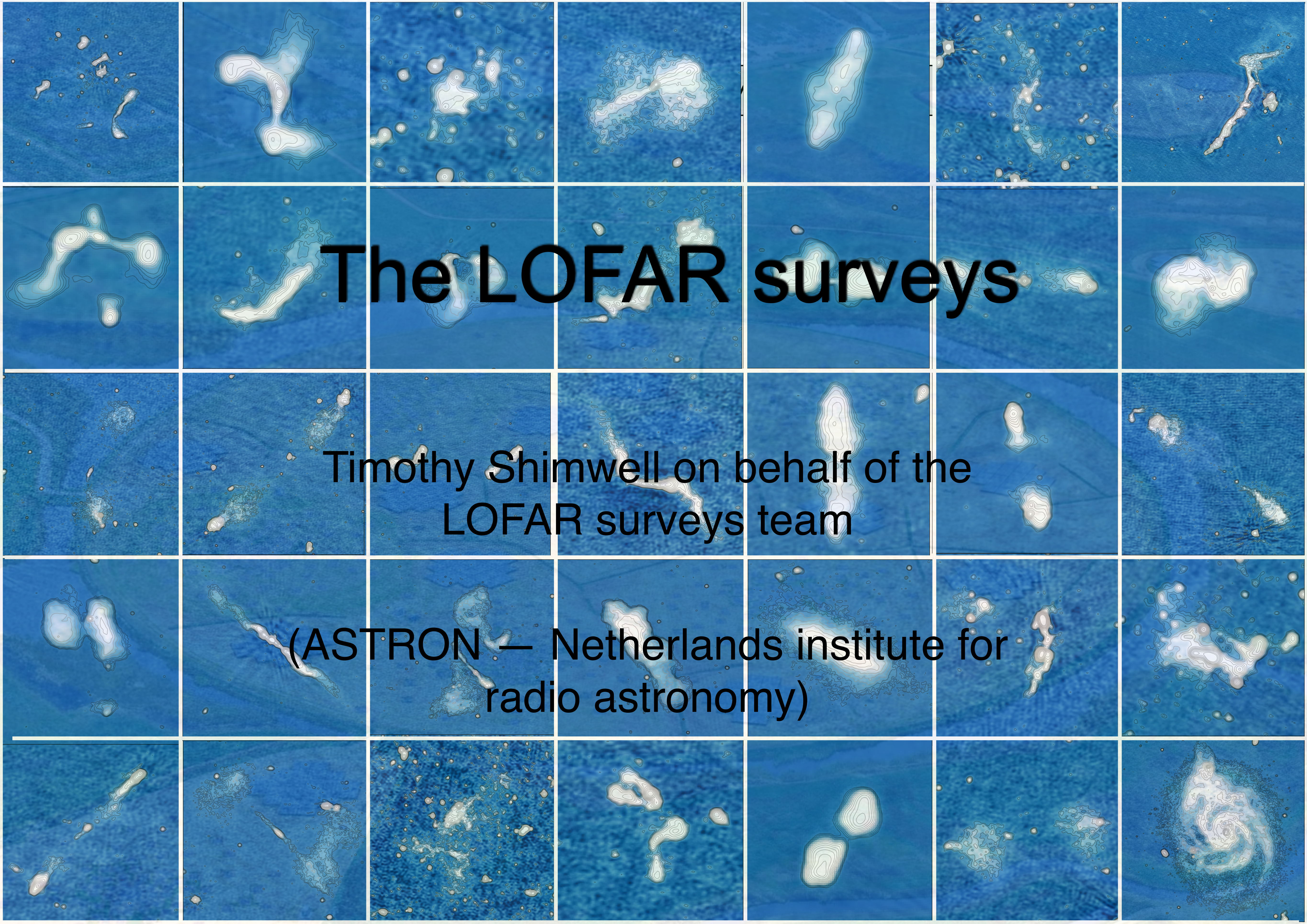


The LOFAR surveys

Timothy Shimwell on behalf of the
LOFAR surveys team

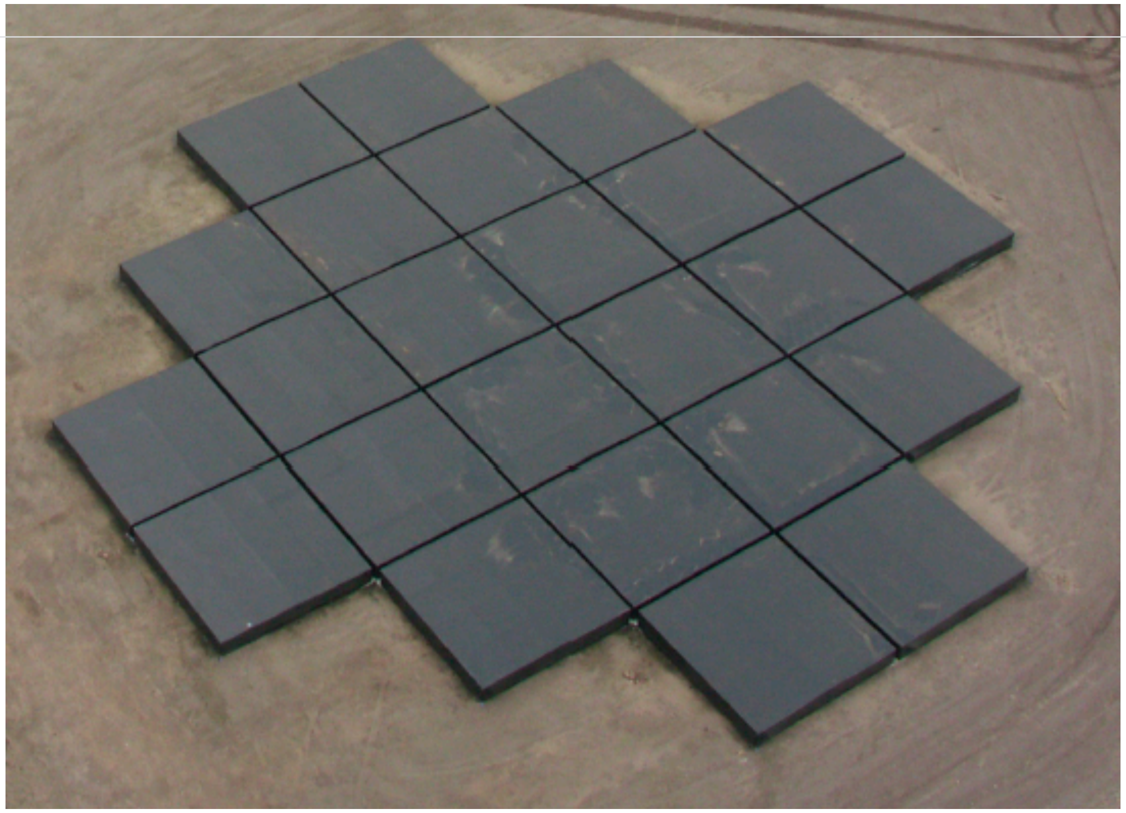
(ASTRON — Netherlands institute for
radio astronomy)

The LOFAR surveys team

190 members from ~30 institutes, over 6,000 hours of observations, well over 10PB of data and lots of hard work.

LOFAR

High band antenna (HBA; 110-250MHz)

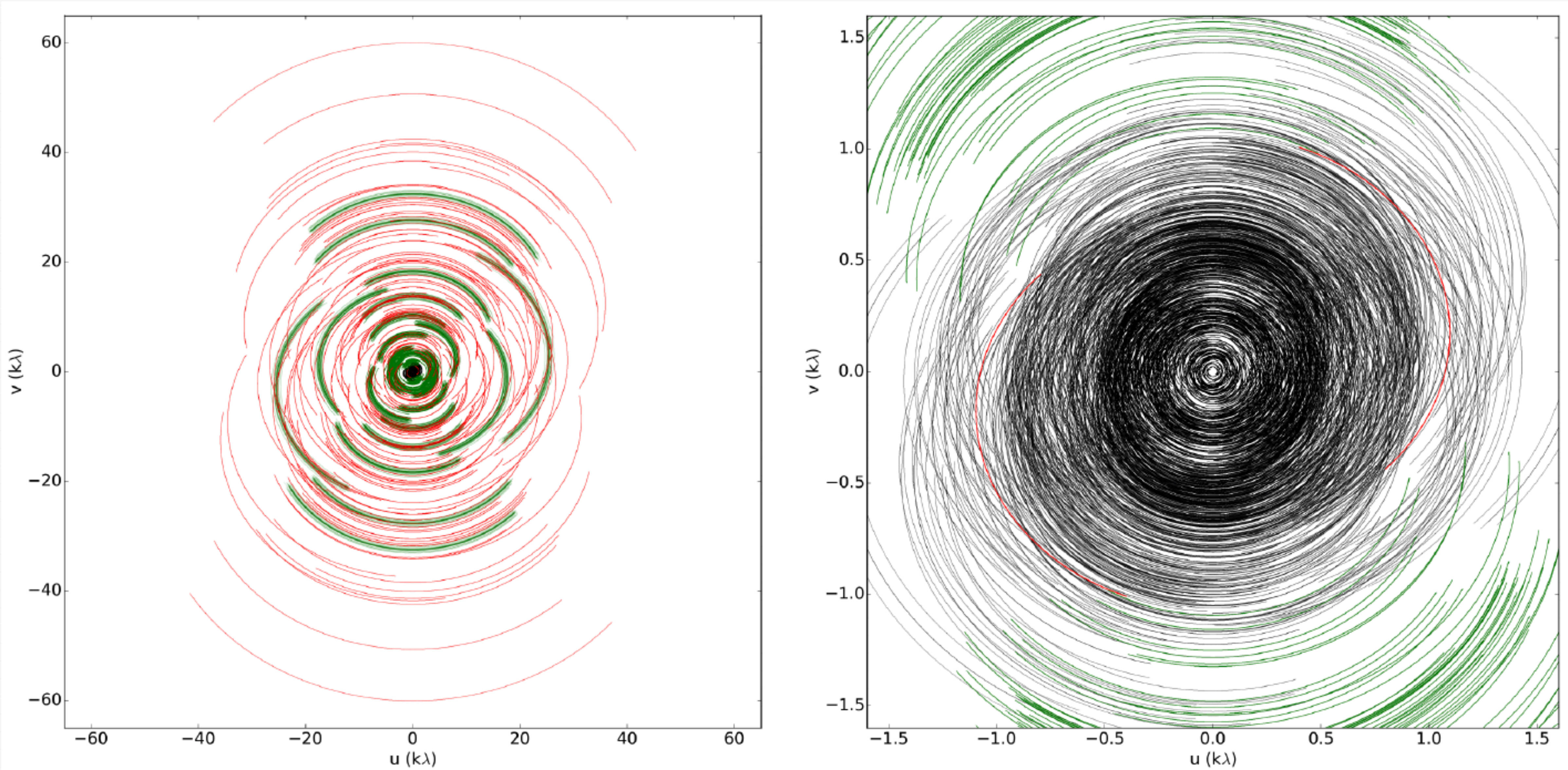


Low band antenna (LBA; 1090MHz)

- 24 core (<2km or 2’ resolution), 14 remote (<120km or 5” resolution) and 13 international stations (<1600km or 0.25’’ resolution)
- The total HBA collecting area is up to 70,000 square metres.
- Sensitive (in 8 hrs HBA 0.1mJy/beam and LBA ~1mJy/beam)

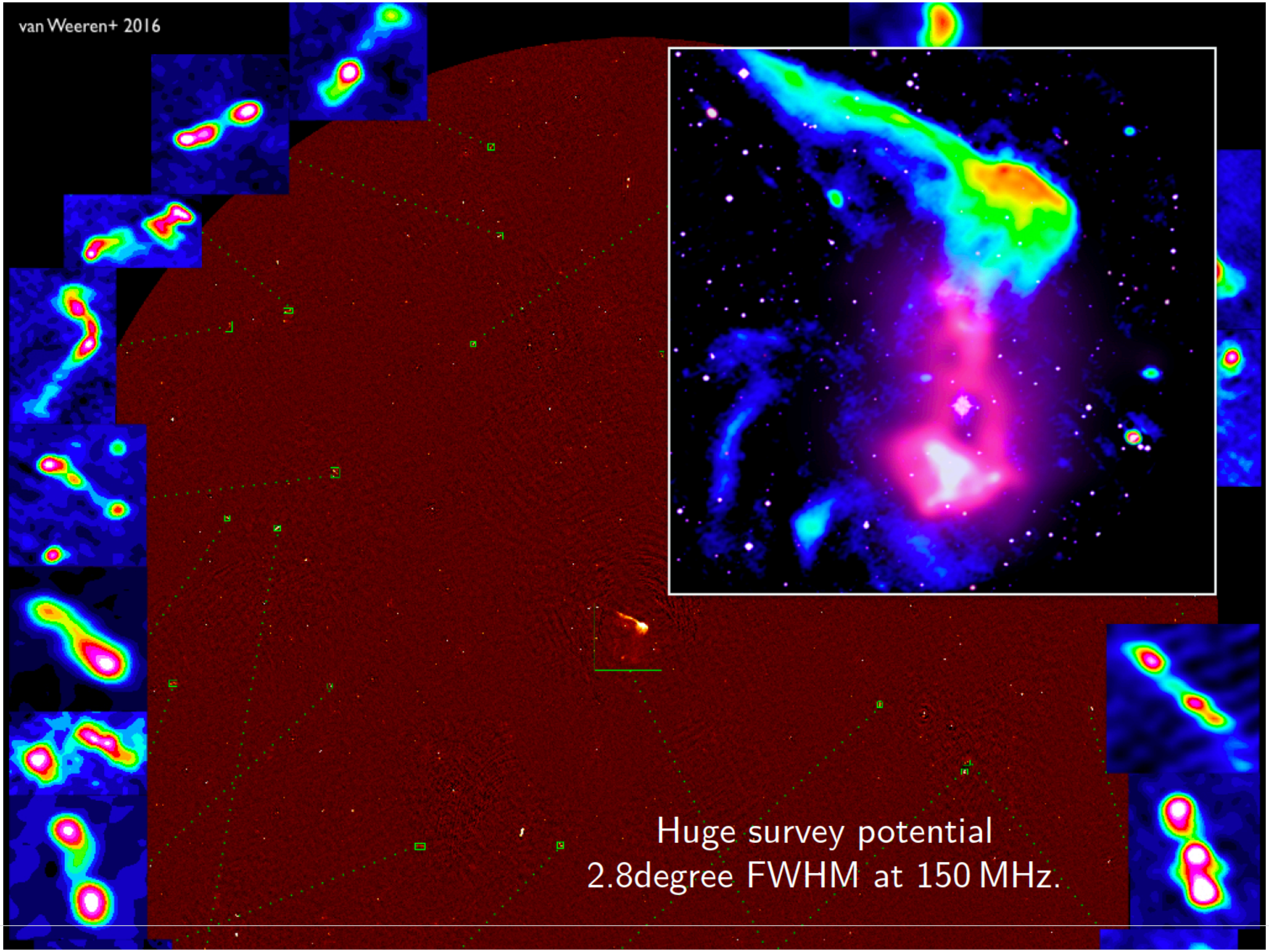
A LOFAR core station with two HBA and one LBA.

LOFAR



High angular resolution (6”) combined with excellent surface brightness sensitivity.
Recover very extended emission and image at high resolution.

LOFAR



Huge challenges with wide field imaging (20,000x20,000 pixels), ionospheric errors severe at 6arcsec resolution, serious beam model errors and massive data rates (16TB per dataset).

