Very Long Baseline Interferometry

with the International LOFAR Telescope (ILT)

Dr. Leah Morabito

Frontend research at low radio frequency

April 2023

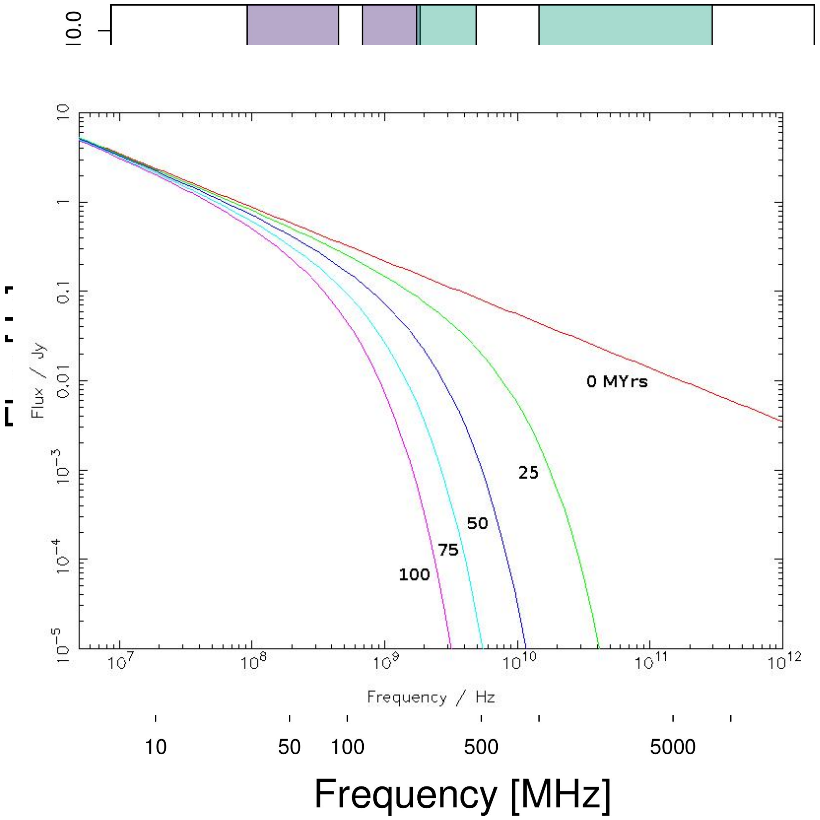
UK Research and Innovation

Durham University

Outline

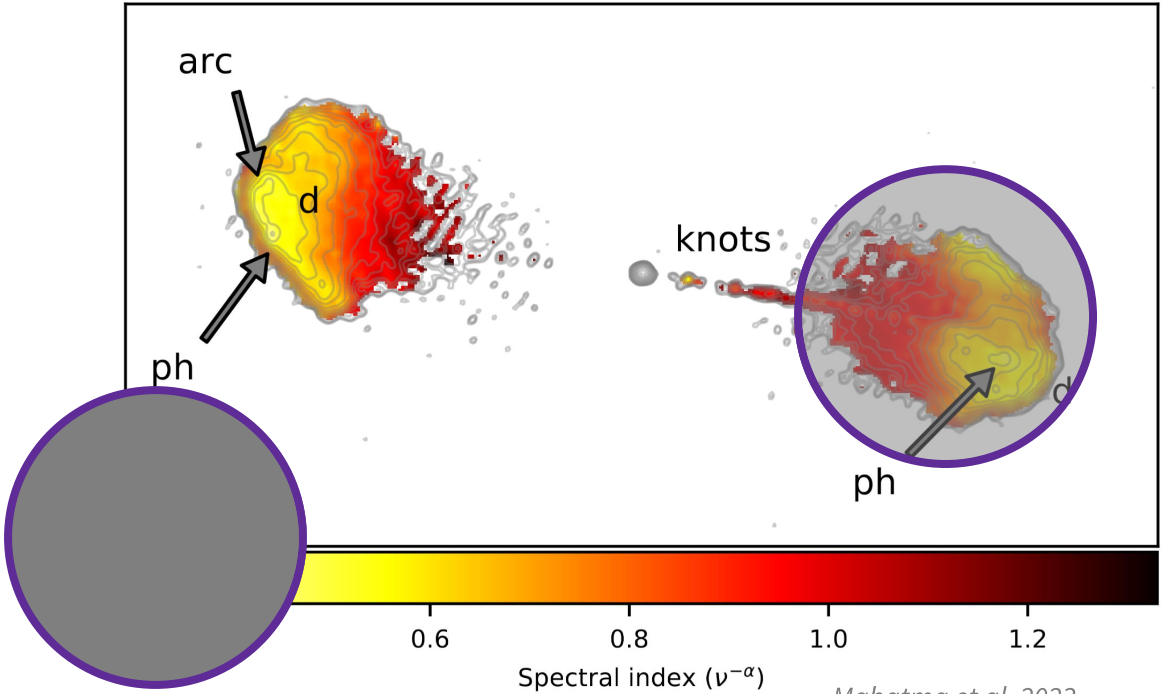
- Why low frequencies?
- Why high resolution?
- Science highlights

Why low frequencies?



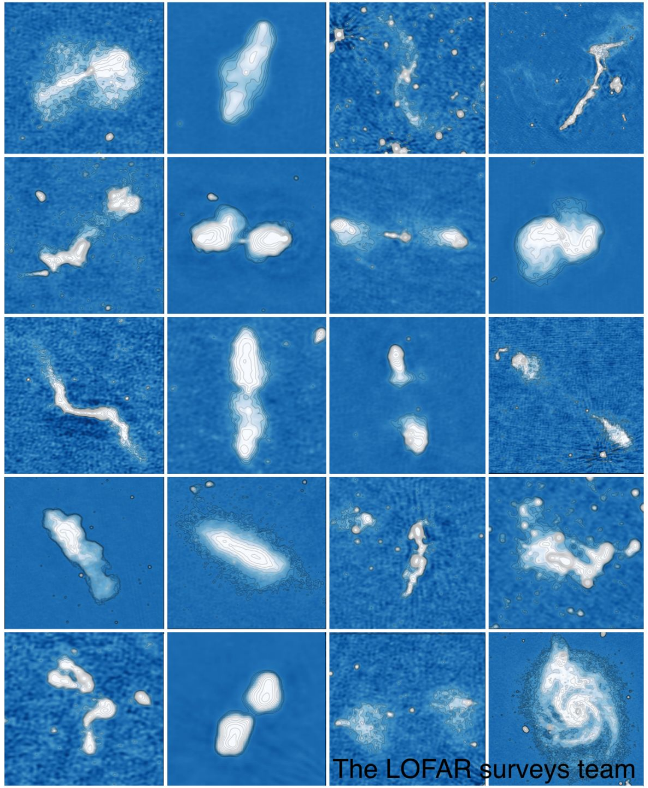
- Synchrotron sources are brighter at low frequencies
- Only way to measure low frequency absorption
- Lower rest frequencies can be reached for high-redshift sources
- Anchor spectral modelling to assess spectral ageing

Why high resolution?

