ASTRON

Netherlands Institute for Radio Astronomy

LOFAR Science

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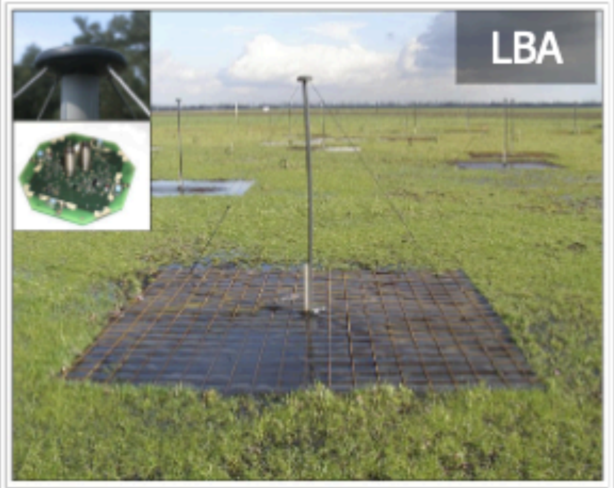
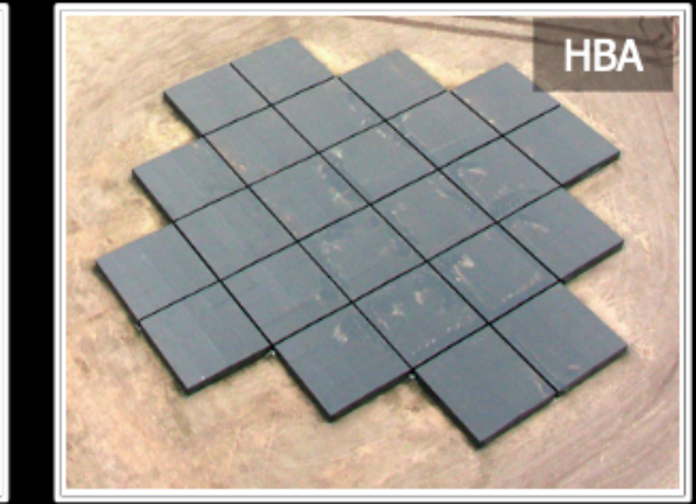
(ASTRON and Leiden University

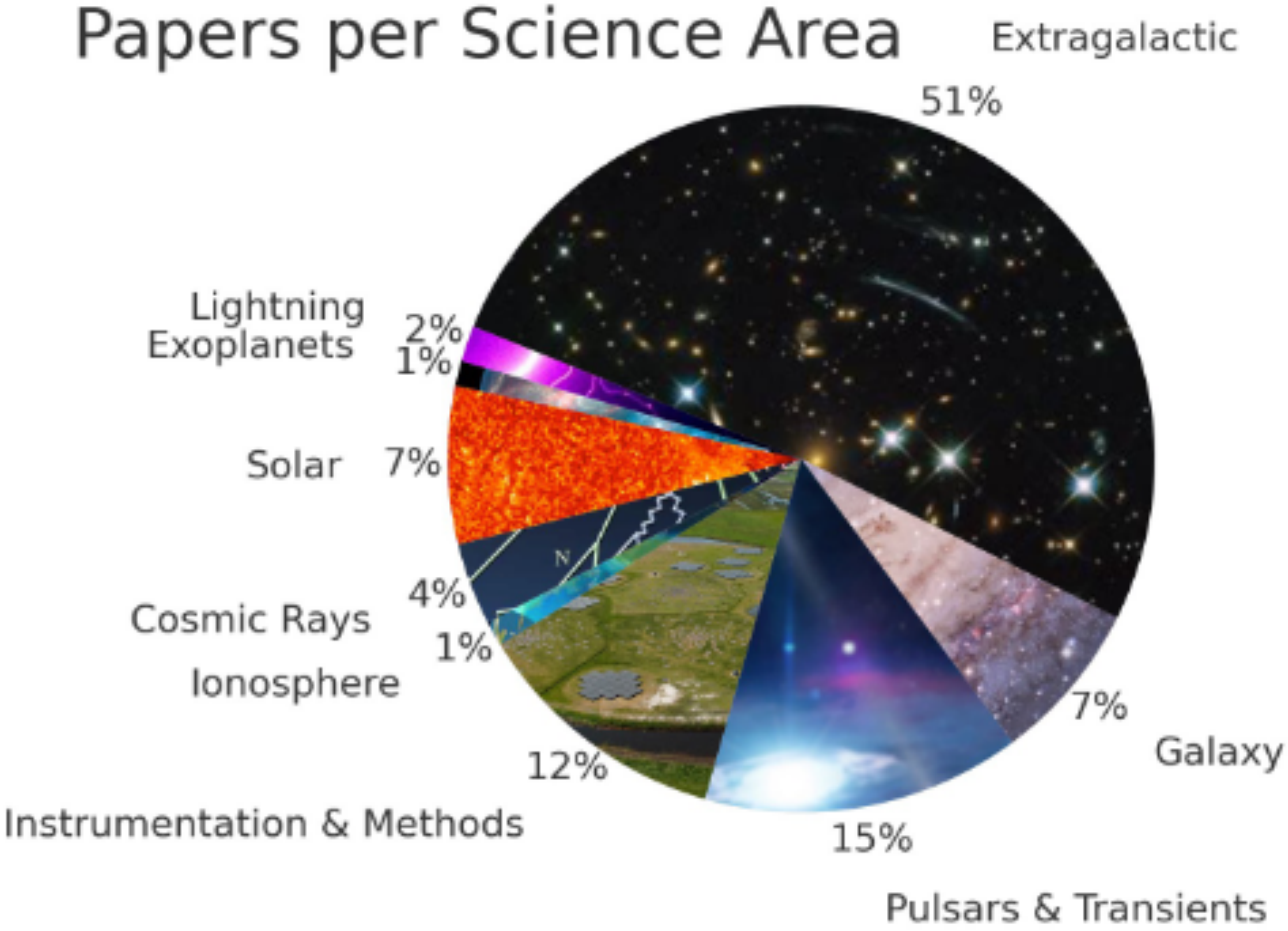
LOFAR: KEY FACTS

- Array of 51 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

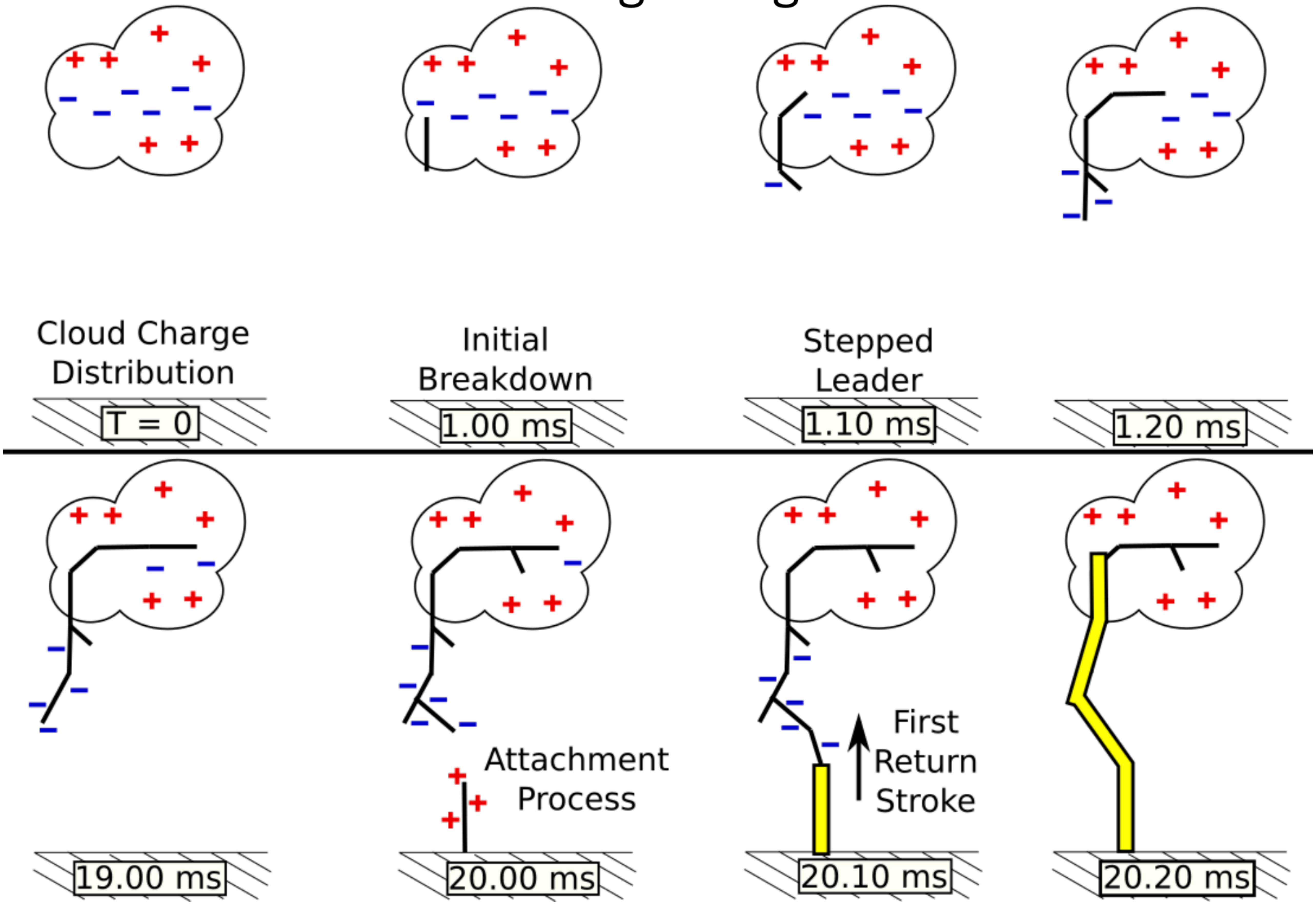




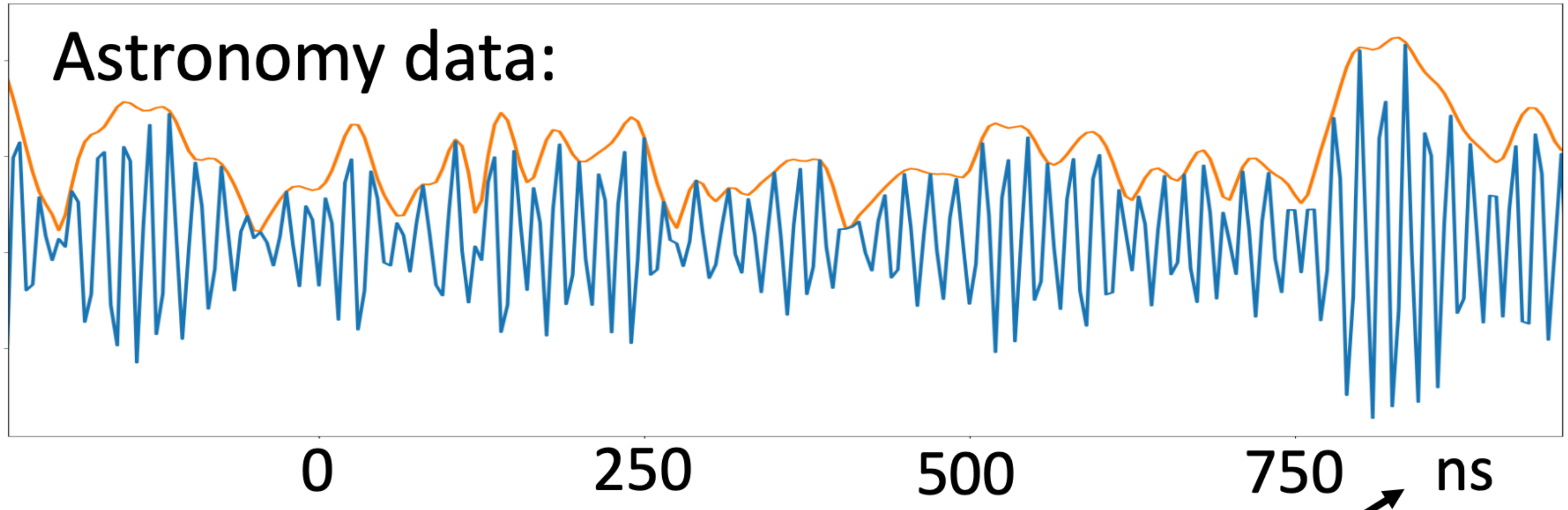
Papers per Science Area



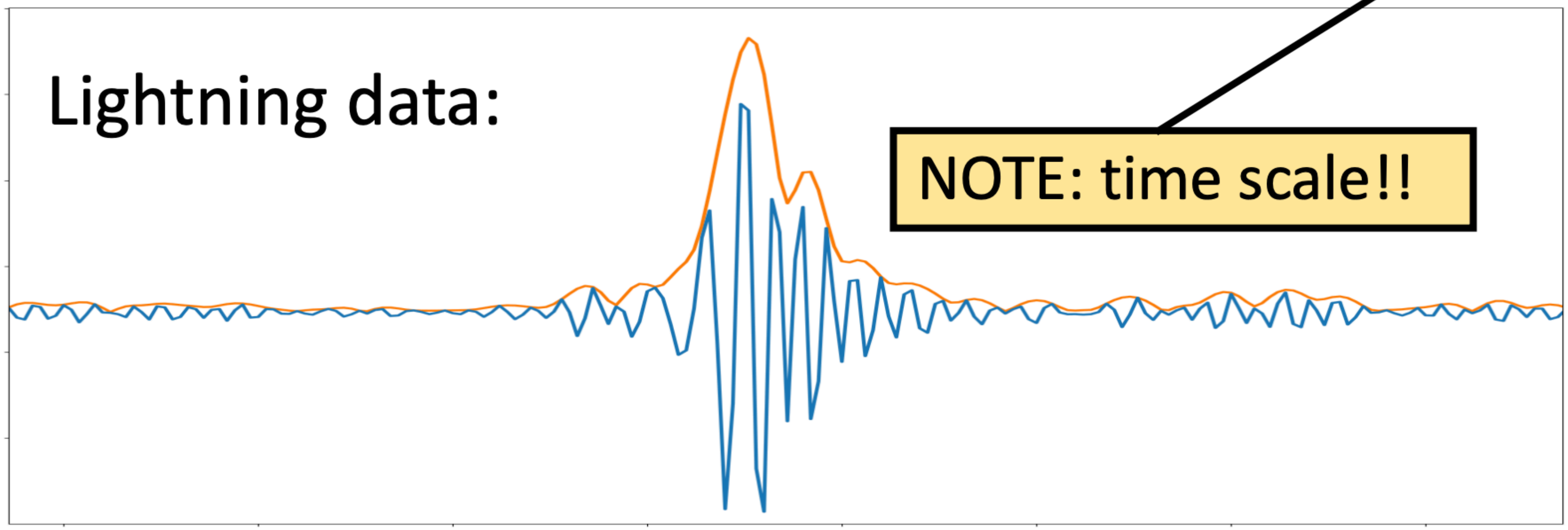
The Basic Lightning Processes



Lightning vs Astronomy Transient Buffer Data (raw voltages)


Astronomy data:

- Looks like noise
- Need Beamforming


Lightning data:

NOTE: time scale!!

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

Lightning

Hare+ 2023

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

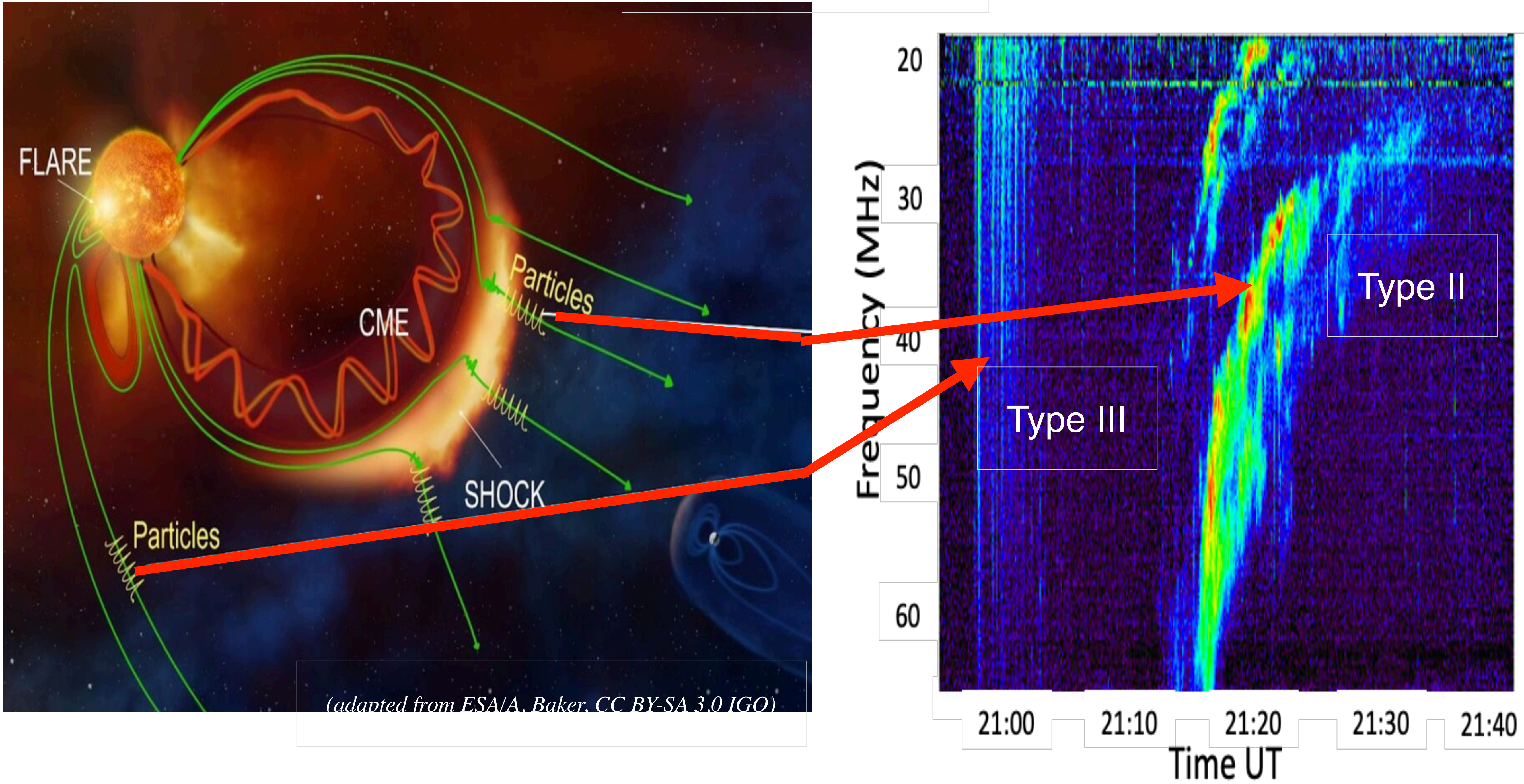
The Big Questions in Lightning

- 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



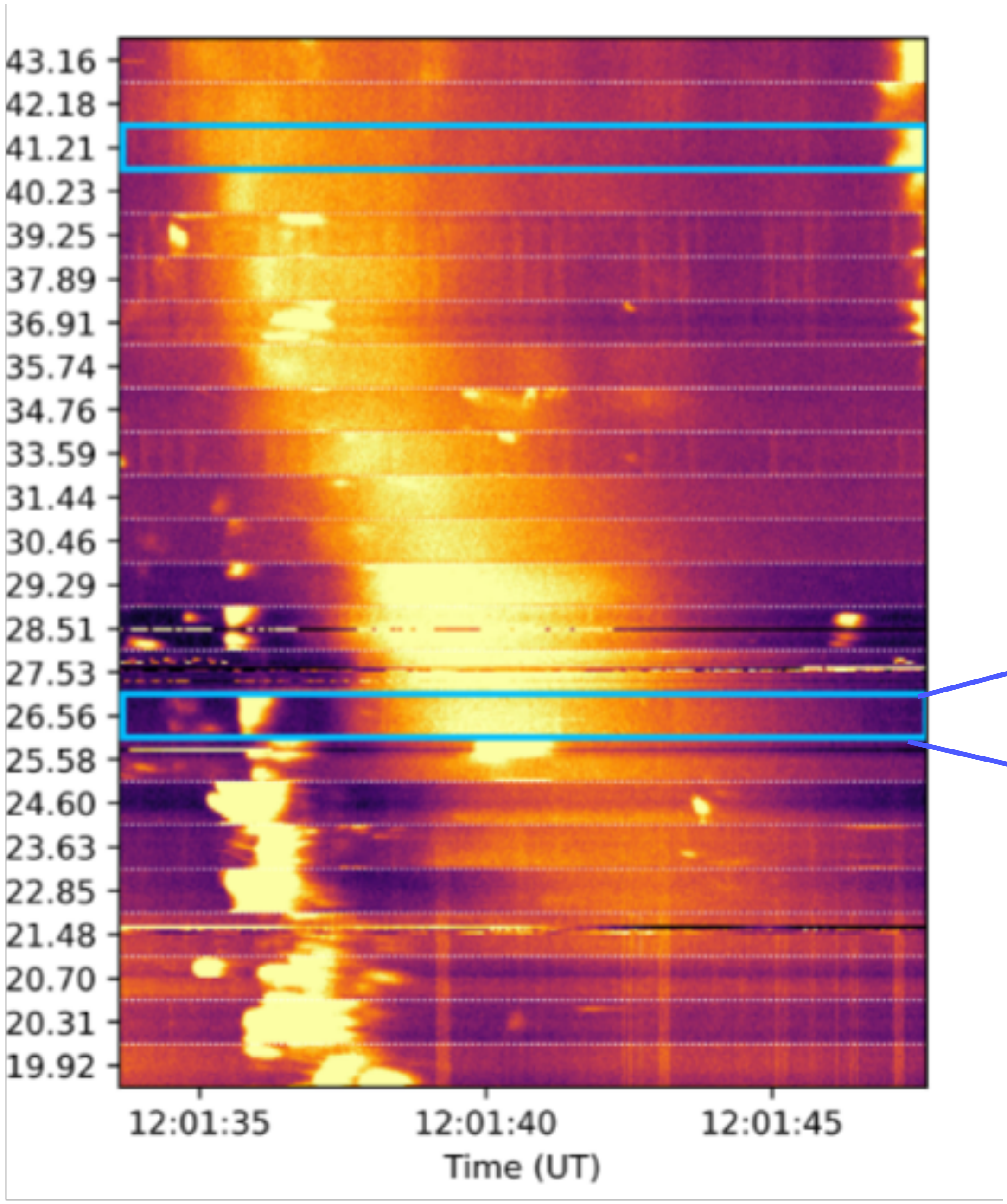
(adapted from ESA/A. Baker, CC BY-SA 3.0 IGO)

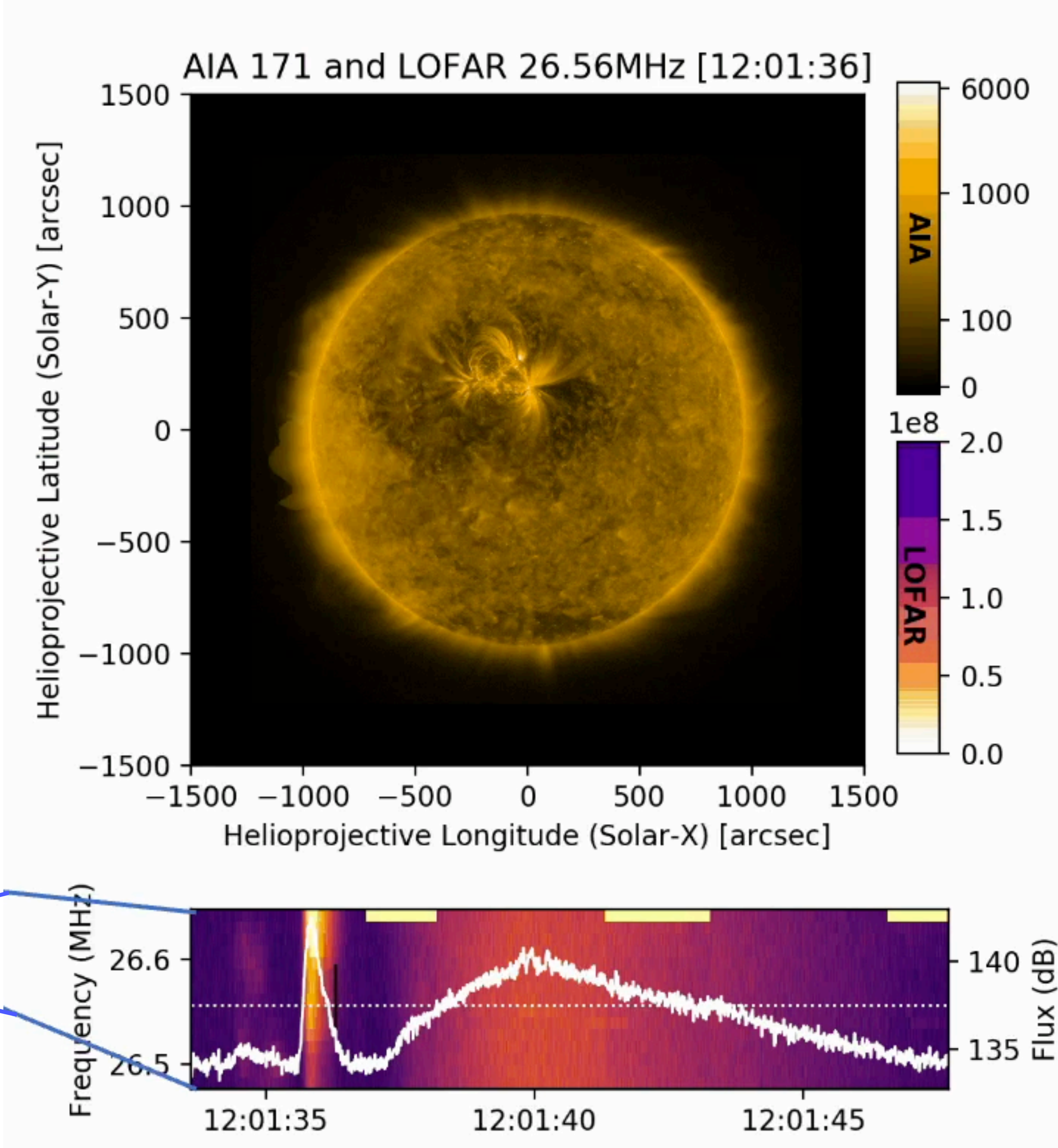
Type II bursts are plasma emission associated with corona mass ejections

Type III are energetic electrons associated with flares

Solar physics

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

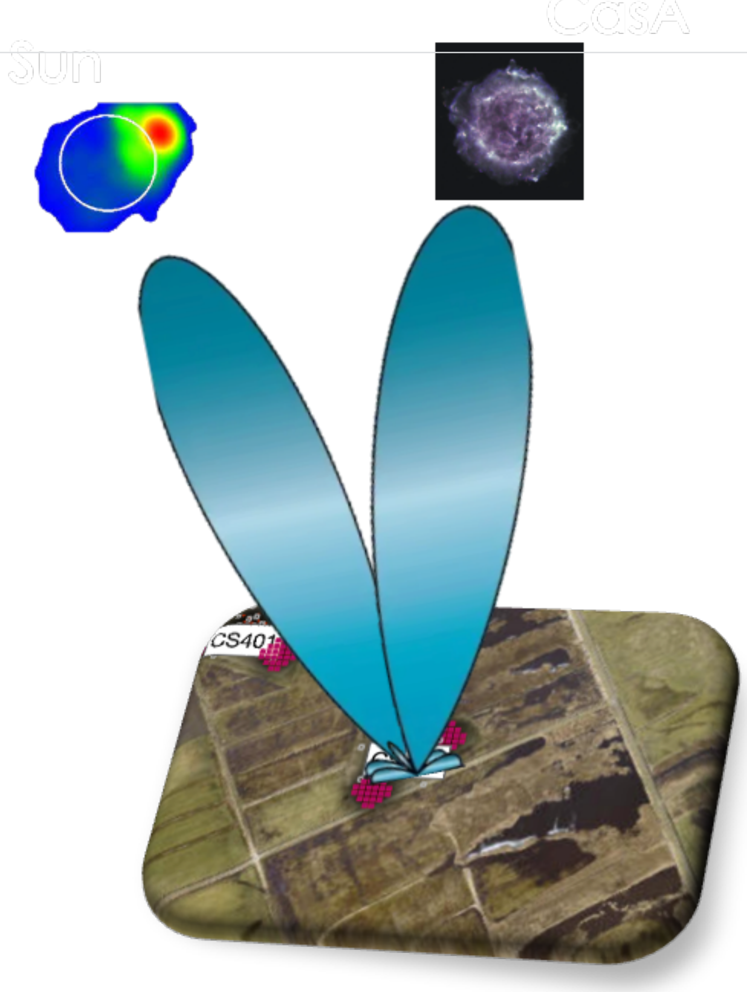


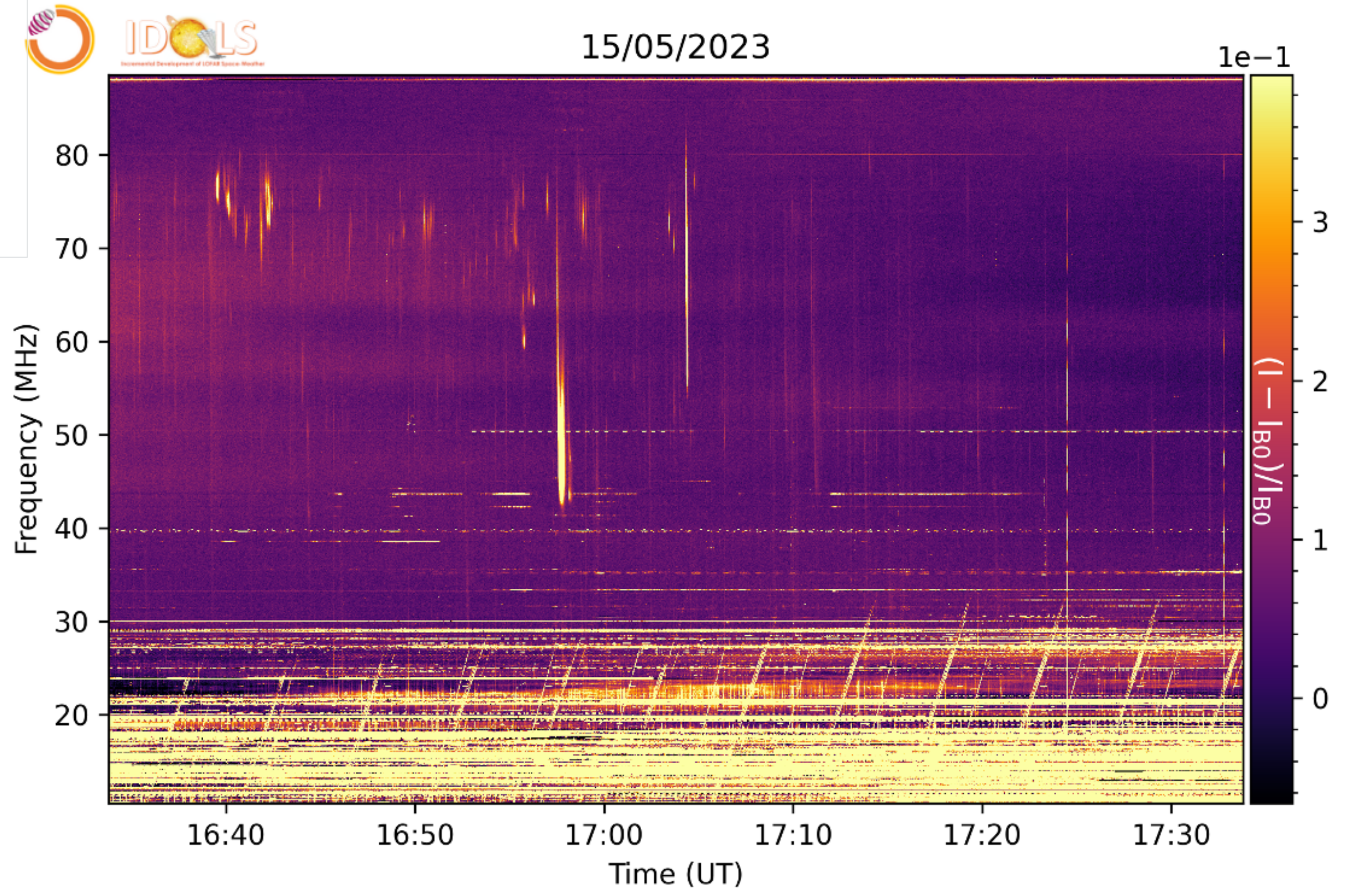


Zhang, Zucca, Sridhar, Wang and al. A&A 2020

Incremental Development of LOFAR Space Weather (IDOLS)

