

Netherlands Institute for Radio Astronomy (ASTRON)
and
Kapteyn Institute Groningen

Me in a “nutshell”

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

erc
European Research Council
Established by the European Commission
Supporting top researchers from anywhere in the world

RadioLife

Senior astronomer at ASTRON - Netherlands Institute for Radio Astronomy
and affiliated as professor at the Kapteyn Institute University of Groningen

email morganti@astron.nl r.morganti@rug.nl
web page http://www.astron.nl/~morganti
no social media

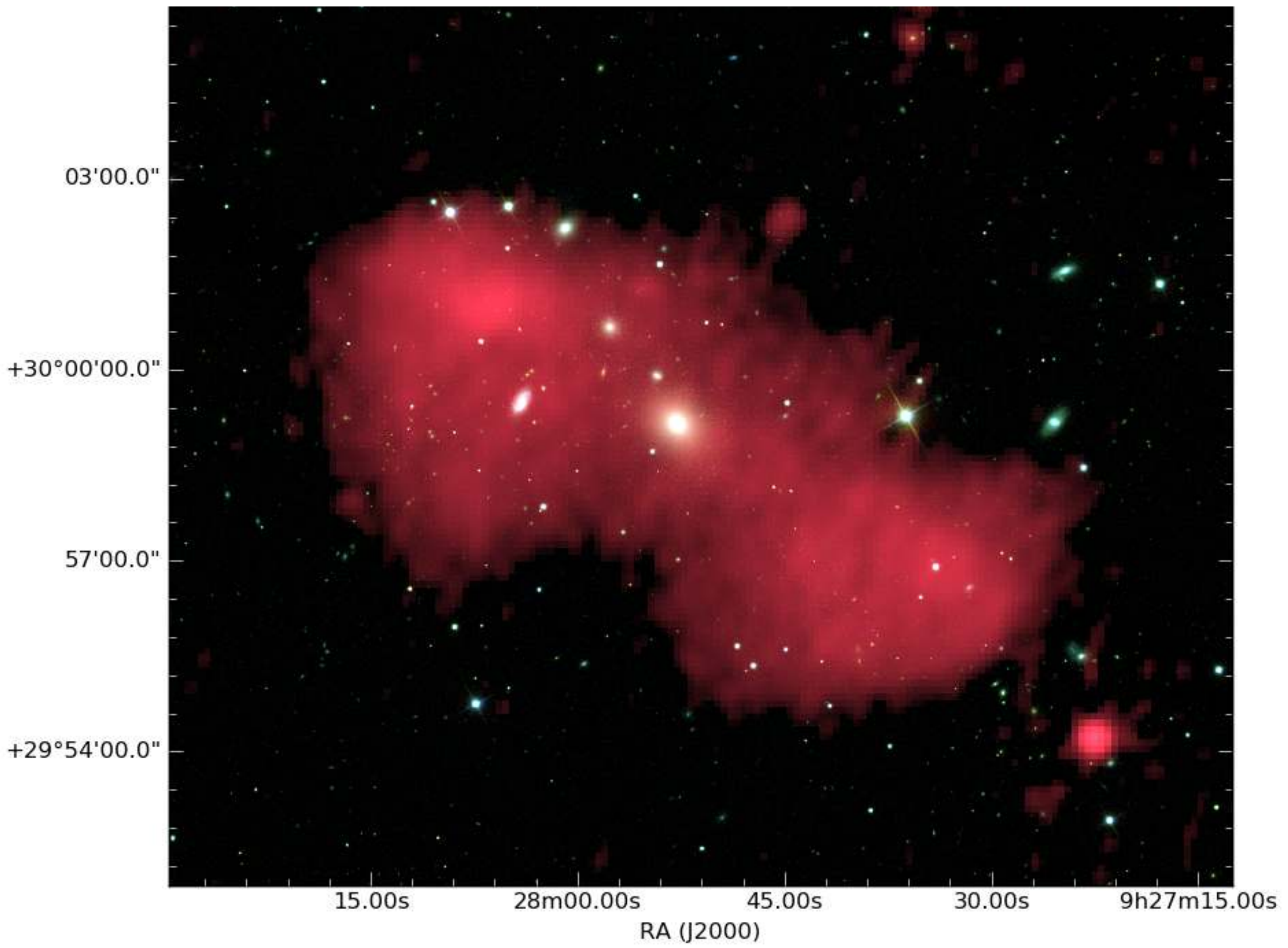
Me in a “nutshell”

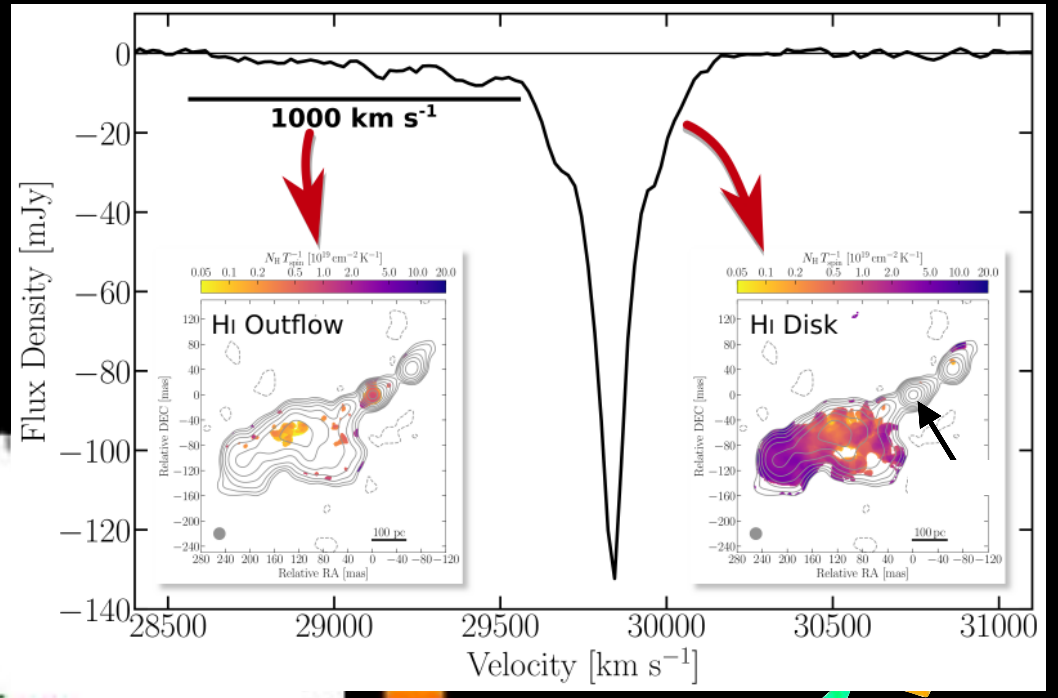
http://www.astron.nl/~morganti

My expertise: technical and science - **observer**
Radio astronomer ➔ LOFAR, Apertif-WSRT,
SKA-pathfinders/precursors

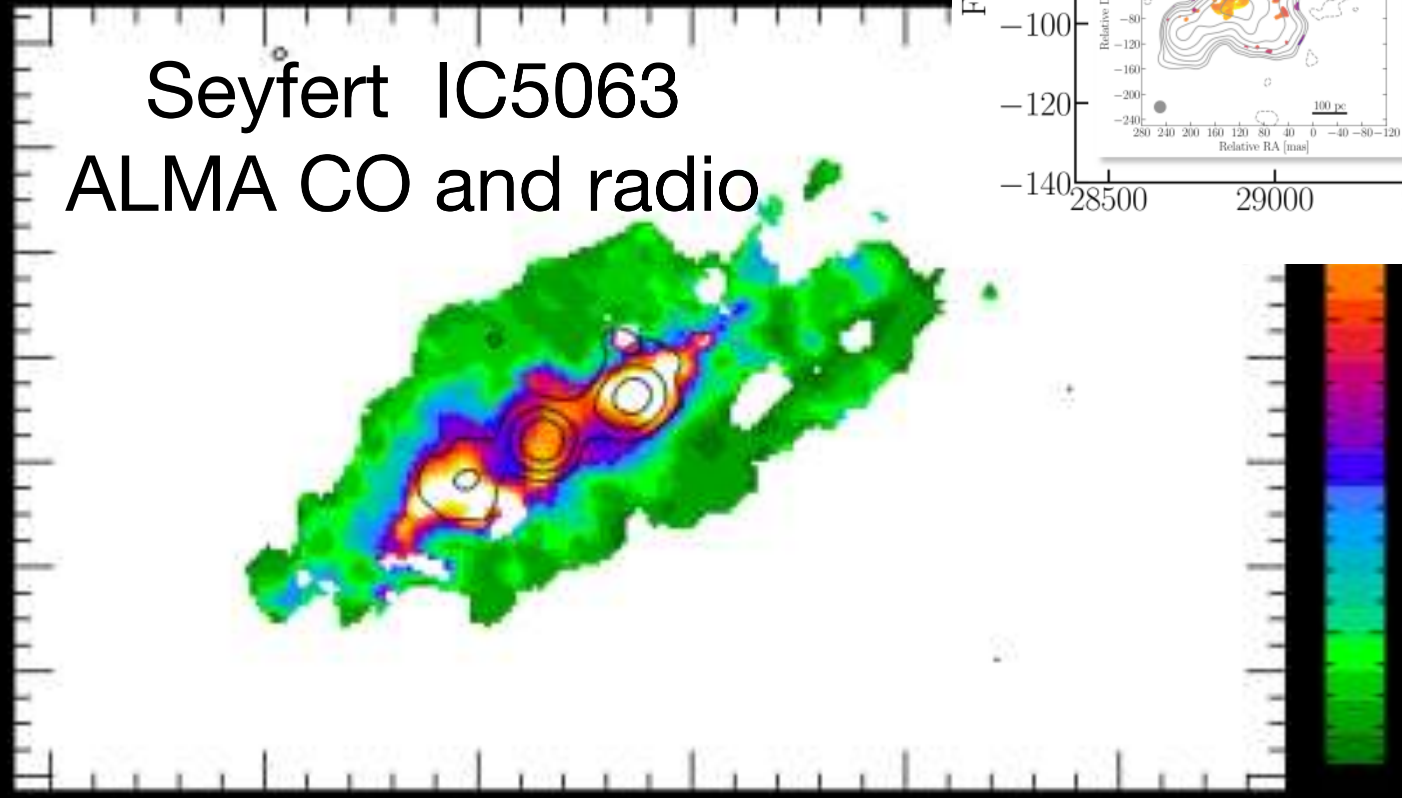
Radio AGN (jets/lobes) and their role in galaxy evolution
Interaction of jets with cold gas - 21cm HI (WSRT, VLA, GMRT …)
and cold molecular gas (ALMA, NOEMA)
and warm ionised gas, optical emission lines (ESO telescopes)

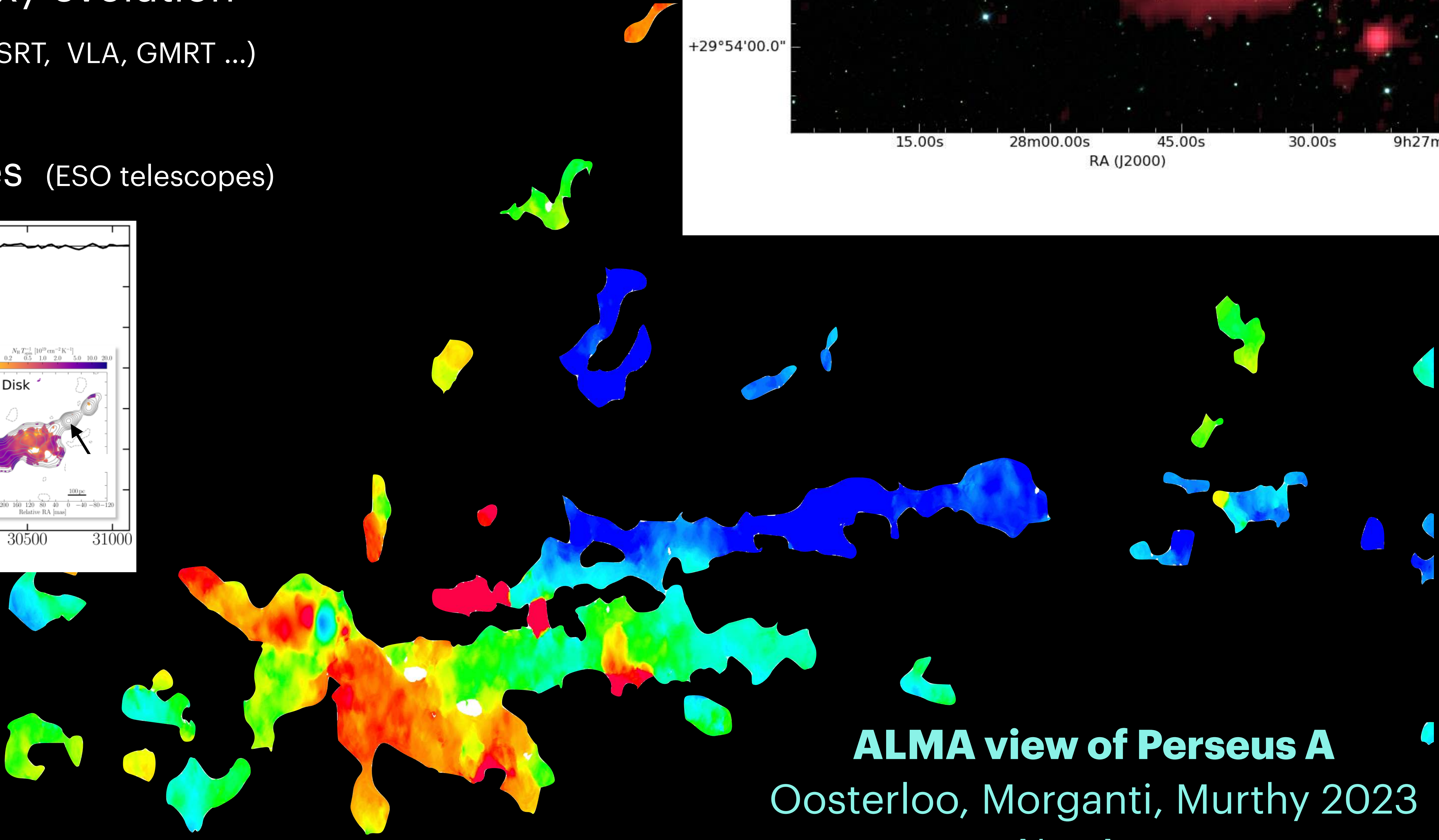
LOFAR image of the remnant B2 0924+30
Shulevski et al. 2017





Seyfert IC5063
ALMA CO and radio





ALMA view of Perseus A
Oosterloo, Morganti, Murthy 2023
Nat Astr

Themes of the lectures

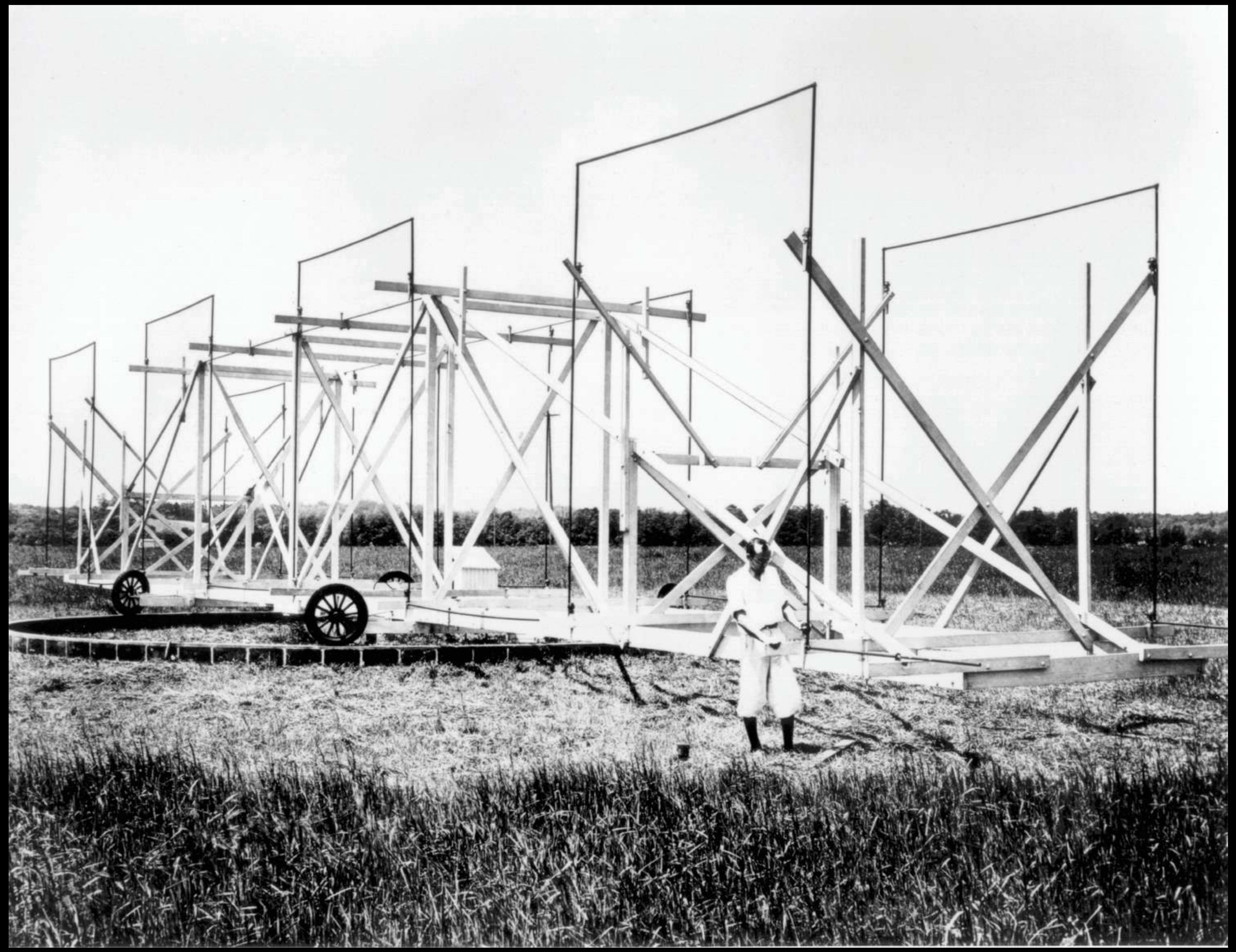
- **An introduction to radio-astronomy and radio surveys**
- From radio quiet to radio loud AGN: properties and recent results
- Radio galaxies and their life cycle
- The impact of radio jets on the interstellar medium and galaxy evolution

… if you would have **radio** eyes!

