Tracing Supermassive Black Hole Jet Activity from Sub-Kiloparsec to Megaparsec Scales in Giant Radio Galaxies using LOFAR and LOFAR-VLBI

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HERA 2026, Warsaw

Outline

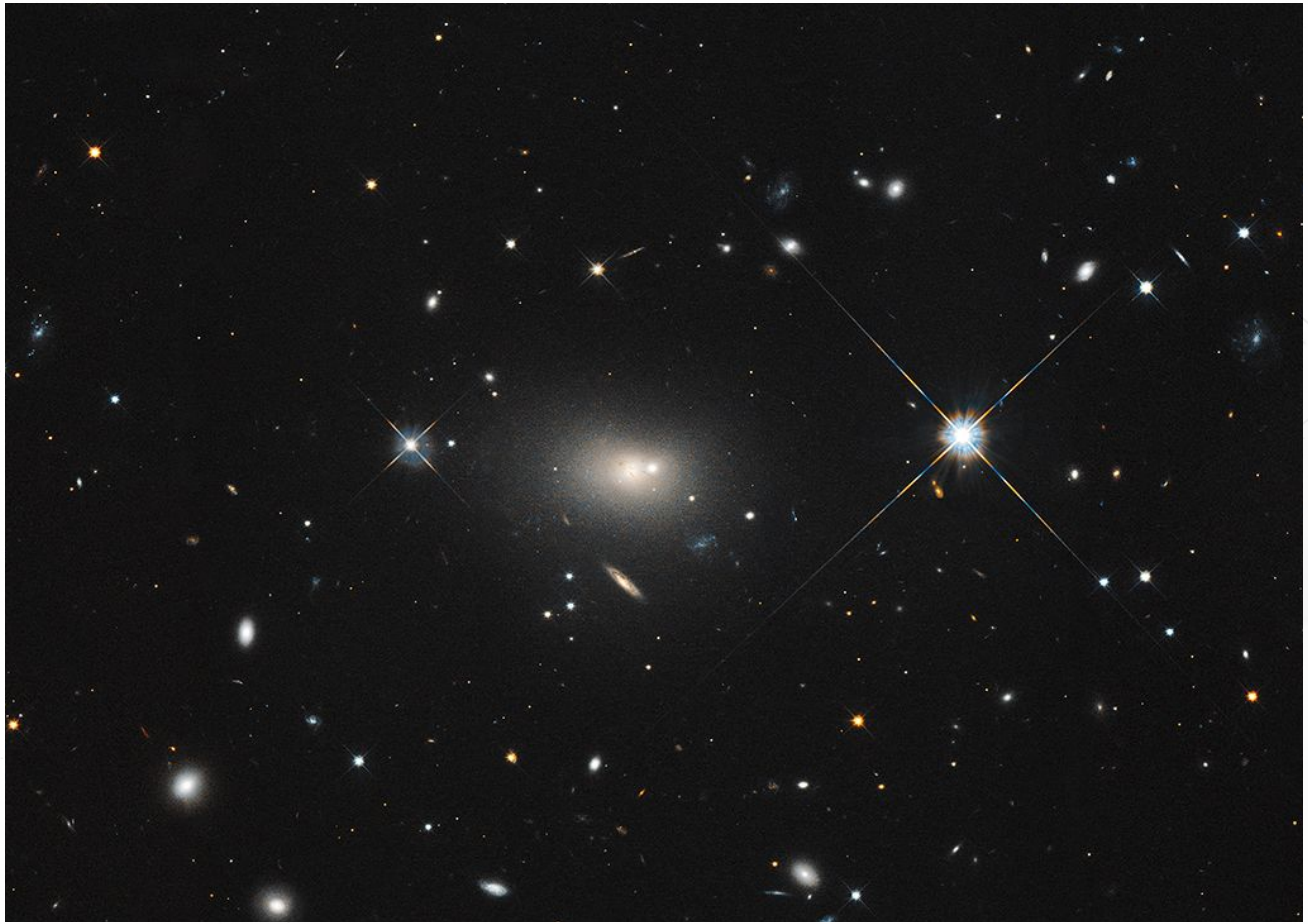
- Why giant radio galaxies ?
- Two GRGs: from Mpc to sub-kpc scales
- What LOFAR-VLBI reveals
- Implication for SMBH jet activity