A LOFAR station has been dedicated to continuously monitor the Sun and the Ionosphere for the past 2 years



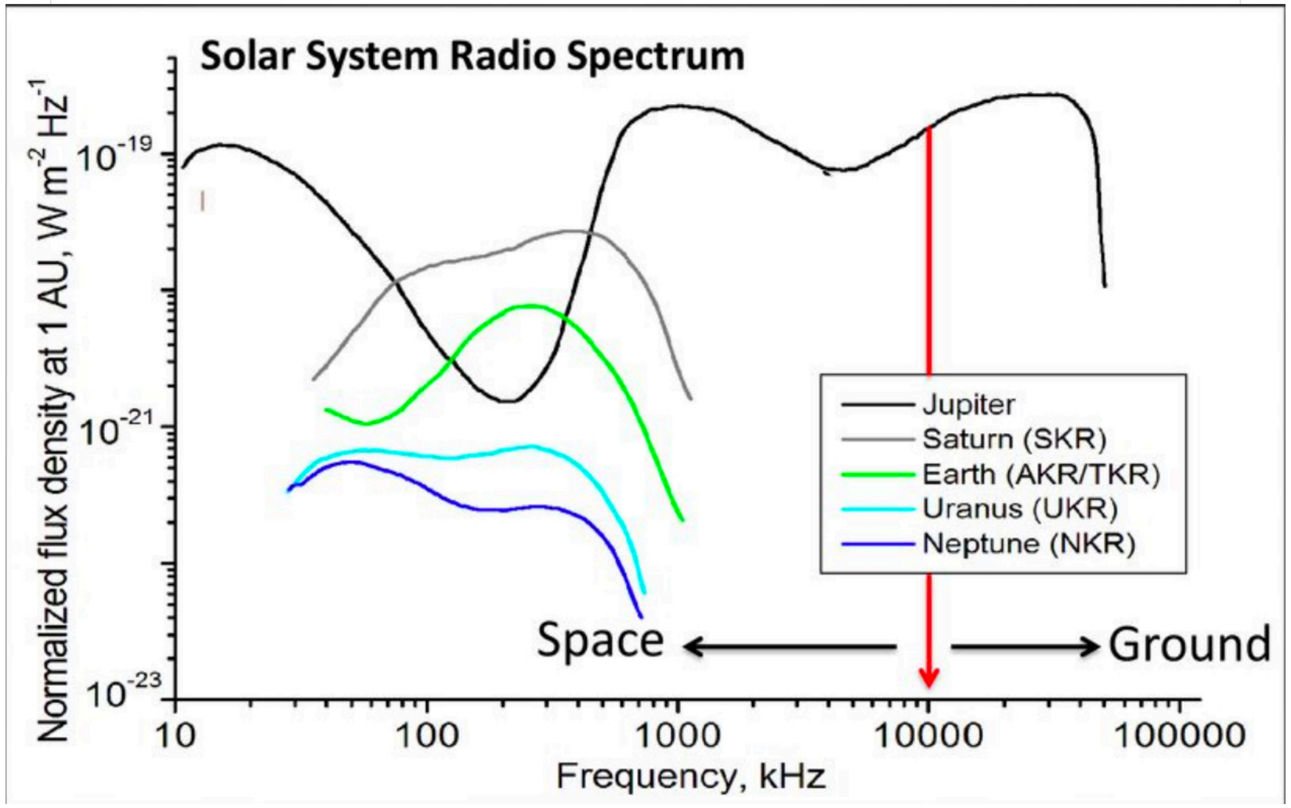


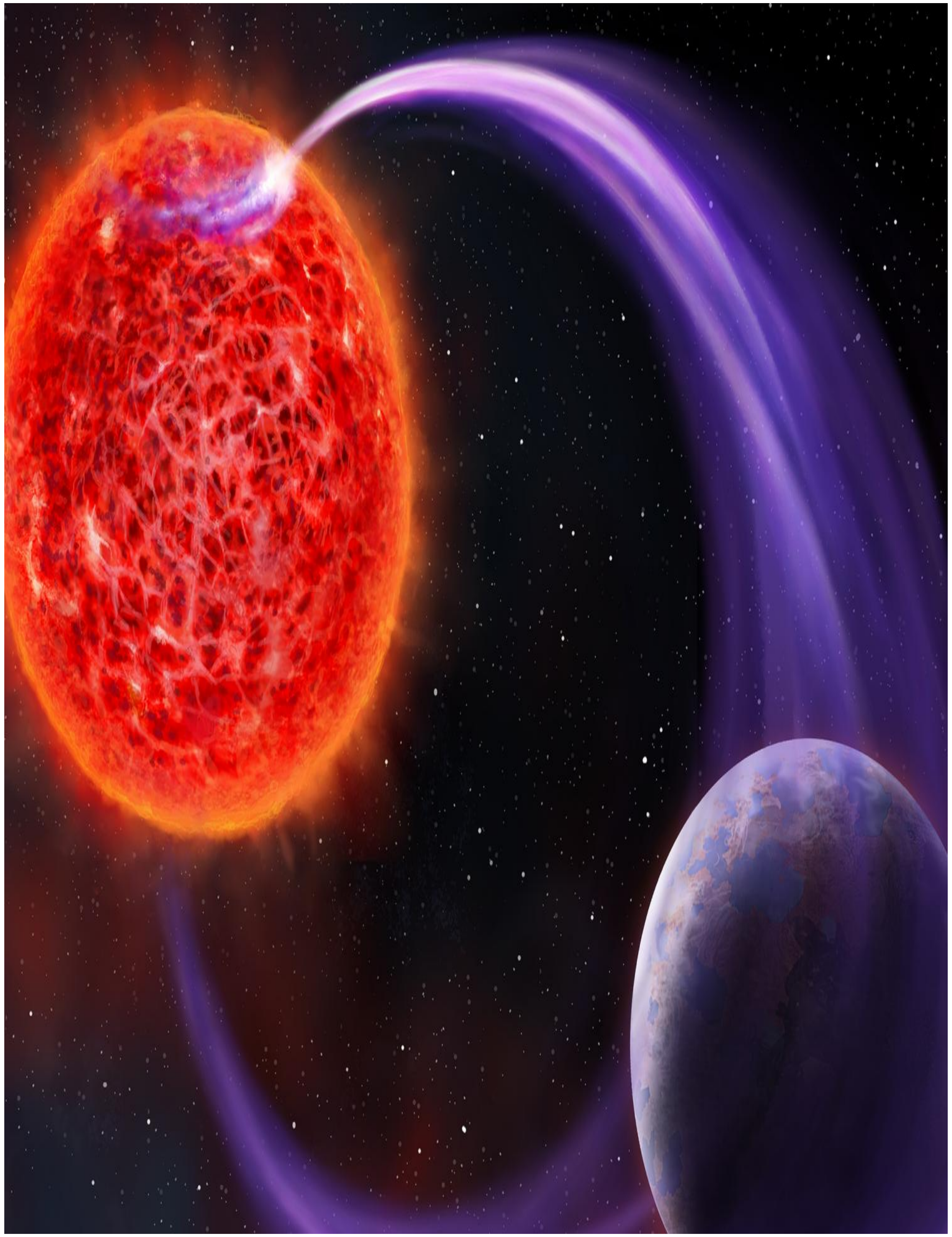
https://spaceweather.astron.nl/SolarKSP/data/website/

Stars/planets

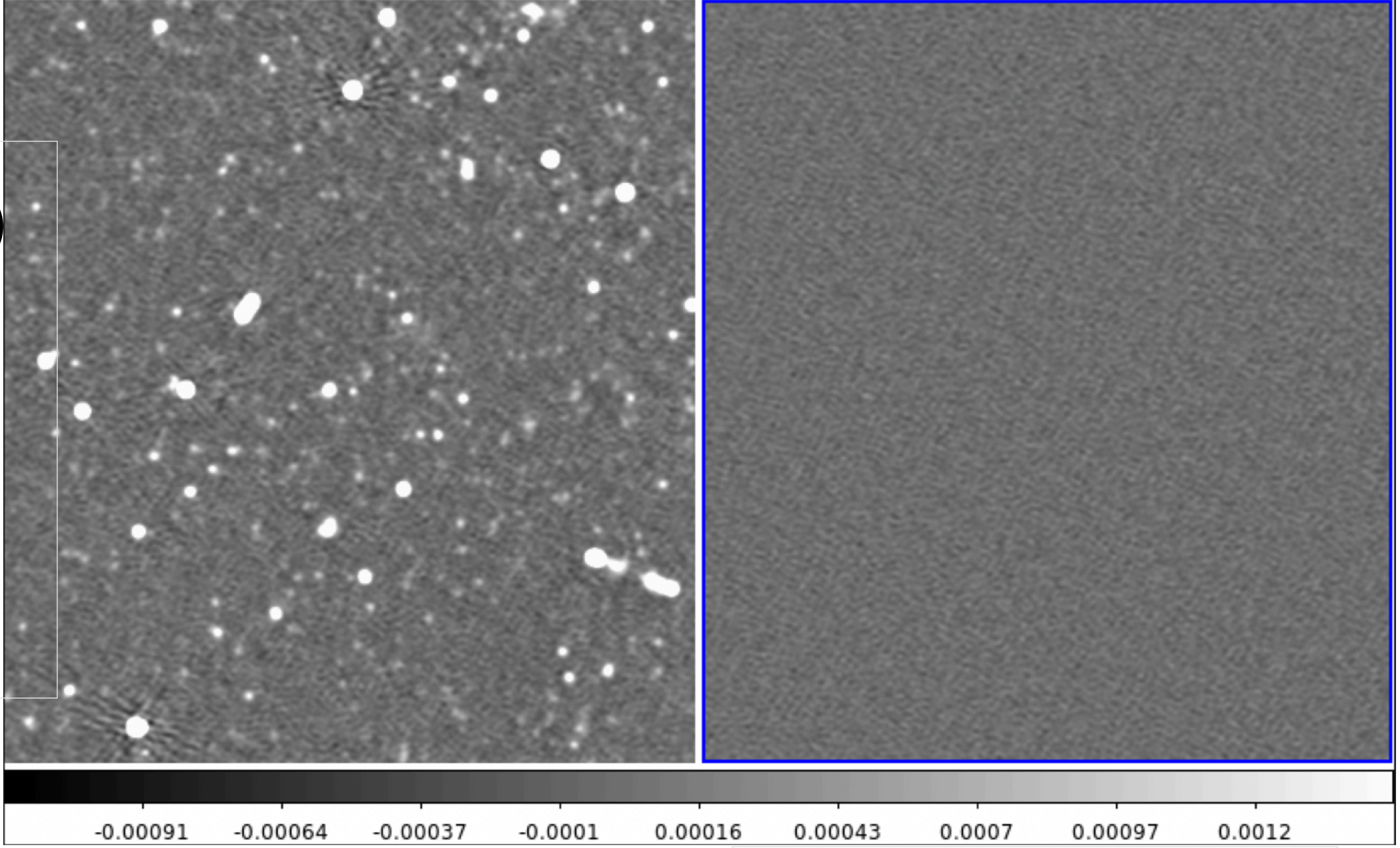
Time variable circular polarisation fraction >10% at LOFAR HBA frequencies expected for:

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

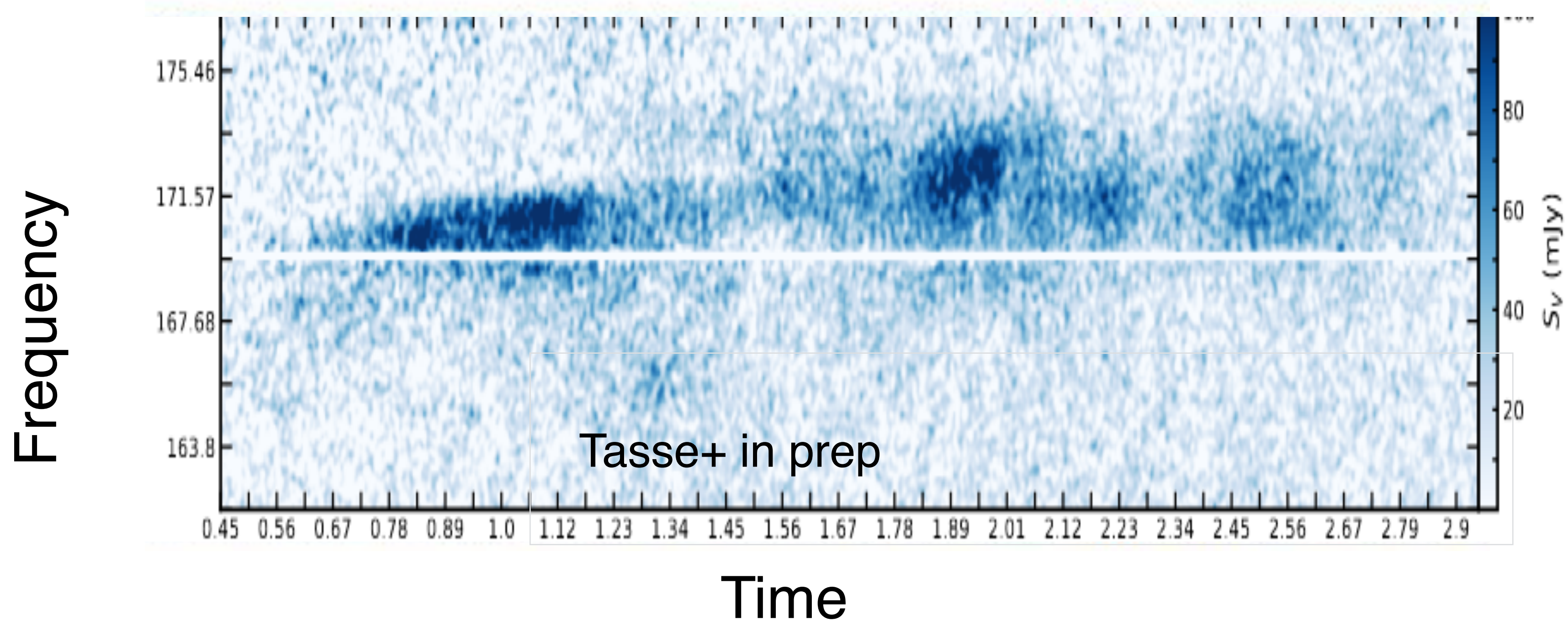




Leakage from I (left) to V (right) in HBA imaging only 0.06% allowing discovery of faint circularly polarised signals.



Dynamic spectra

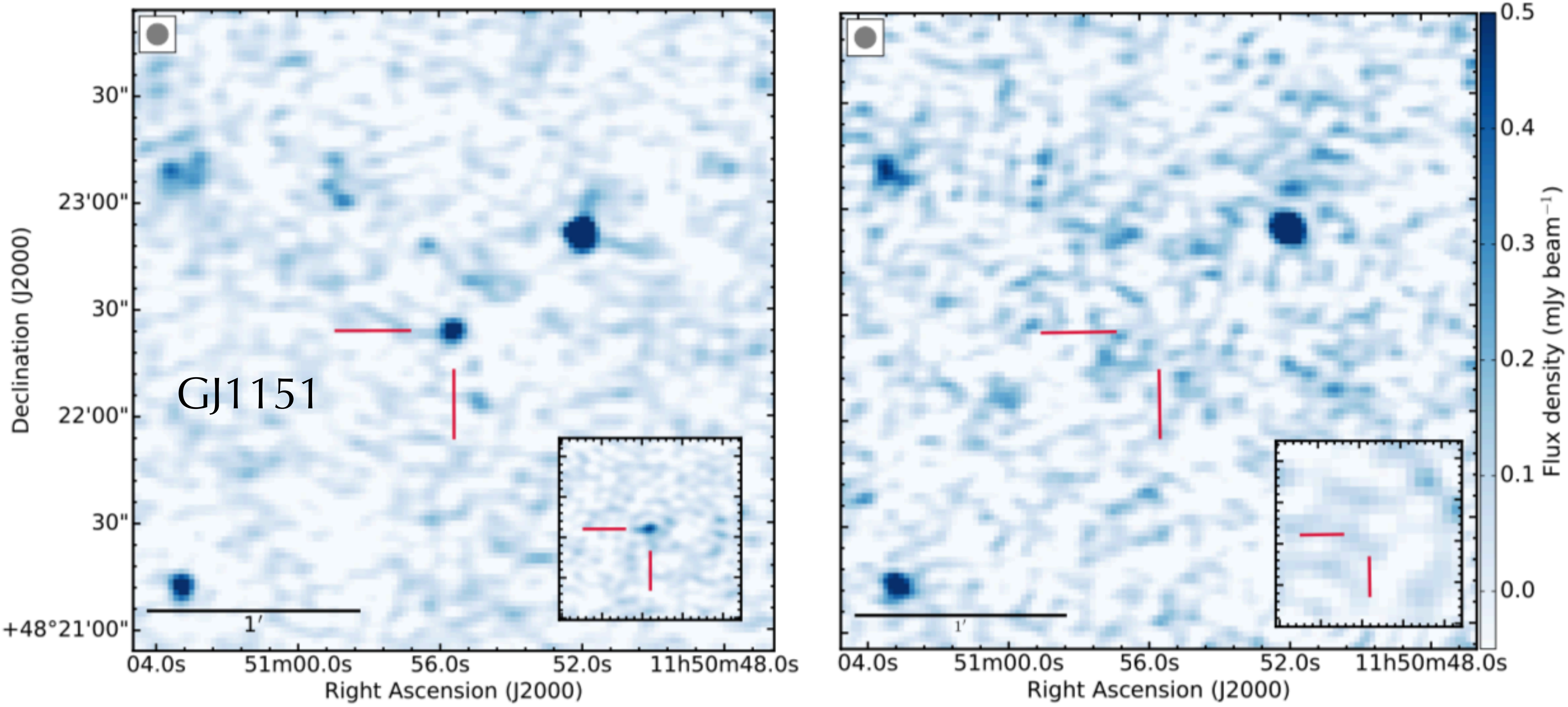


Tasse+ in prep

Ability to rapidly study time and frequency dependence of target sources

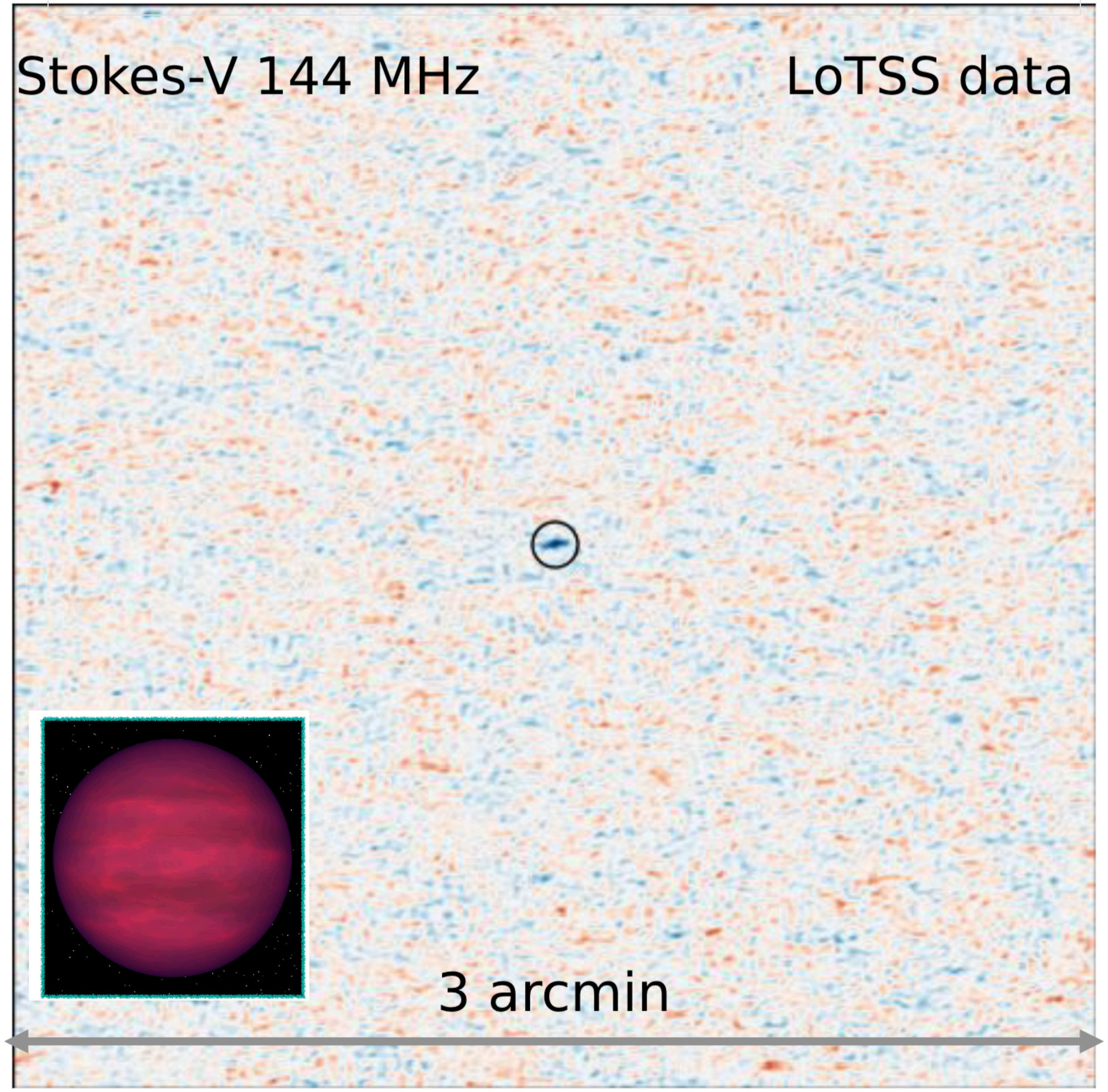
Analysis of LoTSS-DR2 led to ~40 stars and 2 brown dwarfs (Callingham+ 2021) including:

First quiescent star



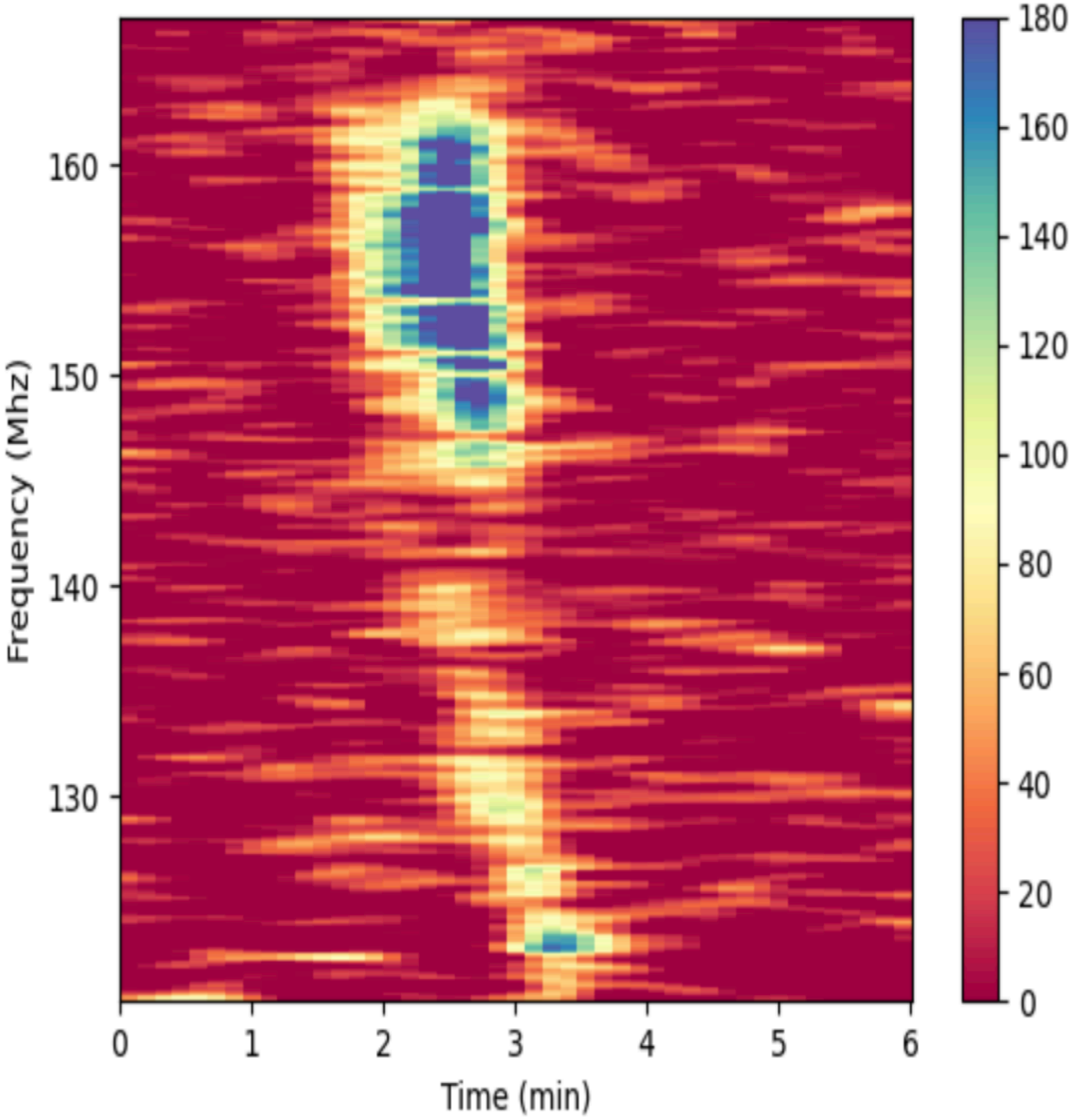
Vedantham++ 2020

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



Vedantham+ 2020

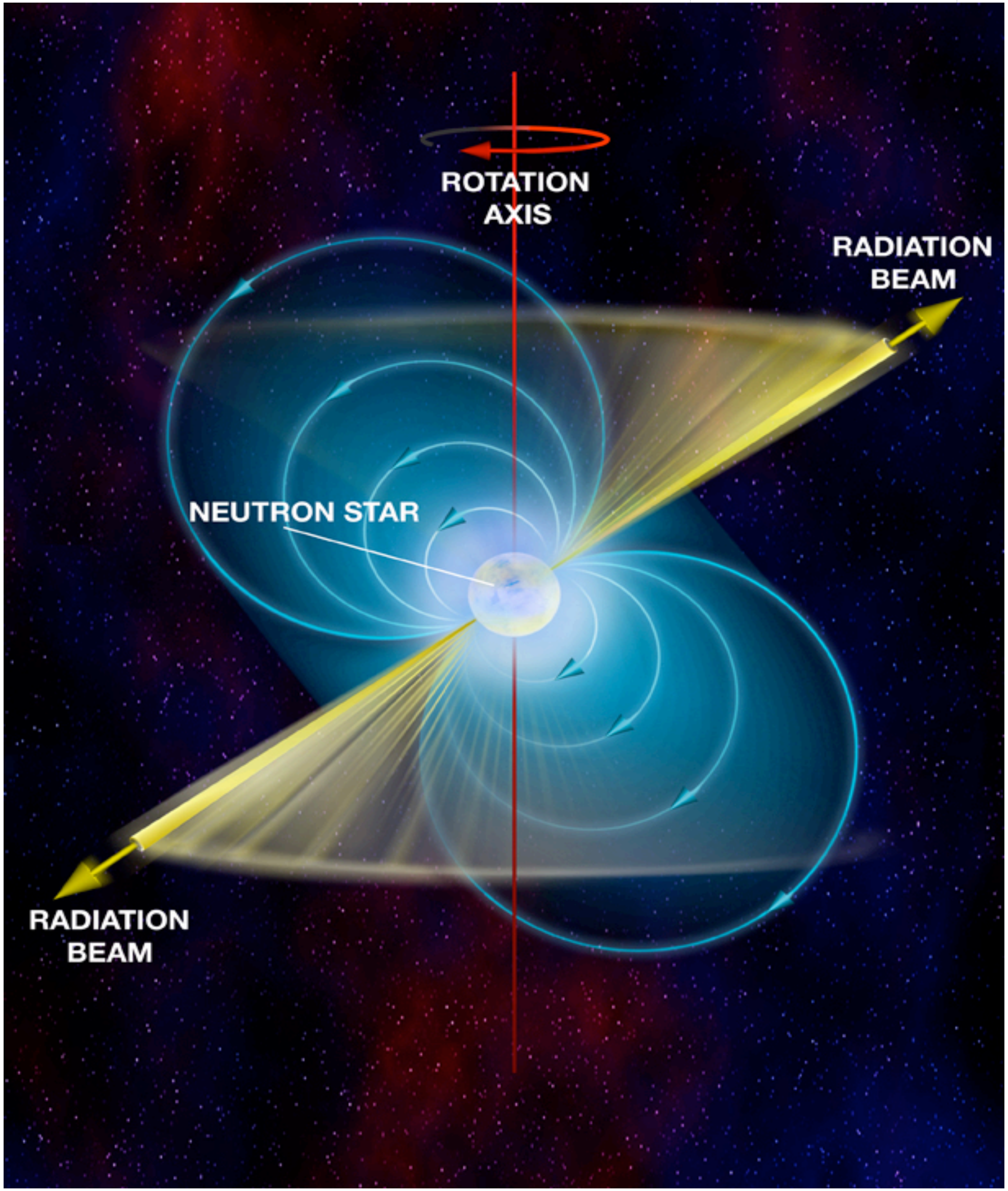
First Type II burst on another star



Keers et al. in prep

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

Pulsars

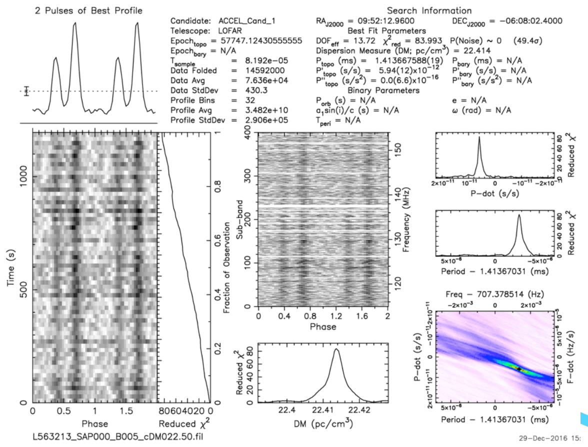


Pulsars are natural laboratories to study...

