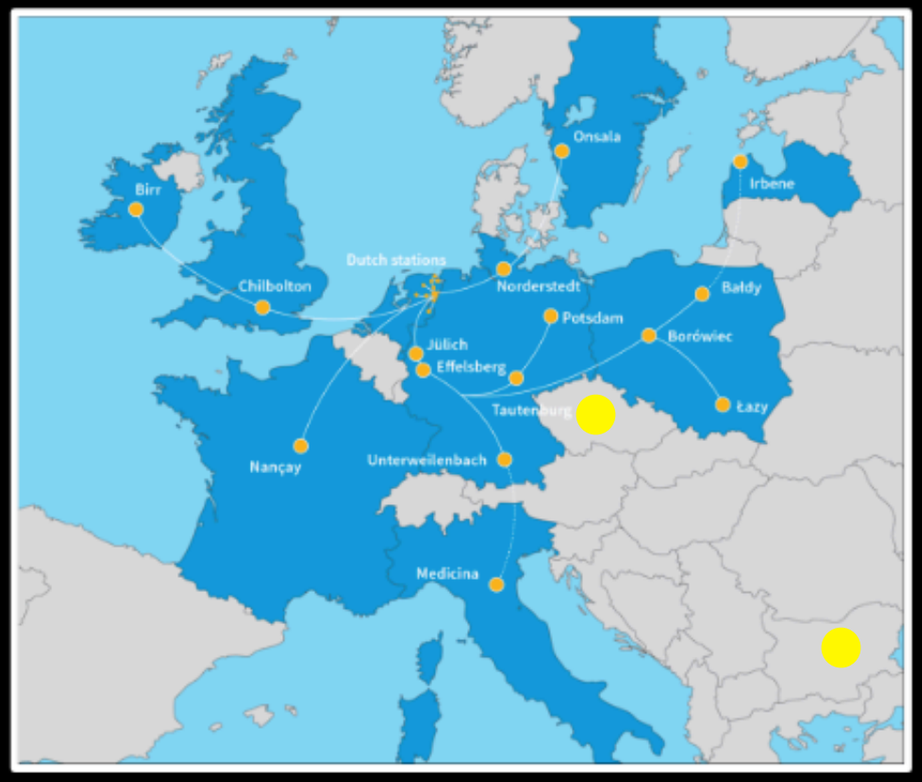
Netherlands Institute for Radio Astronomy

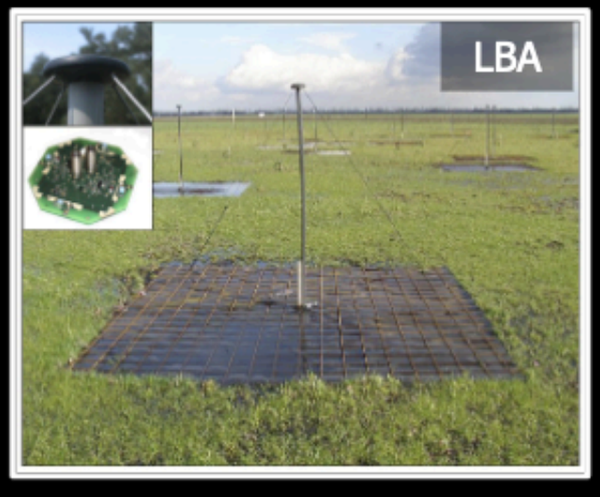
LOFAR Science

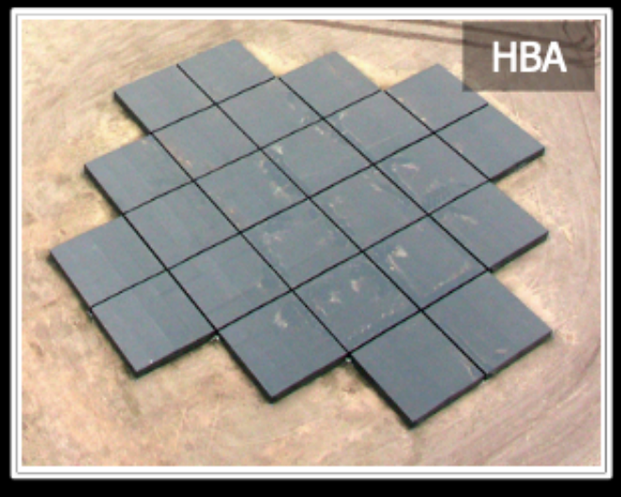
Timothy Shimwell
(ASTRON)

LOFAR: KEY FACTS



- Array of ~~51~~ 56 dipole antenna stations distributed across EU
- 10-250 MHz
- Low band antenna (LBA; 10-90 MHz); High Band Antenna (HBA; 110-250 MHz)
- Several observing modes (imaging, BF, BF+IM, TBB)
- Responsive telescope
- 96 MHz bandwidth (multi-beam option)
- Big data: important technological pathfinder for next-gen facilities and data intensive astronomy

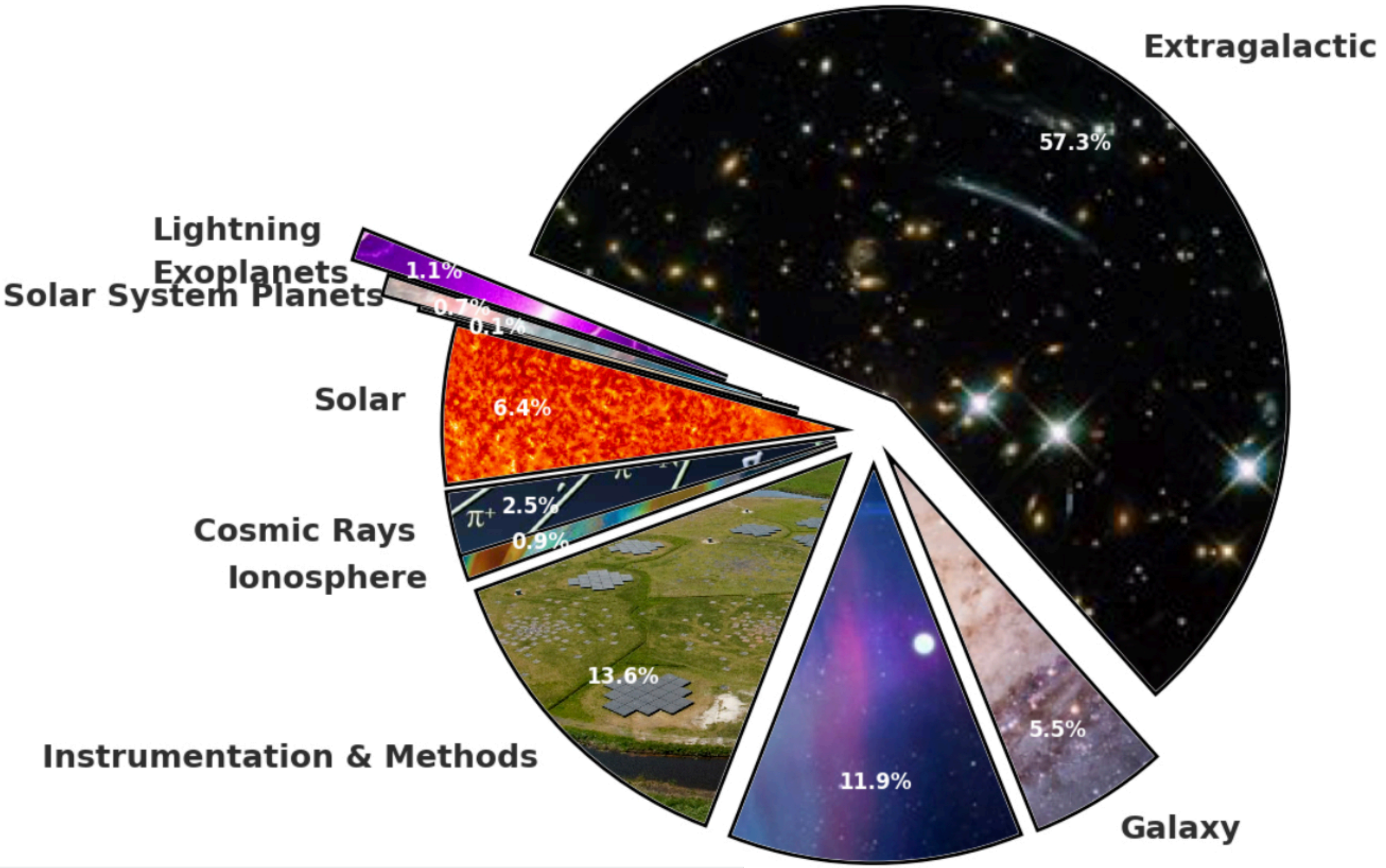






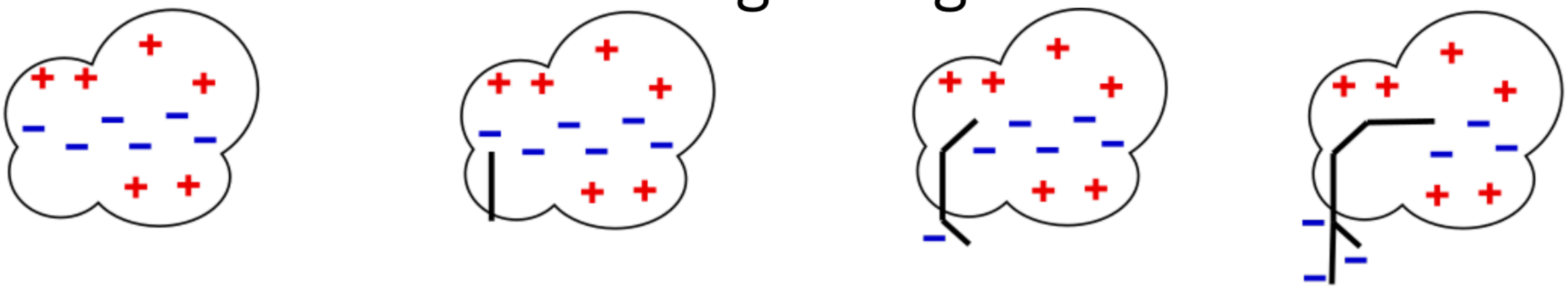


Publication overview per science area

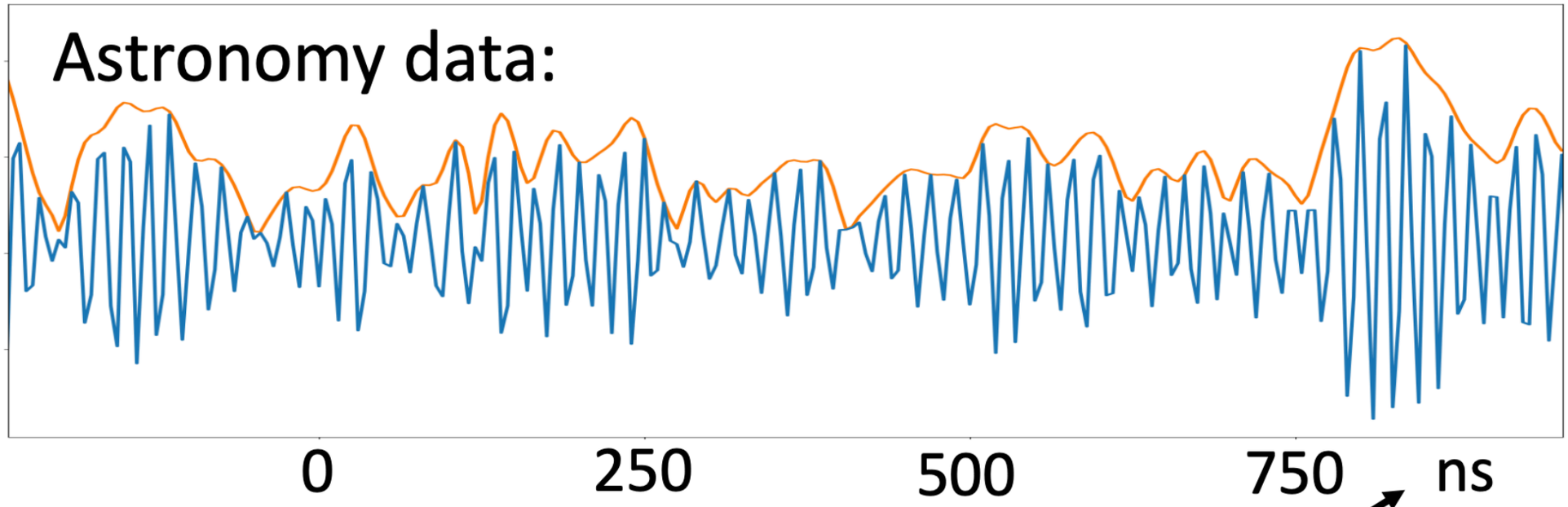


From: https://science.astron.nl/telescopes/lofar/science-with-lofar/lofar-papers/

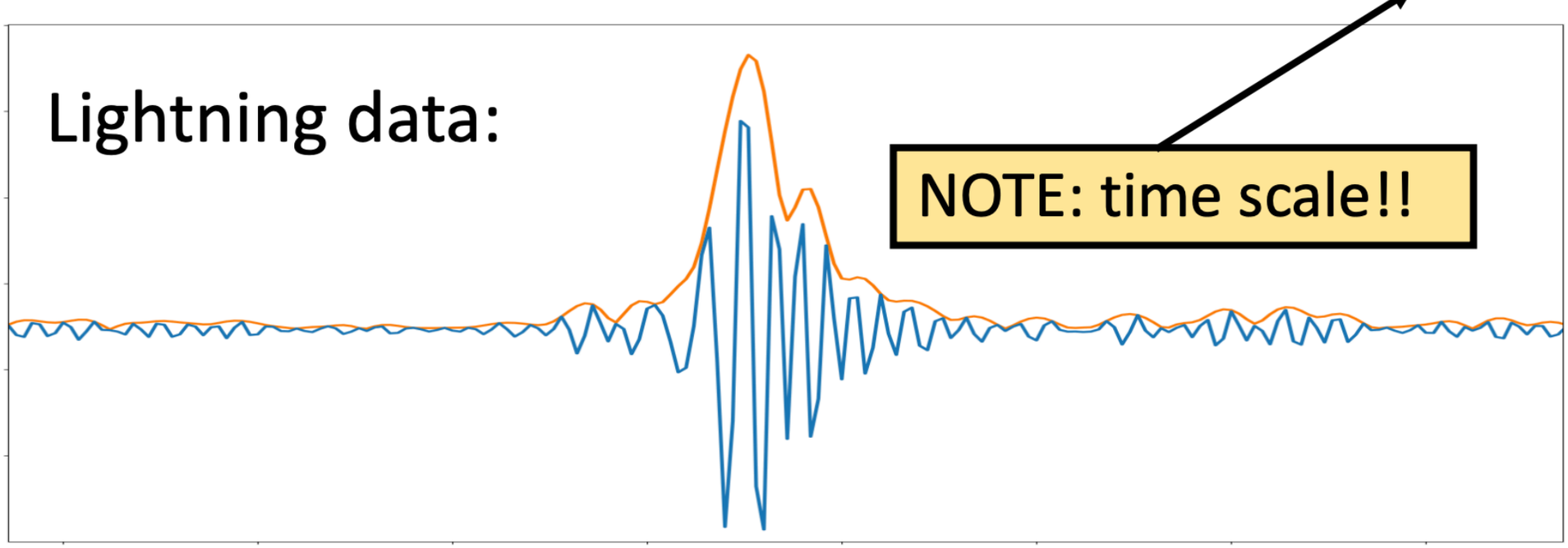
The Basic Lightning Processes



Lightning vs Astronomy Transient Buffer Data (raw voltages)



- Looks like noise
- Need Beamforming



- Discrete Pulses
- Easy to get time-of-arrival
- Beamforming not required

Lightning

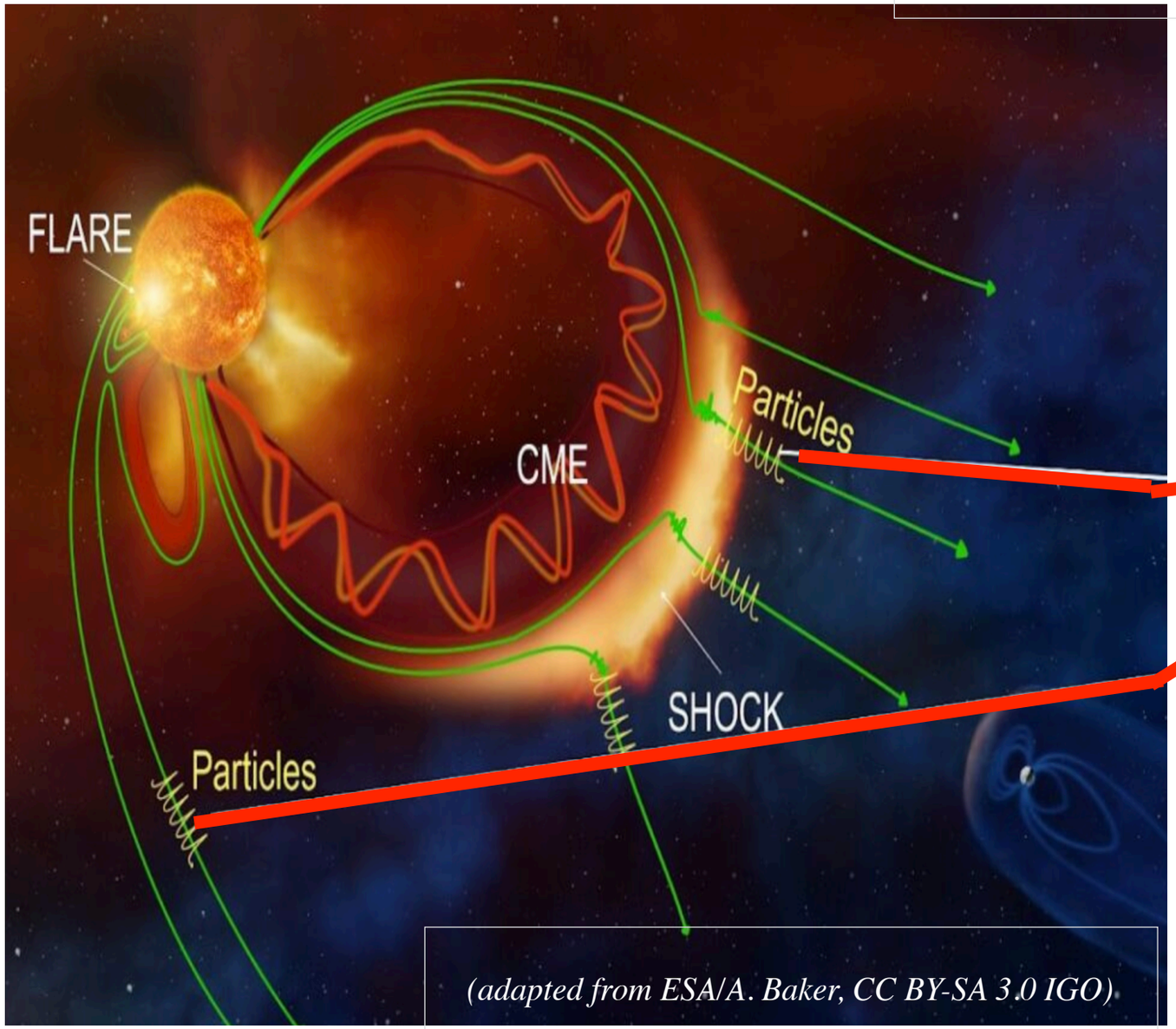


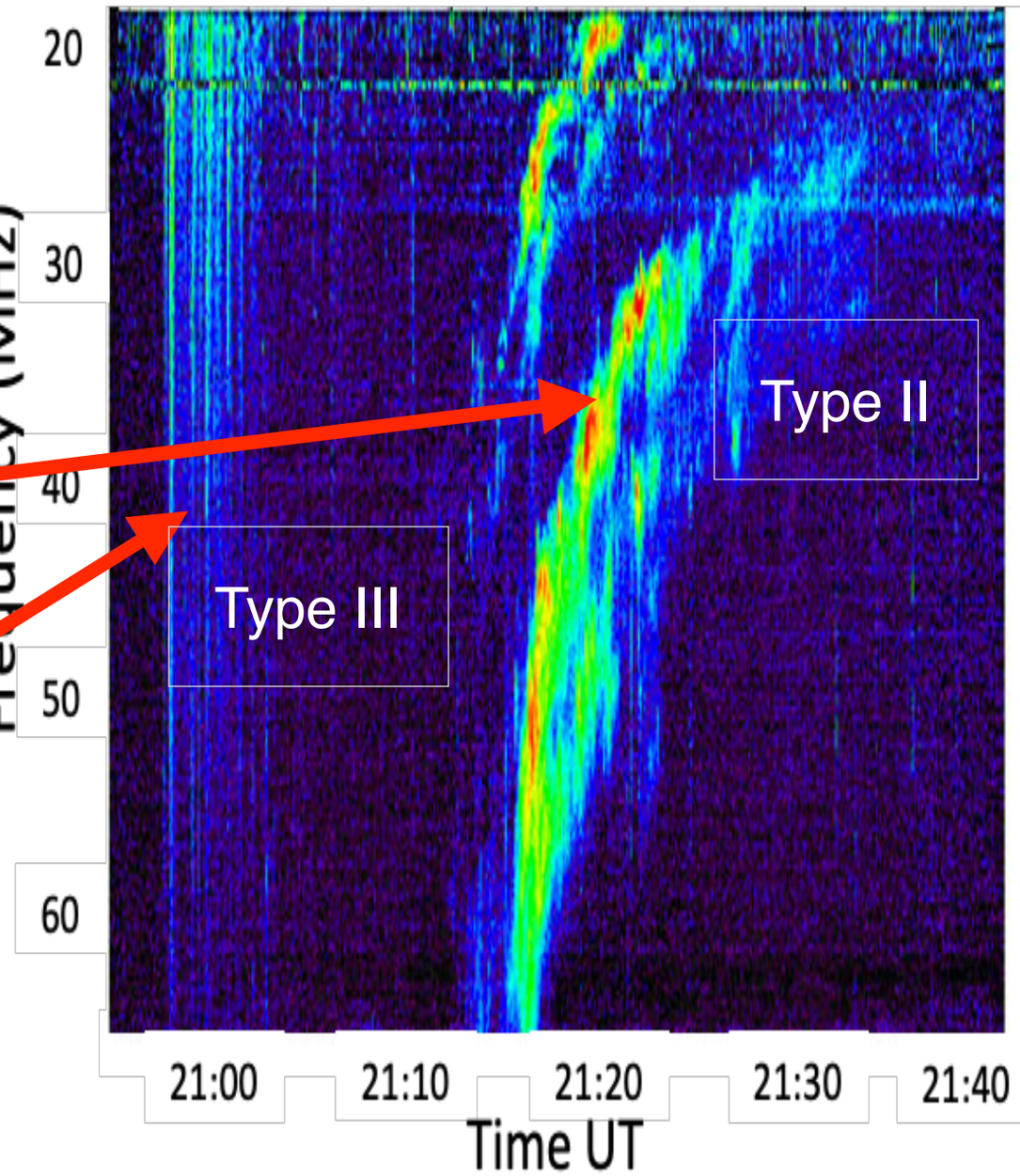
Incredible world-leading 3-D imaging ability of lightning. 1-10m spatial resolution, ns time resolution and locating 1,000s of sources per lighting flash

The Big Questions in Lightning

- How does lightning get started?
  - Measured electric fields are too small to make a spark via typical mechanisms
- How does lightning grow?
  - The plasma physics is extremely complex, and too complicated for current computers to model
- How does lightning emit gamma rays?
  - This strongly depends on how the lightning grows

Solar physics



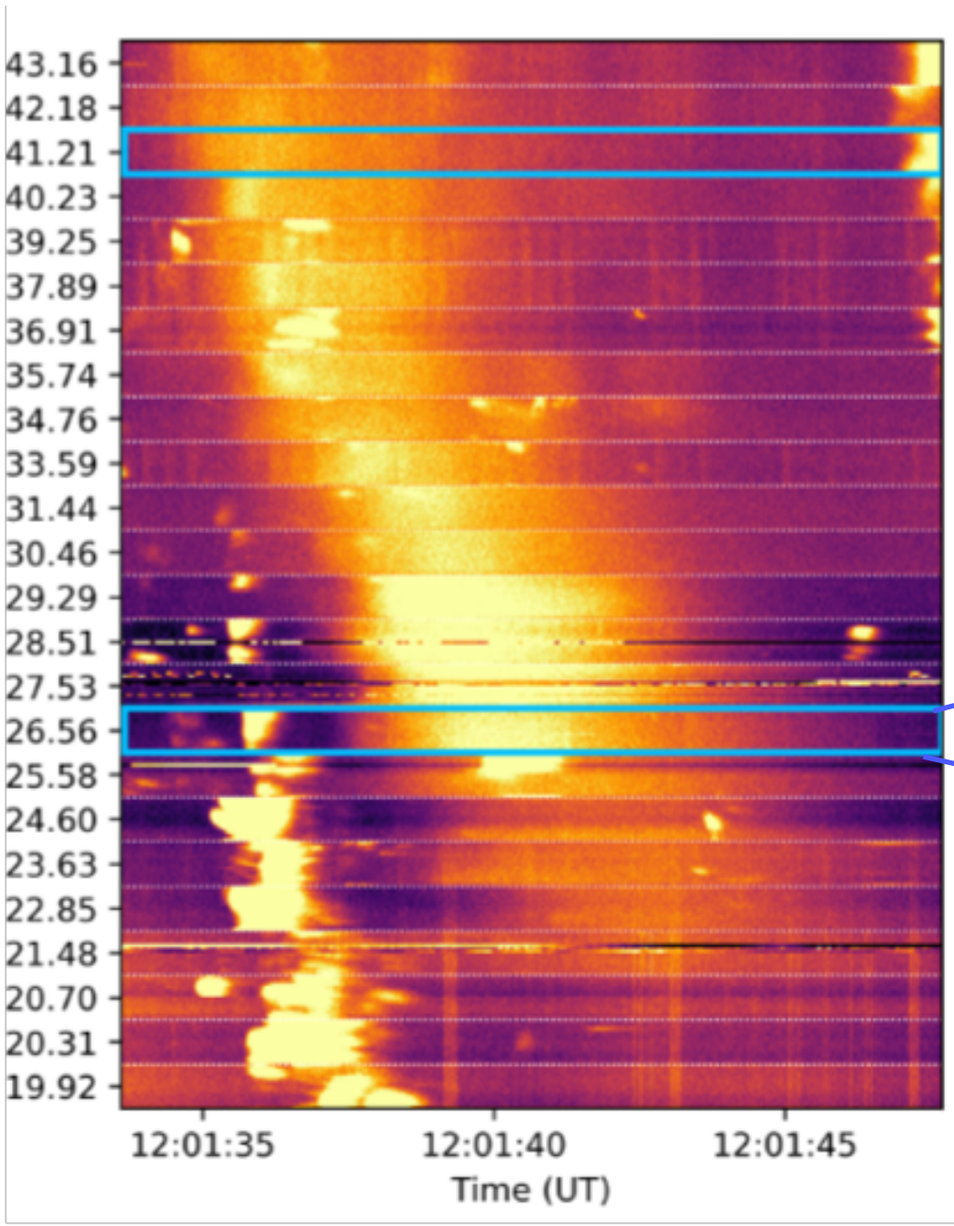


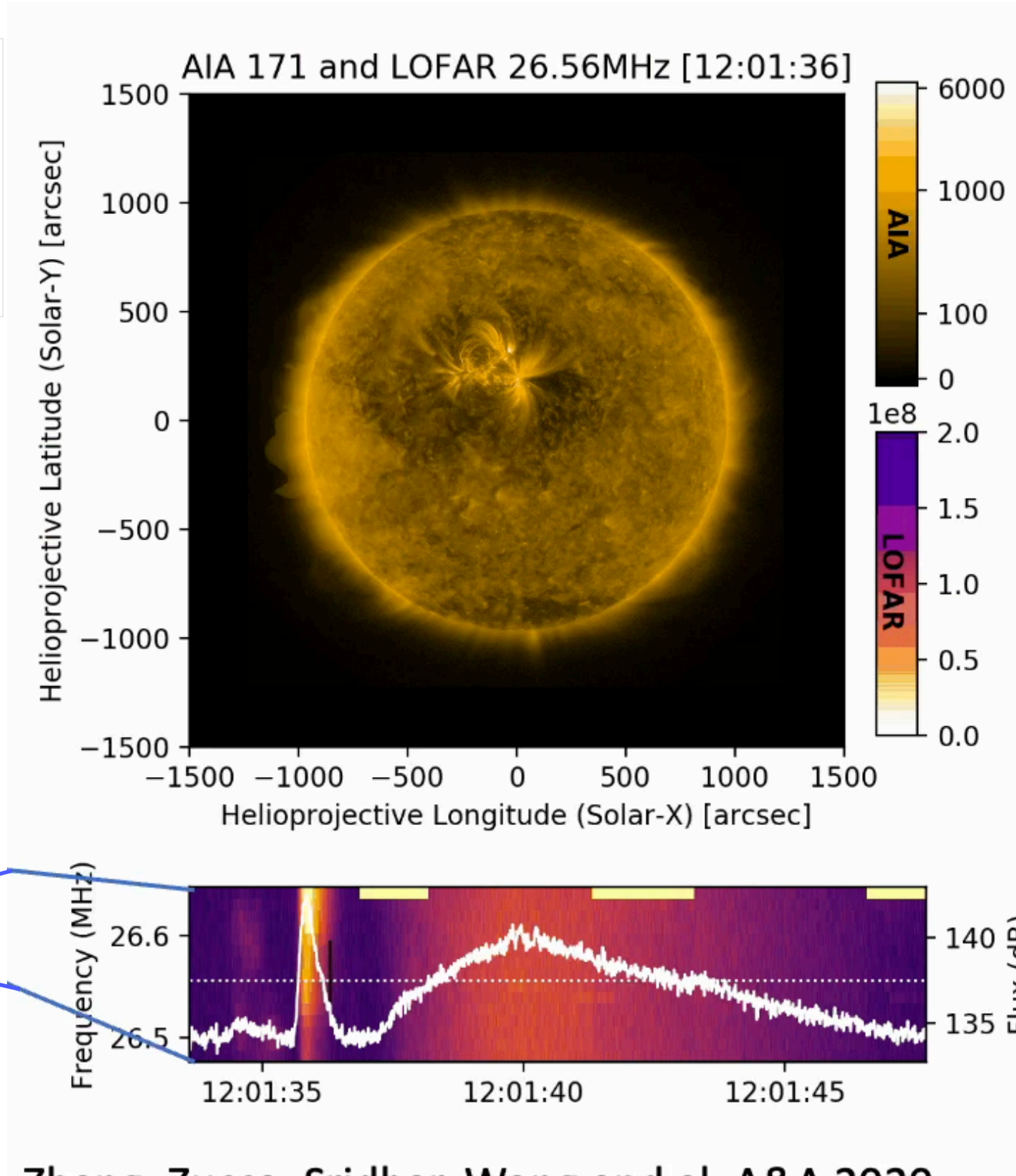
Type II bursts are plasma emission associated with corona mass ejections

Type III are energetic electrons associated with flares

Solar physics

LOFAR measurement of a Type III burst with simultaneous imaging and dynamic spectra