Scientific aims of the LOFAR surveys

- Highest redshift radio sources: George Miley
- Clusters and cluster halo sources: Gianfranco Brunetti & Marcus Brüggen
- Evolution of AGN and star forming galaxies: Philip Best
- Detailed studies of low-redshift AGN: Raffaella Morganti
- Nearby Galaxies: Krzysztof Chyzy & John Conway
- Gravitational lensing: Neal Jackson
- Galactic radio sources: Glenn White & Marijke Haverkorn
- Cosmological studies: Matt Jarvis

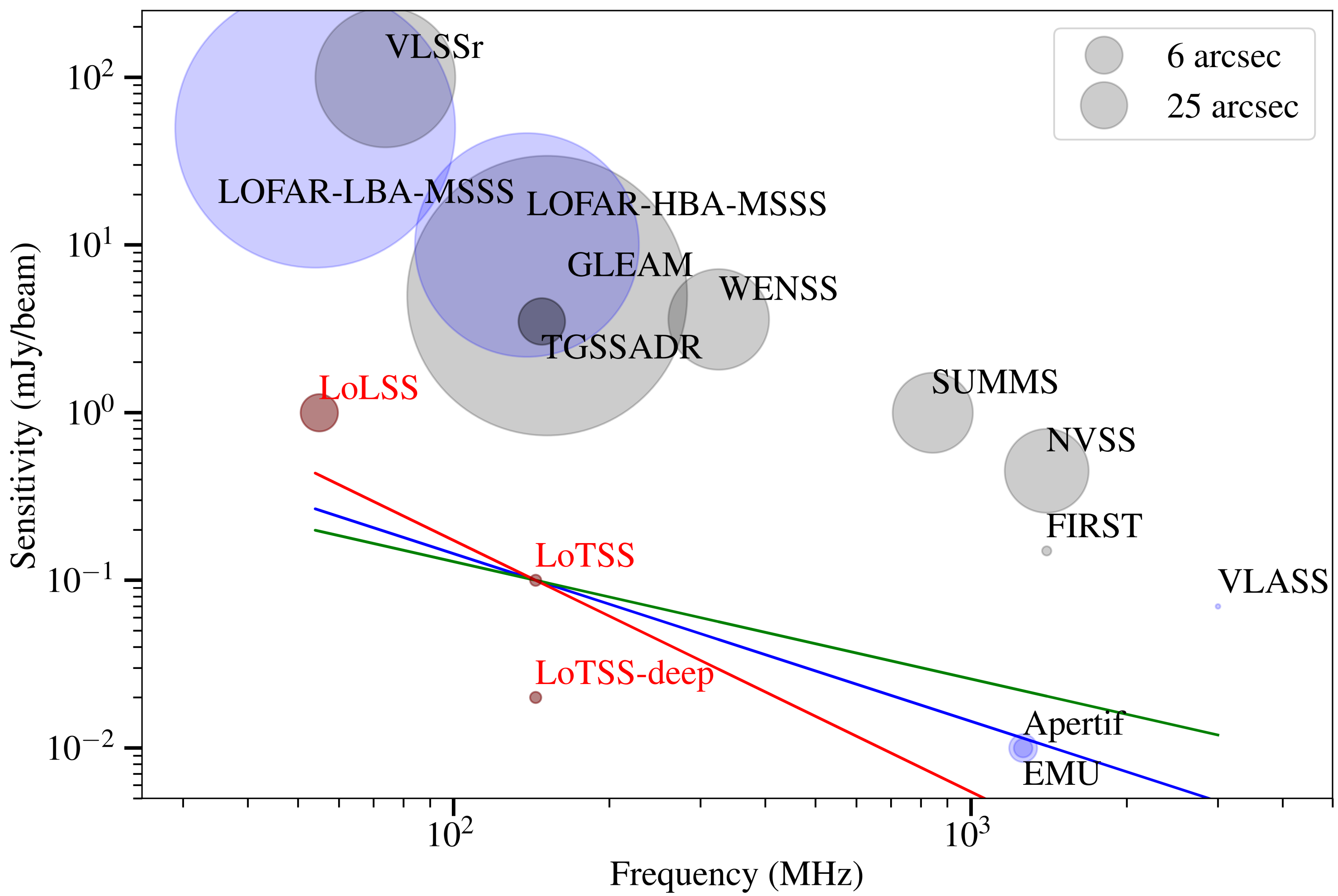
Collaborations with the LOFAR magnetism, transient and the EoR groups

The LOFAR surveys

~14,000hrs of LOFAR HBA observations are required for **LoTSS**. 120-168MHz, 6" resolution, 0.1mJy/beam noise. Over 35% complete

Over 500hrs on **LoTSS deep** fields (primarily ELAIS-N1, Lockman hole and Bootes). 120-168MHz, 6" resolution, ~0.02mJy/beam noise

LBA survey, **LoLSS**, only preliminary region done to date (just a few percent). 42-66MHz, 15" resolution, 1mJy/beam noise) — de Gasperin talk on Friday.



Green $\alpha = -0.7$, blue $\alpha = -1.0$, red $\alpha = -1.5$

The LOFAR Two-metre Sky Survey (LoTSS) — data release 1

T. W. Shimwell, C. Tasse, M. J. Hardcastle, A. P. Mechev, W. L. Williams, P. N. Best, H. J. A. Rottgering, J. R. Callingham, T. J. Dijkema, F. de Gasperin, D. N. Hoang, B. Hugo, M. Mirmont, J. B. R. Oonk, I. Prandoni, D. Rafferty, J. Sabater, O. Smirnov, R. J. van Weeren, G. J. White, M. Atemkeng, L. Bester, E. Bonnassieux, M. Bruggen, G. Brunetti, K. T. Chyzy, R. Cochrane, J. E. Conway, J. H. Croston, A. Danezi, K. Duncan, M. Haverkorn, G. H. Heald, M. Iacobelli, H. T. Intema, N. Jackson, M. Jamrozy, M. J. Jarvis, R. Lakhoo, M. Mevius, G. K. Miley, L. Morabito, R. Morganti, D. Nisbet, E. Orru, S. Perkins, R. F. Pizzo, C. Schrijvers, D. J. B. Smith, R. Vermeulen, M. W. Wise, L. Alegre, D. J. Bacon, I. M. van Bemmel, R. J. Beswick, A. Bonafede, A. Botteon, S. Bourke, M. Brienza, G. Calistro Rivera, R. Cassano, A. O. Clarke, C. J. Conselice, R. J. Dettmar, A. Drabent, C. Dumba, K. L. Emig, T. A. Ensslin, C. Ferrari, M. A. Garrett, R. T. Genova-Santos, A. Goyal, G. Gurkan, C. Hale, J. J. Harwood, V. Heesen, M. Hoeft, C. Horellou, C. Jackson, G. Kokotanekov, R. Kondapally, M. Kunert-Bajraszewska, V. Mahatma, E. K. Mahony, S. Mandal, J. P. McKean, A. Merloni, B. Mingo, S. Mooney, B. Nikiel-Wroczynski, S. P. O'Sullivan, J. Quinn, W. Reich, C. Roskowinski, A. Rowlinson, F. Savini, A. Saxena, D. J. Schwarz, A. Shulevski, S. S. Sridhar, H. R. Stacey, S. Urquhart, M. H. D. van der Wiel, E. Varenius, B. Webster, A. Wilber

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Kenneth J Duncan, J. Sabater, H. J. A. Rottgering, M. J. Jarvis, D. J. B. Smith, P. N. Best, J. R. Callingham, R. Cochrane, J. H. Croston, M. J. Hardcastle, B. Mingo, L. Morabito, D. Nisbet, I. Prandoni, T. W. Shimwell, C. Tasse, G. J. White, W. L. Williams, L. Alegre, K. T. Chyzy, G. Gurkan, M. Hoeft, R. Kondapally, A. P. Mechev, G. K. Miley, D. J. Schwarz, R. J. van Weeren

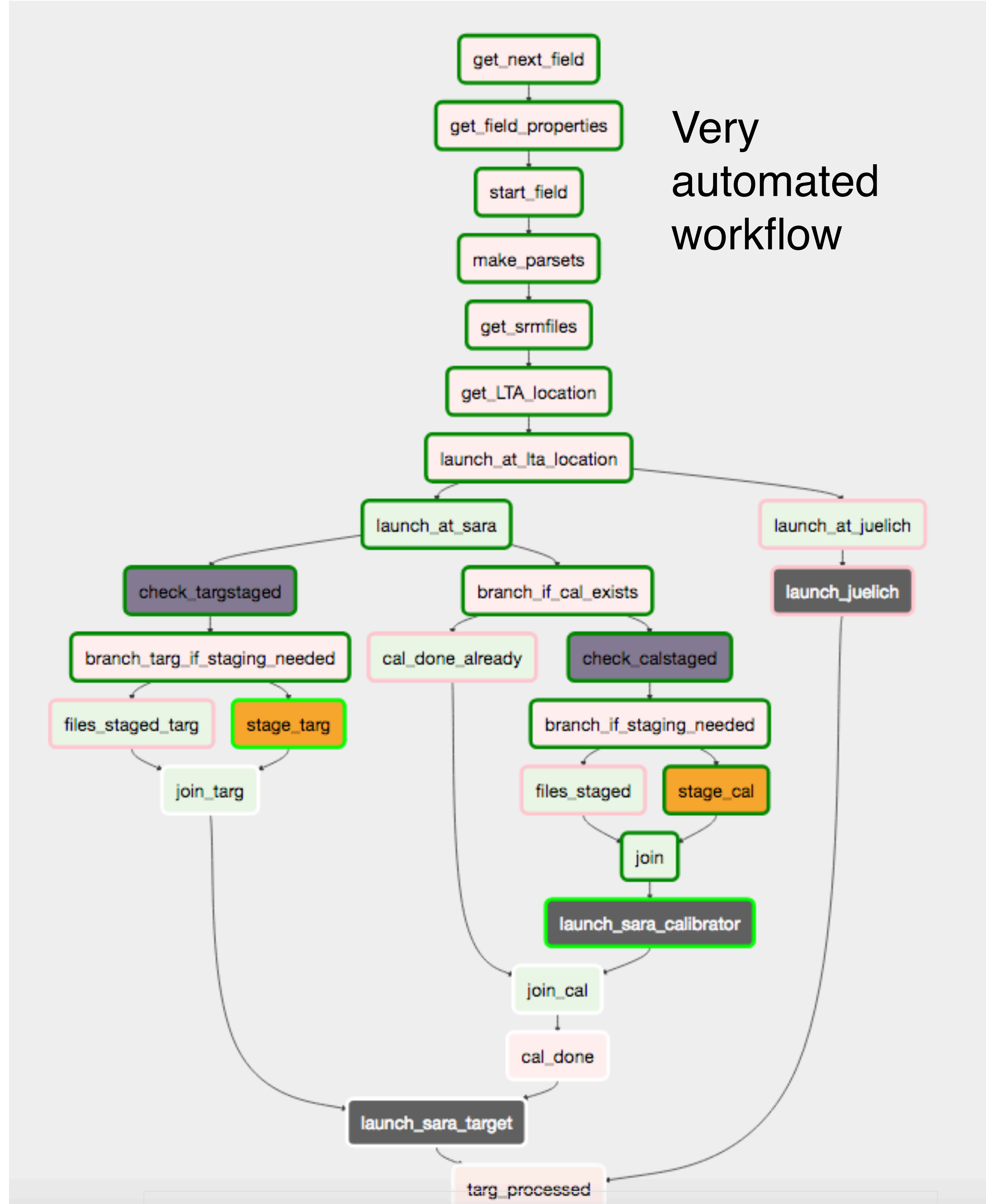
The data processing pipelines used for LoTSS

All data processing pipelines for LoTSS have been made public.

To process the >10PB of existing data the pipeline is implemented on the LOFAR archive compute facilities. This allows us to process ~16Tb of data within ~6hrs on each site.

Around 50% of existing LoTSS data have been processed with this pipeline.

The main bottleneck in data processing is getting the data out of the LOFAR archive.

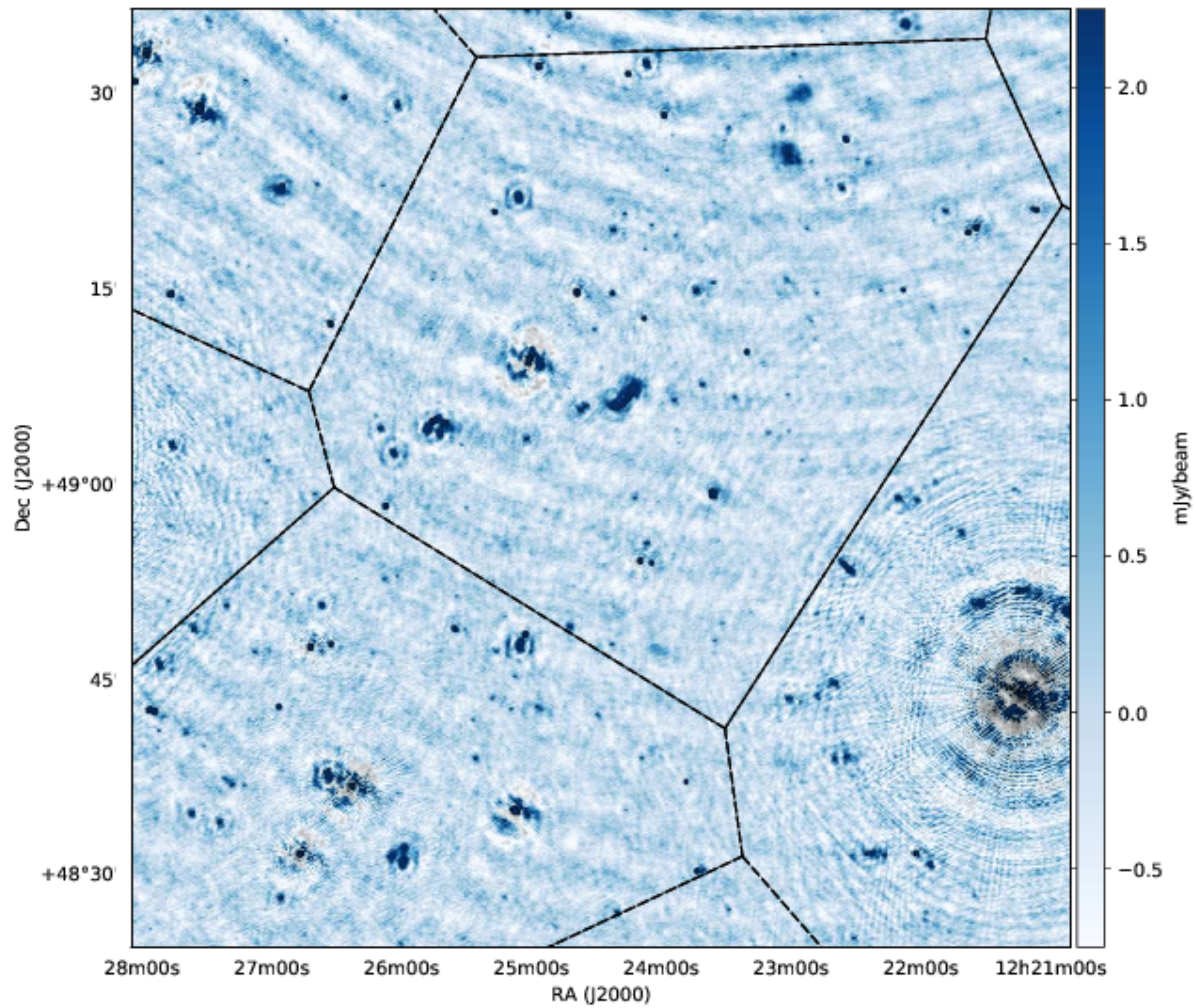


Very automated workflow

LTA processing: Mechev, Drabent, Oonk, Shimwell, et al.

The data processing pipelines used for LoTSS

- .Wide field image created covering the full field of view
- Image tessellated to define facets.
- Calibration solutions obtained for all directions simultaneously using the model from entire wide field image.
- Imaging repeated with direction dependent calibration solutions applied and a better model constructed.
- Several self calibration cycles performed.



DDF-pipeline is public. It makes use of DDFacet and kMS for calibration and imaging (Tasse+ 2014, Smirnov+ 2015, and Tasse+ 2017). It produces science quality images in 4-6 days of processing but requires powerful (>200GB) nodes.