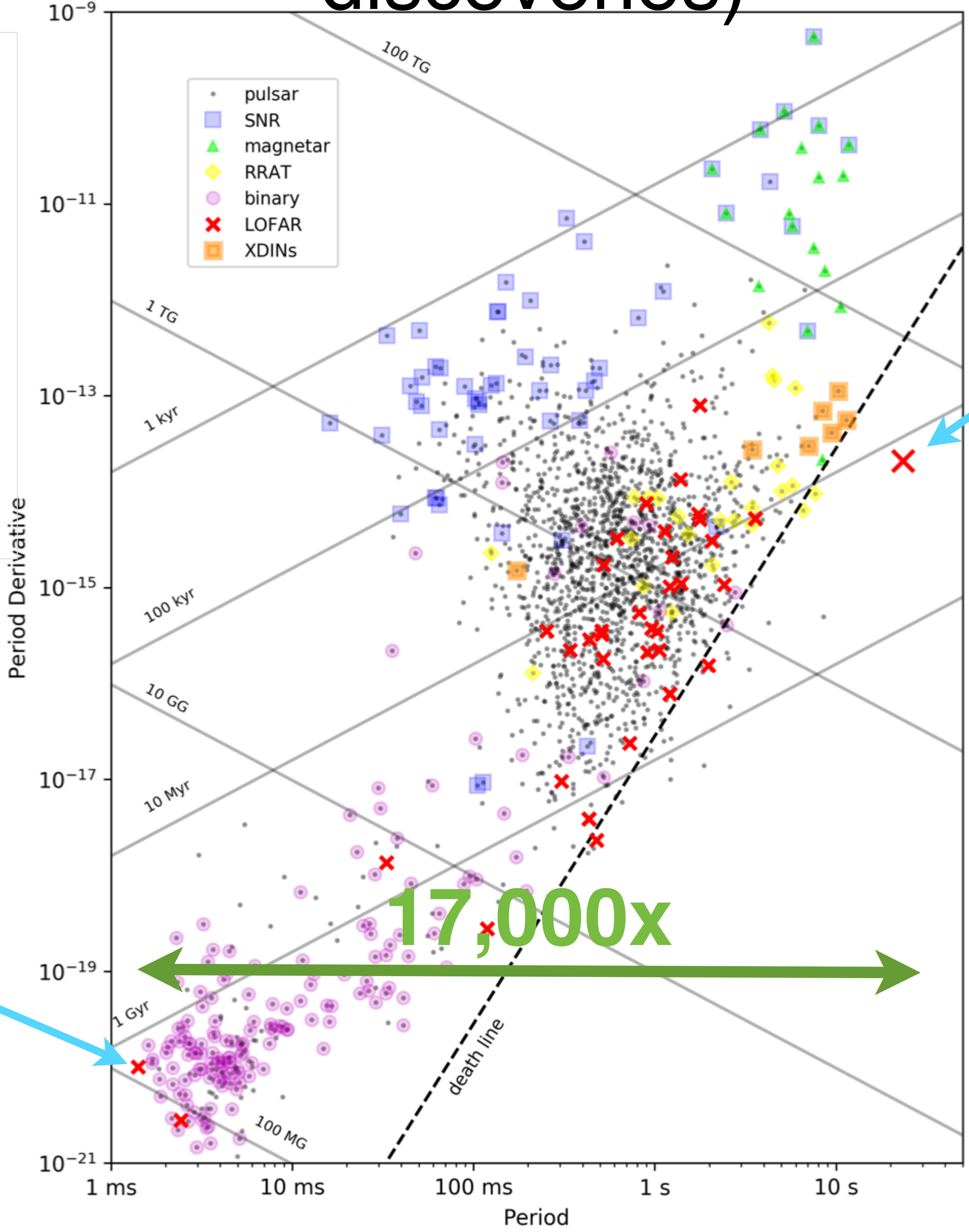
- **Gravity**
- **Particle physics**
- **Stellar evolution**
- **Interstellar medium**
- **Accretion**

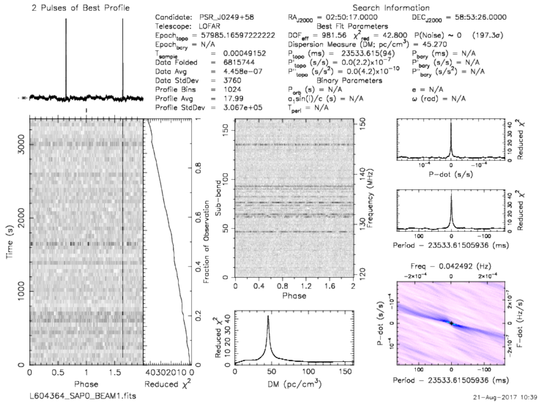
LOFAR has detected >300 pulsars so far (including ~8 discoveries)

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



707Hz
1.41ms



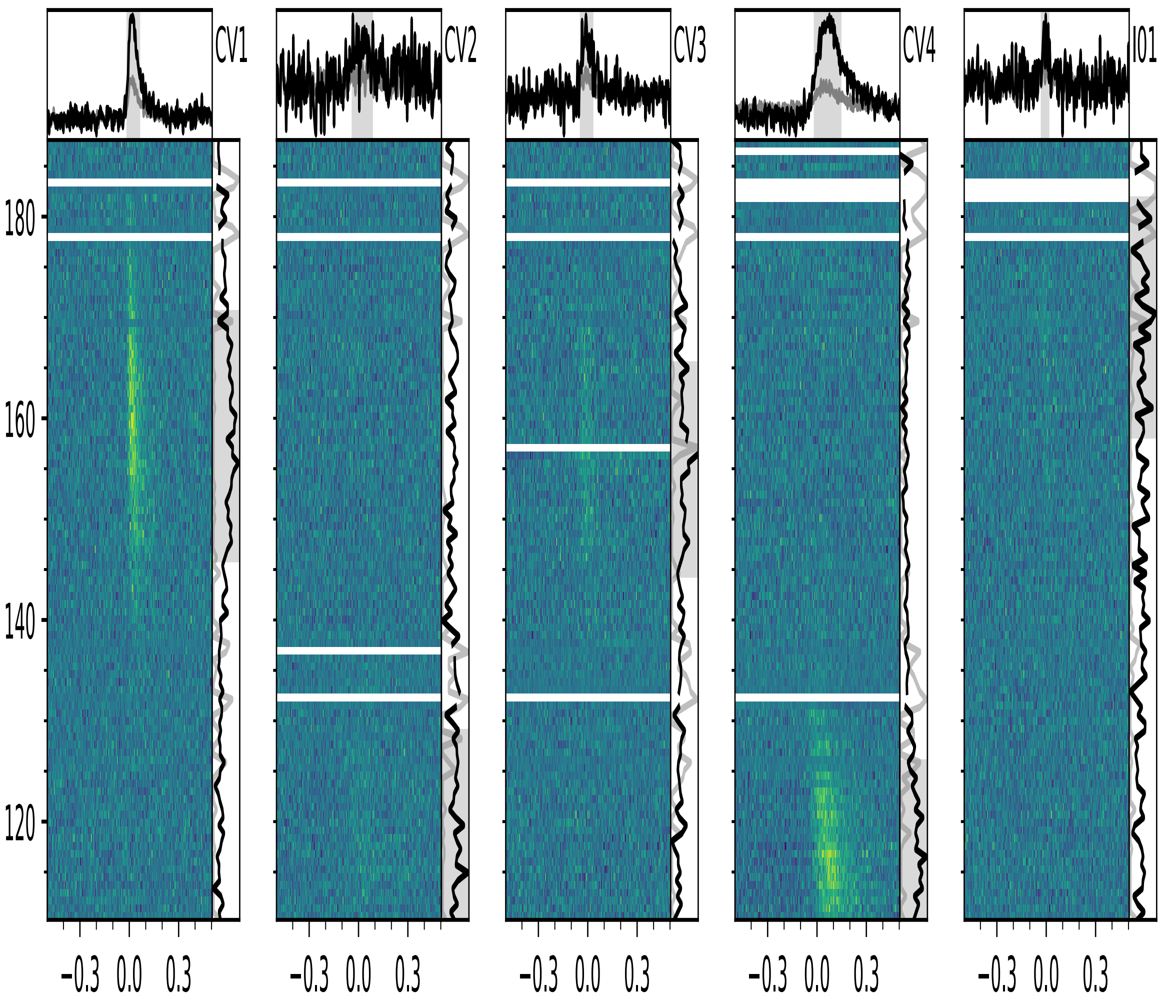


0.042Hz
23,533.6ms

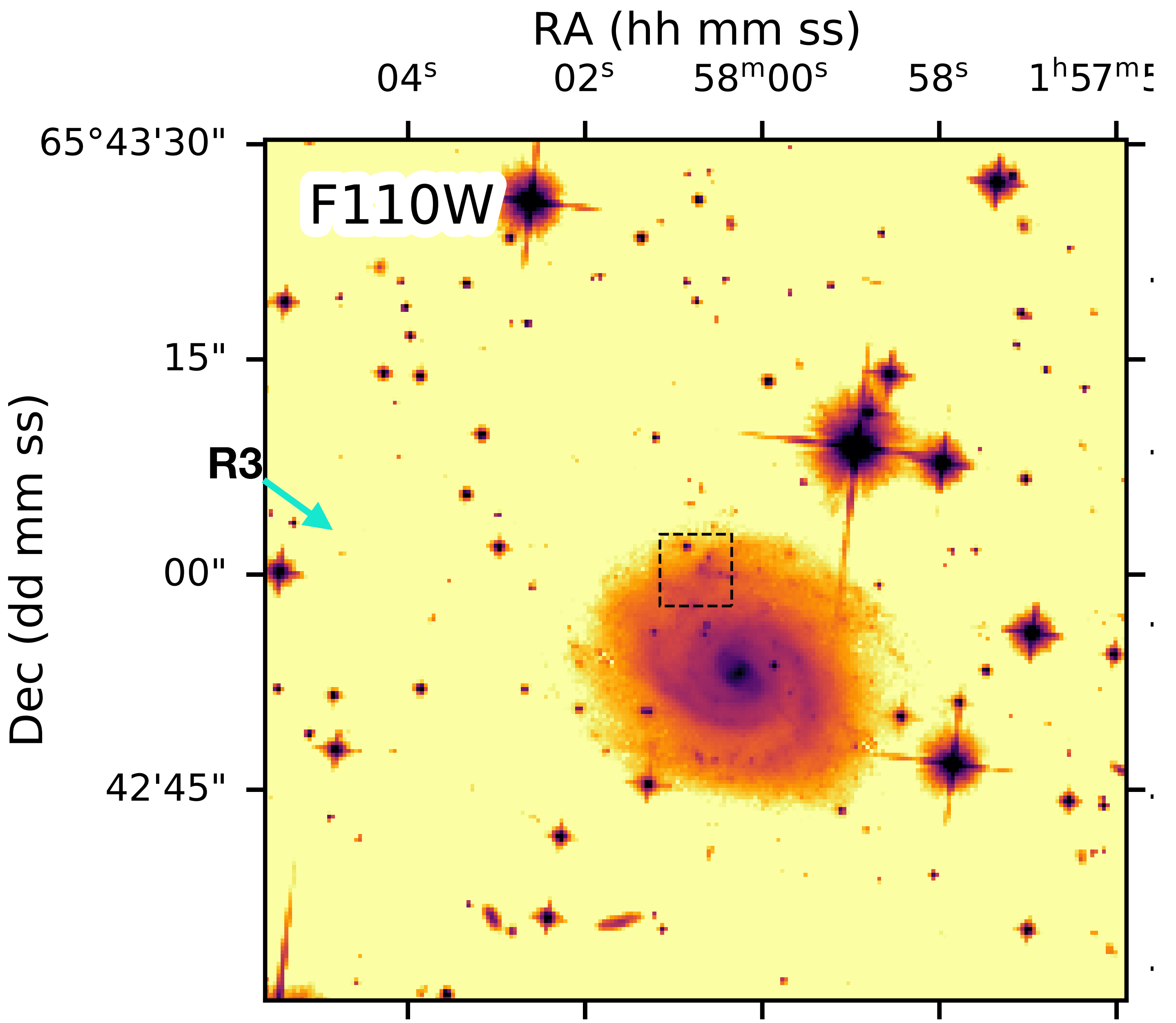
- see van der Wateren et al. 2023

Also a Fast Radio Burst

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

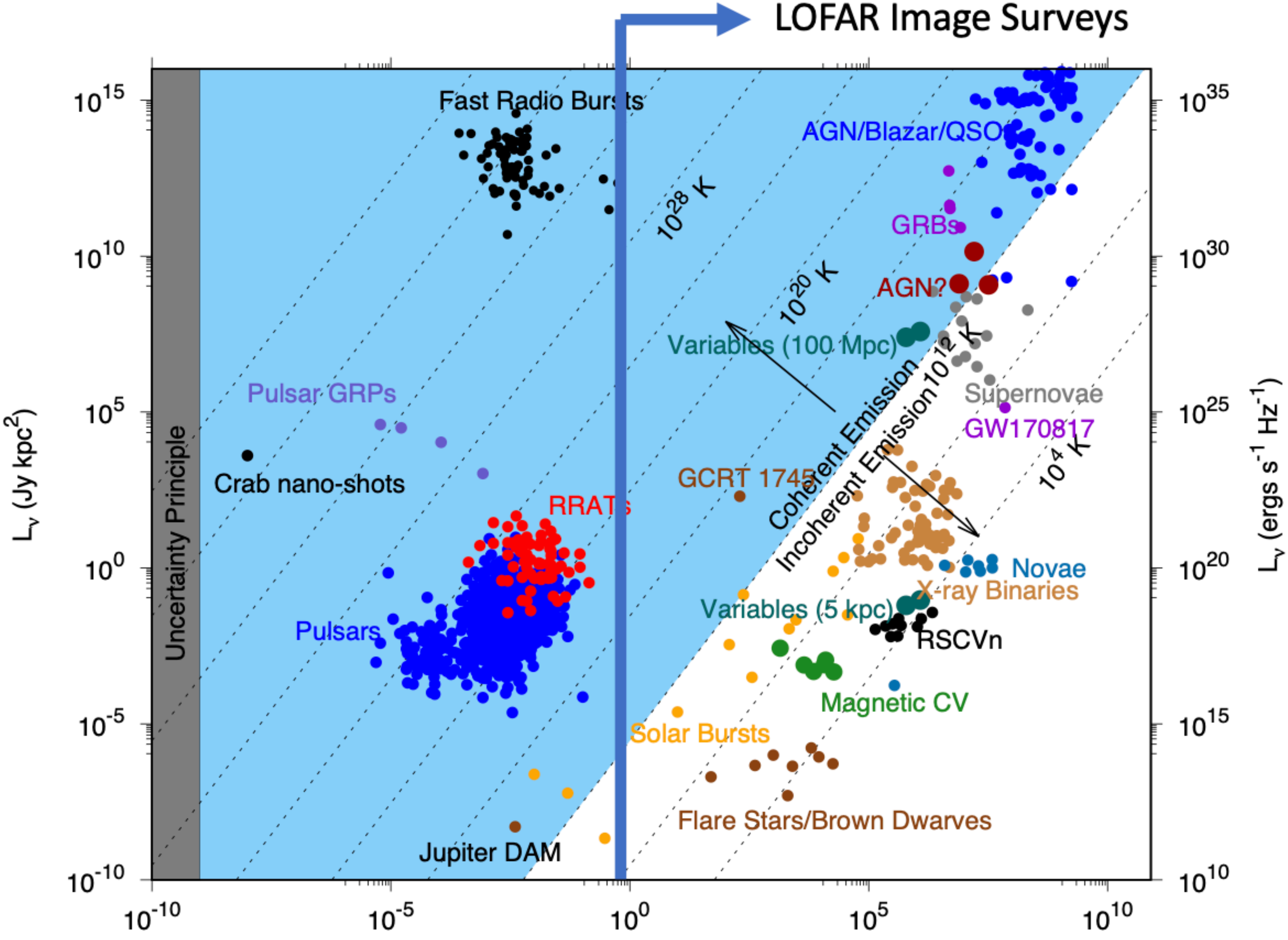


Pleunis, Michilli, Bassa, JH et al. 2021



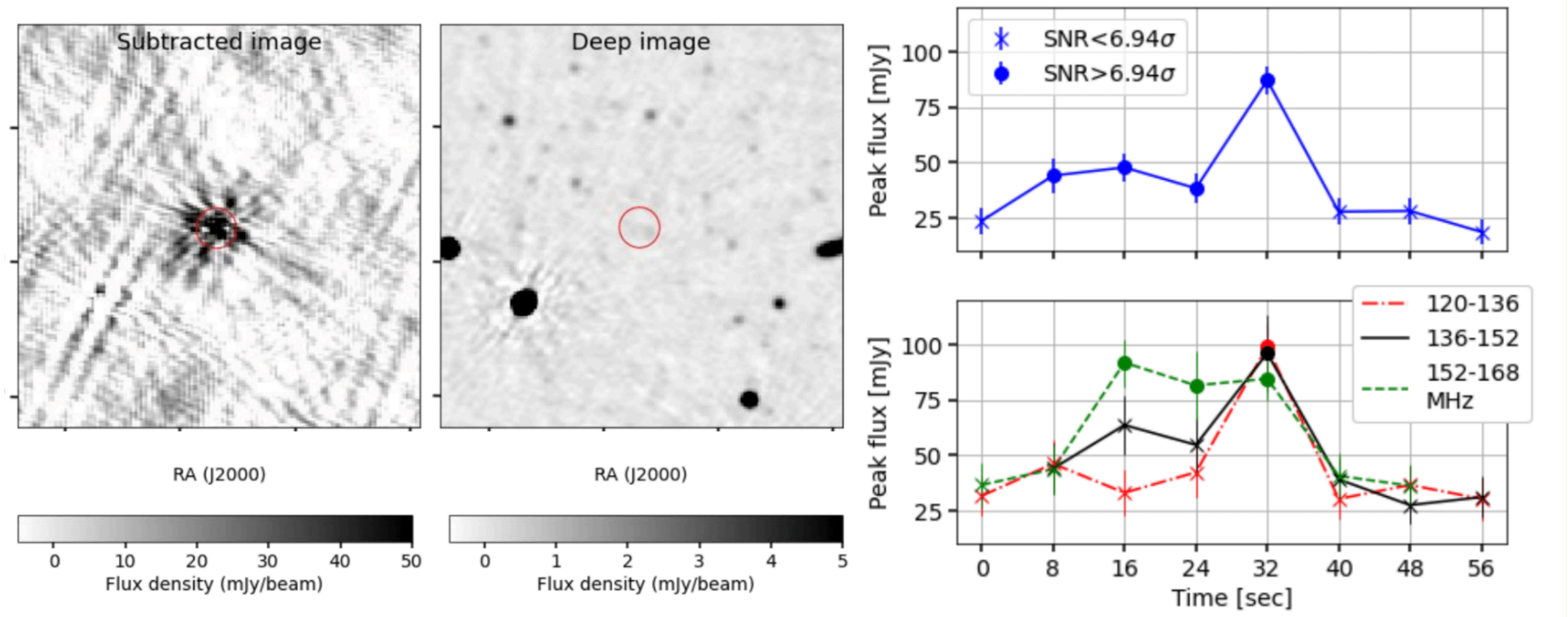
Tendulkar, Gil de Paz, Kirichenko, JH et al. 2021

Transients



ietka et al. (2015), Rowlinson et al. (2022)

Discovering new transients

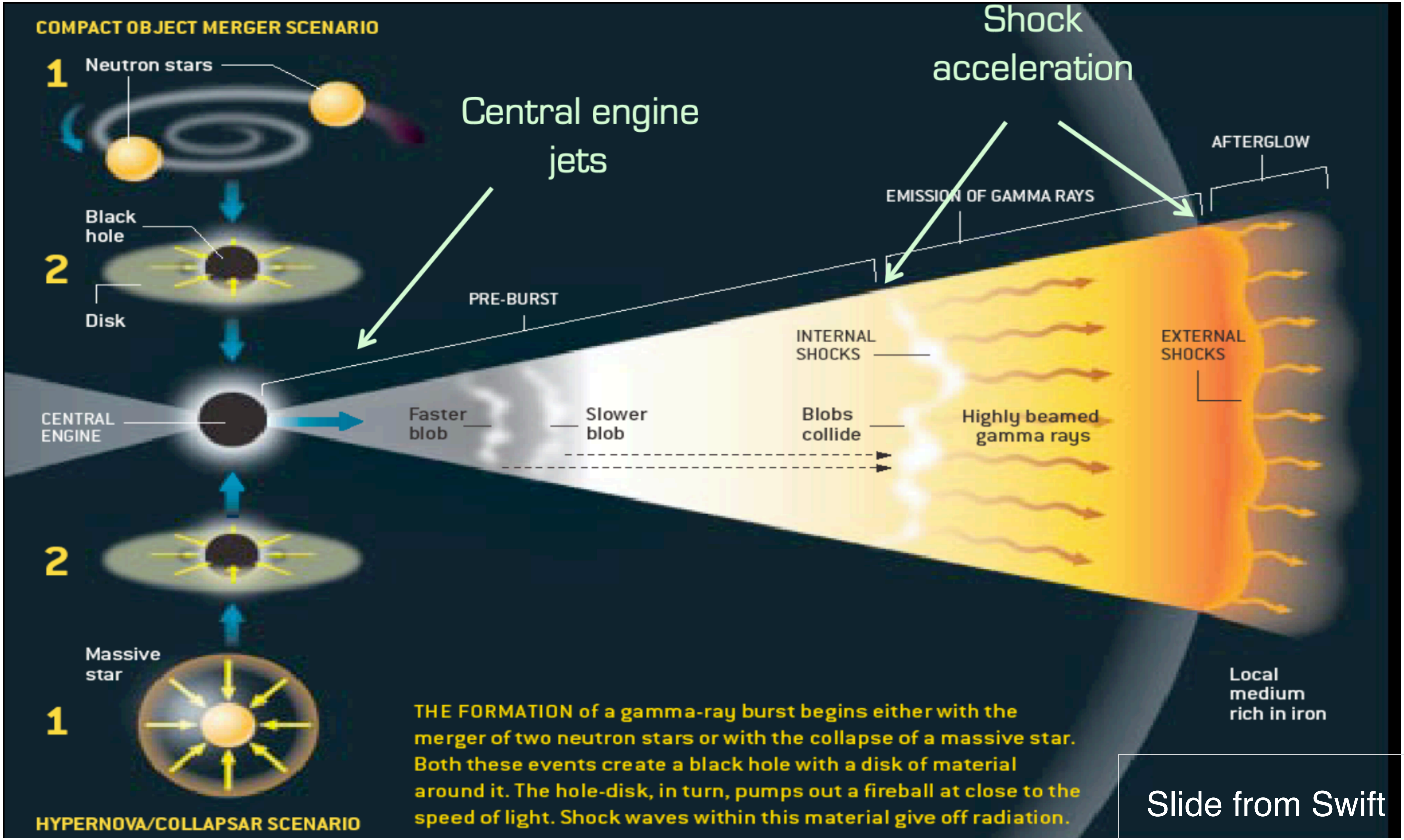


de Ruiter et al. (in prep)

Searching large areas of residual LOFAR HBA surveys data by imaging at 8 seconds cadence.

Characterisation of known transient sources

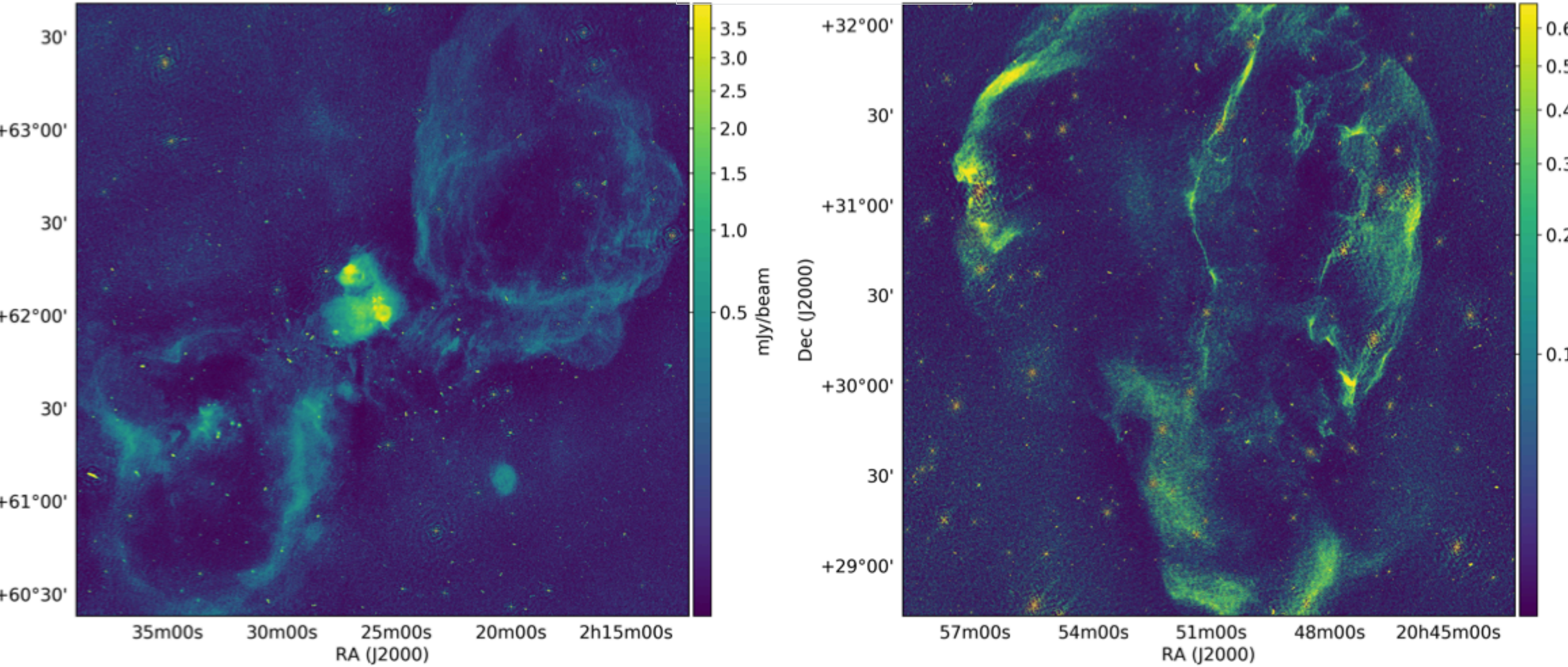
LOFAR can respond to Gamma Ray Bursts within 4.5 mins and has provided deepest limits on early time radio emission and a tentative detection (Rowlinson+)



THE FORMATION of a gamma-ray burst begins either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk, in turn, pumps out a fireball at close to the speed of light. Shock waves within this material give off radiation.