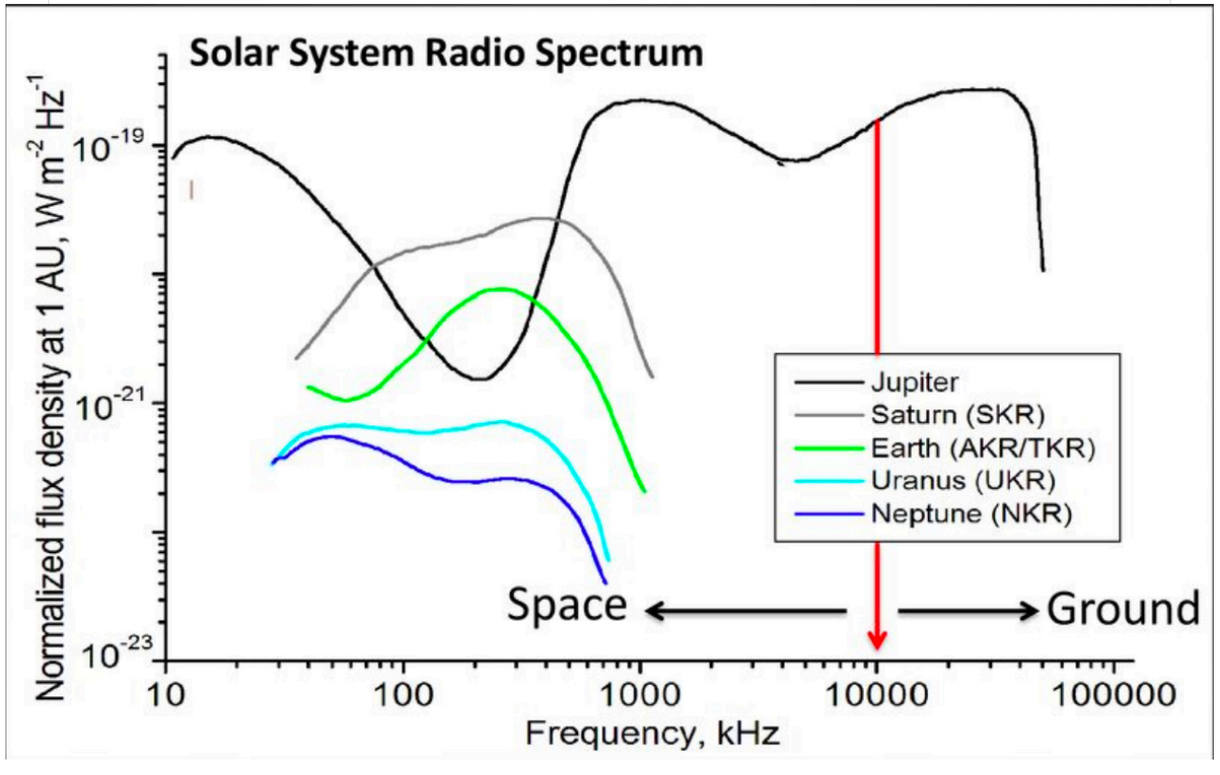


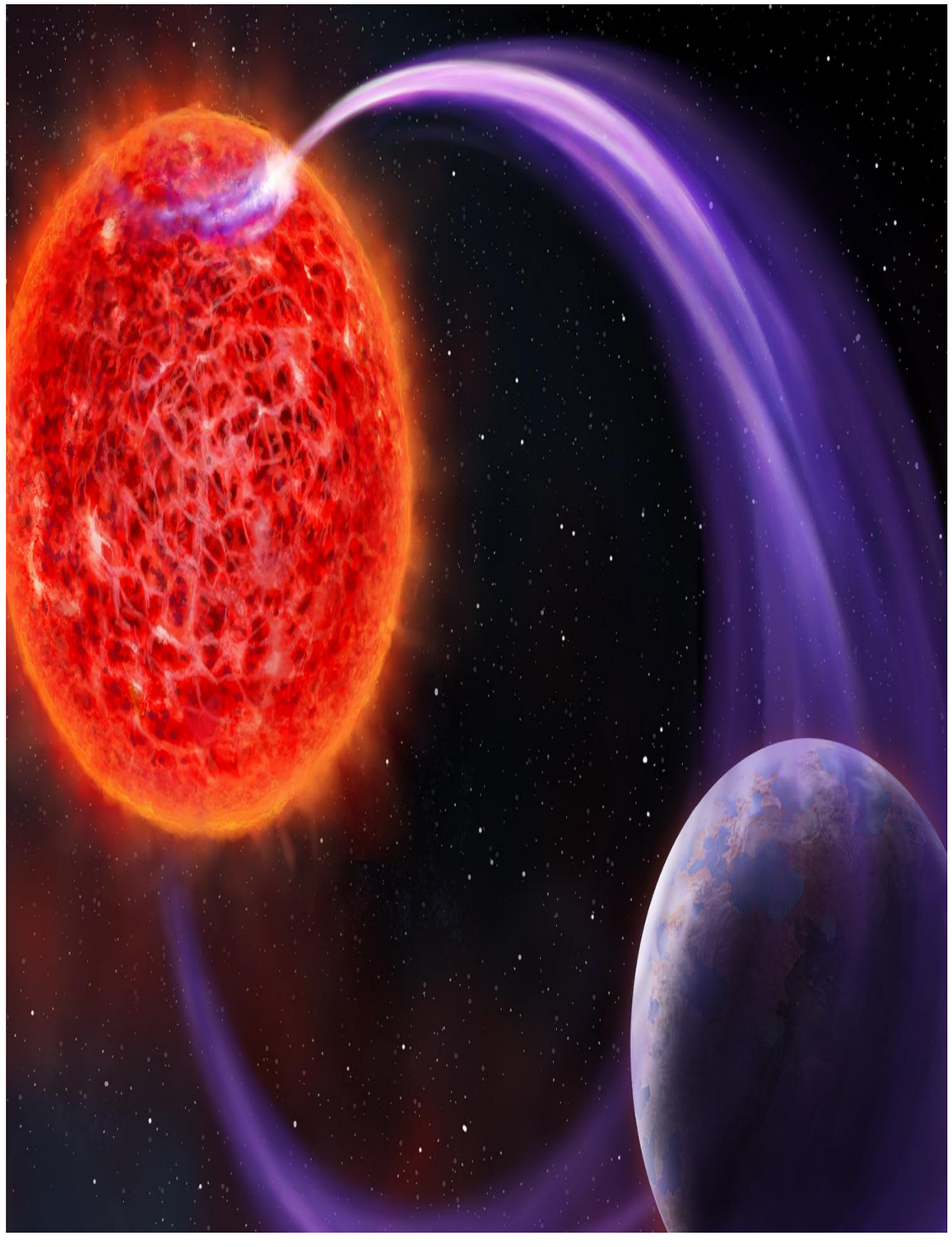
Zhang, Zucca, Sridhar, Wang and al. A&A 2020

Stars/planets

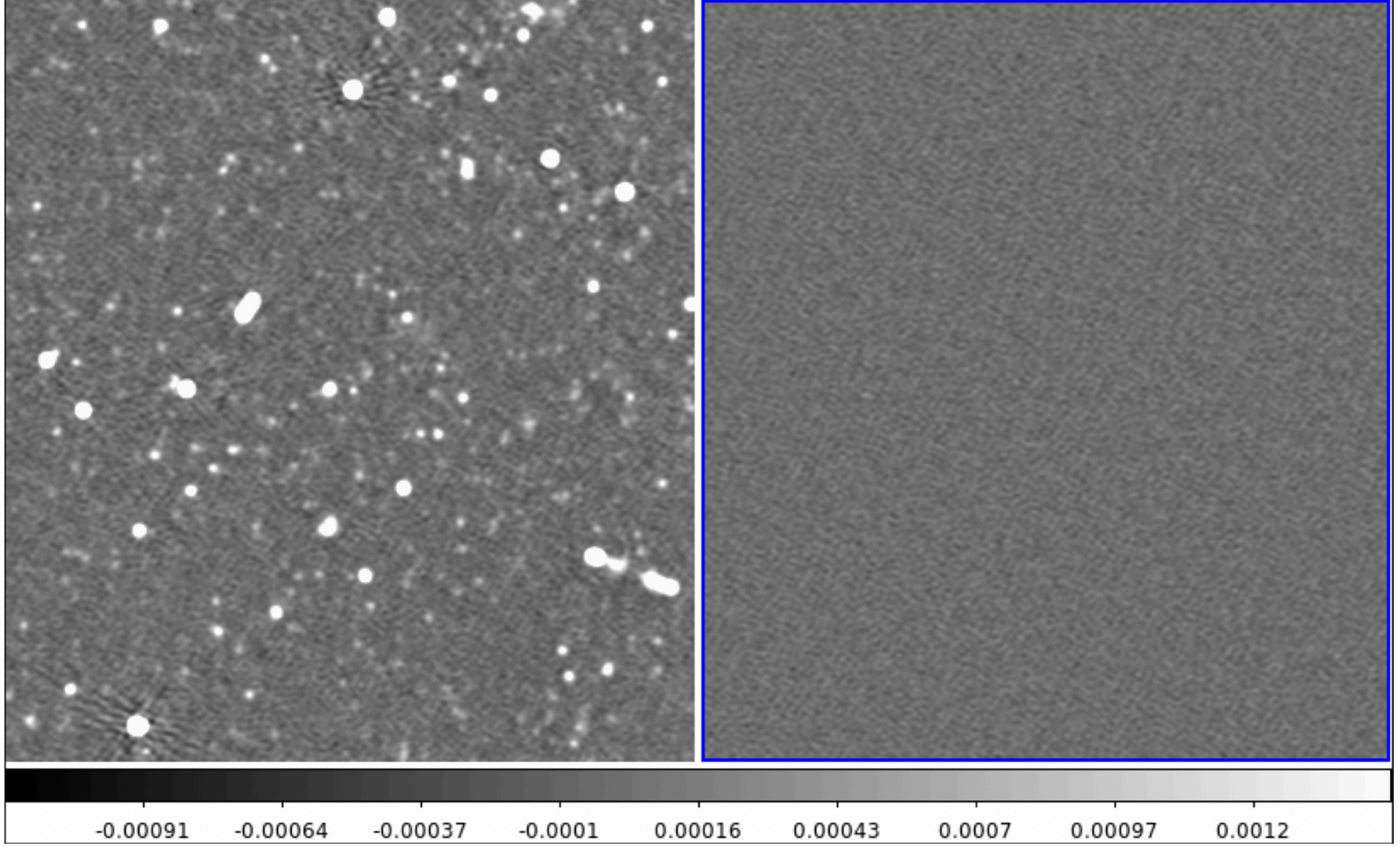
Time variable circular polarisation fraction >10% at LOFAR frequencies expected for:

- Star-planet interactions
- Chromospherically active stars
- Brown dwarfs
- Direct detection of exoplanets

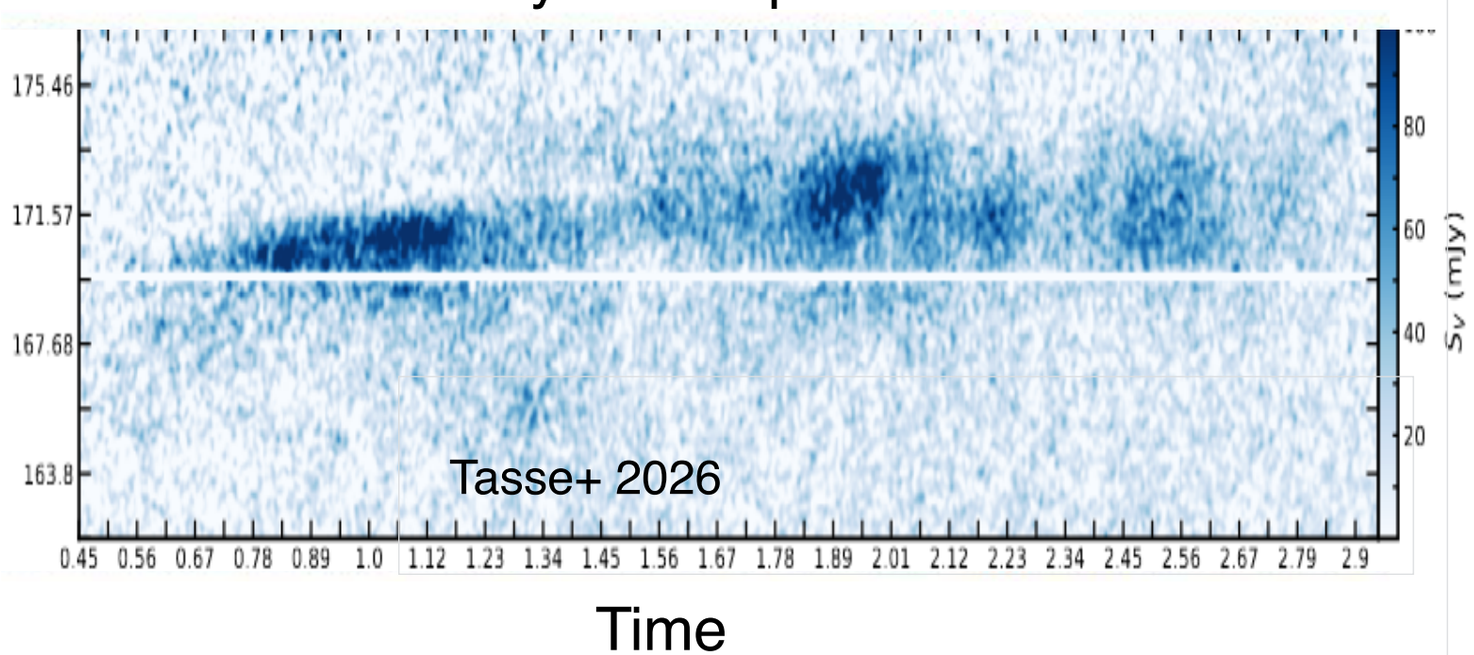




Leakage from I (left) to V (right) in HBA imaging only 0.06% allowing discovery of faint circularly polarised signals.



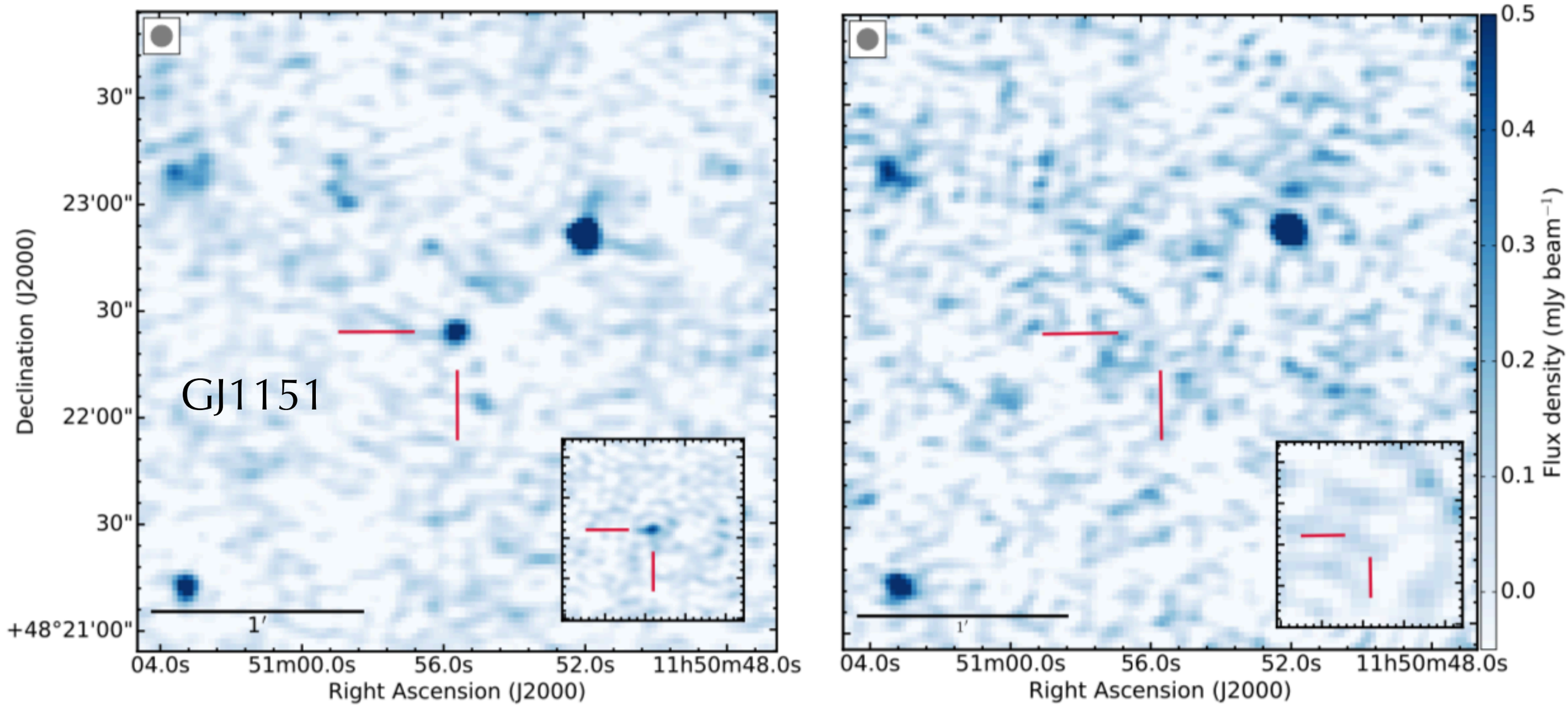
Dynamic spectra



Ability to rapidly study time and frequency dependence of target sources (> 200,000 in LoTSS)

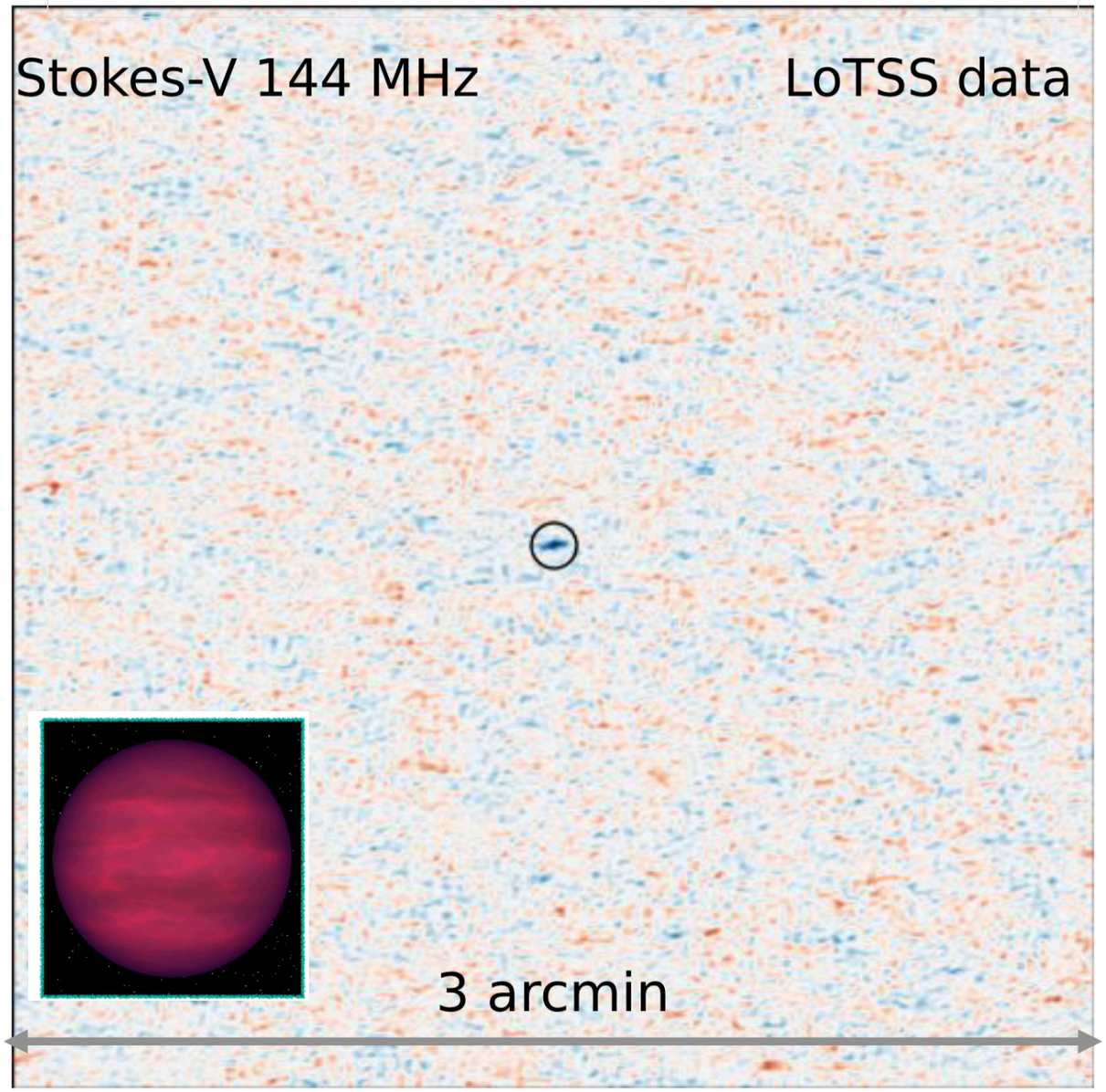
Analysis of LoTSS-DR2 led to ~40 stars and 2 brown dwarfs (Callingham+ 2021, Tasse+ 2026) including:

First quiescent star



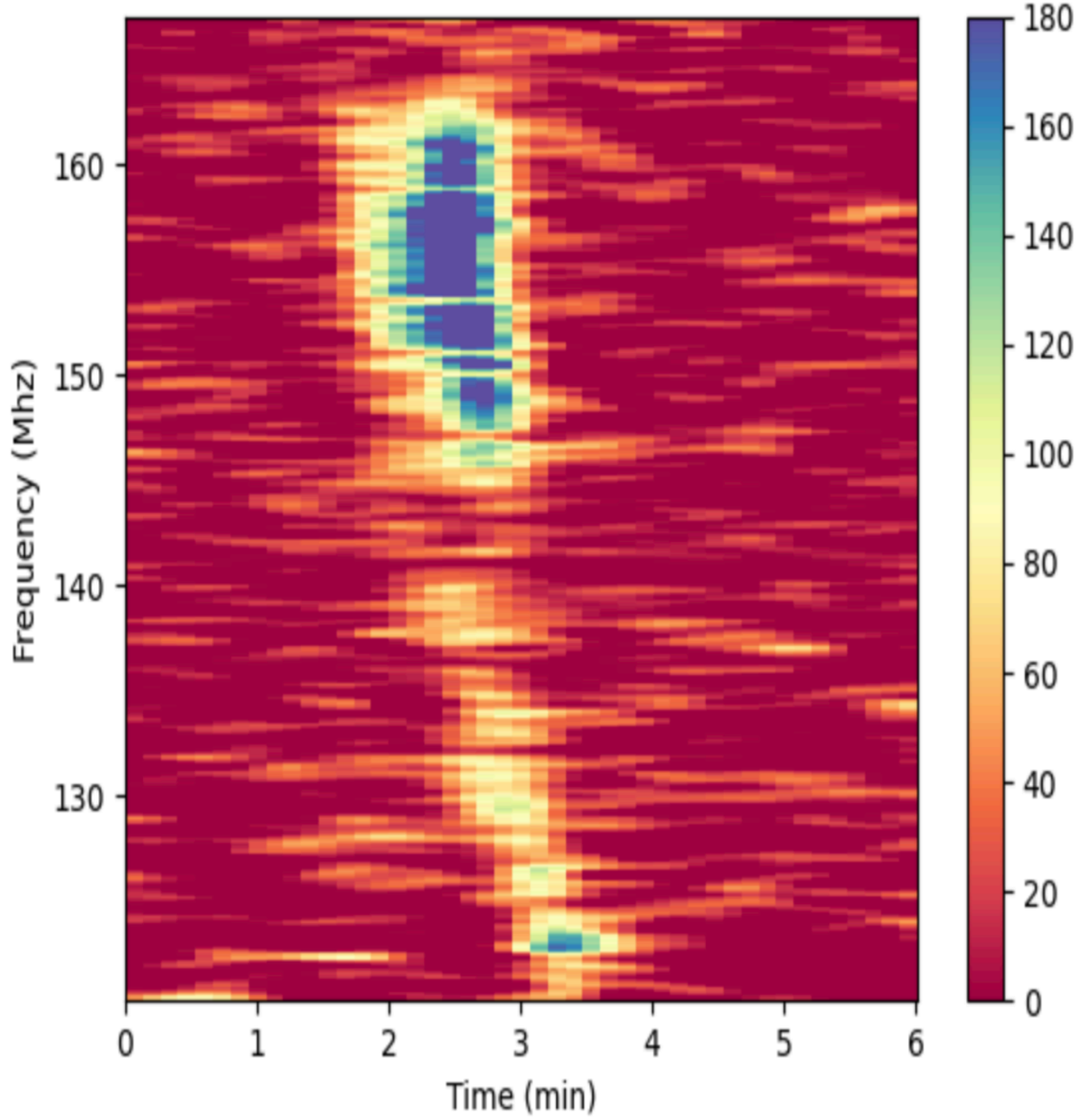
Vedantham++ 2020

First radio discovery of a sub-stellar object (Elegast - brown dwarf)



Vedantham+ 2020

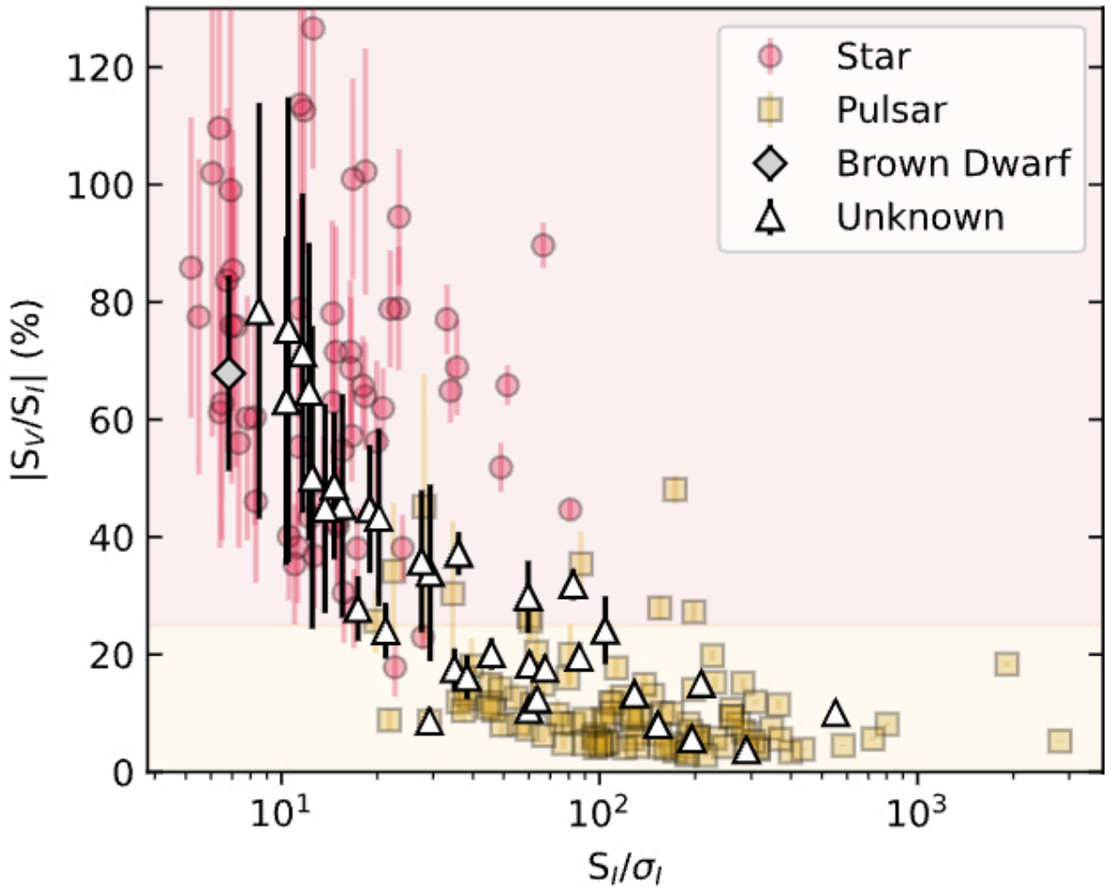
First Type II burst on another star



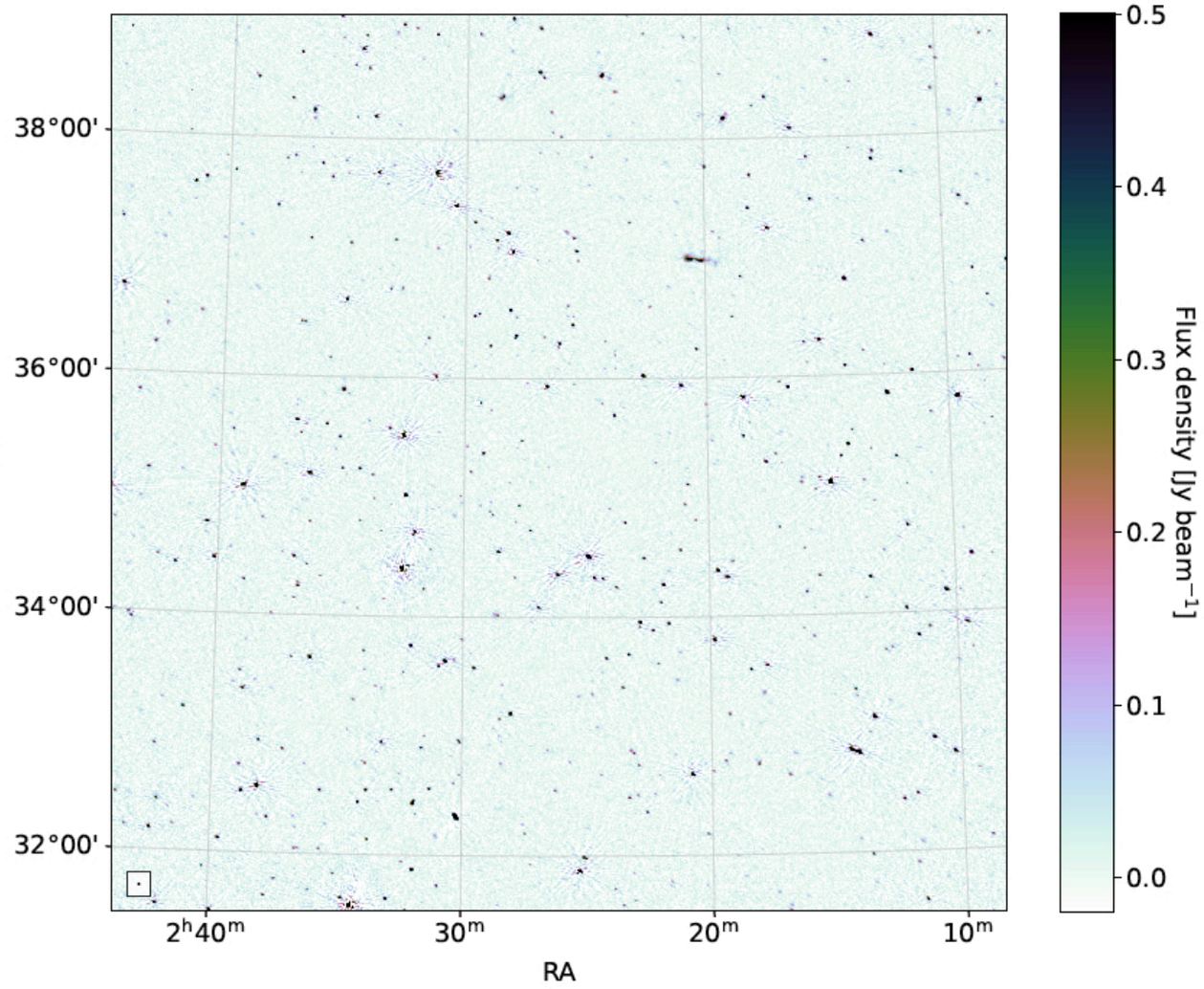
Callingham+ 2026

Lots of new unique science (star-planet interaction, magnetism in the coldest brown dwarfs, coronal structure & acceleration physics)

Much more to come from e.g. LoTSS-DR3, LoLSS and LoDeSS

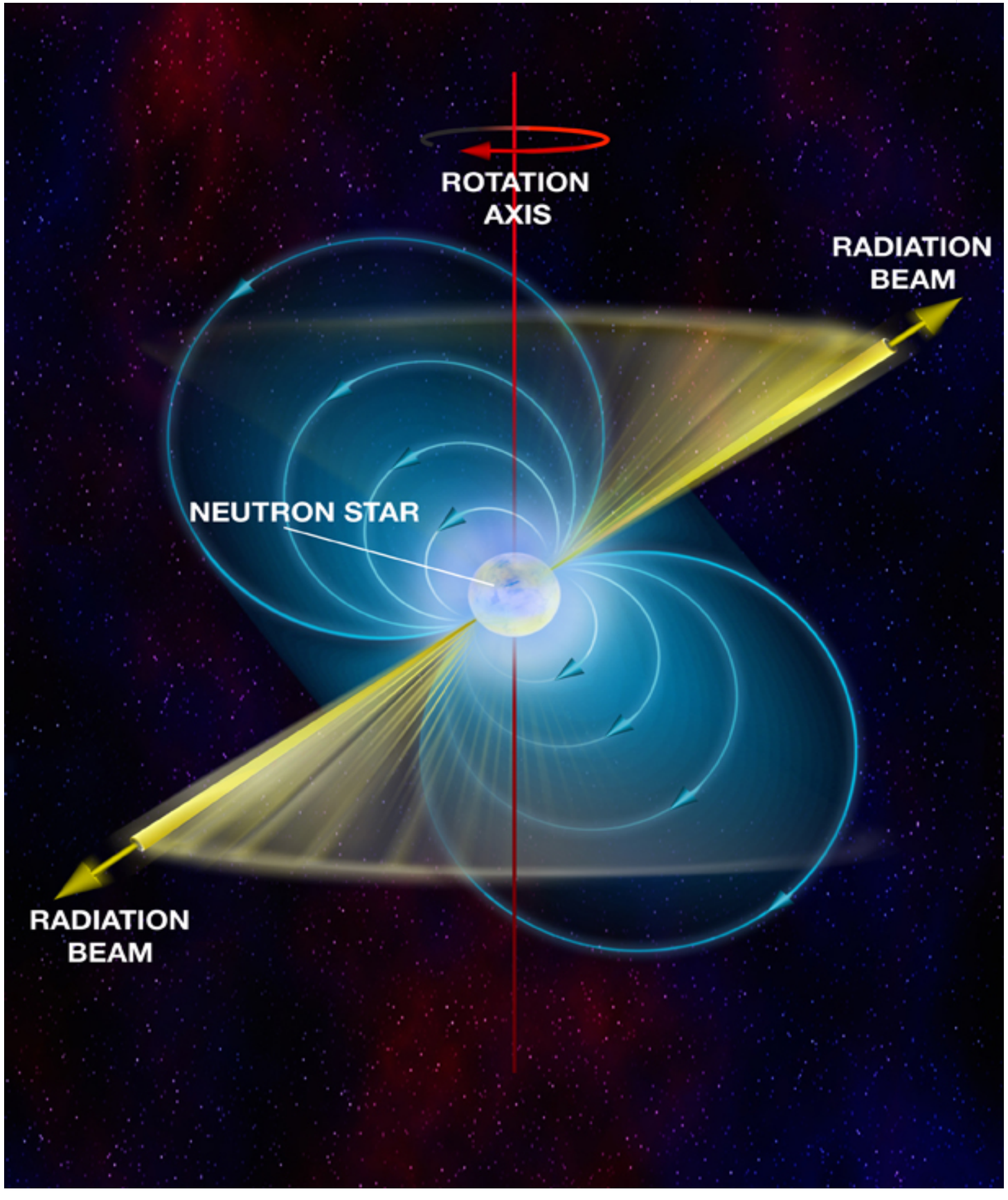


At least 58 stars in V-LoTSS-DR3 and many unknown objects that may be unknown brown dwarfs (Koo+ in prep)



An example 10-30MHz LoDeSS image for which exoplanets are a key motivation (Condon+ sub)

Pulsars

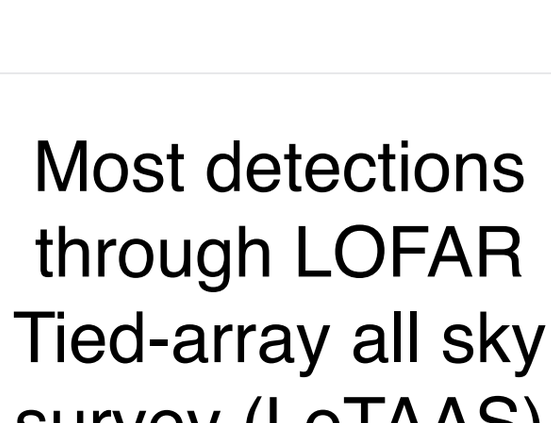


Pulsars are natural laboratories to study...

