VLBI studies with the International LOFAR Telescope

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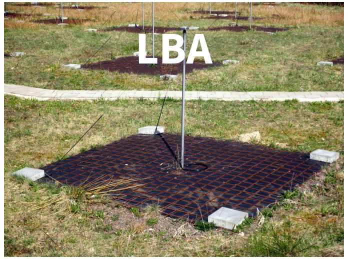
UK Research and Innovation
Durham University

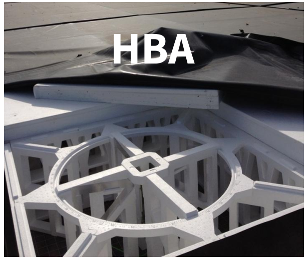
Outline

- The LOw Frequency ARray (LOFAR)
- Why low frequencies?
- Extending to higher resolution
    - Long Baseline Calibrator Survey
    - Calibration strategy / demonstration
- Enabling science – highlights
- Future work

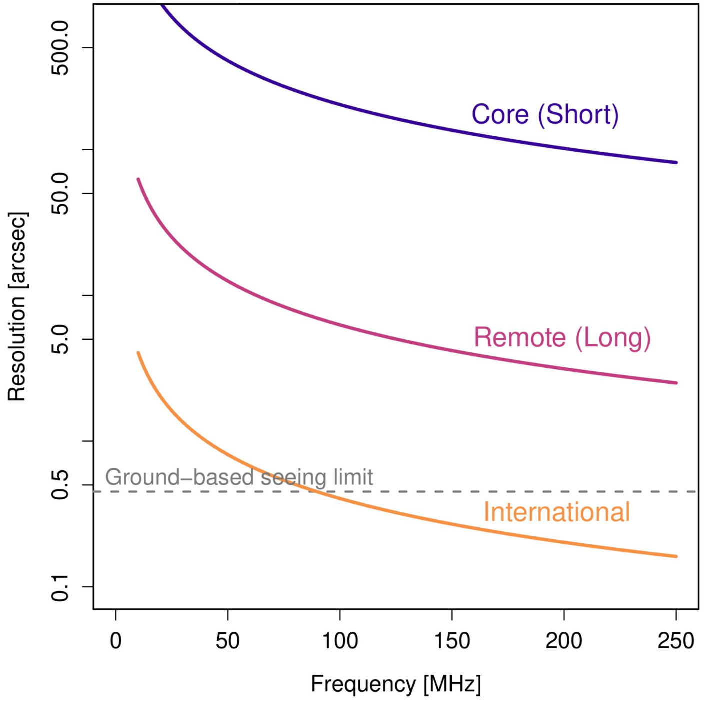
The International LOFAR Telescope (ILT)

- Phased array operating <200 MHz
  - Low Band Antenna (LBA): 10 - 90 MHz
  - High Band Antenna (HBA): 110 - 240 MHz
- Large fractional bandwidth (48 MHz)
- Flexible spectral resolution
- Wide instantaneous field of view
- Multi-beaming capabilities
- Flexible angular resolution

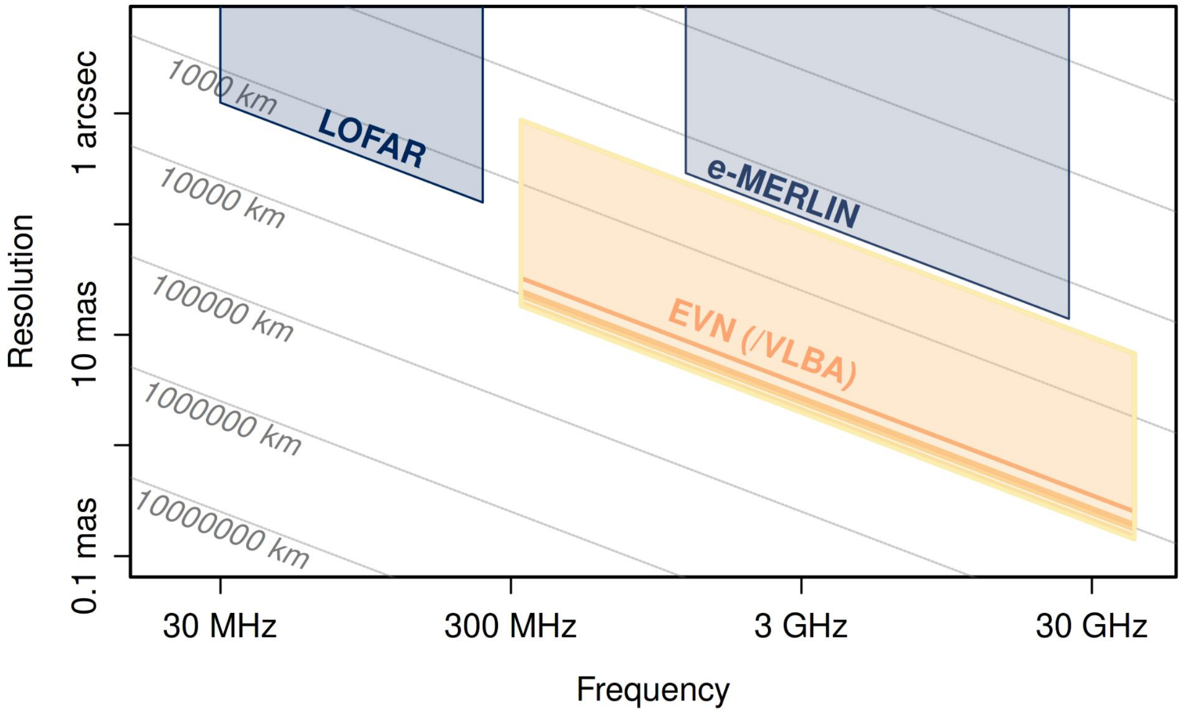




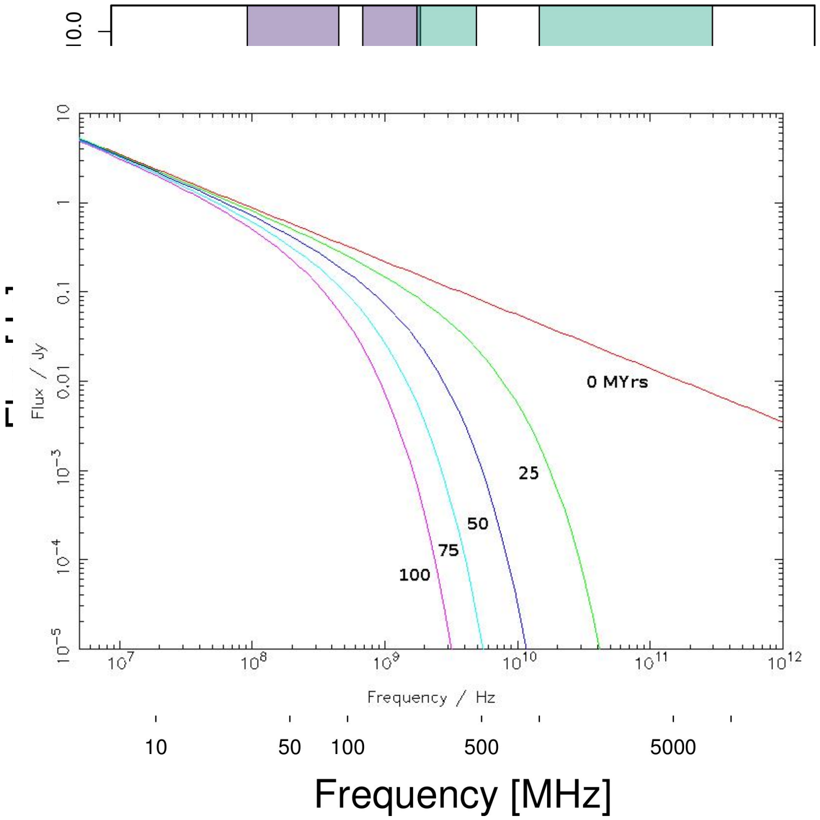
The International LOFAR Telescope (ILT)



Comparison with other facilities



What low frequency brings to the table

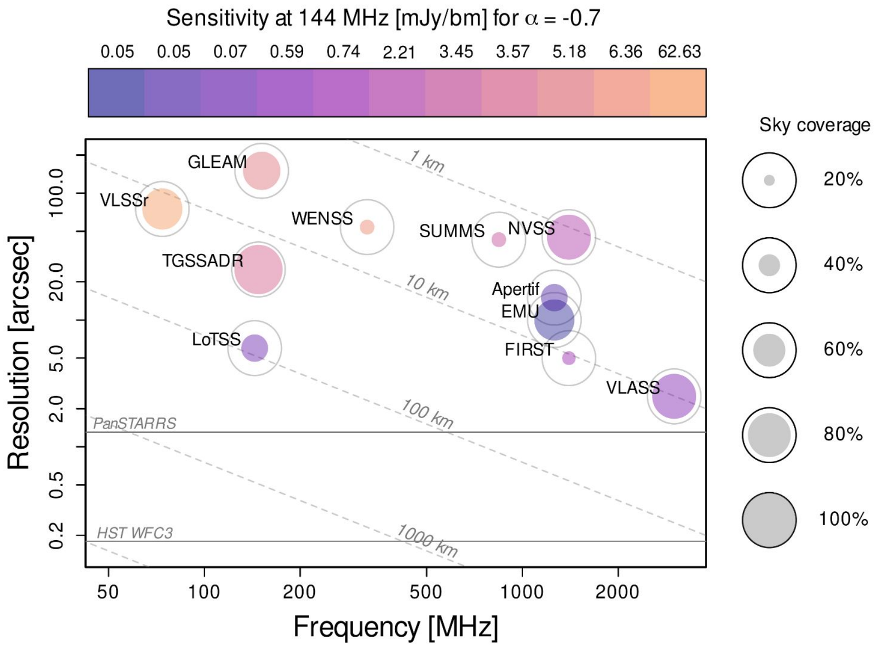


- Synchrotron sources are brighter at low frequencies
- Only way to measure low frequency absorption
- Lower rest frequencies can be reached for high-redshift sources
- Anchor spectral modelling to assess spectral ageing

Spectral index has come up in the majority of talks this week!

