VLBI with the International LOFAR Telescope

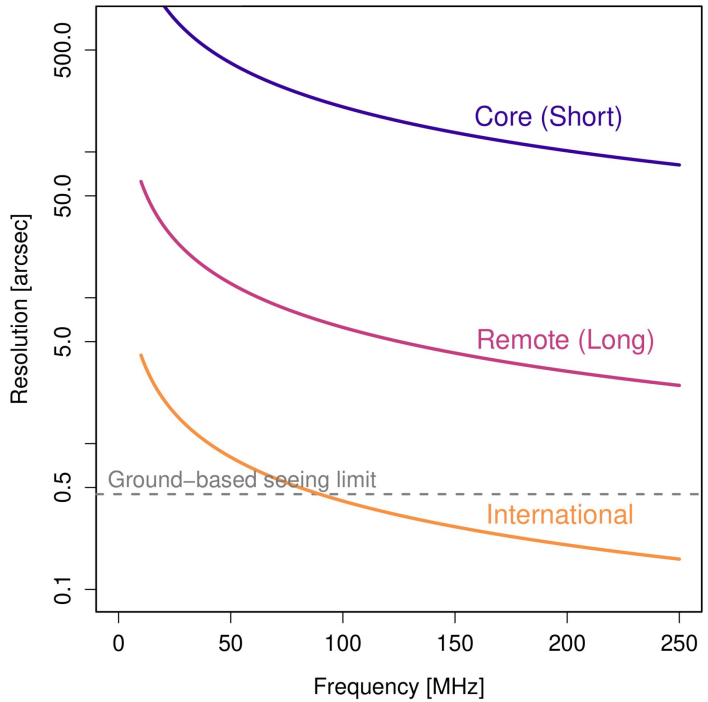
LOFAR Family Meeting, 12 - 16 June 2023, Olsztyn, Poland

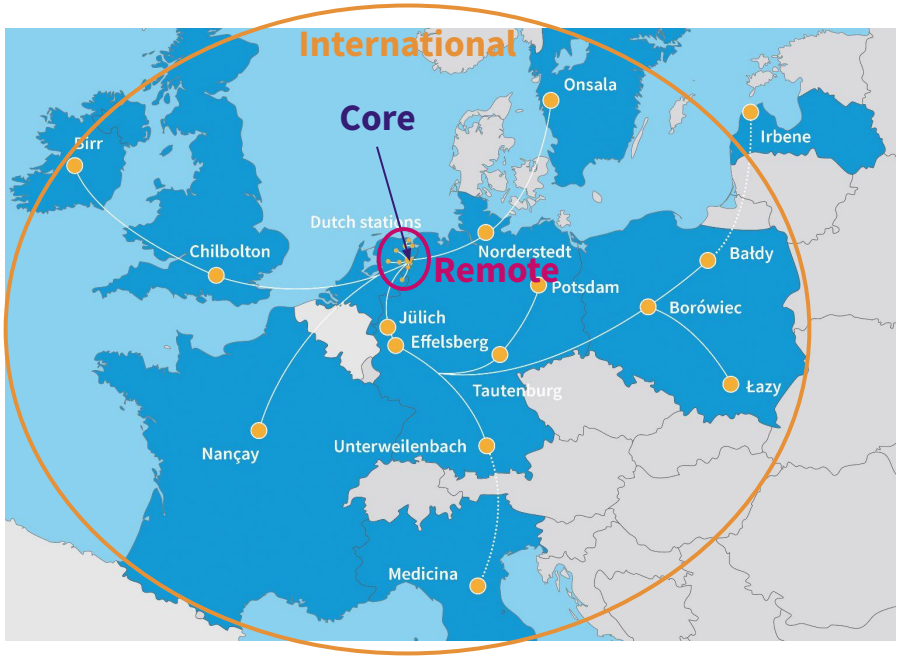
Dr. Leah Morabito
UKRI Future Leaders Fellow & Assoc Prof

UK Research and Innovation
Durham University

@AstroRadioLeah

The International LOFAR Telescope





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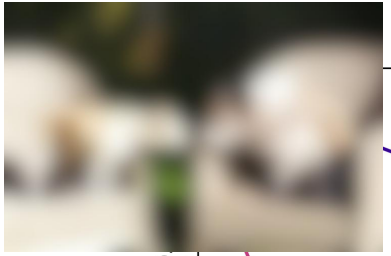
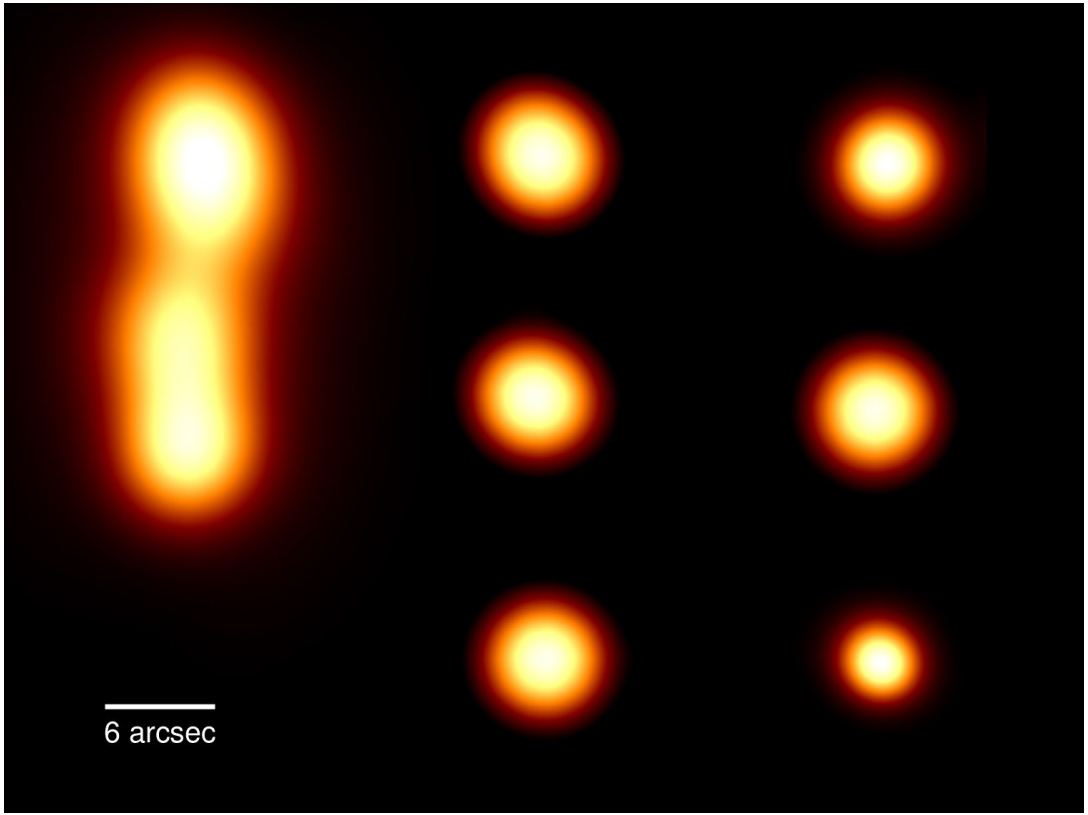


The International LOFAR Telescope

What does that improvement look like?



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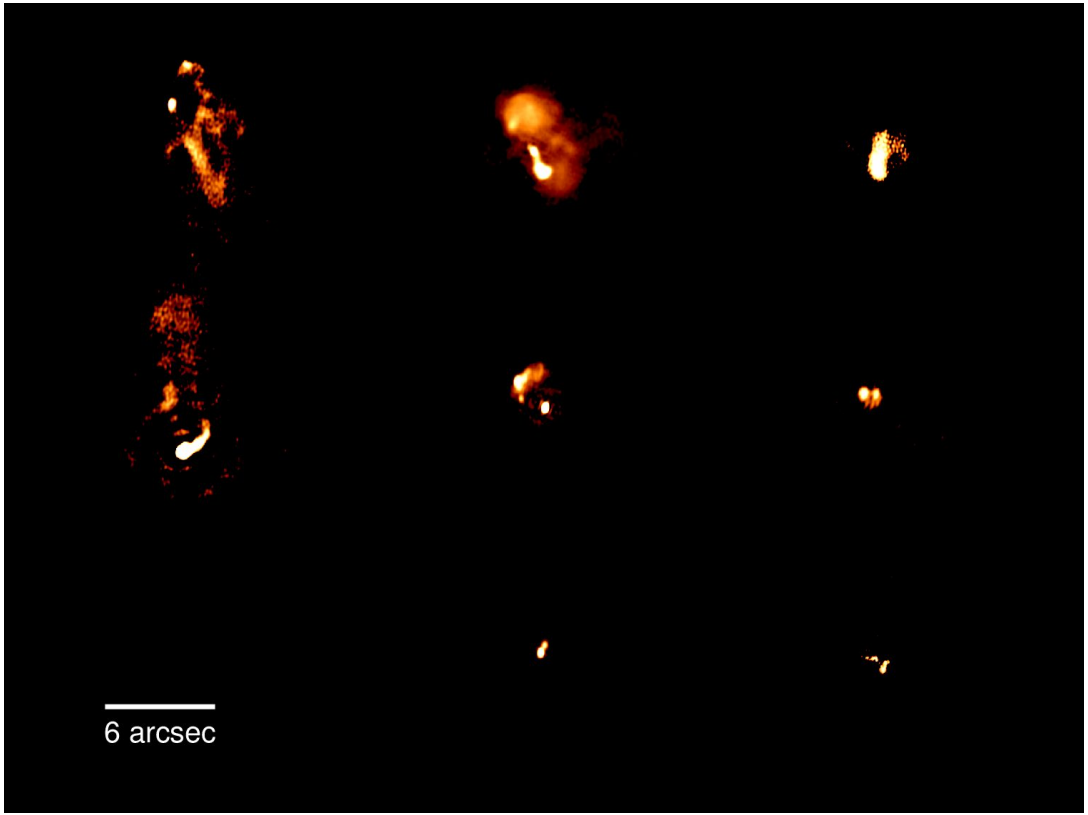

