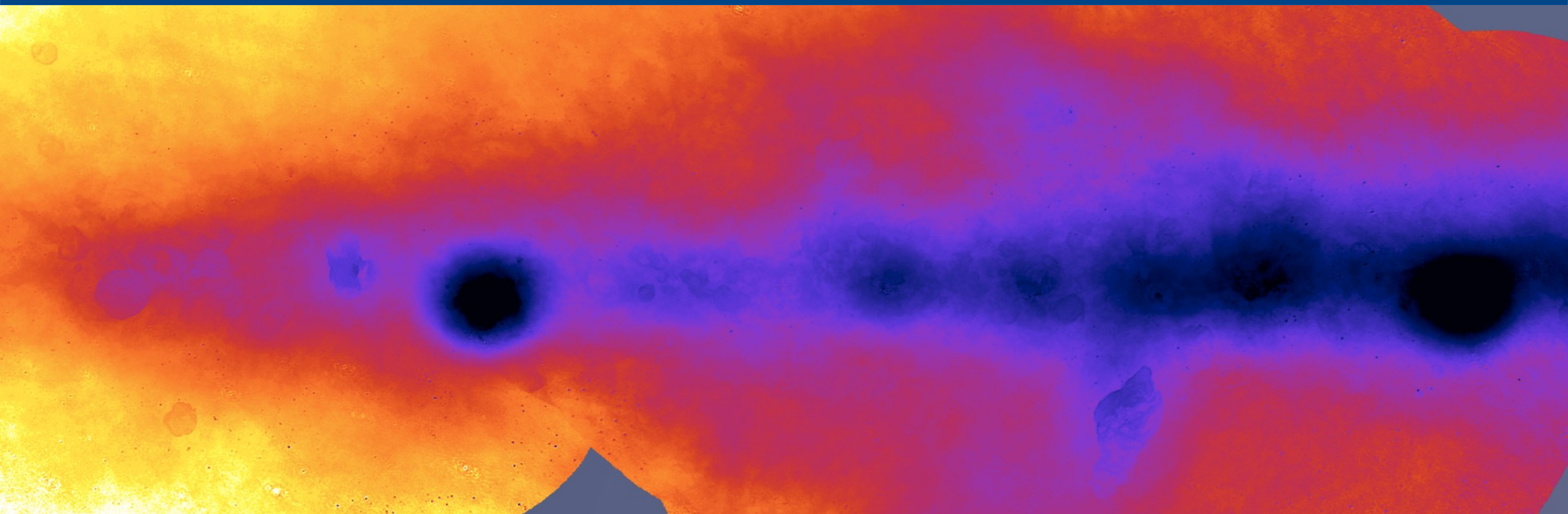


LoTSS DR3



University of
Hertfordshire **UH**

Martin Hardcastle

LOFAR Annual Meeting Dublin 08/06/26

On behalf of Tim Shimwell, Cyril Tasse and the Surveys KSP team



LOFAR-UK

- Mostly summarizing published paper!
- See <https://doi.org/10.1051/0004-6361/202557749>
- For data products see <https://lofar-surveys.org/dr3.html>
- For VO access see https://vo.astron.nl/browse/lotss_dr3/q

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Astronomy
Astrophysics

The LOFAR Two-metre Sky Survey

VII. Third Data Release

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ABSTRACT

We present the third data release of the LOFAR Two-metre Sky Survey (LoTSS-DR3). The survey images cover 88% of the northern sky and were created from 12 950 h of data (18.6 PB) accumulated over 10.5 years. Producing the images took 20 million core hours of processing through direction-independent and direction-dependent calibration pipelines that correct for instrumental effects as well as spatially and temporally varying ionospheric distortions. In our 120–168 MHz continuum mosaic images with an angular resolution of 6'' (9'' below declination 10°) we catalogue 13 667 877 sources, formed from 16 943 656 Gaussian components. The scatter in the astrometric precision approximately follows the expected noise-like behaviour but with an additional systematic component of at least 0.24'' that is likely due to calibration imperfections. The random flux density scale error is 6%, while the systematic offset was previously shown to be within 2%. The median sensitivity of our mosaics is 92 $\mu\text{Jy beam}^{-1}$, improving to 68 $\mu\text{Jy beam}^{-1}$ at high observing elevations, but degrading to 183 $\mu\text{Jy beam}^{-1}$ at the celestial equator due to station area projection effects. Completeness simulations, accounting for realistic source models, time- and bandwidth-smearing effects, and astrometric errors, indicate that we detect more than 95% of compact sources with integrated flux densities exceeding 9 times the local root mean square (RMS) noise. However, the recovered source counts in a particular integrated flux density bin do not match the injected counts until flux densities exceed 45 times the local RMS noise. The Euclidean-normalised differential source counts derived from the survey constrain the radio source population over five orders of magnitude and are in good agreement with previous deep and wide-area surveys. All data products are publicly available, including catalogues, individual-field Stokes I , Q , U , and V images, mosaicked Stokes I images, and uv data with associated direction-dependent calibration solutions.

Key words. instrumentation: interferometers – catalogues – surveys – radio continuum: general

1. Introduction

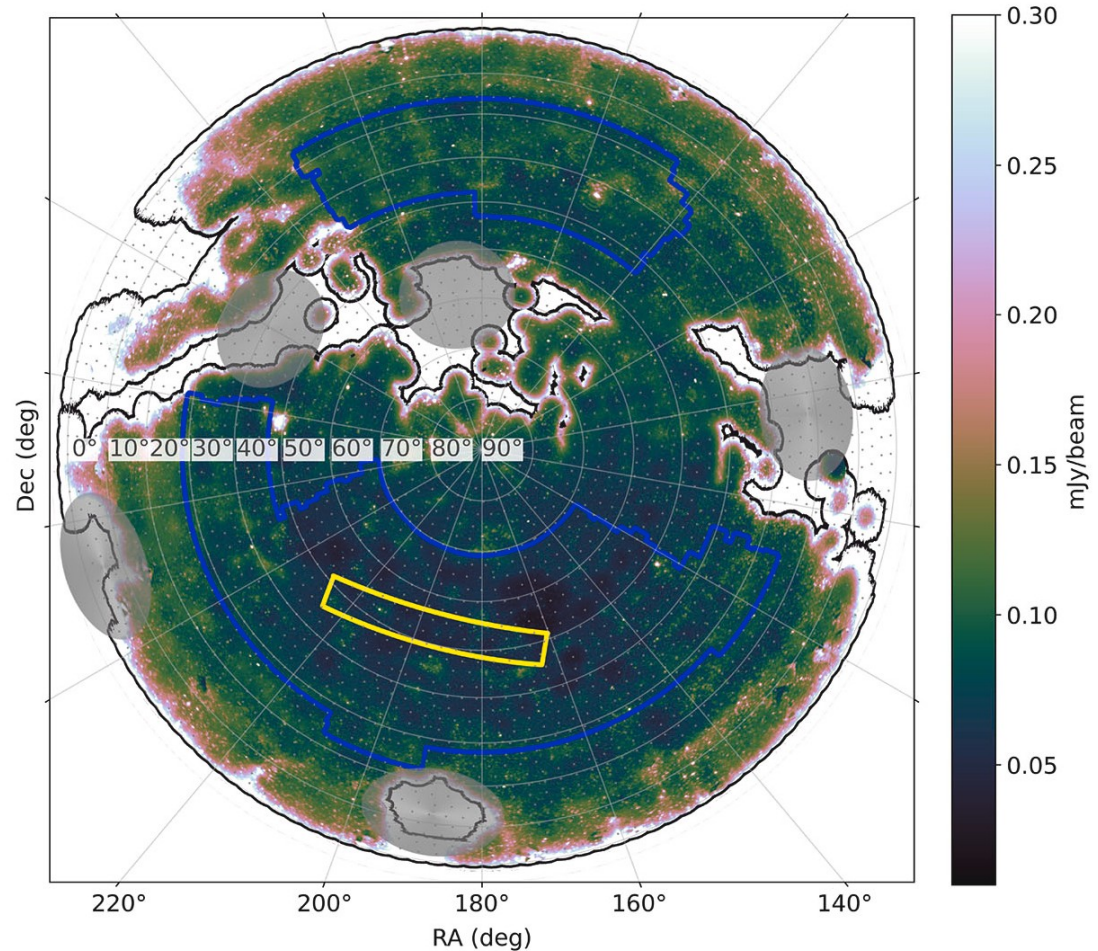
The Low Frequency ARray (LOFAR; van Haarlem et al. 2013) Two-metre Sky Survey (LoTSS; Shimwell et al. 2017) is a 120–168 MHz imaging survey of the entire northern sky. The primary observational aim of the survey is to produce total intensity images with a root mean square (RMS) noise of $\sim 100 \mu\text{Jy beam}^{-1}$ at an angular resolution of 6'' under optimal observing elevations. However, other science-ready data products are also being produced, including: lower-angular-

resolution images with a higher surface brightness (e.g. Oei et al. 2022); Stokes Q and U image cubes at several resolutions (e.g. Erceg et al. 2022 and O'Sullivan et al. 2023); Stokes V images (e.g. Callingham et al. 2023); and dynamic spectra of selected variable sources (e.g. Tasse et al. 2025). In addition to these products, we provide radio source catalogues and uv data together with the associated calibration solutions. The uv data can be easily post-processed and tailored to a particular science case by, for example, tuning calibration and imaging parameters to study faint diffuse emission (van Weeren et al. 2021) or creating source-subtracted data and snapshot images