LOFAR Two-metre Sky Survey

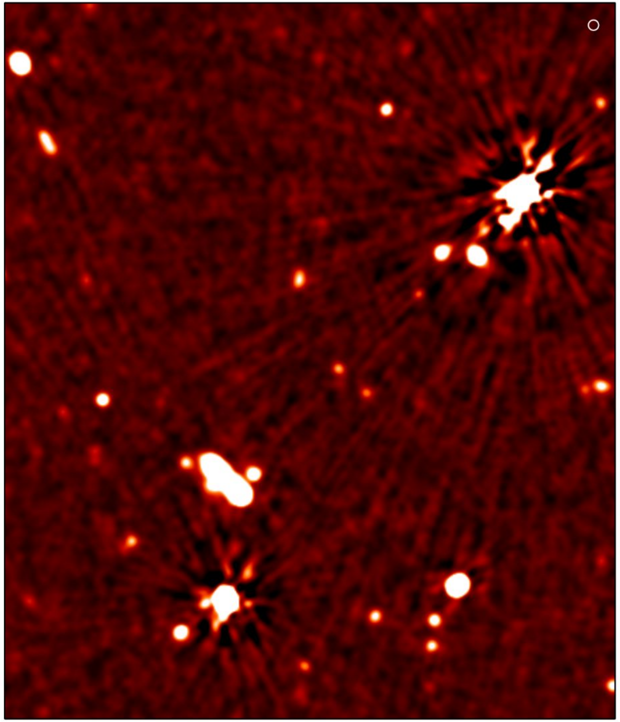
- Using HBA, Dutch stations
  - 6" resolution @ 150 MHz
- Wide area: Northern Sky
  - Data release 1 *Shimwell et al. 2019*
  - Data release 2 *Shimwell et al. 2022*
- Deep Fields
  - Lockman Hole
  - Boötes
  - ELAIS-N1
- Multi-wavelength data
  - Wide area cross-matched with optical, IR
  - Deep Fields have excellent ancillary data



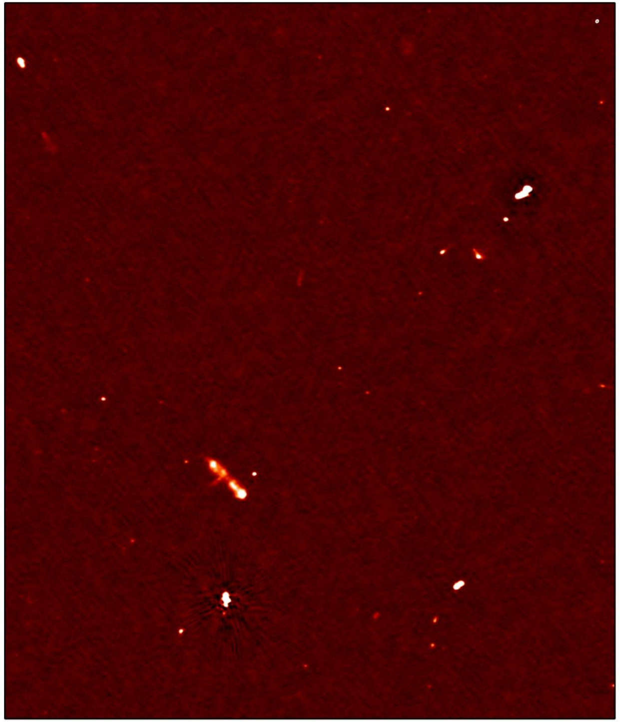
Over 200 science papers using LoTSS data!

The main challenge at low frequencies

Before ionospheric correction



After ionospheric correction



More info on direction-dependent calibration: *Tasse et al. (2014, 2017), Yatawatta (2015), van Weeren (2016)*

Challenges in extending to higher resolution

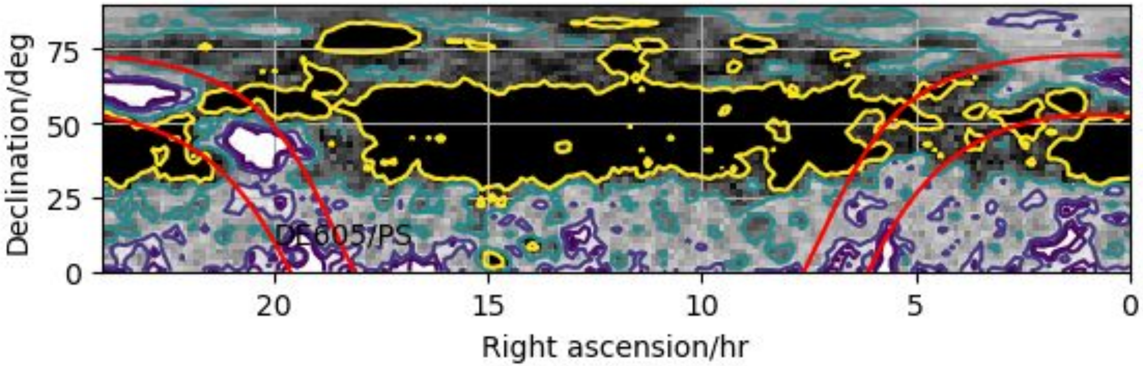
- **Ionosphere:** requires directional dependent calibration
- **Data volume:** datasets are 4-20TB per observation
- **Clocks:** remote and international stations on individual clocks
- **Calibrators:** need ‘Goldilocks’ calibrators for resolution / frequency
- **Source characteristics:** low-frequency absorption, source structure

How do we handle this?

Long Baseline Calibrator Survey (LBCS)

Covers entire Northern sky for HBA *(Jackson et al, 2022, 2016)*

- Multi-beaming with 3 MHz, 3 min observations of calibrator candidates
- ~30,000 sources in final catalogue, about 1 good calibrator per square degree

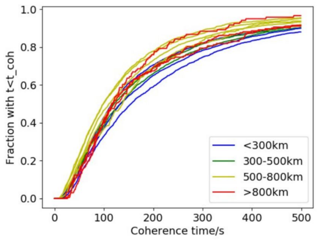


- Accepted commissioning proposal to extend to LBA (PI: Jackson)

Long Baseline Calibrator Survey (LBCS)

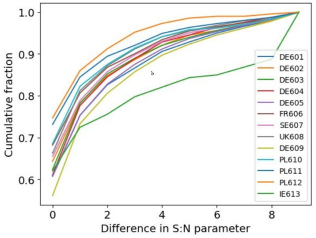
Quality indicators / metrics

Atmospheric coherence statistics



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

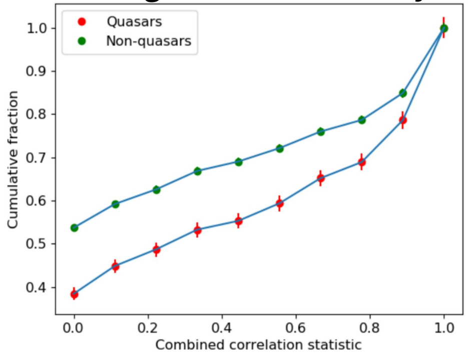
Reproducibility



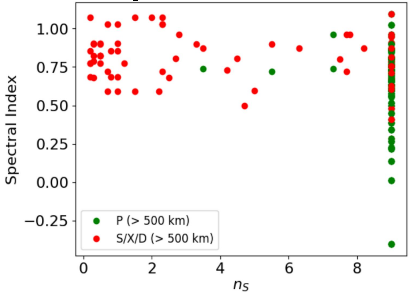
Sources observed more than once: results very similar for all baselines