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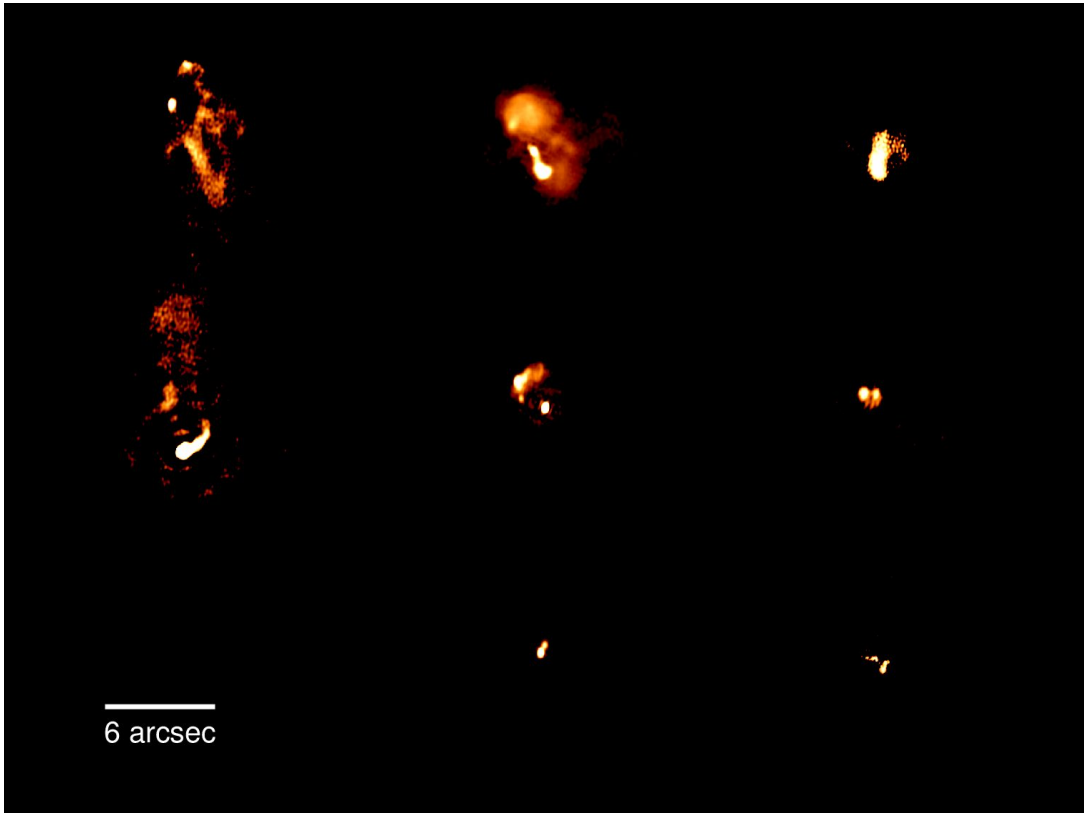

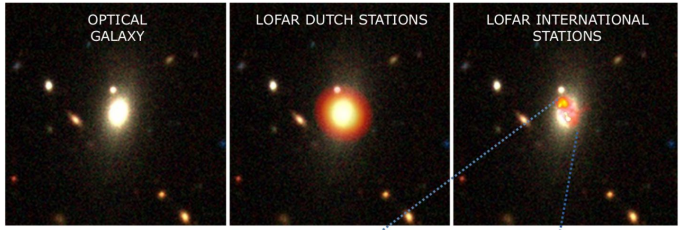

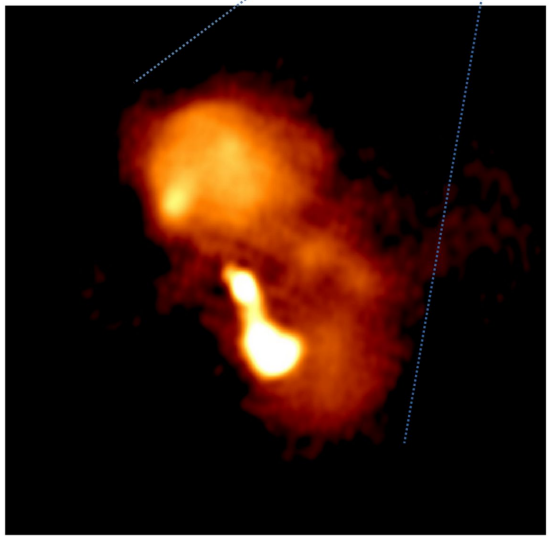

why high resolution at low frequencies?

VLBI processing of ILT data

AGN science with VLBI

Future plans

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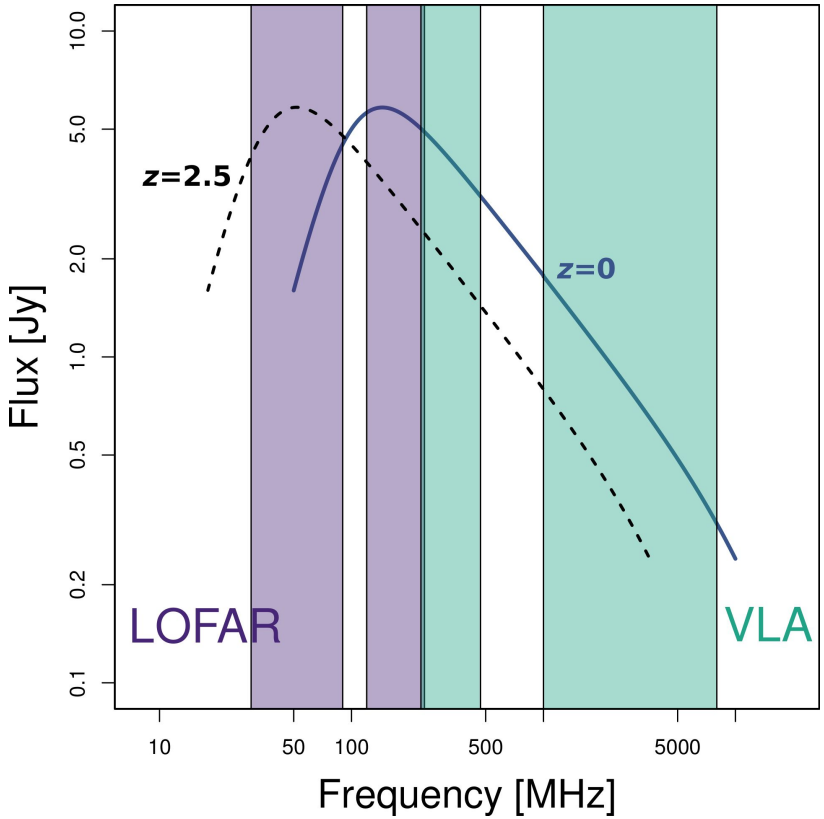
Why low frequencies?



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

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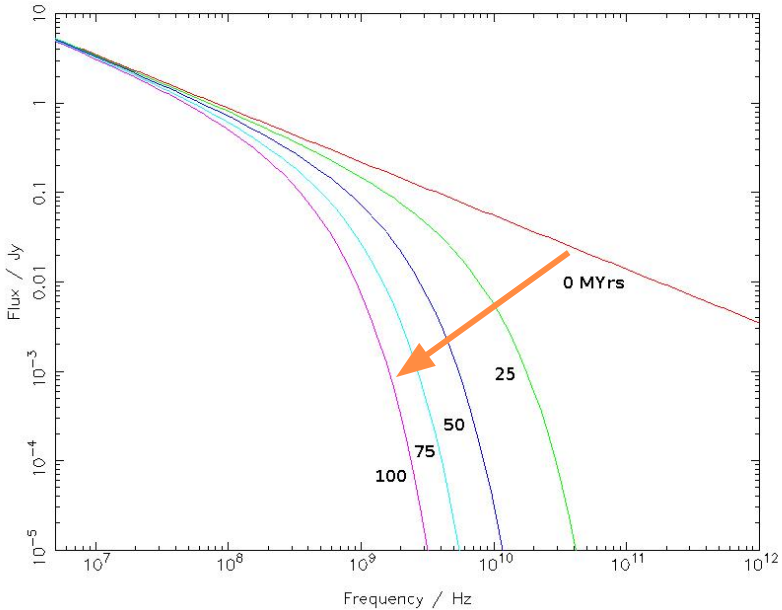
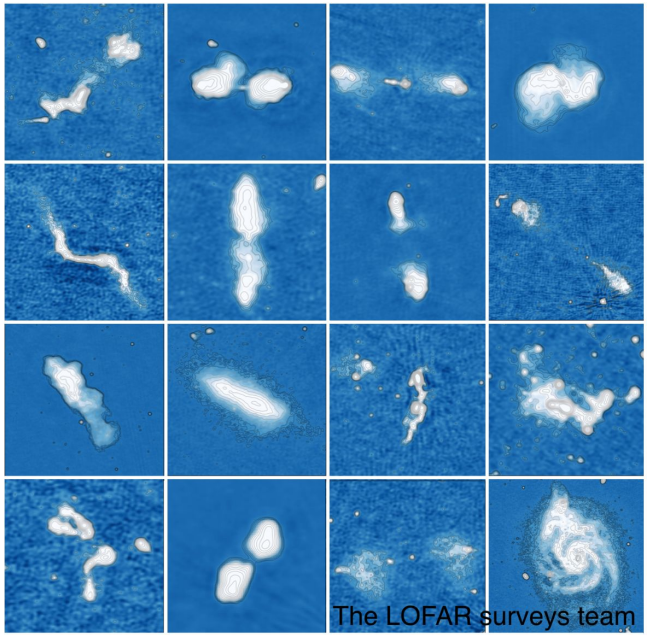


- Synchrotron sources are brighter at low frequencies
- Only way to measure low frequency absorption
- Lower rest frequencies can be reached for high-redshift sources
- Required to anchor modelling to measure spectral age

Why high resolution?

Source diversity in LoTSS



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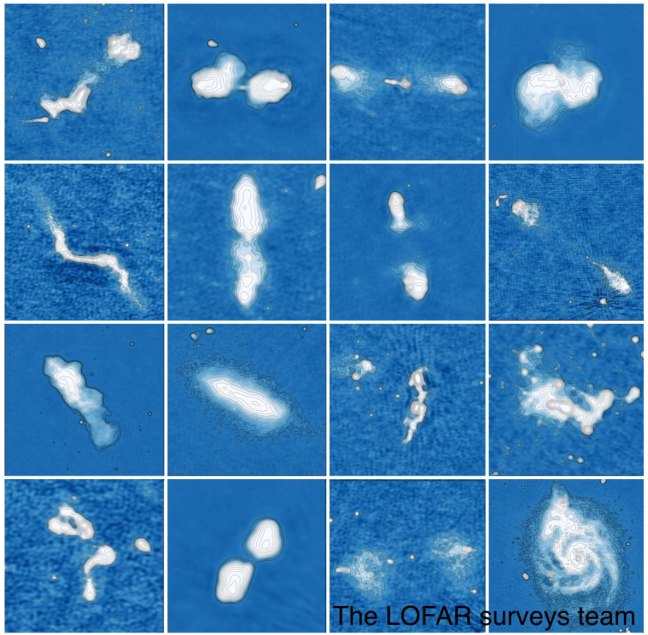

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The rest are unresolved.