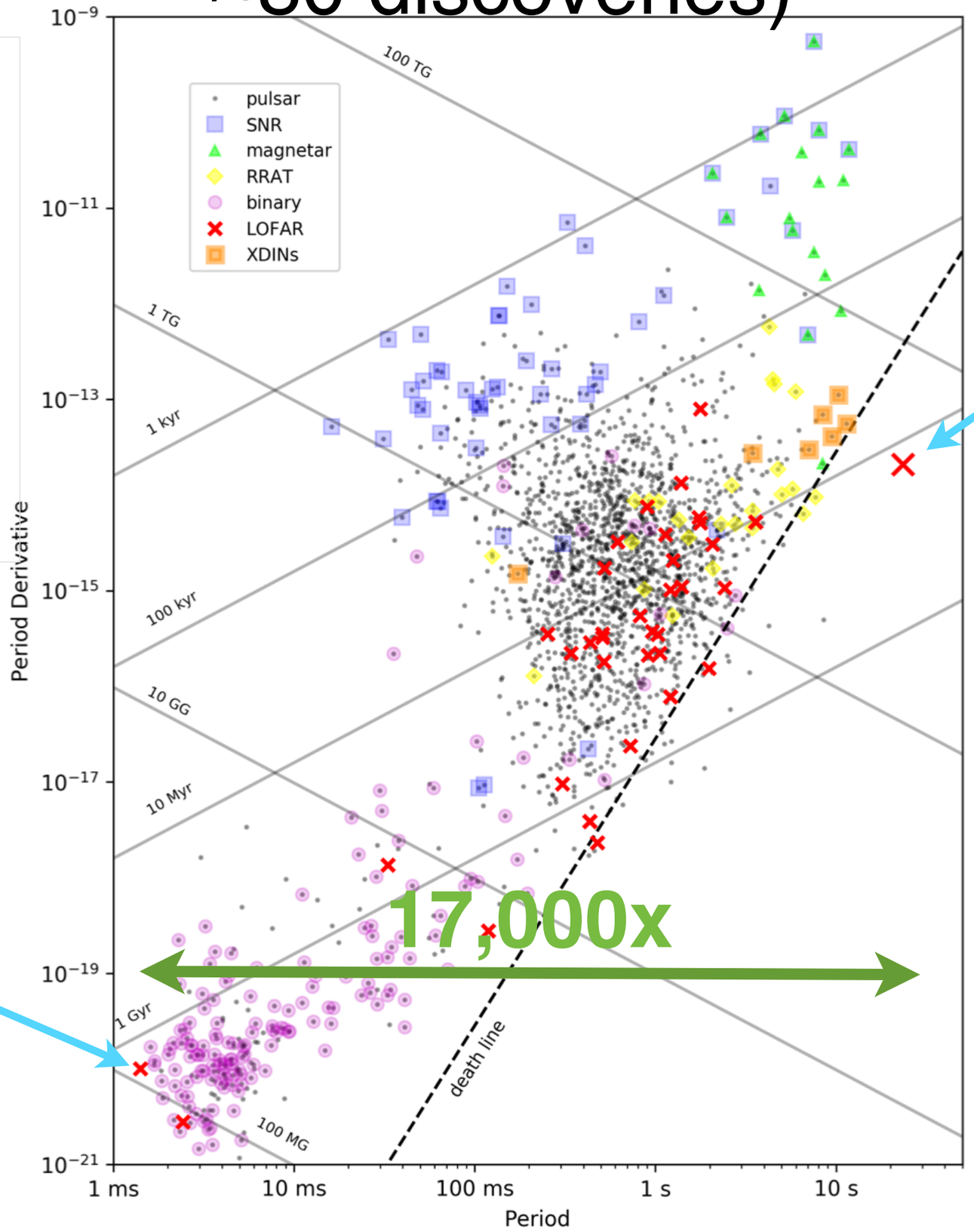
- **Gravity**
- **Particle physics**
- **Stellar evolution**
- **Interstellar medium**
- **Accretion**

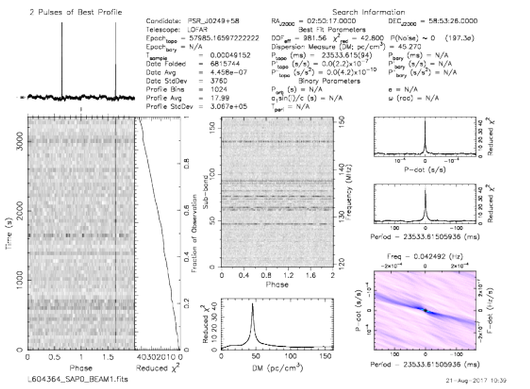
LOFAR has detected >300 pulsars so far (including ~80 discoveries)

Most detections through LOFAR Tied-array all sky survey (LoTAAS) but a few through LoTSS imaging survey



707Hz
1.41ms



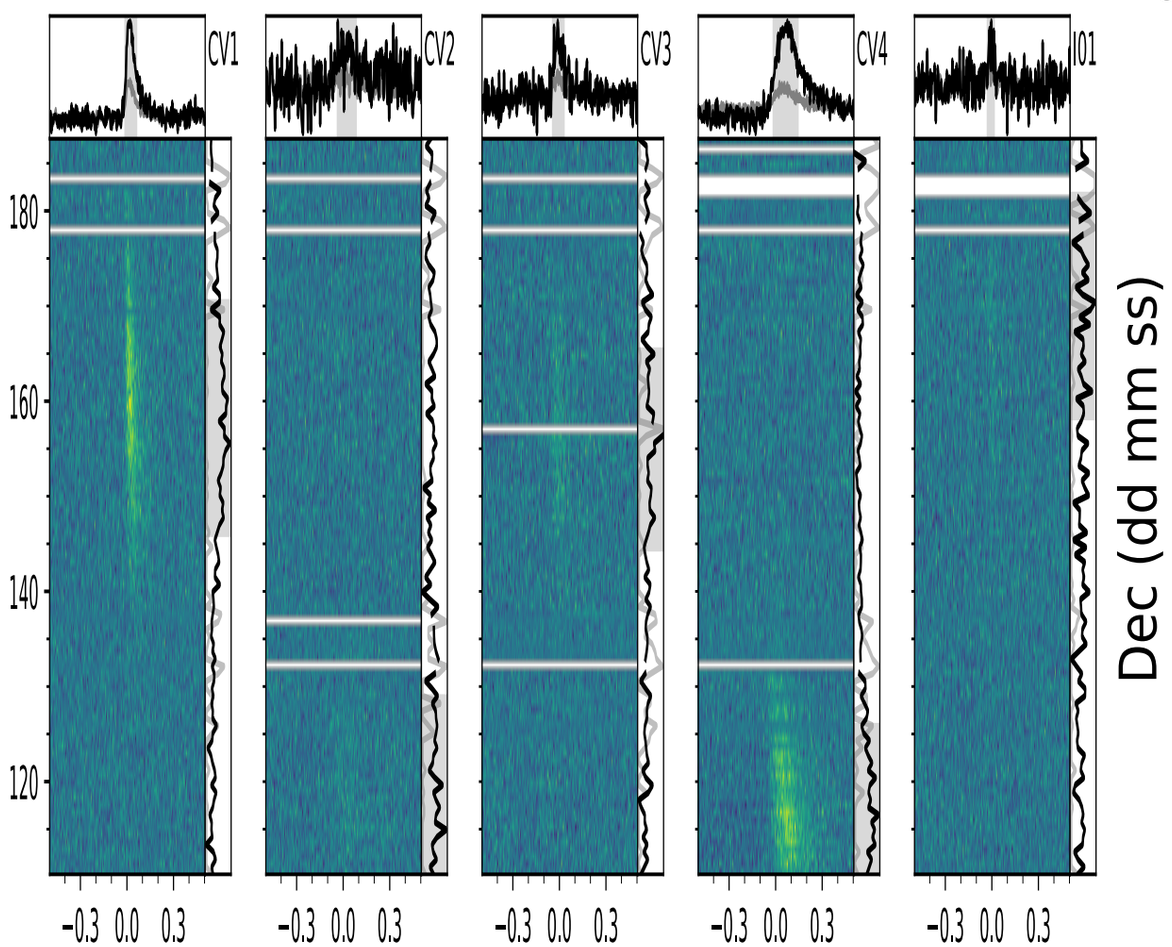


0.042Hz
23,533.6ms

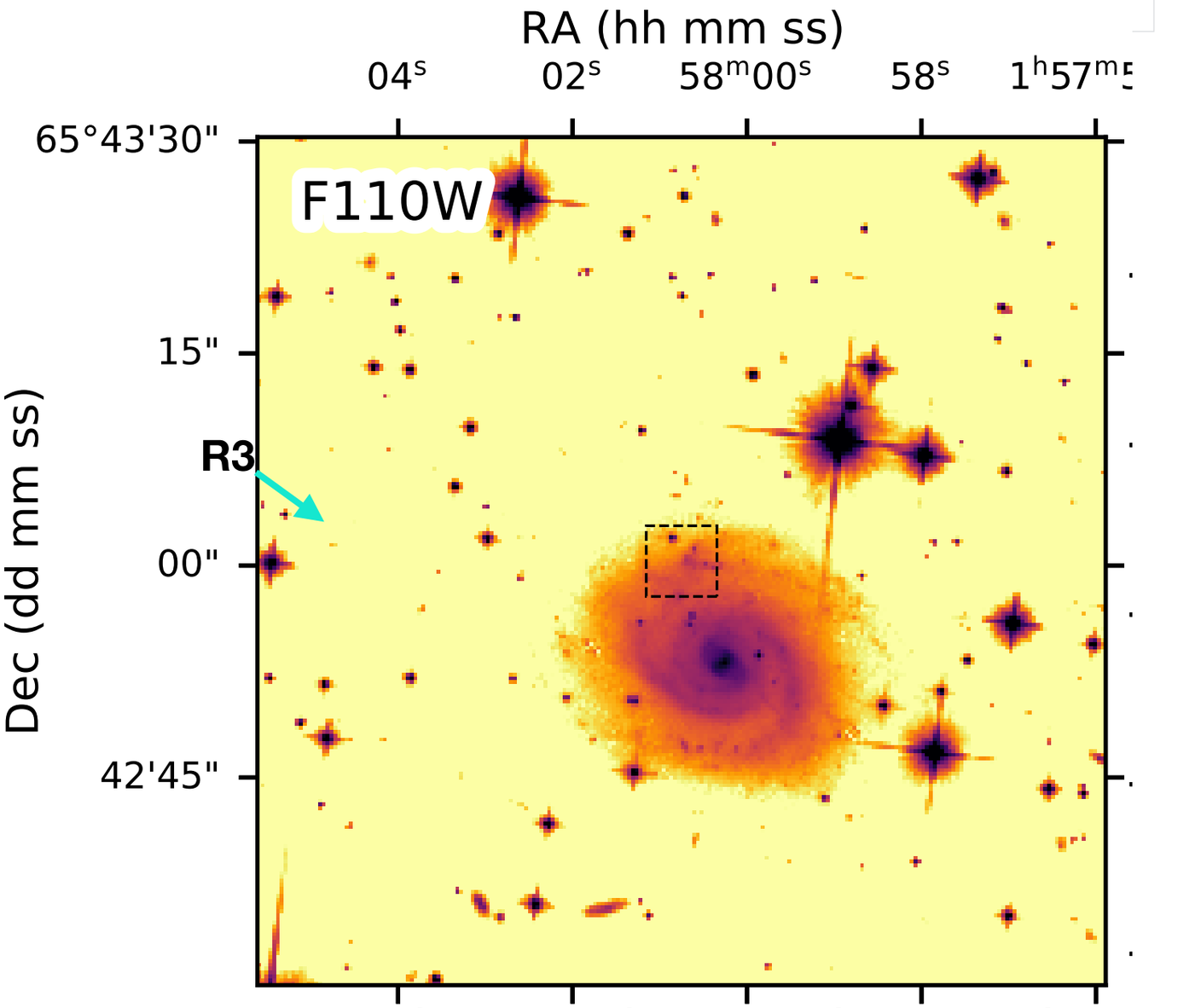
- see van der Wateren et al. 2023

Also a Fast Radio Burst characterised using tied-array beam observations

e.g FRB 20180916B (“R3”) is visible down to 110MHz



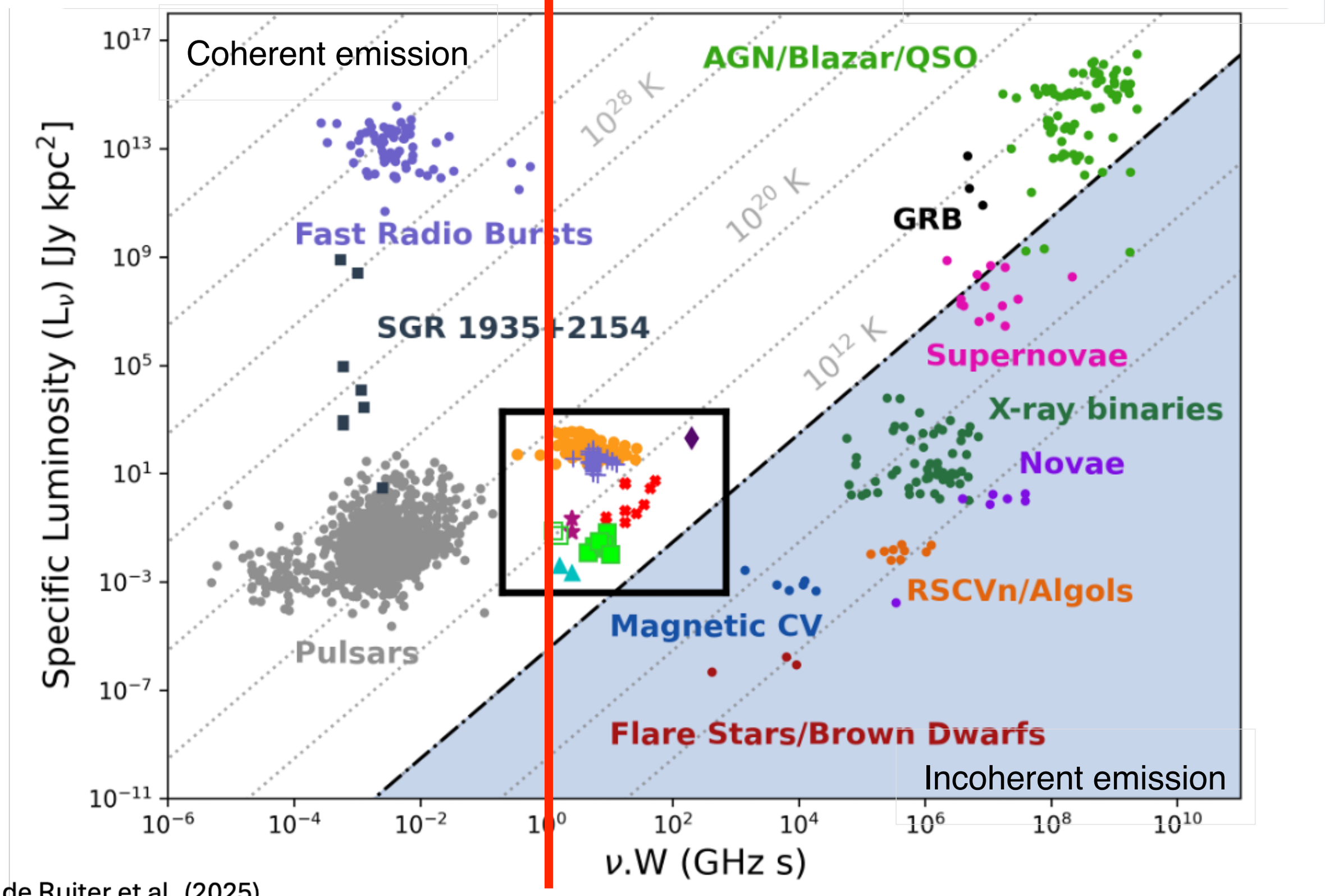
Pleunis, Michilli, Bassa, JH et al. 2021



Tendulkar, Gil de Paz, Kirichenko, JH et al. 2021

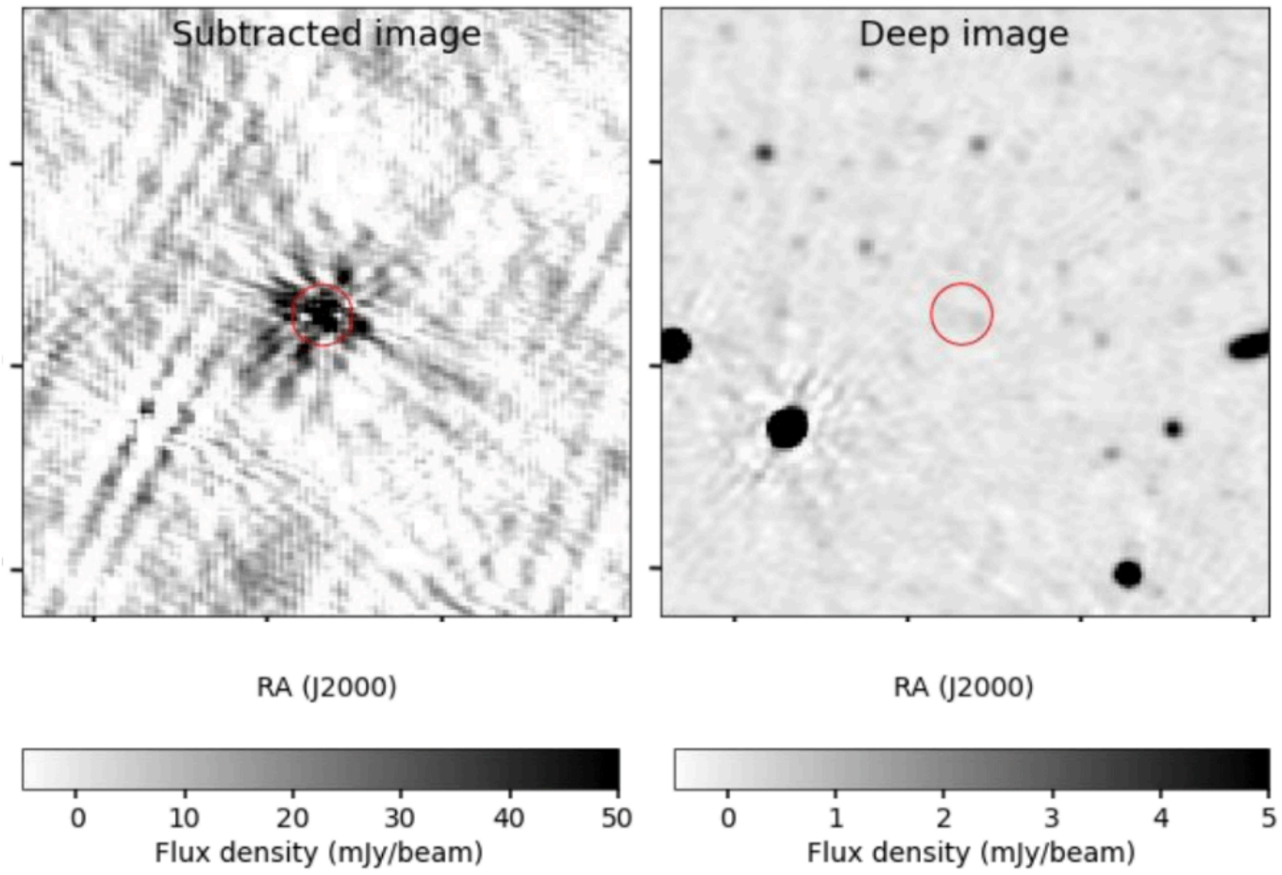
Transients

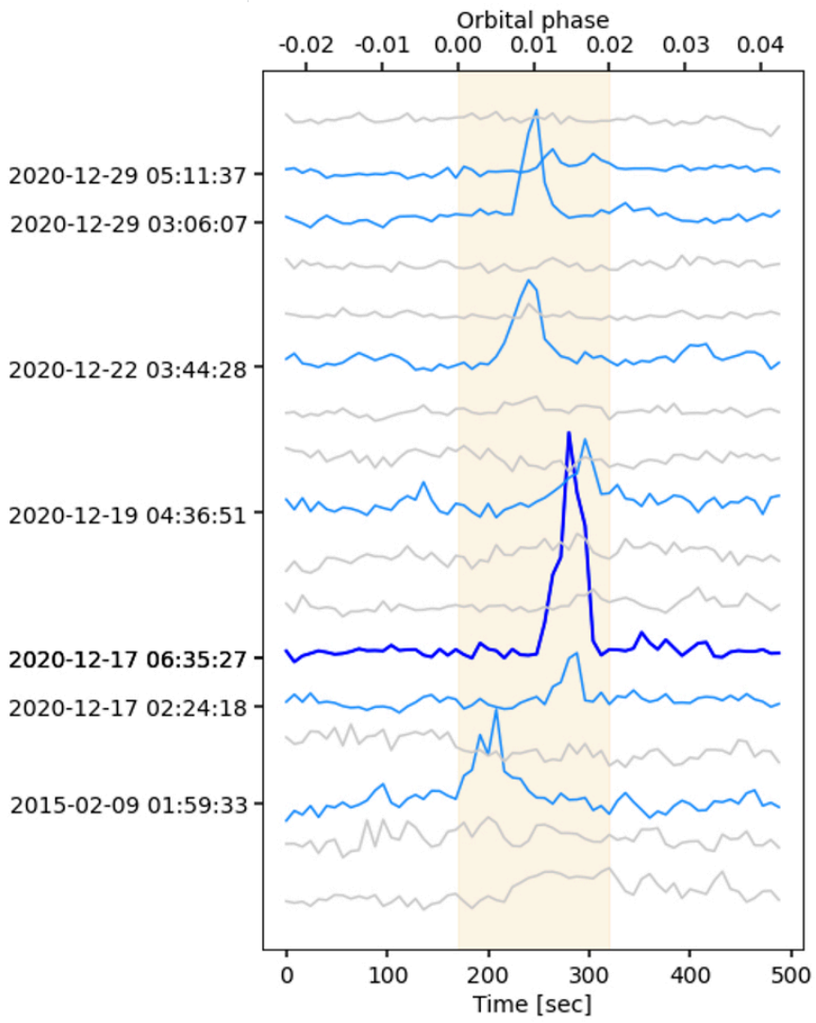
LOFAR imaging surveys



de Ruiter et al. (2025)

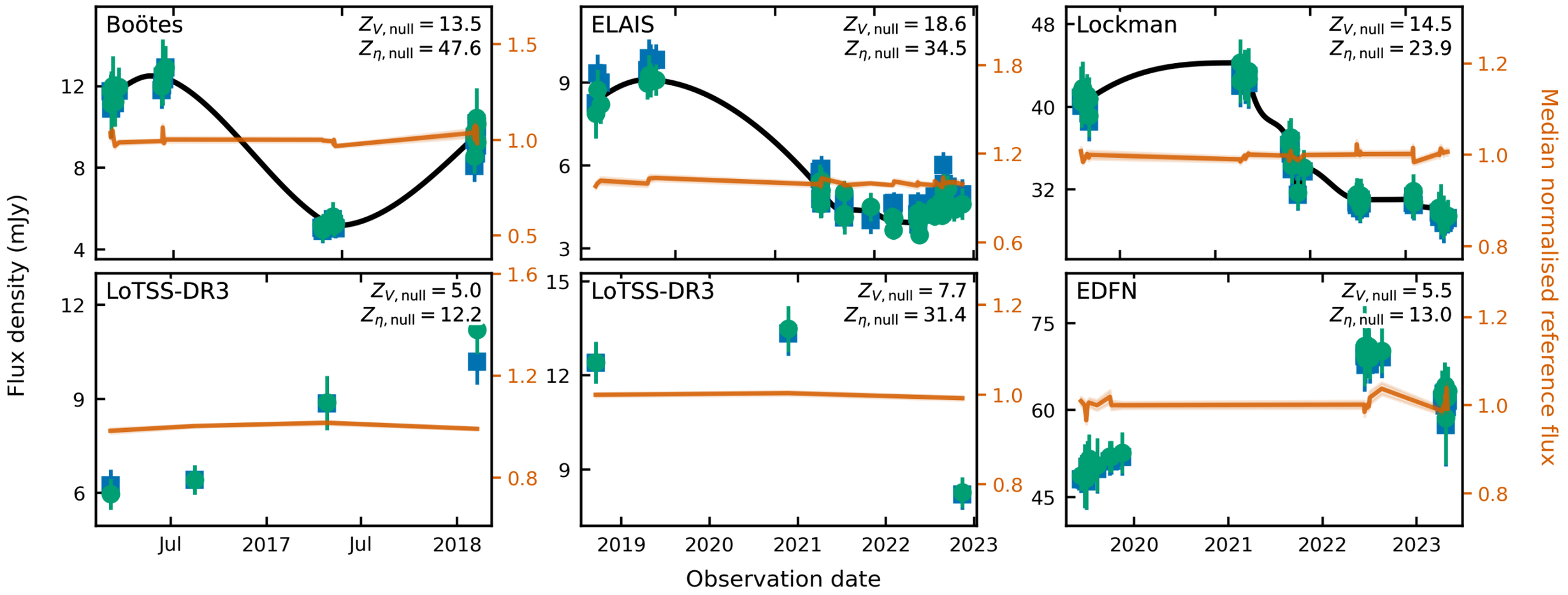
Discovering new transients





Searching large areas of residual Stokes I or Stokes V LOFAR HBA surveys data by imaging at 8 seconds - 4 mins cadence. Several long period transients found, e.g. de Ruiter+ 2024, 2025 (M Dwarf White Dwarf binary) and Bloot et al+ sub (White Dwarf plus companion)

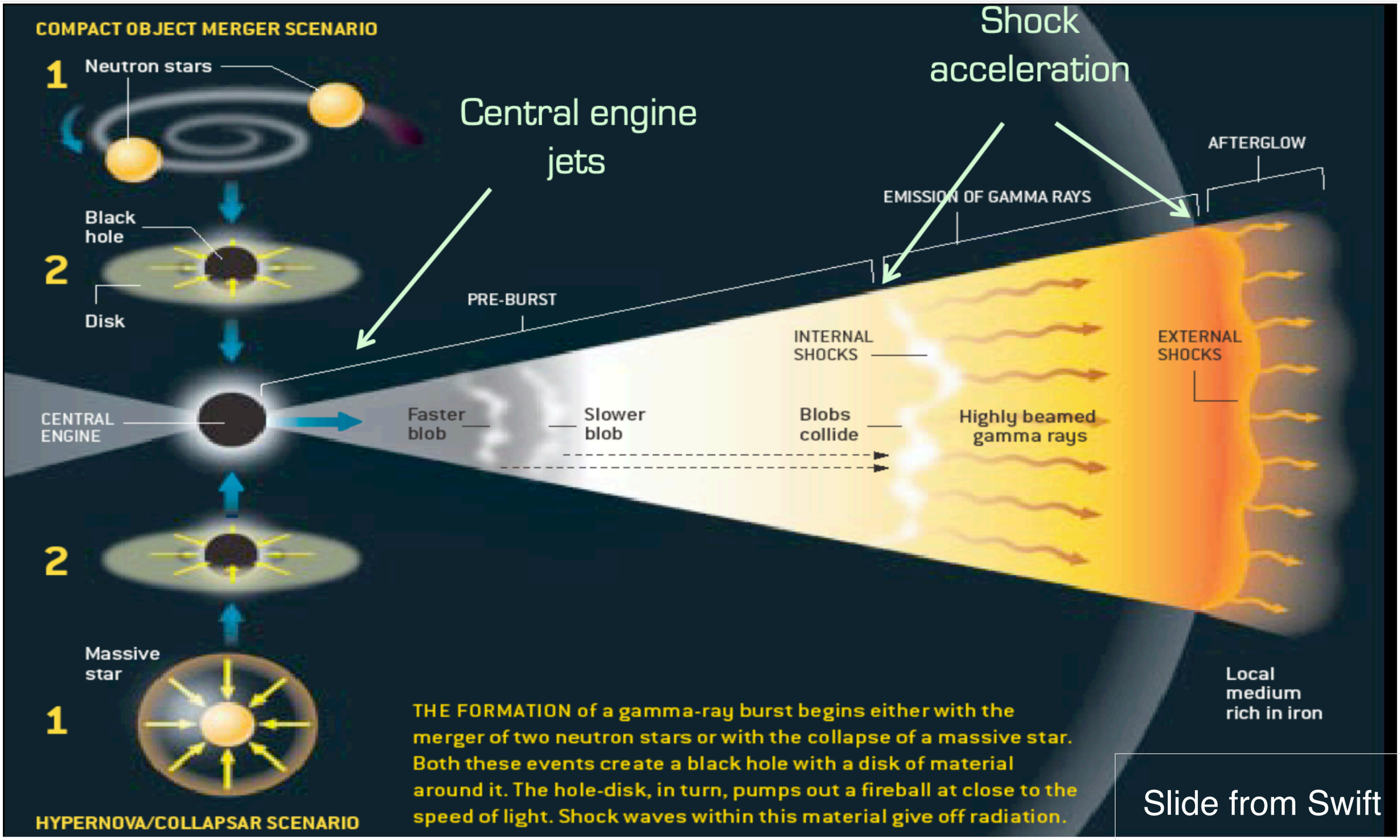
Constraining variability



Example variable sources in the LoTSS-Deep and LoTSS-DR3 datasets. The vast majority of the 1,000-1,500 detected are AGN but some pulsars and stars (Shimwell+ in prep)