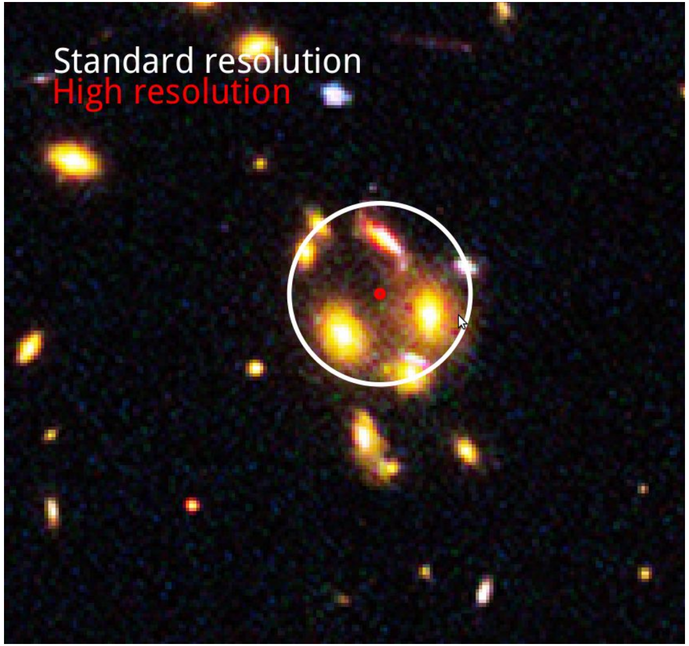


Mahatma et al. 2023

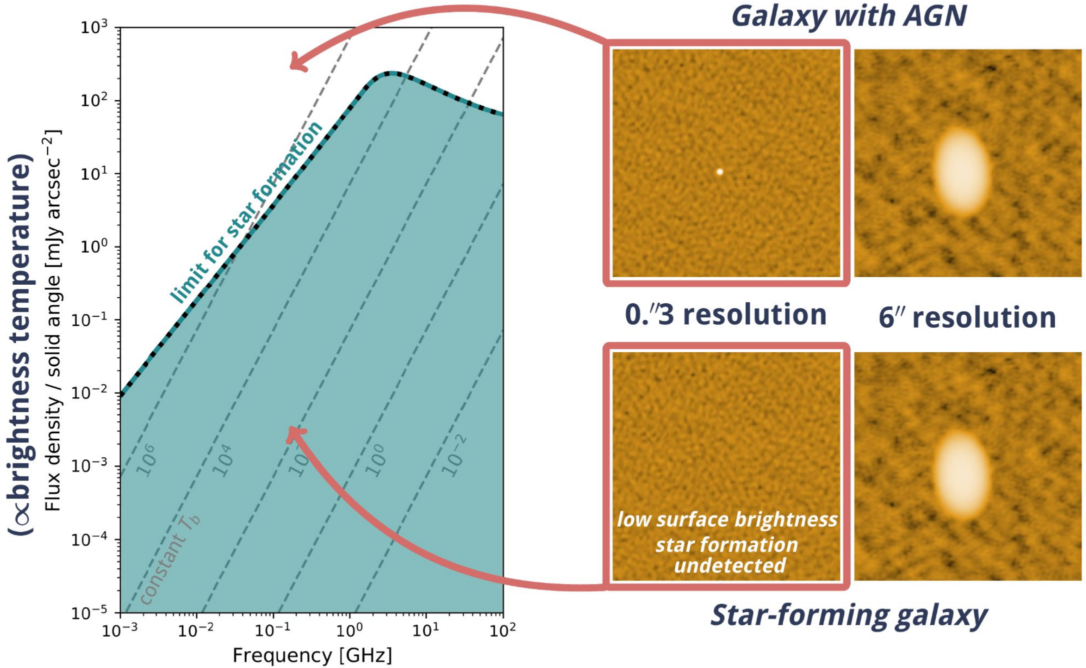
Why high resolution?



The reality is that this only represents ~5 - 10% of sources. ***The rest are unresolved.***



Why high resolution at low frequencies?



adapted from Morabito et al. 2022

Star formation from a normal galaxy has a limit to the amount of **flux density** per **solid angle** (*Condon 1992*)

This depends on:

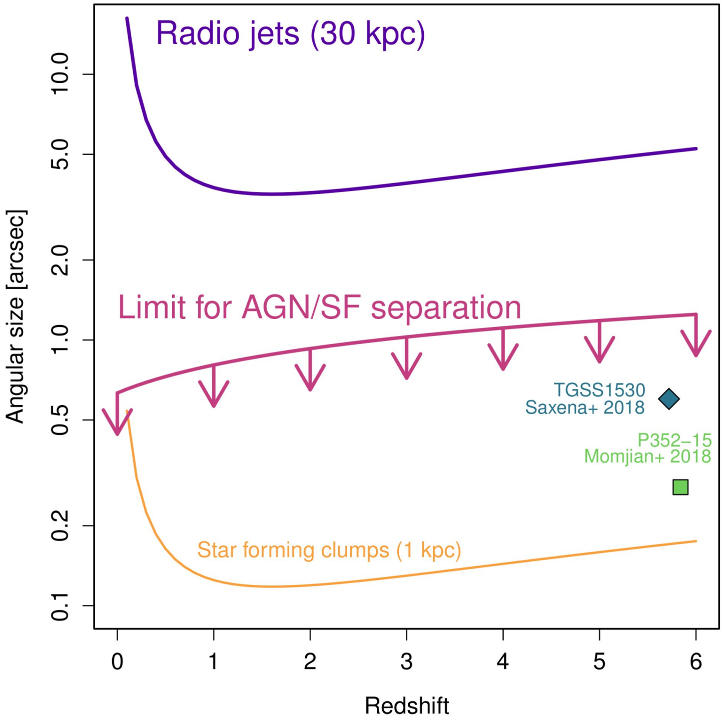
- Observed frequency
- Frequency at which τ = 1
- Electron temperature
- Redshift
- Spectral index

Historically measured with VLBI ≳ 1 GHz

can reach this with International LOFAR Telescope observations

Observables: Flux density, size information

Why high resolution at low frequencies?



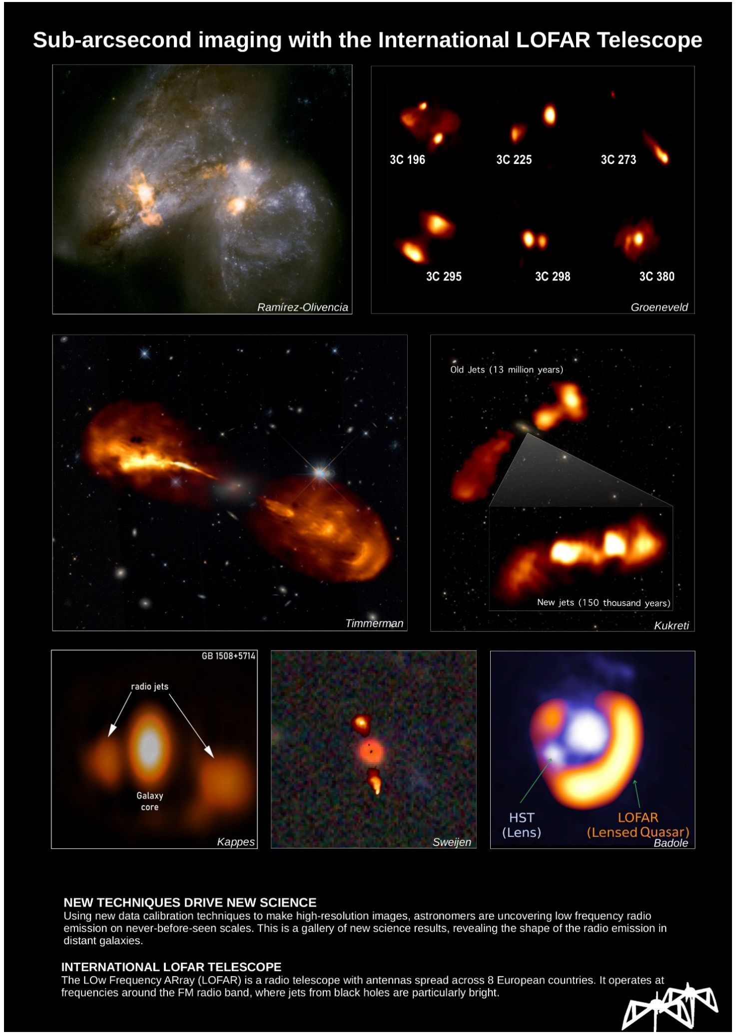
Science cases include:

- Radio jets in active galactic nuclei (AGN)
    - Identifying jets in distant sources
    - Spectral modelling of nearby sources
    - Galaxy-scale jets
- Spatially resolved studies of star formation
- Jets from compact objects (e.g., young stellar objects)
- Localisation of Fast Radio Bursts (FRBs)
- *…. fill in the blank!*

Science highlights

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

- More than doubling the number of scientific results using LOFAR VLBI!
- Most papers lead by early career researchers
- Calibration demo and LBCS papers

