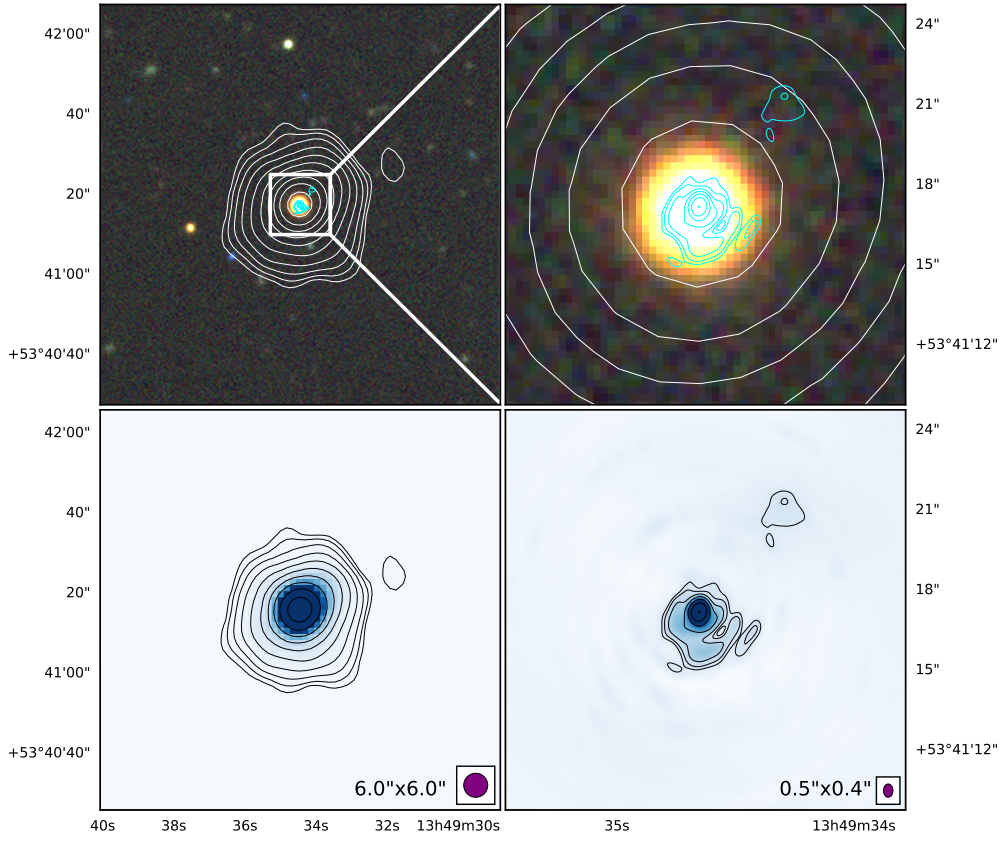
High resolution at low frequencies
sub-arcsecond surveying with LOFAR

EAS 2020 (EWASS) SS16

Leiden (virtual), NL

29 June 2020



Leah Morabito

Durham University

JUMPING JIVE
Joint Institute for VLBI ERIC

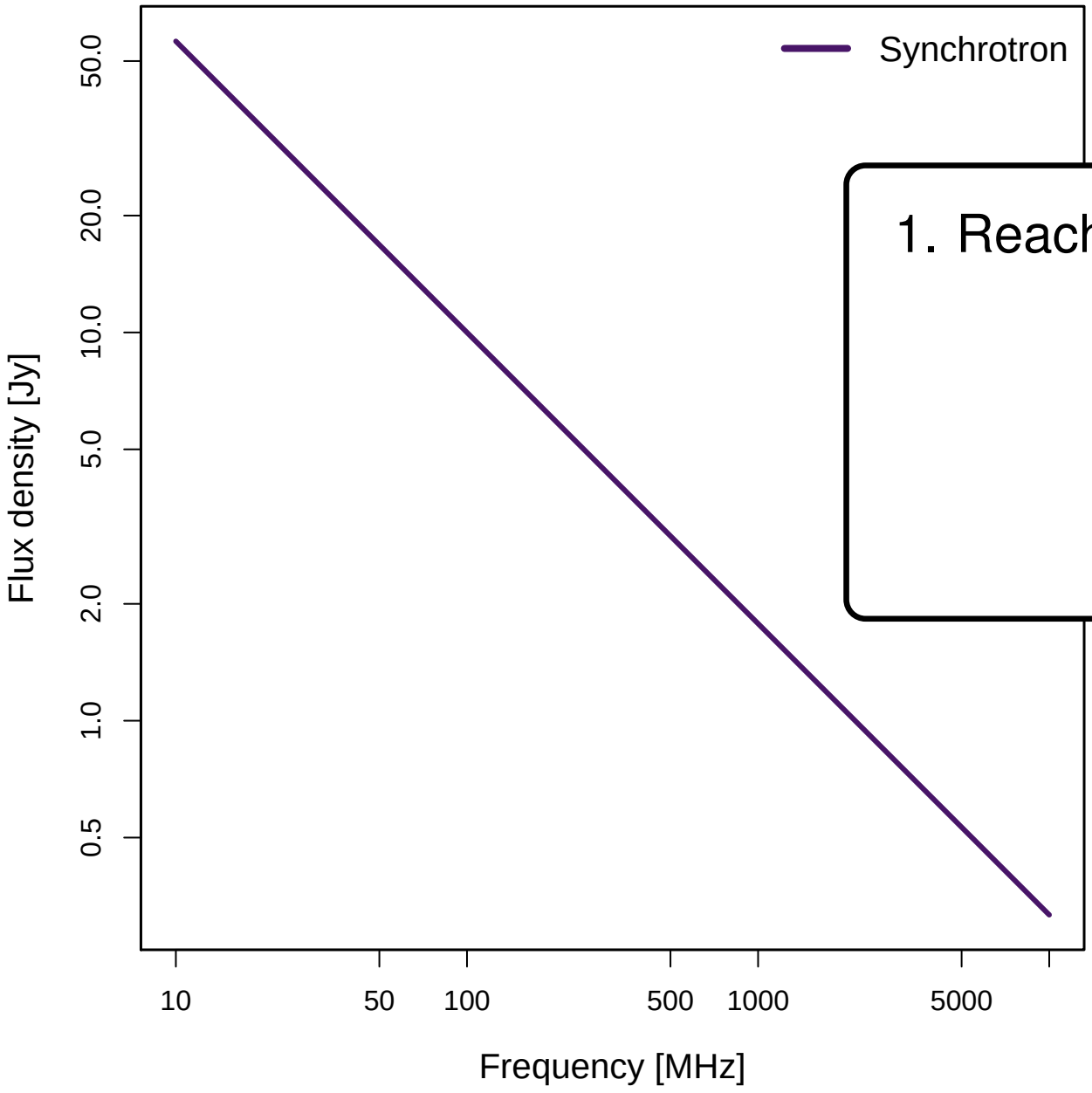
Thanks to collaborators

Busy week ASTRON 2018

Busy week Durham 2019

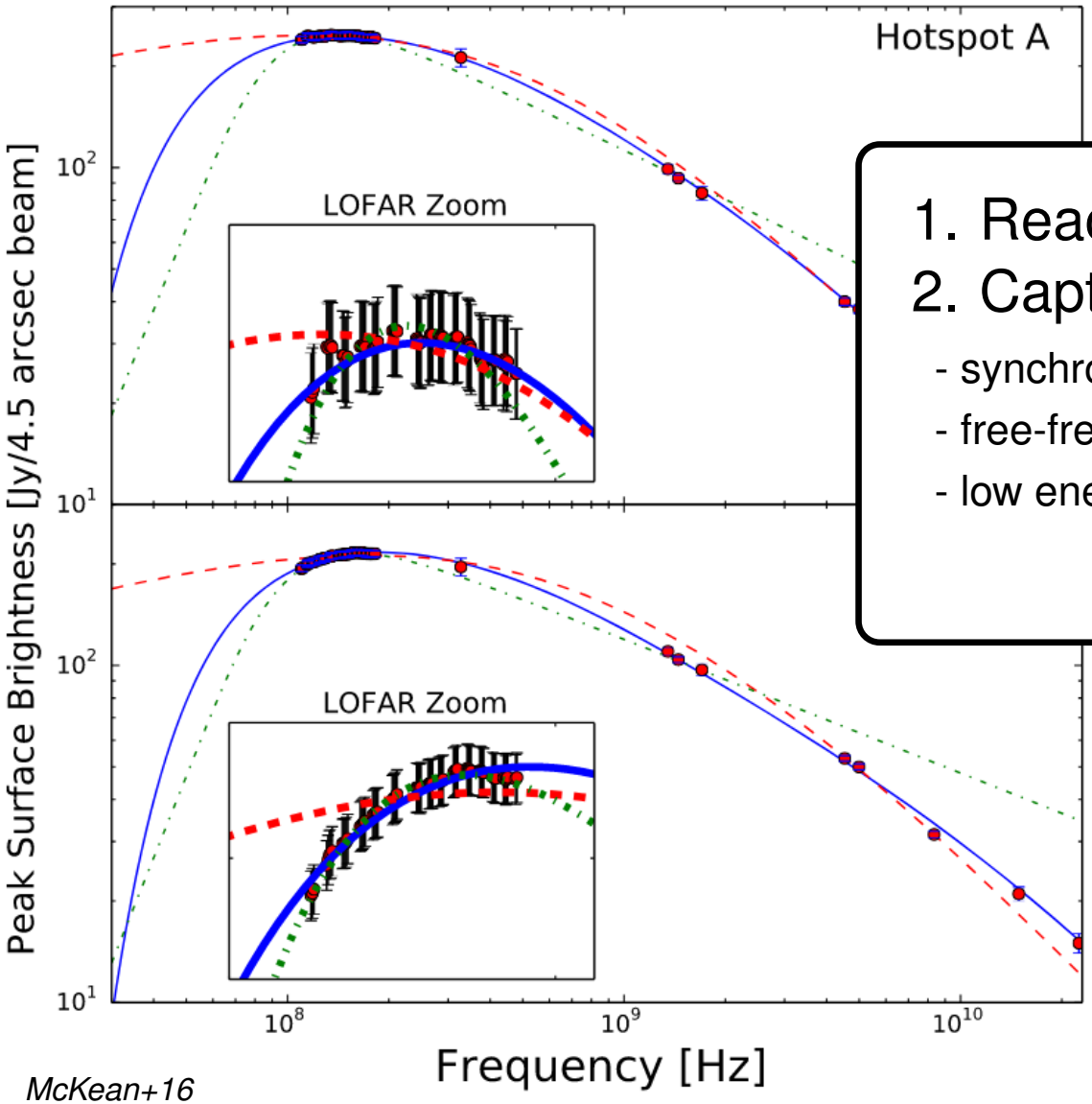
N. Jackson, A. Drabent, S. Mooney, F. Sweijen, S. Badole, E. Bonnasieux, D. Venkattu, M. Iacobelli, O. Wucknitz, A. Deller, M. Hardcastle, T. Shimwell, J. Croston, A. Kappes, A. Tagore, J. Moldón, M. Brentjens, T. Carozzi, G. Gaigals, C. Roskowinski, ASTRON support scientists + others

Why low frequencies?



1. Reach fainter population

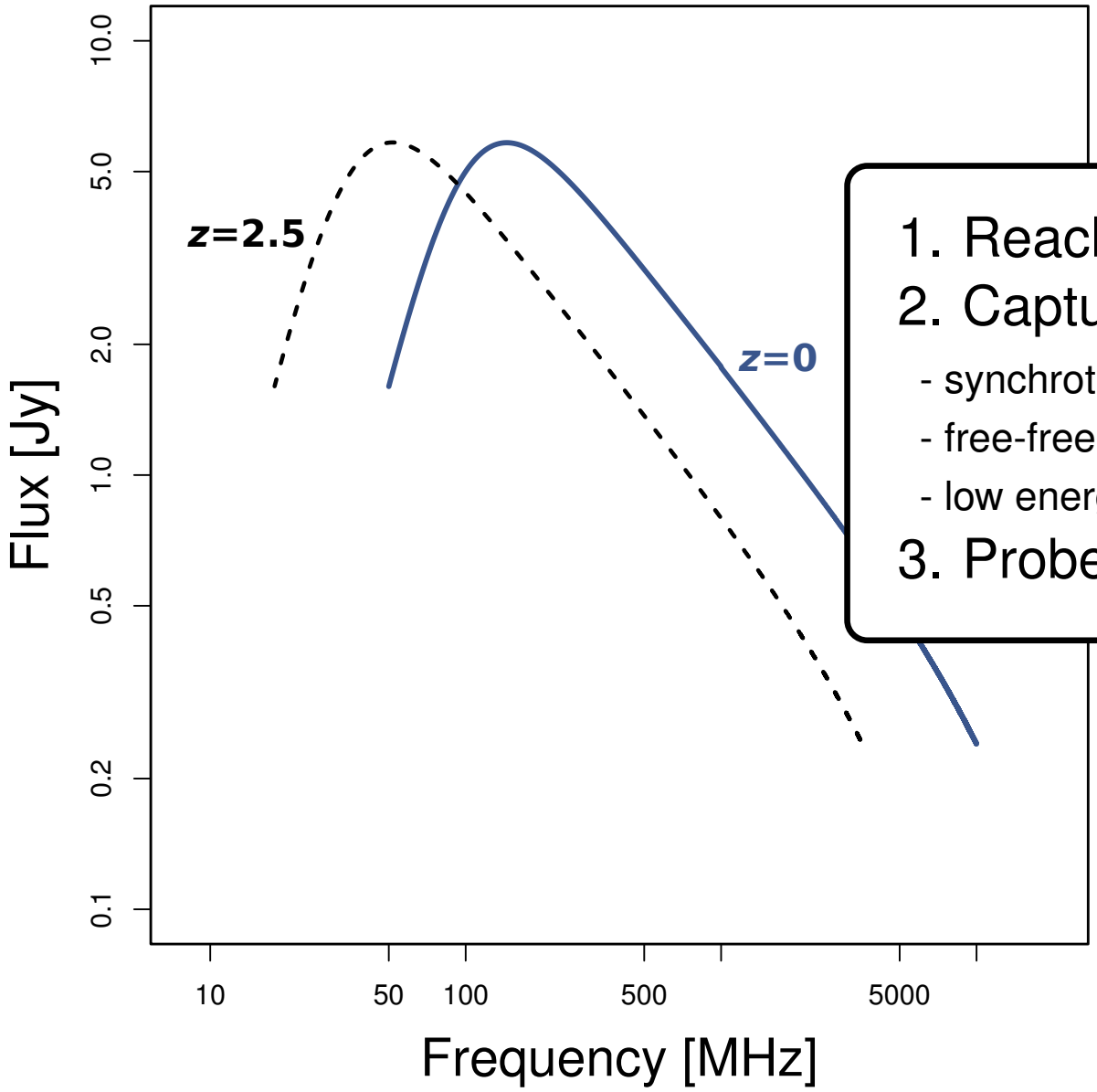
Why low frequencies?



