ASTRON

Netherlands Institute for Radio Astronomy

LOFAR

LOFAR: recent highlights and future prospects

Jess Broderick (ASTRON)

[with input from Tim Shimwell (Leiden), Francesco de Gasperin (Leiden), Jason Hessels (ASTRON/Amsterdam) and George Heald (CASS)]

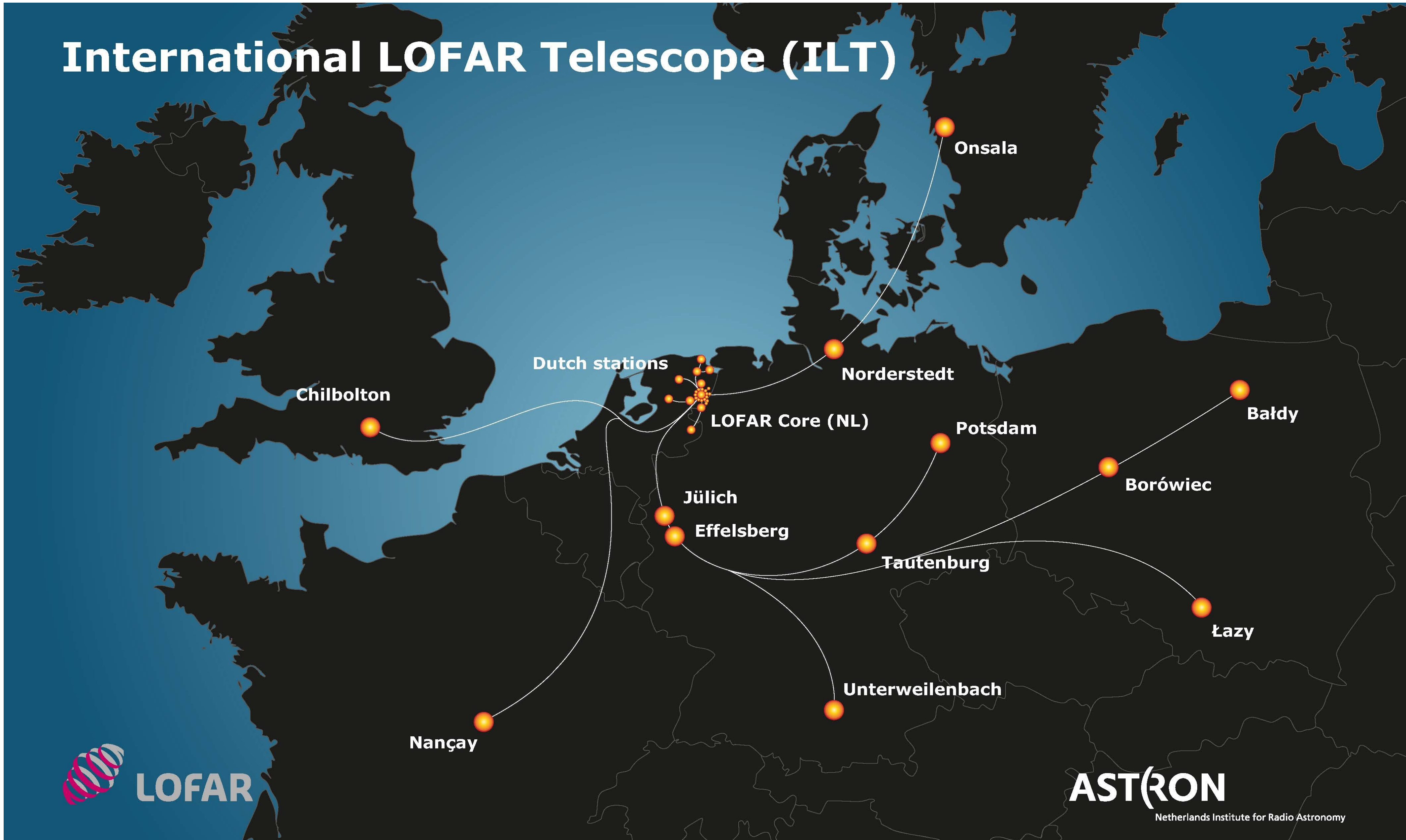
Talk outline

* Multifrequency Snapshot Sky Survey (MSSS)
* LOFAR Tier 1 HBA Survey (LoTSS)
* LOFAR Tier 1 LBA Survey (LoLSS)
* Plans for LOFAR 2.0

van Haarlem et al. 2013, A&A, 556, A2

Stations:
24 Dutch core
14 Dutch remote
12 international
(+ Ireland, Latvia)

Frequency range:
LBA - 30-80 MHz
HBA - 110-240 MHz



Talk outline

* Multifrequency Snapshot Sky Survey (MSSS)
* LOFAR Tier 1 HBA Survey (LoTSS)
* LOFAR Tier 1 LBA Survey (LoLSS)
* Plans for LOFAR 2.0

van Haarlem et al. 2013, A&A, 556, A2

Stations:
24 Dutch core
14 Dutch remote
12 international
(+ Ireland, Latvia)

Frequency range:
LBA - 30-80 MHz
HBA - 110-240 MHz

MSSS: LOFAR's first imaging survey

M*S*S*S MULTIFREQUENCY SNAPSHOT SKY SURVEY

MSSS-LBA

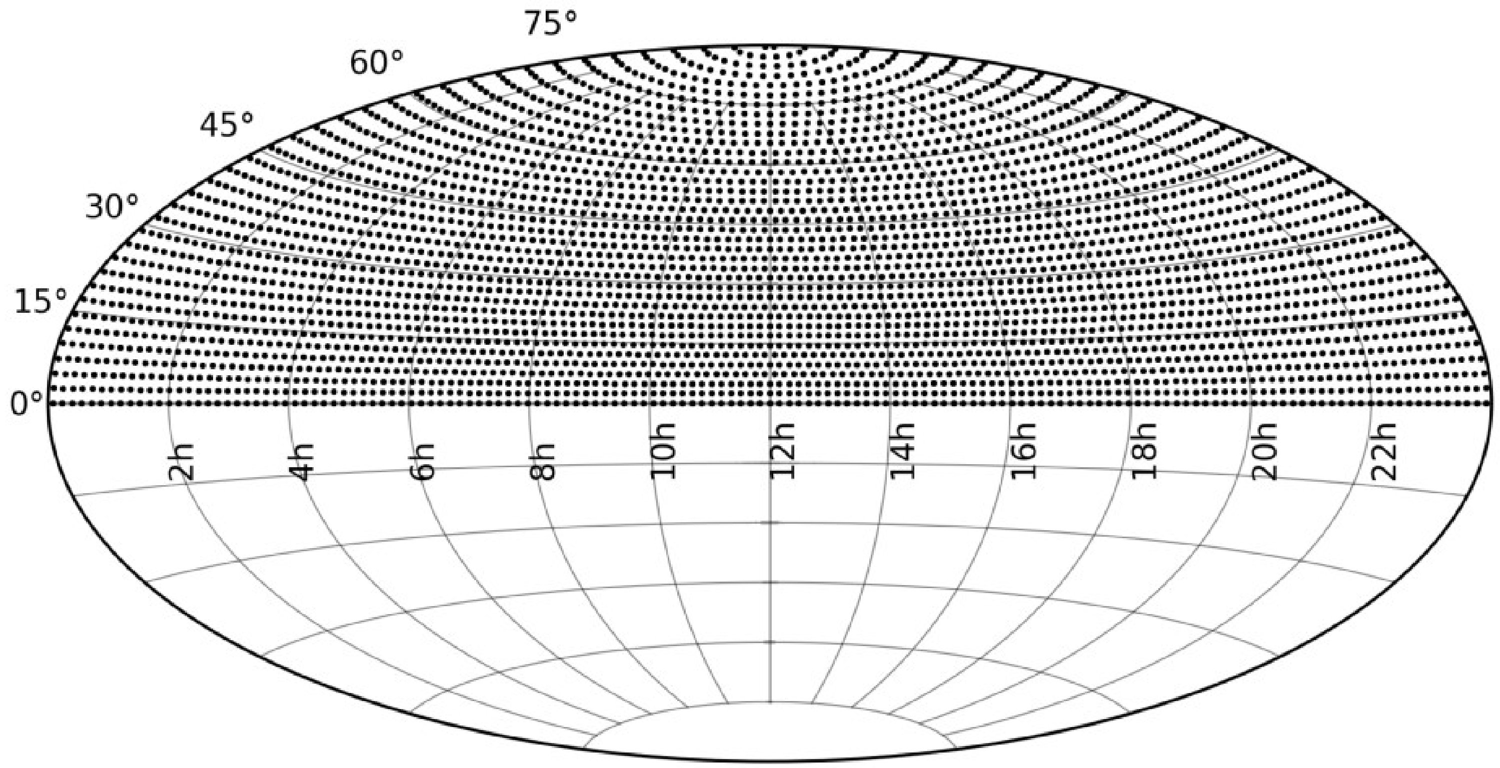
Frequency: 30-75 MHz
(8 × 2 MHz bands)
Resolution: ≤100 arcsec
Sensitivity: ≤15 mJy/beam
Area: 20,000 square degrees
Number of Fields: 660
Simultaneous ~10° beams: 5
Time per field: 9 x 11 min
Test observations resuming

MSSS-HBA

Frequency: 119-158 MHz
(8 × 2 MHz bands)
Resolution: 45 arcsec
Sensitivity: ≤5 mJy/beam
Area: 20,000 square degrees
Number of Fields: 3616
Simultaneous ~4° beams: 6
Time per field: 2 x 7 min
Observations 100% complete

Goals: obtain broadband sky model, shakedown LOFAR operations

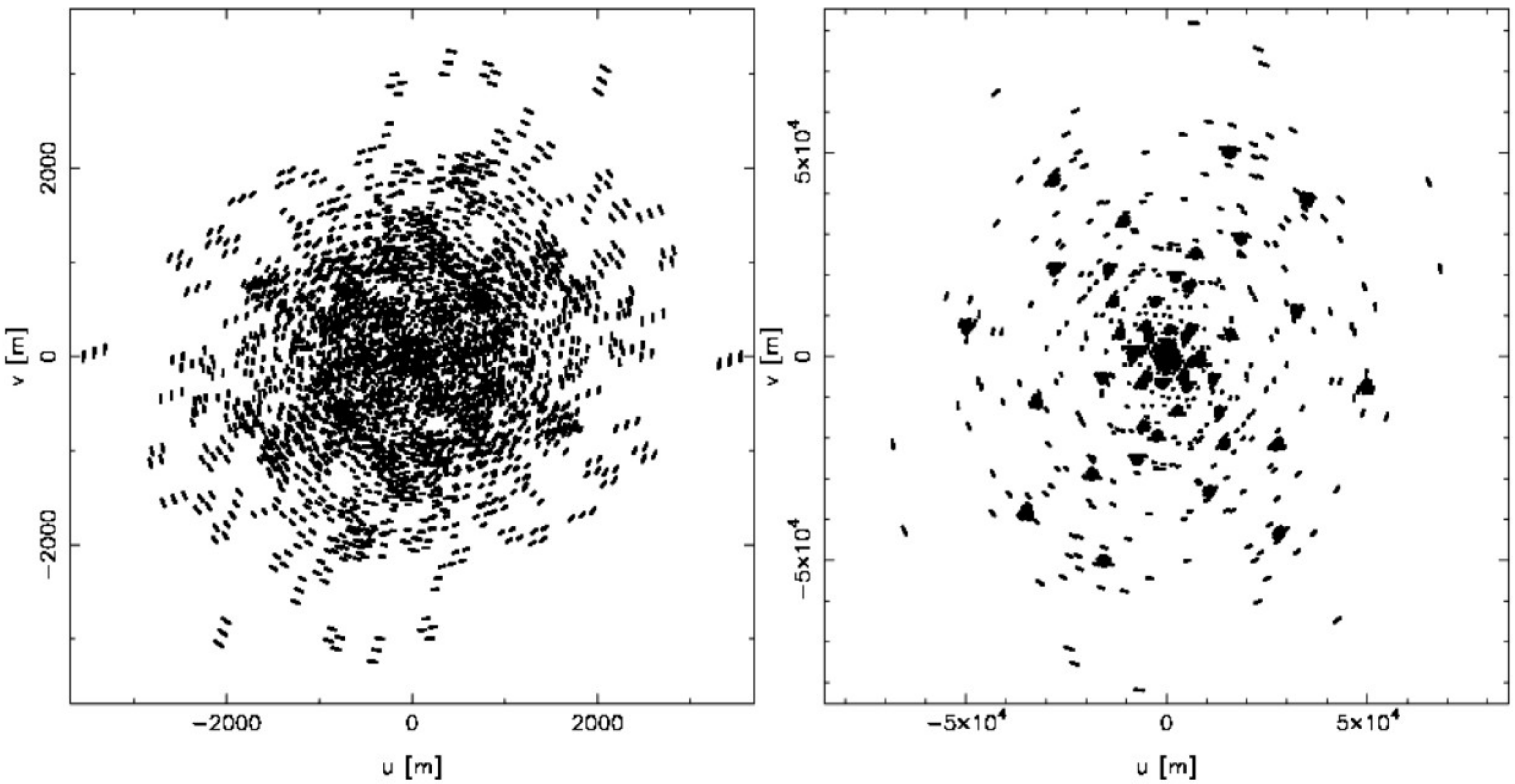
MSSS: LOFAR's first imaging survey



Heald et al. (2015)

3616 fields – approx. 200h to complete survey (inc. overheads)

Example *u*,*v* coverage

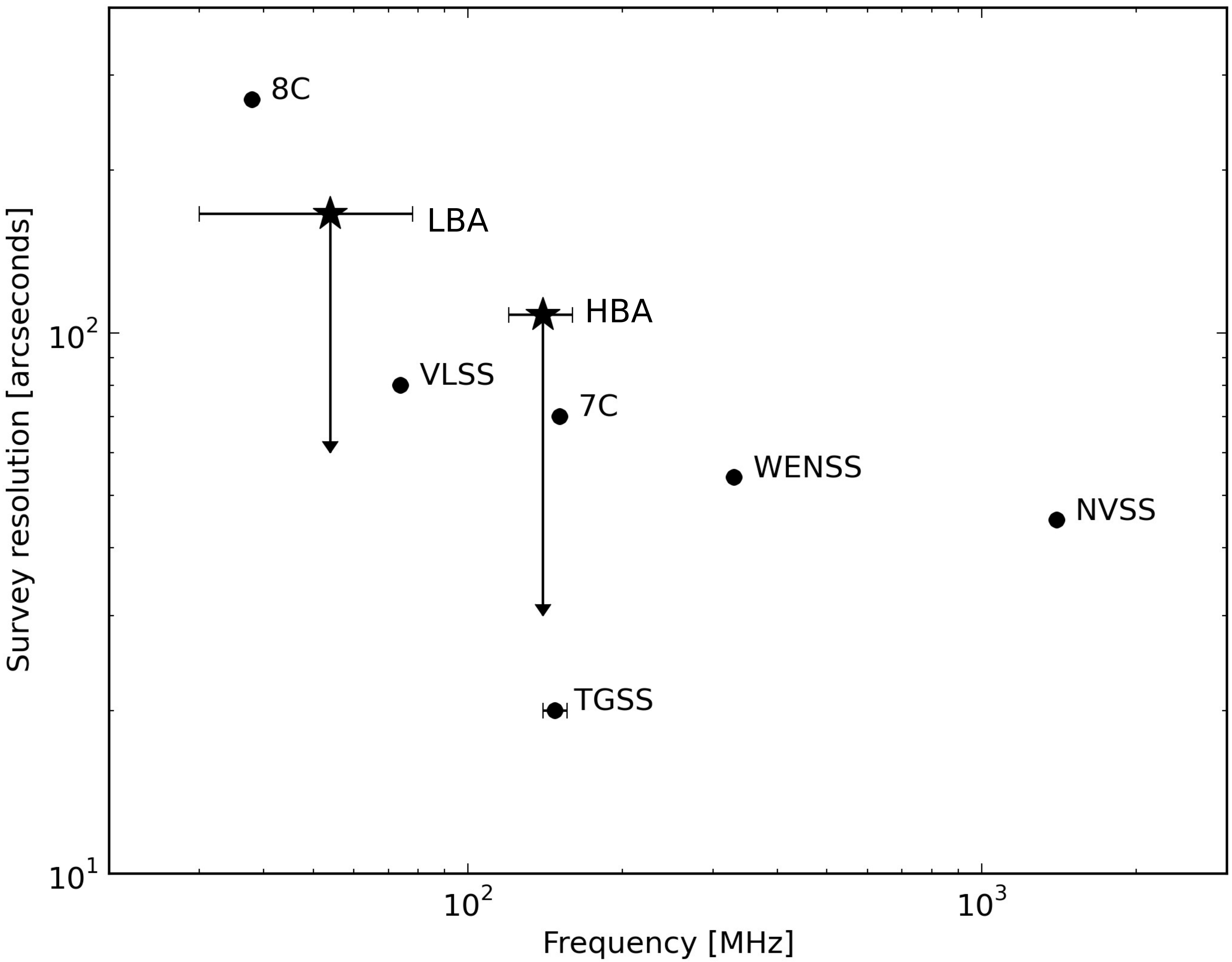


Thanks to the MSSS Team!

Björn Adebahr, Mike Bell, Laura Bîrzan, Annalisa Bonafede, Justin Bray, Rene Breton, Jess Broderick (co-PI), Joe Callingham, Therese Cantwell, Dario Carbone, Patti Carroll, Yvette Cendes, Krzysztof Chyży, Alex Clarke, Judith Croston, Soobash Daiboo, Francesco de Gasperin, Emilio Enriquez, Richard Fallows, Jamie Farnes, Chiara Ferrari, Jon Gregson, Gulay Gurkan Uygun, Martin Hardcastle, Jeremy Harwood, Tom Hassall, George Heald (PI), Volker Heesen, Jason Hessels, Andreas Horneffer, Marco Iacobelli, Vibor Jelić, David Jones, Wojciech Jurusik, Georgi Kokotanekov, Giulia Macario, John McKean, Poppy Martin, Carlos Martinez, Leah Morabito, Cornelia Müller, David Mulcahy, Błażej Nikiel-Wroczyński, Natalia Nowak, André Offringa, Emanuela Orrú, Rosita Paladino, V.N. Pandey, Gosia Pietka, Roberto Pizzo, Mamta Pommier, Peeyush Prasad, Luke Pratley, David Rafferty, Aarthi Ramesh, Chris Riseley, Huub Röttgering, Antonia Rowlinson, Pepe Sabater, Anna Scaife, Bart Scheers, Kati Sendlinger, Aleksandar Shulevski, Charlotte Sobey, Carlos Sotomayor, Adam Stewart, Andra Stroe, John Swinbank, Cyril Tasse, Sander ter Veen, Jonas Trüstedt, Valentina Vacca, Alexander van der Horst, Bas van der Tol, Sjoert van Velzen, Reinout van Weeren, Glenn White, Wendy Williams, Michael Wise

Improving the angular resolution

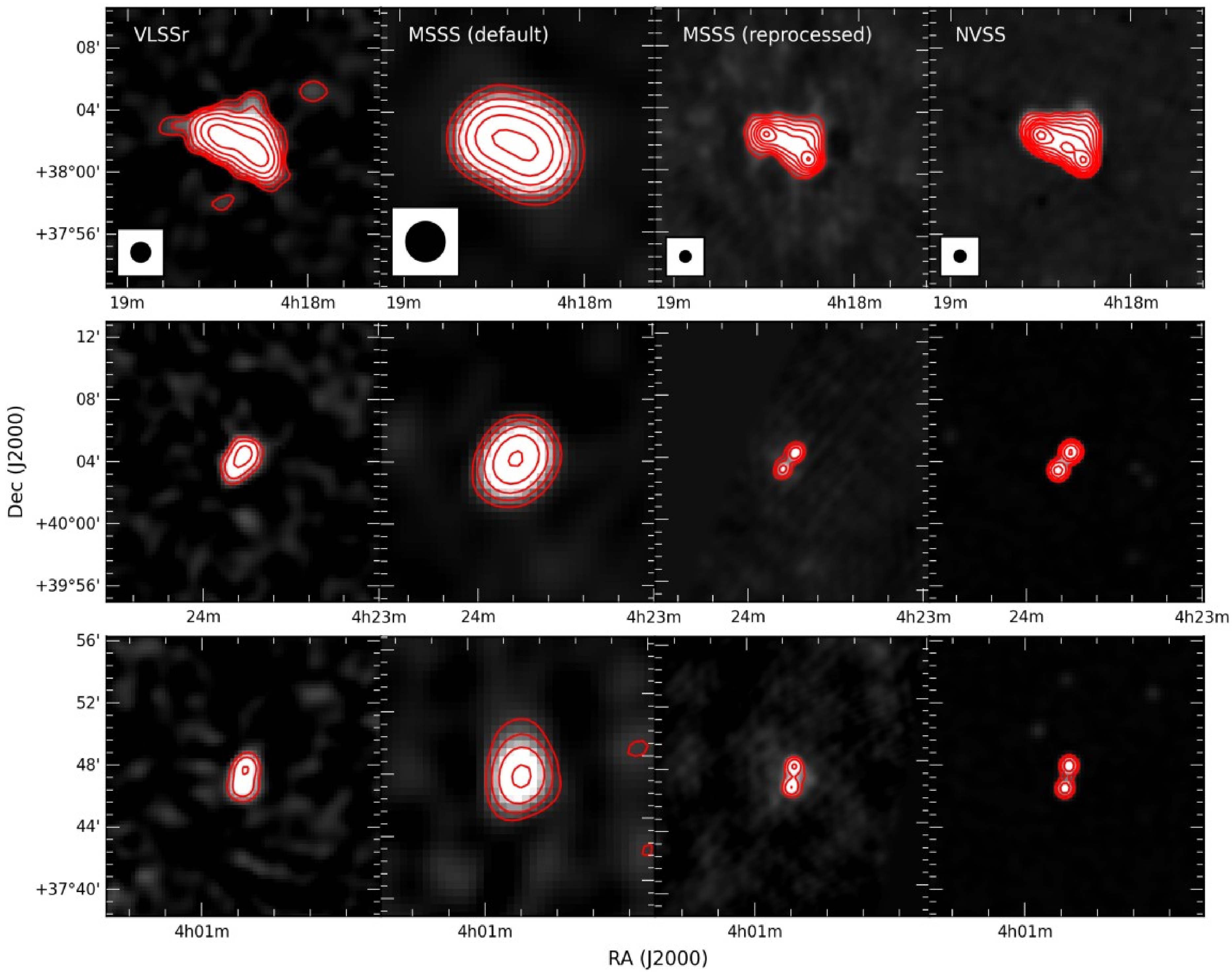
Heald et al. (2015)



* **Improved angular resolution** gives MSSS a niche in the scientific literature, and significant legacy value. **New target → 45 arcsec**, i.e. identical to the 1.4 GHz NRAO VLA Sky Survey (NVSS; Condon et al. 1998). **Only modest computing requirements needed for re-imaging**.

Improving the angular resolution

Heald et al. (2015)



* **Improved angular resolution** gives MSSS a niche in the scientific literature, and significant legacy value. **New target → 45 arcsec**, i.e. identical to the 1.4 GHz NRAO VLA Sky Survey (NVSS; Condon et al. 1998). **Only modest computing requirements needed for re-imaging**.

A quick comparison

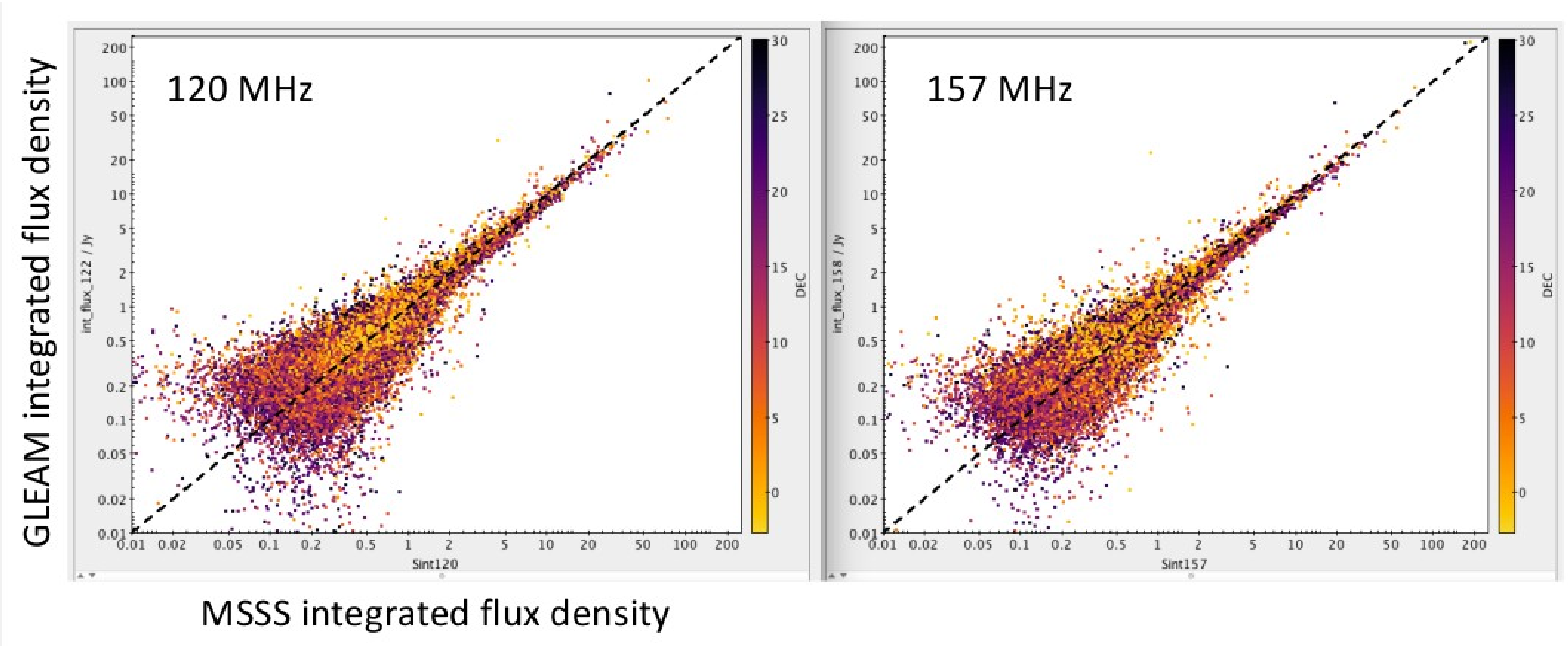
Survey	Sky coverage (deg^2)	Frequency Coverage (MHz)	Resolution (arcsec)	RMS noise level (mJy beam^{-1})	No. sources detected
MSSS-HBA (Heald et al. in prep.)	20 600	119-158 MHz (8 x 2 MHz)	45	<5	>250 000
TGSS (Intema et al. 2017)	36 900	140-156	25	3.5	624 000
GLEAM (Hurley-Walker et al. 2017)	24 800	72-231	120	10	307 000

* MSSS highly complementary to the MWA GLEAM survey (Hurley-Walker et al. 2017) and the TIFR GMRT Sky Survey (TGSS; Intema et al. 2017). These three surveys will provide a truly all-sky interferometric low-frequency radio catalogue!

MSSS-HBA current status

* MSSS 100 deg^2 verification field (MVF): Heald et al. 2015, A&A, 582, A123 (2 arcmin resolution).