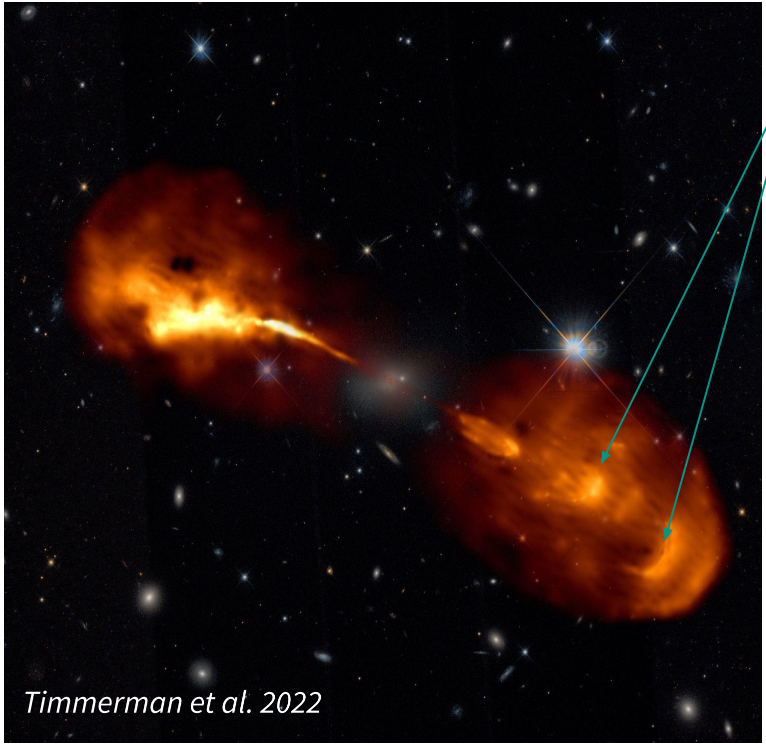


Sub-arcsecond imaging with the International LOFAR Telescope

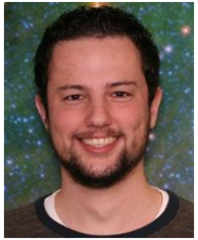
NEW TECHNIQUES DRIVE NEW SCIENCE
Using new data calibration techniques to make high-resolution images, astronomers are uncovering low frequency radio emission on never-before-seen scales. This is a gallery of new science results, revealing the shape of the radio emission in distant galaxies.

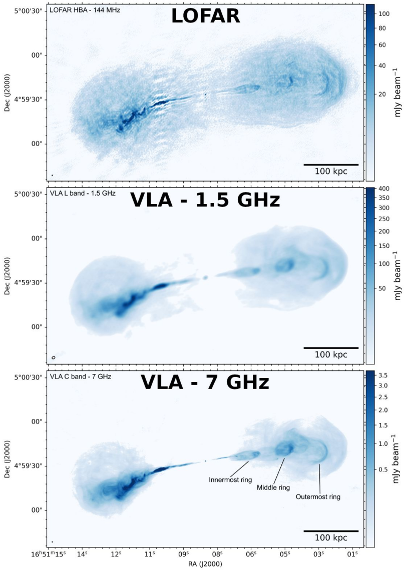
INTERNATIONAL LOFAR TELESCOPE
The LOw Frequency ARray (LOFAR) is a radio telescope with antennas spread across 8 European countries. It operates at frequencies around the FM radio band, where jets from black holes are particularly bright.

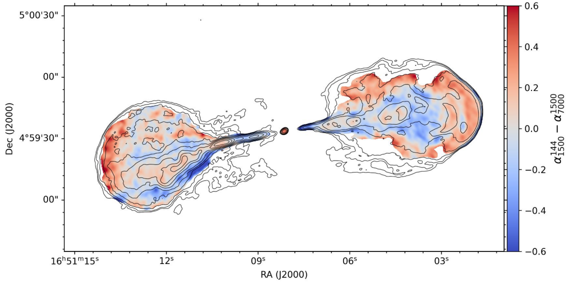
Jets from active galactic nuclei


Timmerman et al. 2022

The origin of the rings in Hercules A
(Timmerman et al., 2022)

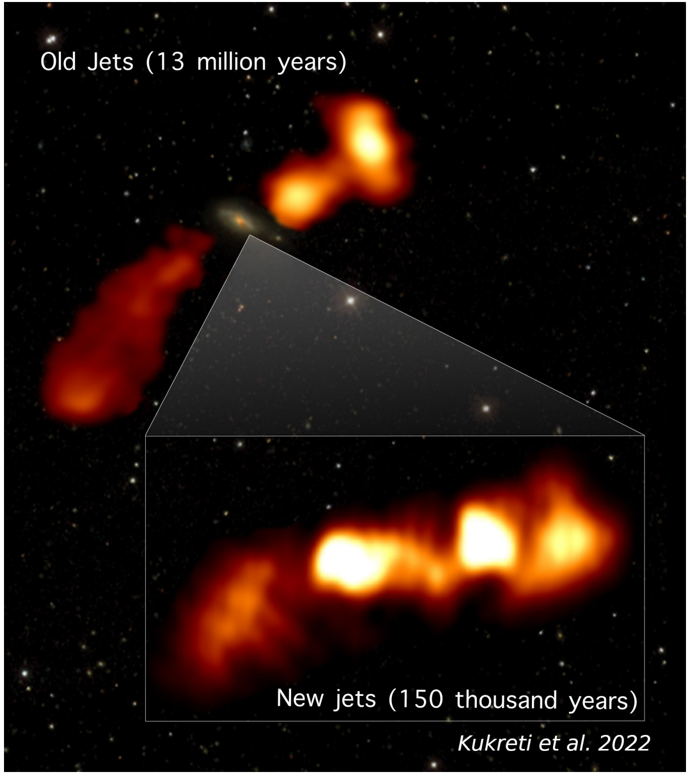






Spectral information - aided by LOFAR - shows rings are consistent with the active galactic nuclei intermittently turning 'on' and 'off'

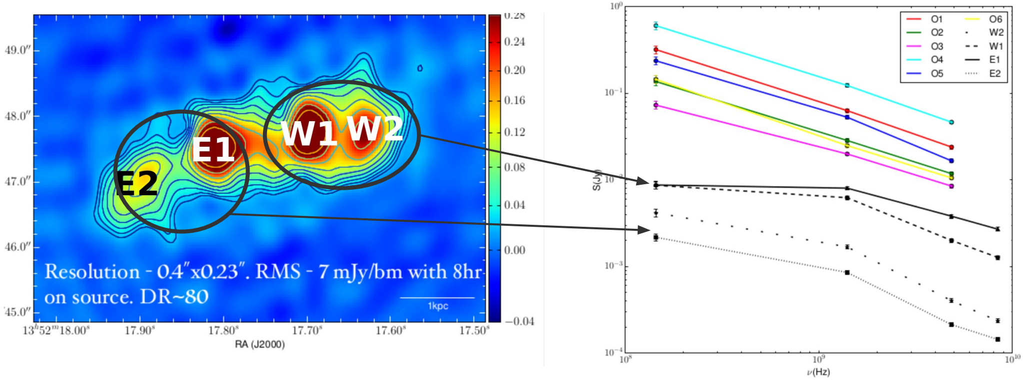
Jets interacting with the interstellar medium