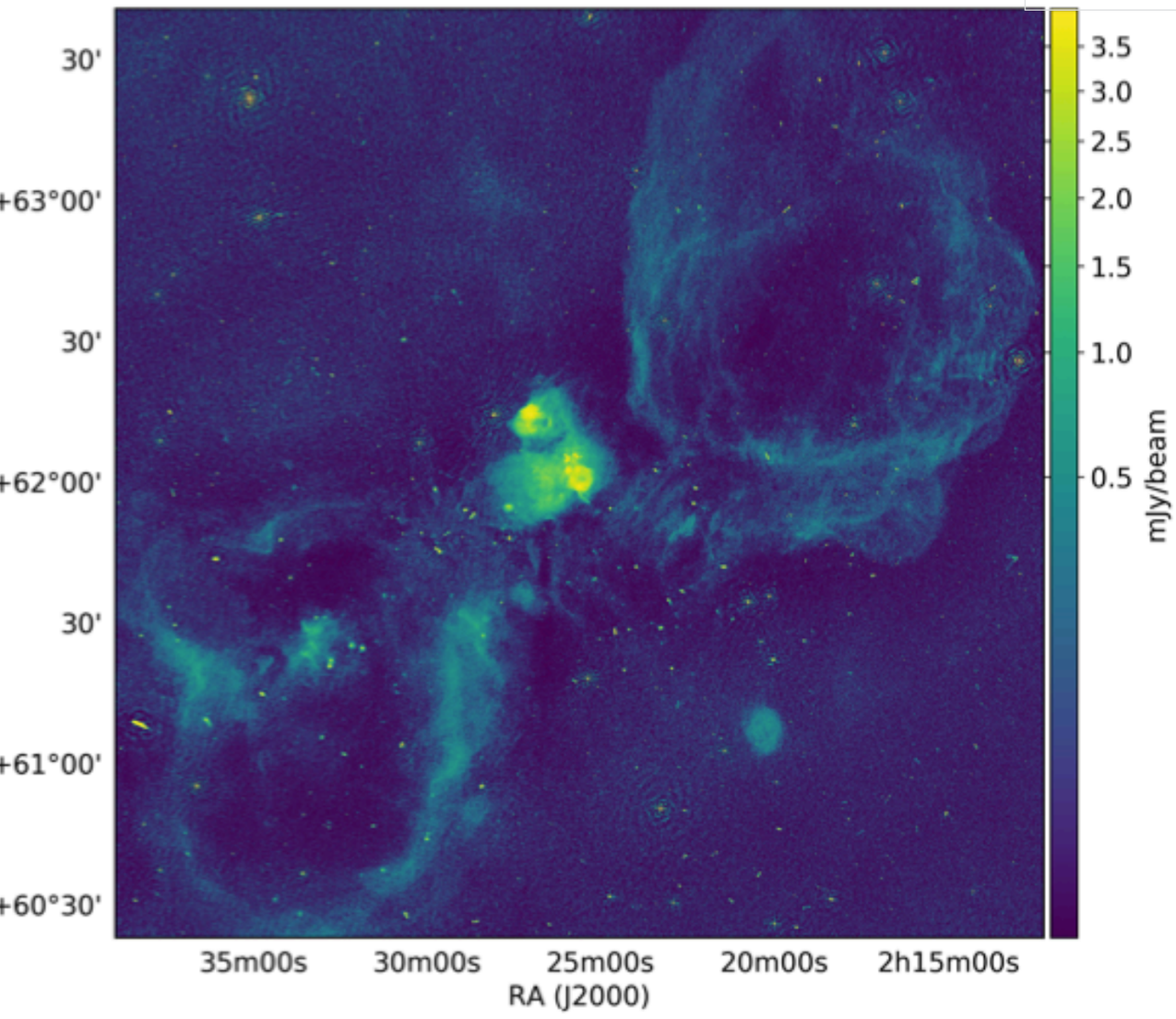
Characterisation of known transient sources

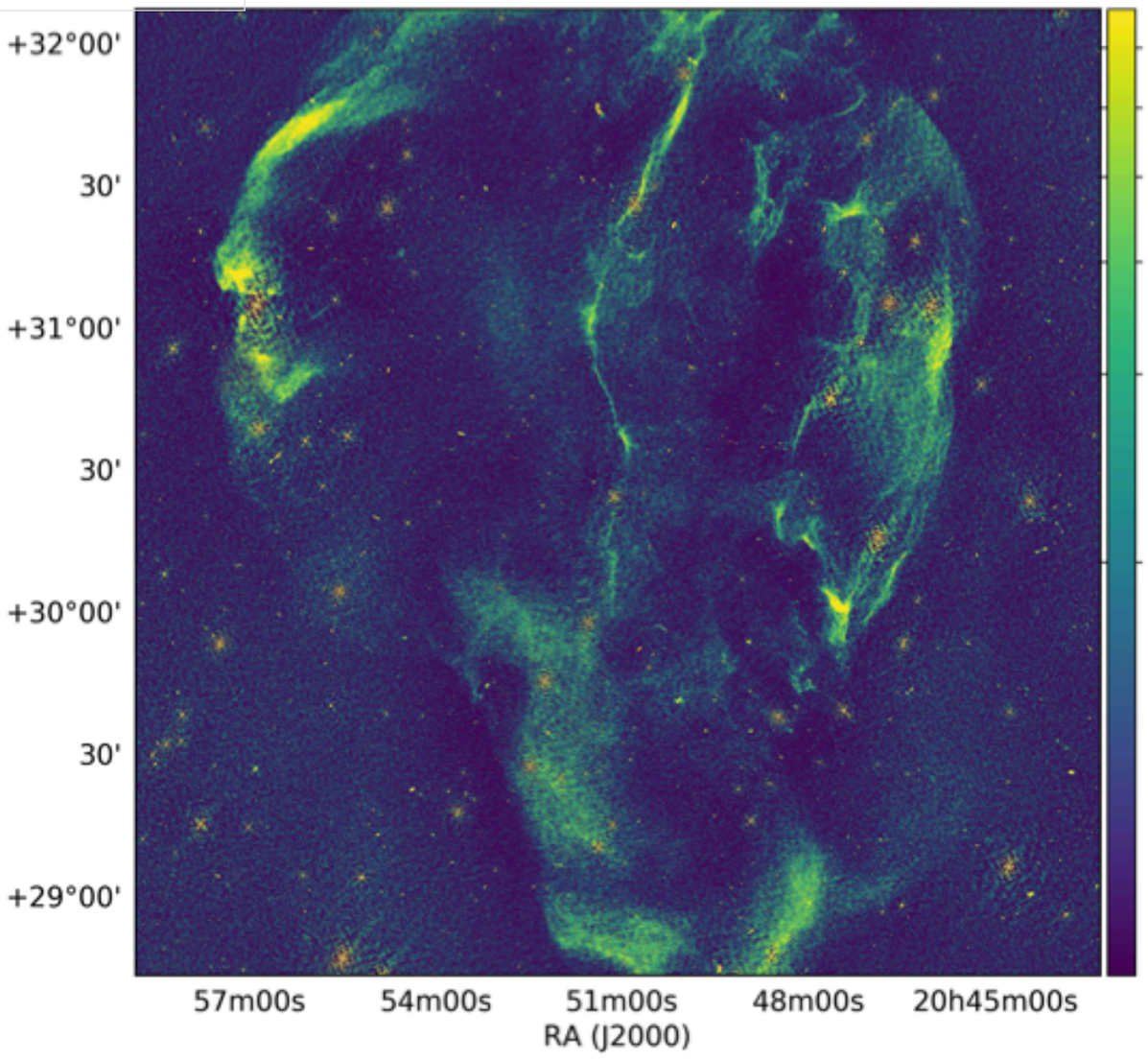
LOFAR can respond to Gamma Ray Bursts within 4.5 mins and has provided deepest limits on early time radio emission and a tentative detection (Rowlinson+)



Slide from Swift

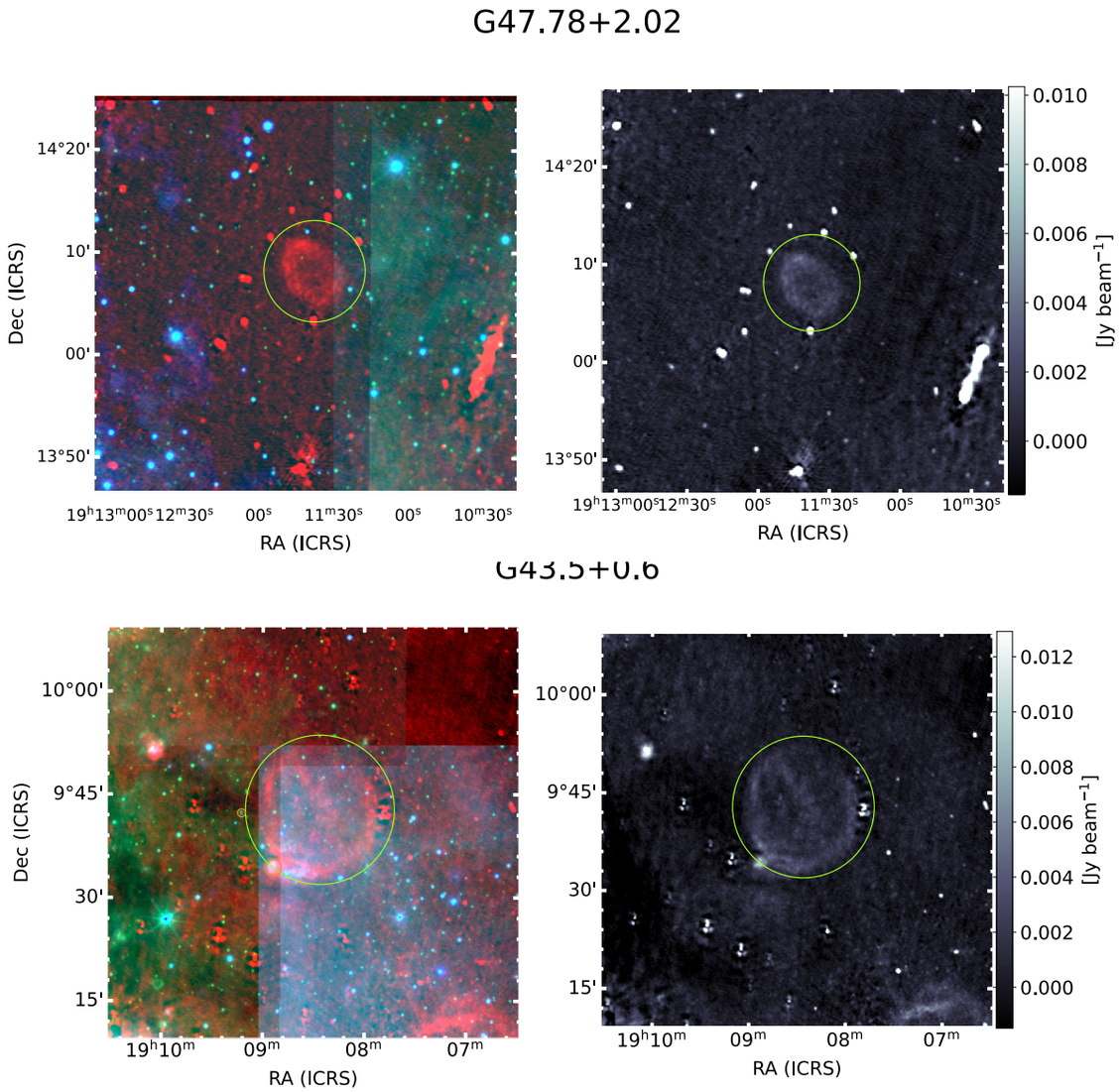
Milky Way

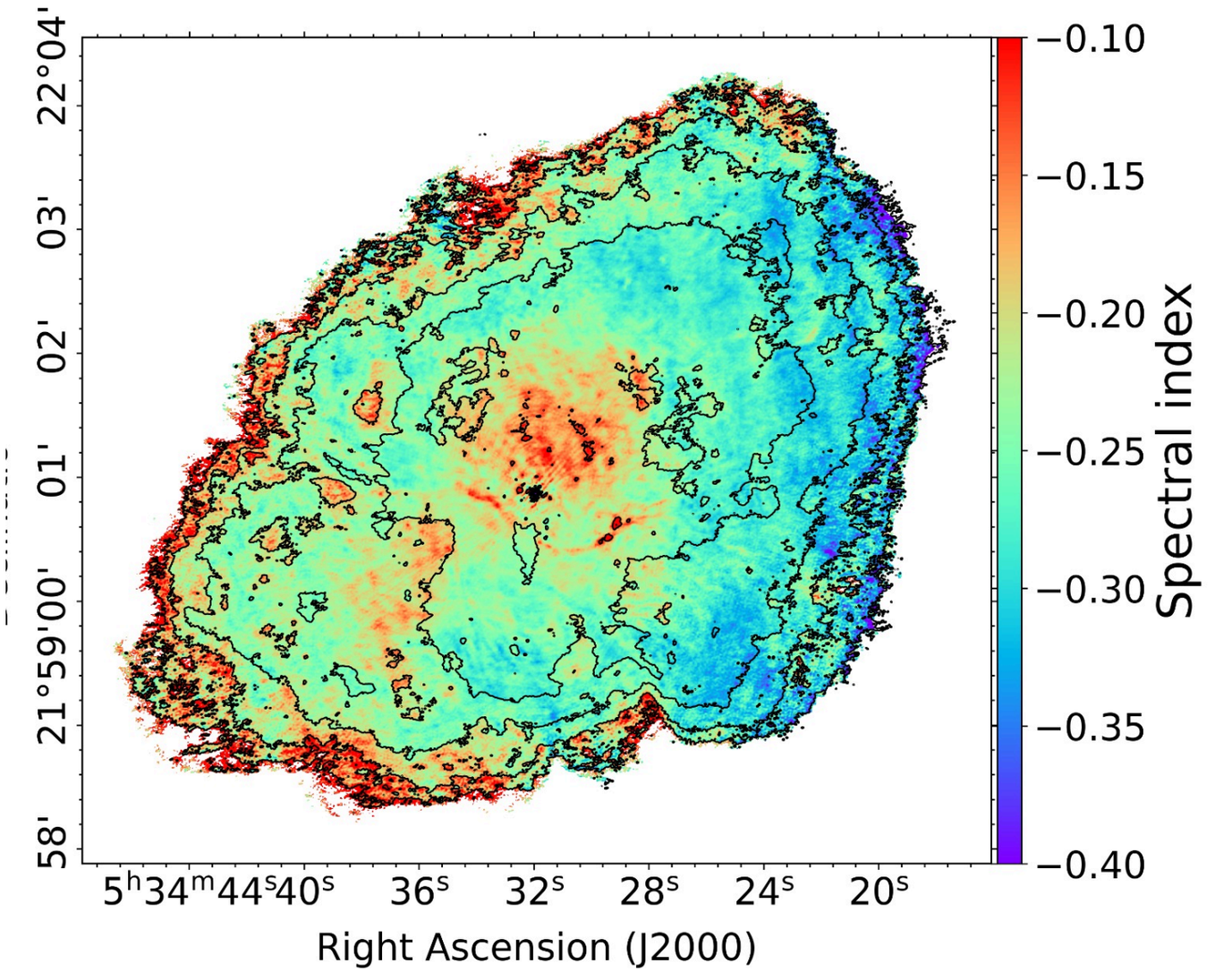




LoTSS-DR3 mosaics of the W3/W4/HB3 star forming region and the Cygnus loop supernova remnant (calibrated in 45 different directions for each individual pointing)

Discovering and characterising supernova





- Discovery of 16 new SNRs and confirmation of 8 previously identified candidates (Tsalapatas+ 2024)

The Crab Nebula with the ILT (LOFAR — L-band)
[Arias, Timmerman+ in prep.]

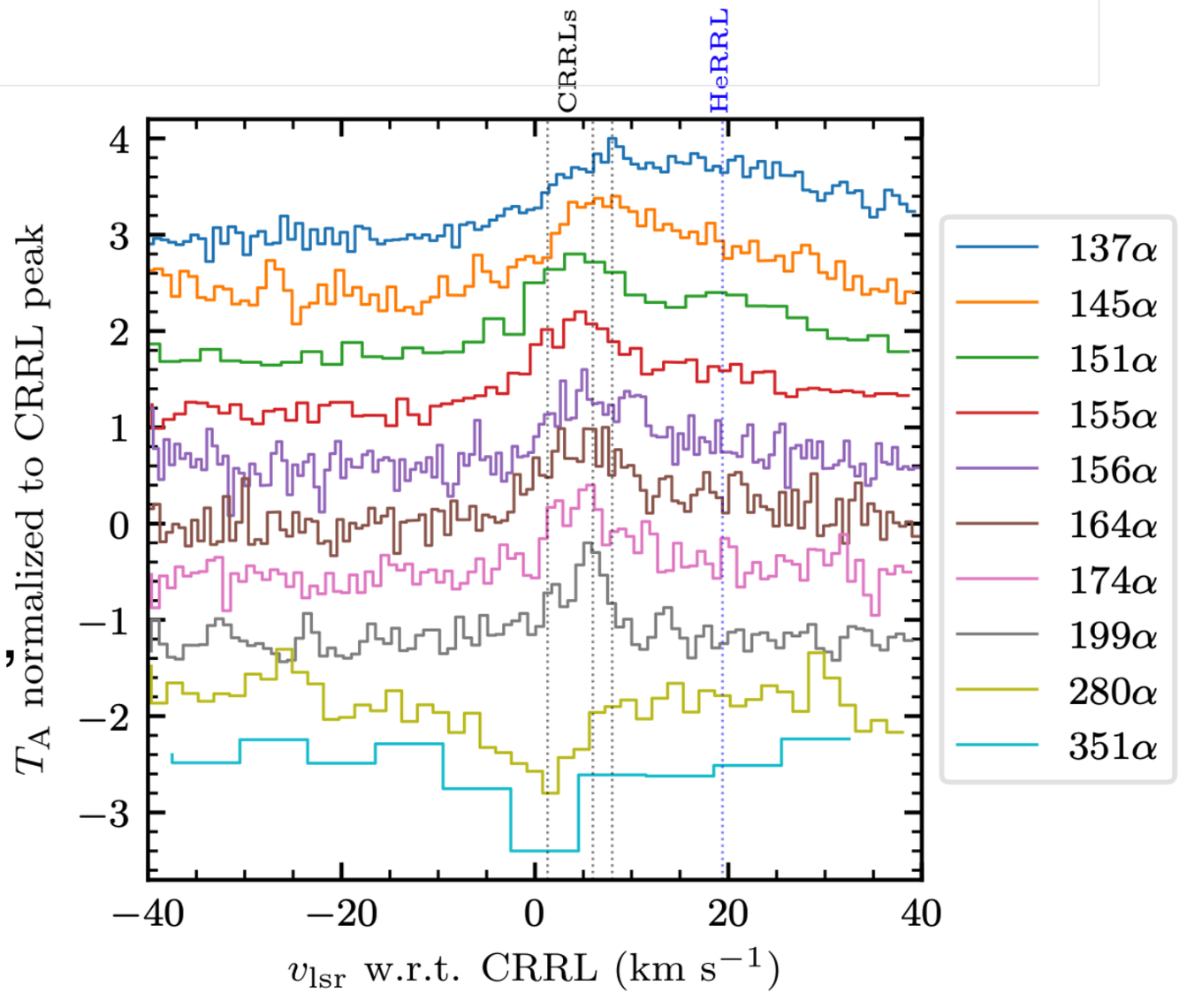
Recombination lines

Carbon recombination lines trace of the cold neutral medium and are very sensitive to gas conditions.

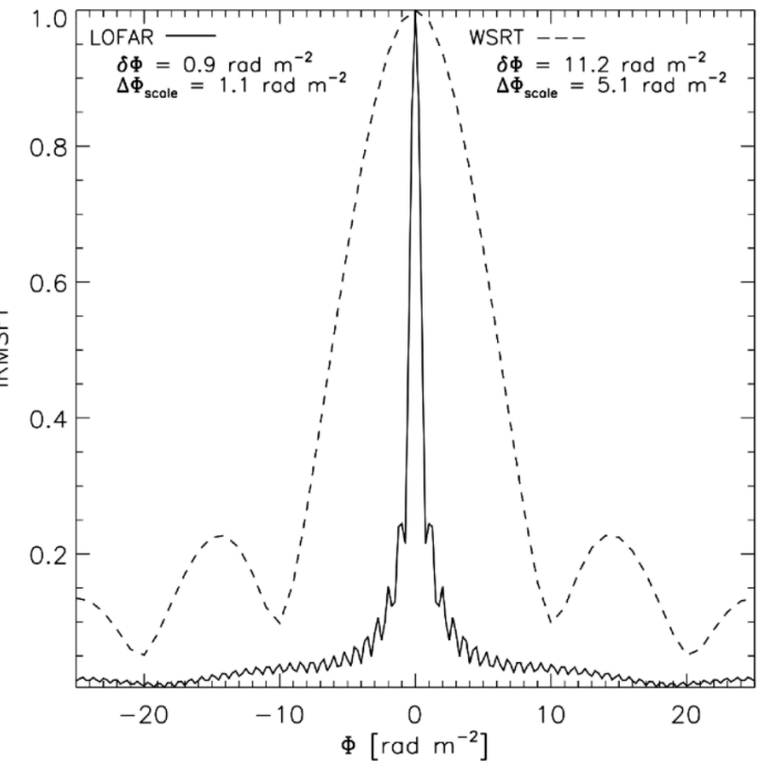
Largest bound atoms in space and detectable at cosmological distances (Emig+)

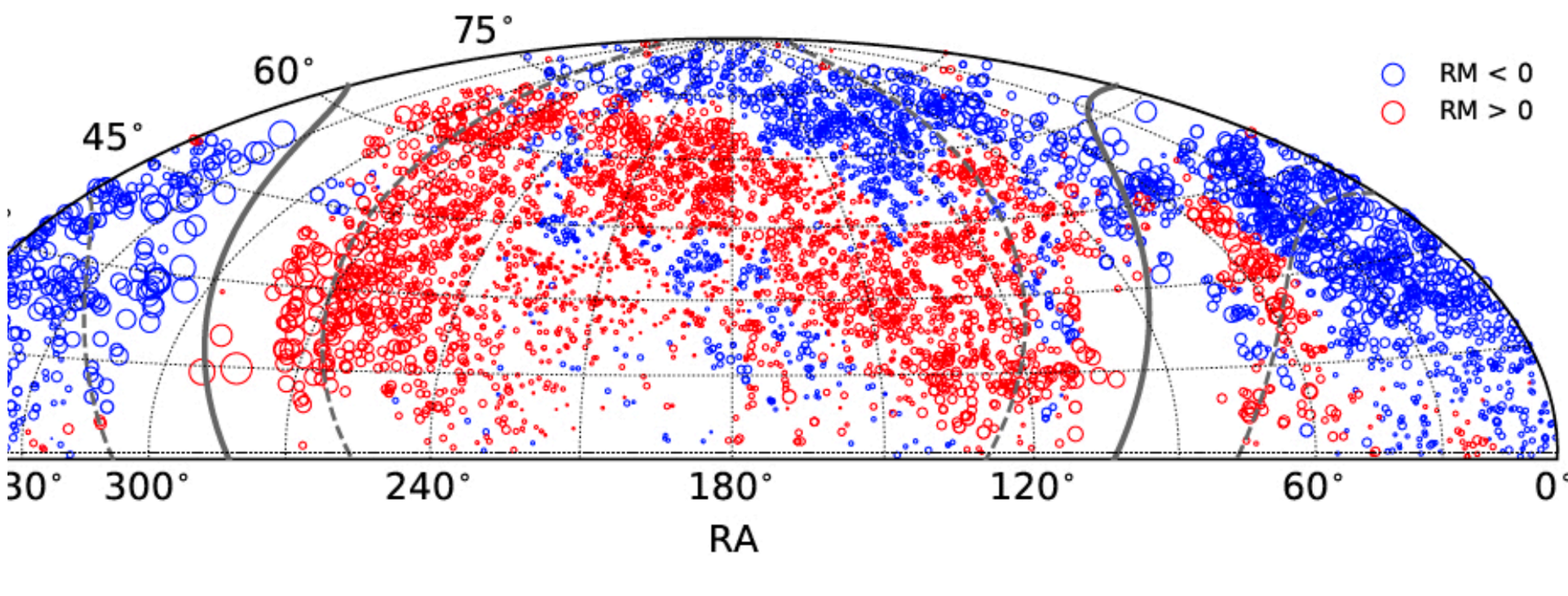
RRL spectra towards M 42 around the carbon feature. The RRLs correspond to α lines with principal quantum numbers 137, 145, 155, 156, 164, 174, 199, 280, and 351.

[Salas+ 17, 22]



Galactic magnetic field





O’Sullivan sub. - 5104 (0.04% of sources) highly precise extragalactic sources discovered in linear polarisation. Precise RM characterisation (0.1 rad m^–2 - due to low frequency) and low I-Q or I-U leakage (0.2%)

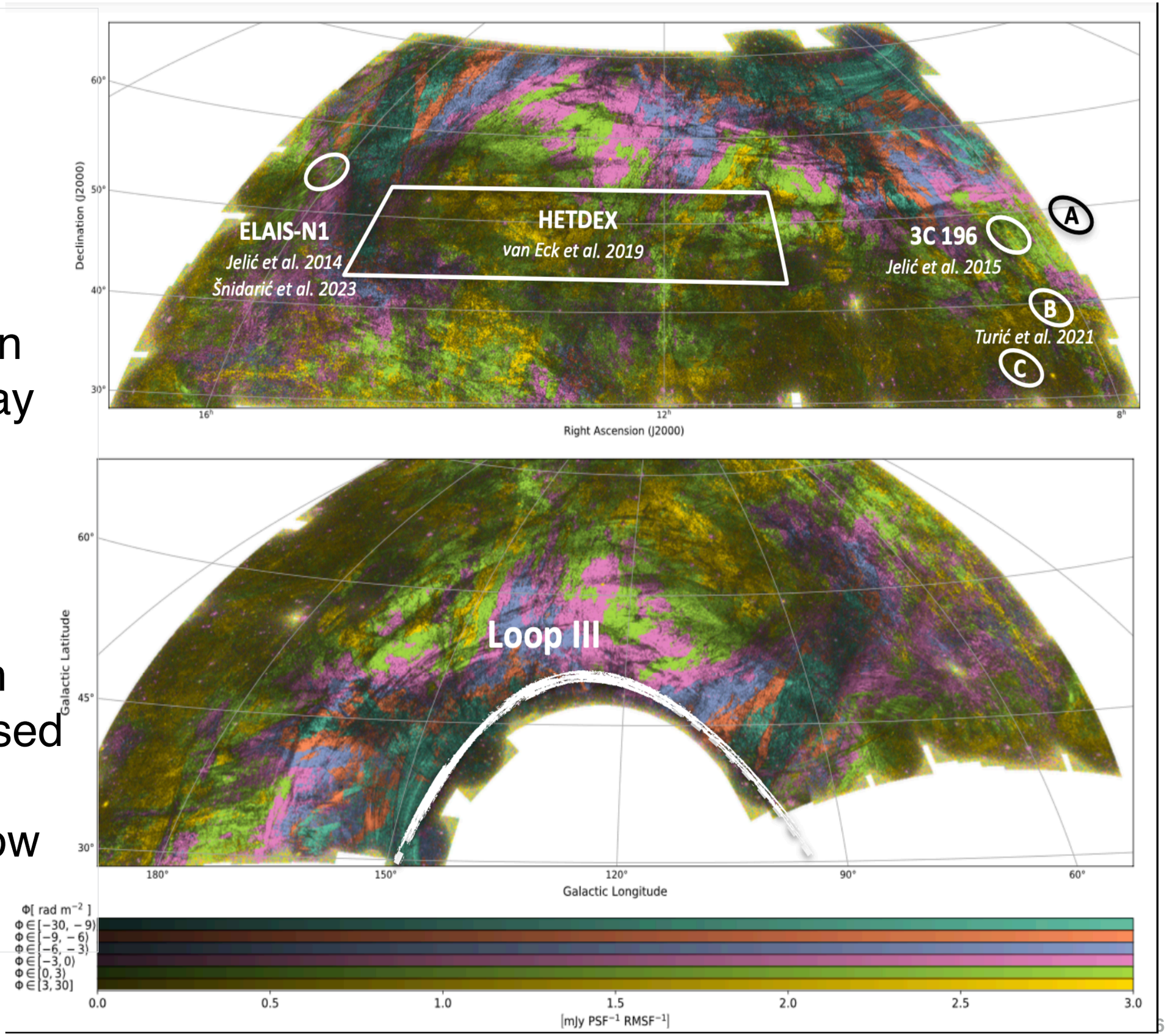
Measurements enter into model of Milky Way magnetic field e.g. Hutschenreuter 2022.

Structure within the galactic magnetic field - e.g. Erceg 2022+

Polarisation measurements of very diffuse background.

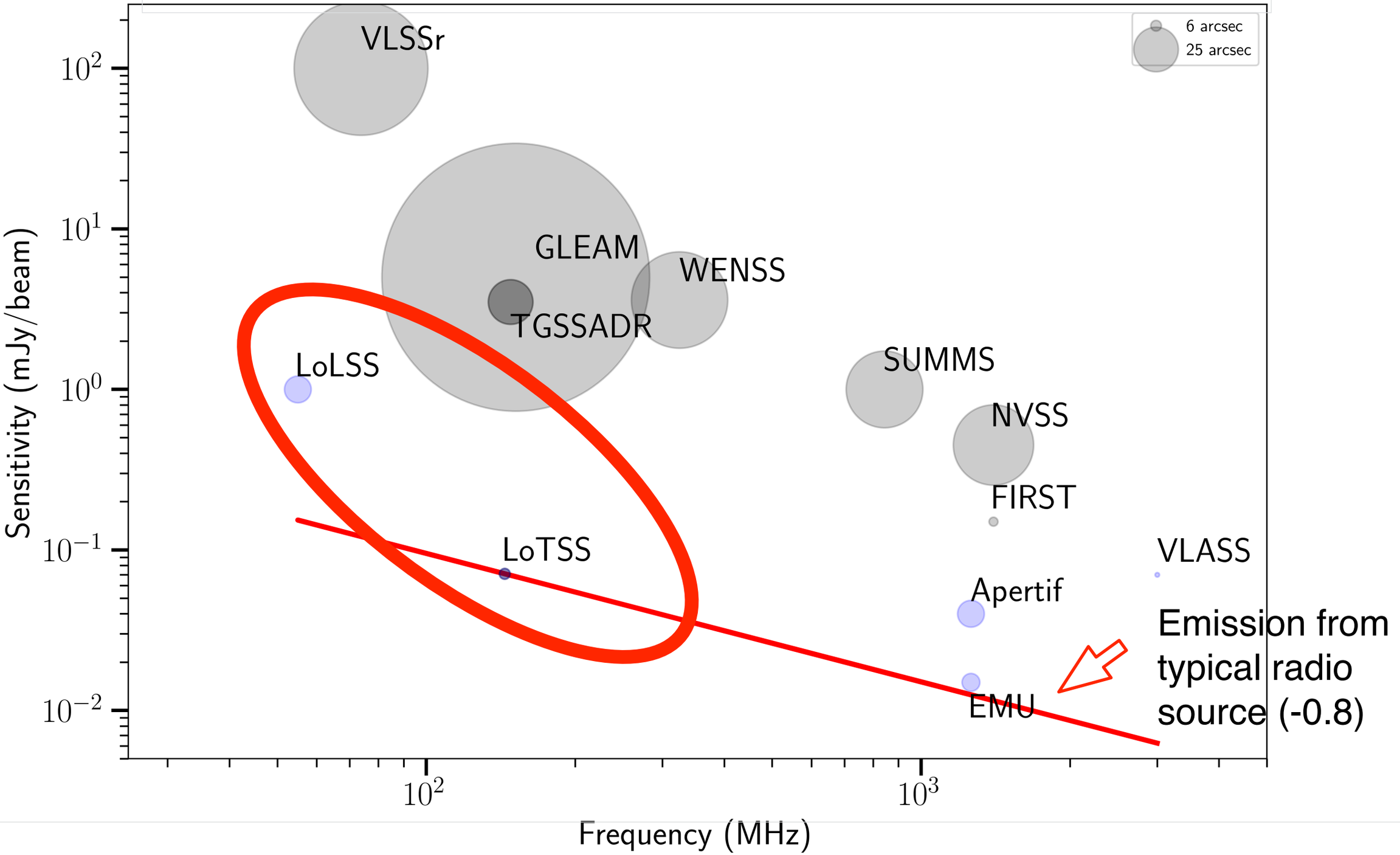
Polarised emission at different Faraday depths originates from different distances

Can correlate with e.g. Planck polarised dust map or HI filaments that follow magnetic fields.