McKean+16

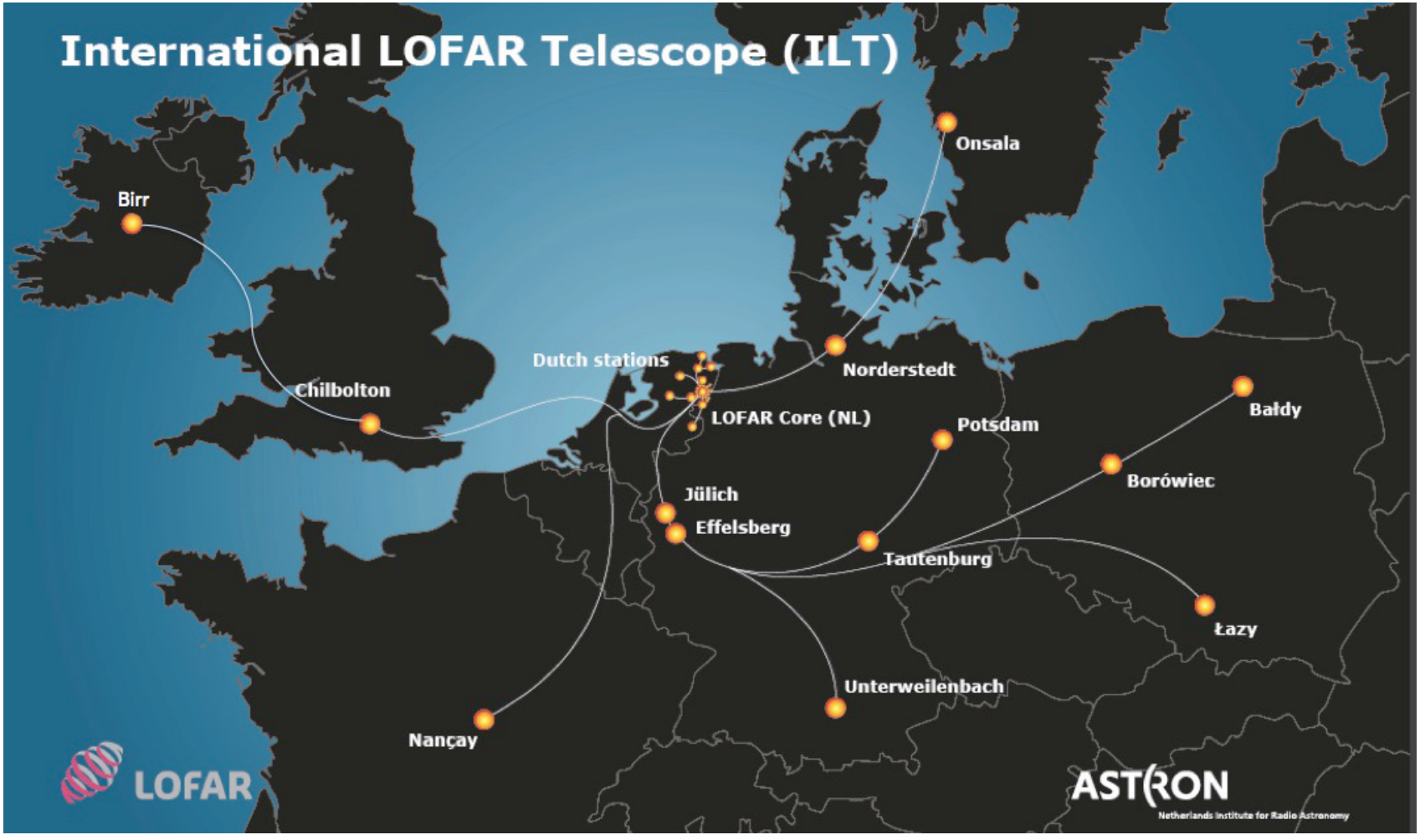
1. Reach fainter population
2. Capture low-ν absorption
   - synchrotron self absorption
   - free-free absorption
   - low energy cutoff

Why low frequencies?

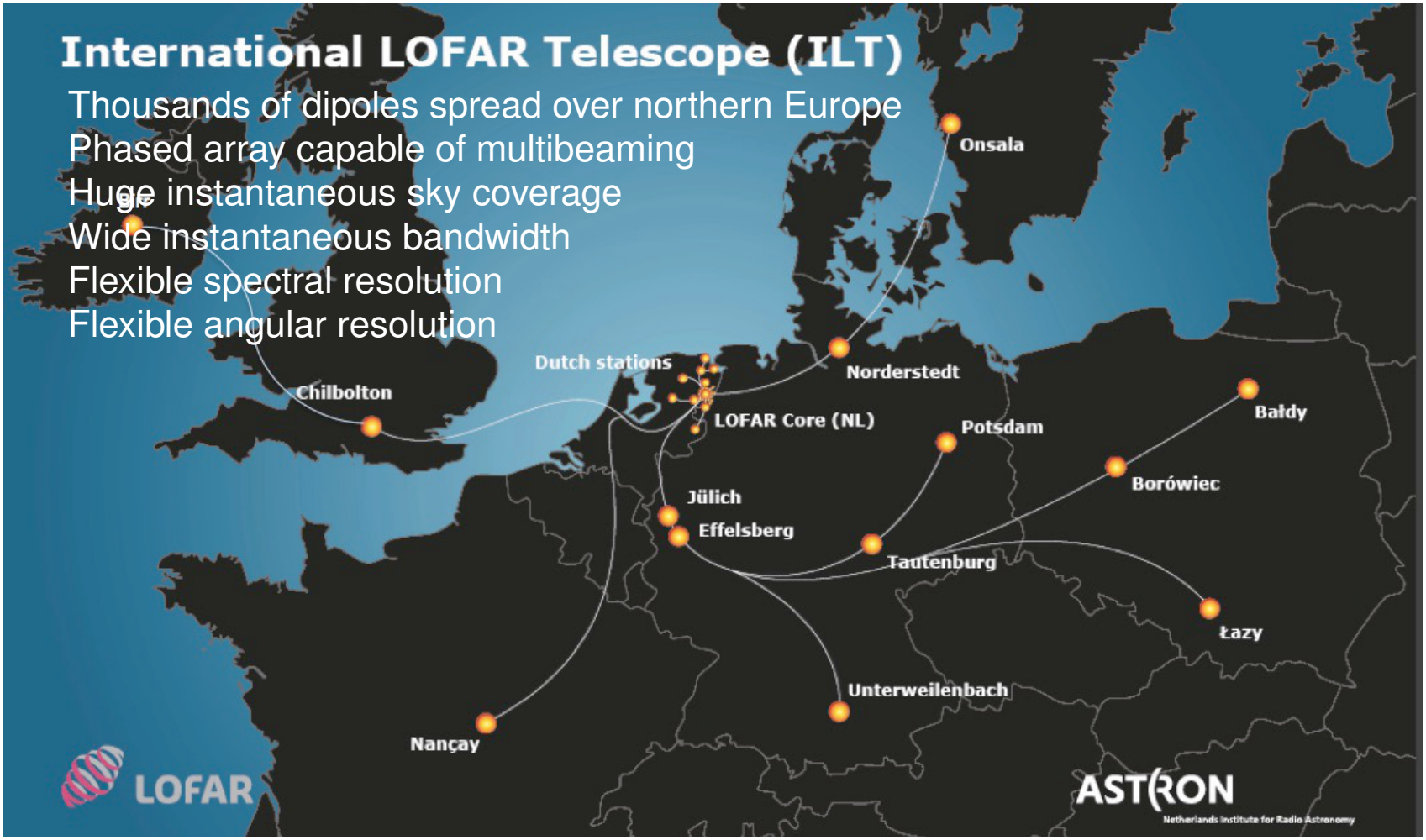


1. Reach fainter population
2. Capture low-ν absorption
   - synchrotron self absorption
   - free-free absorption
   - low energy cutoff
3. Probe lower ν_{rest} for high-z