Kukreti et al. 2022

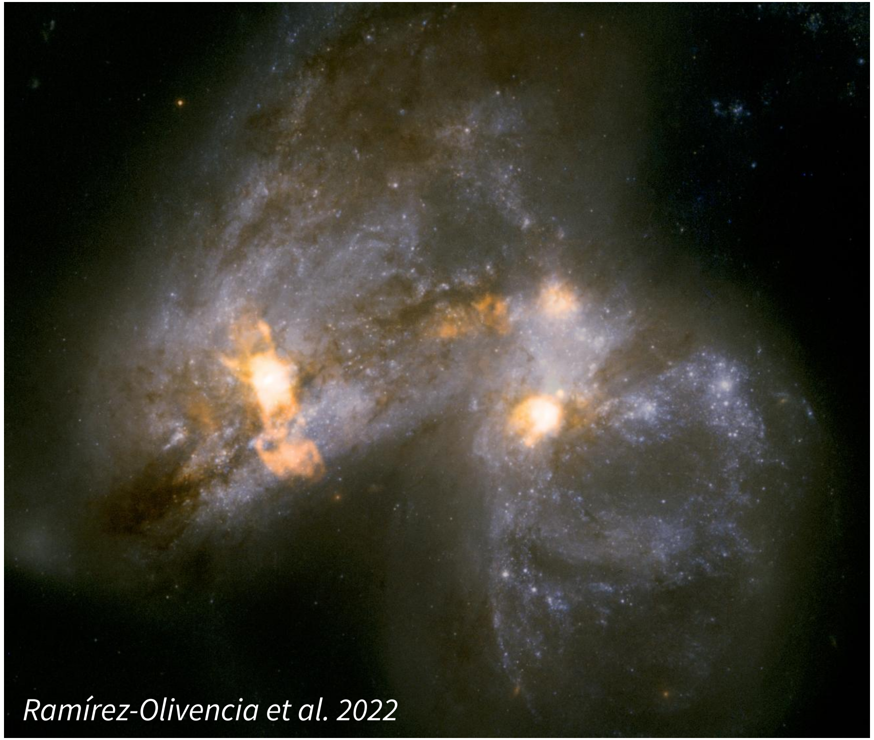
Restarted jets interacting with host galaxy

(Kukreti et al., 2022)

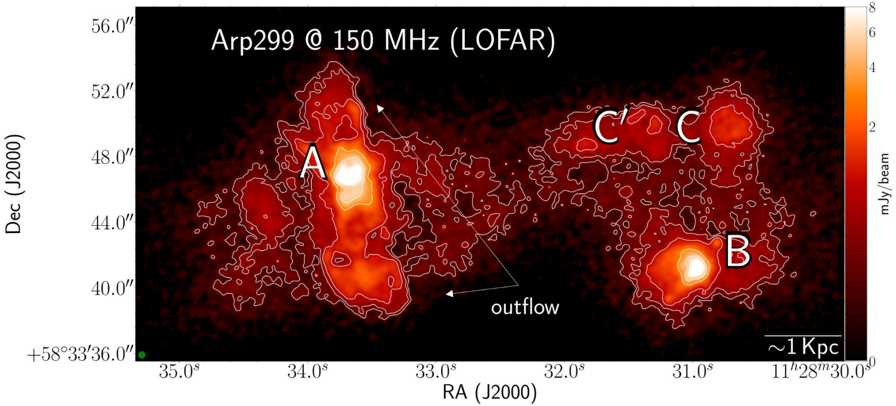


Low-frequency spectra in young jet components show evidence for interaction with interstellar medium

Star formation in nearby galaxies

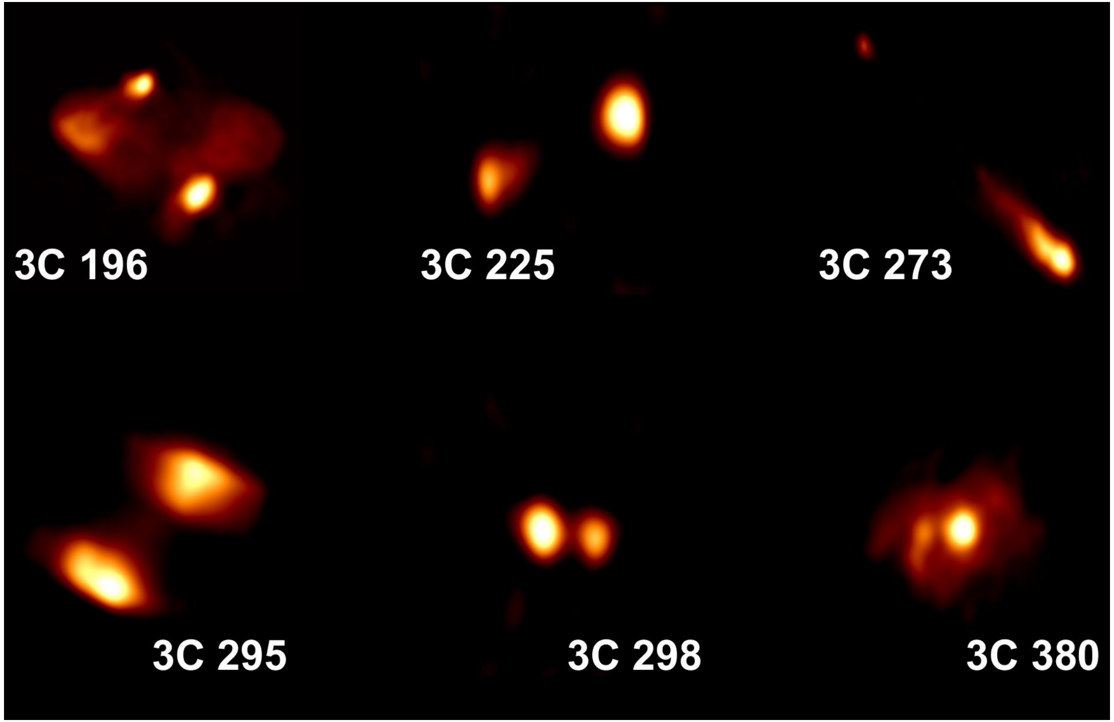


Nuclear emission in merging galaxy *(Ramírez-Olivencia et al. 2022)*



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.*

Widefield – the T_b AGN population

940 AGN identified using T_b

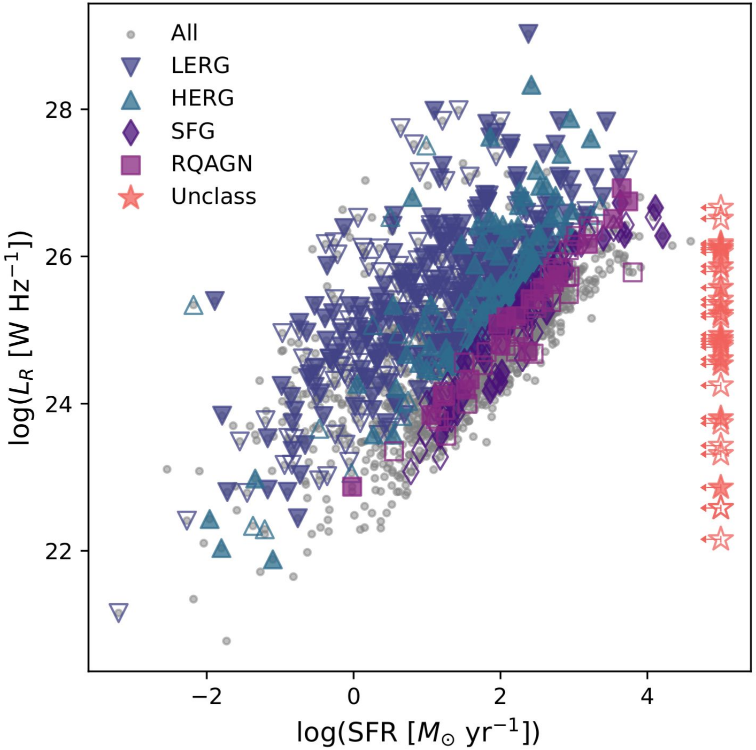
- 83% have AGN ids from SED fitting and/or photometric identification
- **160 *NEW* identifications!**

Percent of sub-population which are T_b AGN:

- HERGs: 68%
- LERGs: 57%
- Unclassified: 61%
- **RQAGN: 32%**
- **SFG: 20%**

Implies radio-quiet populations have more than one radio emission mechanism present

Morabito+ 2022



Moving into the realm of science exploitation

before 2022

The LOFAR long baseline snapshot calibrator survey
Moldón, J. et al., 2015, Astronomy and Astrophysics, 574, A73

Subarcsecond international LOFAR radio images of the M82 nucleus at 118 MHz and 154 MHz
Varenius, E. et al., 2015, Astronomy and Astrophysics, 574, A114

Subarcsecond international LOFAR radio images of Arp 220 at 150 MHz. A kpc-scale star forming disk surrounding nuclei with shocked outflows
Varenius, E. et al., 2016, Astronomy and Astrophysics, 593, A86