Science with LBCS

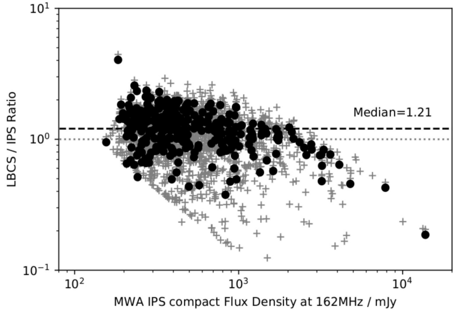
Testing Unification Theory



Compact sources are flat



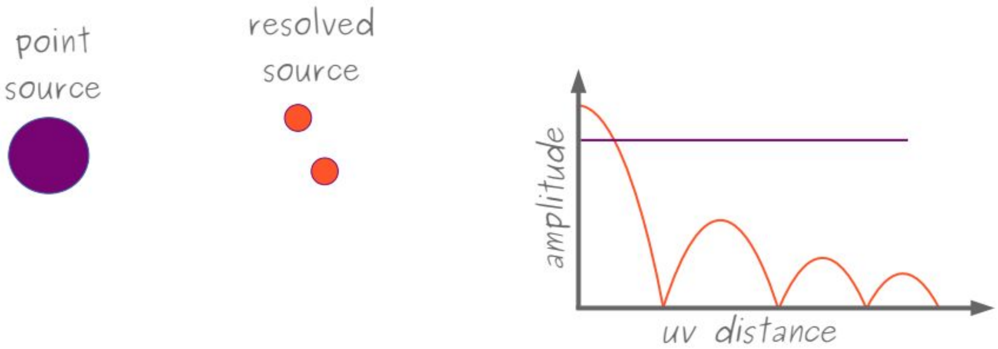
Interplanetary Scintillation



In conjunction with MWA; J. Morgan

Developing a calibration strategy

Calibration at high resolution has to handle lower signal to noise on long baselines

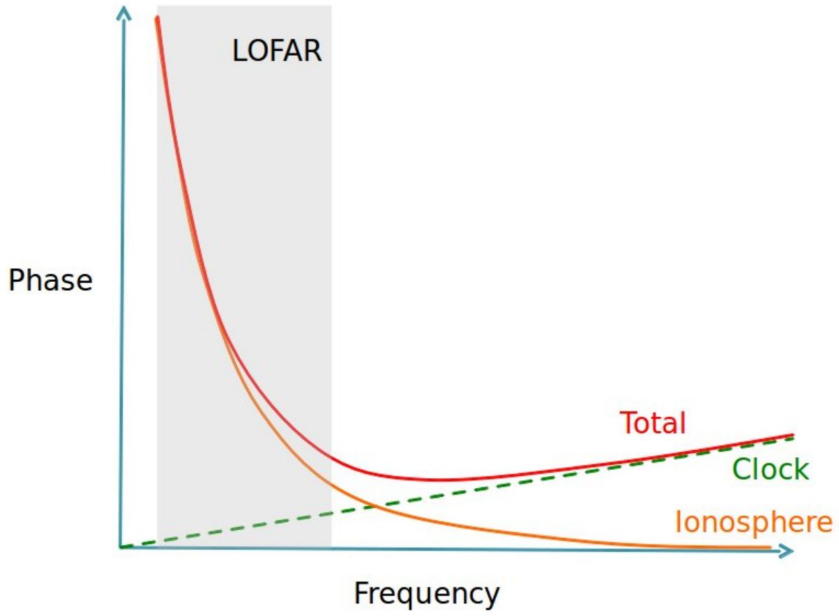


To cope with this a technique called ***fringe-fitting*** was developed to increase the solution intervals by solving for *delays* and *rates* in addition to a phase offset:

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

Developing a calibration strategy

Fringe-fitting algorithms have, until very recently, only been able to cope with *non-dispersive delays* (i.e., phase is linear with frequency)

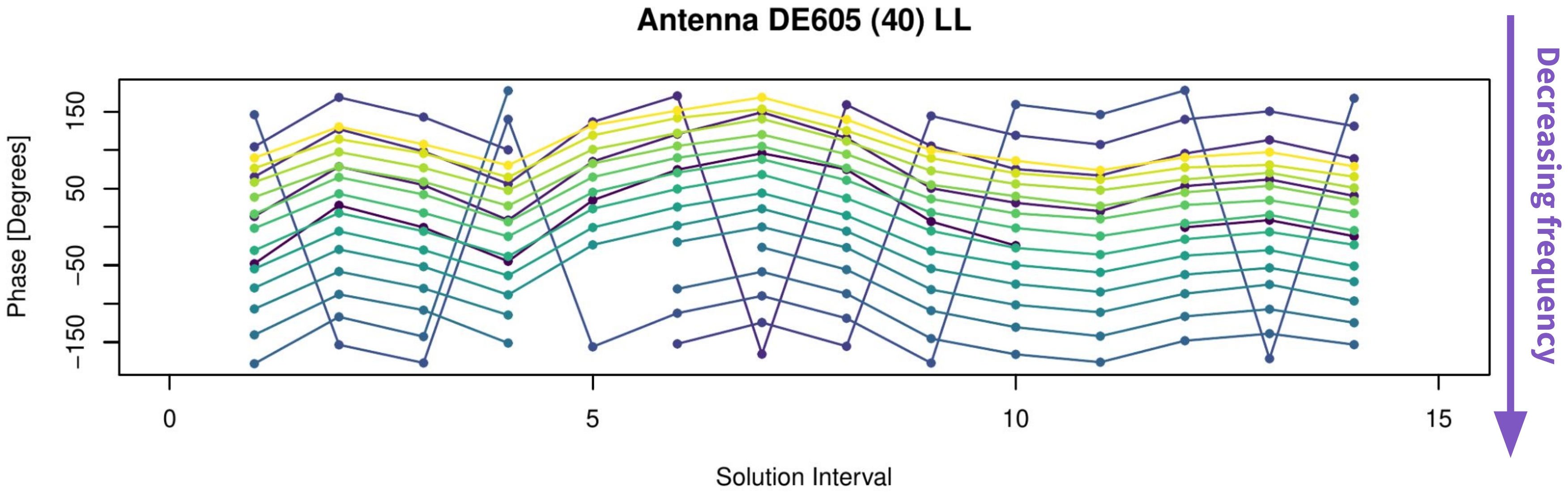


LOFAR is dominated by ***dispersive delays*** due to the ionosphere

Image courtesy J. Moldón

Developing a calibration strategy

Dispersive delays from Low Band Antenna (LBA) can be up to ~1 µs!



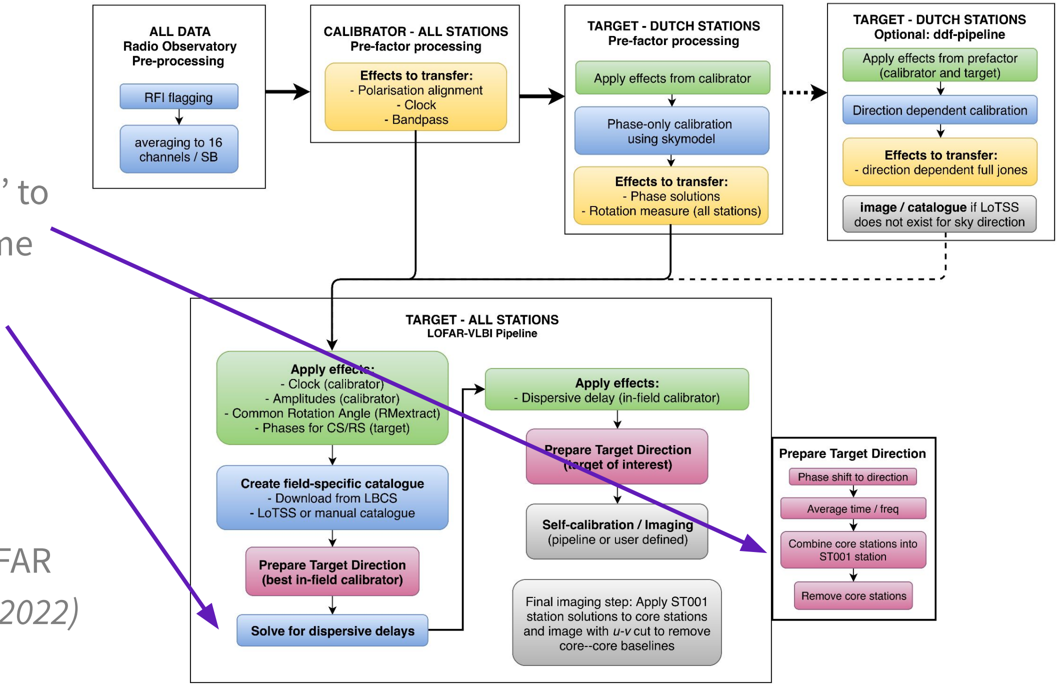
Developing a calibration strategy

Use LOFAR-native tools to:

- Correct clock offsets (τ = 100 - 200 ns)
- Combine core stations into a 'super-station' to help anchor calibration / reduce data volume
- Solve for dispersive delay (τ ~ 200 - 300 ns)