Slide from Swift

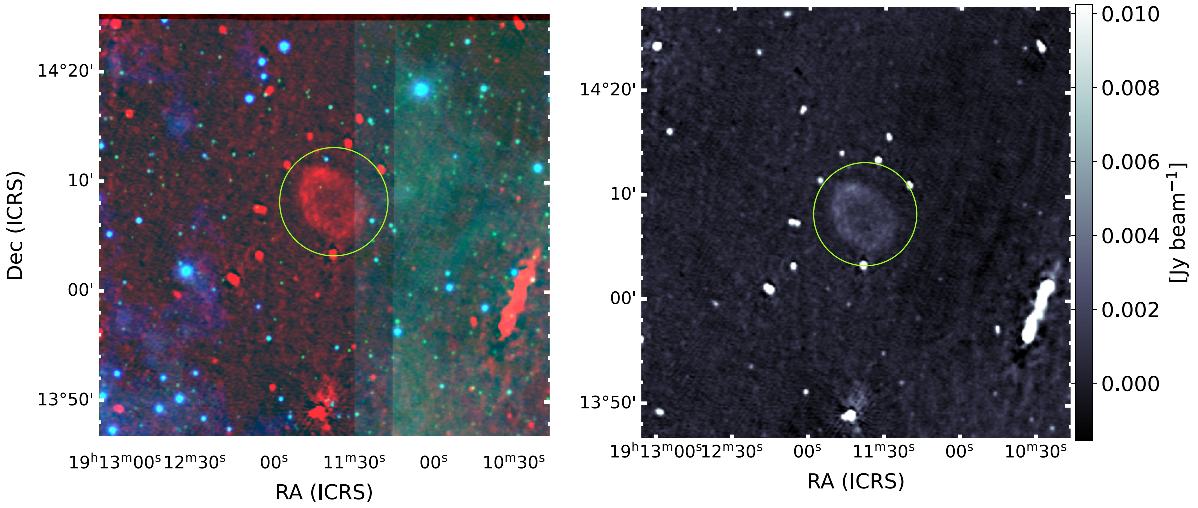
Milky Way



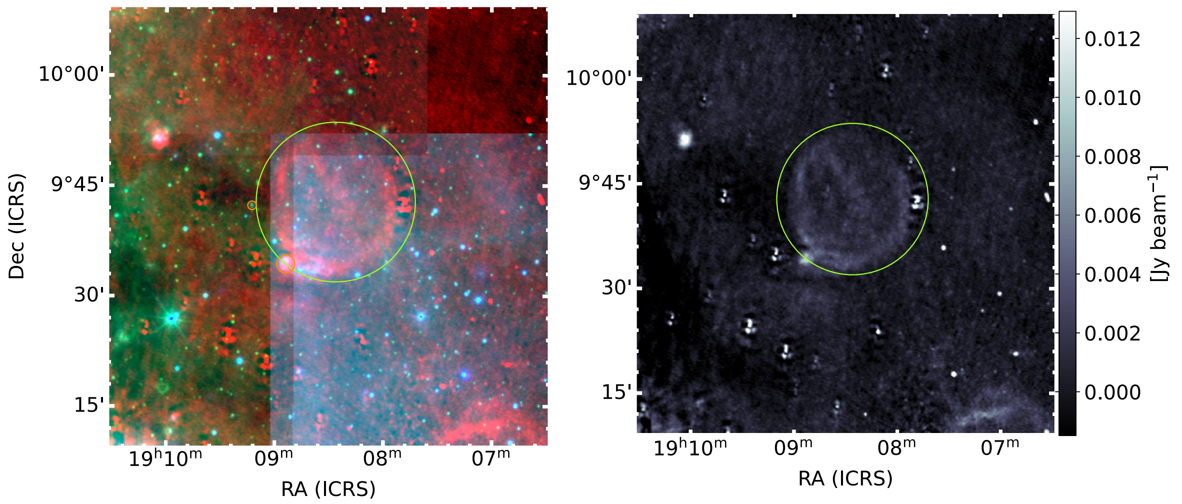
Imaging potential shown in these LoTSS mosaics of the W3/W4/HB3 star forming region and the Cygnus loop supernova remnant (calibrated in 45 different directions for each individual pointing)

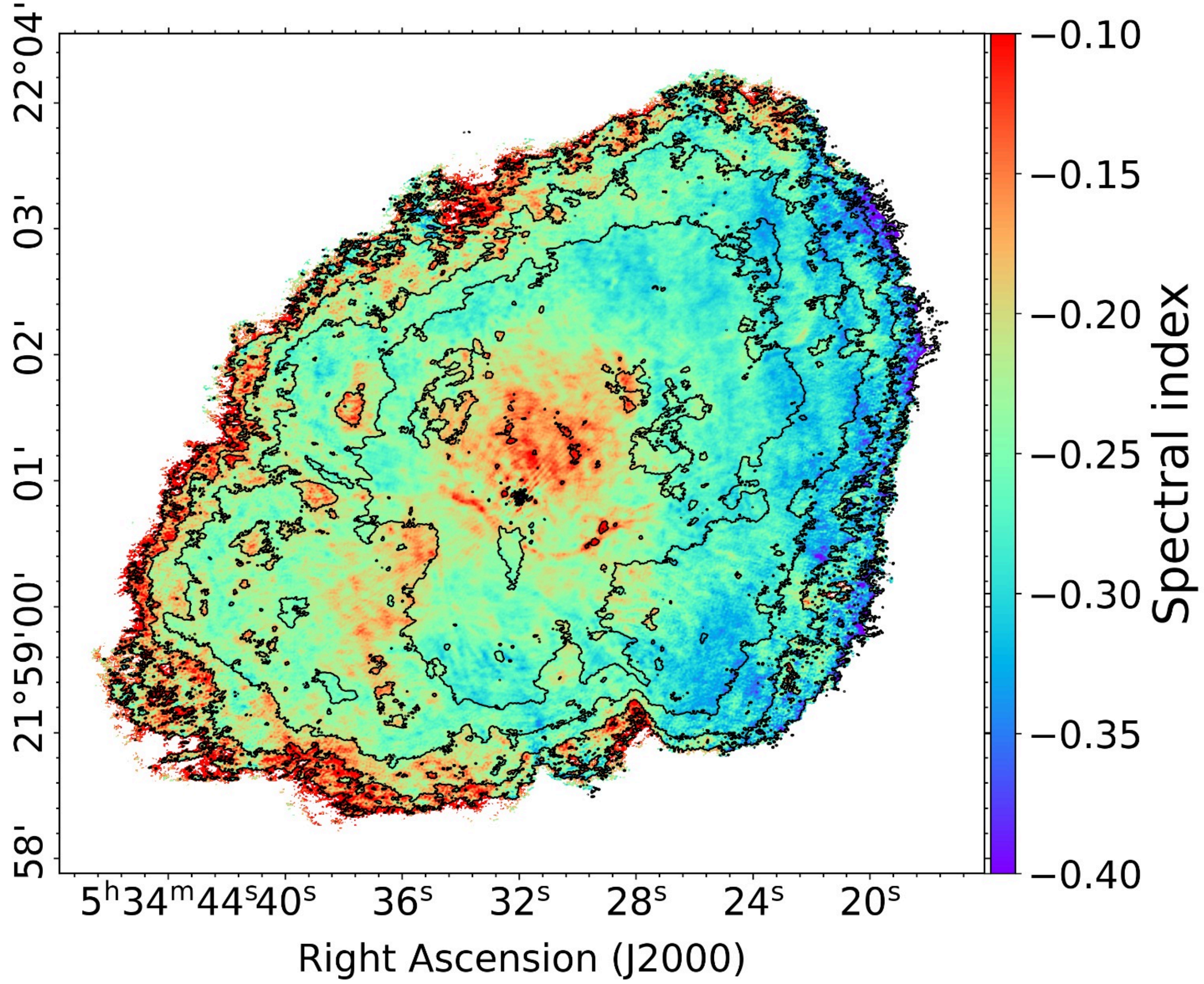
Discovering and characterising supernova

G47.78+2.02



G43.5+0.6





- Discovery of 16 new SNRs and confirmation of 8 previously identified candidates (Tsalapatas, Arias+ in prep)

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

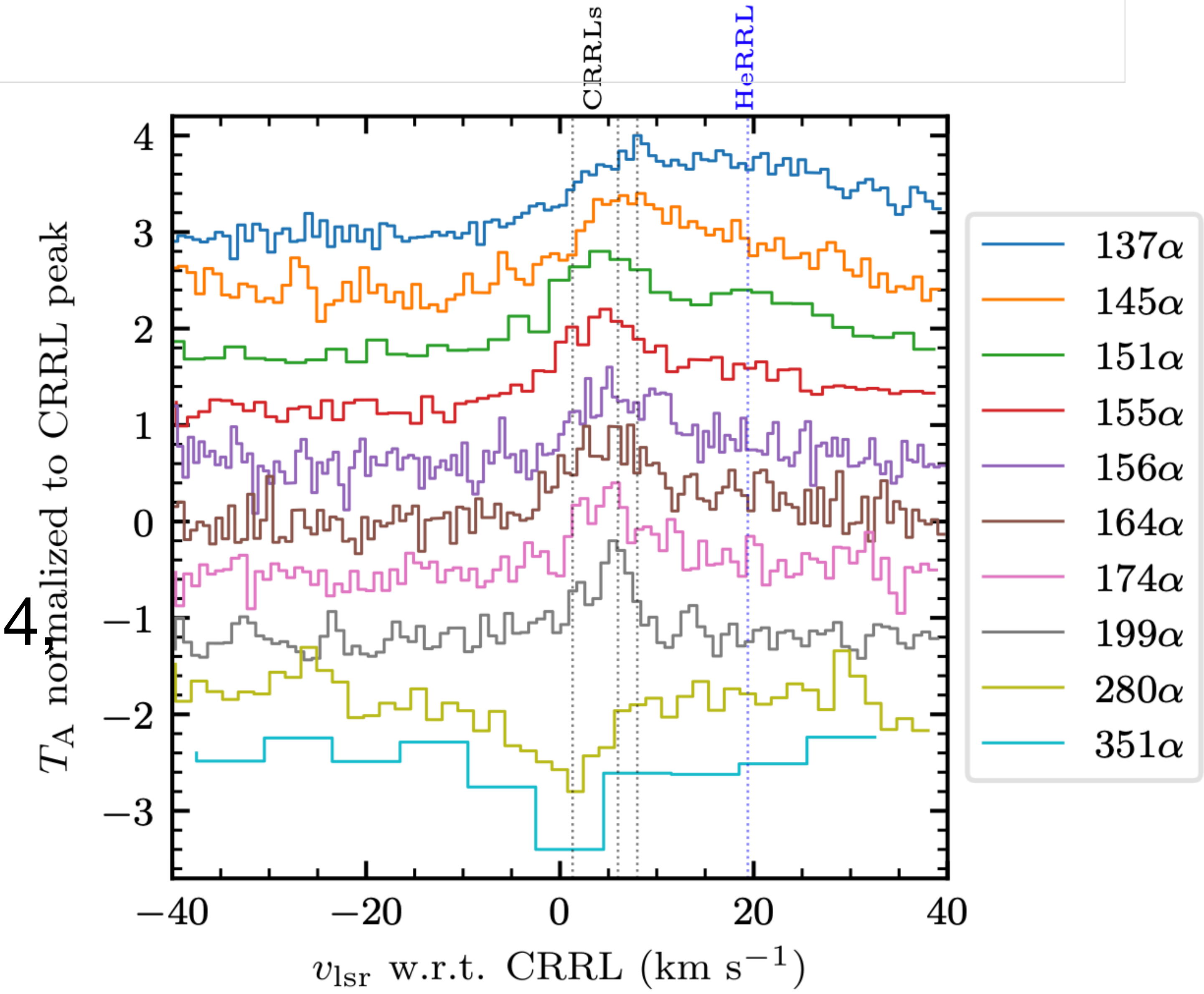
Recombination lines

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

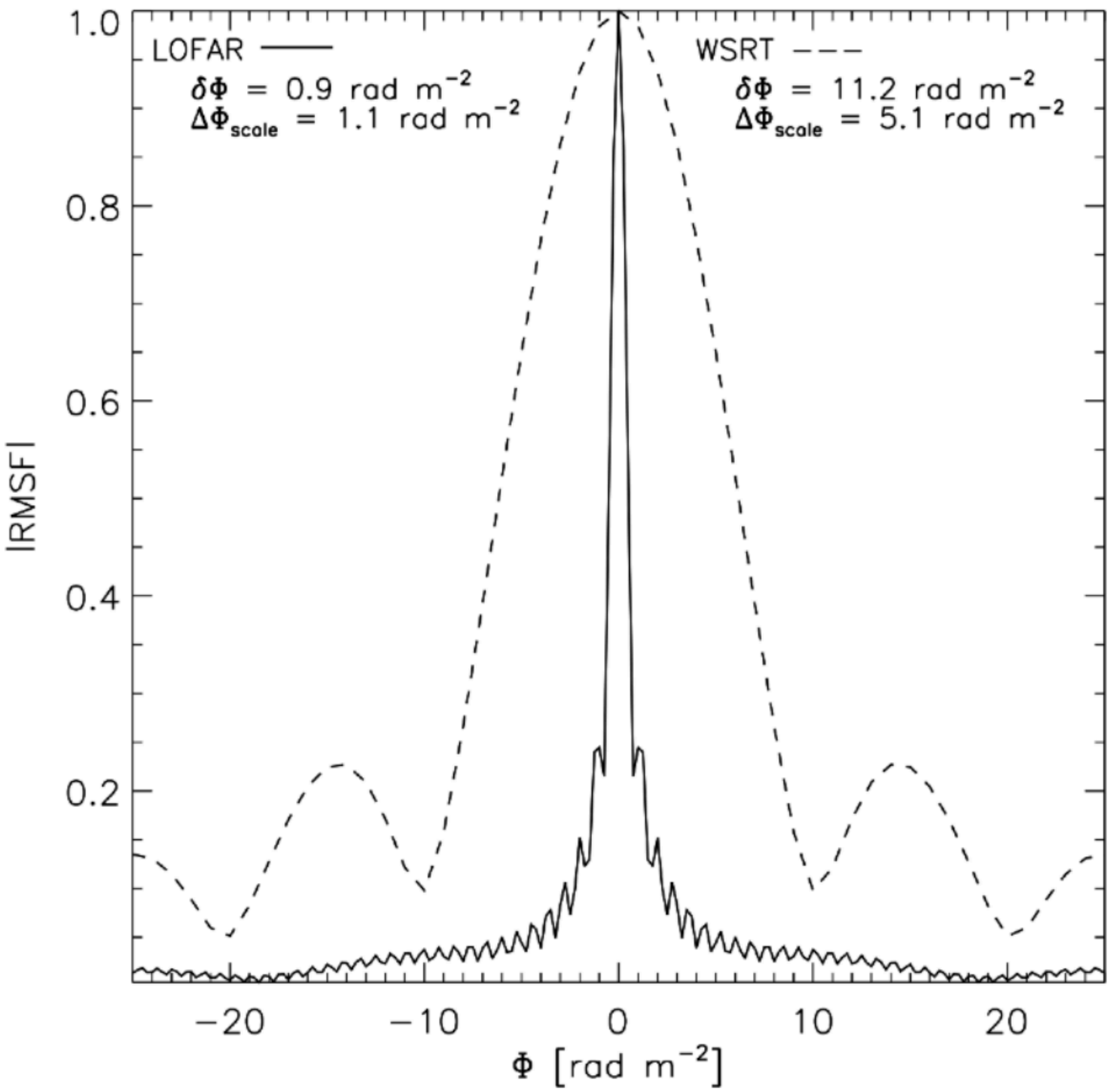
Largest bound atoms in space and detectable at cosmological distances (Emig+)

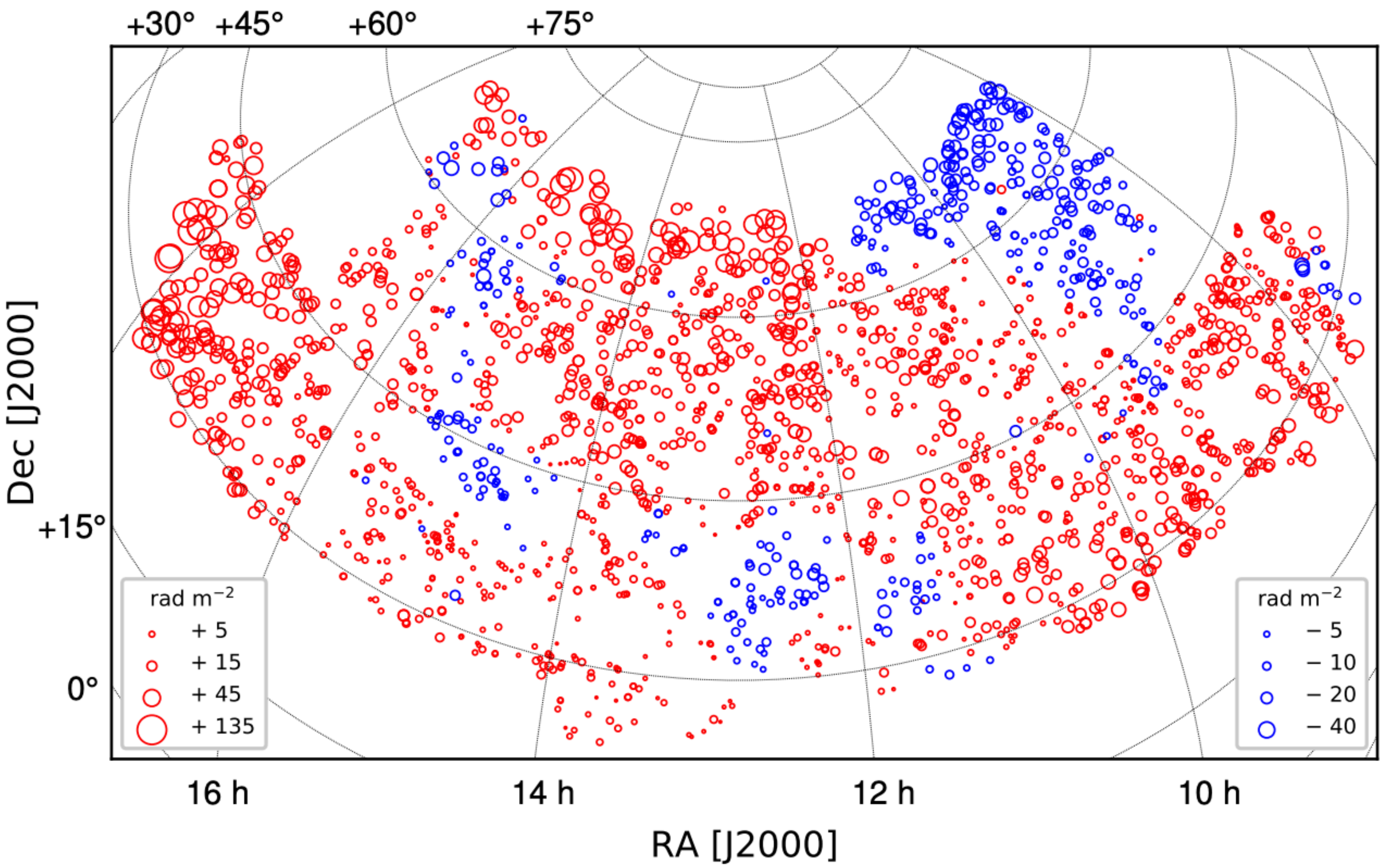
RRL spectra towards M 42 around the carbon feature. The RRLs correspond to α lines with principal quantum numbers 137, 145, 155, 156, 164, 174, 199, 280, and 351.

[Salas+ 17, 22]



Galactic magnetic field





O'Sullivan 2023+ - 2461 (0.2% 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%)

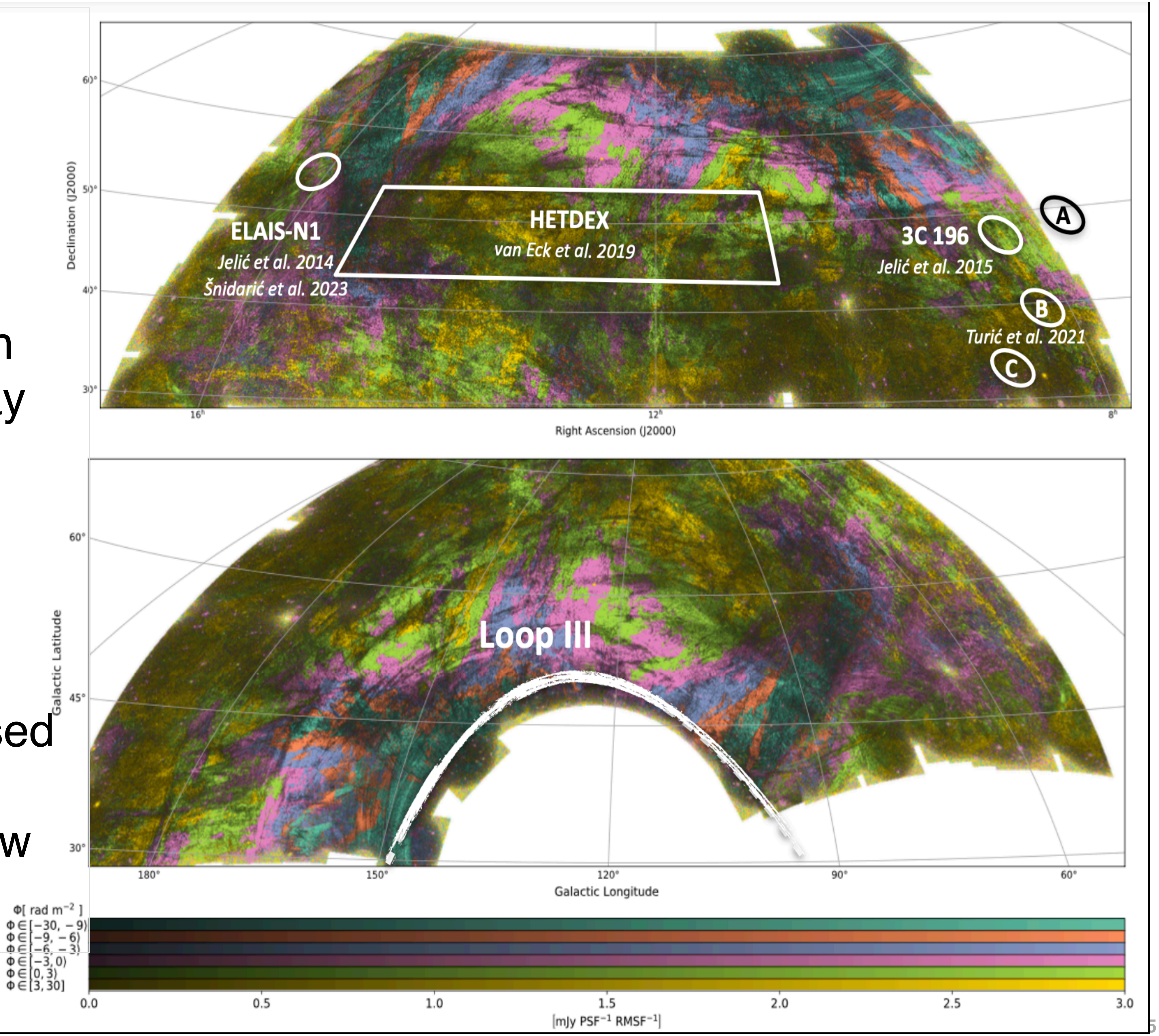
Measurements enter into model of Milky Way magnetic field e.g. Hutschenreuter 2022.

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

Polarisation measurements of very diffuse background.

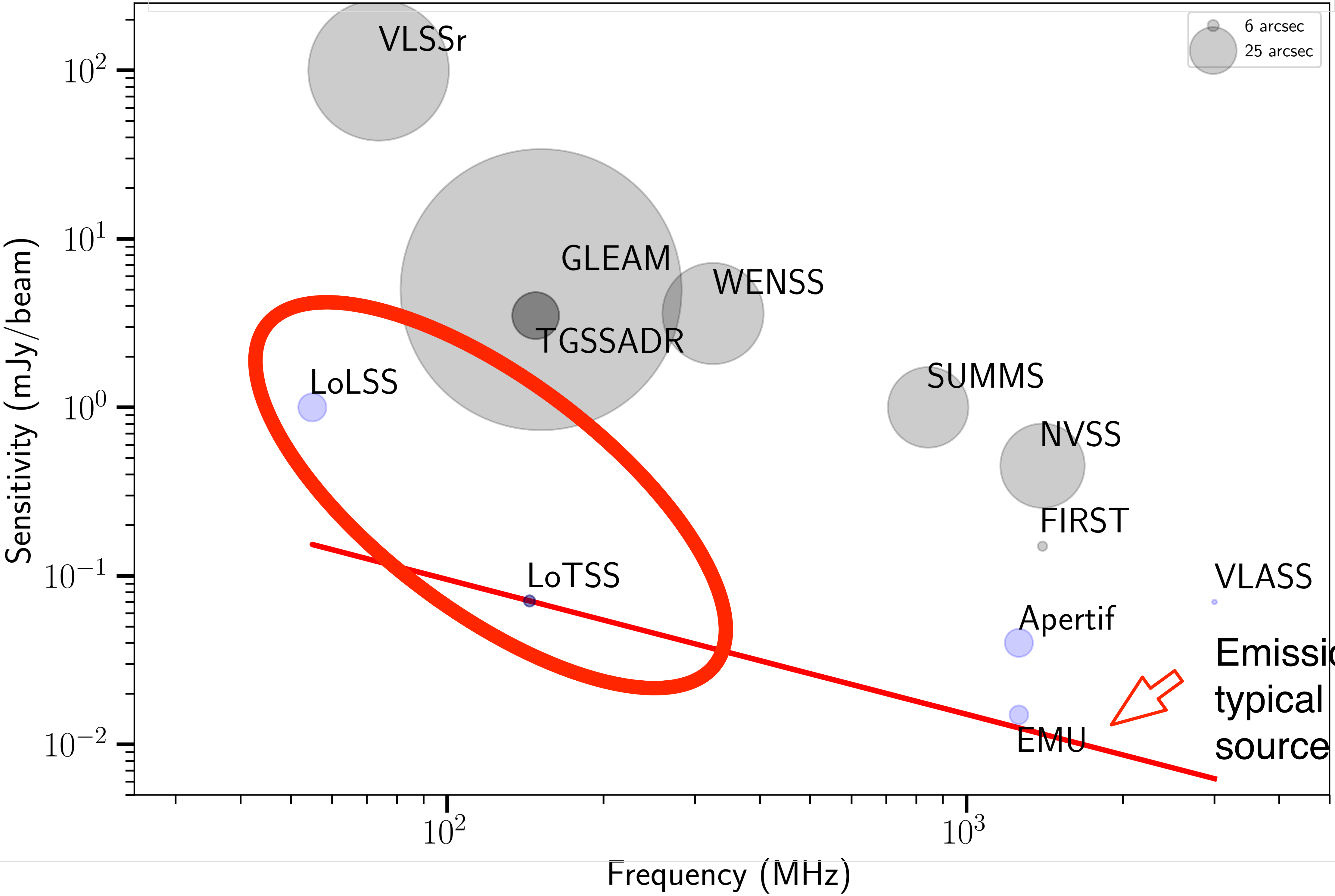
Polarised emission at different Faraday depths originates from different distances

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



Extragalactic imaging science

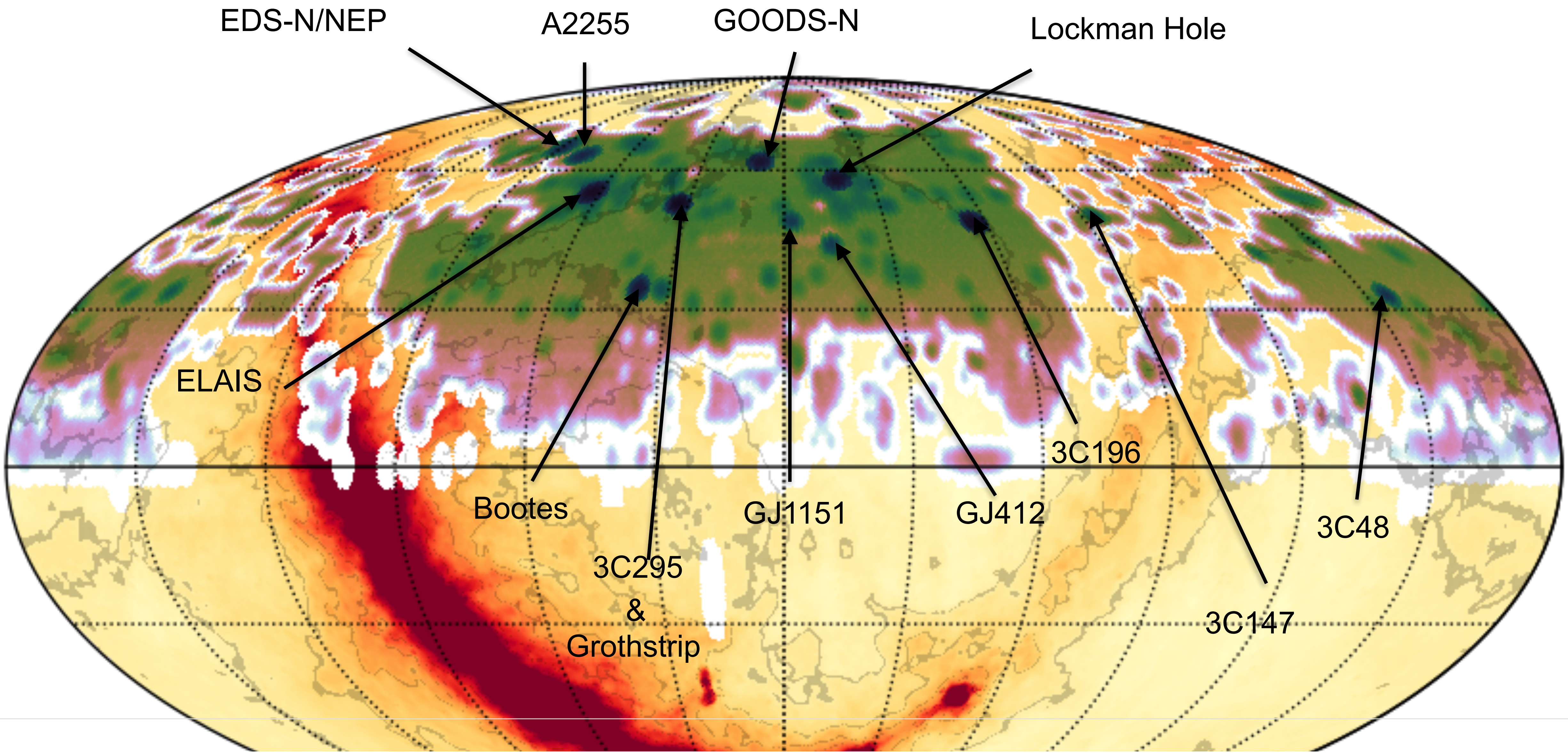
LOFAR is a world-leading wide area imaging instrument.



Emission from typical radio source (-0.8)

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.