an ”active” super massive black hole emitting jets of plasma

Hercules A with *the* VLA R - *Perley, W. Cotton, and U. Rao (NRAO/AUI/NSF).*

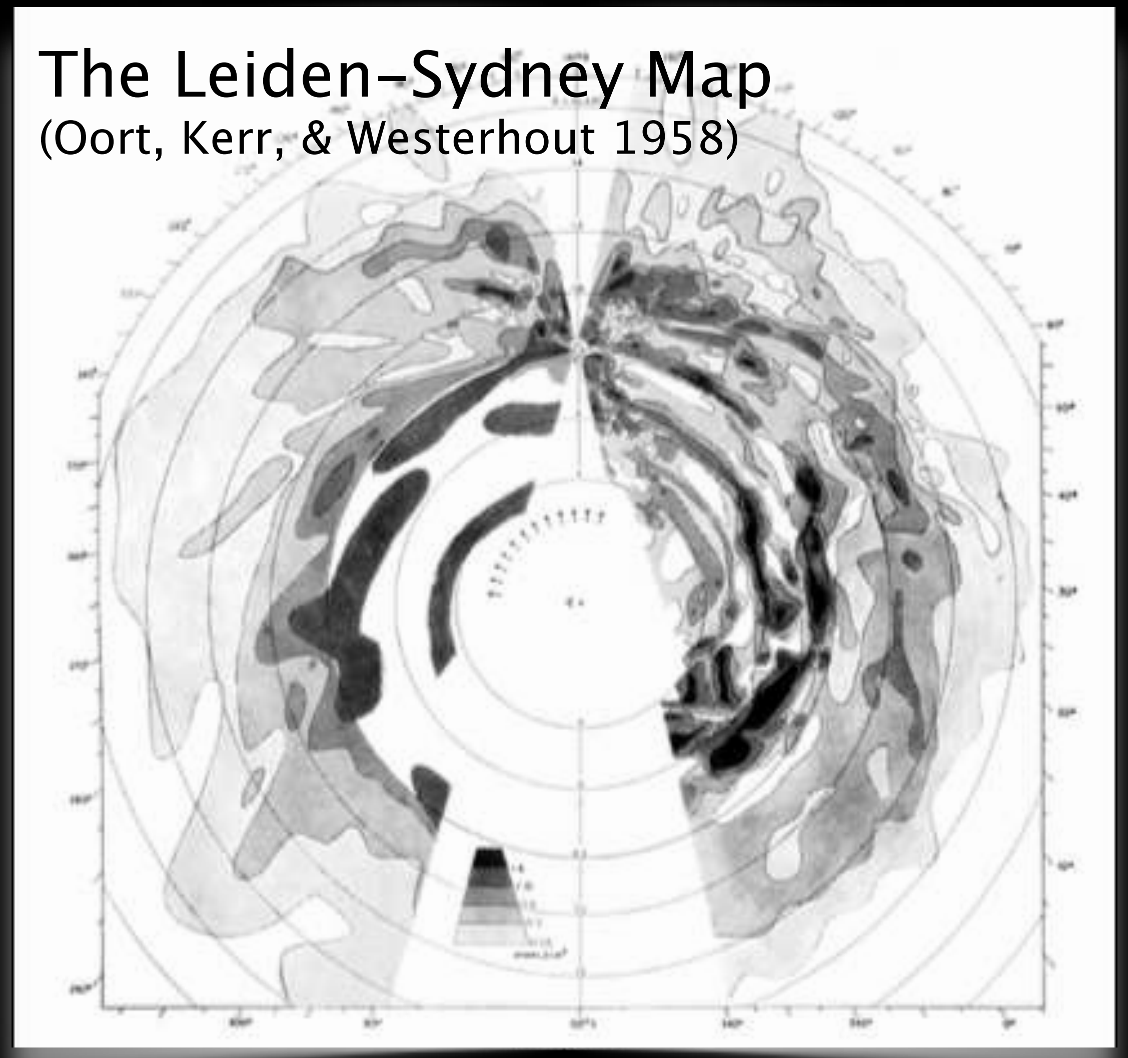
Radio astronomy: an historical note



chosen frequency of 20.5 MHz (wavelength about 14.5 meters)

Karl Jansky 1933 ➙ identifying sources of noise for overseas radio communications of the Bell Lab - “noise” shifted 4 min each day, direction Sagittarius

Most of the use of radio wavelengths for astronomy happened after WWII with “recycled “radars

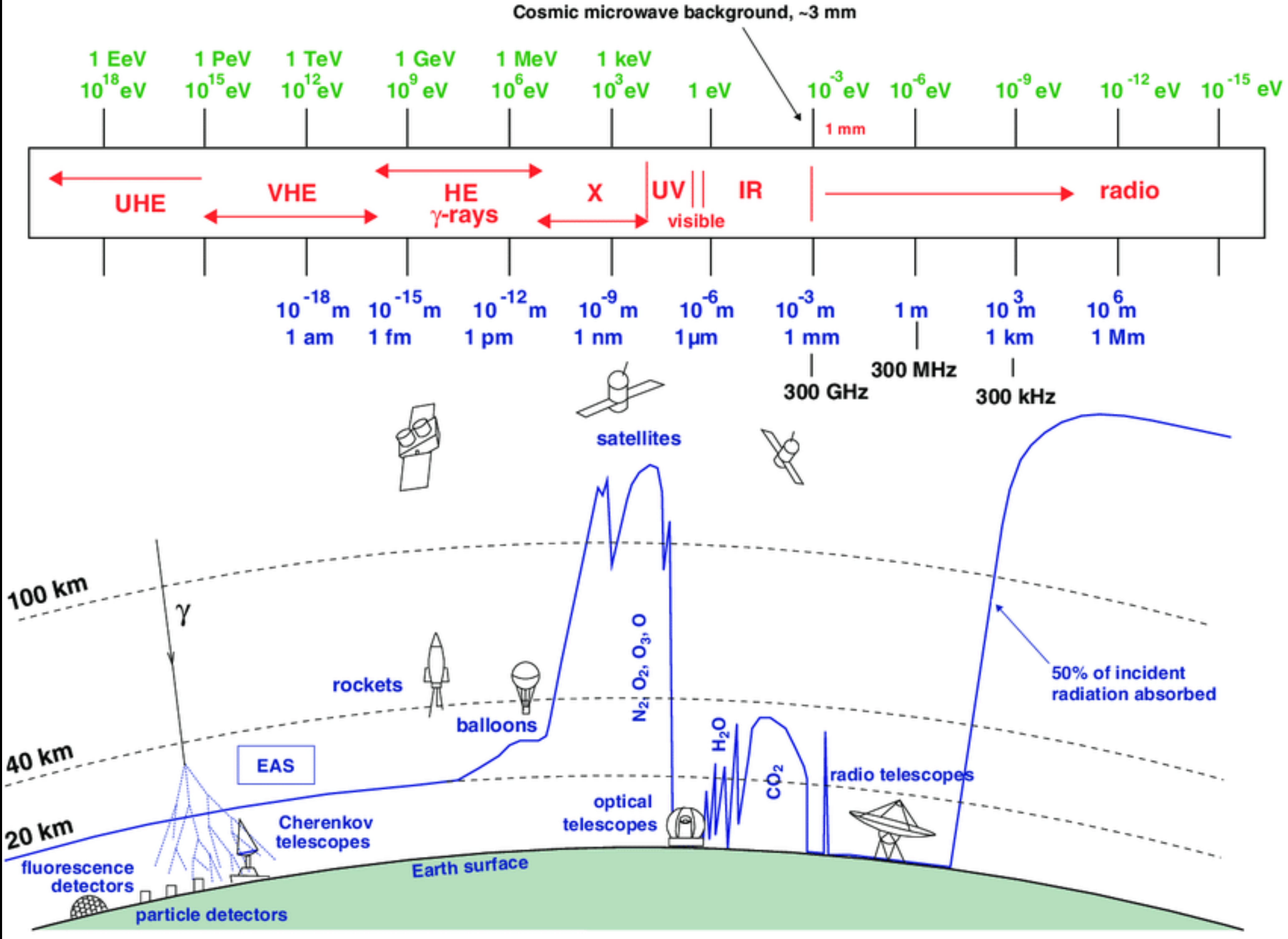


unit of radio flux: Jansky

1 Jy = 10^{-26} W m^{-2} Hz^{-1}

prediction of the HI 21cm line Van de Hulst 1945
map of MW not limited by obscuration
Westerhout 1957 (using Kootwijk)

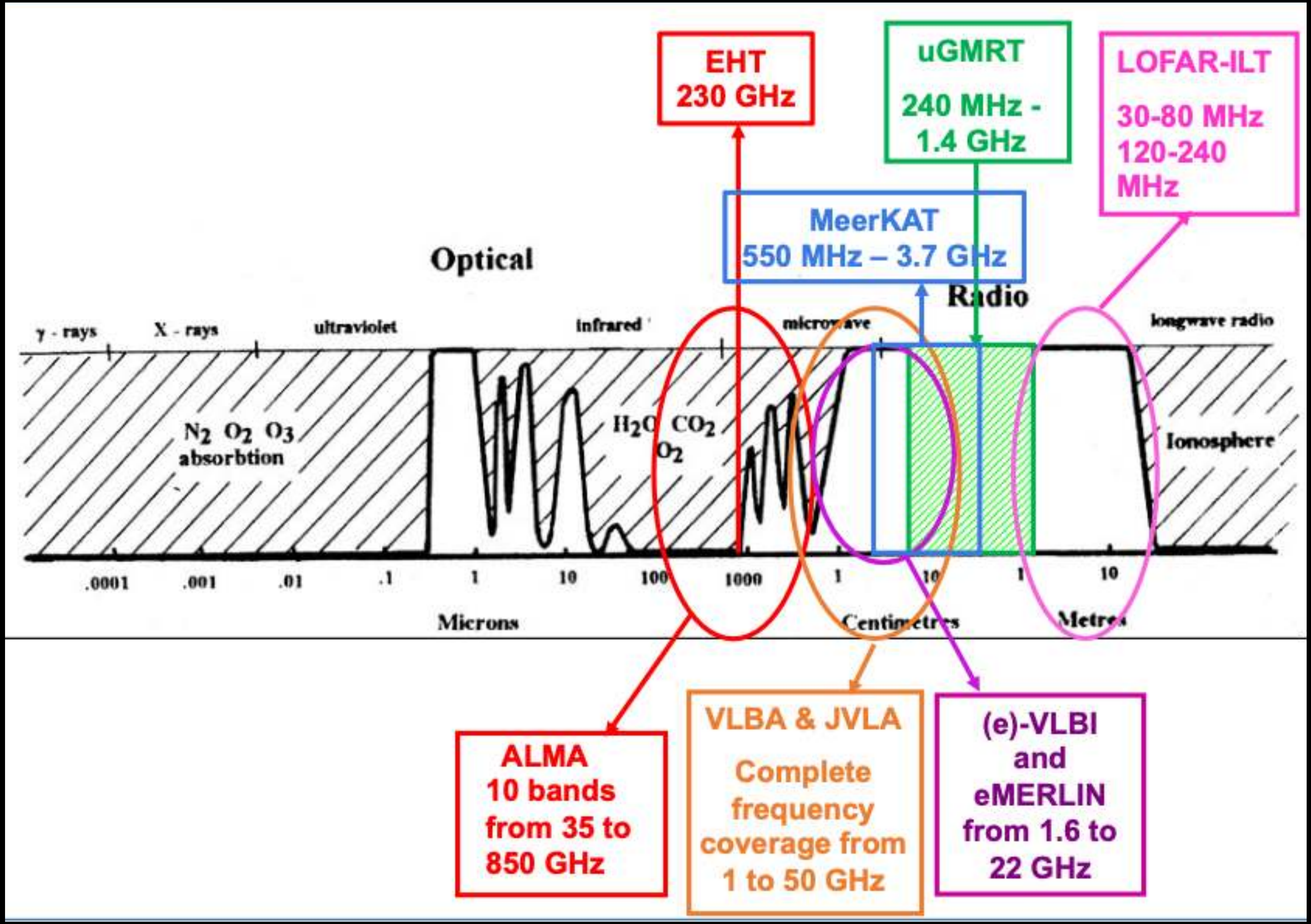
Transparency of the atmosphere ....

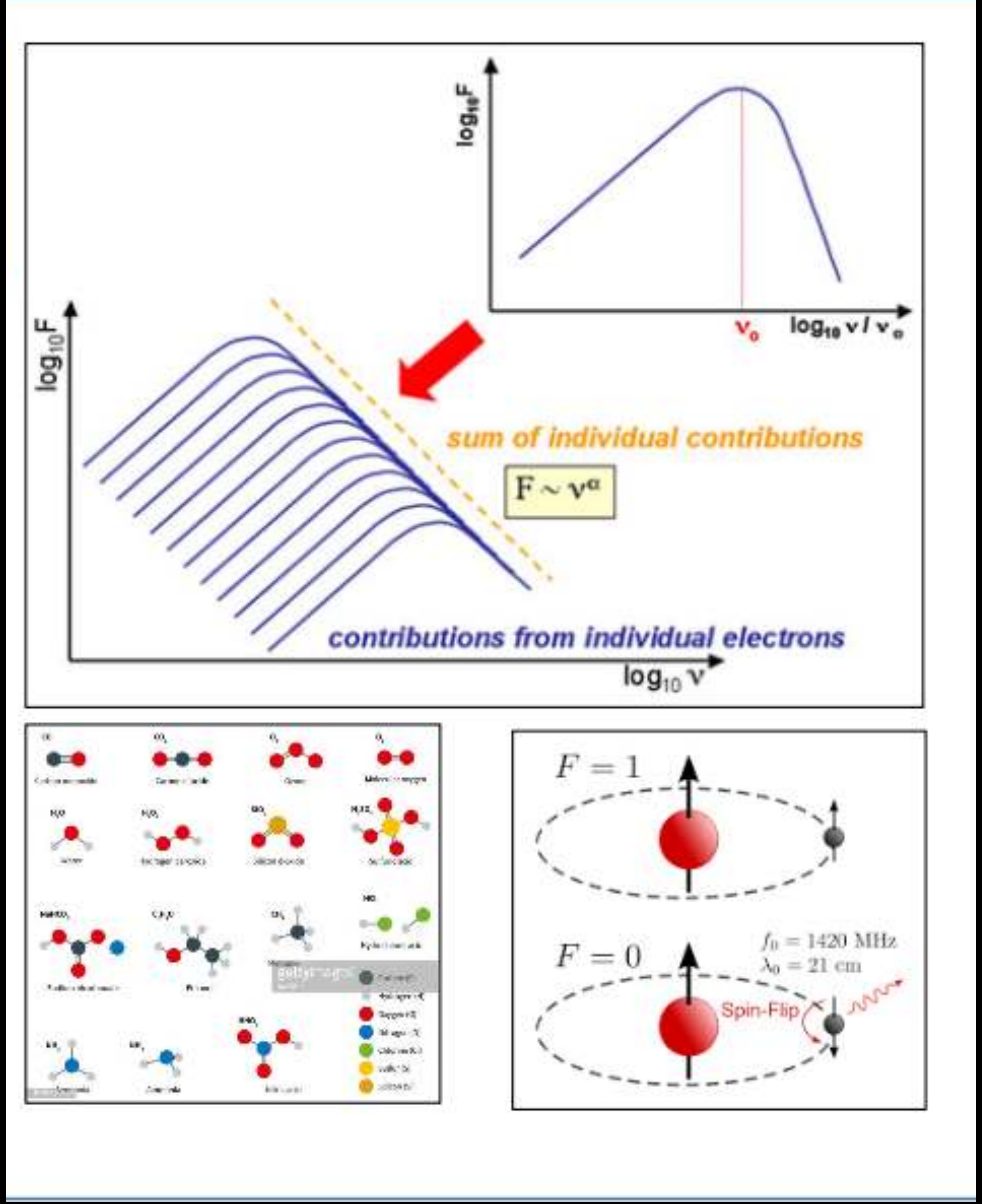


radio were the first wavelengths - outside the optical window - used for observing/studying the sky

Radiotelescopes and science

WSRT-Apertif
ATCA and ASKAP MWA





Continuum and line emission

Limitation of the radio: the angular resolution

Angular resolution for typical radio frequencies

Observing wavelength (m)

Resolution (radiants)

$$\theta \approx \frac{\lambda}{D_{max}}$$

Diameter of the telescope (m)

Single dish 100m ➝ more than 100 arcsec resolution at 21 cm (1.4 GHz)

largest single dish (non steerable) ➝ FAST (China) ~ 500 m

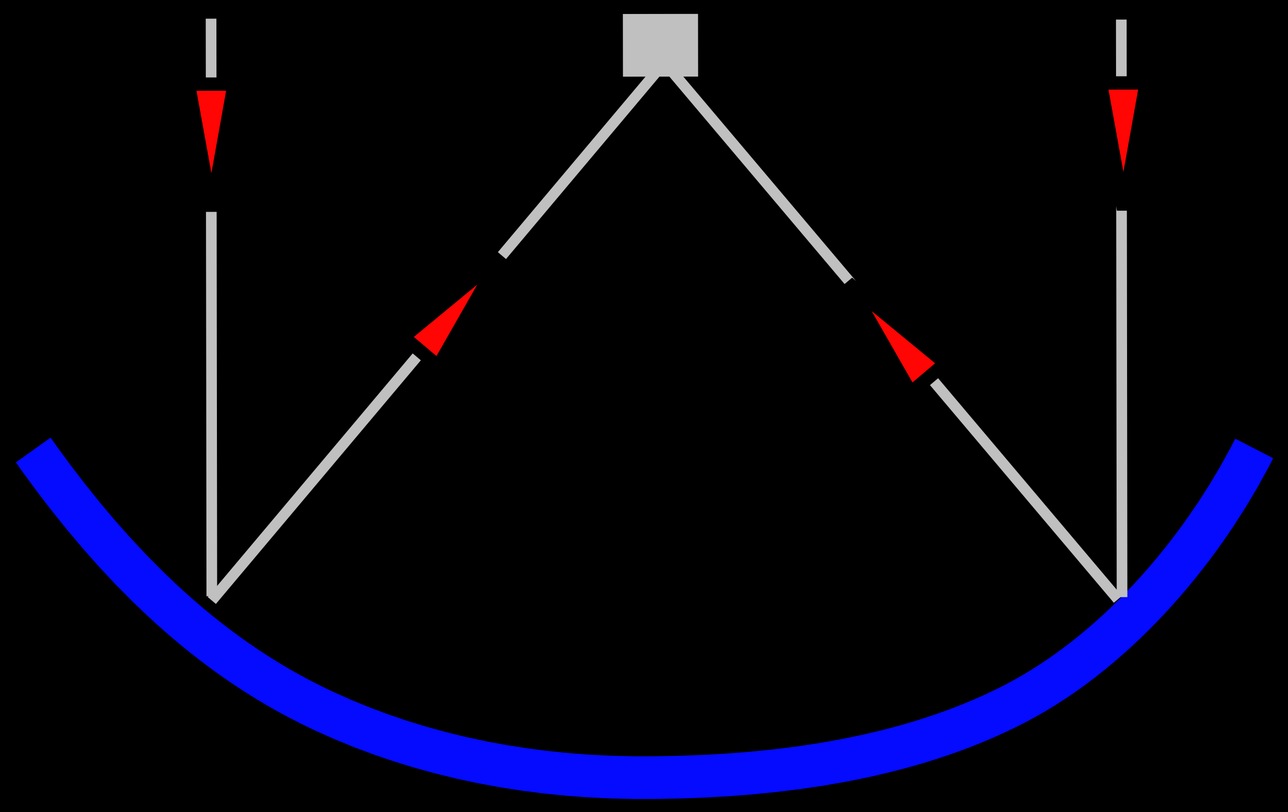
but to obtain 1 arcsec resolution at 1.4GHz a dish of ~20 km is needed!