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LoTSS wide-area

- Original aim was to survey all of the northern sky to a sensitivity around 0.1 mJy/beam at 6 arcsec resolution
- DR1: 400 sq. deg:
- DR2: 5,700 sq. deg: 4.4 million sources
- DR3: 19,000 sq. deg: 13.7 million sources
- 2551/3168 of the original pointings observed and processed in the LOFAR1.0 era. Most of the missing coverage is in the Galactic plane or associated with A-team sources (Virgo, Cygnus, Cas, Taurus, Hercules).
- Target sensitivity achieved except at low dec/Gal b



Overview



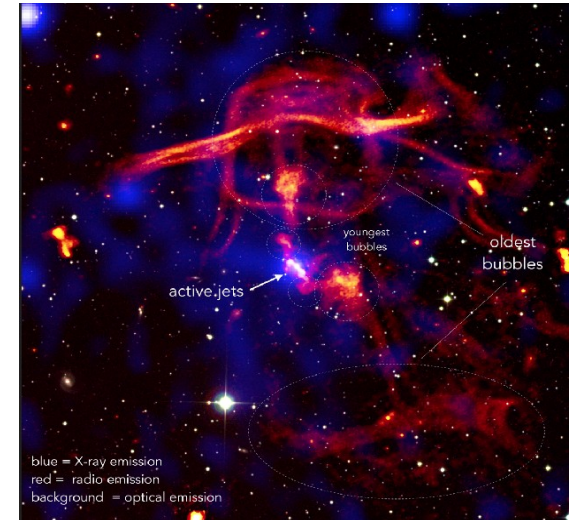
18.6PB of data split between ~3 million files and stored at 3 LOFAR archive locations. 0.6 PB transported to processing locations over internet



12,950 hrs of telescope time utilising 100 proposals from 2013 to mid 2024



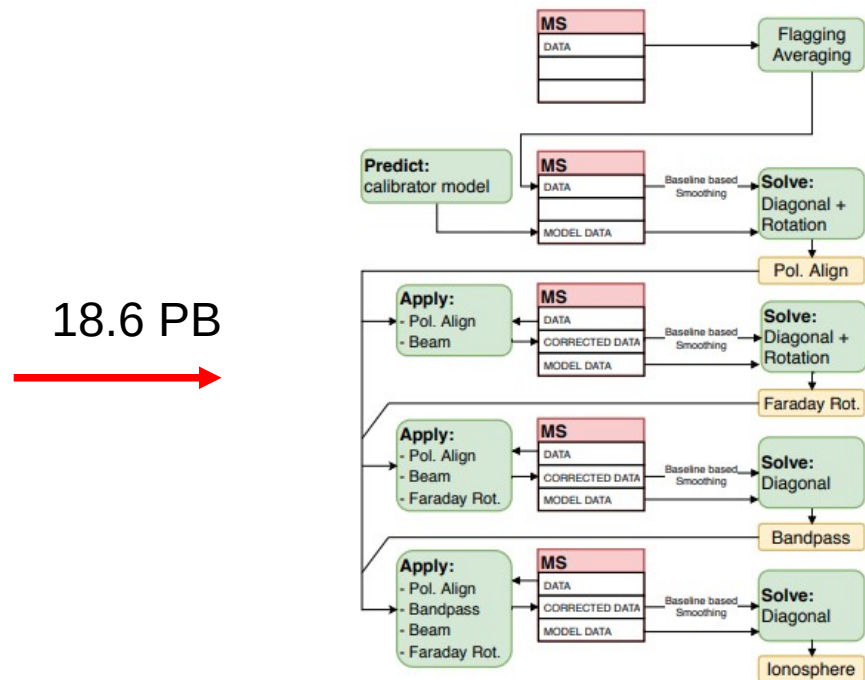
590TB of final data products (images, cubes, dynamic spectra, visibilities, calibration solutions, etc) covering 88% of northern sky



2,551 final science quality images. Created using 20 million core hours, averaging 400cpu in continuous use for 6 years.

How we did it

Prefactor/Prefactor 3/ LINC on LTA sites



Original strategy by van Weeren+18; key tools DP3, Dysco, AOFlagger

DDF-pipeline on remote sites

```

/* On 60 LOFAR HBA subbands */
/* DI initial deconv and clustering */
1.1  $\hat{\mathbf{x}}_v \leftarrow I(\mathbf{v}_6, \mathbf{J}_{\Omega} = \mathbf{1}, \mathbf{B}_{\Omega});$ 
1.2  $\Omega_n \leftarrow C(\hat{\mathbf{x}}_v);$ 
/* DI calibration and imaging */
1.3  $\hat{\mathbf{x}}_v \leftarrow I(\mathbf{v}_6, \mathbf{B}_{\Omega_n});$ 
1.4  $\mathbf{v}_6^c \leftarrow \mathcal{K}(\mathbf{v}_6, \hat{\mathbf{x}}_v, \mathbf{B}_{\Omega_n} | \text{full}, \delta t_0, \delta v_0, \Omega_0);$ 
1.5  $\hat{\mathbf{x}}_v \leftarrow I(\mathbf{v}_6^c, \mathbf{B}_{\Omega_n});$ 
/* Bootstrapping the flux density scale */
1.6  $\mathbf{v}^c \leftarrow \mathcal{B}(\mathbf{v}_6^c);$ 
/* Phase only DD calibration and imaging */
1.7  $\hat{\mathbf{J}} \leftarrow \varphi \circ \mathcal{F} \circ \mathcal{K}(\mathbf{v}_6^c, \hat{\mathbf{x}}_v, \mathbf{B}_{\Omega_n} | \text{scalar}, 1 \text{min}, 2 \text{MHz}, \Omega_n);$ 
1.8  $\hat{\mathbf{x}}_v \leftarrow I(\mathbf{v}_6^c, \hat{\mathbf{J}} \mathbf{B}_{\Omega_n});$ 
/* DD calibration and imaging */
1.9  $\hat{\mathbf{J}} \leftarrow \mathcal{F} \circ \mathcal{K}(\mathbf{v}_6^c, \hat{\mathbf{J}} \mathbf{B}_{\Omega_n}, \hat{\mathbf{x}}_v | \text{scalar}, 1 \text{min}, 2 \text{MHz}, \Omega_n);$ 
1.10  $\hat{\mathbf{x}}_v \leftarrow I(\mathbf{v}_6, \hat{\mathbf{J}} \mathbf{B}_{\Omega_n});$ 
/* DI calibration and imaging */
1.11  $\mathbf{v}_6^c \leftarrow \mathcal{K}(\mathbf{v}_6, \hat{\mathbf{J}} \mathbf{B}_{\Omega_n}, \hat{\mathbf{x}}_v | \text{full}, \delta t_0, \delta v_0, \Omega_0);$ 
1.12  $\hat{\mathbf{x}}_v \leftarrow I(\mathbf{v}_6^c, \hat{\mathbf{J}} \mathbf{B}_{\Omega_n});$ 

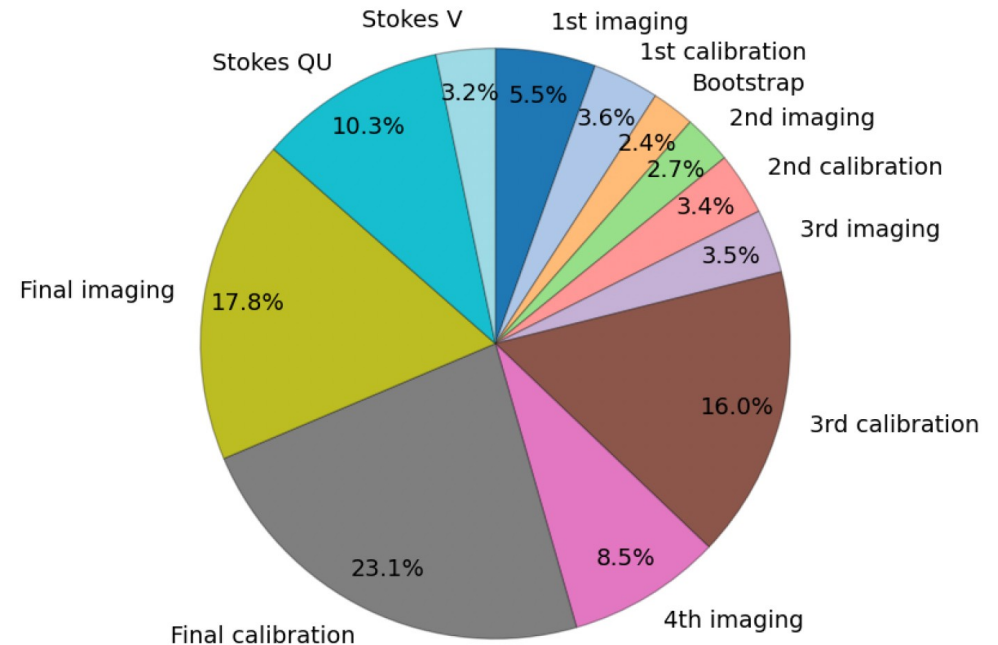
/* On 240 LOFAR HBA subbands */
/* DD calibration */
1.13  $\hat{\mathbf{J}} \leftarrow \mathcal{F} \circ \mathcal{K}(\mathbf{v}_{24}, \mathbf{B}_{\Omega_n}, \hat{\mathbf{x}}_v | \text{scalar}, 1 \text{min}, 2 \text{MHz}, \Omega_n);$ 
/* DI calibration */
1.14  $\mathbf{v}_{24}^c \leftarrow \mathcal{K}(\mathbf{v}_{24}, \hat{\mathbf{J}} \mathbf{B}_{\Omega_n}, \hat{\mathbf{x}}_v | \text{full}, \delta t_0, \delta v_0, \Omega_0);$ 
/* DD imaging */
1.15  $\hat{\mathbf{x}}_v \leftarrow I(\mathbf{v}_{24}^c, \hat{\mathbf{J}} \mathbf{B}_{\Omega_n});$ 
/* DD calibration */
1.16  $\hat{\mathbf{J}} \leftarrow \mathcal{F} \circ \mathcal{K}(\mathbf{v}_{24}^c, \mathbf{B}_{\Omega_n}, \hat{\mathbf{x}}_v | \text{scalar}, 1 \text{min}, 2 \text{MHz}, \Omega_n);$ 
/* Slow DD calibration */
1.17  $\hat{\mathbf{J}}_s \leftarrow \mathcal{K}(\mathbf{v}_{24}^c, \hat{\mathbf{J}} \mathbf{B}_{\Omega_n}, \hat{\mathbf{x}}_v | \text{scalar}, 43 \text{min}, 2 \text{MHz}, \Omega_n);$ 
/* Final imaging steps */
1.18  $\hat{\mathbf{x}}_v \leftarrow I(\mathbf{v}_{24}^c, \hat{\mathbf{J}}_s \mathbf{B}_{\Omega_n});$ 
1.19 Facet-based astrometric correction (see Shimwell et al. 2019, for details);
    
```