* HBA catalog 'v0.3': internal release late 2016, 138,000 sources, resolution ~3-3.5 arcmin. New flux scale bootstrapping technique (Hardcastle et al. 2016) applied and verified. In-band flux densities now considered reliable; reliability of flux scale checked e.g. through cross-matching with GLEAM. **Important step forward!**



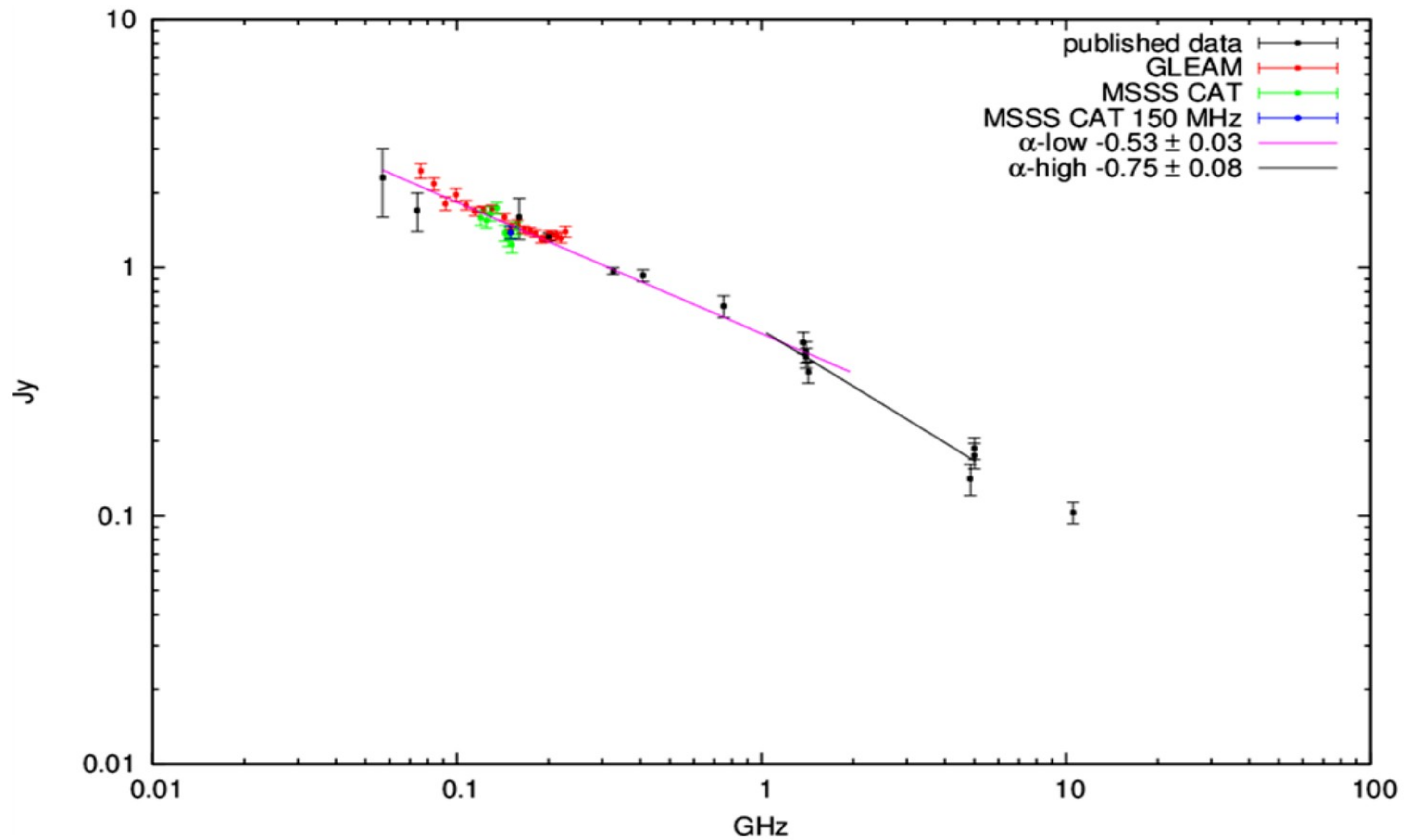
Heald, Hurley-Walker

MSSS-HBA current status

* MSSS 100 deg^2 verification field (MVF): Heald et al. 2015, A&A, 582, A123 (2 arcmin resolution).

* HBA catalog 'v0.3': internal release late 2016, 138,000 sources, resolution ~3-3.5 arcmin. New flux scale bootstrapping technique (Hardcastle et al. 2016) applied and verified. In-band flux densities now considered reliable; reliability of flux scale checked e.g. through cross-matching with GLEAM. **Important step forward!**

NGC 3627

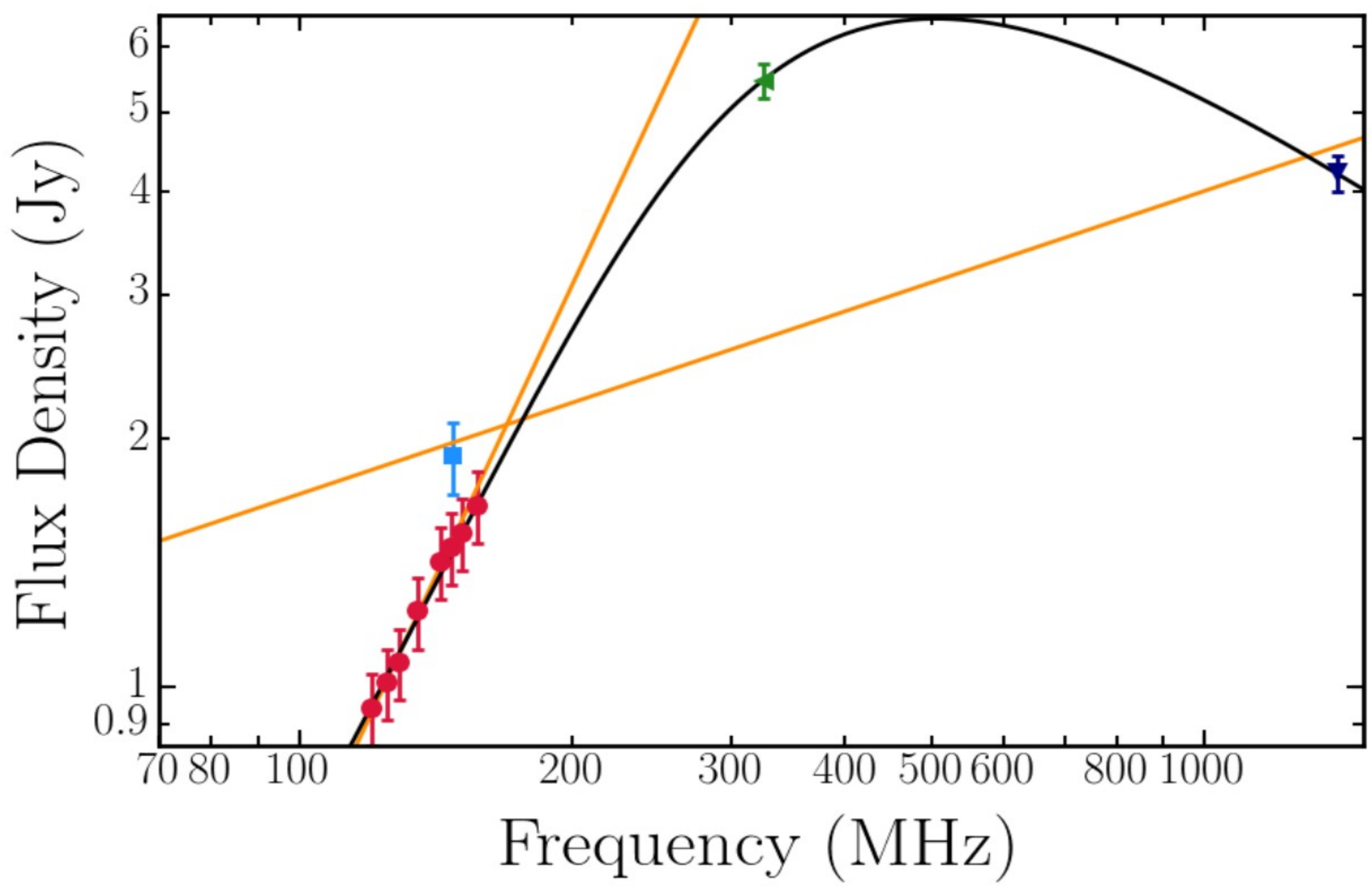


Using MSSS to investigate galaxy SEDs - Chyży et. al. in prep.

MSSS-HBA current status

* MSSS 100 deg^2 verification field (MVF): Heald et al. 2015, A&A, 582, A123 (2 arcmin resolution).

* HBA catalog 'v0.3': internal release late 2016, 138,000 sources, resolution ~3-3.5 arcmin. New flux scale bootstrapping technique (Hardcastle et al. 2016) applied and verified. In-band flux densities now considered reliable; reliability of flux scale checked e.g. through cross-matching with GLEAM. **Important step forward!**



Using MSSS to investigate peaked-spectrum sources – Callingham et al.

MSSS-HBA current status

* Now working in earnest to re-image the HBA survey at 45-arcsec resolution (i.e. working towards a 'v1' public release later this year).

* Standard imaging product: 100 deg^2 mosaics, each composed of tens of individual HBA fields. Total number: 214.

* Imaging with WSClean (Offringa et al. 2014) with full-band deconvolution. Mosaicking with bespoke script (pyrap.images). Flux scale bootstrapping technique as in v0.3. Source finding with PyBDSF.

* Using previous direction-independent calibration solutions. No further self-calibration.

* Good progress made over the last few months, prior to very recent CEP3 cluster upgrade. Most of sky > +35° Dec. re-imaged. Approximately 30 mosaics generated; initial assessments of image quality and reliability. Some inconsistencies across survey area currently being addressed. TGSS used as a reference catalogue.

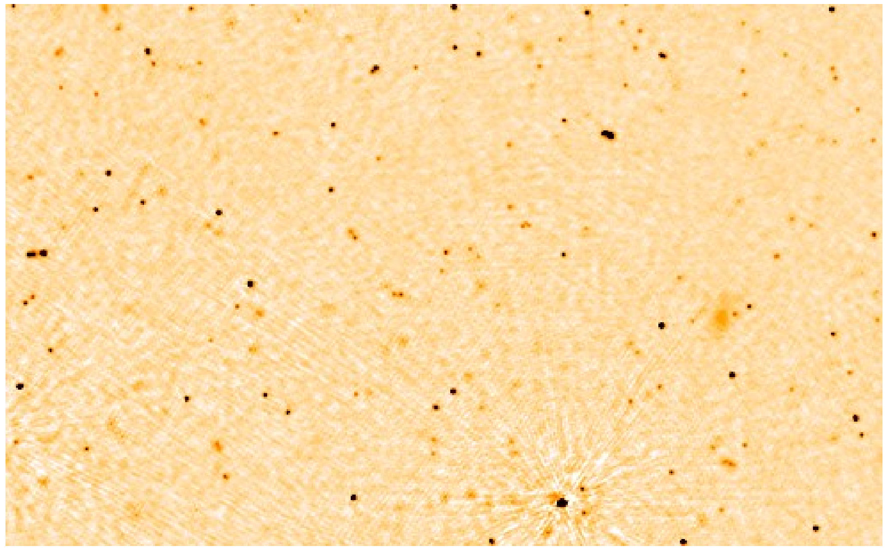
MSSS-HBA current status

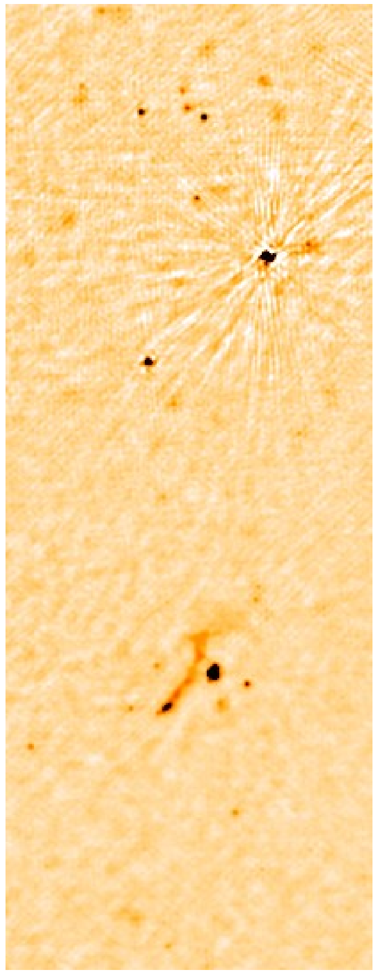
* Re-imaging team: **Chris Riseley (CASS)**, **Gulay Gurkan Uygun (CASS)**, George Heald, Rene Breton, Martin Hardcastle, Alex Clarke, Joe Callingham, Błażej Nikiel-Wroczyński, Jess Broderick.

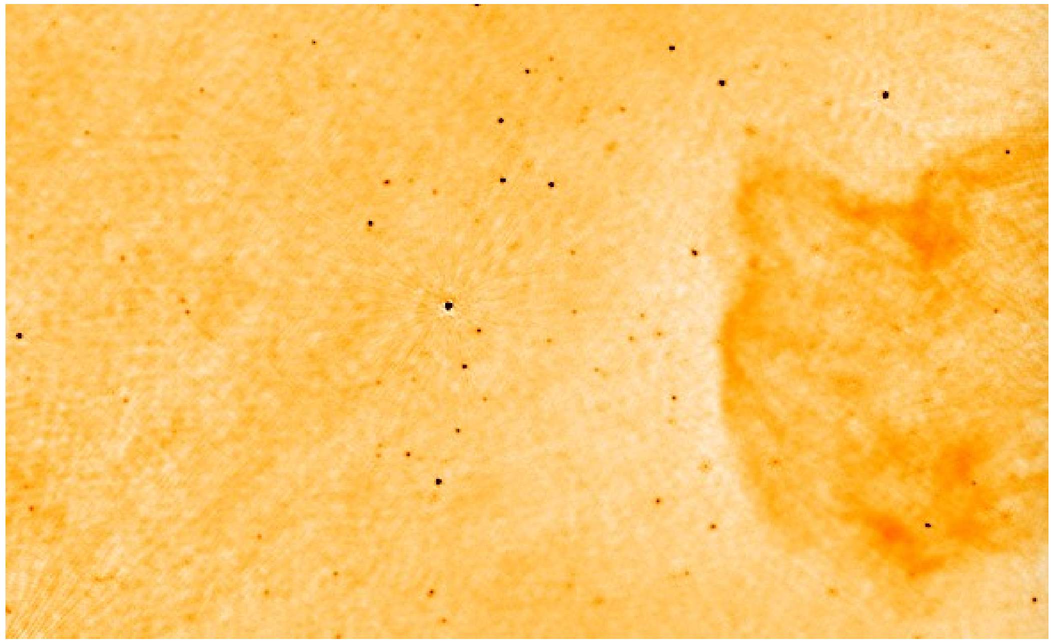
* Also thanks to Krzysztof Chyzy, Glenn White, Marco Iacobelli, Emanuela Orrú and Aleksandar Shulevski for early feedback.

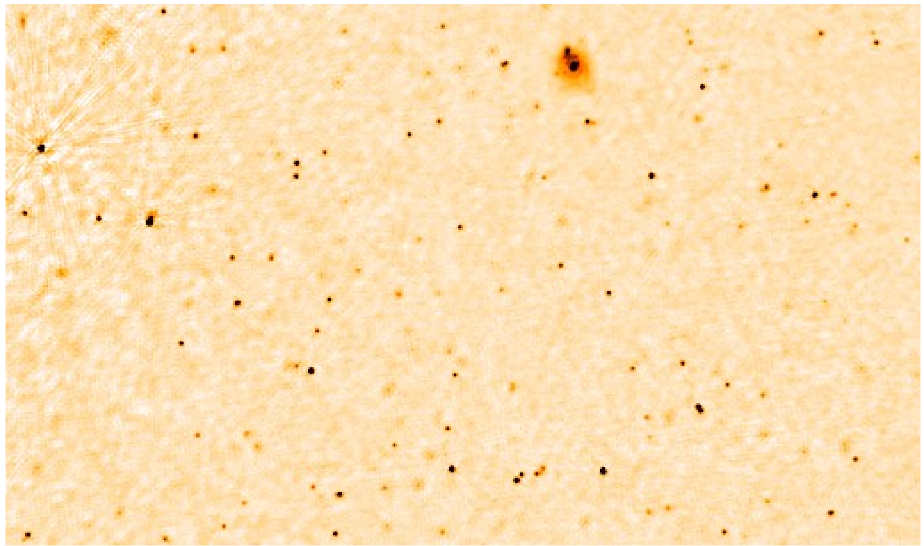
Some examples of image quality

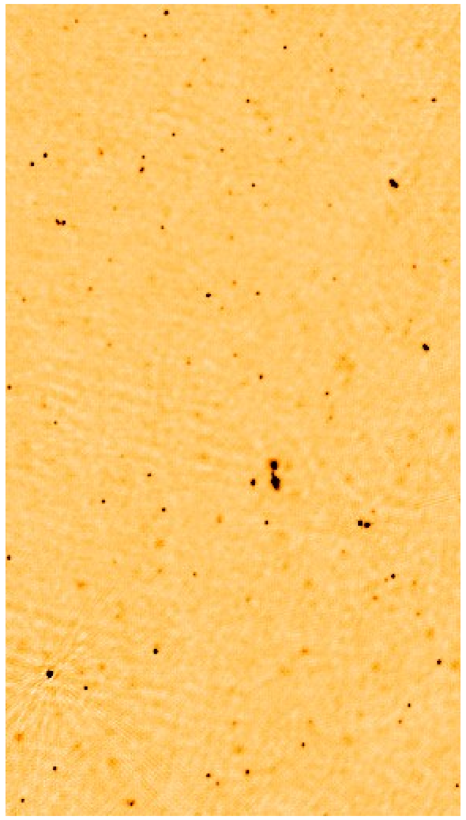
Riseley, Gurkan Uygun, Heald

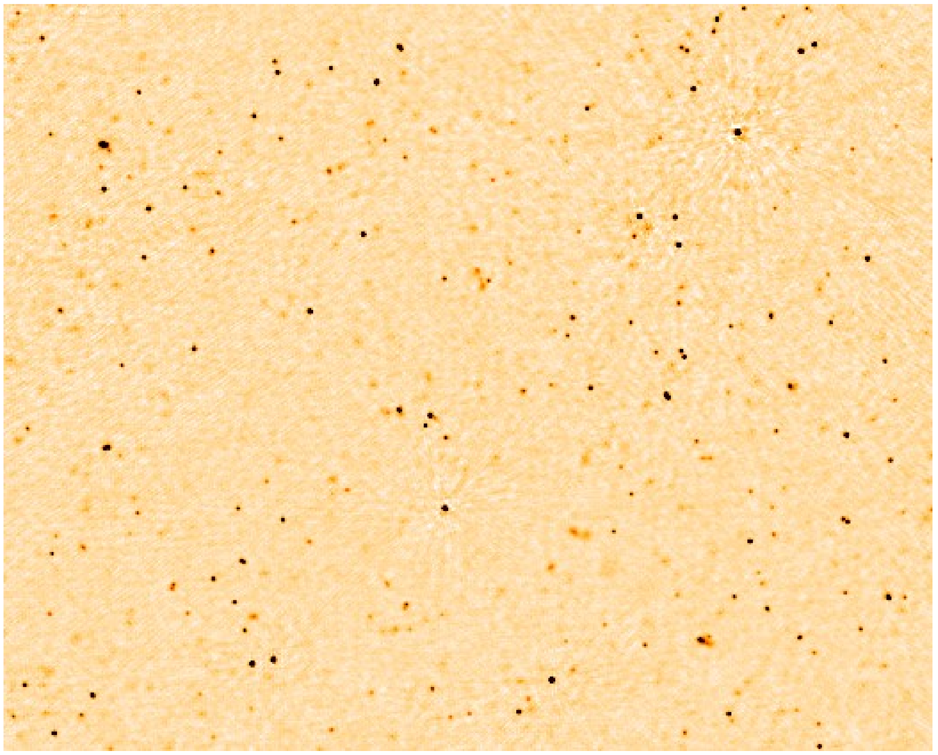


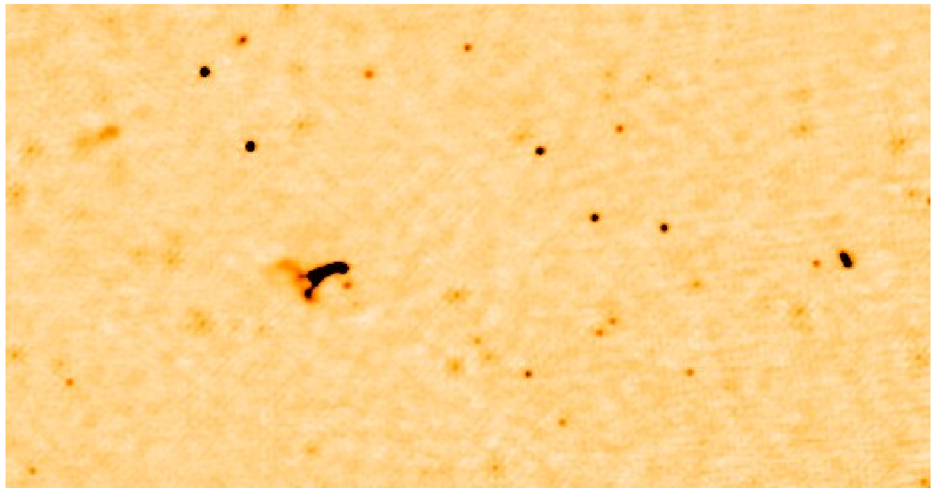






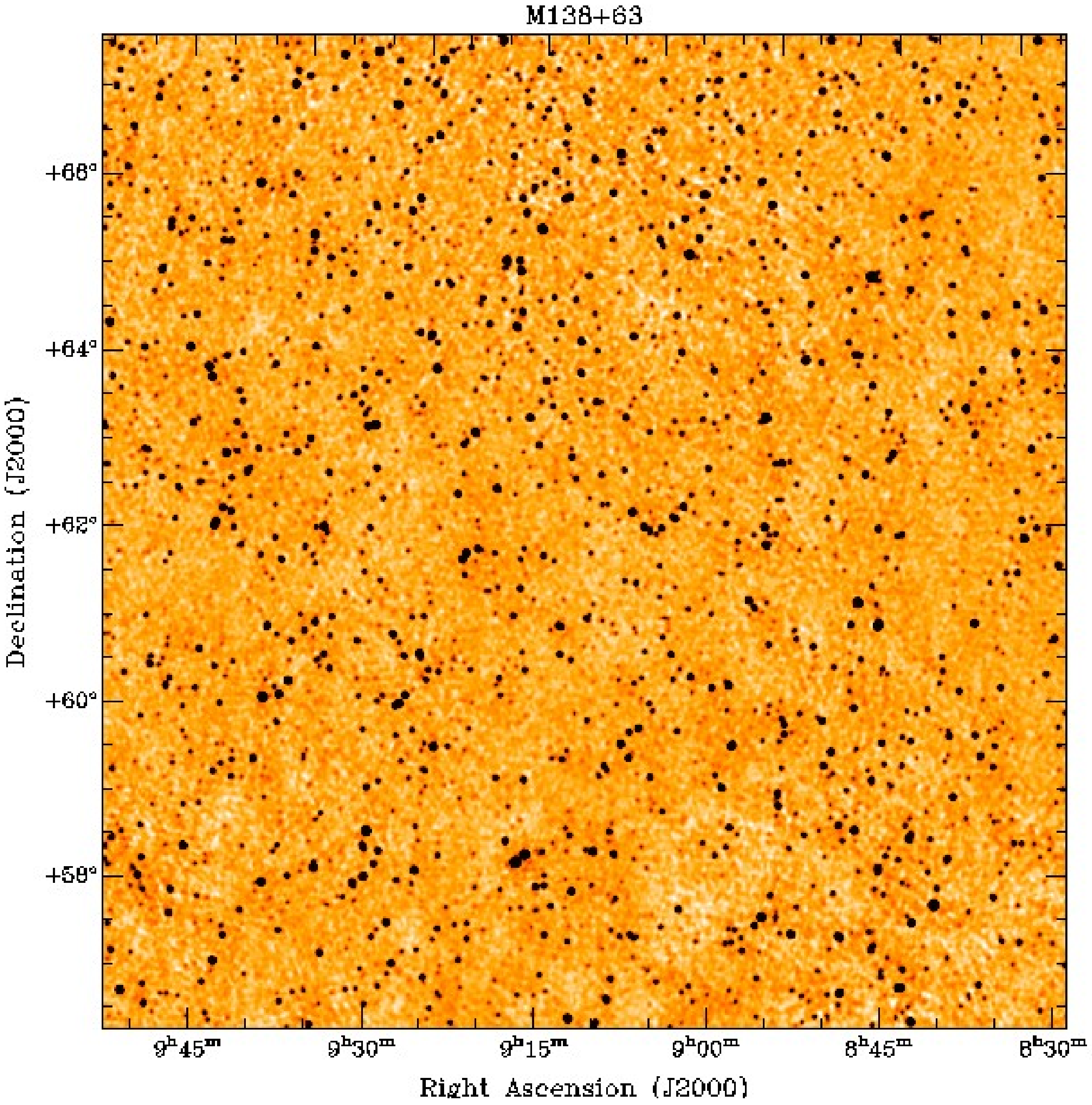


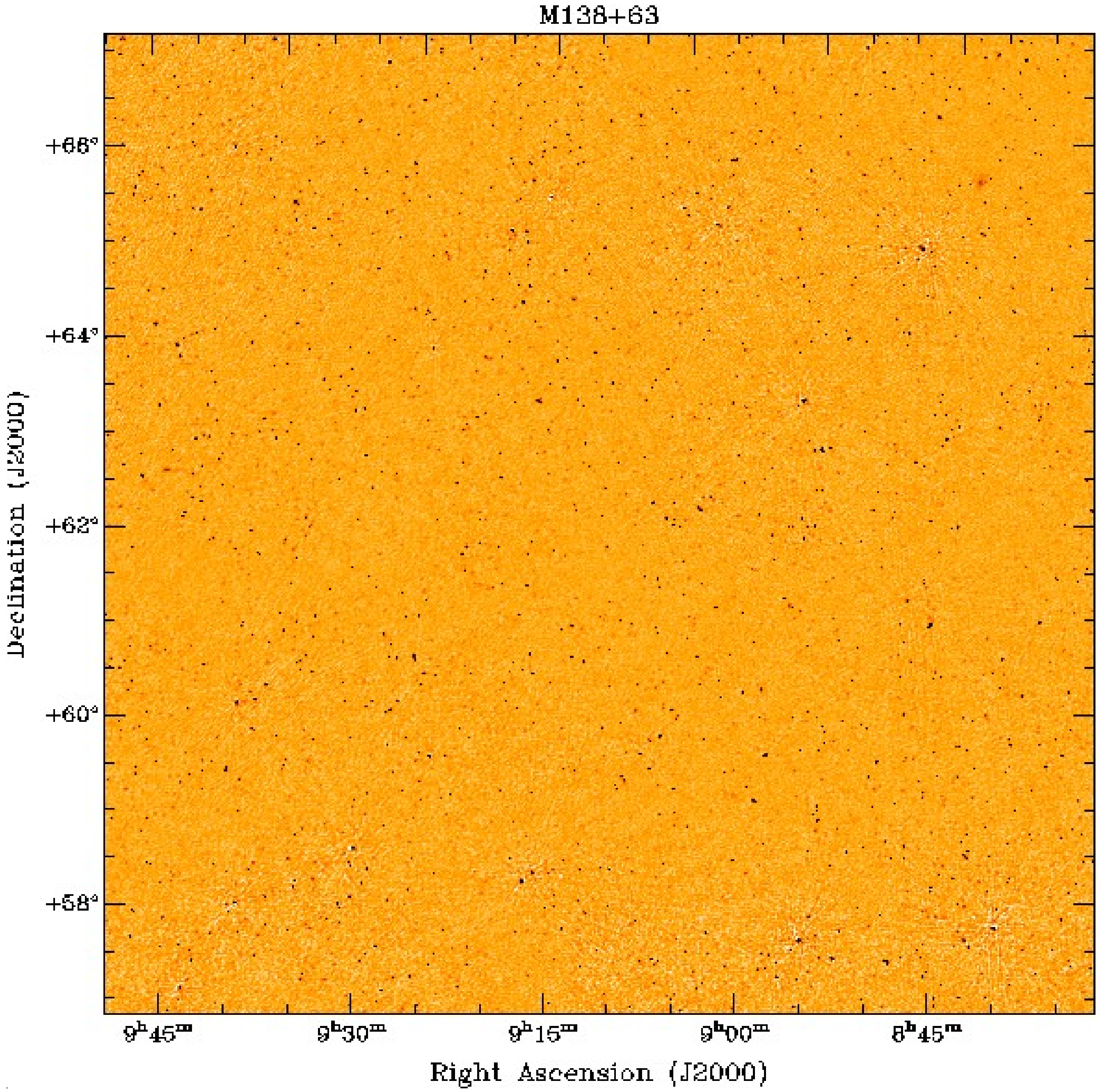




Mosaic improvements

Riseley, Gurkan Uygun, Heald





Resolution 185 arcsec

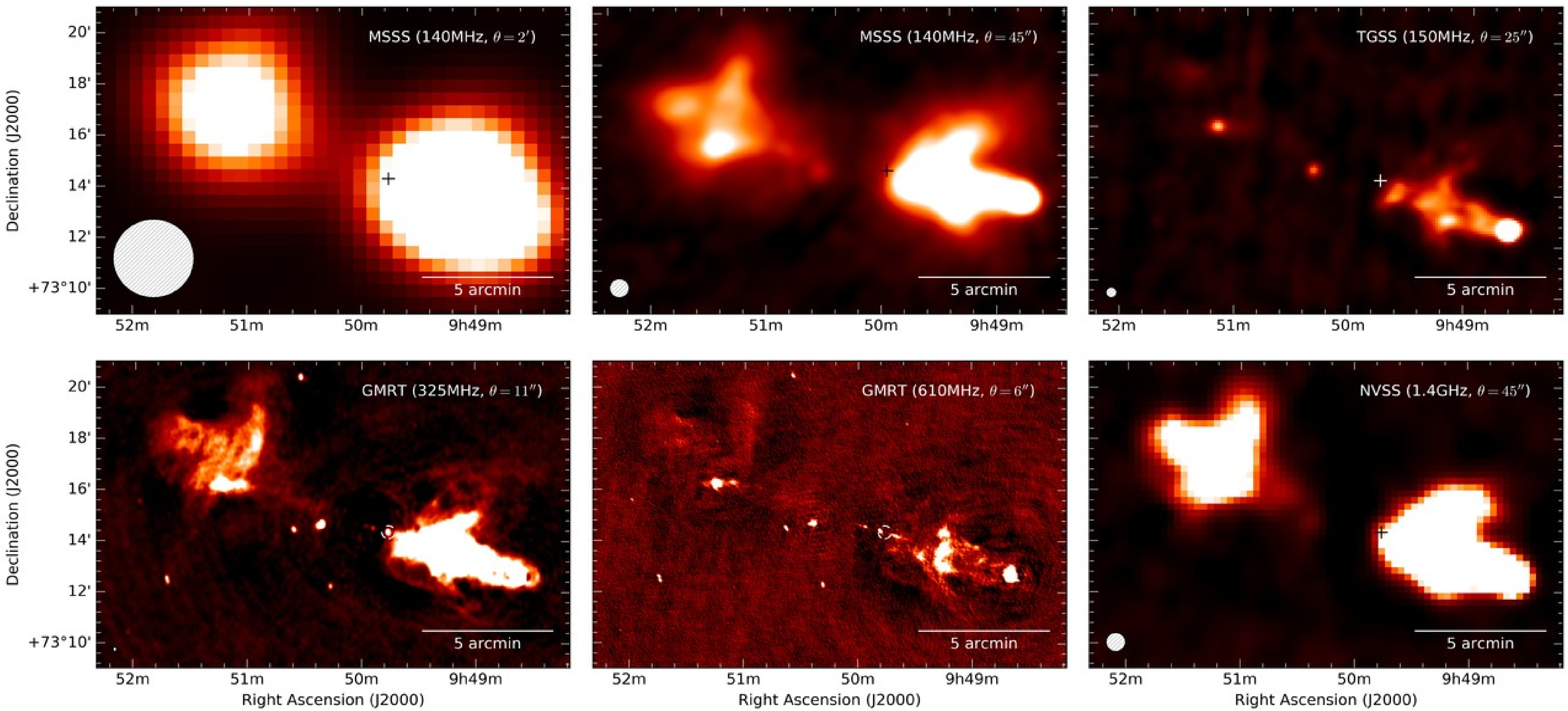
RMS 10.5 mJy $beam^{-1}$

Resolution 45 arcsec

RMS 2.6 mJy $beam^{-1}$

Giant radio galaxy example

Riseley



* 4C +73.08 (z = 0.0581). GRG; projected linear size 1.38 Mpc.

