Scientific exploitation of LOFAR international baseline observations

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Feb 2023

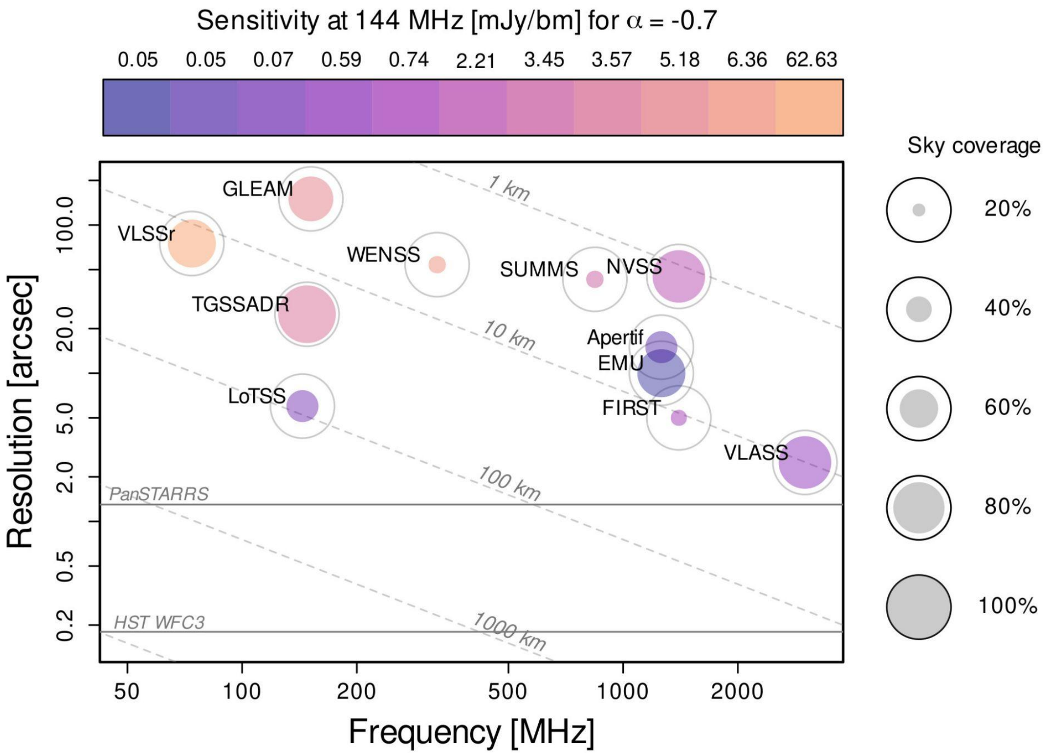
National SKA Science Day Sweden

UK Research and Innovation

Durham University

LOFAR: a great survey instrument!

- Wide field of view
- High sensitivity
- ~arcsec resolution



__Comparisons__

LOFAR Two-metre Sky Survey (LoTSS)

- 150 MHz, 6” resolution, 70 µJy/bm

Faint Images of the Radio Sky at 21cm (FIRST)

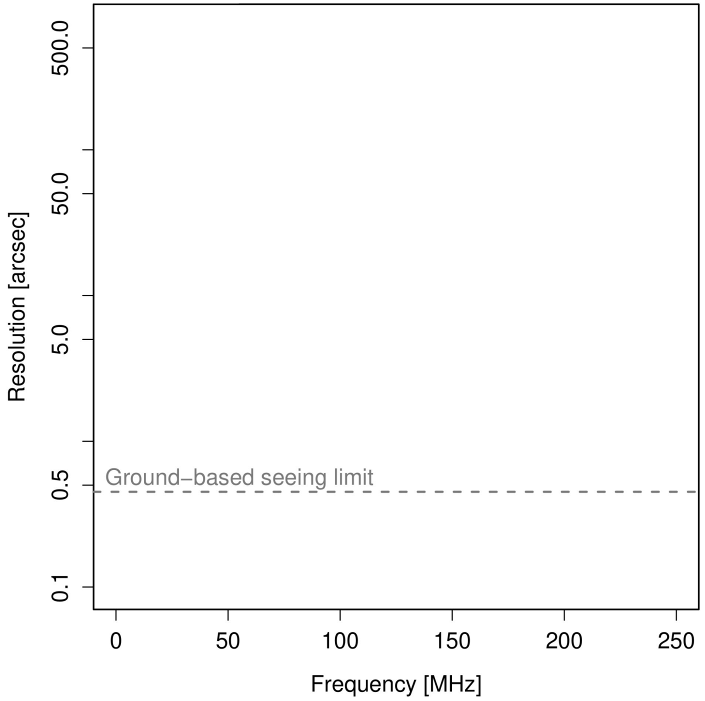
- 1.4 GHz, 5” resolution, 150 µJy/bm

VLA Sky Survey (VLASS)

- 3 GHz, 2.5” resolution, 69 µJy/bm (combined)

~300 science papers using LoTSS data!

The International LOFAR Telescope (ILT)



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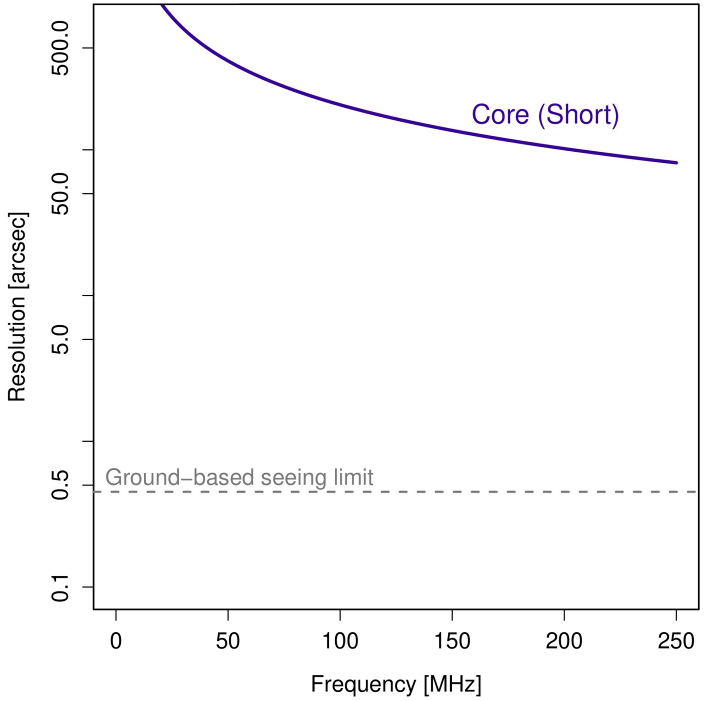

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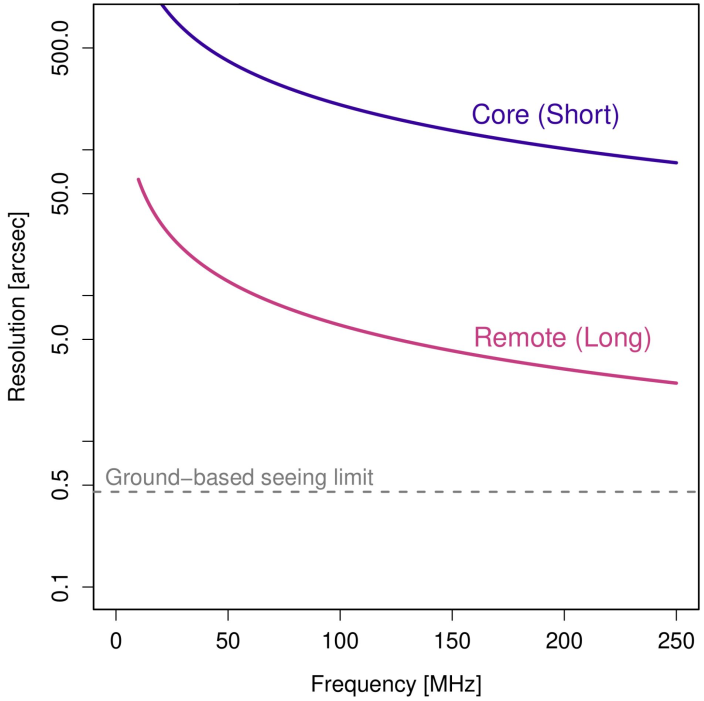

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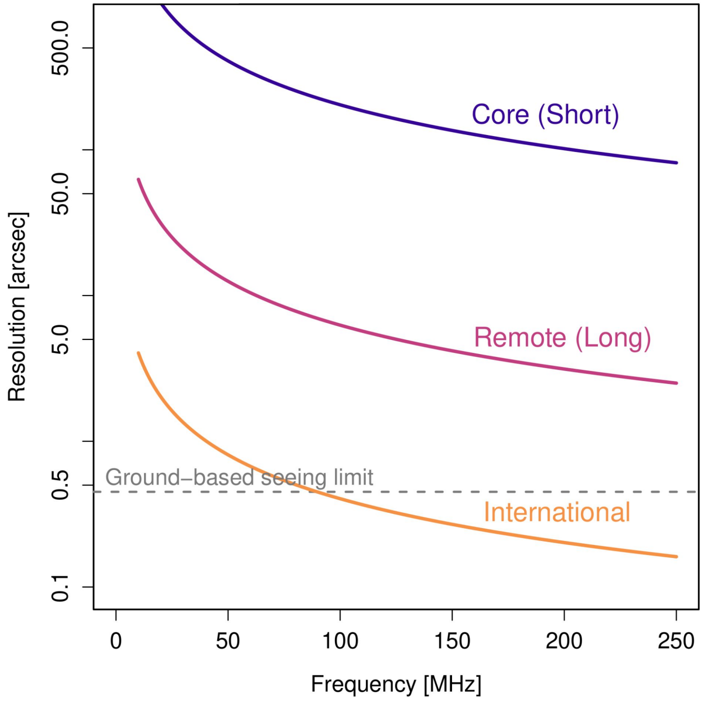

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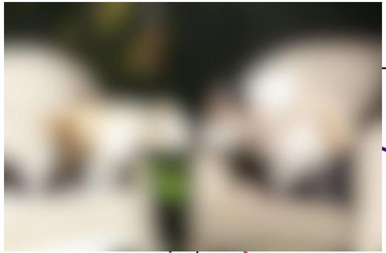