0.6 PB final
products

Current strategy by Tasse+21, key tools DDFacet, kMS

Computational costs

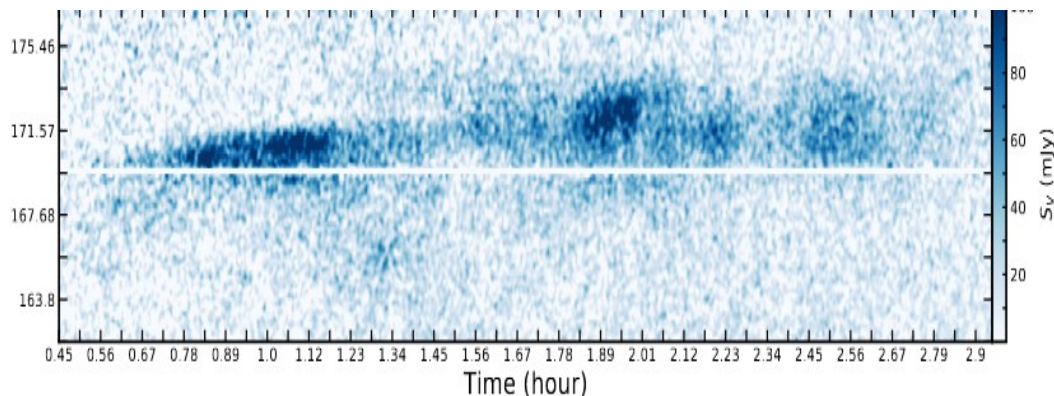
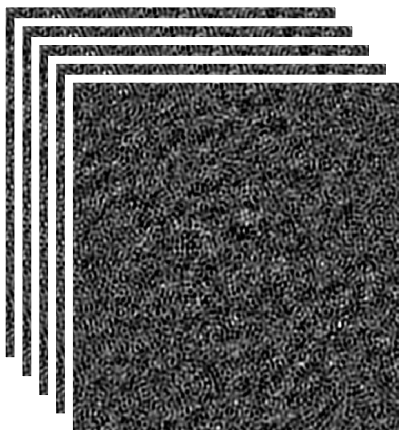
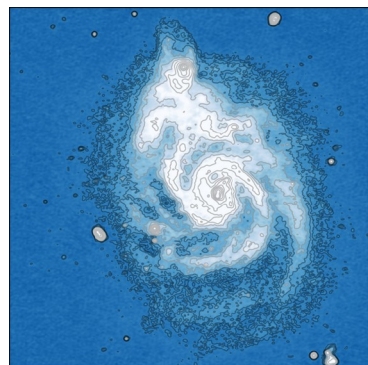
- Bulk processing began in 2017/18
- LINC processing used 150-4,300 core hours per field depending on demixing and selfcalibration options. In total 4.2 million core hours
- LINC executed on compute local to data (i.e. JUWELS, Spider, Grid)
- DDF-pipeline processing took 6,200 core hours per field on average over ~6 years. Typical fields on a modern node about 4,500 core hours. In total 16 million core hours.
- DDF-pipeline executed on LOFAR-UK (Herts), SURF Spider (NWO grant) and Leiden. Data transported from and to SURF.
- Reprocessing (see later) another ~ 3 million core hours...



Breakdown of timing of 75hrs on 60 CPU DDF-pipeline run of 8hr observation with 48MHz bandwidth.

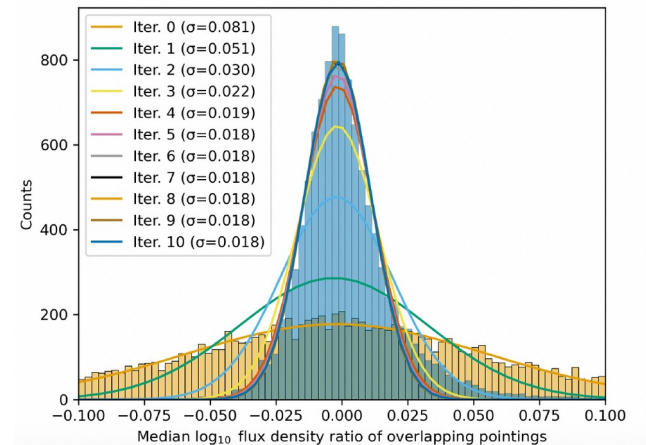
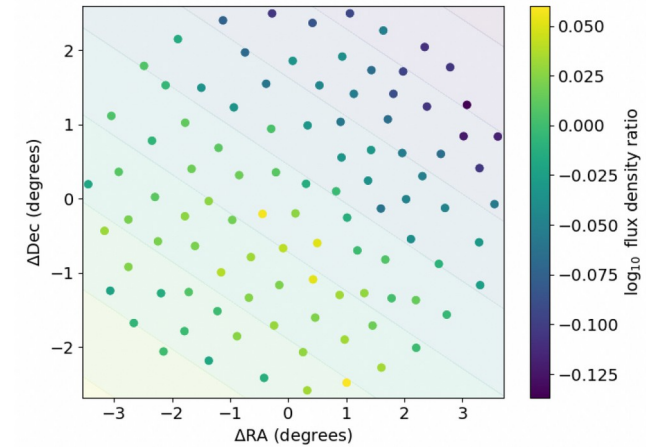
LoTSS basic and derived data products

- Field products (2,551 pointings):
 - 6-arcsec Stokes I image
 - 20-arcsec Stokes I image
 - 6-arcsec Stokes V image*
 - 20-arcsec dirty Stokes QU cube
 - 60-arcsec dirty Stokes QU cube
 - Dynamical spectra per field*
 - Calibrated visibilities and DD solutions per field
- Mosaic products (1,580 mosaics covering Healpix NSIDE=16 pixels; beam and rms weighted)
 - 6-arcsec Stokes I mosaic
 - 20-arcsec Stokes I mosaic
 - Source and Gaussian catalogues
- Combined source and Gaussian catalogues
- HIPS images usable through Aladin