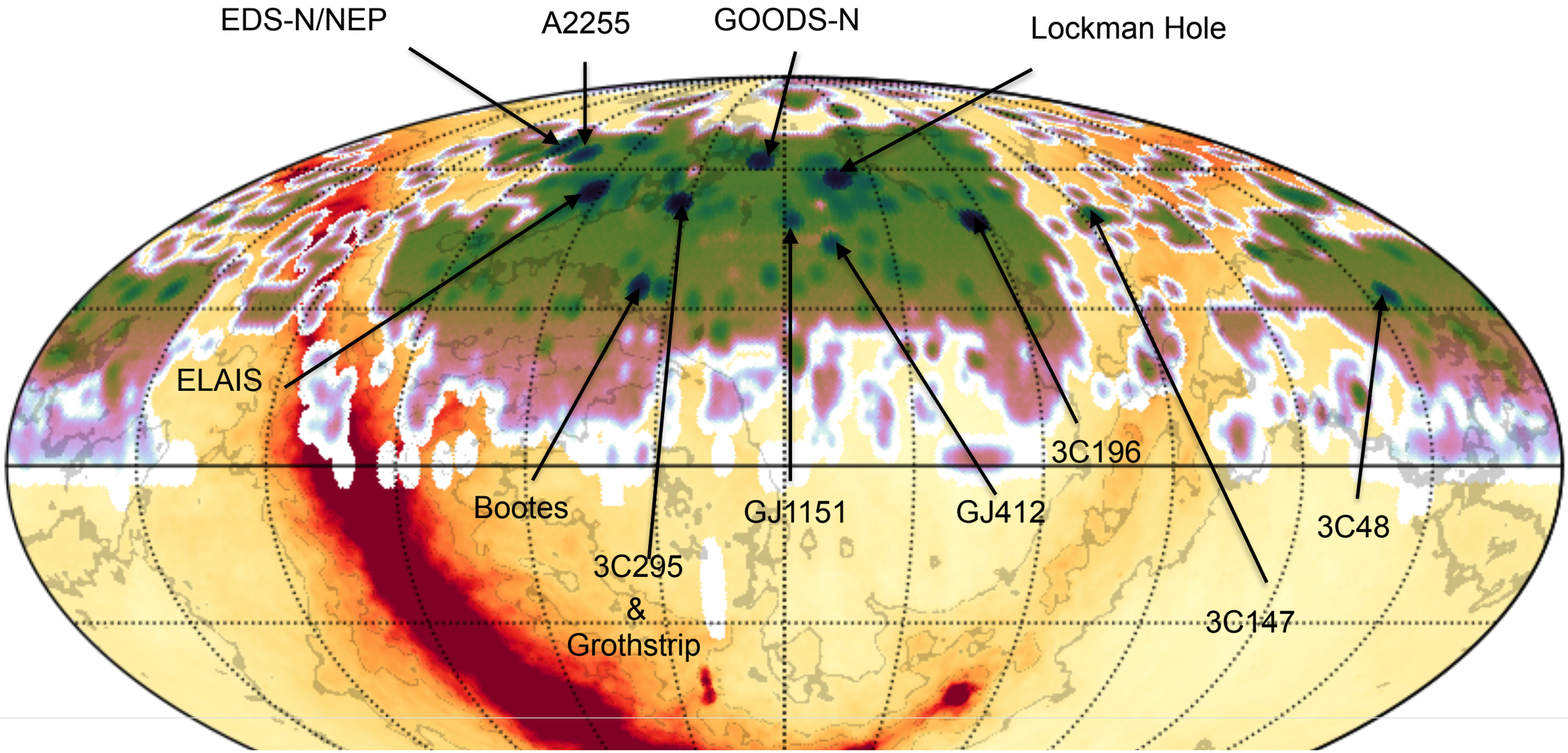
Extragalactic imaging science

LOFAR is a world-leading wide area imaging instrument.



LoTSS: Shimwell et al., 2017 & 2019, 2022 (radio), Williams et. al., 2019, Duncan et al 2019, Hardcastle 2023 (multi-wavelength). LoLSS: De Gasperin et al., 2019, 2023.

LOFAR is a world-leading wide area imaging instrument - both surface brightness sensitivity and resolution.

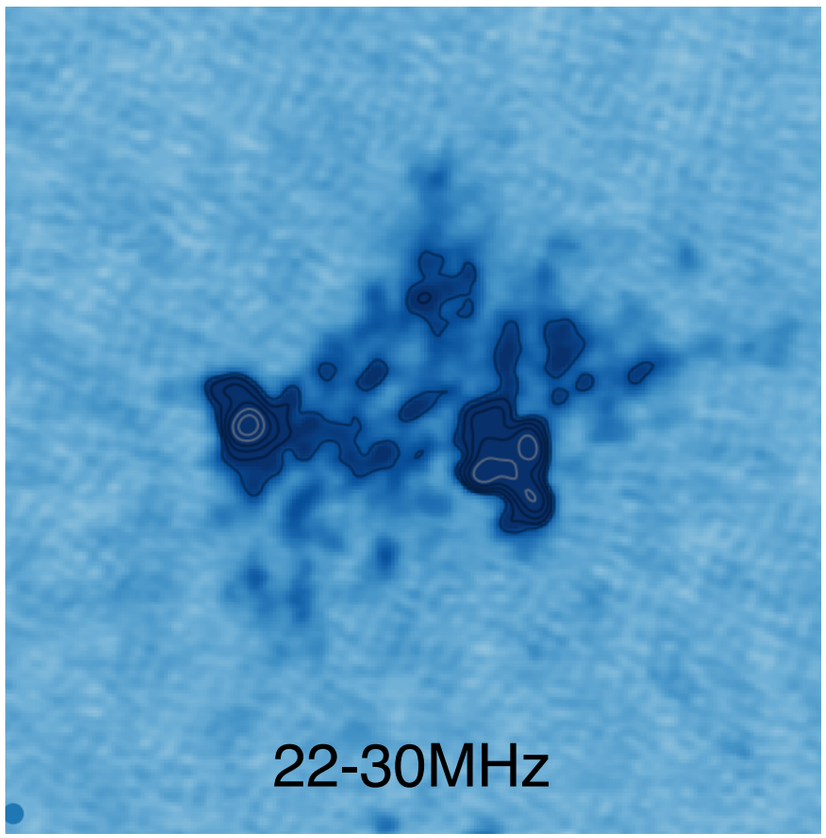


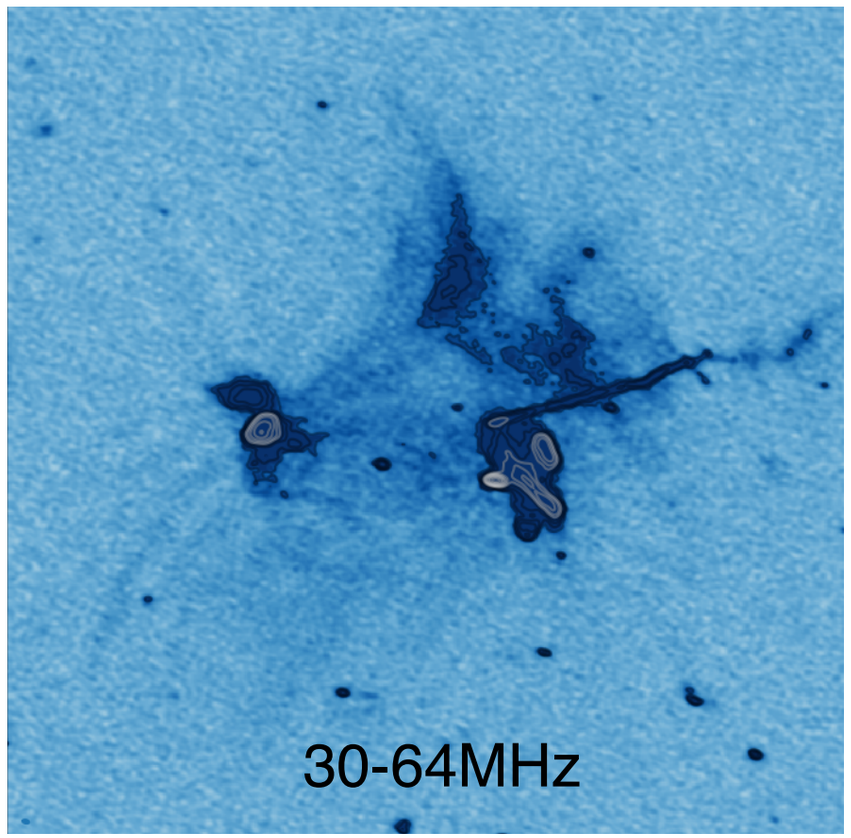
15,000hrs and 15PB of LOFAR HBA imaging data in archive. 85% of sky surveyed including several deep fields with up to 550hr integrations. Processing cost of ~20 million cpu hours.

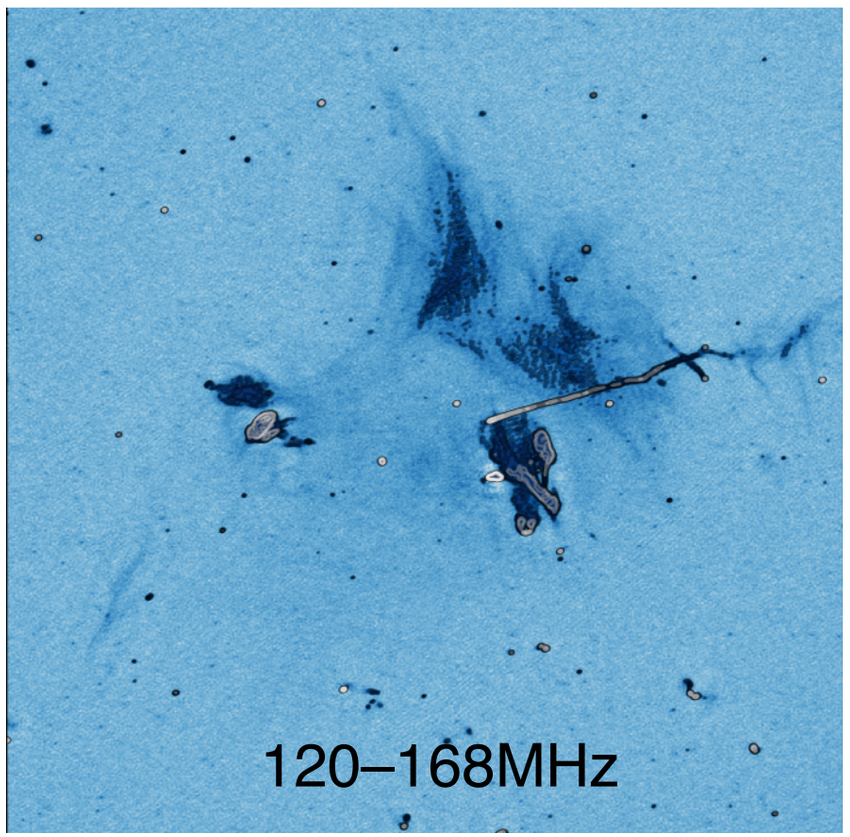
LBA 99% of sky observed above dec 24. Over 1,000 hrs integration.

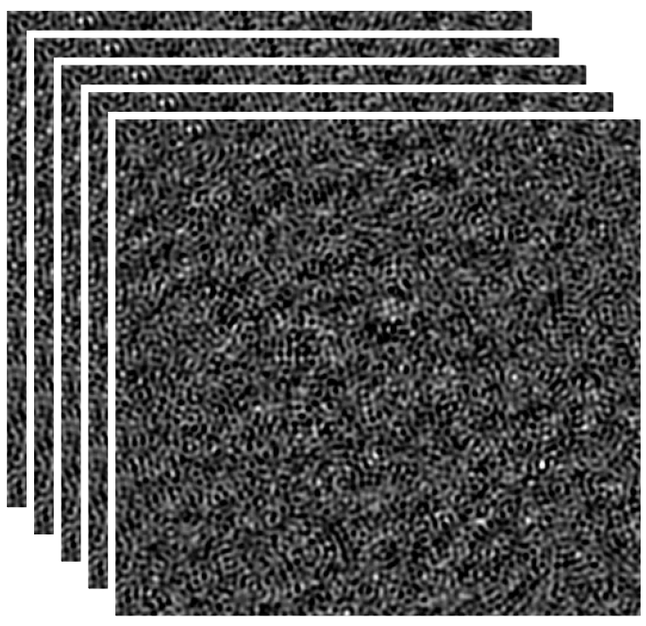
To-date about 13,500 million sources in images - 90% are new.

Science ready products over vast areas of sky.

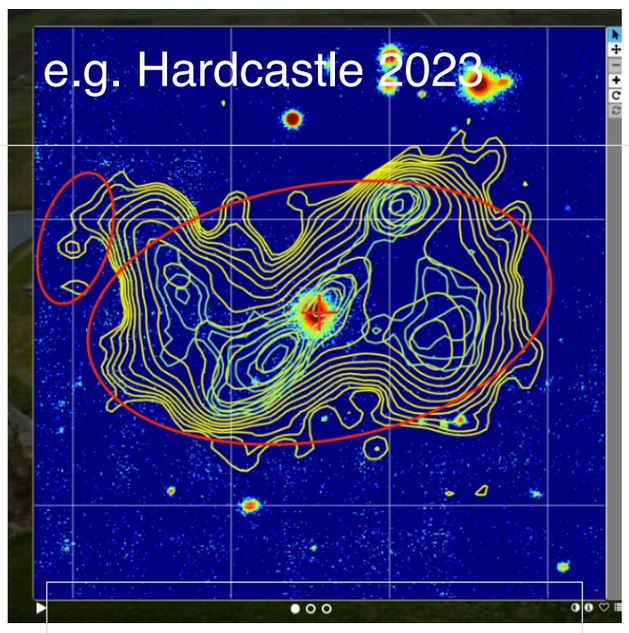






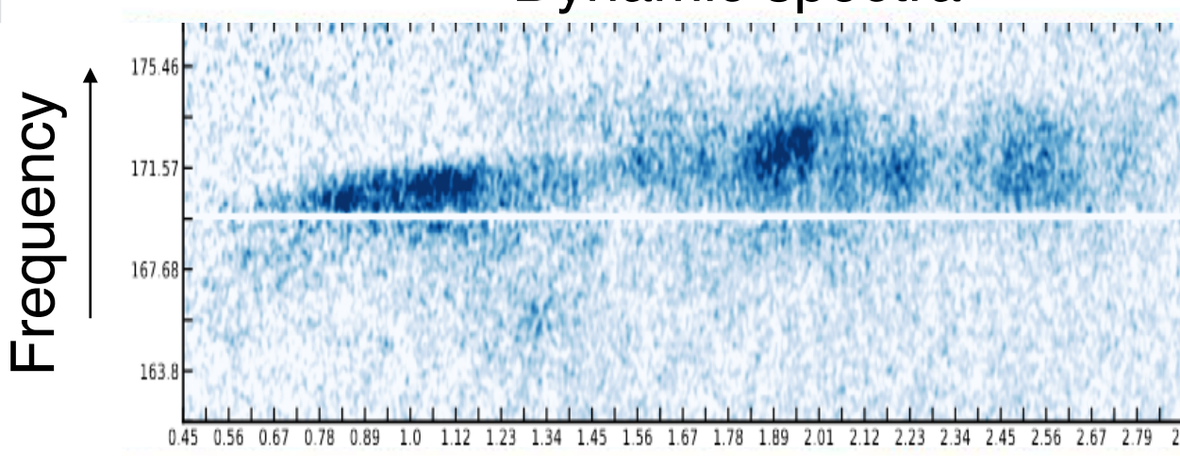


Polarisation cubes



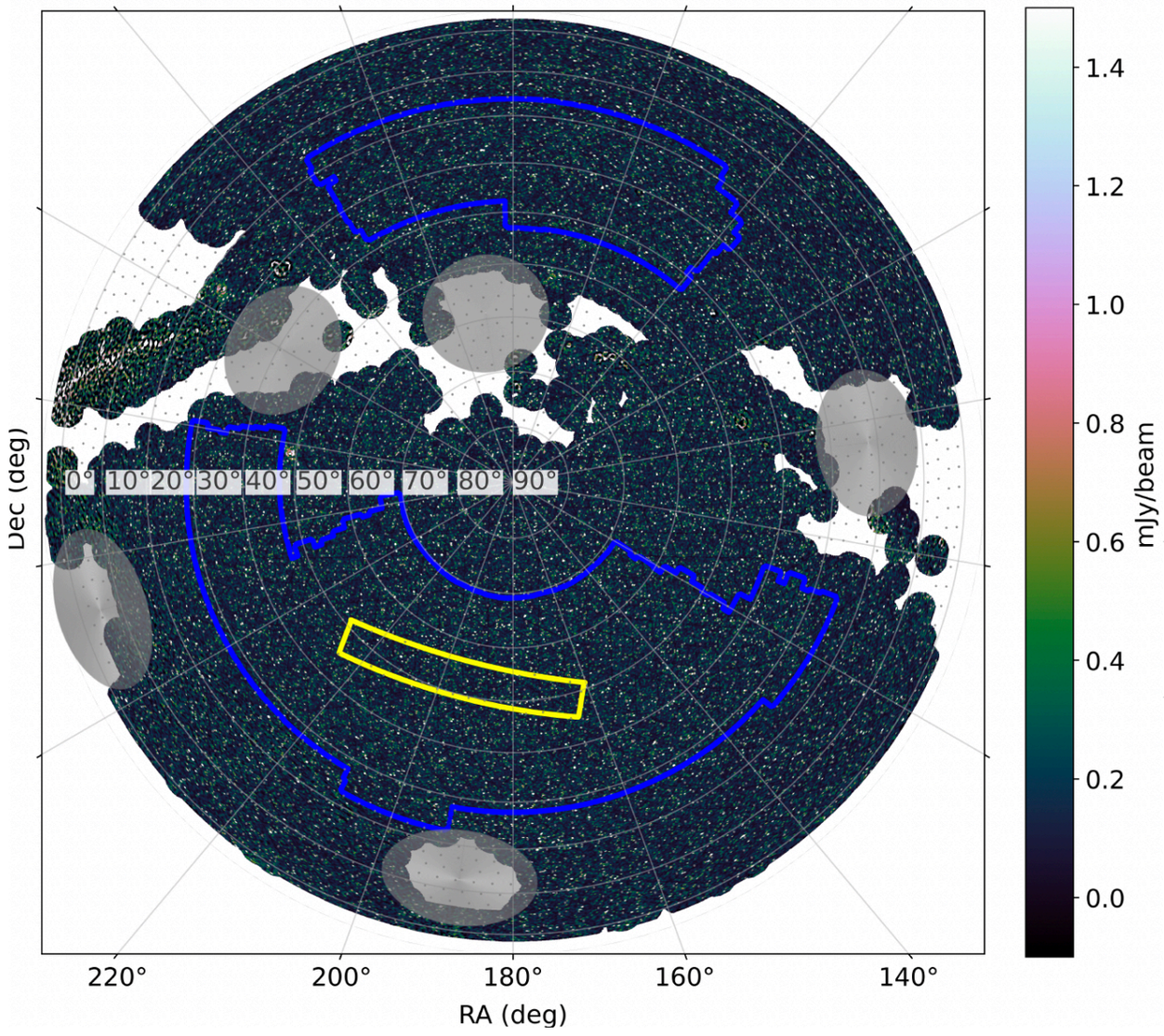
Cross matching

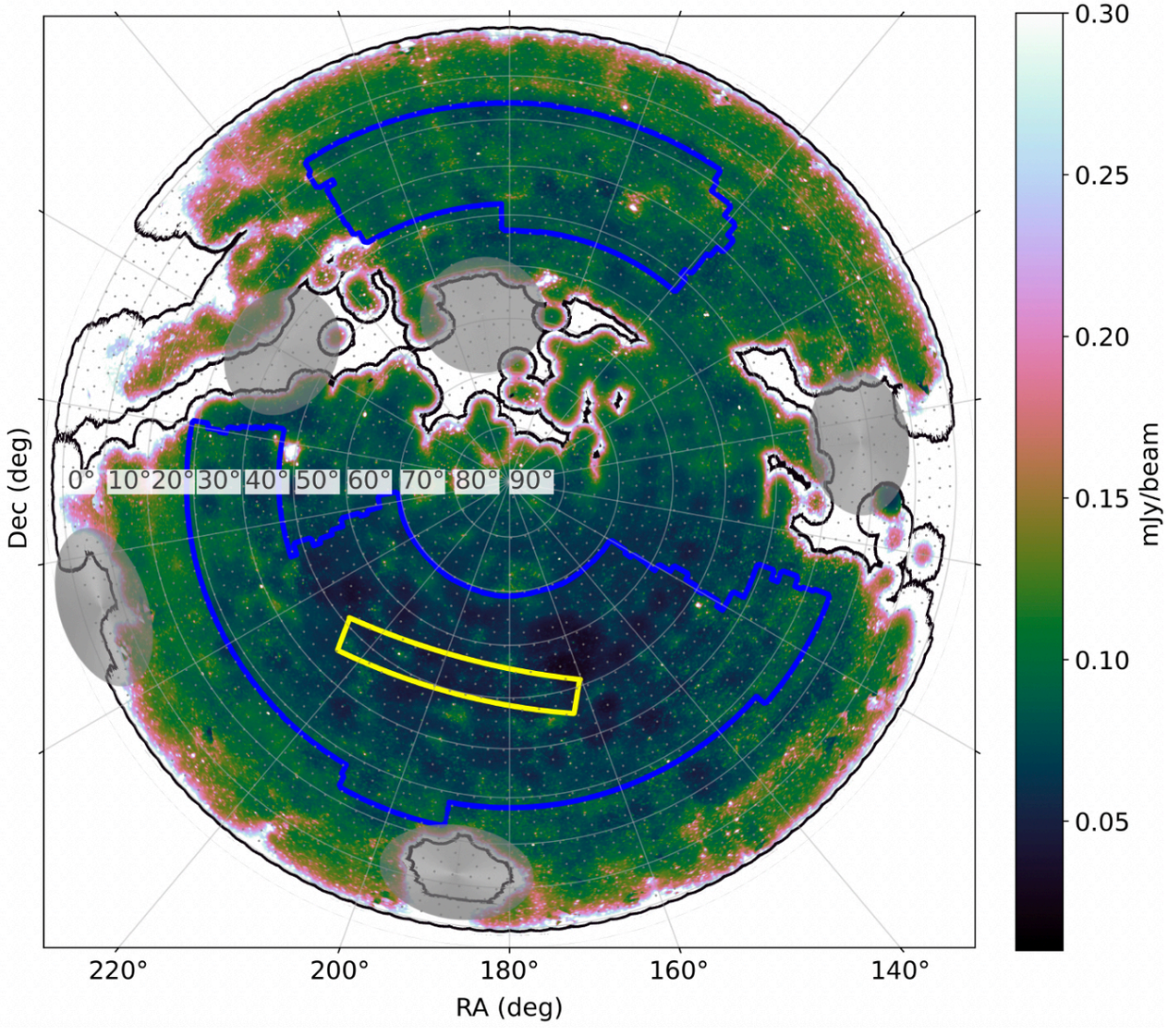
Dynamic spectra



LOFAR Two Metre Sky Survey DR3 (LoTSS-DR3)

13.7 million radio sources (>80% new)



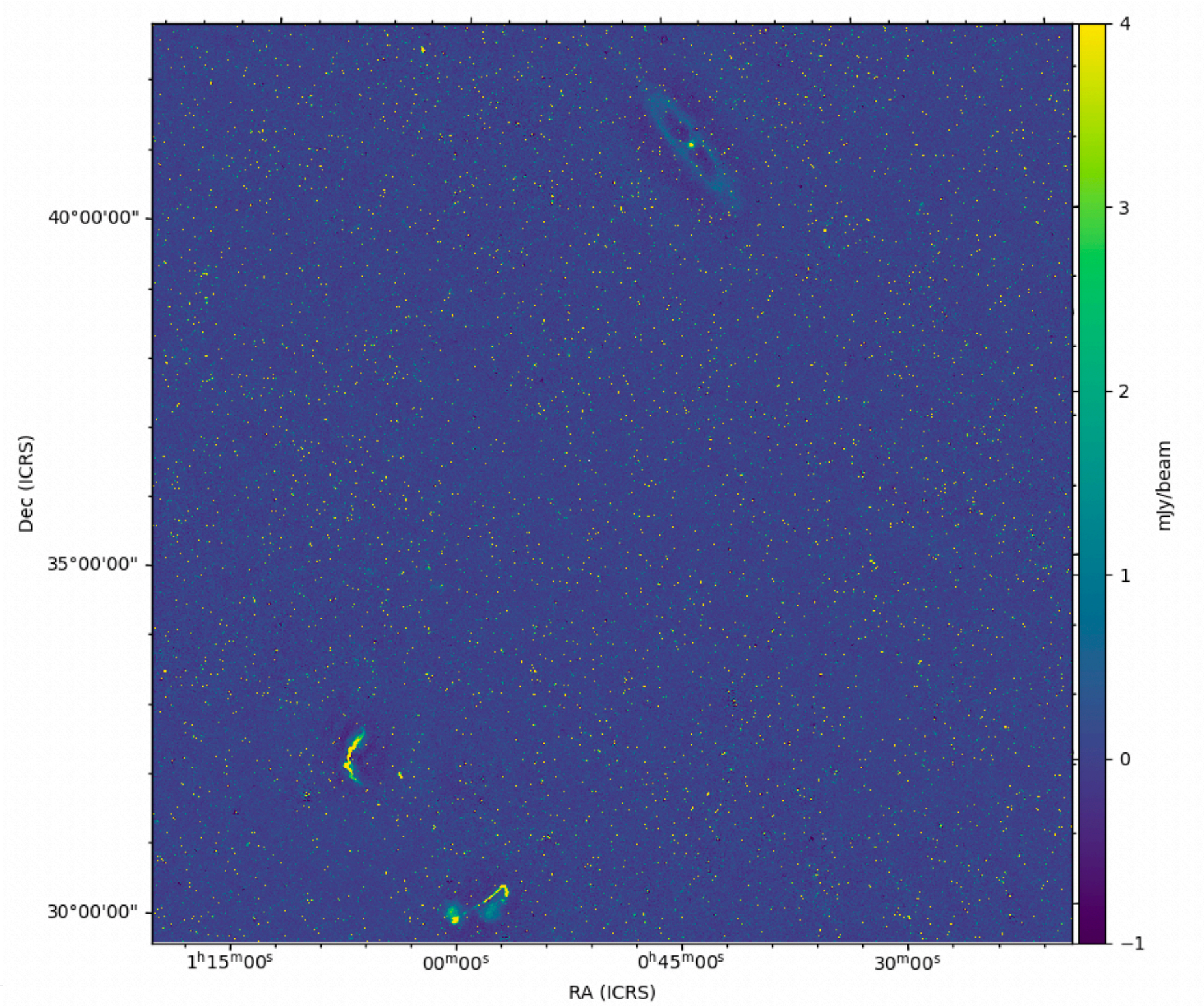


- 89% of the northern sky. Region missing mainly moderate galactic latitude and within 10 deg of CygA, CasA, HerA, VirA, TauA. 8hrs per field above Dec 10 and 12hrs below. All 120-168MHz.

https://lofar-surveys.org/public_hips/LoTSS_DR3_high_hips/

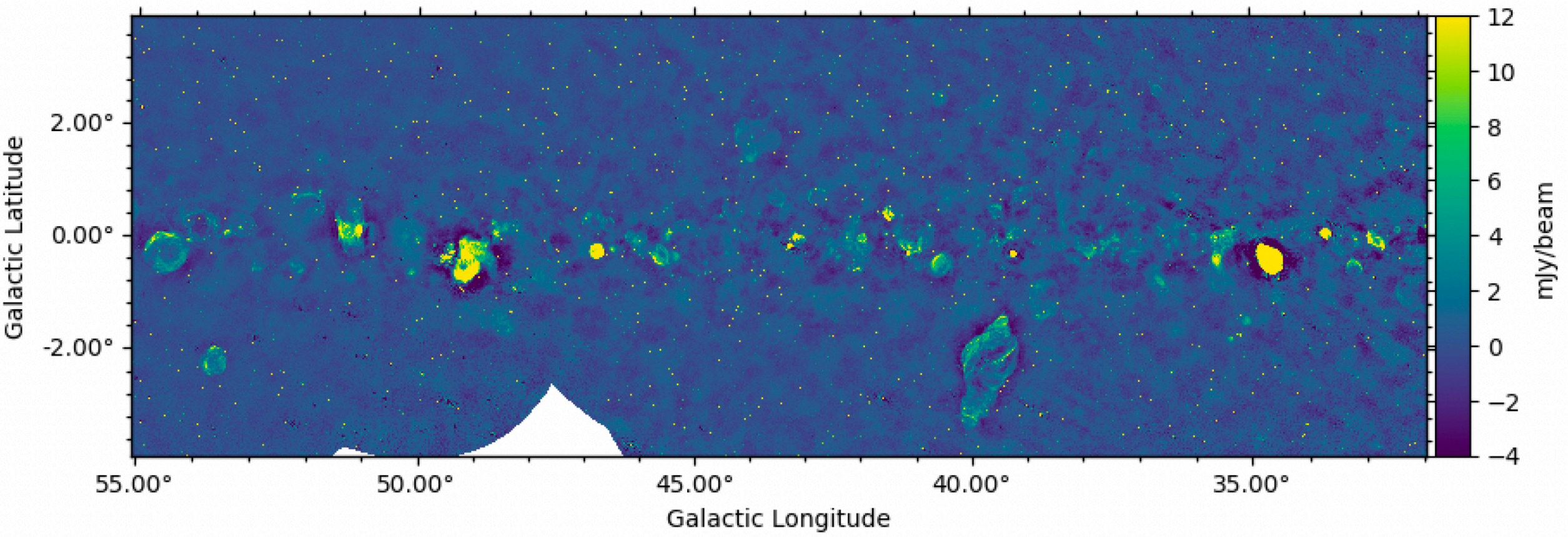
LoTSS data releases: Shimwell+ 2017 (survey description, 2% badly),
2019 (DR1, 2%), 2022 (DR2, 23%) , 2026 (DR3, 89%)

LOFAR Two Metre Sky Survey DR3 (LoTSS-DR3)

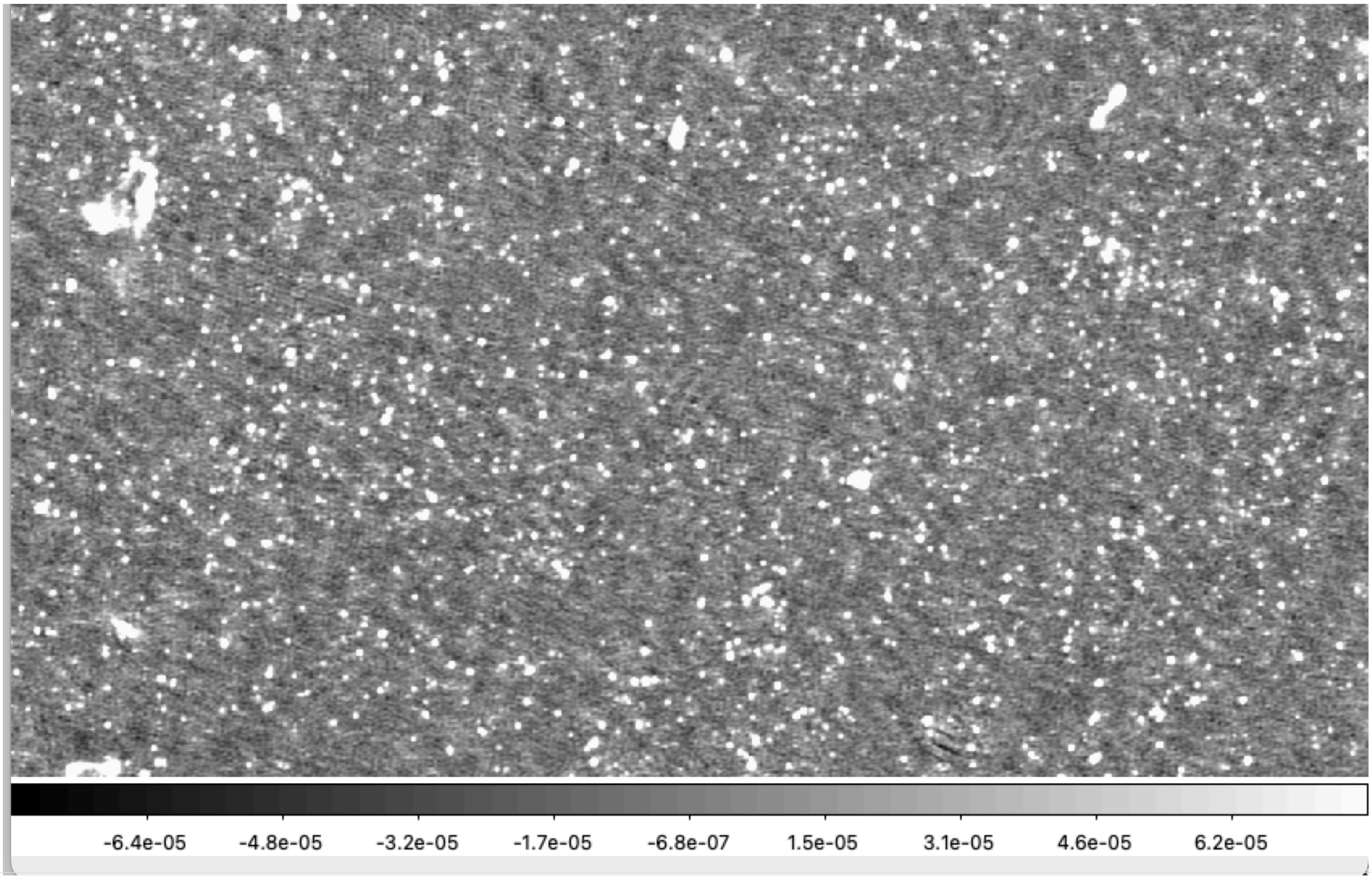


Example 200 square-degree region of LoTSS-DR3. Showing ~150,000 detected sources. Prominent structures in this image include NGC 315, 3C31 and M 31.