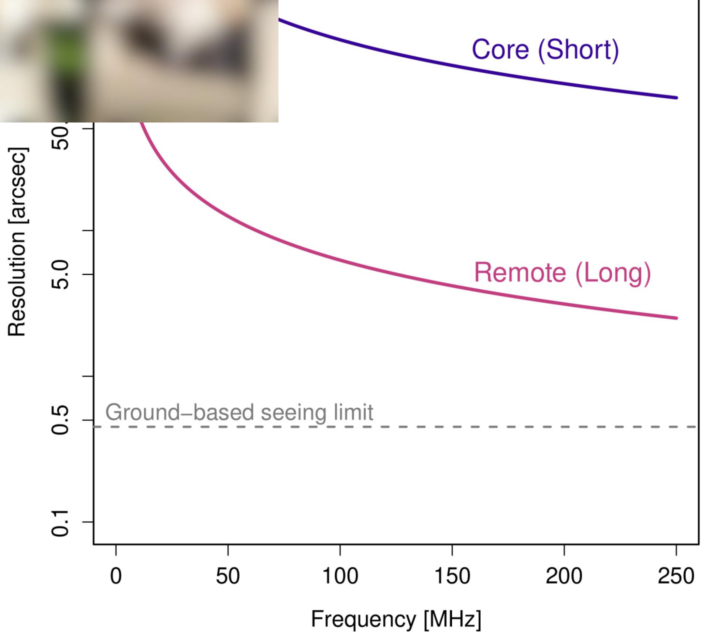

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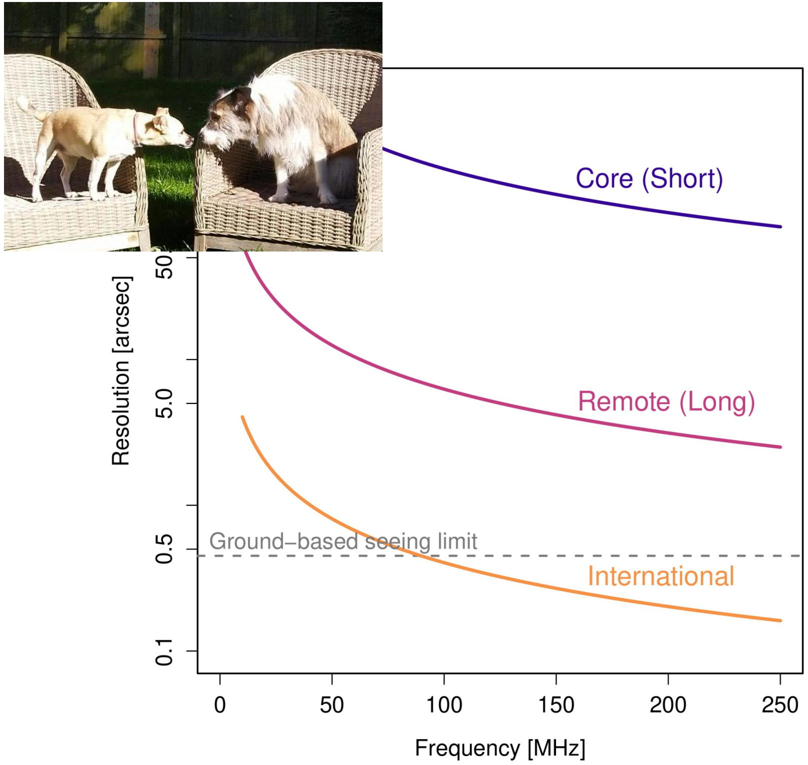
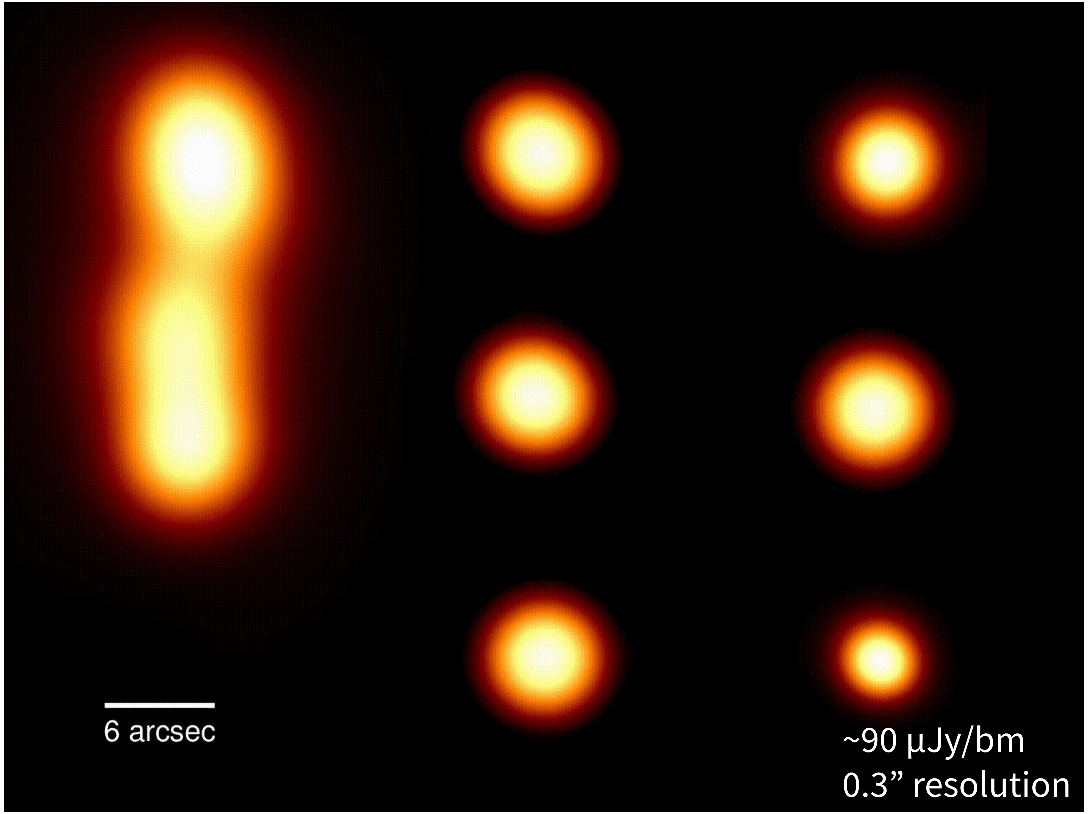
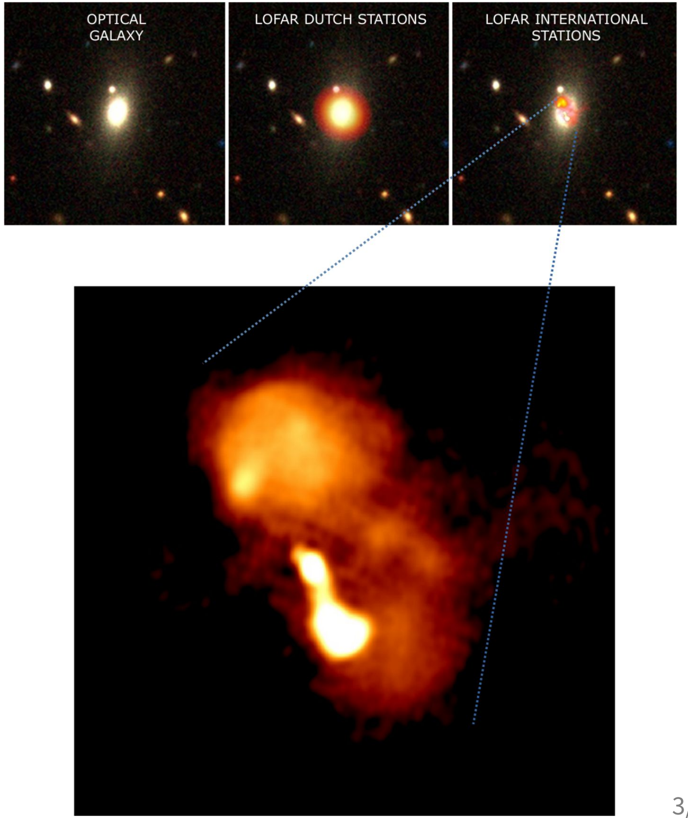


What do we get with sub-arcsecond resolution?





Challenges in high resolution at MHz frequencies

- **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

Challenges in high resolution at MHz frequencies

- **Ionosphere:** requires directional dependent calibration → **pathfinder for SKA-Low**
- **Data volume:** datasets are 4-20TB per observation → **SKA-like data volumes *now***
- **Clocks:** remote and international stations on individual clocks
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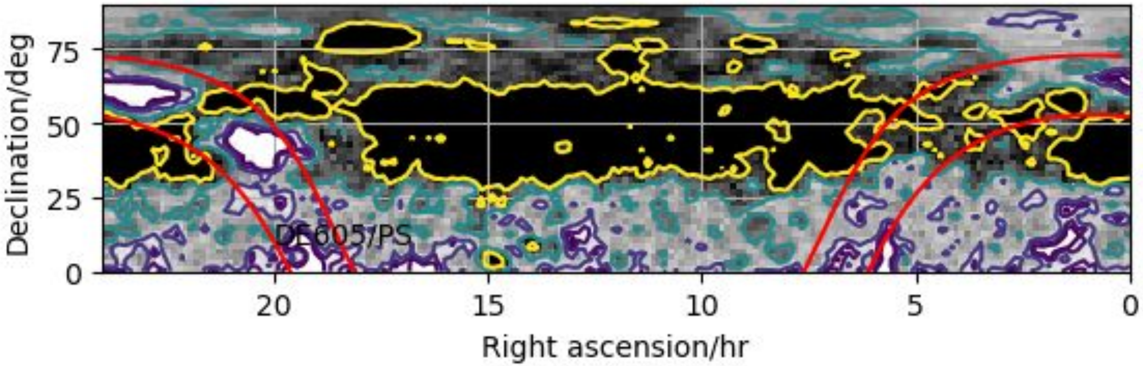
Long Baseline Calibrator Survey (LBCS)

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



- Extending this to LBA (PI: Jackson)

Developing a user-friendly calibration strategy

LoTSS processing
Full array – instrumental effects
Dutch array – phases

de Gasperin et al. 2019

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LOFAR-VLBI pipeline
Dispersive delay
Phase calibration

Techniques
- Combine core stations
- Solve directly for TEC
- Phase-shift & average to reduce FOV

Morabito et al. 2022

Calibration uses LOFAR-native tools but borrowing from VLBI techniques

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Morabito et al. 2022

Widefield LOFAR-VLBI
Residual delay across field
Directional phase / amplitude self-cal

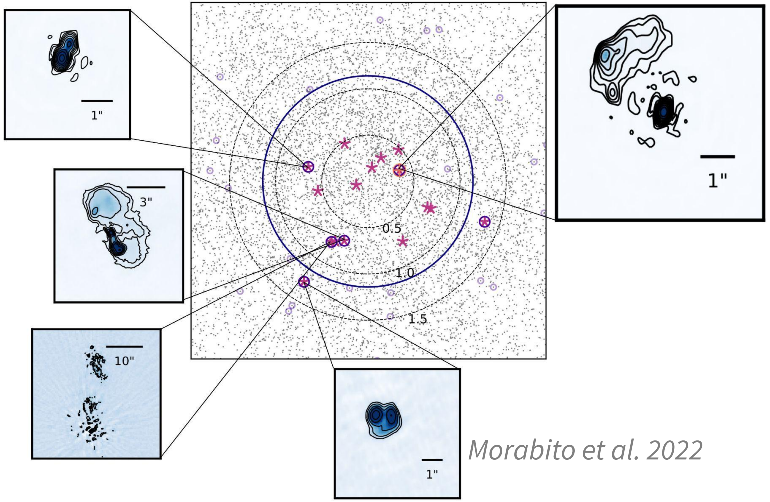
Techniques
- Facet-based imaging
- Combine facets for final image