LOFAR VLBI studies at 55 MHz of 4C 43.15, a z = 2.4 radio galaxy
Morabito, Leah K. et al., 2016, Monthly Notices of the Royal Astronomical Society, 461, 2676

Sub-arcsecond imaging of Arp 299-A at 150 MHz with LOFAR: Evidence for a starburst-driven outflow
Ramírez-Olivencia, N. et al., 2018, Astronomy and Astrophysics, 610, L18

LOFAR Observations of 4C+19.44: On the Discovery of Low-frequency Spectral Curvature in Relativistic Jet Knots
Harris, D. E. et al., 2019, The Astrophysical Journal, 873, 21

LOFAR measures the hotspot advance speed of the high-redshift blazar S5 0836+710
Kappes, A. et al., 2019, Astronomy and Astrophysics, 631, A49

Decoherence in LOFAR-VLBI beamforming
Bonnassieux et al., 2020, Astronomy and Astrophysics, 637, A51

Sub-arcsecond imaging with the International LOFAR Telescope. I. Foundational calibration strategy and pipeline
Morabito, L. K. et al., 2022, Astronomy and Astrophysics, 658, A1

Sub-arcsecond imaging with the International LOFAR Telescope. II. Completion of the LOFAR Long-Baseline Calibrator Survey
Jackson, N. et al., 2022, Astronomy and Astrophysics, 658, A2

High-resolution international LOFAR observations of 4C 43.15. Spectral ages and injection indices in a high-z radio galaxy
Sweijen, F. et al., 2022, Astronomy and Astrophysics, 658, A3

Sub-arcsecond LOFAR imaging of Arp 299 at 150 MHz. Tracing the nuclear and diffuse extended emission of a bright LIRG
Ramírez-Olivencia, N. et al., 2022, Astronomy and Astrophysics, 658, A4

special issue

Origin of the ring structures in Hercules A. Sub-arcsecond 144 MHz to 7 GHz observations
Timmerman, R., and 20 colleagues, 2022, Astronomy and Astrophysics, 658, A5

Unmasking the history of 3C 293 with LOFAR sub-arcsecond imaging
Kukreti, Pranav et al., 2022, Astronomy and Astrophysics, 658, A6

High-resolution imaging with the International LOFAR Telescope: Observations of the gravitational lenses MG 0751+2716 and CLASS B1600+434
Badole, S. et al., 2022, Astronomy and Astrophysics, 658, A7

The resolved jet of 3C 273 at 150 MHz. Sub-arcsecond imaging with the LOFAR international baselines
Harwood, J. J. et al., 2022, Astronomy and Astrophysics, 658, A8

Pushing sub-arcsecond resolution imaging down to 30 MHz with the trans-European International LOFAR Telescope
Groeneveld, C. et al., 2022, Astronomy and Astrophysics, 658, A9

Spectral analysis of spatially resolved 3C295 (sub-arcsecond resolution) with the International LOFAR Telescope
Bonnassieux, Etienne et al., 2022, Astronomy and Astrophysics, 658, A10

Subarcsecond view on the high-redshift blazar GB 1508+5714 by the International LOFAR Telescope
Kappes, A. et al., 2022, Astronomy and Astrophysics, 663, A44

Deep sub-arcsecond wide-field imaging of the Lockman Hole field at 144 MHz
Sweijen, F. et al., 2022, Nature Astronomy, 6, 350

Identifying active galactic nuclei via brightness temperature with sub-arcsecond international LOFAR telescope observations
Morabito, Leah K. et al., 2022, Monthly Notices of the Royal Astronomical Society, 515, 5758

Measuring cavity powers of active galactic nuclei in clusters using a hybrid X-ray-radio method. A new window on feedback opened by subarcsecond LOFAR-VLBI observations
Timmerman, R. et al., 2022, Astronomy and Astrophysics, 668, A65

Piercing the dusty veil of hyper-luminous infrared galaxies: Sub-arcsecond 144 MHz ILT observations of HLIRGs in the Lockman Hole
Sweijen, F. et al., 2023, Astronomy and Astrophysics, 671, A85

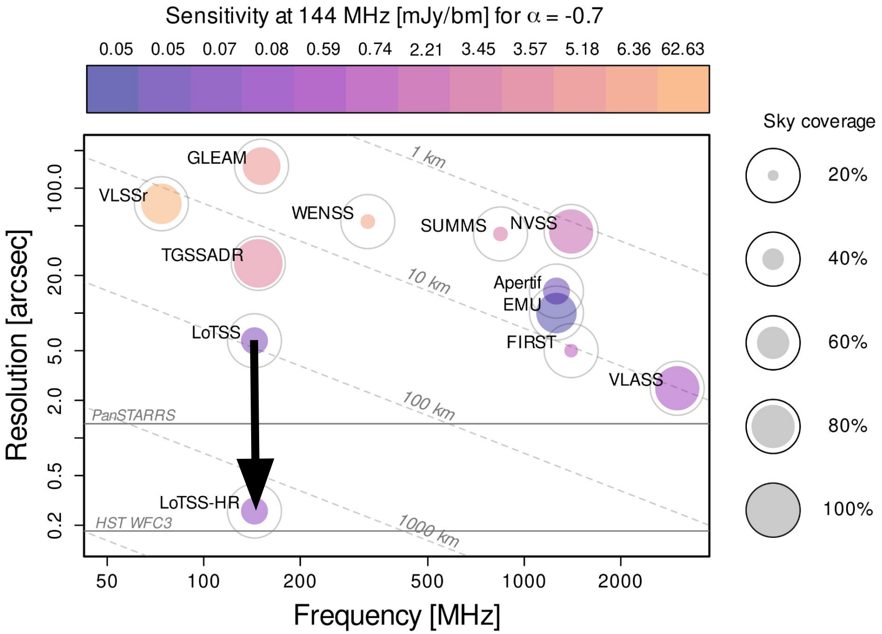
A low-frequency sub-arcsecond view of powerful radio galaxies in rich-cluster environments: 3C 34 and 3C 320
Mahatma, V. H. et al., 2023, Monthly Notices of the Royal Astronomical Society, 520, 4427

widefield, polarisation, larger studies

LoTSS High Resolution (LoTSS-HR)

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

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



LoTSS High Resolution (LoTSS-HR) Deep Fields

	Lockman Hole	**ELAIS-N1**	**Boötes**	**NEP**
# observations	39	130	24	9
# Dutch processed	23	48	14	0
# obs. with intl stations	25	102	21	9
Average # intl stations	12.5	12.1	9.8	12.4