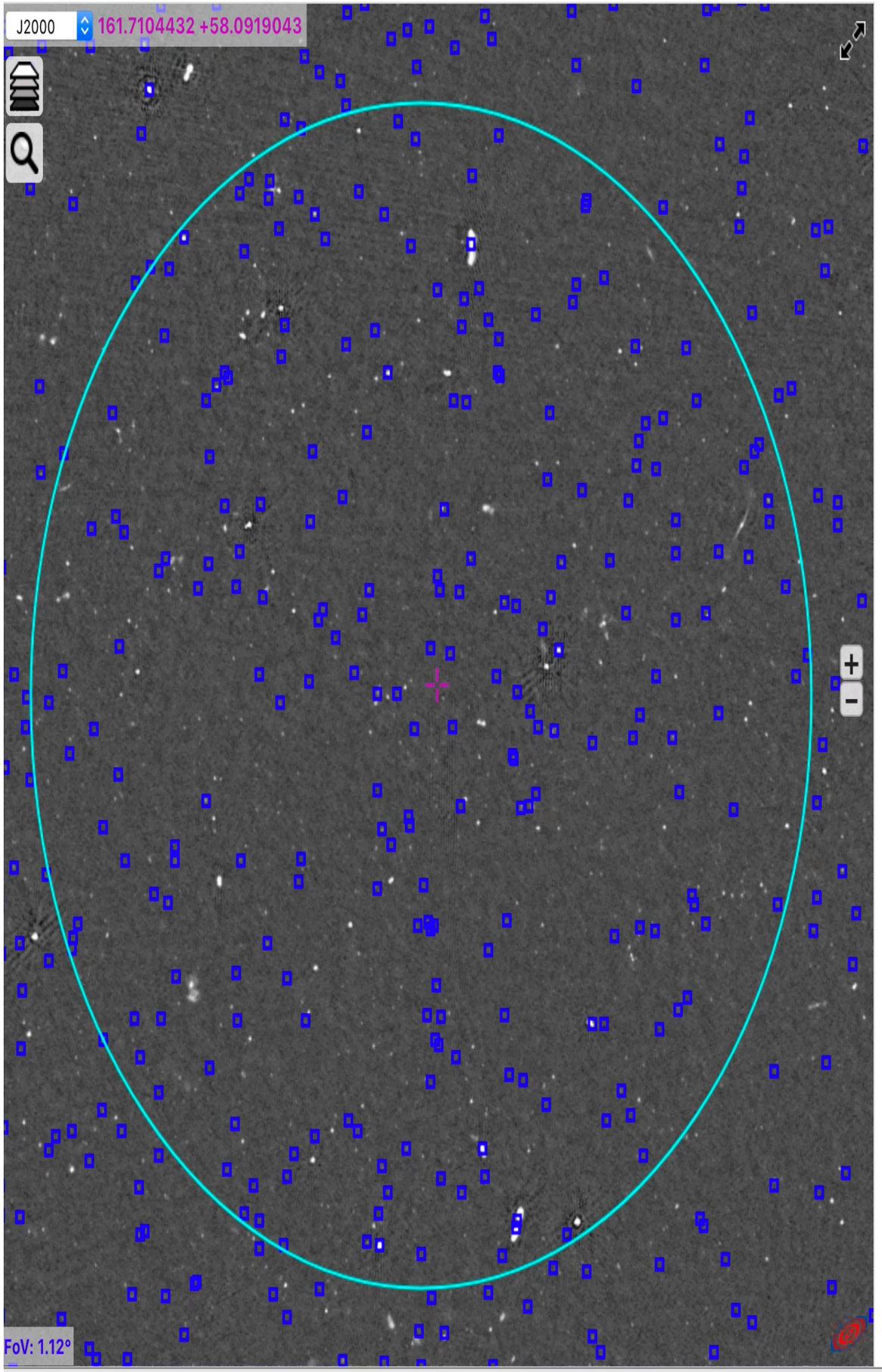
LOFAR Two Metre Sky Survey DR3 (LoTSS-DR3)

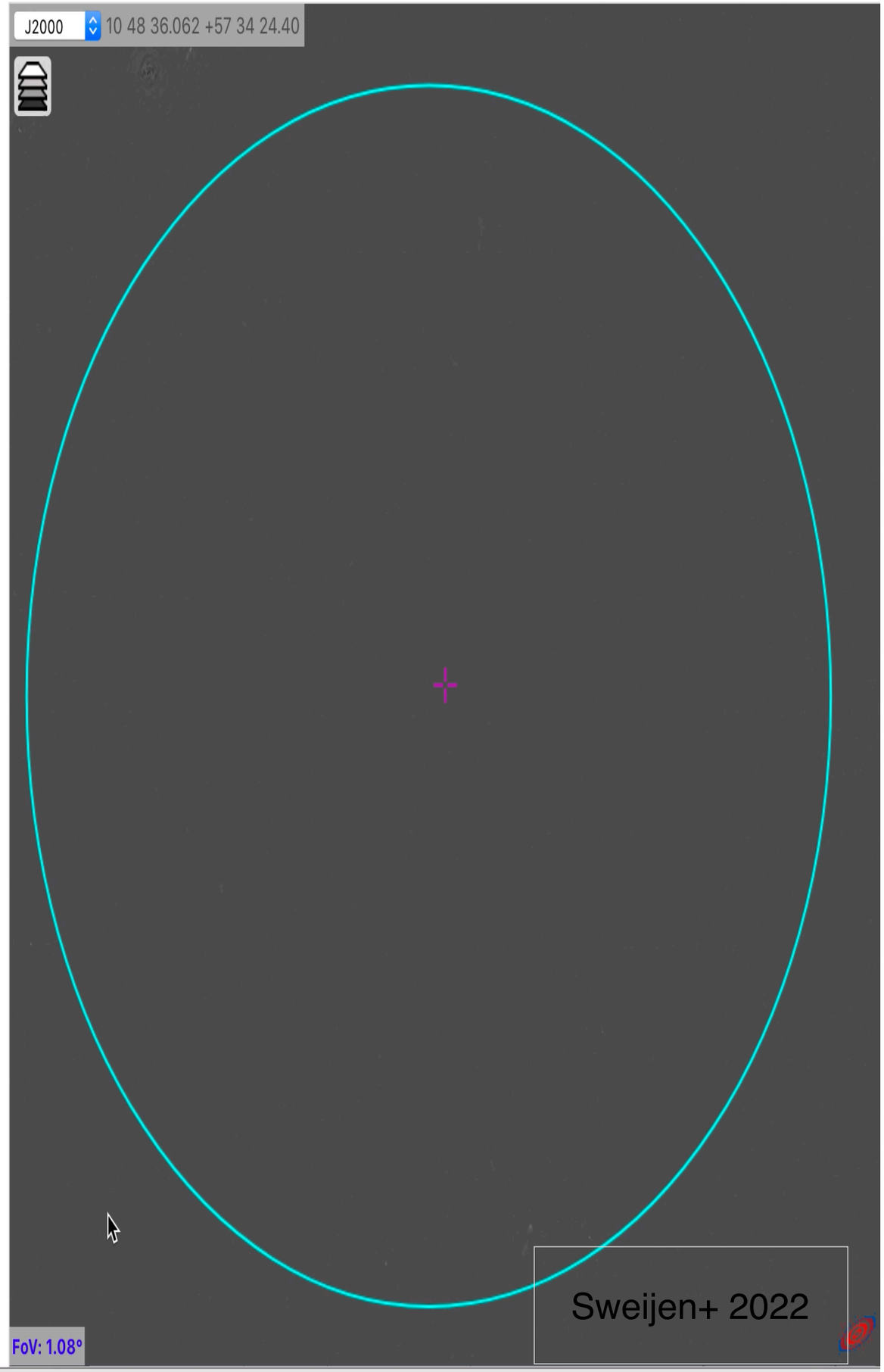


The 190 square-degree region of LoTSS-DR3 with the highest density of known supernova remnants. The area includes several prominent supernova remnants, such as SNR G054.4-00.3, G049.2-00.7, G043.9+01.6, G039.7-02.0, and G034.7-00.4.



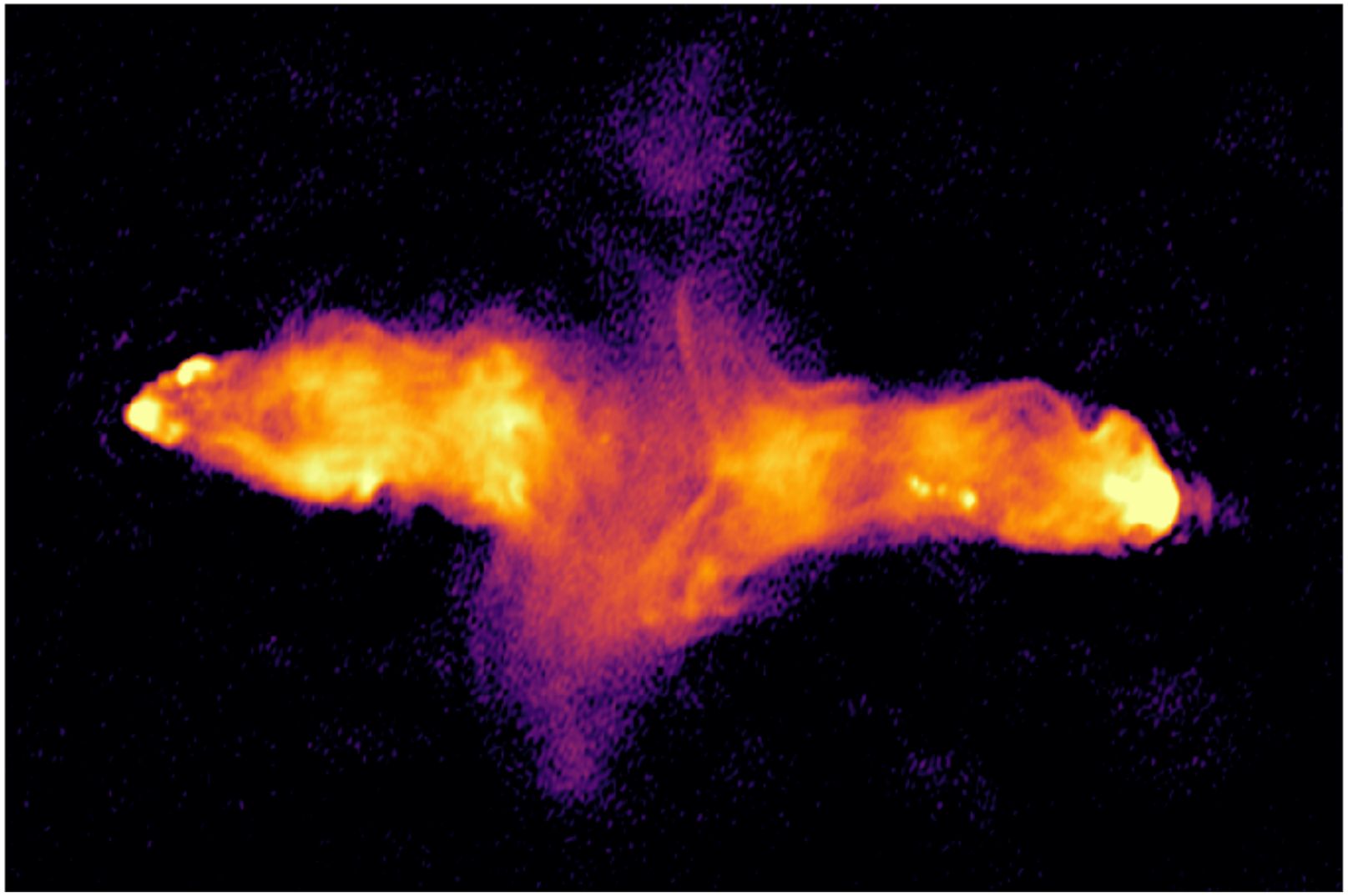
Deepest images around 10-12uJy/beam rms at 6” resolution (very confusion limited)

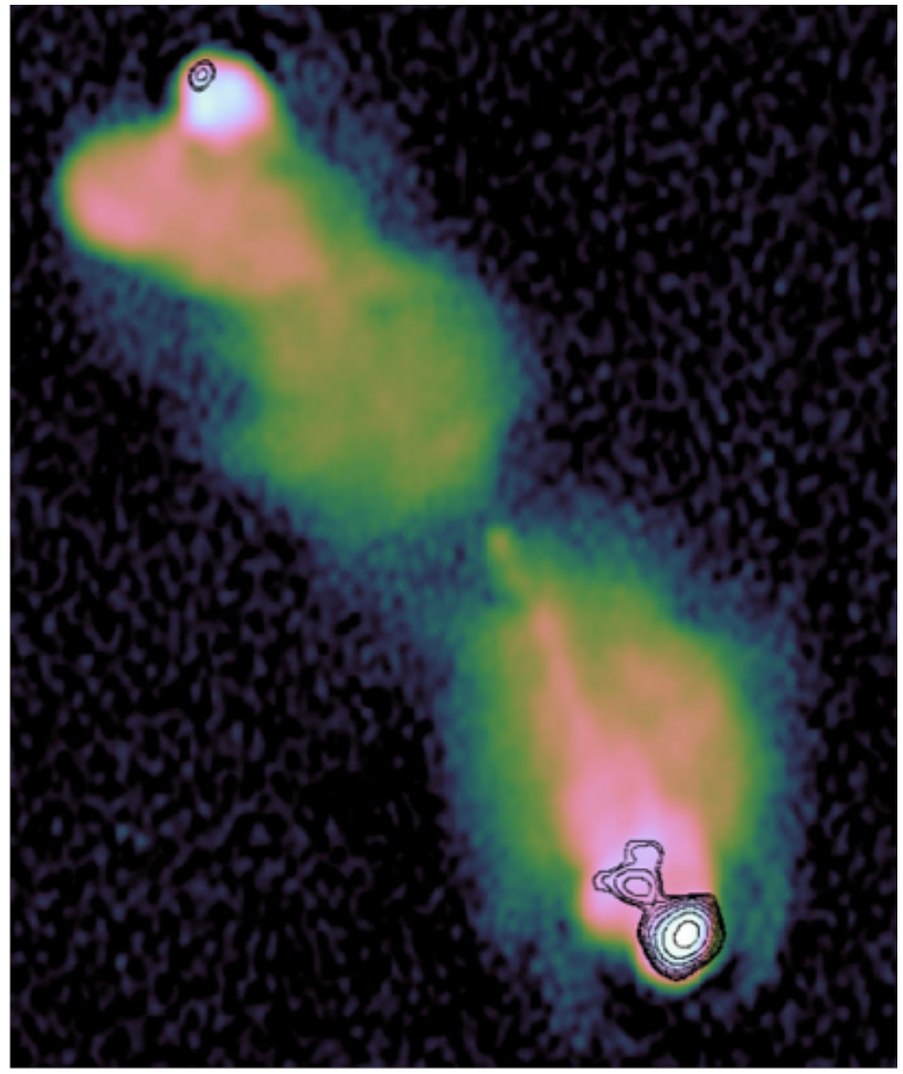

J2000
161.7104432 +58.0919043
FoV: 1.12°


J2000
10 48 36.062 +57 34 24.40
FoV: 1.08°
Sweijen+ 2022

It is now becoming more routine to create high resolution images of interesting targets

Mahatma+23





van Weeren+ 2026

Latest LOFAR long baseline studies include up to 30 datasets and map either selected sources over wide regions or the full field of view to high depth (Timmerman+ sub, de Jong+ sub)

Active Galactic Nuclei and star formation

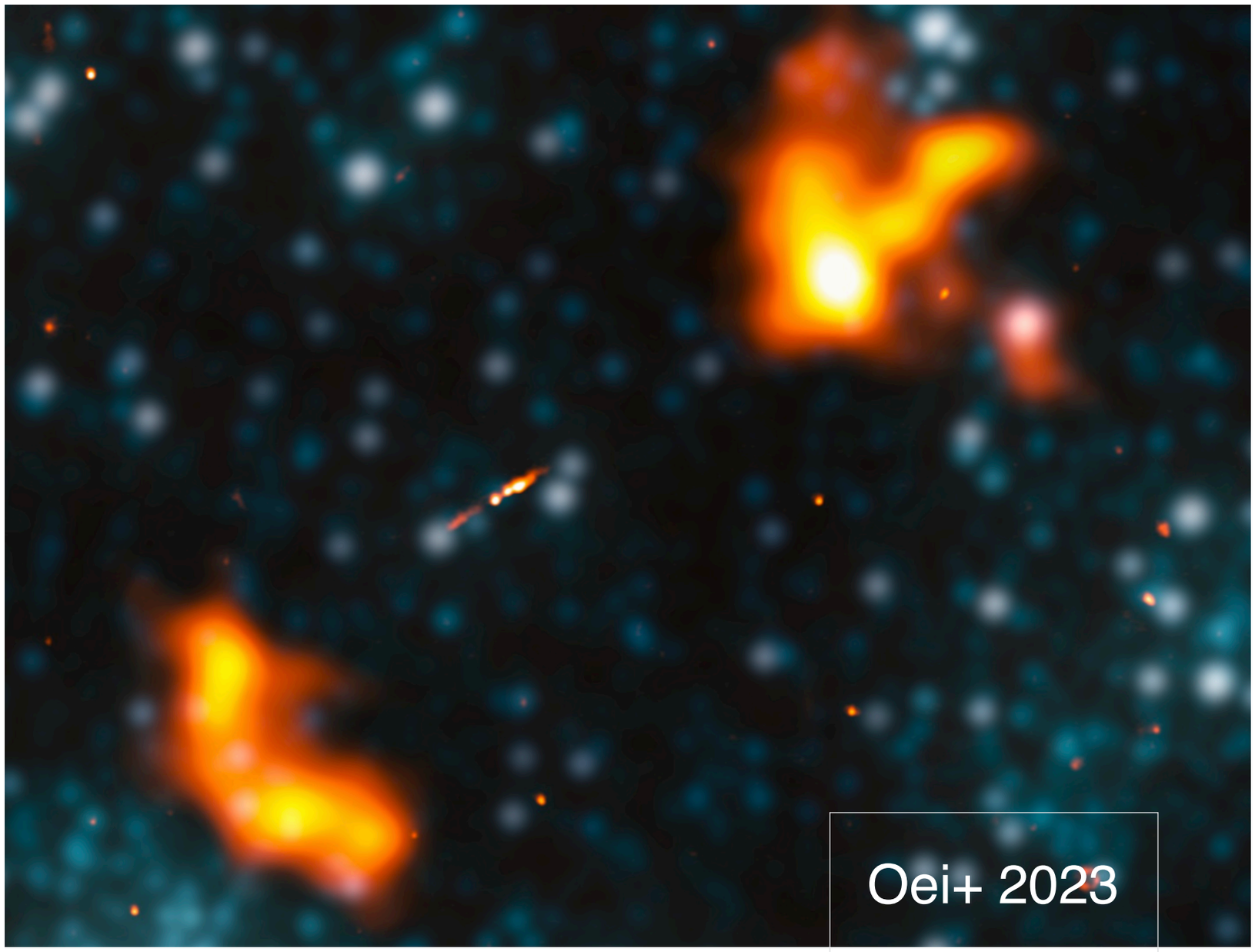
Huge samples of all kinds of AGN. For example Giant Radio Galaxies (>0.7Mpc).

LOFAR images have:

- Revealed the largest giant radio galaxies (5MPc)

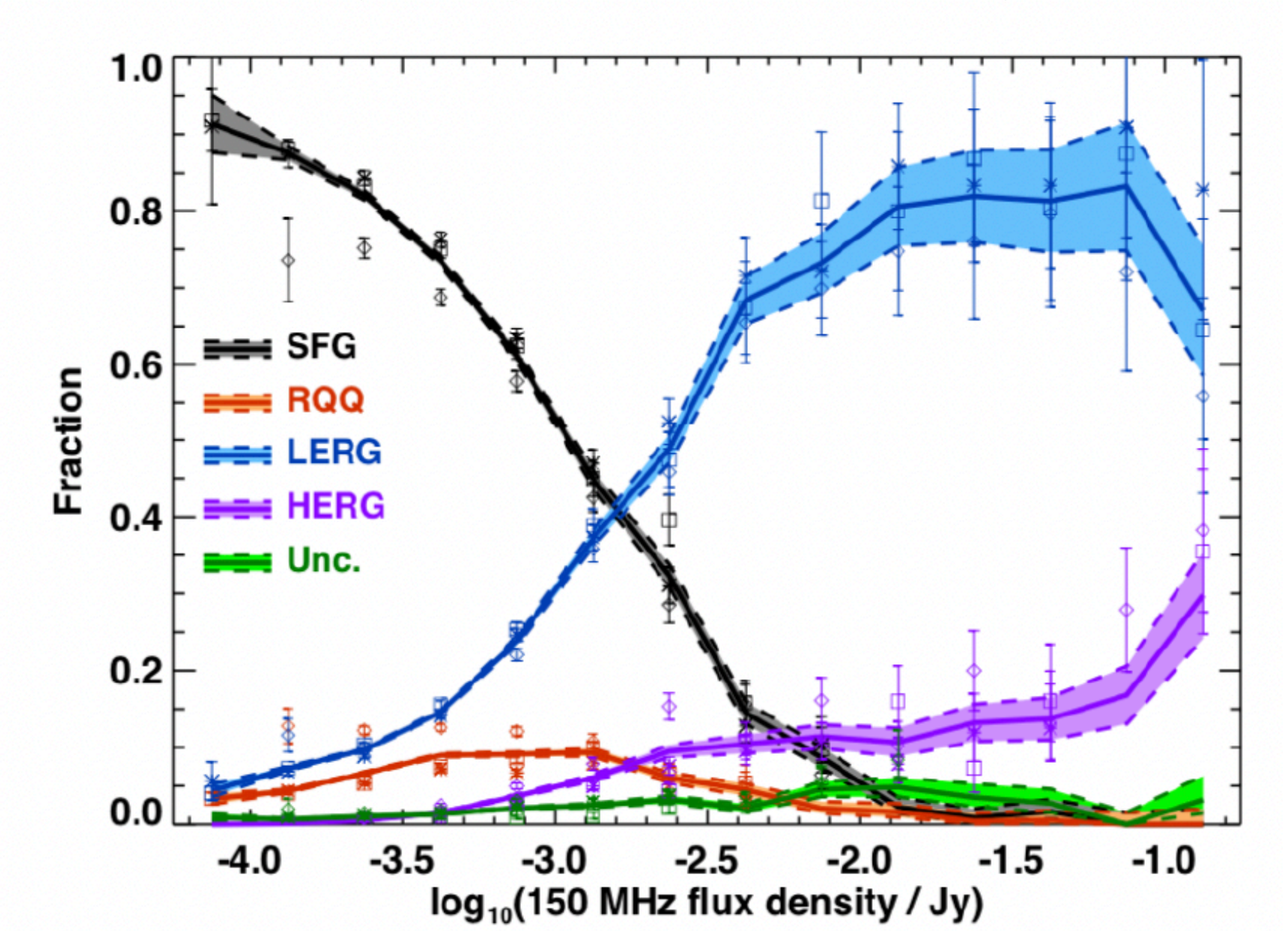
- Tripled the number of know giant radio galaxies (~1,000 to ~ 3,000)

- Found rare hosts such as spiral galaxies.



Active Galactic Nuclei and star formation

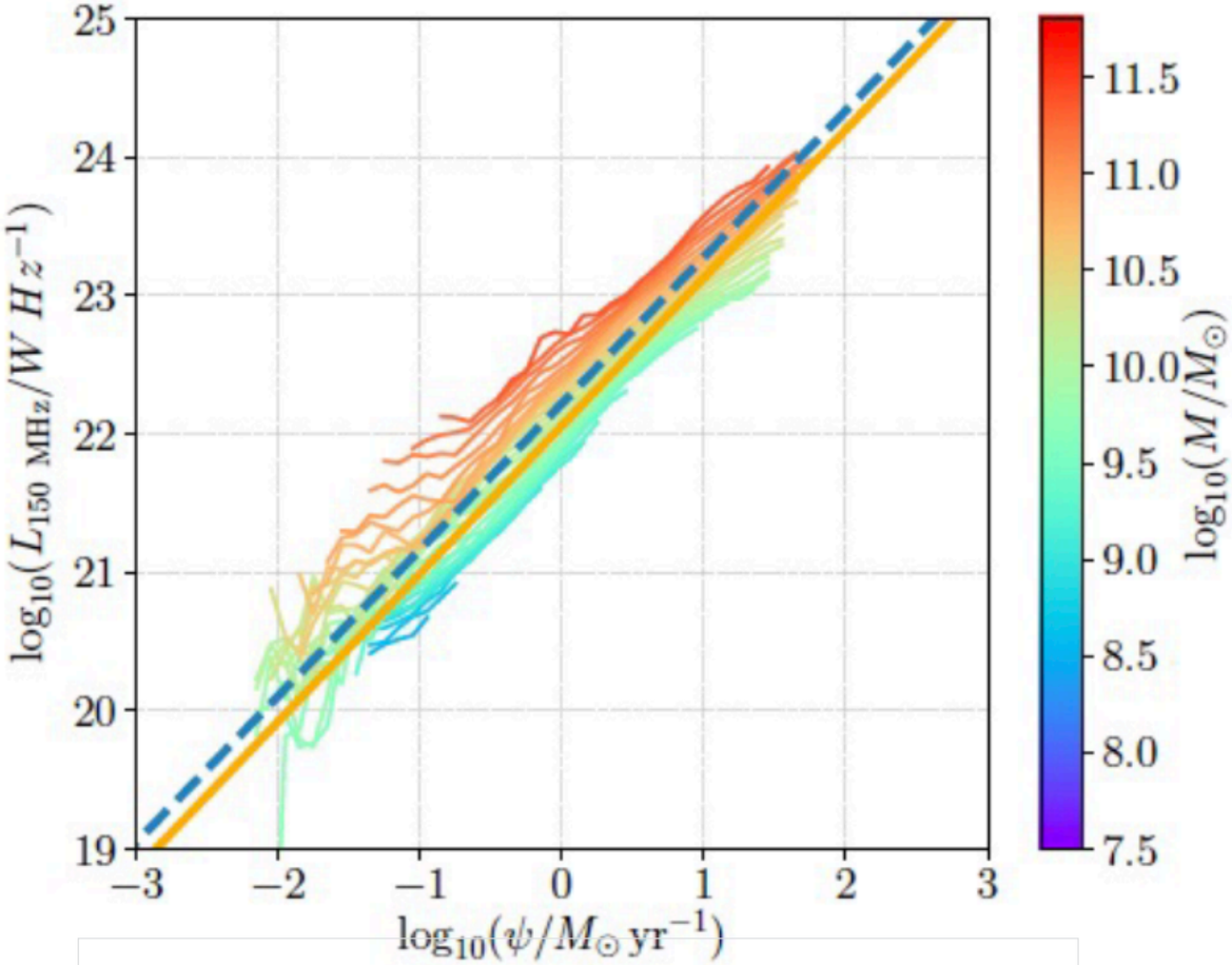
Many statistical studies



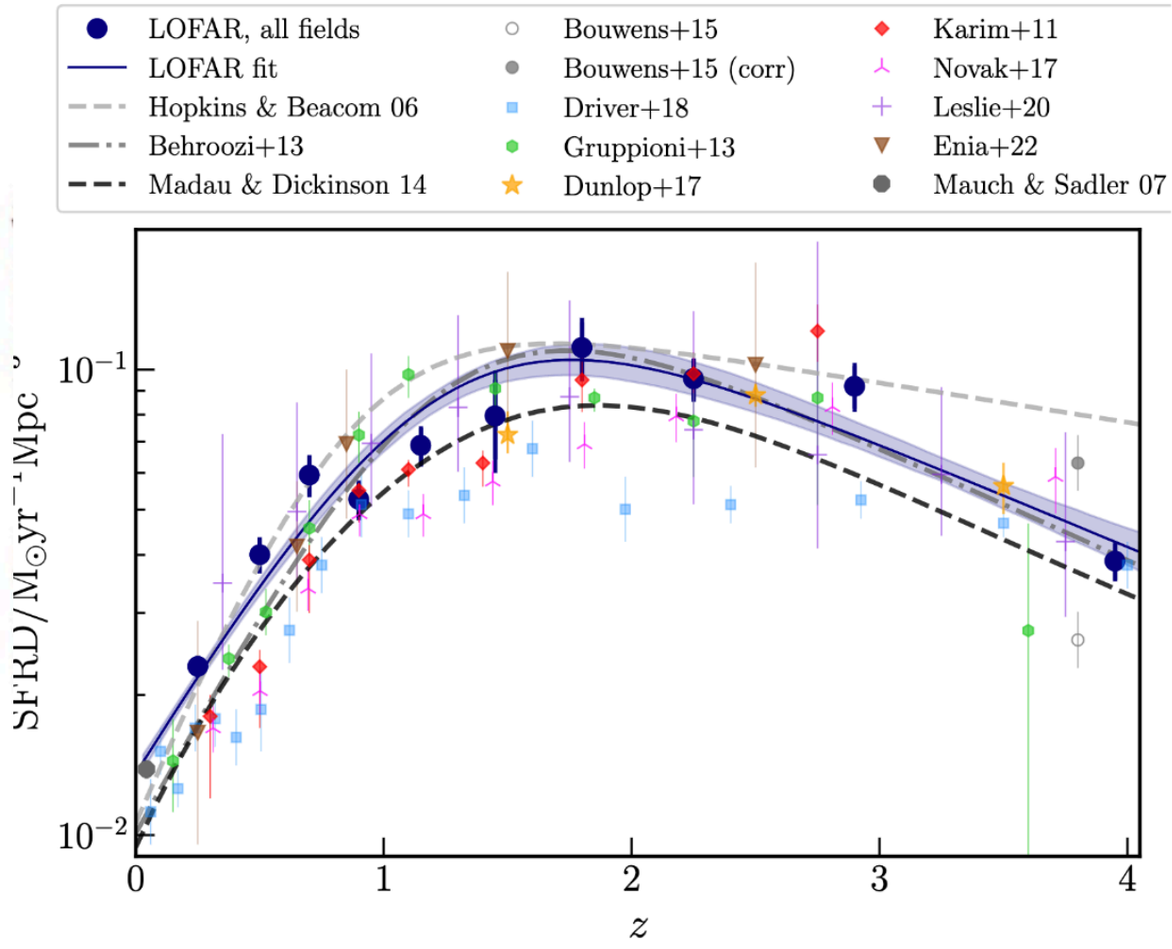
The population fraction of star-forming galaxies (SFGs), radio-quiet quasars (RQQs), low-excitation radio galaxies (LERGs), high-excitation radio galaxies (HERGs) and unclassified objects (Unc/Unclass). Best+ 2023

Active Galactic Nuclei and star formation

Many statistical studies



Probing the star formation vs radio luminosity relation using 118,000 multi wavelength detected LOFAR sources (Smith+ 2021)



Measuring the evolution of the star formation rate density (Cochrane+ 2023)

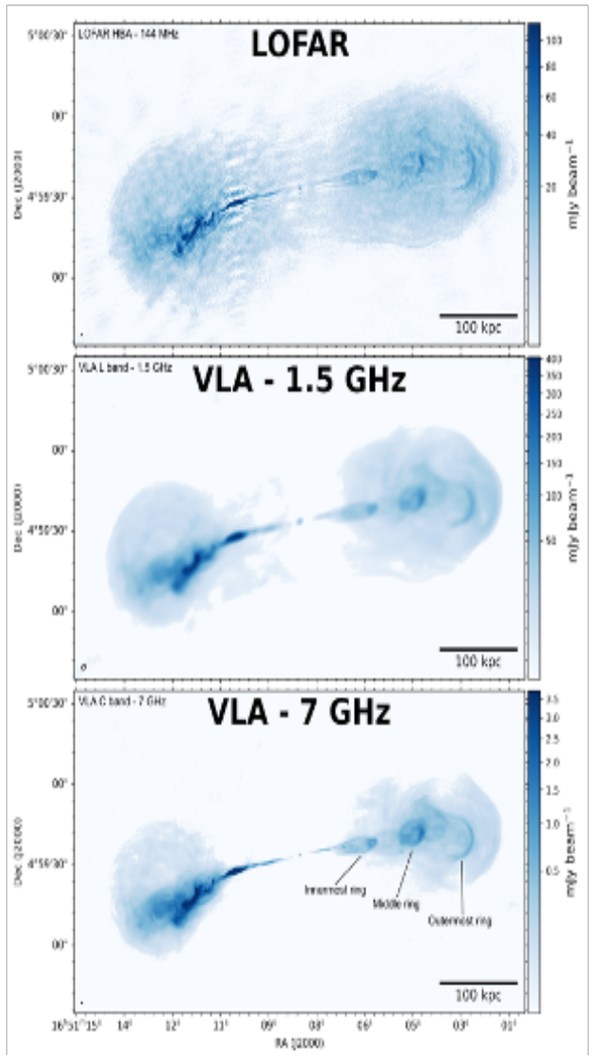
Active Galactic Nuclei and star formation

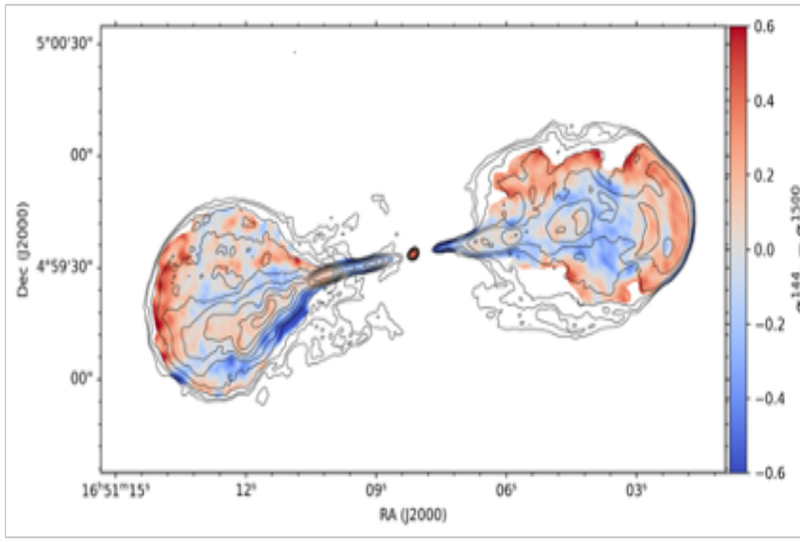
The sensitivity and resolution allows for detailed studies of individual targets too.