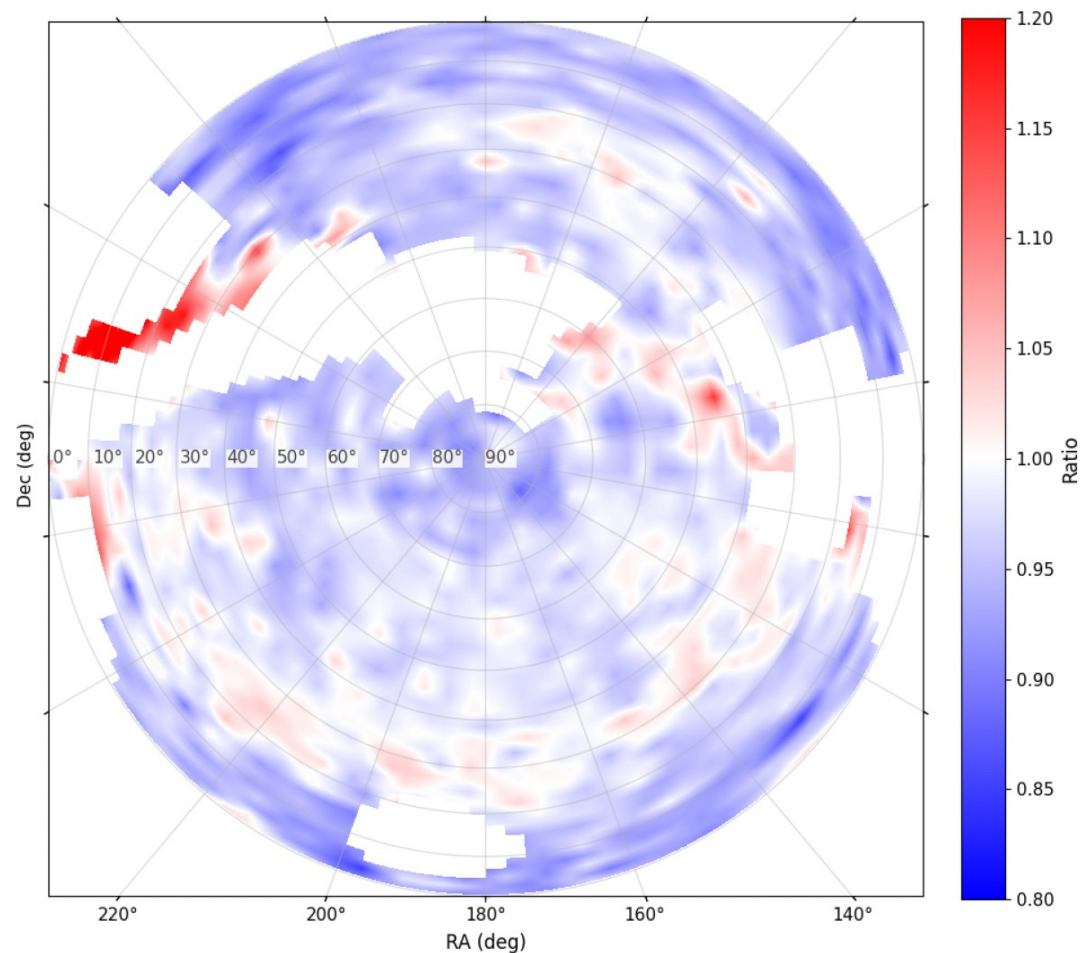
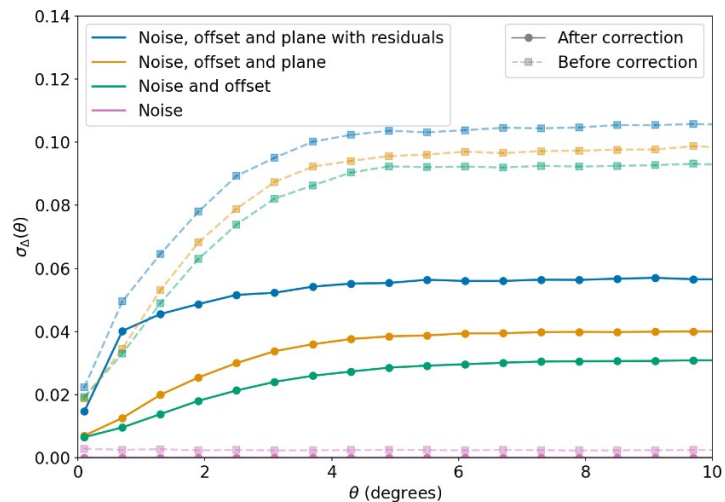
DR3 flux density scale

- Flux density scale of each LoTSS pointing is set from NVSS (NVSS/5.912). Assuming average NVSS to LoTSS flux density ratio of several hundred sources.
- We now also attempt to account for variations across the field of view.
- Each individual pointing catalogue is cross-matched with neighbouring pointings.
- A plane is fitted to the measured flux density ratios
- Iteratively derive corrections which are applied in mosaicing

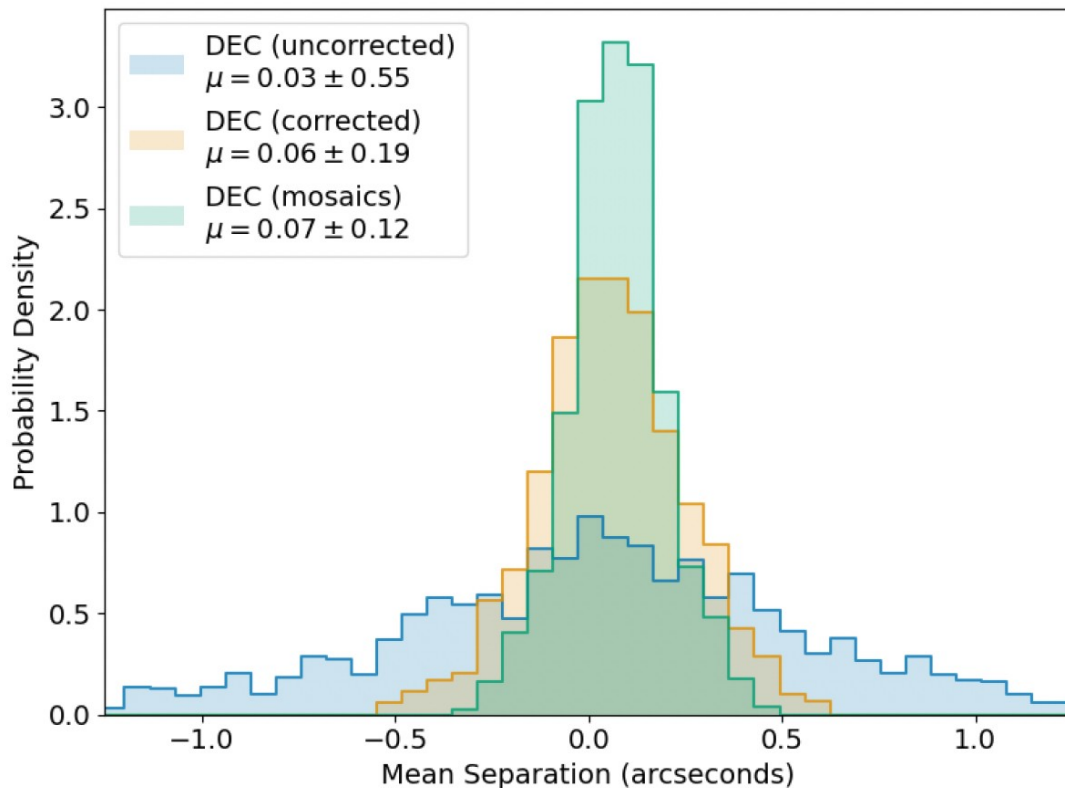


DR3 flux density scale

- Checks derived from
 - Comparison with NVSS – standard deviation of flux ratio 6%
 - Source counts per healpix mosaic – standard deviation of correction factor 4%
- Reasonable to assume a 6% flux scale accuracy overall – adjacent sources will be better...