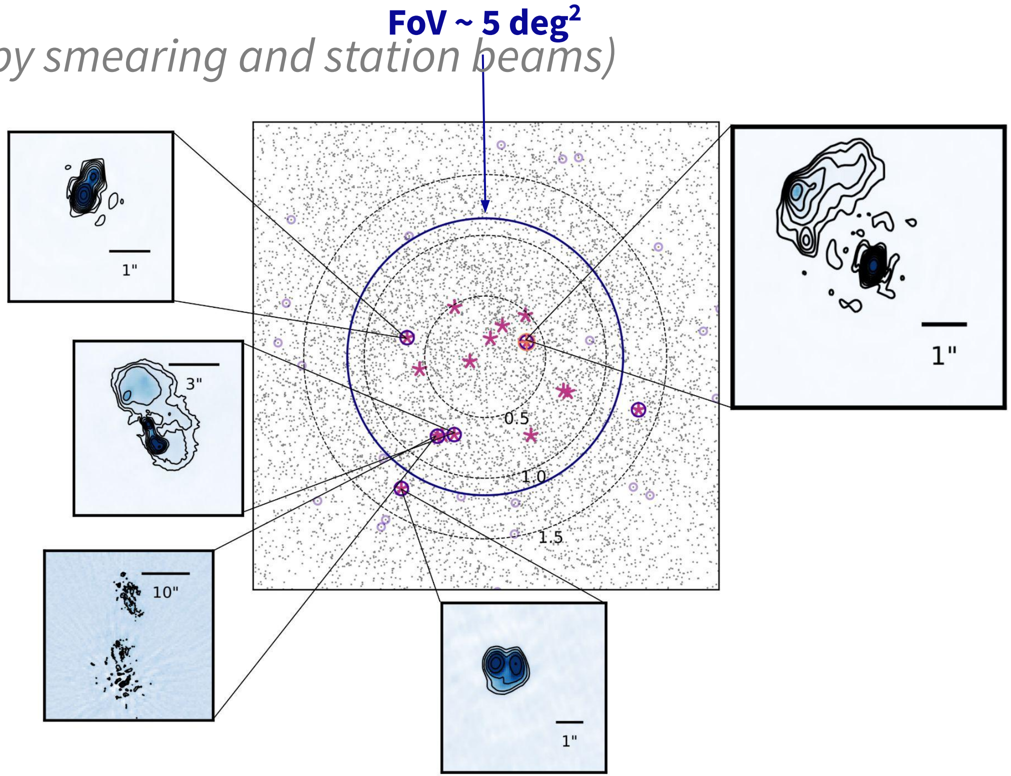
Publicly available on github *(Morabito et al. 2022)*

Built as an extension to the processing for the LOFAR Two-metre Sky Survey *(Shimwell et al. 2017,2019,2022)*



Demonstration: P205+55

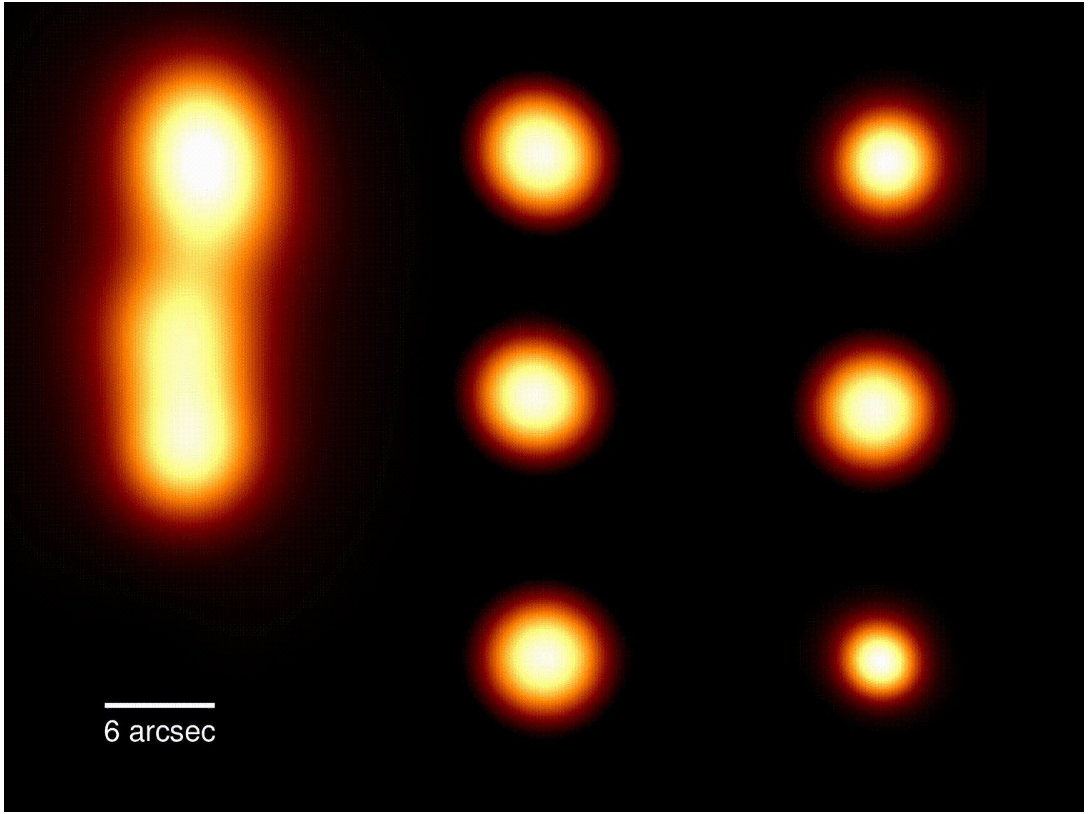
Field of view limited to 1.25° radius *(by smearing and station beams)*

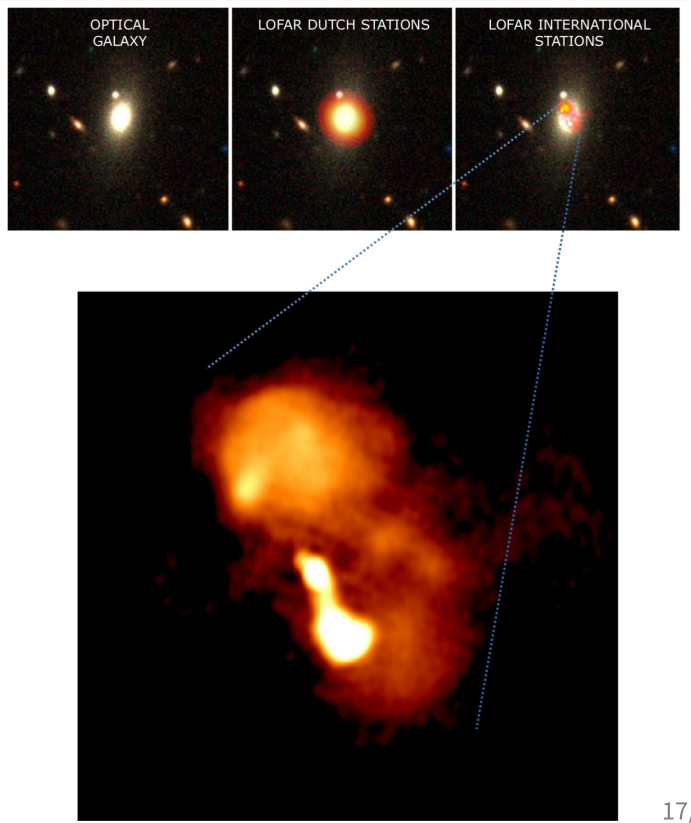


1. Find dispersive delays on best LBCS in-field calibrator
2. Transfer to other LBCS calibrators
3. Propagate phase-referencing around the field

Full demonstration: Morabito et al. (2022)

Demonstration: P205+55



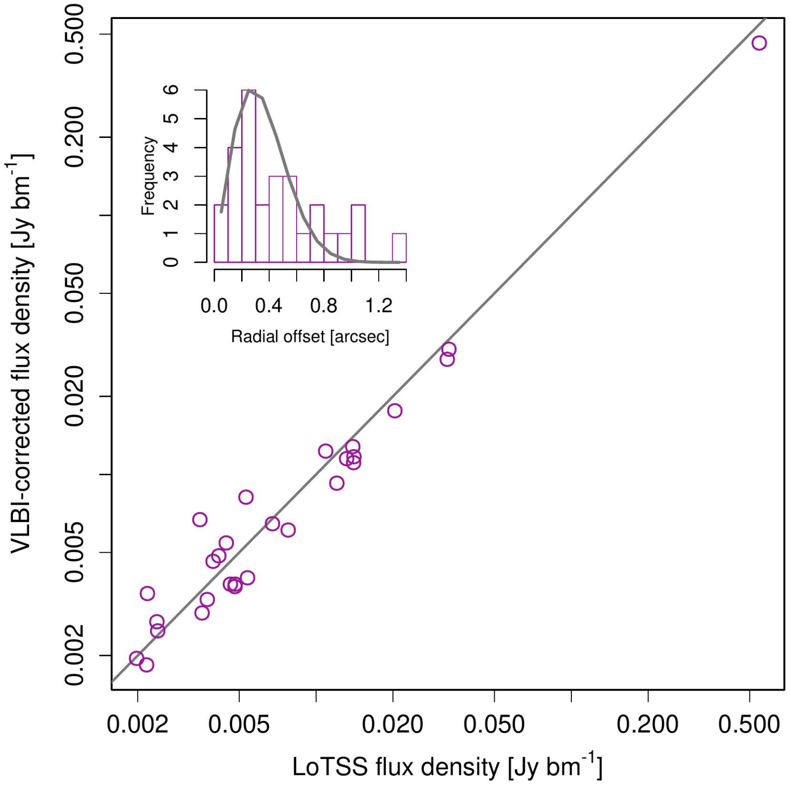


Demonstration: P205+55

Astrometry and flux density scale

Compare original LoTSS image with 6” image made after transferring VLBI solutions to Dutch dataset