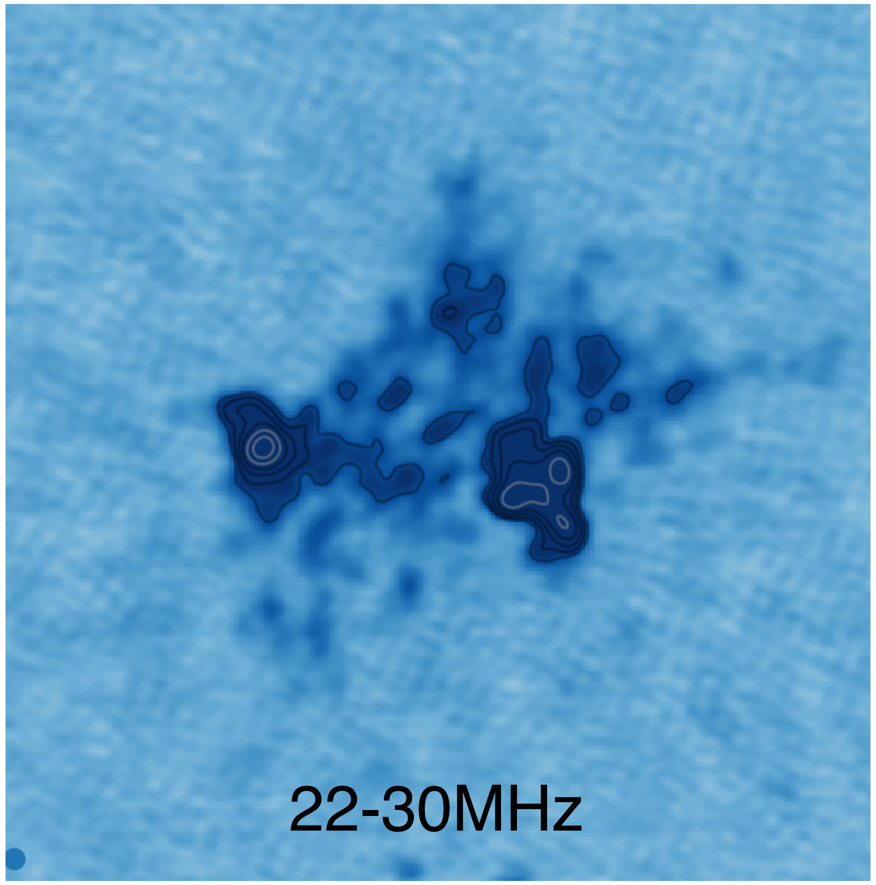


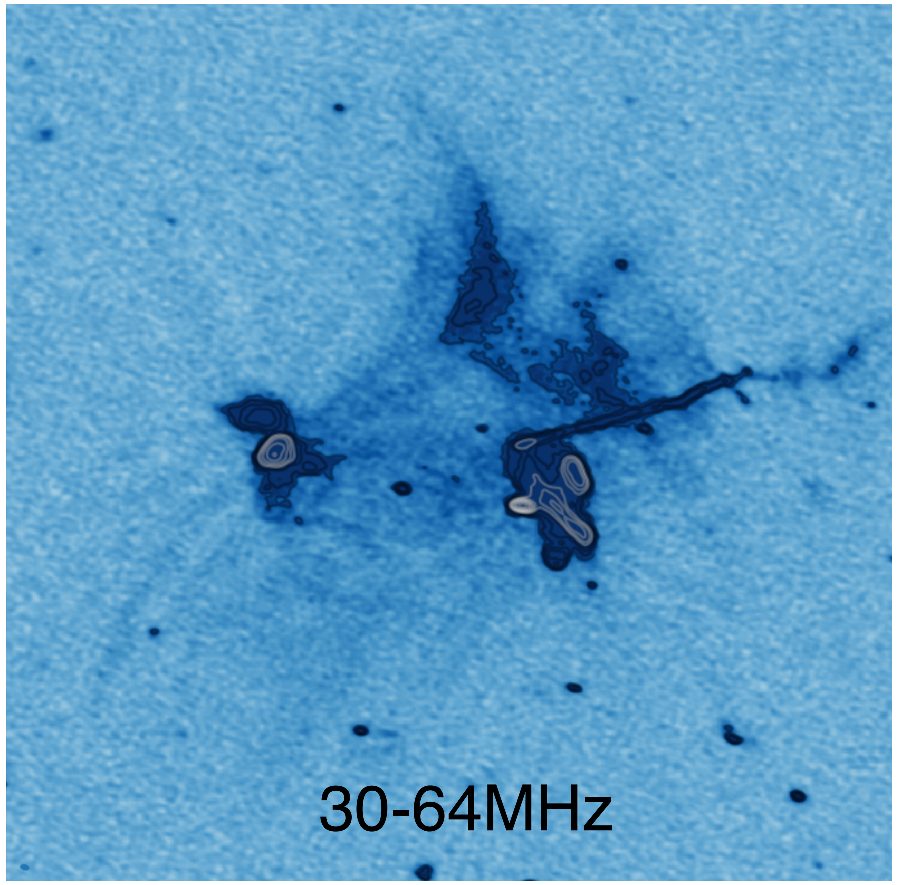
15,000hrs and 15PB of LOFAR HBA imaging data in archive. 85% of sky surveyed including several deep fields with up to 550hr integrations. Processing cost of ~20 million cpu hours.

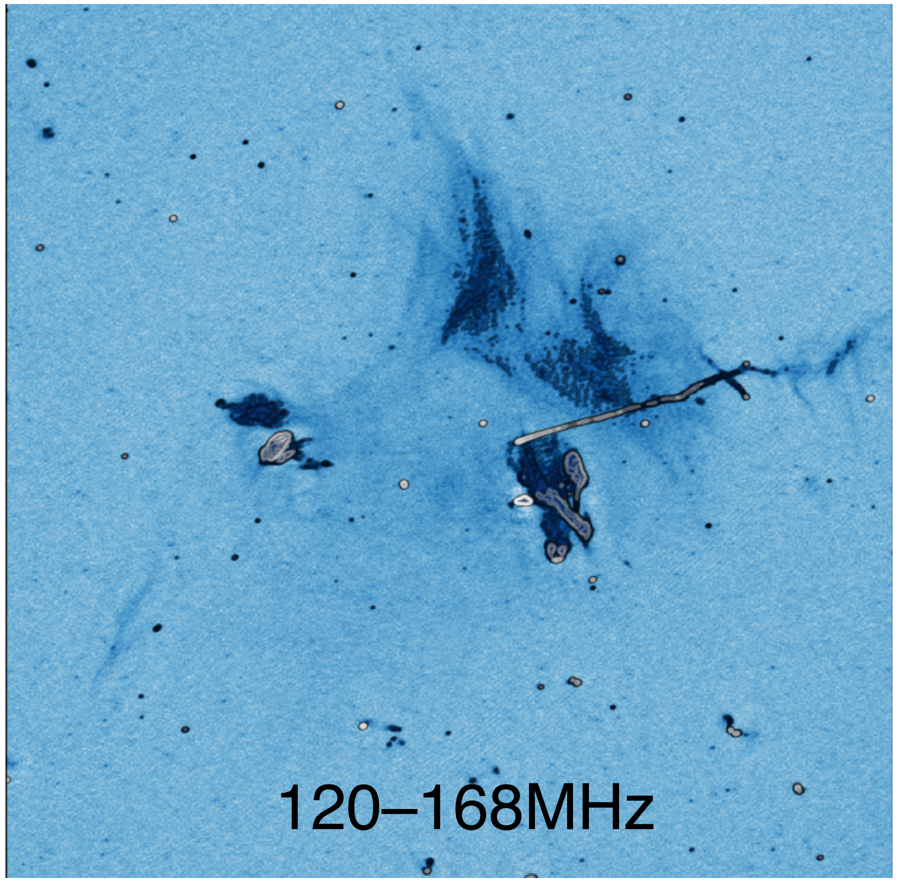
LBA 99% of sky observed above dec 24. Over 1,000 hrs integration.

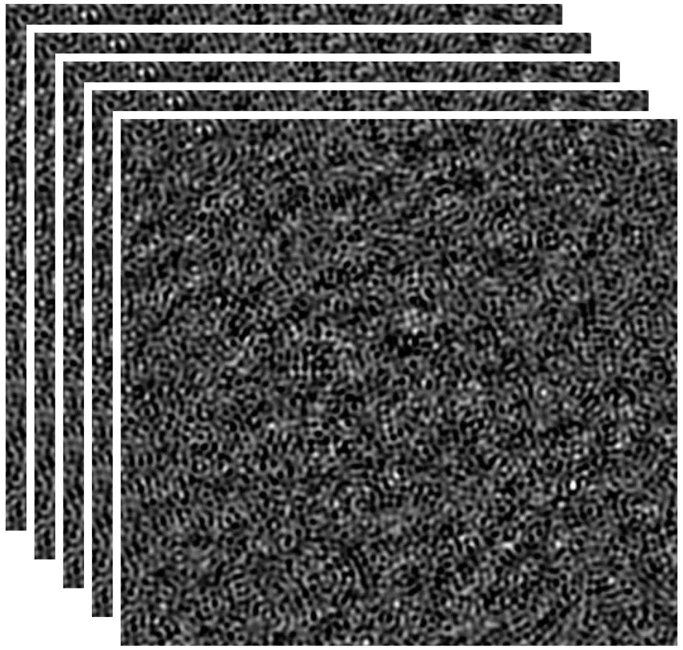
To-date about 10,000 million sources in images - 90% are new.

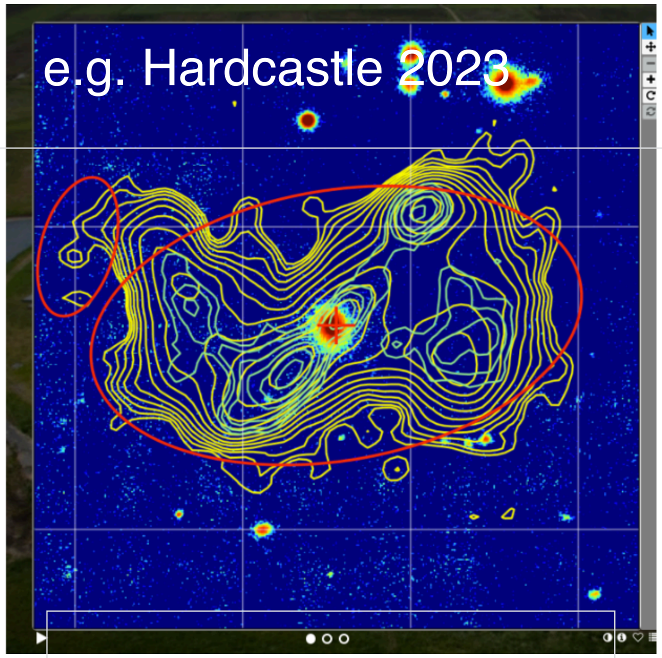
Science ready products over vast areas of sky.


22-30MHz


30-64MHz

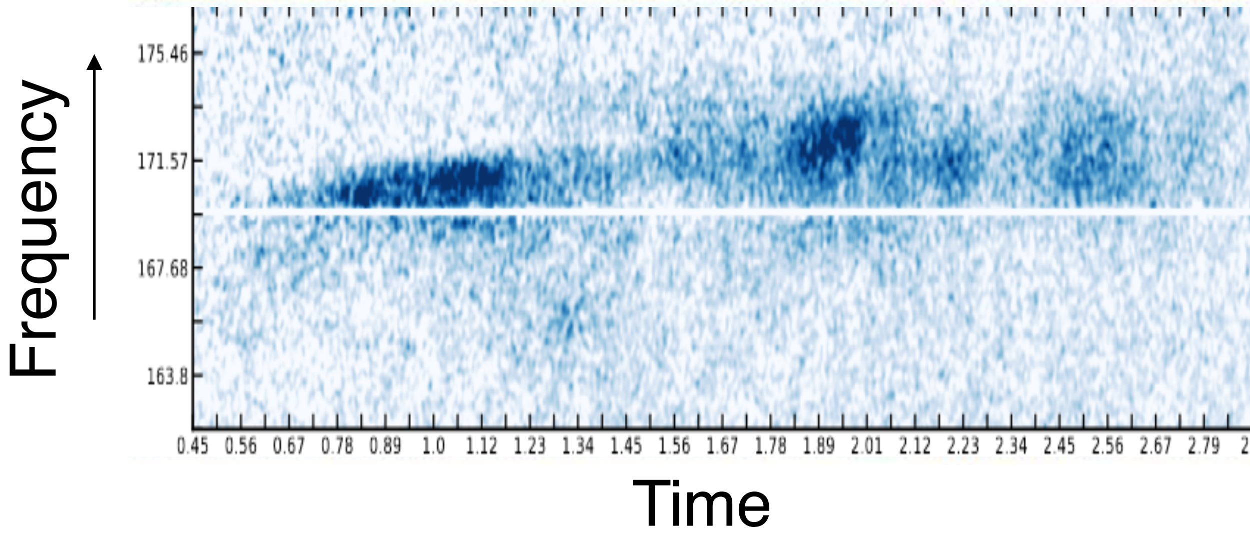

120–168MHz

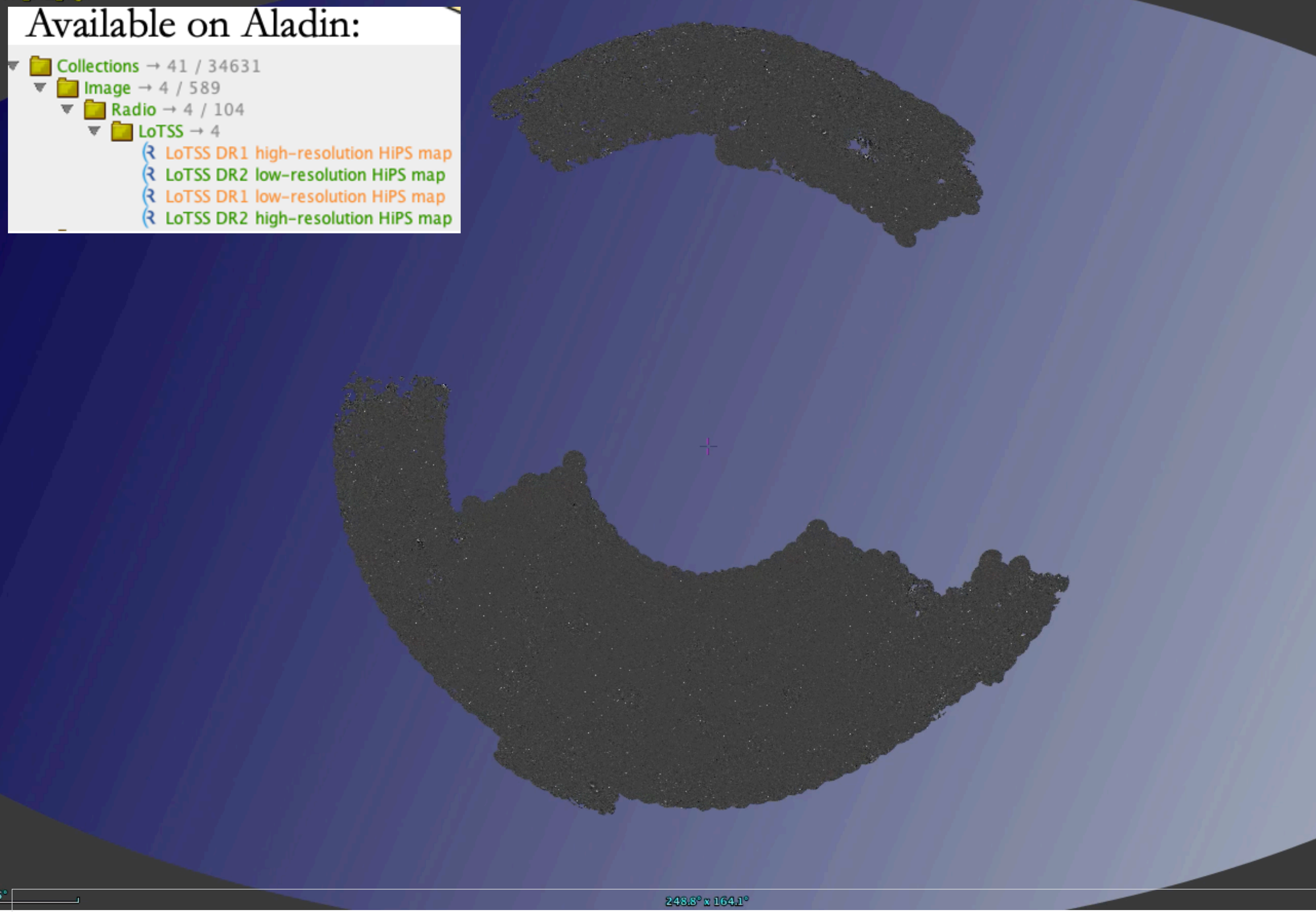

Polarisation cubes


e.g. Hardcastle 2023

Cross matching

Dynamic spectra



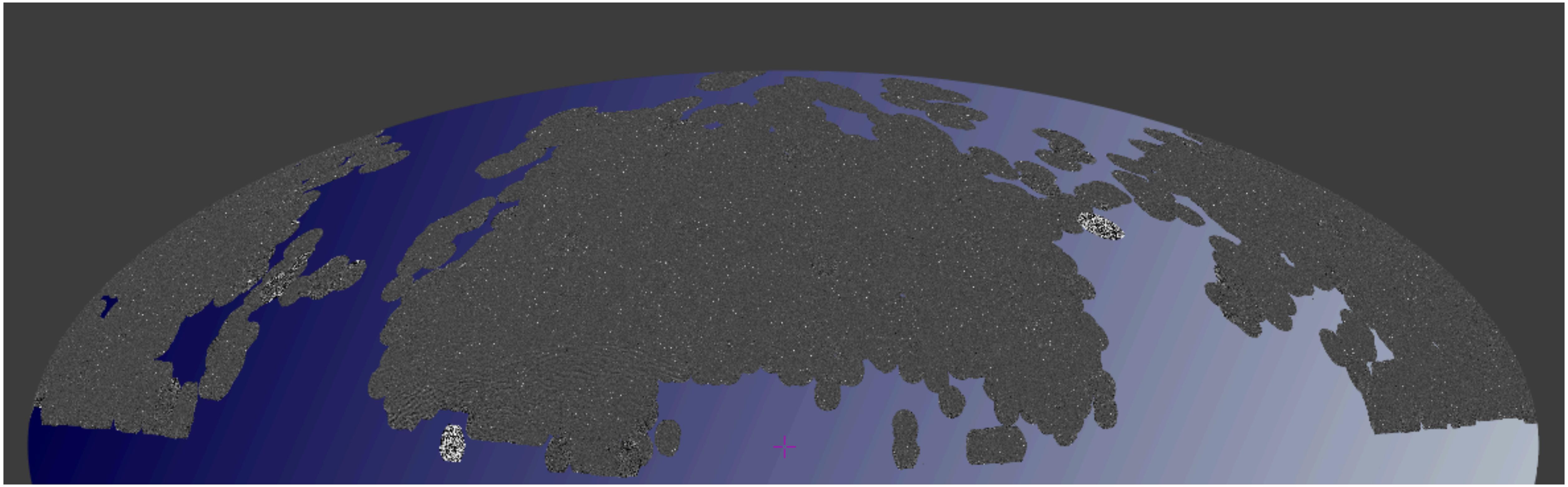


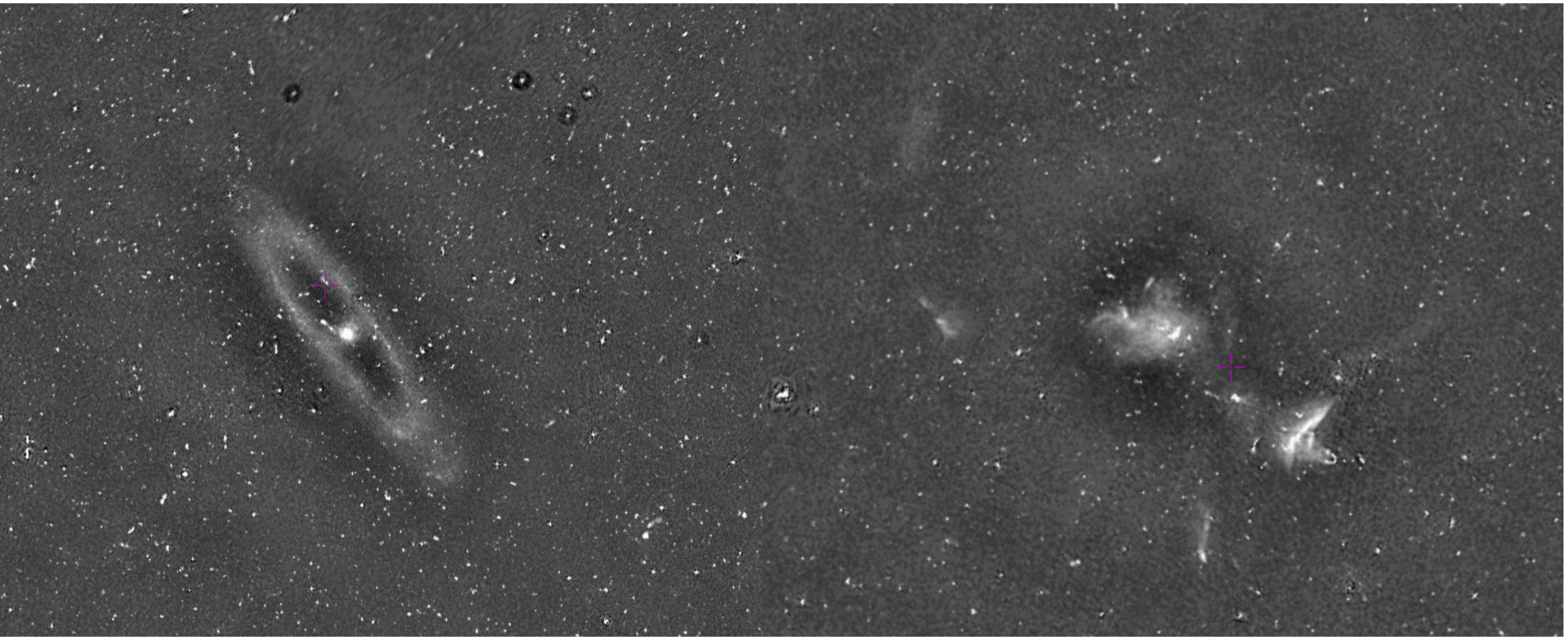
Available on Aladin:

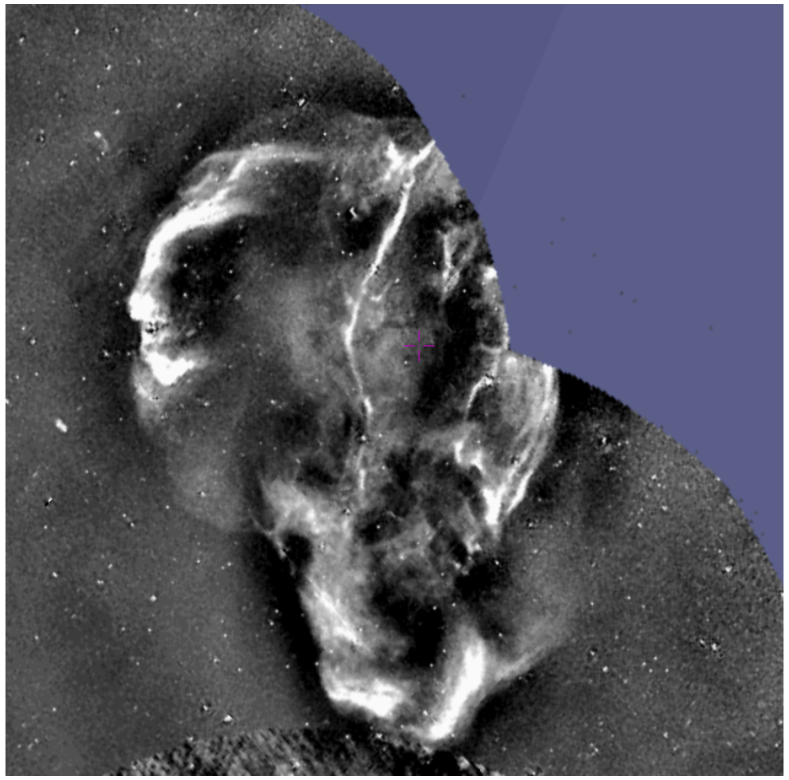
- Collections → 41 / 34631
  - Image → 4 / 589
    - Radio → 4 / 104
      - LoTSS → 4
        - LoTSS DR1 high-resolution HiPS map
        - LoTSS DR2 low-resolution HiPS map
        - LoTSS DR1 low-resolution HiPS map
        - LoTSS DR2 high-resolution HiPS map

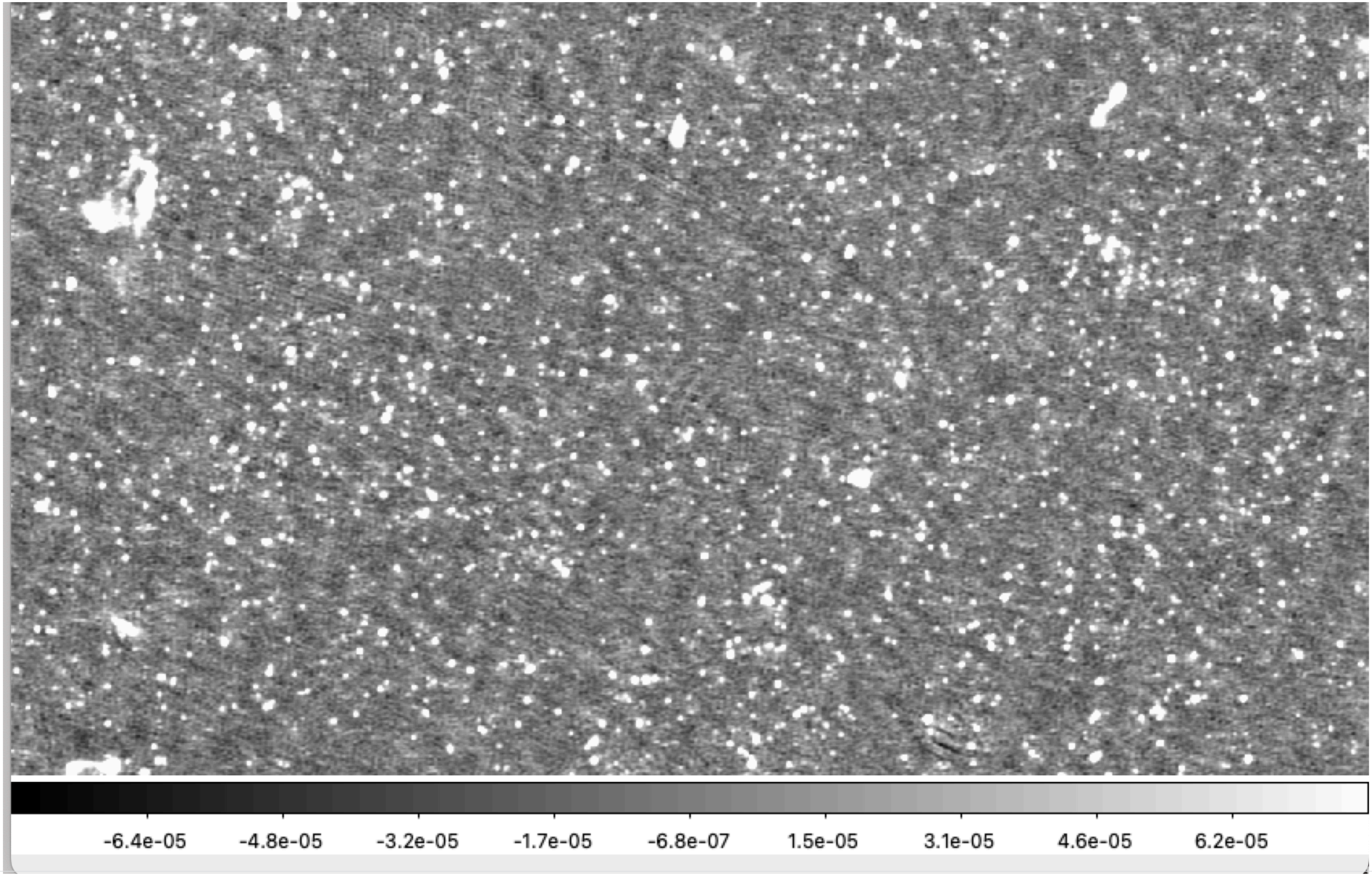
https://lofar-surveys.org/public_hips/LoTSS_DR2_high_hips/

Latest maps cover even wider area and will be made public when possible (likely 1-2 years)