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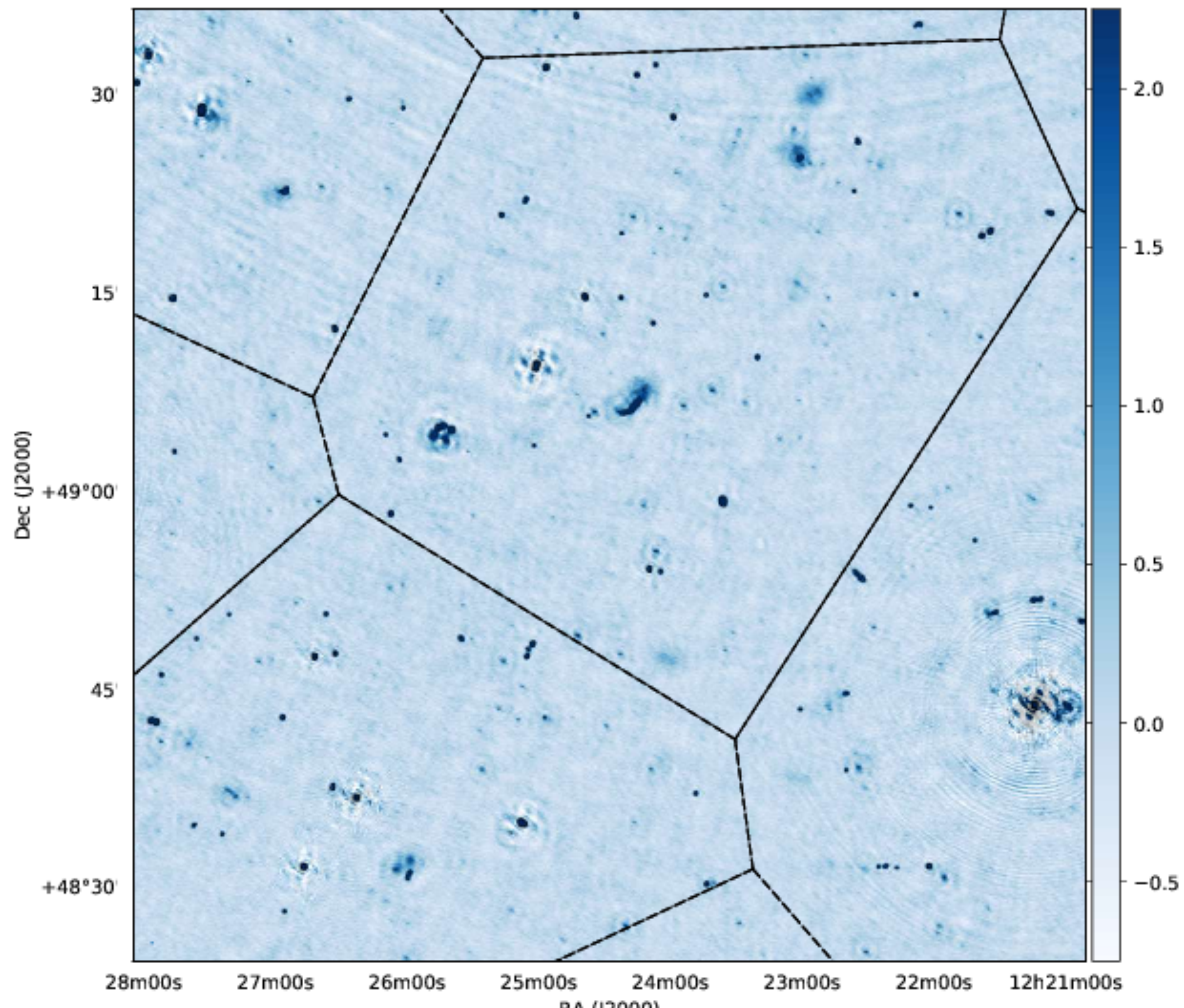

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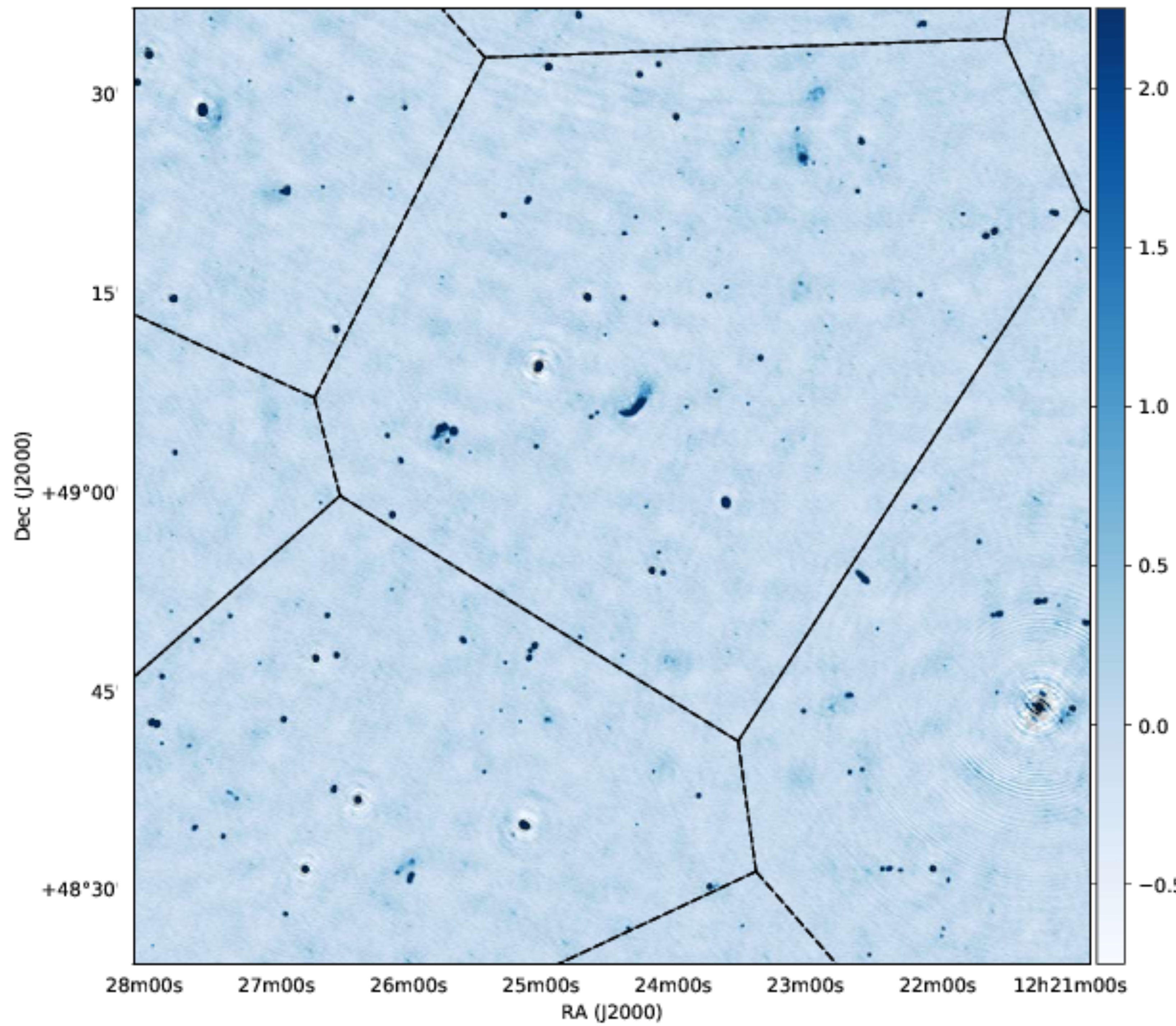

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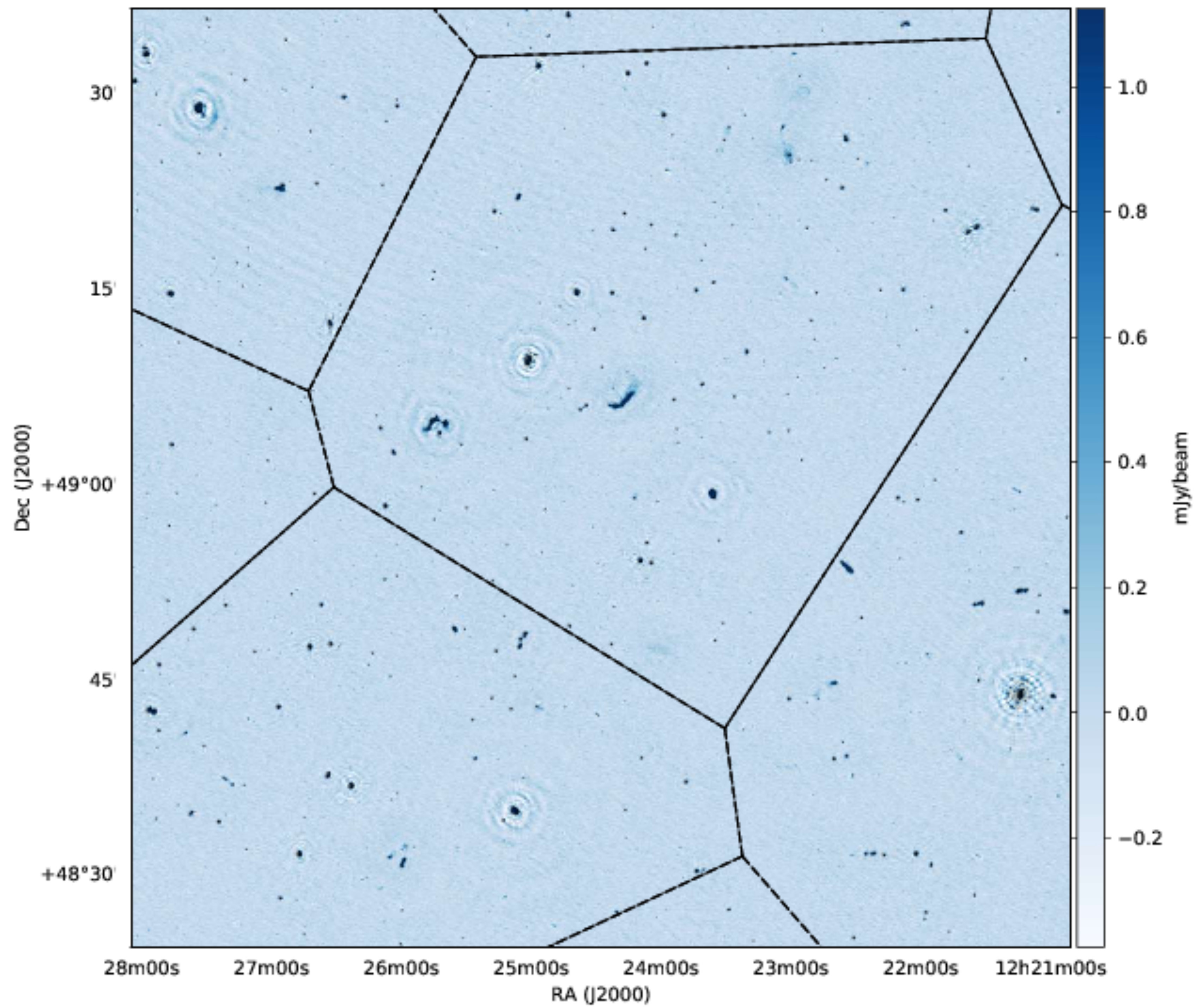

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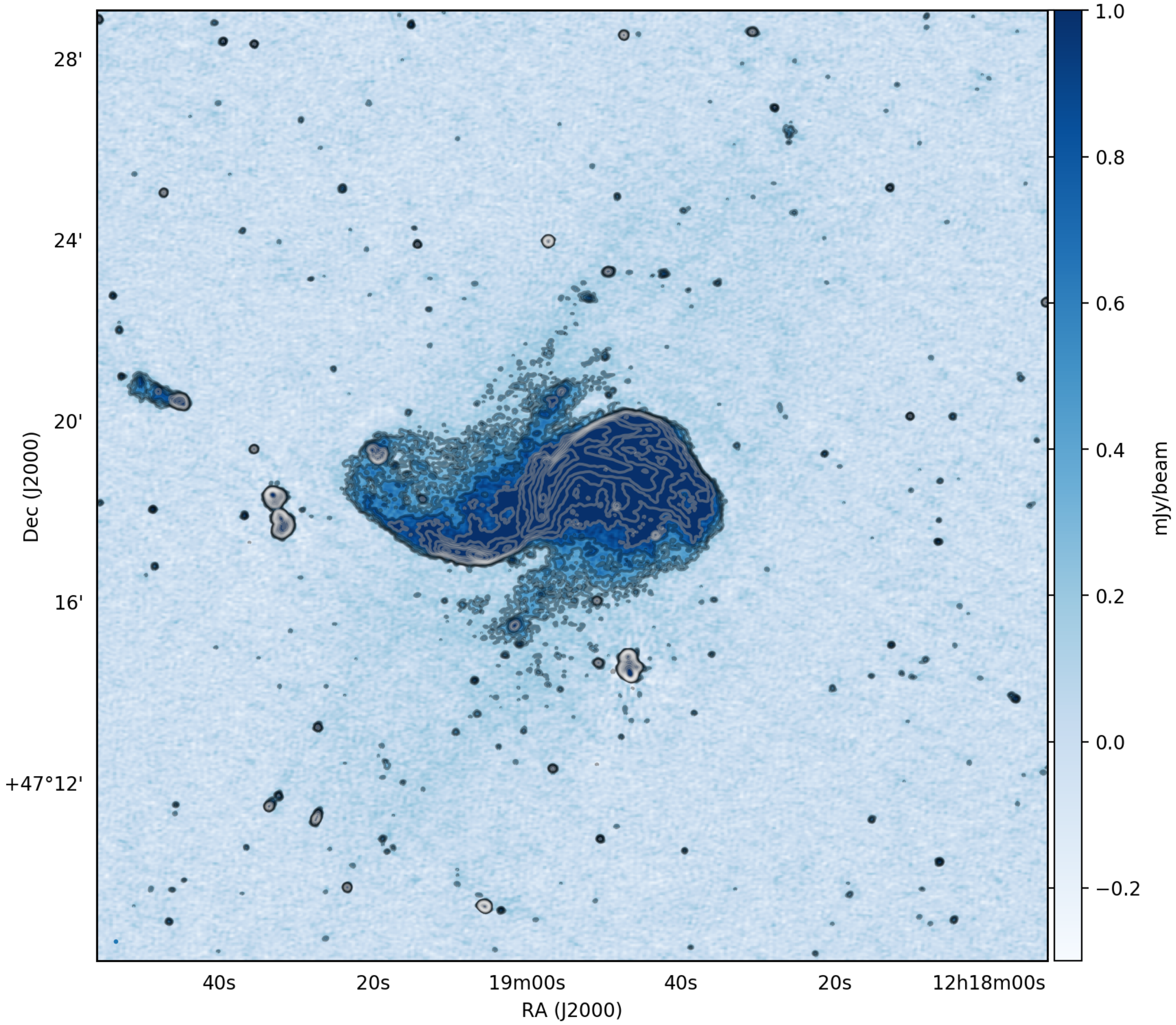
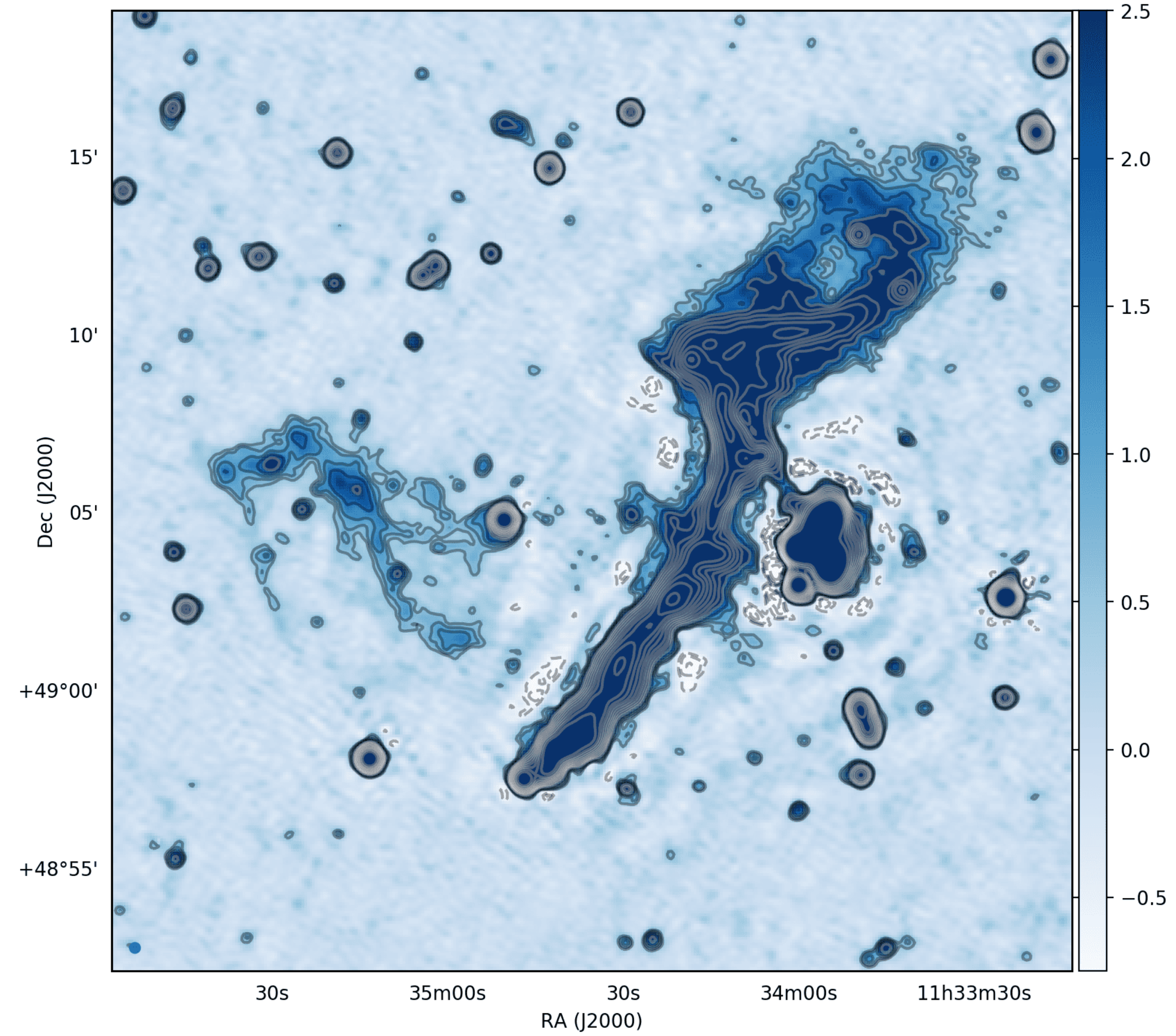
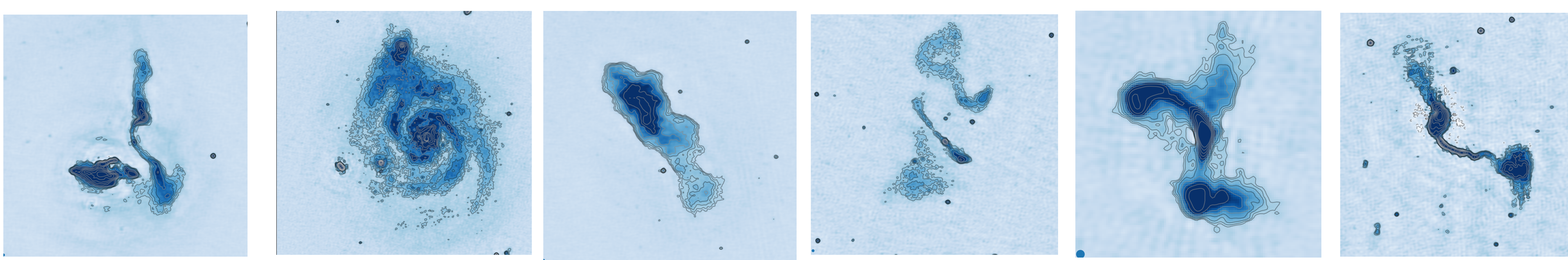
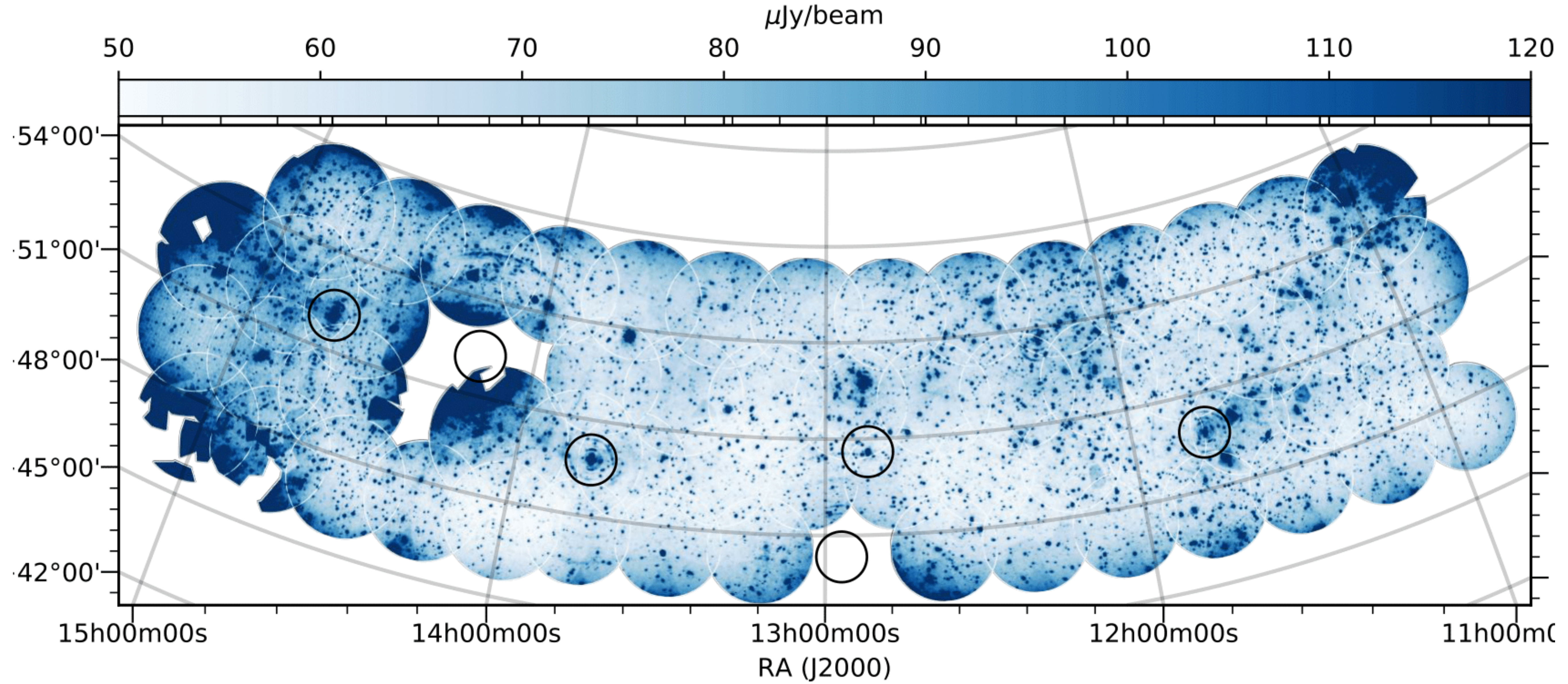