* 45-arcsec MSSS image comparable to NVSS map; much better in terms of resolving structure than previous 2-arcmin image. MSSS recovering more diffuse emission than in TGSS.

MSSS science

MSSS science projects

* Planning under way for 37 science projects.

* Examples (e.g. see the LOFAR wiki for further details):

• SNRs and HII regions

• Galaxy SEDs

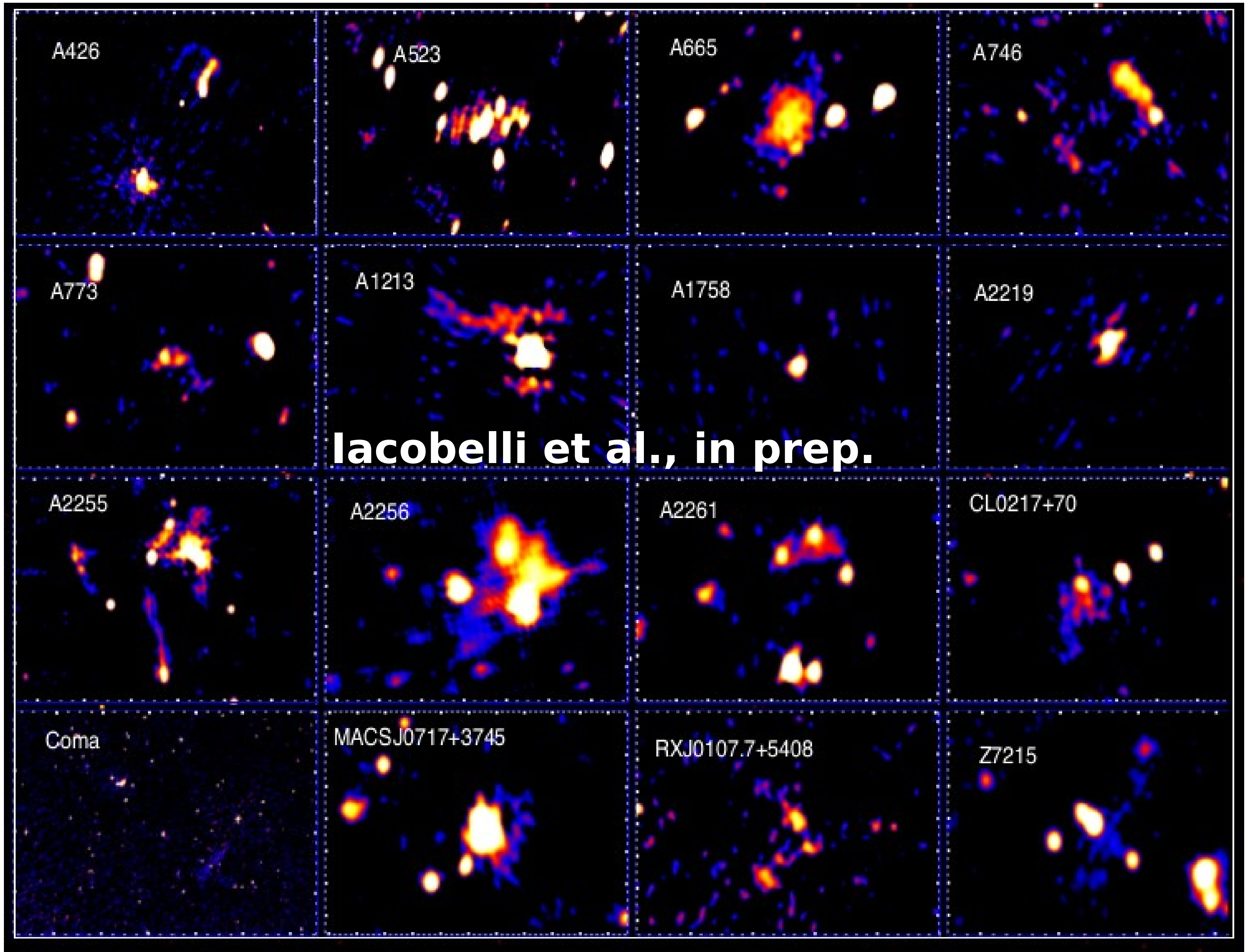
• Cluster halos

• Pulsars

• Transients (e.g. MSSS-LBA NCP transient; Stewart et al. 2016)

• GRGs

* Early science for MSSS team members, prior to public release.

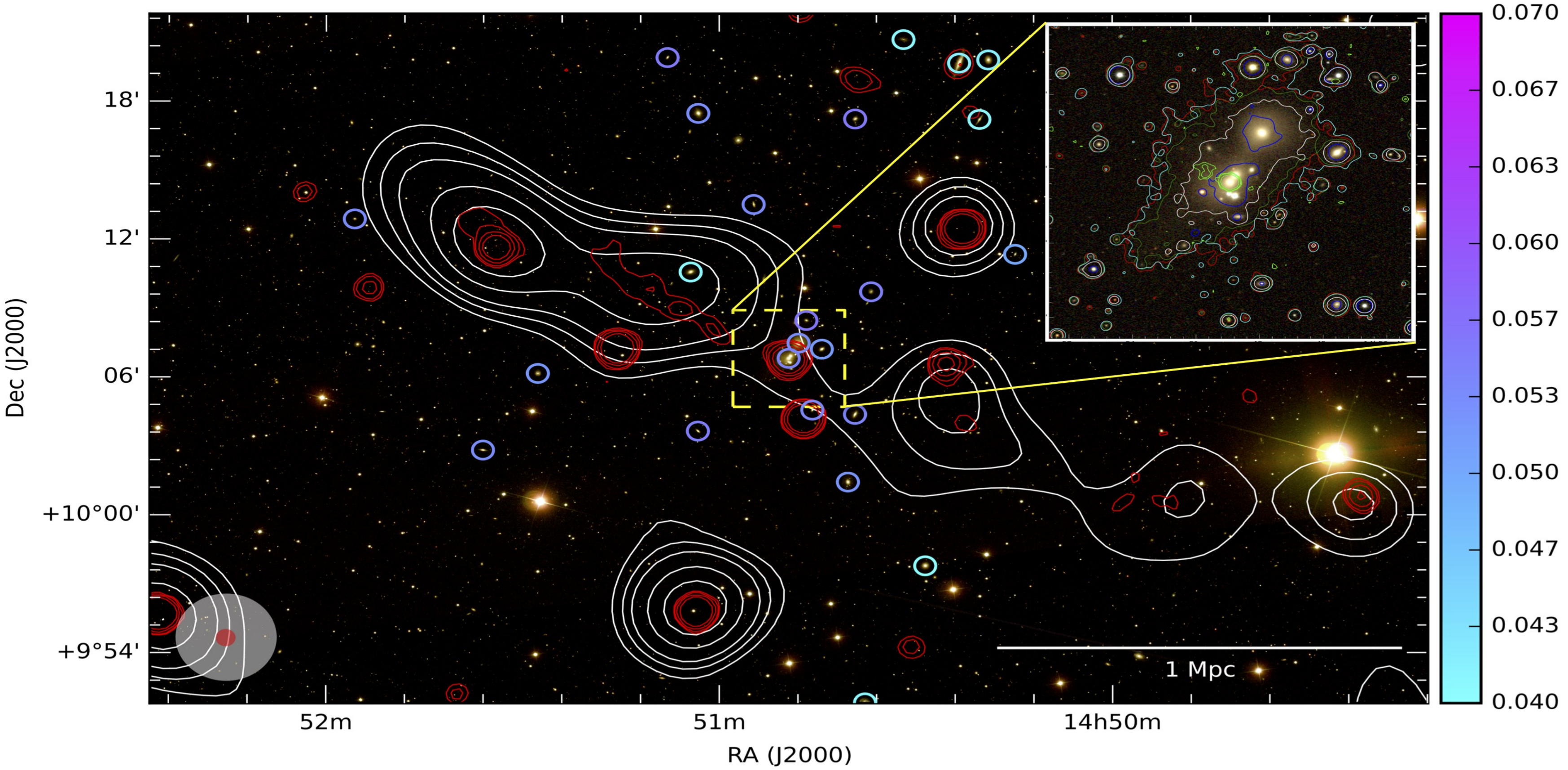


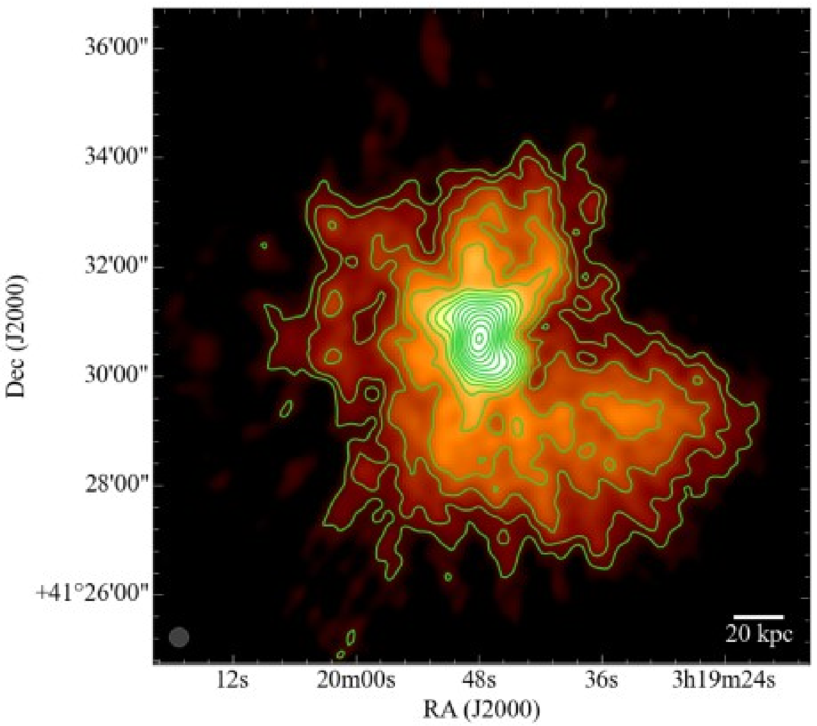
Two recent MSSS papers

* Alex Clarke et al., 'Discovery of a 2.56 Mpc giant radio galaxy associated with a disturbed galaxy group', 2017, A&A, 601, A25 (arXiv:1702.01571)

and

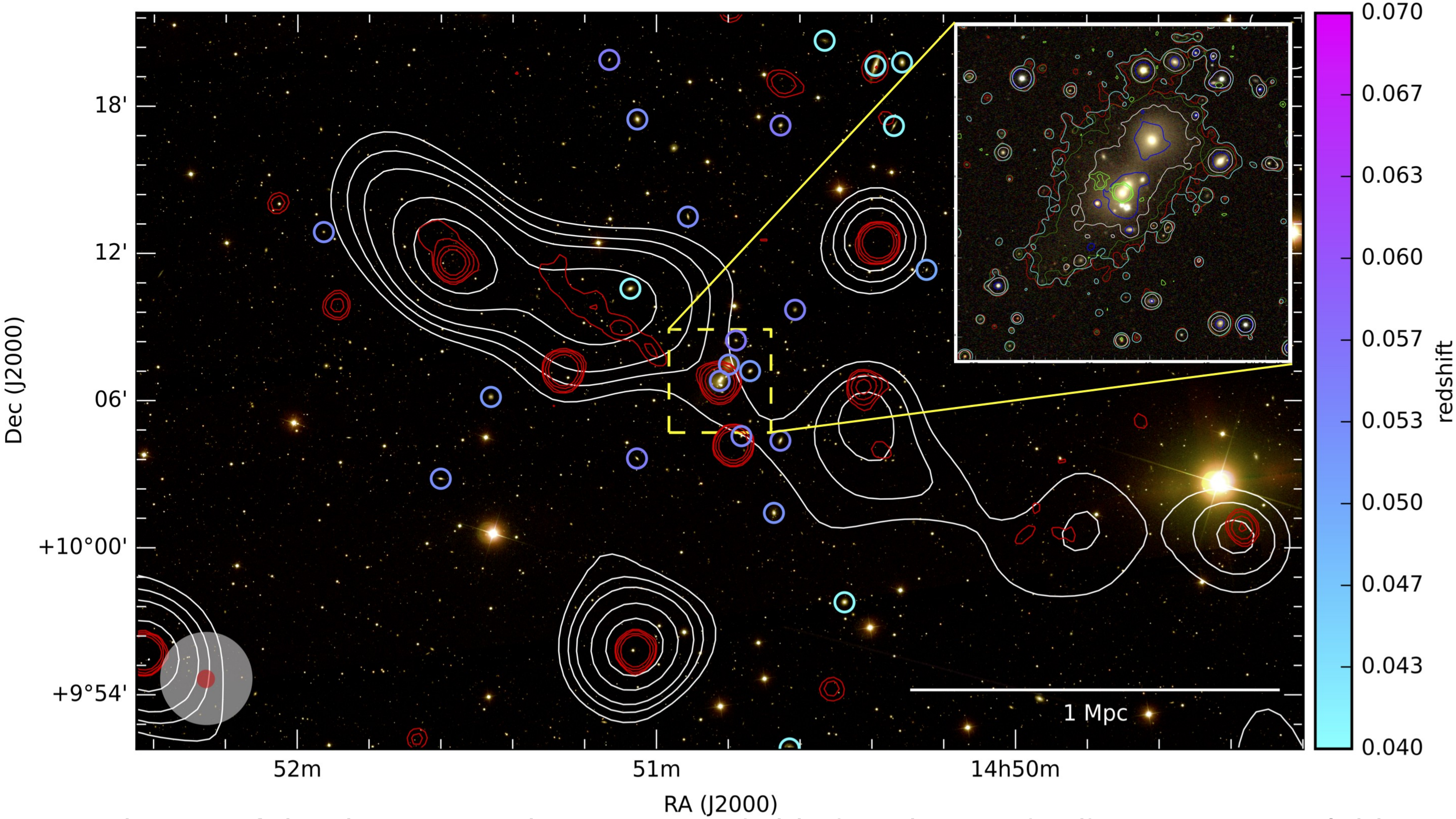
* Georgi Kokotanekov et al., 'The Scaling Relation between AGN Cavity Power and Radio Luminosity at Low Radio Frequencies', 2017, A&A, in press; arXiv:1706.00225)





Two recent MSSS papers

Clarke et al. 2017



* ASTRON image of the day 2017 Feb. 10. LOFAR (white) and NVSS (red) contours overlaid on composite SDSS image. Inset: FIRST (lime green) contours; other contours smoothed SDSS bands.
* Projected linear size 2.56 Mpc; physical size > 2.72 Mpc. One of the largest known radio galaxies!

Polarisation studies: MAPS project

* MAPS: MSSS All-sky Polarisation Survey

* Further processing of MSSS data on Radboud University Nijmegen cluster ('Coma').

* High angular resolution → avoid beam depolarisation.

* Superb Faraday depth resolution (~1.3 rad m^{-2}).

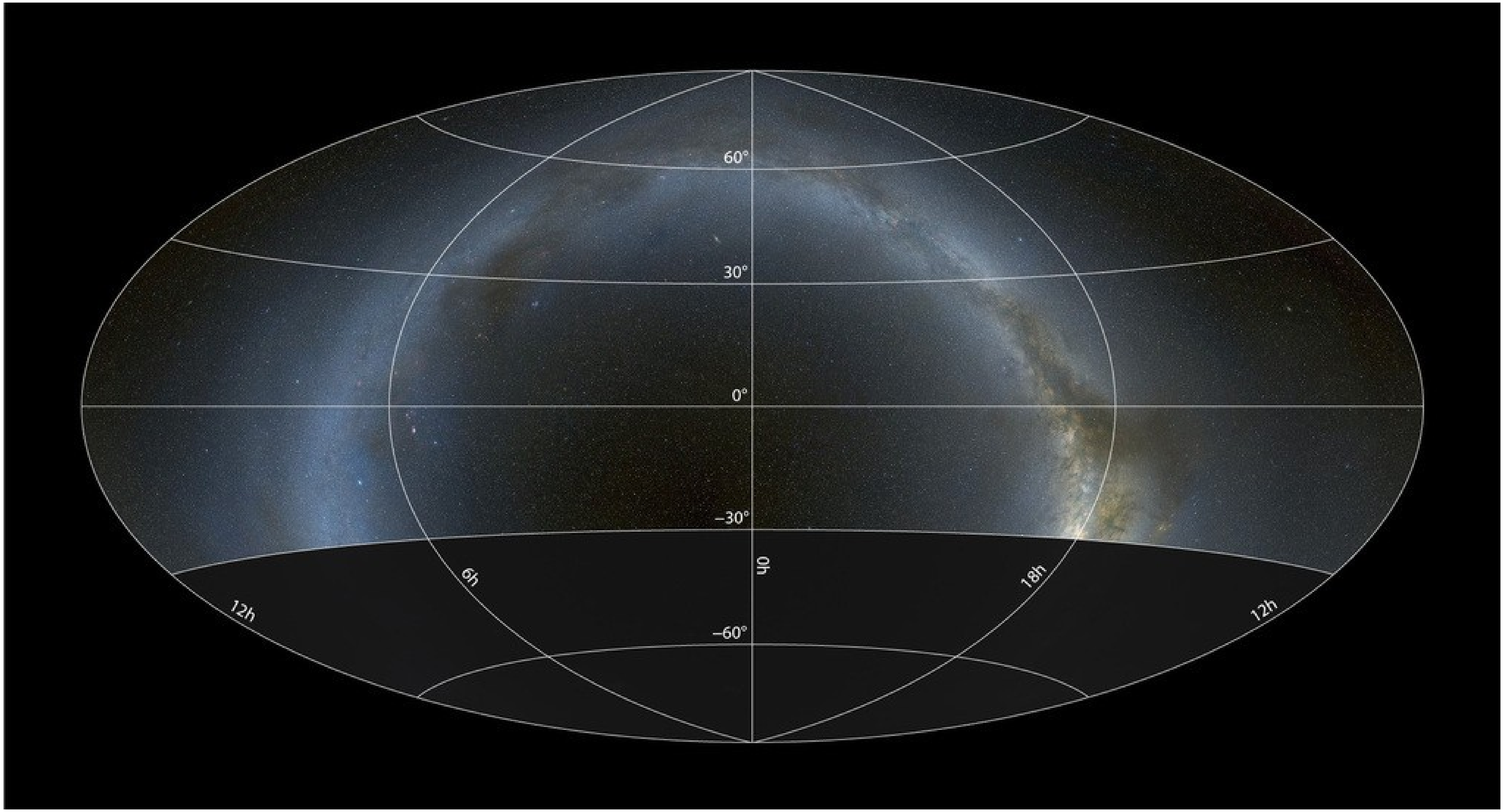
* Good inner *uv* coverage → sensitive to Galactic foreground.

* Range of science topics, including Galactic ISM magnetism, RM grids, searches for low-frequency polarisation calibrators, depolarisation of radio galaxies, and searches for pulsars and brown dwarfs.

David Mulcahy, Jamie Farnes, George Heald, Andreas Horneffer and the MSSS team, in collaboration with the LOFAR magnetism key science project

Polarisation studies: MAPS project

LOFAR ASTRON



Farnes, Mulcahy

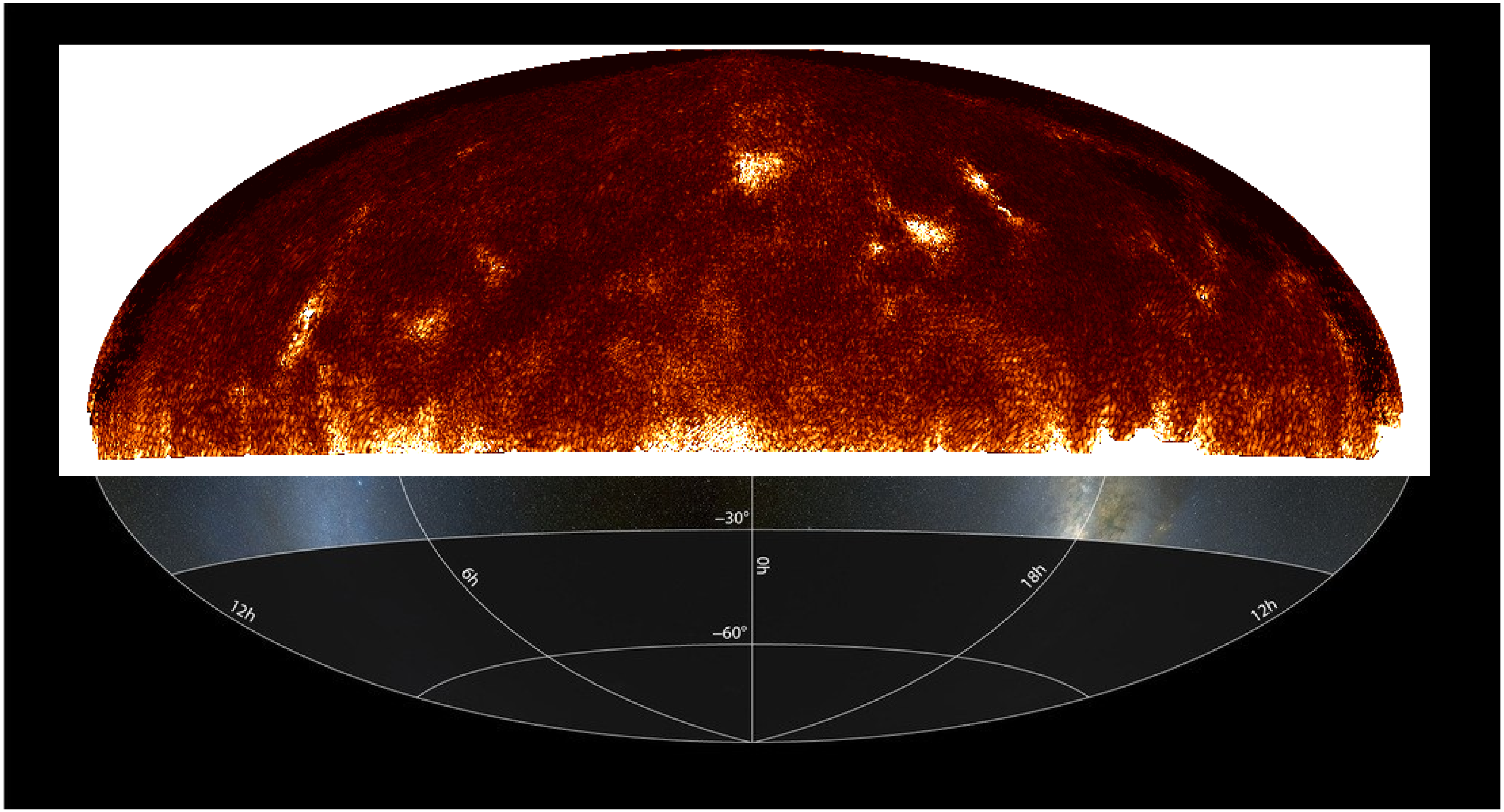
* *Very preliminary* map of LOFAR polarised intensity at 150 MHz (single channel). 50 arcmin resolution ('MAPS-Low'). Internal data release later this year.

* Working towards a 45-arcsec data product over the next few years.

MAPS

M.S.S.S All-sky Polarisation Survey

Polarisation studies: MAPS project



Farnes, Mulcahy

* *Very preliminary* map of LOFAR polarised intensity at 150 MHz (single channel). 50 arcmin resolution ('MAPS-Low'). Internal data release later this year.

* Working towards a 45-arcsec data product over the next few years.

MAPS

M.S.S.S All-sky Polarisation Survey

What to look forward to from MSSS

* Mosaicking effort now restarting on five CEP3 nodes.

* HBA data products in hand by ~August/October (northern regions first). Data products remain password-protected before public release; loaded into ASTRON VO server (vo.astron.nl).

* Early science papers: late 2017 + 2018.

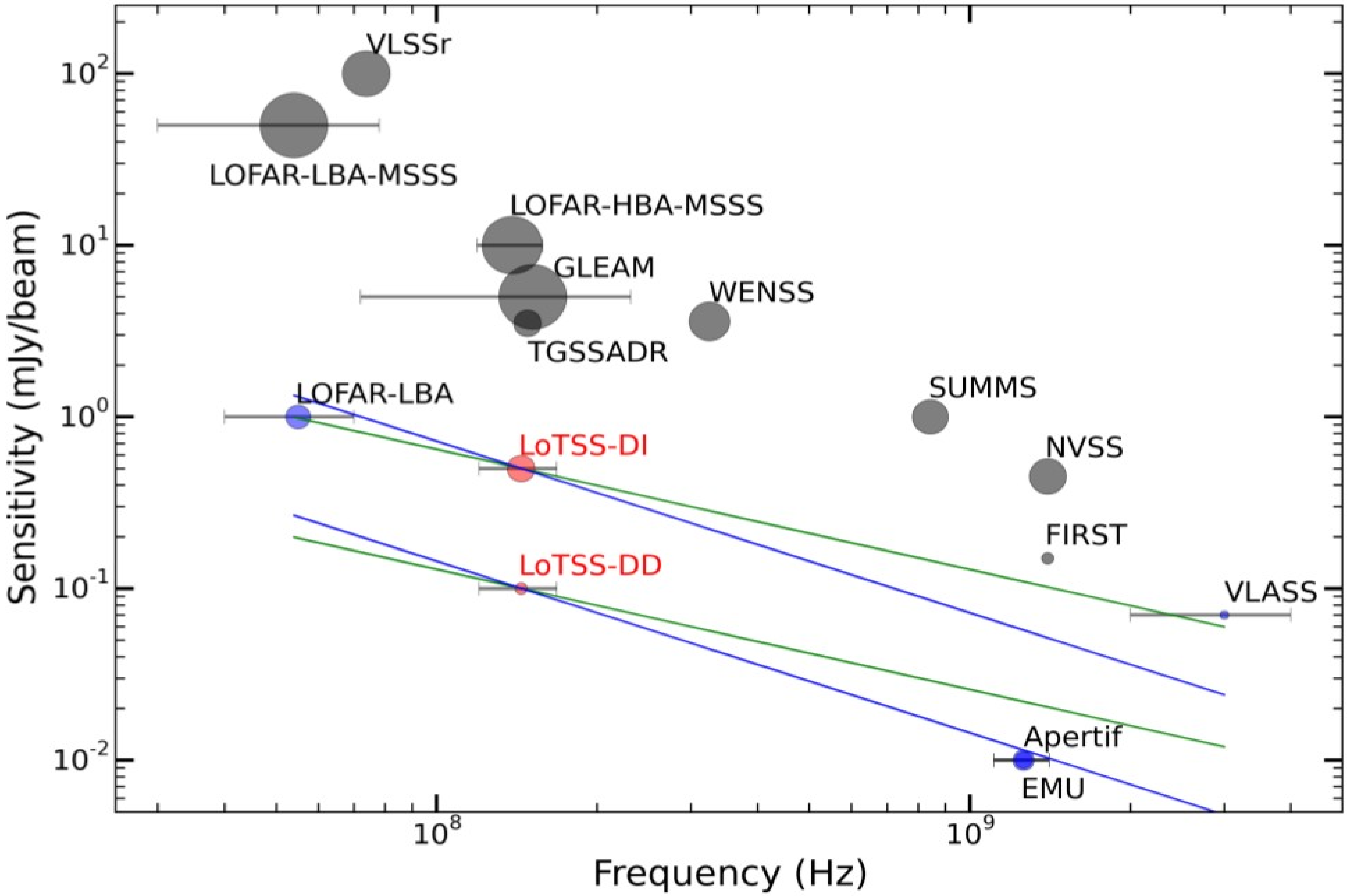
* **HBA public release and accompanying paper (Heald et al., in prep.) by end of 2017.**

* Exact catalogue format to be determined, but will be ~40 columns per source.