Sweijen et al. 2022

Wide-field VLBI with LOFAR

LOFAR-VLBI pipeline

Application: wide area surveys

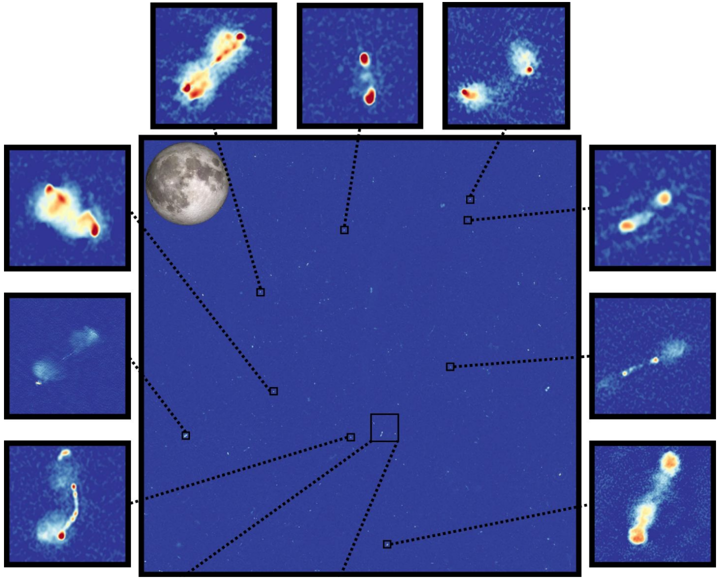


Morabito et al. 2022

Field of View limited to radius ~1.25 deg (~5 deg^2)

Widefield LOFAR-VLBI

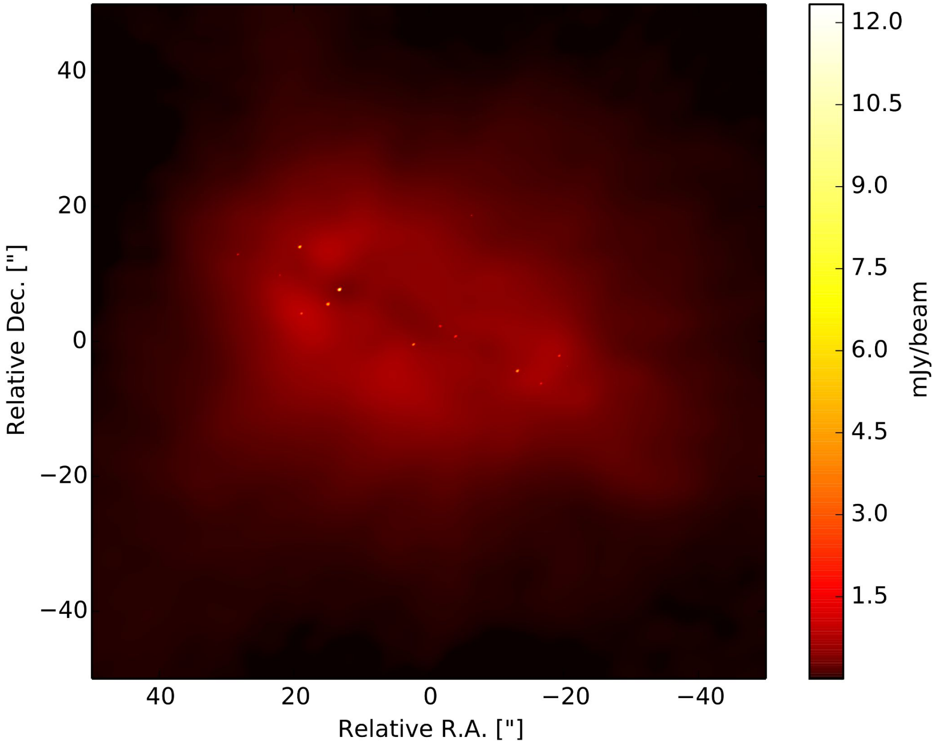
Application: deep field surveys



Sweijen et al. 2022

Early results

Varenius et al. 2015



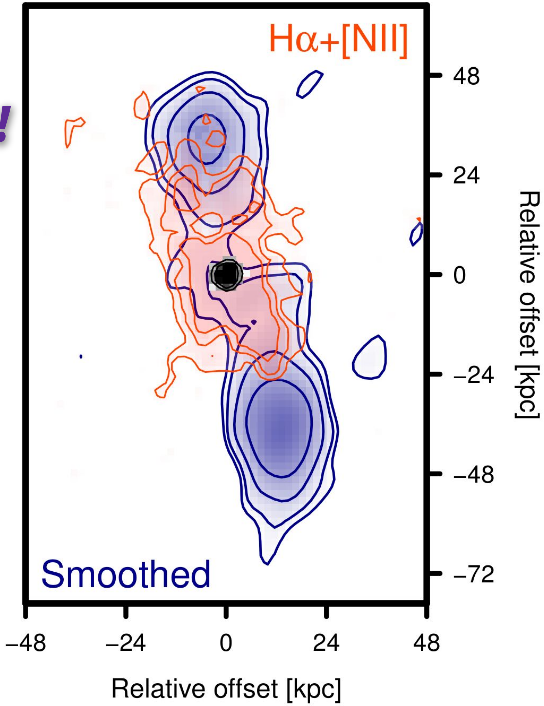
Set the record for high resolution at MHz freqs!

- **Compact objects:** seven new objects, investigated radio spectra of those previously detected at higher frequencies
- **Diffuse emission:** associated with outflow, reduced brightness in region of edge-on star-forming disk

Early results

Morabito et al. 2016

LBA – 55 MHz!

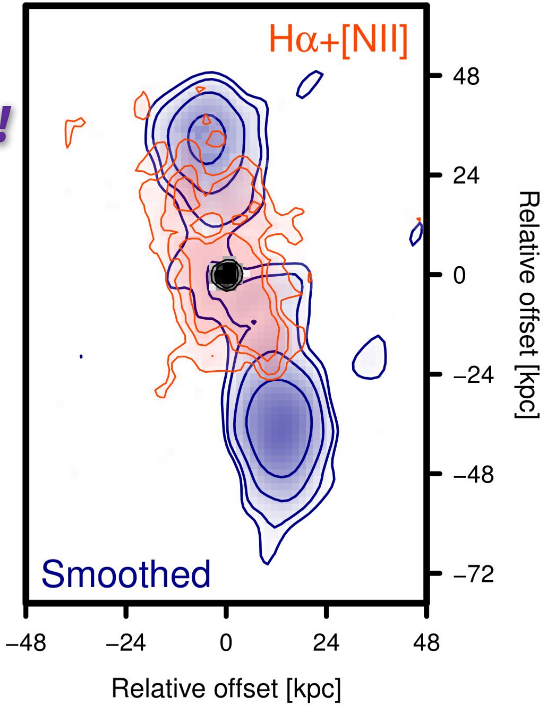


Set the record at <100 MHz!

Early results

LBA – 55 MHz!

Morabito et al. 2016



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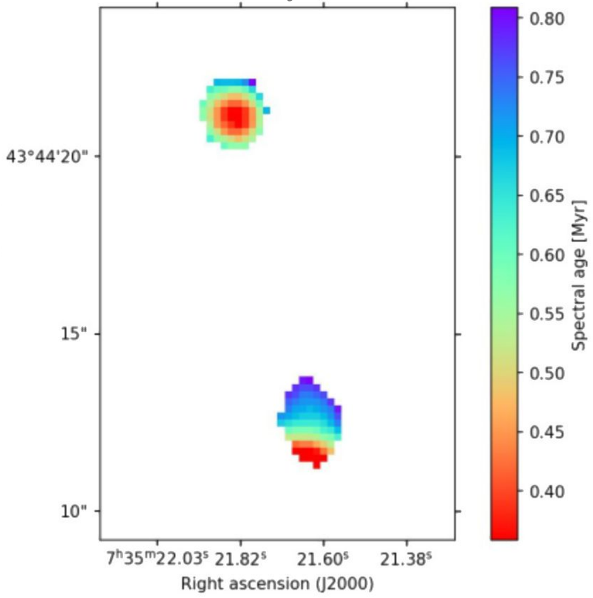
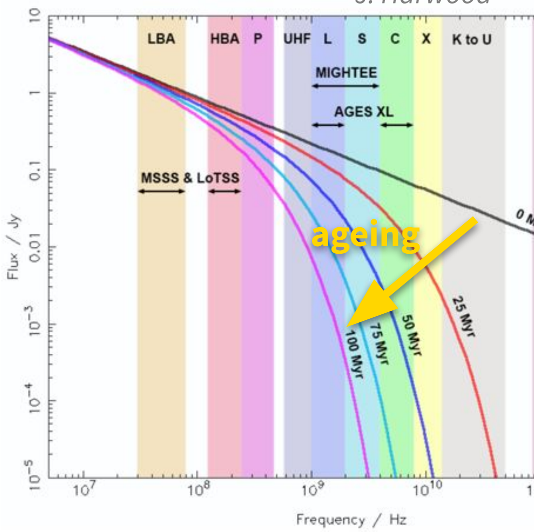


Later spectral modelling including HBA

J. Harwood



Science exploitation

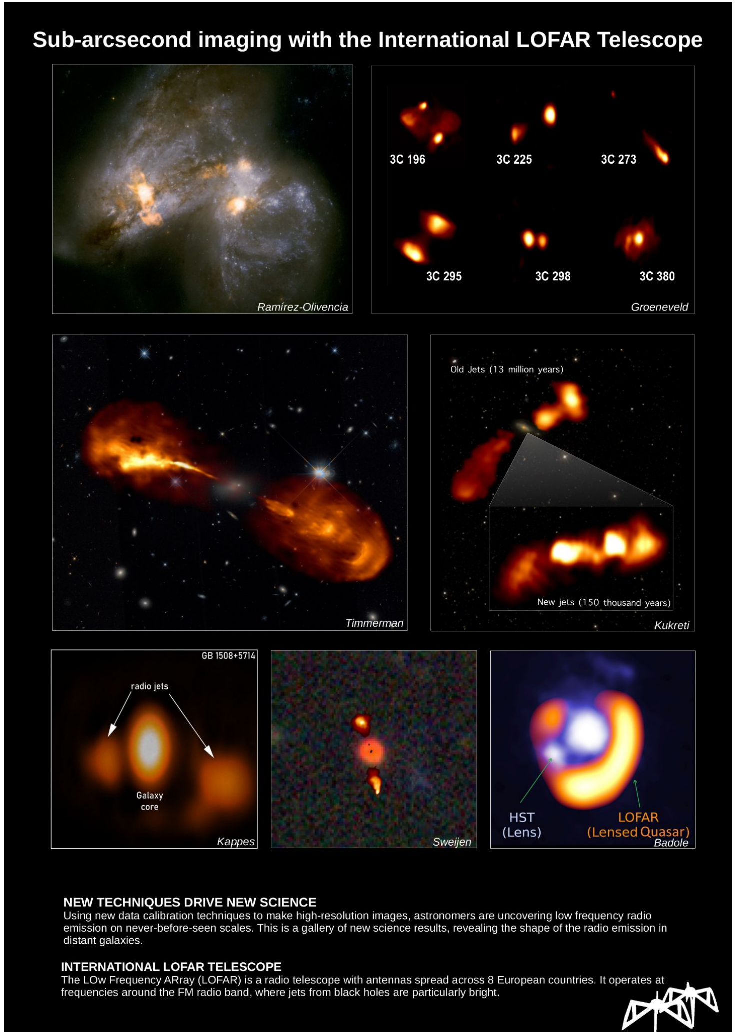
Many science cases, including:

- Jets launched from active galactic nuclei
- Jets interacting with the interstellar medium
- Star formation in nearby galaxies
- Brightness temperature identification of AGN

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

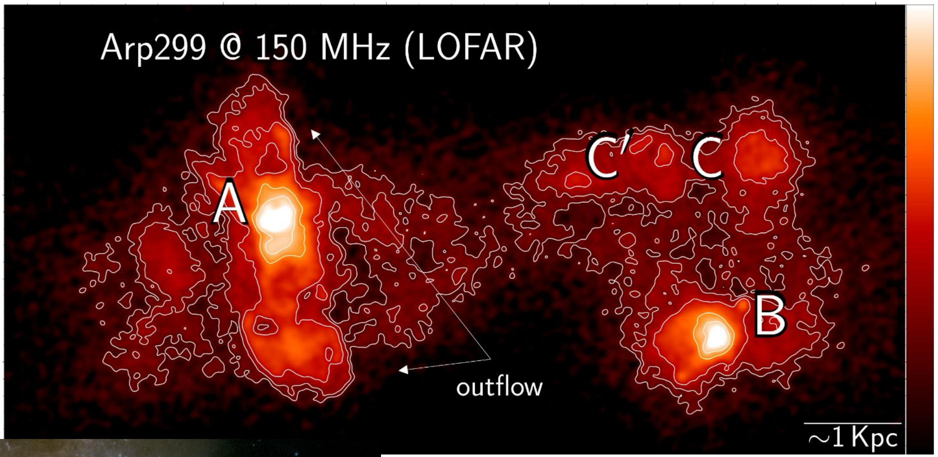
- More than doubling the number of scientific results using LOFAR sub-arcsec resolution!
- Most papers lead by early career researchers

Nature Astronomy article on full-field imaging *(Sweijen et al. 2022)*



(Ultra) Luminous Infrared Galaxies

Ramírez-Olívencia et al. 2022



Spatially separated radio spectra allows modelling of absorption; favours clumpy model

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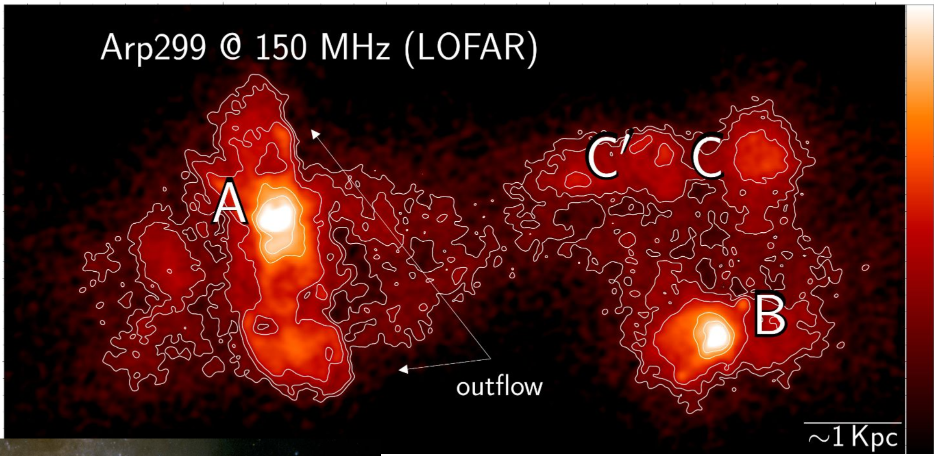

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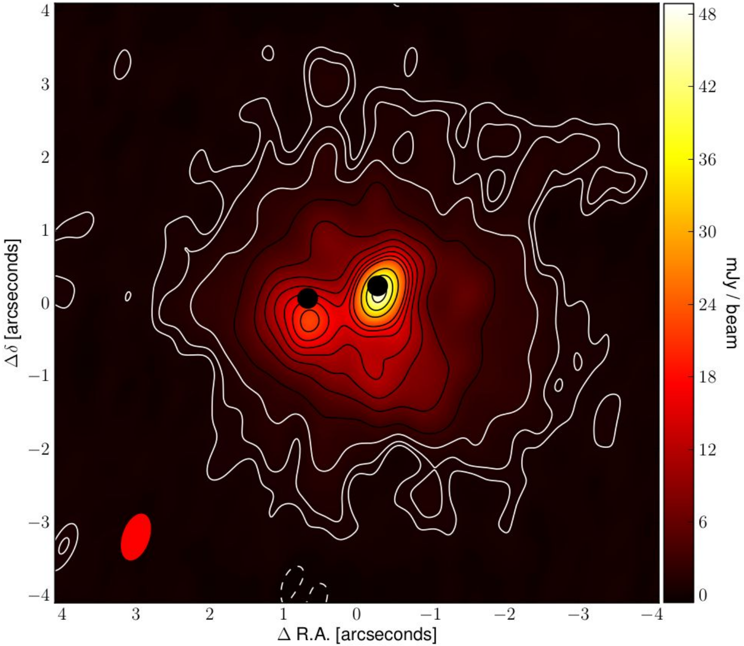

Spatial resolution is crucial for estimating accurate star formation rates

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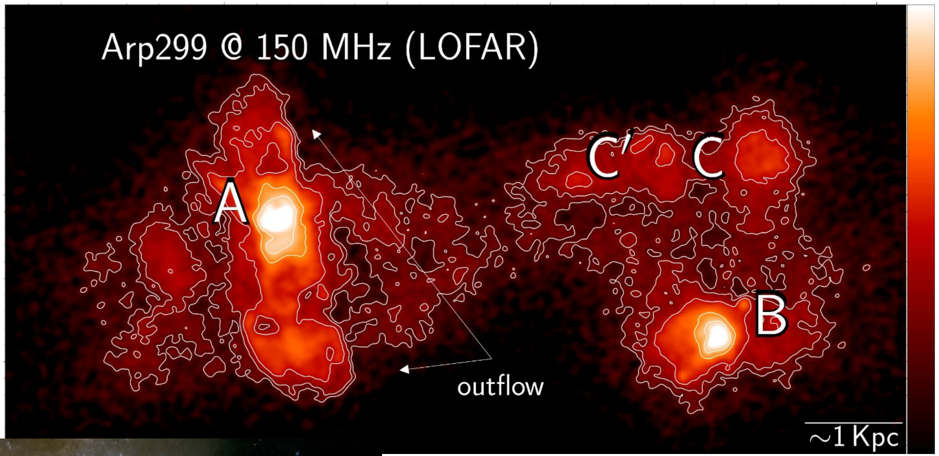

Spatially separated radio spectra allows modelling of absorption; favours clumpy model

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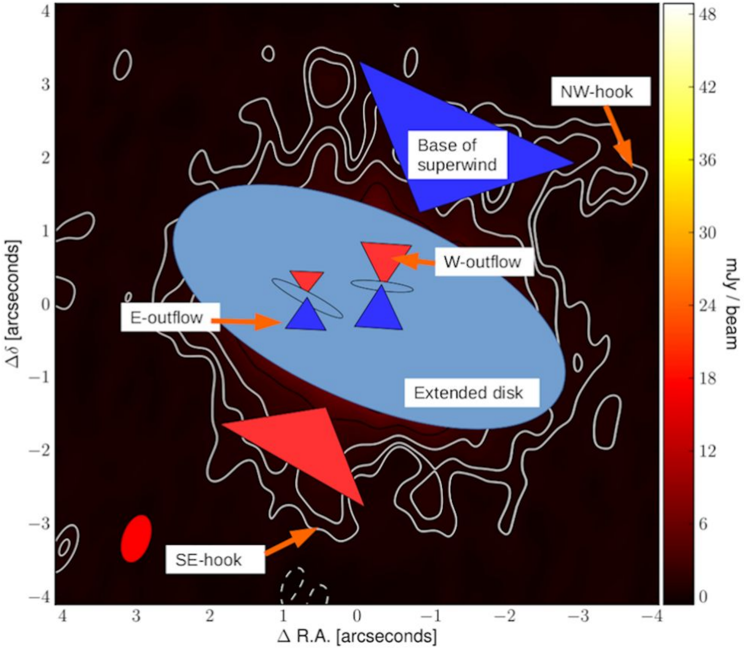
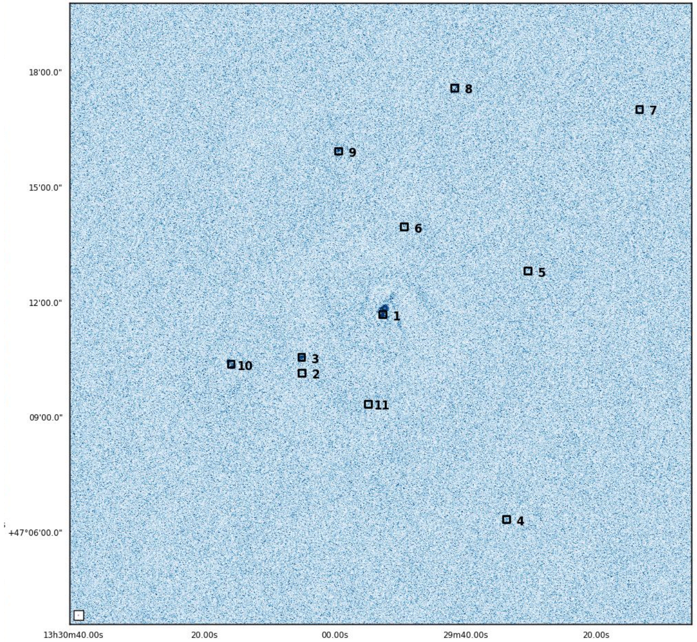


Spatial resolution is crucial for estimating accurate star formation rates

Star formation / supernovae remnants in M51

Venkattu et al, in prep



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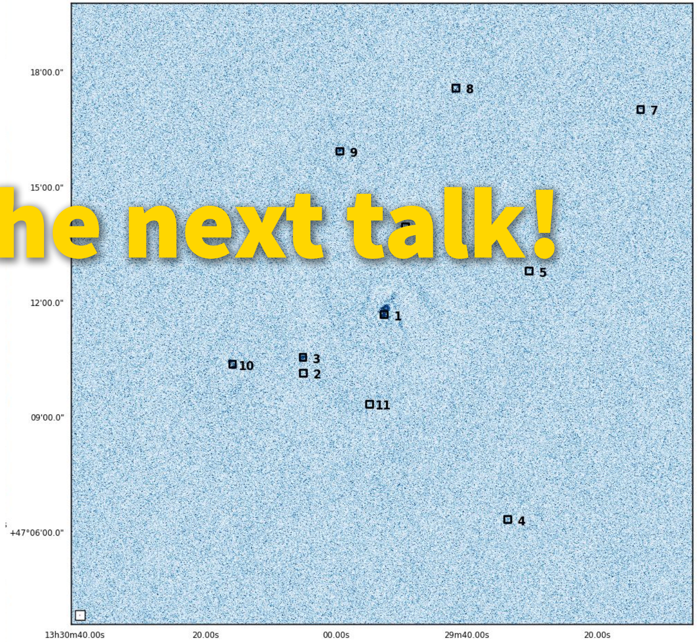


Stay tuned for the next talk!