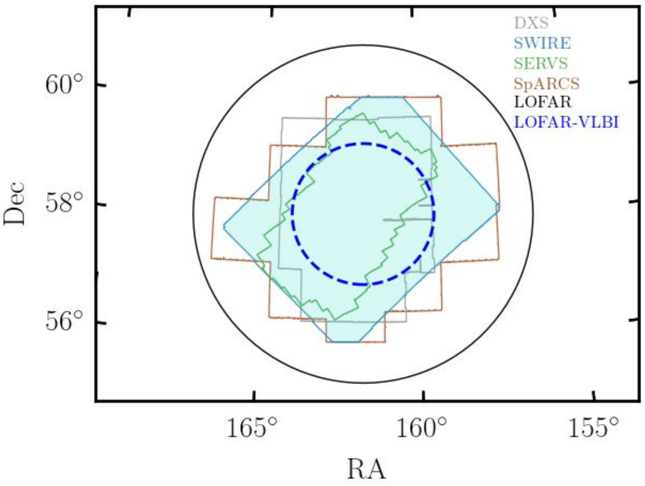
1st 8 hours: Sweijen et al. 2022

J. de Jong

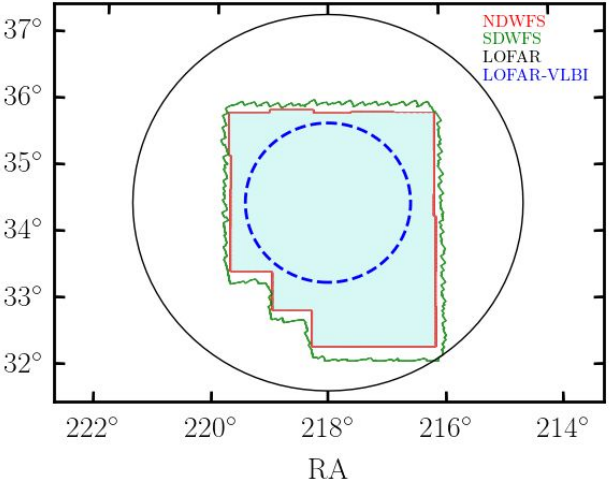
E. Escott

M. Bondi

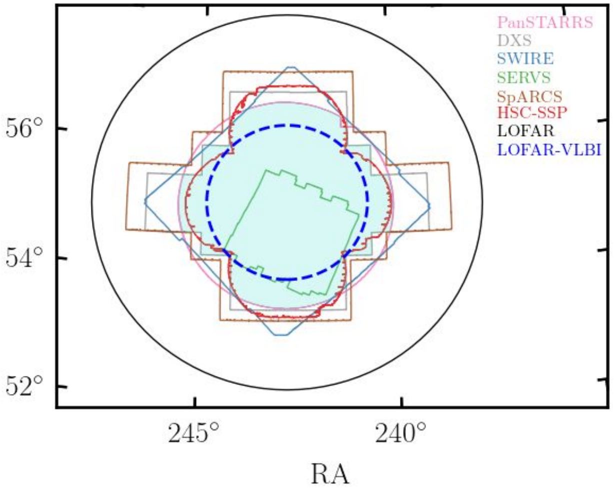
The Deep Fields - data overview



Lockman Hole



Boötes

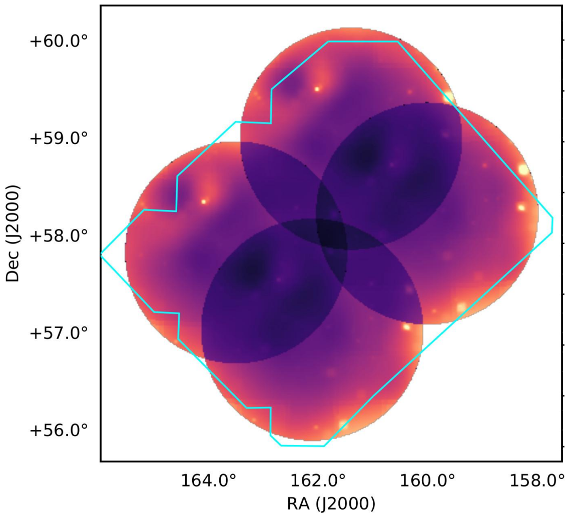


ELAIS-N1

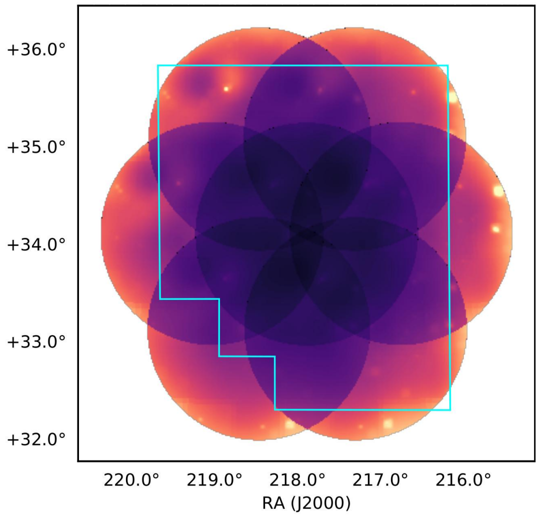
Images by R. Kondapally, adapted from A&A, 648, A3