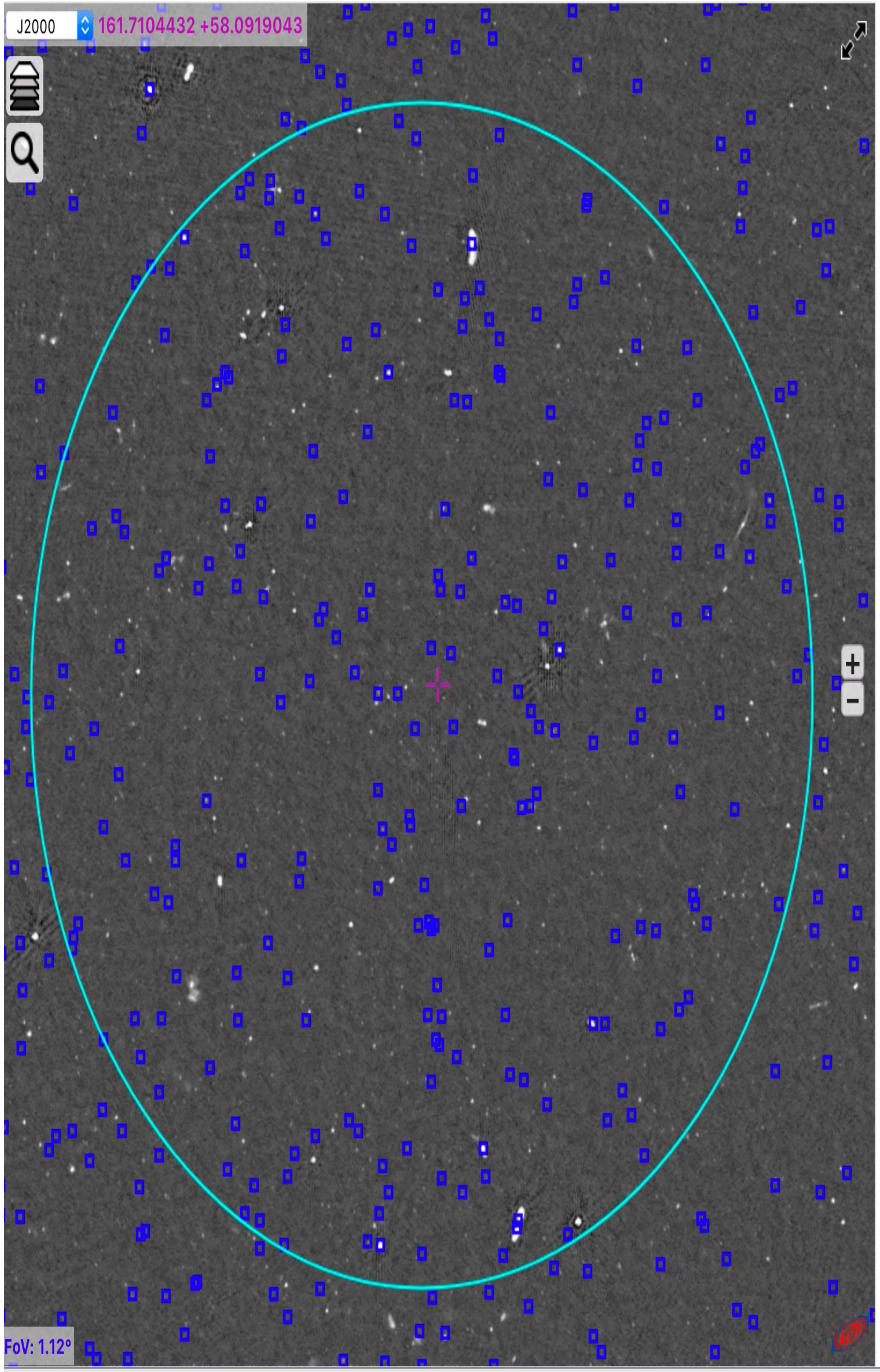


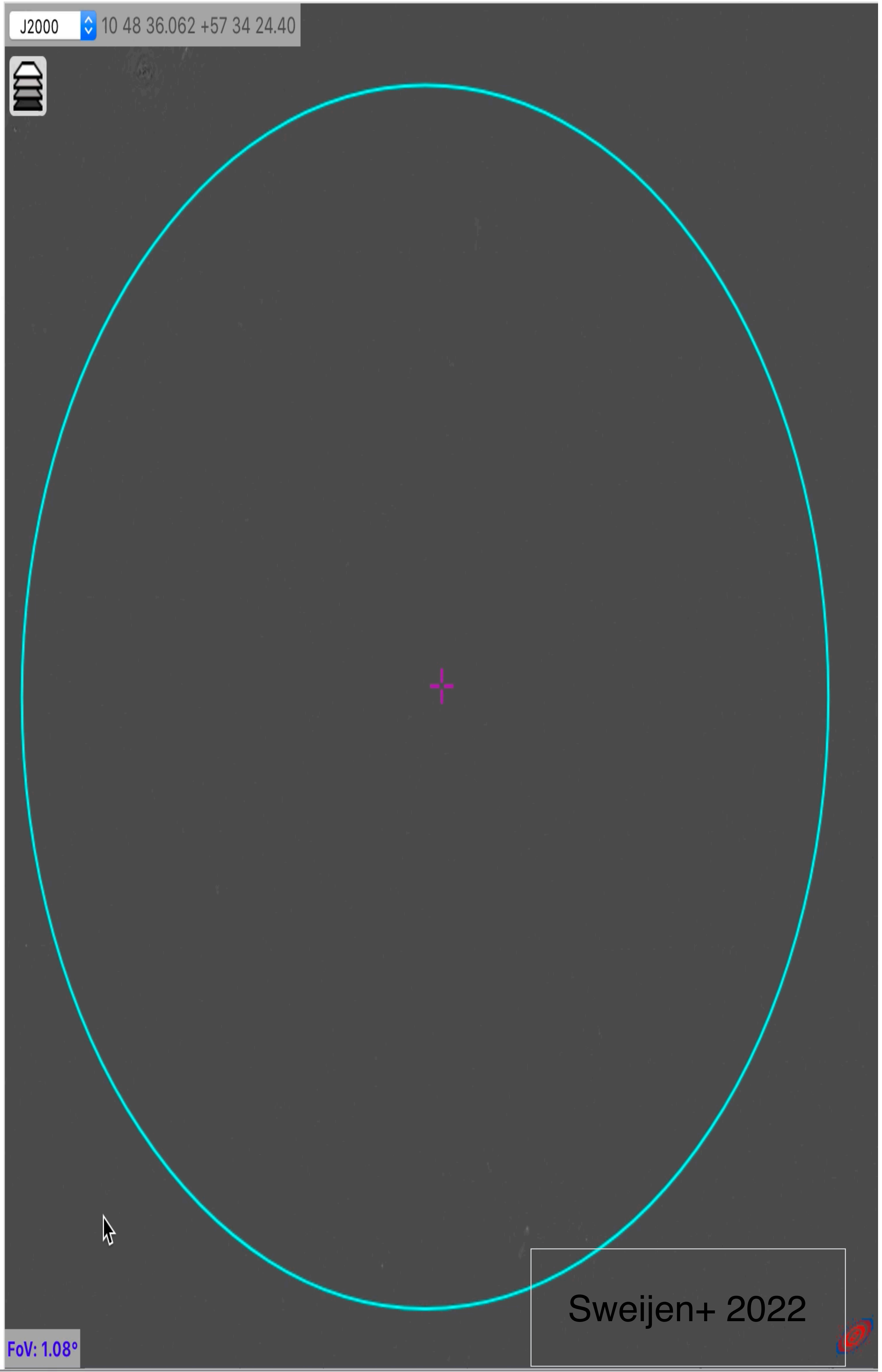






Deepest images around 10-12uJy/beam rms at 6” resolution (very confusion limited)





Sweijen+ 2022

Active Galactic Nuclei and star formation

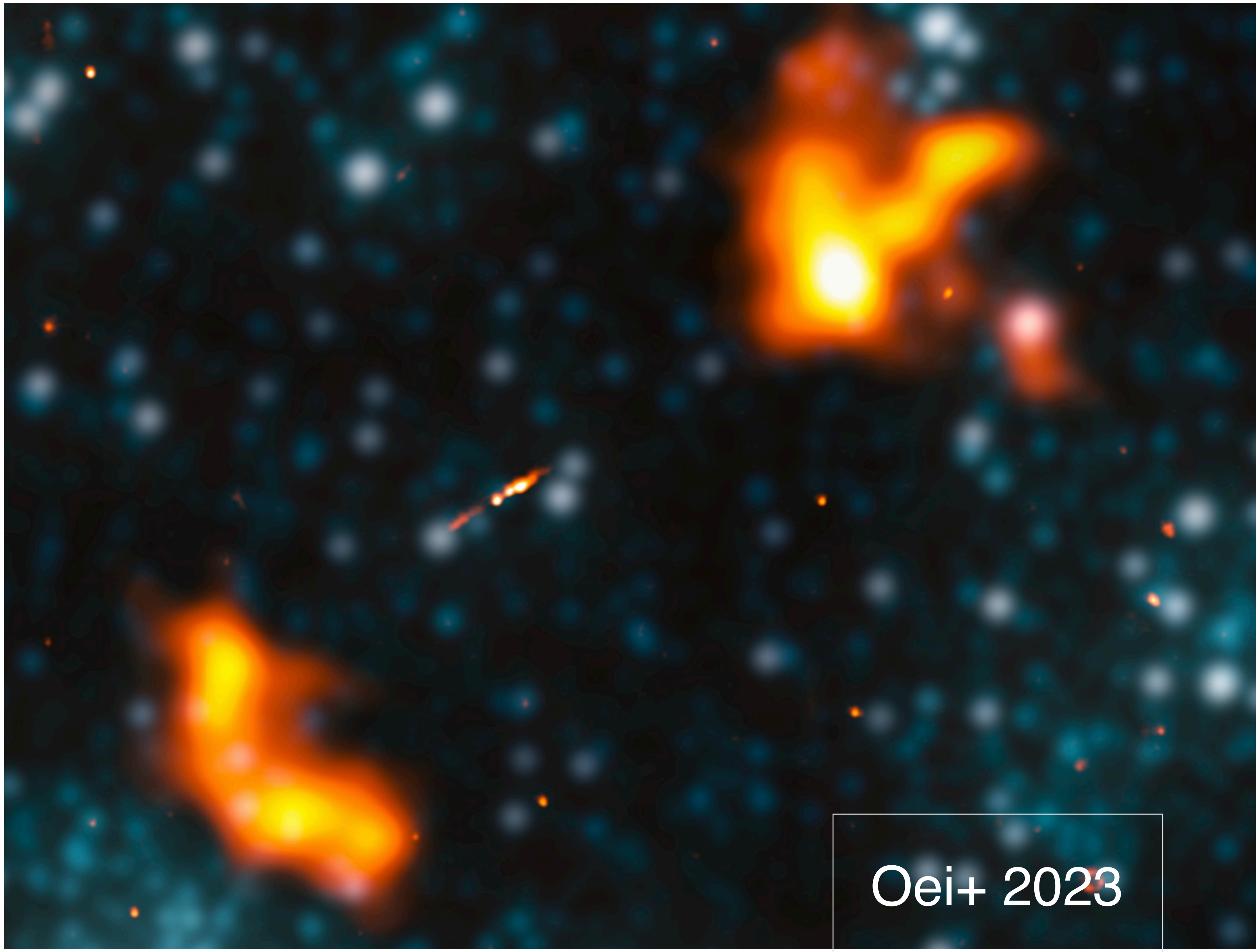
Huge samples of all kinds of AGN. For example Giant Radio Galaxies (>0.7Mpc).

LOFAR images have:

- Revealed the largest giant radio galaxies (5MPc)

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

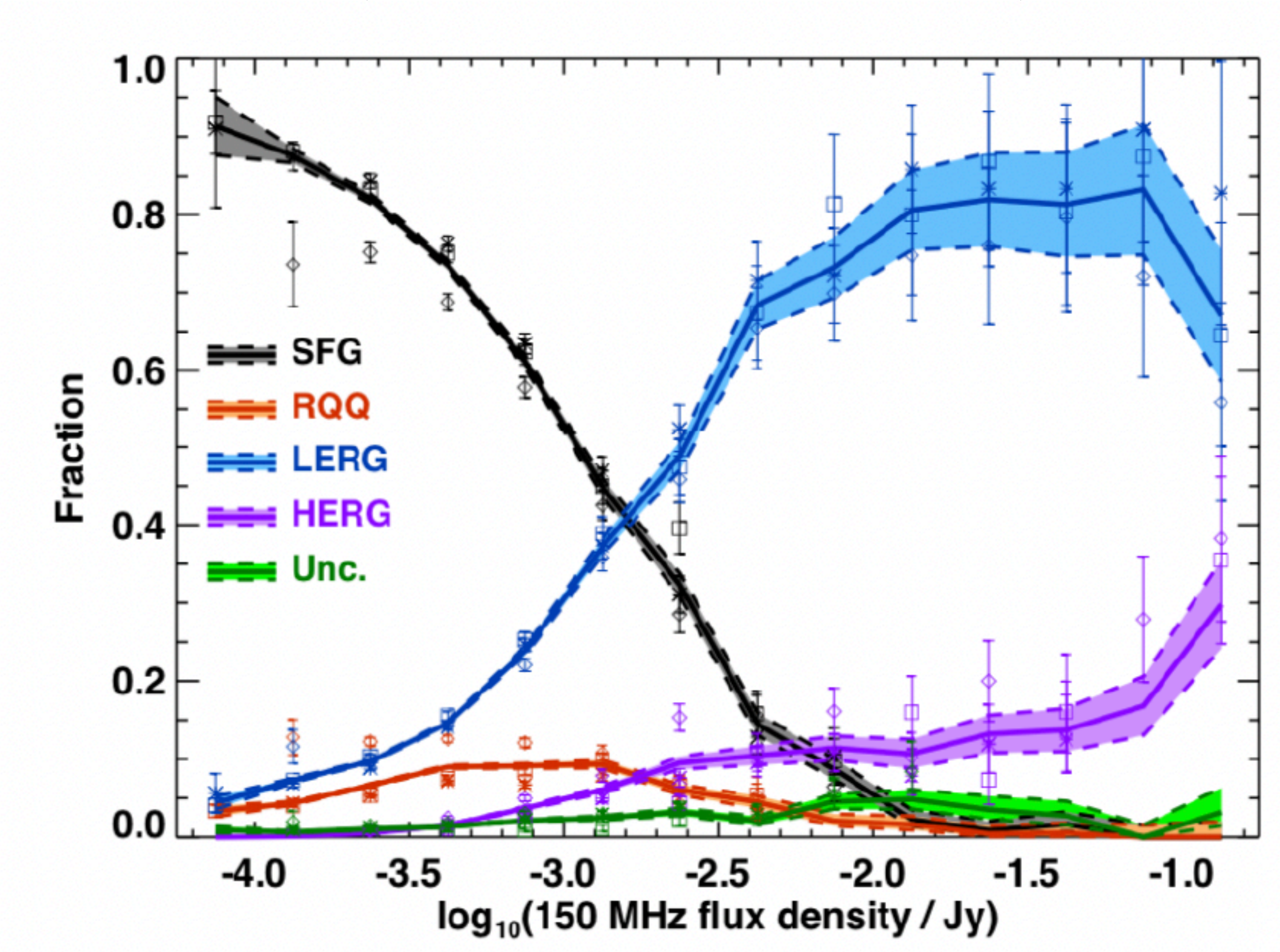
- Found rare hosts such as spiral galaxies.



Oei+ 2023

Active Galactic Nuclei and star formation

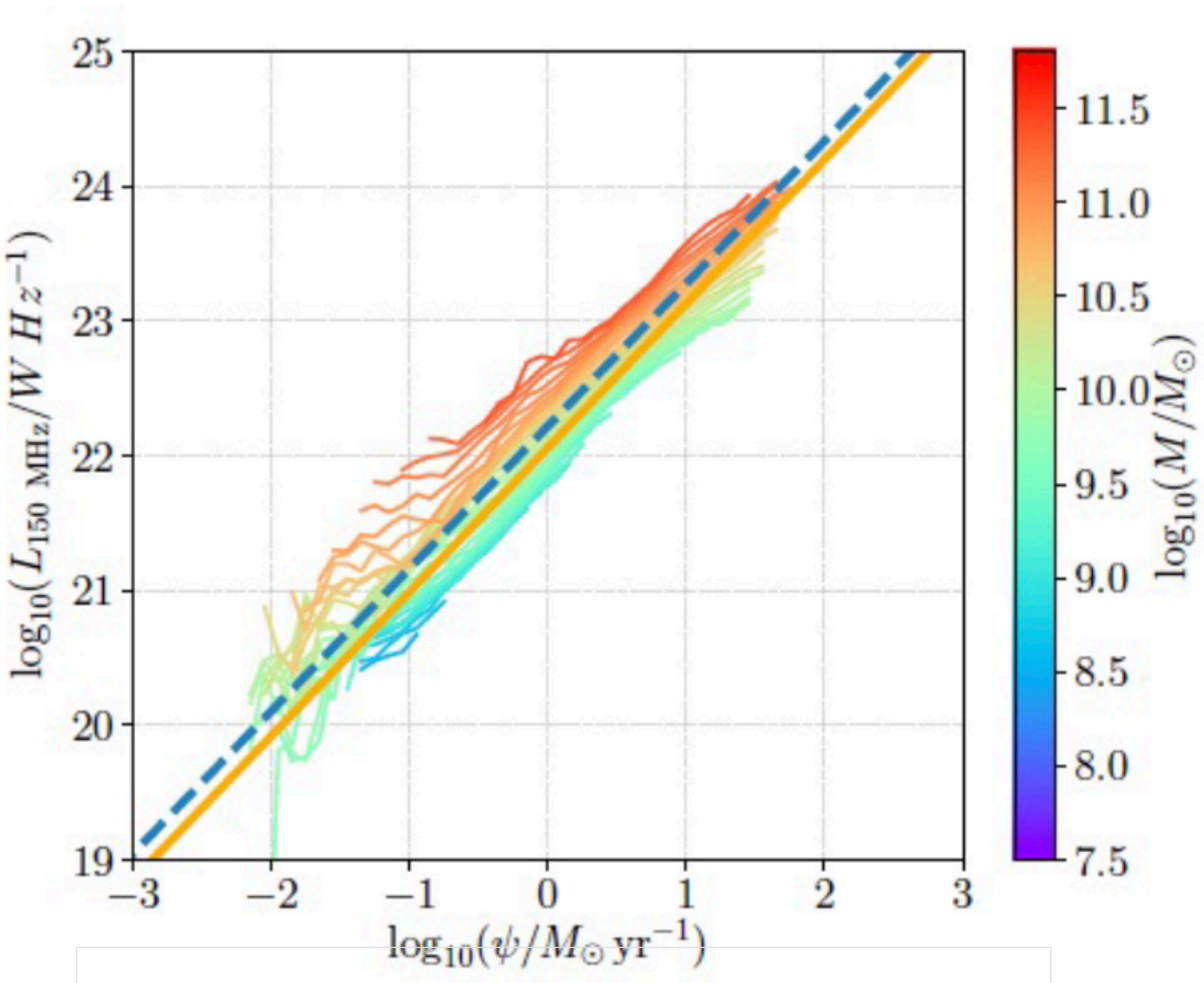
Many statistical studies

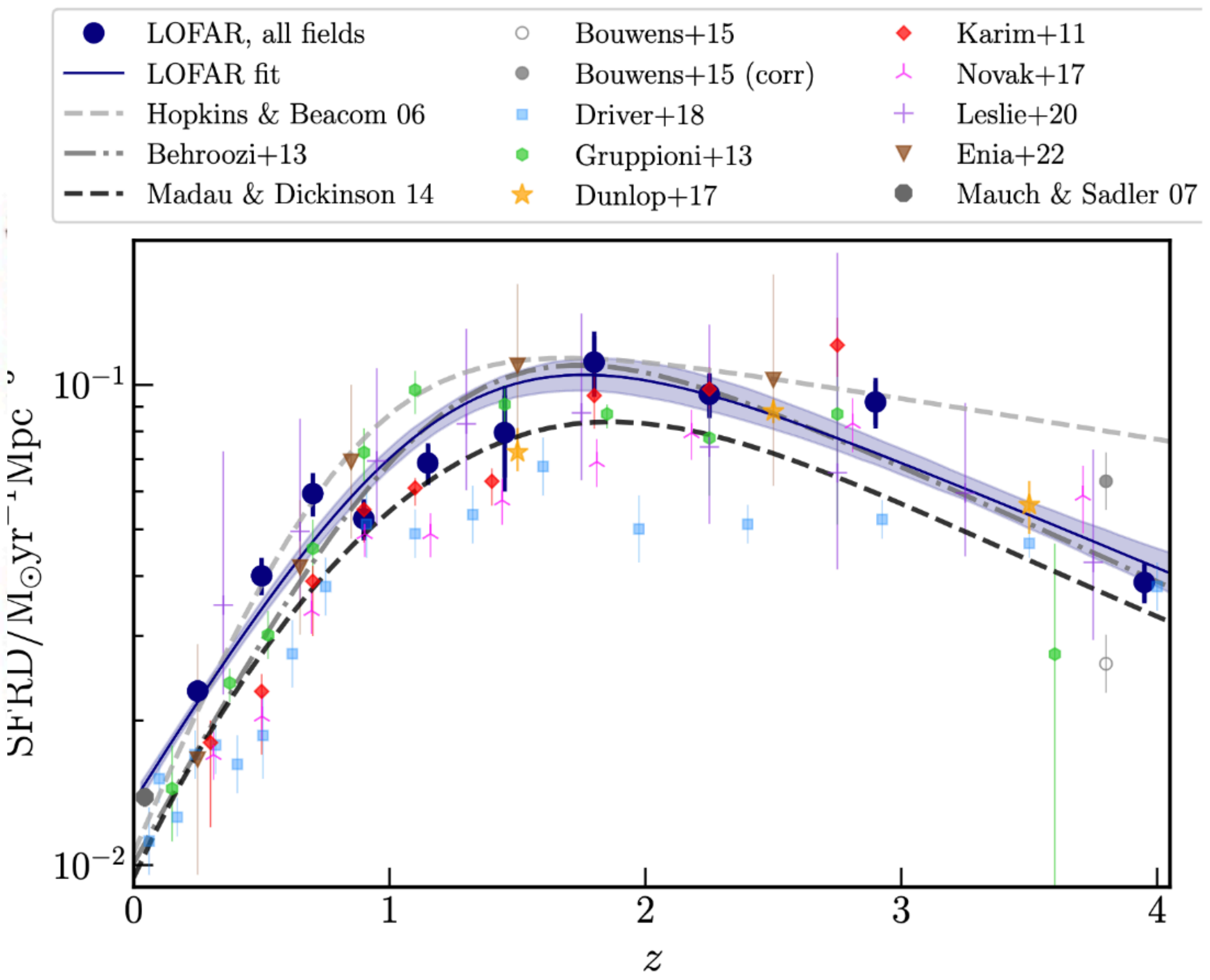


The population fraction of star-forming galaxies (SFGs), radio-quiet quasars (RQQs), low-excitation radio galaxies (LERGs), high-excitation radio galaxies (HERGs) and unclassified objects (Unc/Unclass). Best+ 2023

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)

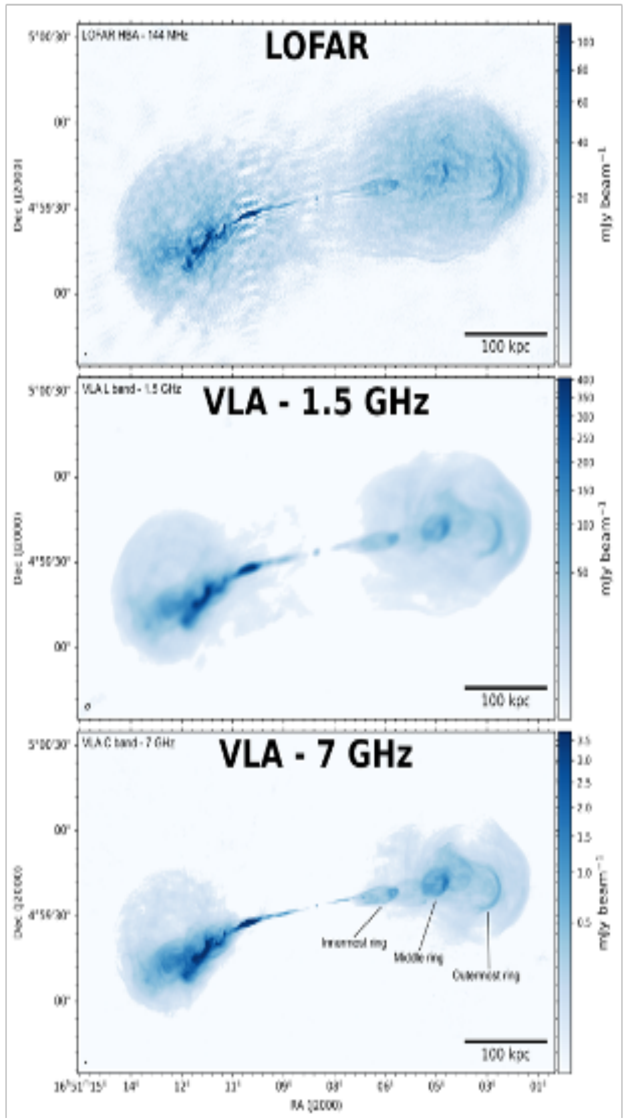
Active Galactic Nuclei and star formation

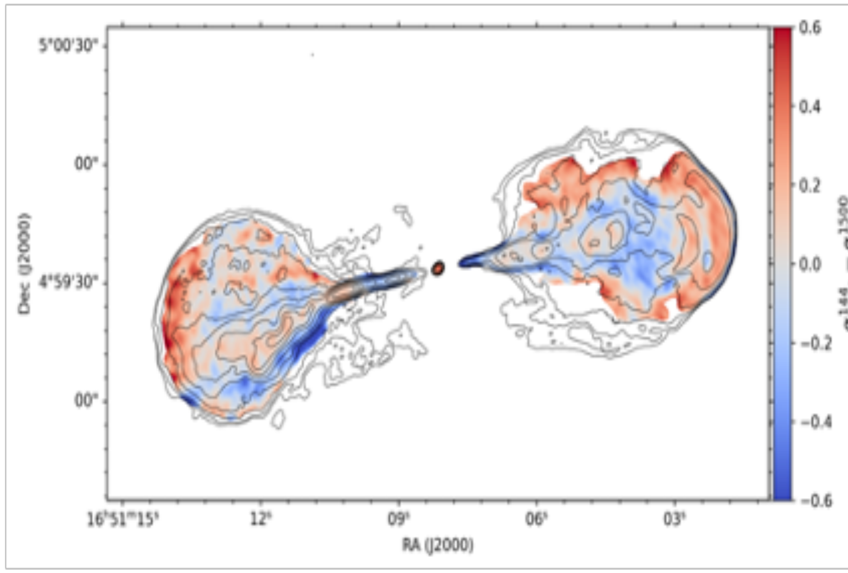
The sensitivity and resolution allows for detailed studies of individual targets too.

Timmerman et al. 2022

The origin of the rings in Hercules A

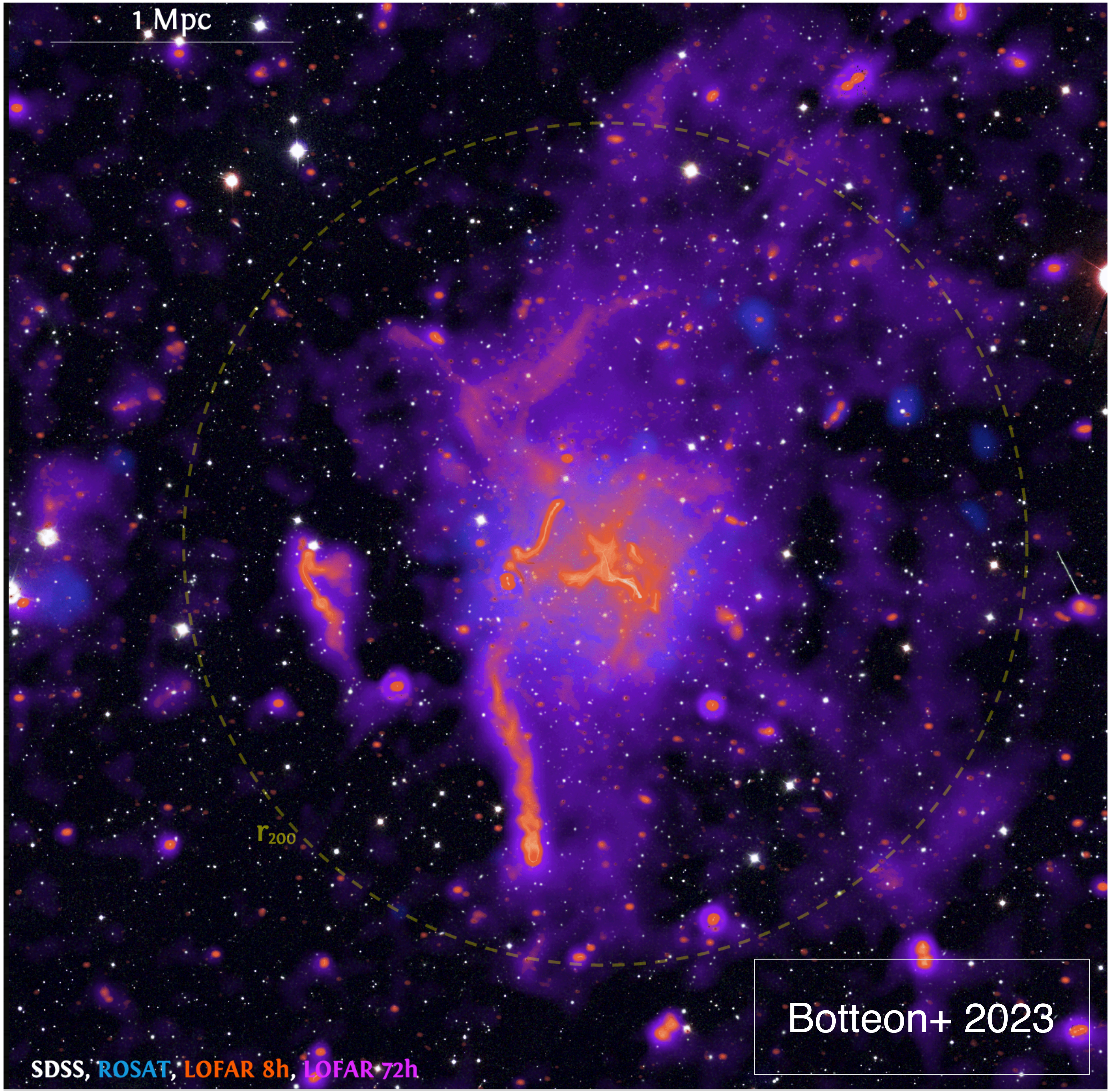
(Timmerman et al., 2022)





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

Extra galactic - Galaxy clusters

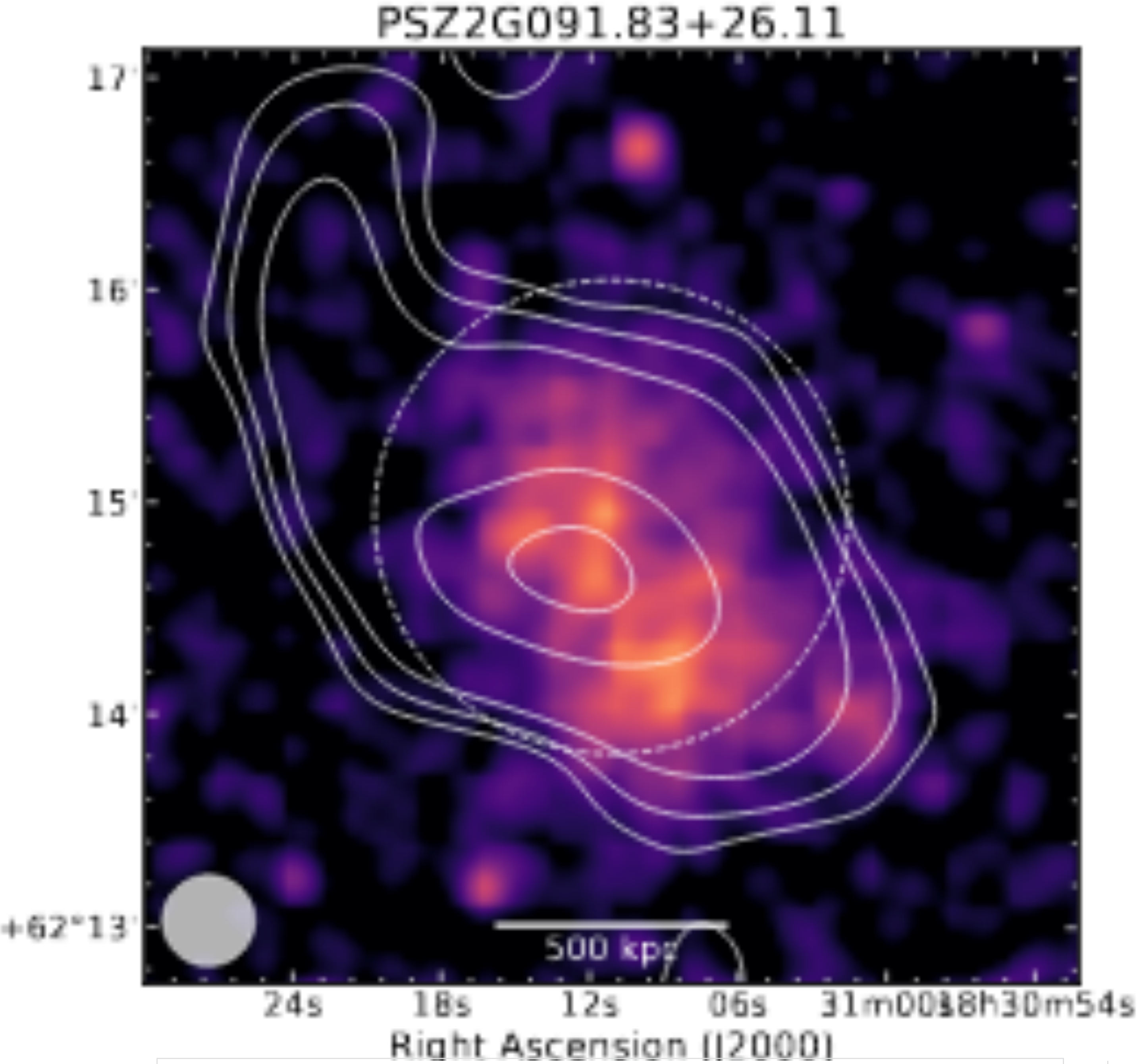


Cluster environments full of shocks and turbulence which accelerate particles.