Following the jet across six orders of magnitude

SMBH→ sub-kpc jet → kpc jet → 100 kpc → Mpc radio lobes

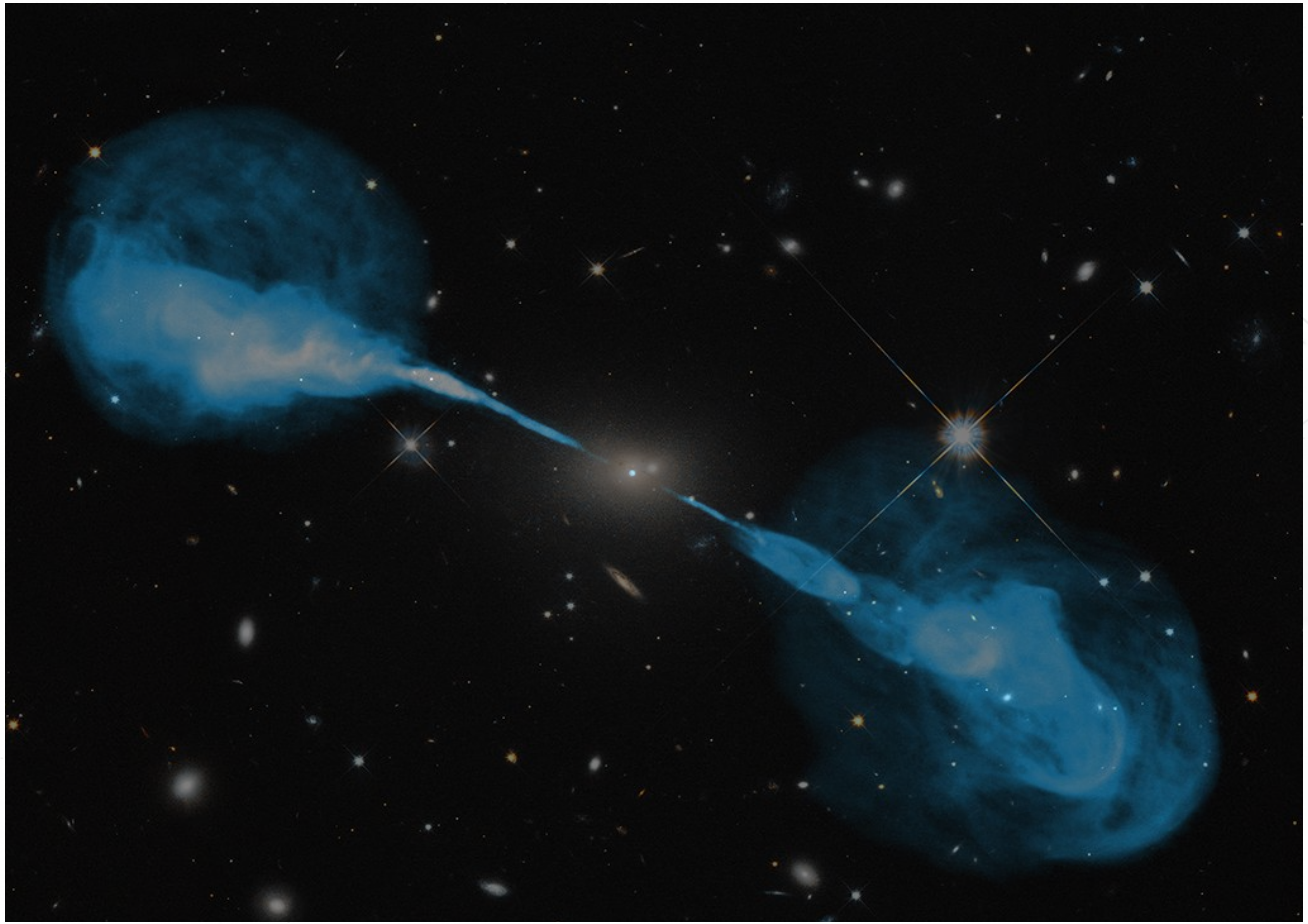
Can we connect the compact, recent jet activity to the large-scale radio structure?

What does a radio galaxy look like ?