The Deep Fields - observing strategy

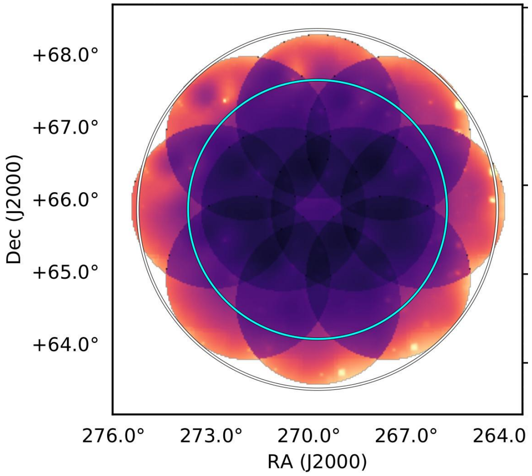
Cycle 16 implemented dithering pattern



Lockman Hole

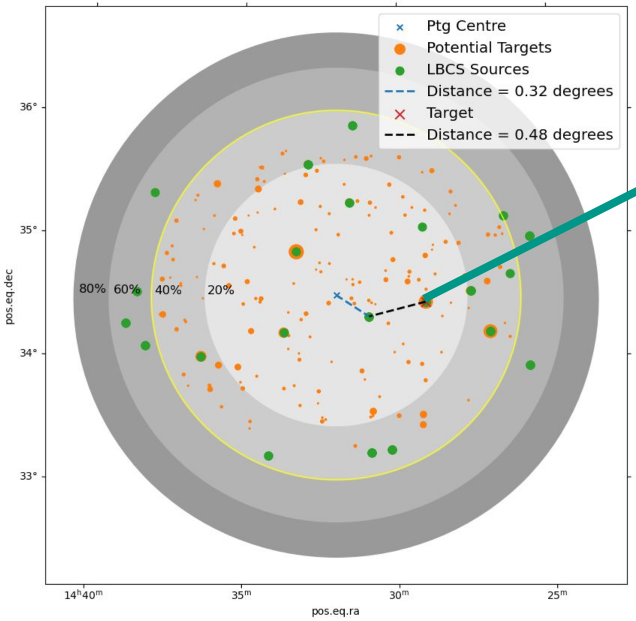


Boötes

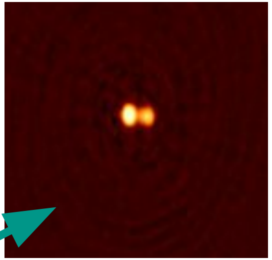


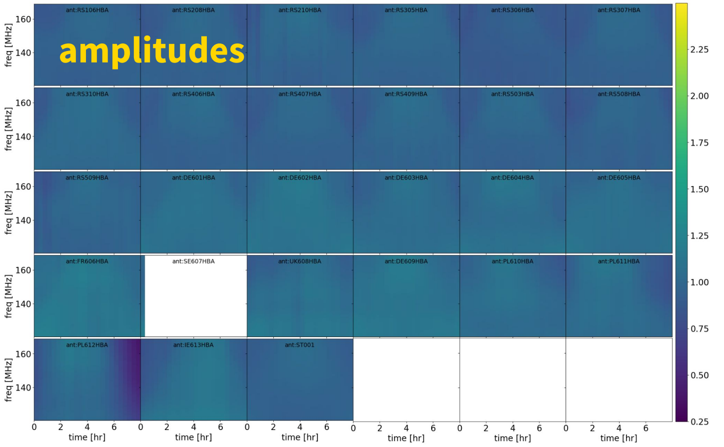
NEP

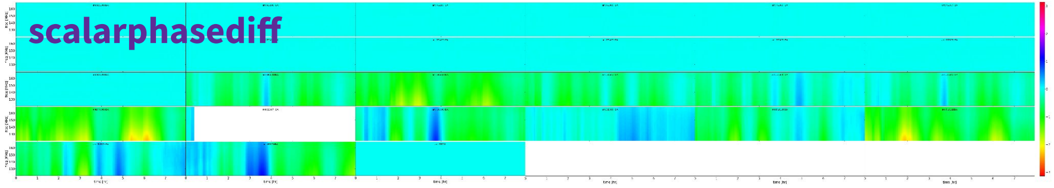
LoTSS Deep Fields - Boötes

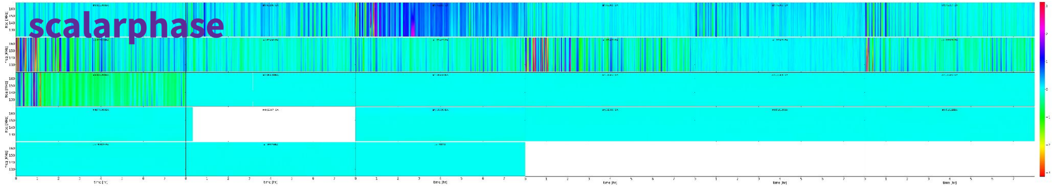


plot generated by https://github.com/jwpetley/lofar_plotting



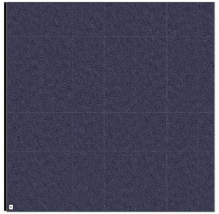


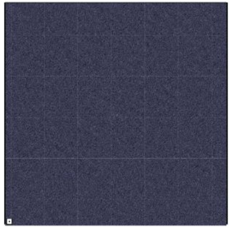


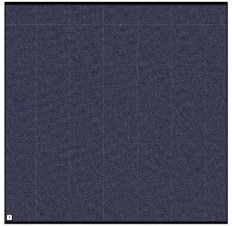


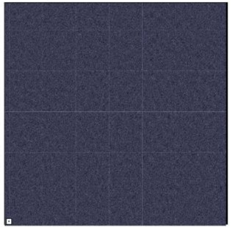
E. Escott, self-calibration using https://github.com/rvweeren/lofar_facet_selfcal