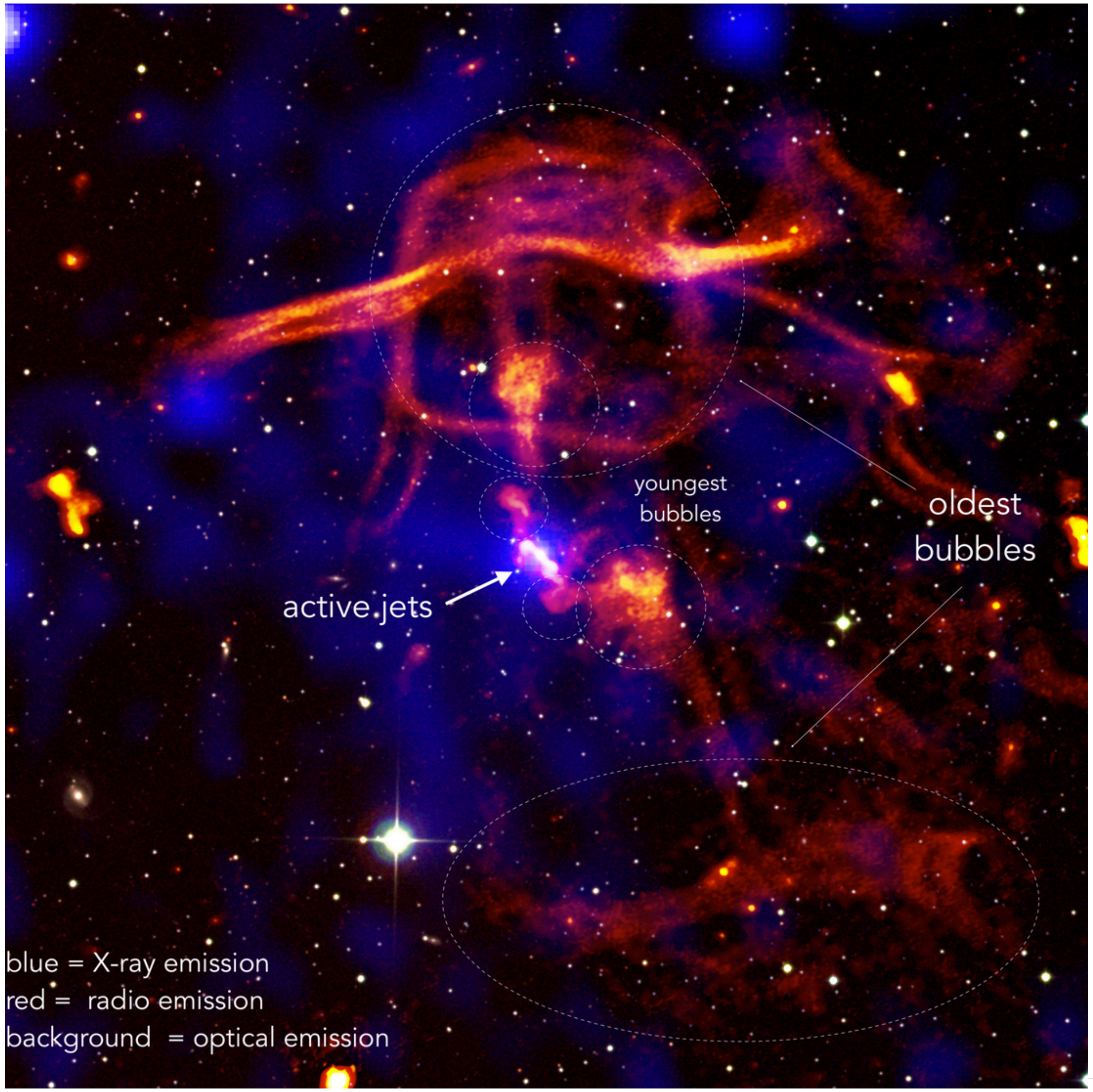
Accelerated particles in the weak cluster fields produce steep spectrum radio emission.

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

Galaxy clusters

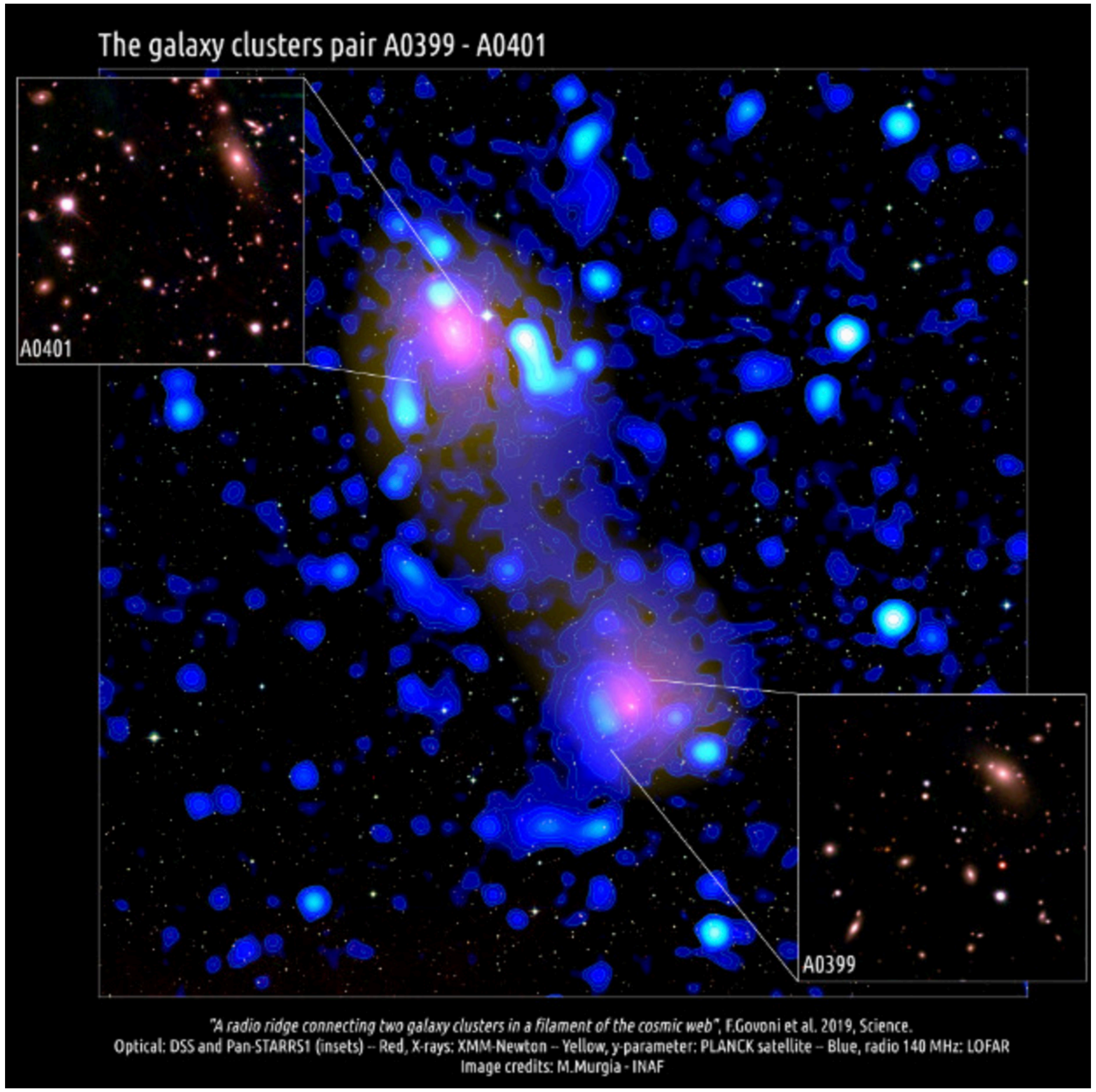


Higher than expected magnetic fields in clusters at high-z Di Gennaro + 2020

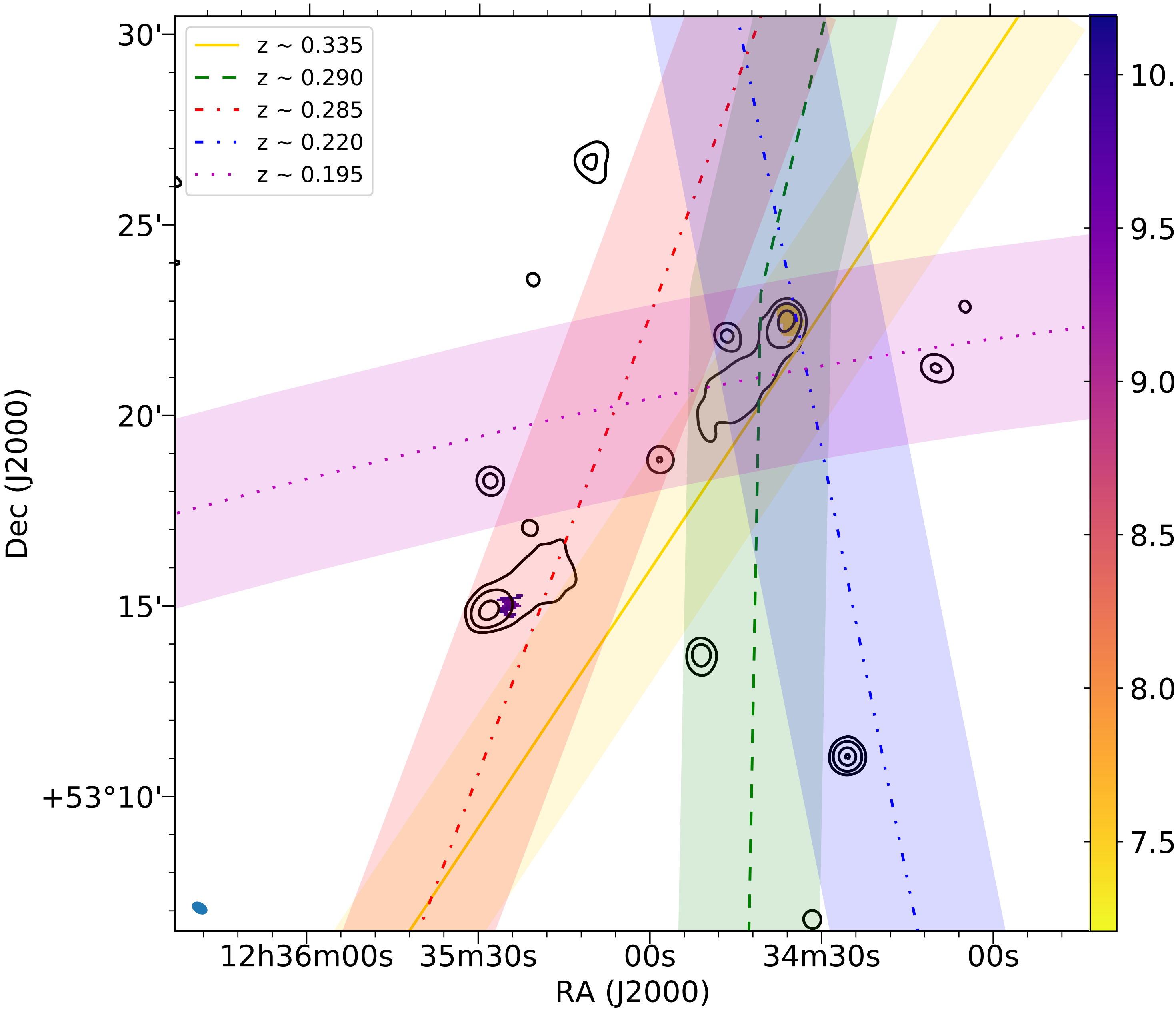


Complex particle acceleration in clusters - Brienza+ 2021

Beyond galaxy clusters


The galaxy clusters pair A0399 - A0401

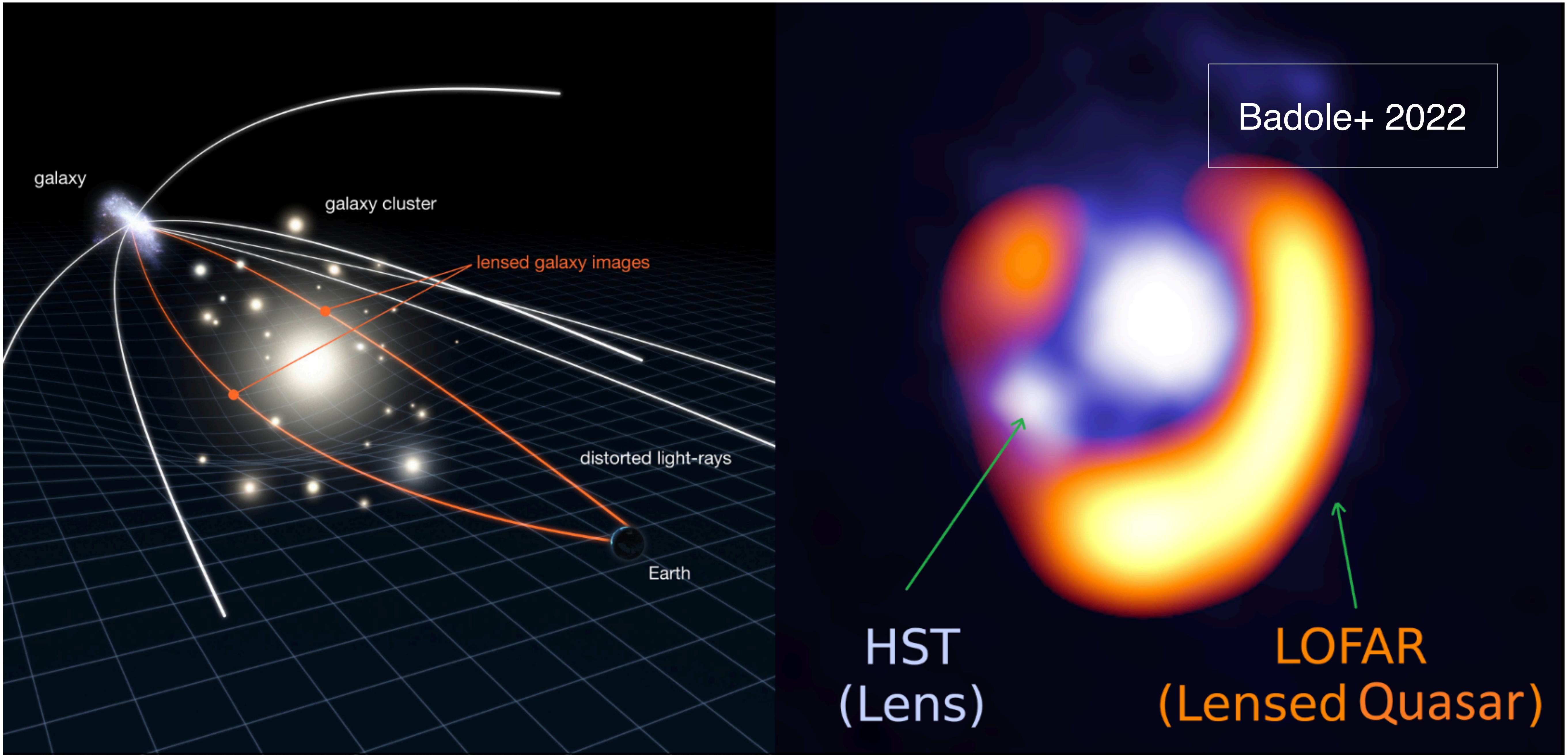
"A radio ridge connecting two galaxy clusters in a filament of the cosmic web", F.Govoni et al. 2019, Science.
Optical: DSS and Pan-STARRS1 (insets) -- Red, X-rays: XMM-Newton -- Yellow, y-parameter: PLANCK satellite -- Blue, radio 140 MHz: LOFAR
Image credits: M.Murgia - INAF



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.

Cosmology

- Characterise stochastic process of **cosmic large scale structure**
  Motivation: Is the sample fair (complete, etc.)? Are radio sources drawn from a Poisson process?
  Probe: **Counts-in-cells** (LoTSS-DR1: Siewert et al. 2020)

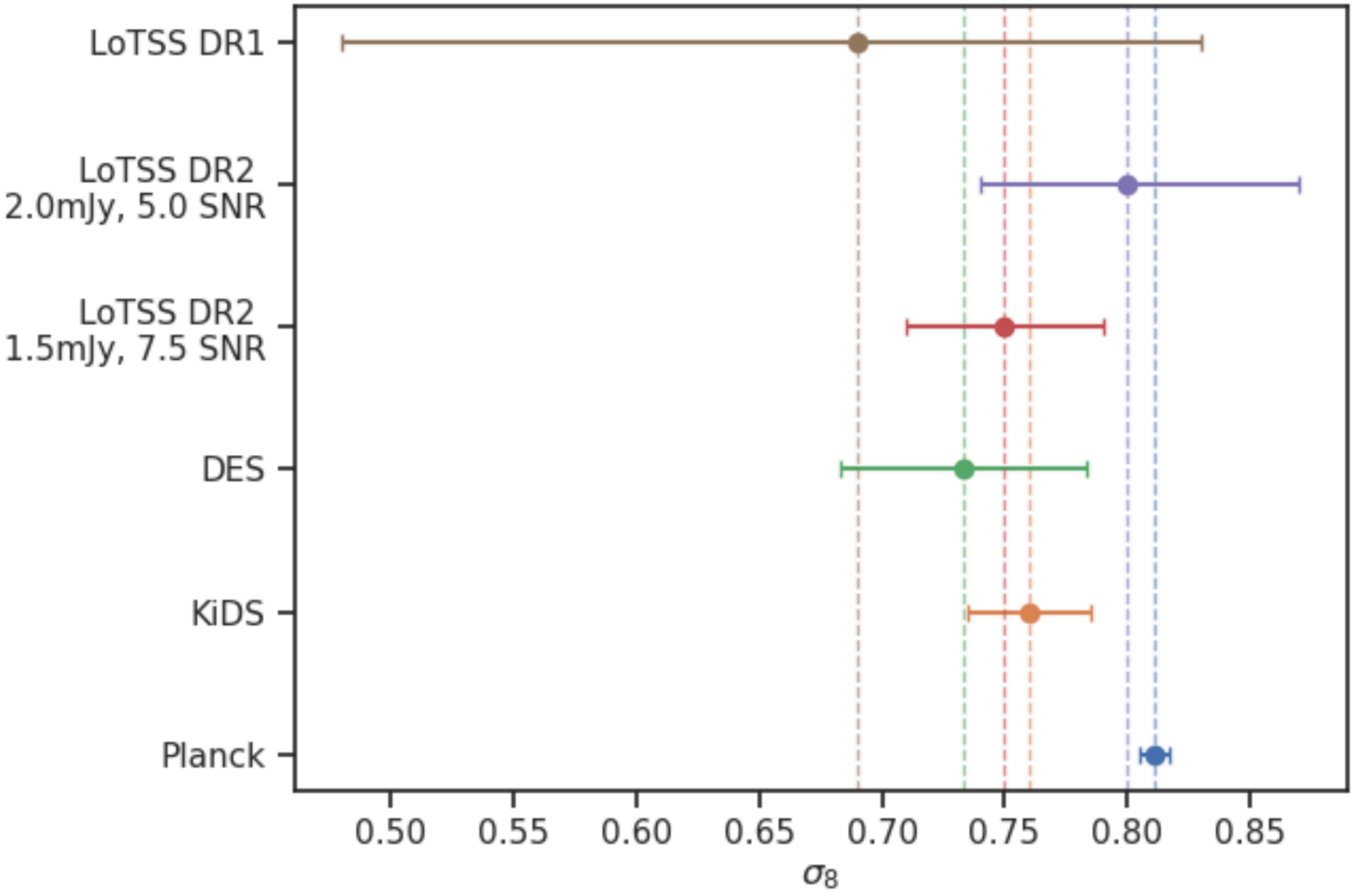
- Constrain **cosmological parameters**
  Motivation: Several tensions in cosmology: H_0, S_8/σ_8, curvature, …
  No evidence for non-Gaussianity so far: two-point statistics
  Probe: **Auto- and cross-correlations at small angles**
  (LoTSS-DR1: Siewert et al. 2020, Alonso et al. 2021, Tiwari et al. 2022)

- Does the **rest-frame of matter** agree with the CMB frame?
  Motivation: Excess of radio source and quasar count dipoles (Secreste et al. 2022, Wagenveld et al. 2023)
  Frequency dependence of radio source count dipole? (Siewert et al. 2021)
  Challenge to the Cosmological Principle (for recent summary see e.g. Peebles 2022)
  Probe: **Dipole in radio source counts**

Clustering strength

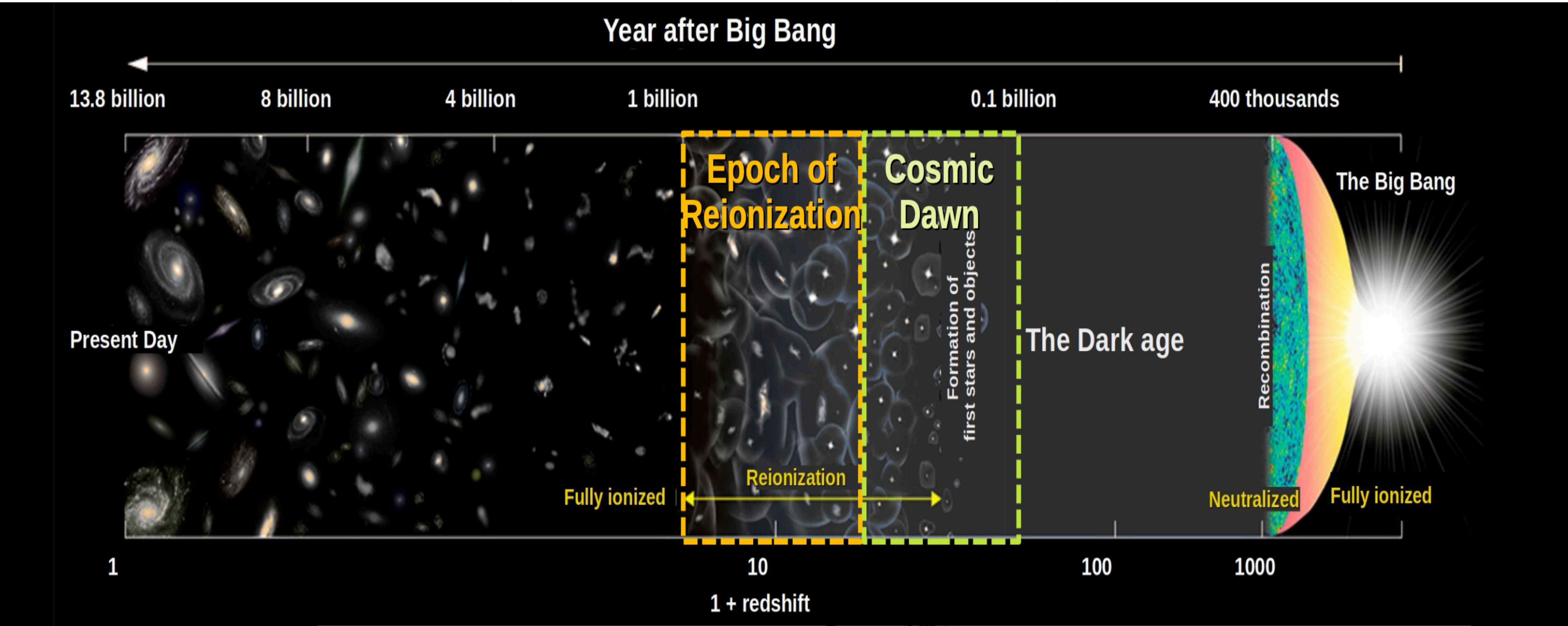
Can LOFAR help to resolve the σ_8 tension ?

- σ_8 measures rms matter density fluctuation in a ball of radius 8 h^{-1} Mpc
- **Major improvement** from DR1 Alonso et al. 2021 to DR2 Nakoneczny et al. in prep.
- Results depend on signal-to-noise ratio (SNR) and flux density cut and change within 1σ
- **LOFAR starts to be competitive with dedicated surveys like DES and KiDS**



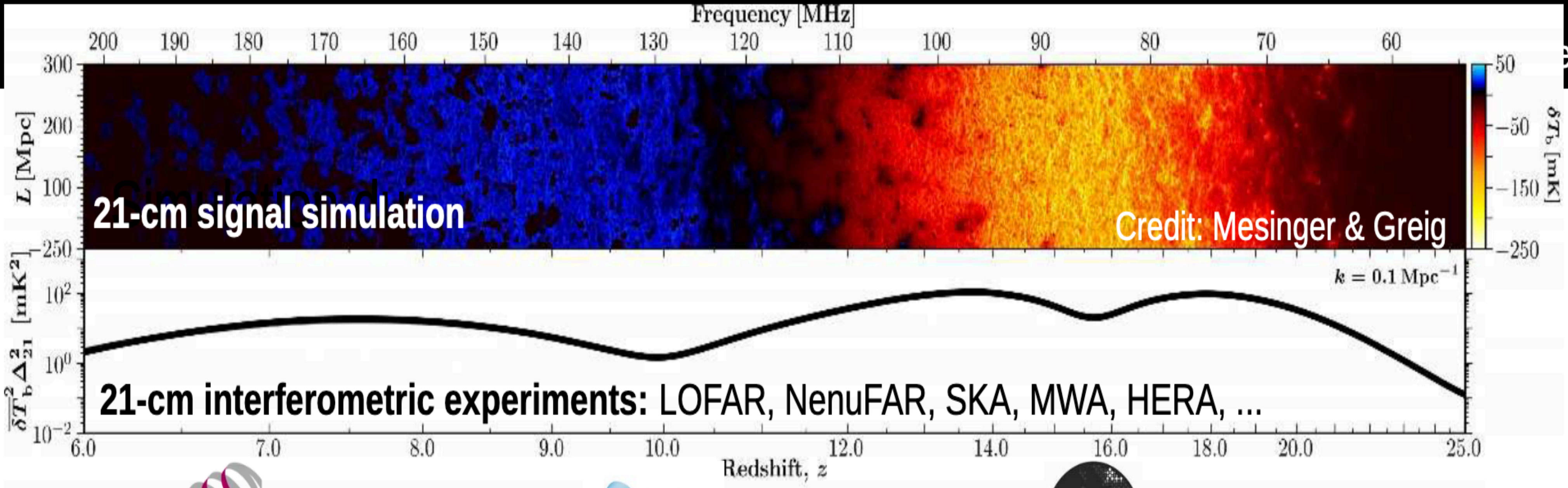
Nakoneczny et al. in preparation

Epoch of reionisation



edit: NAOJ

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

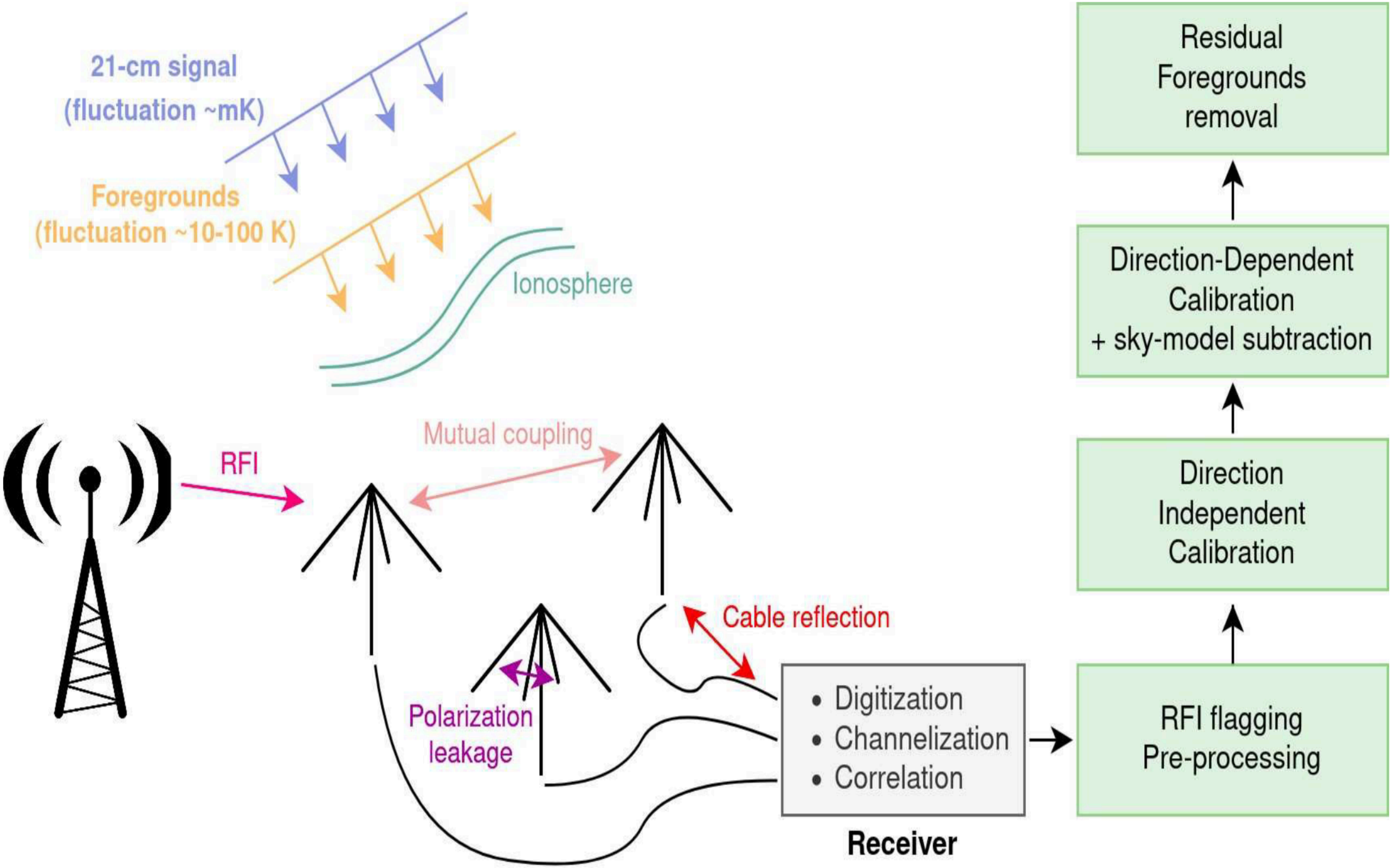


Credit: Mesinger & Greig

21-cm interferometric experiments: LOFAR, NenuFAR, SKA, MWA, HERA, ...