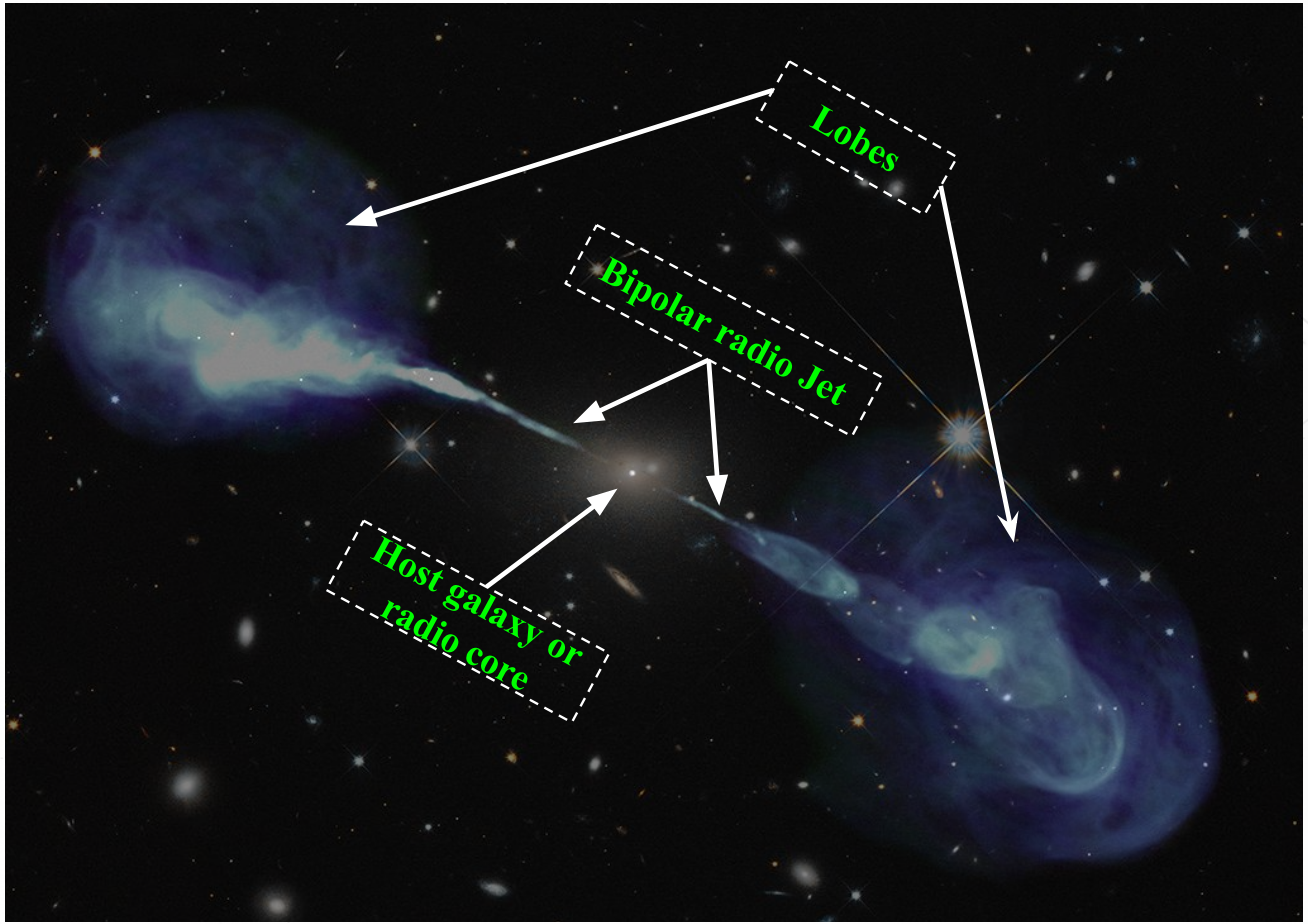
Hercules-A

Optical host + Radio structure



Hercules-A galaxy in optical (credit HST)