- LoTSS has 20 mas offset from PanSTARRS → radial offsets of high resolution image compared to LoTSS is 28 mas
- Flux density – scatter around one-to-one line is 14% when comparing compact sources in LoTSS to 6” image



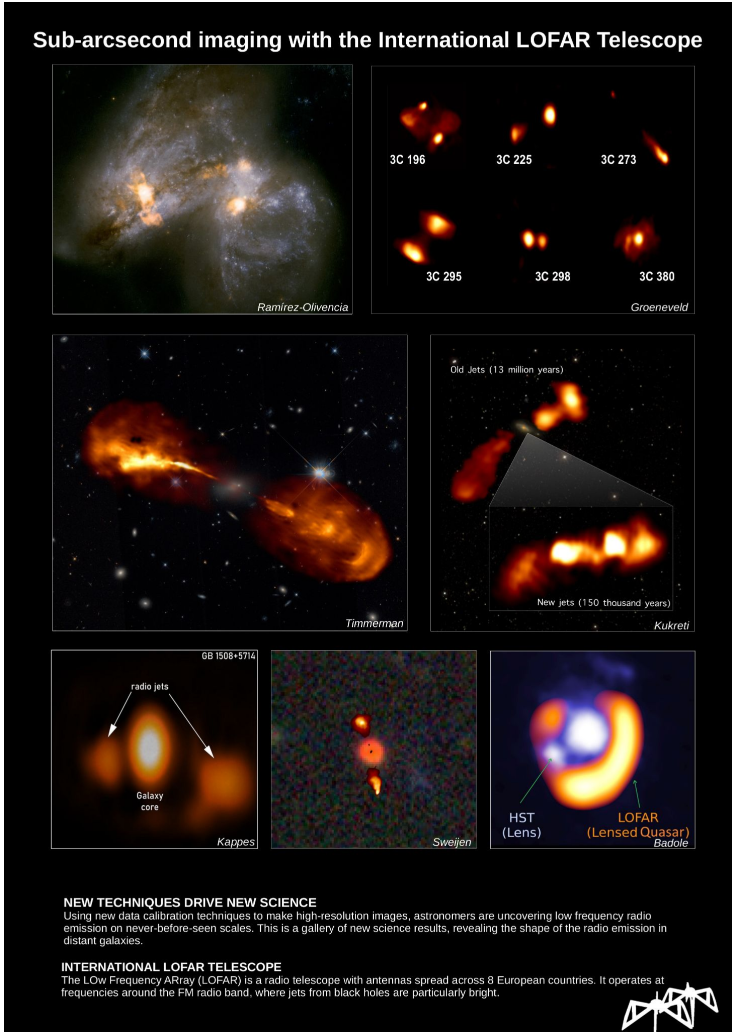
Enabling science

With this kind of resolving power, we can study:

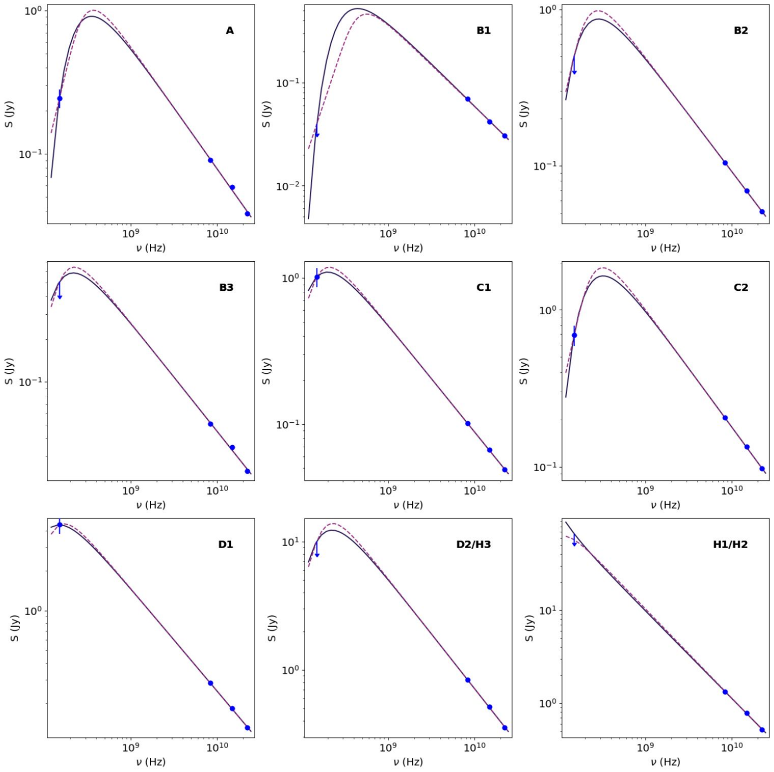
- Jets launched from active galactic nuclei
- Jets interacting with the interstellar medium
- Star formation in nearby galaxies

Special issue of Astronomy & Astrophysics with 10 new articles *(published Jan 2022)*

- More than doubling the number of scientific results using LOFAR sub-arcsec resolution!
- Most papers lead by early career researchers

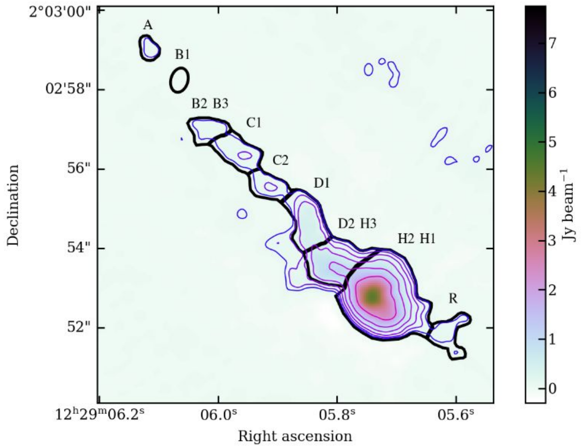


The jet in 3C273



Low-ν properties of jet in 3C273

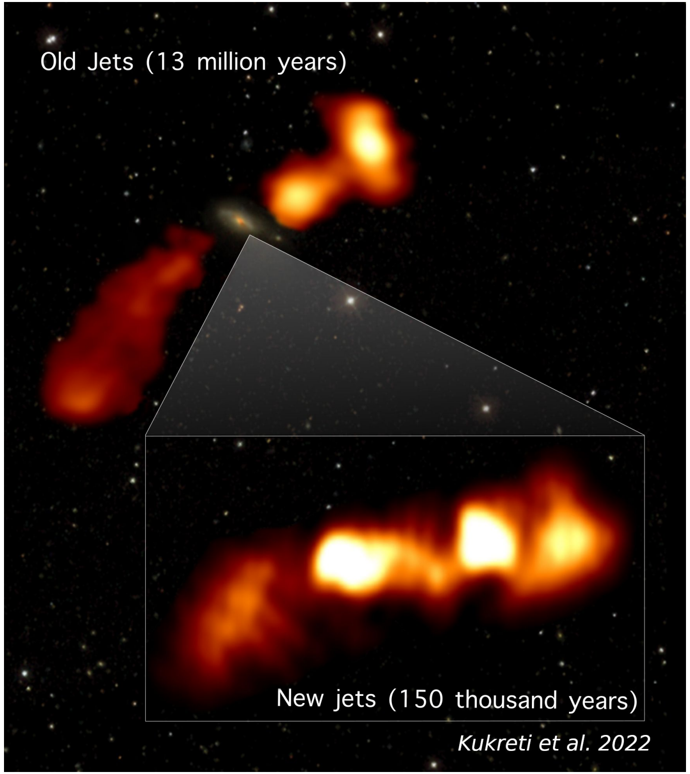
(Harwood, Mooney et al., 2022)



Jet power consistent with high frequencies

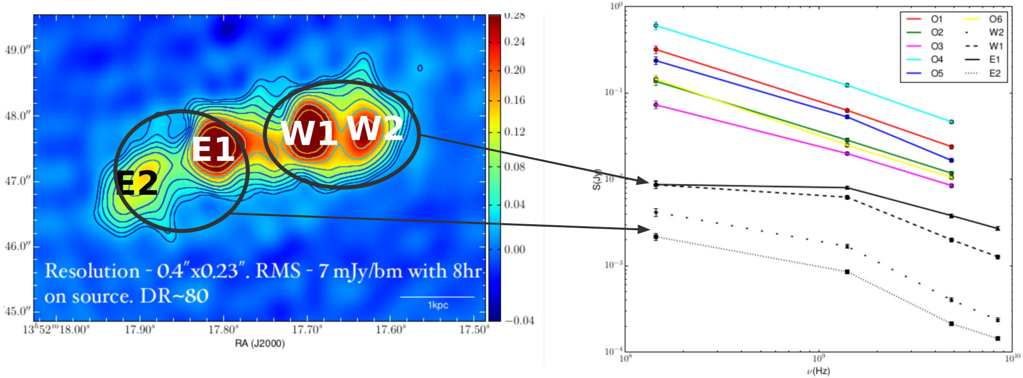
Low-ν high resolution enabled spectral modelling of individual components!

