Low frequency imaging surveys in total intensity and polarization

George Heald
CSIRO Science Leader
SALF-IV, 14 December 2017

Background image: LoTSS (Shimwell et al, in prep)

Topics

- LOFAR Multifrequency Snapshot Sky Survey (MSSS)
  - Progress toward 45" HBA data release
  - Polarimetry -- the MAPS project
- Galactic and Extragalactic All-sky MWA (GLEAM) Survey
  - New developments
  - (POGS: go have a chat with Chris Riseley!)
- LOFAR Two-metre Sky Survey (LoTSS)
  - What to expect in 2018 -- the HETDEX region
  - Polarimetry with LoTSS

LOFAR MSSS

MSSS: LOFAR's first imaging survey

MSSS-LBA

Frequency: 30-75 MHz (8 x 2 MHz)
Resolution: ≤100 arcsec
Sensitivity: ≤15 mJy/beam
Area: 20,000 square degrees
Number of Fields: 660
Simultaneous ~10° beams: 5
Test observations continue

MSSS-HBA

Frequency: 120-160 MHz (8 x 2 MHz)
Resolution: ≤120 arcsec
Sensitivity: ≤5 mJy/beam
Area: 20,000 square degrees
Number of Fields: 3616
Simultaneous ~4° beams: 6
All-sky public catalog in prep

MSSS: LOFAR's first imaging survey

MSSS-LBA

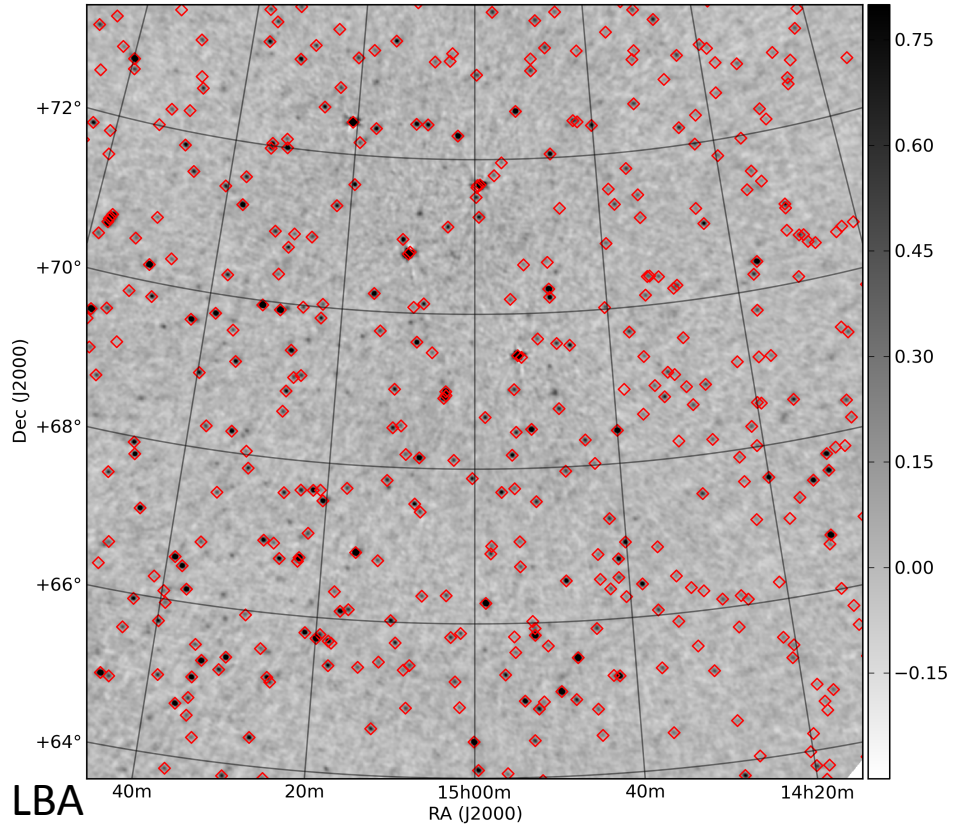
Frequency: 30-75 MHz (8 x 2 MHz)
Resolution: ≤100 arcsec
Sensitivity: ≤15 mJy/beam
Area: 20,000 square degrees
Number of Fields: 660
Simultaneous ~10° beams: 5
Test observations continue

MSSS-HBA

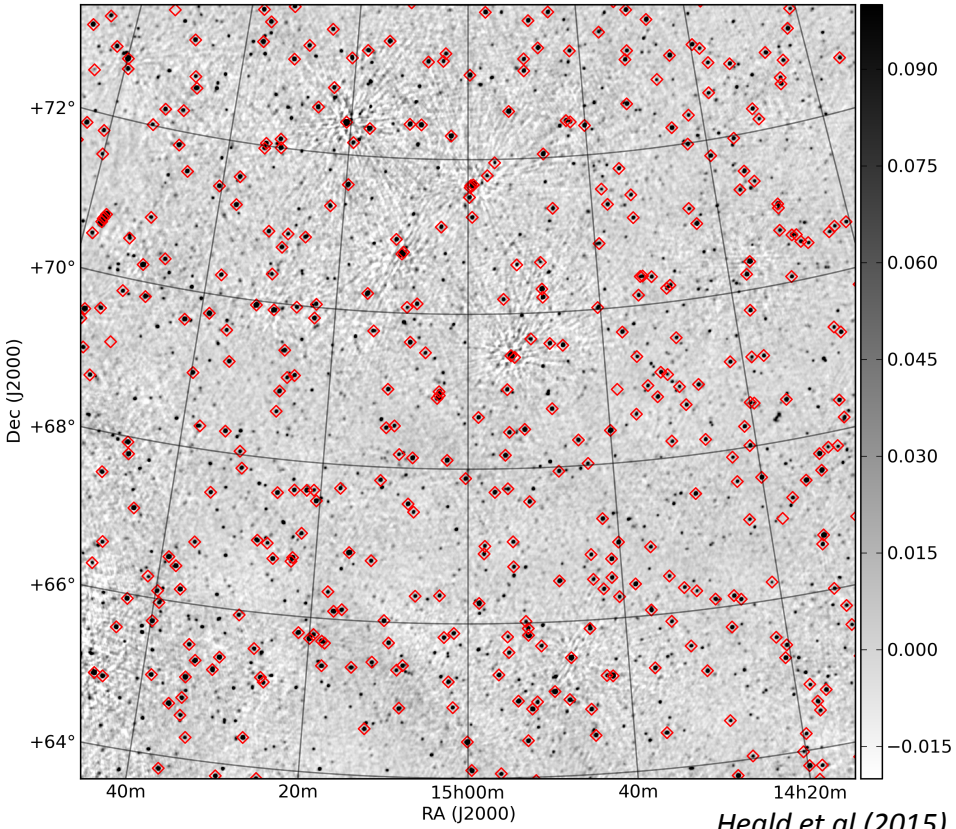
Frequency: 120-160 MHz (8 x 2 MHz)
Resolution: ~~≤120 arcsec~~ **45 arcsec**
Sensitivity: ≤5 mJy/beam
Area: 20,000 square degrees
Number of Fields: 3616
Simultaneous ~4° beams: 6
All-sky public catalog in prep

MSSS Verification Field

HBA mosaic



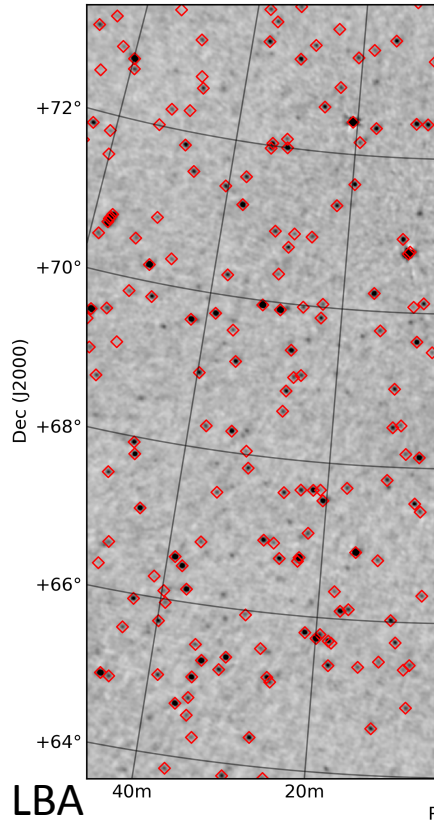
LBA



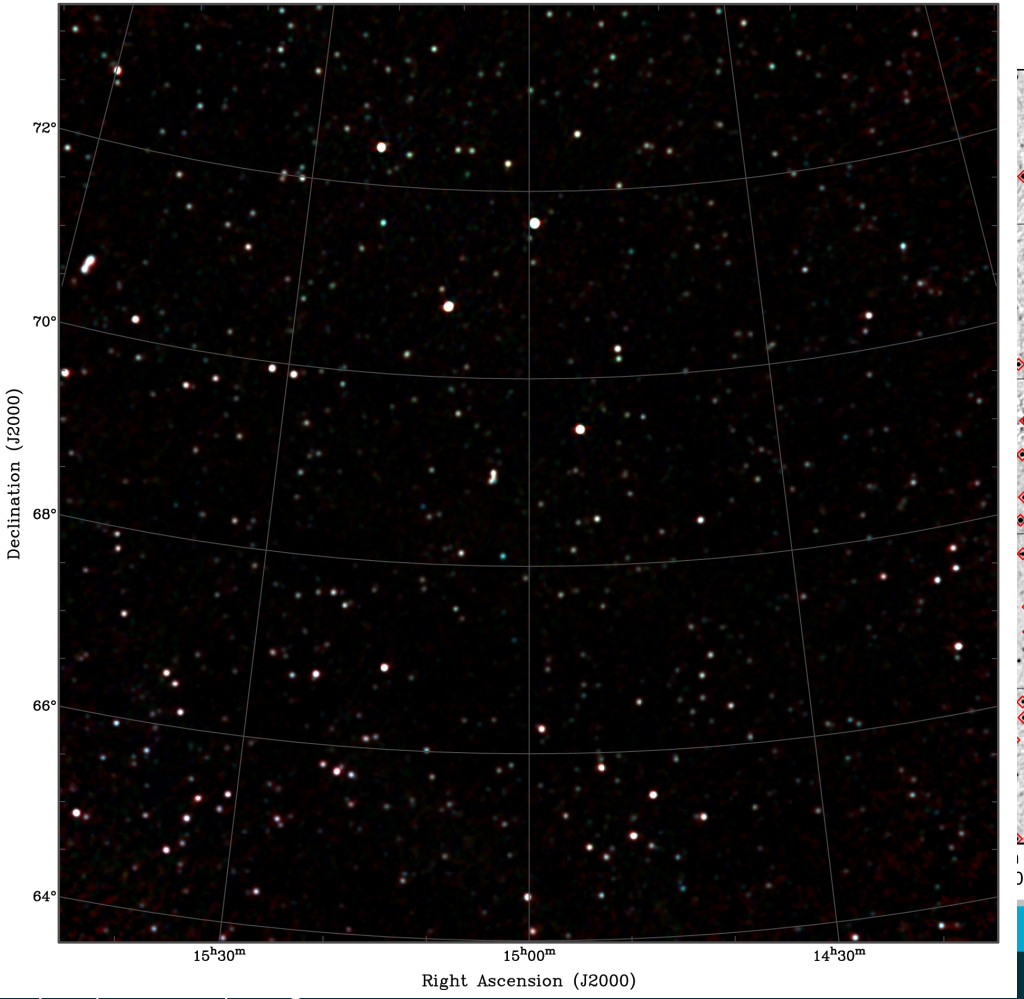
Heald et al (2015)

Ionospheric correction applied

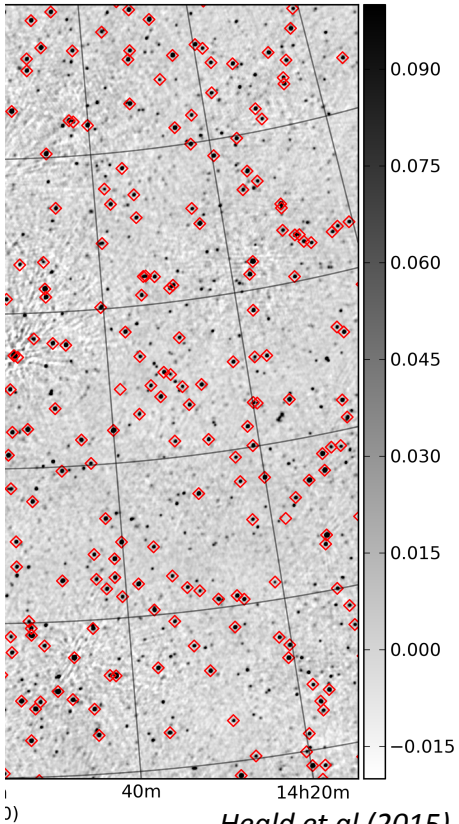
MSSS Verifi



LBA



HBA mosaic



Heald et al (2015)

Ionospheric correctio

MSSS Verification Field (MVF)

- Survey overview published in A&A (2015, A&A 582, 123)
- Key facts & figures:
- Verification field of 100 square degrees, ~1200 sources
- HBA completeness 100 mJy
- LBA completeness 550 mJy
- ~2’ resolution
- ~200,000 sources in full catalog

A&A 582, A123 (2015)
DOI: 10.1051/0004-6361/201425210

Astronomy & Astrophysics

The LOFAR Multifrequency Snapshot Sky Survey (MSSS)

I. Survey description and first results

G. H. Heald[1,2], R. F. Pizzo[1], E. Orrú[1], R. P. Breton[3], D. Carbone[4], C. Ferrari[5], M. J. Hardcastle[6], W. Jurusik[7], G. Macario[5], D. Mulcahy[8,3], D. Rafferty[9], A. Asgekar[1,*], M. Brentjens[1], R. A. Fallows[1], W. Frieswijk[1], M. C. Toribio[1], B. Adebahr[8], M. Arts[1], M. R. Bell[10], A. Bonafede[9], J. Bray[3], J. Broderick[3,11], T. Cantwell[3], P. Carroll[12], Y. Cendes[4], A. O. Clarke[3], J. Croston[3], S. Daiboo[13], F. de Gasperin[9], J. Gregson[14], J. Harwood[1,6], T. Hassall[3], V. Heesen[3], A. Horneffer[8], A. J. van der Horst[4], M. Iacobelli[15,1], V. Jelić[2,1], D. Jones[16], D. Kant[1], G. Kokotanekov[4], P. Martin[3], J. P. McKean[1,2], L. K. Morabito[15], B. Nikiel-Wroczyński[7], A. Offringa[1], V. N. Pandey[1], M. Pandey-Pommier[17], M. Pietka[3,11], L. Pratley[18], C. Riseley[3], A. Rowlinson[19], J. Sabater[20], A. M. M. Scaife[3], L. H. A. Scheers[21], K. Sendlinger[22], A. Shulevski[2], M. Sipior[1], C. Sobey[8,1], A. J. Stewart[11,3], A. Stroe[15], J. Swinbank[4], C. Tasse[23,24,25], J. Trüstedt[26,27], E. Varenius[28], S. van Velzen[29], N. Vilchez[1], R. J. van Weeren[30], S. Wijnholds[1], W. L. Williams[15,1], A. G. de Bruyn[1,2], R. Nijboer[1], M. Wise[1], A. Alexov[31], J. Anderson[32], I. M. Avruch[33,2], R. Beck[8], M. E. Bell[19], I. van Bemmel[1,34], M. J. Bentum[1,35], G. Bernardi[30], P. Best[20], F. Breitling[36], W. N. Brouw[1,2], M. Brüggen[9], H. R. Butcher[37], B. Ciardi[10], J. E. Conway[28], E. de Geus[1,38], A. de Jong[1], M. de Vos[1], A. Deller[1], R.-J. Dettmar[22], S. Duscha[1], J. Eislöffel[39], D. Engels[40], H. Falcke[16,1], R. Fender[11], M. A. Garrett[1,15], J. Grießmeier[41,42], A. W. Gunst[1], J. P. Hamaker[1], J. W. T. Hessels[1,4], M. Hoeft[39], J. Hörandel[16], H. A. Holties[1], H. Intema[15,43], N. J. Jackson[44], E. Jütte[22], A. Karastergiou[11], W. F. A. Klijn[1], V. I. Kondratiev[1,45], L. V. E. Koopmans[2], M. Kuniyoshi[46,8], G. Kuper[1], C. Law[47], J. van Leeuwen[1,4], M. Loose[1], P. Maat[1], S. Markoff[4], R. McFadden[1], D. McKay-Bukowski[48,49], M. Mevius[1,2], J. C. A. Miller-Jones[50,4], R. Morganti[1,2], H. Munk[1], A. Nelles[16], J. E. Noordam[1], M. J. Norden[1], H. Paas[51], A. G. Polatidis[1], W. Reich[8], A. Renting[1], H. Röttgering[15], A. Schoenmakers[1], D. Schwarz[52], J. Sluman[1], O. Smirnov[25,24], B. W. Stappers[44], M. Steinmetz[36], M. Tagger[41], Y. Tang[1], S. ter Veen[16], S. Thoudam[16], R. Vermeulen[1], C. Vocks[36], C. Vogt[1], R. A. M. J. Wijers[4], O. Wucknitz[8], S. Yatawatta[1], and P. Zarka[13]

(Affiliations can be found after the references)

Received 24 October 2014 / Accepted 20 July 2015

ABSTRACT

We present the Multifrequency Snapshot Sky Survey (MSSS), the first northern-sky Low Frequency Array (LOFAR) imaging survey. In this introductory paper, we first describe in detail the motivation and design of the survey. Compared to previous radio surveys, MSSS is exceptional due to its intrinsic multifrequency nature providing information about the spectral properties of the detected sources over more than two octaves (from 30 to 160 MHz). The broadband frequency coverage, together with the fast survey speed generated by LOFAR’s multibeaming capabilities,

MSSS Verification Field (MVF)

- Survey overview published in A&A (2015, A&A 582, 123)
- Key facts & figures:
- Verification field of 100 square degrees, ~1200 sources
- HBA completeness 100 mJy
- LBA completeness 550 mJy
- ~2’ resolution
- ~200,000 sources in full catalog

A&A 582, A123 (2015)
DOI: 10.1051/0004-6361/201425210

Astronomy & Astrophysics

The LOFAR Multifrequency Snapshot Sky Survey (MSSS)

I. Survey description and first results

G. H. Heald[1,2], R. F. Pizzo[1], E. Orrú[1], R. P. Breton[3], D. Carbone[4], C. Ferrari[5], M. J. Hardcastle[6], W. Jurusik[7],

R. Vermeulen[1], C. Vocks[8], C. Vogt[1], R. A. M. J. Wijers[9], O. Wucknitz[3], S. Yatawatta[1], and P. Zarka[10]

(Affiliations can be found after the references)