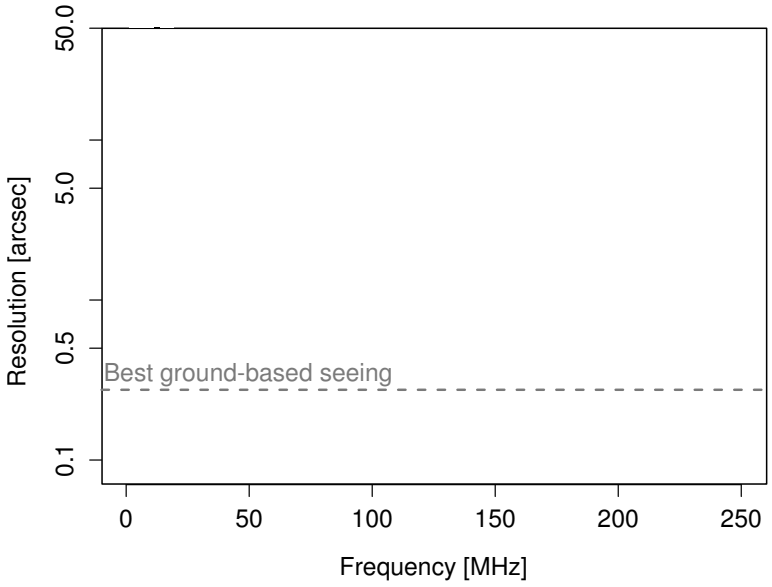
The Low Frequency Array

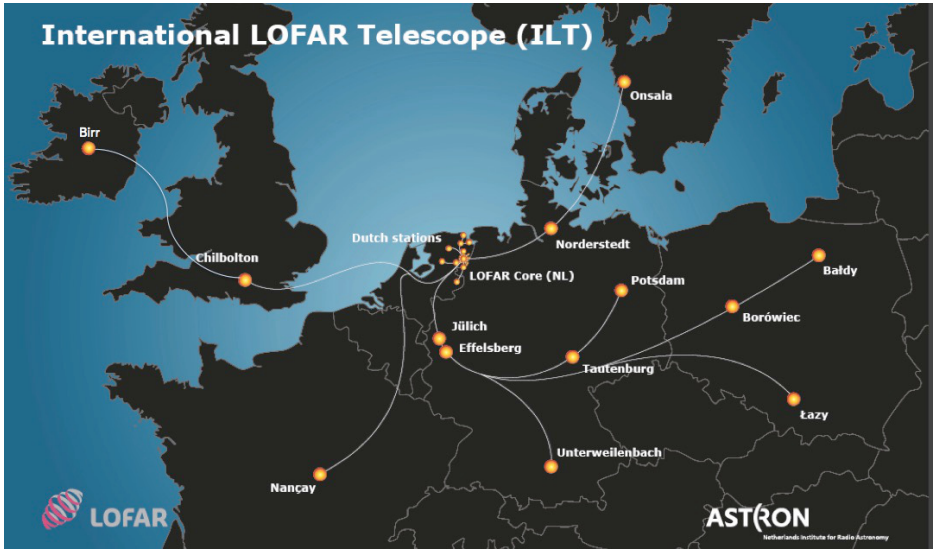


The Low Frequency Array

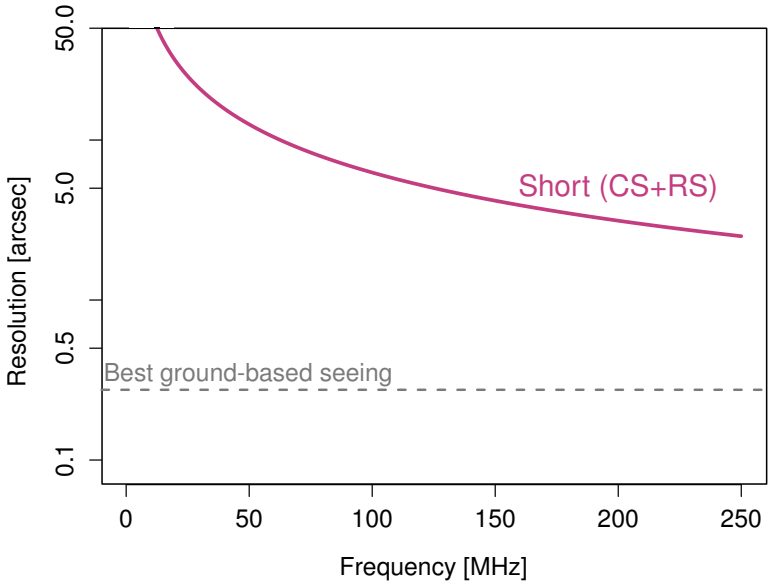


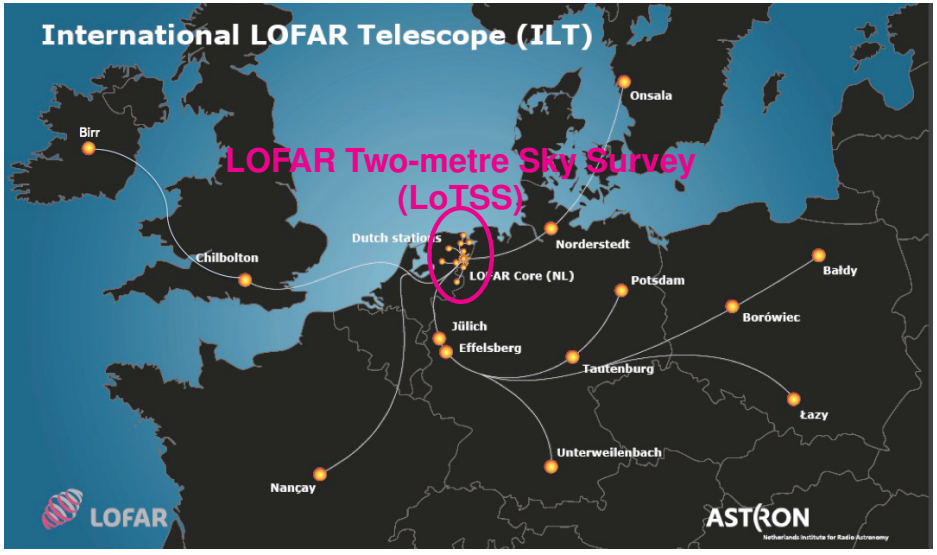
The Low Frequency Array



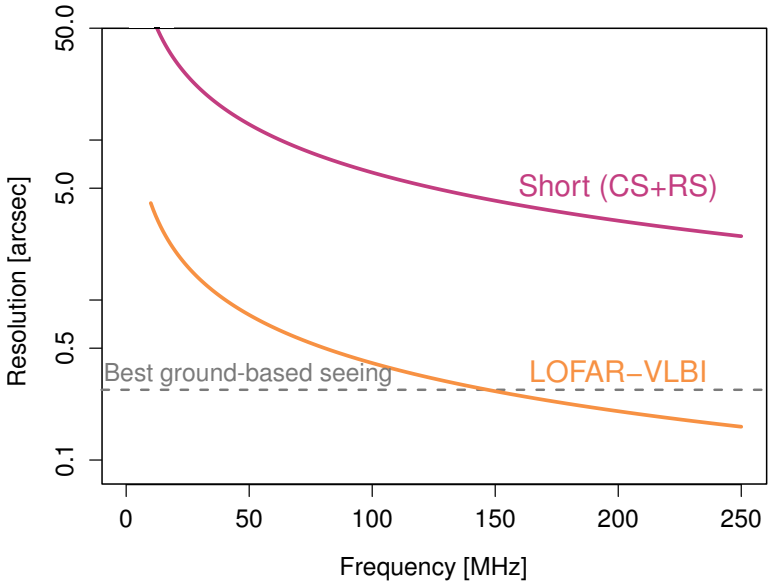


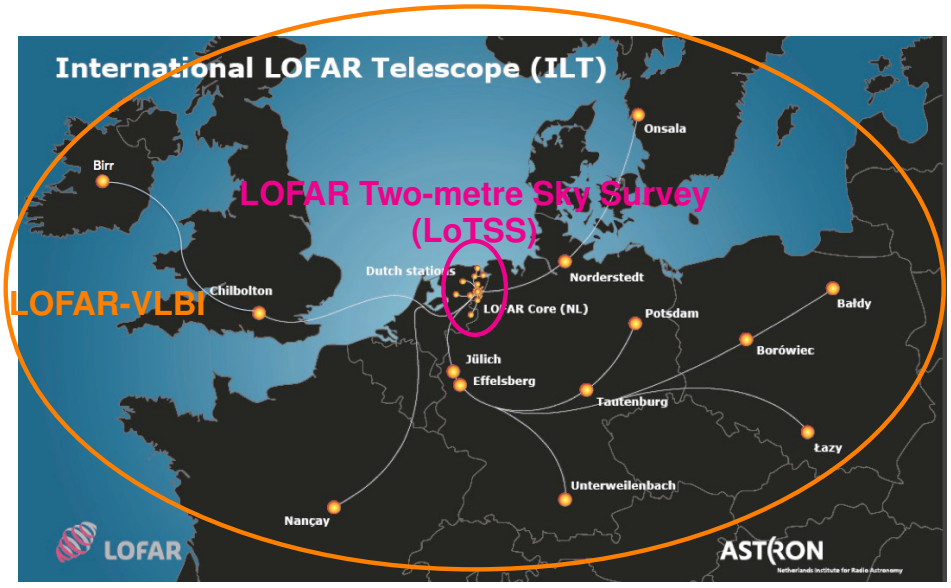
The Low Frequency Array



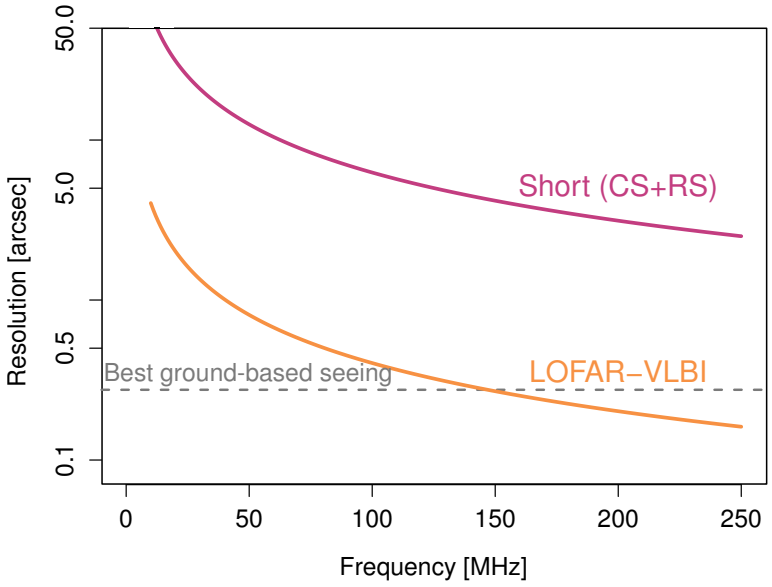


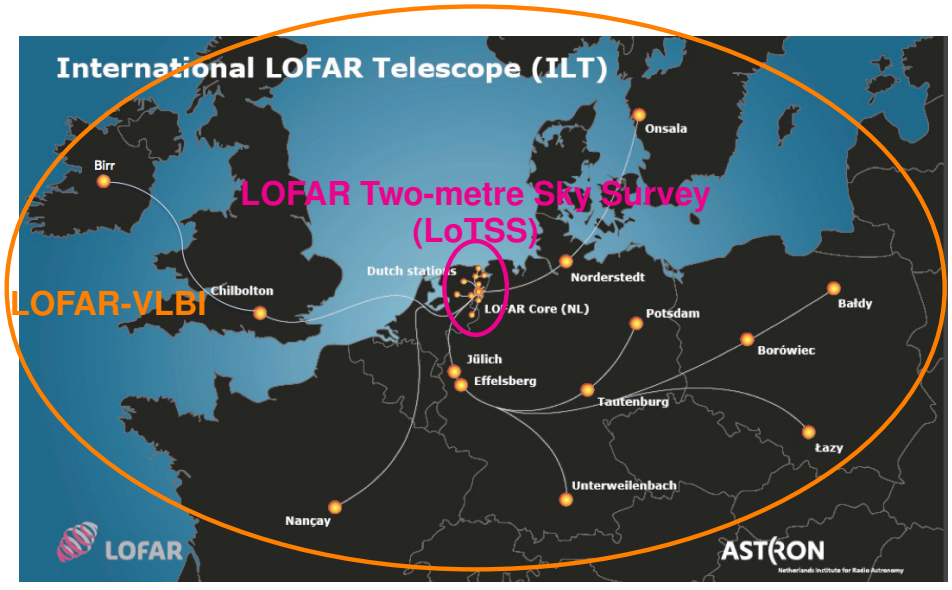
The Low Frequency Array





The Low Frequency Array



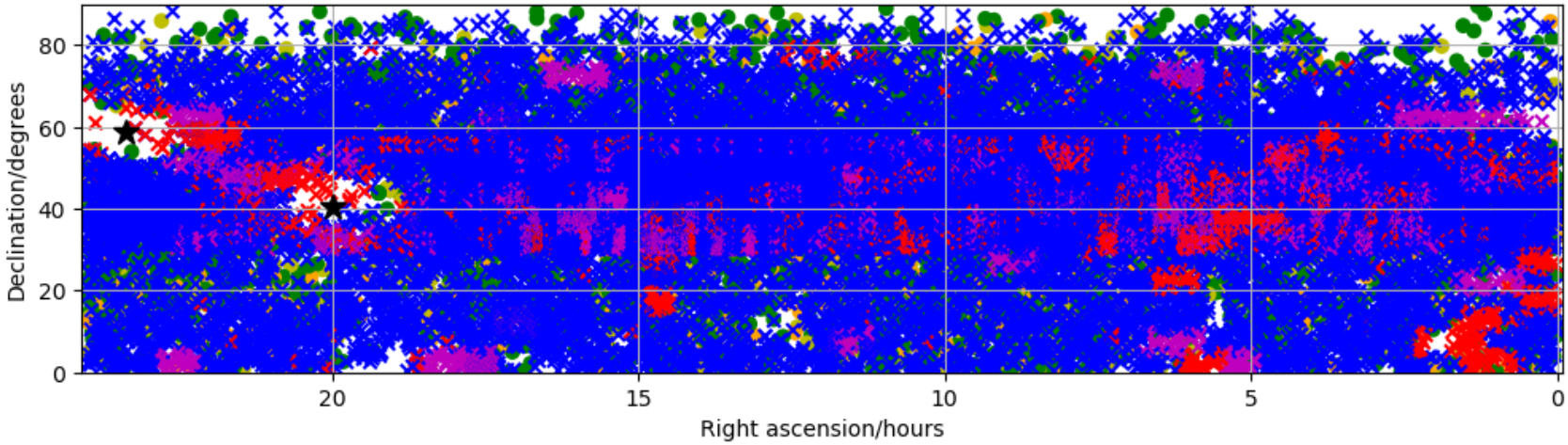


Combining signals from 25,000+ dipoles is very challenging

Data Volume	typical observations are 4 - 20 TB
Clocks	independent station clocks have to be synchronized
Correlator model	baselines up to 2000 km mean lower tolerance for errors
Ionopshere	can be wildly varying with larger impact for longer baselines
Calibrators	need ‘Goldilocks’ calibrators: compact and bright enough
Source structure	*not everything is a point source ...*

LBCS: the Long Baseline Calibrator Survey

Jackson+ 2016, Badole+ in prep.

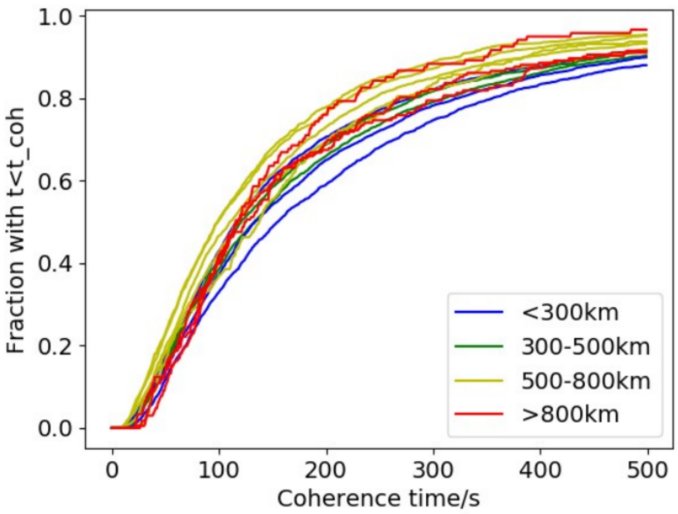


- Selection: bright at low ν, flat low-ν spectral index
- Multibeaming: groups of 30 with 3 MHz bandwidth, 3 minutes each
- Finished 3 months ago – 25,000 sources!
- Covers all Northern sky except around Cas A / Cyg A
- Coherence statistics to baselines of $\sim$2000 km
- **About one good calibrator per square degree**

LBCS: the Long Baseline Calibrator Survey

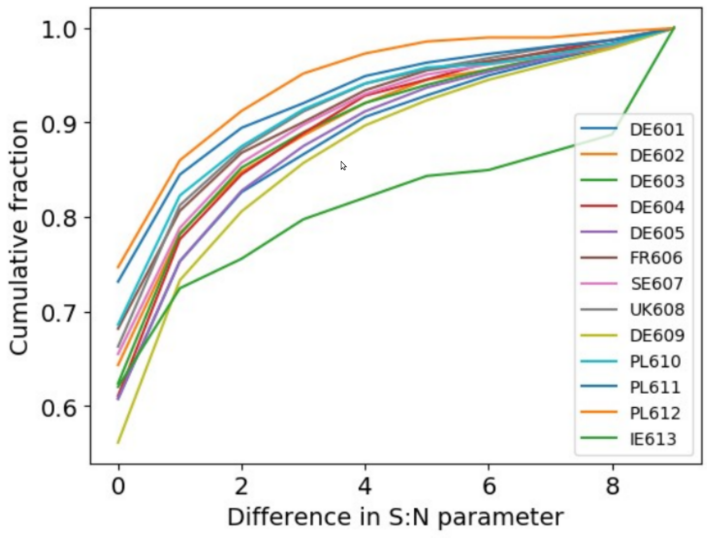
Jackson+ 2016, Badole+ in prep.