LOFAR SKA NenuFAR

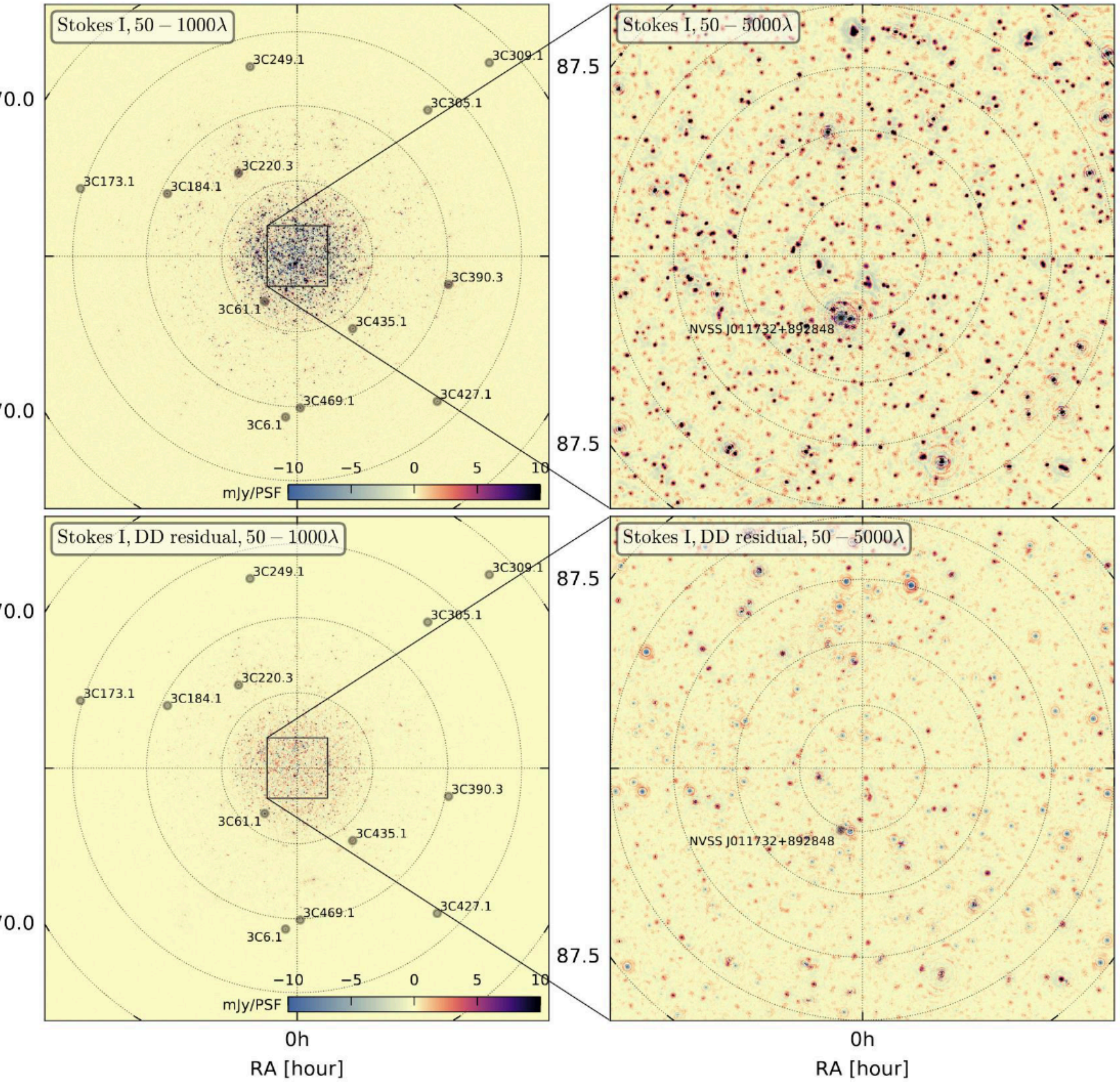
Epoch of reionisation



Epoch of reionisation

Wide-field Image

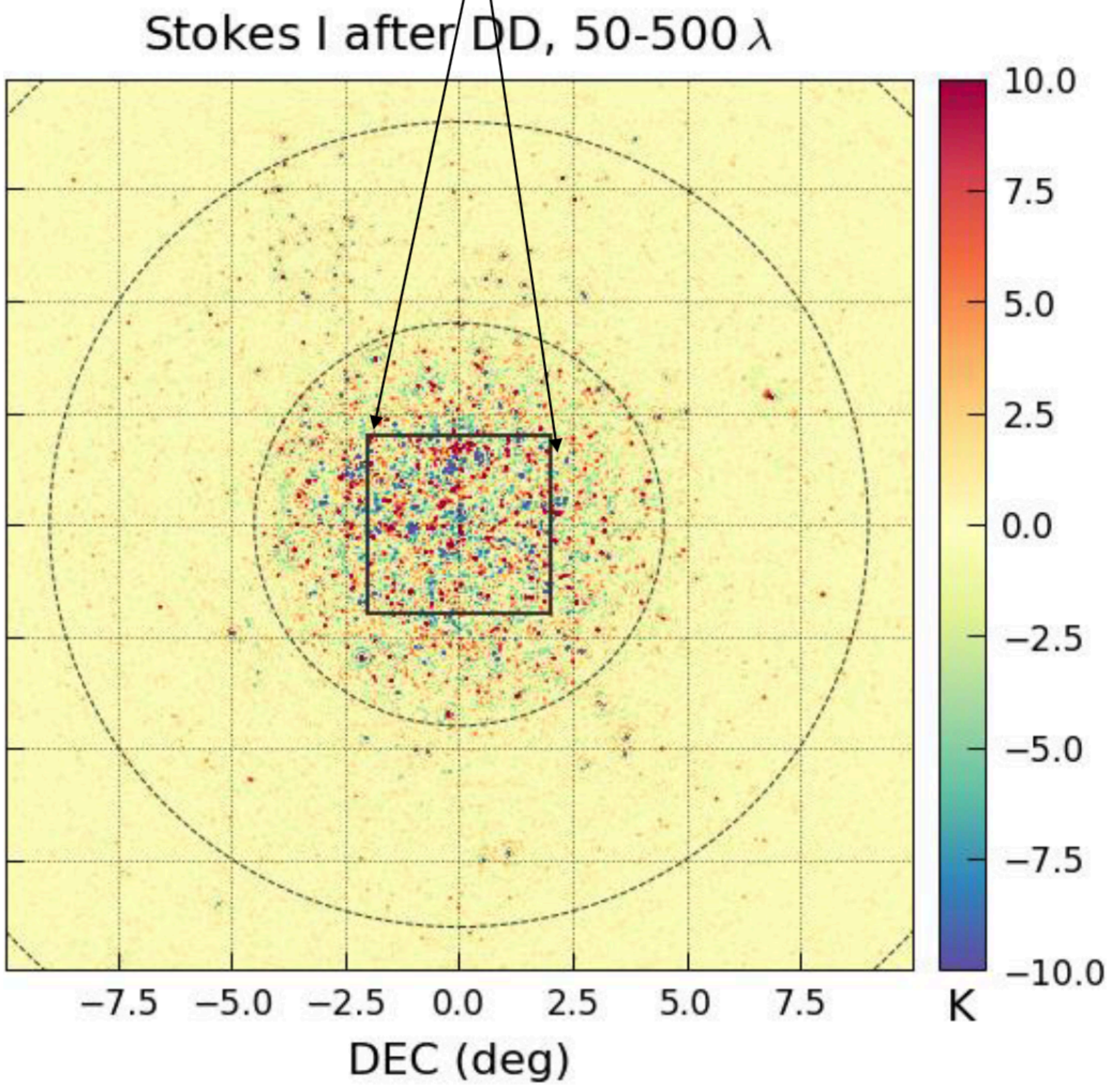
Zoom-in



Post Sky-Model Subtraction

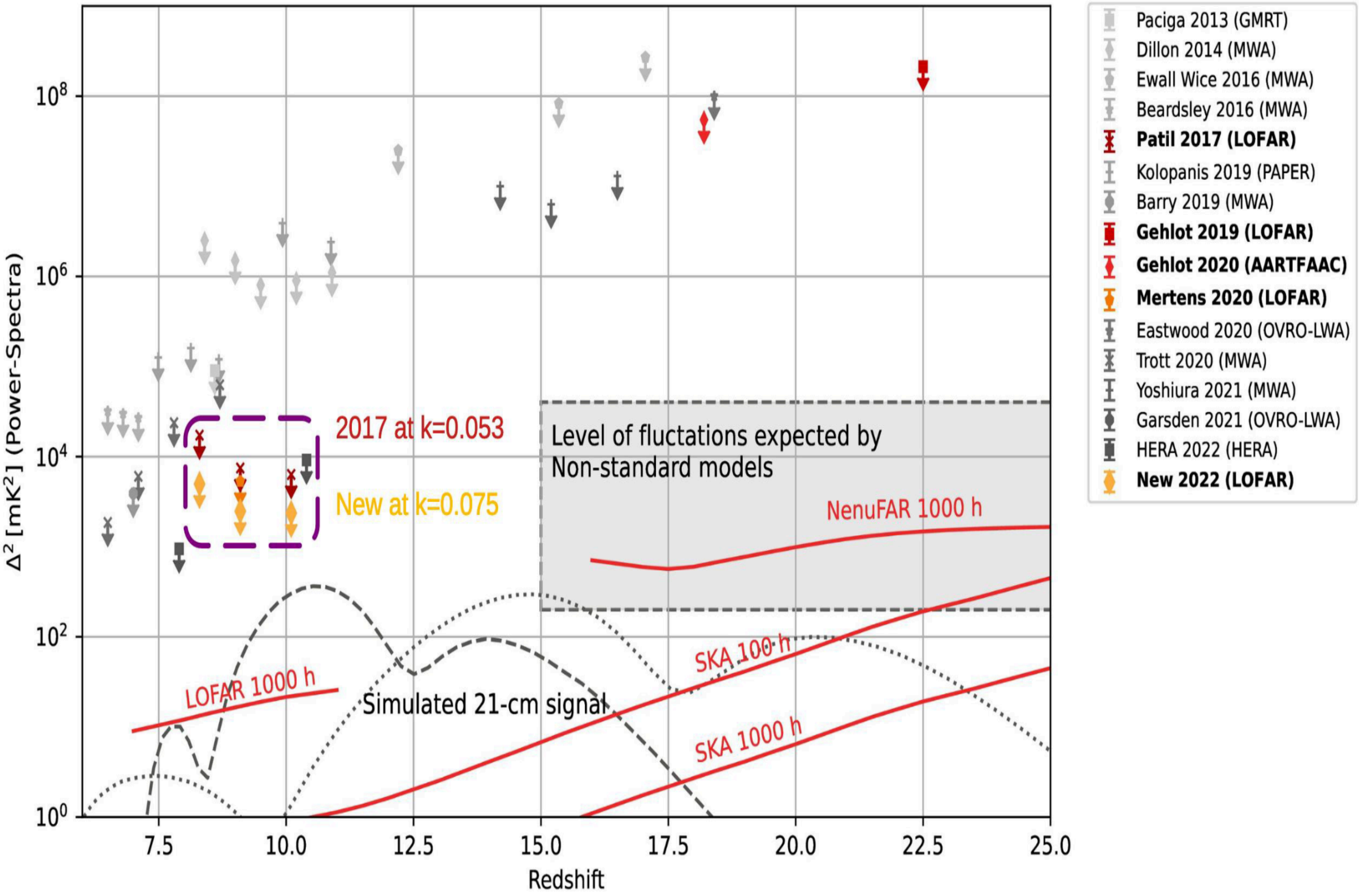
Zoom-in

Inner 4x4 where we look for the signal



Mertens et al. 2020

Epoch of reionisation



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)

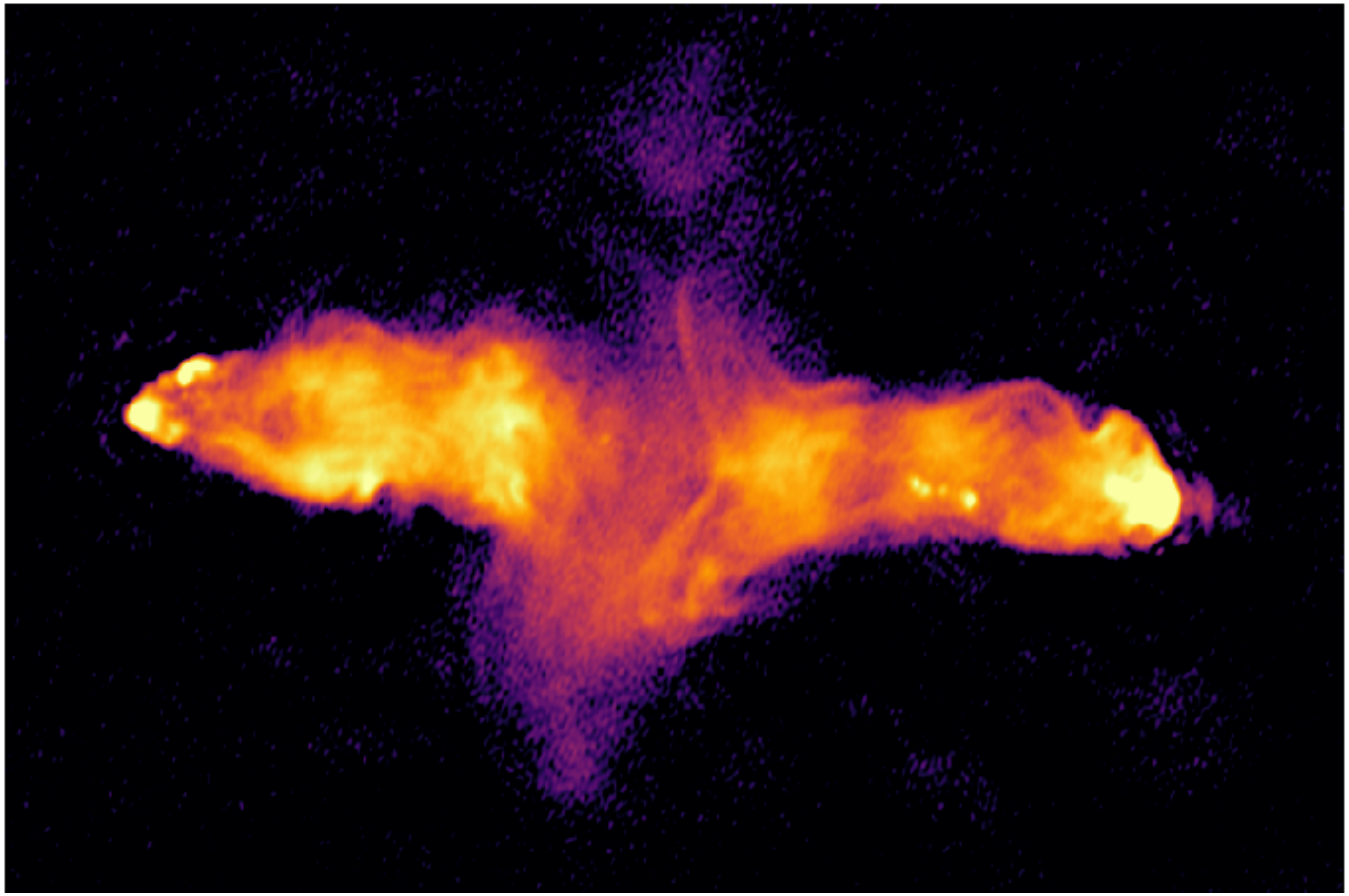
(Euclid Deep Field North, ELAIS-N1, Lockman Hole, Boötes)

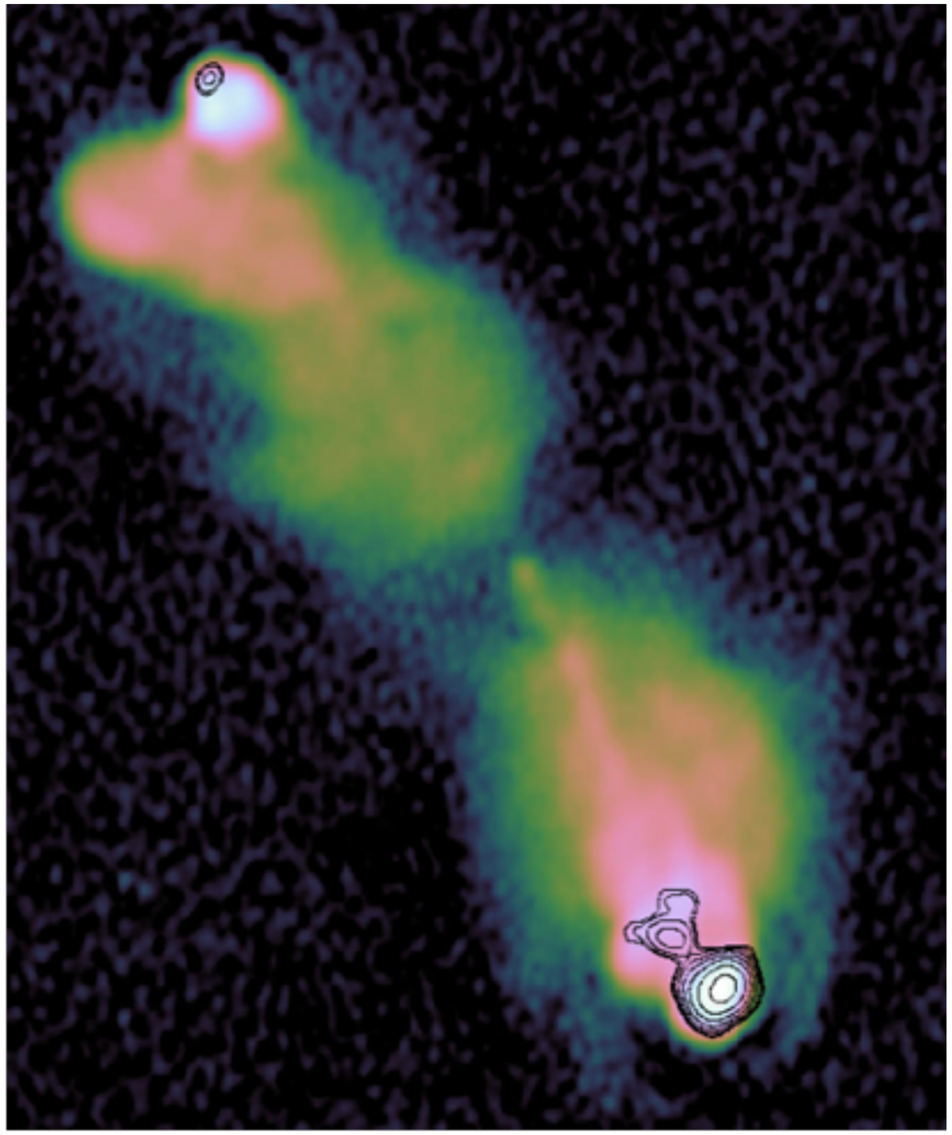
Surveys starting Spring 2024…

Some upcoming developments

More routine high resolution imaging

Mahatma+23

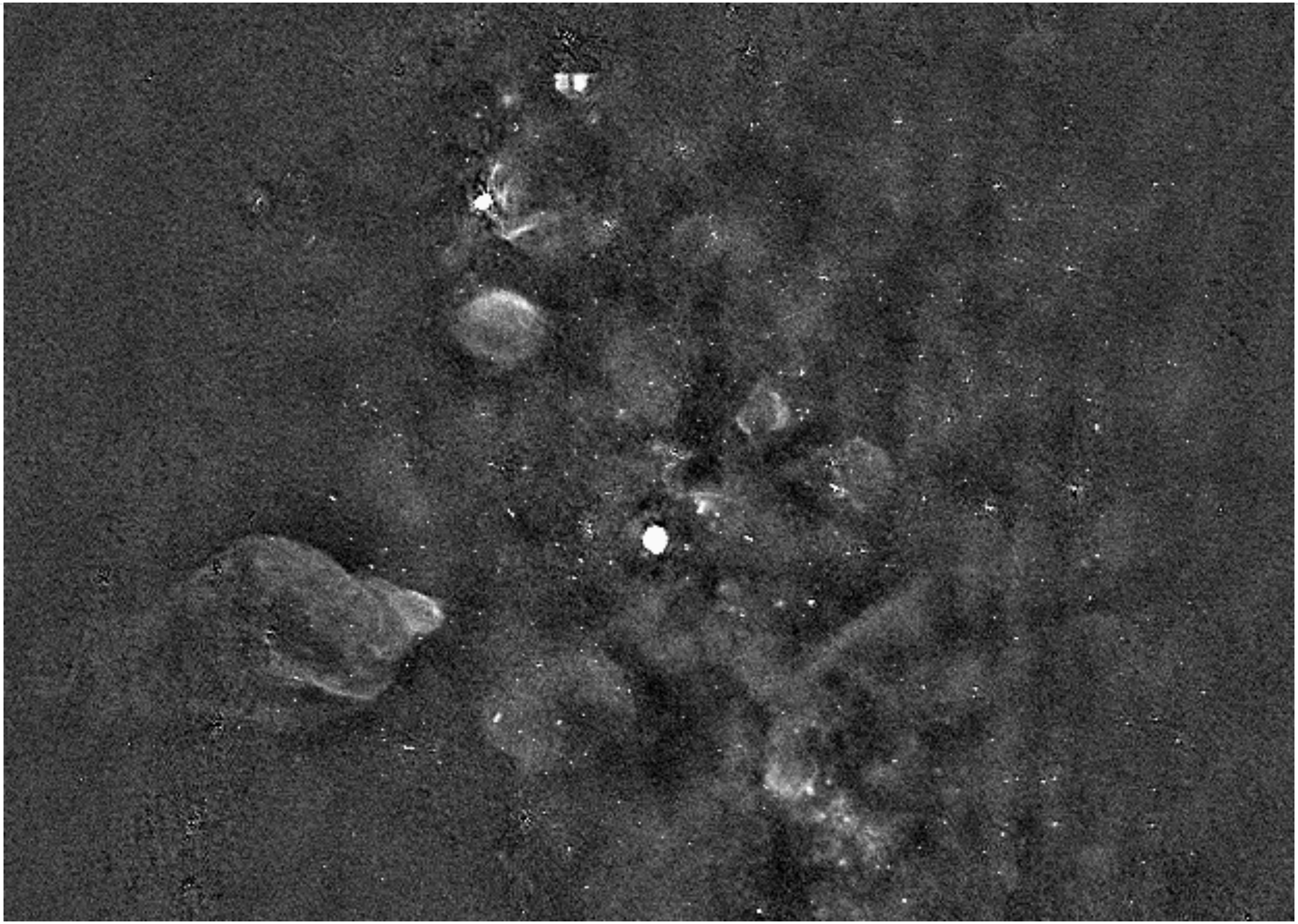




van Weeren et al., in prep.

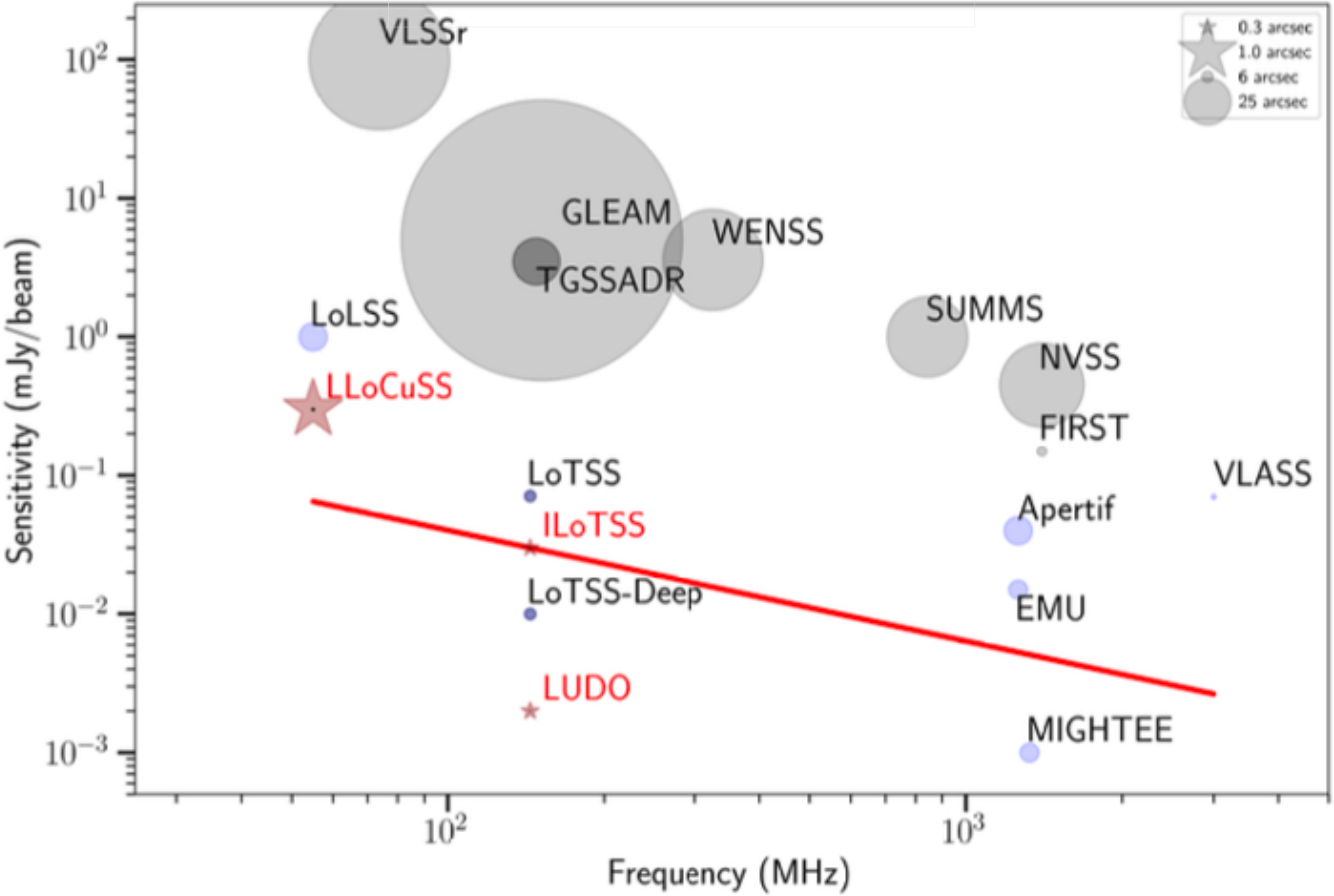
Some upcoming developments

Imaging the most complex parts of the galaxy in the northern hemisphere



Some upcoming developments

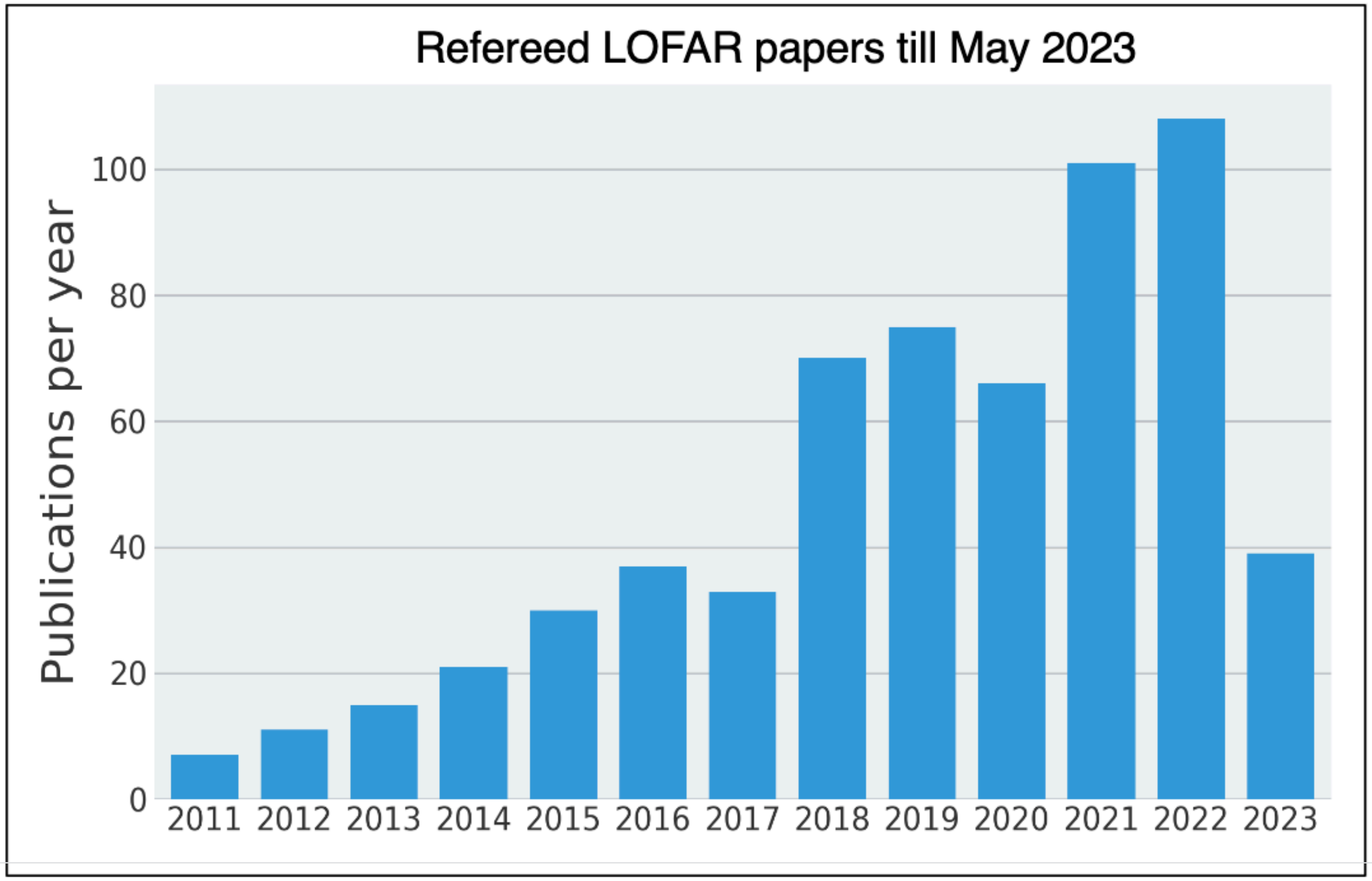
New possibilities with LOFAR2.0



Summary

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

Major upgrade of LOFAR coming soon making it an even better instrument (better LBA sensitivity, faster observing)



LOFAR output is in the top 10% of all astronomy facilities.