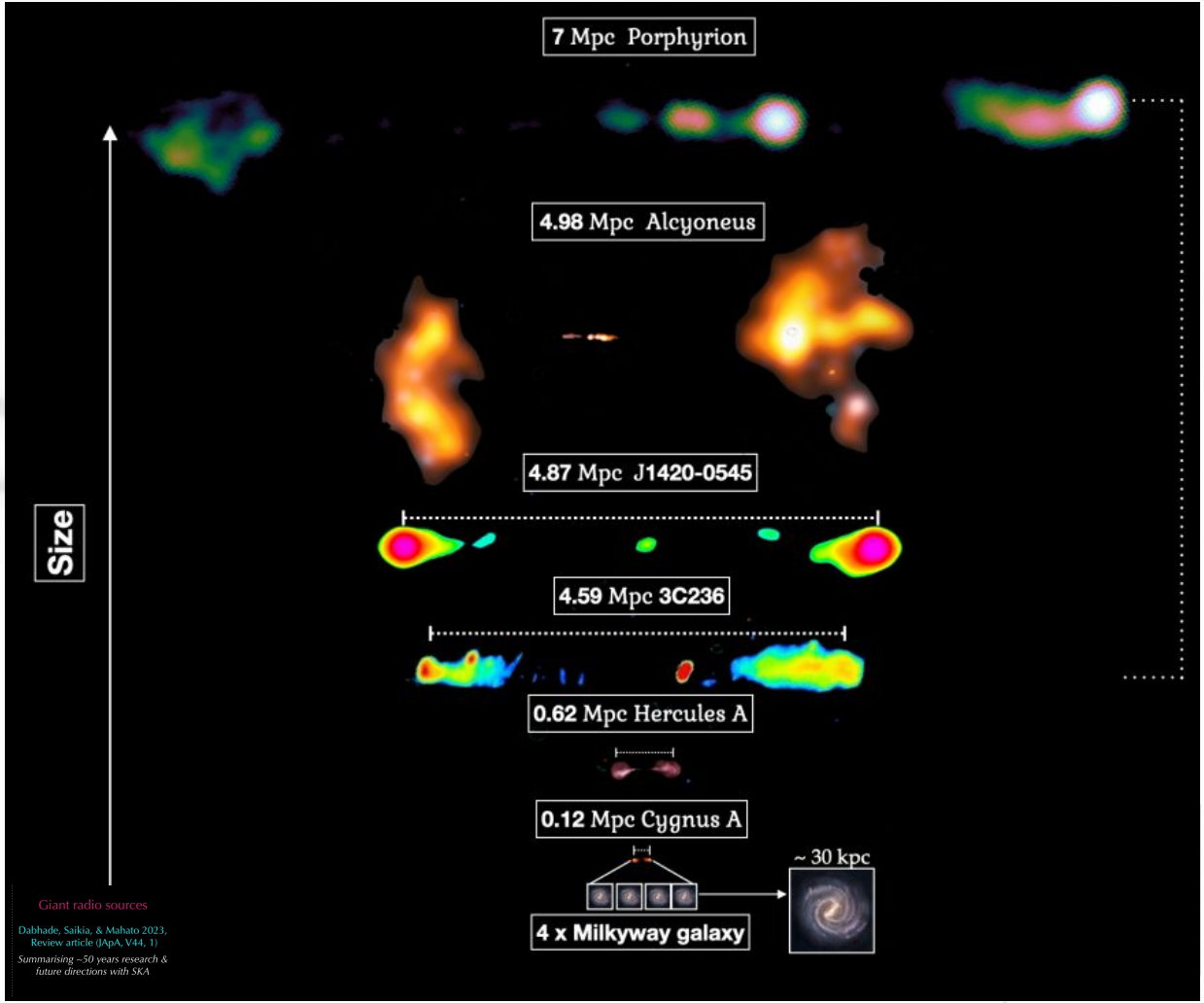
Hercules-A galaxy in radio (credit - VLA)



Giant Radio Galaxies (GRG)

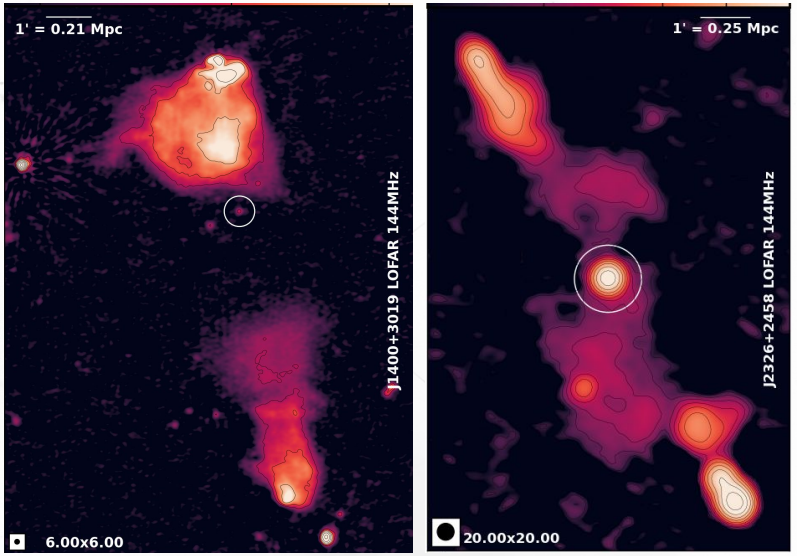
RG **> 0.7 Mpc** → GRG.