Atmospheric coherence statistics



Coherence time is worse on longer baselines, but the effect is not huge

Reproducibility



Sources observed more than once: results very similar for all baselines

High resolution imaging with LOFAR

We developed a calibration strategy for high resolution imaging at < 200 MHz, building on some VLBI techniques

High resolution imaging with LOFAR

We developed a calibration strategy for high resolution imaging at < 200 MHz, building on some VLBI techniques

fringe-fitting, which estimates *delay* and *rate* in addition to phase errors:

$$\Delta\phi_{\nu,t} = \phi_0 + \left(\frac{\delta\phi}{\delta\nu}\Delta\nu + \frac{\delta\phi}{\delta t}\Delta t\right)$$

does not account for *dispersive* effects, which are dominant at low frequencies:

$$\Delta\phi_{\nu,t} \propto \nu^{-2}$$

solve directly for dispersive delays before self-cal

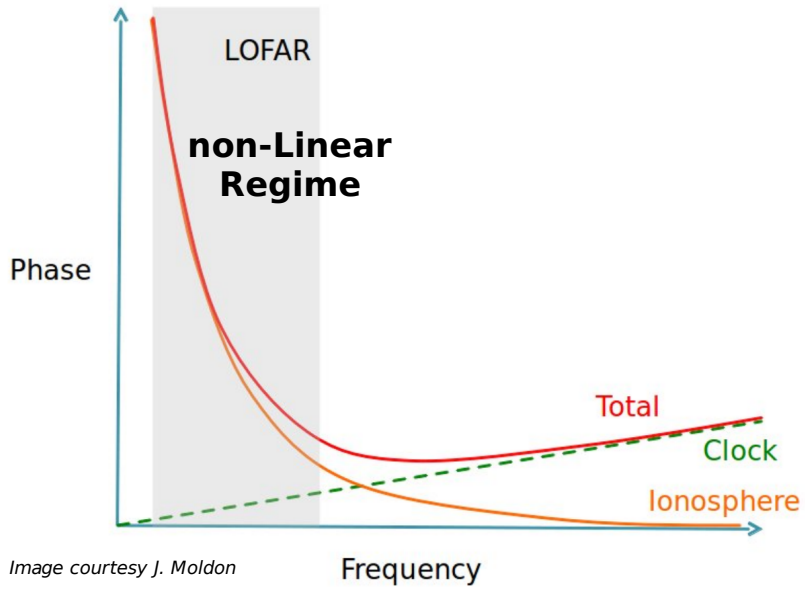


Image courtesy J. Moldon

High resolution imaging with LOFAR

We developed a calibration strategy for high resolution imaging at < 200 MHz, building on some VLBI techniques

fringe-fitting, which estimates *delay* and *rate* in addition to phase errors:

$$\Delta\phi_{\nu,t} = \phi_0 + \left(\frac{\delta\phi}{\delta\nu}\Delta\nu + \frac{\delta\phi}{\delta t}\Delta t\right)$$

does not account for *dispersive* effects, which are dominant at low frequencies:

$$\Delta\phi_{\nu,t} \propto \nu^{-2}$$

solve directly for dispersive delays before self-cal

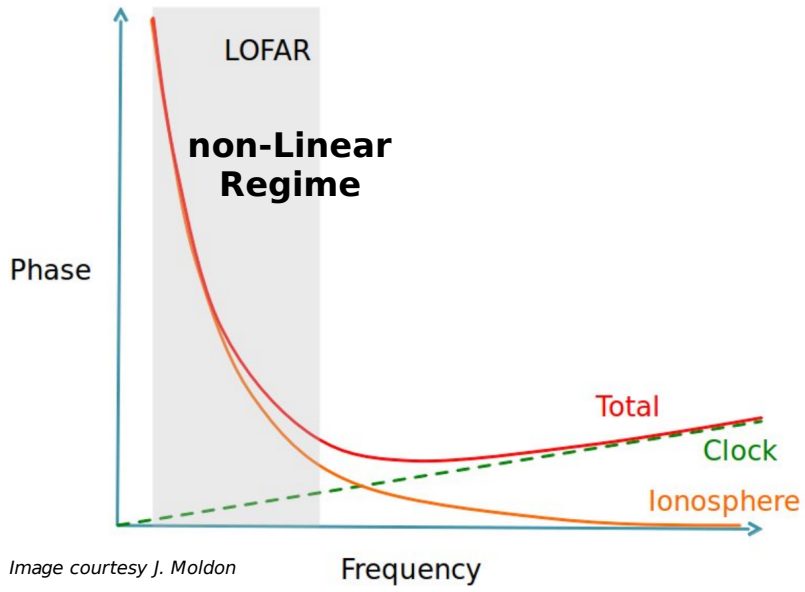


Image courtesy J. Moldon

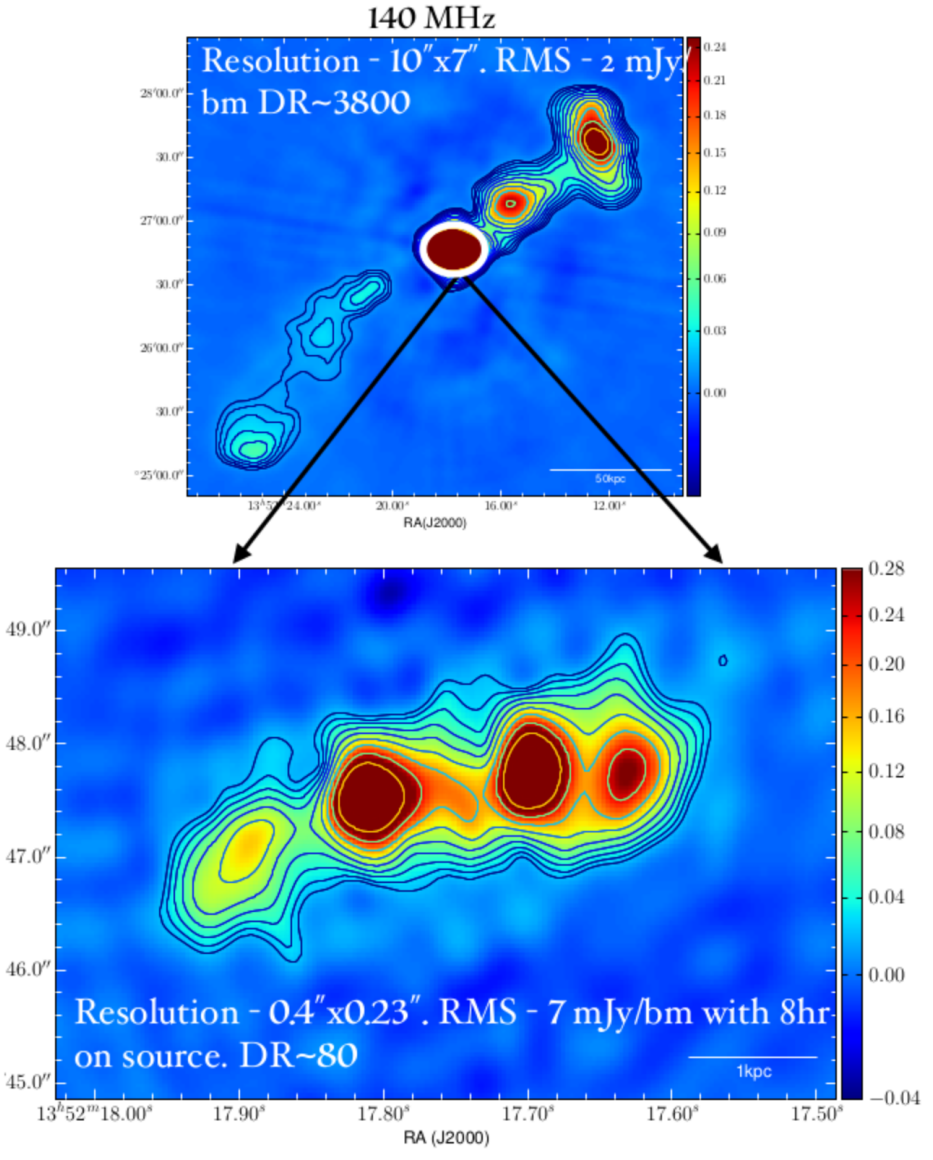
A pipeline exists, with a major software release early June 2020

L. Morabito, N. Jackson, F. Sweijen, S. Mooney, A. Drabent, S. Badole, J. Croston, E. Bonnasieux, D. Venkattu, M. Iacobelli, M. Pommier, A. Kappes, + others

Paper to be submitted by end of 2020

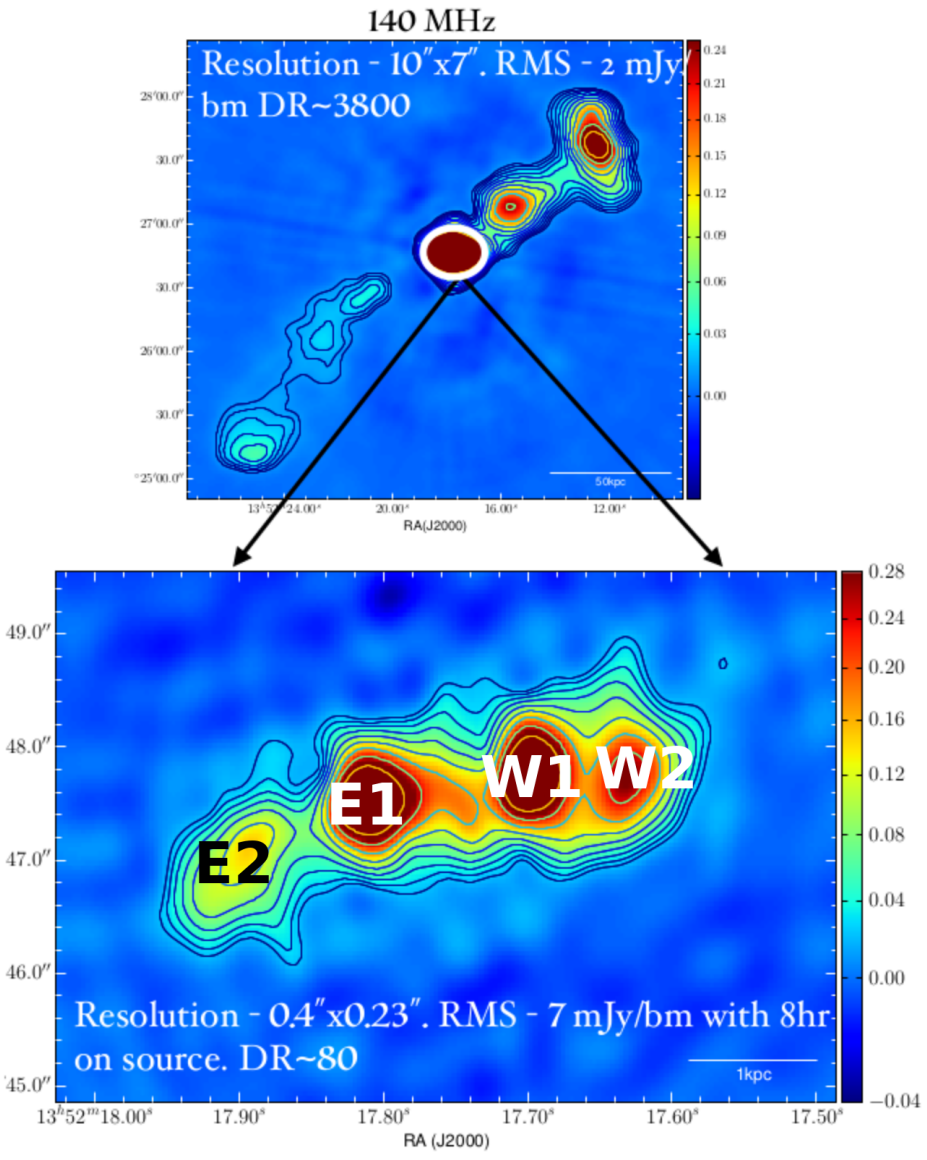
Science highlights

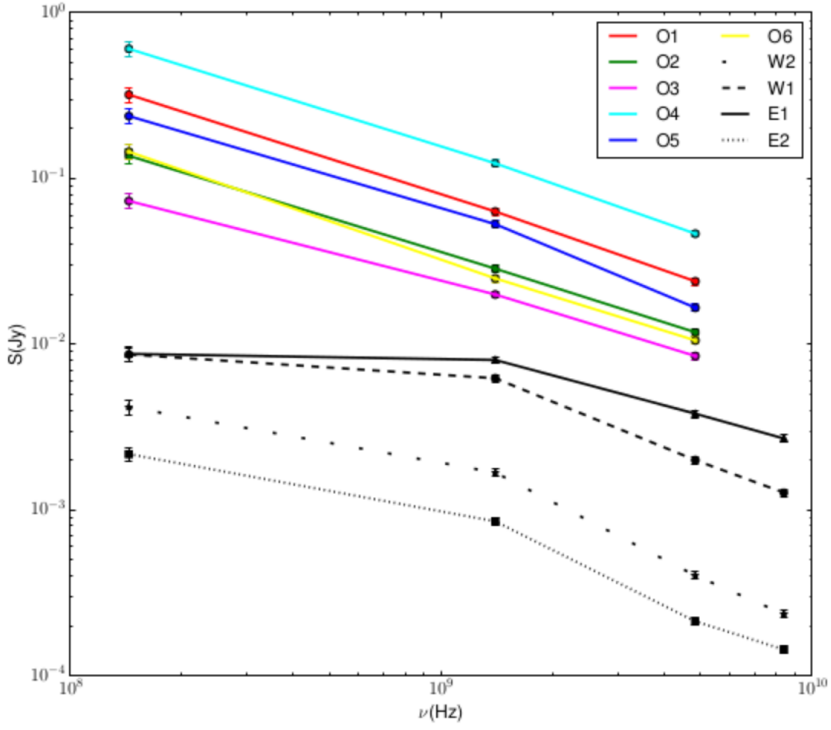
3C 293 *(P. Kukreti+ in prep.)*



Science highlights

3C 293 *(P. Kukreti+ in prep.)*



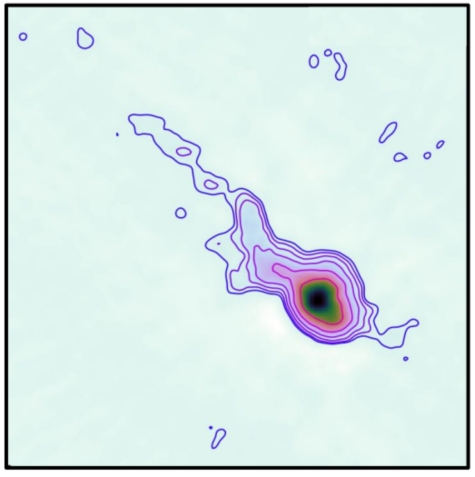


Inner lobes have turnover in spectra, consistent with free-free absorption and western lobe receding

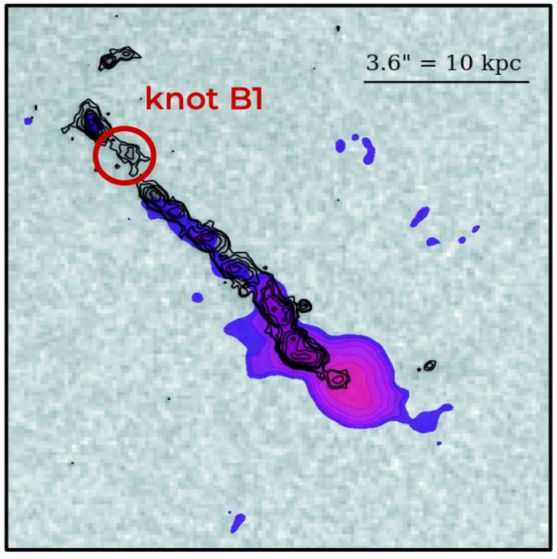
consistent with jet/ISM interaction as traced by ionised outflows