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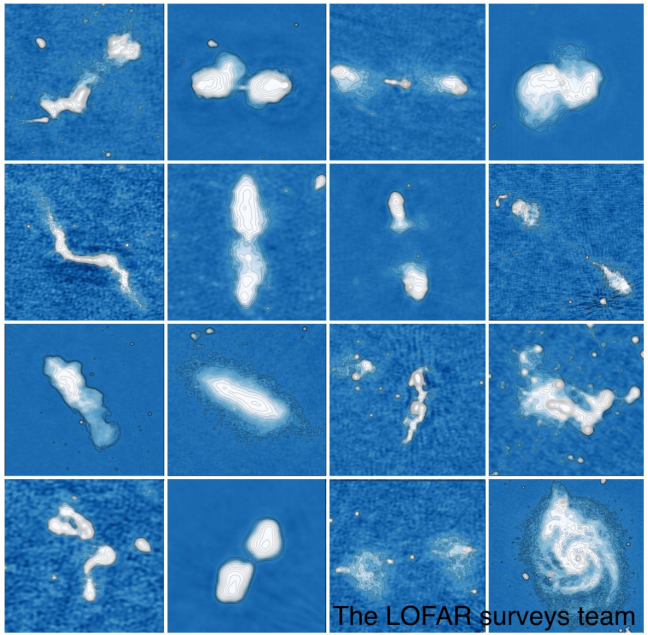

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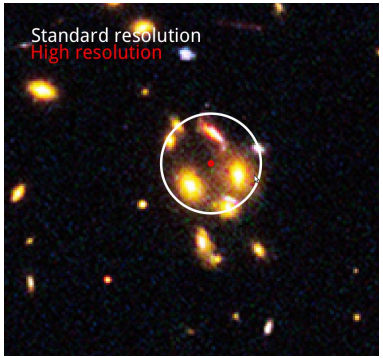

with high resolution, we can:

identify host galaxy

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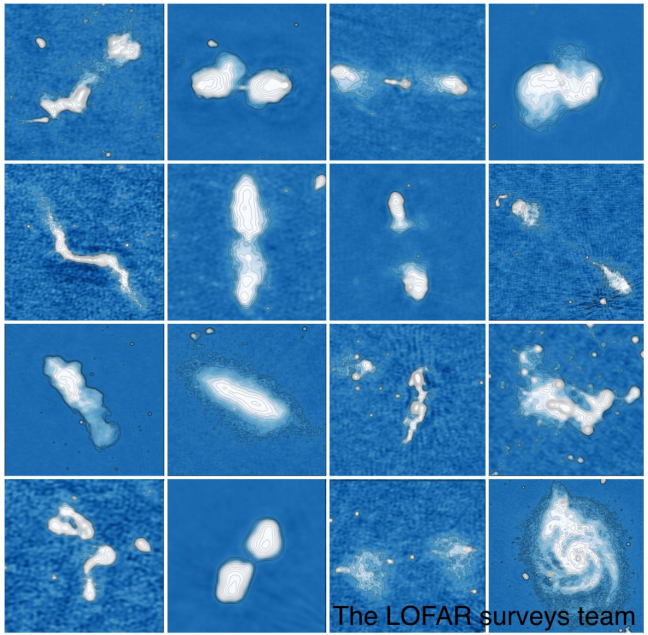

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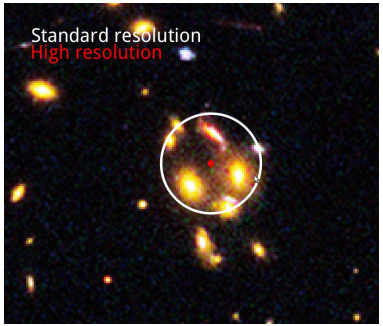

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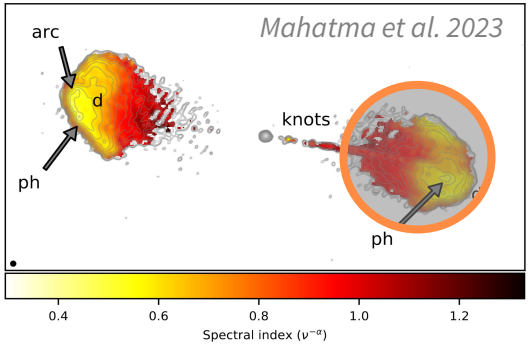
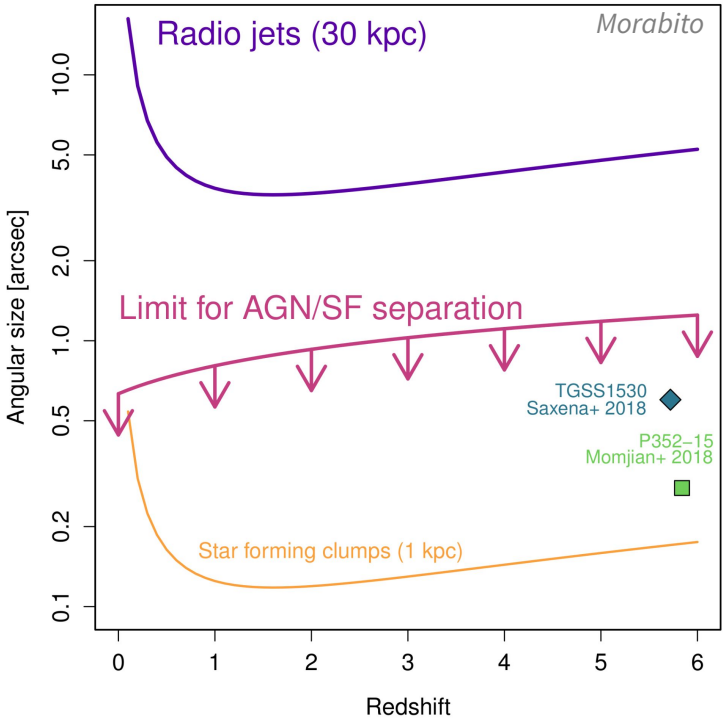


resolve (sub-)structure

Why high resolution at low frequencies?



Science cases include:

- Radio jets in active galactic nuclei (AGN)
- Spatially resolved studies of star formation
- Compact / stellar objects
- Localisation of Fast Radio Bursts (FRBs)
- *…. fill in the blank!*

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Future plans

Brief review: Developing a calibration strategy

LoTSS processing
Full array – instrumental effects
Dutch array – phases

de Gasperin et al. 2019

Calibration uses LOFAR-native tools but borrowing from VLBI techniques

LOFAR-VLBI pipeline
Dispersive delay
Phase calibration

Techniques
- Combine core stations
- Phase-shift & average to reduce FOV

Morabito et al. 2022

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

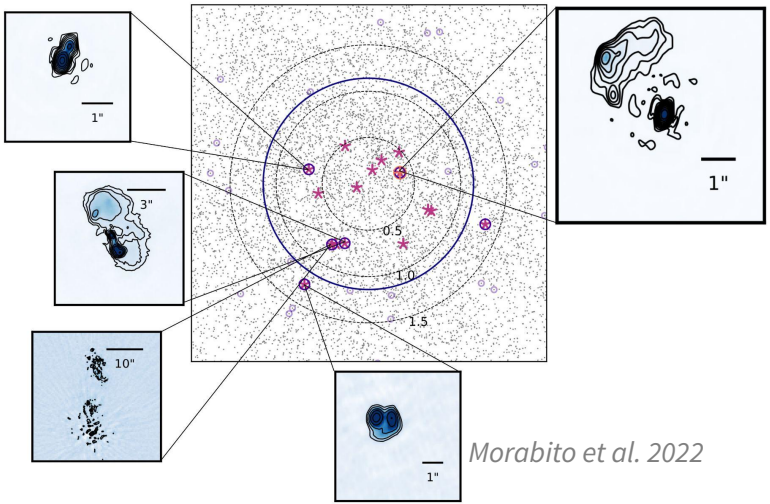
Techniques
- Facet-based imaging
- Combine facets for final image

Sweijen et al. 2022

The ILT as a VLBI instrument: two modes

LOFAR-VLBI pipeline

Application: wide area surveys, single targets



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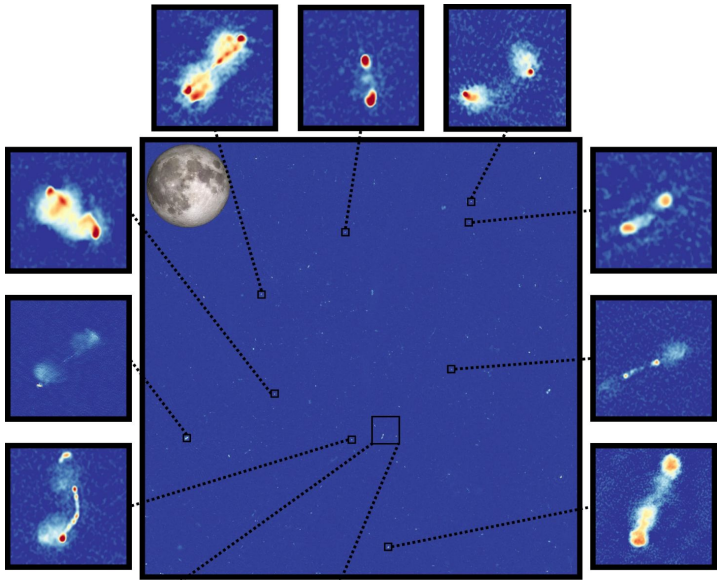
Widefield LOFAR-VLBI

Application: deep field surveys



Sweijen et al. 2022

Enabling science

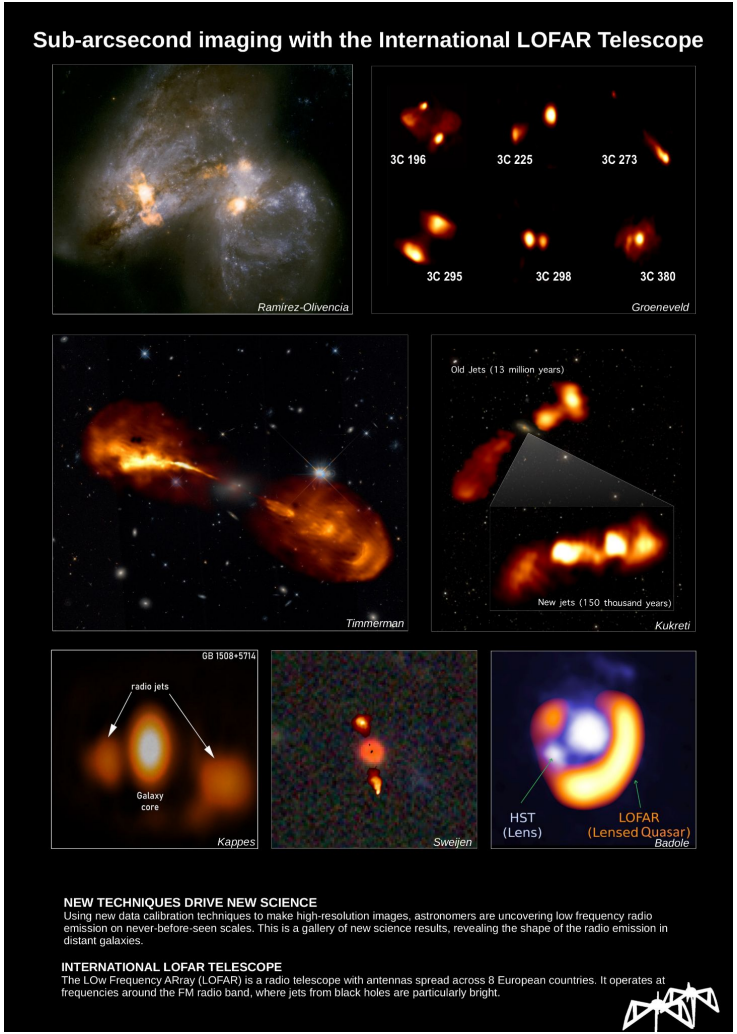
With this kind of resolving power, we can study:

- 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

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



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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

VLBI with LOFAR is becoming ***mainstream***!