* VO server flexibility - SAMP connection (e.g. enabling use of TOPCAT and Aladin). Also investigating ways to better visualise and query the data (e.g. using the WorldWide Telescope – Aleksandar Shulevski leading efforts).

The LOFAR tiered HBA/LBA surveys

Shimwell et al. (2017)



* MSSS-HBA will have significant legacy value, but LOFAR is capable of much deeper, higher-resolution surveys....

The LOFAR tiered HBA/LBA surveys

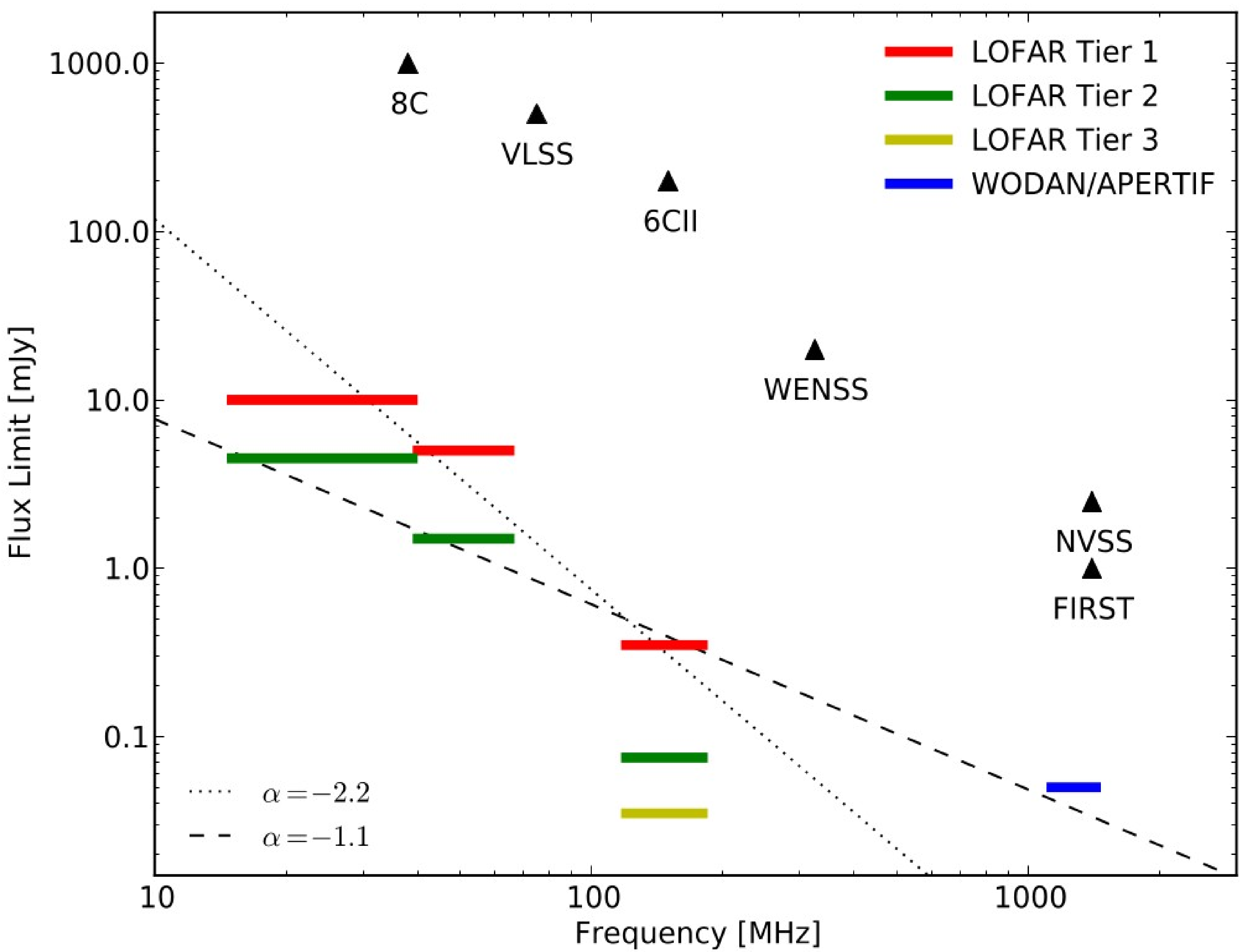
Röttgering

* LOFAR Surveys Key Science Project:

PI: Röttgering (Leiden)

Core team: Best, Brüggen, Brunetti, Chyży, Conway, Haverkorn, Heald, Jackson, Jarvis, Lehnert, McKean, Miley, Morganti, Scaife, Tasse, White, Wise

135 members from ~50 institutions



LoTSS – Tier 1 HBA survey

* LOFAR Two-metre Sky Survey - 'LoTSS'

* Northern sky

* 3170 pointings

* Median pointing separation 2.58 degrees

* Integration time per field 8 hr. Total ~13000 hr.

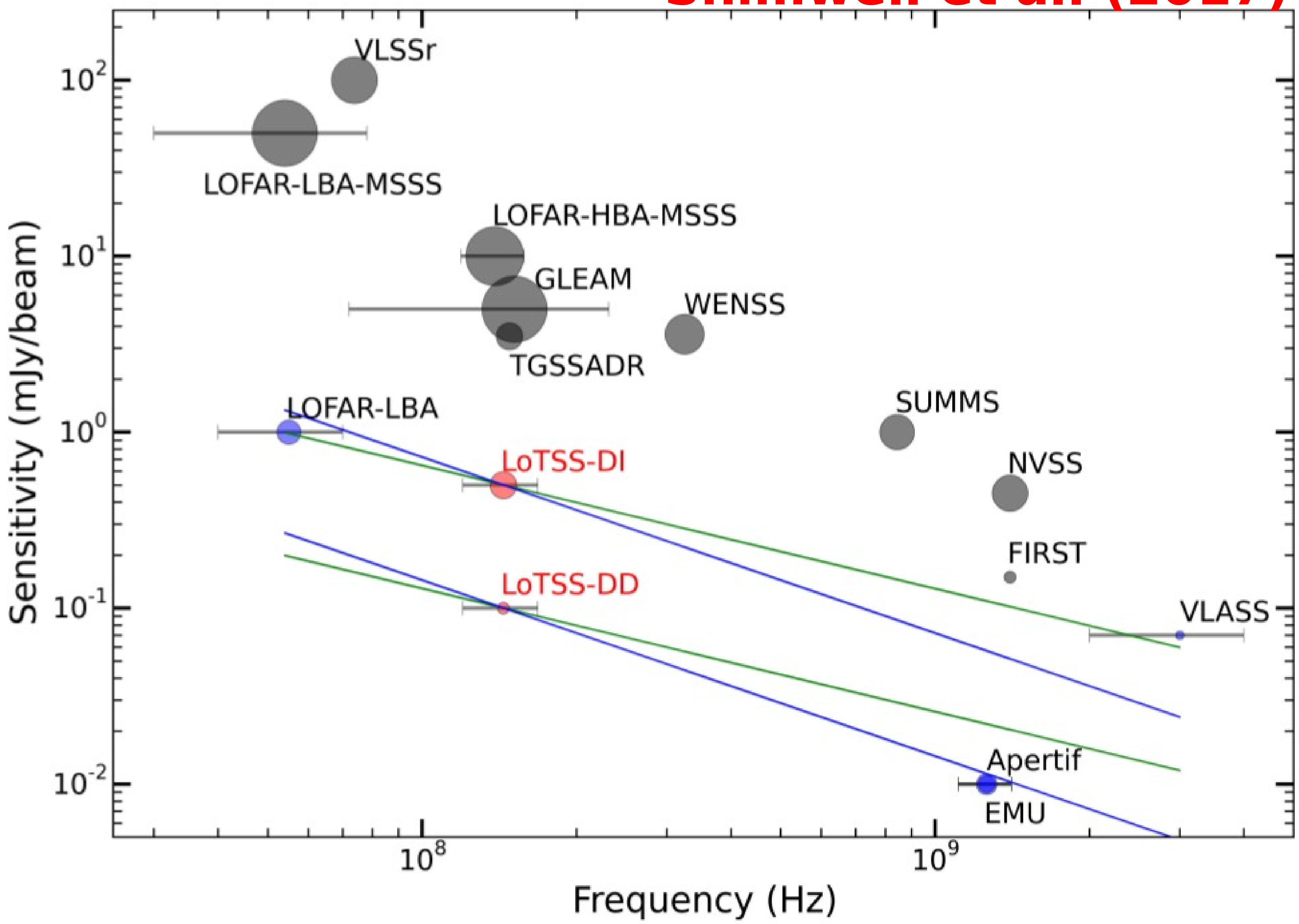
* 120-168 MHz

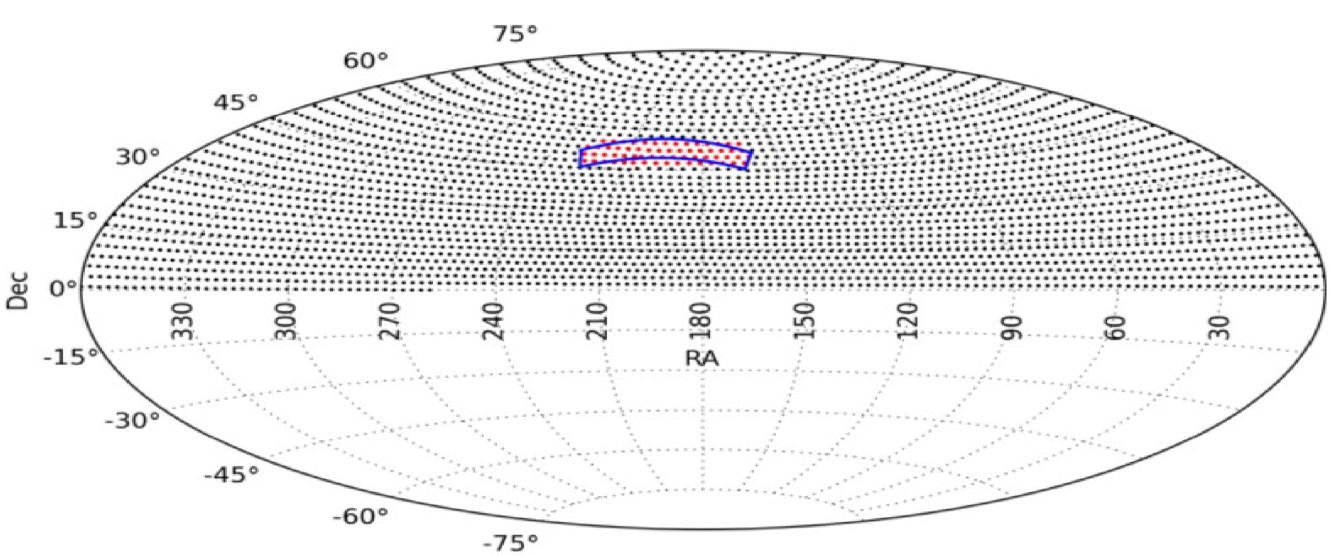
* Angular resolution 5 arcsec

* Sensitivity 100 μJy beam^{-1}

* Survey description, and preliminary Tier-1 data products from the HETDEX Spring Field (400 deg^2) - Shimwell et al. 2017, A&A, 598, A104; also see vo.astron.nl

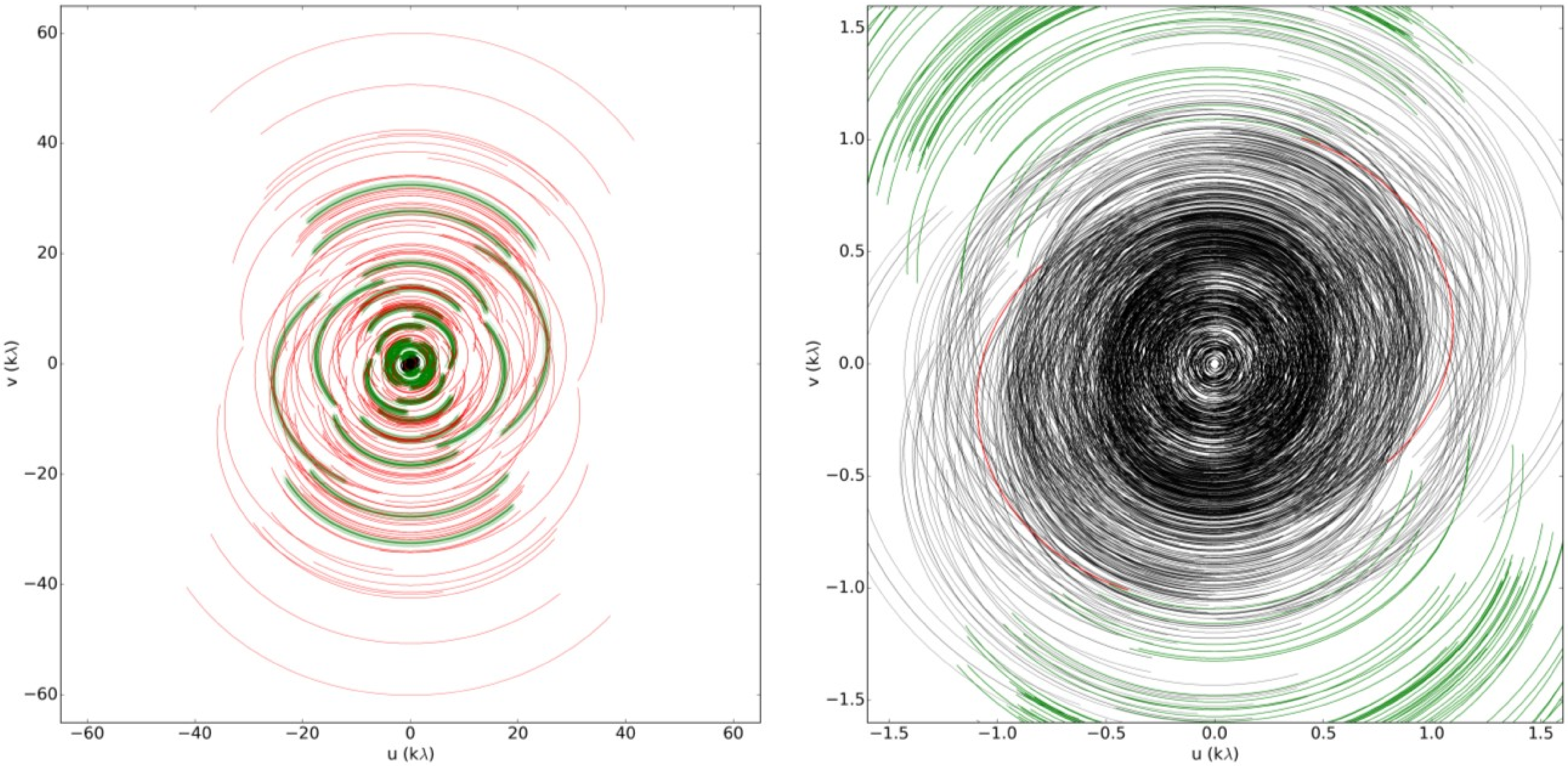
Shimwell et al. (2017)





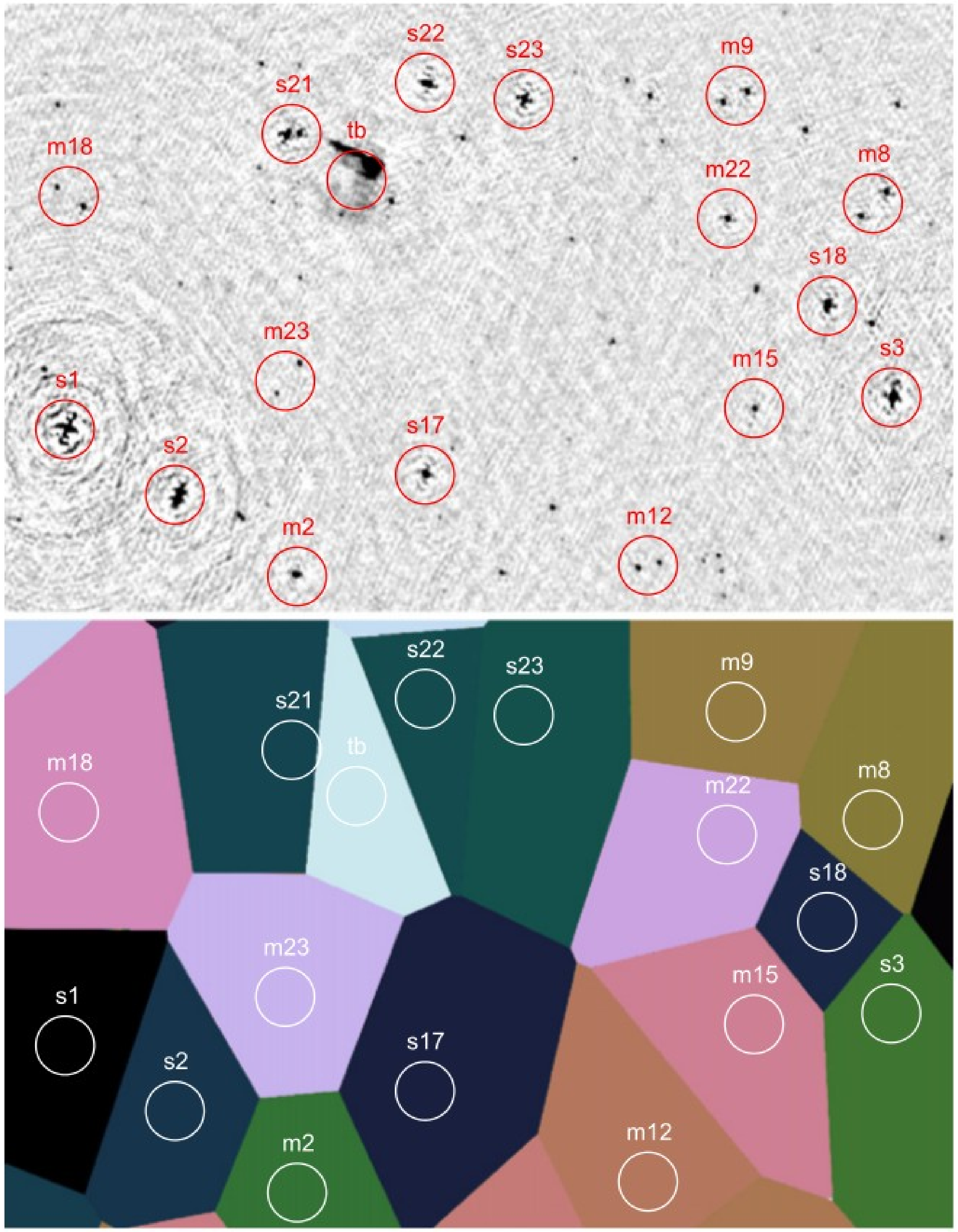
LoTSS – Tier 1 HBA survey

Shimwell et al. (2017)



Monochromatic u,v coverage per 8-hr LoTSS observation
(not including international stations)

LoTSS calibration



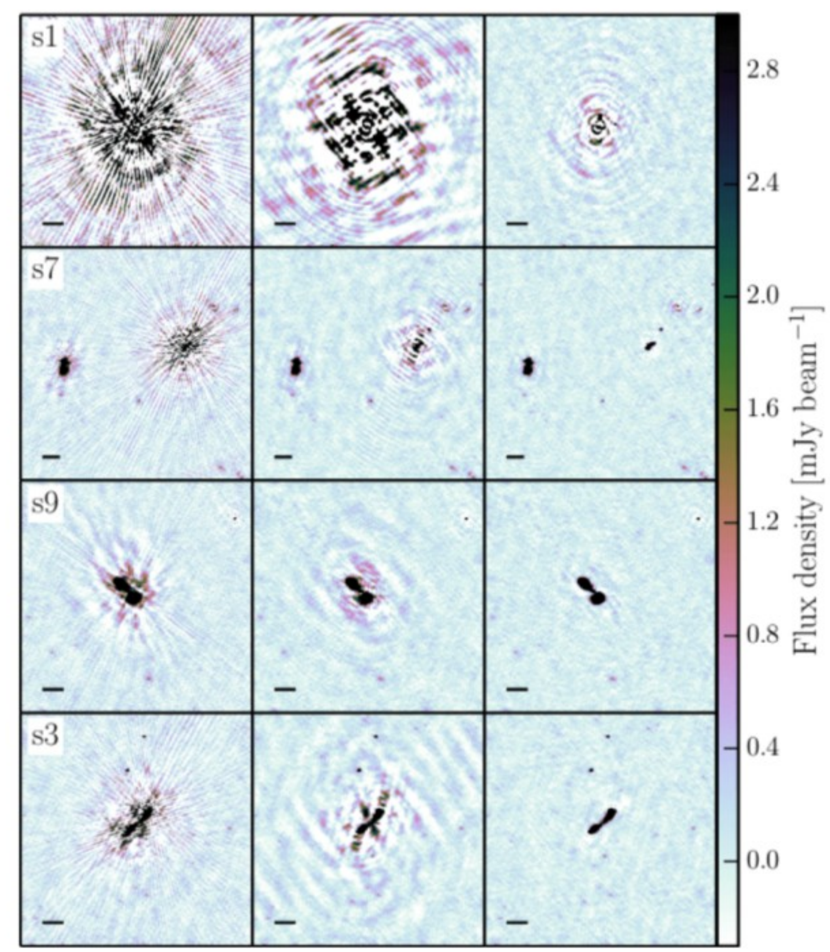
van Weeren et al. (2016)

* Direction-dependent calibration using facet technique.

* Fully automated calibration and imaging pipeline (Hardcastle, Shimwell, Tasse, Williams et al.).

* Runtime ~3-4 days per pointing.

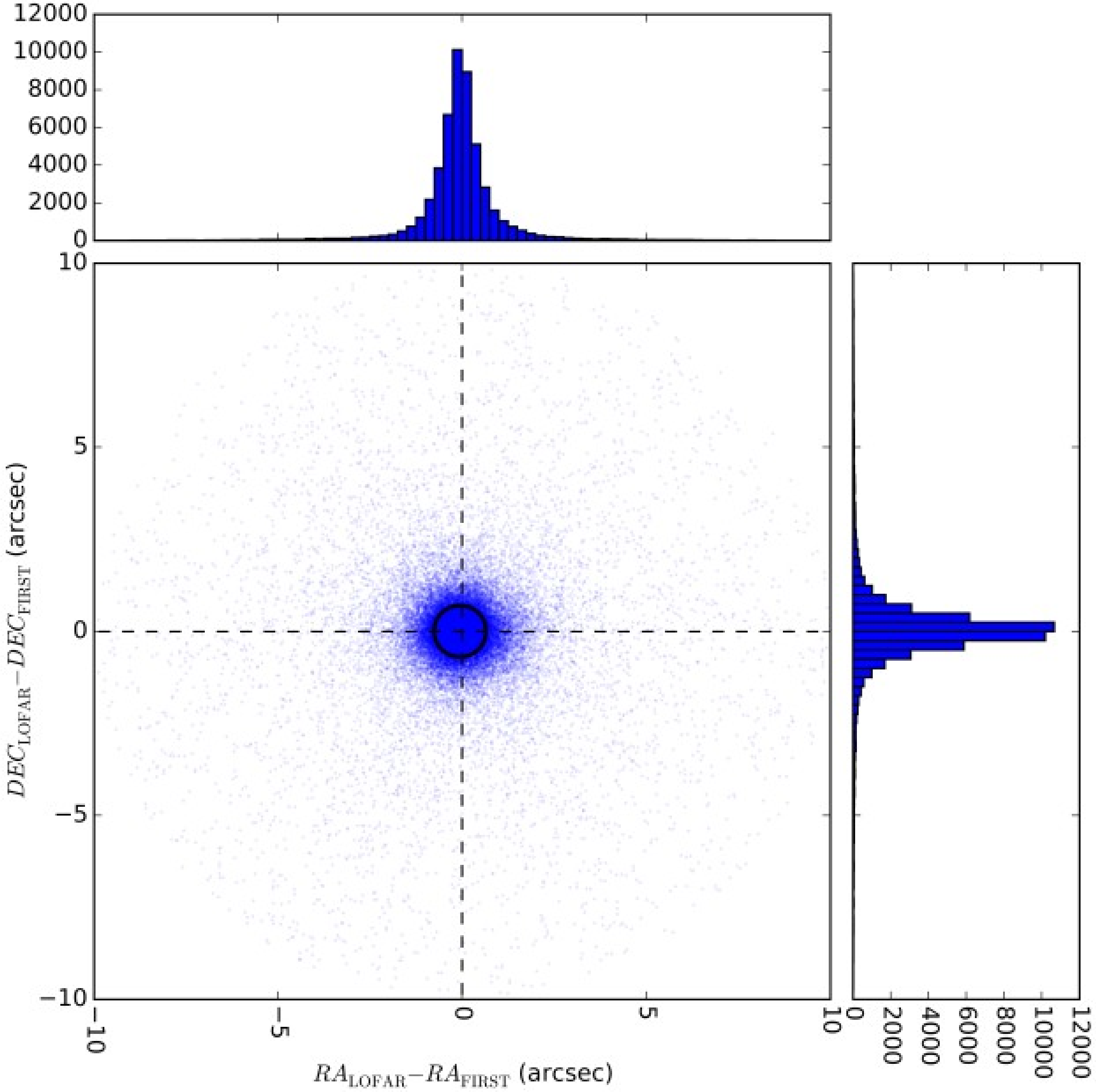
* Processing on LTA/GRID facilities (e.g. SURFsara) vital (50 PB in total for LoTSS). Implementation by Mechev, Oonk, Shimwell.



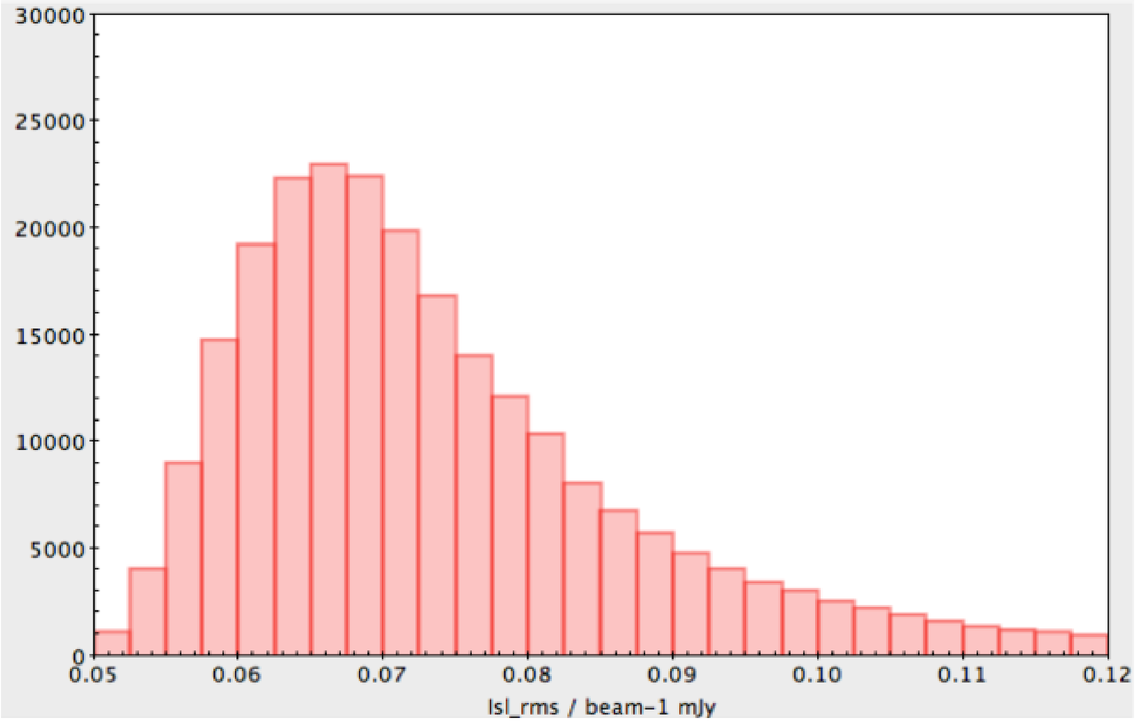
Williams et al. (2016)

>1 science-quality image being produced per day.