Example image after DD calibration. Note that improving direction dependent calibration and imaging routines is ongoing research.

LoTSS data release 1 — visit lofar-surveys.org



6” resolution, a median noise of 0.07mJy/beam, a source density 10 times higher than NVSS or FIRST, 90% complete at 0.45mJy/beam and astrometric accuracy of 0.2”.

LoTSS-DR1 was published Feb 2019 together with ~25 science papers from the SKSP. The catalogues and images are public.

LoTSS data release 1 — visit lofar-surveys.org

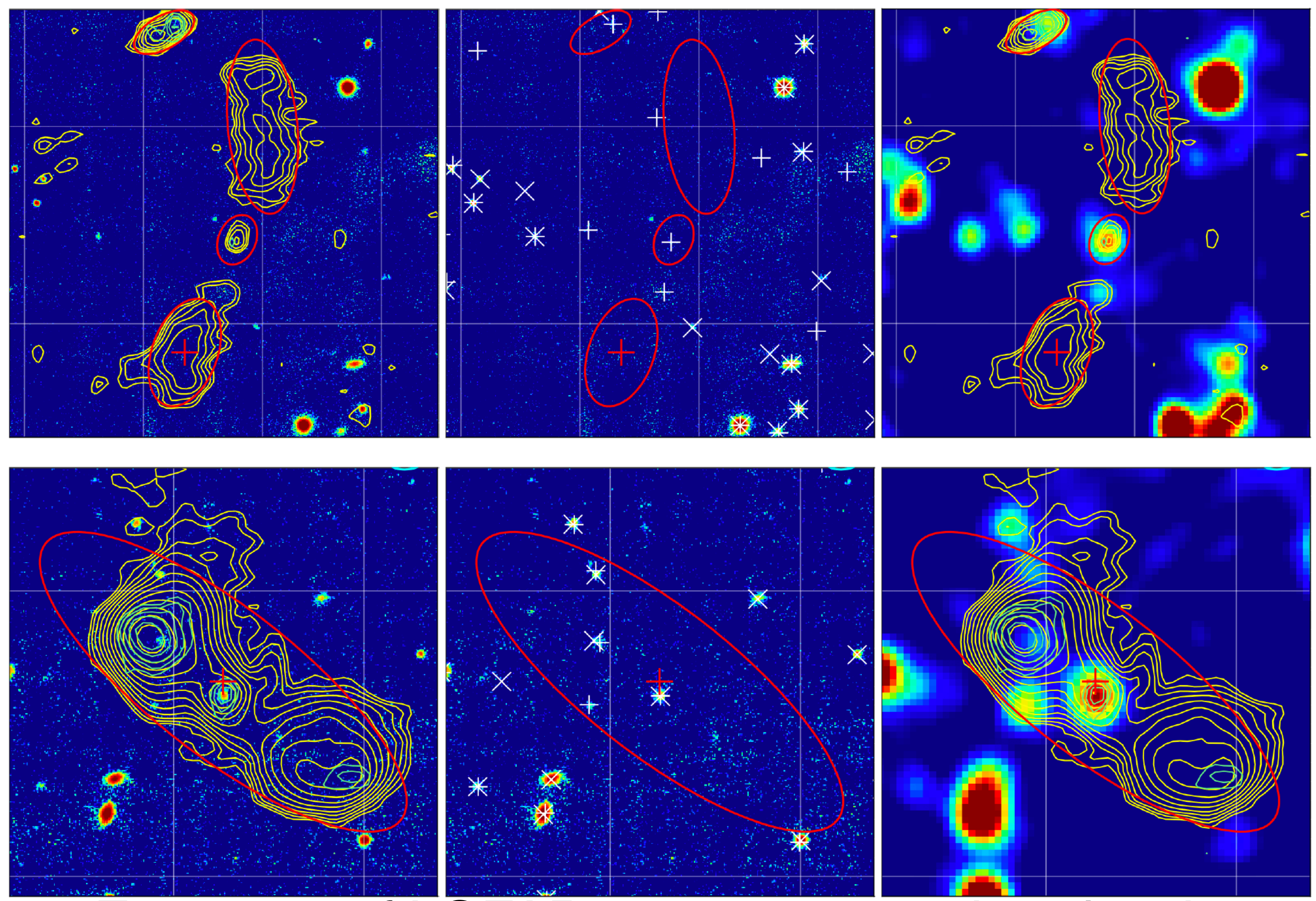
325,694 entires in the raw PyBDSF catalogue.

Corresponds to 318,520 radio sources after deblending, artefact rejection and joining multiple component sources (including extensive efforts to visually inspect ~10,000 sources).

231,716 have counterparts in Pan-STARRS or WISE and for these photometric redshifts are are estimated.

	Number	Number with ID	ID fraction
All Sources	318,520	231,716	0.73
LR	299,730	221,269	0.74
LGZ	11,989	7,144	0.60
Deblending	2,435	2,338	0.96
Bright galaxy	965	965	1.00
No ID possible	3,401	0	0.00

The final LoTSS-DR1 catalogue contains radio sources, optical counter parts and photometric redshifts.



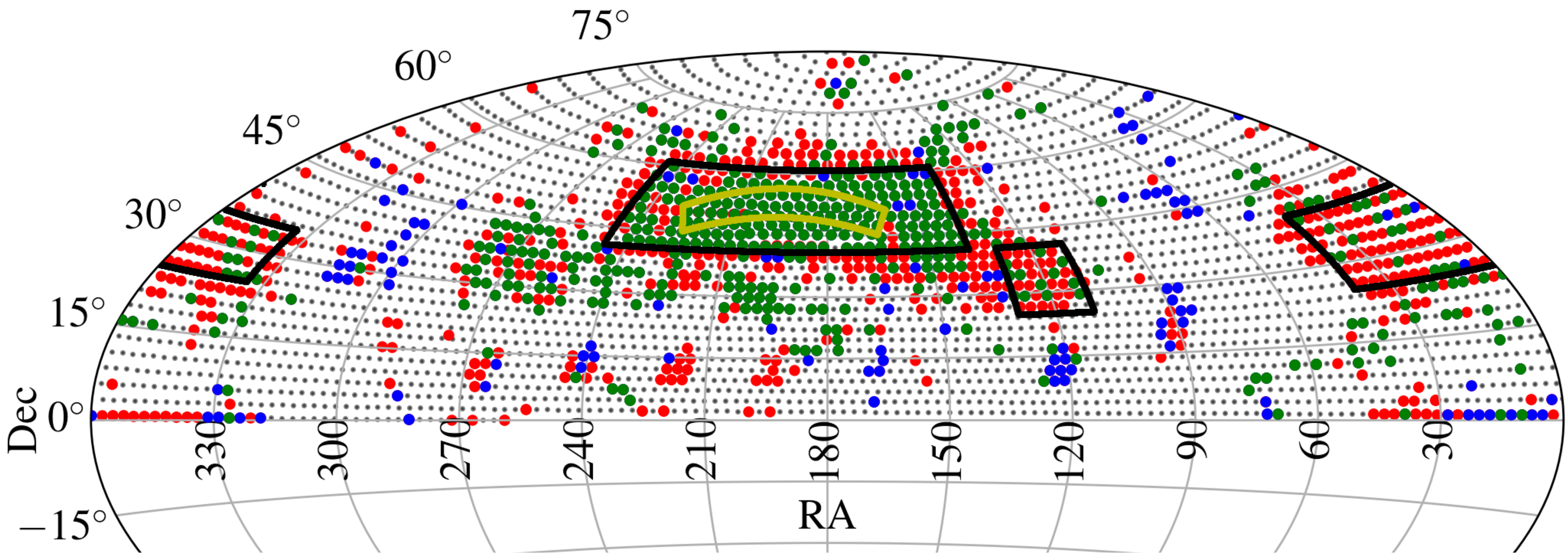
Examples of LOFAR galaxy zoo entries showing LoTSS, FIRST, Pan-STARRS and WISE images.

Williams, Duncan, Hardcastle, Sabatar et al.

LoTSS data release 1 — visit lofar-surveys.org

All LoTSS-DR1 products (images, raw radio catalogues, cross matched source catalogues, redshift estimates) will be public upon publication of a dedicated edition of A&A in Feb 2019. Release is described in Shimwell+ 2018, Williams+ 2018 and Duncan+ 2018 and is accompanied by ~25 scientific papers — all are accepted and on astro-ph

LoTSS internal data release 2



Eventually LoTSS-DR2 will cover around 2,000 square degrees. All is observed and ~1/2 of this area is processed (other areas are processed too) and well over 2,000,000 sources are already detected

(green fully processed, blue direction independent calibration complete, red observed but not calibrated)

A new pipeline for LoTSS-DR2

Nearly a year of development went the new DR2 pipeline.

Approximately 14 nodes are running the pipeline in parallel to produce more than 2 fully calibrated images each day (90% of the processing is done in Hertfordshire, the remaining 10% in Leiden, Bologna and Hamburg)

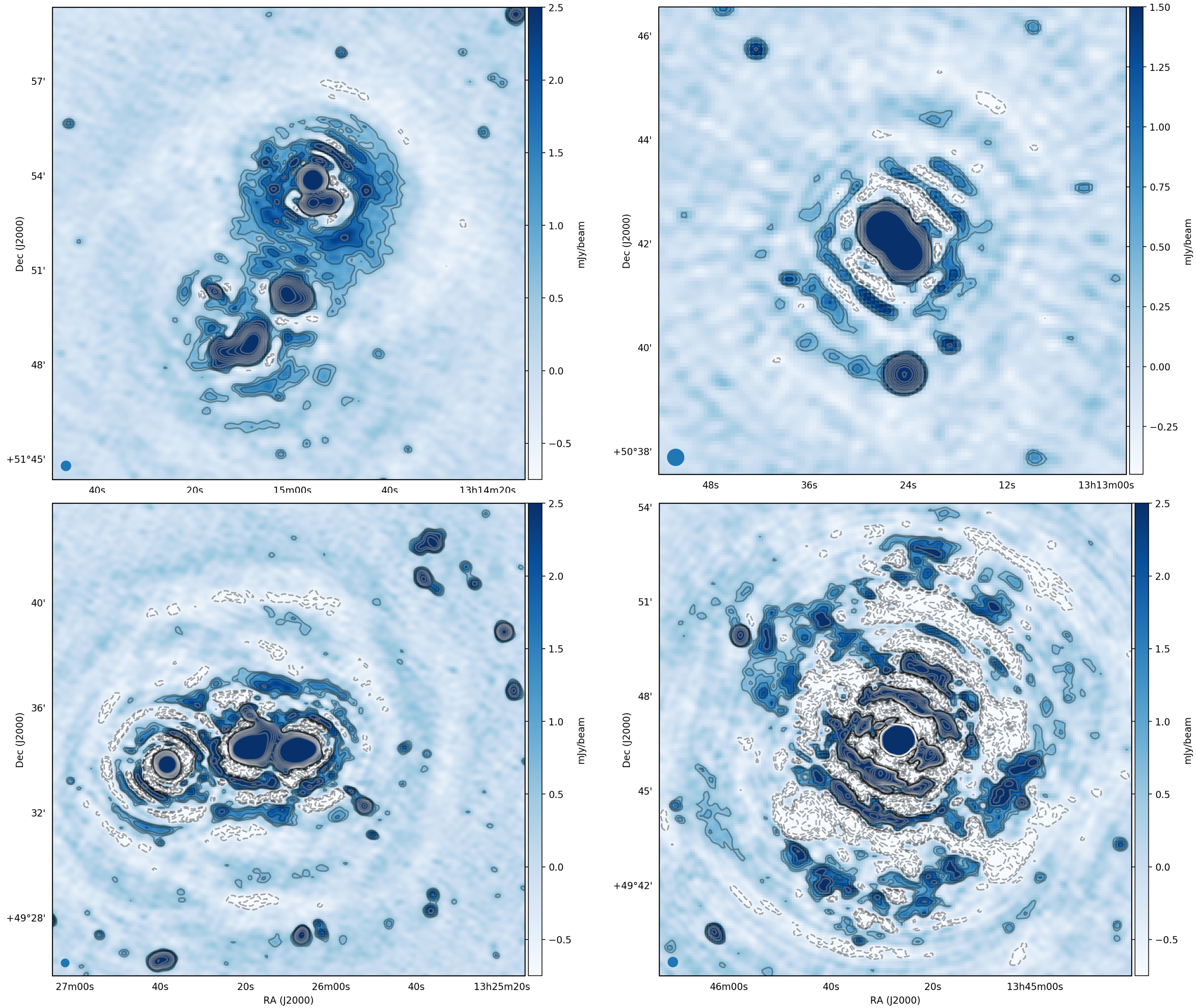
Main differences:

- Deeper deconvolution — More very faint sources (about 10% more)
- Redoing the direction independent calibration during direction dependent pipeline — Higher dynamic range
- Better deconvolution and shorter uv-min in the calibration — No more artificial halos and holes

DDF-pipeline: Tasse, Hardcastle, Shimwell

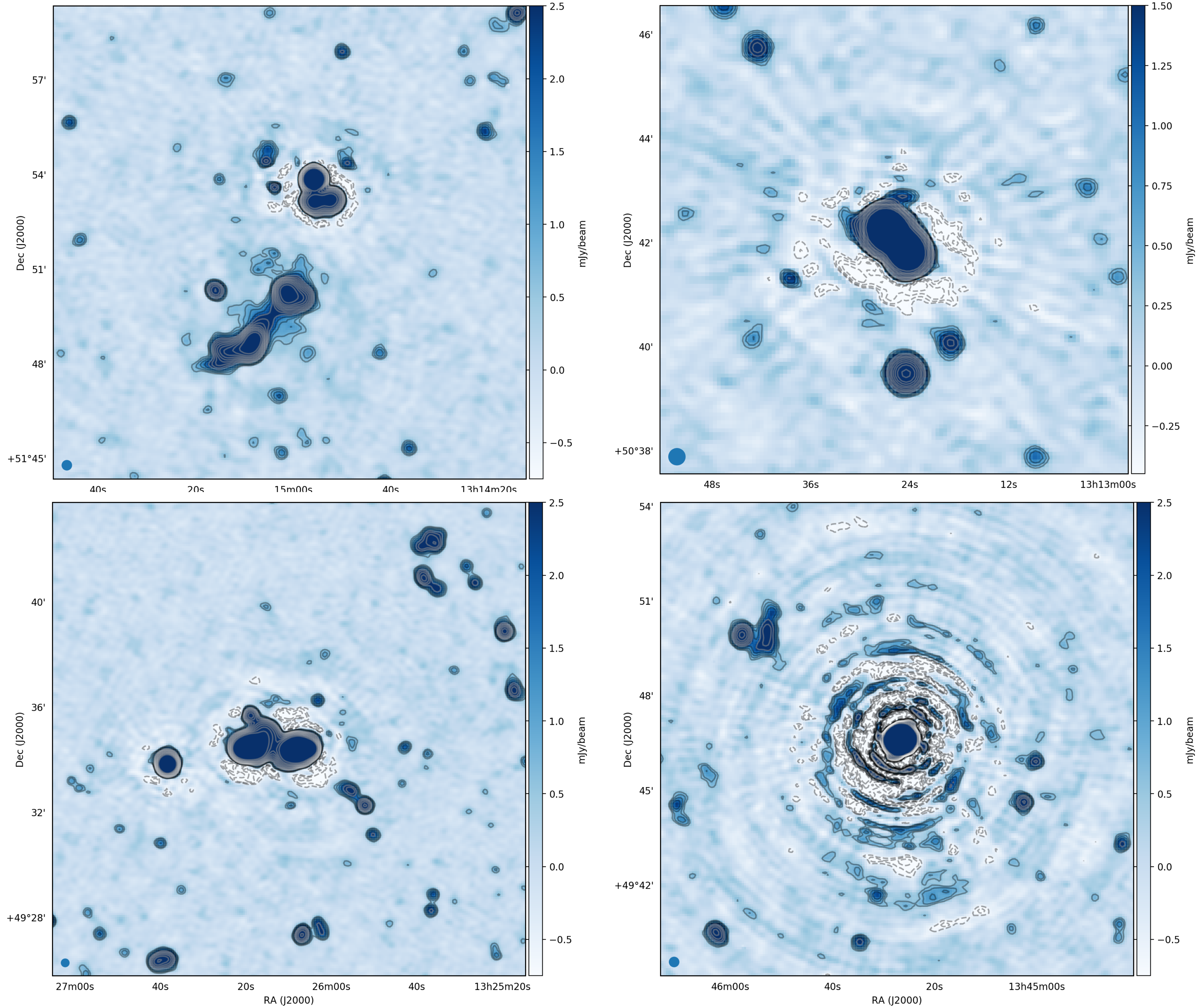
Improvements in LoTSS-DR2

DR1 has quite a low dynamic range (~10% of the area has a >15% enhanced noise) which resulted in an ~5% failure rate for extragalactic fields



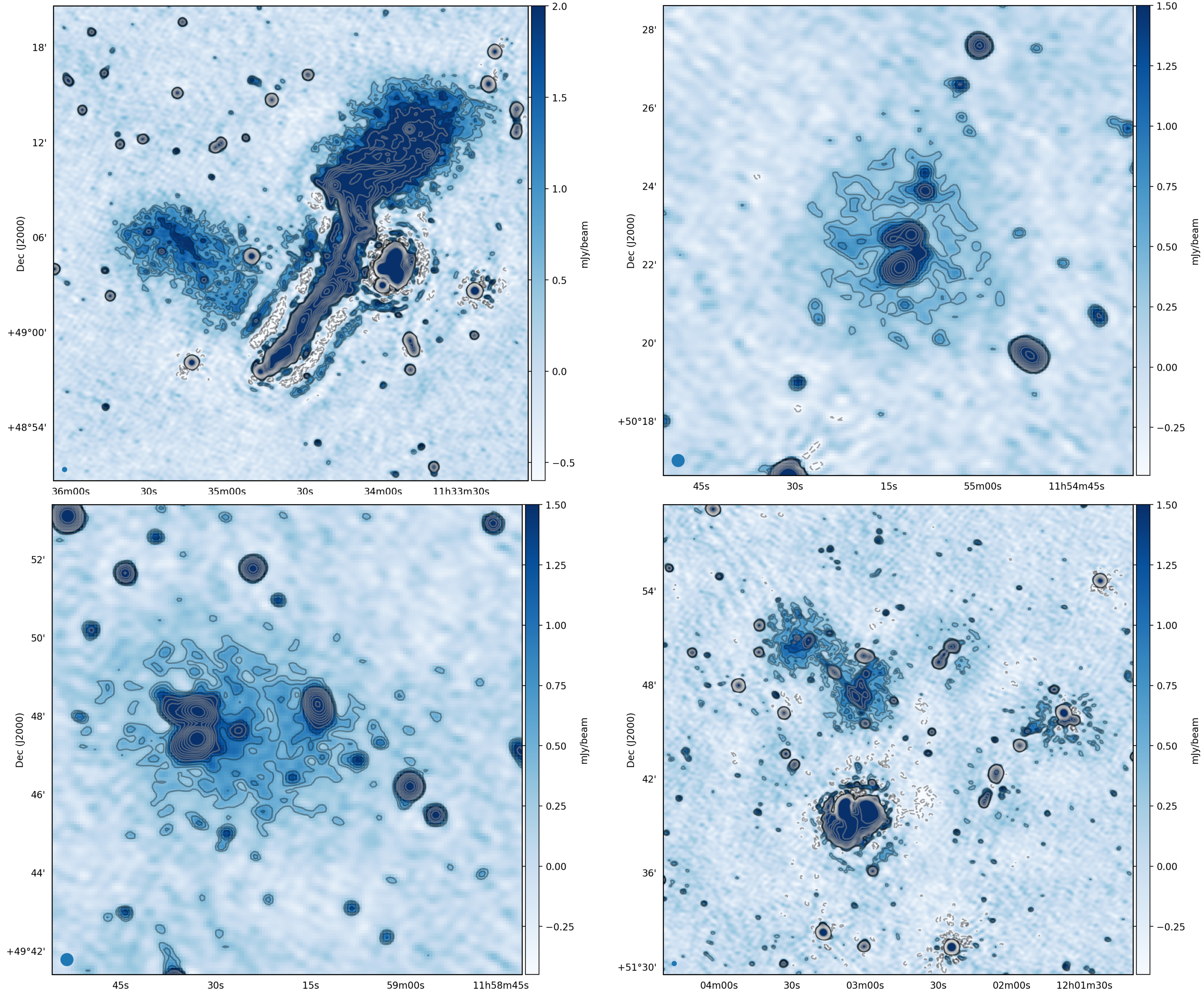
Improvements in LoTSS-DR2

DR2 improves the dynamic range significantly.



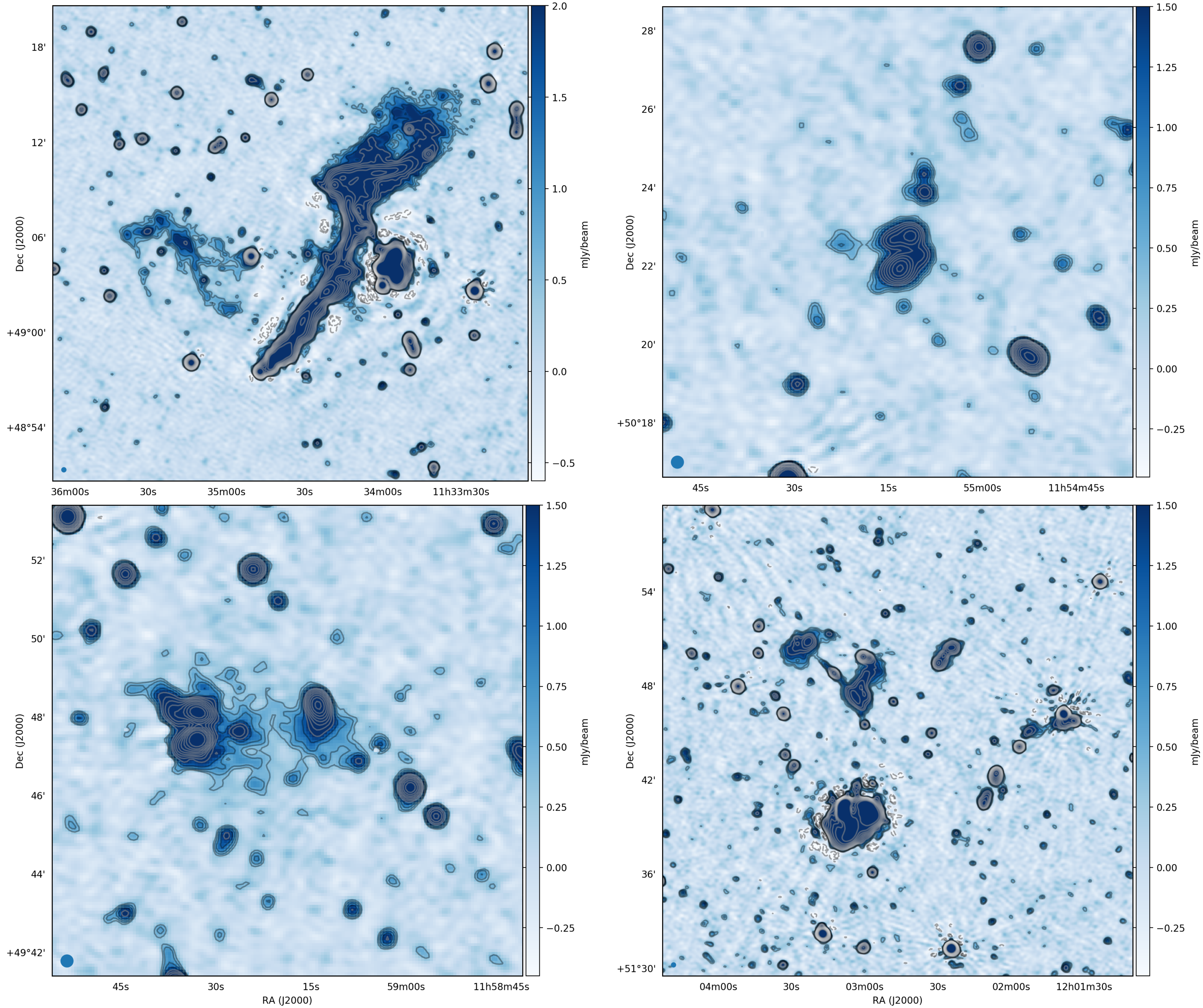
Improvements in LoTSS-DR2

DR1 has artificial halos and holes mainly around extended sources.



Improvements in LoTSS-DR2

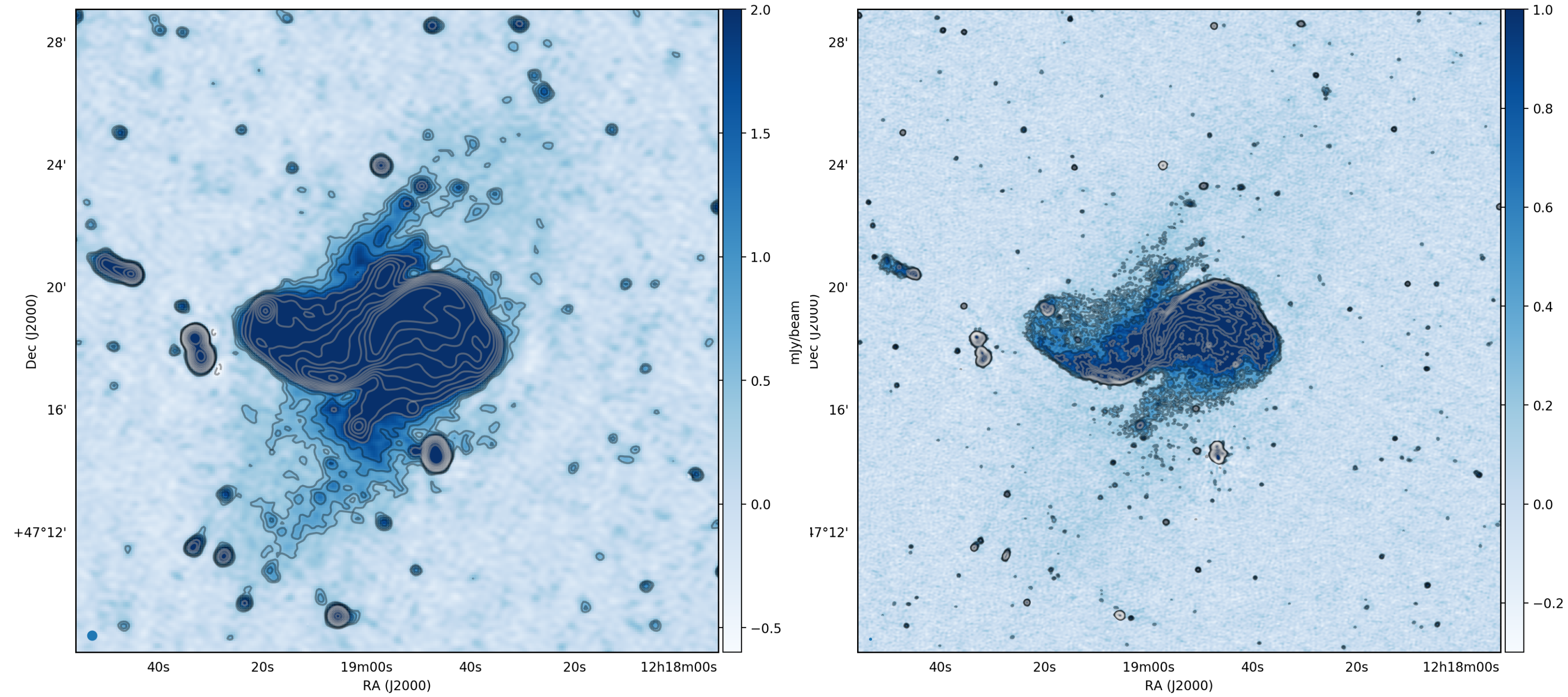
DR2 essentially removes these artificial halos and holes.