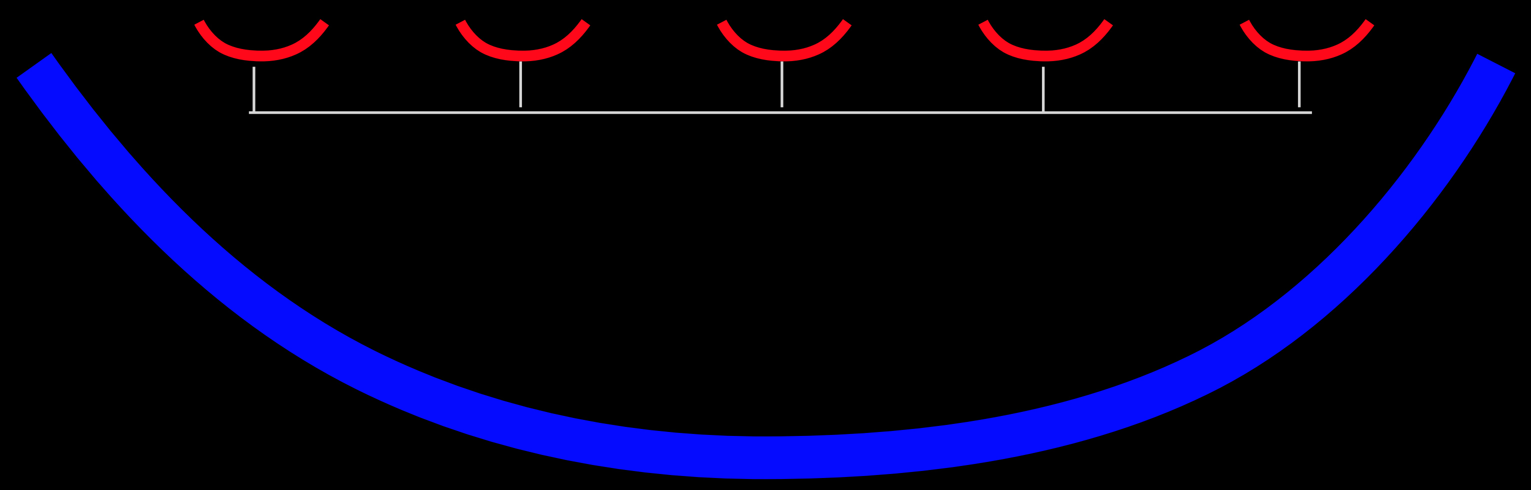
D	lambda		lambda/D in radiants		approximate resolution of the observations	
m	cm	GHz	Theta	deg	arcsec	
100	21	1.43	0.0021	0.060191083	216.69	single dish
3000	21	1.43	0.00007	0.002006369	7.22	interferometer (e.g. WSRT)
27000	21	1.43	7.7778E-06	0.00022293	0.80	larger configuration JVLA
200	0.2	150.00	0.00001	0.000286624	1.03	ALMA compact configuration
2000	0.2	150.00	0.000001	2.86624E-05	0.10	ALMA
15000	0.2	150.00	1.3333E-07	3.82166E-06	0.01	ALMA extended configuration

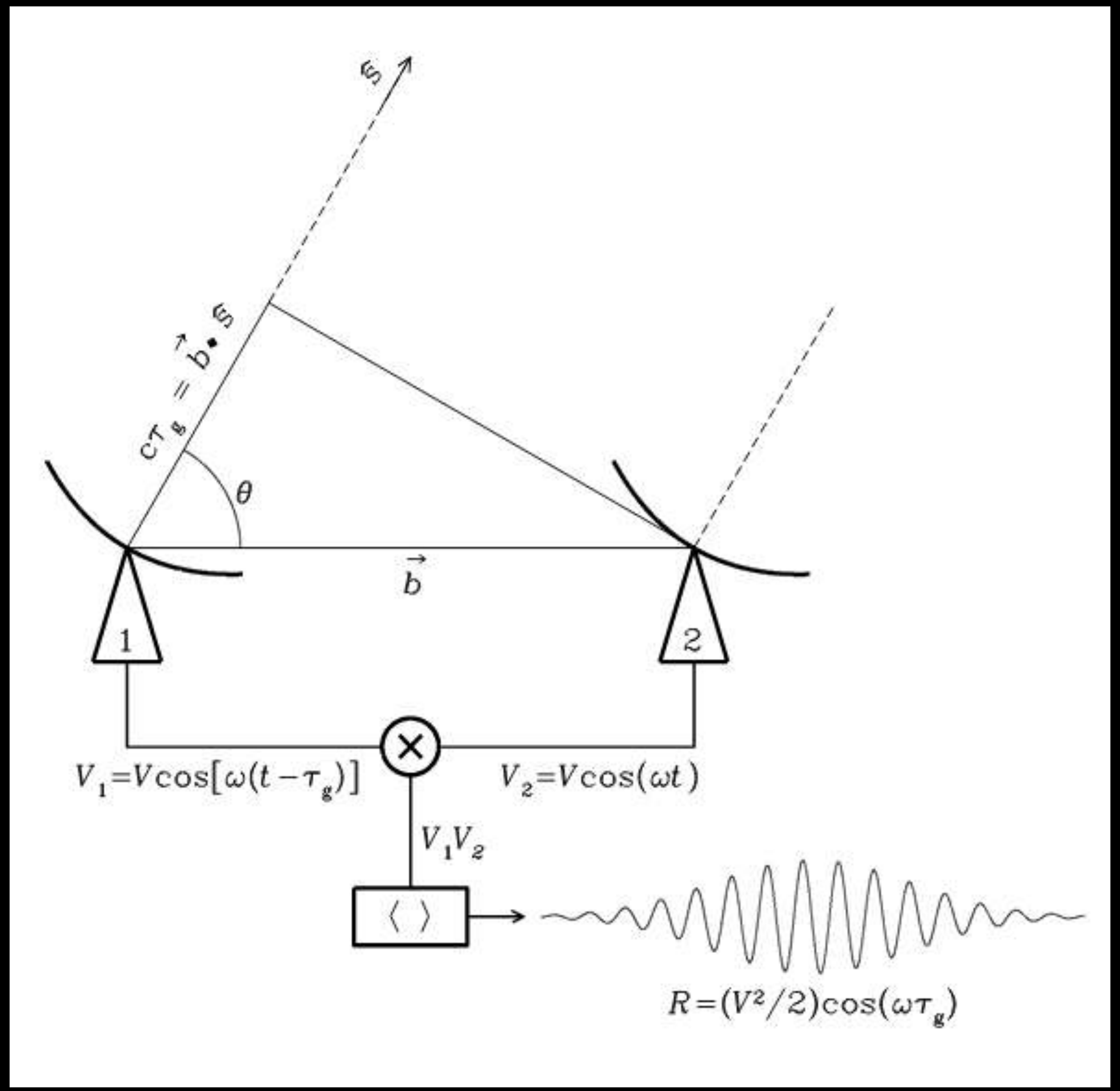
FAST telescope (China)

How works a radiotelescope?

- In order to have sharp images we need a very large dish ➔ resolution = λ/D
- Far too large to be built...
- Trick: have many relatively small dishes linked together ➔ interferometry

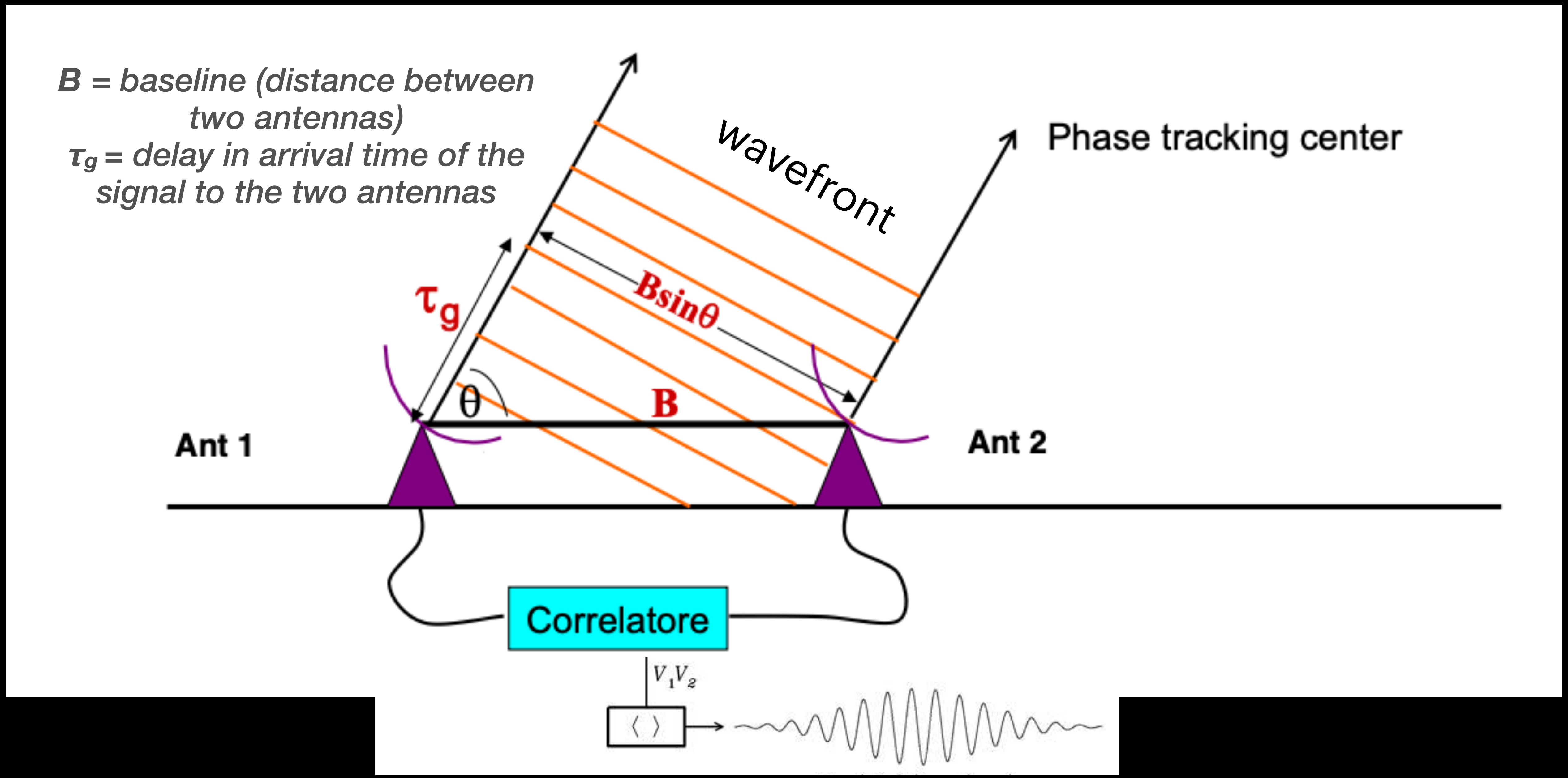


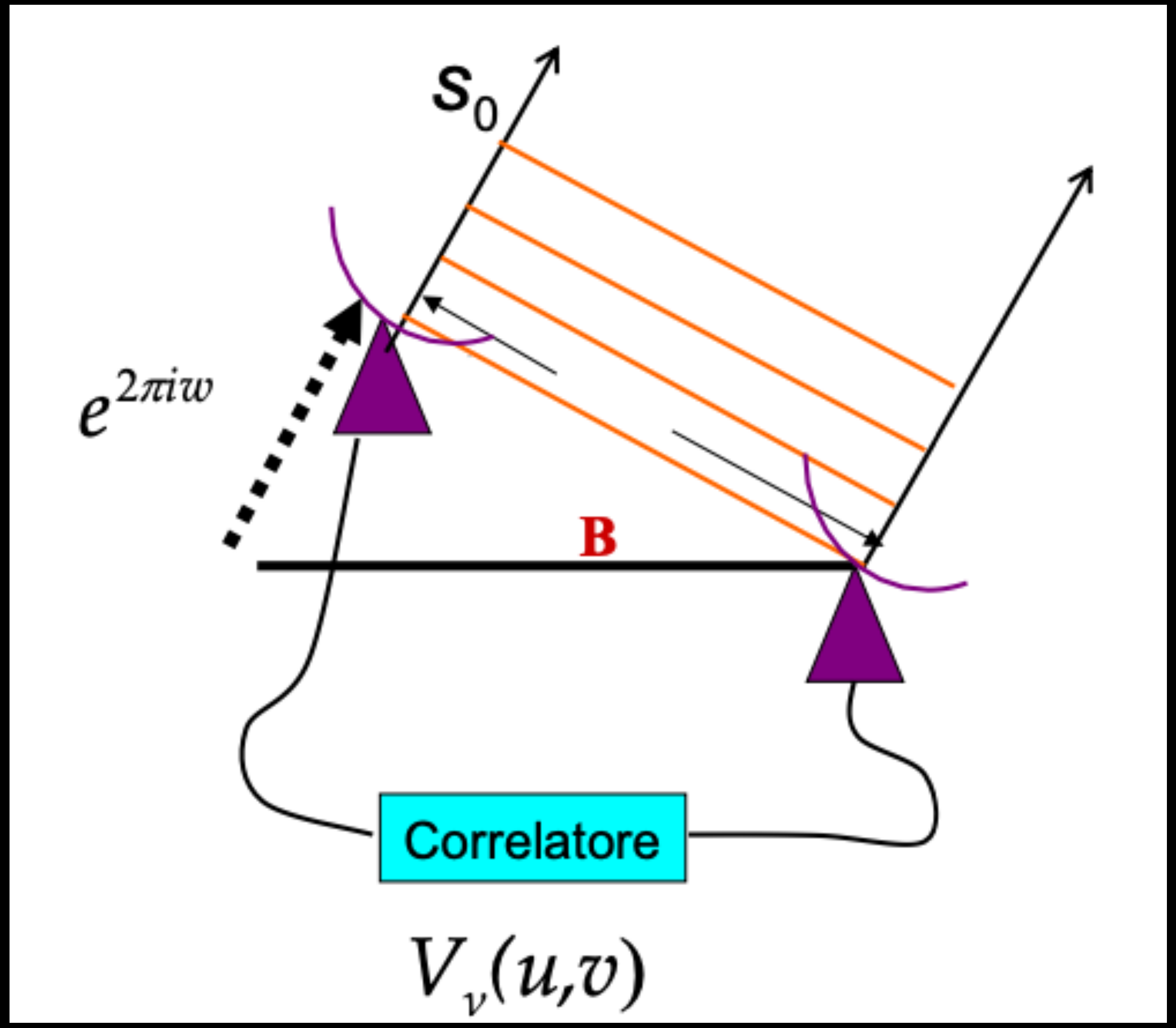




How does an interferometer work?

- all antennas pointing to the same source
- each antenna receives the signal at a slightly different time
- the correlator combines the signal for each pair of antennas after compensating for the delay in arrival time





compensating for τ_g

the delay changes continuously with time...

$$V_\nu(u,v) = \iint I_\nu(l,m) e^{-2\pi i(lu+mv)} dl dm$$

Output of the correlator (measured) *Source brightness (we want to find)*

the Fourier transform of the correlator output gives the sky image

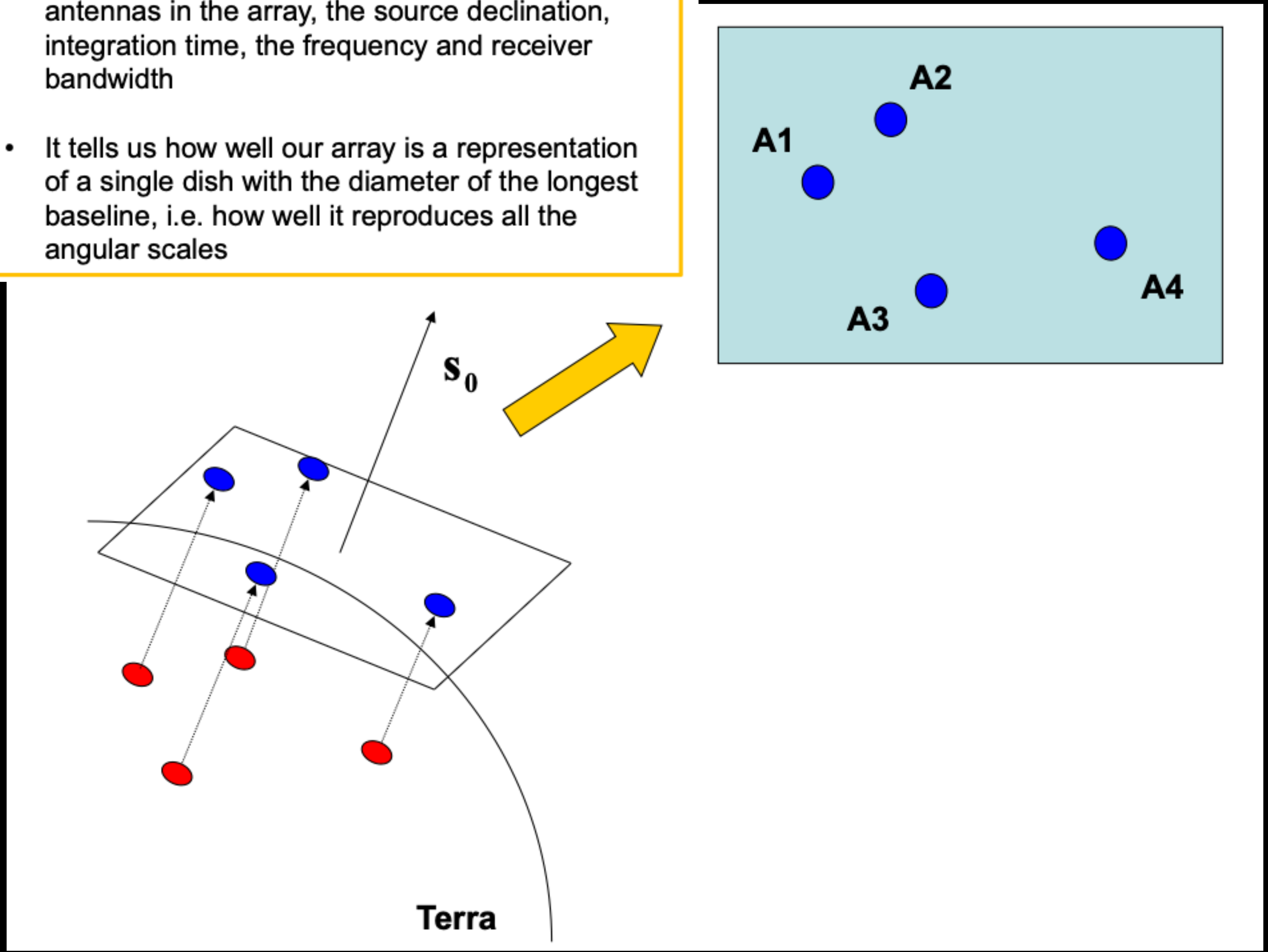
Further help from aperture synthesis

(effect of earth rotation)

Interferometer with *n* antennas has *n(n-1)/2* independent baselines: the more, the better to obtain a good coverage of the uv plane

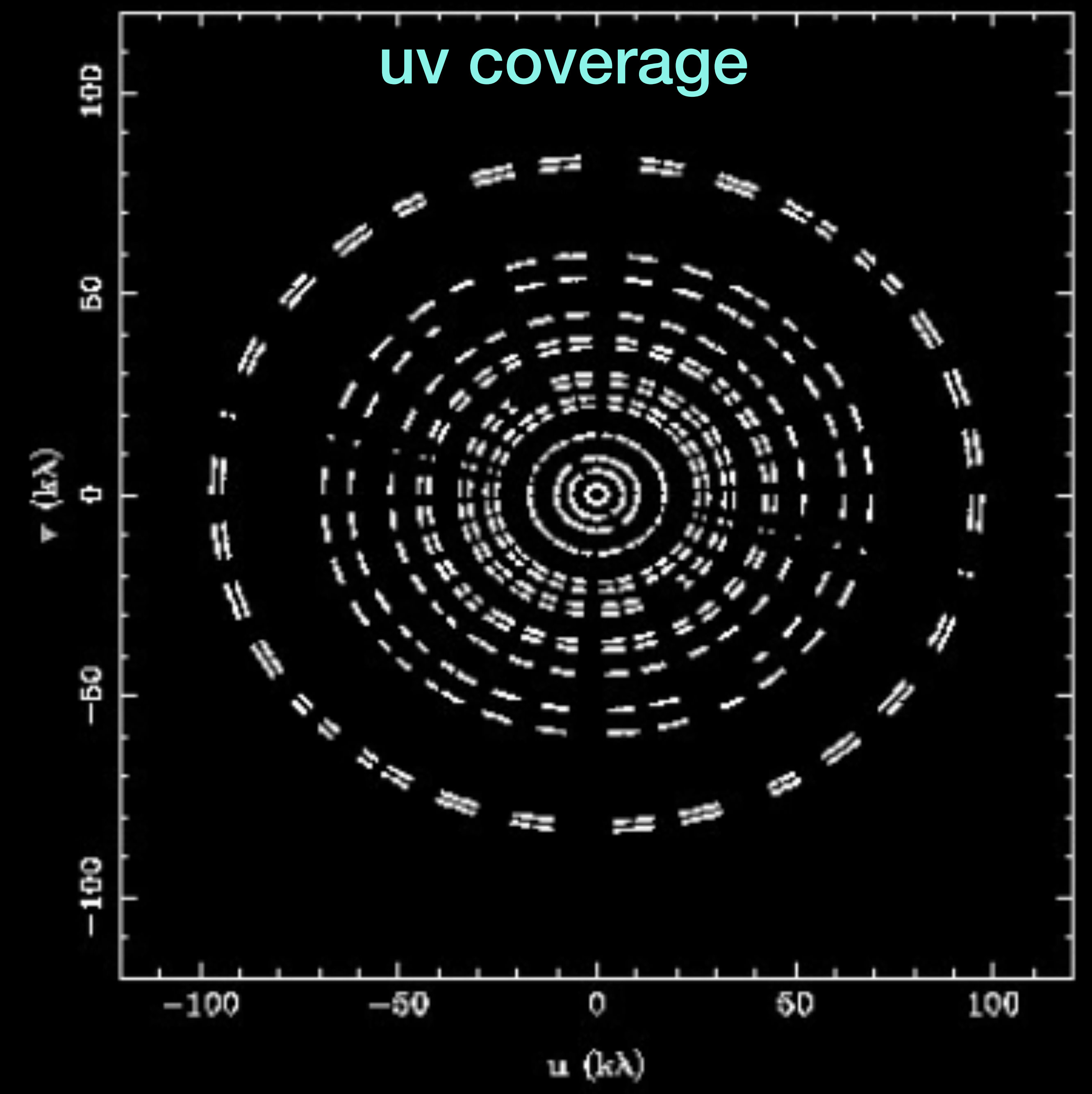
+ earth rotation

- The u-v coverage depends on the number of antennas in the array, the source declination, integration time, the frequency and receiver bandwidth
- It tells us how well our array is a representation of a single dish with the diameter of the longest baseline, i.e. how well it reproduces all the angular scales