Among the largest structures produced by SMBH jet activity



Why do some radio galaxies become exceptionally large ?

1. **Low-density environment**
2. **Powerful central engine**
3. **Recurrent/restarted activity**
4. **Long evolutionary timescale**



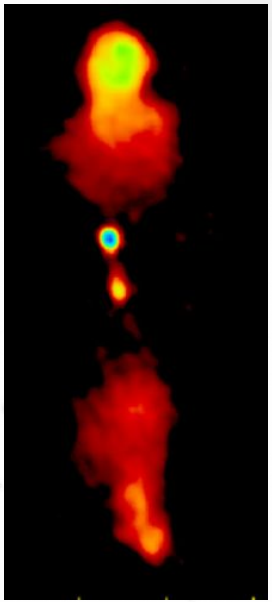
Sethi et. al. in prep

No single factor is sufficient; several may contribute

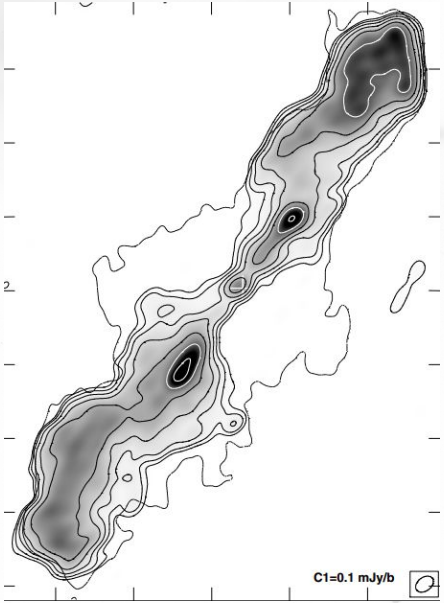
Recurrent activity

Recurrent activity in GRGs

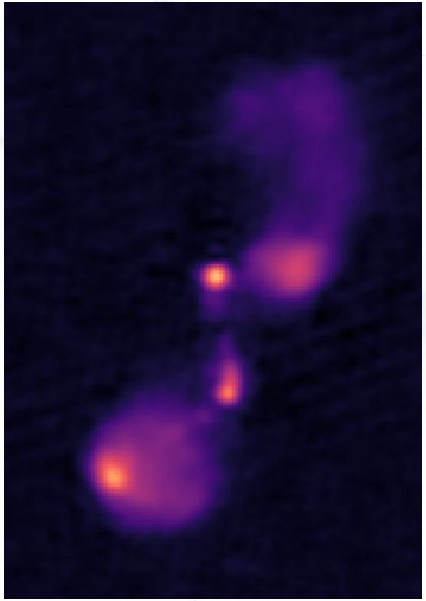
Multiple episodes of jet activity have been identified in some GRGs.