Science highlights

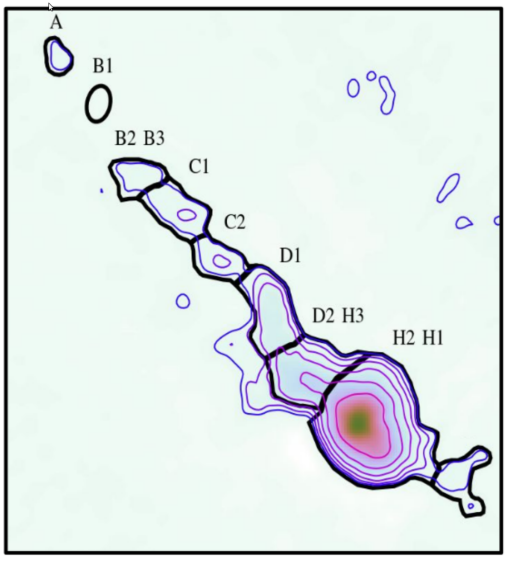
3C 273 *(S. Mooney+ in prep.)*



LOFAR (image, contours)



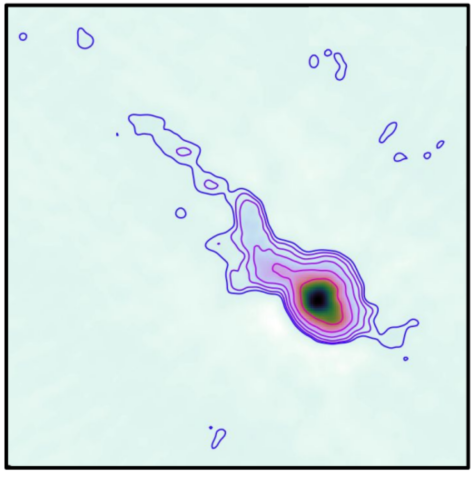
HST (image, contours),
LOFAR (filled contours)



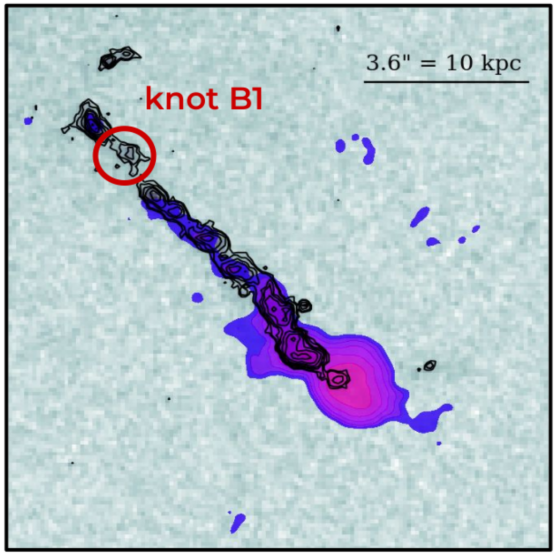
LOFAR image with knots marked

Science highlights

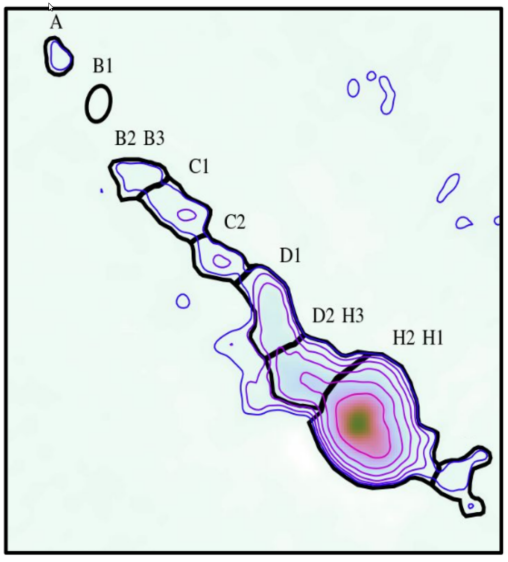
3C 273 *(S. Mooney+ in prep.)*



LOFAR (image, contours)



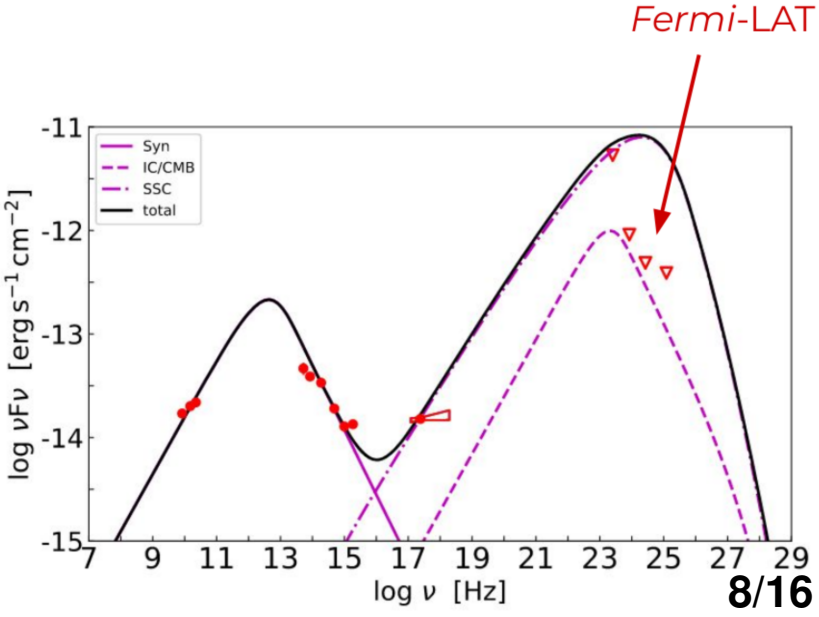
HST (image, contours),
LOFAR (filled contours)



LOFAR image with knots marked

Radio SED can help constrain X-ray emission mechanisms

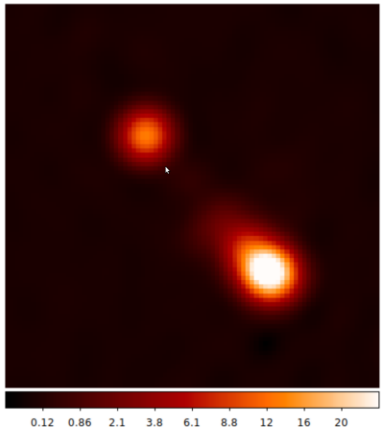
LOFAR will extend radio by 1-2 orders of magnitude



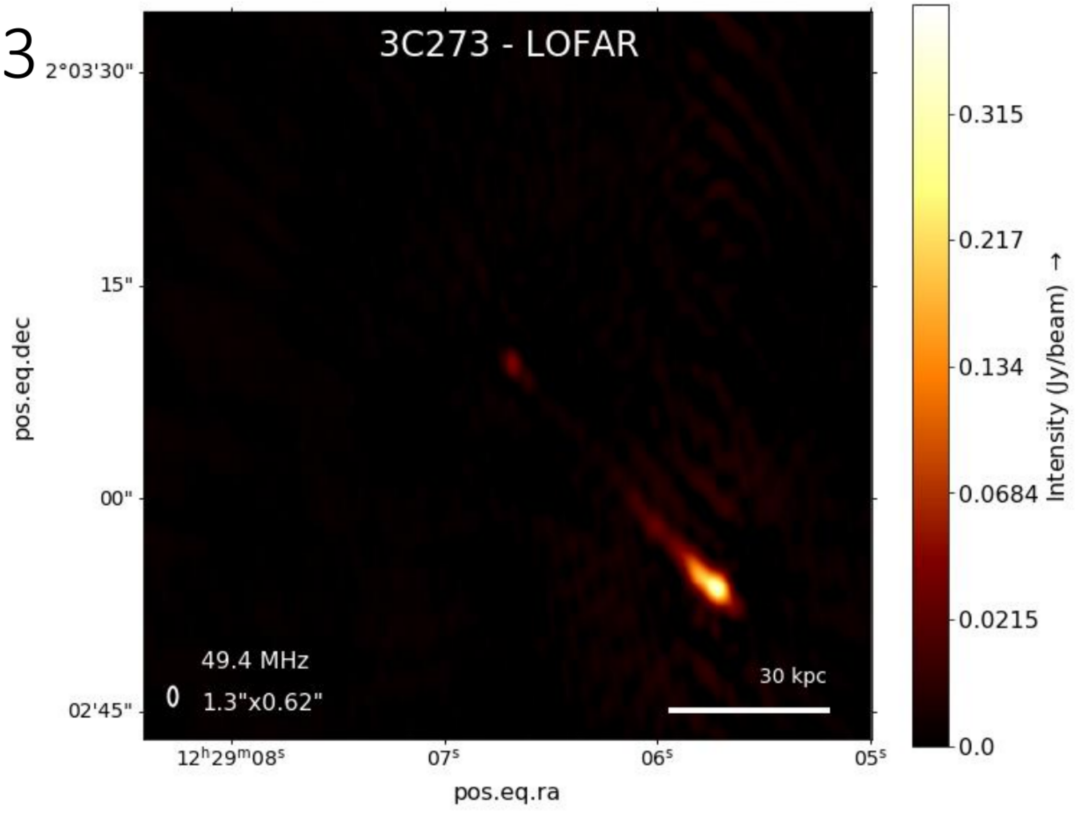
Science highlights

LBA results ∼50 MHz! *(C. Groeneveld+ in prep.)*

Results – 3C 273



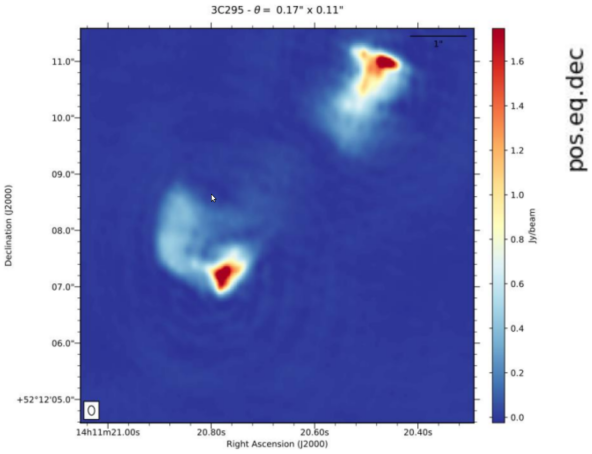
VLA P-band
Credit: Perley, Taylor (1991)