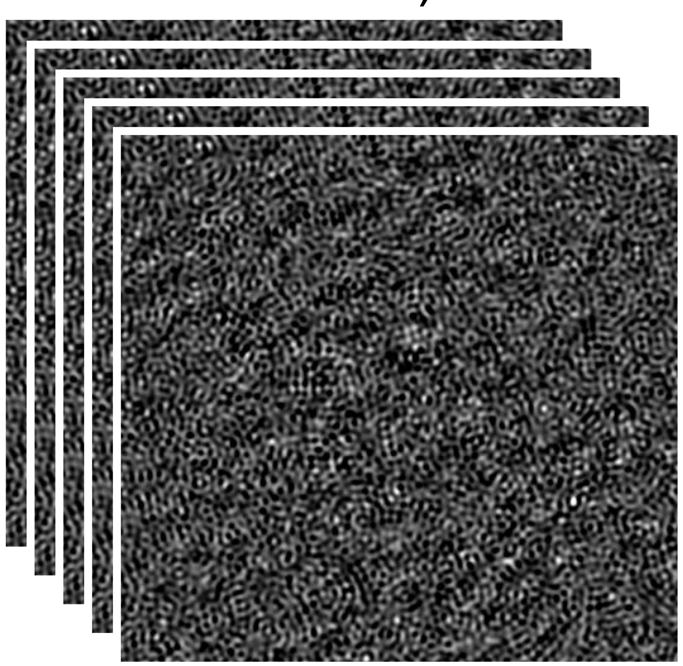
New data products in LoTSS -DR2

Current pipeline products:

- 6” resolution Stokes I image
- 20” resolution Stokes I image
- 3 channel images over band
- 20” resolution Stokes V image
- 20” resolution Stokes QU cubes (480 planes)
- Very low resolution Stokes QU cubes (480 planes)
- Dynamic spectra of targeted sources
- Data calibrated in a particular direction with all other source subtracted (allows easy reimaging, source subtraction etc)



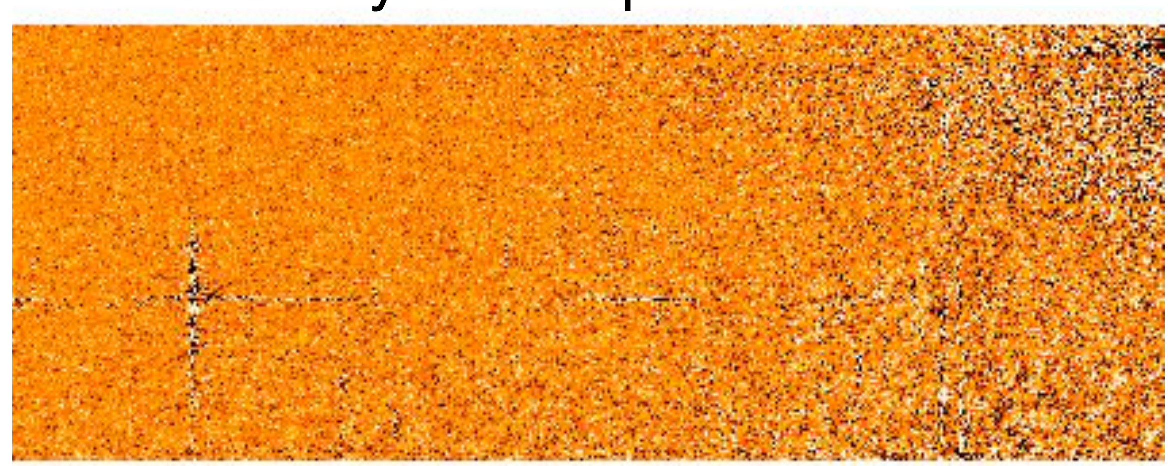
Stokes I images at high (6”) and low (20”) resolution



Polarisation cubes

Dynamic spectra

Frequency



Time

To enable further processing we also keep:

- Facet layout
- Calibration solutions
- Data

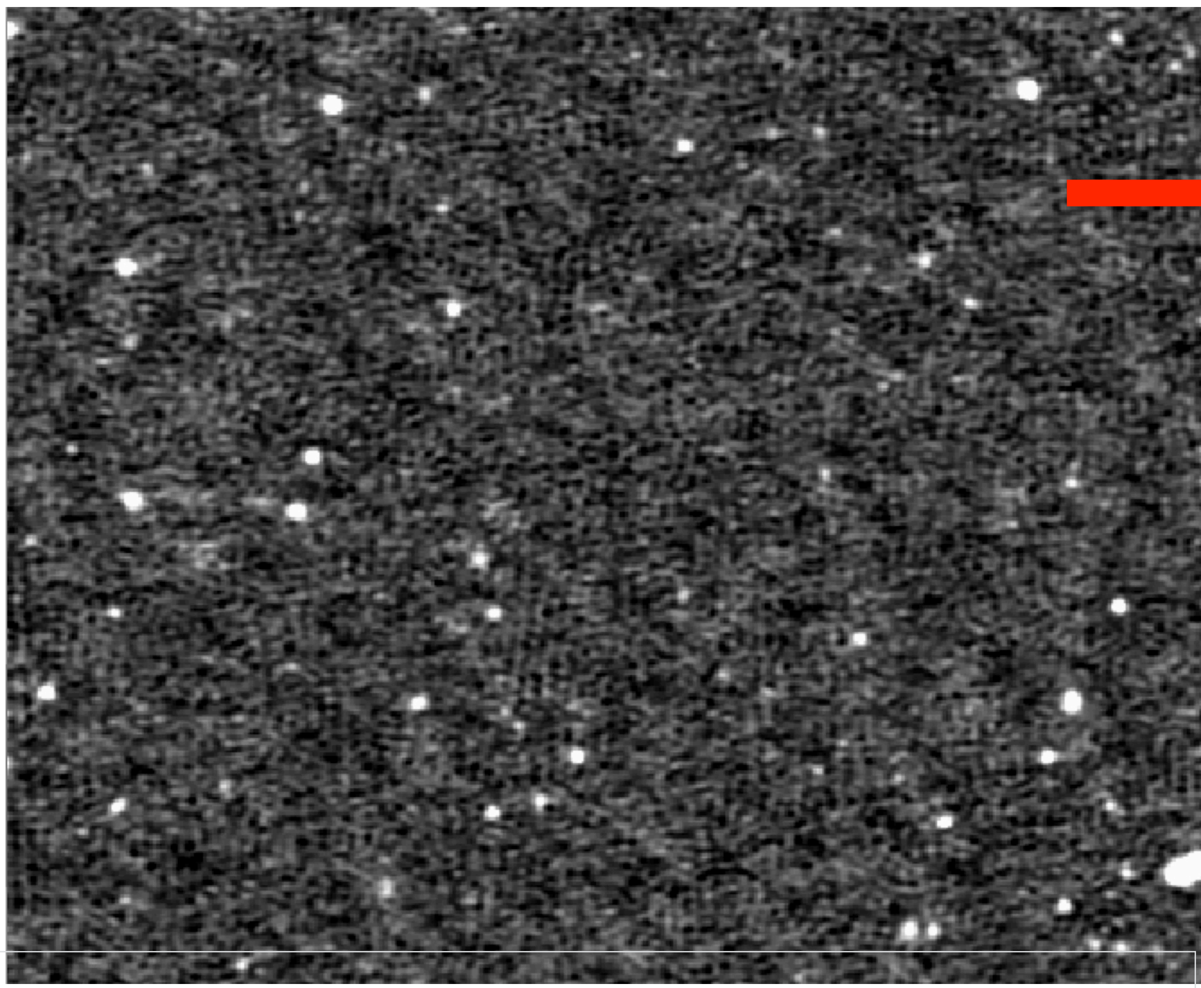
DDF-pipeline: Tasse, Hardcastle, Shimwell+

LoTSS deep fields

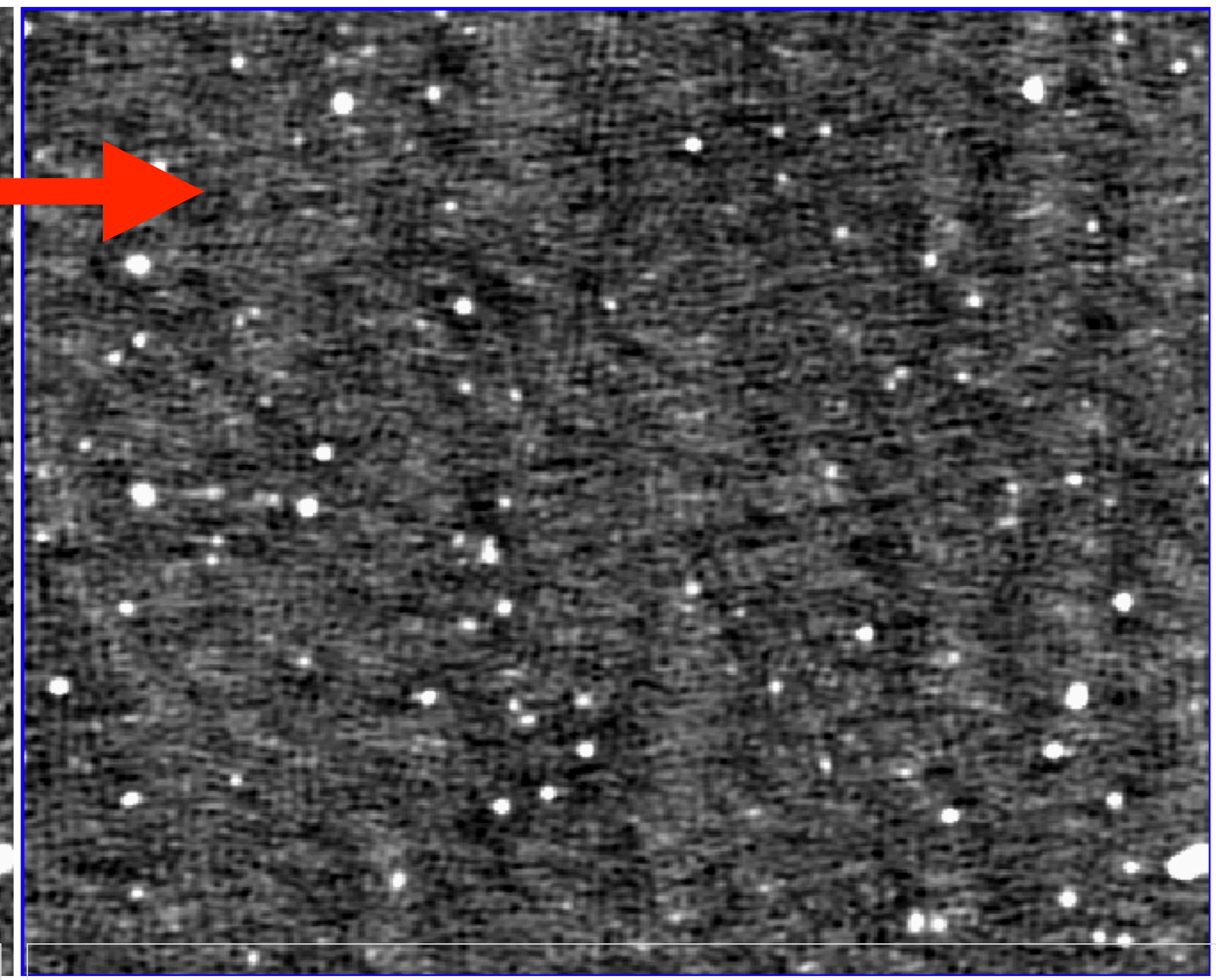
Over ~150hrs gathered towards several important extragalactic fields (Lockman hole, Elais-N1, Bootes so far) and processing of 100s of hrs of data in the region of the north celestial pole in collaboration with the LOFAR EoR group.

Tests in Elais-N1 indicate we can get optical identifications for ~98% of the radio sources.

Internal data release imminent (same products as LoTSS). Date of public data release TBD.



LoTSS depth (~100microJy/beam) — 1000 sources per square degree. Colour scale is 3 times deep field scale.



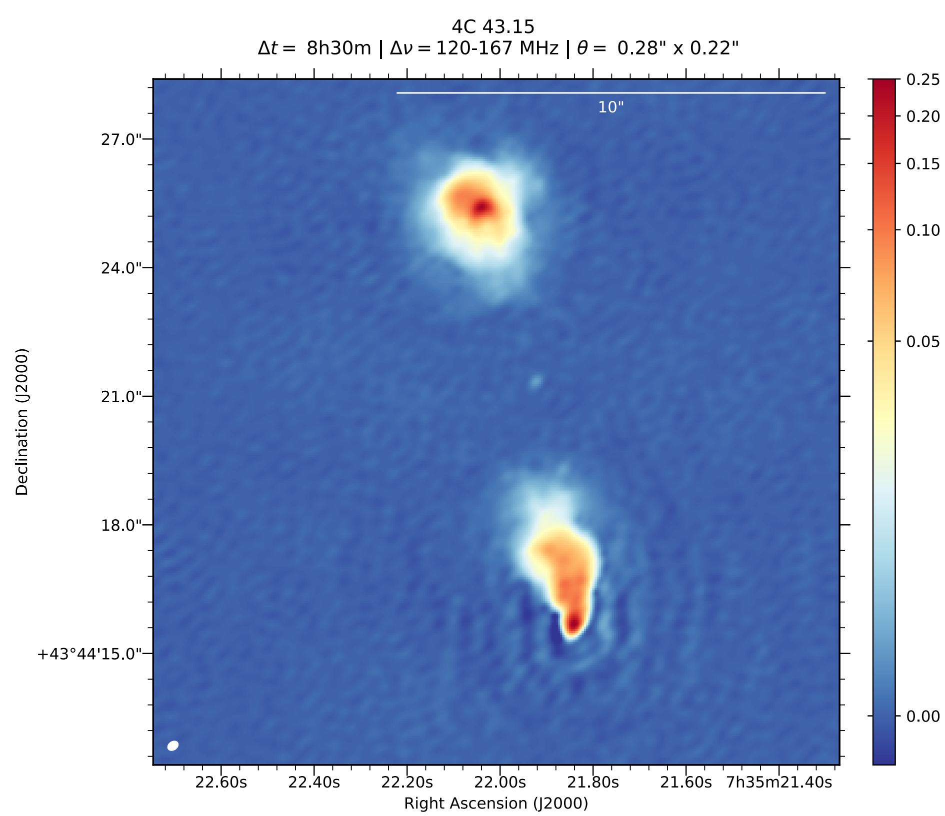
Deep field (~30microJy/beam) — 4200 sources per square degree in the most sensitive region.

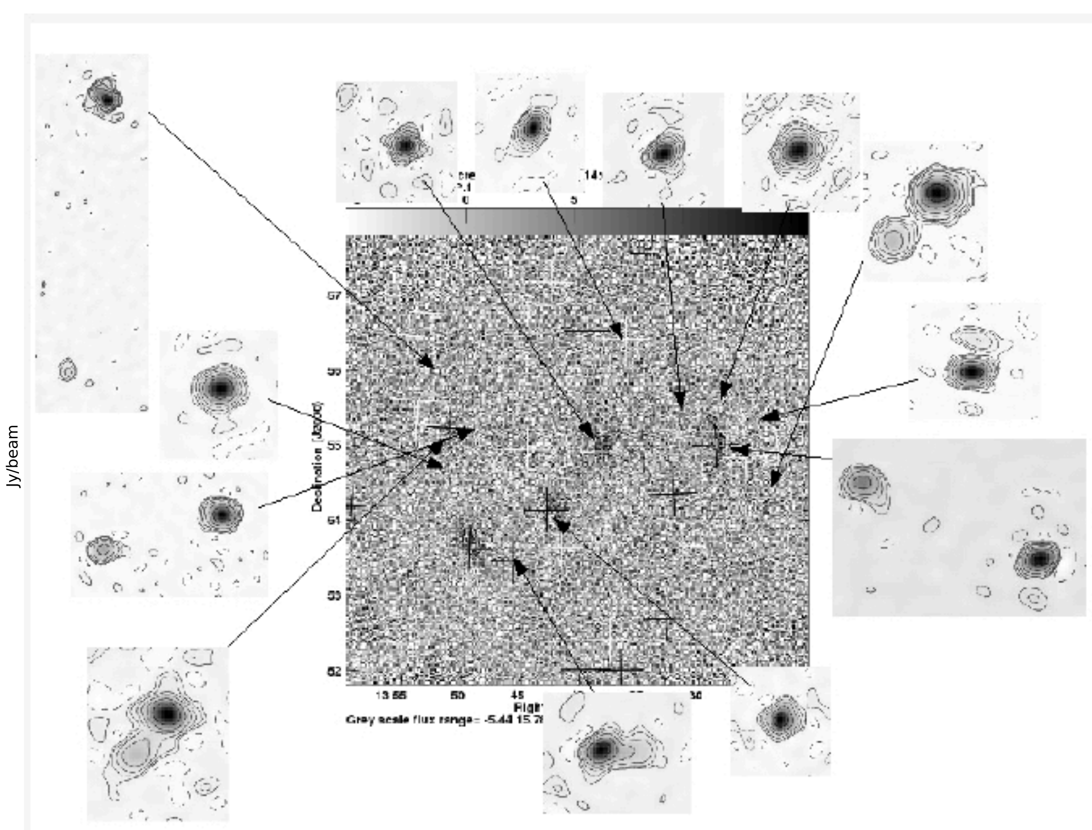
Furthering the LOFAR surveys

Optical followup — WEAVE-LOFAR (Smith+ 2016) will use WEAVE on the WHT and soon begin obtaining spectra for ~a million LOFAR sources.

Radio recombination lines — LoTSS data have sufficient frequency resolution for spectral line work and the data are being analysed to search for RRLs (e.g. Emig+ 2018).