As the earth moves, the distance of the pair of telescopes (projected baseline) - as seen by the source - changes
➙ filling the uv plane

Each point an integration time (from a few sec to a minute)



Example: 12h observations with the Australian Compact Array (6 antennas)

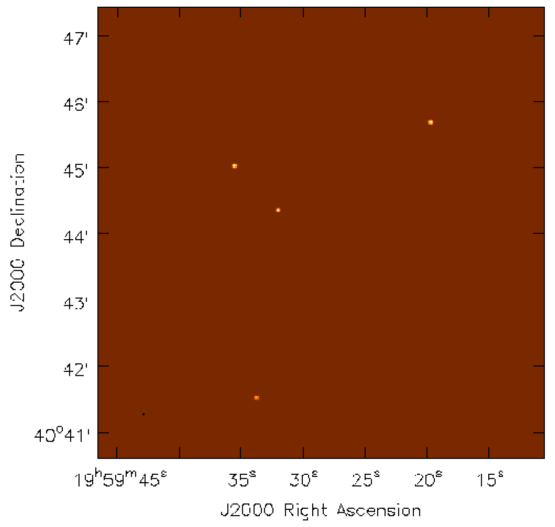
Advantages of more antennas: the case of the JVLA

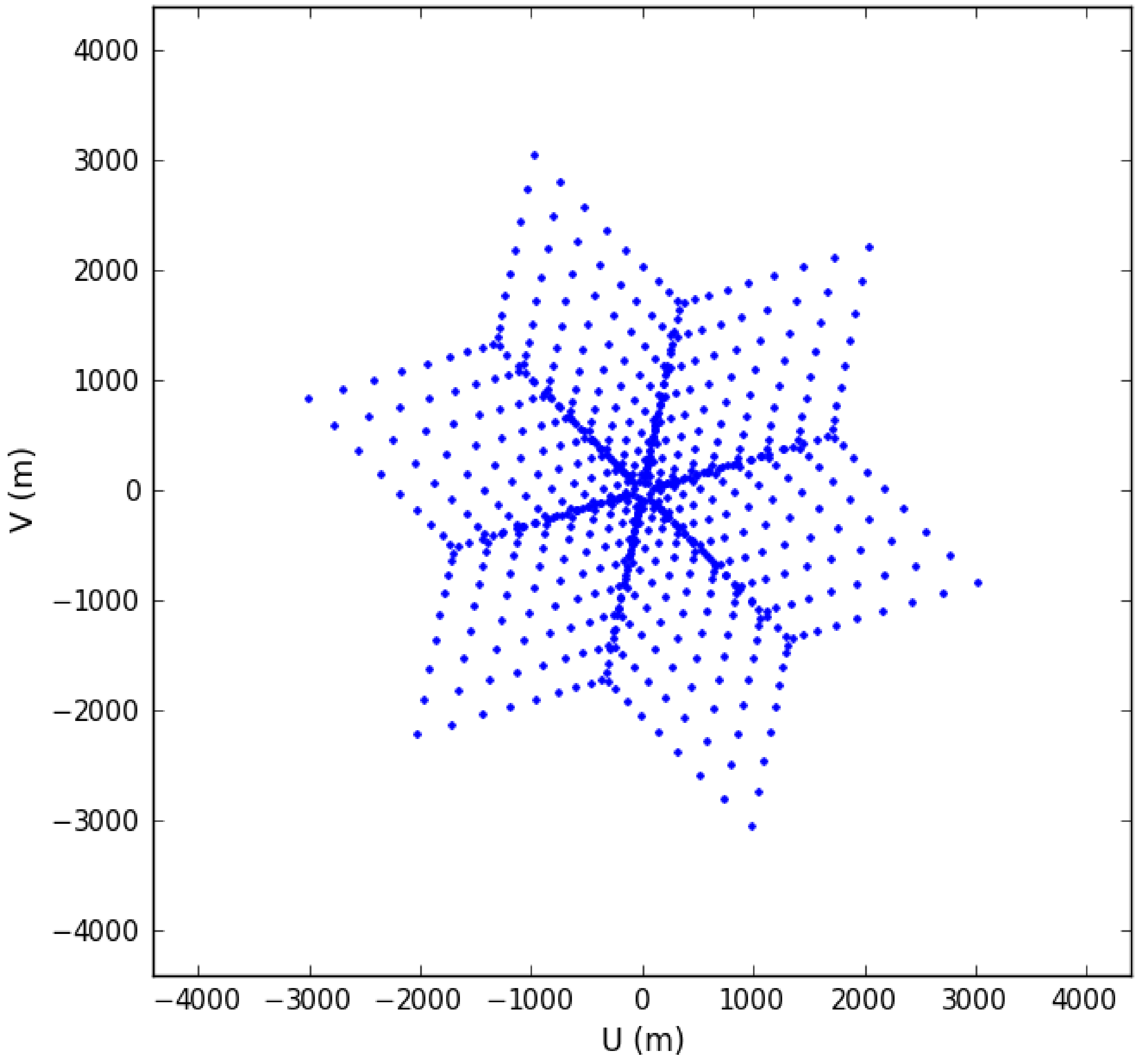
Spatial Frequency (uv) coverage + Observed Image

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \frac{1}{\lambda} \begin{bmatrix} R(h,\theta) \end{bmatrix} \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix}$$

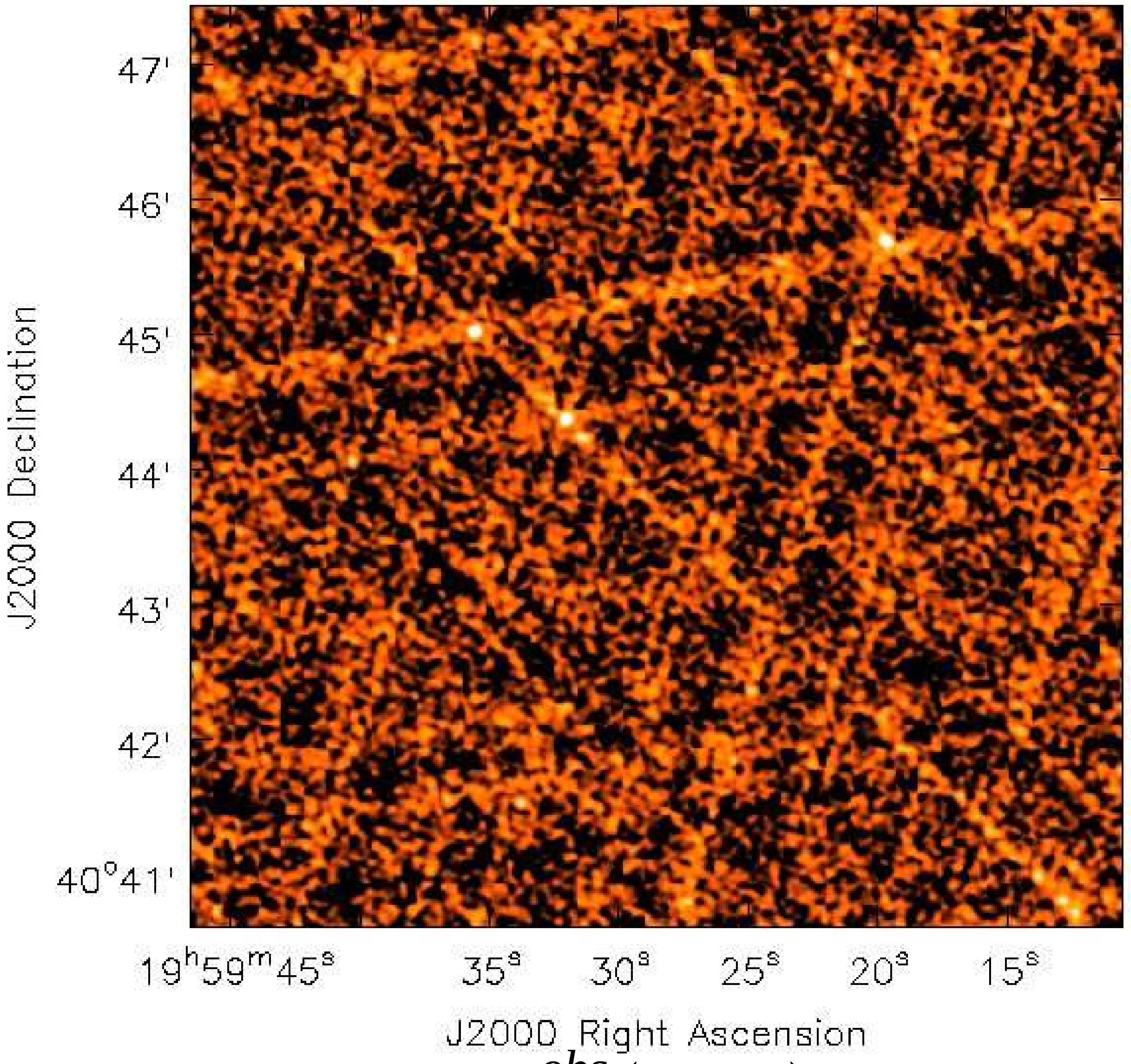
Image of the sky using 27 antennas

short “snap shot” (few minutes observing time)





$S(u,v)$

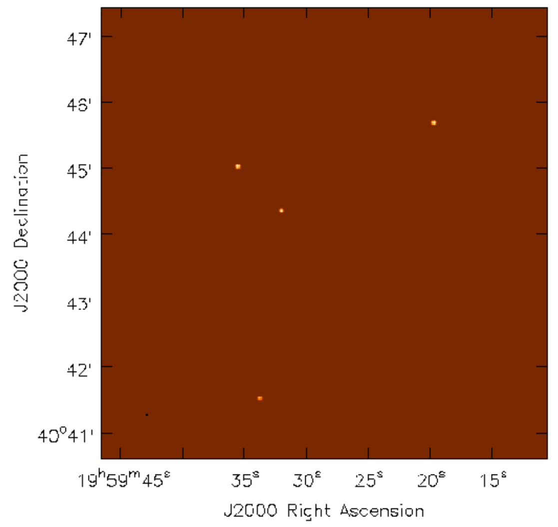


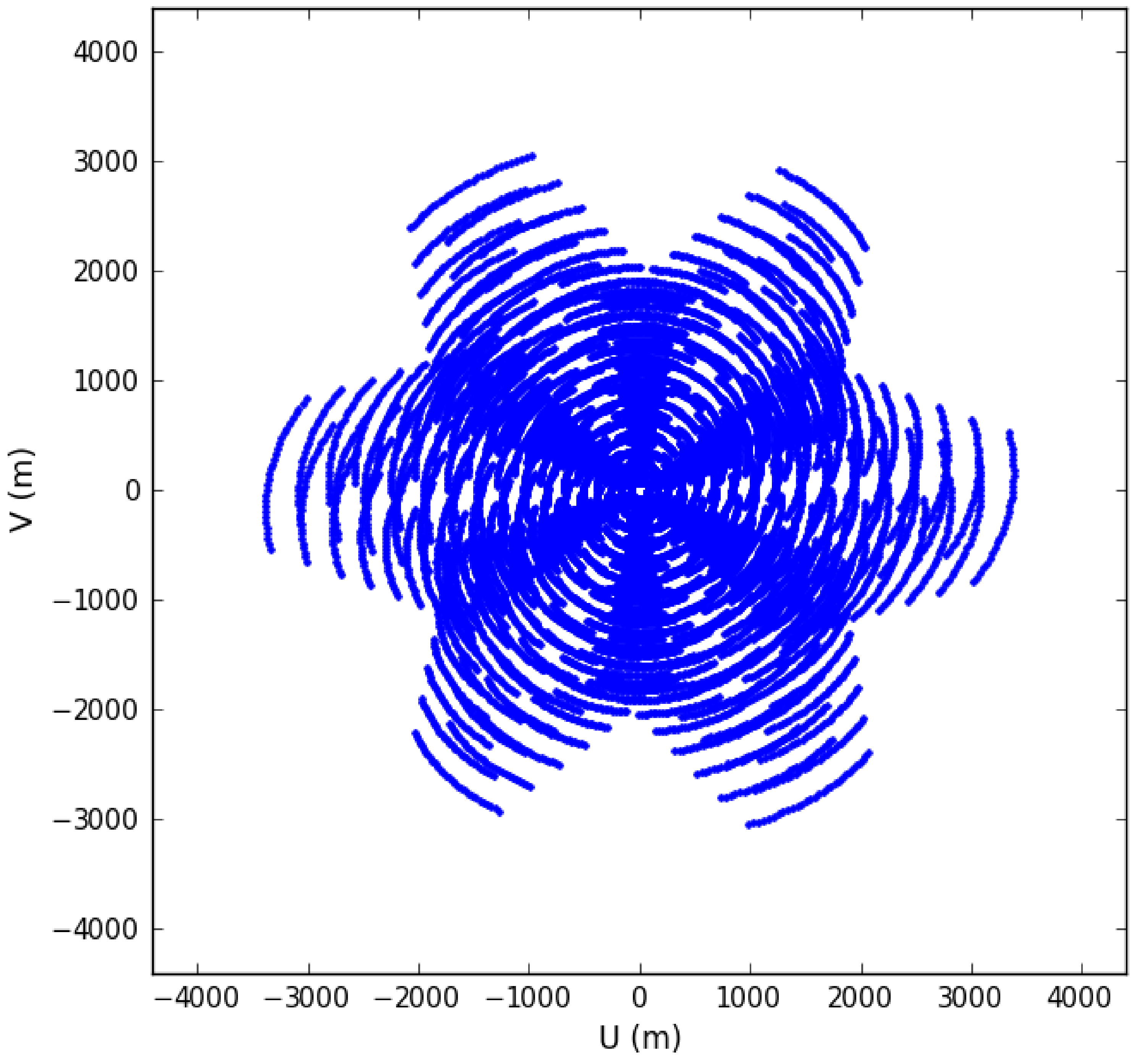
$I^{obs}(l,m)$

Spatial Frequency (uv) coverage + Observed Image

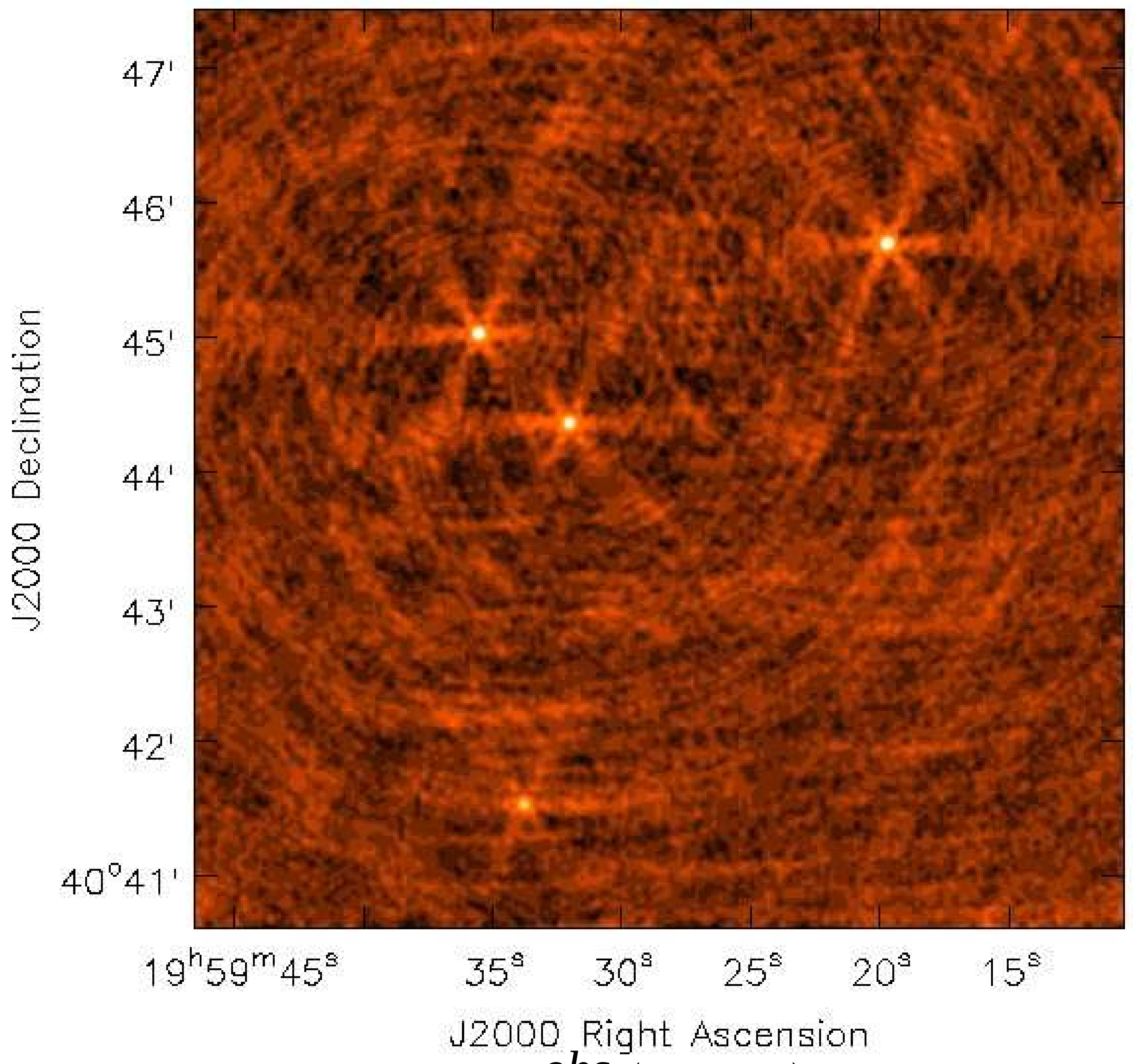
$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \frac{1}{\lambda} \begin{bmatrix} R(h,\theta) \end{bmatrix} \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix}$$

Image of the sky
using 27 antennas
over 2 hours
'Earth Rotation Synthesis'