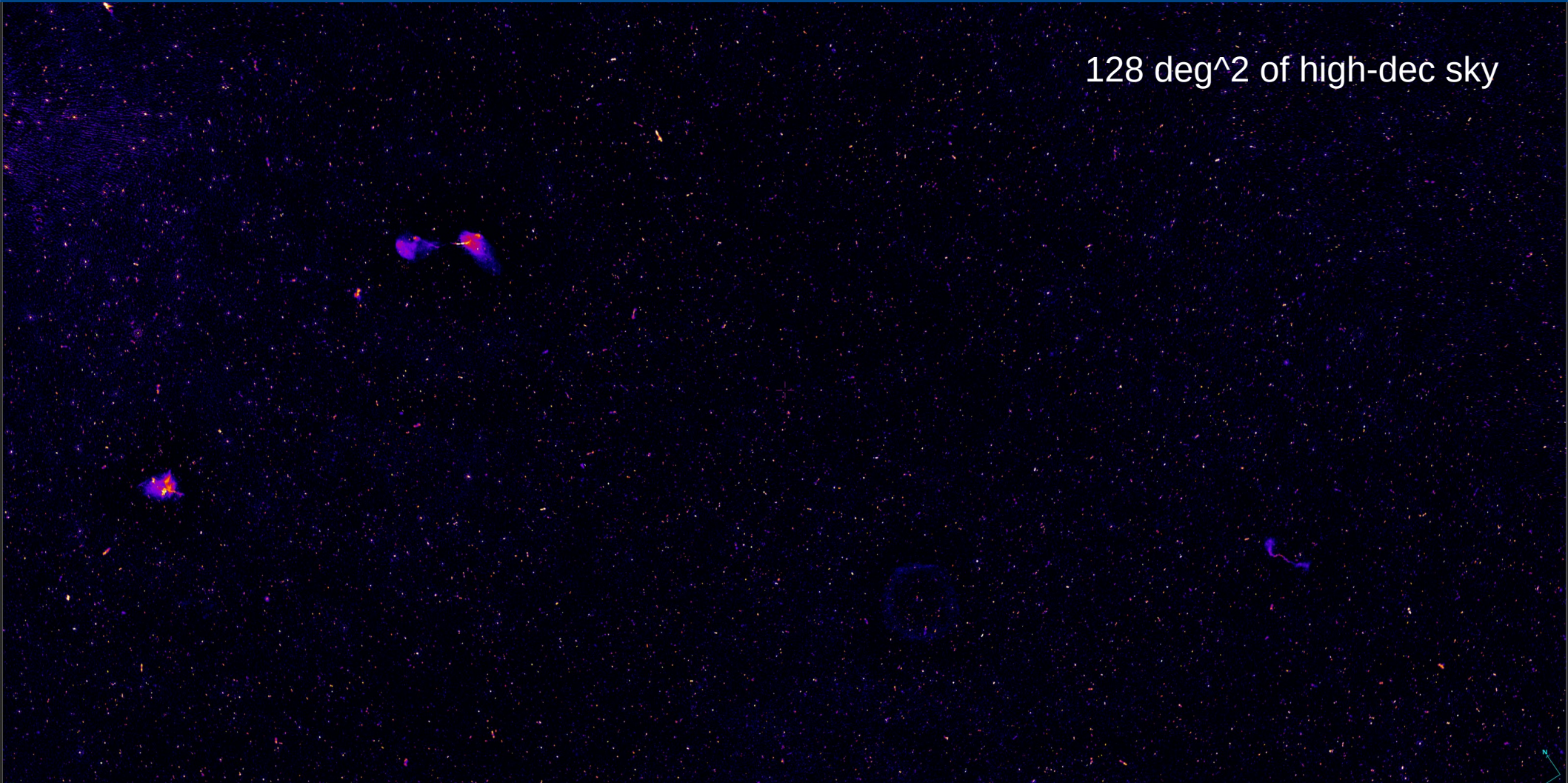


- Astrometric refinement through cross-match with Pan-STARRS DR2 optical catalogue (Flewelling+ 2020).
- Applied in mosaicing per facet where a good astrometric solution can be derived
- Improves offsets between LoTSS and FIRST.



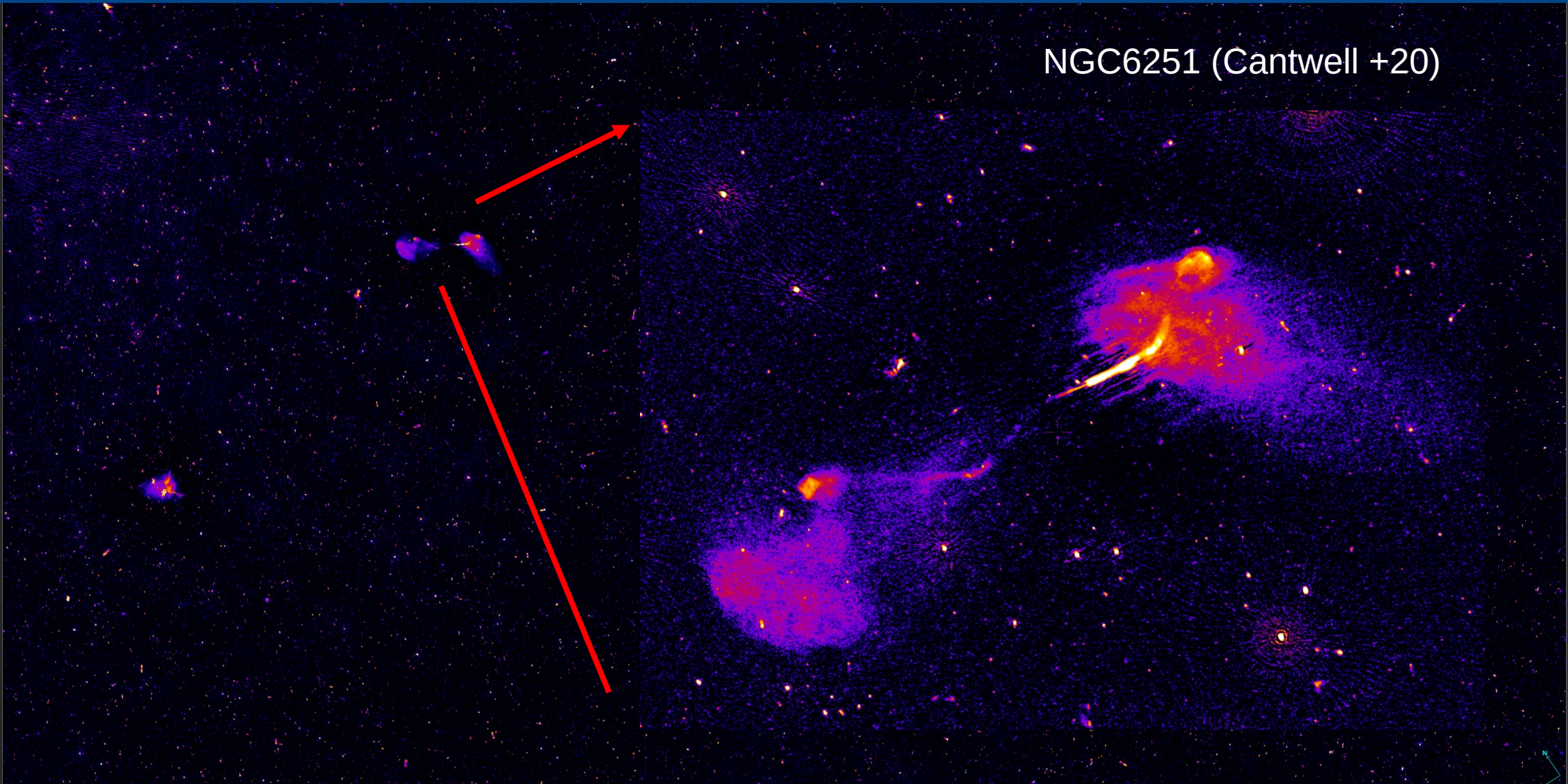
DR3 imaging (6 arcsec resolution)

128 deg² of high-dec sky



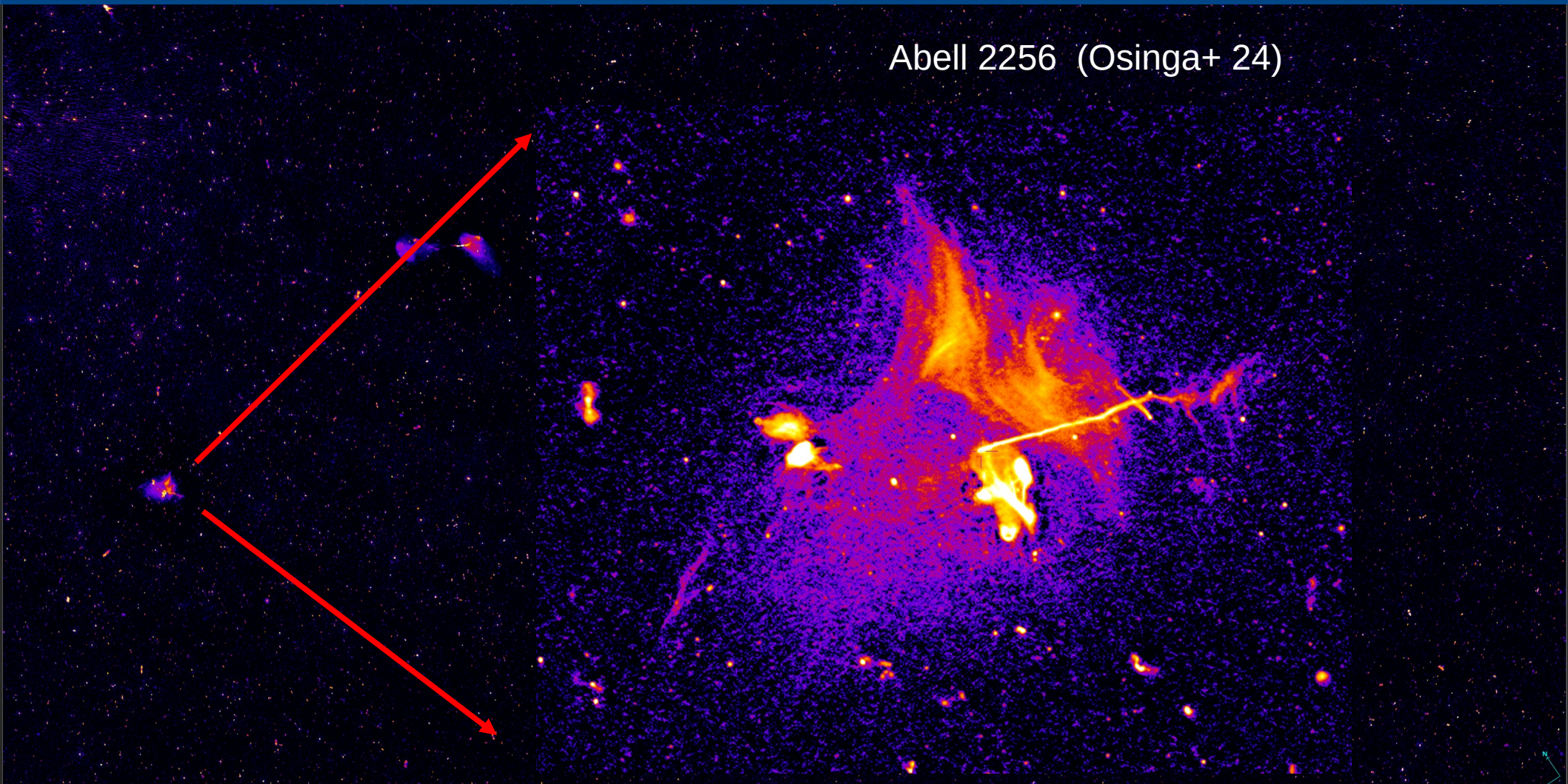
DR3 imaging

NGC6251 (Cantwell +20)