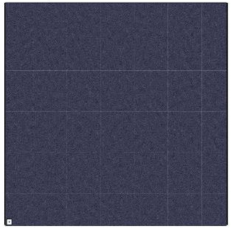
LoTSS Deep Fields - Boötes

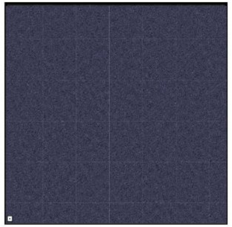

ILTJ143728.73+344546.5

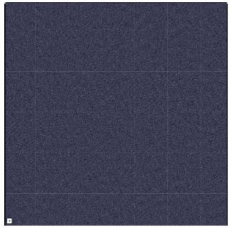

ILTJ142614.84+350616.1

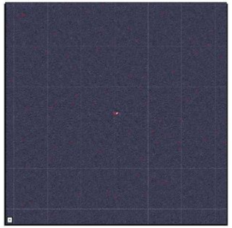

ILTJ142616.62+335326.6

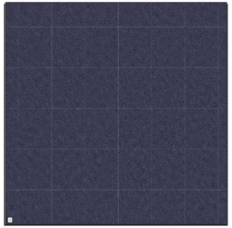

ILTJ142734.79+352544.0

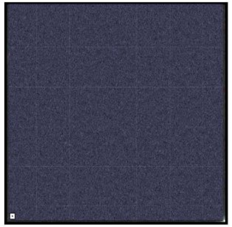

ILTJ143219.53+341728.8

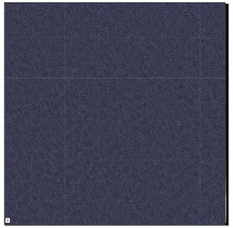

ILTJ142753.81+345248.4

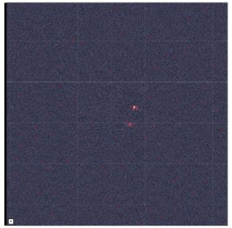

ILTJ143138.53+354128.8

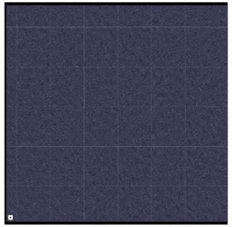

ILTJ143157.95+341650.0

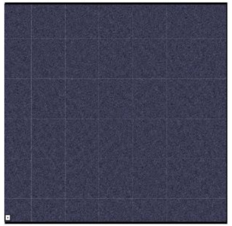

ILTJ143217.05+345228.1


ILTJ143247.56+324851.0


ILTJ143345.11+345939.9

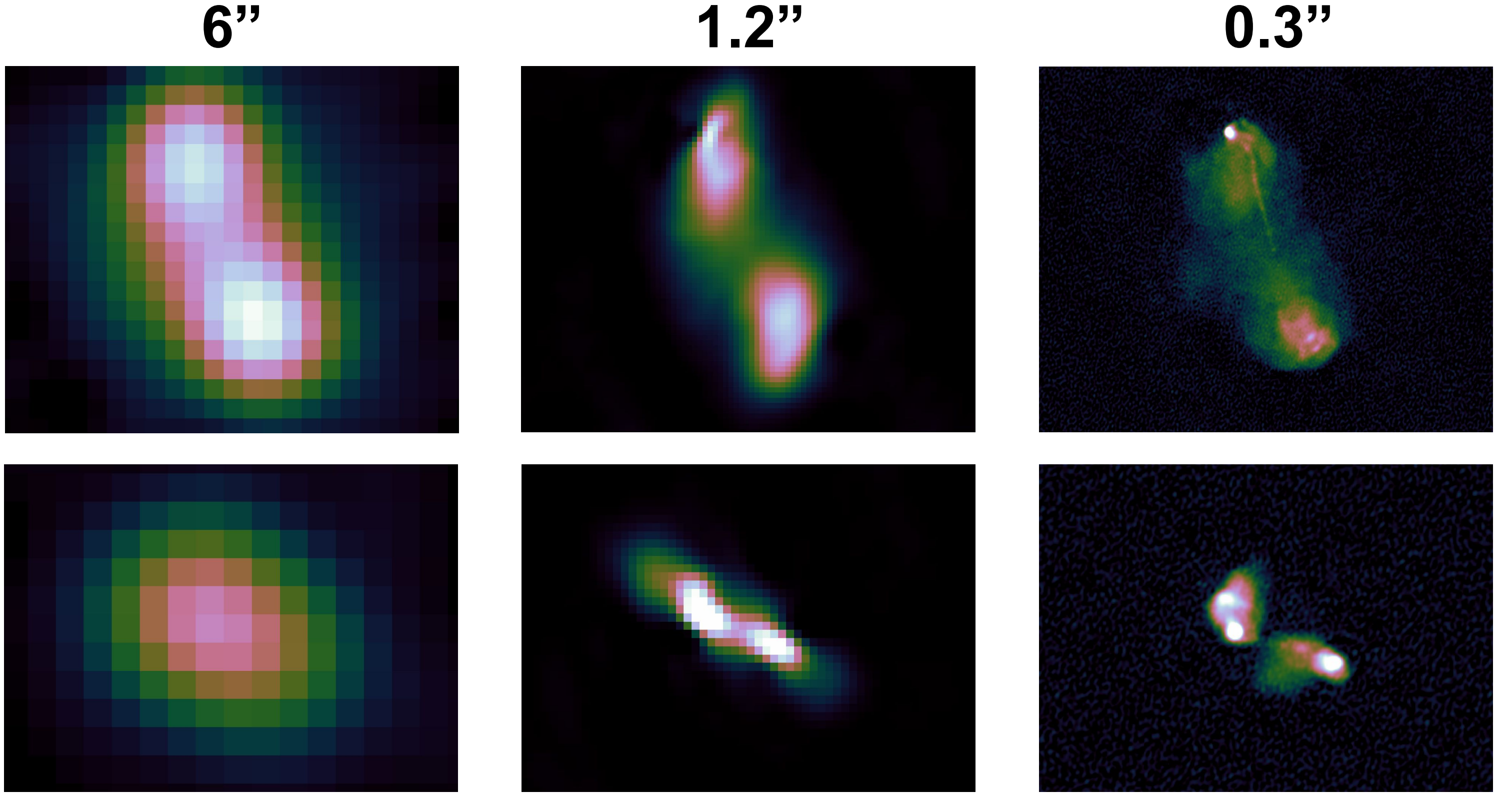

ILTJ143445.82+332818.1


ILTJ143607.81+343241.9


ILTJ143651.51+343602.0

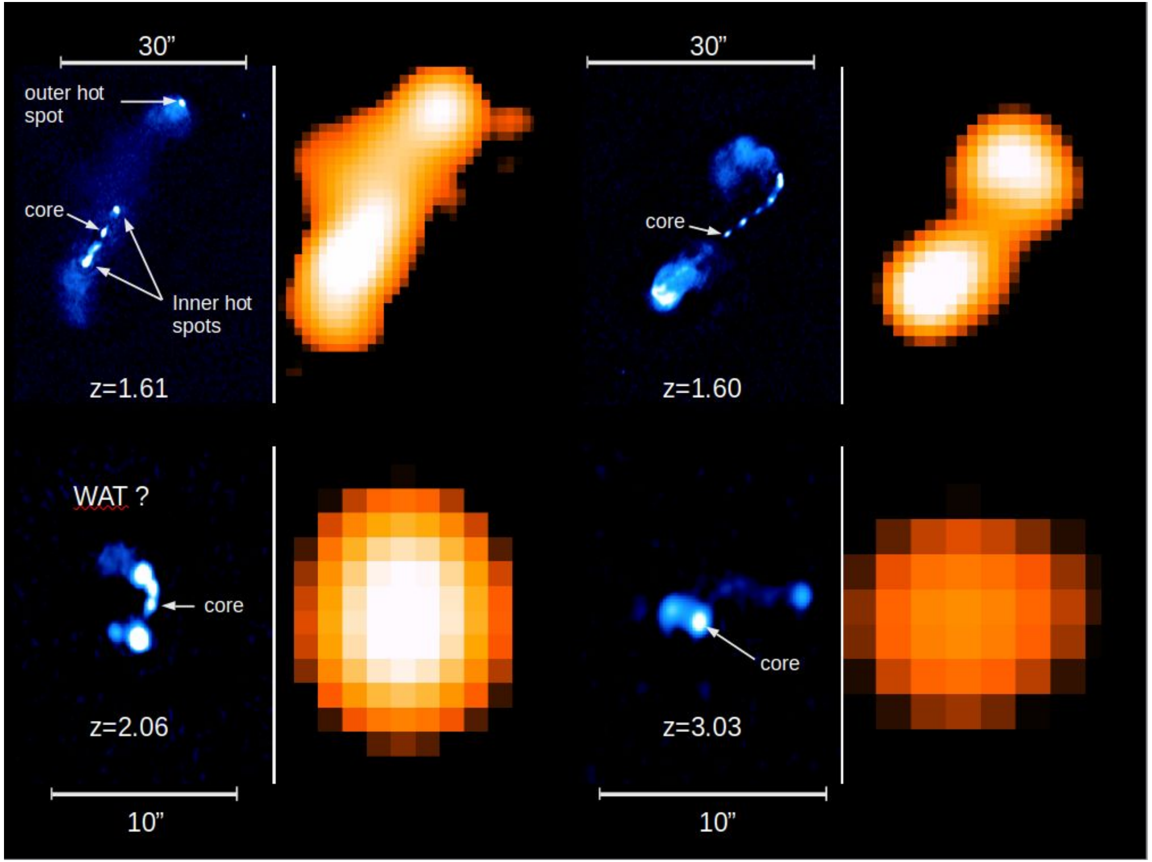
AGN with [OIII] outflows
E. Escott, in preparation

LoTSS Deep Fields - ELAIS-N1



J. de Jong, in preparation

North Ecliptic Pole (synergy with JWST)



M. Bondi, in preparation

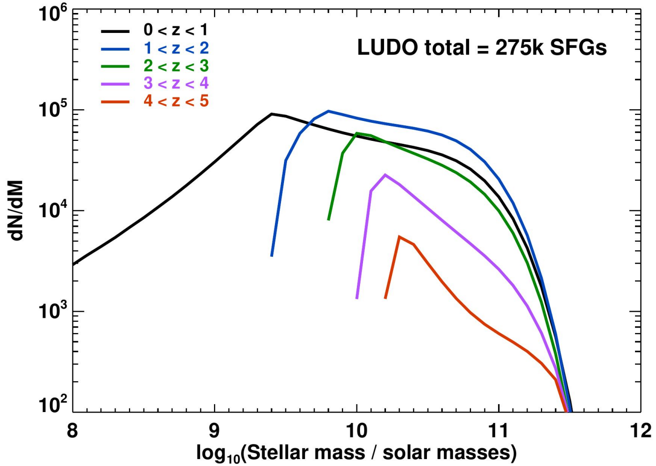
The future: LOFAR2.0

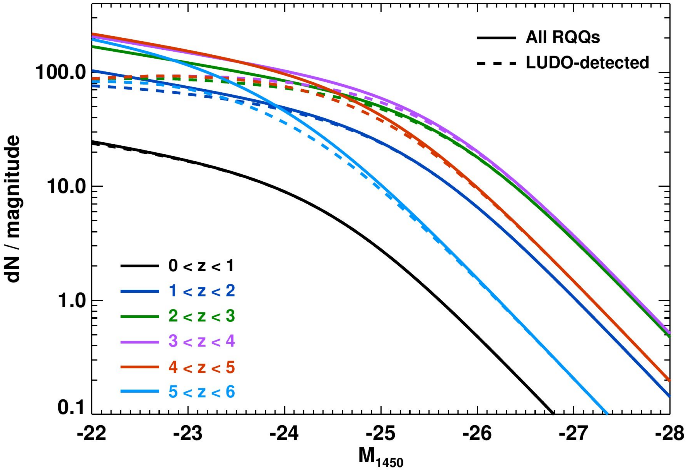
LOFAR2.0 Ultra Deep Observation (LUDO)
PIs: Morabito, Best

Euclid Deep Field North (EDFN)

- 3,000 hours on single field
- target rms = 2 µJy/beam at 150 MHz
- include international stations
- Sky density of 75,000 sources per deg^2
- 3.7 deg^2

Transformational study for star forming galaxies and radio quiet AGN out to z ~ 6





Take home messages

High resolution at low frequencies will remain a unique capability even in the era of the Square Kilometre Array (SKA), which enables many science cases.

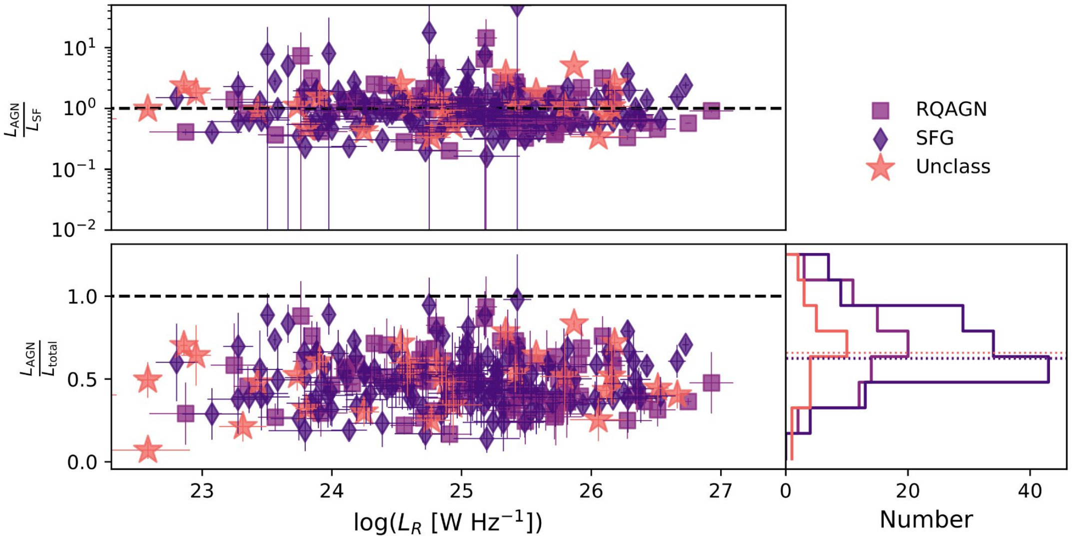
Science exploitation of VLBI with LOFAR is at a point of exponential growth. It is more user friendly than ever before, and there is support to get you started!

High resolution radio surveys are within our reach … stay tuned!

Separating AGN activity and star formation

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



$L_{\mathrm{AGN}}/L_{\mathrm{total}}$

Class	Median
RQAGN	0.49±0.17
SFG	0.49±0.15
Unclass	0.52±0.17
Total	**0.49±0.16**

Morabito+ 2022