$S(u,v)$

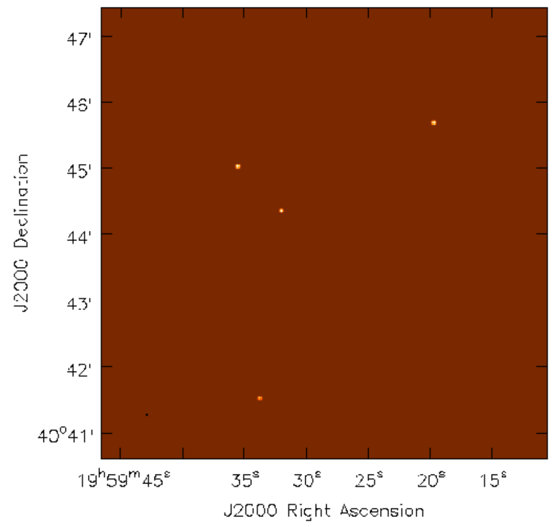


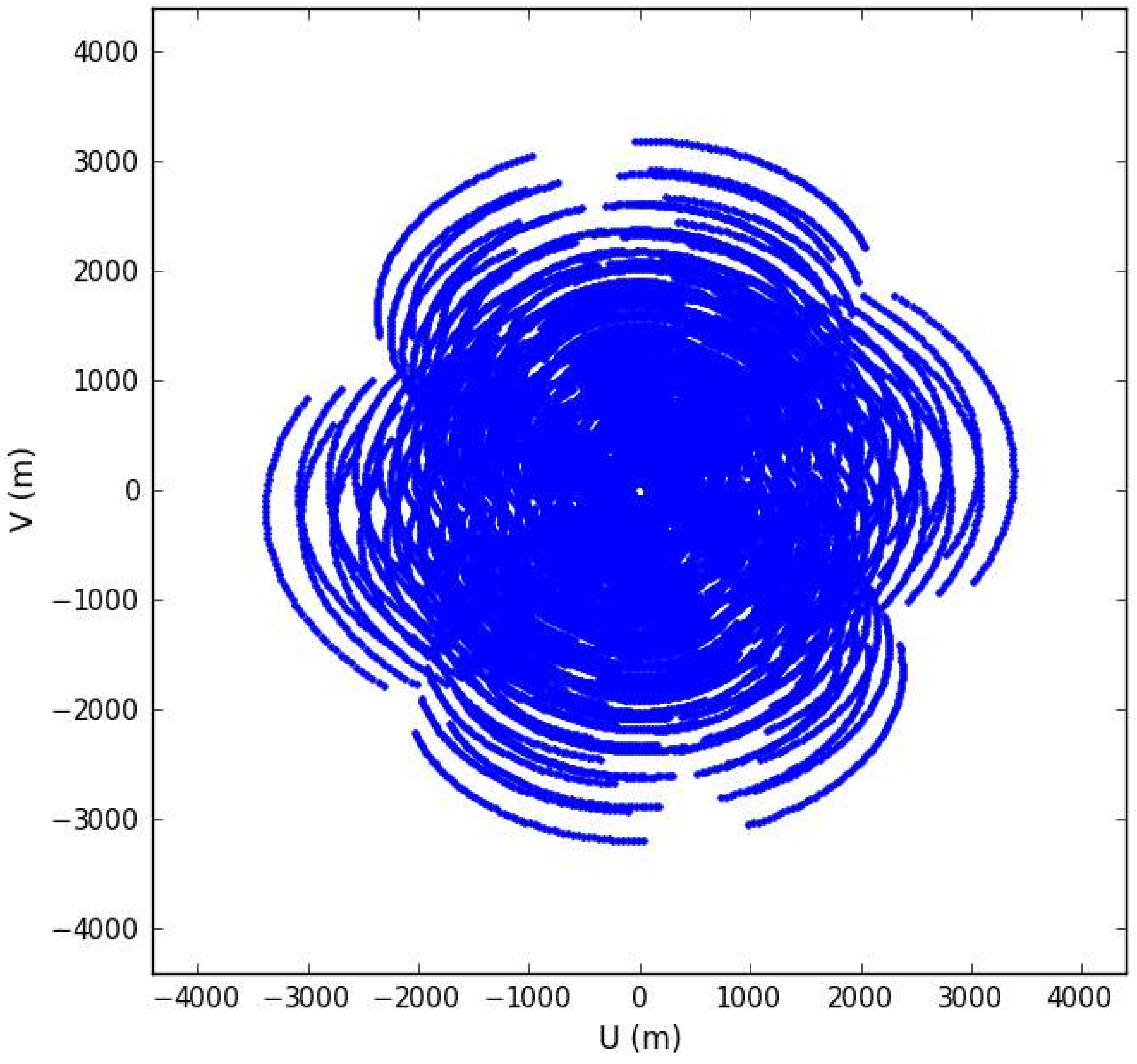
$I^{obs}(l,m)$

Spatial Frequency (uv) coverage + Observed Image

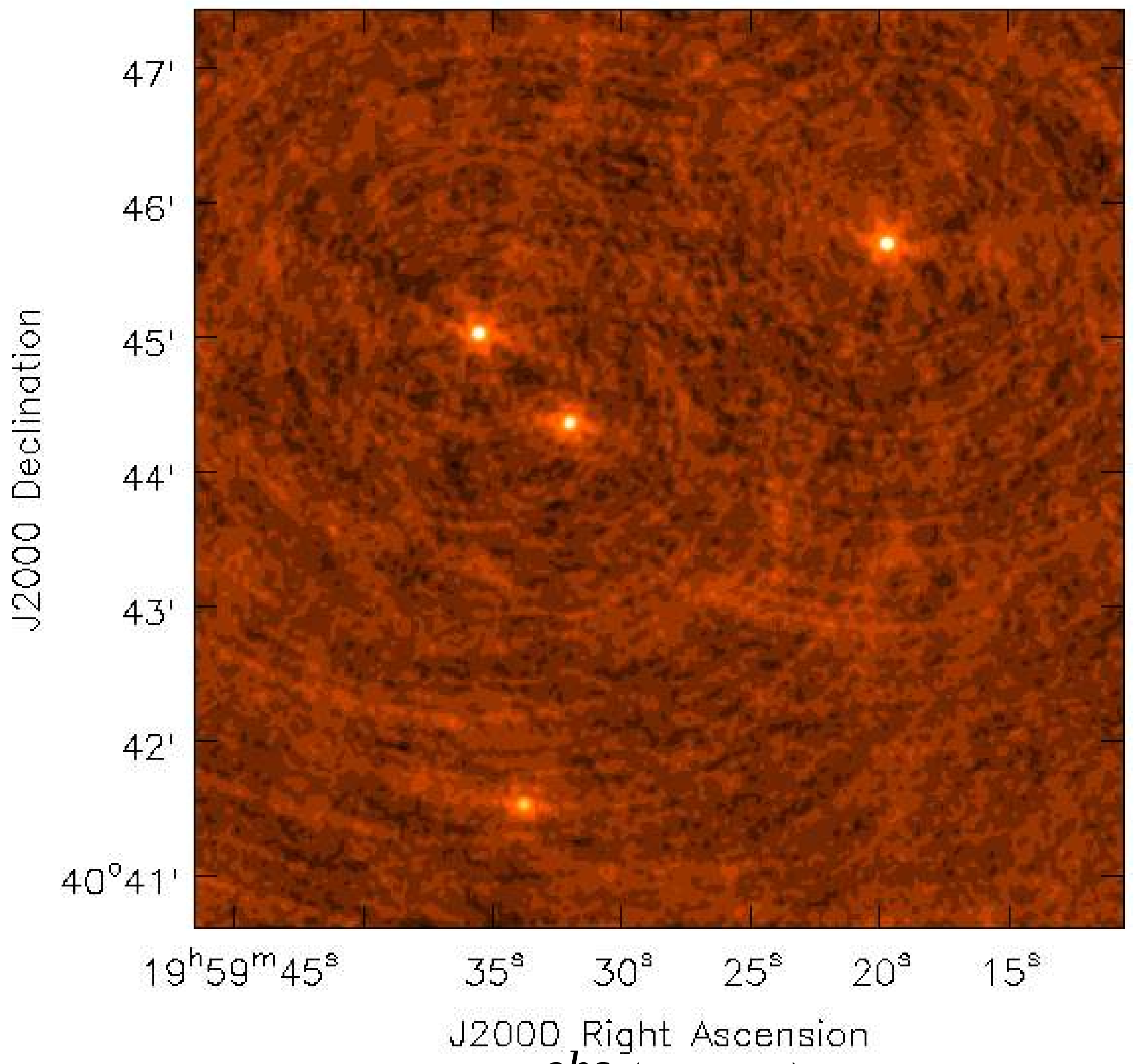
$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \frac{1}{\lambda} \begin{bmatrix} R(h,\theta) \end{bmatrix} \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix}$$

Image of the sky
using 27 antennas
over 4 hours
'Earth Rotation Synthesis'





$S(u,v)$

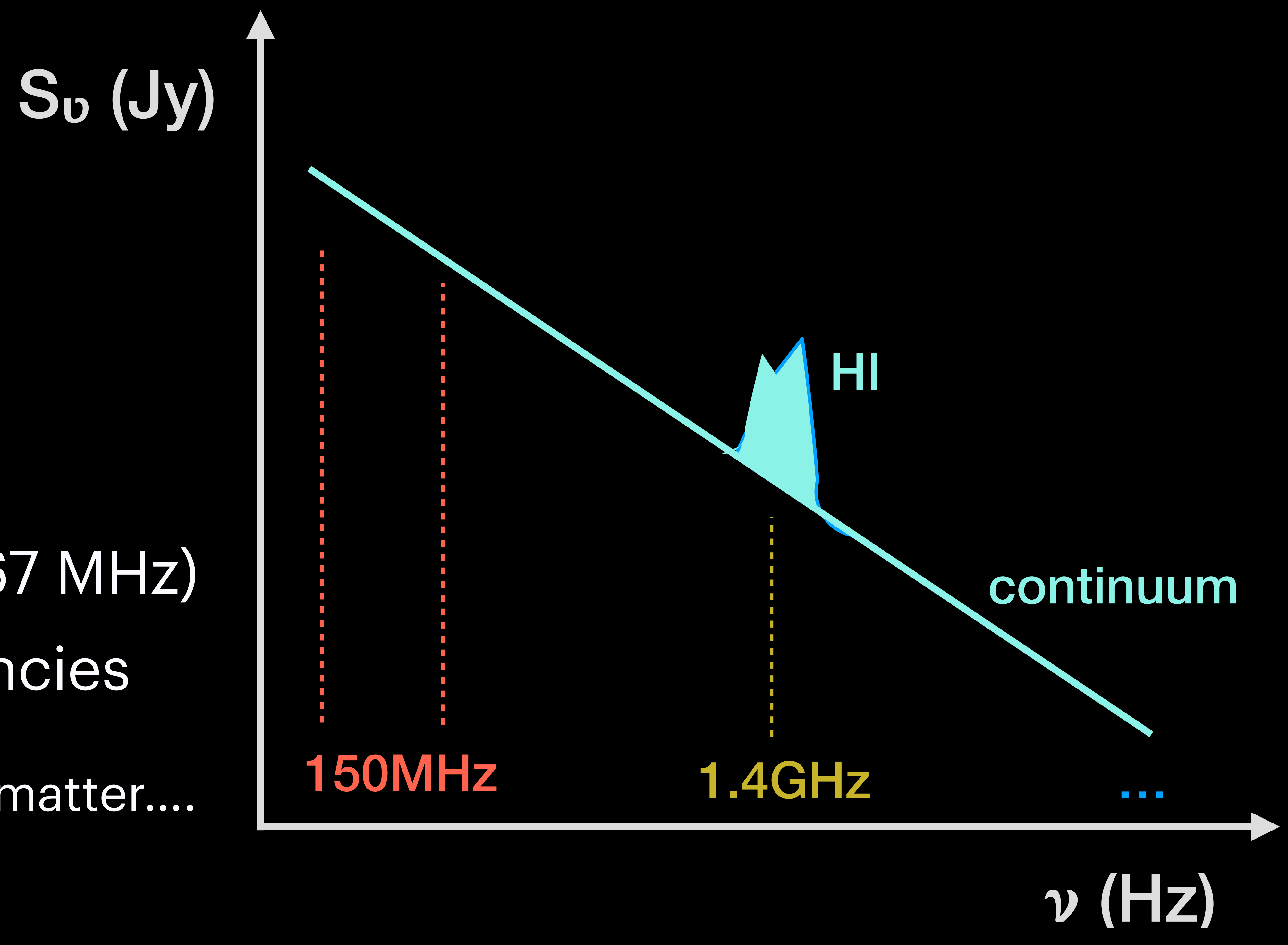


$I^{obs}(l,m)$

the "shape" of the sources is defined by how filled the uv-coverage is: further "cleaning process is necessary to improve the quality of the image

Questions on this part?

What can you learn from radio observations?



Tracing atomic neutral hydrogen (HI) 1420 MHz (and OH 1665-1667 MHz) and **other molecules (like carbon monoxide, CO)** at higher frequencies

resolved structures to learn about rotation, galaxy mergers, interaction, dark matter….

Radio continuum - star formation (radio-FIR….), extended emission

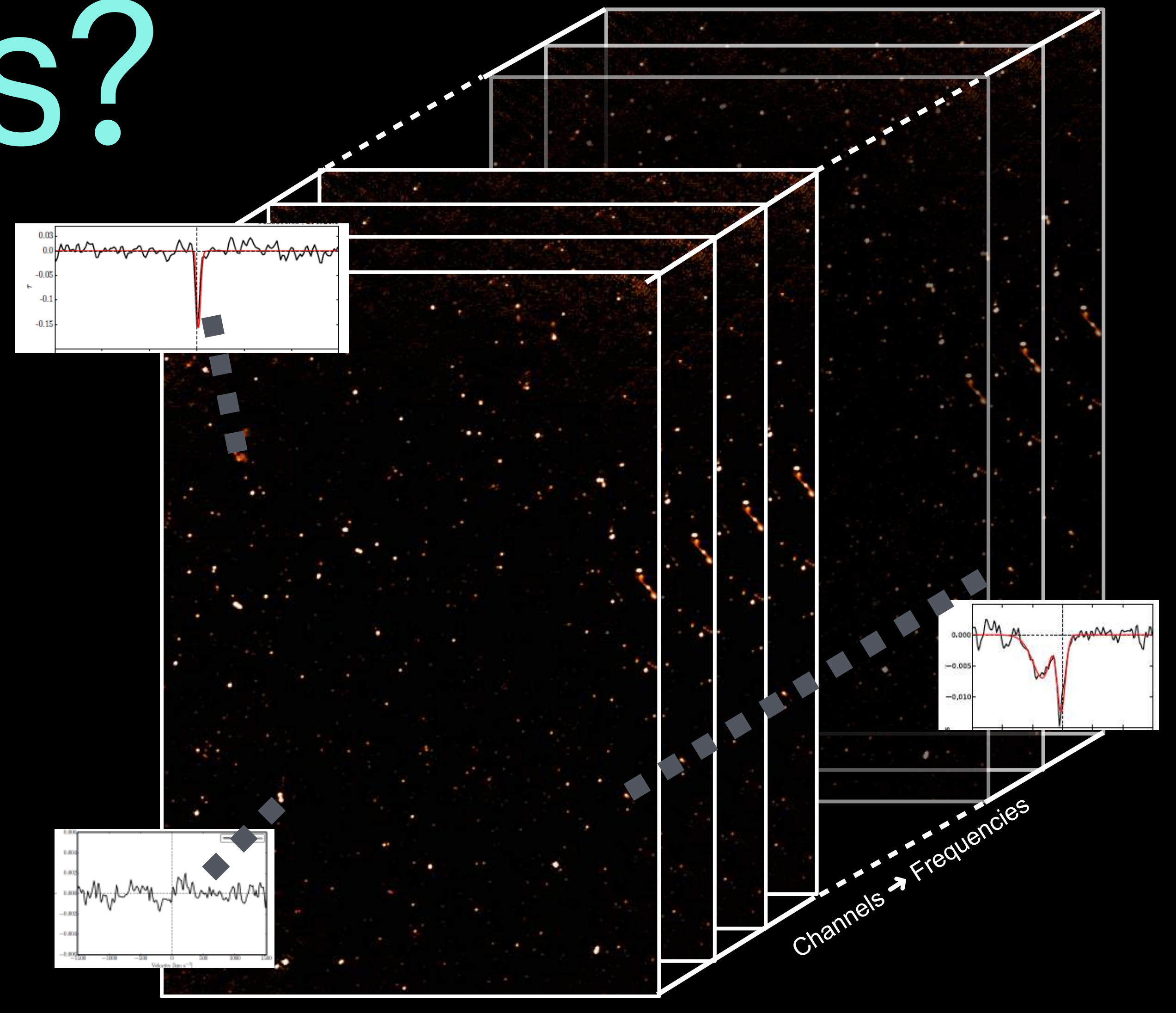
tracing AGN: jets/lobes

If more frequencies are available: spectral indices ➔ tracing the ageing etc.

Polarisation - distribution of magnetic field, rotation measure (density….)

What are the important parameters when we plan radio observations?

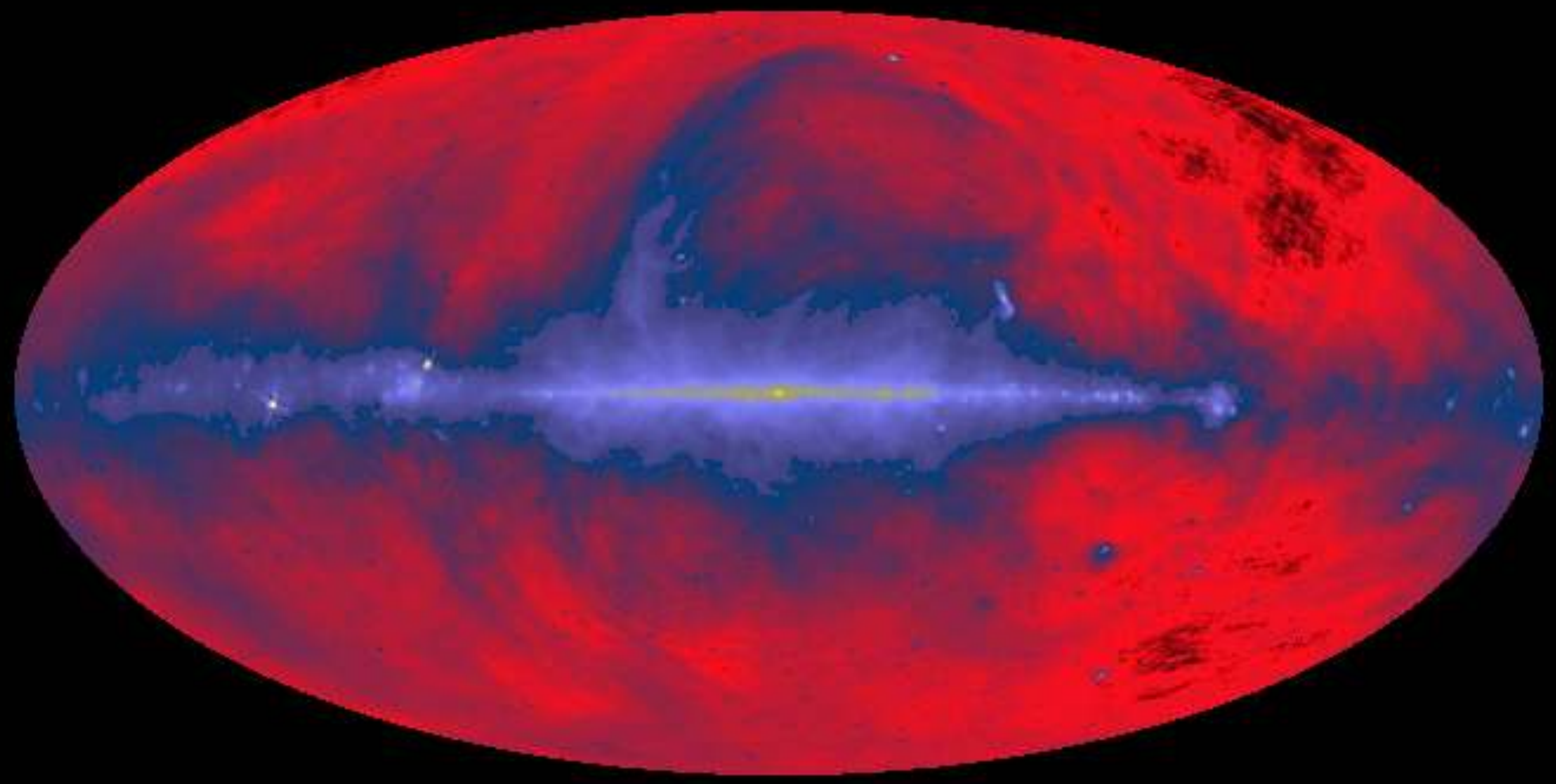
or you look for an observation in the archive...