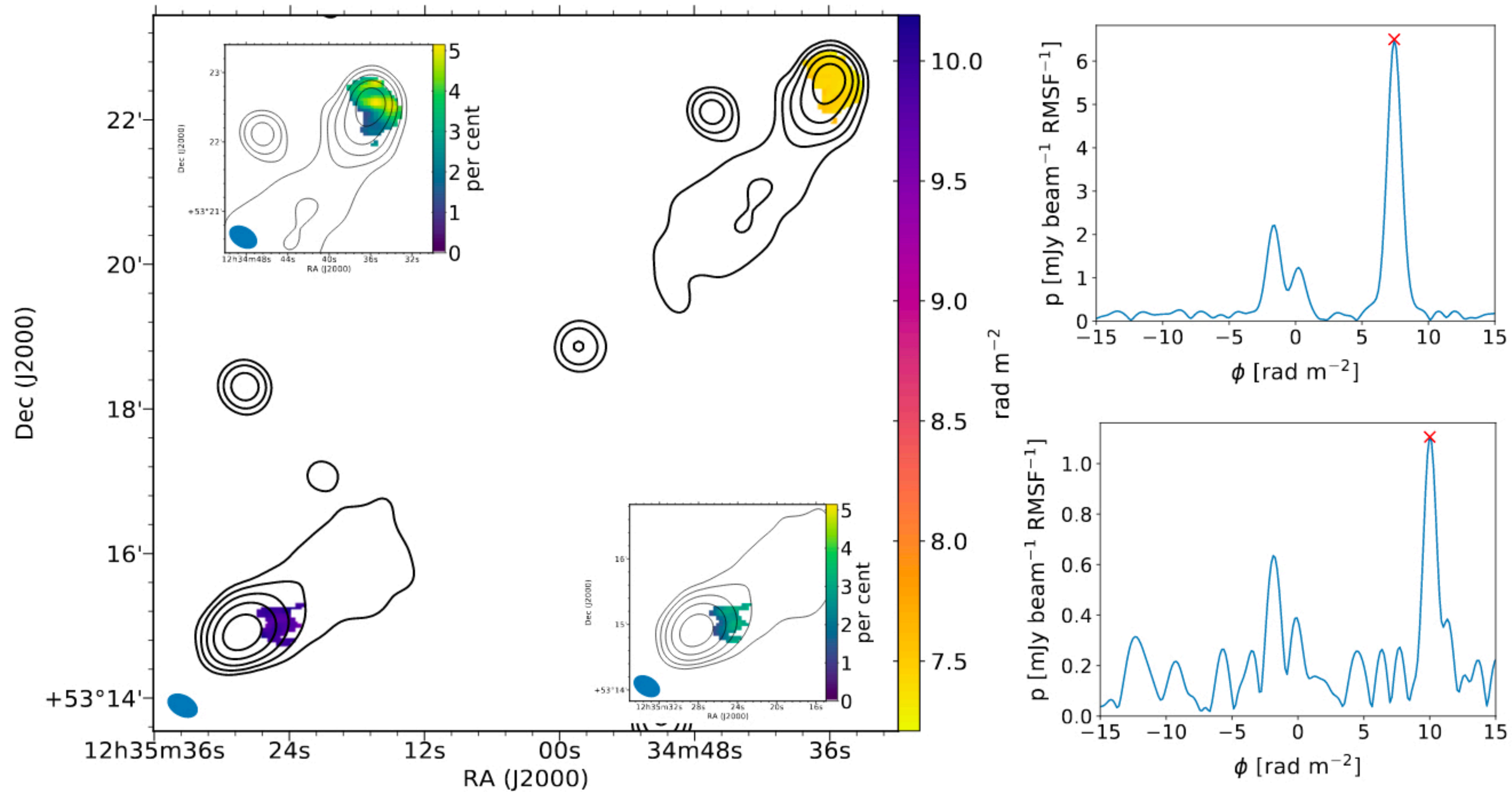
0.3arcsec resolution — LOFAR surveys data are recorded using the full international LOFAR array allowing for 0.3" imaging over the entire surveyed region (images from Sweijen, van Weeren, Jackson, Morabito+)





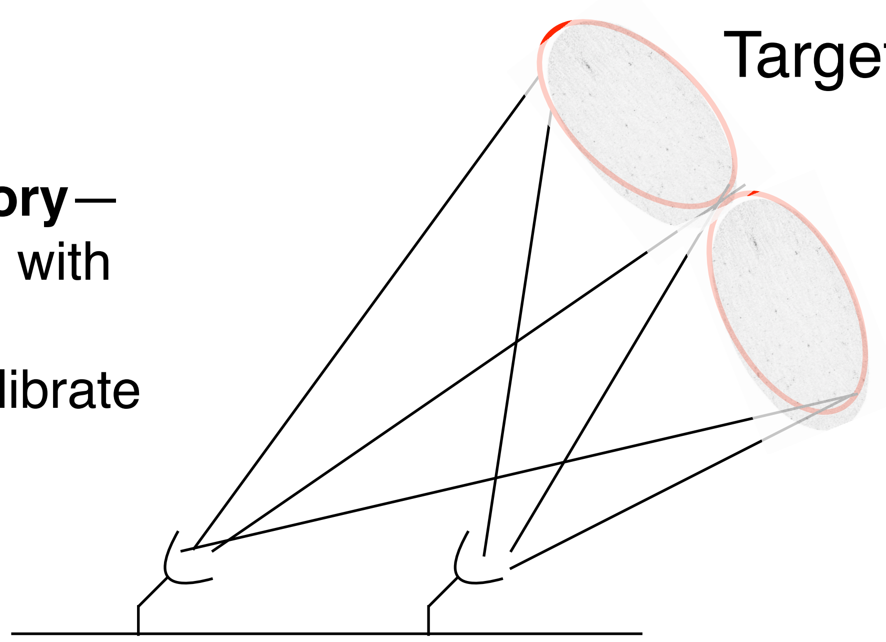
Furthering the LOFAR surveys

Polarisation — LoTSS produces QU cubes and V images. Approximately 1 source per square degree in QU cubes (images from O'Sullivan+ 2018 and also see van Eck+ 2018).



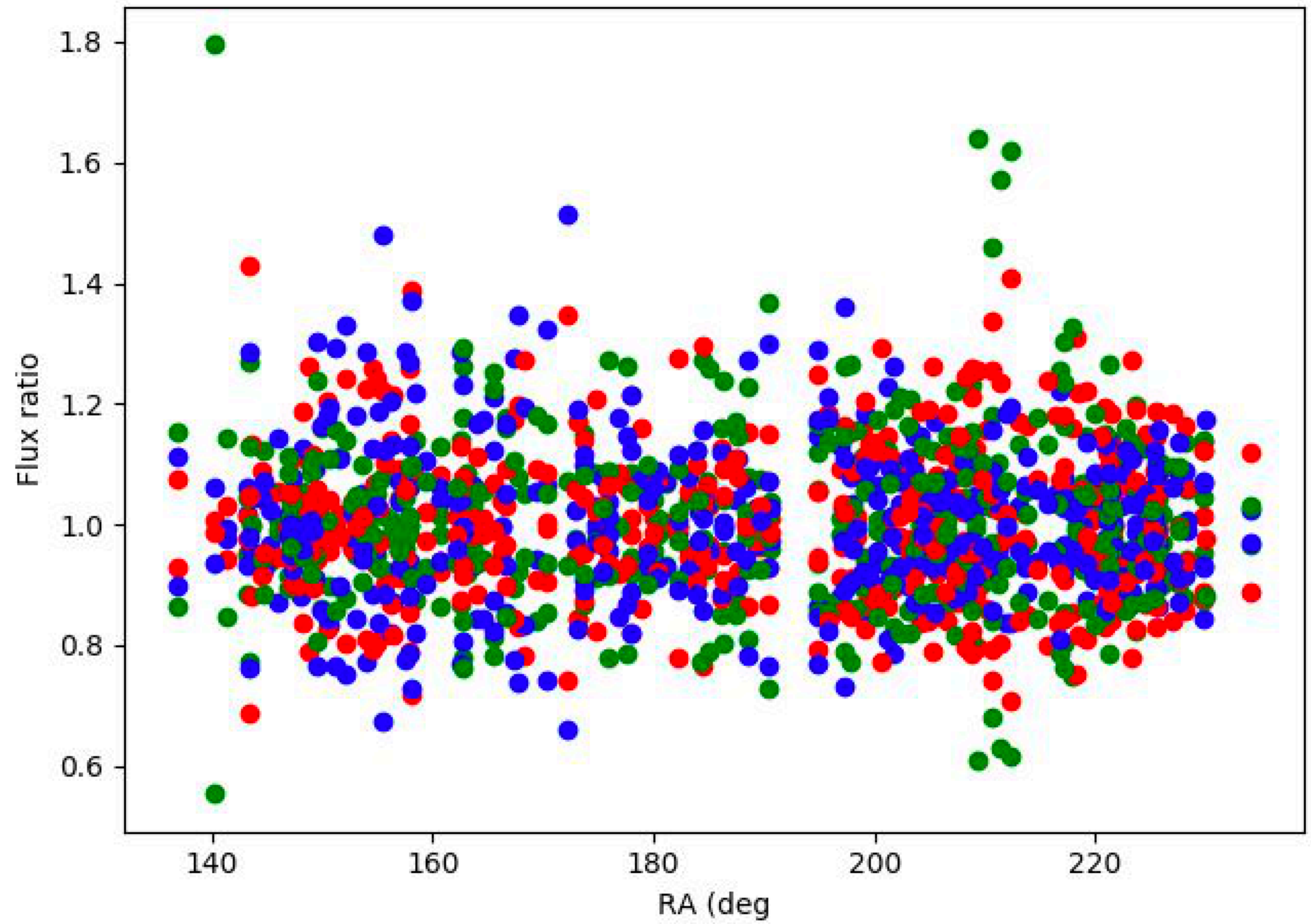
Towards LOFAR 2.0 — better LBA calibration, improved observing efficiency, better long baseline uv-coverage

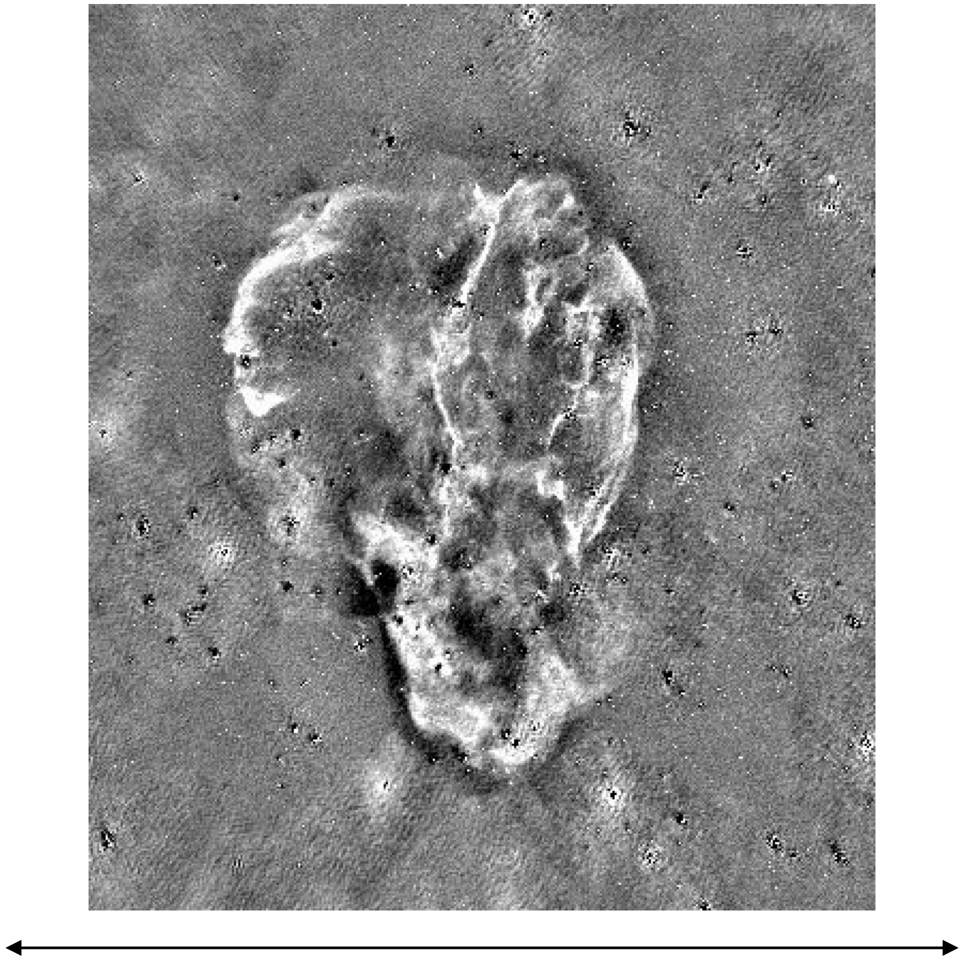
Working with the observatory— LOFAR users can coobserve with the LOFAR surveys and the surveys team helps users calibrate and image their data.



Furthering the LOFAR surveys

The LoTSS flux scale is not yet very accurate — The LOFAR beam models make precise calibration of the flux difficult. Currently our flux uncertainty is approximately 20% — the plot shows the flux ratio of sources in overlapping regions (colours are different attempts to fix it).





8 degree

Both galactic and low declination fields are difficult — e.g LoTSS images of the Cygnus loop show emission over huge areas that are very hard to accurately model and calibrate against. At low declination the primary beam gets larger, the sensitivity decreases and getting enough signal for calibration becomes harder.

Some results and ongoing studies

Searches for low-frequency emission from other stars have only detected an extraordinarily active flare-star that is not representative of the wider stellar population (Lynch+ 2017)

First low-freq detection of a quiescent red dwarf.