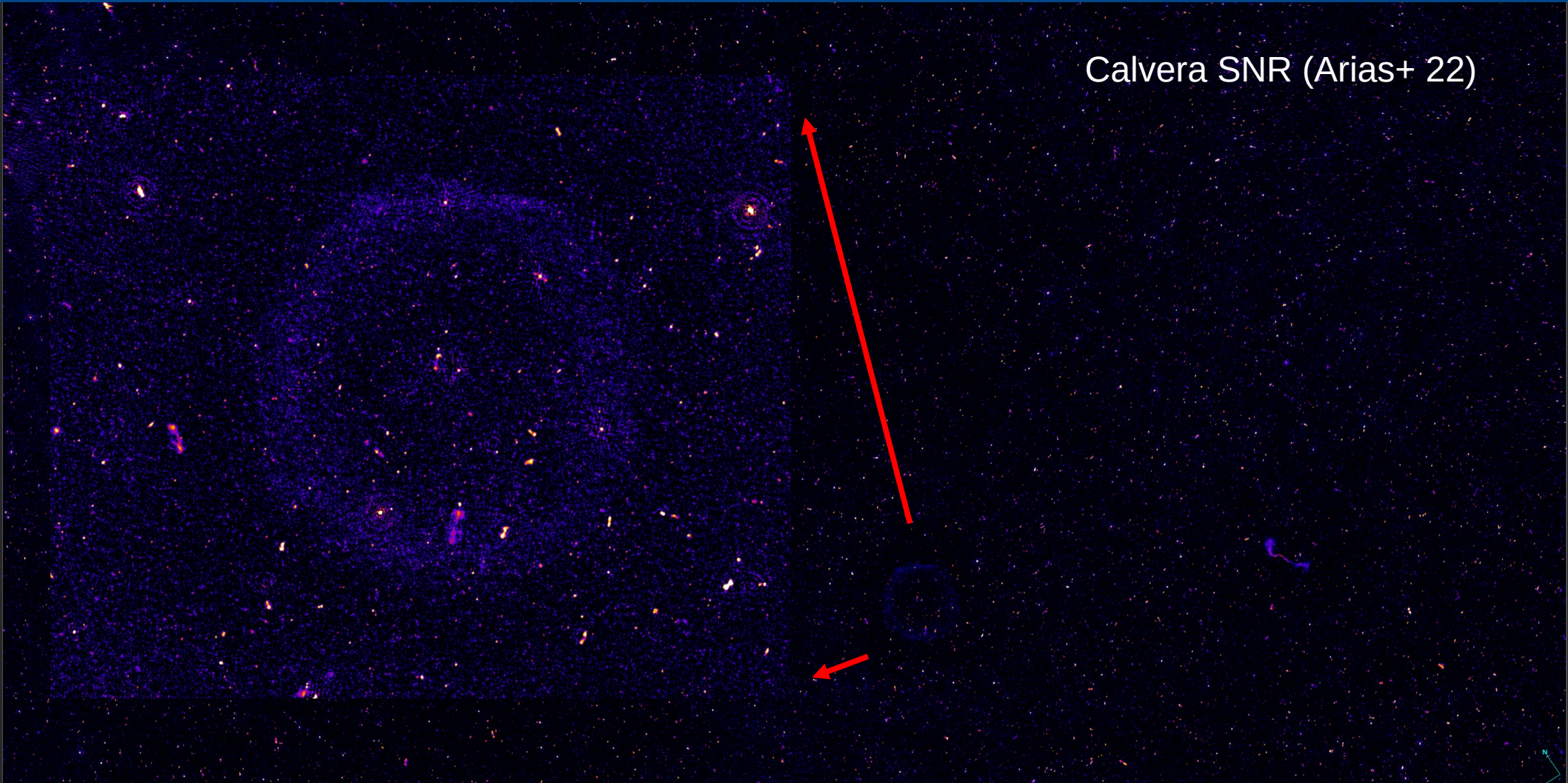
DR3 imaging

Abell 2256 (Osinga+ 24)



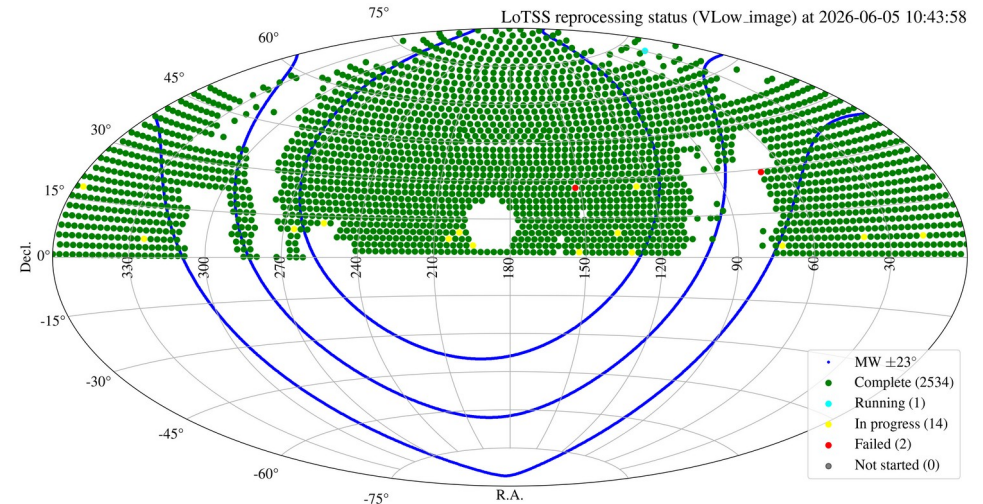
DR3 imaging

Calvera SNR (Arias+ 22)