Ongoing Work

Wide area (individual sources)

- Post-processing LoTSS

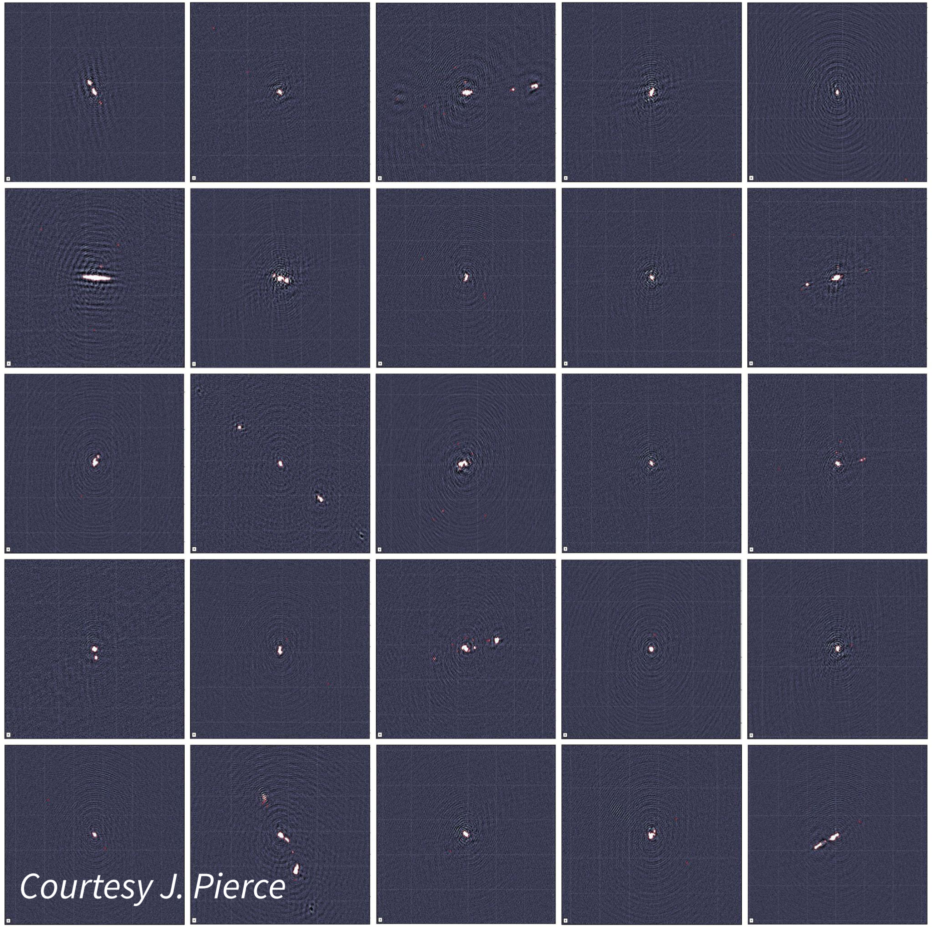
Deep fields (full FoV)

Lockman, Boötes, ELAIS-N1

- Initial imaging + going deeper
- Intermediate resolution ~1”

LOFAR2.0

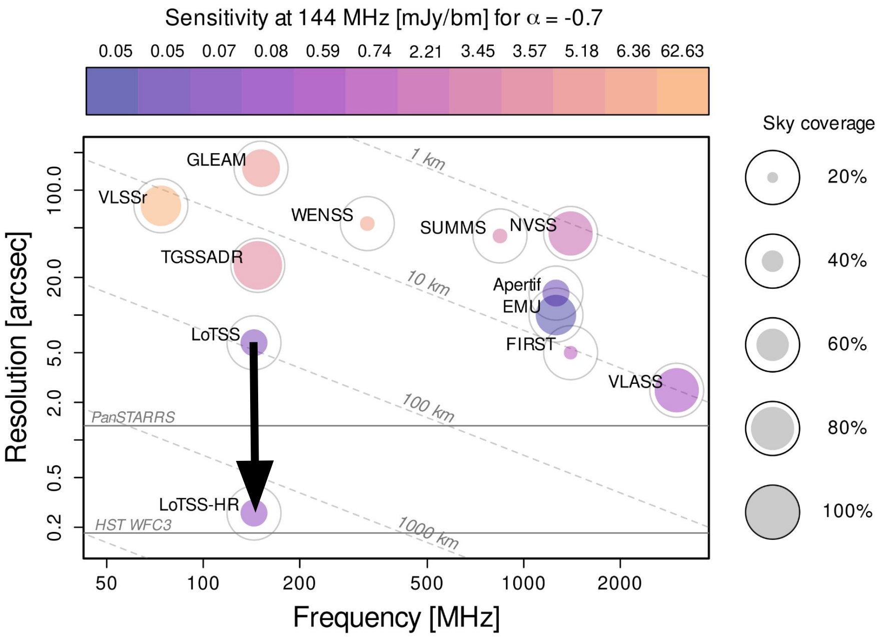
- LOFAR2.0 Ultra Deep Observation: Euclid Deep Field North *(PIs: Best, Morabito)*



LOFAR Two-metre Sky Survey + High Resolution

Post-processing LoTSS at high resolution will yield ***the first sub-arcsecond Northern sky radio survey***

	LoTSS	LoTSS-HR	VLASS
resolution	6”	0.3”	2.5”
Area [deg^2]	20,000	20,000	33,885
noise	70 μJy/bm	~50 μJy/bm	69 μJy/bm
Sources per deg^2	780	~50 (> 10 mJy)	~148



Main takeaways

- The International LOFAR Telescope (ILT) provides otherwise inaccessible spatially resolved information at low frequencies - particularly powerful when combined with higher frequency observations at similar resolutions

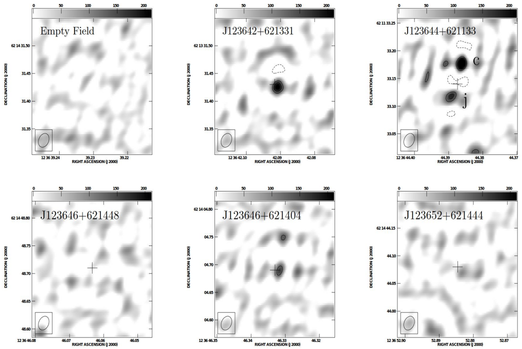
- Sweden has a strong track record with LOFAR-VLBI, focused on detailed studies of star-forming and starburst galaxies

- LOFAR-VLBI is becoming more accessible thanks to our Long Baseline Working Group, which is driven by active early career researchers

Extra slides

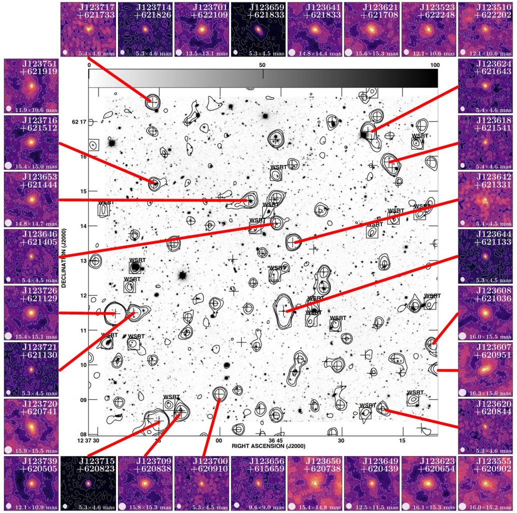
Higher resolution at cost of Field of View (FoV)

Wide-field Very Long Baseline Interferometry (VLBI)



Garrett et al. 2001

Multiple simultaneous phase centre observing
(Deller et al. 2011, Morgan et al. 2011, Keimpema et al. 2015)



Radcliffe et al., 2018

<u>EVN observations of HDF</u>

- ★ 1.6 GHz
- ★ 0.025” resolution
- ★ 42 µJy/bm noise
- ★ 5 arcmin^2 FoV

3 sources detected

<u>EVN observations of HDF</u>

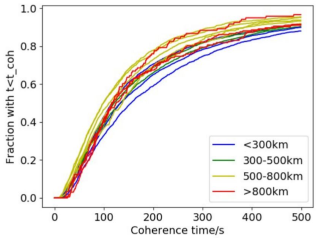
- ★ 1.6 GHz
- ★ 0.05 - 0.016” resolution
- ★ 10 - 40 µJy/bm noise
- ★ ~177 arcmin^2 FoV (+bright sources <25 arcmin)

31 sources detected

Long Baseline Calibrator Survey (LBCS)

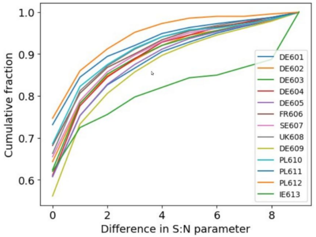
Quality indicators / metrics

Atmospheric coherence statistics



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

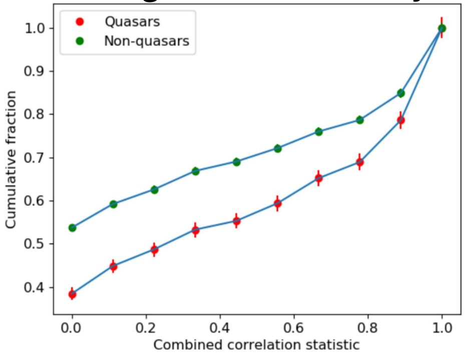
Reproducibility



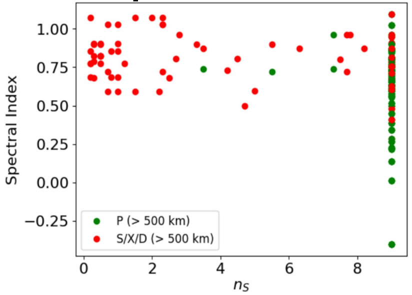
Sources observed more than once: results very similar for all baselines