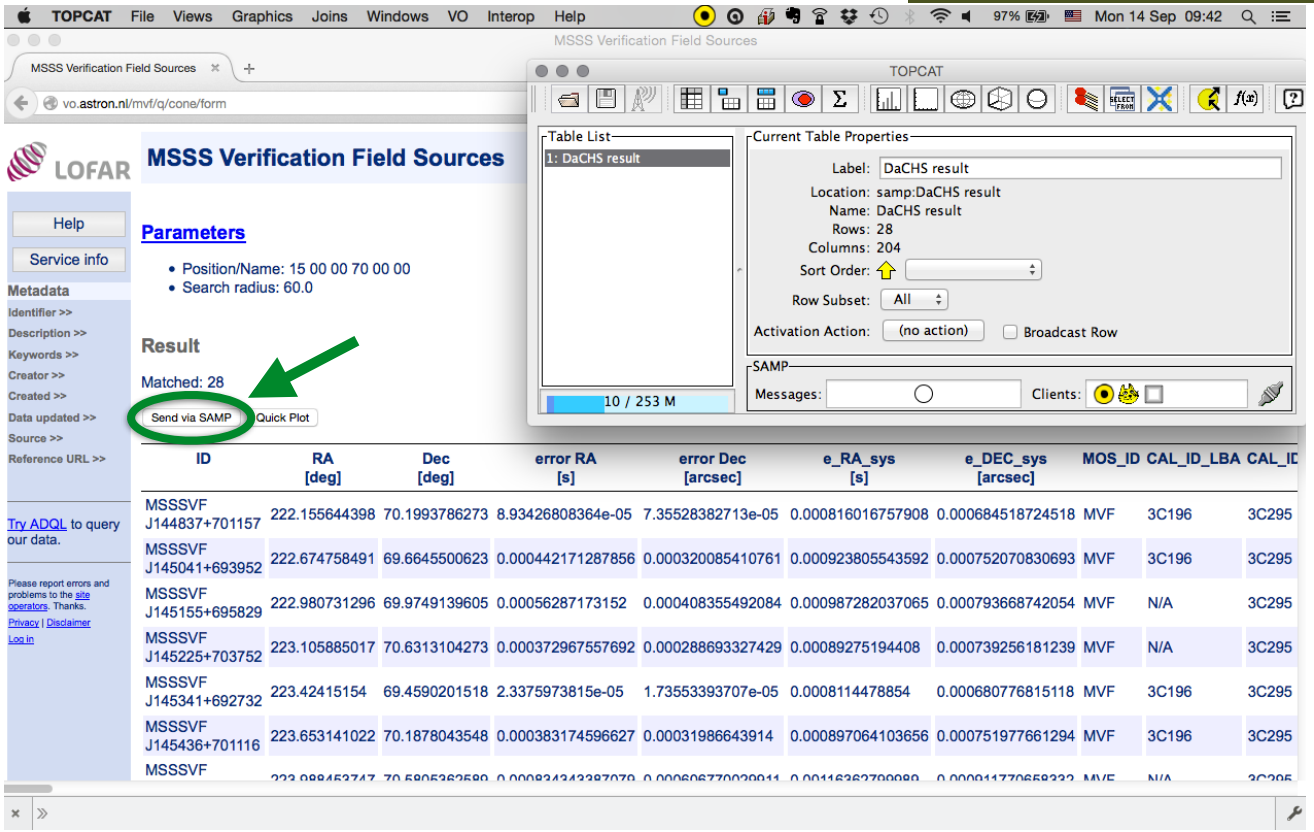
Received 24 October 2014 / Accepted 20 July 2015

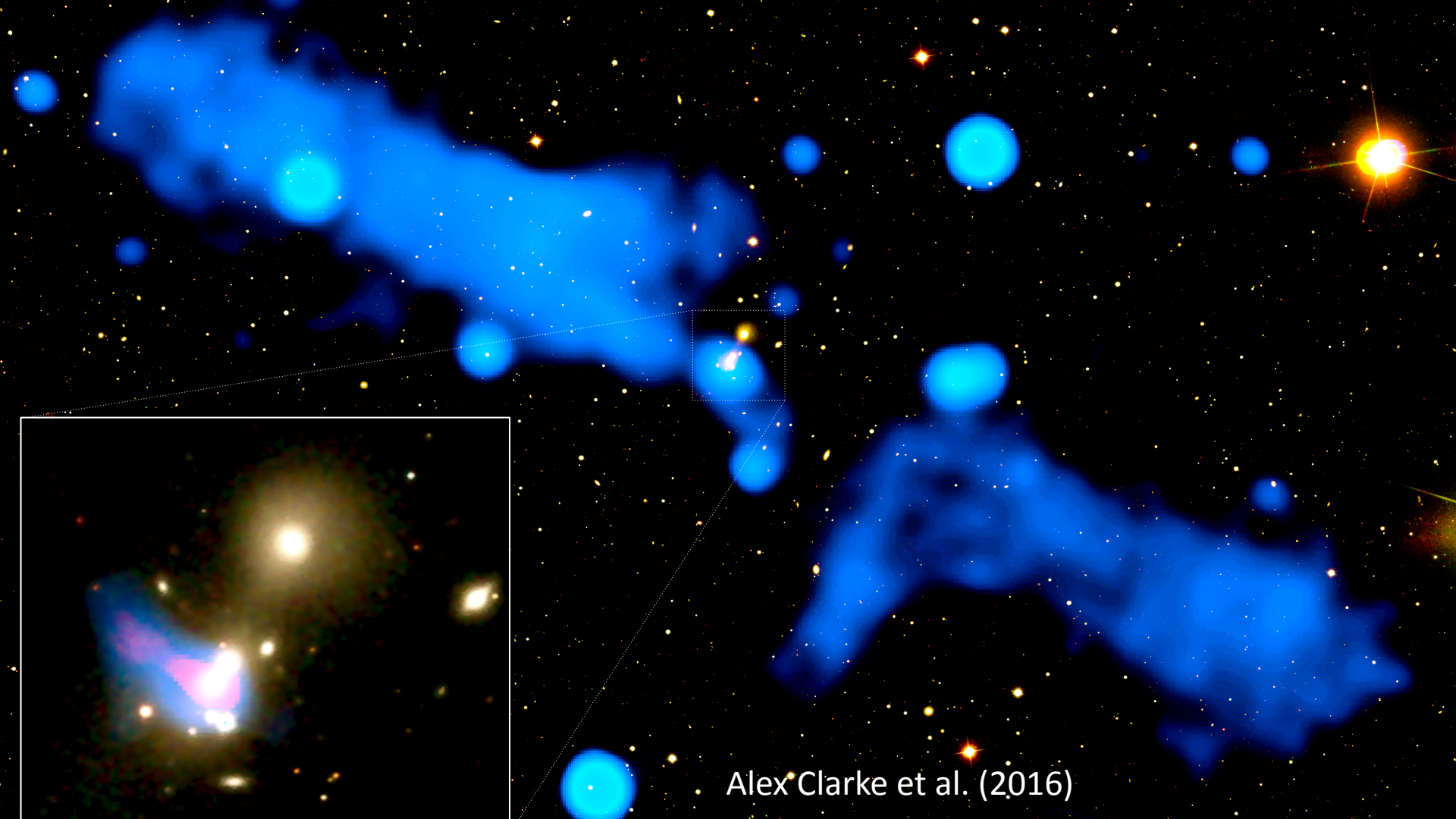
ABSTRACT

We present the Multifrequency Snapshot Sky Survey (MSSS), the first northern-sky Low Frequency Array (LOFAR) imaging survey. In this introductory paper, we first describe in detail the motivation and design of the survey. Compared to previous radio surveys, MSSS is exceptional due to its intrinsic multifrequency nature providing information about the spectral properties of the detected sources over more than two octaves (from 30 to 160 MHz). The broadband frequency coverage, together with the fast survey speed generated by LOFAR’s multibeaming capabilities,

MVF Data Release

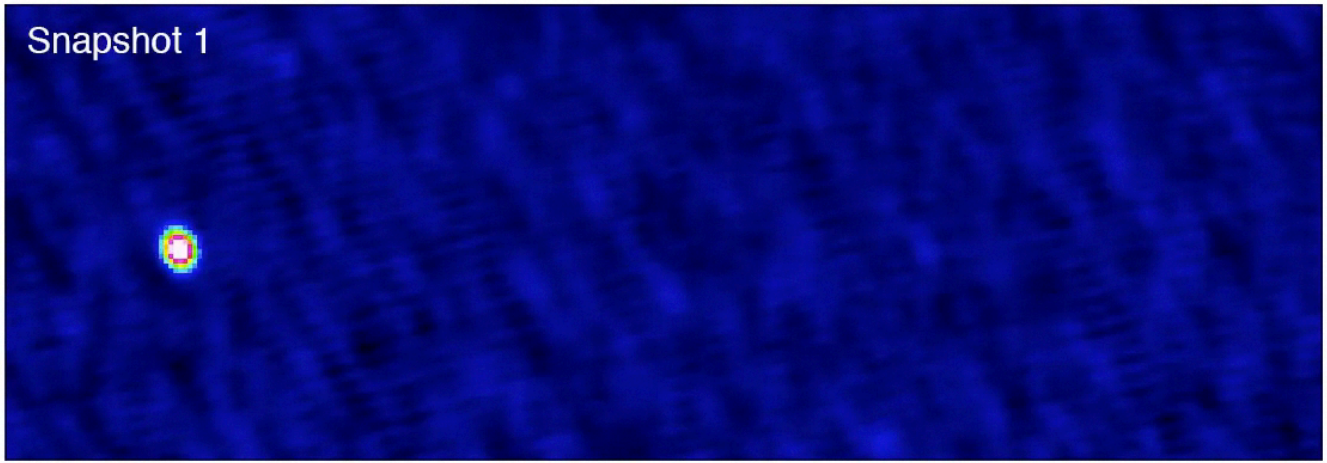
- Hosted at http://vo.astron.nl




Alex Clarke et al. (2016)

MSSS Transients

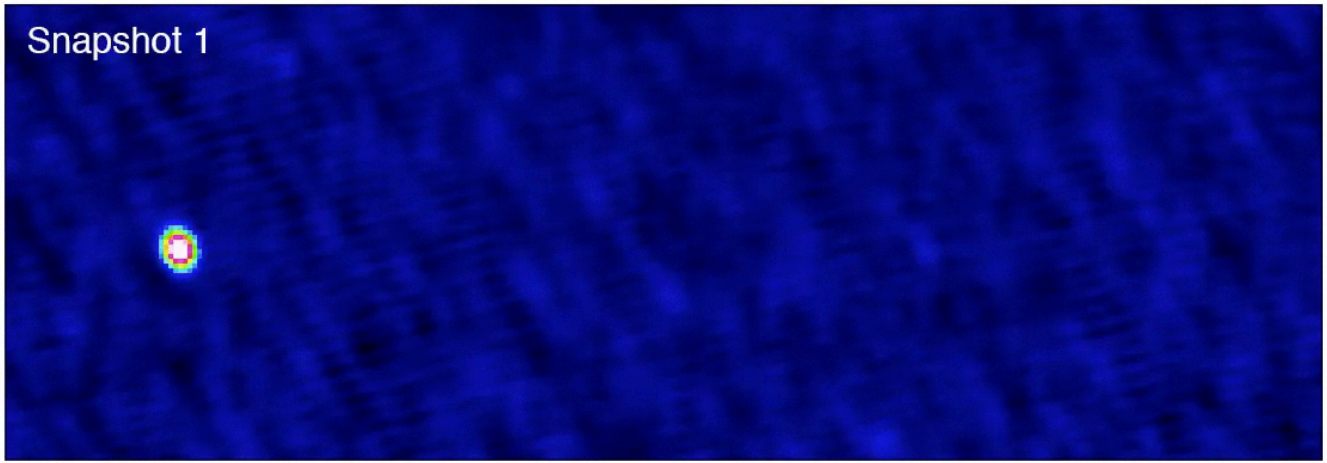
- MSSS-LBA: 1 beam always on NCP (200 kHz BW at 60 MHz); both LBA and HBA are multi-epoch



- First MSSS-LBA transient (Stewart et al 2016, MNRAS 456, 2321)
- Appears in one 11-min snapshot, flux density 15-25 Jy beam^{-1}
- Implied rate for $\Delta t \sim 10$min is 3.9 (+14.7, -3.7) x 10^{-4} day^{-1} deg^{-2}
  (~8 transients of this nature per hemisphere per day!)

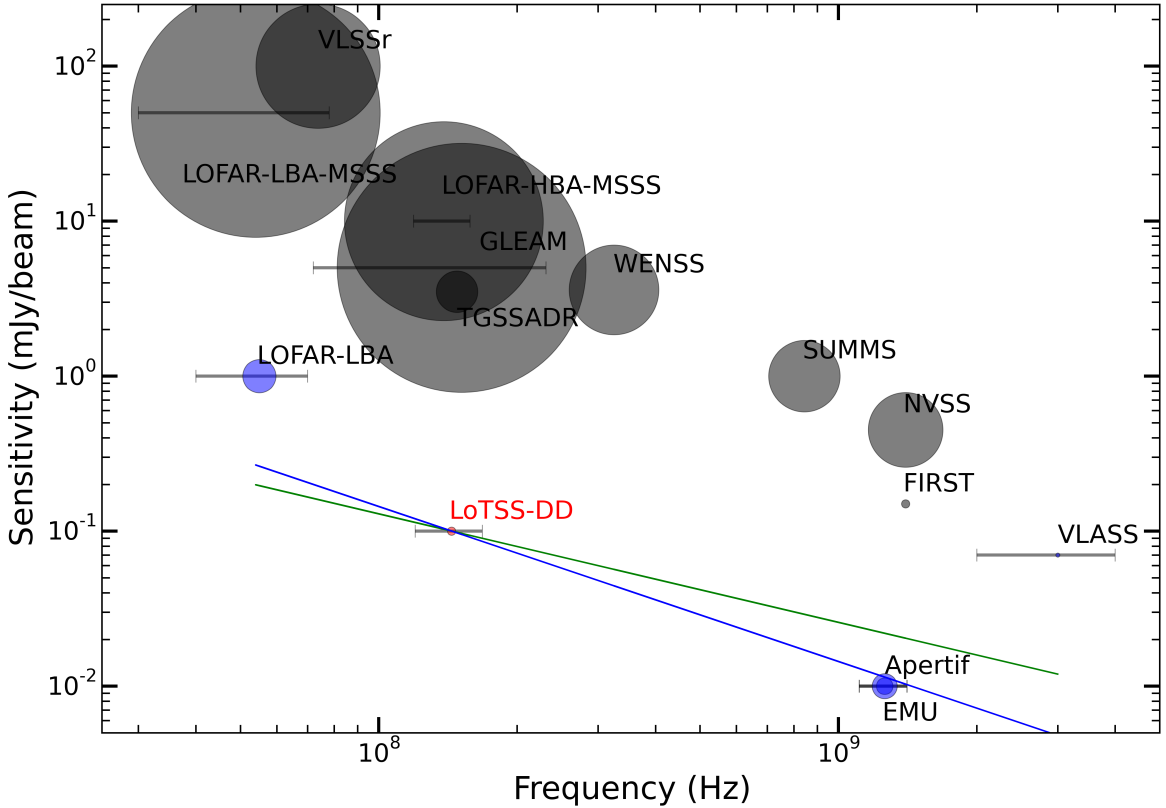
MSSS Transients

- MSSS-LBA: 1 beam always on NCP (200 kHz BW at 60 MHz); both LBA and HBA are multi-epoch



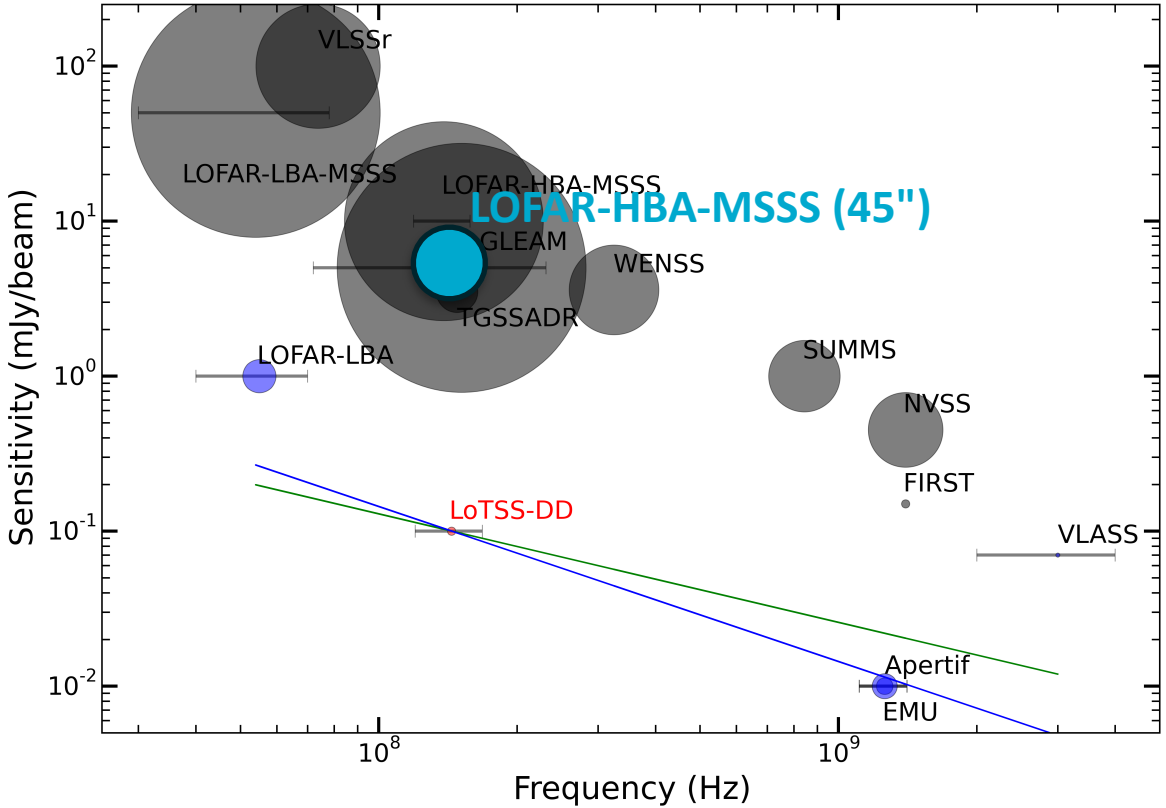
- First MSSS-LBA transient (Stewart et al 2016, MNRAS 456, 2321)
- Appears in one 11-min snapshot, flux density 15-25 Jy beam^{-1}
- Implied rate for $\Delta t \sim 10$min is 3.9 (+14.7, -3.7) x 10^{-4} day^{-1} deg^{-2}
  (~8 transients of this nature per hemisphere per day!)