The origin of the rings in Hercules A

(Timmerman et al., 2022)

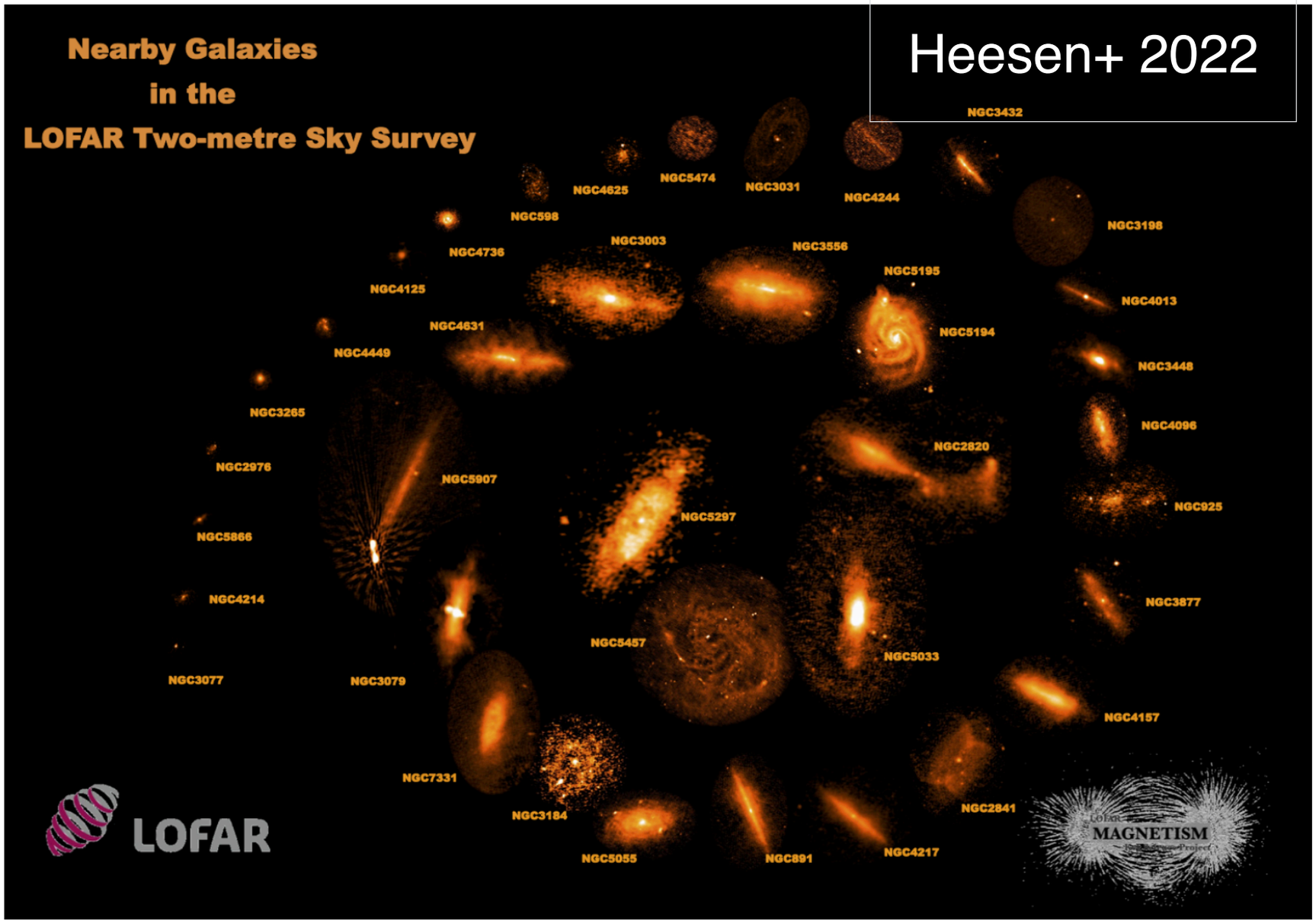




Spectral information - aided by LOFAR - shows rings are consistent with the active galactic nuclei intermittently turning 'on' and 'off'

Nearby galaxies

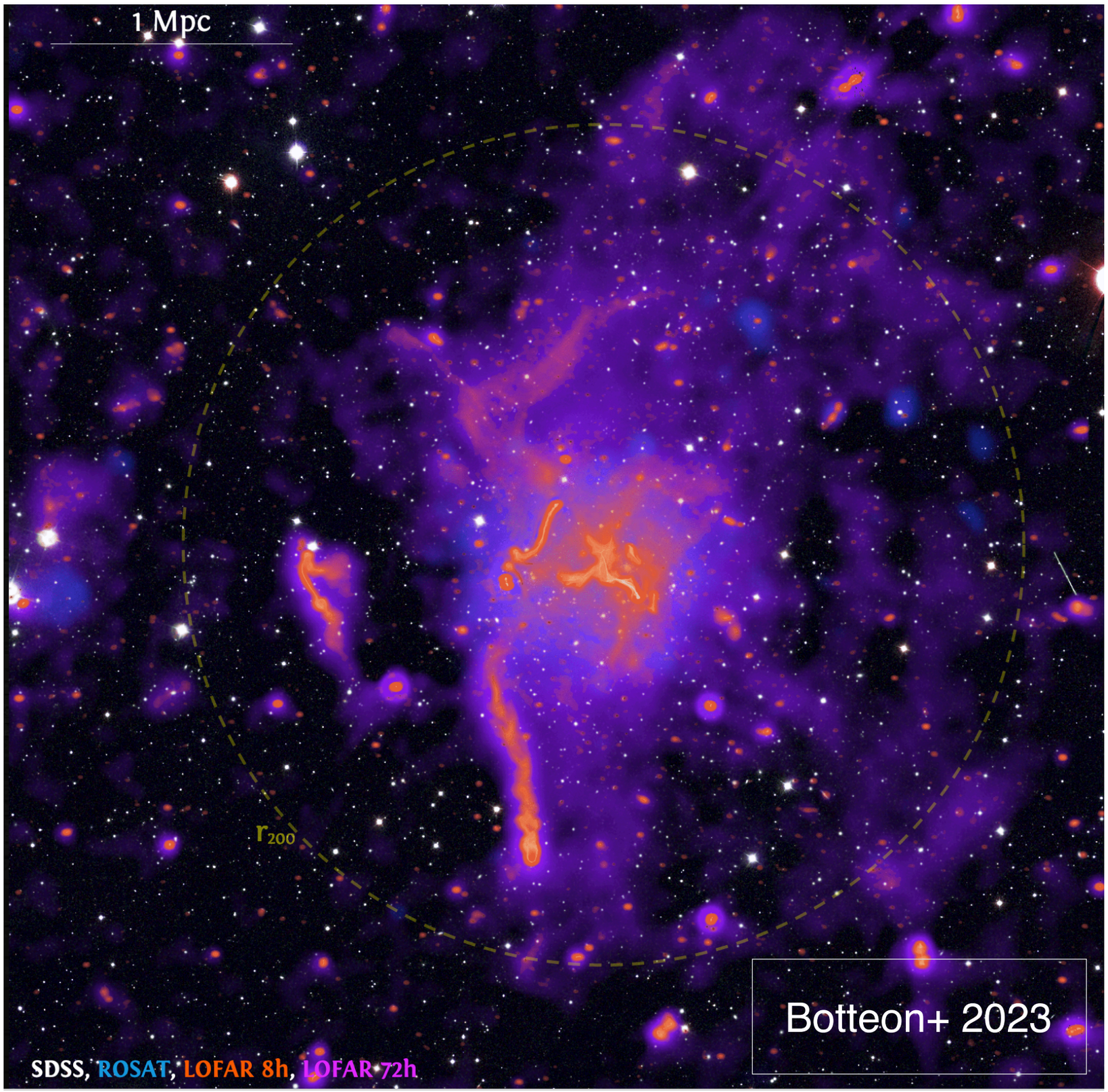
Heesen+ 2022



Spectacular highly resolved images of large samples of nearby galaxies.

Insights into star formation, cosmic ray electrons, magnetic fields. Finds e.g. that the radio - star formation rate holds for both globally and locally.

Extra galactic - Galaxy clusters

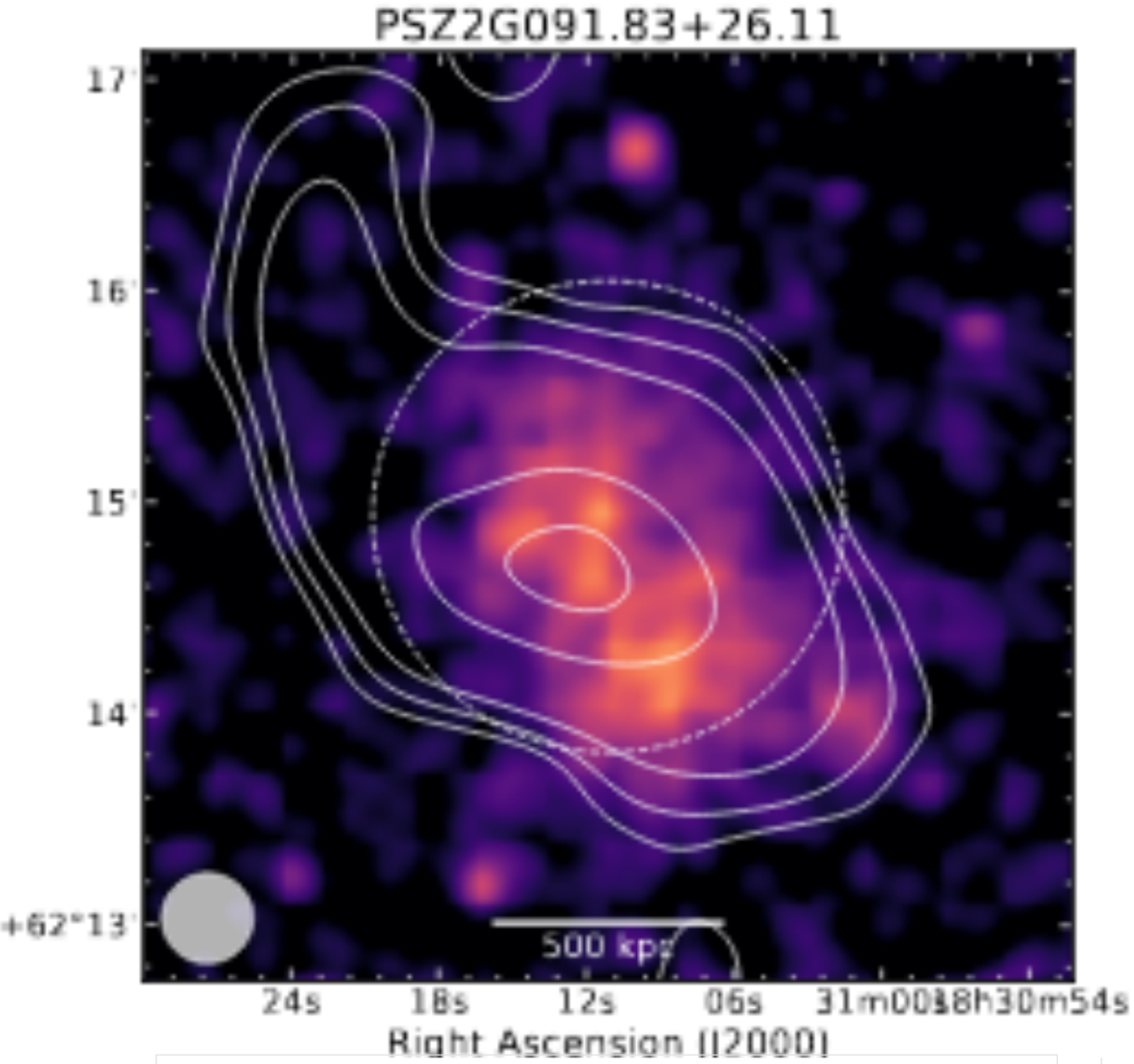


Cluster environments full of shocks and turbulence which accelerate particles.

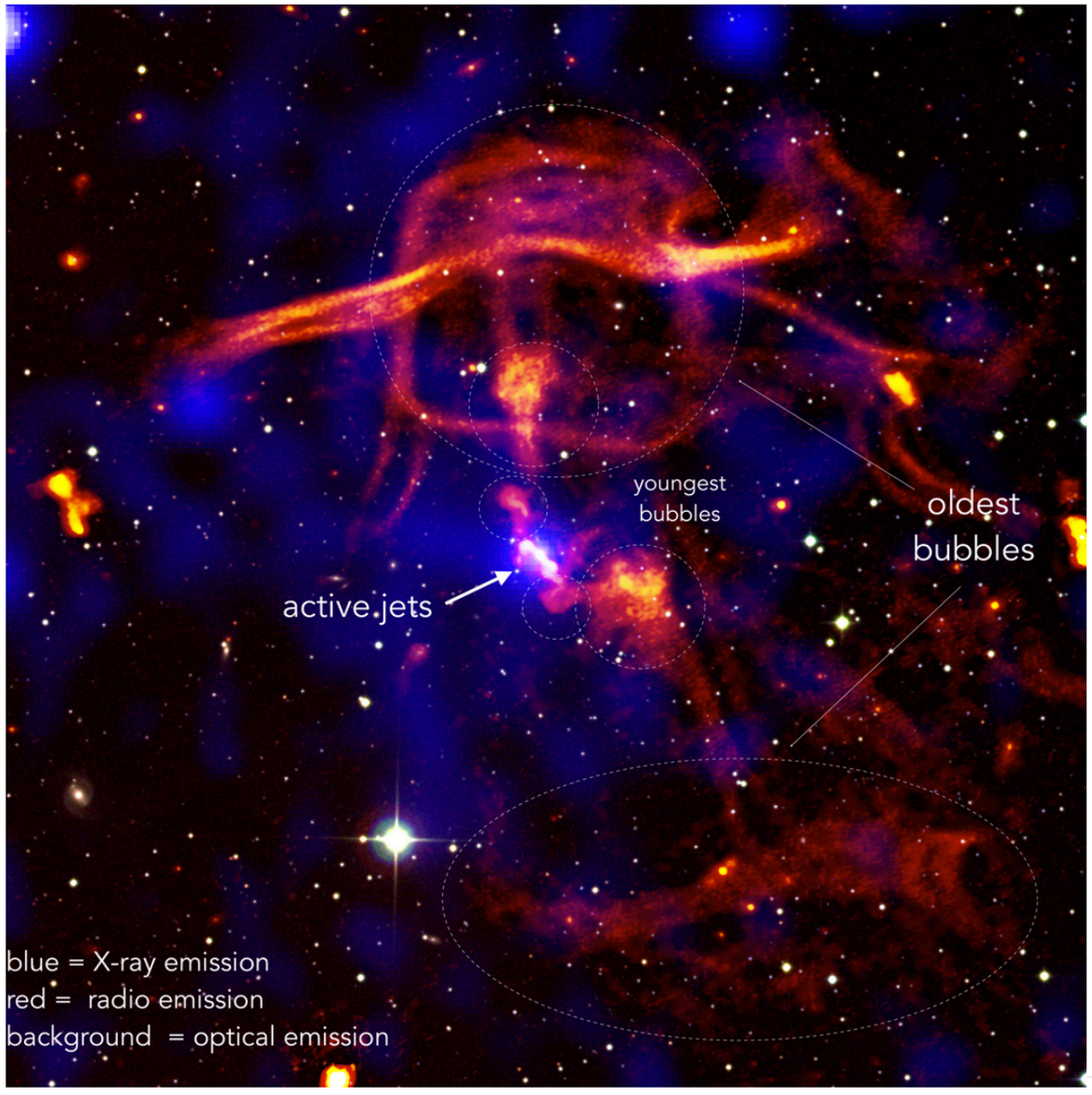
Accelerated particles in the weak cluster fields produce steep spectrum radio emission.

Rare emission (~200 cases) where ~1/2 have been LOFAR discoveries.

Galaxy clusters

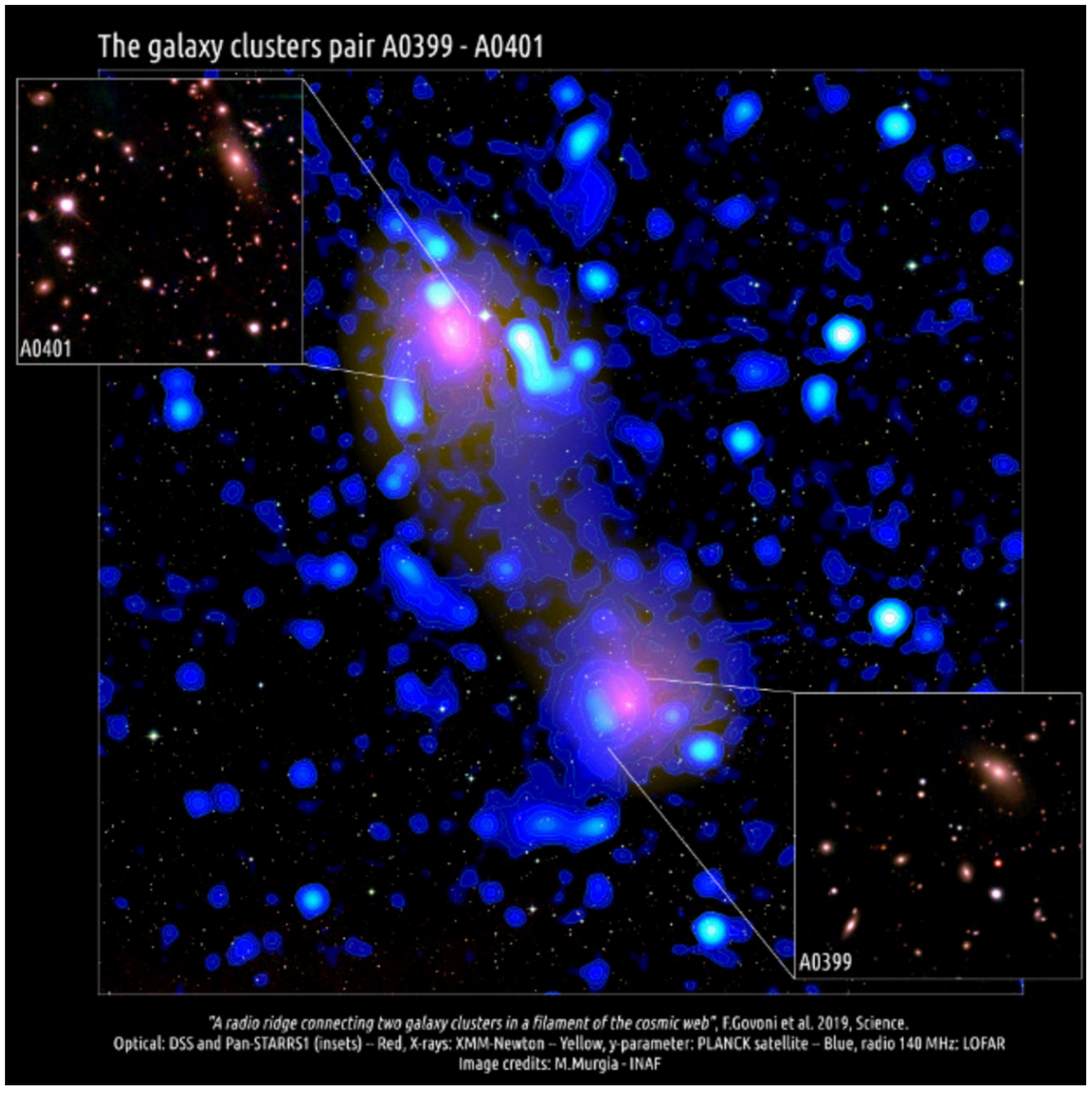


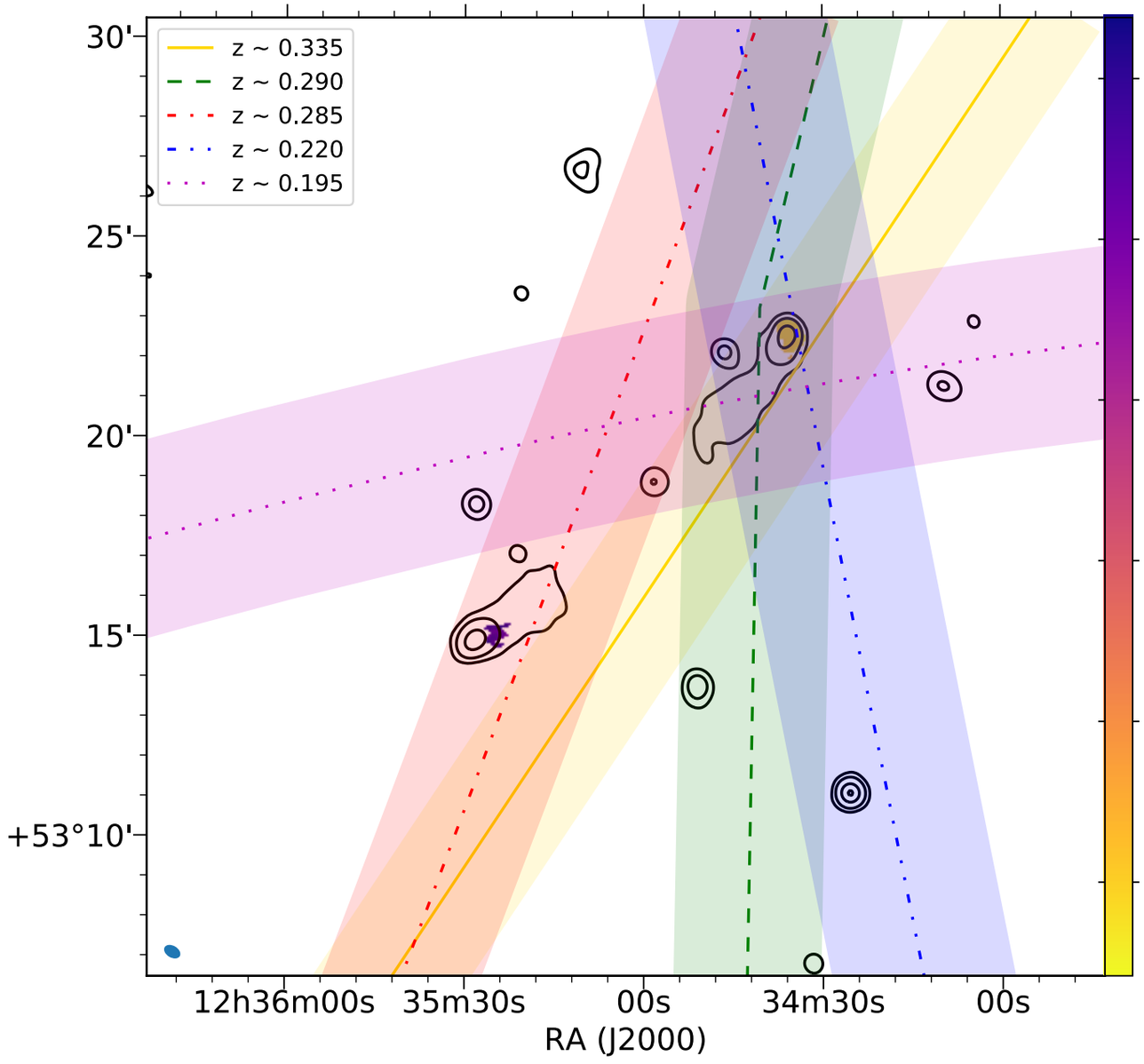
Higher than expected magnetic fields in clusters at high-z Di Gennaro + 2020



Complex particle acceleration in clusters - Brienza+ 2021

Beyond galaxy clusters

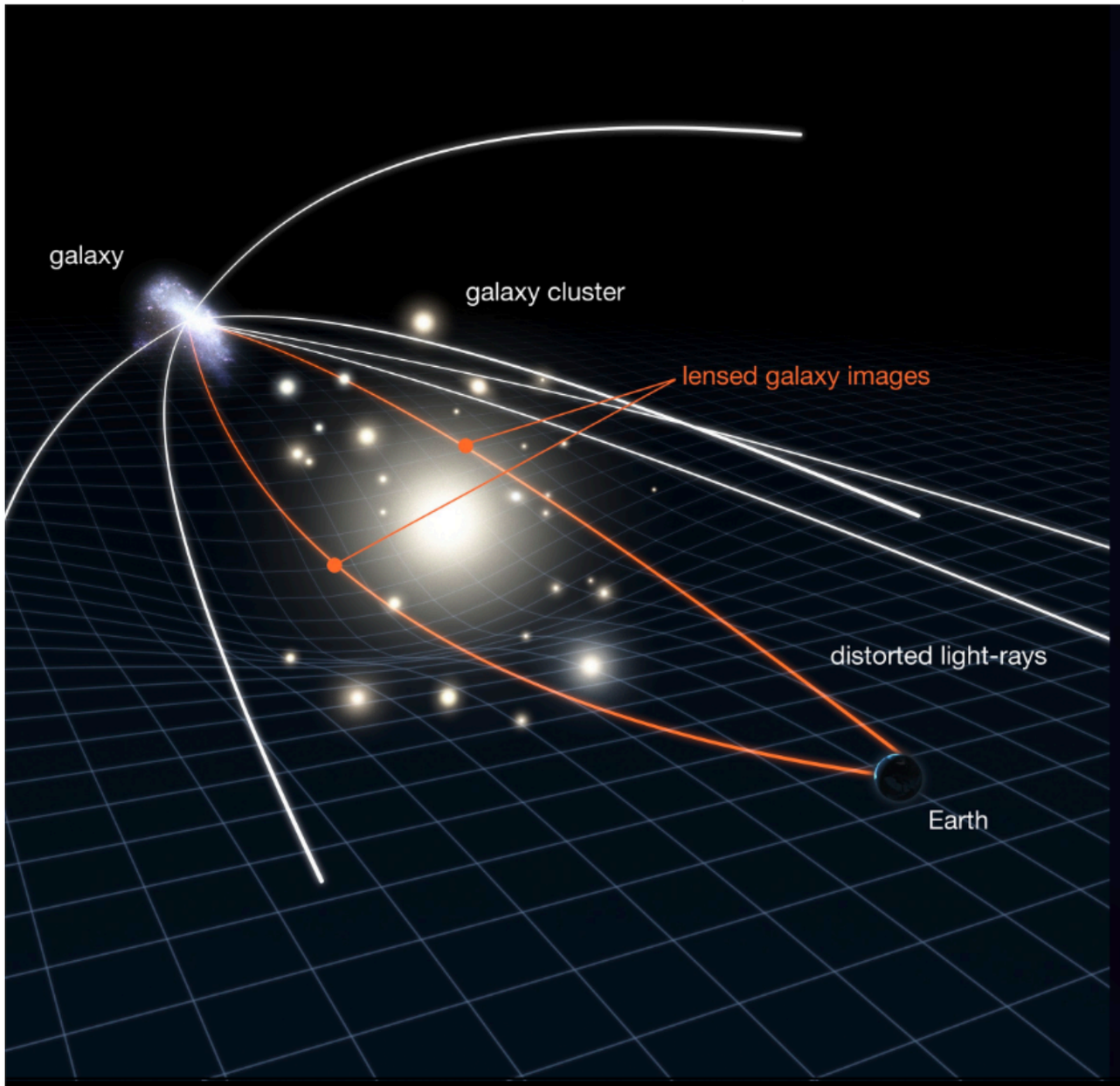


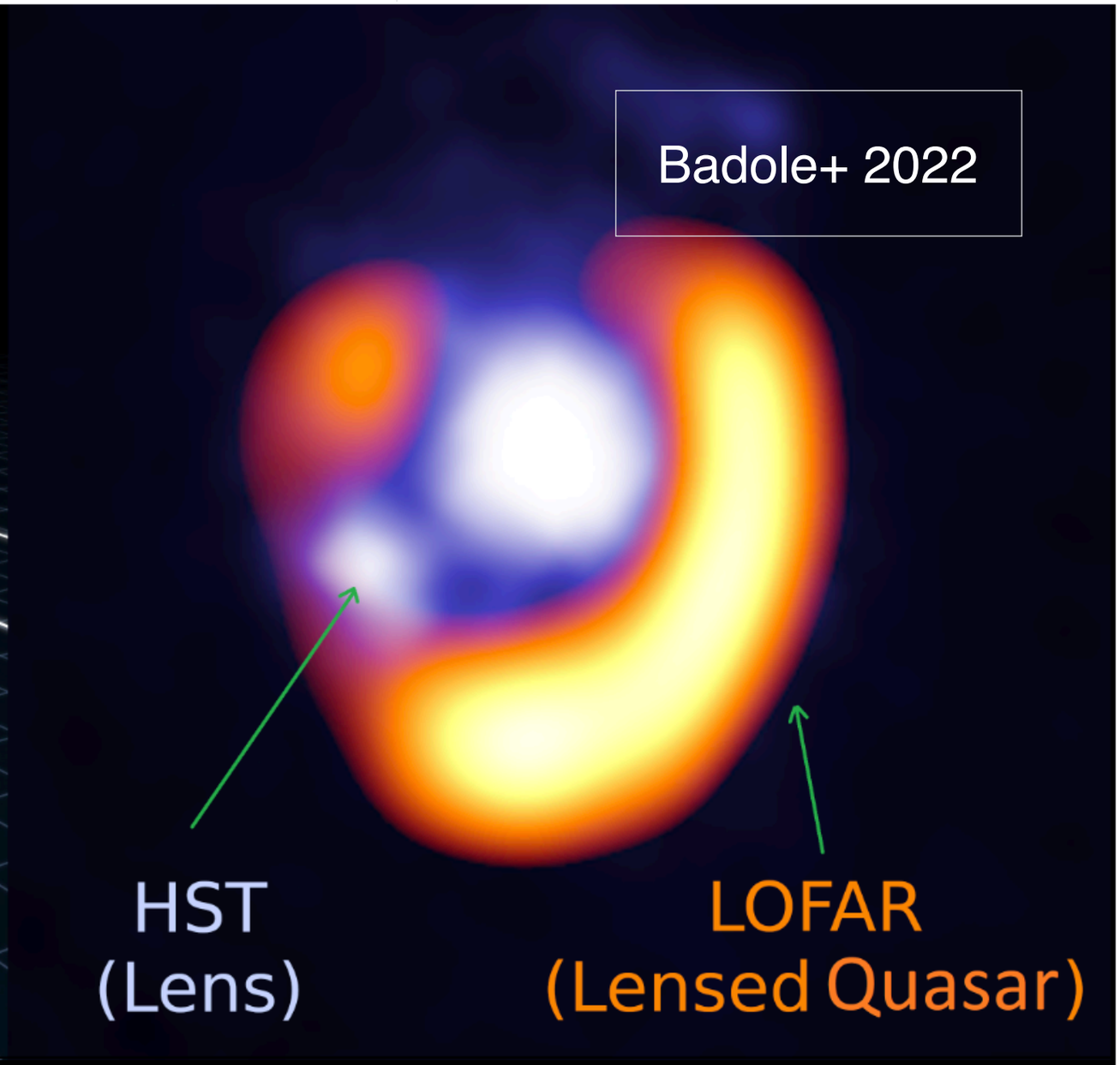


Detecting emission in filaments between clusters (e.g. Govoni+ 2019)

Probing the intergalactic magnetic field with faraday rotation measurements of a gaint radio galaxy - O' Sullivan+ 2019.