Jets interacting with the interstellar medium



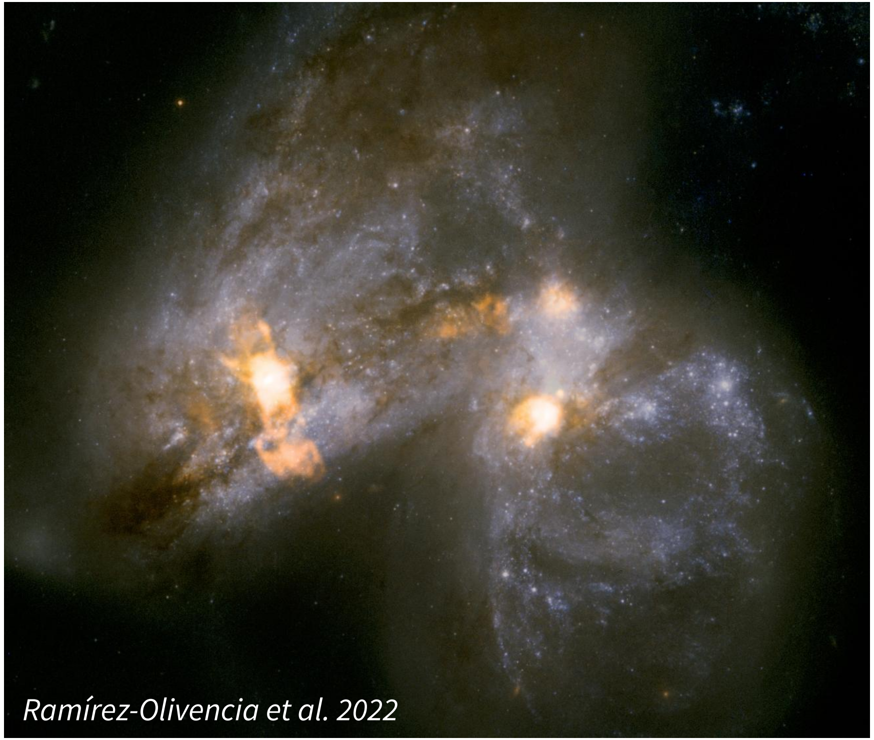
Restarted jets interacting with host galaxy

(Kukreti et al., 2022)



Low-frequency spectra in young jet components show evidence for interaction with interstellar medium

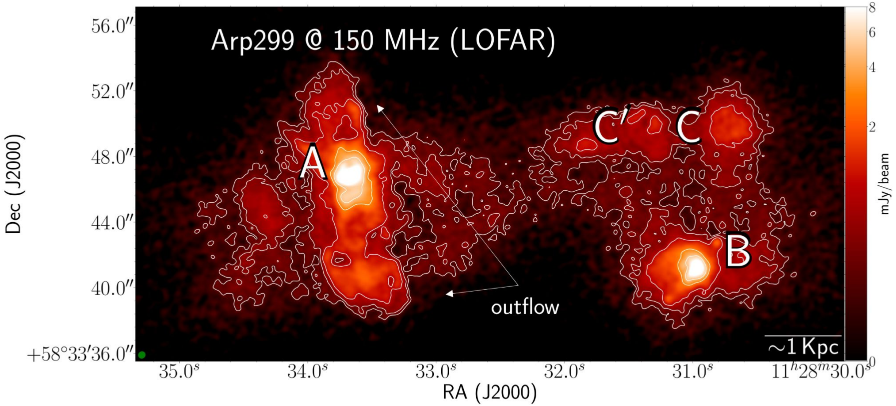
Star formation in nearby galaxies



Ramírez-Olivencia et al. 2022

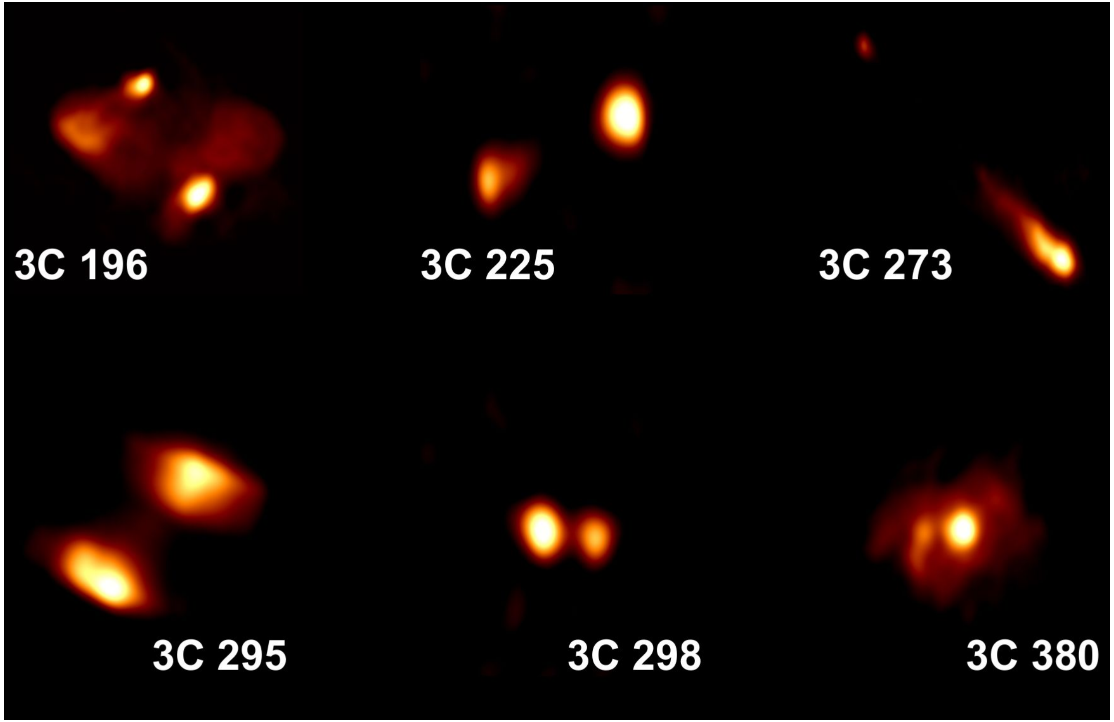
Nuclear emission in merging galaxy

(Ramírez-Olivencia et al. 2022)



LOFAR images reveal diffuse emission in outflow powered by a starburst, possibly triggered by merger with galaxy hosting an active galactic nucleus

Extending to < 100 MHz with the LBA



Breaking the record!
(Groeneveld et al. 2022)

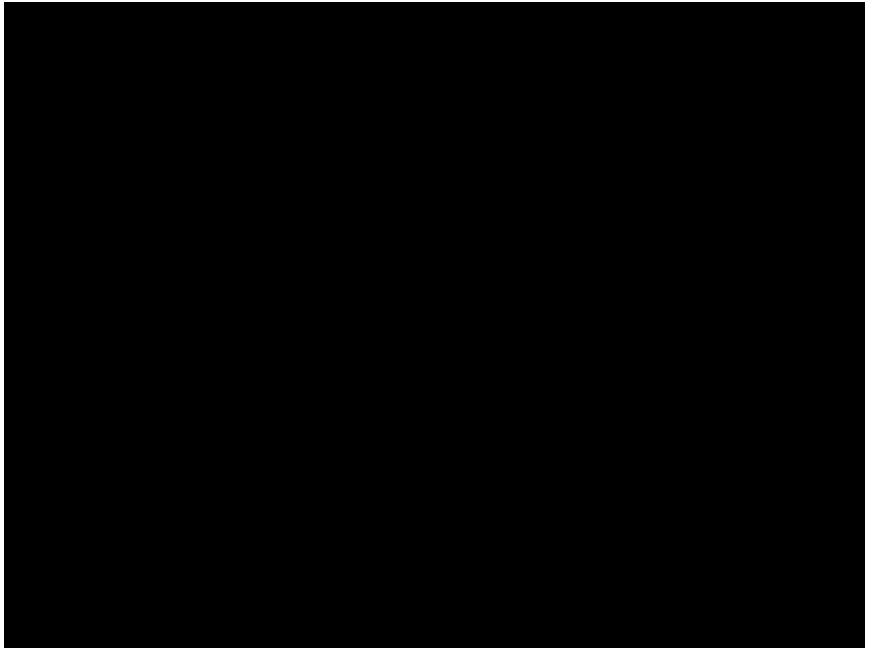
These are the highest resolution images ever made below 100 MHz! *They allow us to study the jet ages and conditions.*