MSSS-HBA: now at 45" resolution



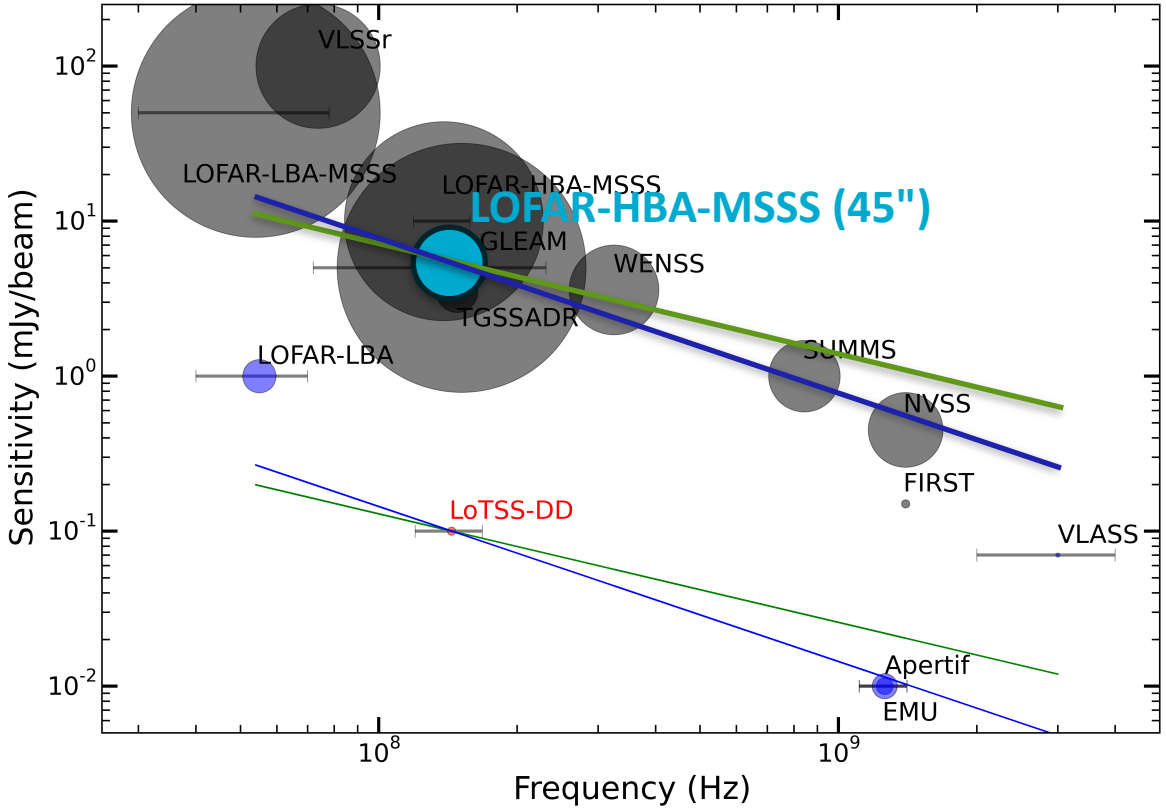
Shimwell et al (2016)

MSSS-HBA: now at 45" resolution



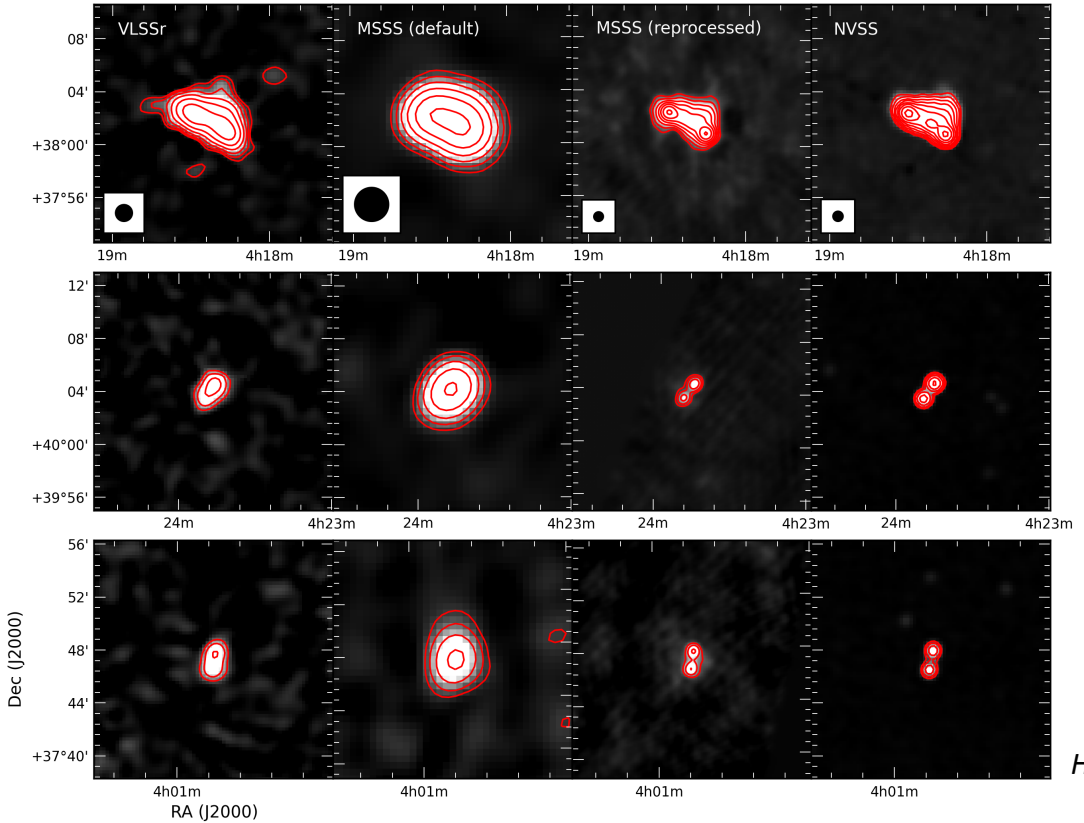
Shimwell et al (2016)

MSSS-HBA: now at 45" resolution



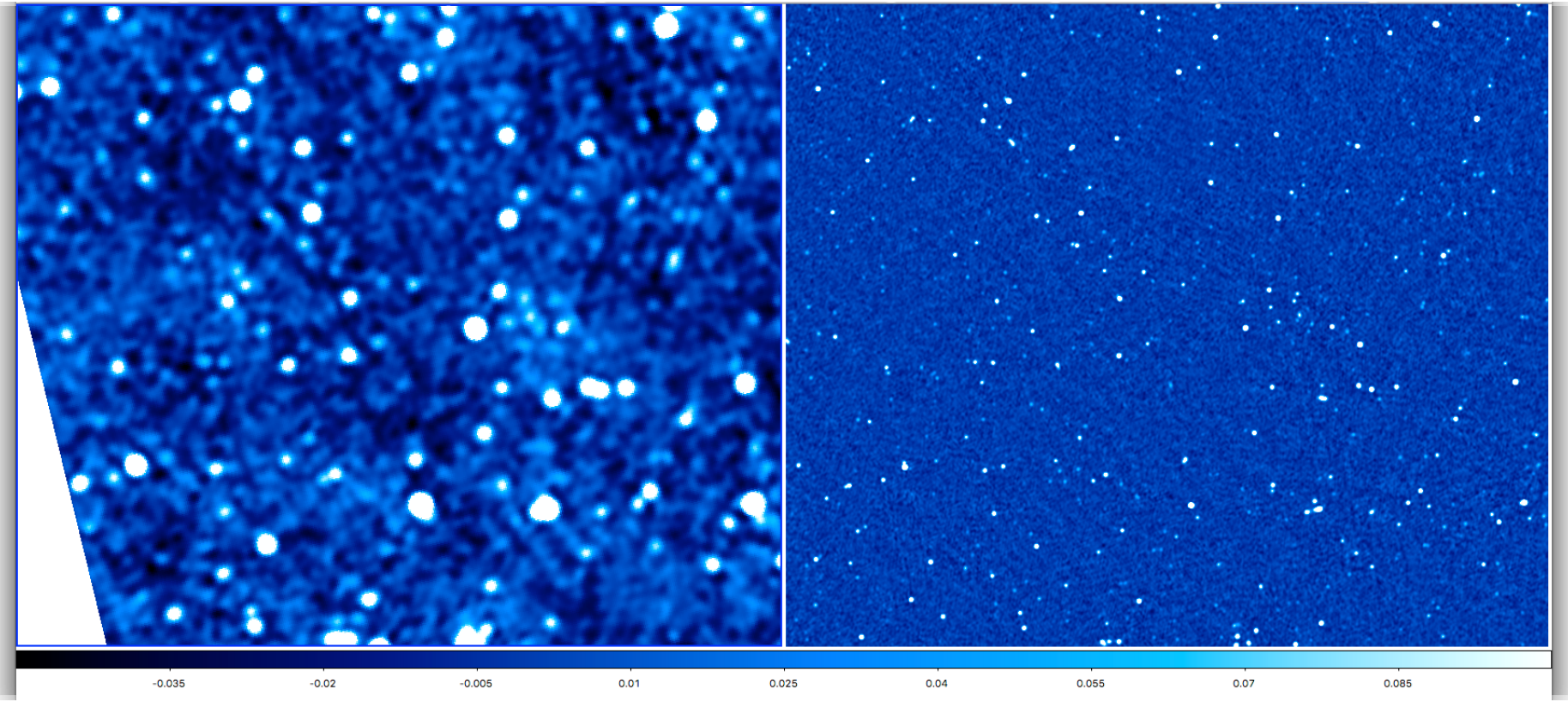
Shimwell et al (2016)

MSSS-HBA: now at 45" resolution

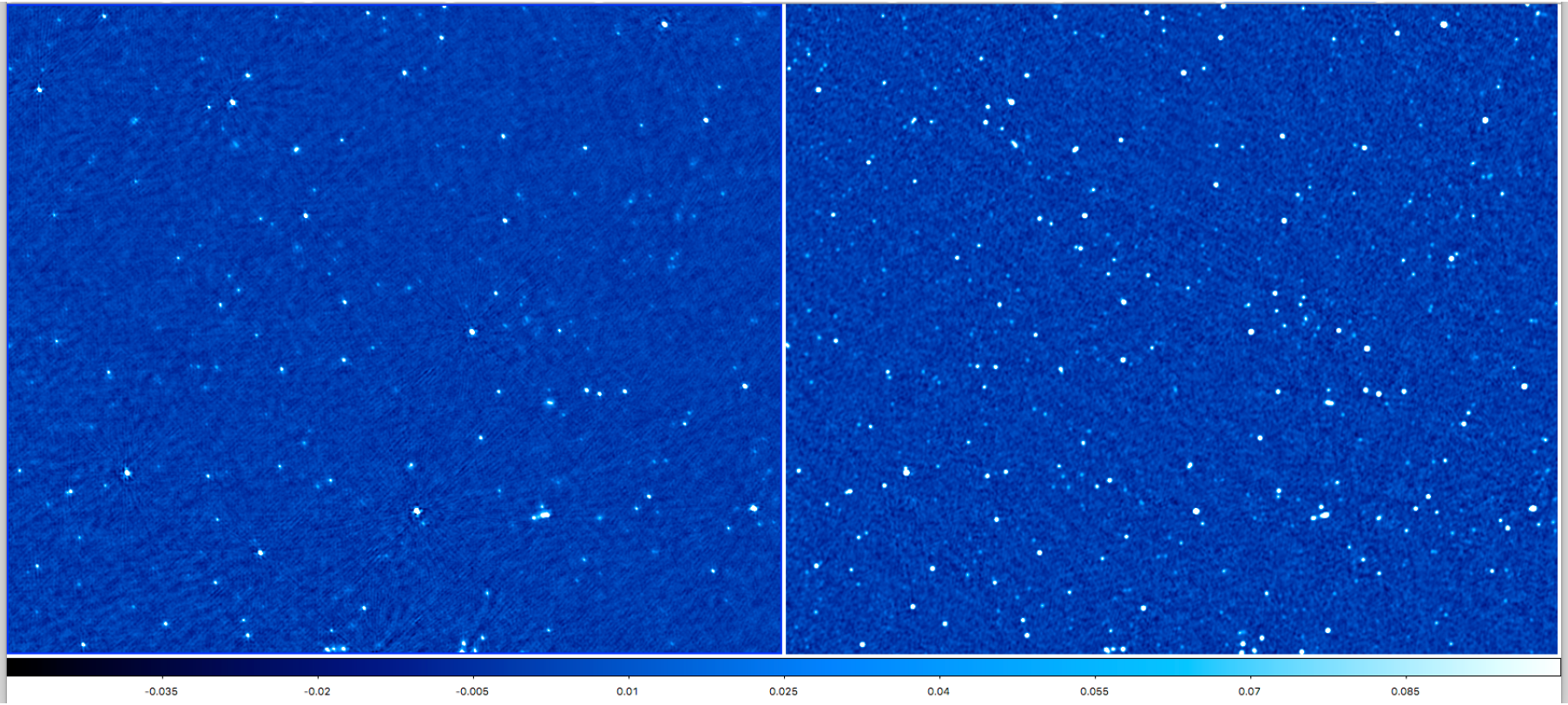


Heald et al (2015)

MSSS-HBA: now at 45" resolution



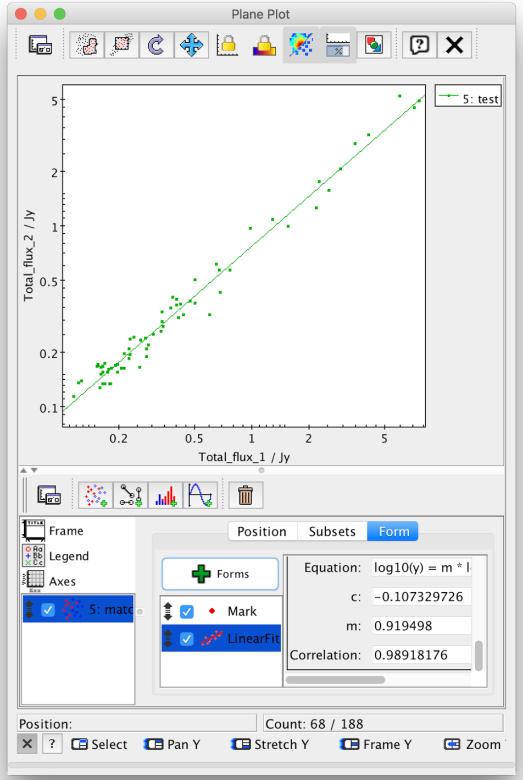
MSSS-HBA: now at 45" resolution



Test MSSS image courtesy Chris Riseley (CASS)

When will it be public?

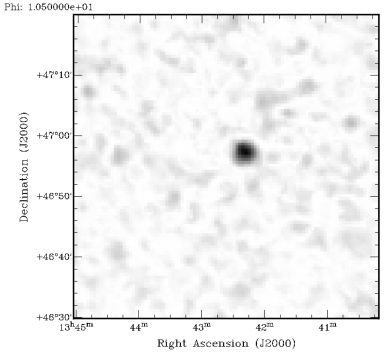
- Flux scale verification ongoing
  - Recent progress (here in Sydney!) seems to have addressed some systematics, residual errors now at the few percent level
- Imaging pipeline ready, modulo small tweaks
- Aim is to release δ>+30° first (short timescale), then continue to equator
- Release data products will include
  - 100 square degree mosaics
  - Multifrequency catalog (8 bands 120-160 MHz)
    - Expected to contain ~200,000 sources

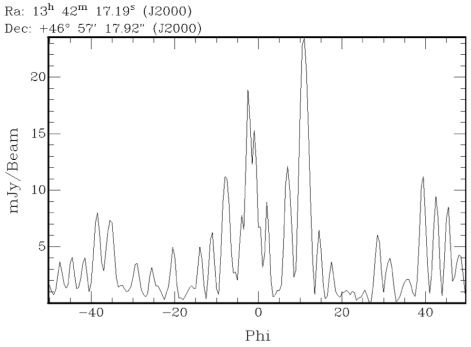


MSSS All-sky Polarization Survey: MAPS

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

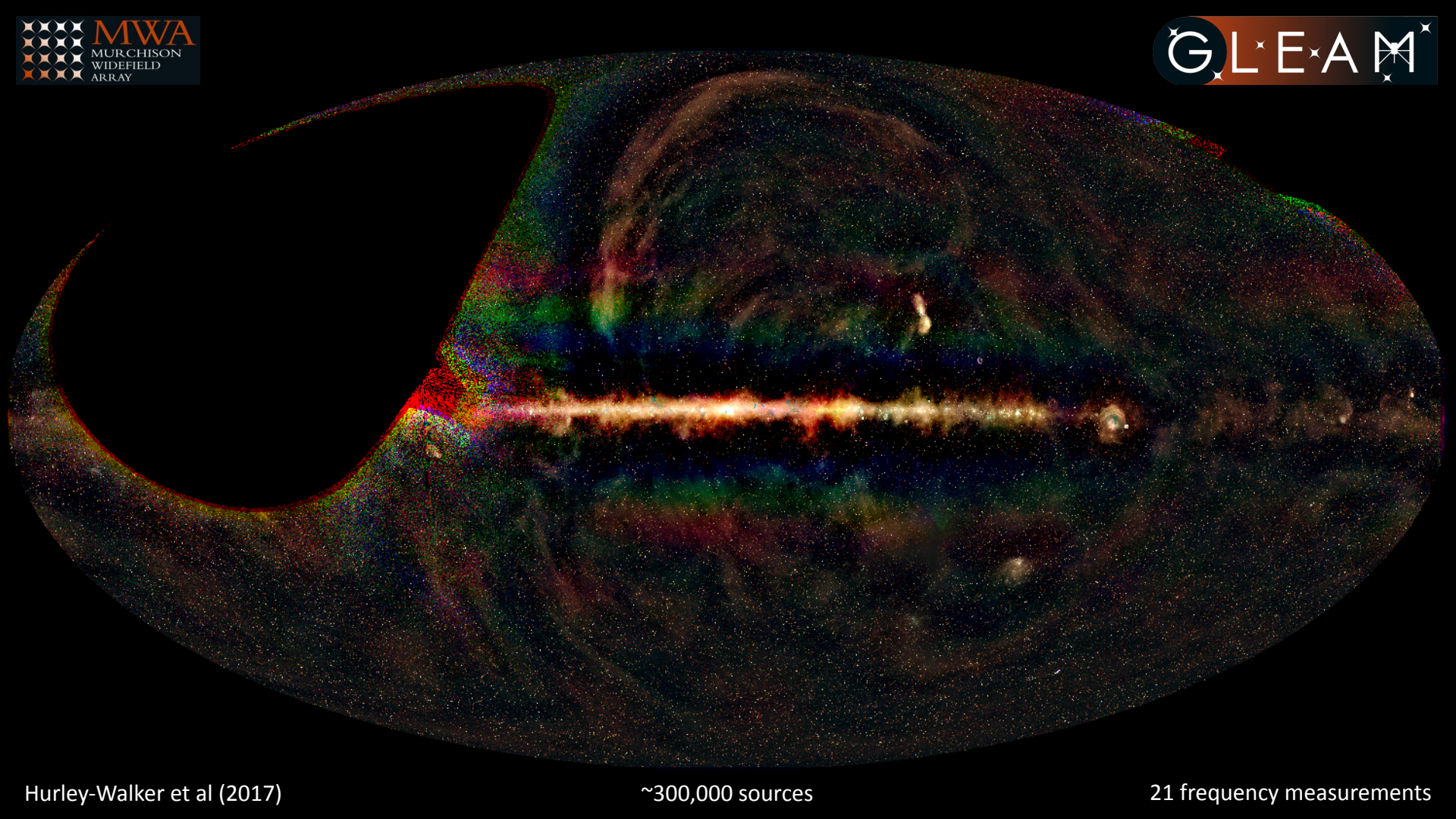
- Projected to be a three-tier polarization survey
  - Tier 1: 50' resolution, for diffuse polarization structures (Largest scale ISM magnetic structures; e.g. Lenc et al 2017)
  - Tier 2: 2-8' resolution for intermediate scales
  - Tier 3: 45" resolution (Extragalactic point sources; e.g. Van Eck et al, submitted)
- Early planning for MAPS to be used for SKA SDP prototyping (Farnes)