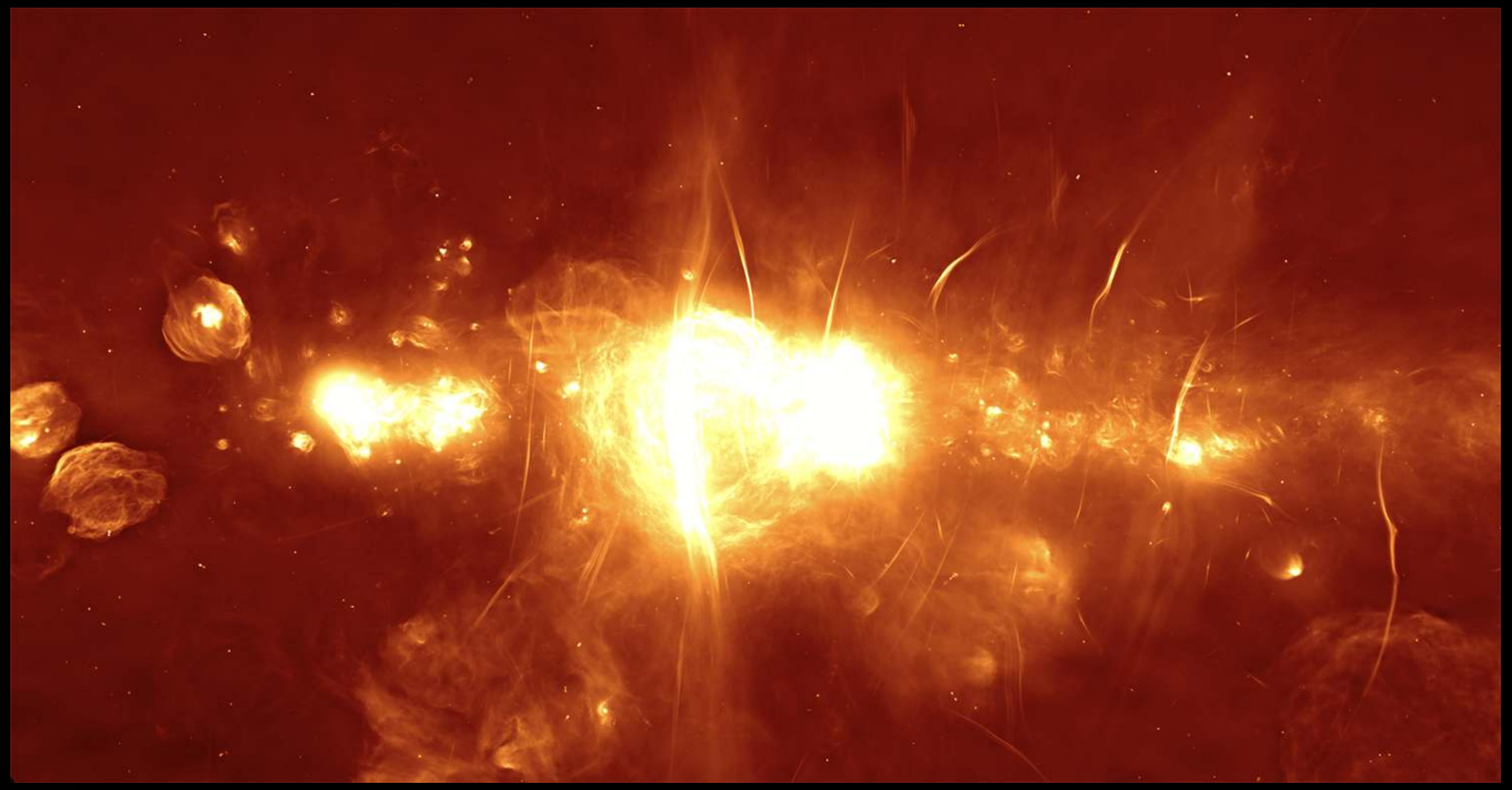


- continuum and/or lines (images and data cubes)
- frequency or frequency range (spectral studies, e.g. HI 21 cm)
- angular resolution → *every radio telescope covers certain frequencies and certain resolutions...*
- noise to reach
- situation of radio frequency interferences (RFI)

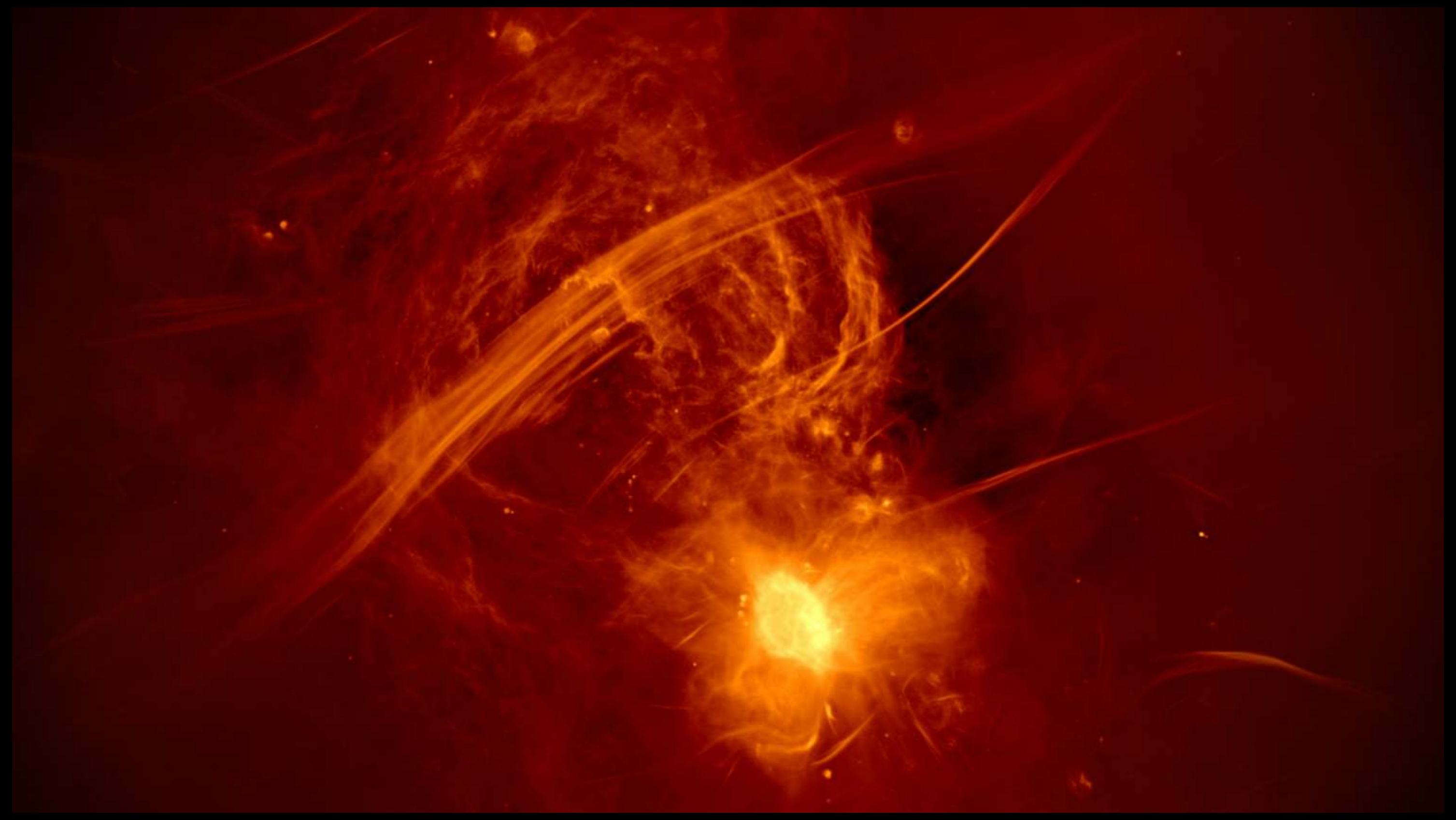
Radio observations can be done night and day (with some exceptions)

The sky at radio wavelengths: what can we see?





MeerKat images - I. Heywood, SARAO



but here we will look far beyond...

...for example, radio galaxies

Radio telescopes you should know…

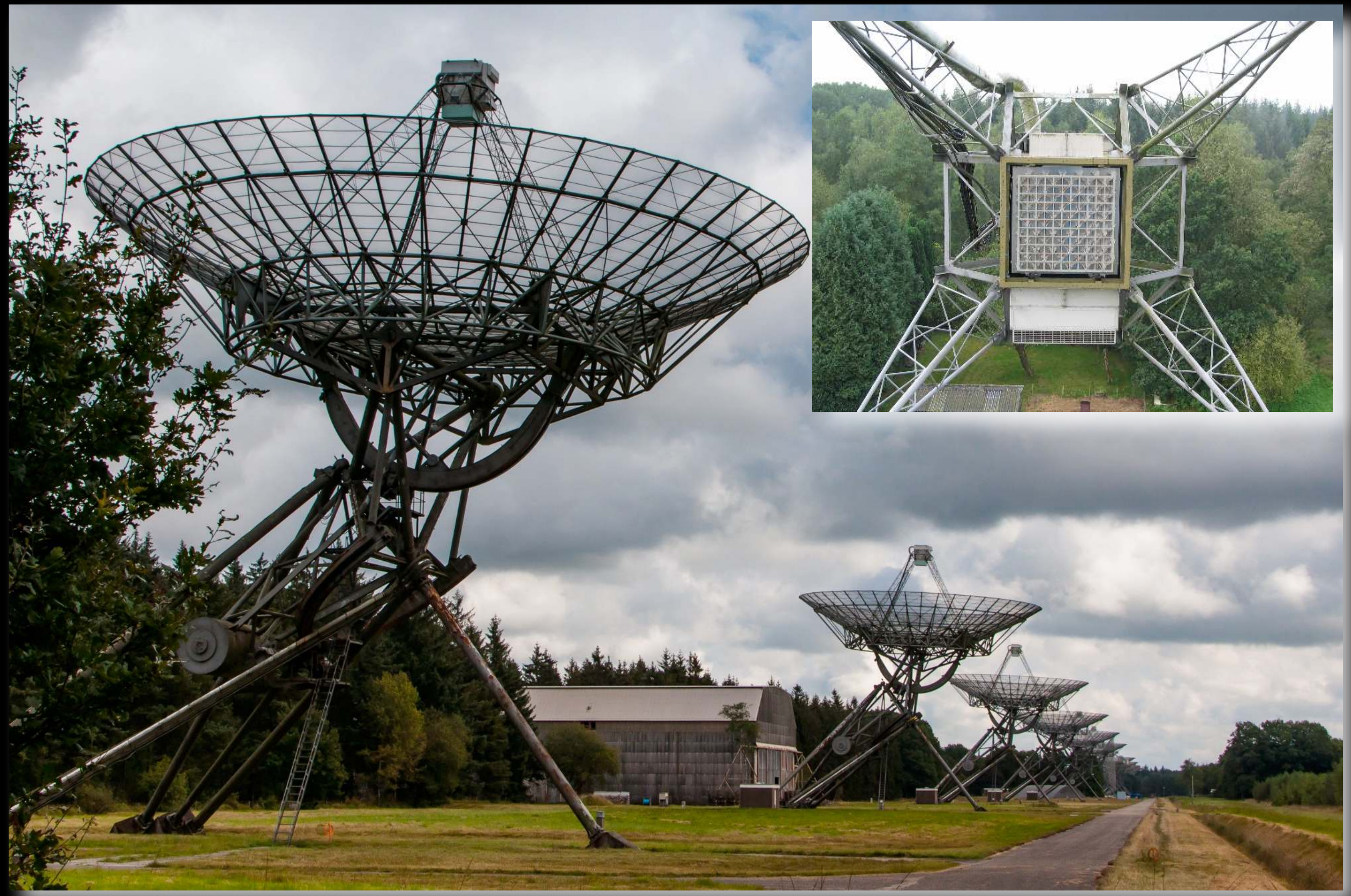
Connected antennas

JVLA: Karl Jansky Very Large Array (USA)
GMRT: Giant Metrewave Radio Telescope (India)
WSRT-Apertif: Westerbork Synthesis Radio Telescope (Netherlands)
ATCA: Australian Telescope Compact Array (Australia)
MeerKat: Karoo Array Telescope (South Africa)
ALMA: Atacama Large Millimeter Array (Chile)
LOFAR: LOw Freqeuncy ARray (Netherlands + European countries)
ASKAP: Australian Square Kilometre Array Pathfinder (Australia)
MWA: Murchison Widefield Array (Australia)

SKA: Square Kilometre Array (Australia and South Africa)

Location as remote as possible to avoid RFI…which however can come from the sky (e.g. satellites for telecommunication…)

Same examples: ATCA, WSRT classic east-west



- Westerbork 14 antennas - 3 km
- ATCA 6 antennas - 6 km

Sparse arrays

- GMRT, JVLA, MeerKat and ASKAP with more antennas can fill faster a good uv-coverage

difference in the accuracy of the surface of the antennas: depends on the frequencies covered
→ to observe at higher frequencies requires better surface of the dishes

ALMA

- Very high frequencies (> 100 GHz) ➙ located at 5000m altitude ➙ observes at higher frequencies
- Very dense array: about 60 antennas

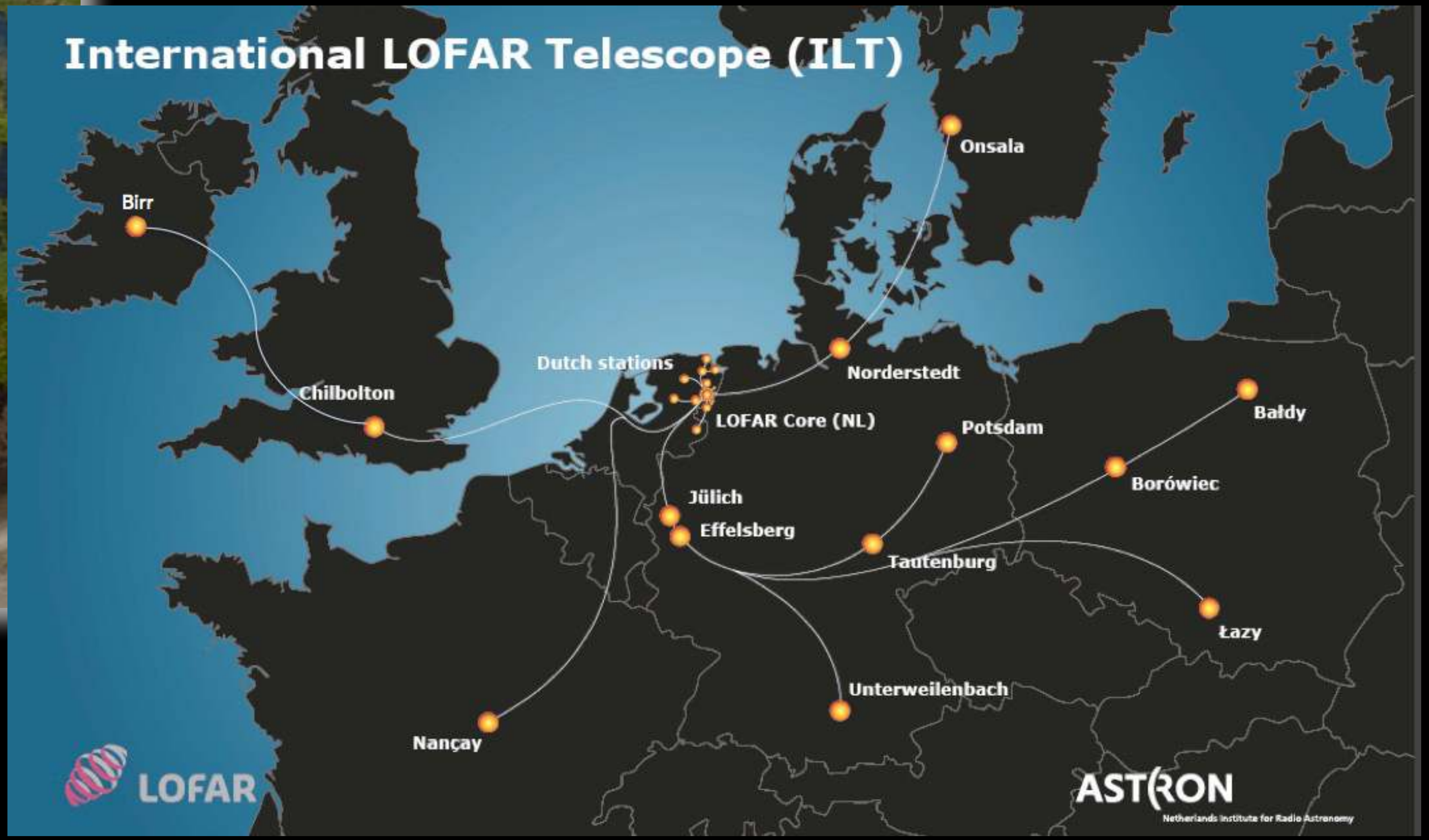
Low frequency telescopes (not dishes)

- low frequencies LOFAR and MWA → unlike GMRT no dishes but just dipoles (much cheaper!)
- large field of view ideal for surveys