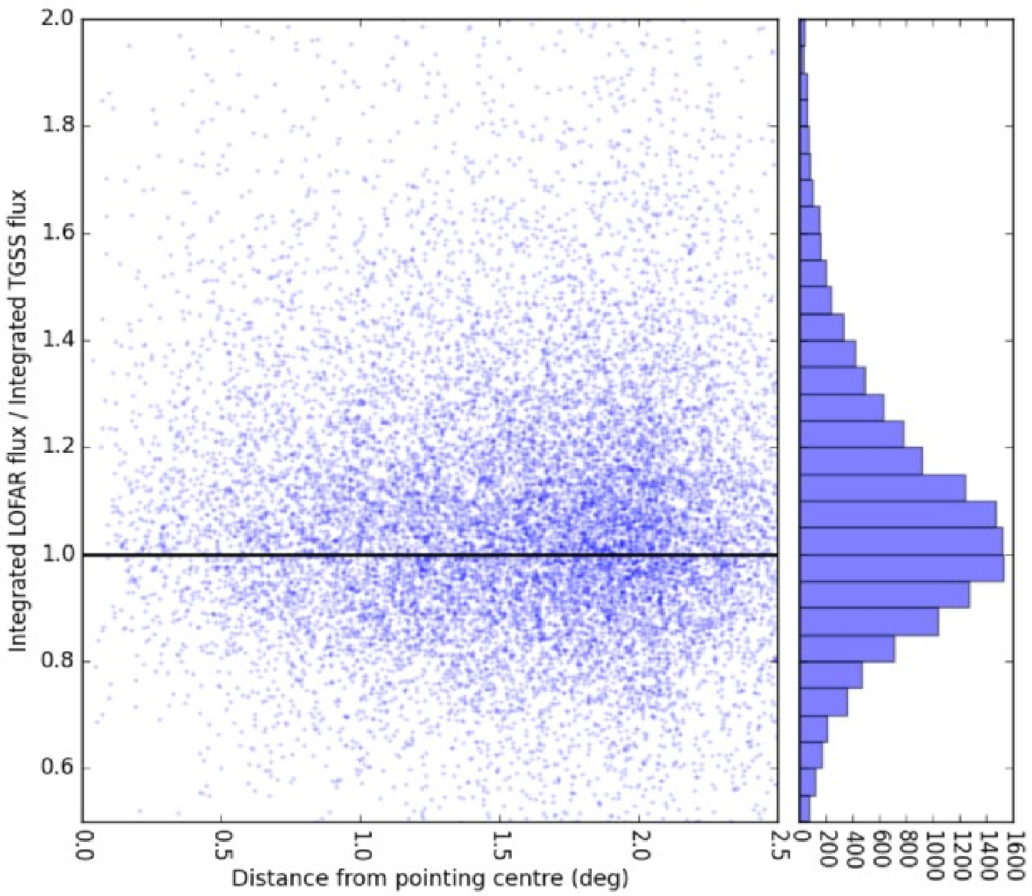
Quality control



* Standard deviation of offsets from FIRST is 1.3 arcsec.



* Noise level typically 70 μJy beam^{-1}.



* Flux densities consistent with TGSS.

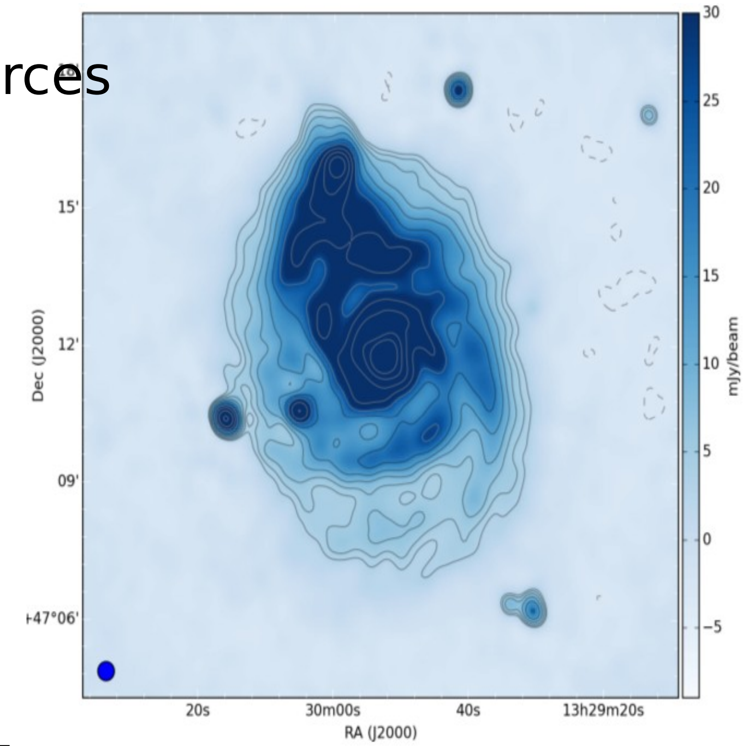
Shimwell

LoTSS science drivers

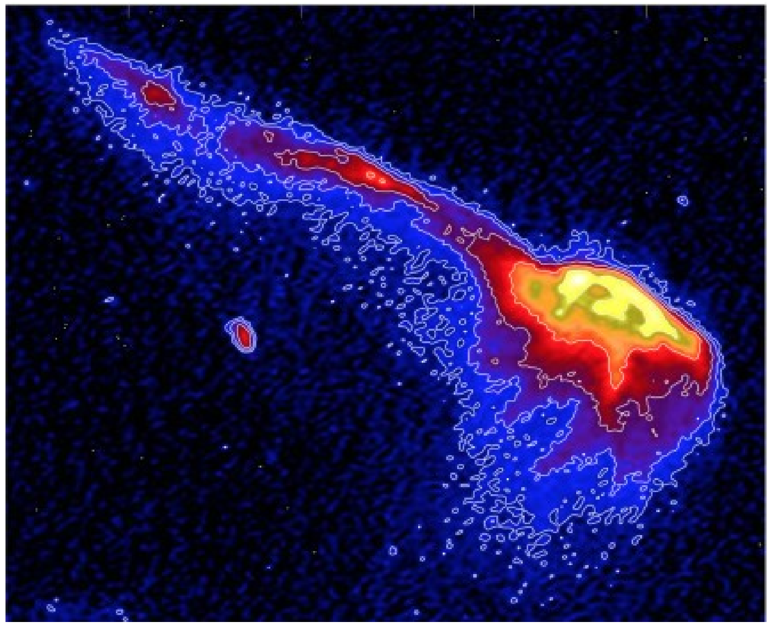
LOFAR ASTRON

* Highest-redshift radio sources
* Distant starforming galaxies
* Clusters and cluster halo sources
* AGN at moderate redshifts
* Gravitational lensing
* Detailed studies of low-redshift AGN
* Nearby galaxies
* Cosmological studies
* Galactic radio sources

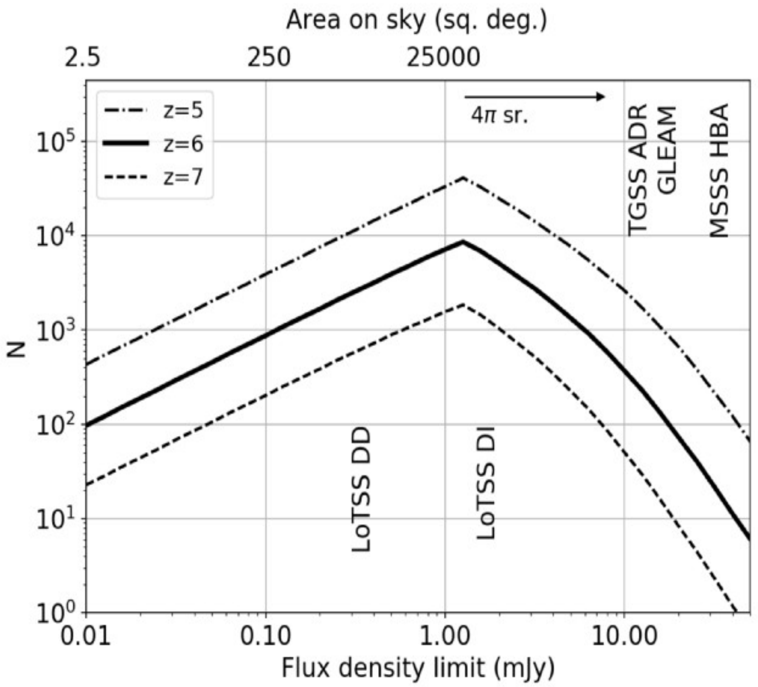
> 75 active projects at present



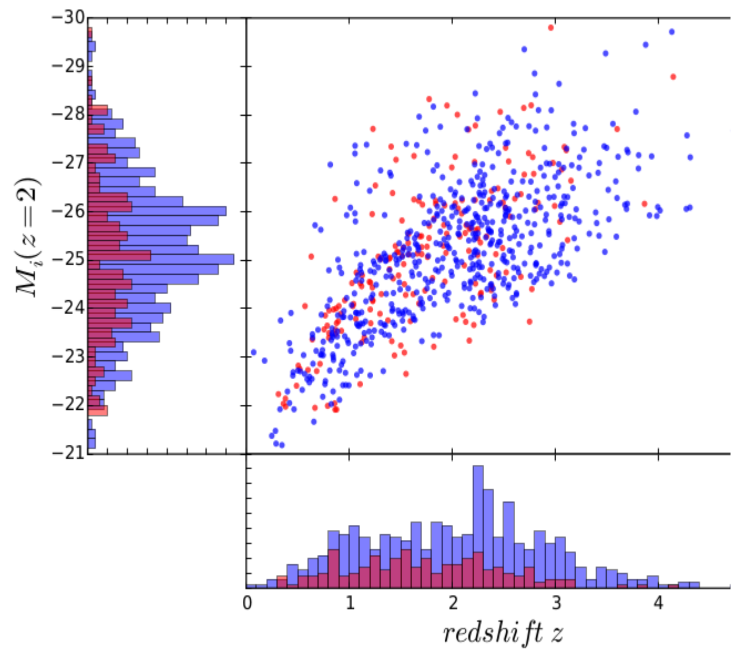
Shimwell et al. 2017



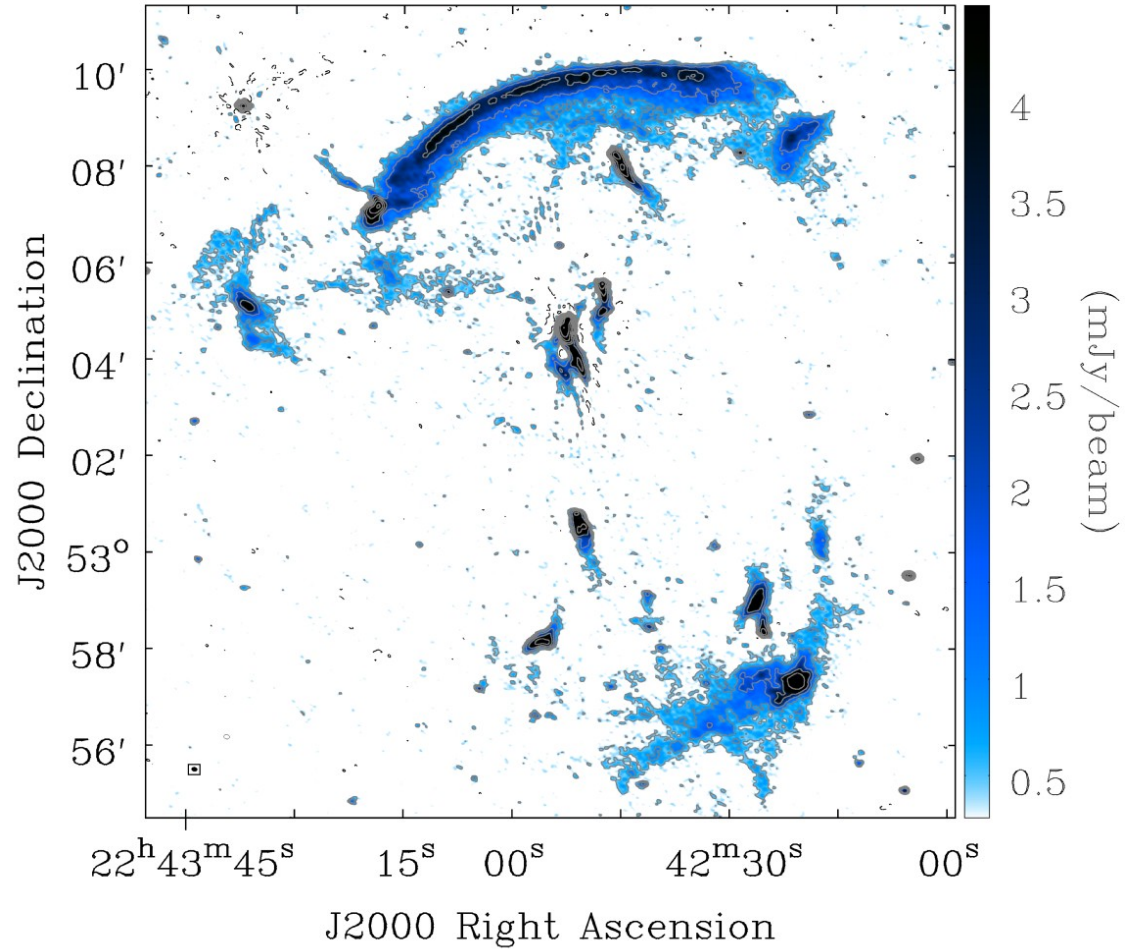
van Weeren et al. (2016)