4C+47.38
Munro & Mulcahy

GLEAM



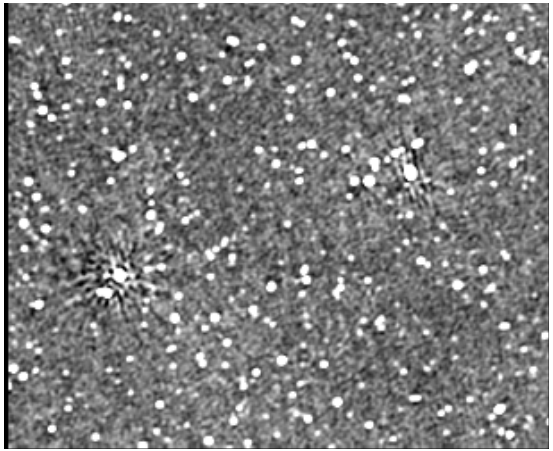
Hurley-Walker et al (2017)

~300,000 sources

21 frequency measurements

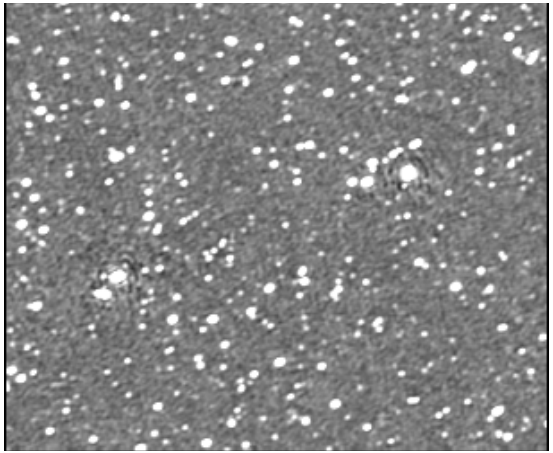
GLEAM Year 2 catalogue

- Combine subset of first 2 years of GLEAM observations
- Major improvements to GLEAM processing pipeline
    1. Use GLEAM year 1 catalogue as initial model for calibration
    2. Use more accurate primary beam model to improve flux scale
    3. Optimal running of WSClean to reduce sidelobe confusion noise
- Within 5000 deg^2 area of sky, 40-60% reduction in rms noise
- 110,934 sources > 5 sigma
- Increase in fraction of detected star-forming galaxies
    - Determine local radio luminosity function of AGN and star-forming galaxies at 150 MHz (Tom Franzen)
    - Study low-frequency spectra of star-forming galaxies (Nick Seymour, Tim Galvin)



GLEAM year 1
170-231 MHz mosaic

HA = 0h



GLEAM year 1+2
200-231 MHz mosaic

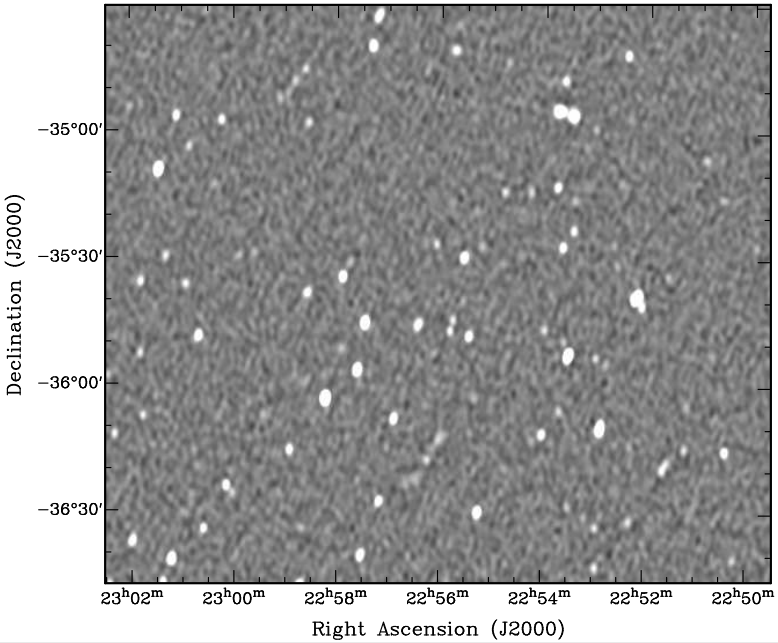
HA = -1, 0, +1h

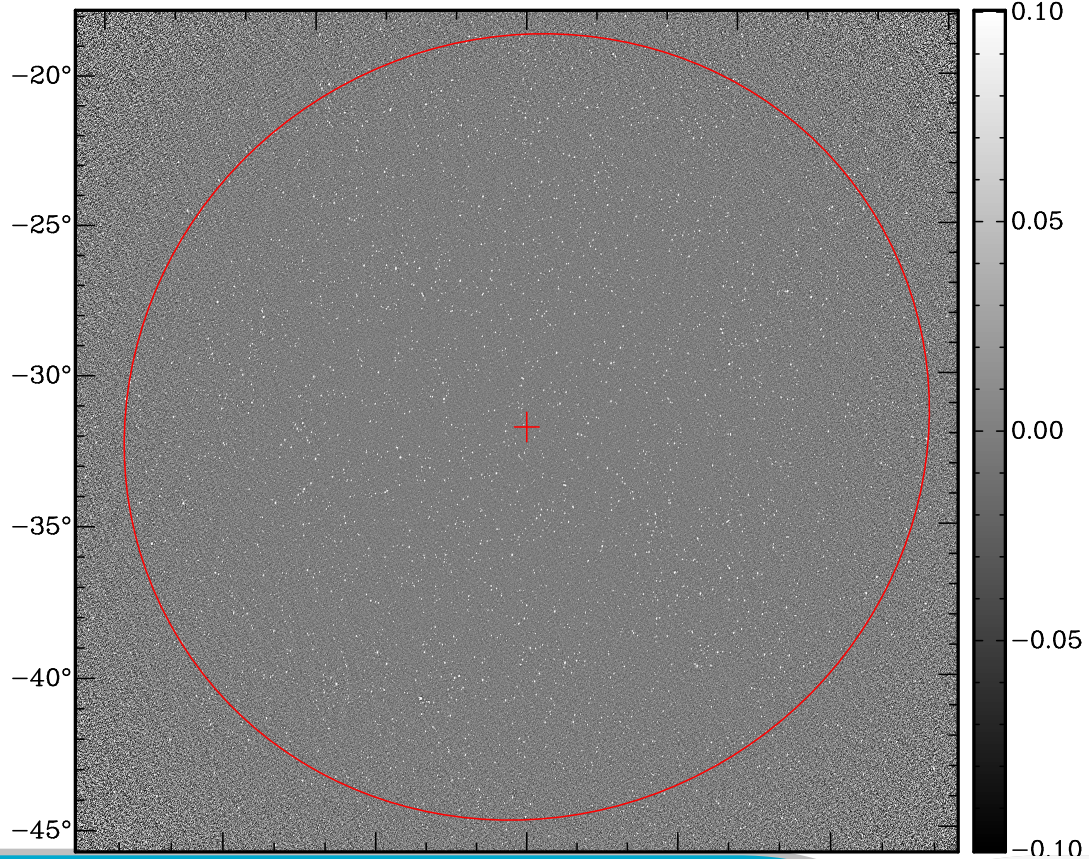
Slide courtesy of Tom Franzen

Coming soon: GLEAM-X and MIDAS

Preliminary images using ~50% of Phase 2 array

- Expanded array opens capability for wide-area (GLEAM-X) and deep (MIDAS) surveys at higher resolution



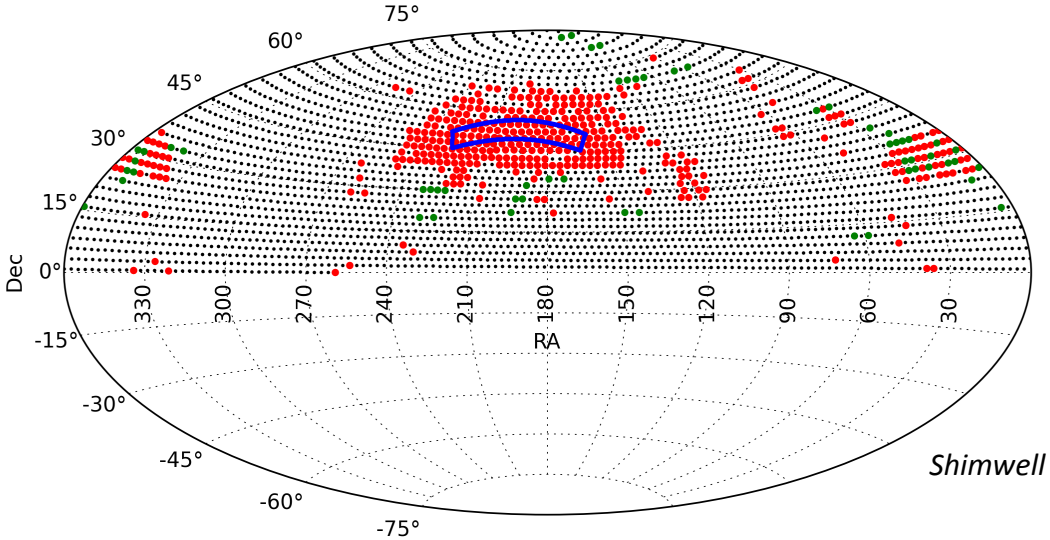


Images courtesy of Tom Franzen

LoTSS

LOFAR Two-metre Sky Survey (LoTSS)

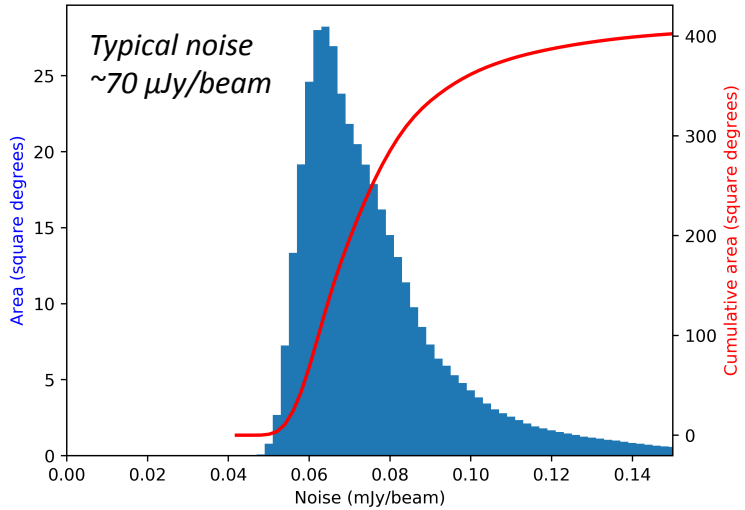
- Deep, high-resolution imaging survey of the Northern sky
- Headline characteristics: 100 μJy/beam @6" resolution, at 150 MHz
- 3170 pointings (over 13% complete), 8h each
- PI Röttgering, overseeing core team that organizes 8 science working groups

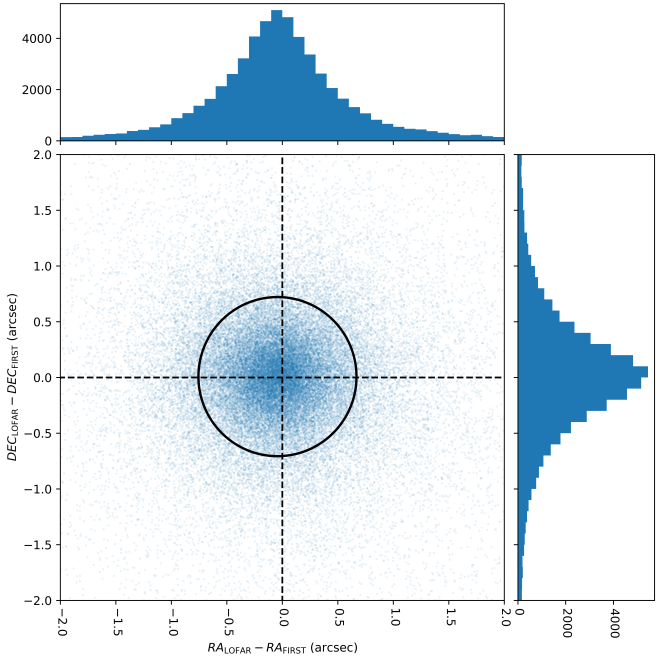


Shimwell et al (in prep)

LoTSS initial 6" data release

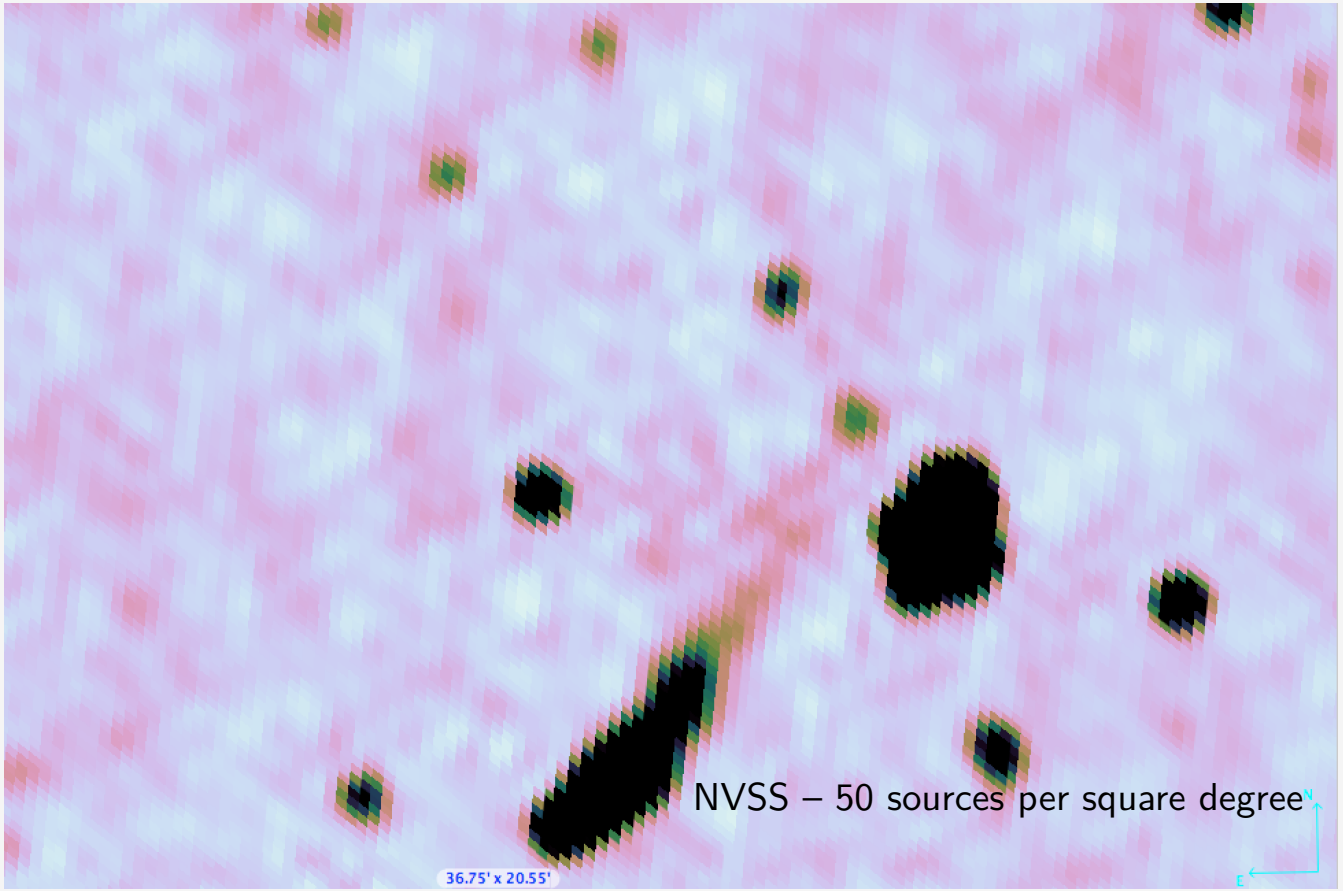
- Generated from 63 direction-dependent calibrated datasets
  - Robust direction-independent calibration & imaging pipeline (Shimwell et al 2017)
  - KillMS & DDFacet (Cyril Tasse)
  - Pipeline available on github