- *Radio galaxies in Abell 2255: insights from LOFAR-VLBI* De Rubeis
- *High-resolution low-frequency probes of X-ray emitting knots in blazar jets* Digambar Shetgaonkar
- *Radio-mode feedback in high-redshift galaxy clusters with the International LOFAR Telescope* Timmerman
- *Extended, AGN-induced inverse-Compton emission from the*
- *distant, bright radio galaxy 4C39.24* Pfeifer
- *The LOFAR-View of Ram-Pressure Stripping in the Virgo*
- *Cluster* Edler
- *LOFAR view of SNRe identified with XMM-Newton in the*
- *Andromeda galaxy* Bonnassieux
- *Sub-arcsecond resolution imaging of M51 with the International LOFAR Telescope* Venkattu
- Poster: *ELAIS-N1 at sub-arcseconds, towards a wide-field survey pipeline* de Jong

widefield, polarisation, larger studies

why high resolution at low frequencies?

VLBI processing of ILT data

AGN science with VLBI

Future plans

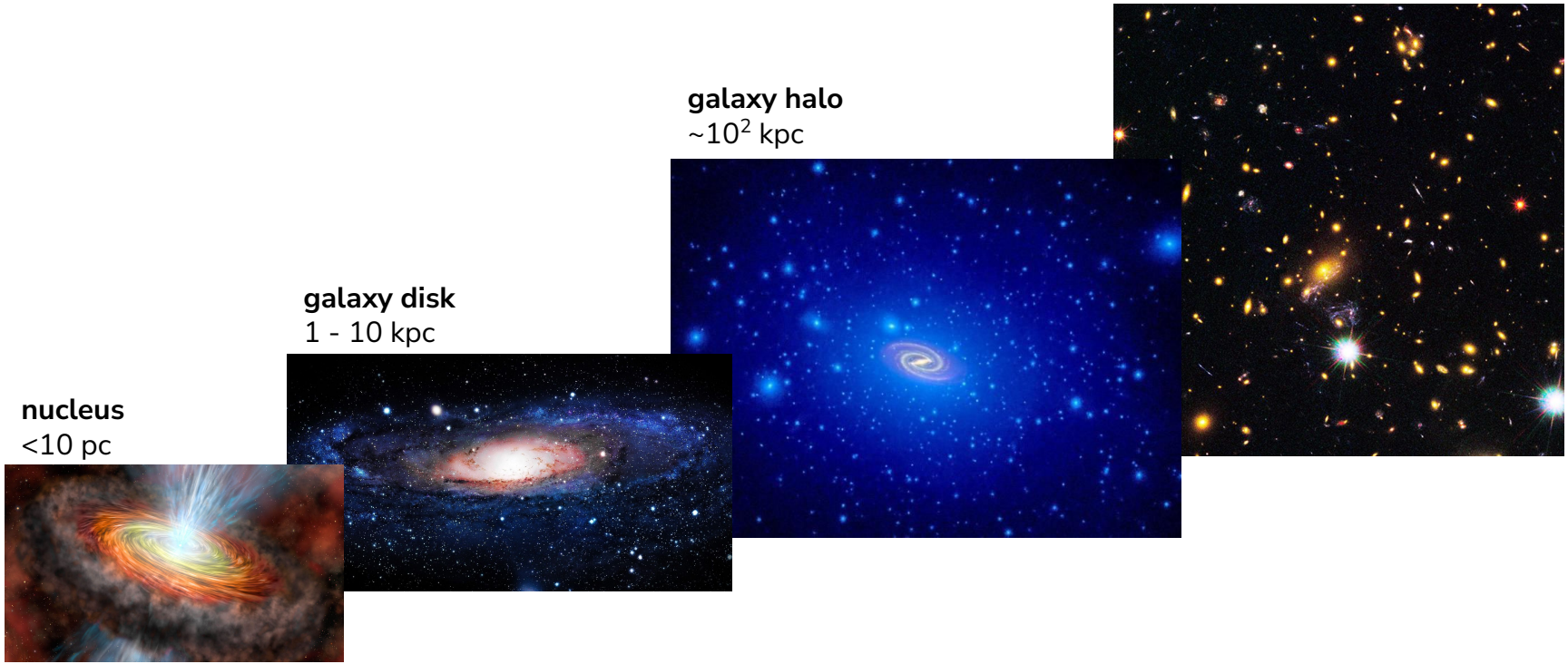
On what spatial scales is radio emission in AGN?

galaxy cluster
up to a few Mpc

galaxy halo
~10^2 kpc

galaxy disk
1 - 10 kpc

nucleus
<10 pc



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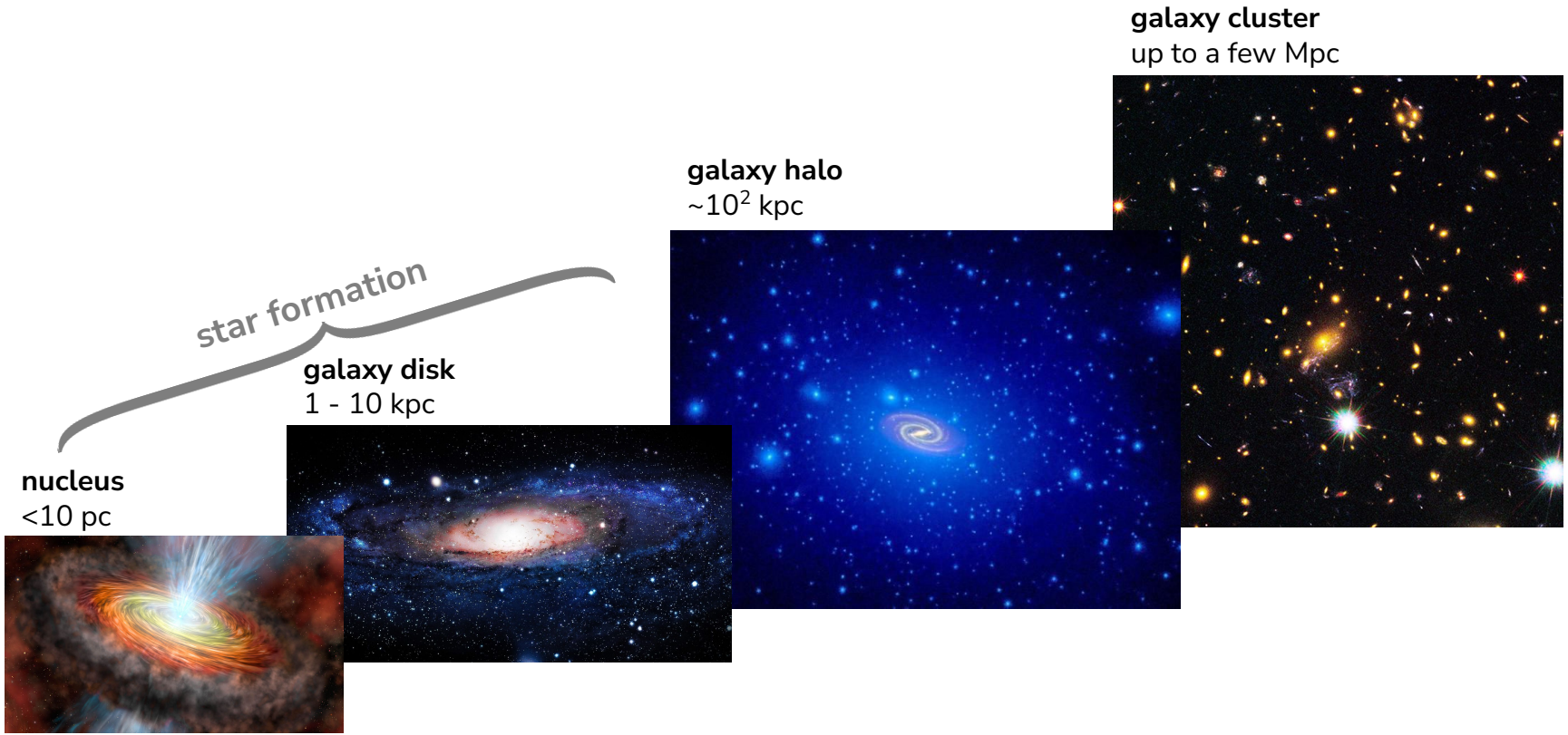
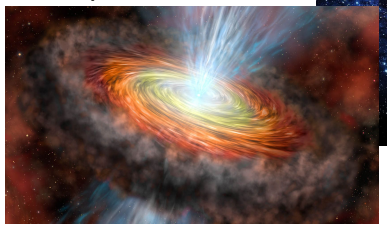


On what spatial scales is radio emission in AGN?

winds (?)

star formation

nucleus
<10 pc



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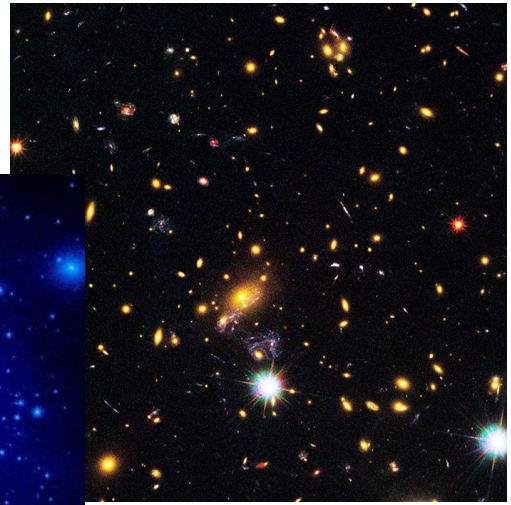