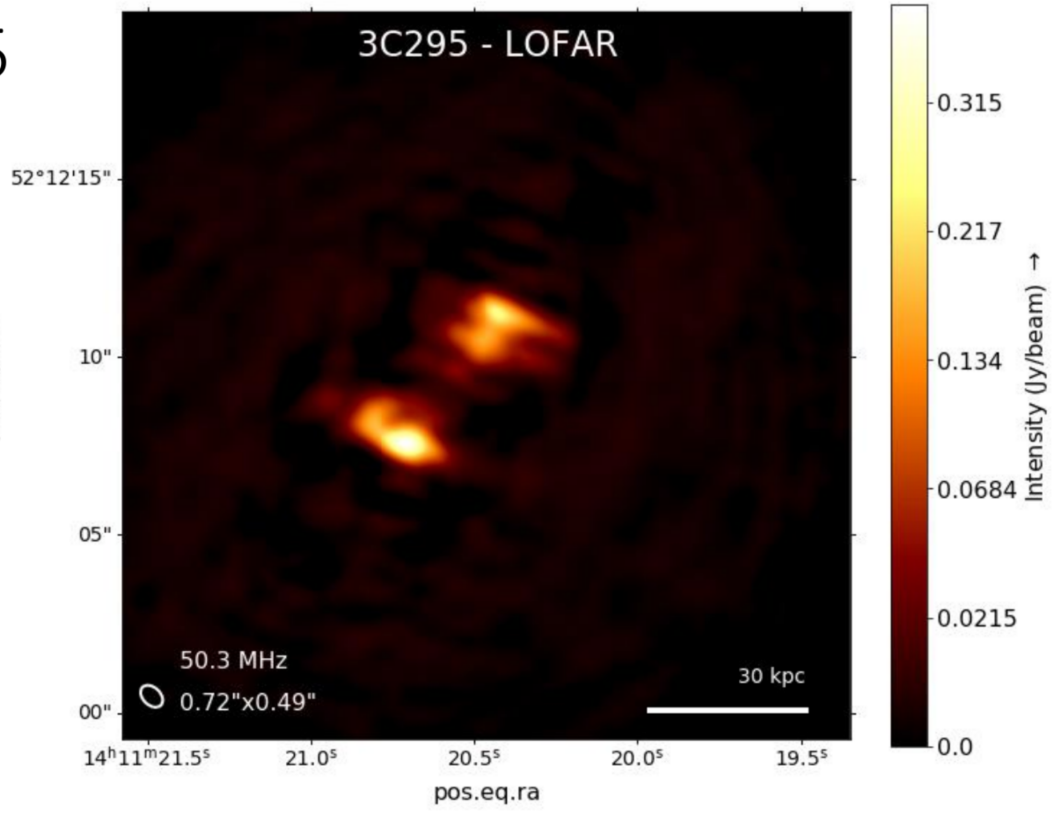
Science highlights

LBA results ∼50 MHz! *(C. Groeneveld+ in prep.)*

Results – 3C 295



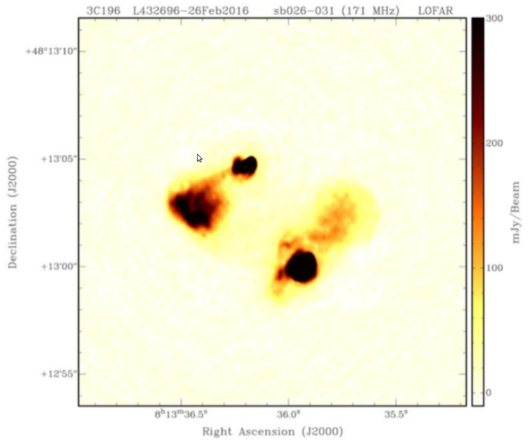
Credit: Frits Sweijen



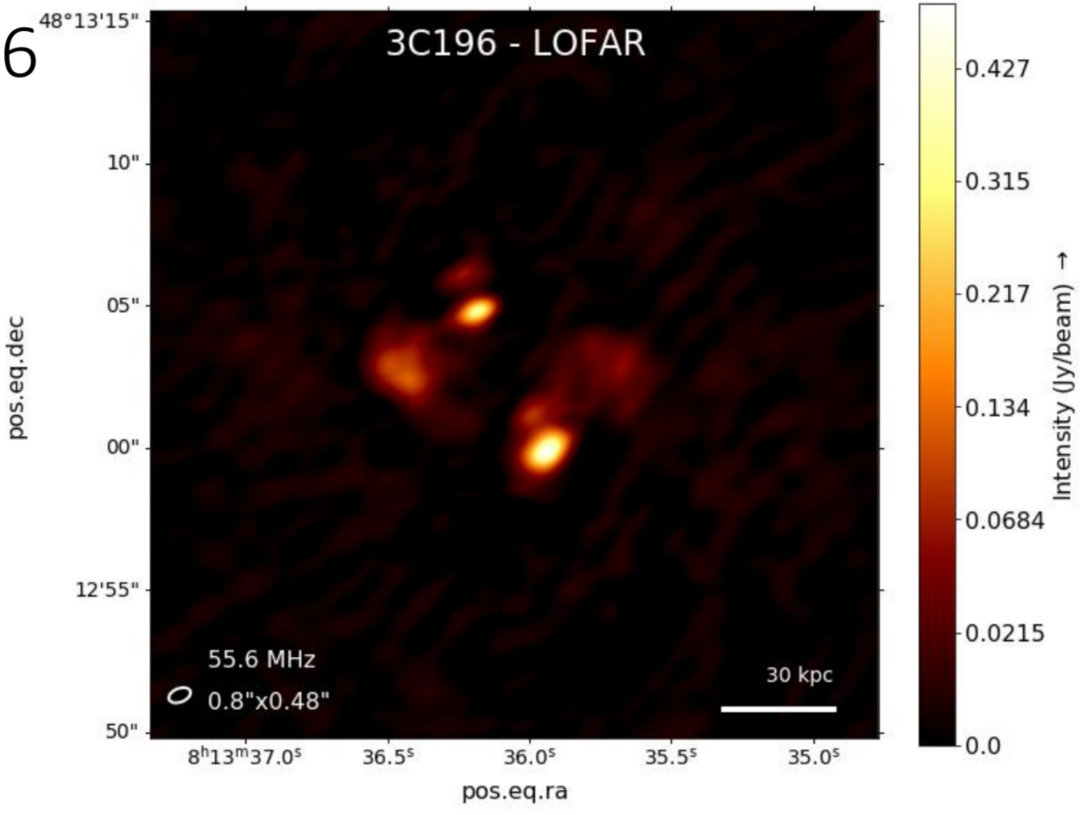
Science highlights

LBA results ∼50 MHz! *(C. Groeneveld+ in prep.)*

Results – 3C 196



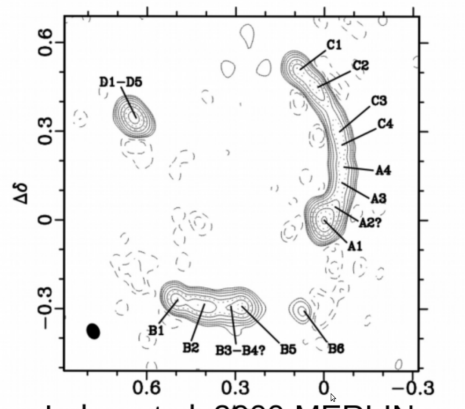
Credit: Ger de Bruyn



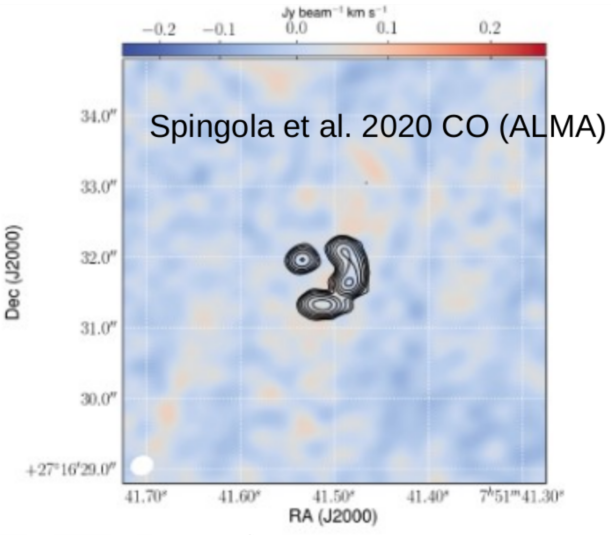
Science highlights

Gravitational Lenses *(D. Venkattu, N. Jackson+ in prep.)*

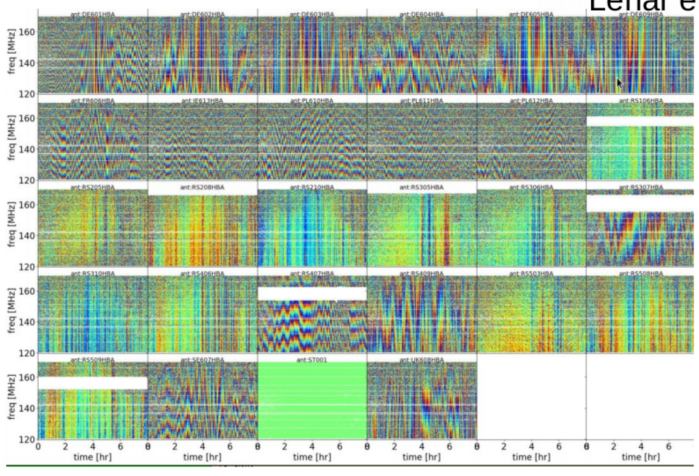
MG0751+2716

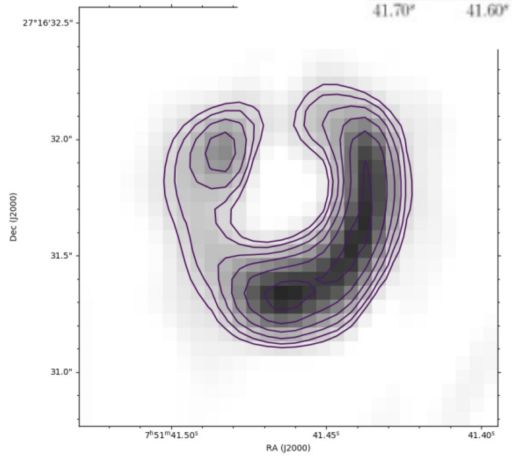


Lehar et al. 2000 MERLIN



Spingola et al. 2020 CO (ALMA)





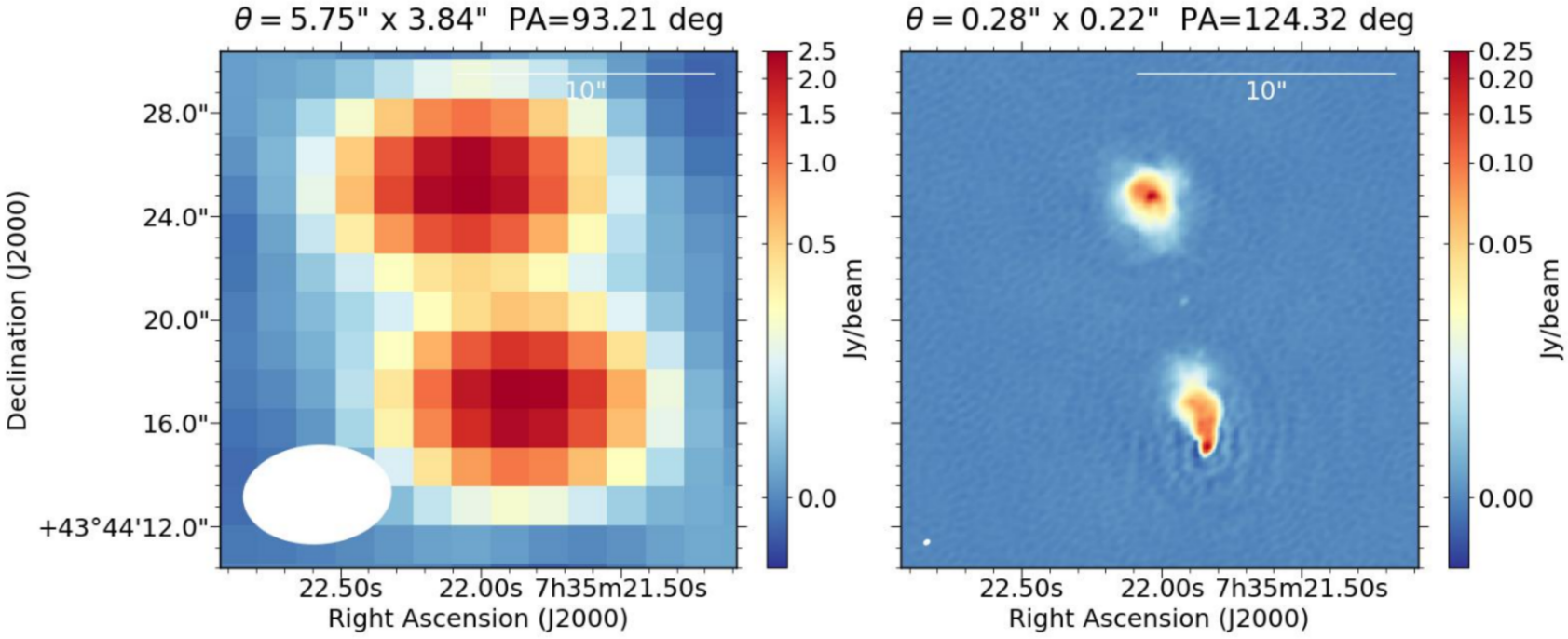
I-LOFAR 150MHz

Modelling to do

(Venkattu et al.)

Science highlights

4C 43.15 ($z = 2.429$) *(F. Sweijen+ in prep.)*



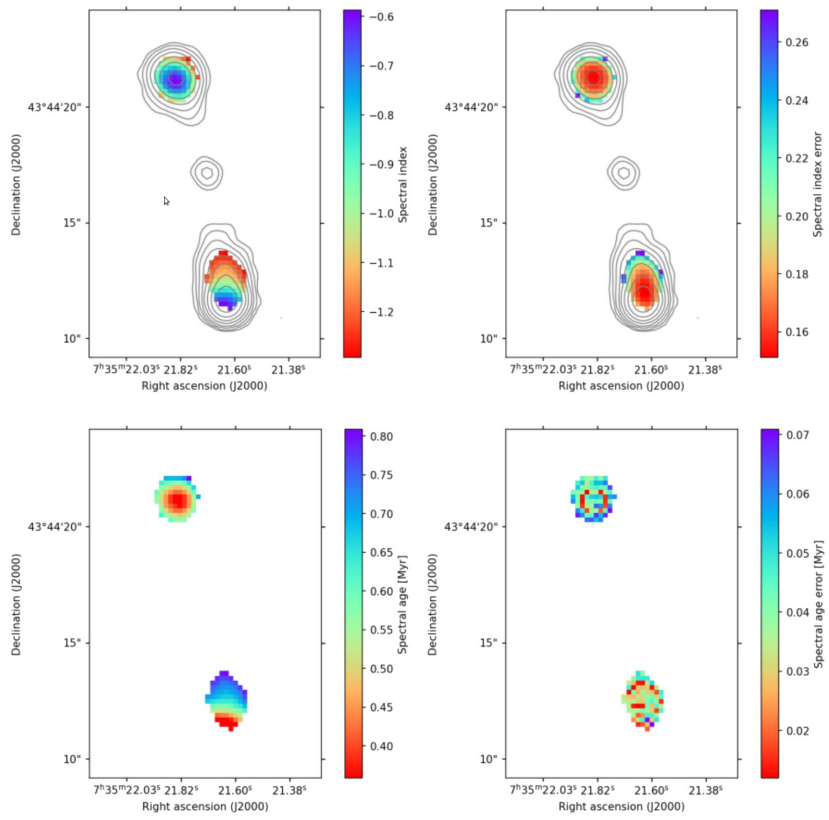
Science highlights

4C 43.15 ($z = 2.429$) *(F. Sweijen+ in prep.)*

Results

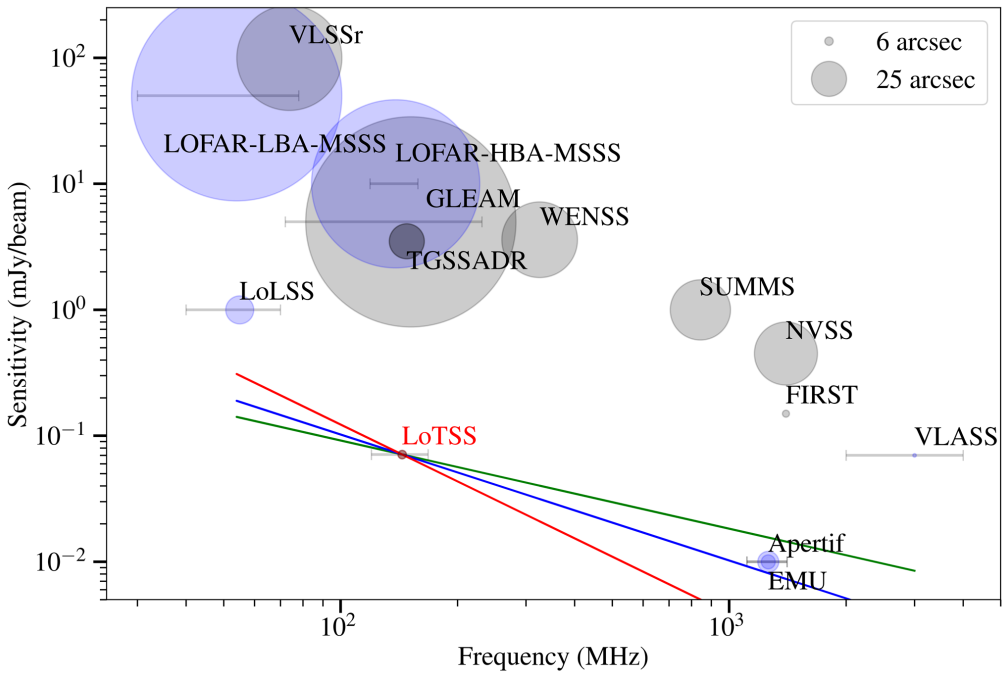
- Strong magnetic field, but close to CMB
  - B = 5.2 nT and B_{CMB} = 3.7 nT
- Spectral index (top) and age (bottom) distribution at 0.9'' resolution