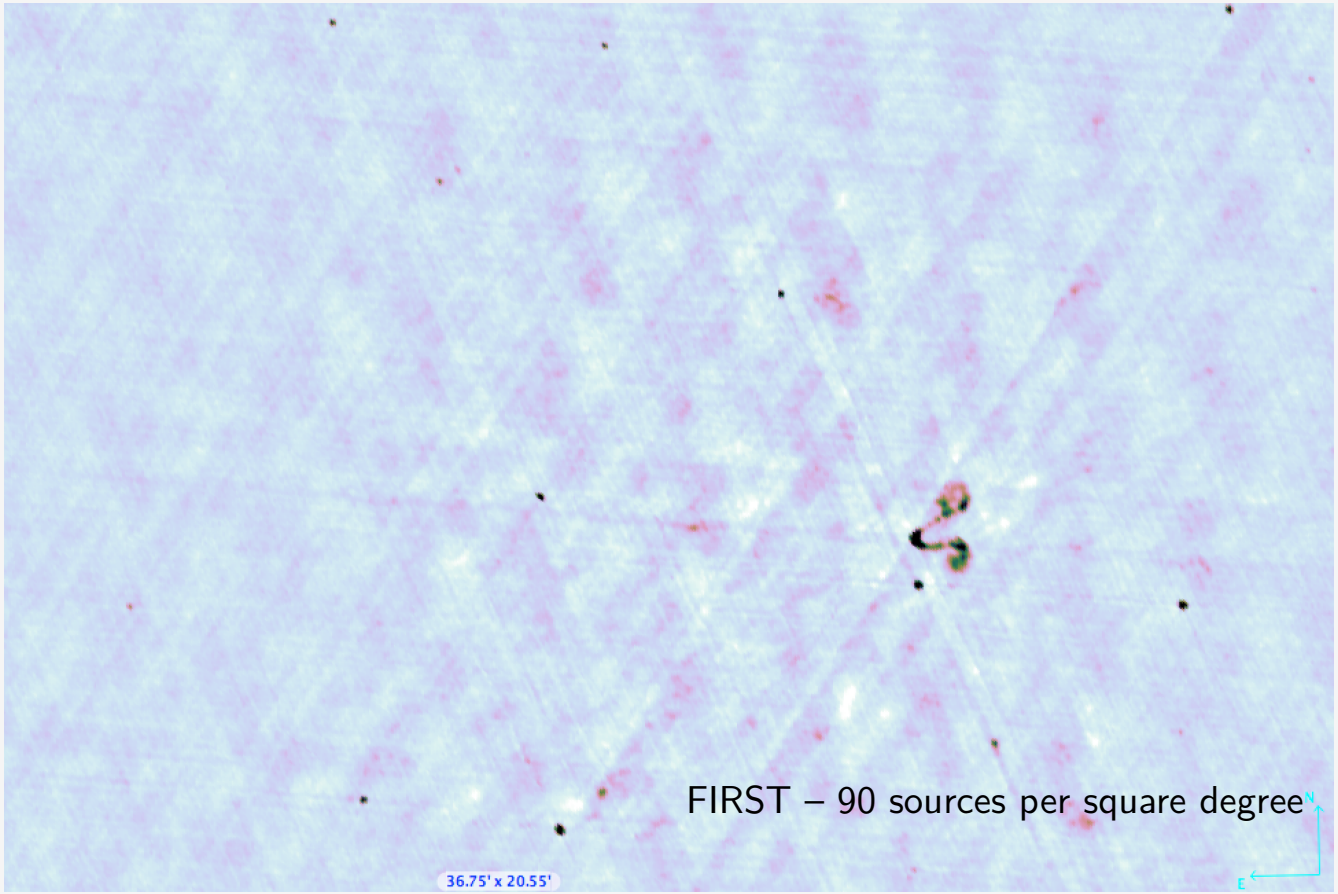


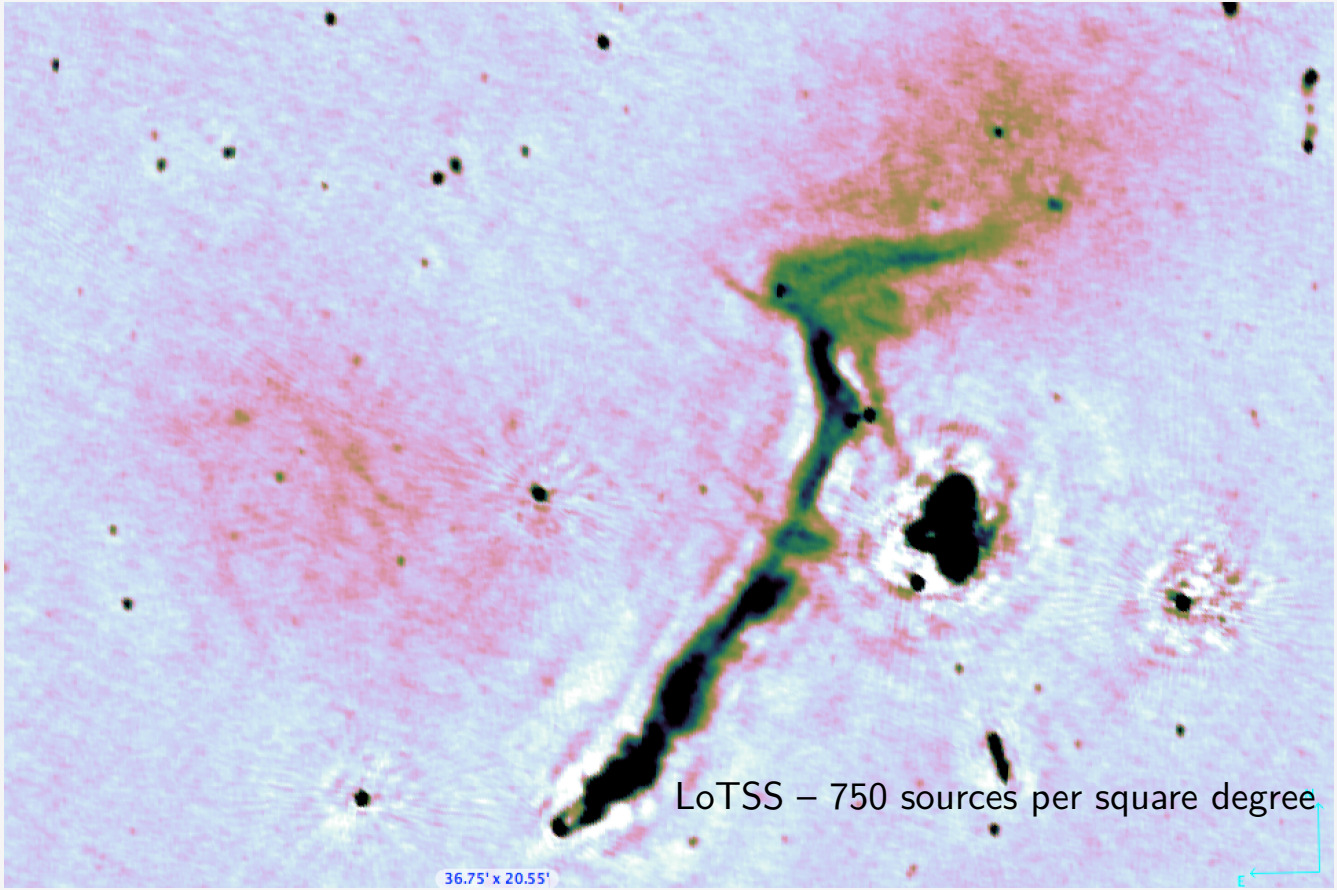


Astrometric rms offset ~1.2" wrt FIRST

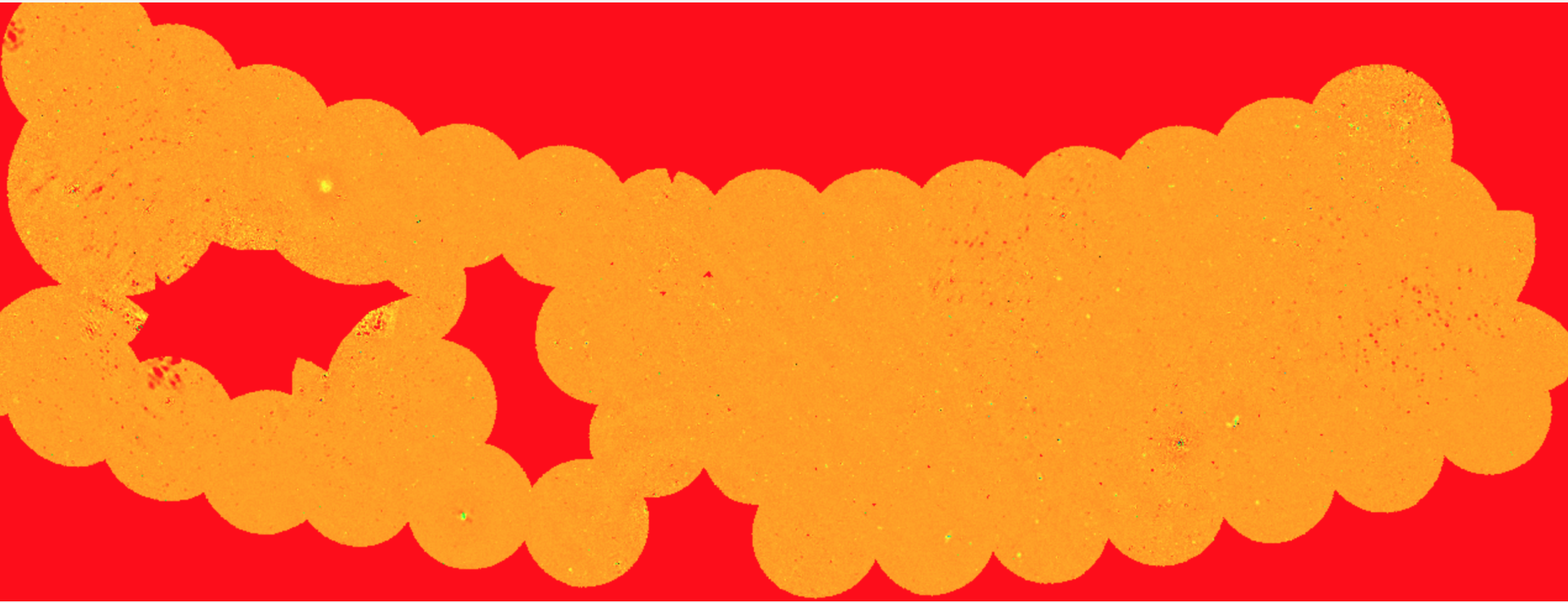
Shimwell et al (in prep)


NVSS – 50 sources per square degree
36.75' x 20.55'
N
E

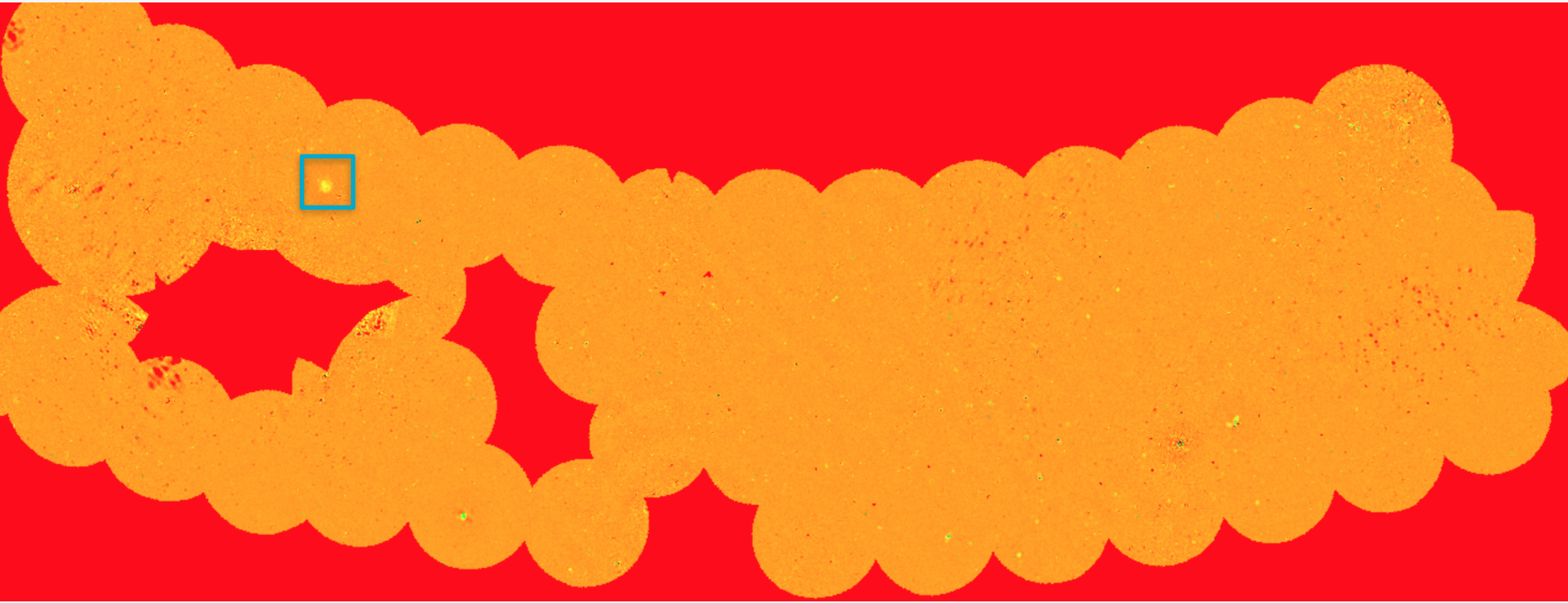

FIRST – 90 sources per square degree
36.75' x 20.55'
N
E


LoTSS – 750 sources per square degree
36.75' x 20.55'