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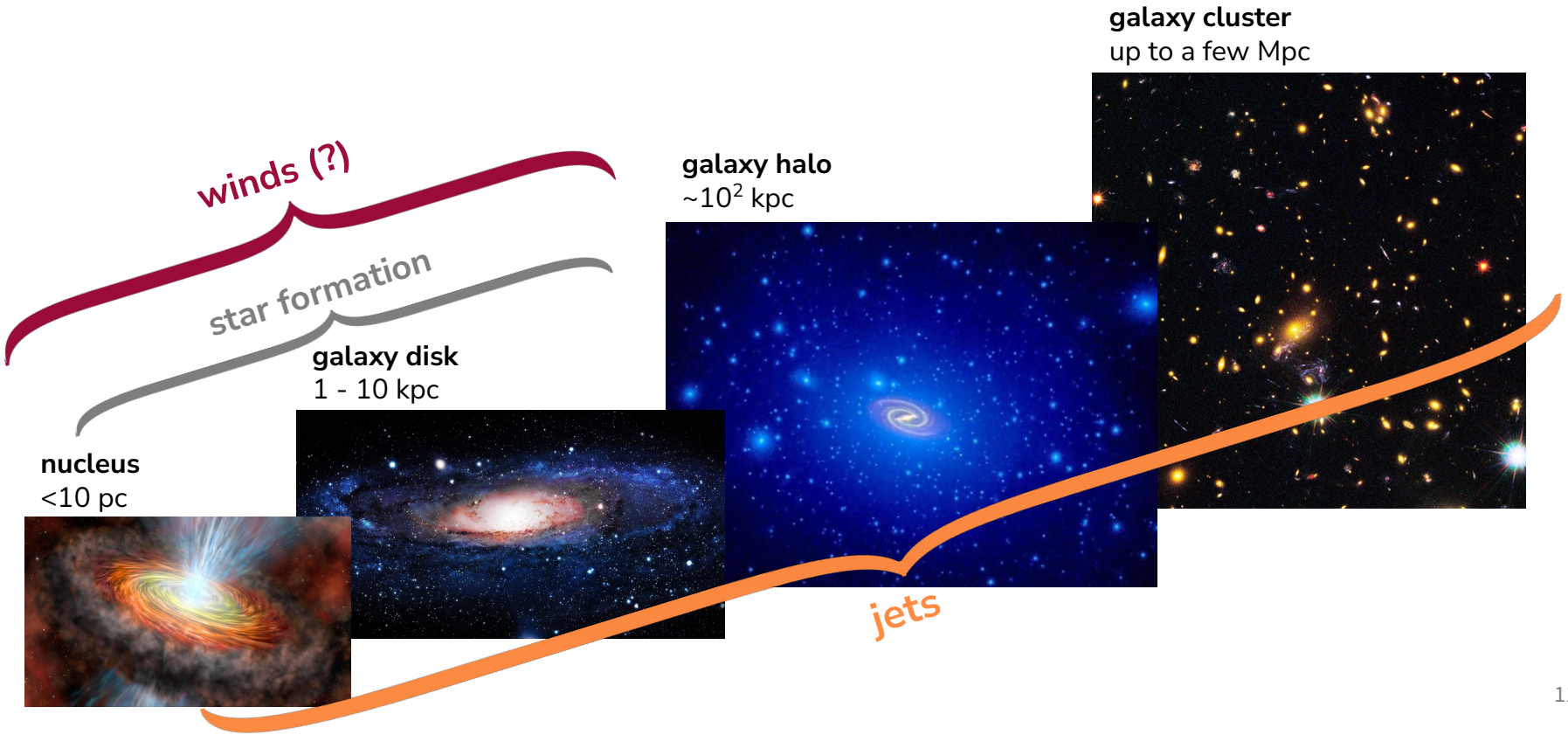


Radio Loud AGN: distant galaxies

4C 43.15 @ *z*=2.4, LBA through VLA

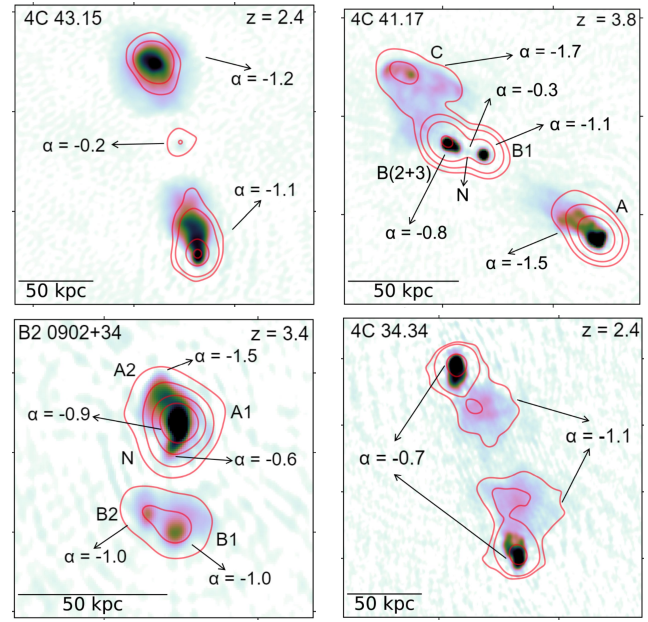
Sweijen et al. 2022,
Morabito et al. 2016

Radio Loud AGN: distant galaxies

4C 43.15 @ *z*=2.4, LBA through VLA

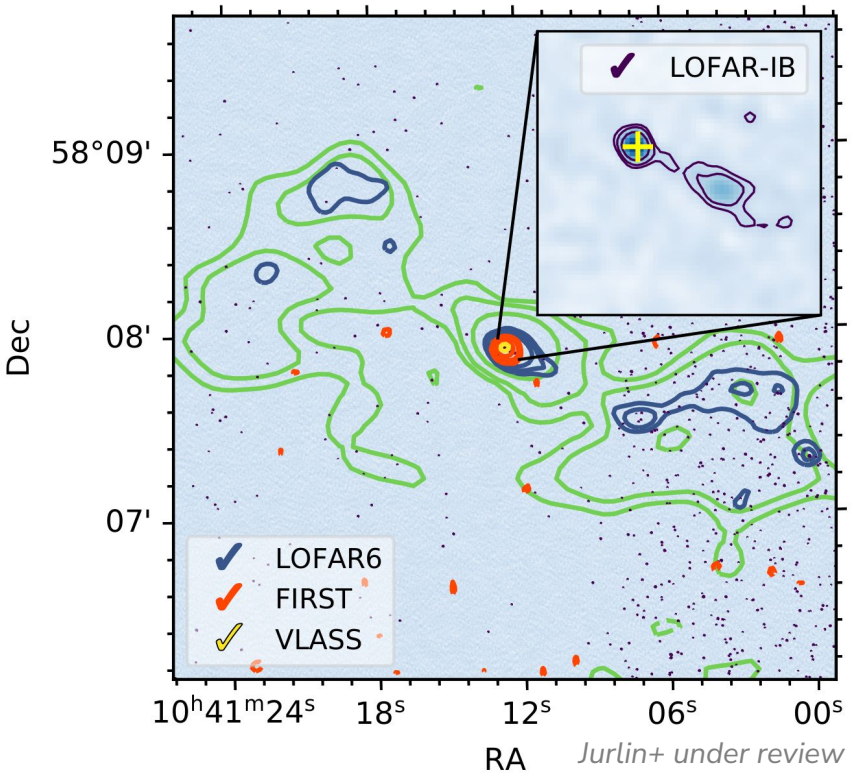
Sweijen et al. 2022, Morabito et al. 2016

Expanding the sample at *z* > 2!



Cordun et al. 2023

Life cycles of AGN



Jurlin+ under review

LOFAR 18” resolution

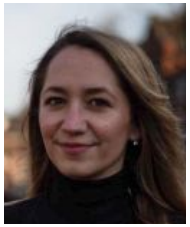
LOFAR 6” resolution

FIRST 5” resolution

VLASS 2.5” resolution

LOFAR 0.25” resolution

} *restarted AGN!*



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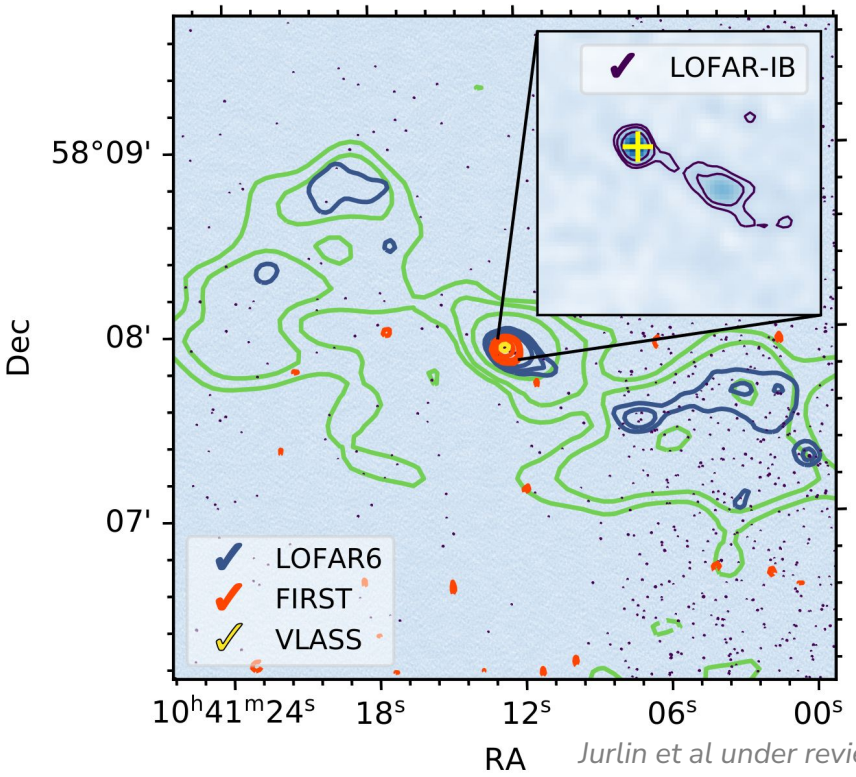