Saxena et al. 2017

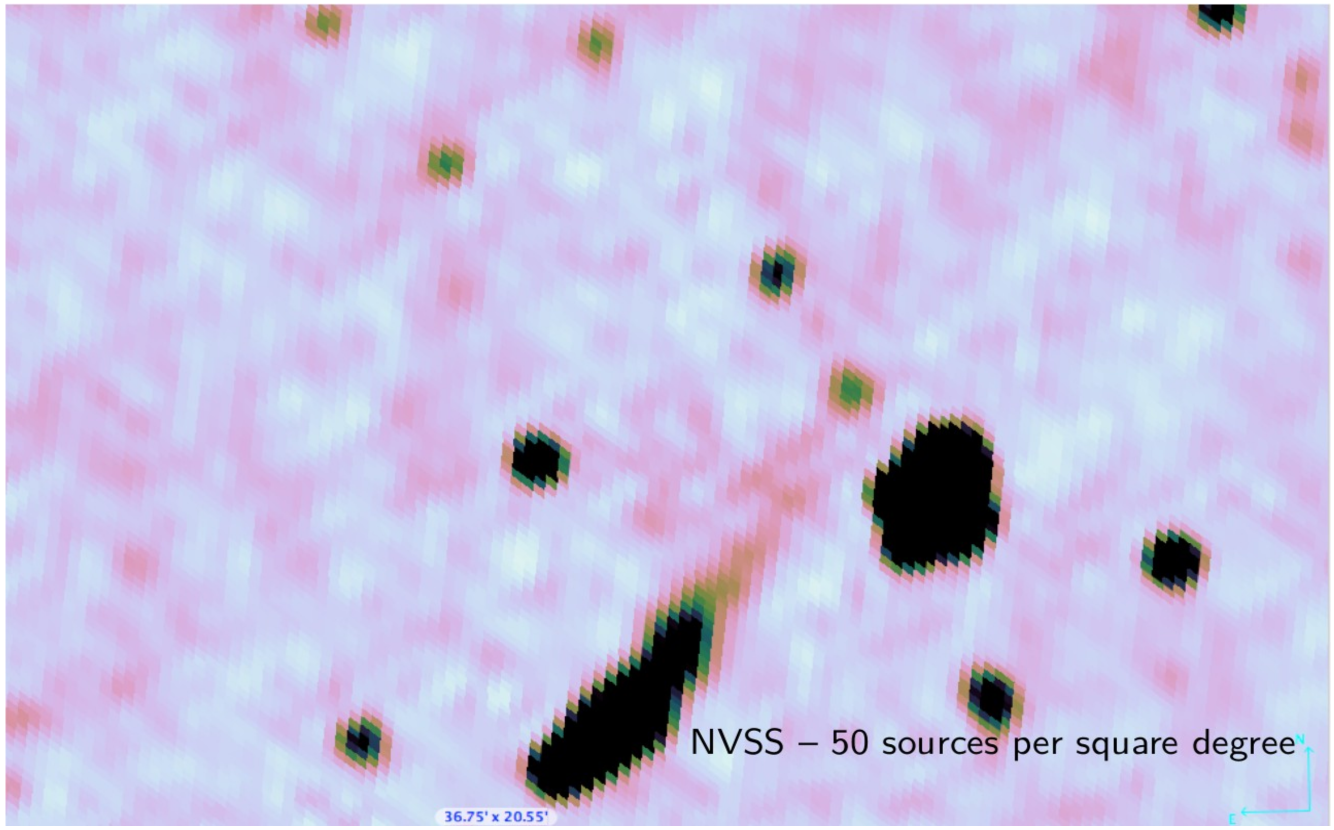


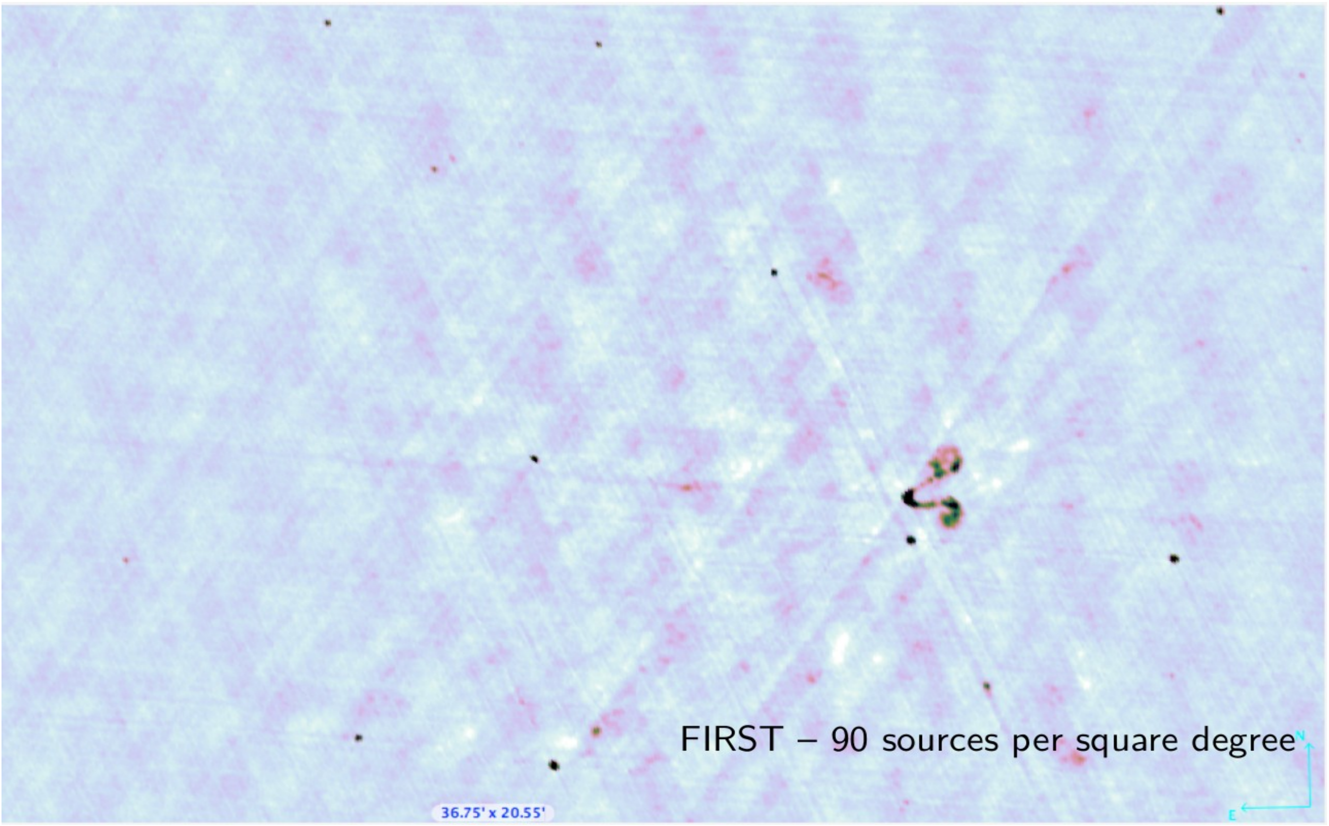
Shimwell et al. 2017

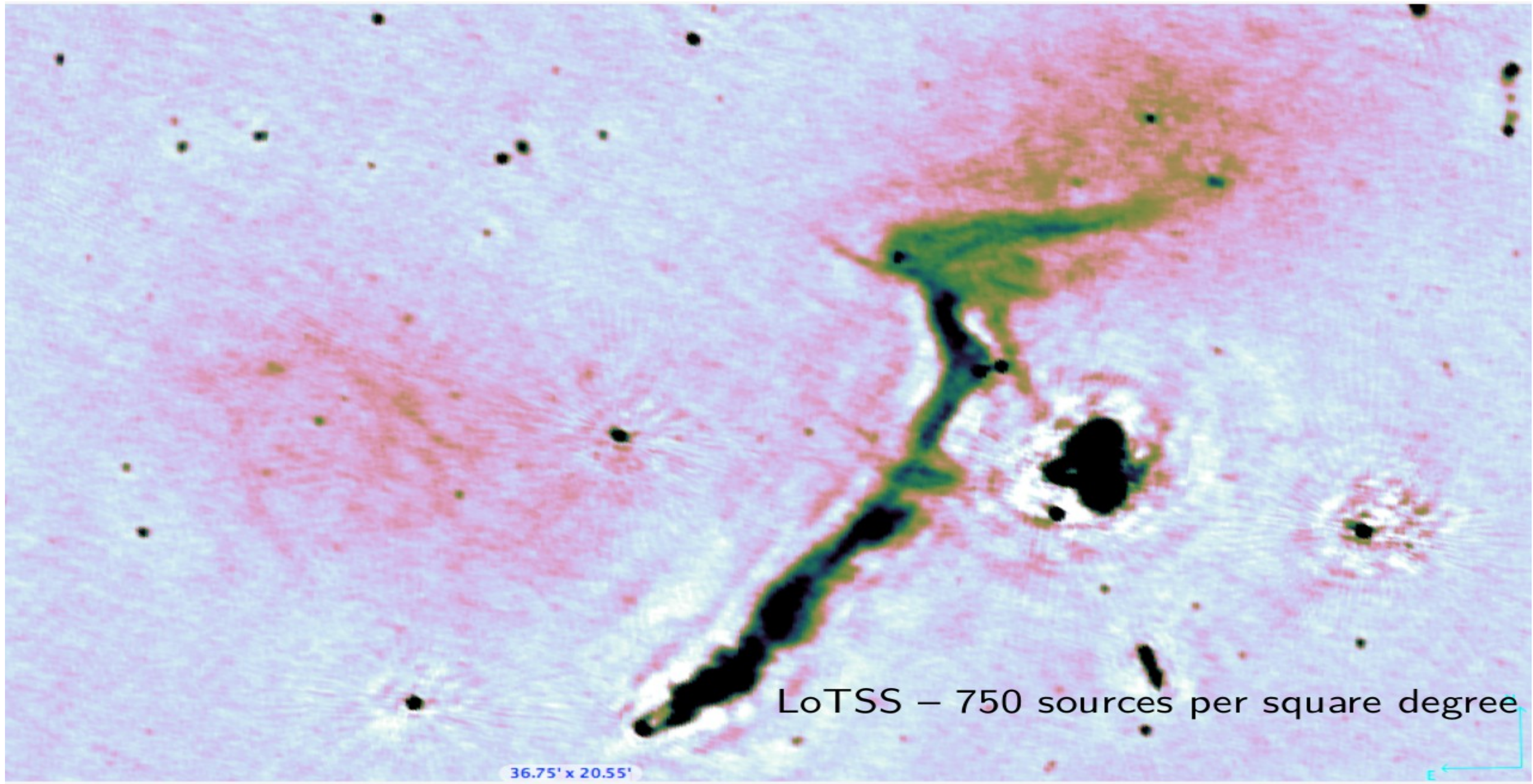


Hoang et al. (2017), submitted

Illustrating the scientific potential of LoTSS

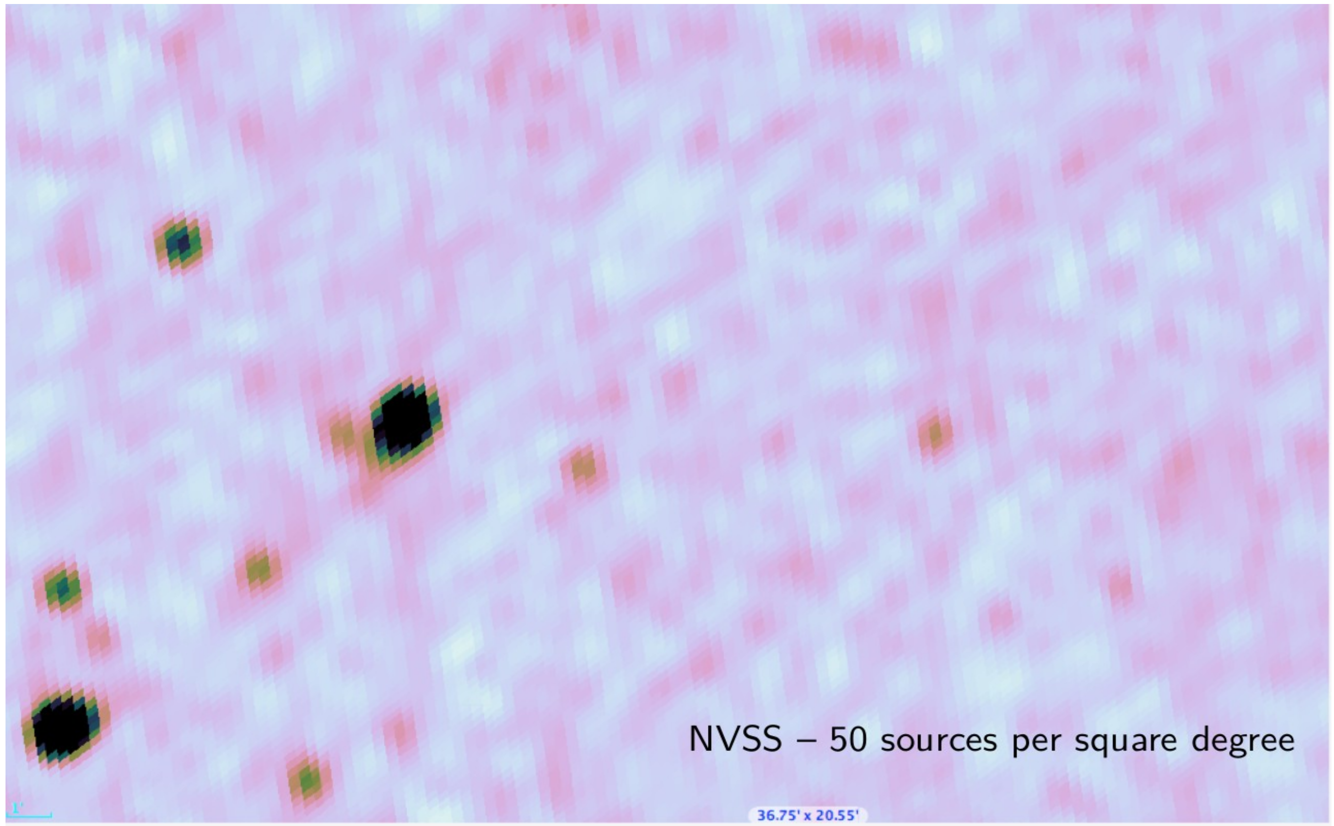


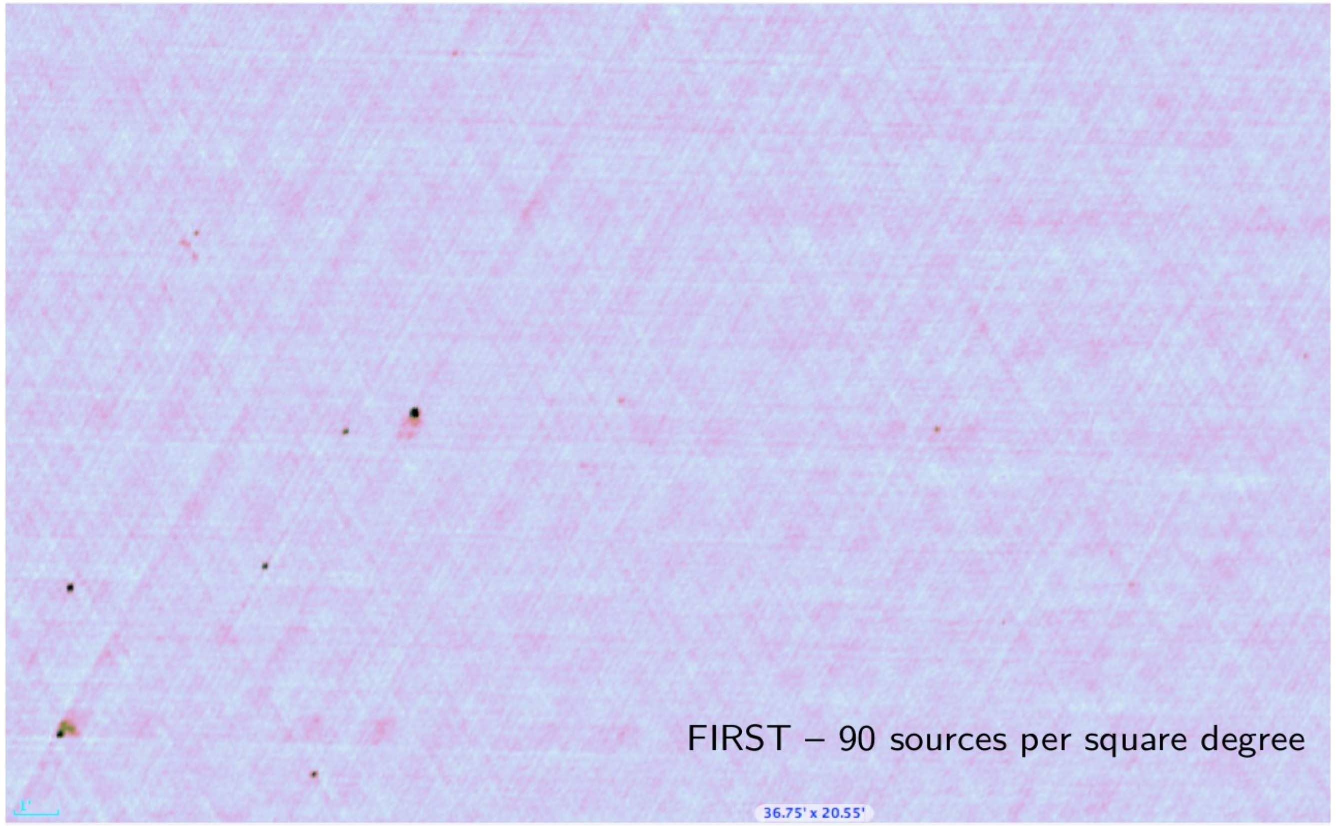


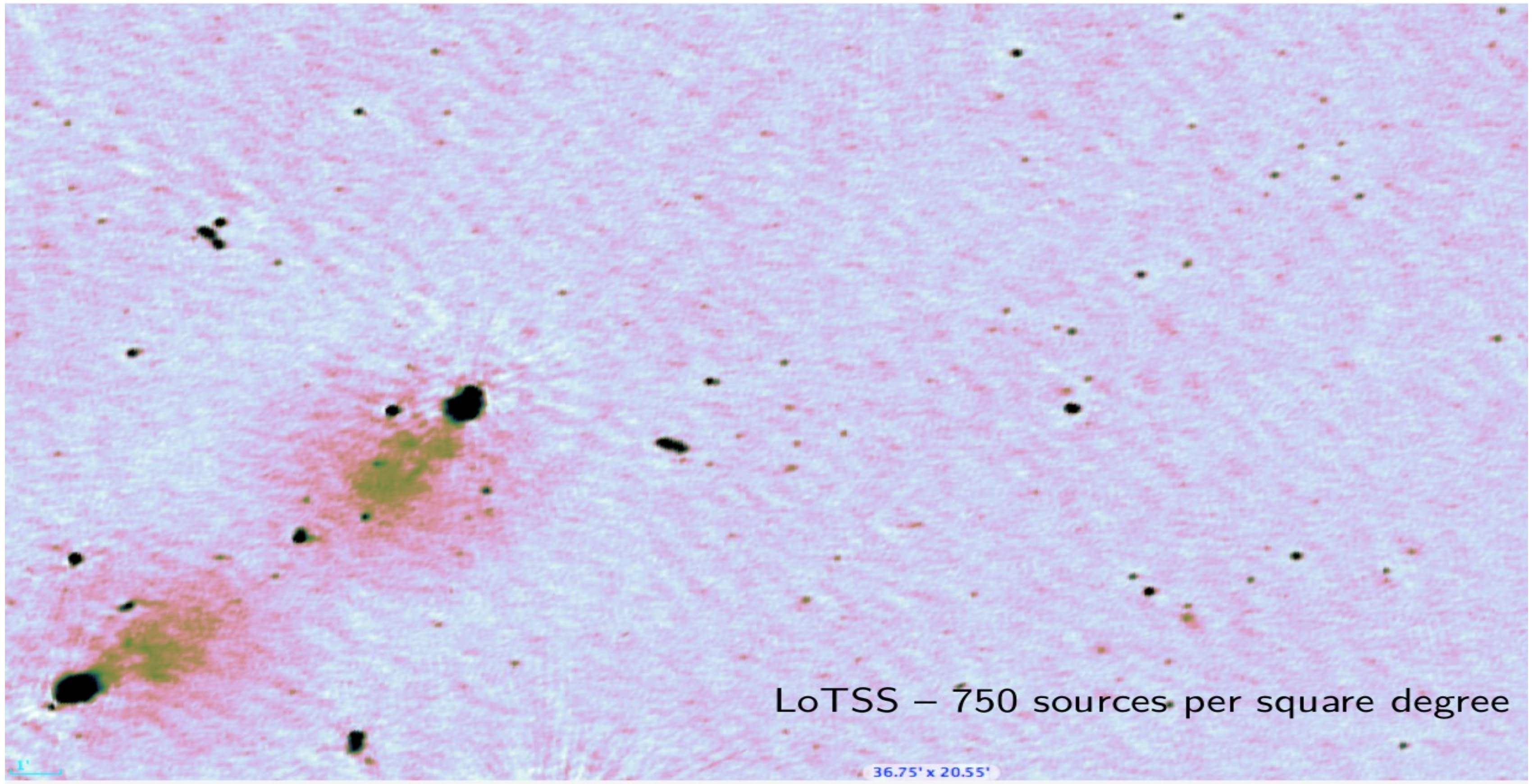


Shimwell

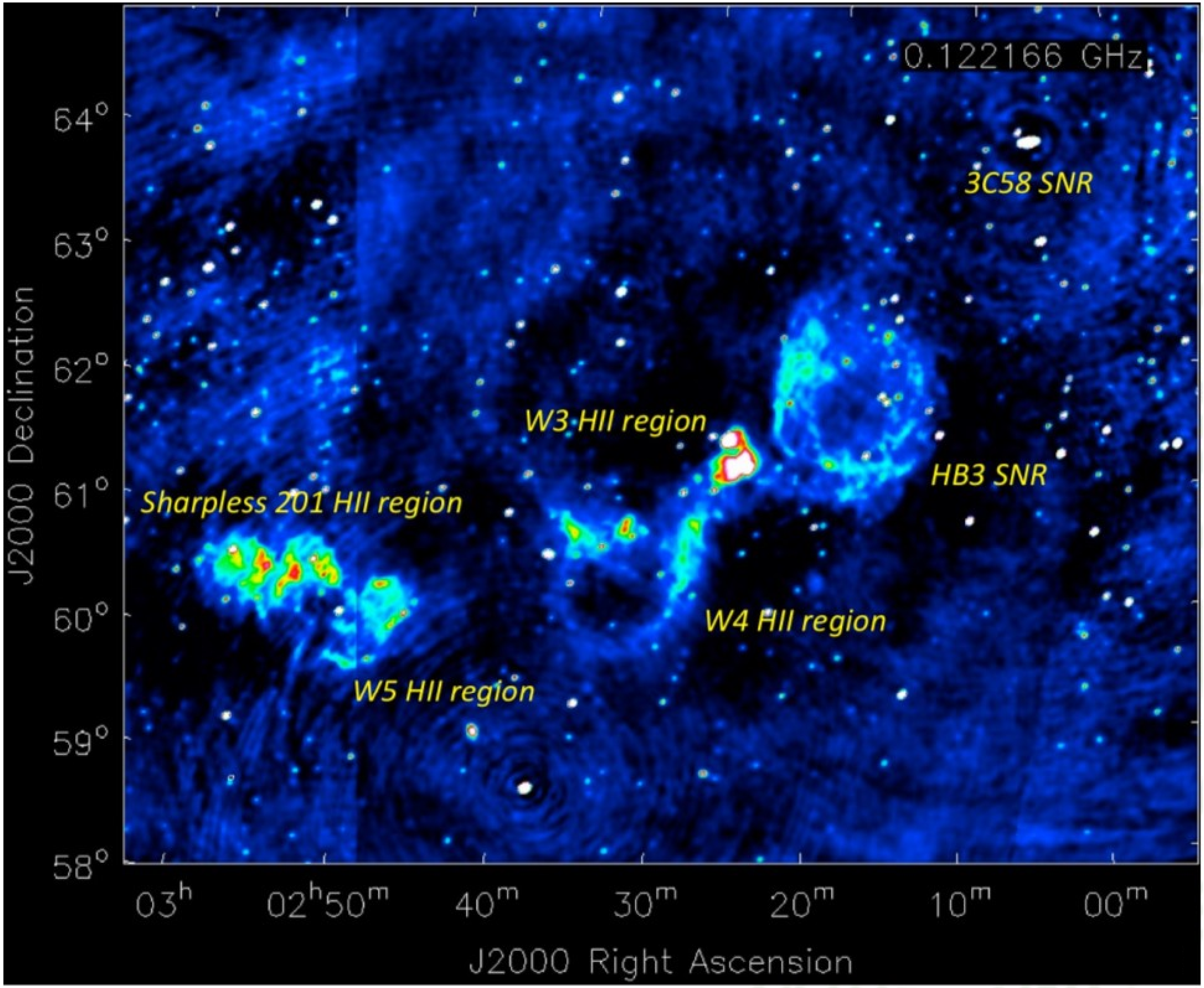
Illustrating the scientific potential of LoTSS





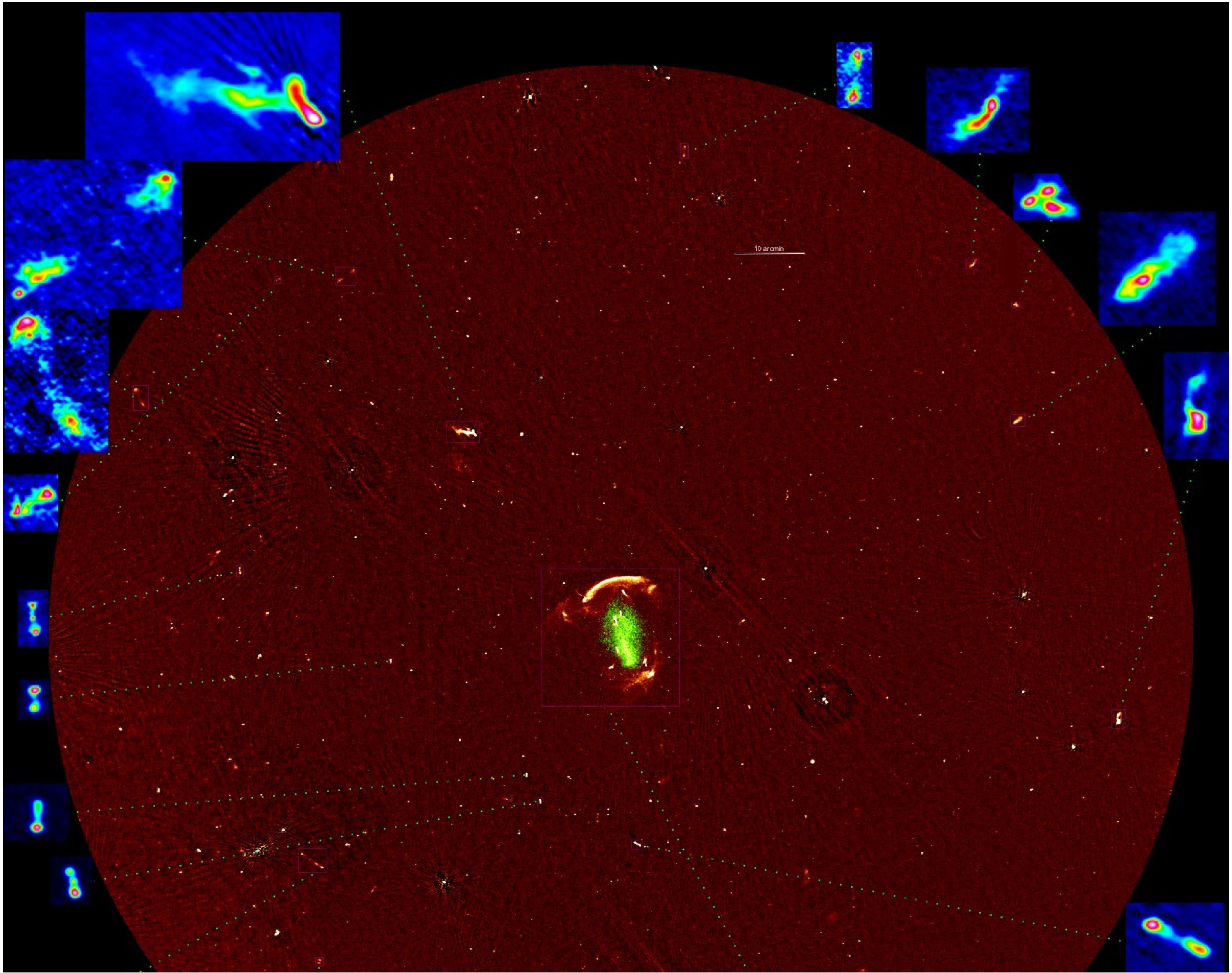


Shimwell



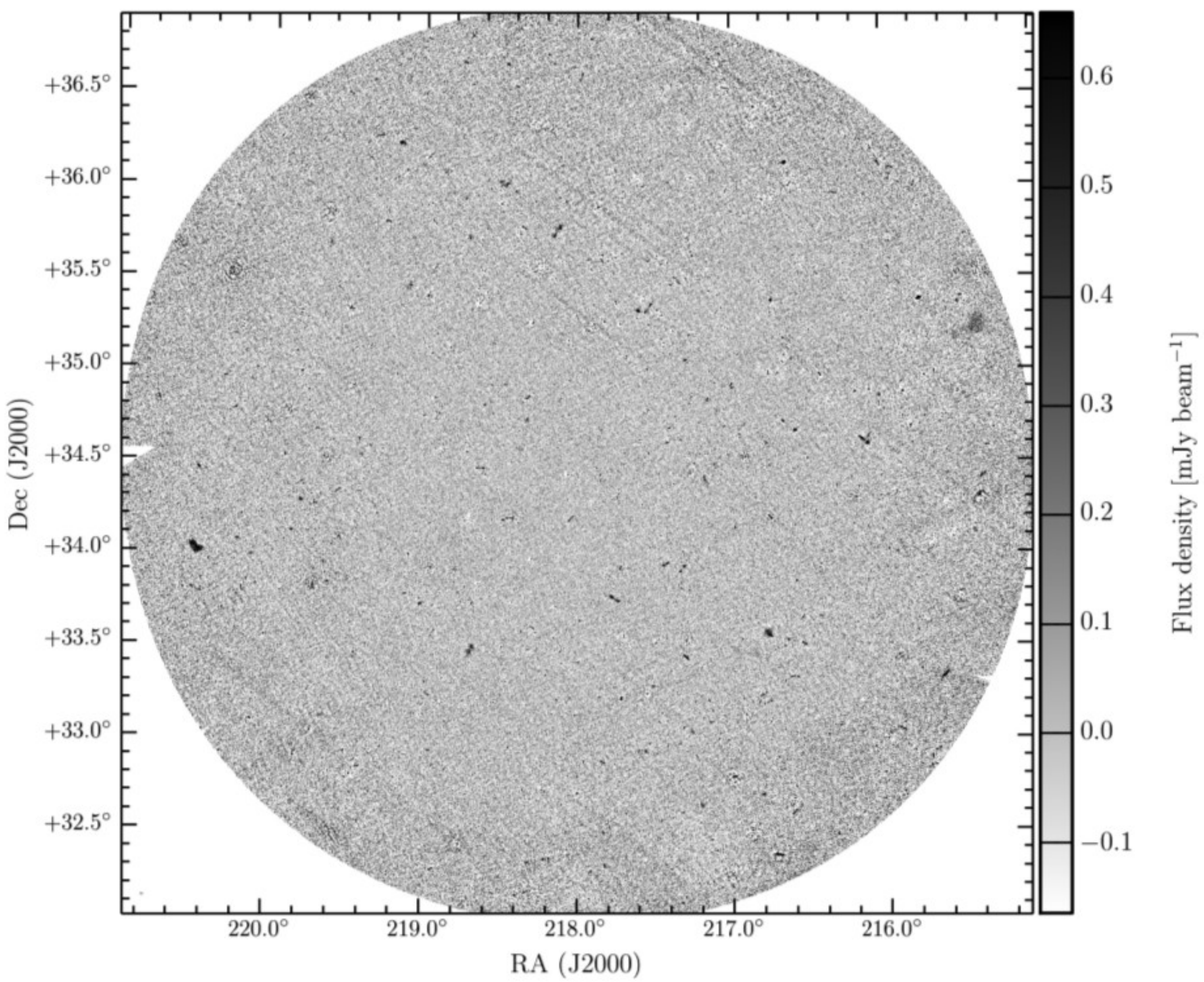
White et al. - 122 MHz, 20 sub-bands, preliminary map
(although routinely imaging complex Galactic fields remains challenging)

Illustrating the scientific potential of LoTSS



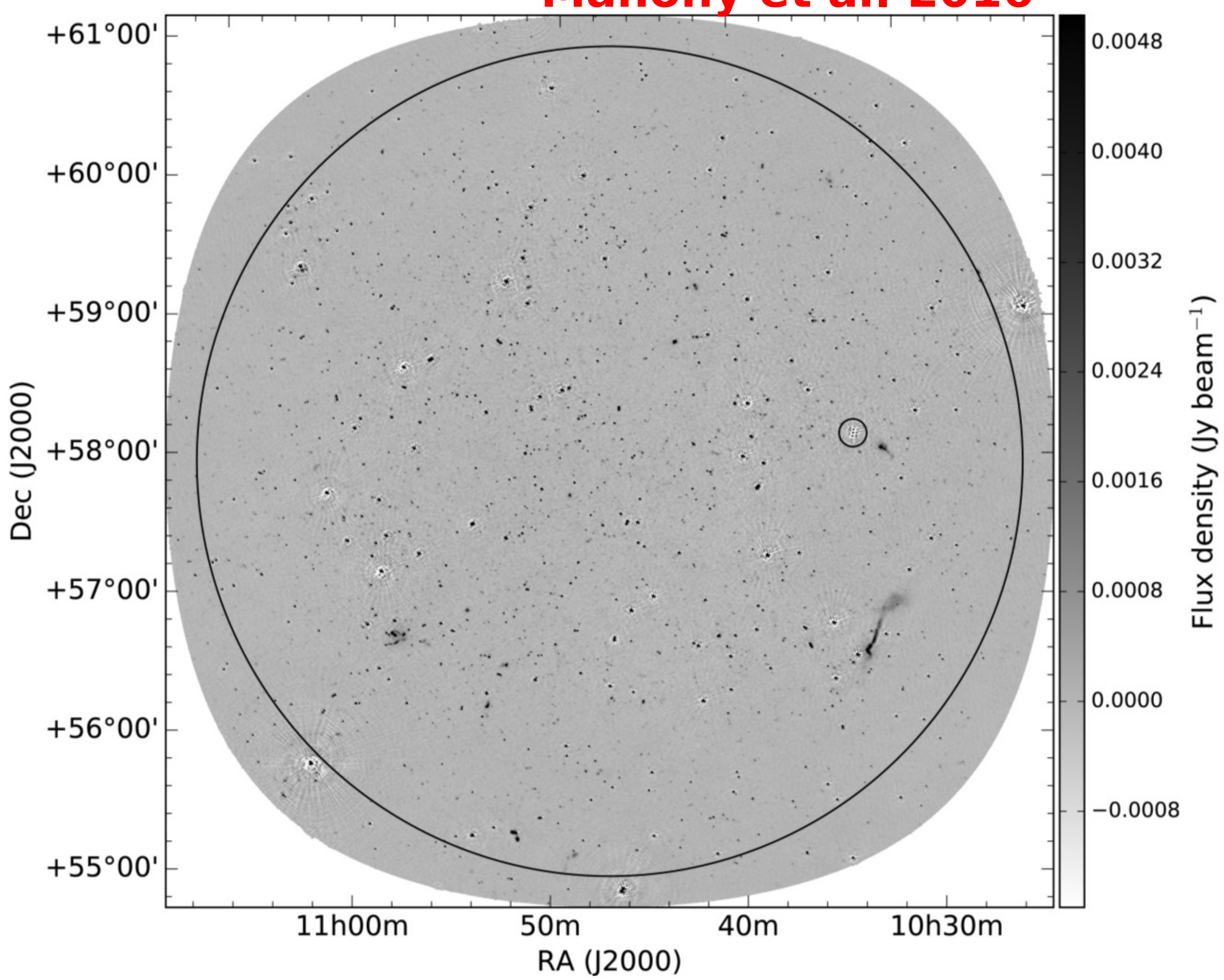
Working towards Tier 2/3 depths

Williams et al. 2016



* Boötes field; resolution ~6.5 arcsec, RMS 110 μJy beam^{-1} at field centre.

Mahony et al. 2016

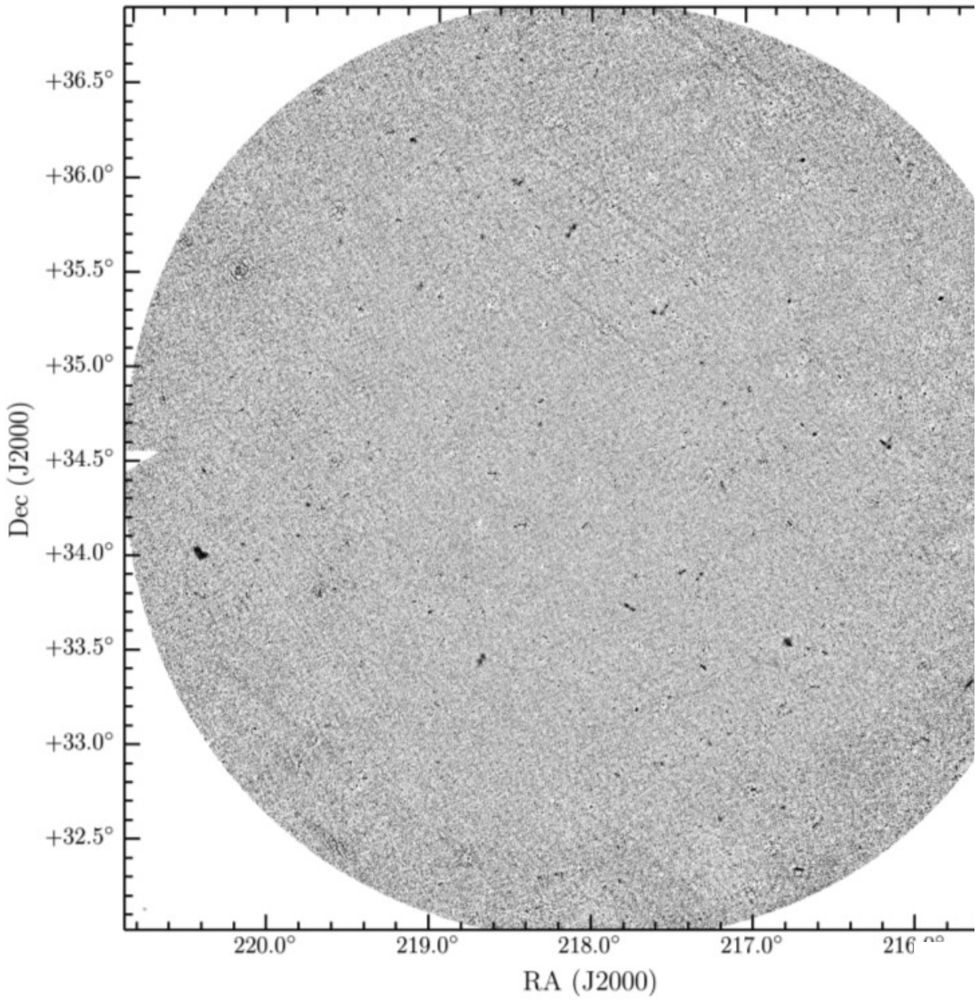


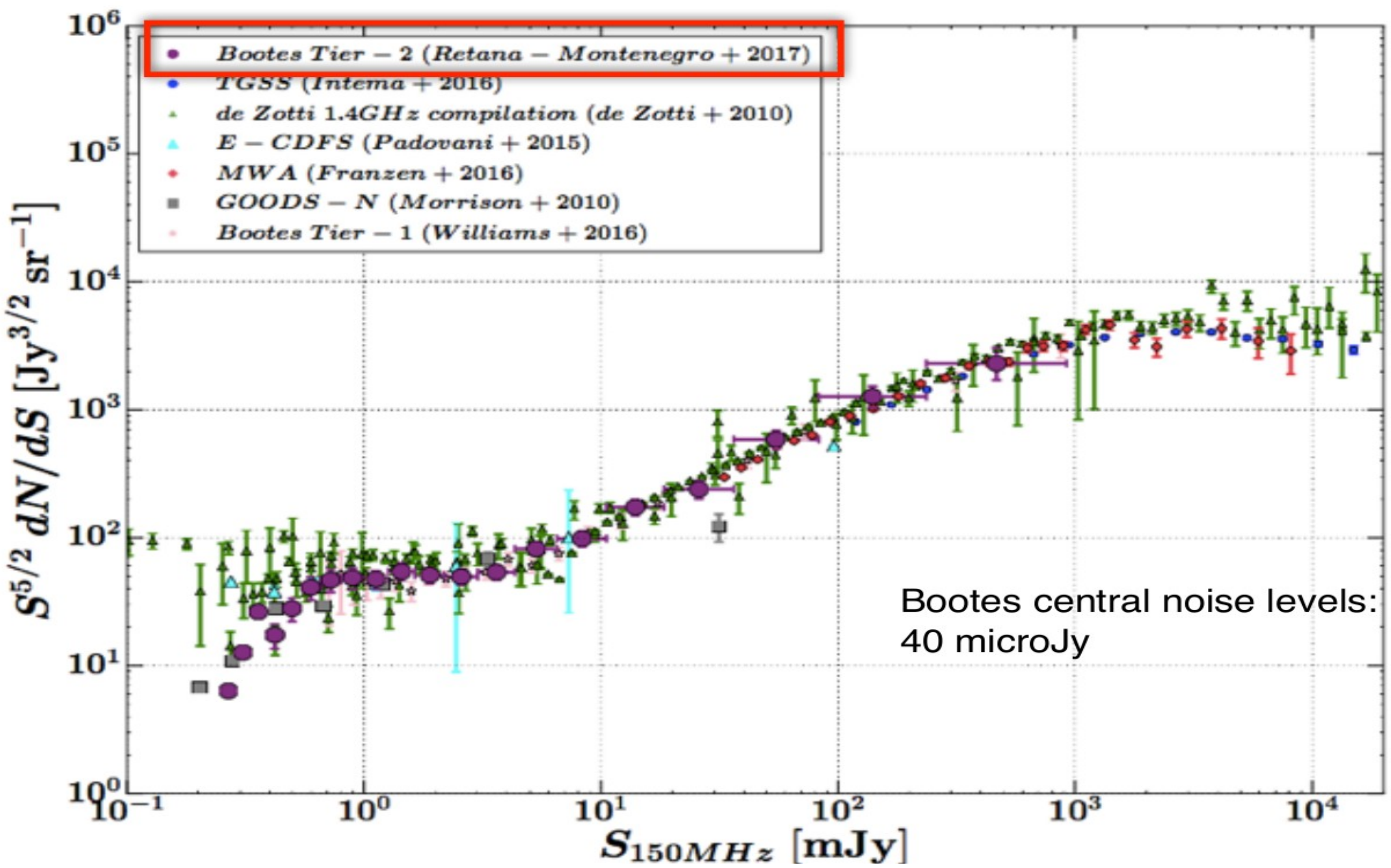
* Lockman Hole; resolution ~17 arcsec, RMS 160 μJy beam^{-1} at field centre.

* Tens - few hundred hours integration time for a selection of well studied fields with legacy multi-wavelength data (examples above; also see Hardcastle et al. 2016).