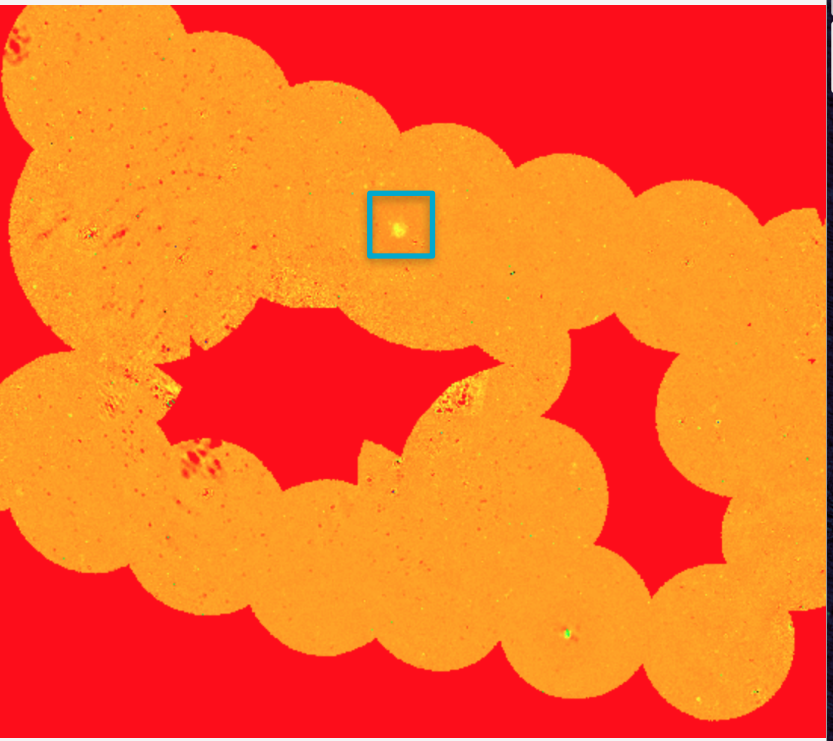
Nearby galaxies in LoTSS

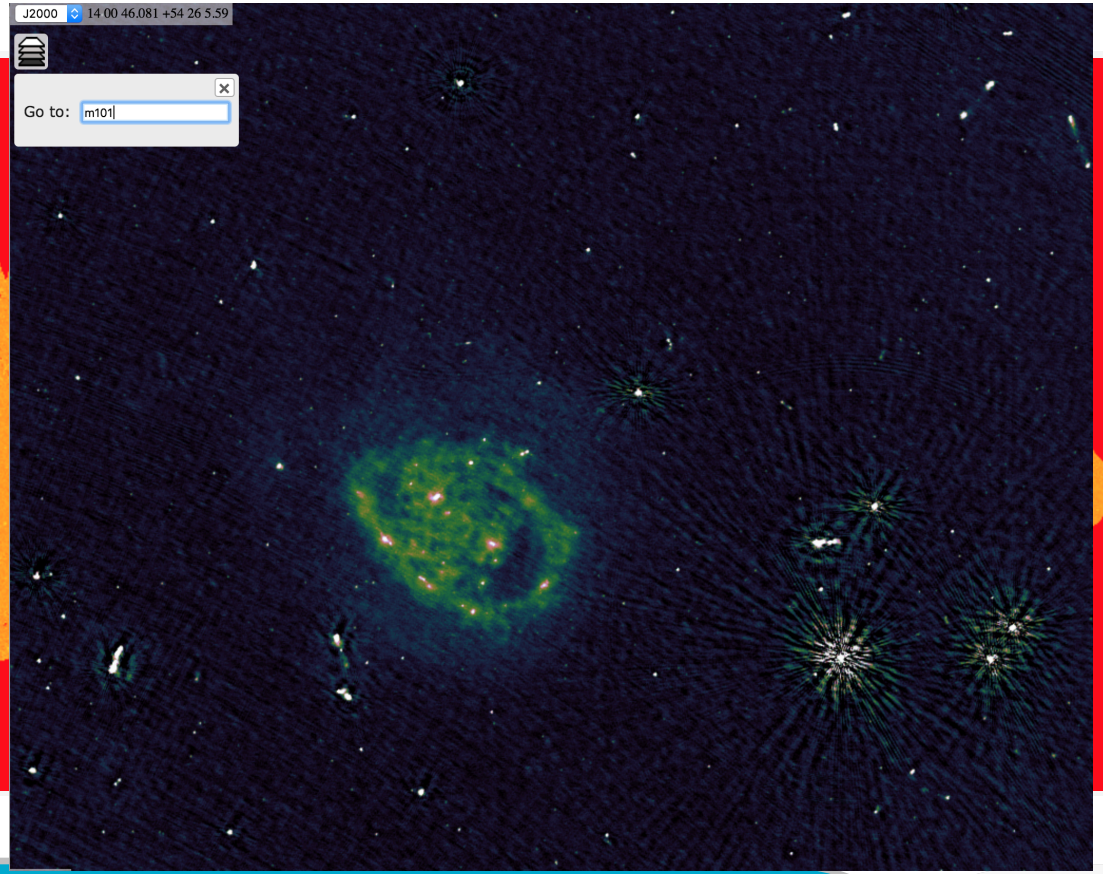


Nearby galaxies in LoTSS

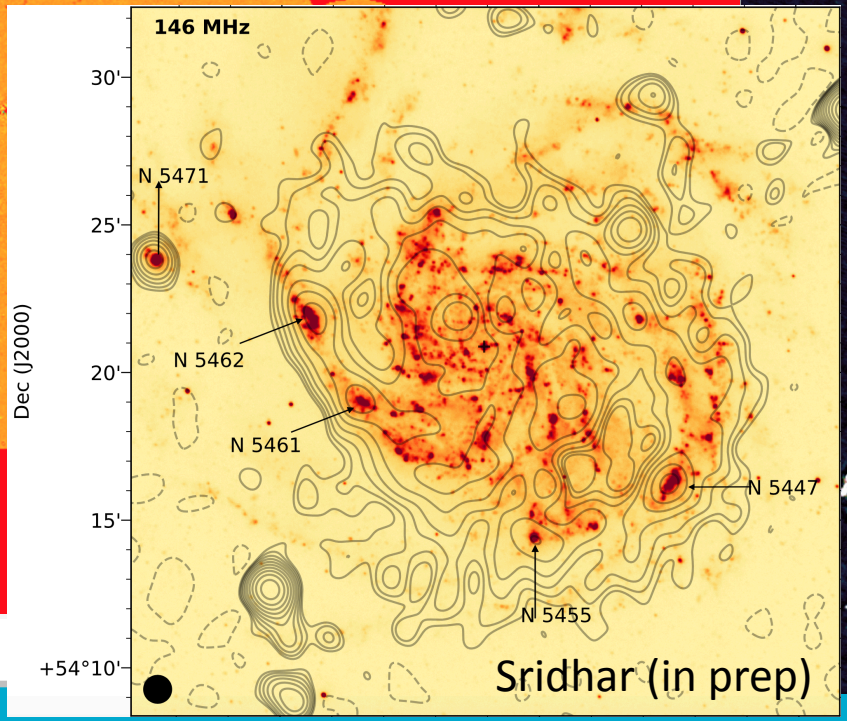


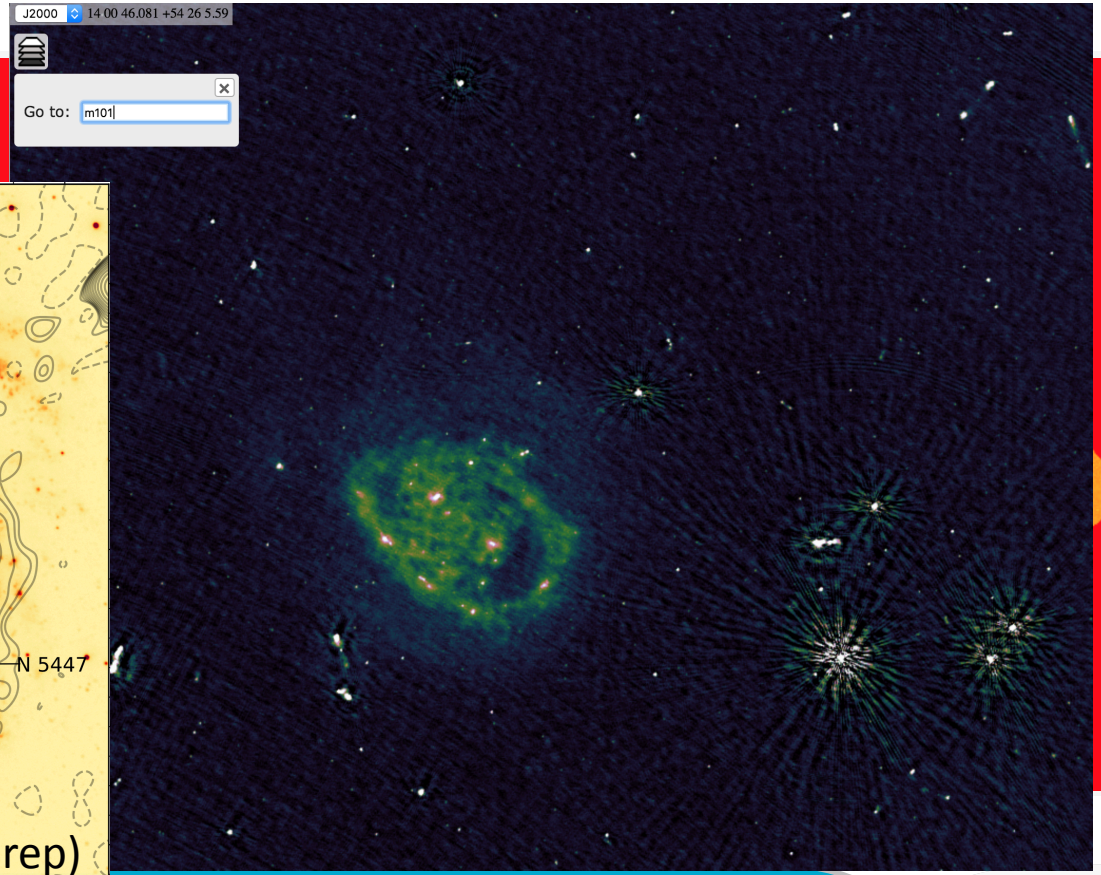
Nearby galaxies in LoTSS





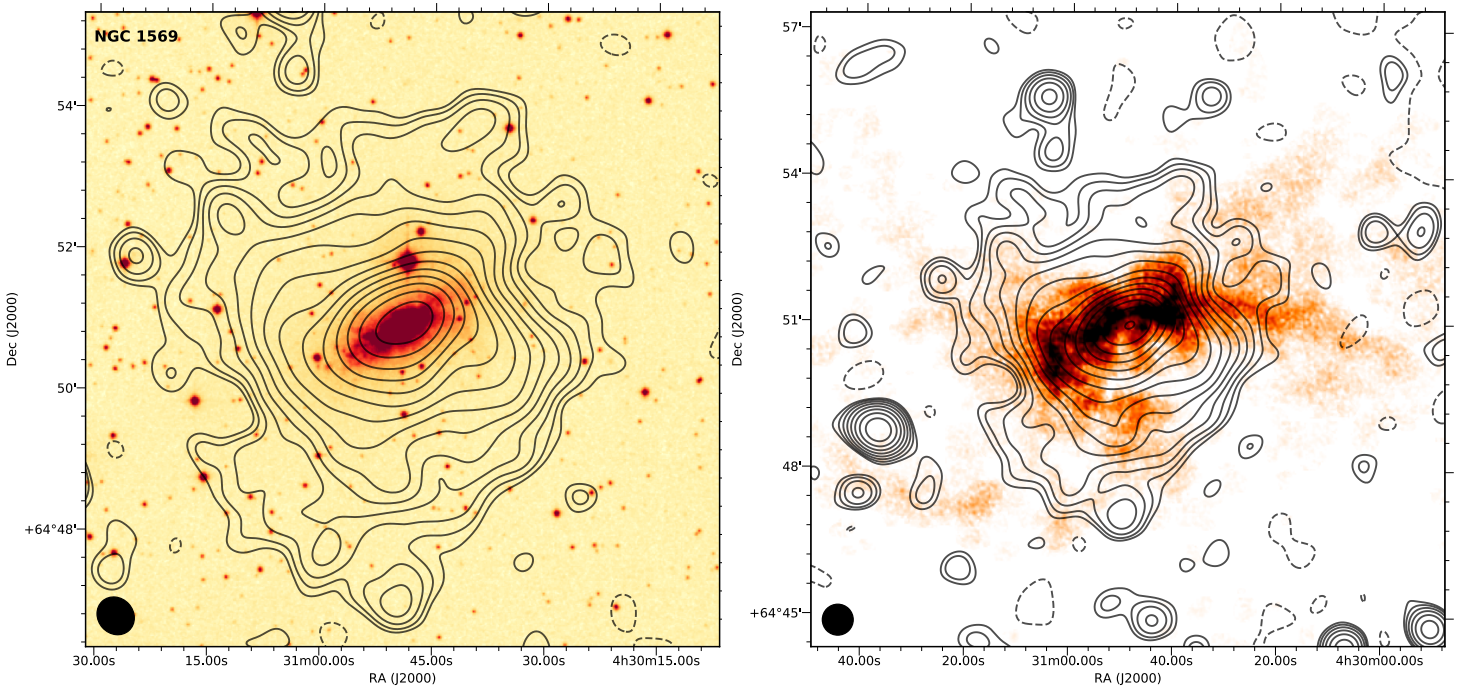
Nearby galaxies in LoTSS



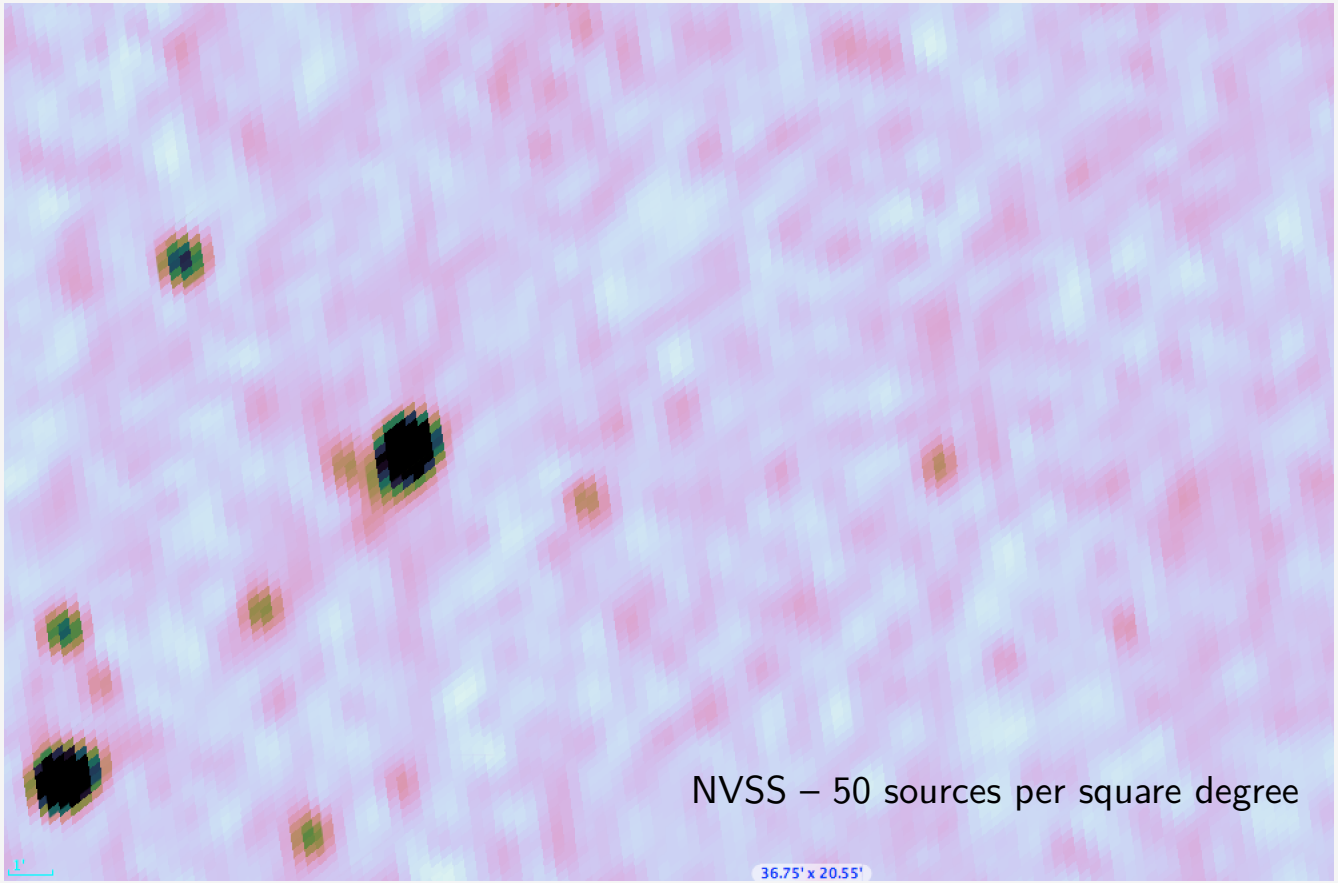


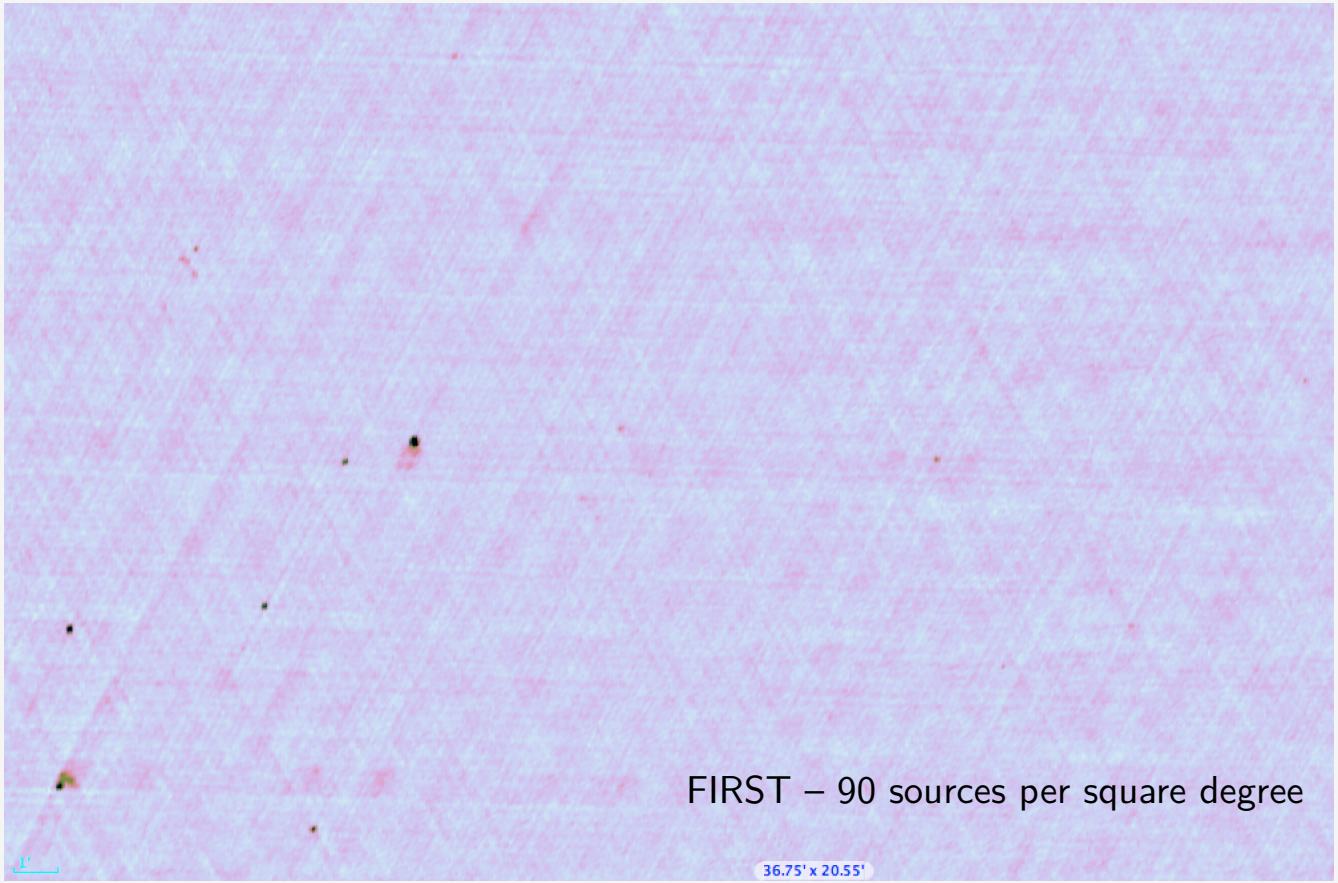
Nearby galaxies in LoTSS

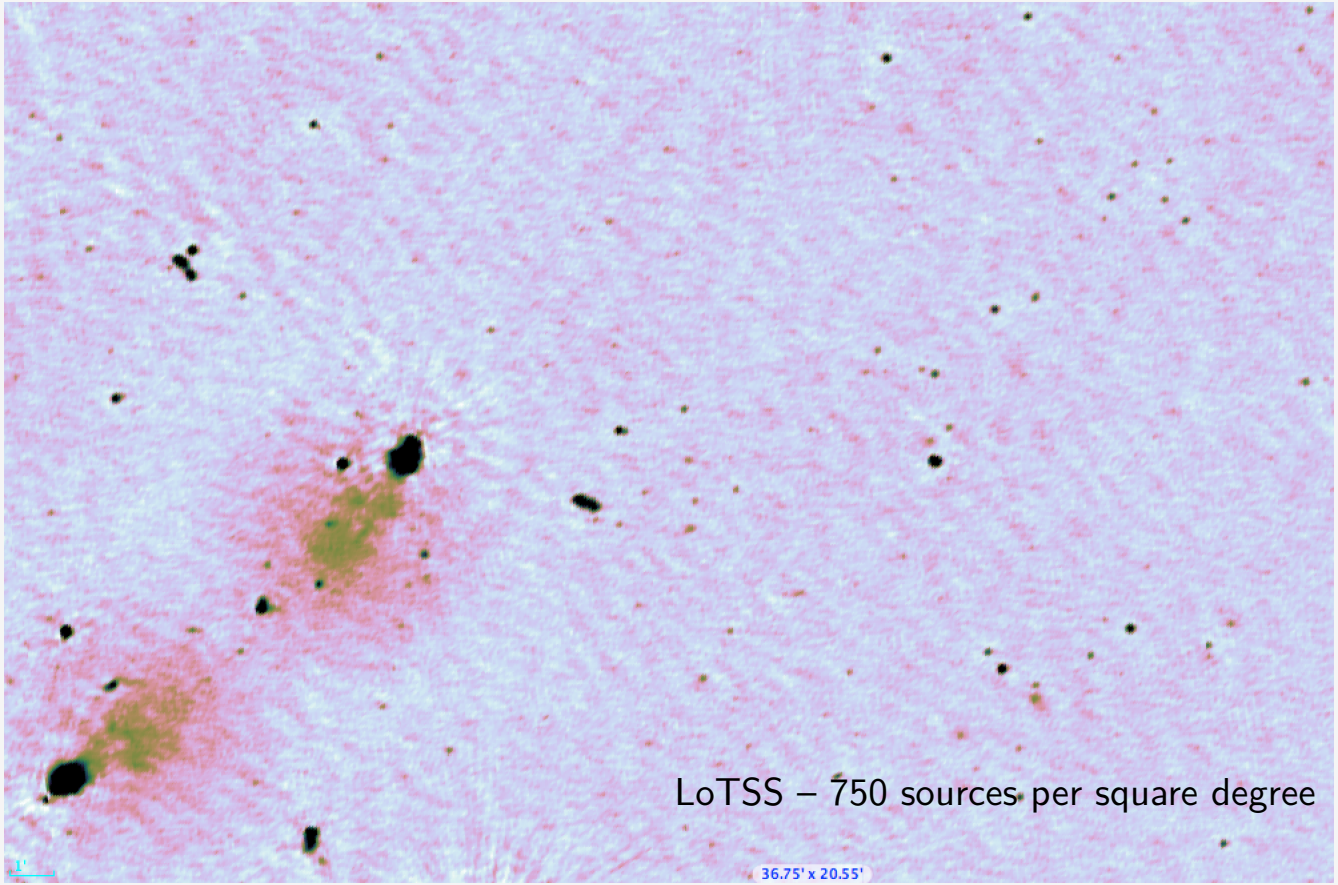
- Dwarf galaxy project (Sridhar et al) illustrating expected image fidelity from LoTSS-like calibration and imaging - eventually all galaxies in the Northern sky will be provided!