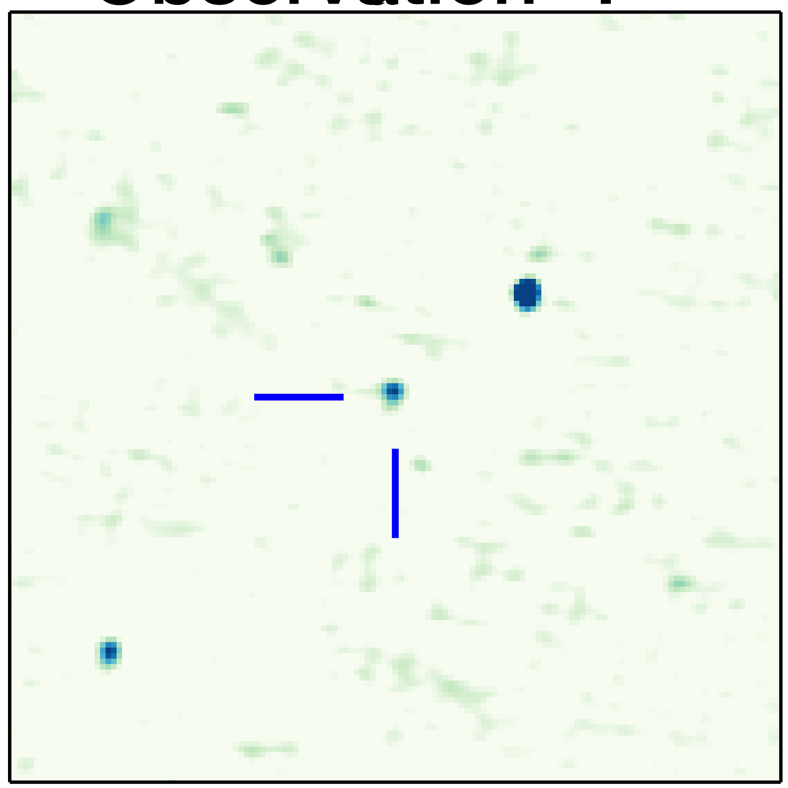
$$S_I = 800\,\mu\mathrm{Jy}$$

$$S_V = 500\,\mu\mathrm{Jy}$$

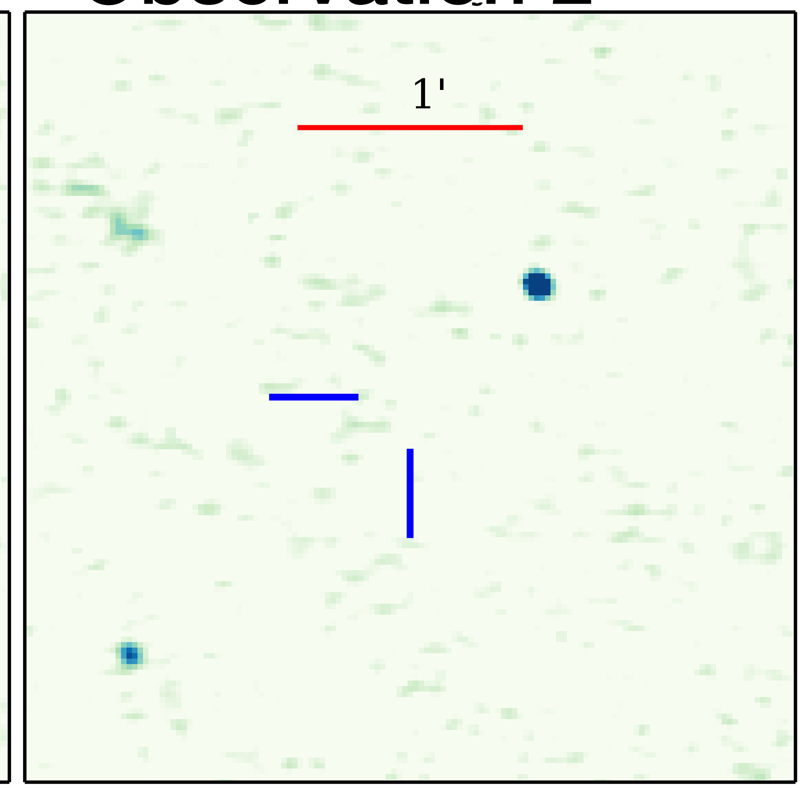
$$\tau > 8^{\mathrm{h}}$$

$$\Delta\nu/\nu \sim 1$$

Observation 1



Observation 2



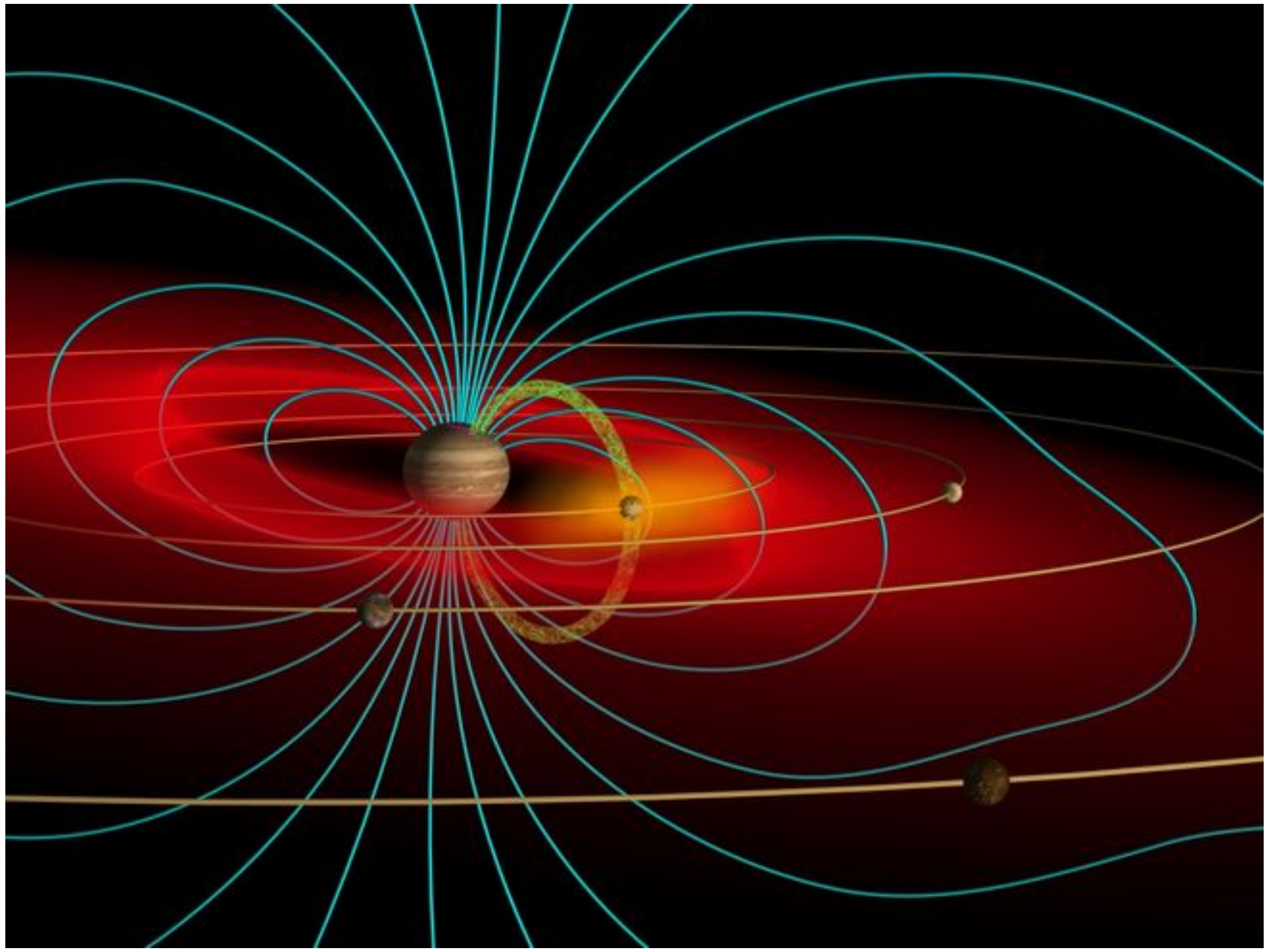
— The emission is highly polarised so unlike the long duration incoherent gyrosynchrotron emission.
— It is long duration so unlike the highly polarised burst emission.

Vedantham, Callingham, Shimwell et al. submitted

Some results and ongoing studies

The emission is phenomenologically very similar to ultracool dwarf and gas giant auroral cyclotron emission.

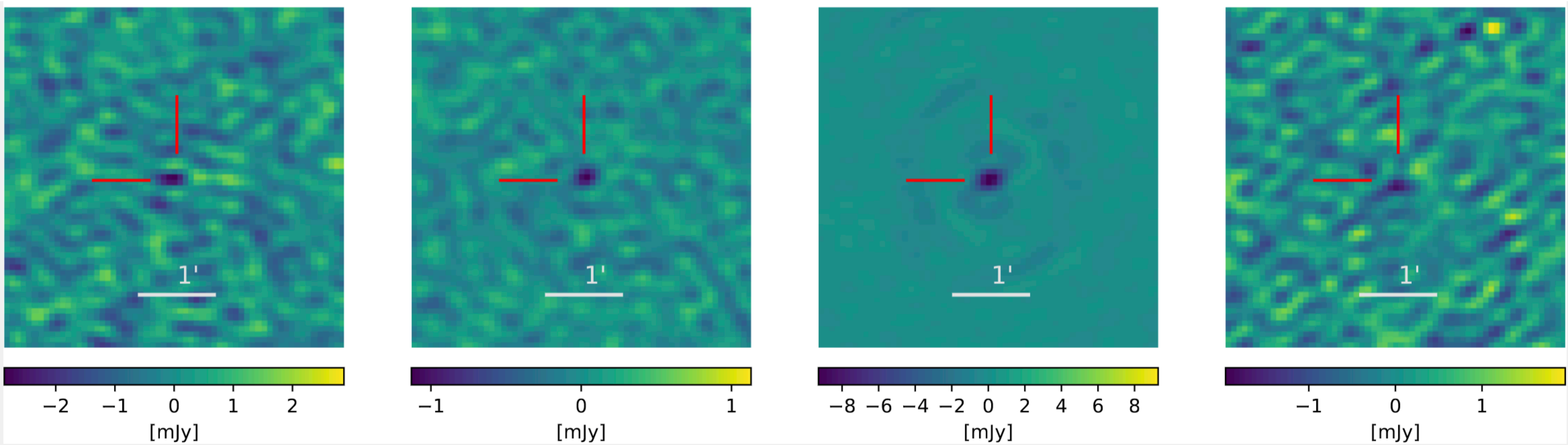
Auroral emissions are thought to be driven by either a breakdown of co-rotation of equatorial plasma with the magnetic field or sub-Alfvenic interaction with an orbiting body.



The current required to produce the observed radio emission cannot be generated by the stars slow rotation. Hence for this star (rotation 3000 hours) we favour a sub-Alfvenic interaction of its magnetospheric plasma with a short-period exoplanet — Vedantham, Callingham, Shimwell et al. submitted.

Some results and ongoing studies

Obs 1 Obs 2 Obs 3 Obs 4



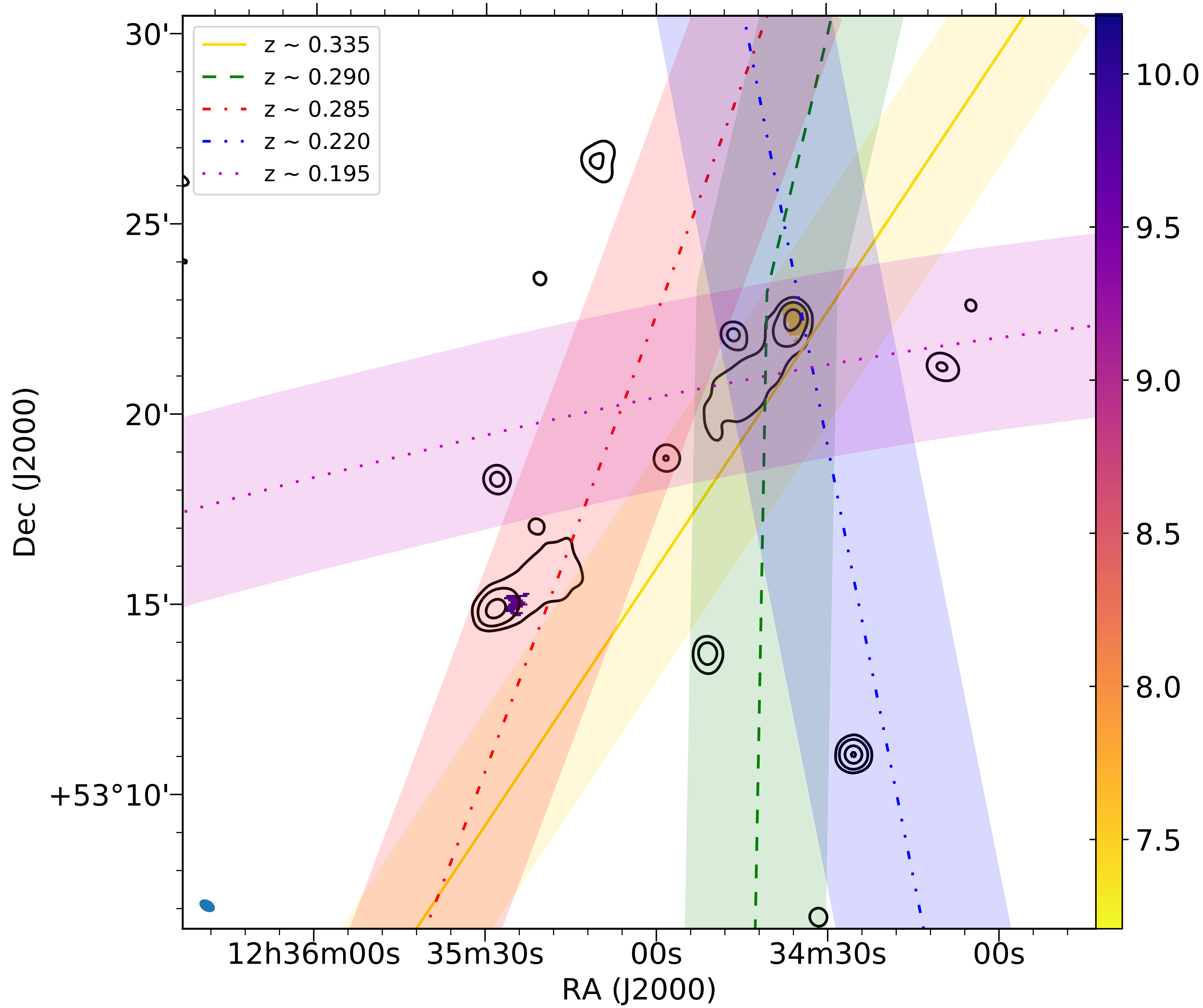
Over 20 more stars (including 7 other M-dwarfs with little chromospheric activity (Halpha and X-ray) and other e.g flare stars, rotational variables) have have also been detected — Callingham, Shimwell, Vedantham in prep

The M-dwarfs are also very slow rotators so we presently think the most natural explanation is a star-planet magnetic interaction (e.g. Jupiter-Io) . We are searching for periodicity now to establish this planet hypothesis

Some results and ongoing studies

- ILT J123459.82+531851.0
  - $z = 0.3448 \pm 0.0003$
  - Linear size: 3.4 Mpc
  - RM difference between lobes of 2.5 ± 0.1 rad/m^2
- More large-scale-structure (LSS) filaments along line of sight to NW lobe
  - $B_{LSS} \sim 0.3$ μG, if *all* RM difference due to filaments
- MHD simulations: small probability (<5%) of all 2.5 rad/m^2 due to IGMF
- Galactic RM variation on 11' scales likely the dominant factor

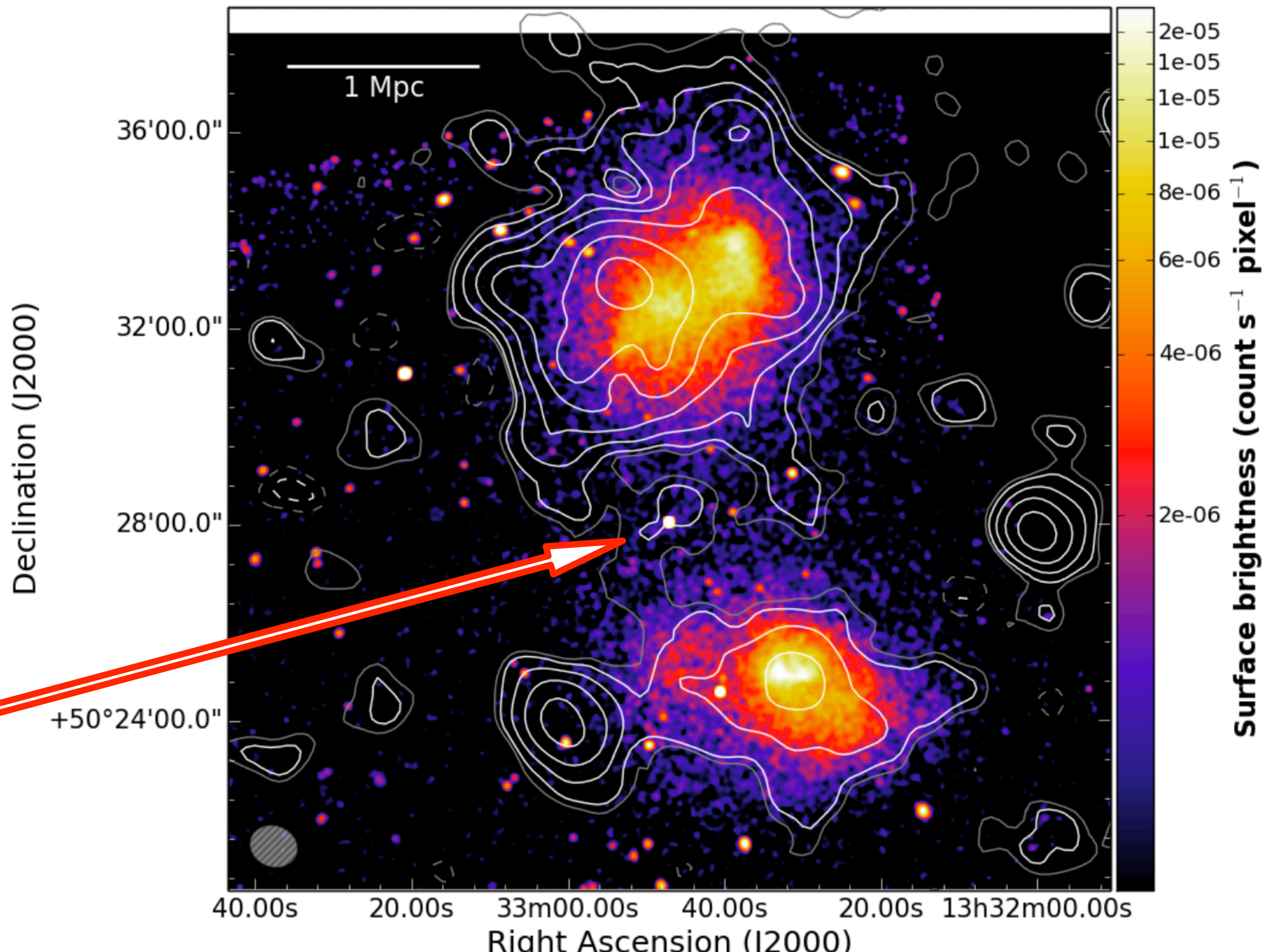
Probing the intergalactic magnetic field with faraday rotation measurements of a gaint radio galaxy - O' Sullivan+ 2019



Now approximately 1 polarised source detected per square degree and about 1,300 detected in total. Aim is to build an rotation measure grid from these to help model the galactic magnetic field.

Some results and ongoing studies

Maybe we are starting to see traces of diffuse radio emission outside of clusters (Botteon+ 2018). Potentially allowing us to constrain the magnetic field in these regions.



A possible radio and X-ray bridge.

Summary

- The products from the LOFAR HBA survey data release 1 (LoTSS-DR1) cover 400 square degrees and contain 325,000 radio sources and over 200,000 with optical ids and redshifts. These are completely public.
- LoTSS-DR2 will cover ~2,000 square degrees and contain ~2,000,000 sources — the most sources of any radio survey to date.
- We have very sensitive maps for three LOFAR HBA deep fields (<30microJy/beam) and we hope to release these in the near future.
- There is a lot of exciting science that can be done with the survey data and it has a huge legacy value.