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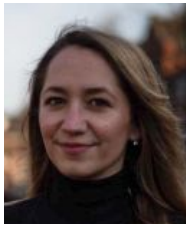
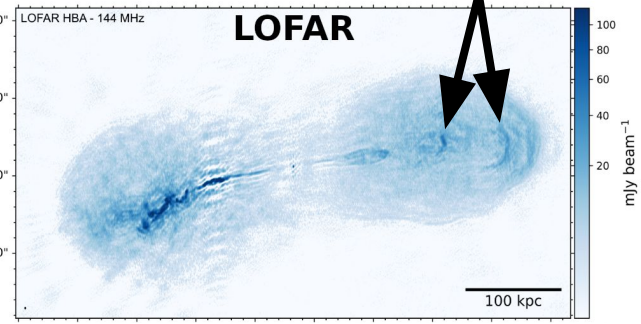
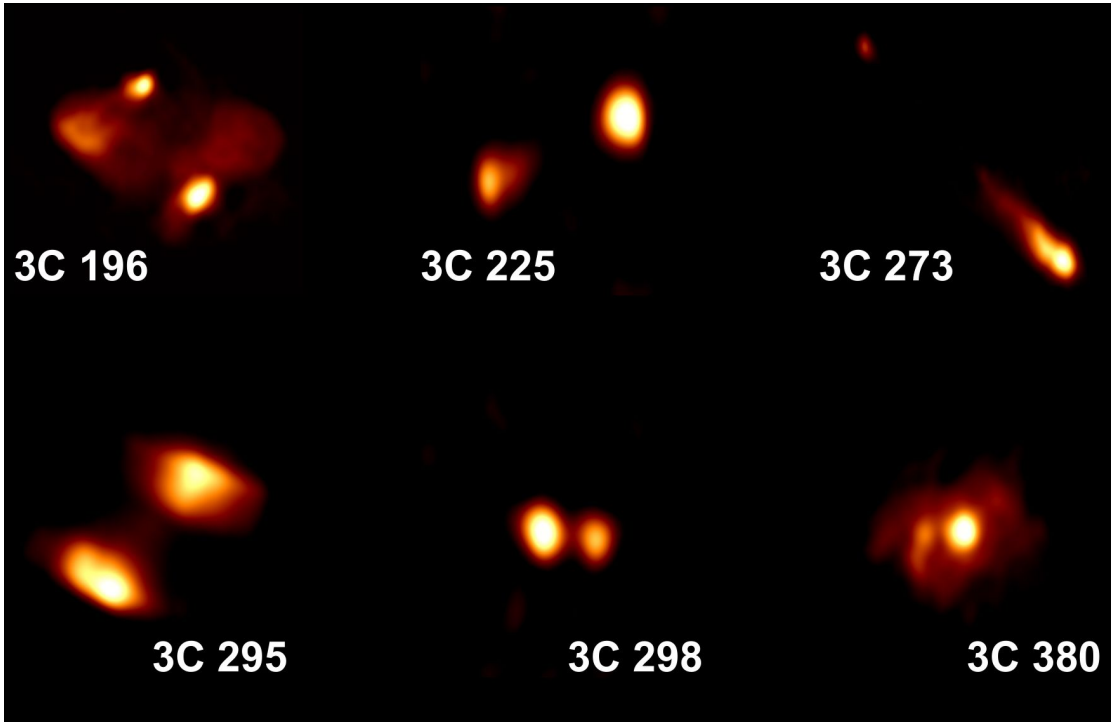


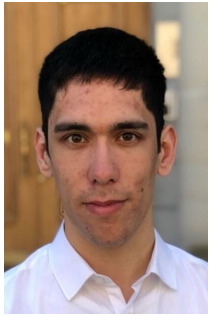
arcs from intermittent activity



Timmerman et al. 2022

Extending to < 100 MHz with the LBA

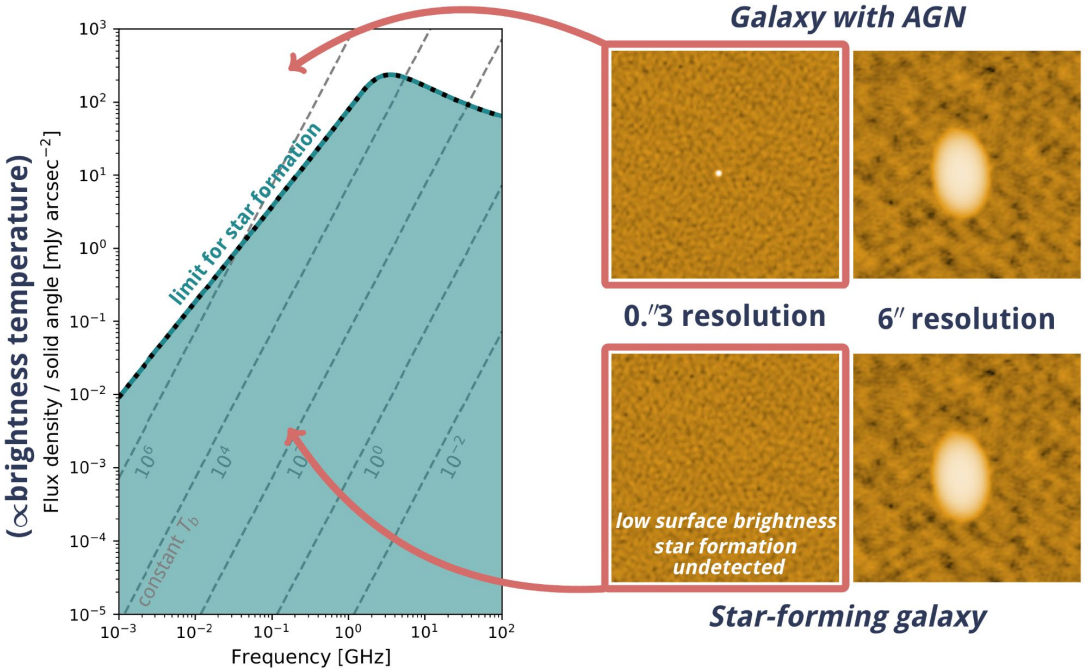




Breaking the record!
(Groeneveld et al. 2022)

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

Diagnosing AGN activity



adapted from Morabito et al. 2022

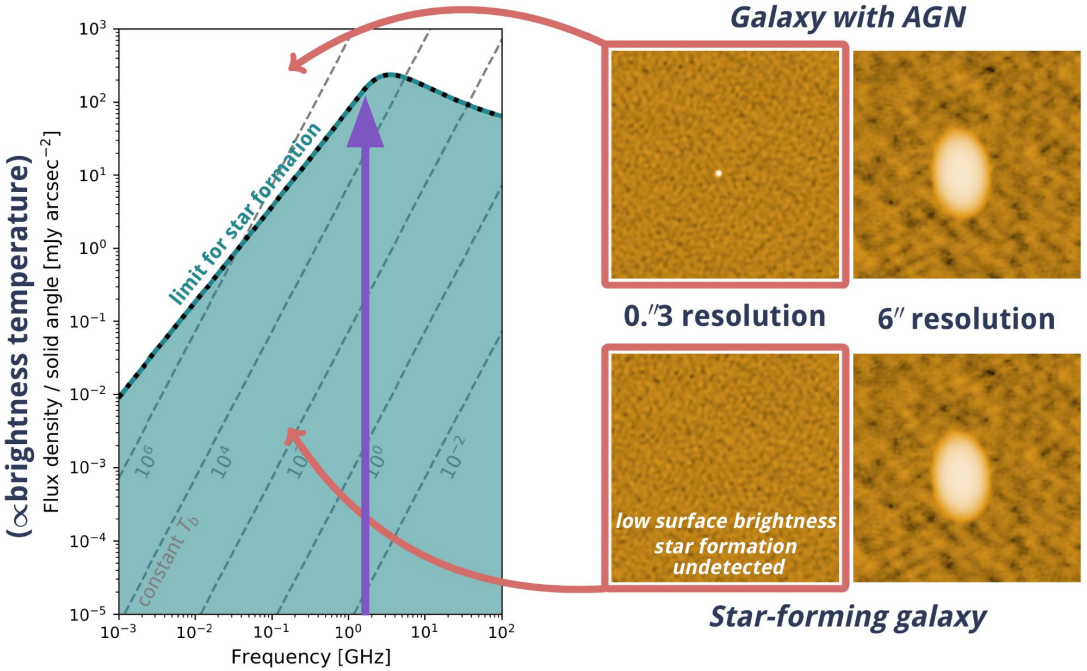
Star formation from a normal galaxy has a limit to the amount of **flux density** per **solid angle** (*Condon 1992*)

This depends on:

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

Observables: Flux density, size information

Diagnosing AGN activity



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Historically measured with VLBI $\gtrsim$ 1 GHz

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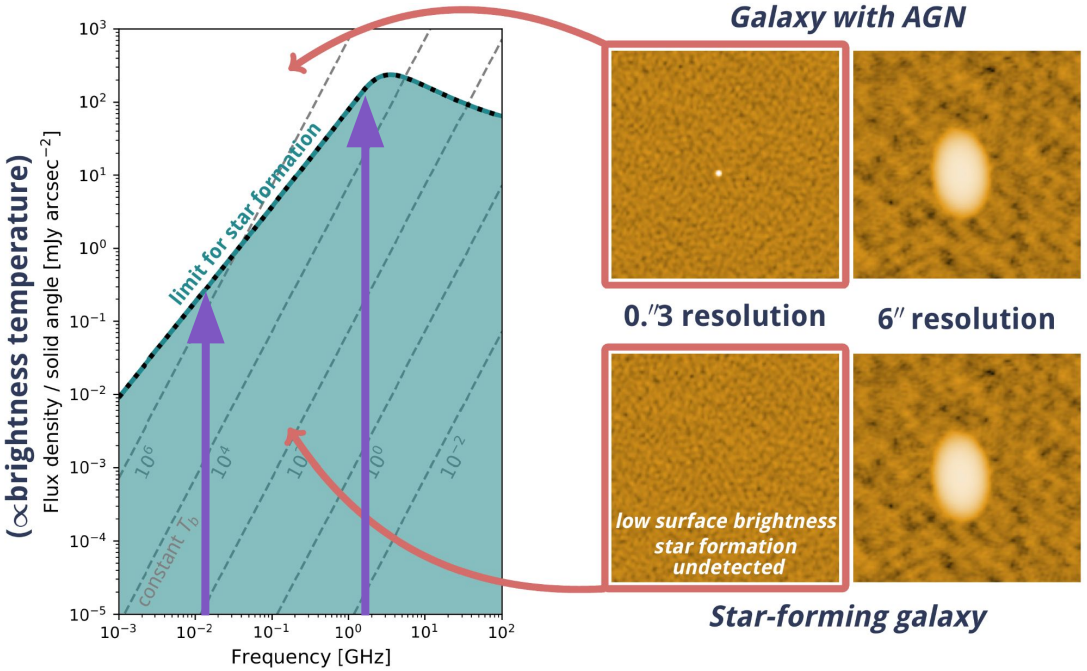

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can reach this with International LOFAR Telescope observations