	North	South
Injection index	-0.8	-0.7
Spectral age [Myr]	0.81 +/- 0.06	0.90 +/- 0.6
Advance speed [*c*]	0.14	0.17



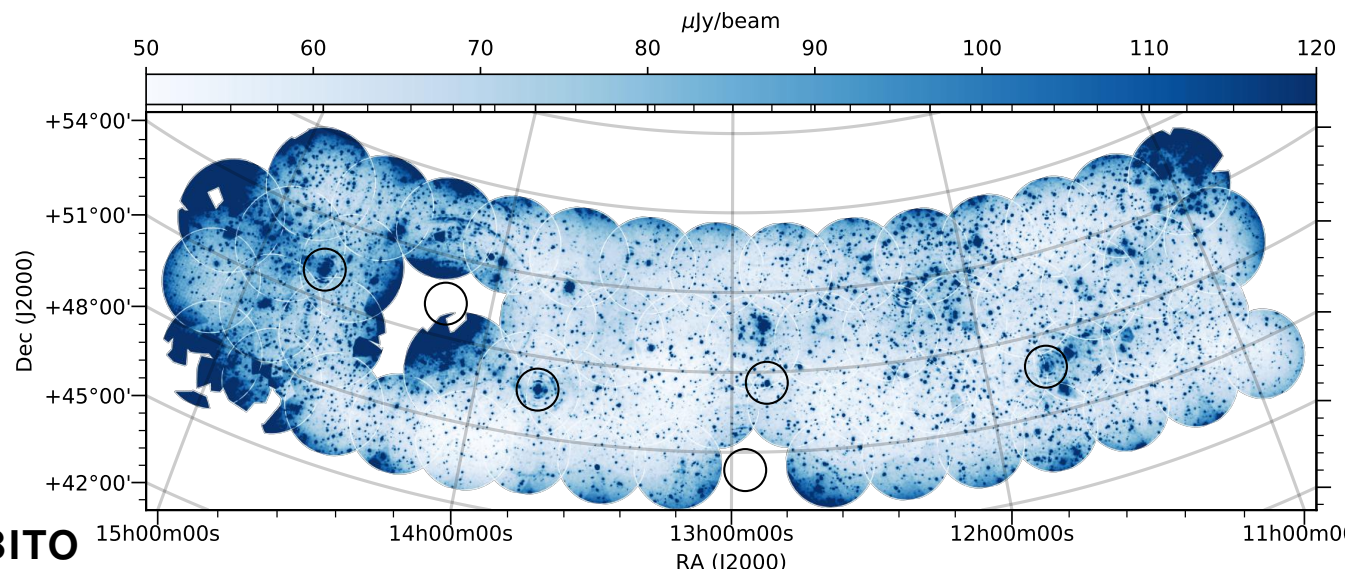
LOFAR Two-metre Sky Survey

Shimwell+19; Williams+19; Duncan+19



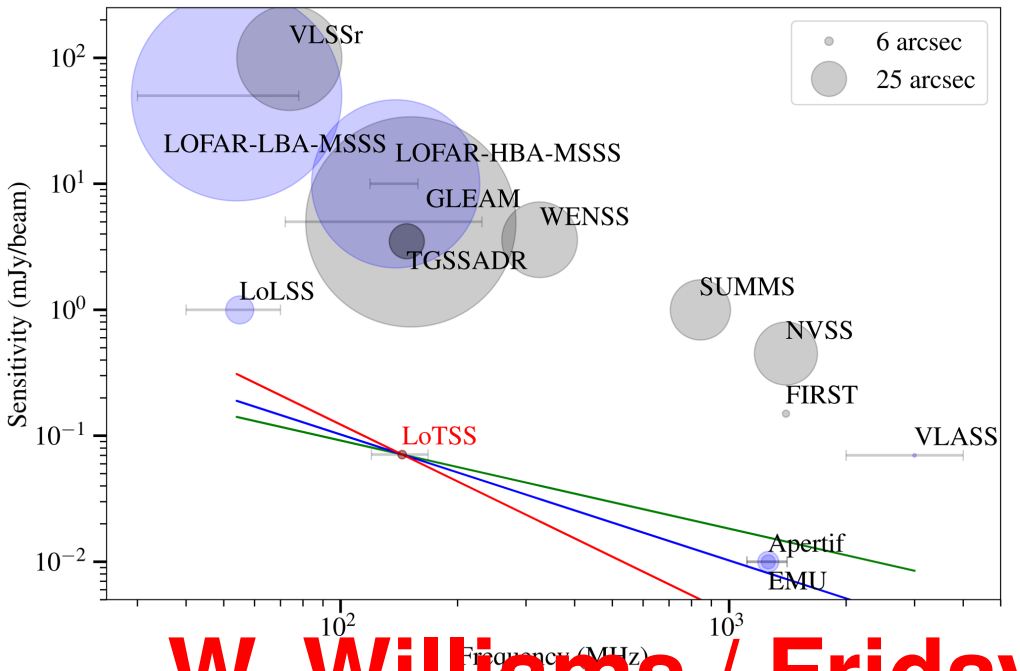
Northern sky survey
Dutch LOFAR stations
120 - 168 MHz
6″ resolution
rms $\sim$ 70 μJy bm^{-1}

Data Release 1, Feb 2019
424 deg^2
320,000+ sources



LOFAR Two-metre Sky Survey

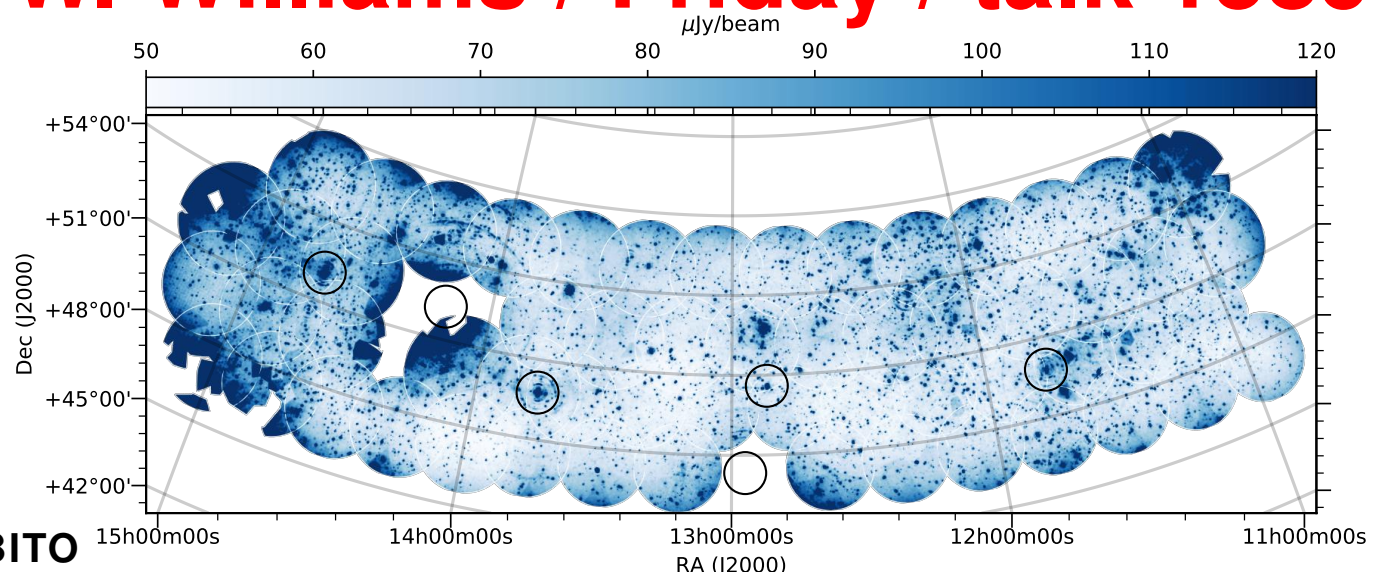
Shimwell+19; Williams+19; Duncan+19



Northern sky survey
Dutch LOFAR stations
120 - 168 MHz
6″ resolution
rms $\sim$ 70 μJy bm^{-1}

Data Release 1, Feb 2019
424 deg^2
320,000+ sources

W. Williams / Friday / talk 1589

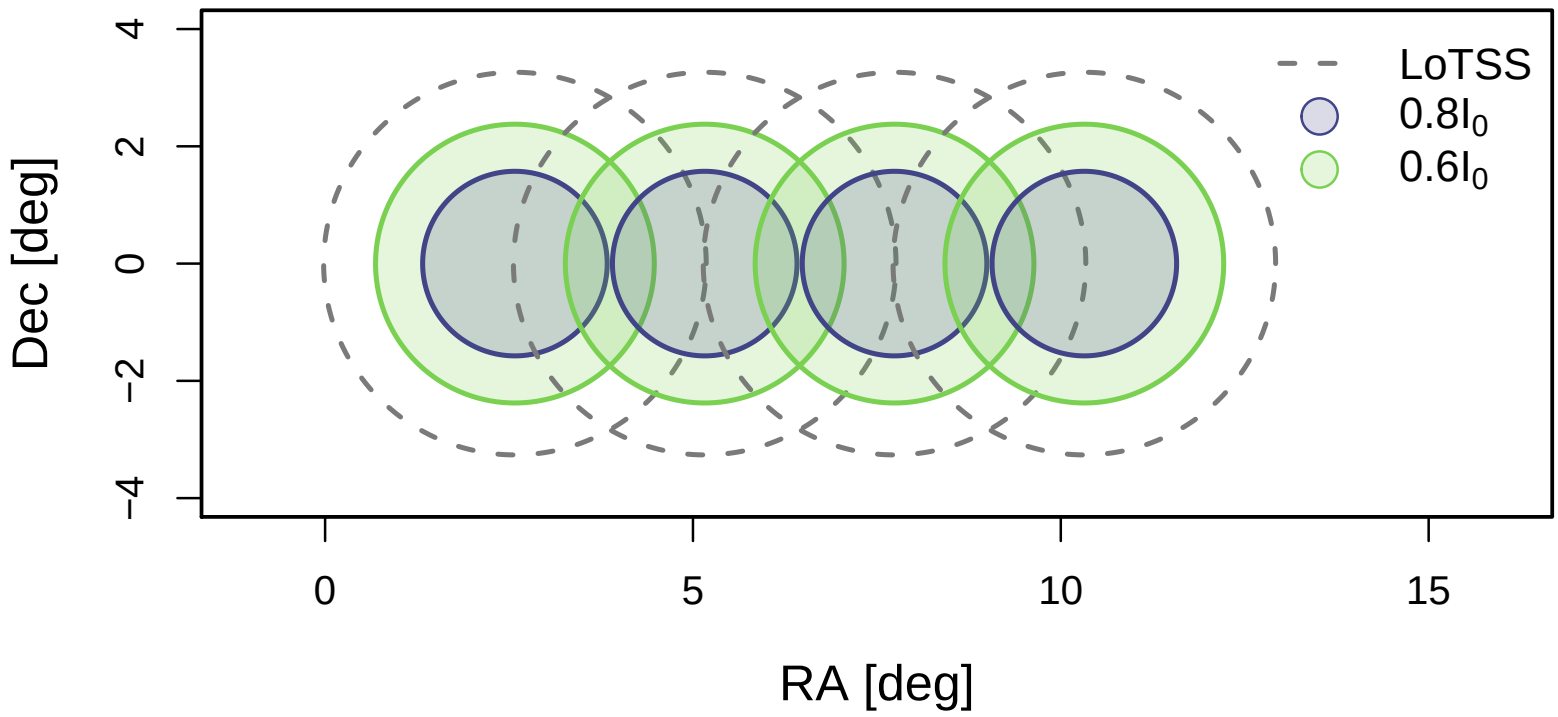


LoTSS at high resolution

Post-processing the LOFAR Two-metre Sky Survey

- Data recorded with all stations, currently only Dutch stations processed
- Entire Northern sky (including Deep fields, e.g. Lockman Hole, etc.)
- Field of view limited by data averaging + station beams