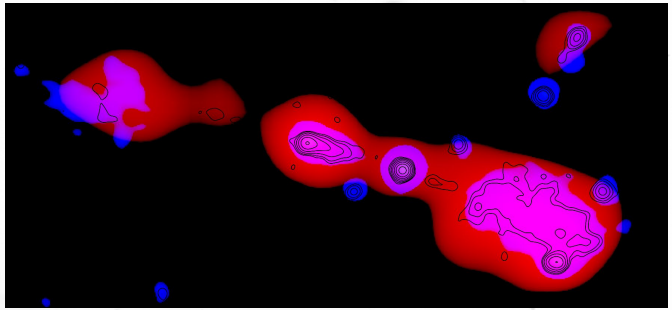
Konar et. al. 2006



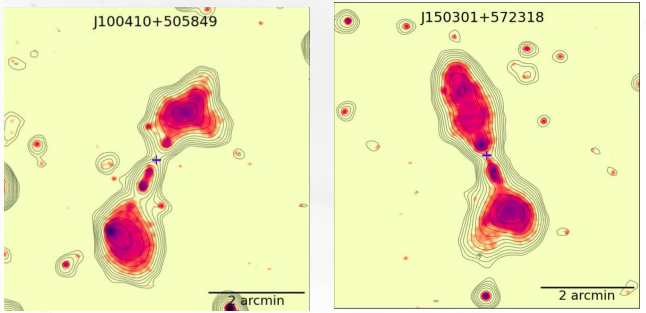
Machalski et. al. 2010



J1328+2752, LoTSS DR3

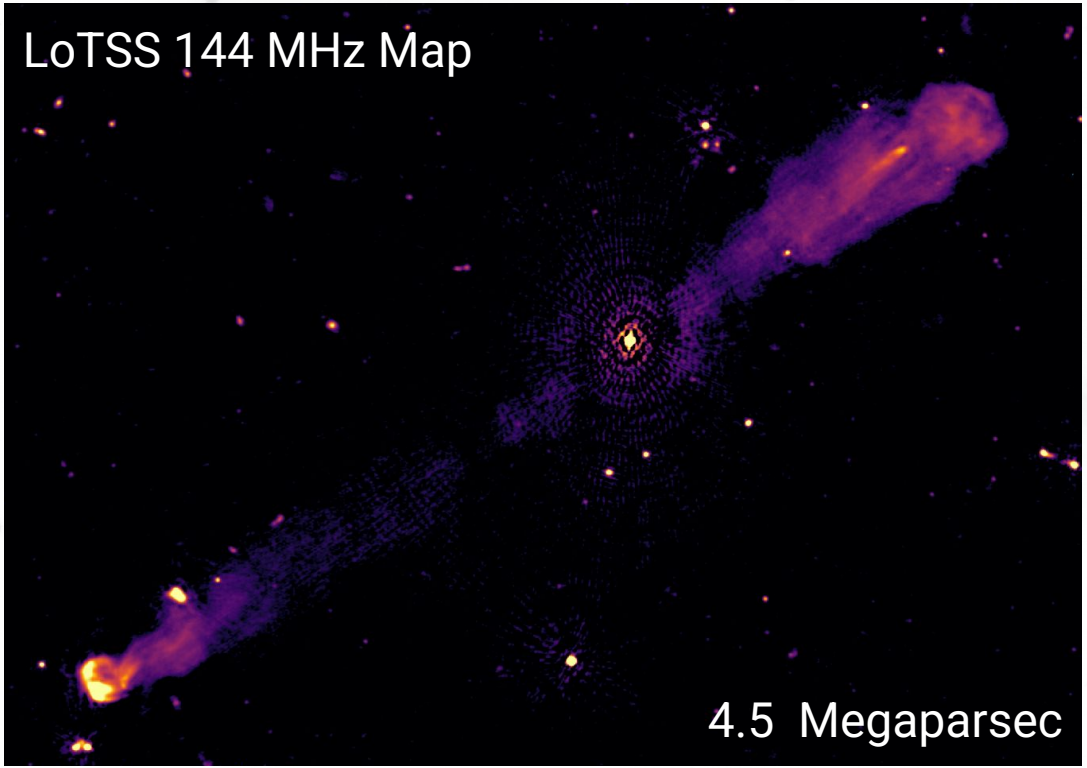