Science with LBCS

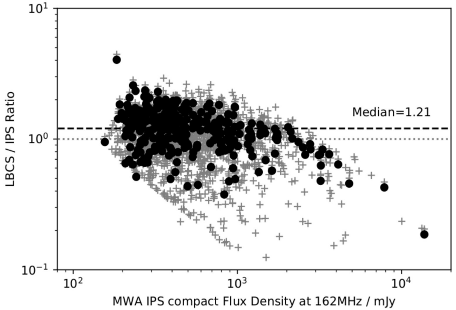
Testing Unification Theory



Compact sources are flat



Interplanetary Scintillation



In conjunction with MWA; J. Morgan

Developing a calibration strategy

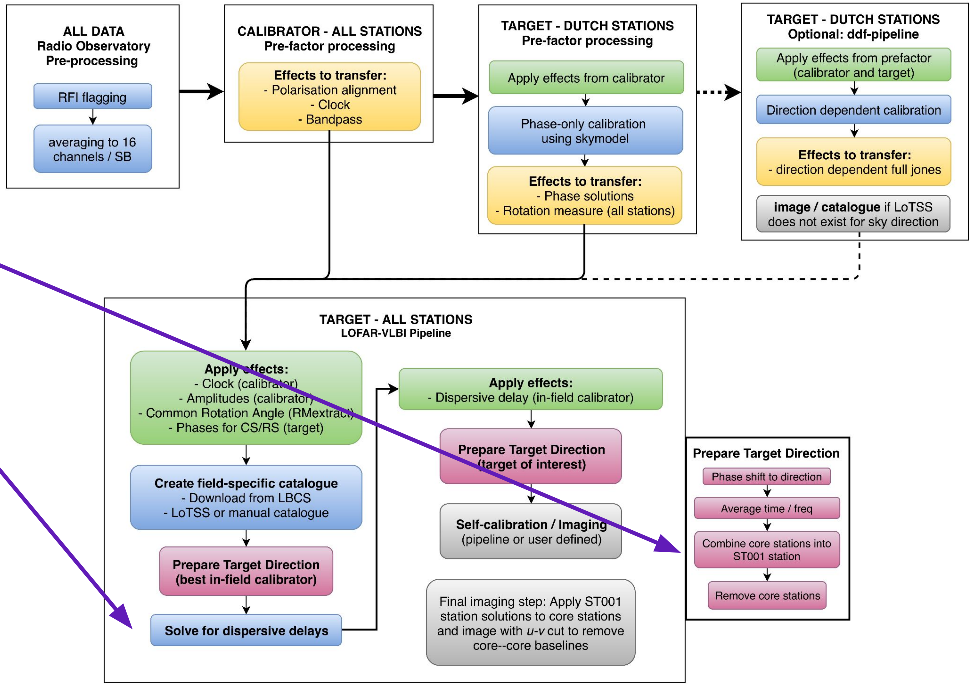
Use LOFAR-native tools to:

- 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)*

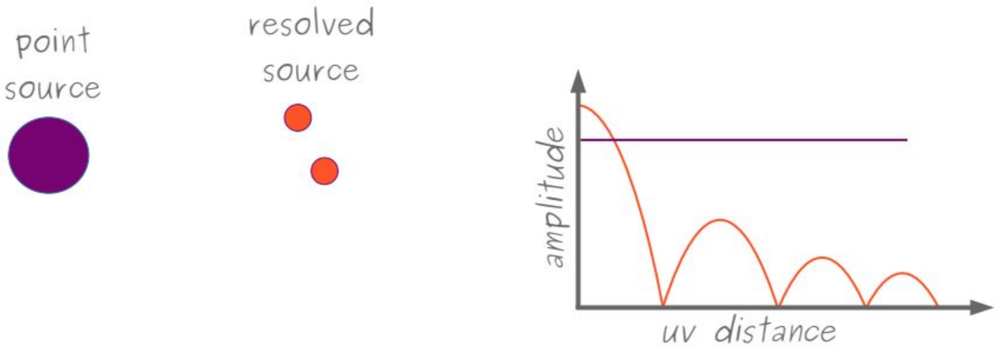
Built as an extension to the processing for the LOFAR Two-metre Sky Survey *(Shimwell et al. 2017,2019,2022)*

Basis for imaging full field of view *(Sweijen et al. 2022)*



Developing a calibration strategy

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

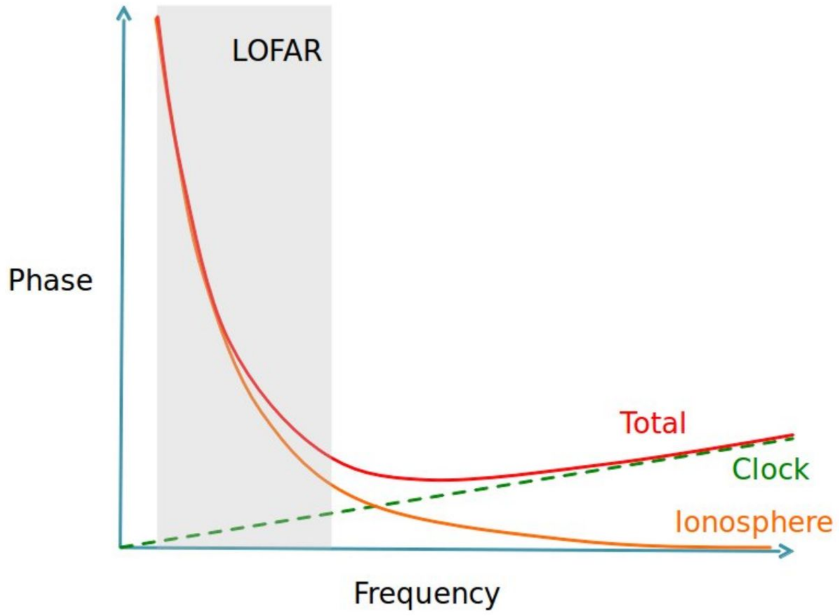


To cope with this a technique called ***fringe-fitting*** was developed to increase the solution intervals by solving for *delays* and *rates* in addition to a phase offset:

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

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

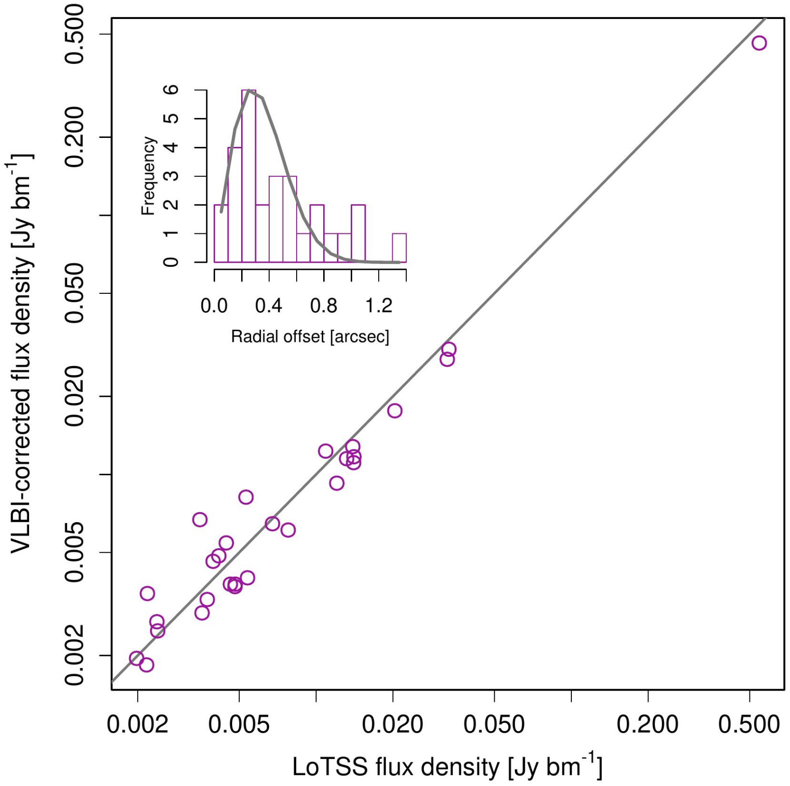
Image courtesy J. Moldón

Demonstration: P205+55

Astrometry and flux density scale

Compare original LoTSS image with 6” image m
Dutch dataset

- LoTSS has 20 mas offset from PanSTARRS → compared to LoTSS is 28 mas
- Flux density – scatter around one-to-one lir sources in LoTSS to 6” image



Brightness temperature at 150 MHz

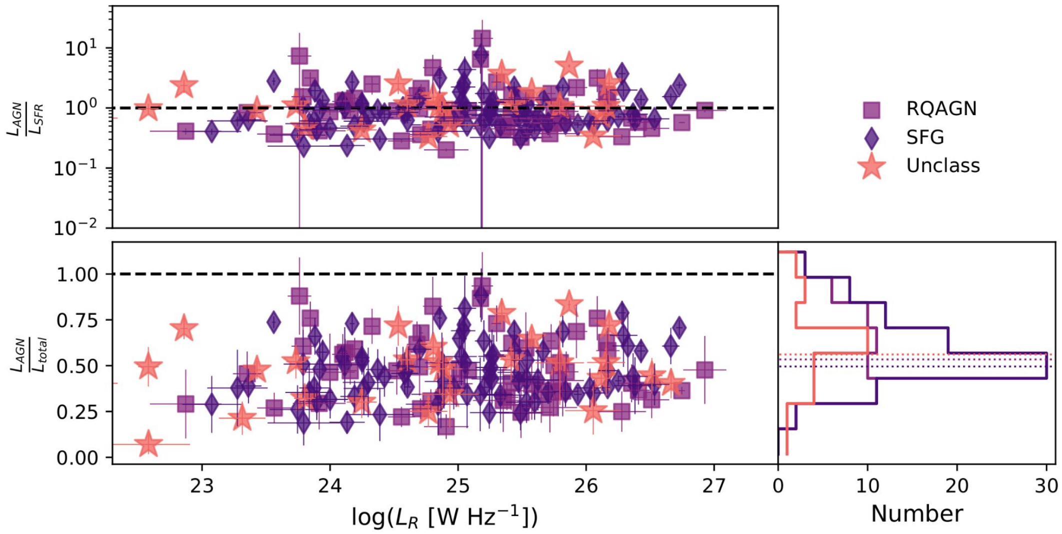
- Identified 795 (790) high brightness temperature sources in Lockman Hole
  - 83% are otherwise identified as AGN (91% when using only peak intensity)
  - ***66 new AGN identifications!***
- Comparison to SED fitting shows:
  - 22% of detected radio-quiet AGN and 12% of star-forming galaxies have high 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:

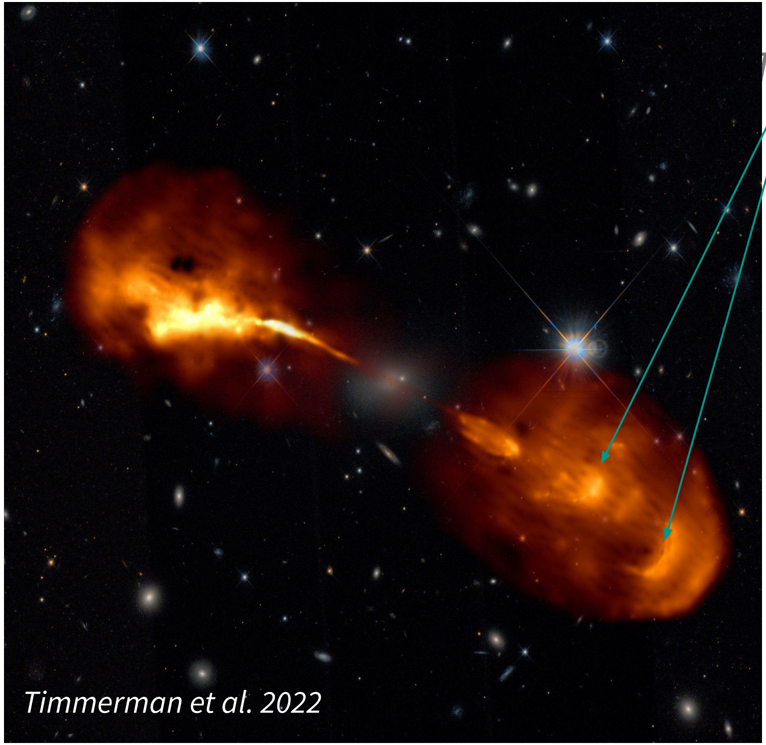
- L_{AGN} = peak intensity, high resolution map
- L_{SFR} = (total flux density, 6” resolution map) - LAGN



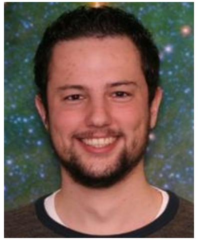
L_{AGN}/L_{SFR}	
Class	Median
RQAGN	0.89±0.69
SFG	0.79±0.42
Unclass	1.07±0.64
Total	**0.90±0.55**

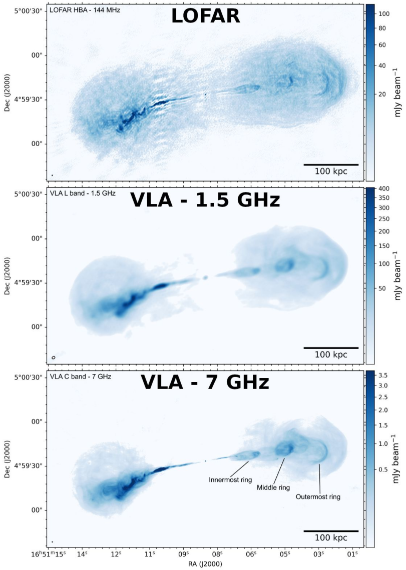
L_{AGN}/L_{total}	
Class	Median
RQAGN	0.47±0.21
SFG	0.44±0.14
Unclass	0.49±0.16
Total	**0.47±0.17**

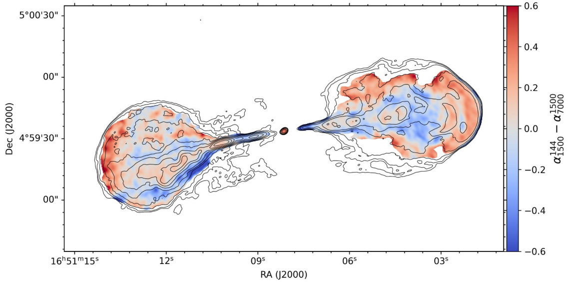
Jets from active galactic nuclei



Timmerman et al., 2022)



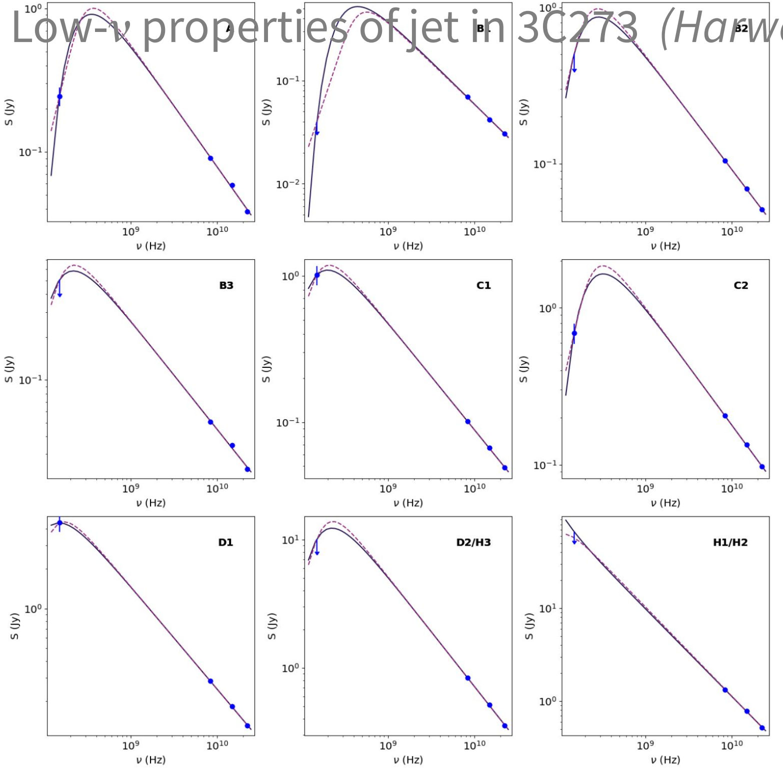


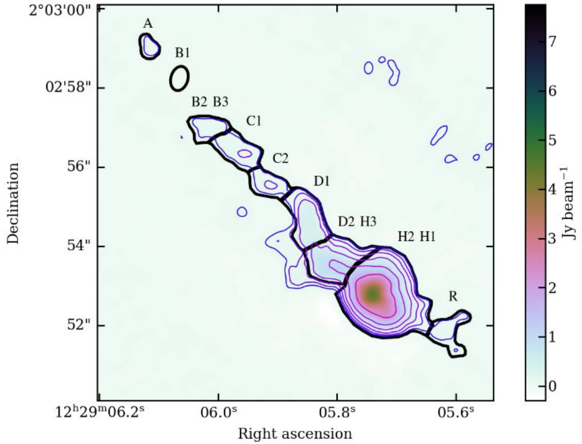


Spectral information - aided by LOFAR - shows rings are consistent with the active galactic nuclei intermittently turning 'on' and 'off'

The jet in 3C273

Low-ν properties of jet in 3C273 *(Harwood, Mooney et al., 2022)*

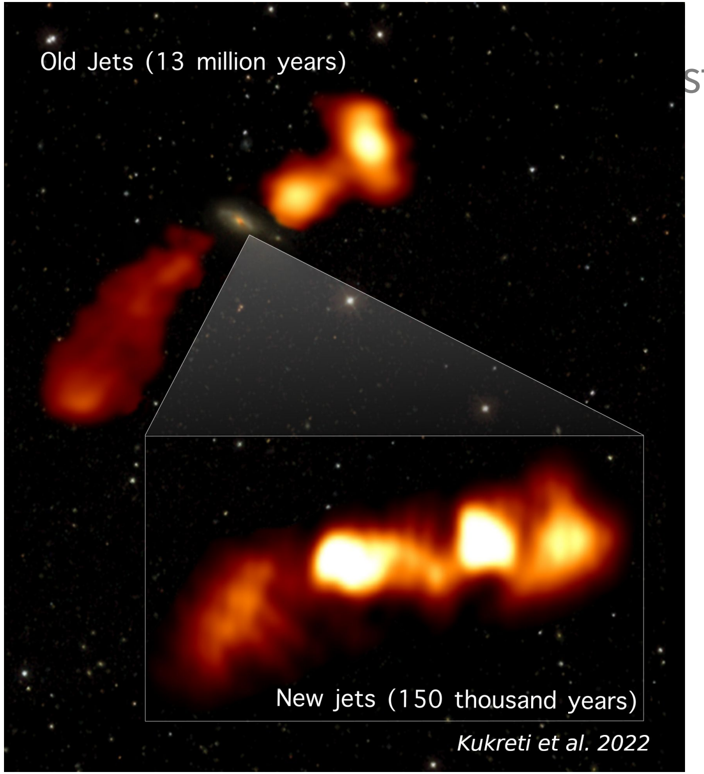




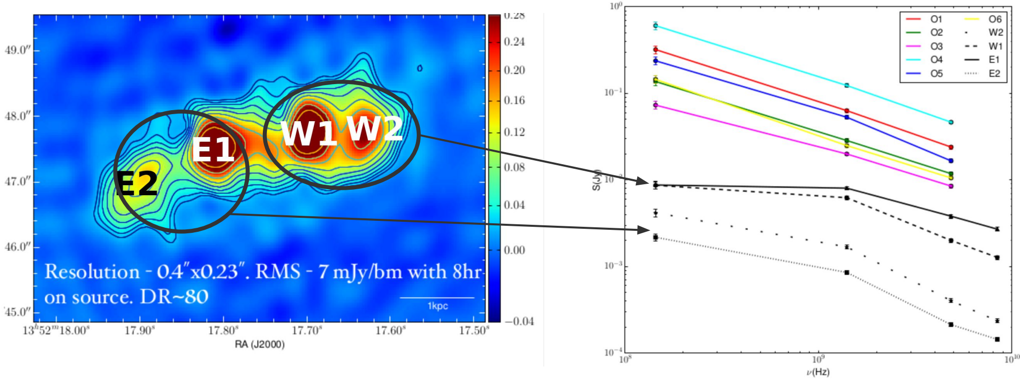
Jet power consistent with high frequencies