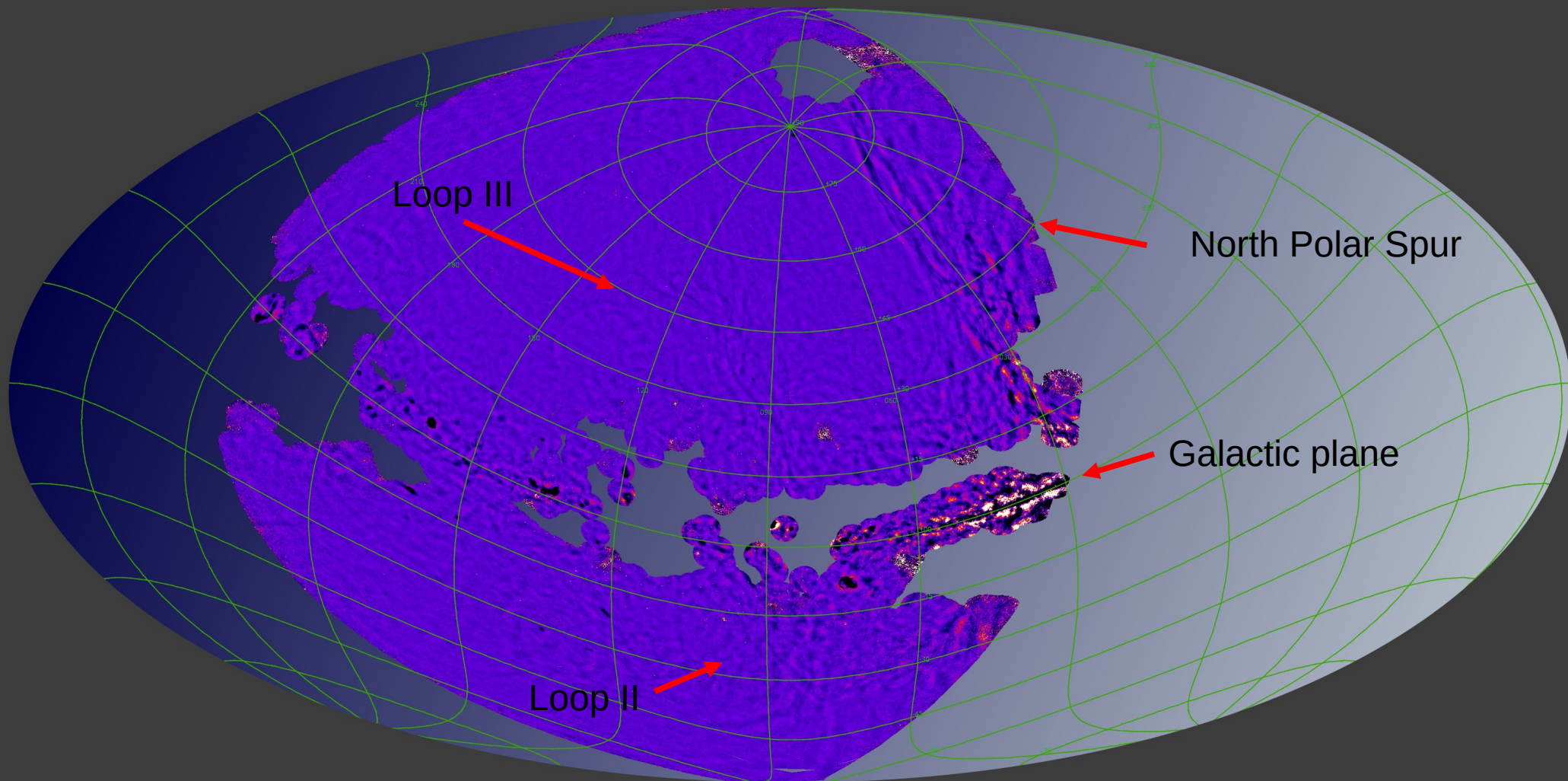


LoTSS reprocessing

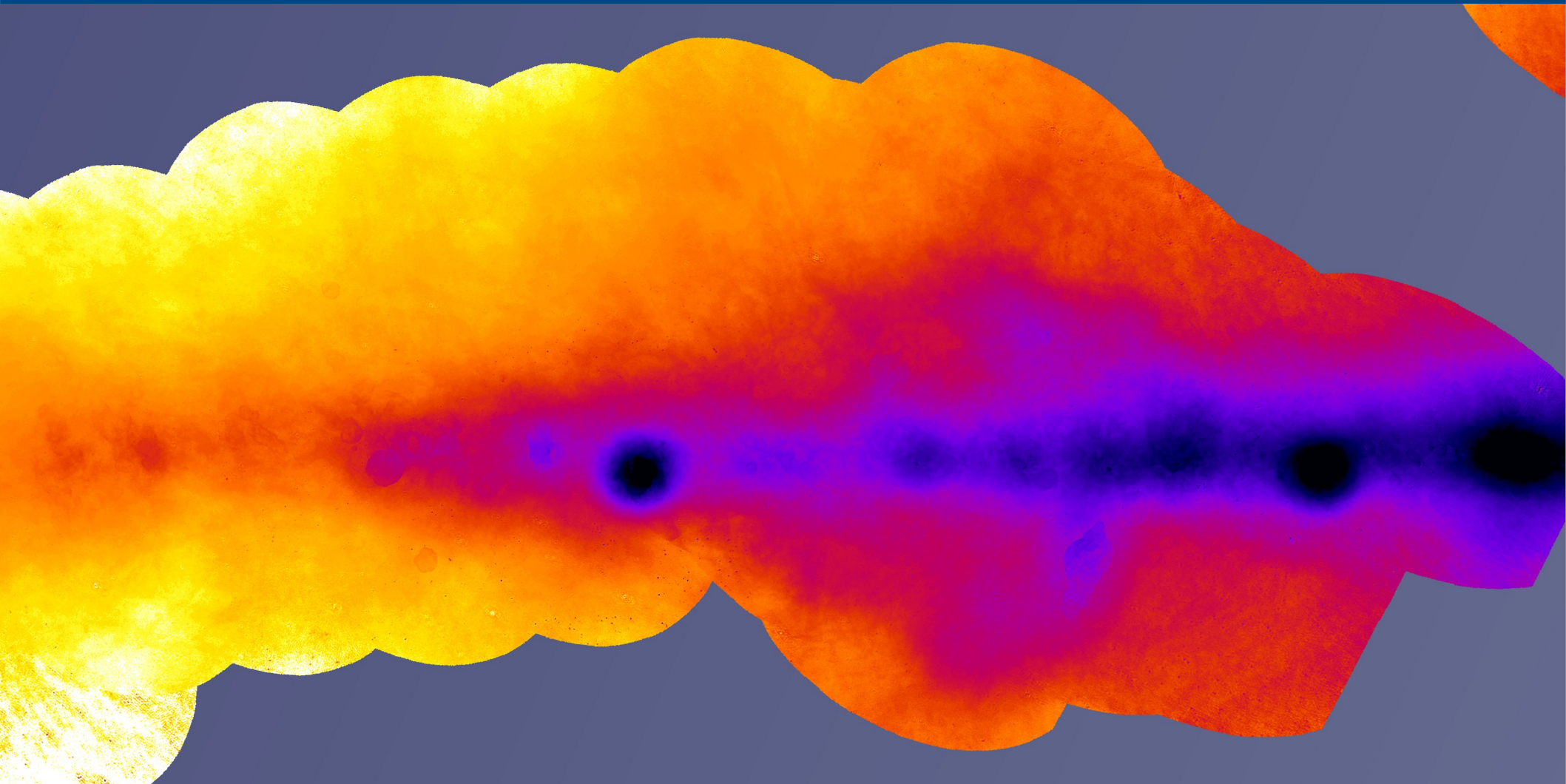
- Started May 2025 once main processing complete
- New data products:
 - Stokes I 60-arcsec images (with and without source subtraction)
 - Fully subtracted residual visibility datasets
 - Fast imaging time cubes
- Improved data products:
 - 6-arcsec Stokes V for all fields
 - Dynamical spectra for all fields



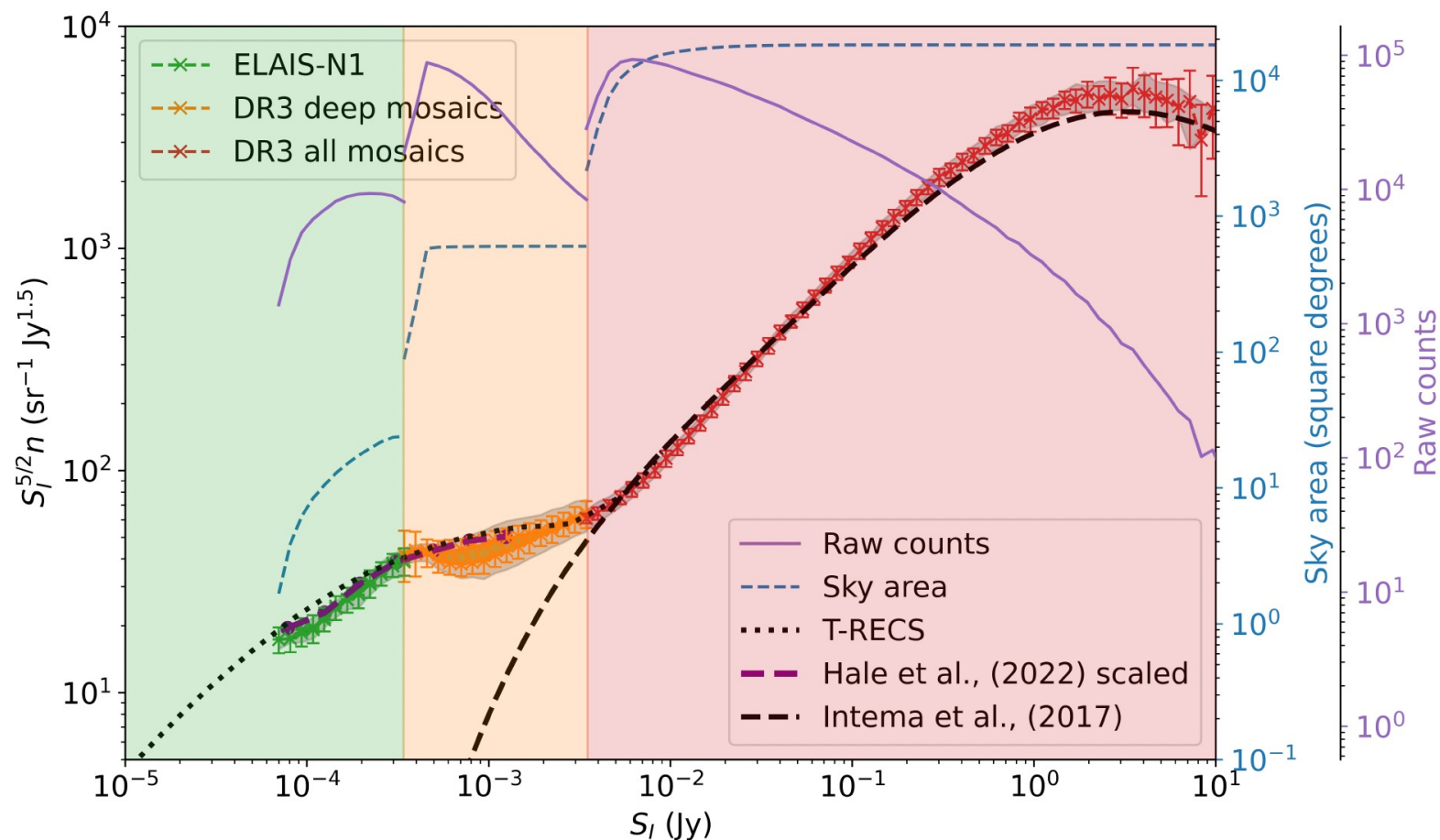
DR3 VLow source-subtracted imaging (1 arcmin resolution)