Optical image: DSS
HI image: THINGS
LOFAR 30" (smoothed)
Sridhar et al (in prep)

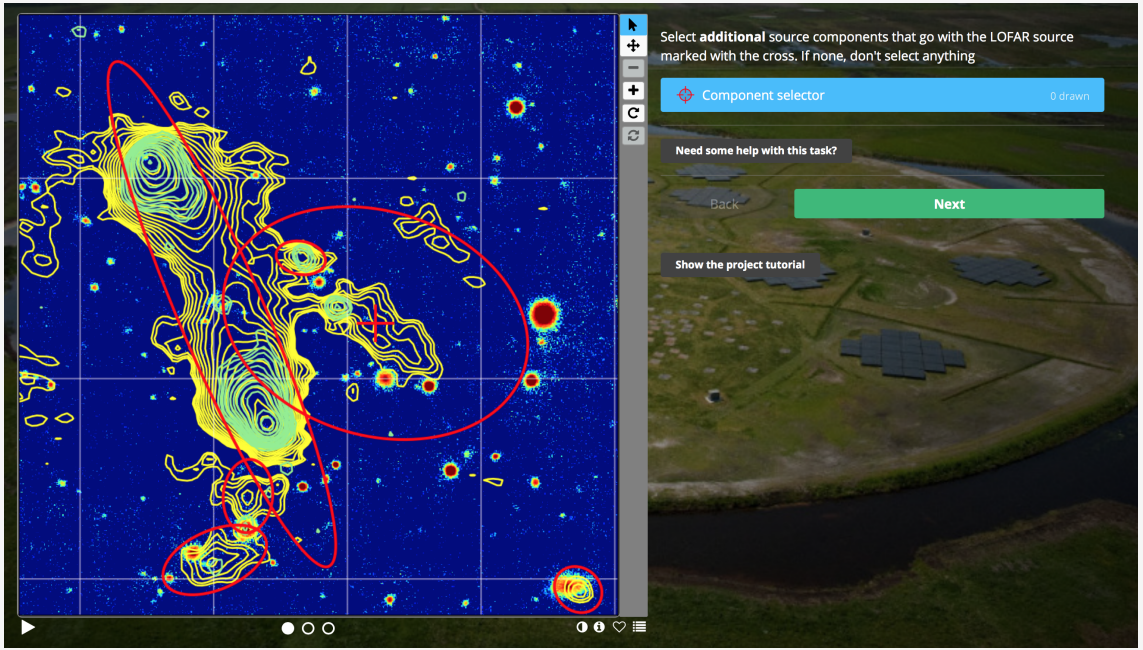

NVSS – 50 sources per square degree
36.75' x 20.55'


FIRST – 90 sources per square degree
36.75' x 20.55'


LoTSS – 750 sources per square degree
36.75' x 20.55'

Source classification

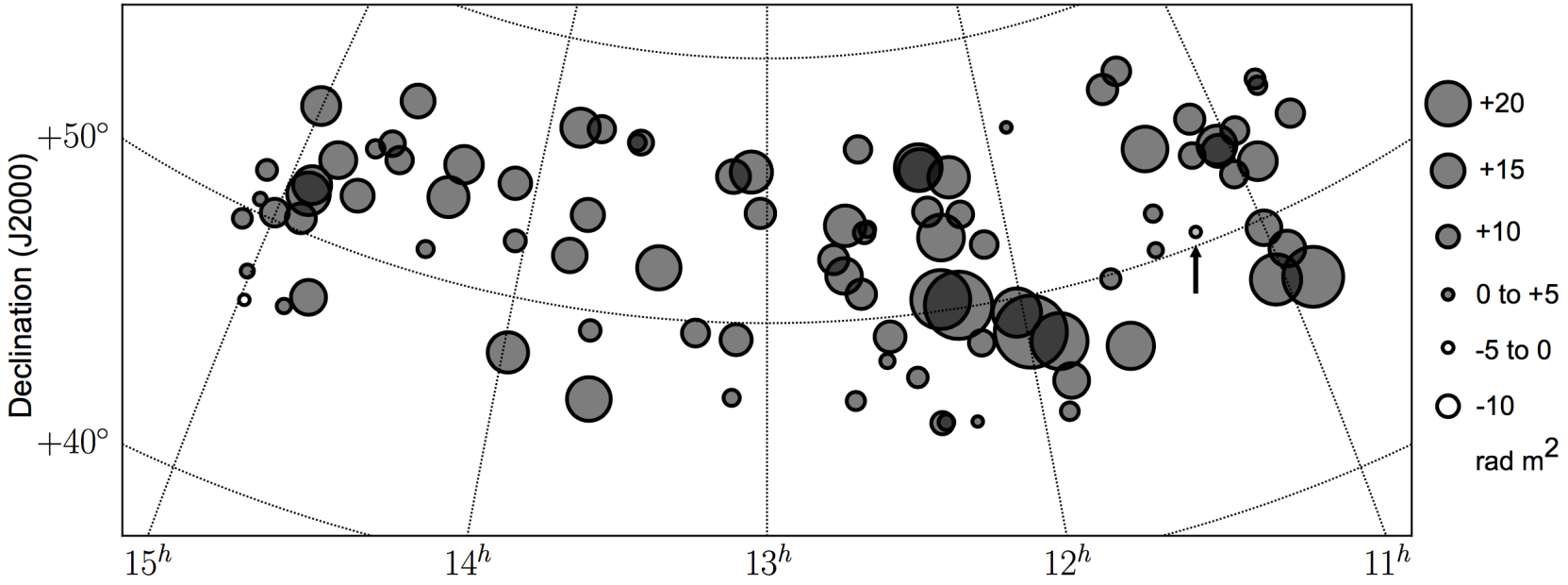
- Of the 350,000 sources in the LoTSS HETDEX data release, most will have an optical ID



Multi-wavelength team – Best, Hardcastle, Williams, Sabater, Duncan and many more

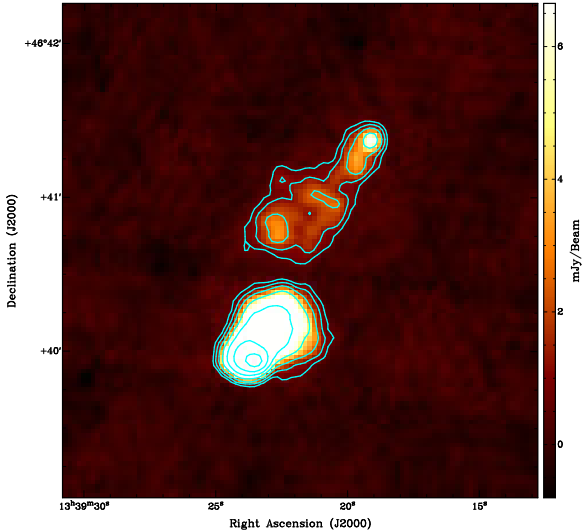
Polarimetry with LoTSS

- **LOFAR Magnetism Key Science Project (MKSP)** working hand-in-hand with LoTSS toward polarimetric catalog at 5-10" resolution with same nominal sensitivity (~100 μJy/beam)
- Initial catalog of 92 polarized sources at 4.3' resolution (Van Eck et al., submitted)



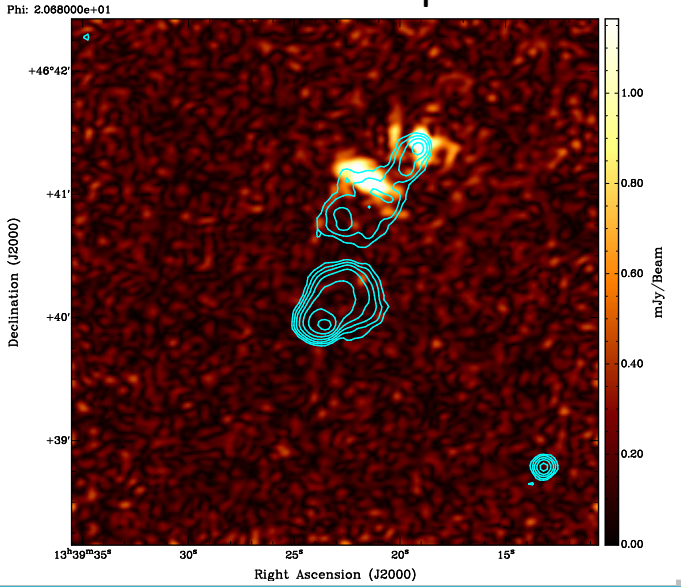
Polarimetry with LoTSS

- **LOFAR Magnetism Key Science Project (MKSP)** working hand-in-hand with LoTSS toward polarimetric catalog at 5-10" resolution with same nominal sensitivity (~100 μJy/beam)
- Demonstrated that direction-dependent calibration does not hamper polarimetry
- GOODS-N field will probe low-frequency polarization number counts at high sensitivity



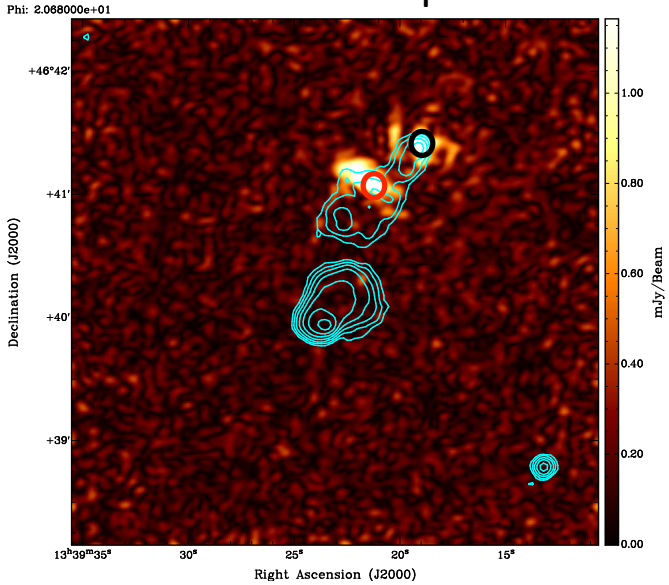
Polarimetry with LoTSS

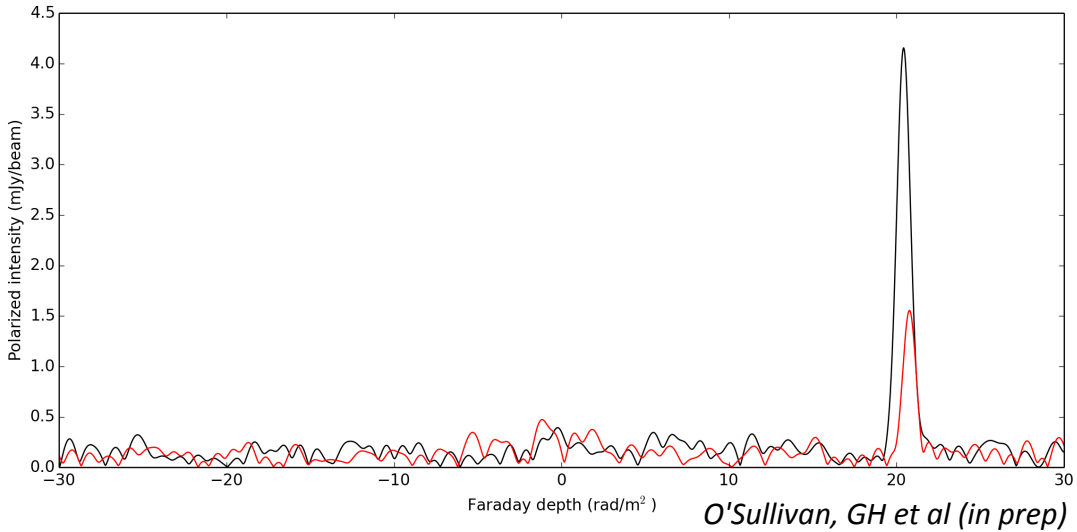
- **LOFAR Magnetism Key Science Project (MKSP)** working hand-in-hand with LoTSS toward polarimetric catalog at 5-10" resolution with same nominal sensitivity (~100 µJy/beam)
- Demonstrated that direction-dependent calibration does not hamper polarimetry
- GOODS-N field will probe low-frequency polarization number counts at high sensitivity



Polarimetry with LoTSS

- **LOFAR Magnetism Key Science Project (MKSP)** working hand-in-hand with LoTSS toward polarimetric catalog at 5-10" resolution with same nominal sensitivity (~100 μJy/beam)
- Demonstrated that direction-dependent calibration does not hamper polarimetry
- GOODS-N field will probe low-frequency polarization number counts at high sensitivity

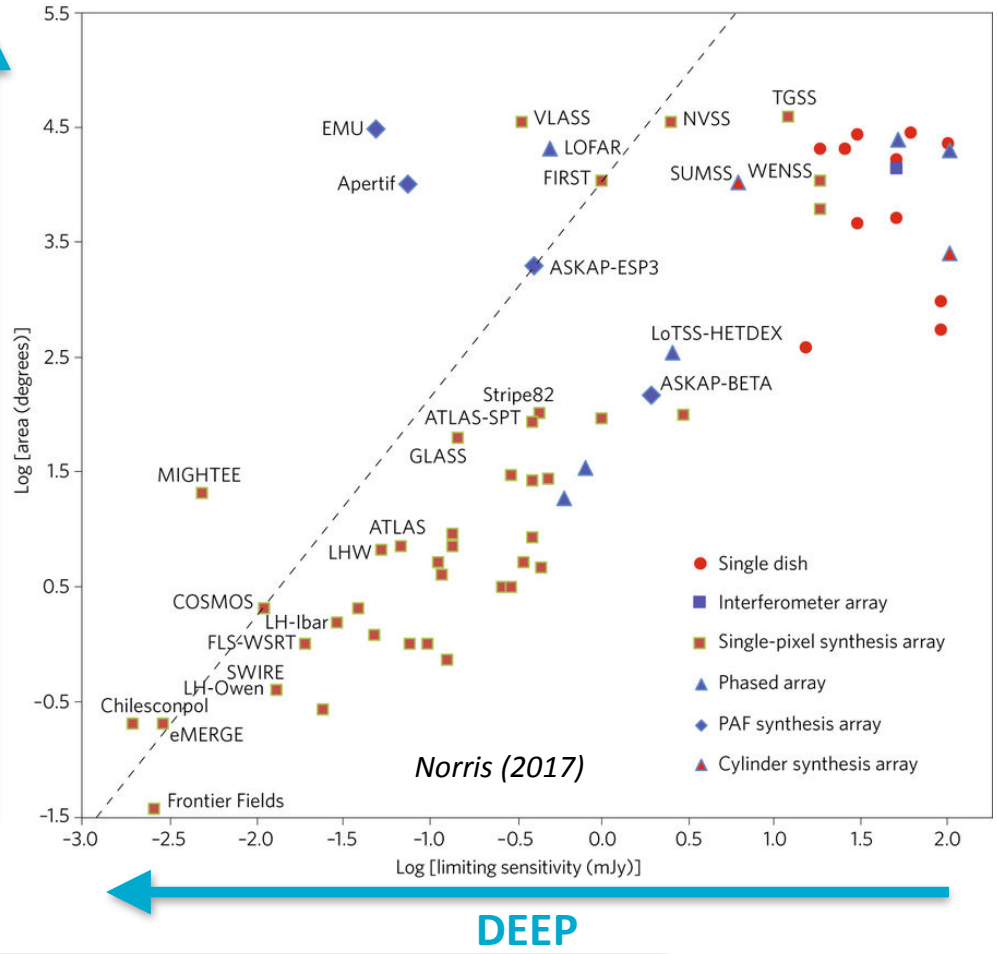




O'Sullivan, GH et al (in prep)

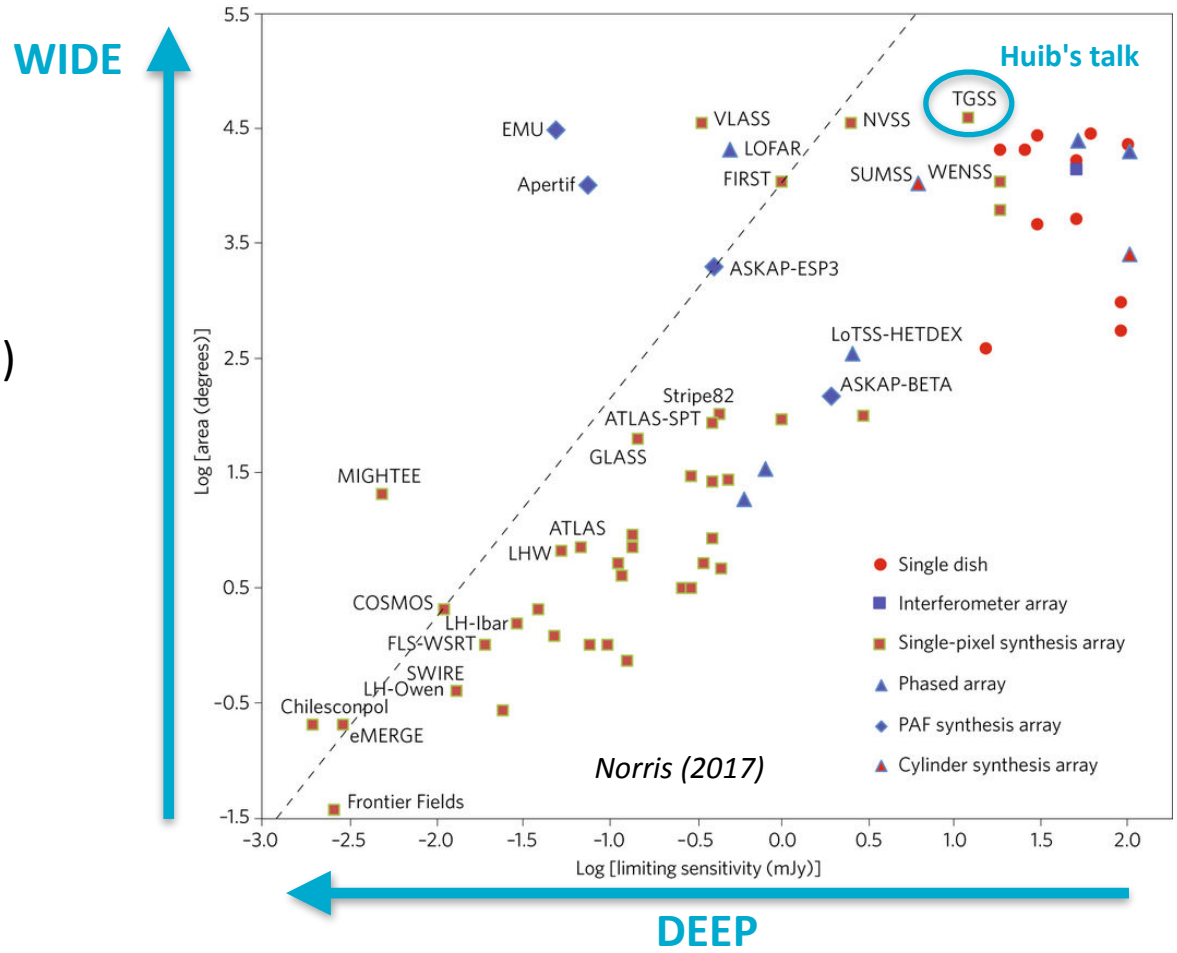
Summary

- Low frequency imaging surveys are ***leading the world!***
  - Broadband (GLEAM, MSSS)
  - Deep, high resolution (LoTSS)