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

Jets interacting with the interstellar medium

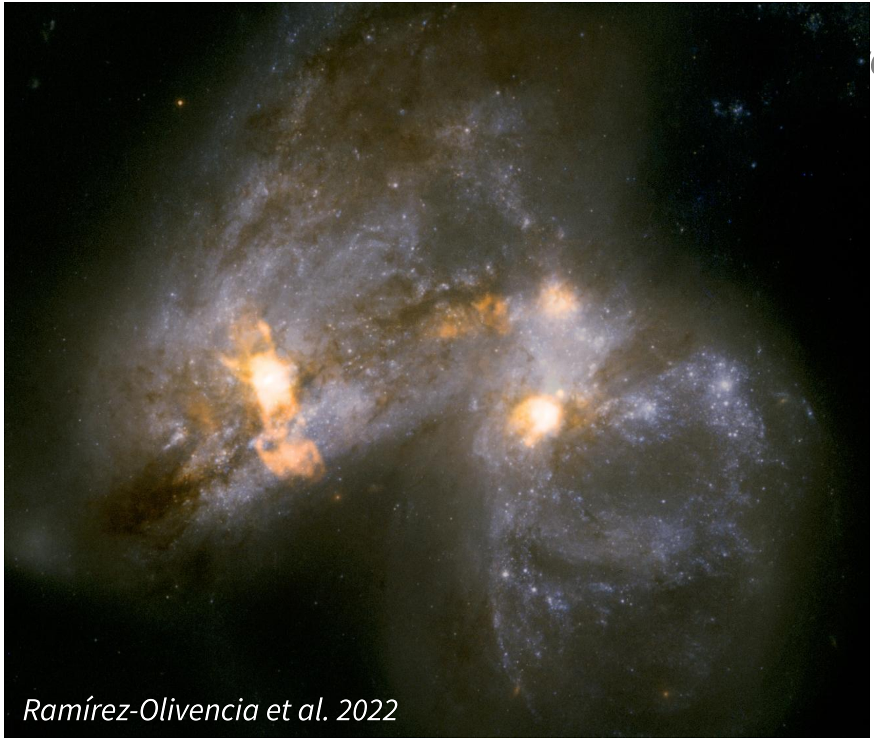


st galaxy *(Kukreti et al., 2022)*

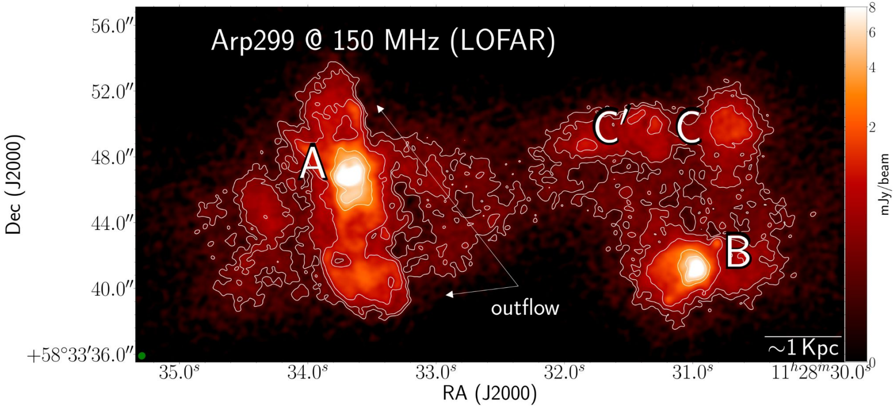


Low-frequency spectra in young jet components show evidence for interaction with interstellar medium

Star formation in nearby galaxies

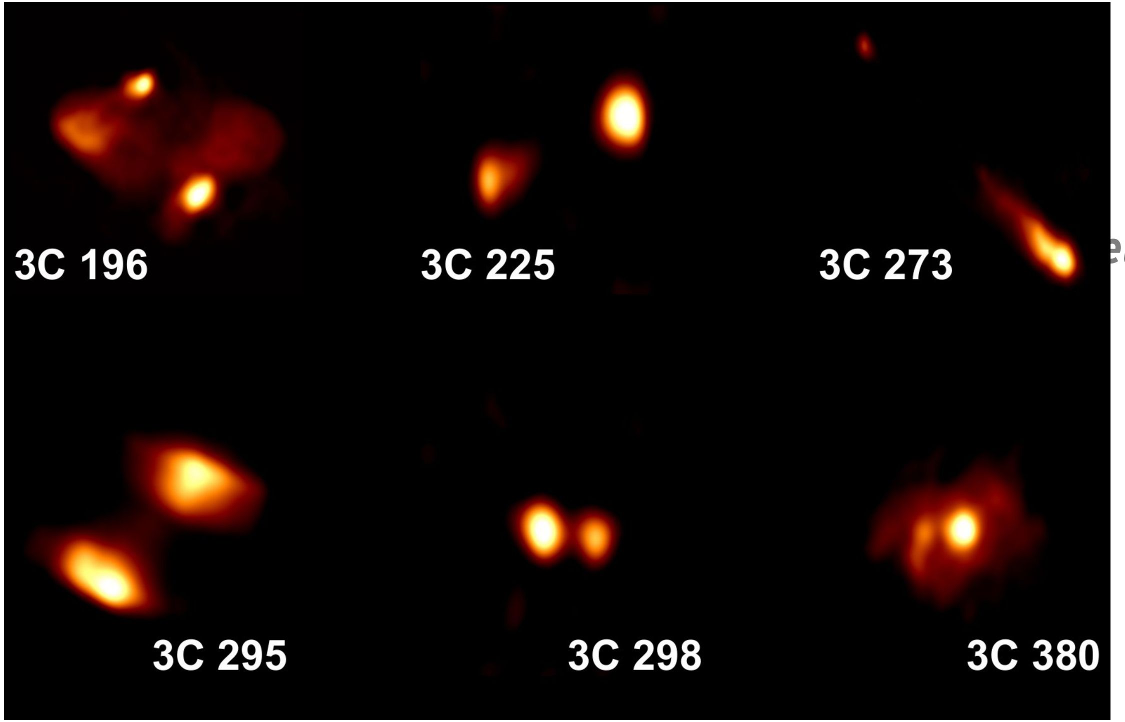


ez-Olivencia et al. 2022)



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

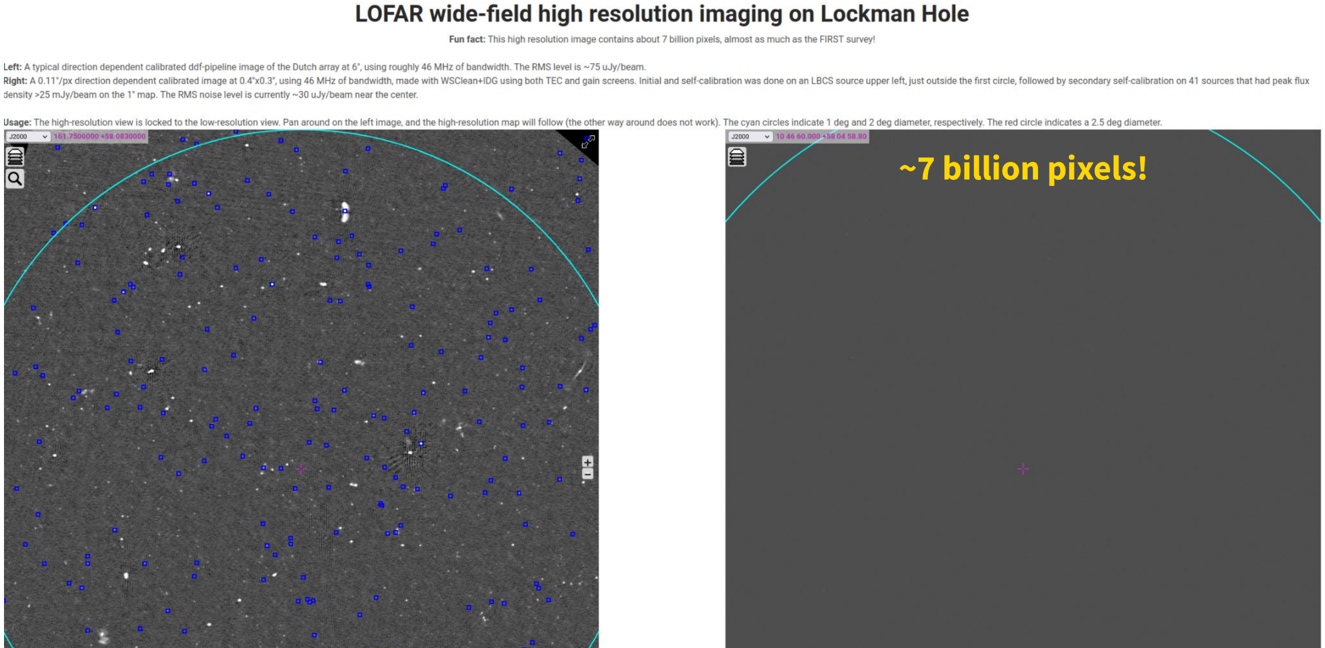


elow 100 MHz! *They allow us to*

Enabling science: the cutting edge

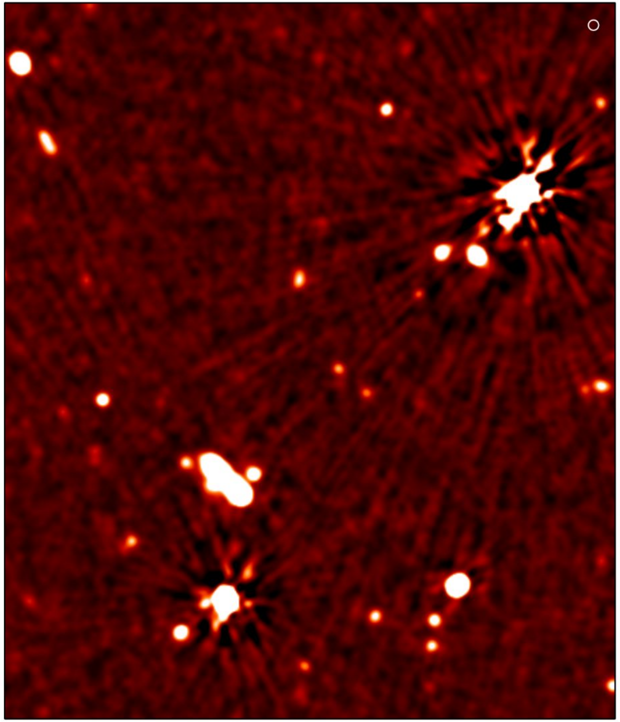
Imaging of complete 5 deg^2 field of view for Lockman Hole *(Sweijen et al. 2022)*

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

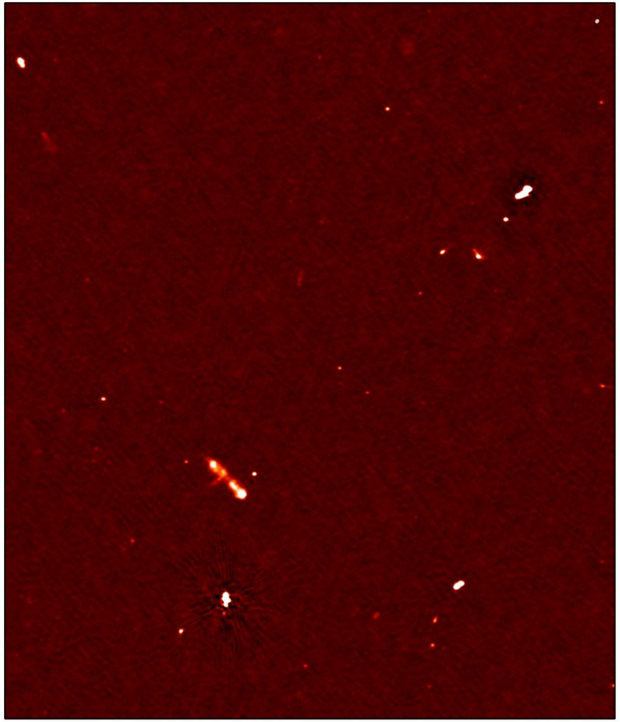


The main challenge at low frequencies

Before ionospheric correction



After ionospheric correction



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