DR3 VLow source-subtracted with Haslam 408-MHz short spacings



DR3 source counts

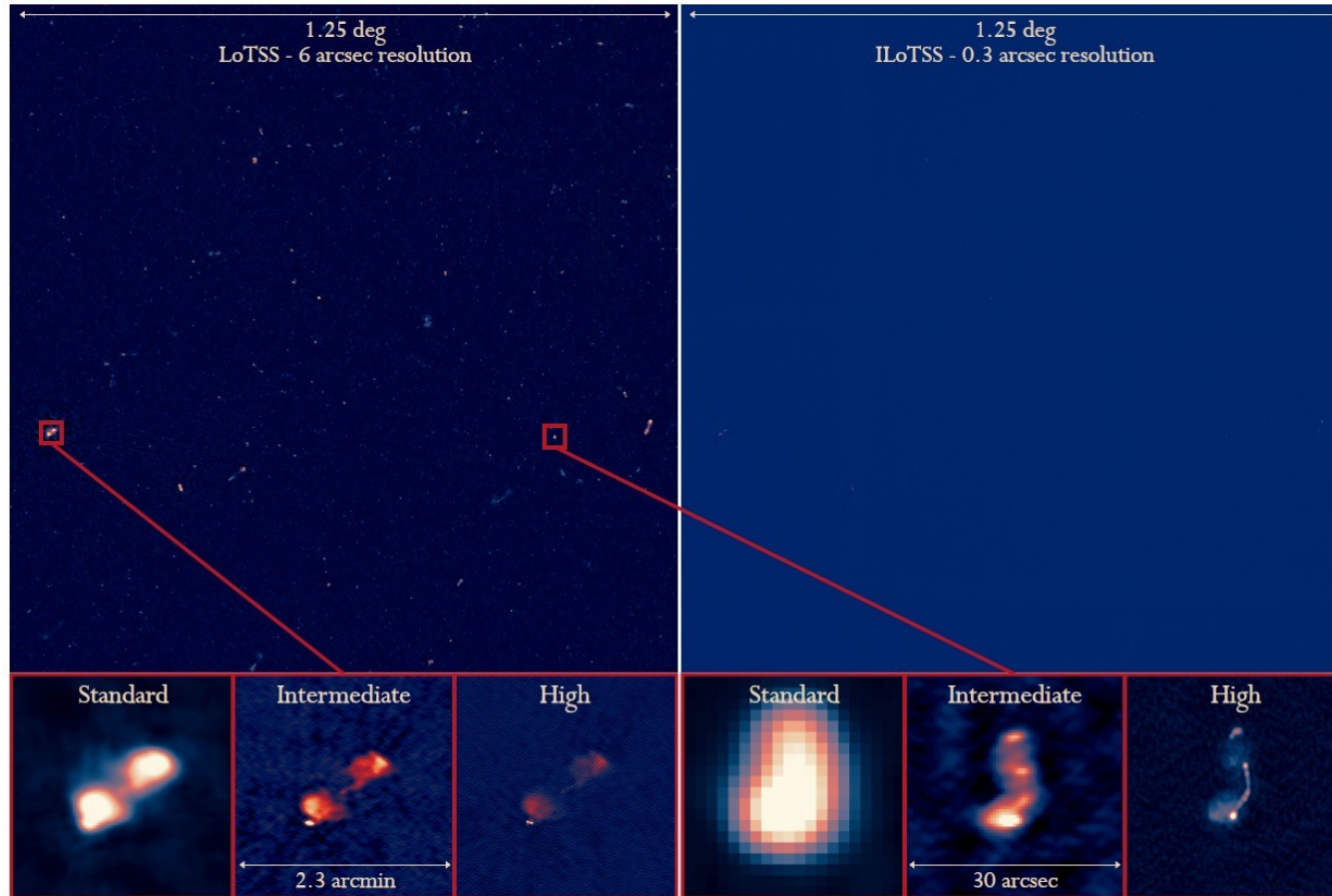


With deep fields to provide the deepest counts.

Completeness corrections derived from simulation

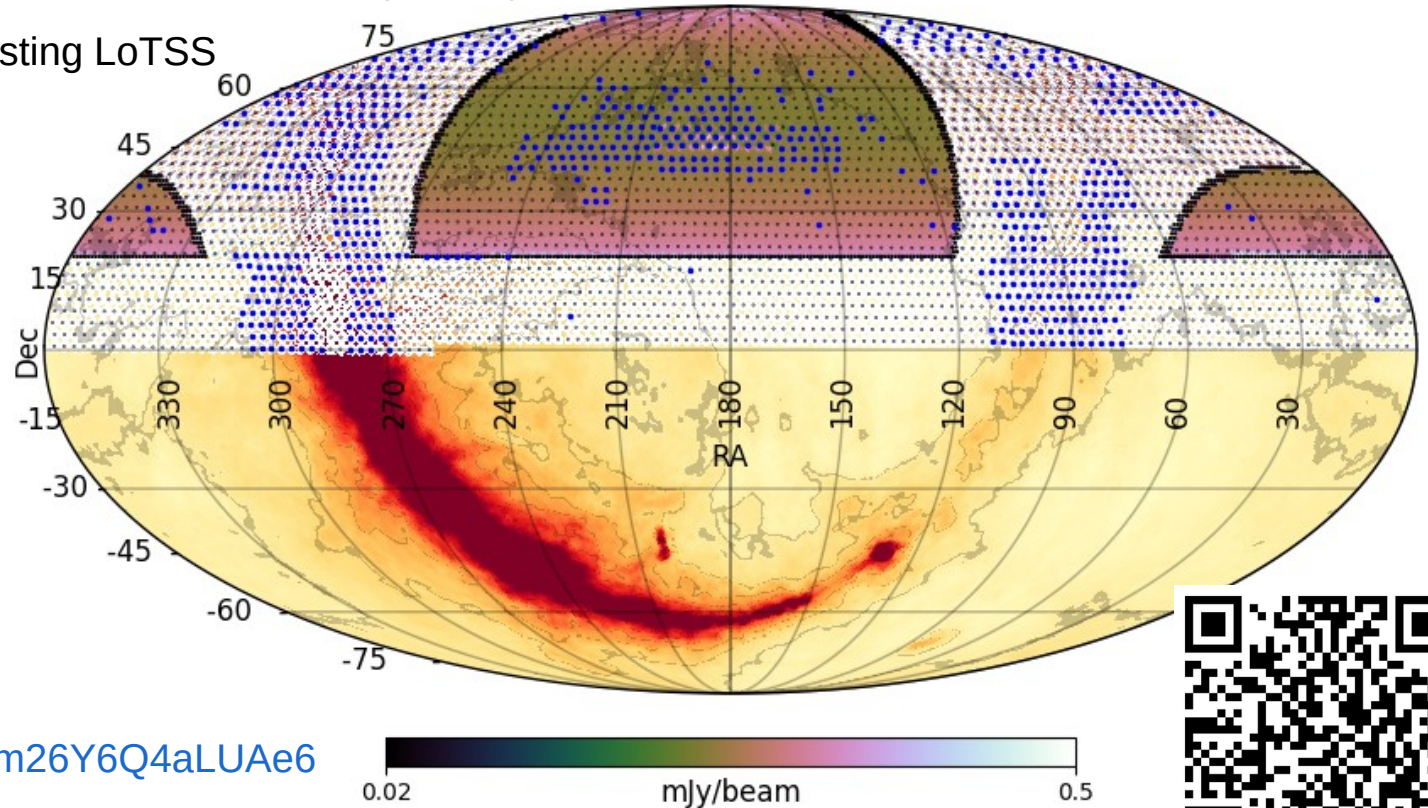
Where next?

- Make use of the international baselines through ILoTSS LOFAR2.0 large programme



Where next?

- Denser grid over high-dec, high- $|b|$ areas
- 8,500 hours of new observations over 3,512 pointings
- Combine with 1000 existing LoTSS pointings with suitable data
- 30 PB of data and ~ 100 million CPU hours for processing
- Ideally also complete the 6-arcsec survey...
- Open project, please join us:



<https://forms.gle/mx3Em26Y6Q4aLU Ae6>

Summary

- LoTSS-DR3 is finished and covers 89% of northern sky.
- 13,664,379 sources
- Median sensitivity of $92\mu\text{Jy/beam}$ at 6" resolution
- 6% random flux density error
- Noise limited astrometric uncertainty plus $\sim 0.24''$ systematic error
- 95% of sources detected at a level of $9\times\text{RMS}$
- Euclidean-normalized differential source counts derived over 5 orders of magnitude
- All data is publicly released - I, Q, U, V maps at several resolutions and uv-data plus calibration solutions.
- Large reprocessing effort to extract more science from the data (transients, faint diffuse structures, targets of interest) nearly complete.
- Science output from collaboration can be seen at <https://lofar-surveys.org/publications.html>
LoTSS has directly led to over 400 publications and been cited over 1,600 times.
- For optical ID plans see Bonny's talk!