Observables: Flux density, size information

The T_b AGN population in Lockman Hole

Morabito et al. 2022

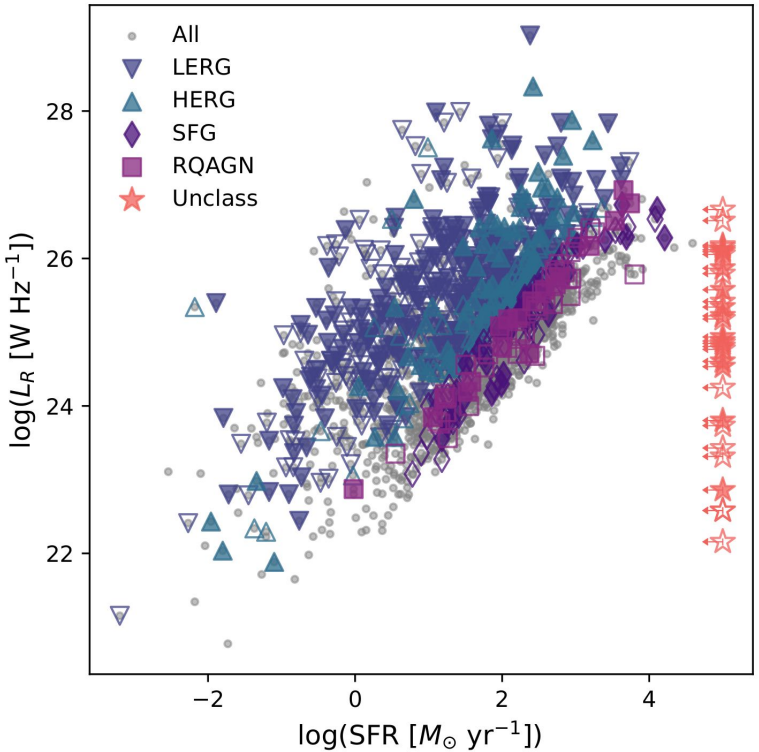
940 AGN identified using T_b

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

Percent of sub-population which are T_b AGN:

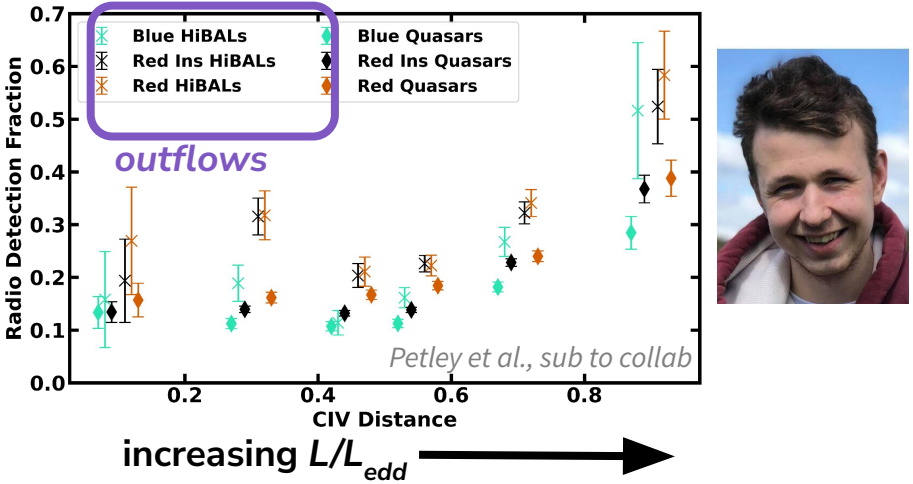
- HERGs: 68%
- LERGs: 57%
- Unclassified: 61%
- **RQAGN: 32%**
- **SFG: 20%**

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



Diagnosing AGN activity

Broad Absorption Line Quasars (BALQSOs)



Diagnosing AGN activity

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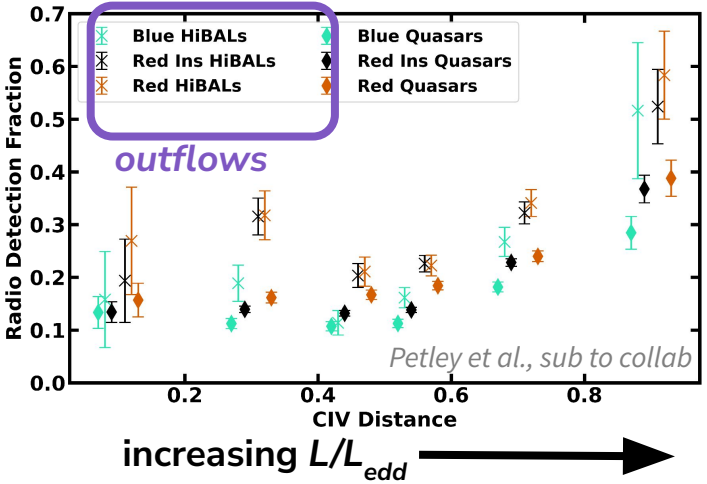

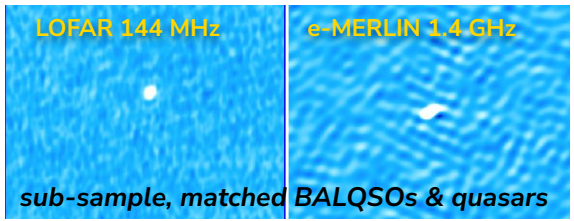

Petley et al., in prep

Diagnosing AGN activity

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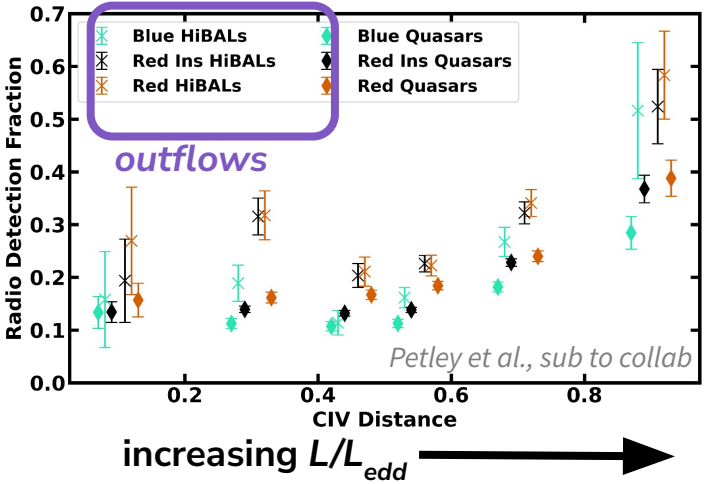
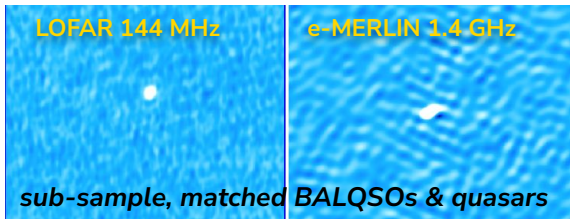
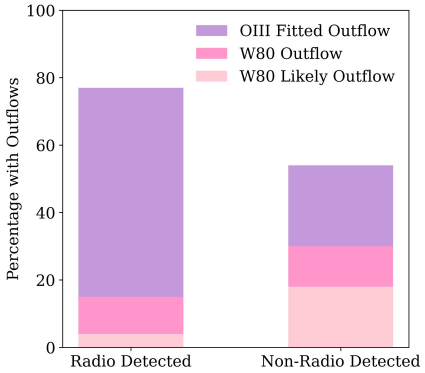




Petley et al., in prep

Ionised outflows [OIII]



Escott et al., in prep

mostly radio-quiet sources

mostly undetected at 0.3”

working on intermediate resolution (1” - 2”)

Diagnosing AGN activity

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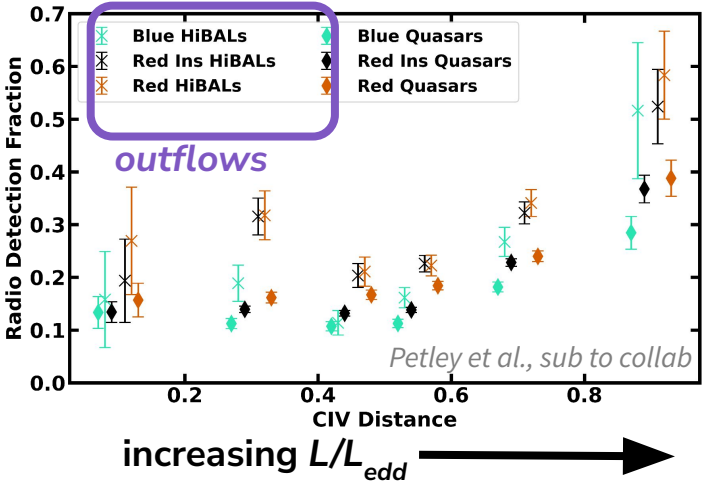

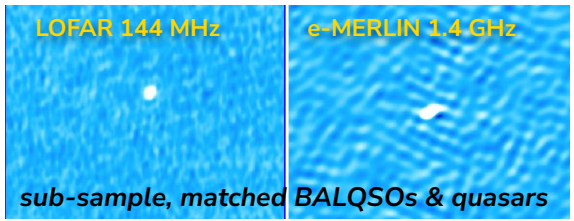

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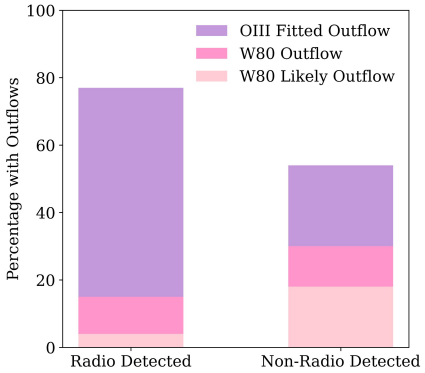

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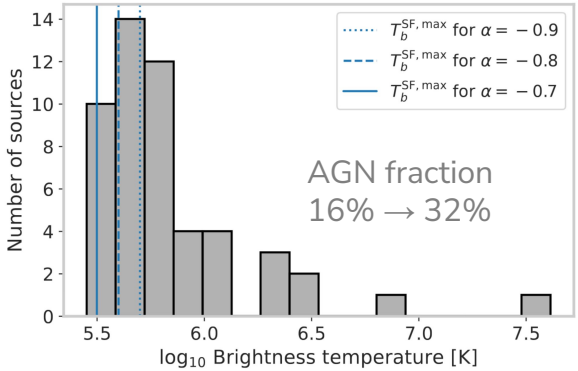
HyLIRGs

Sweijen et al. 2023



why high resolution at low frequencies?