Gravitational lensing

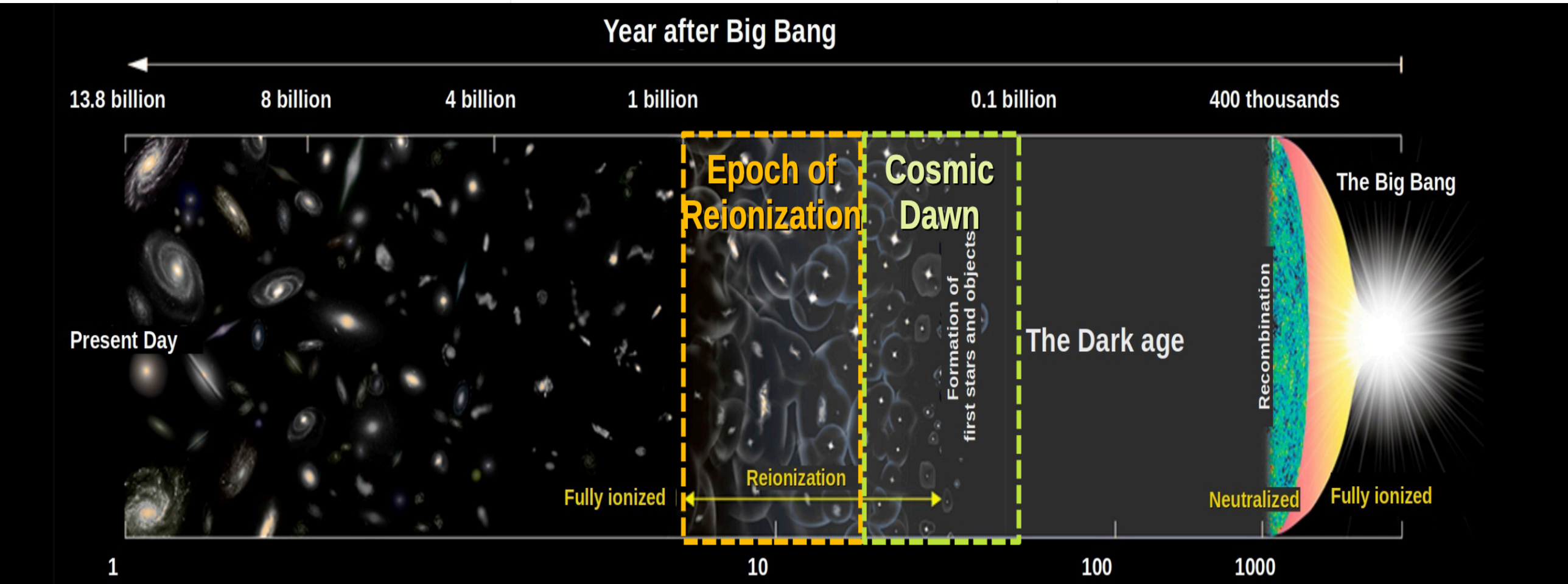




Left: Illustration of gravitational lensing (Image credit: NASA, ESA & L. Calcada). Right: LOFAR image of a lensed quasar, with the lensing galaxy as seen by the Hubble Space Telescope. Radio light from the quasar, emitted when the universe was only about 1/7th of its current age, is bent around the lensing galaxy, producing a spectacular arc.

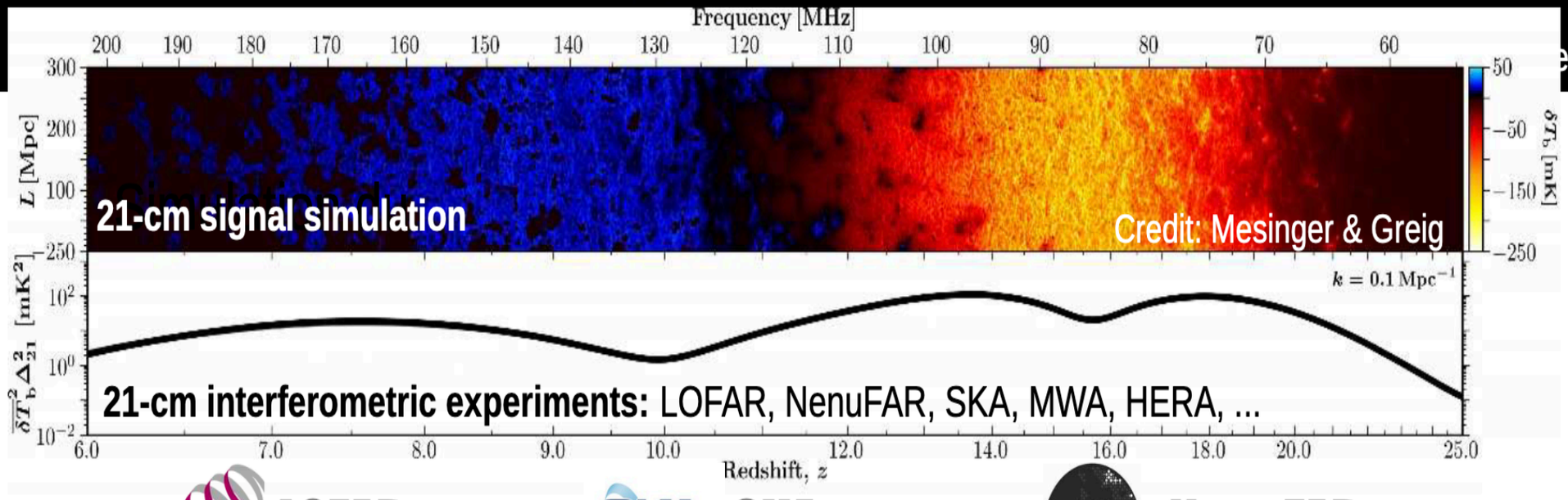
See also e.g. McKean+ 2021 – lensing allows for detection of incredibly faint objects as after correcting for the lensing magnifications can detect ~10 uJy sources.

Epoch of reionisation



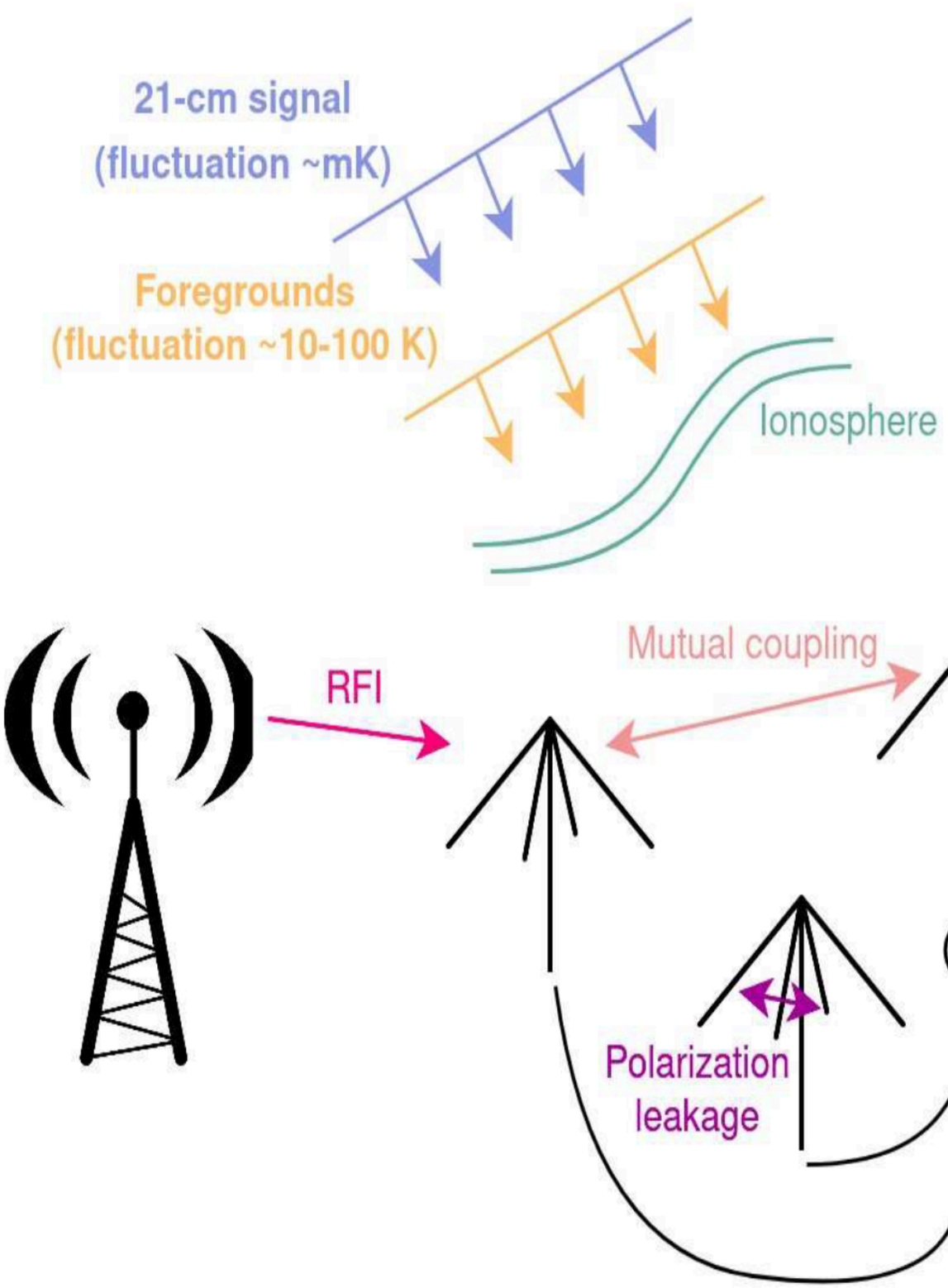
edit: NAOJ

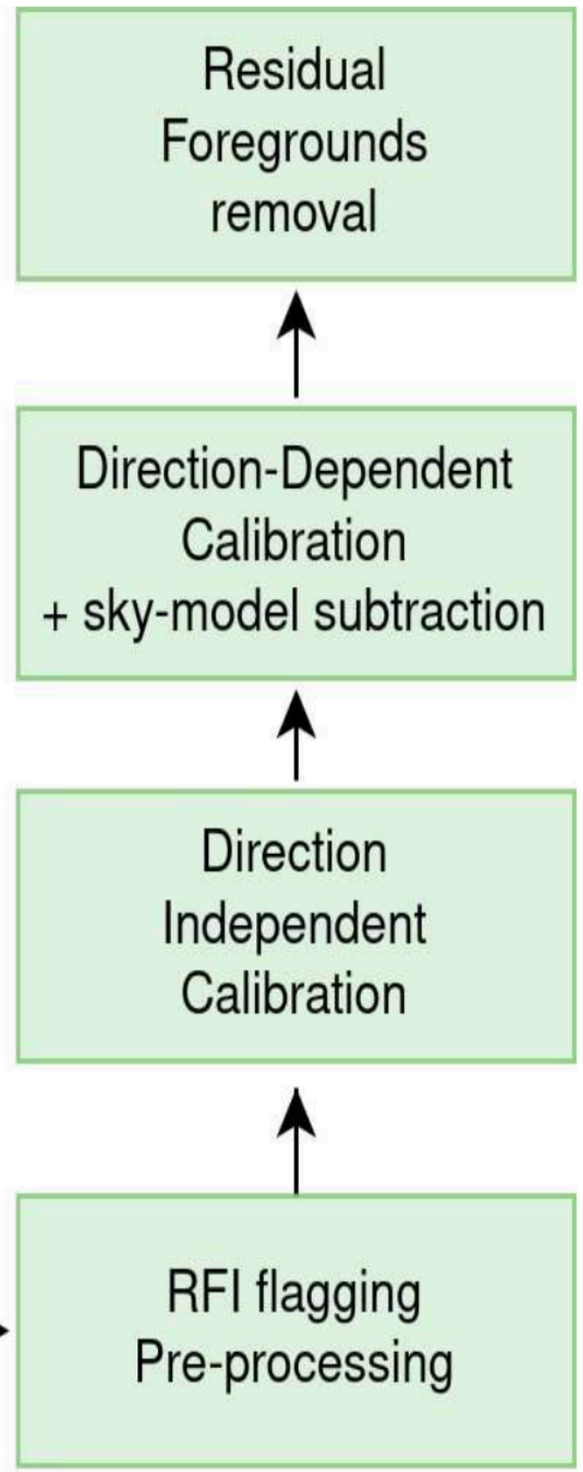
The observation of the **21-cm HI line**, an exceptional probe of the **first Gyr** of our Universe



LOFAR SKA NenuFAR

Epoch of reionisation



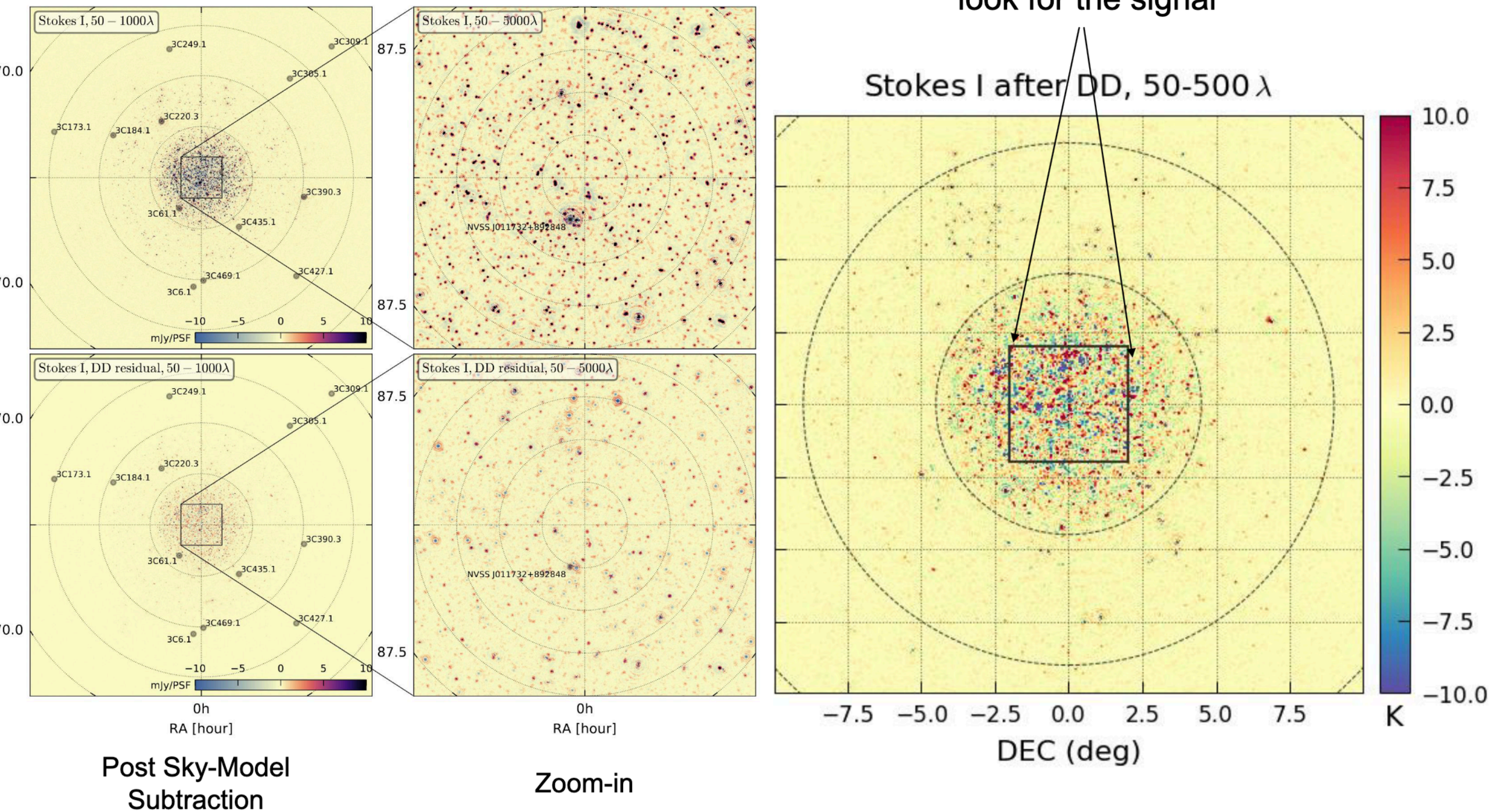


Epoch of reionisation

Wide-field Image

Zoom-in

Inner 4x4 where we look for the signal

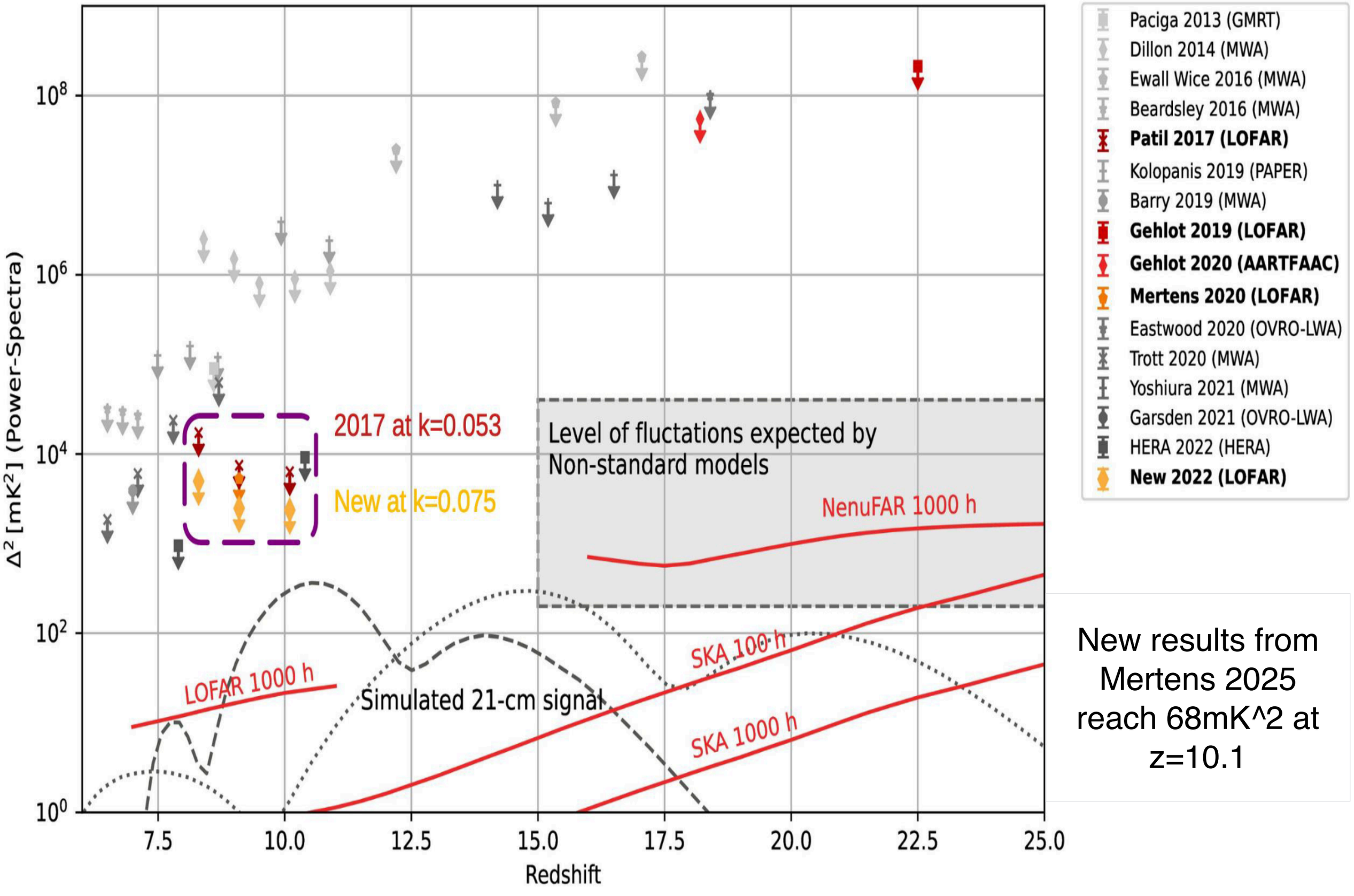


Post Sky-Model Subtraction

Zoom-in

Mertens et al. 2020

Epoch of reionisation



New results from Mertens 2025 reach 68mK^2 at z=10.1

Upcoming developments



WEAVE-LOFAR Survey

Science Team Lead: Dan Smith, U.Herts (Deputy: Ken Duncan, U.Edin)

Optical follow-up **~1 million LOFAR** radio selected targets over three tiers

Spectra provide:

Spectroscopic redshifts
(with ~100% completeness to z~1)

Source classifications
(SF vs AGN, accretion mode etc.)

Kinematic and chemical information
(e.g. outflows)

Wide range of science goals:
Cosmic star-formation and accretion histories, physics of AGN feedback, cosmology studies, …

WIDE
(6,500 SQ.DEG)

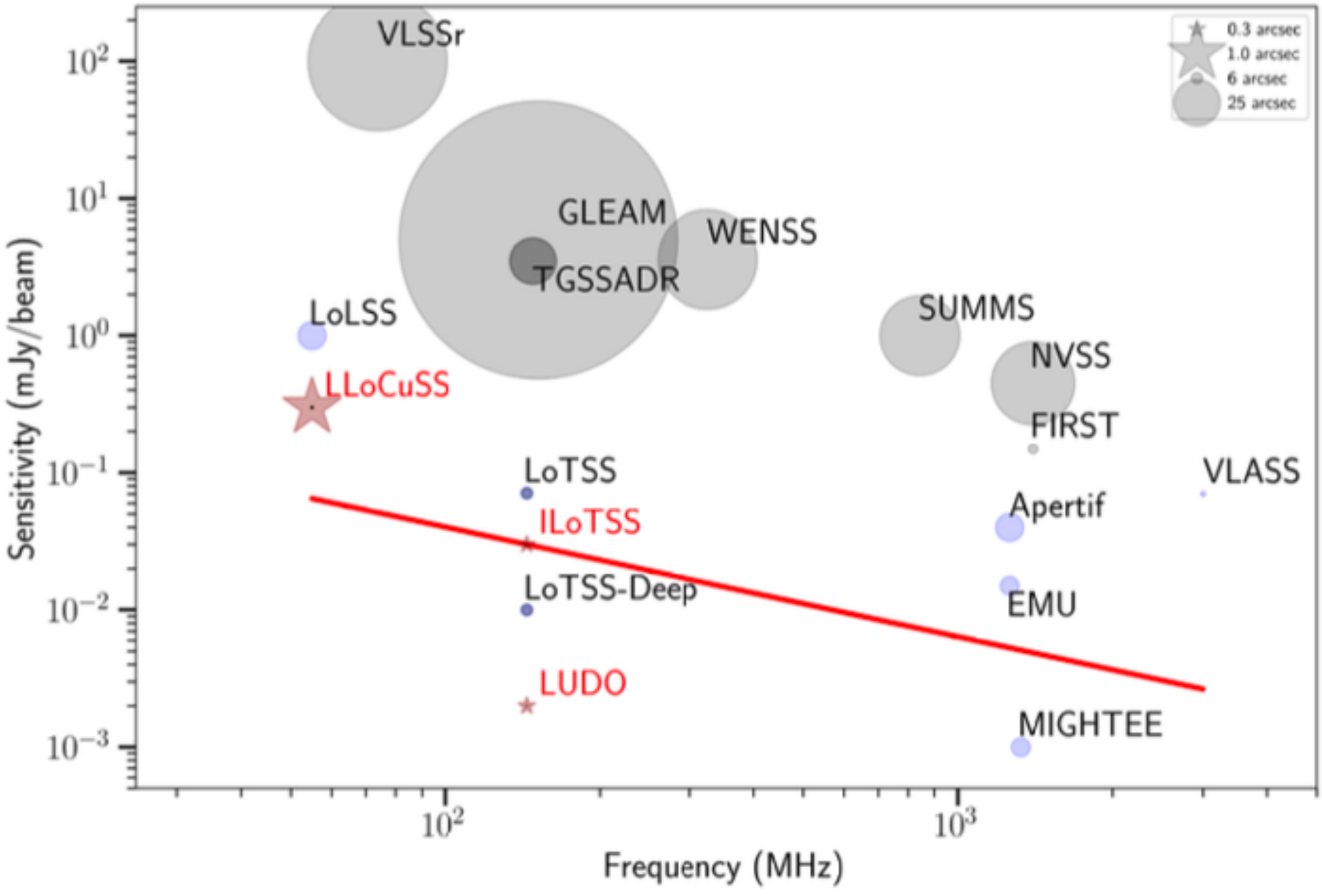
MID
(650-1000 SQ.DEG)

DEEP
(~50 SQ.DEG)

(Euclid Deep Field North, ELAIS-N1, Lockman Hole, Boötes)

Some upcoming developments

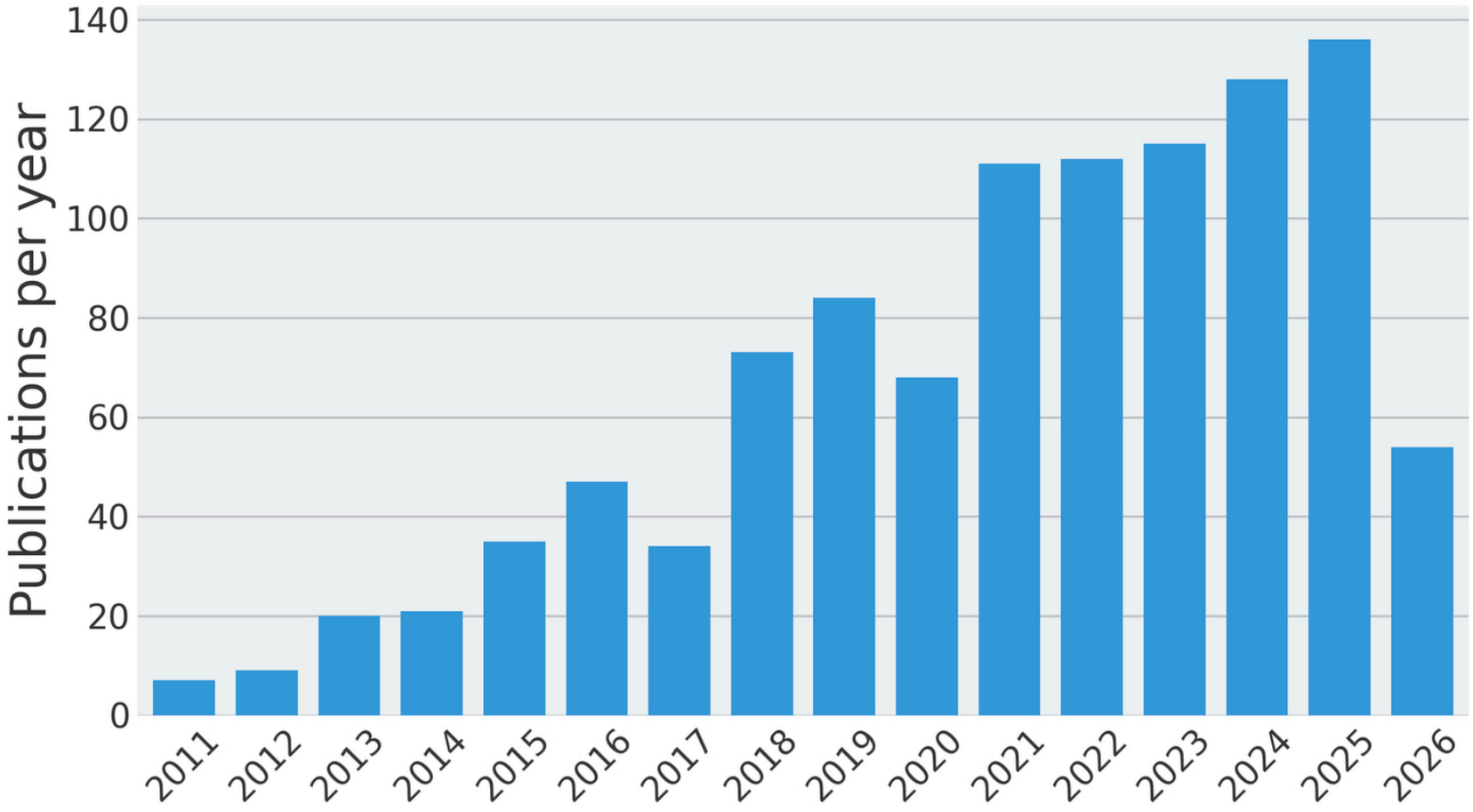
Many new possibilities with LOFAR2.0 to characterise e.g. transients, pulsars, stars, the sun and the extra galactic sky in far more detail than before.



Summary

LOFAR supports world-leading science in many different areas (and growing) and can likely support your science.

After a major upgrade LOFAR will be coming back soon as an even better instrument (better LBA sensitivity, faster observing, better calibrated stations and more)



LOFAR output (1054 publications) is in the top 10% of all astronomy facilities.