Working towards Tier 2/3 depths

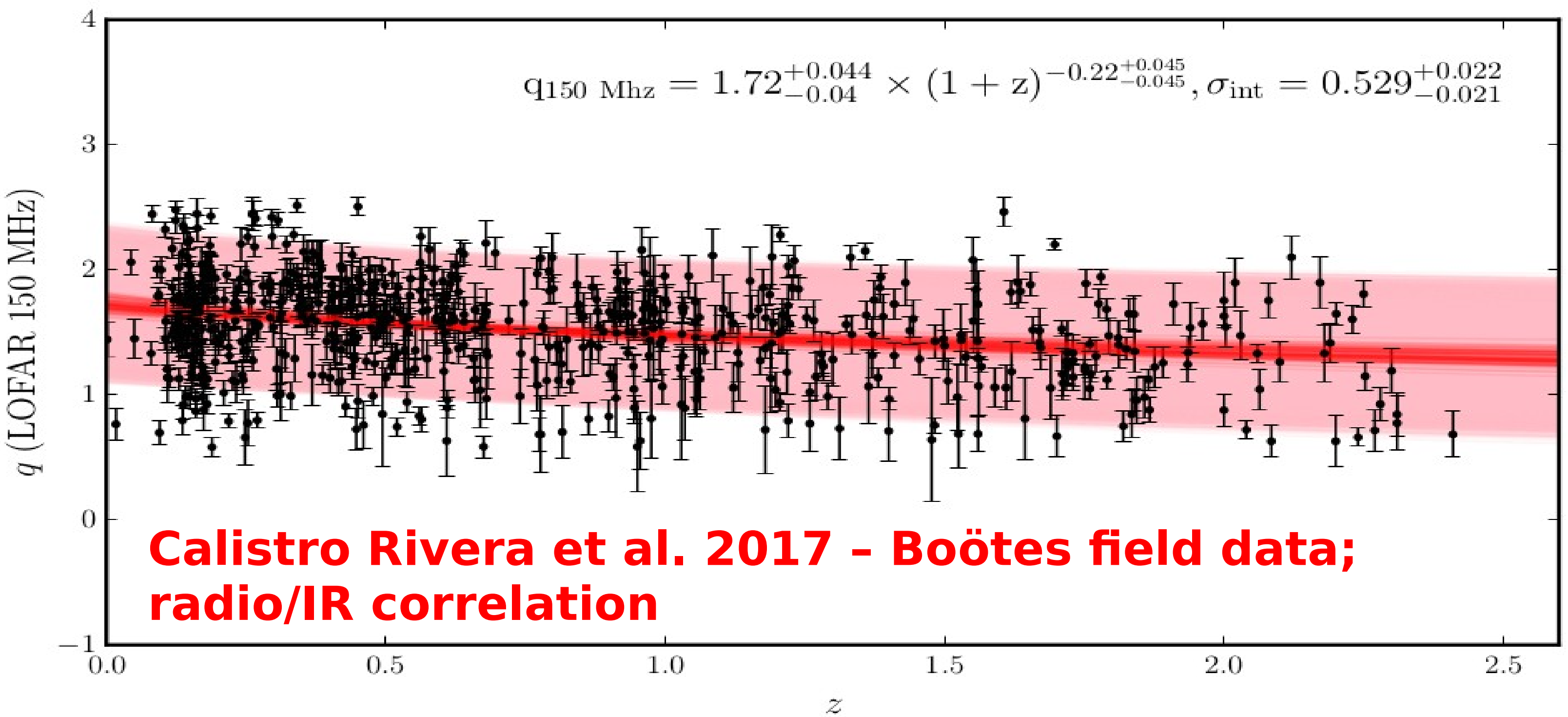
Williams et al. 20





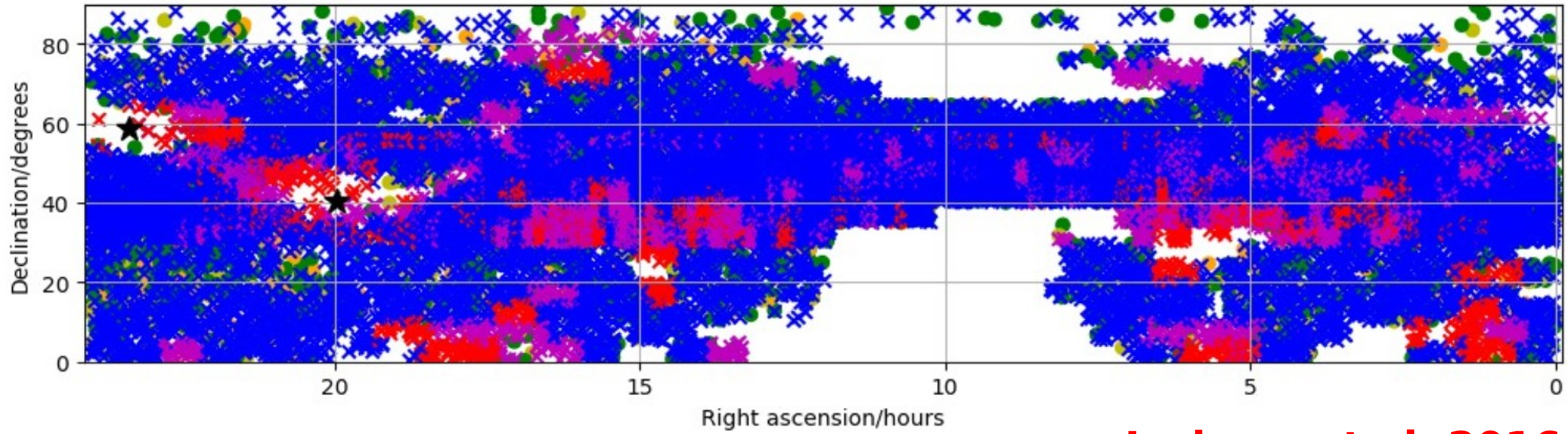
* Boötes field; resolution ~6.5
RMS 110 μJy beam^{-1} at field c

* Tens - few hundred hours inte
legacy multi-wavelength data (

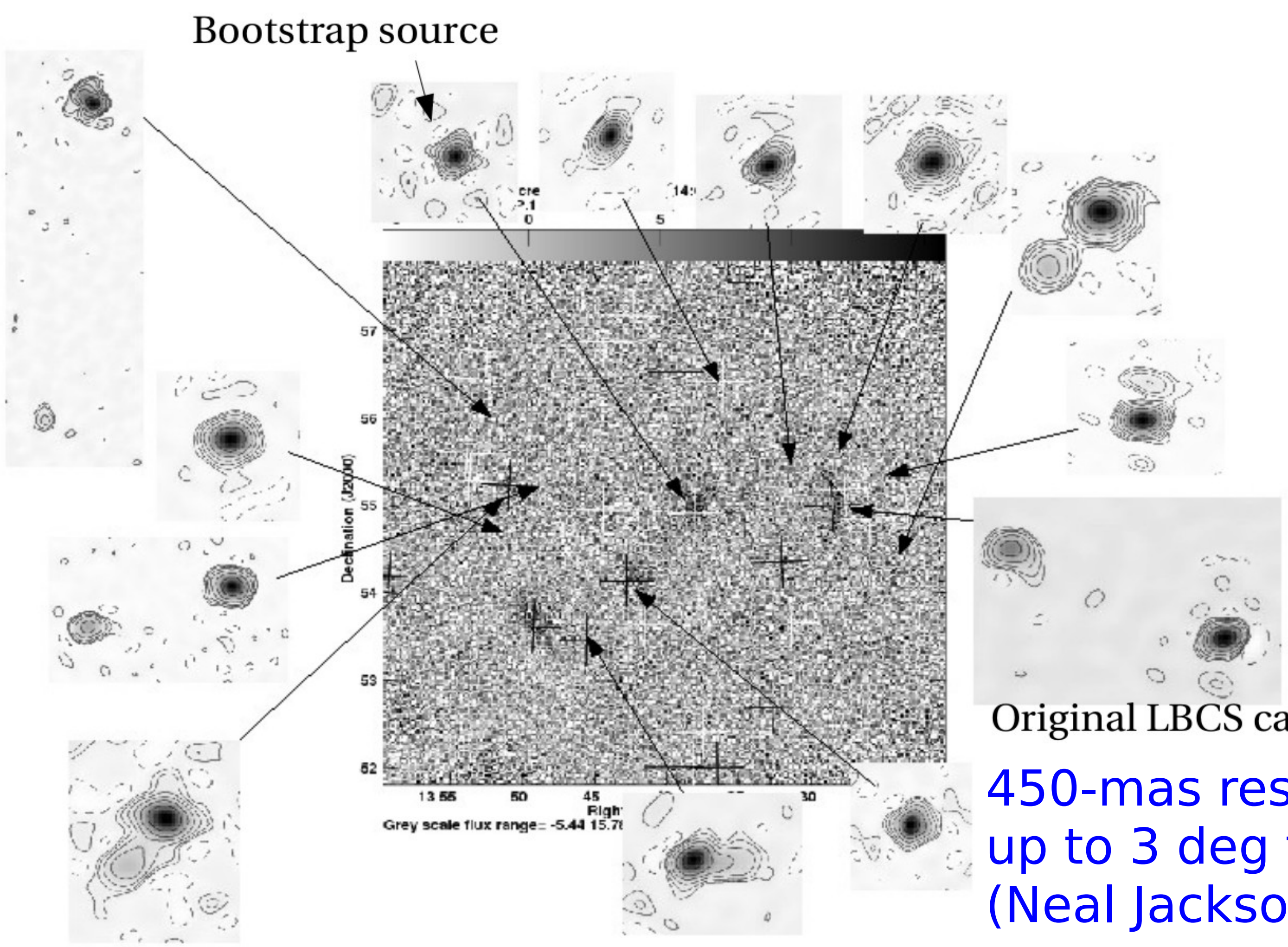


Calistro Rivera et al. 2017 – Boötes field data; radio/IR correlation

Using the international baselines



Jackson et al. 2016



* LBCS: The LOFAR Long-Baseline Calibrator Survey. Database at vo.astron.nl

* LoTSS observations include International stations.

450-mas resolution images,
up to 3 deg from the pointing centre
(Neal Jackson + long-baseline working group)

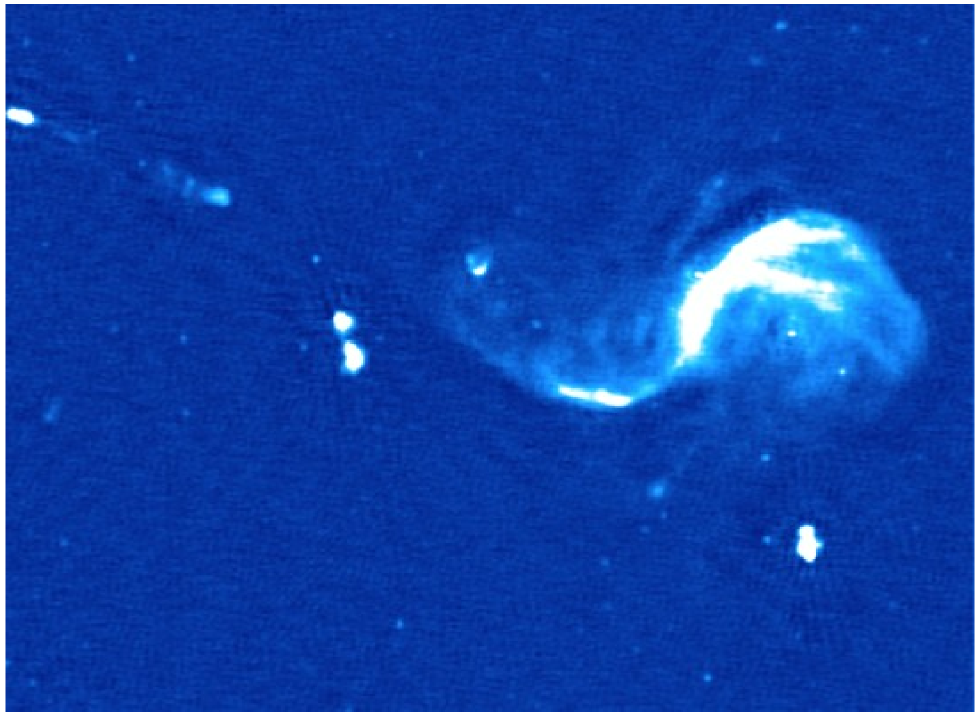
LoTSS – current and future work

* Further observations in current and upcoming LOFAR cycles. Survey ~15% complete by November (i.e. end of Cycle 8). Need increase in observing rate.

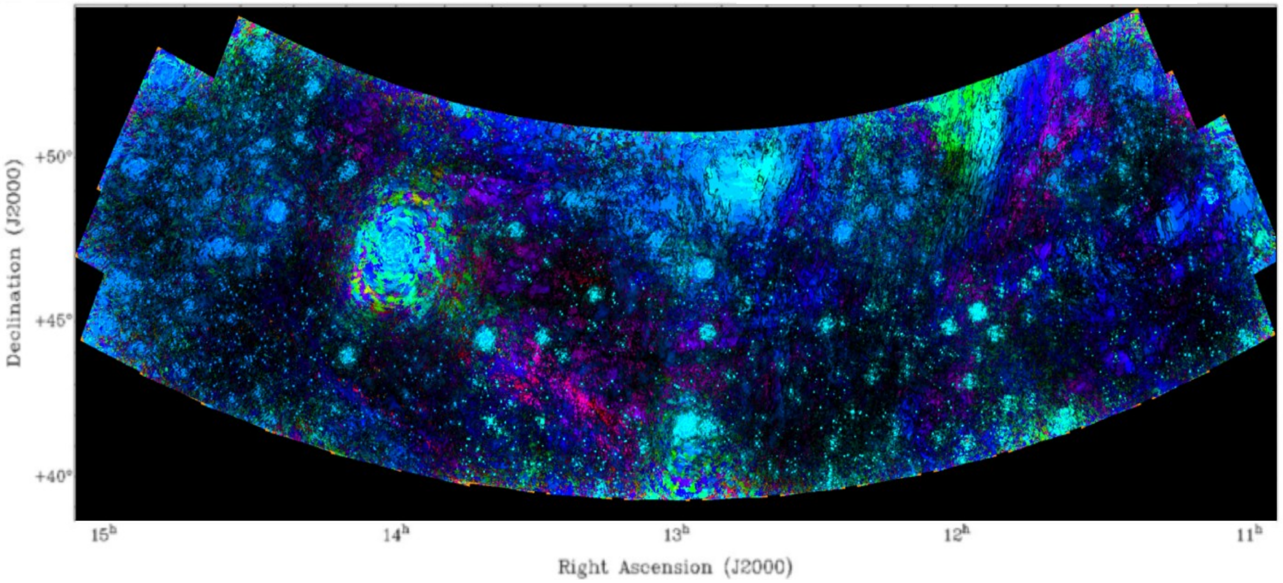
* Scientific exploitation of the data by key project teams. In addition: reprocess all the LoTSS data including international stations (busy week September); also exciting opportunities for polarization science, recombination line studies, transient searches, etc.

* LoTSS first full-quality data release: HETDEX Spring Field, 63 pointings with full, direction-dependent calibration, RMS 100 μJy beam^{-1}, resolution 6 arcsec, > 300,000 sources. Coming soon!

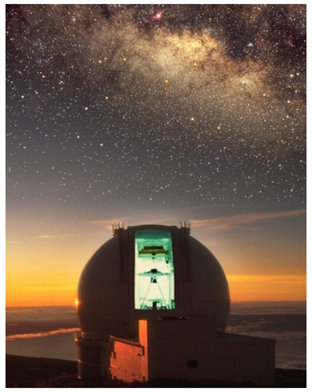
* WEAVE-LOFAR (2018-2019+) – e.g. Smith et al. 2016.

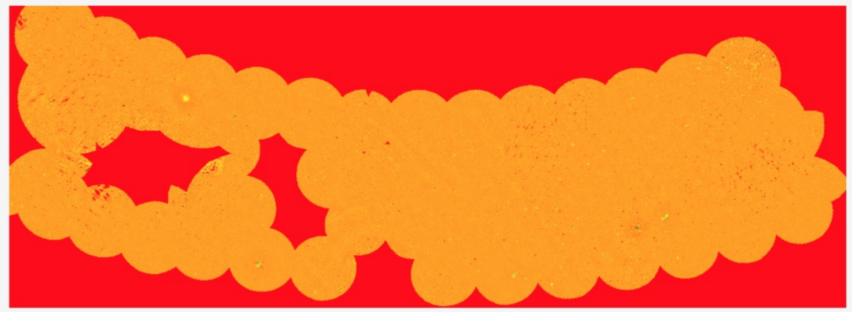


Shimwell et al. in prep.



Van Eck et al. 2017

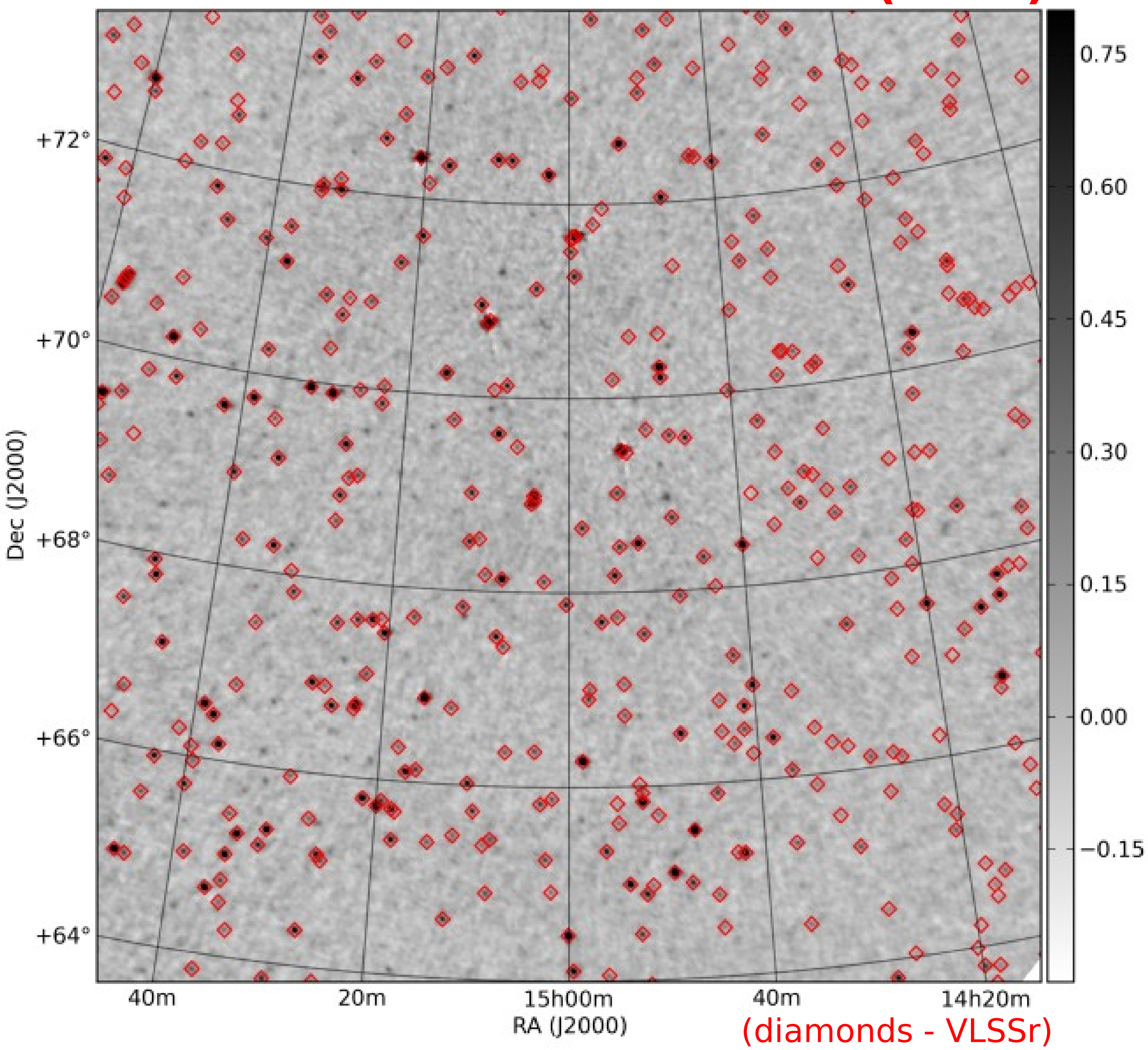




Surveys at very low frequencies

Significant recent improvements!

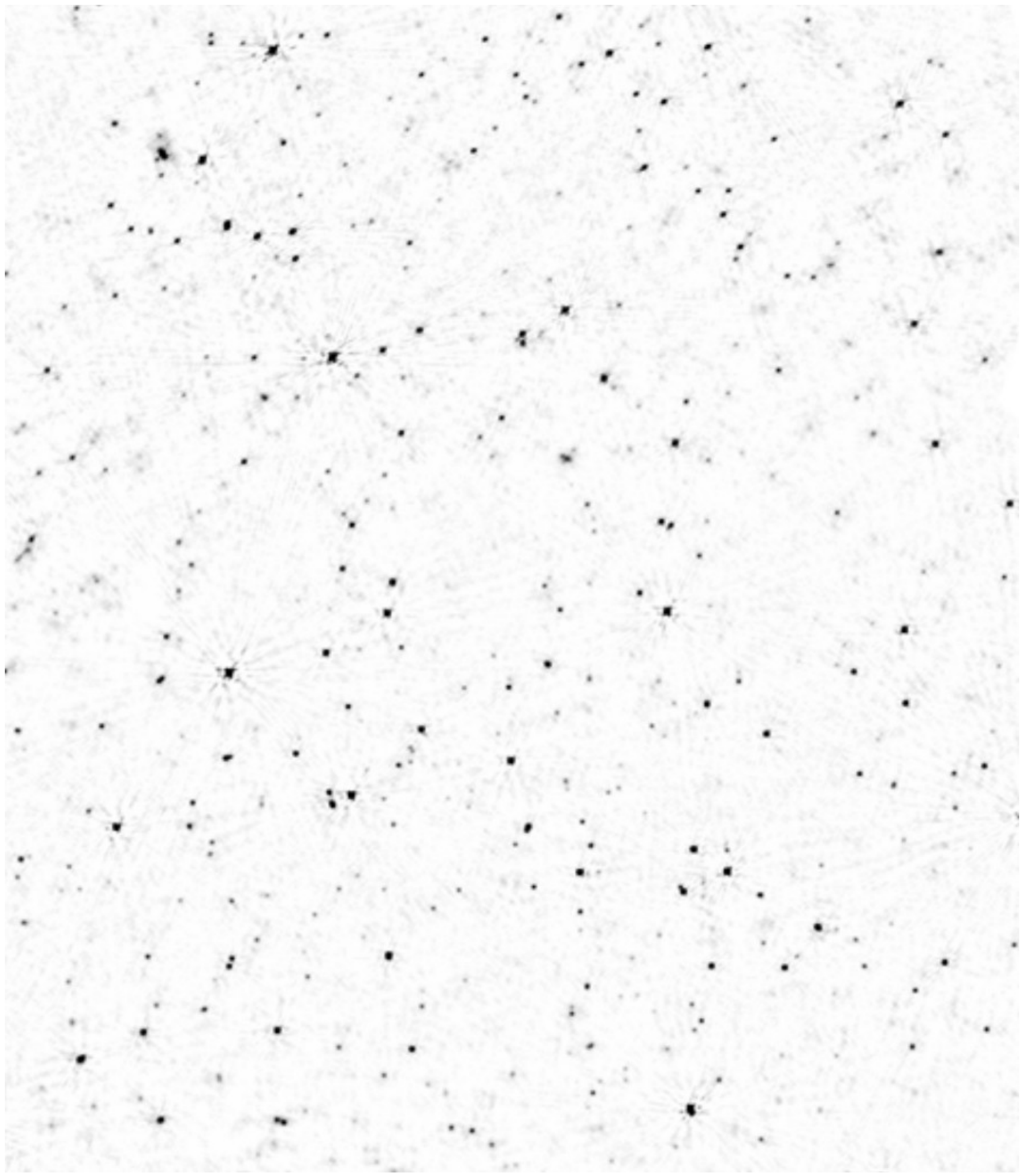
Heald et al. (2015)



(diamonds - VLSSr)

* MSSS-LBA verification field
* Resolution 166 arcsec, RMS 39 mJy beam^{-1}
* Centre frequency 53 MHz (30-75 MHz; 8 × 2 MHz)

2017 – Francesco de Gasperin (Leiden)



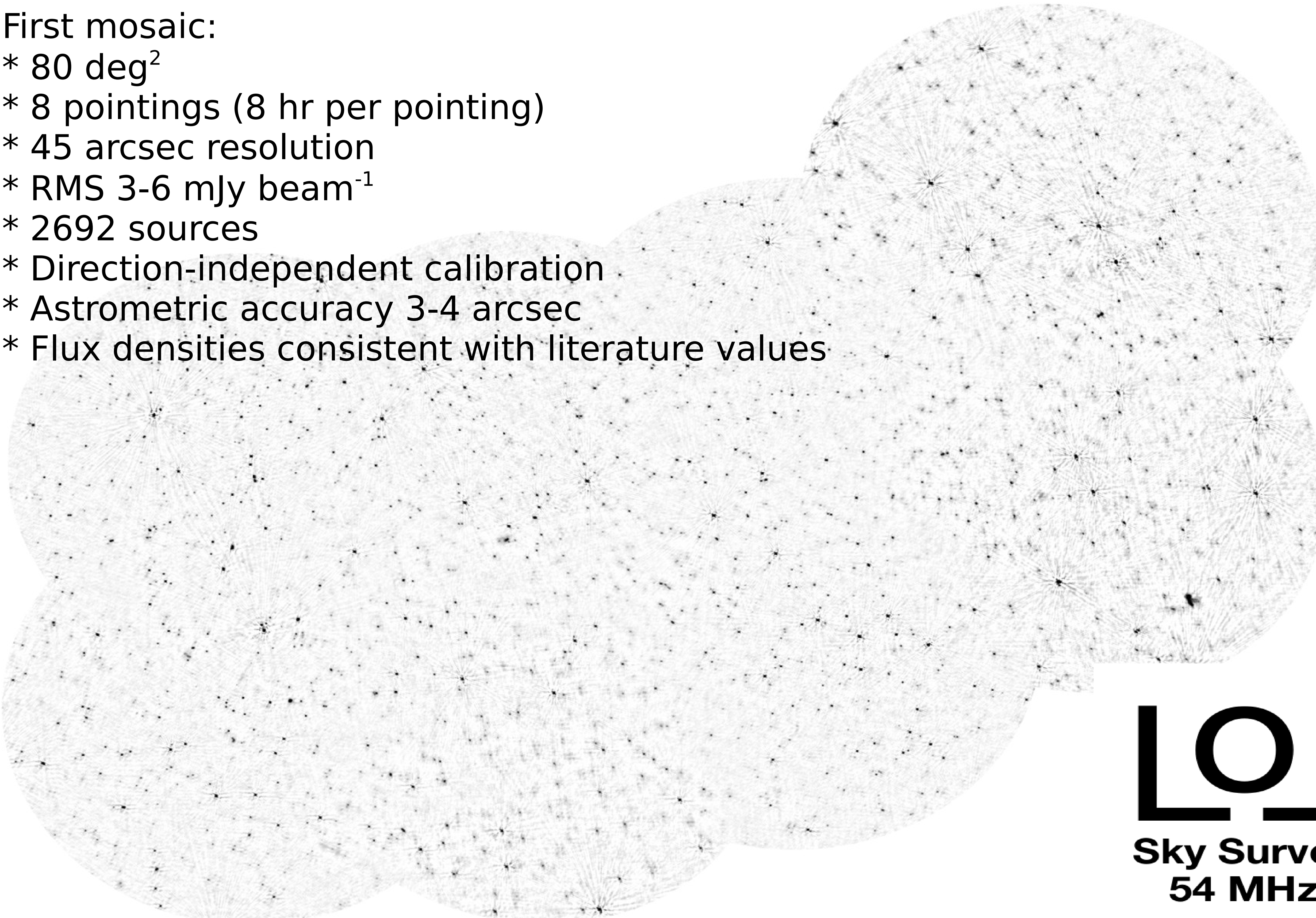
* Part of 'LoLSS' first mosaic
* Resolution 45 arcsec, RMS 5 mJy beam^{-1}
* Centre frequency 54 MHz (42 – 66 MHz)

LoLSS – Tier 1 LBA survey

LOFAR ASTRON

First mosaic:

* 80 deg^2
* 8 pointings (8 hr per pointing)
* 45 arcsec resolution
* RMS 3-6 mJy beam^{-1}
* 2692 sources
* Direction-independent calibration
* Astrometric accuracy 3-4 arcsec
* Flux densities consistent with literature values