VLBI processing of ILT data

AGN science with VLBI

Future plans

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 *(see Philip’s talk!)*

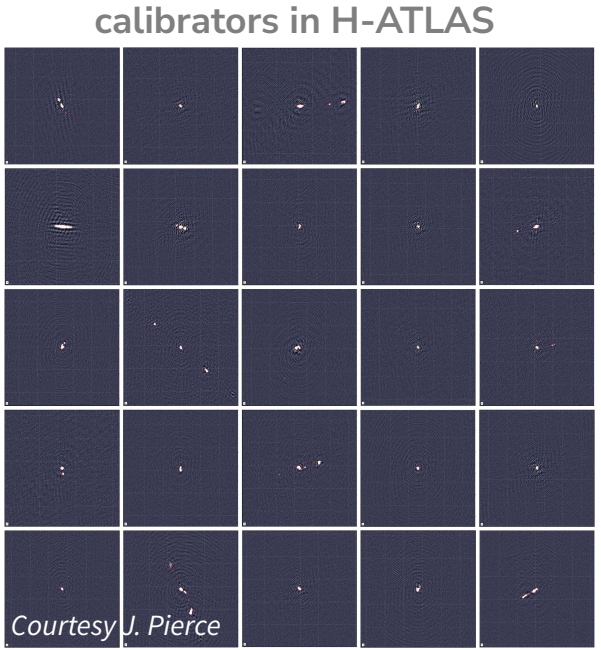
LOFAR Long Baseline Working Group

LoTSS High Resolution (LoTSS-HR)

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

Overall goal:

- **Stage 1:** LOFAR-VLBI pipeline processing of individual sources, S_{int} > 10 mJy
- **Stage 2:** Intermediate resolution images (1” - 2”)
- **Stage 3:** Wide-field VLBI image of every field



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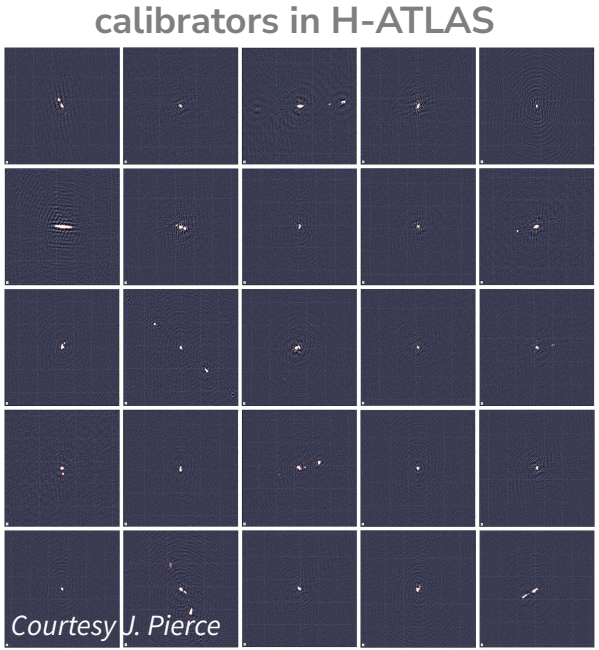

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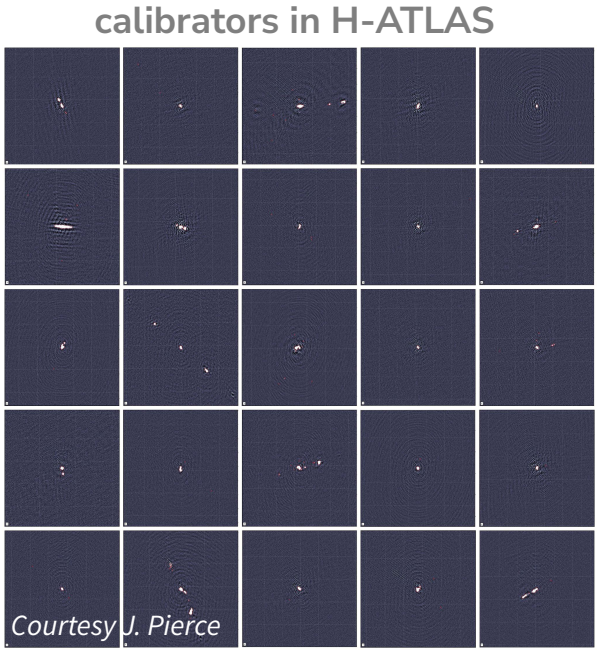
Status:

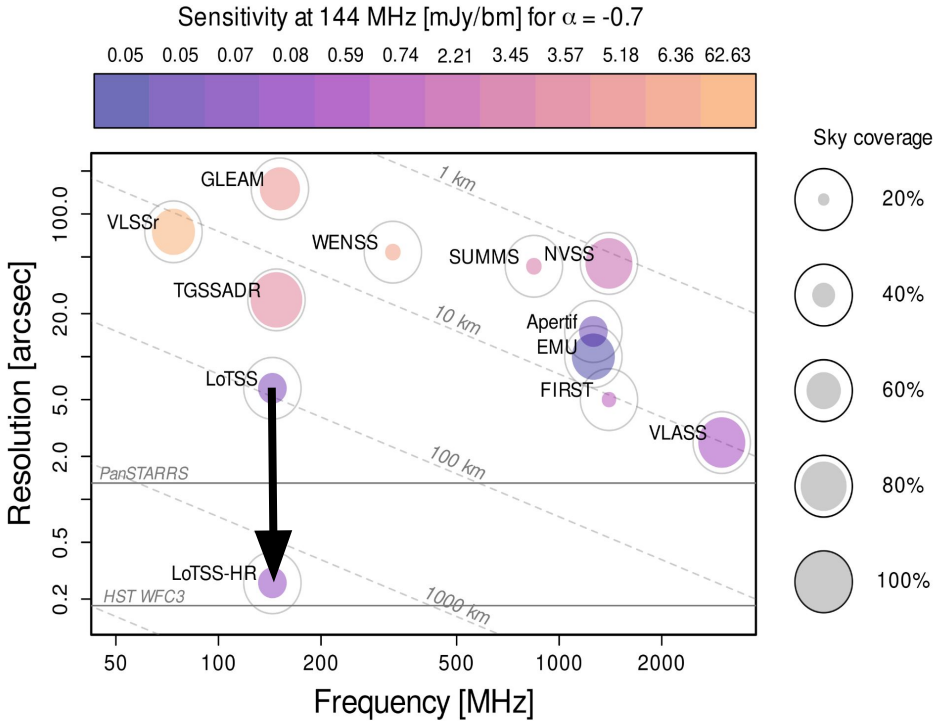
- All standard flux calibrators processed with international stations – about 30% complete
- Automated processing of target fields with LOFAR-VLBI, have started in H-ATLAS area



LoTSS High Resolution (LoTSS-HR)

comparison with other surveys

	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 / deg^2	780	~30	~148

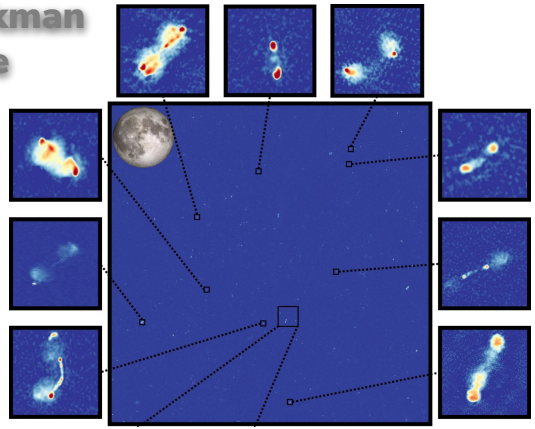


LoTSS High Resolution (LoTSS-HR) Deep Fields

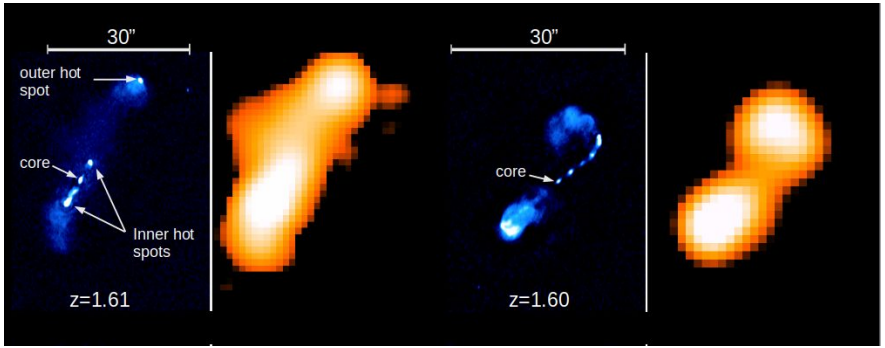
	Lockman Hole	**ELAIS-N1**	**Boötes**	**NEP**
# observations	39	130	24	9
# Dutch processed	23	48	14	0
# obs. with intl stations	25	102	21	9
Average # intl stations	12.5	12.1	9.8	12.4
	Sweijen et al. 2022	*J. de Jong*	*E. Escott*	*M. Bondi*

LoTSS High Resolution (LoTSS-HR) Deep Fields

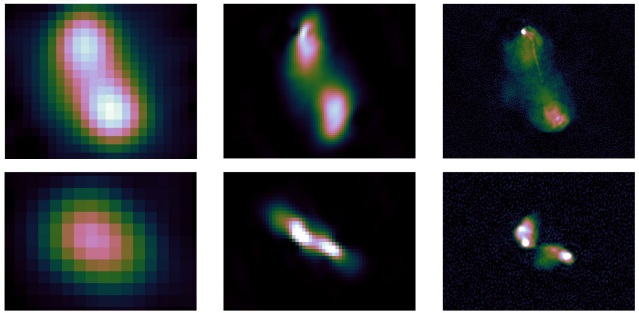
Lockman Hole



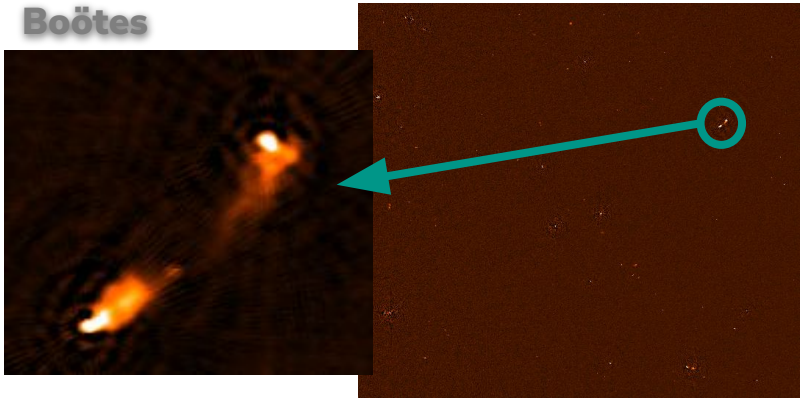
NEP



ELAIS-N1



Boötes



Take home messages:

- Imaging at sub-arcsecond resolution at MHz frequencies is a unique capability which will not be surpassed by any current or planned radio telescope.

- There is clear value for many science cases (including AGN) and pushing to even lower frequencies should be possible with LOFAR2.0

- VLBI with LOFAR is becoming more mainstream, and is a very active area for development! If you're interested in getting involved, contact me! *leah.k.morabito@durham.ac.uk*