MWA - Australia

LOFAR central core - Netherlands

High-Band (150 MHz) and low-band (50 MHz) antennas



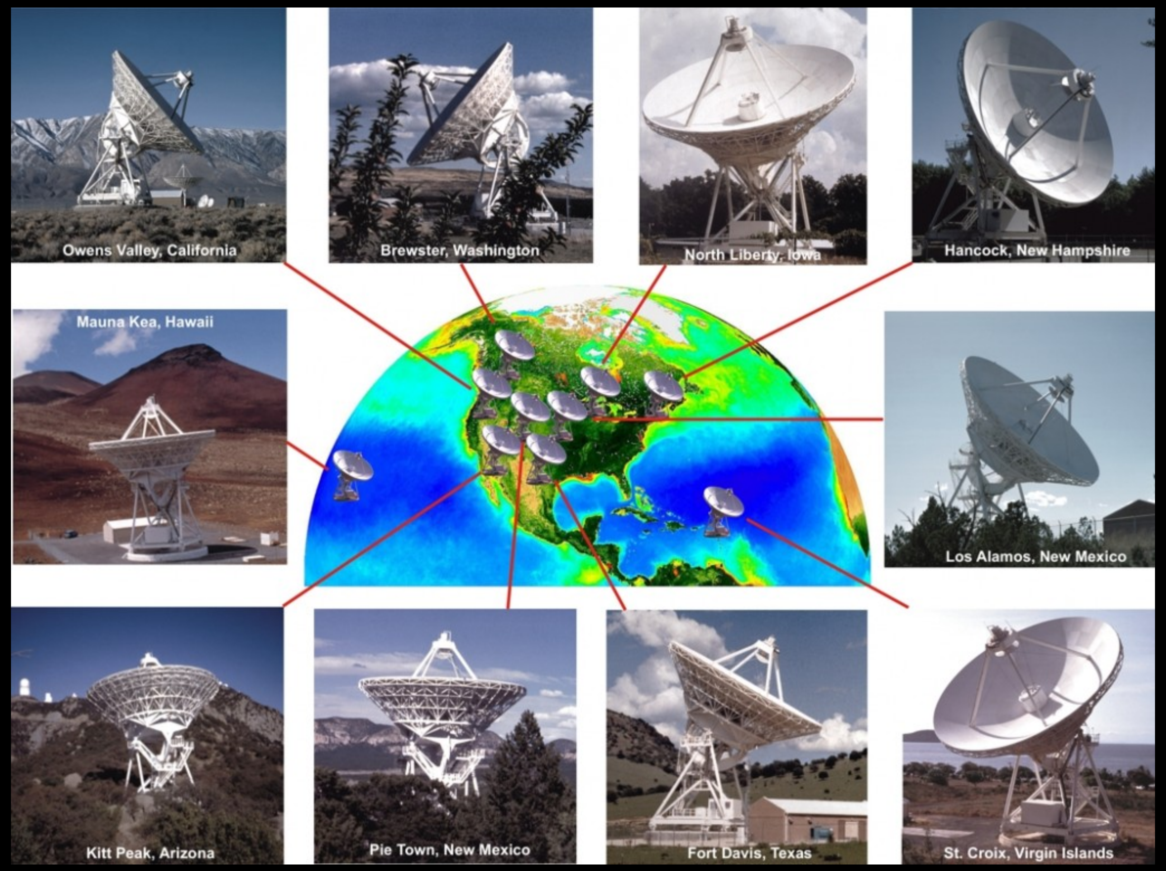
LOFAR International stations

Radio telescopes you should know…

Very long baselines: not physically connected elements

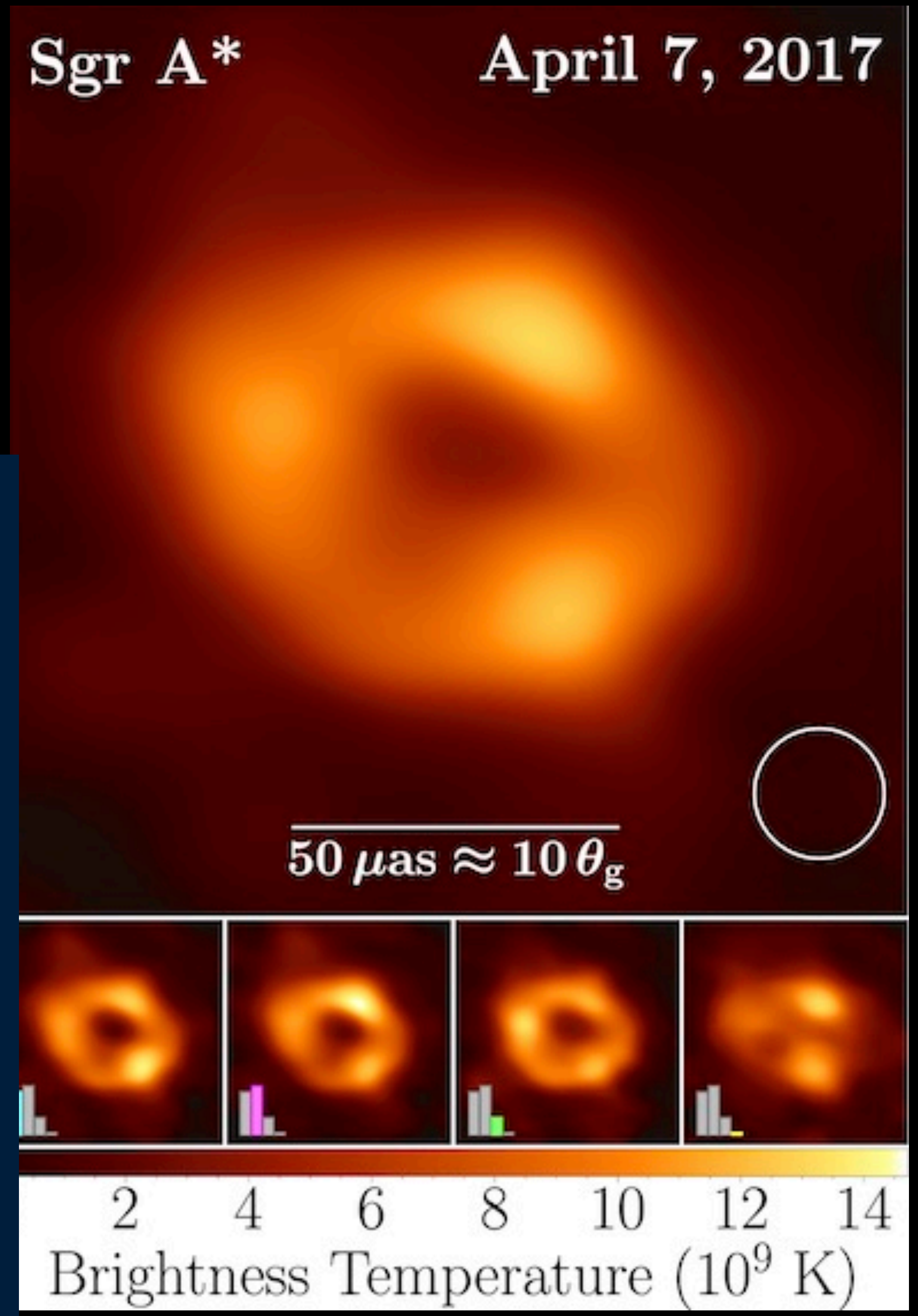
extremely high angular resolution

European VLBI Network

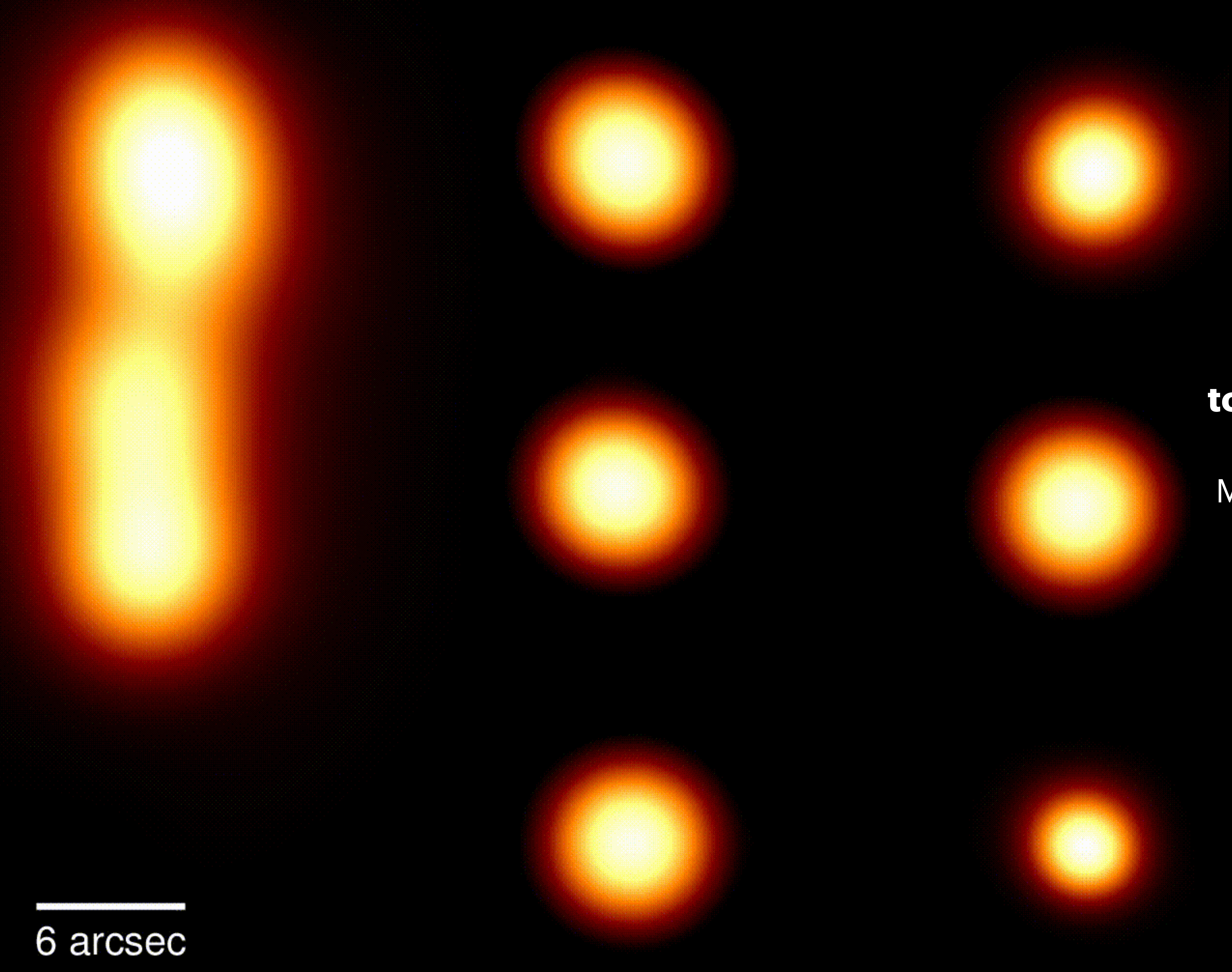


VLBA Network

Event horizon telescope

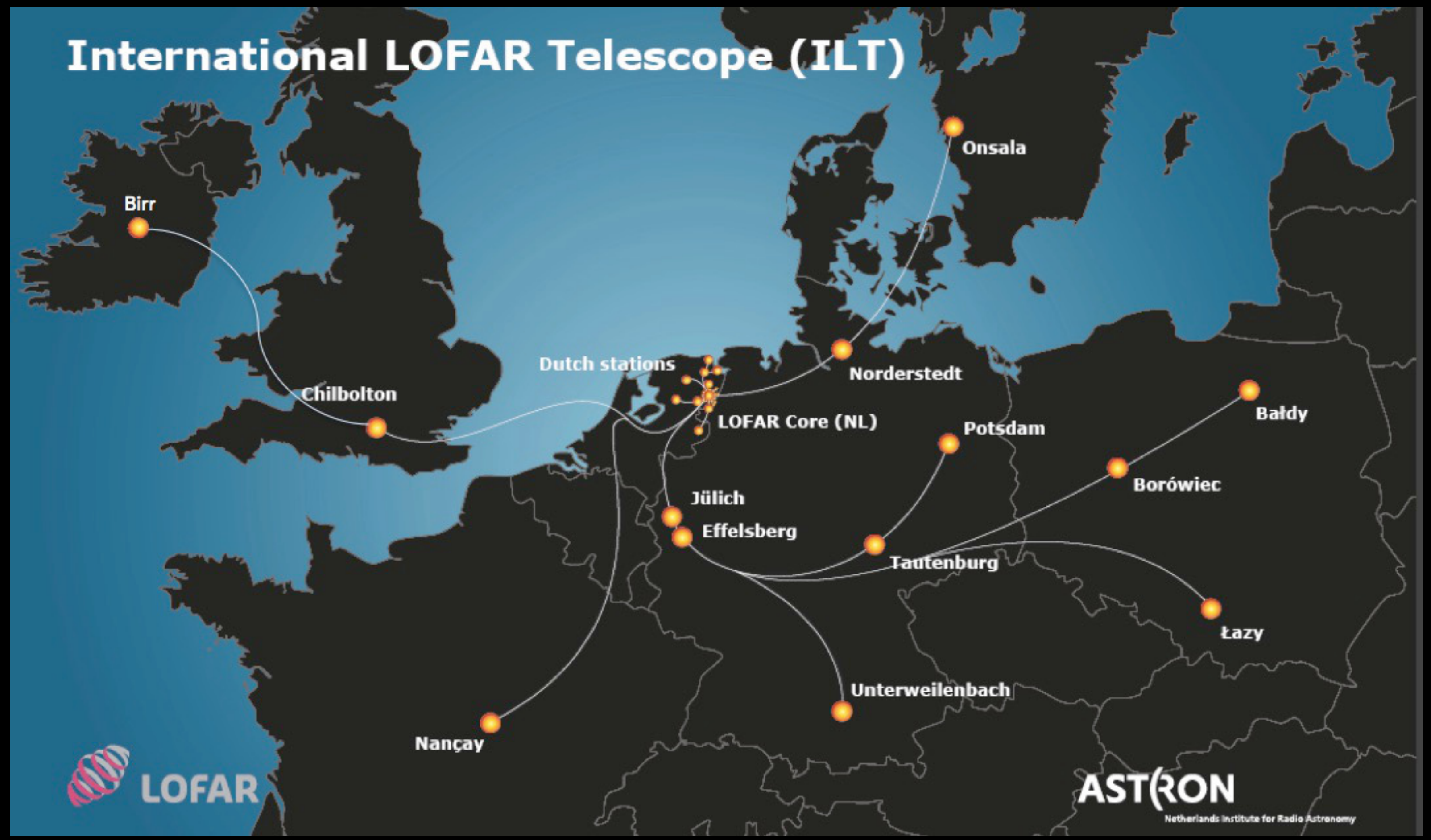


Dutch LOFAR and LOFAR with International baselines



Differences going to high angular resolution:
from dutch baselines 6 arcsec
to international baselines 0.3 arcsec

Morabito et al. 2021 ➔ A&A special issue
Sweijen et al. 2022 Nat Astr

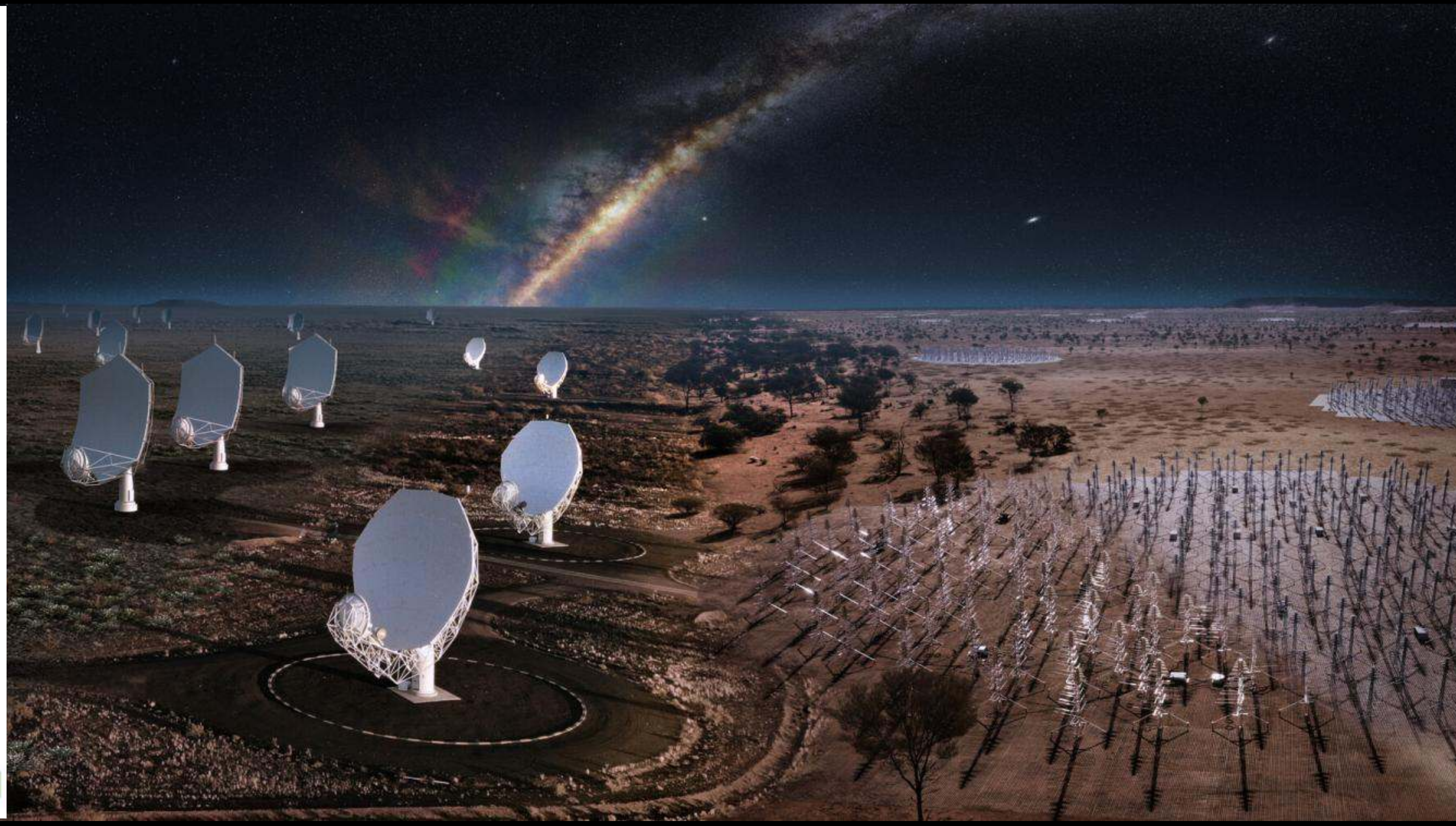


A lot going on in radio astronomy…

Square Kilometre Array (SKA) ➙ in the construction phase

Two sites, two telescopes: SKA-Mid (South Africa)and SKA-Low (Australia)

SKA-mid will include antennas in African countries for VLBI



SKA- Mid
South Africa

SKA-Low
Australia

Questions on this part?

Radio astronomy becoming more accessible for non radio experts

- more radio surveys: some new radio telescopes have large field of view ideal for producing surveys of the sky (see LOFAR)
- pipelines to calibrate data are more common
- archives with multiple products (see ALMA)

Radio images already available:

surveys and processed data on archives

not always easy to make images/cubes from radio observations, but a lot is already available in surveys and archives: there could be your favorite object!

sites like NED, Skyview have links to many of them

Radio continuum at various freqeuncies (mostly 1.4 GHz and 150 MHz)

NVSS - NRAO VLA Sky *Survey* (*NVSS*) is a 1.4 GHz continuum *survey* covering the sky north of -40 deg declination https://www.cv.nrao.edu/nvss/

FIRST - Faint Images of the Radio Sky at Twenty-cm at 1.4 GHz covers 10,000 square degrees http://sundog.stsci.edu/

VLASS - Very Large Array Sky *Survey* (*VLASS*) survey at 2–4 GHz and ~ 2.5" resolution-

TGSS GMRT - TIFR GMRT Sky Survey (TGSS) - 150 MHz - https://vo.astron.nl/tgssadr/q_fits/cutout/form

Apertif WSRT 1.4 GHz - first data release (only part of the northern sky, 1.4GHz and HI data cubes, Adams et al. 2022 - vo.astron.nl

LOFAR - first and second release 150 MHz (Shimwell et al. 2022) and 45 MHz (first release de Gasperin et al. 2023) and famous field - https://lofar-surveys.org/

GLEAM MWA survey - Harley-Wlaker et al. 2017 - https://www.mwatelescope.org/science/galactic-science/gleam/

ASKAP - Rapid continuum survey - Duchesne et al. 2023

ASKAP - EMU coming up...