Enabling science: the cutting edge

Imaging of complete 5 deg^2 field of view for Lockman Hole
Nature Astronomy, Sweijen et al. (2022)

- 8 hour observation
- 0.3” x 0.4” beam
- ~40 µJy/bm rms
- 250,000 cpu hours
- ~ 7 billion pixels!
- ~2,000 sources

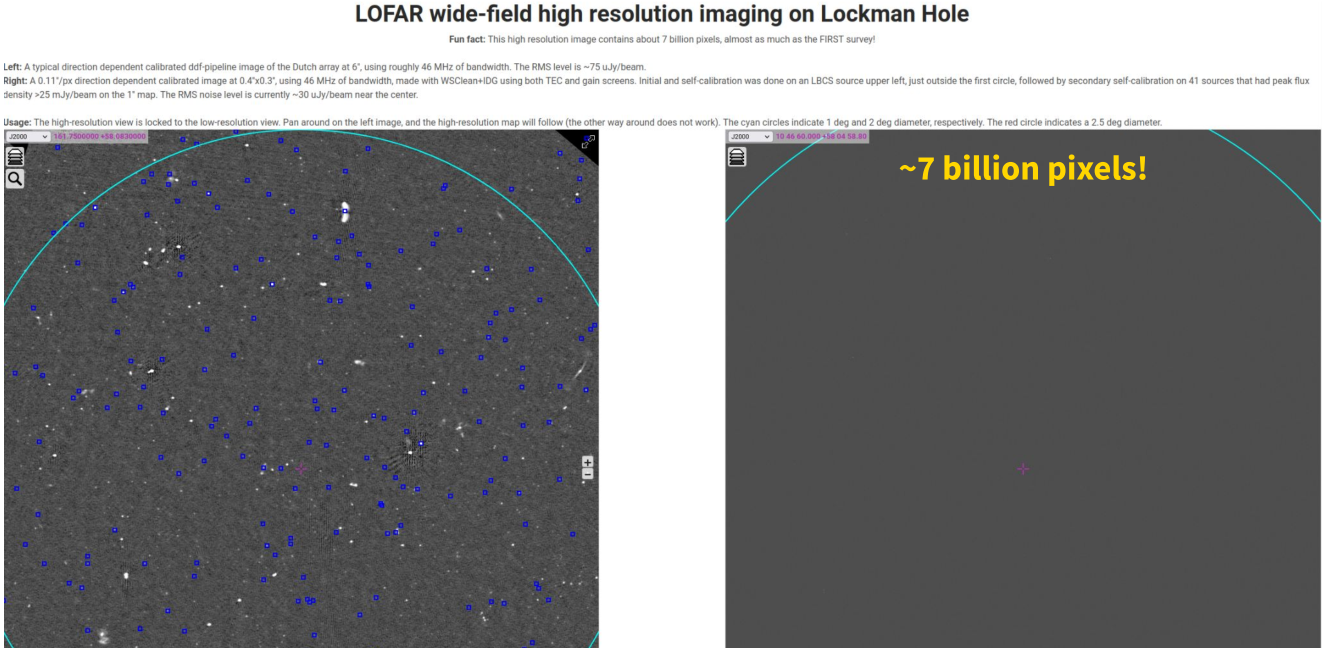
89% of sources are still compact



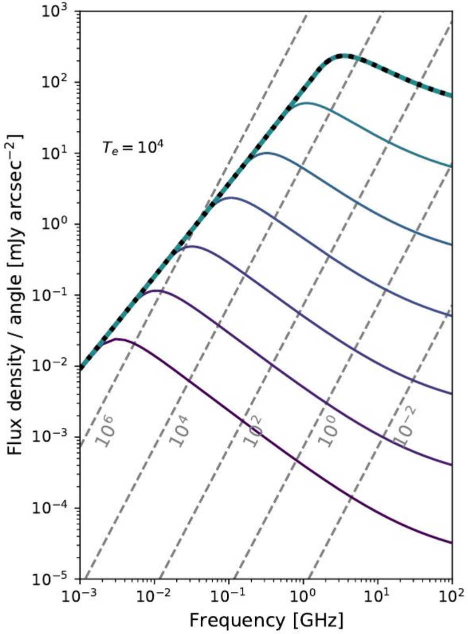
Enabling science: the cutting edge

Imaging of complete 5 deg^2 field of view for Lockman Hole *(Sweijen et al. 2022)*

https://home.strw.leidenuniv.nl/~sweijen/lockman_aladin.php



Enabling science: revisiting T_b at 150 MHz



Also depends on:

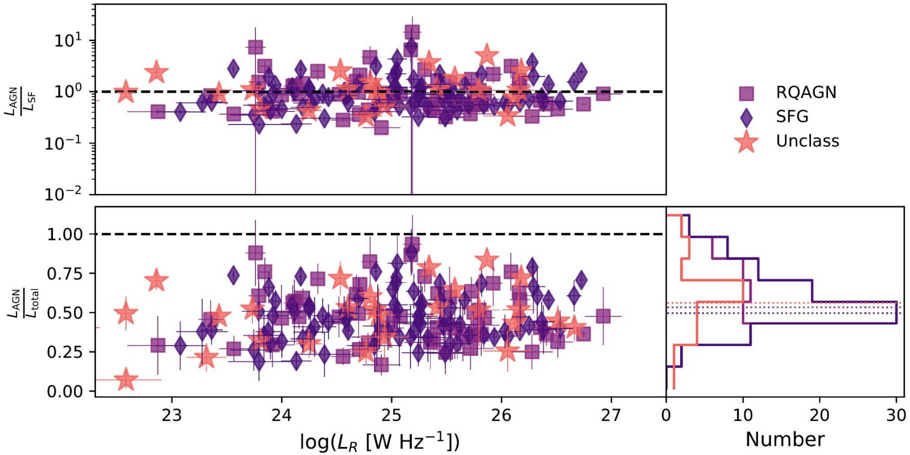
- redshift
- spectral index
- Electron temperature

Identified 795 AGN via brightness temperature in Lockman Hole

- **66 new** + the rest confirmed by SED fitting
- *AGN identifications are reliable!*

Evidence for mix of radio emission mechanisms in radio quiet AGN

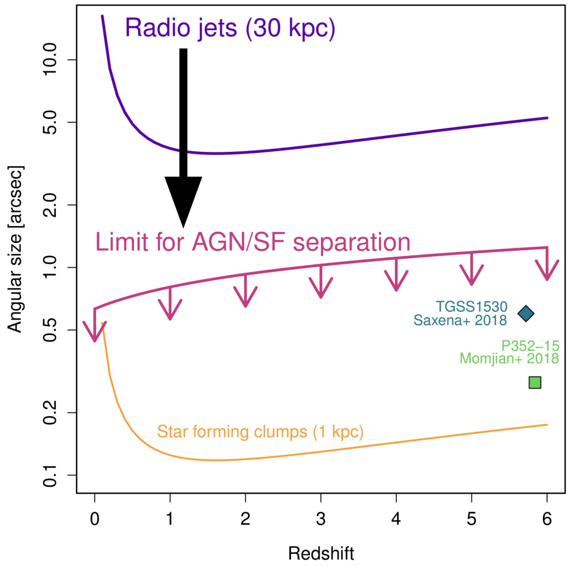
- including that some are ***composite*** SFG / AGN sources

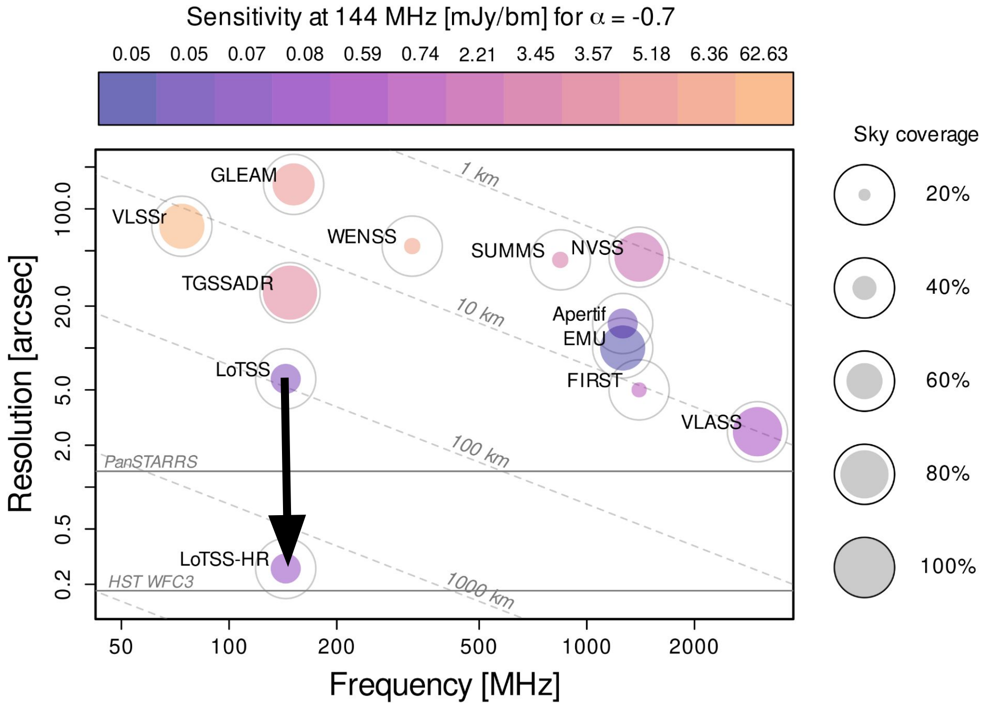


Morabito et al. (submitted)