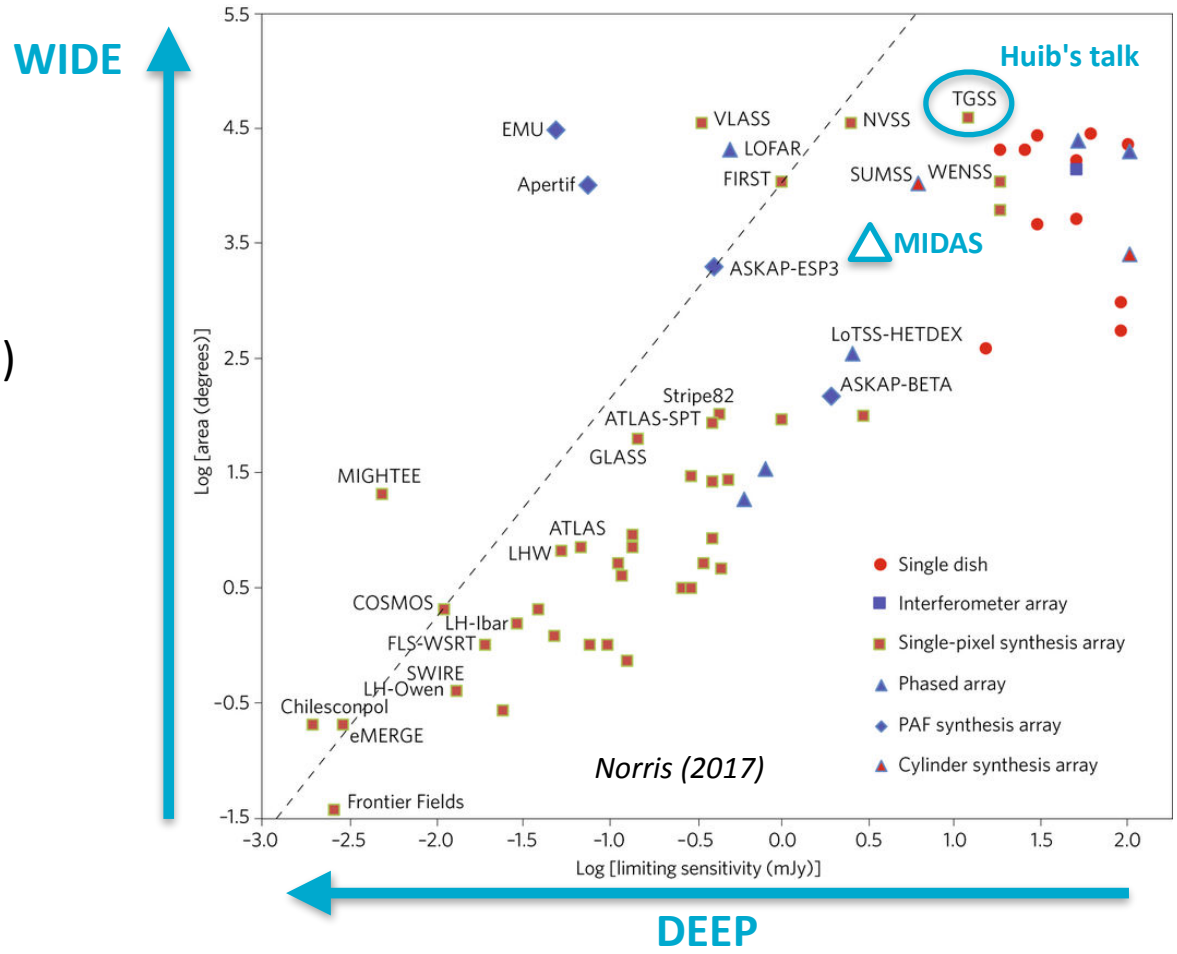
Summary

- Low frequency imaging surveys are ***leading the world!***
  - Broadband (GLEAM, MSSS)
  - Deep, high resolution (LoTSS)



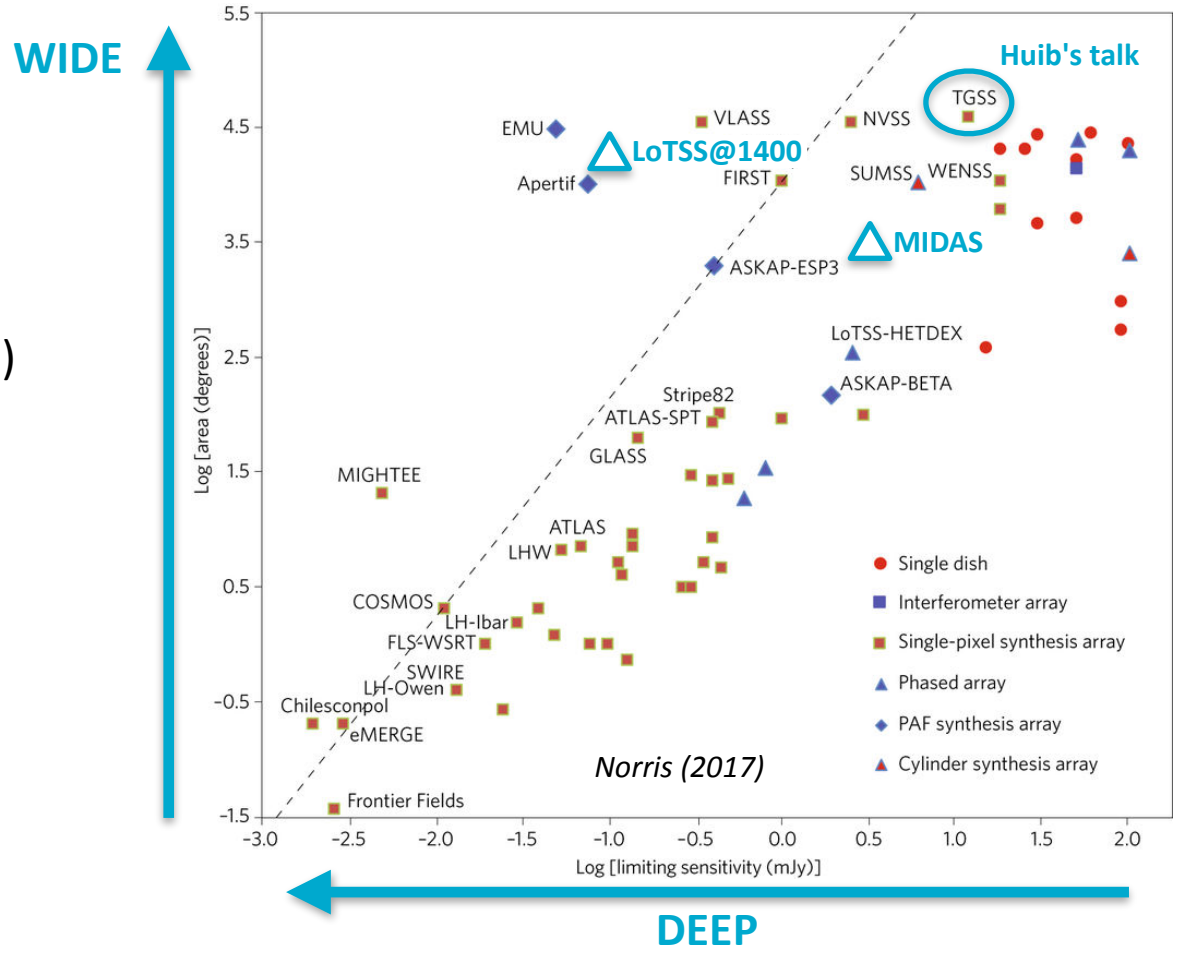
Summary

- Low frequency imaging surveys are ***leading the world!***
  - Broadband (GLEAM, MSSS)
  - Deep, high resolution (LoTSS)



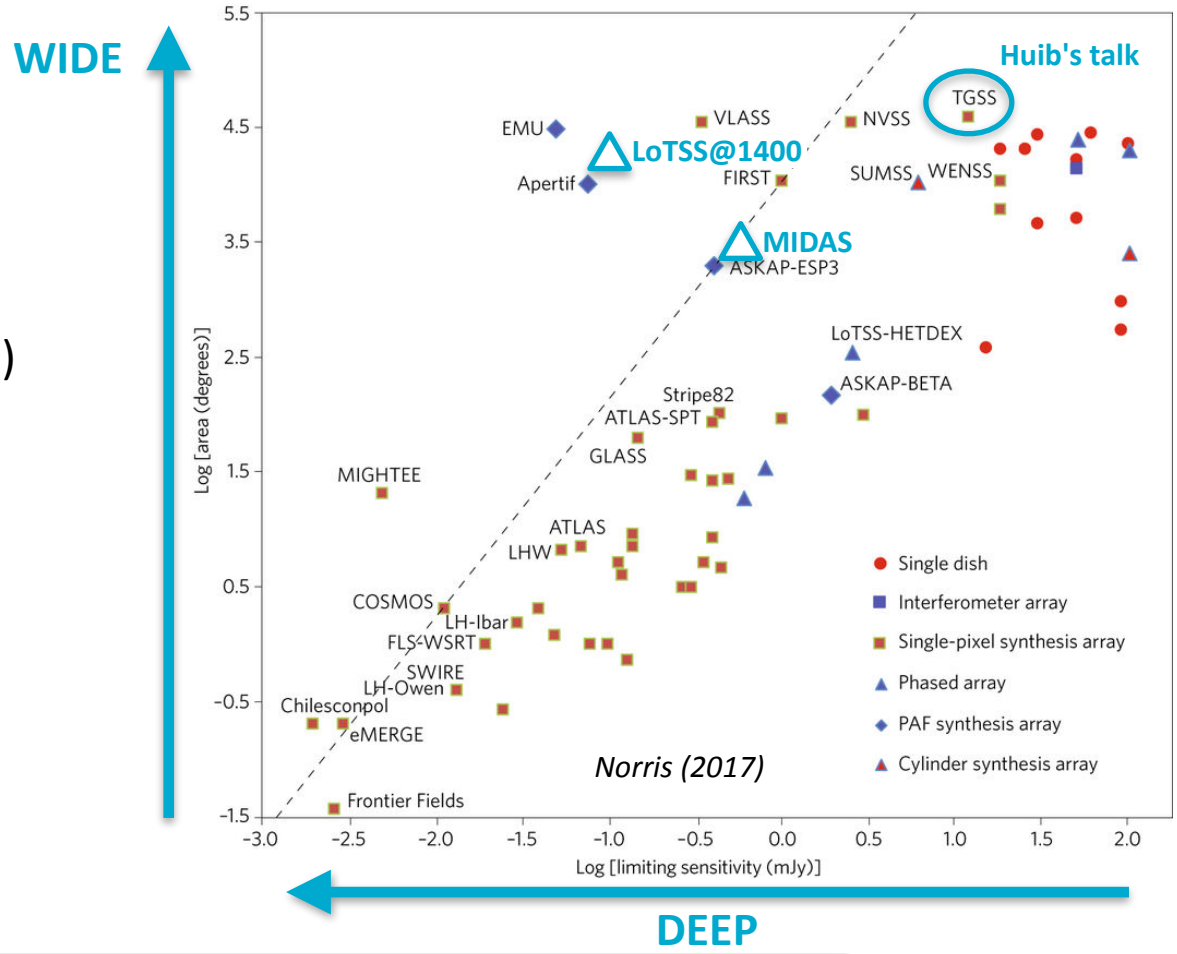
Summary

- Low frequency imaging surveys are ***leading the world!***
  - Broadband (GLEAM, MSSS)
  - Deep, high resolution (LoTSS)



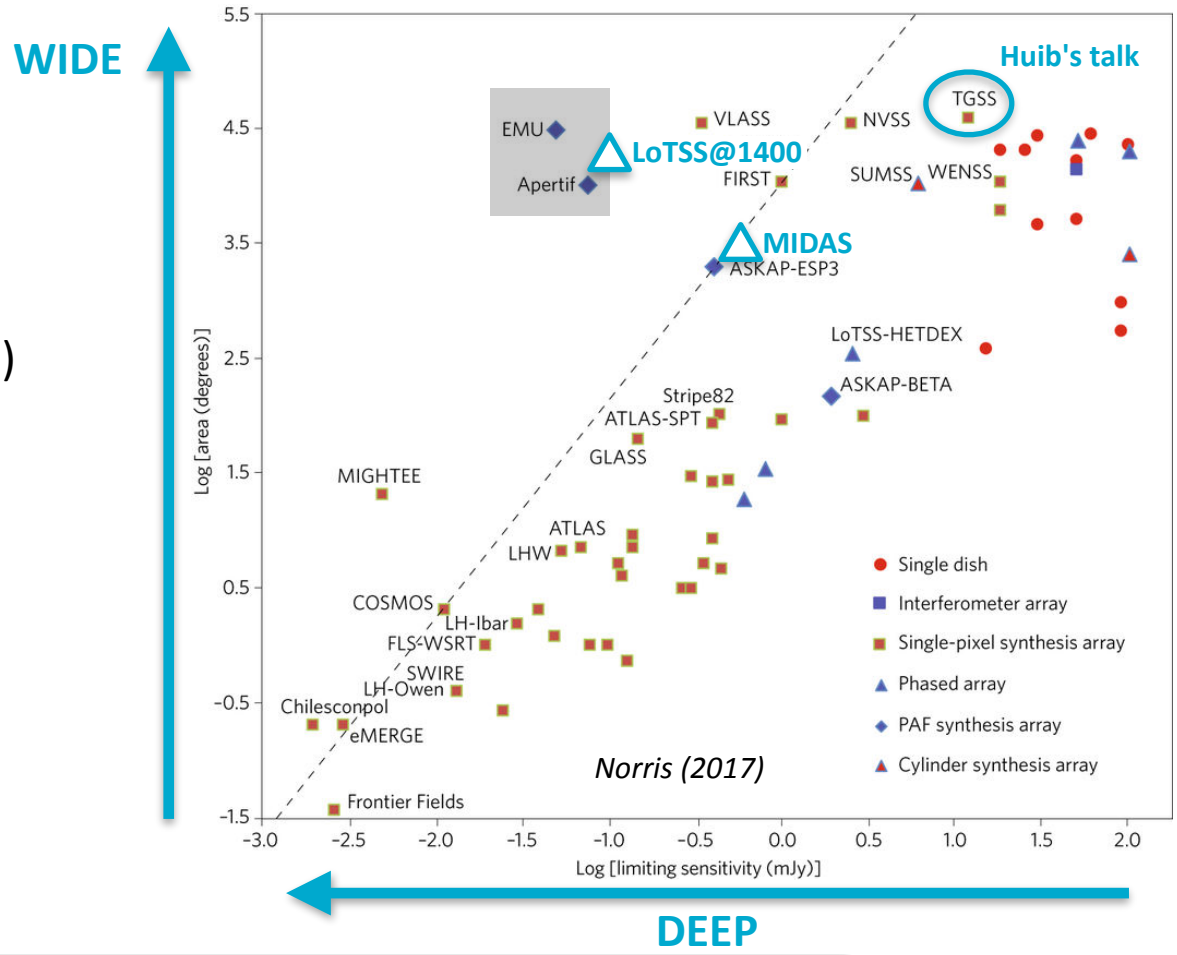
Summary

- Low frequency imaging surveys are ***leading the world!***
  - Broadband (GLEAM, MSSS)
  - Deep, high resolution (LoTSS)



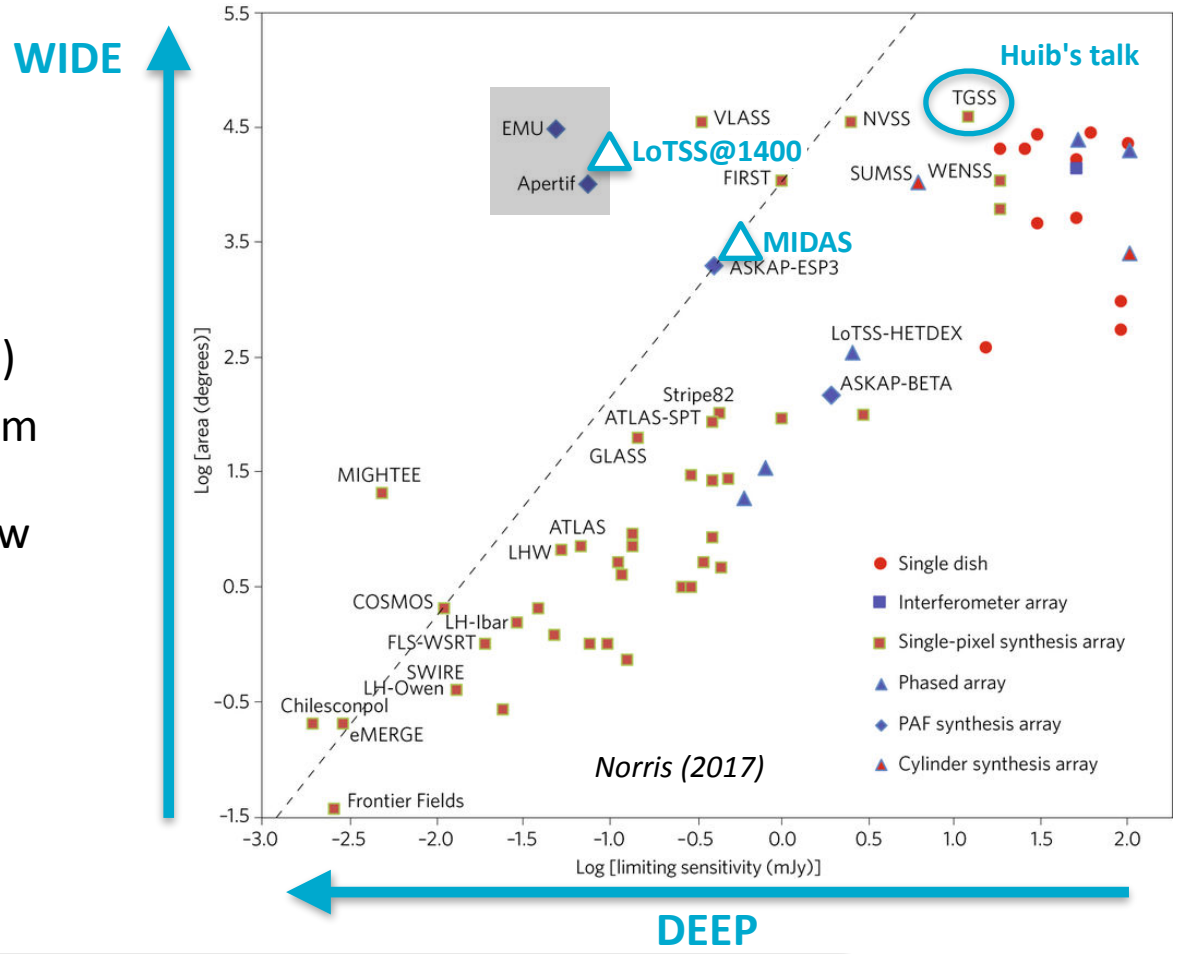
Summary

- Low frequency imaging surveys are ***leading the world!***
  - Broadband (GLEAM, MSSS)
  - Deep, high resolution (LoTSS)



Summary

- Low frequency imaging surveys are ***leading the world!***
  - Broadband (GLEAM, MSSS)
  - Deep, high resolution (LoTSS)
- Polarimetric surveys benefit from same characteristics as total intensity (and are possible at low frequencies!)



Summary

- Low frequency imaging surveys are ***leading the world!***
  - Broadband (GLEAM, MSSS)
  - Deep, high resolution (LoTSS)
- Polarimetric surveys benefit from same characteristics as total intensity (and are possible at low frequencies!)
- When mid-frequency surveys catch up (ASKAP: EMU, POSSUM) we will be in a new regime for understanding various classes of radio sources