Radio images already available:

surveys and processed data on archives

not always easy to make images/cubes from radio observations, but a lot is already available in surveys and archives: there could be your favorite object!

sites like NED, Skyview have link to many of them

HI surveys (low redshift z<0.1):

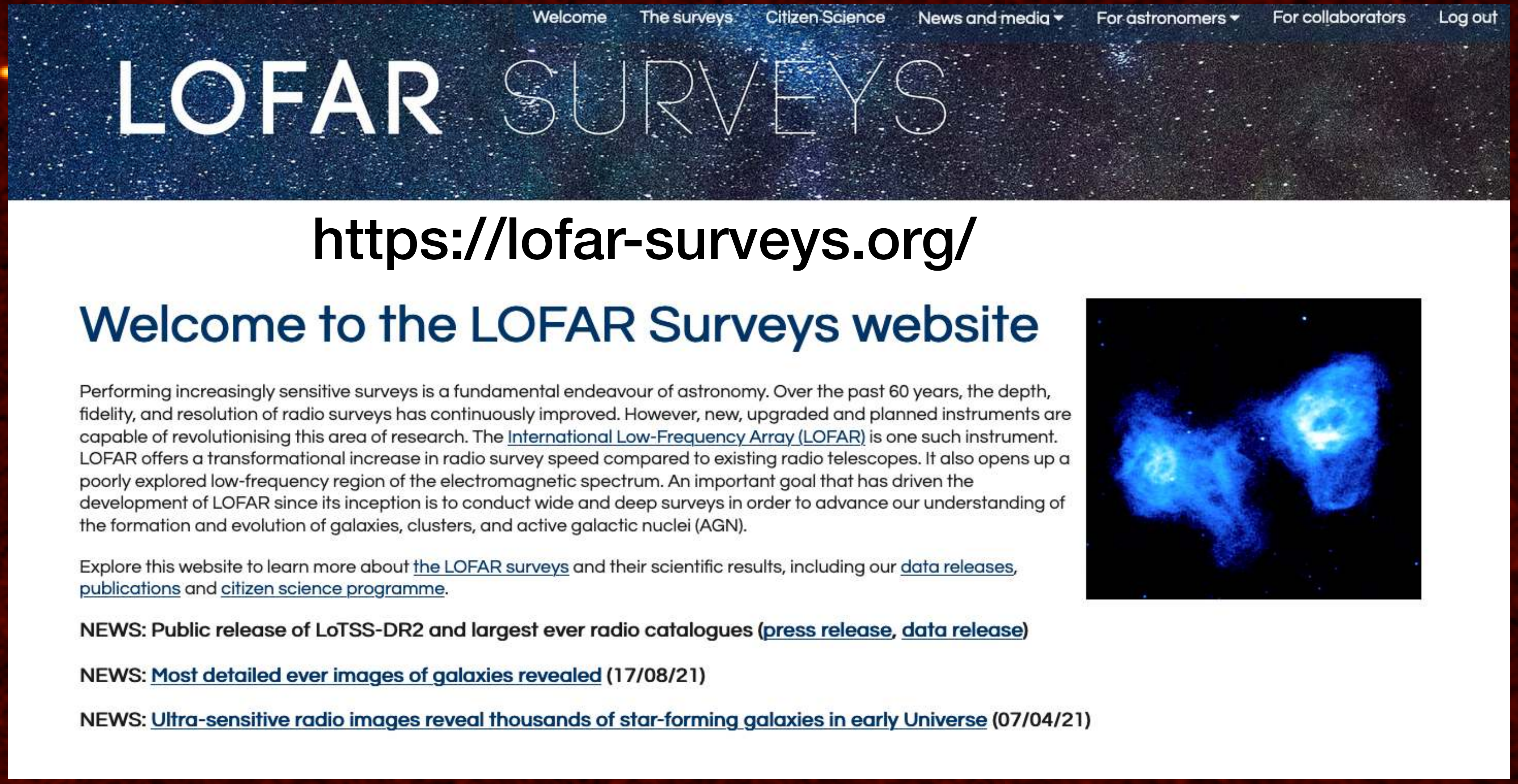
from single dish:
Alfalfa (Arecibo
HIPASS (Parkes telescope) - Data release https://www.atnf.csiro.au/research/multibeam/release/

From interferometer:
ASKAP - WALLABY (z<0.26) - https://www.atnf.csiro.au/research/WALLABY/
MeerKat - MIGHTEE (only 20sqdeg but to high redshift) https://www.mighteesurvey.org/home
Apertif - WSRT (z<0.1 resolution about 20 arcsec) - Adams et al. 2022 - vo.astron.nl

Great archives for line and continuum:

ALMA archive → multiple final products (freq higher than 100 GHz, and molecular lines CO etc.)
JVLA is also implementing some pipeline of the data

Example of small part of sky as seen by LOFAR



https://lofar-surveys.org/

Welcome to the LOFAR Surveys website

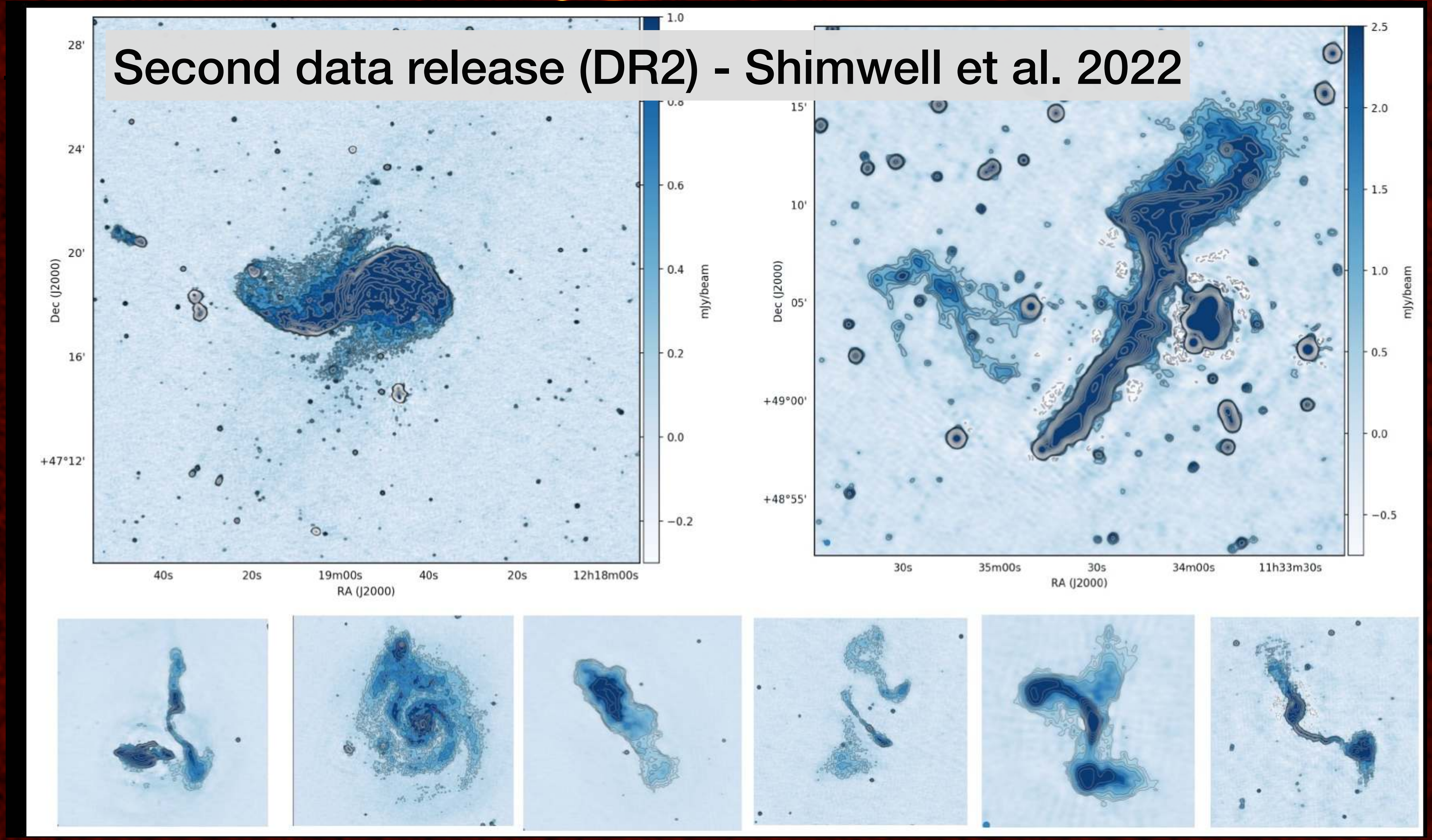
Performing increasingly sensitive surveys is a fundamental endeavour of astronomy. Over the past 60 years, the depth, fidelity, and resolution of radio surveys has continuously improved. However, new, upgraded and planned instruments are capable of revolutionising this area of research. The International Low-Frequency Array (LOFAR) is one such instrument. LOFAR offers a transformational increase in radio survey speed compared to existing radio telescopes. It also opens up a poorly explored low-frequency region of the electromagnetic spectrum. An important goal that has driven the development of LOFAR since its inception is to conduct wide and deep surveys in order to advance our understanding of the formation and evolution of galaxies, clusters, and active galactic nuclei (AGN).

Explore this website to learn more about the LOFAR surveys and their scientific results, including our data releases, publications and citizen science programme.

NEWS: Public release of LoTSS-DR2 and largest ever radio catalogues (press release, data release)

NEWS: Most detailed ever images of galaxies revealed (17/08/21)

NEWS: Ultra-sensitive radio images reveal thousands of star-forming galaxies in early Universe (07/04/21)



Final images at 6 and 20 arcsec resolution

Courtesy W. Williams: Image of radio sources in the Bootes field from LOFAR observations

Using LoTSS

Retrieving images and catalogues:

Public data:

https://lofar-surveys.org/dr2_release.html

Contains links to uv-data, images, mosaics, catalogues, HIPS, polarization products

To bulk download uv-data, images etc use ddf-pipeline (https://github.com/mhardcastle/ddf-pipeline).

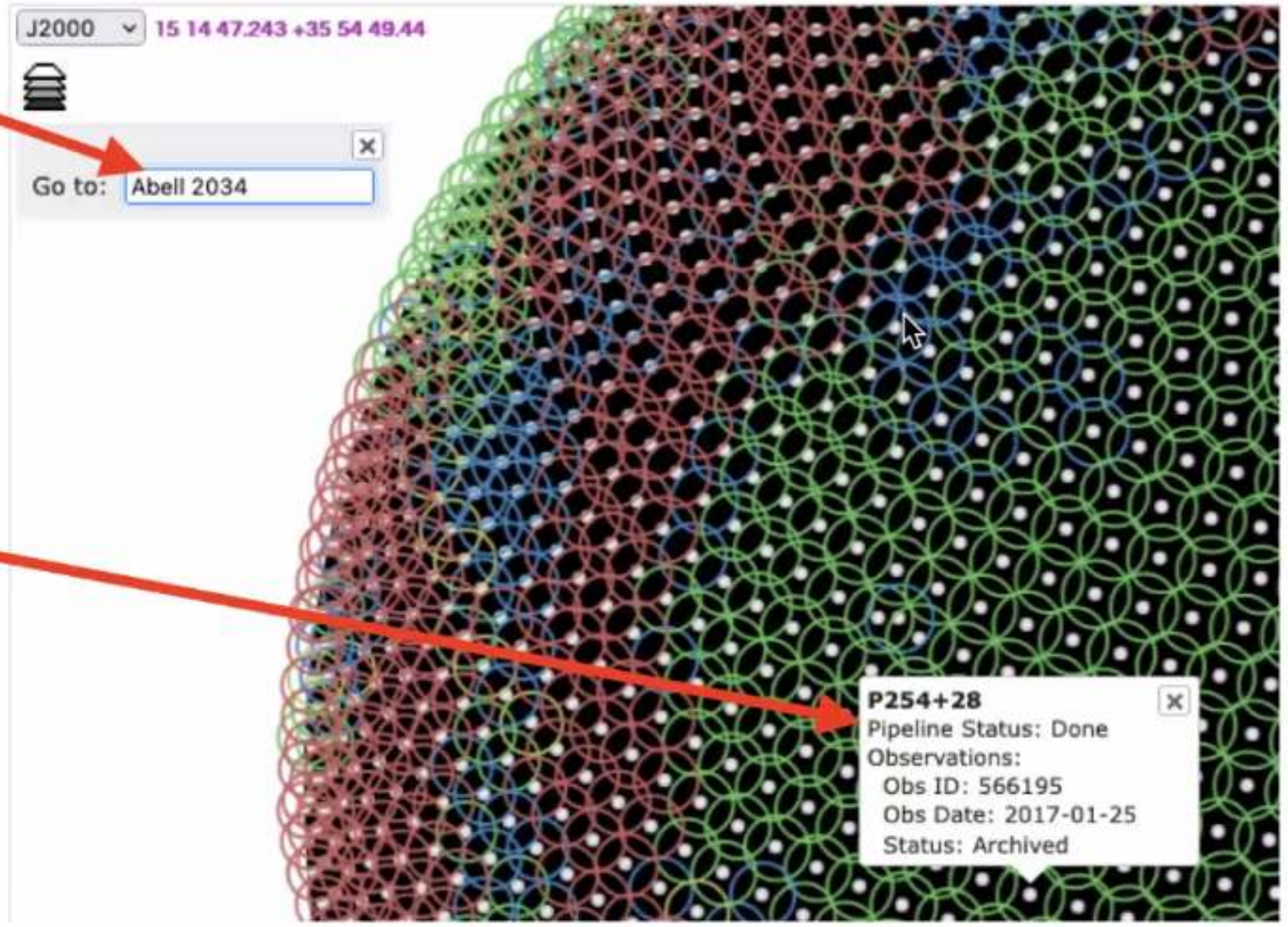
```
export SDR_TOKEN=c49c6bb3-d074-a44d-4fca-1d3f7458055d

from reprocessing_utils import *
do_sdr_and_rclone_download(fieldname,processingdir)
```

Status of observing and processing

https://lofar-surveys.org/lotss-tier1.html

Enter target name or RA/DEC.

See observations of a pointing and status of data processing.



The next steps: expand the statistics using machine learning techniques

One example: Self-organised mapping (Mostert et al. 2022) : classify sources from the LOFAR LoTSS HBA Hetdex area ~400 sq deg

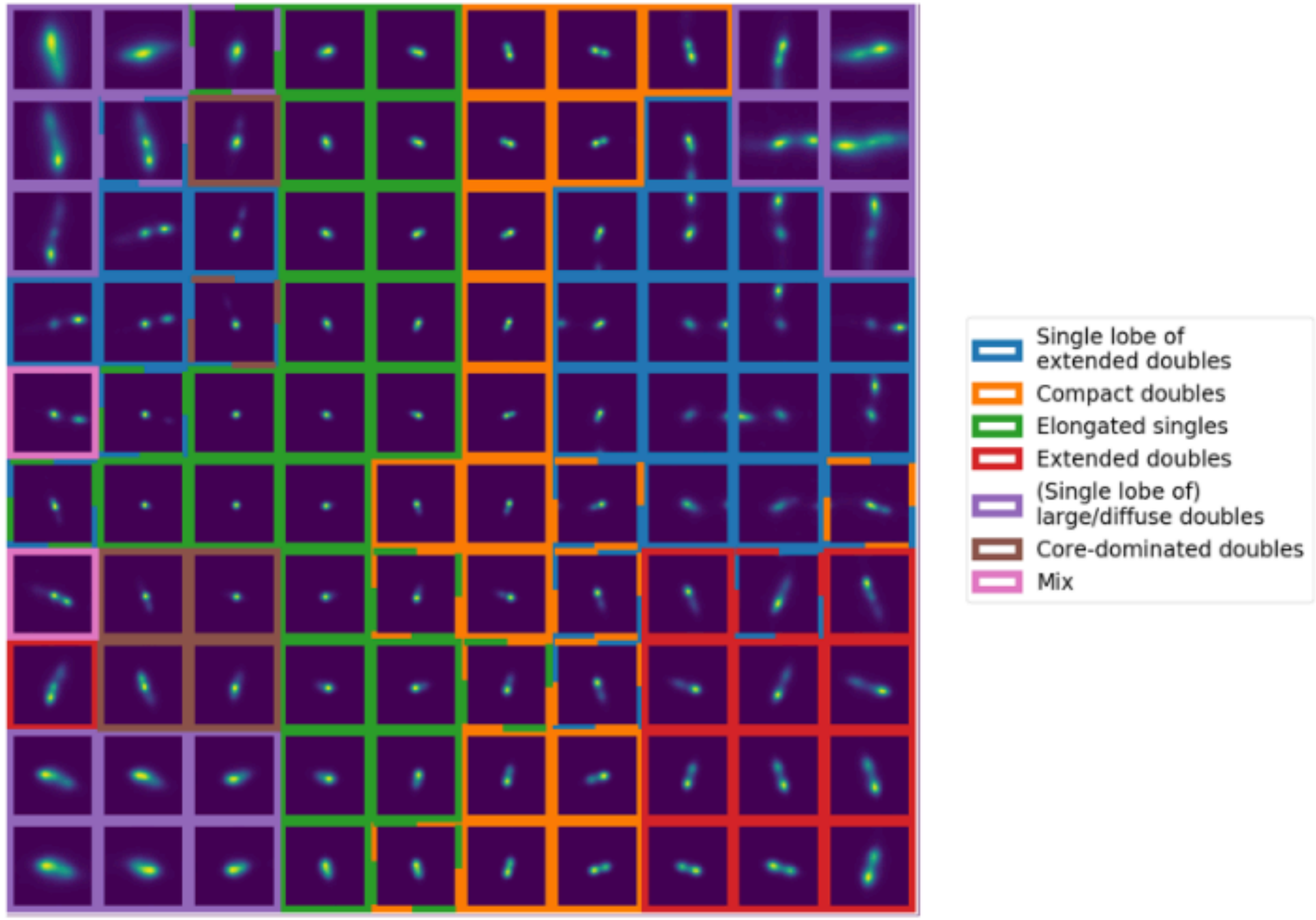


Fig. 6. Final 10 × 10 cyclic SOM manually labelled into seven categories. These categories describe the type of sources that are dominant or most occurring in the set of sources that best matches each of the 100 representative images. If there are multiple dominant types of sources best matching a representative image, the representative image is labelled using multiple categories, which is visualised by the dashed multi-coloured edges.

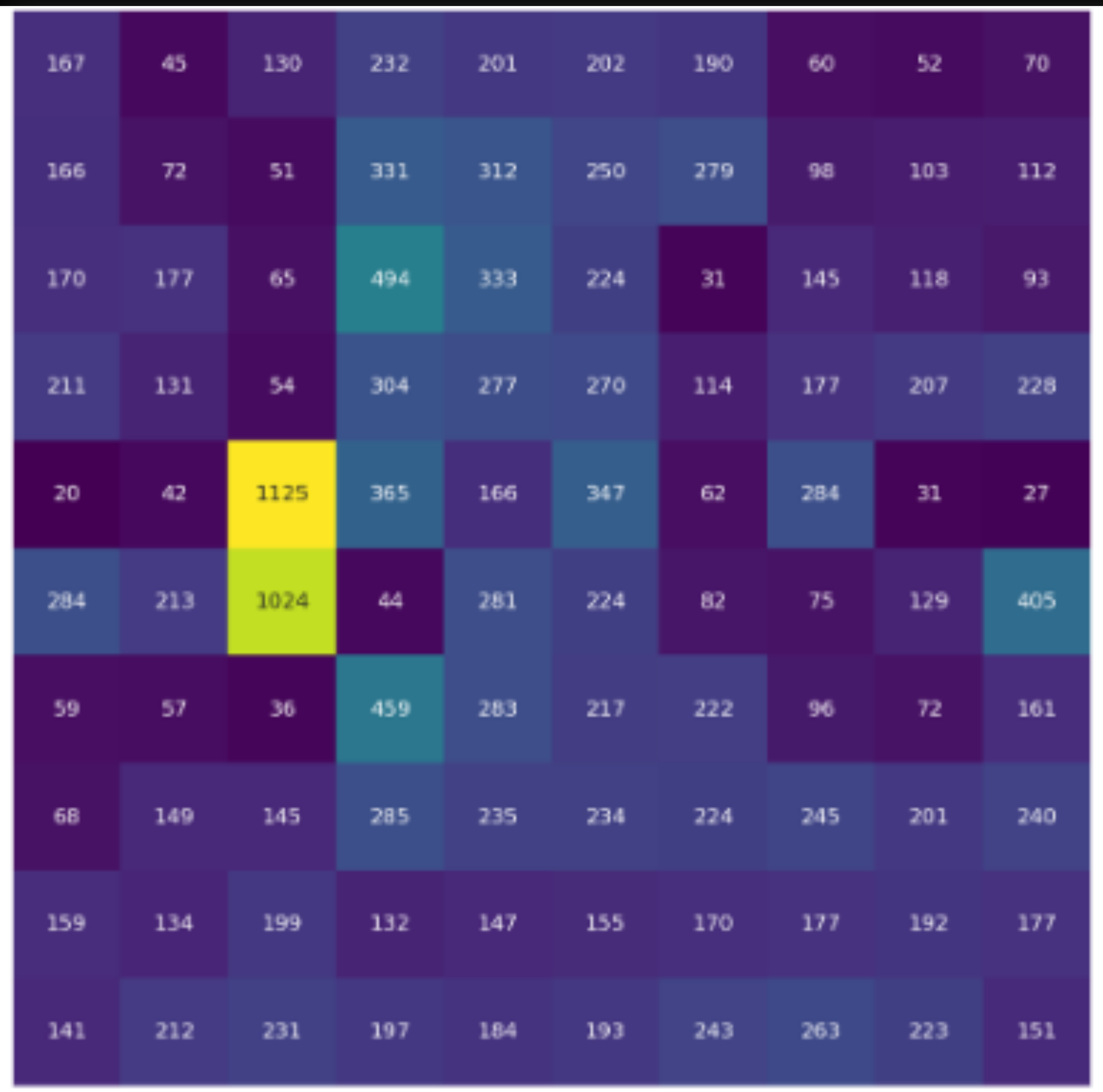


Fig. 7. Heatmap of the 10 × 10 cyclic SOM, indicating the number of sources from our training dataset mapped to each of the representative images shown in Fig. 4.

Used as training set in the
Self-organised Map (SOM) - R. Mostert et al. 2022

https://rafaelmostert.com/lofar/som.php

Summary of Les 1

Radio an important extra eye but interferometry is needed in order to reach interesting angular resolutions for the study of extragalactic objects

Many radio telescopes available depending on the science (and the hemisphere)
➙ new (or upgraded) facilities available and SKA in the construction phase

Handling of the data is more complicated - no direct imaging

but increasing number of surveys, automatic pipelines and useful archive with final data product ➙ radio astronomy is becoming more accessible for non radio astronomer

It can give a extra, complementary view of your favorite source: we will see this for AGN in the next lessons