$\sim$1.15 deg radius at 80 percent intensity still provides good coverage

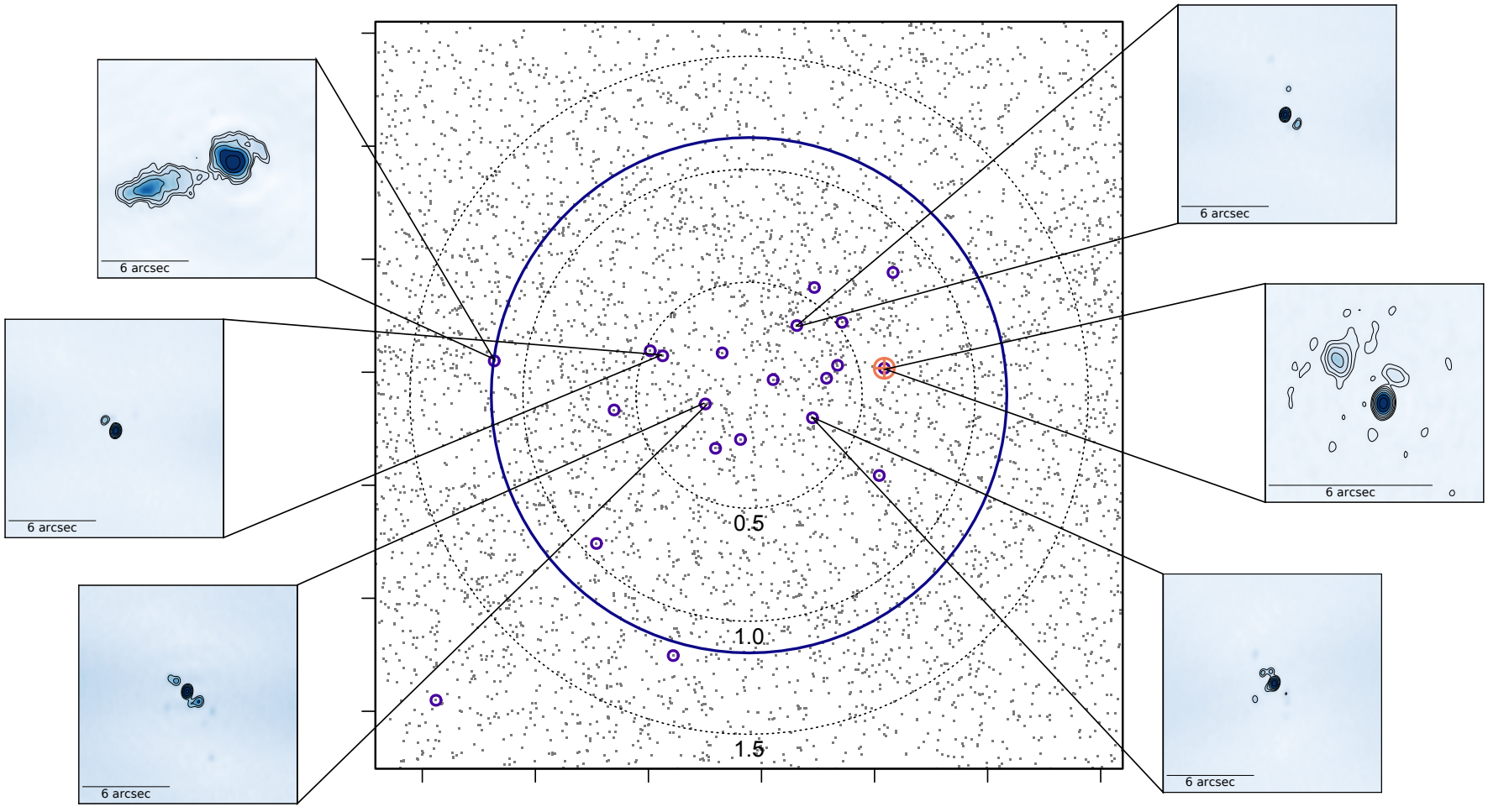


LoTSS at high resolution

P205+55: a typical survey field with several $\sim$Jy sources

LoTSS at high resolution

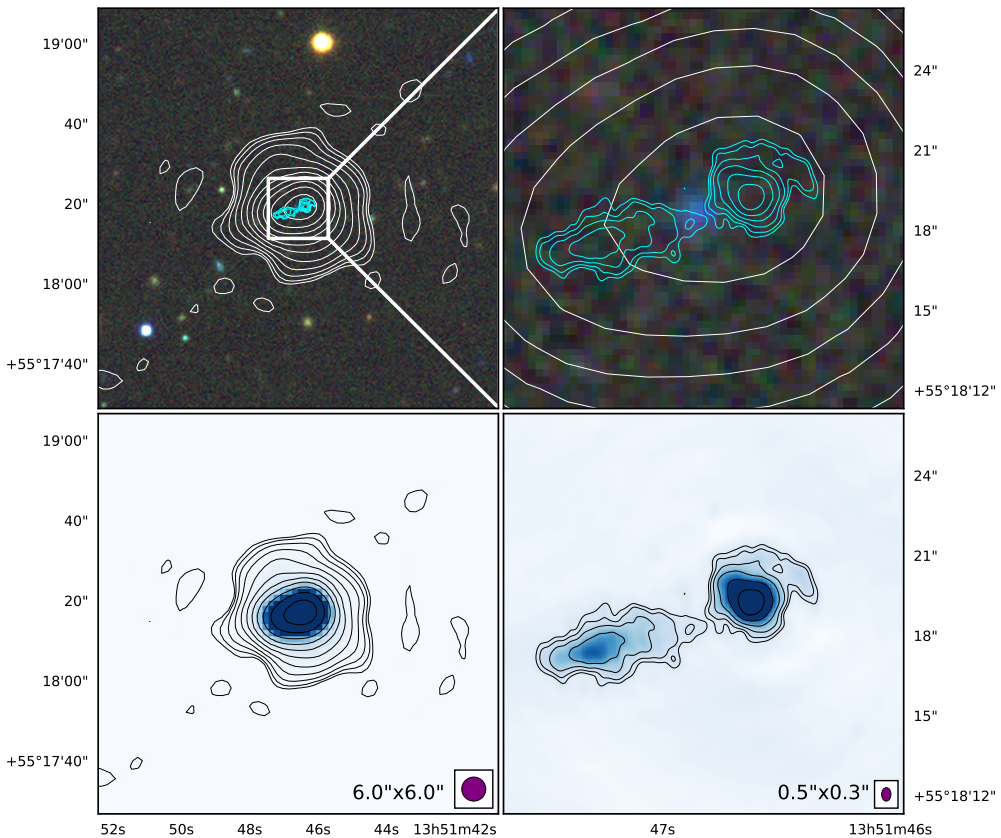
P205+55: a typical survey field with several ∼Jy sources

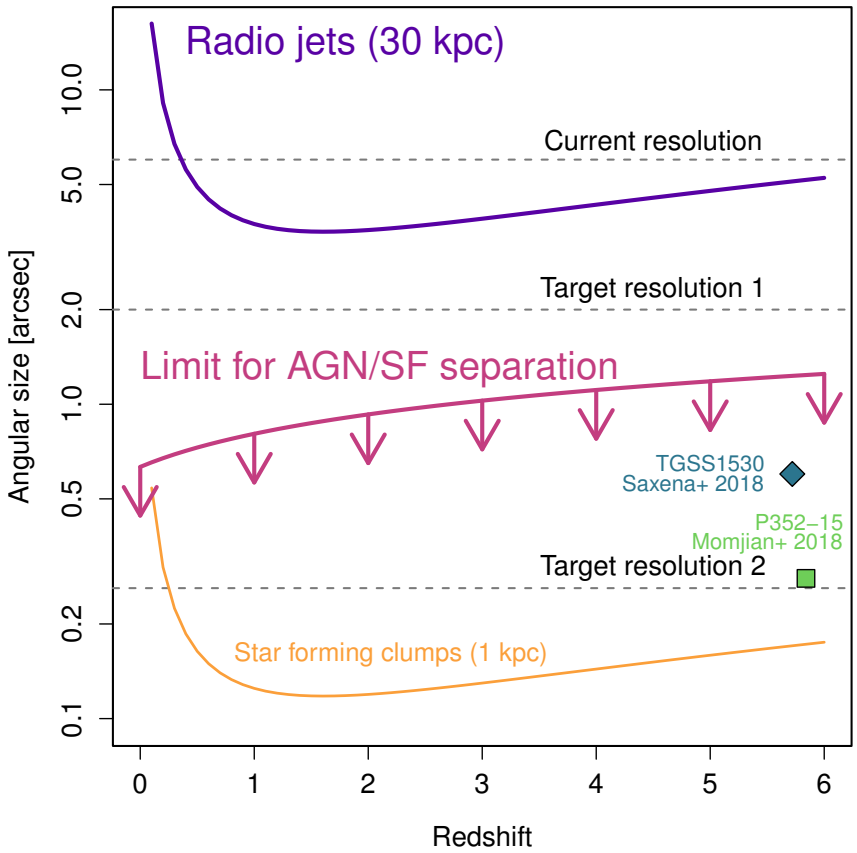


$\sim$ 100 μJy rms noise, 0.3″x0.4″ beam

LoTSS at high resolution

This enables a multitude of science goals

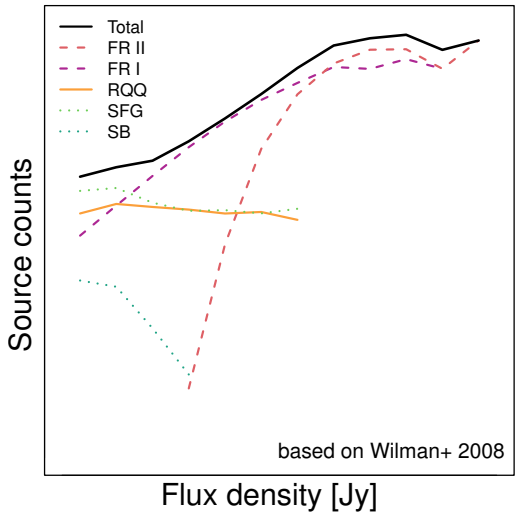


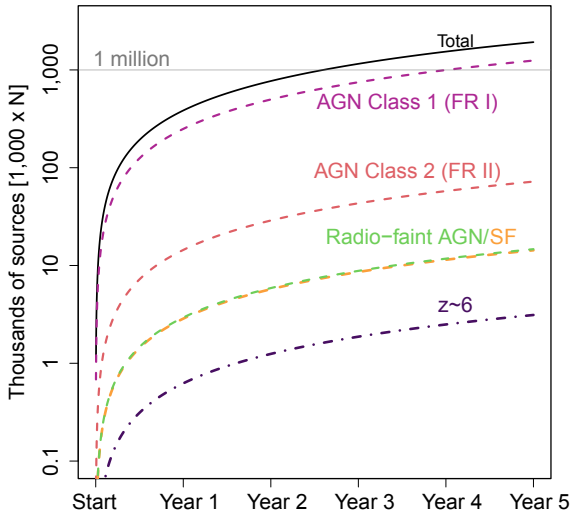


∼85% of sources in LoTSS are unresolved at 6″

Summary

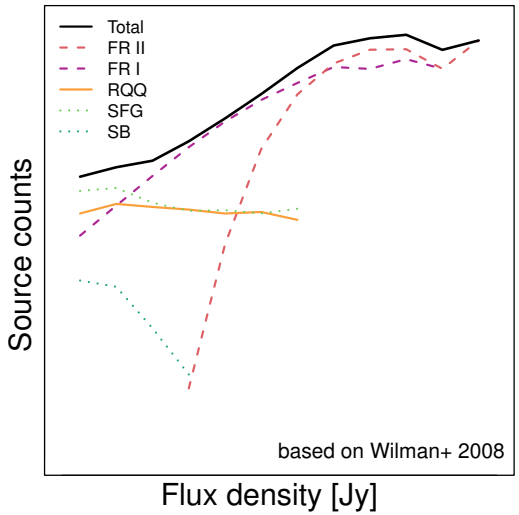
Post-processing LoTSS: an outlook

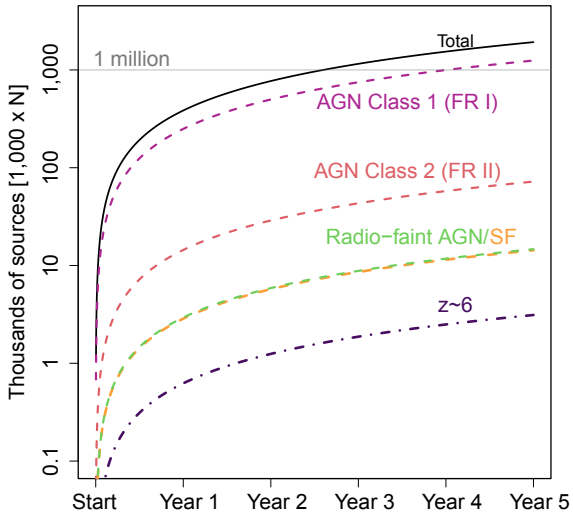




Summary

Post-processing LoTSS: an outlook



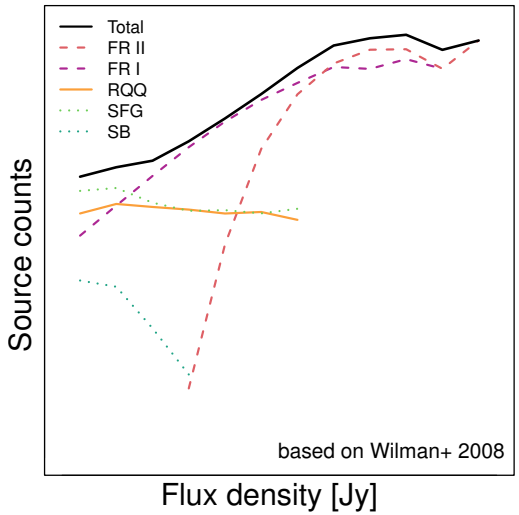


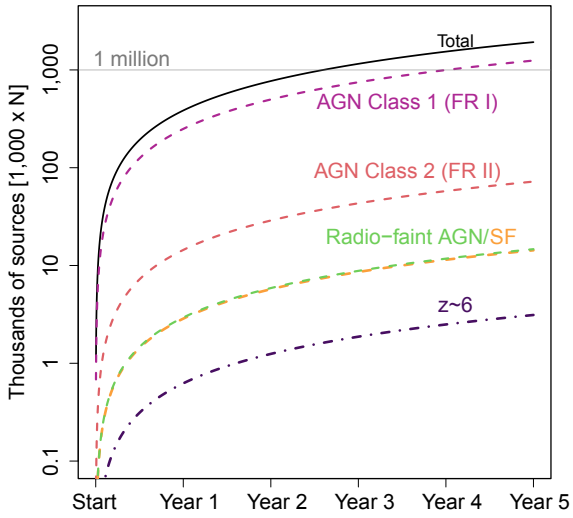
This will be the **first sub-arcsecond wide-area radio survey**

(covering entire Northern sky)

Summary

Post-processing LoTSS: an outlook





This will be the **first sub-arcsecond wide-area radio survey**

(covering entire Northern sky)

Ongoing work

- Preparing a paper splash of initial results on individual objects (2020)
  - Will include papers describing calibration and LBCS
- Scaling up LoTSS post-processing for wide-area surveying at 0.3″
- Widefield imaging of deep fields (see next talk by F. Sweijen!)