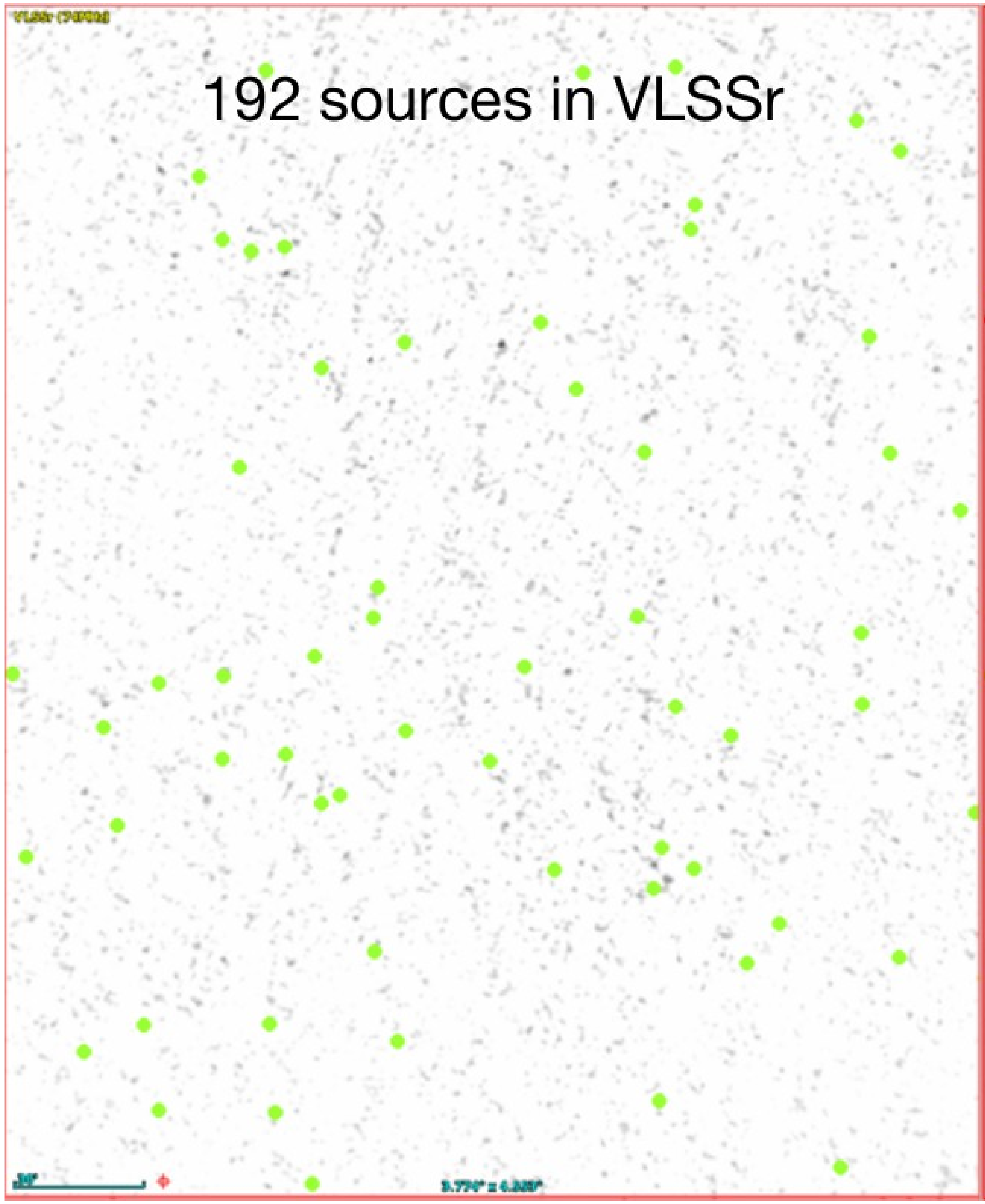
Sky Survey
54 MHz

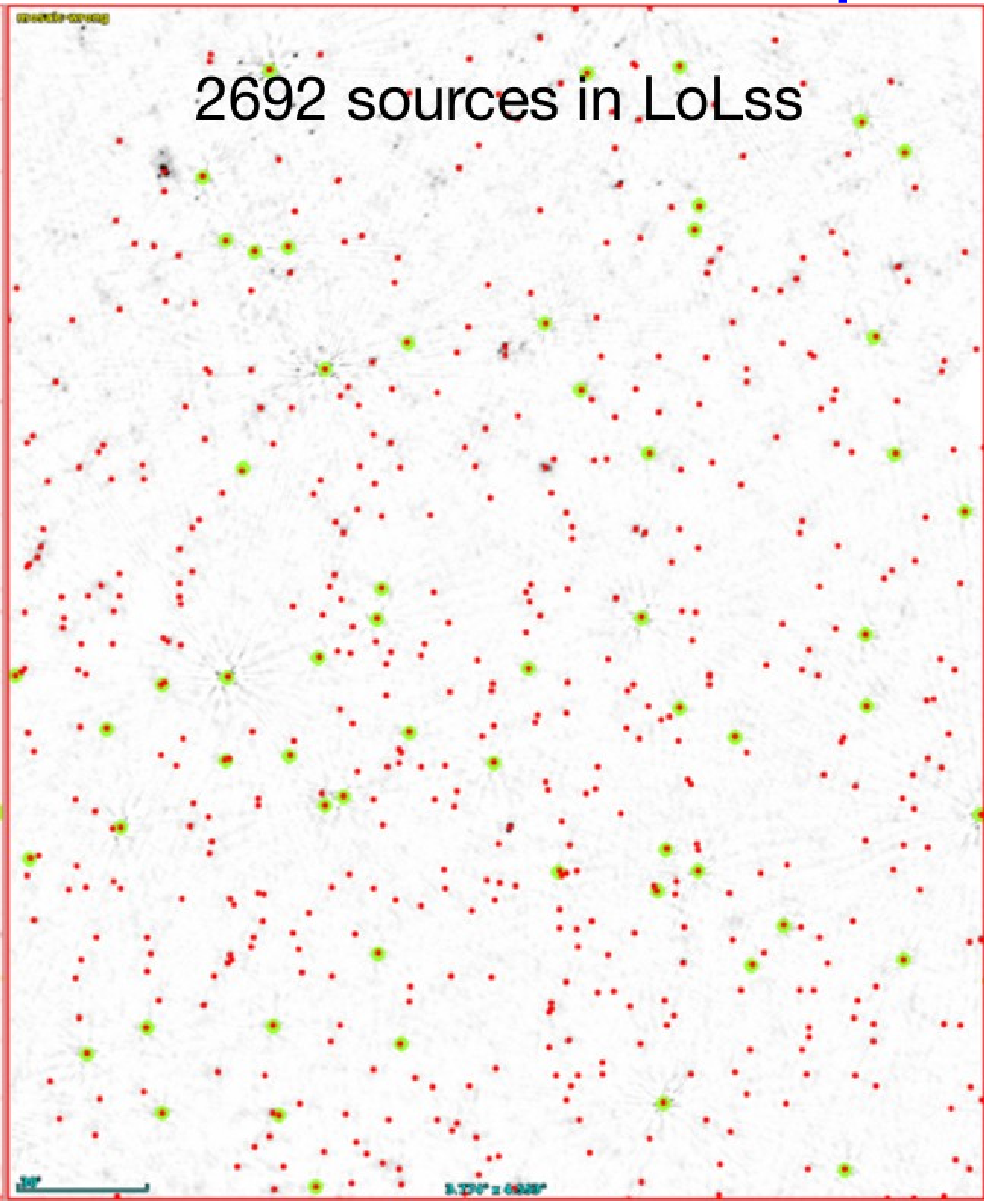
de Gasperin et al.

Synergies with 45-arcsec MSSS-HBA

LoLSS – Tier 1 LBA survey

de Gasperin





74 MHz

Resolution 75 arcsec

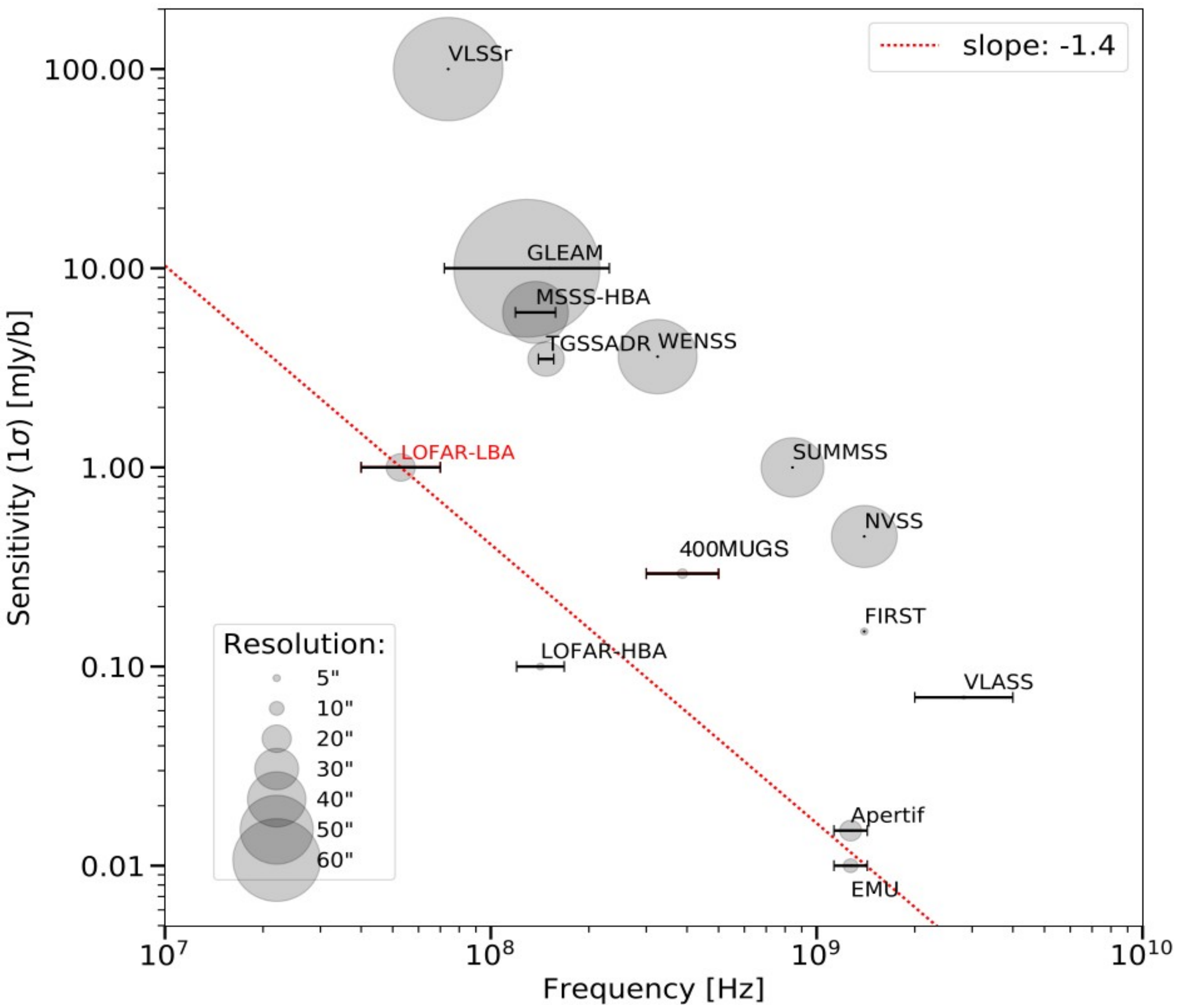
RMS 100 mJy beam^{-1}

54 MHz

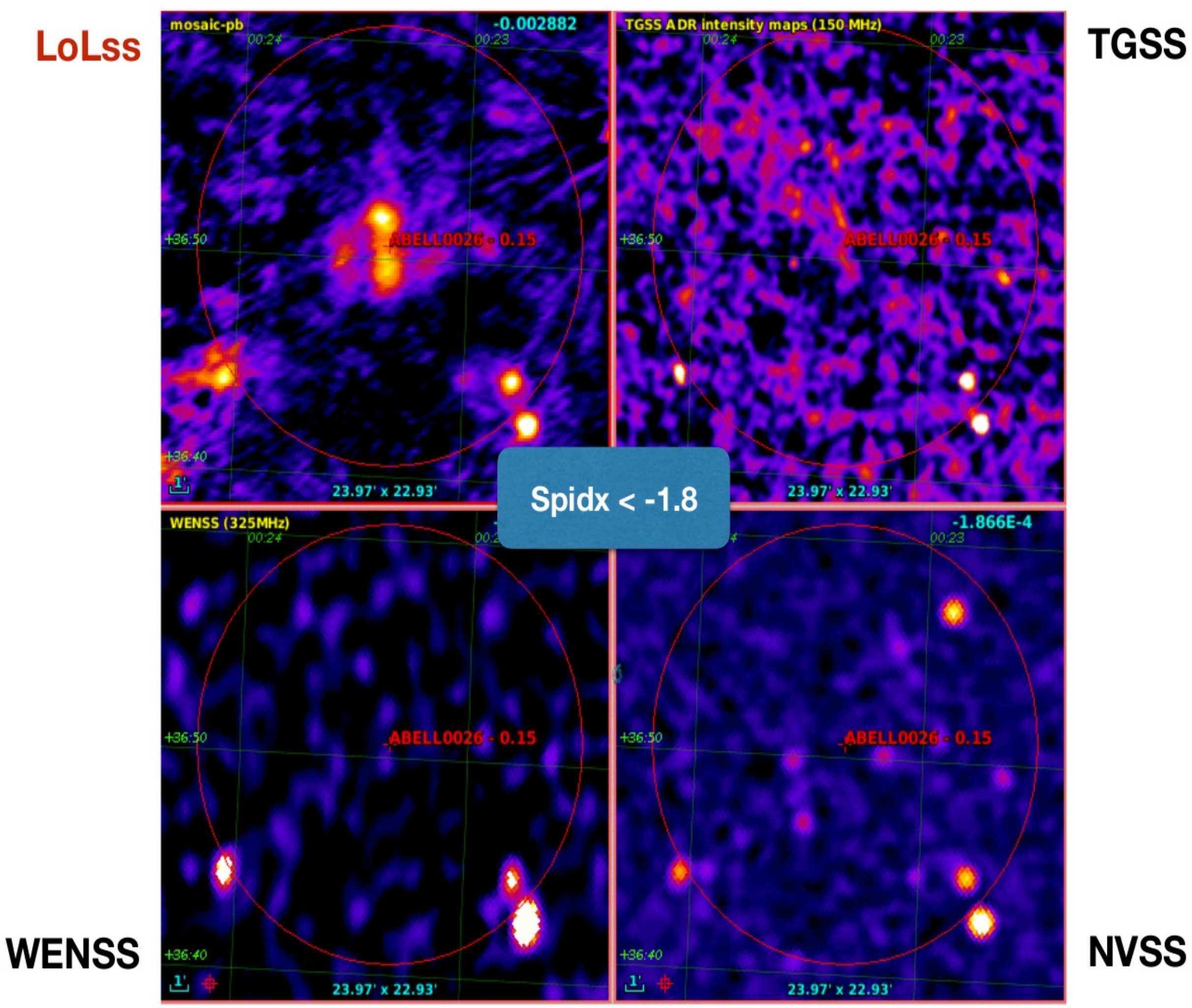
Resolution 45 arcsec

RMS 5 mJy beam^{-1}

New spectral window, new sources…



de Gasperin

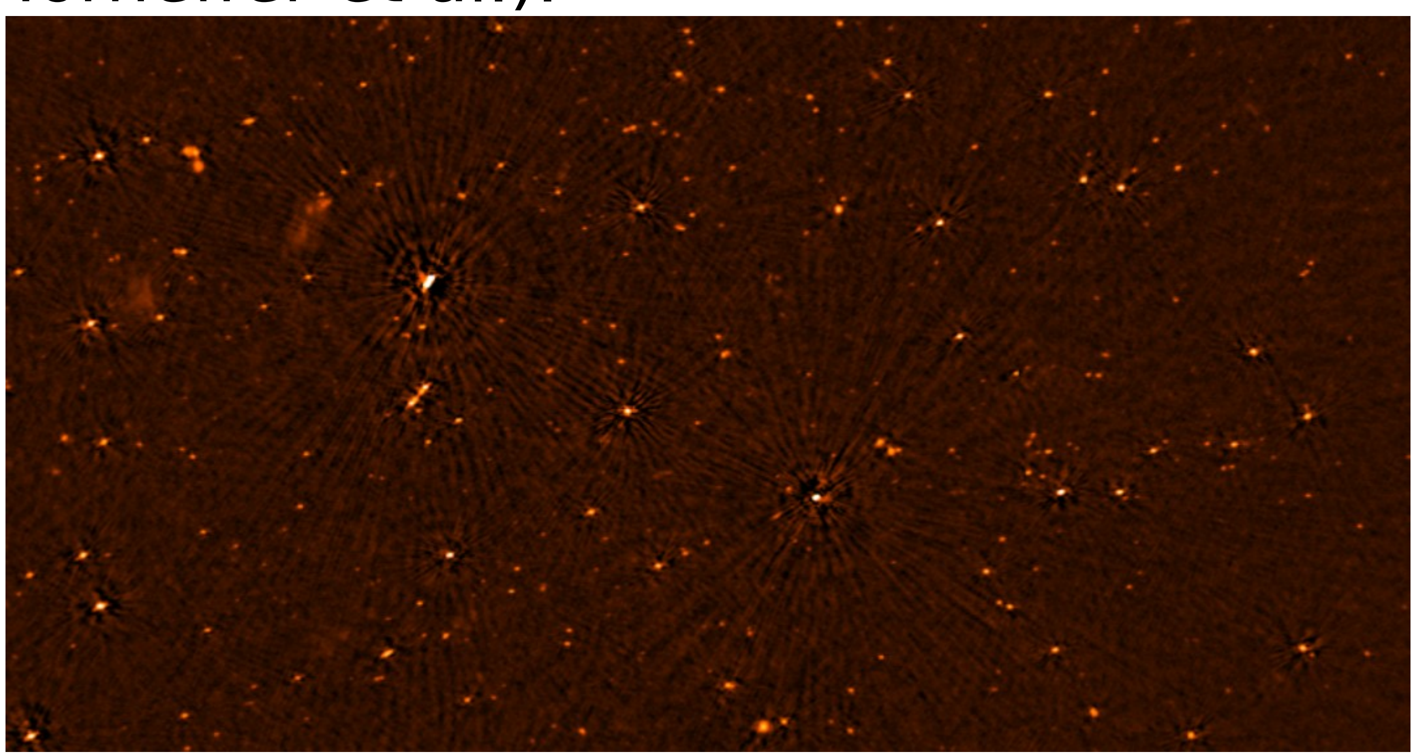


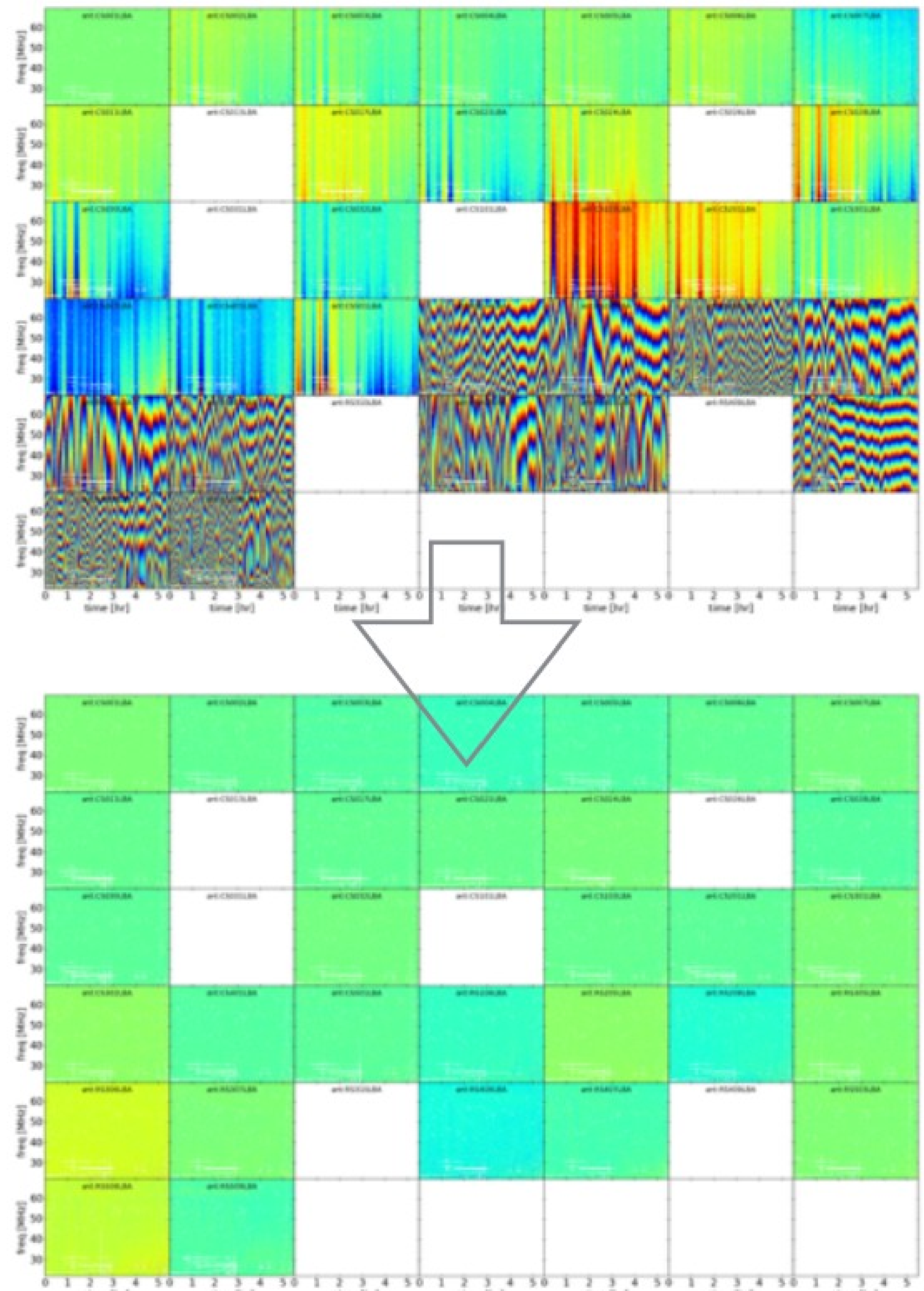
* Target resolution – 15 arcsec
* Target RMS – 1 mJy beam^{-1}
* Northern sky; 42-66 MHz frequency coverage
* Total survey time ~8000 hr (3 simultaneous beams + calibrator)

LoSS - next steps

* Further observations; likely implementation of lucky imaging.

* Further refinements to calibration strategy. Already significant work in this area; LOFAR solution tools (LoSoTo) and 'PiLL' pipeline (de Gasperin, Drabent, Horneffer et al.).





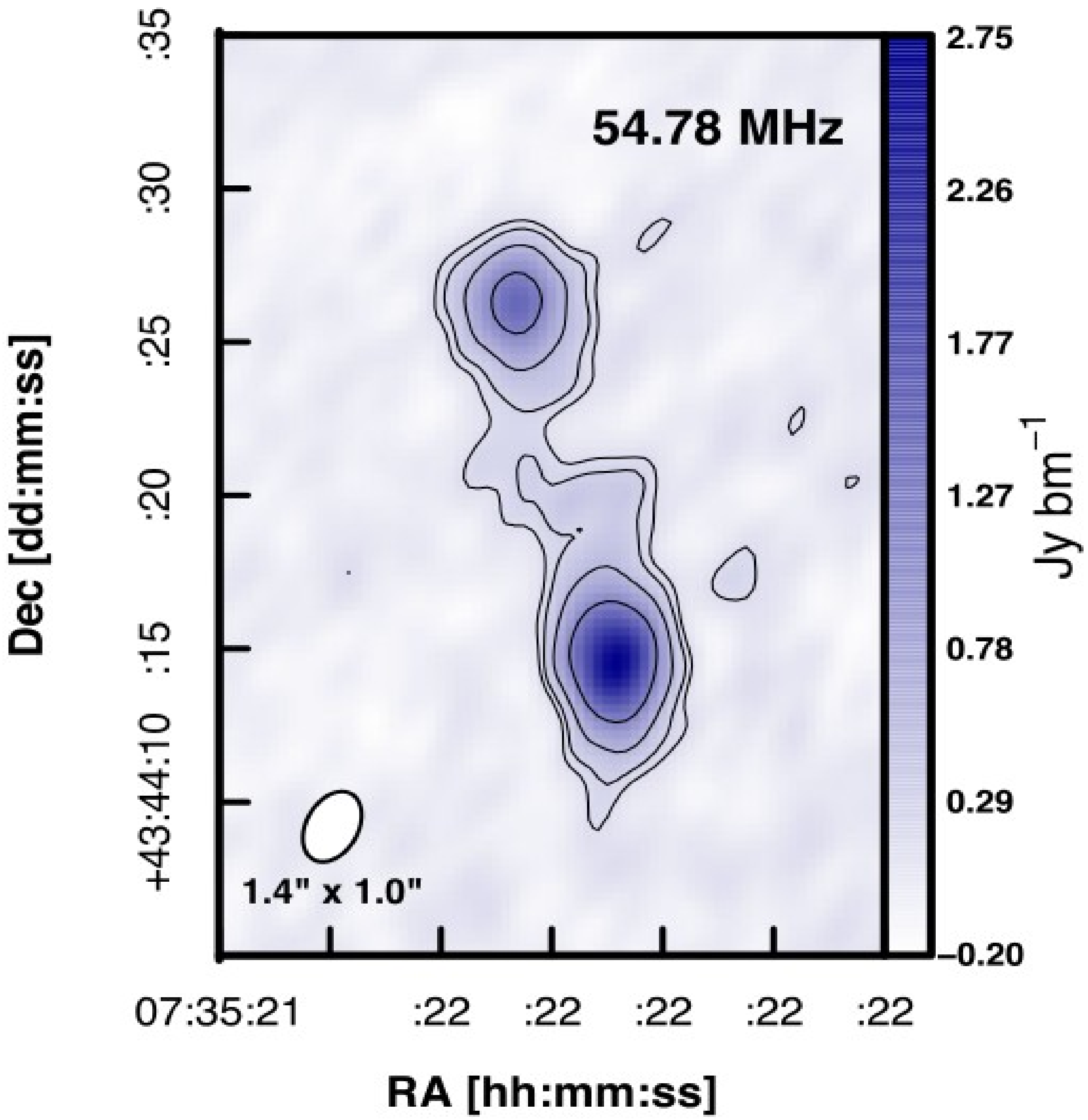
Example LoSoTo plots before/after solving for clock offsets and ionospheric effects.

* Direction-dependent calibration (de Gasperin, Offringa, Dijkema, Mevius). 30 arcsec resolution; RMS 2 mJy beam^{-1}.

LOFAR VLBI at 55 MHz

Technically very challenging but new parameter space to explore!

Morabito et al. 2016



* 4C 43.15; z = 2.4

* RMS 59 mJy beam^{-1}

* Resolution 0.9 arcsec × 0.6 arcsec without smoothing.

The future: LOFAR 2.0

* A staged expansion of the scientific and technical capabilities of LOFAR. Enabling a state-of-the-art and highly-productive telescope from 2020-2030.

* *Lowest frequencies and longest baselines* are LOFAR's unique strengths in the era of the SKA.

* Aspirations ~10 MEuro (+ involvement from international partners).

* Complement and strengthen SKA aspirations. Pathway to SKA2-LOW.

* Funded (NWO-M): COBALT 2.0 'LOFAR Mega Mode' and higher data rate modes (PIs Hessels, Haverkorn, McKean, Röttgering, Rowlinson).

* 2025 roadmap for major Dutch scientific infrastructure – LOFAR 2.0 one of 13 projects selected out of a pool of ~50.

ASTRON 'LEGO' project
(LOFAR Enhanced Generation & Operation)
Project Manager Nico Ebbendorf;
Project Scientist Jason Hessels

The future: LOFAR 2.0

LOFAR ASTRON

* Four possible key enhancements identified:

1. Double or triple station electronics (e.g. use all 96 LBAs per station, HBA+LBA observing).

2. Replace LBA dipoles with new design (e.g. better sensitivity at 30-50 MHz).

3. Build ~6 new Dutch stations (and where are they best placed in terms of improving *u*,*v* coverage?).

4. Build ~6 new international stations (augment 200-1000 km baselines).

* **Big leap forward for survey speed / depth!**

* NWO-Groot proposal; deadline October. Build technical case as part of LEGO; scientific case in consultation with LOFAR community.

Final remarks

* Very bright future for LOFAR continuum survey science! A precursor that is certainly wide awake and roaring!

* MSSS-HBA: a low-frequency counterpart to NVSS. Public release before the end of 2017.

* LoTSS: deep, high-resolution imaging. First results in the literature, with much exciting science still to be done.

* First deep, 80 deg^2 mosaic from LoLSS.

* LOFAR 2.0: working towards a more versatile telescope that will continue to do unique, high-quality survey science.