Future Work

Post-processing LoTSS at sub-arcsec resolution will provide the ***first sub-arcsecond Northern sky survey***





Future Work

Wide area

- Starting in H-ATLAS
- Imaging LoTSS > 10mJy/beam
- Building screens (think MultiView!)

Deep fields (full FoV)

- Lockman, Boötes, ELAIS-N1
- Intermediate resolution ~1”
- Initial imaging + going deeper

LOFAR2.0

- LOFAR2.0 Ultra Deep Observation: Euclid Deep Field North *(PIs: Best, Morabito)*

Future Work

LOFAR is complementary to VLBI at GHz frequencies but …

We are in uncharted territory and will undoubtedly need:

- Spatially matched information from GHz freqs (e.g., e-MERLIN)
- Higher resolution to understand new results (e.g., EVN, VLBA, etc.)
- Polarisation information (Mahatma, O’Sullivan)

Summary

- We are capable of performing sub-arcsecond imaging below 200 MHz with LOFAR, and this is already enabling new science.
- Over the next few years as we start surveying the Northern sky, expect more new and exciting results!
- Complementary higher frequency observations will be crucial to help us understand our new results

Extra slides

Brightness temperature at 150 MHz

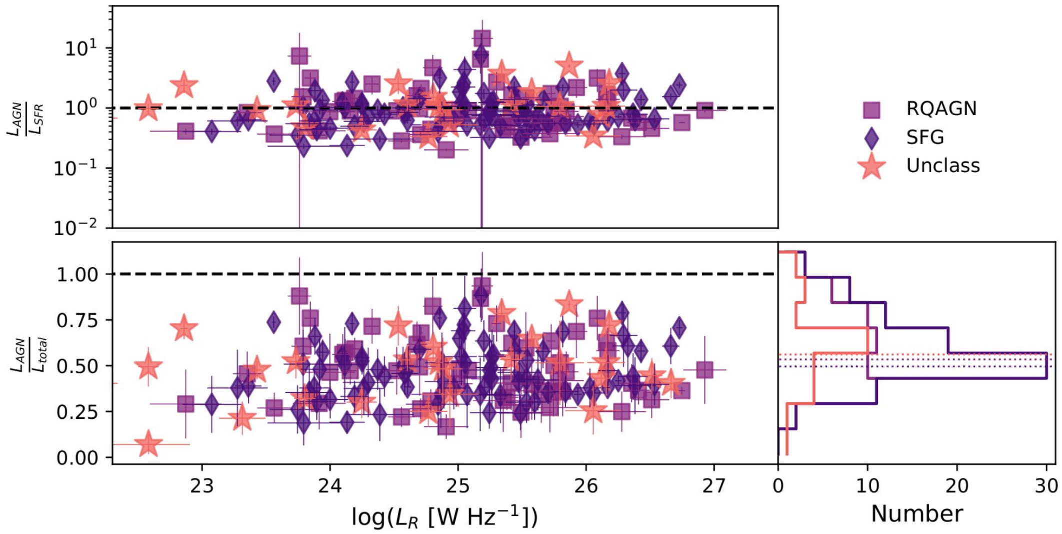
- Identified 795 (790) high brightness temperature sources in Lockman Hole
  - 83% are otherwise identified as AGN (91% when using only peak intensity)
  - ***66 new AGN identifications!***
- Comparison to SED fitting shows:
  - 22% of detected radio-quiet AGN and 12% of star-forming galaxies have high brightness temperatures
    → ***implies mixture of different radio emission mechanisms in populations***
- Detected vs. detectable sources split below 2 mJy
  - Consistent with mixed populations of sources at low flux densities

Using brightness temperature measurements with sub-arcsecond ILT observations is a reliable way to select AGN, in particular when ancillary data is inadequate

How much of the radio emission is due to AGN?

For unresolved, non-radio excess sources, we make the simple assumption that:

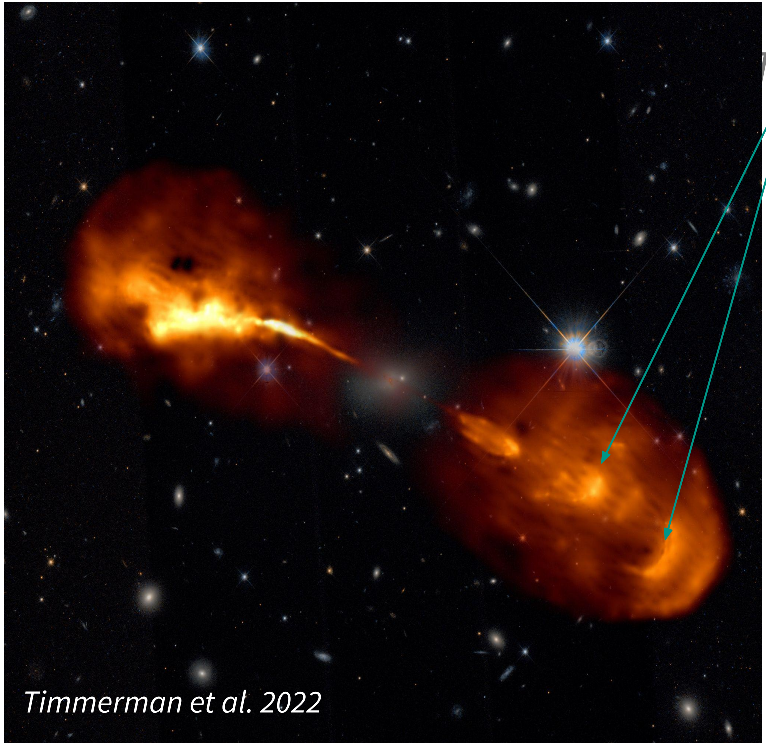
- L_{AGN} = peak intensity, high resolution map
- L_{SFR} = (total flux density, 6” resolution map) - LAGN



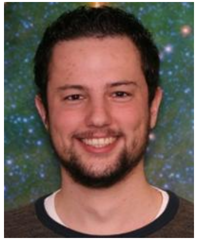
L_{AGN}/L_{SFR}	
Class	Median
RQAGN	0.89±0.69
SFG	0.79±0.42
Unclass	1.07±0.64
Total	**0.90±0.55**

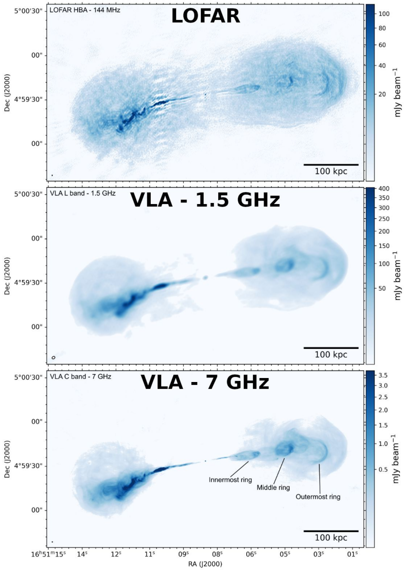
L_{AGN}/L_{total}	
Class	Median
RQAGN	0.47±0.21
SFG	0.44±0.14
Unclass	0.49±0.16
Total	**0.47±0.17**

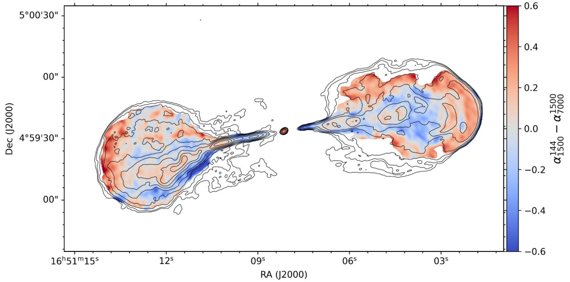
Jets from active galactic nuclei



Timmerman et al., 2022)







Spectral information - aided by LOFAR - shows rings are consistent with the active galactic nuclei intermittently turning 'on' and 'off'