Sethi et. al. 2025, A&A L

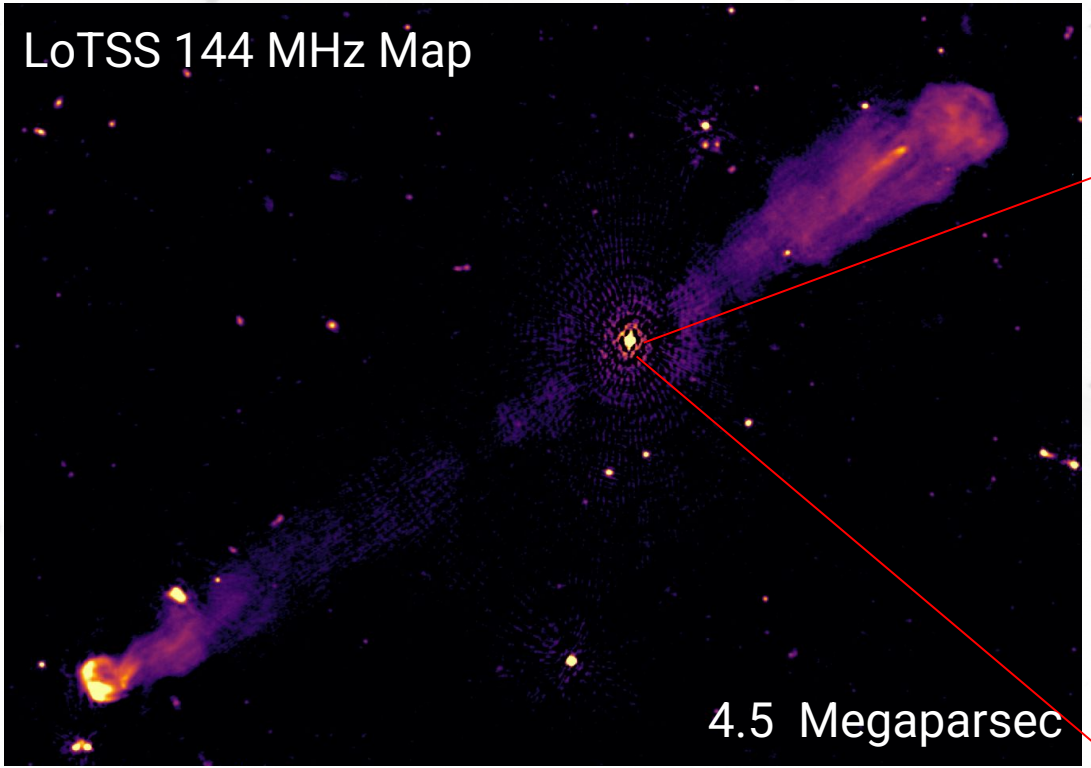


Dabhade et. al. 2025, A&A

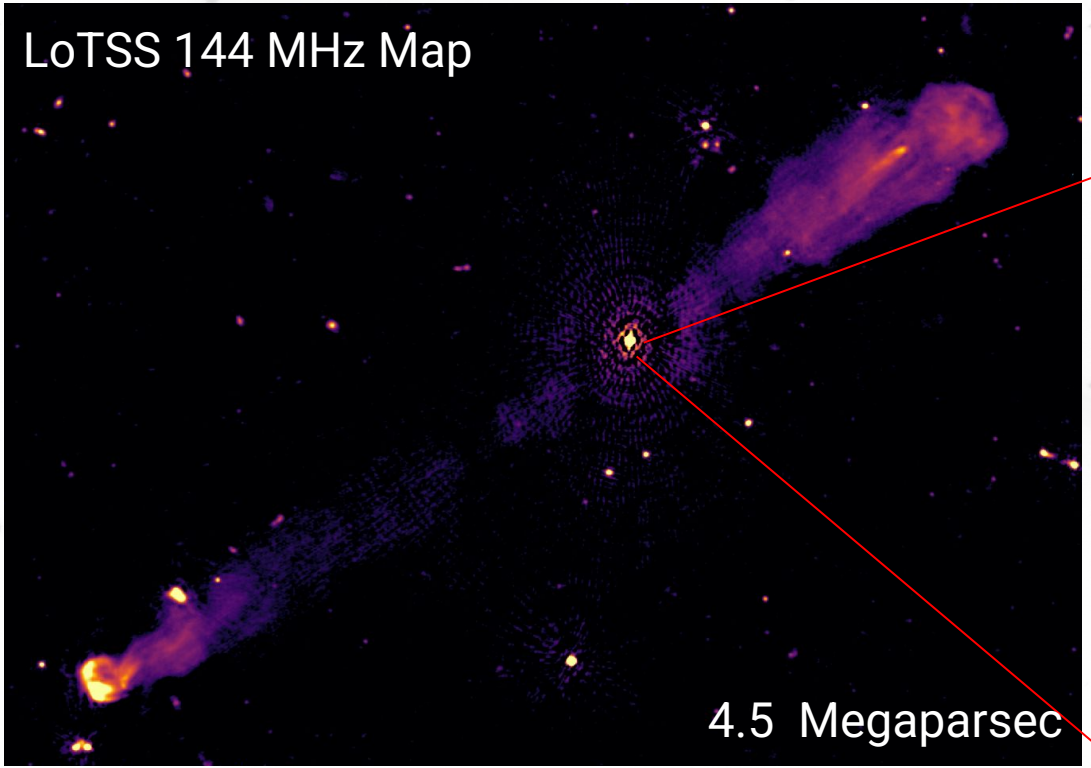
3C 236 : Evidence for a compact, restarted radio structure



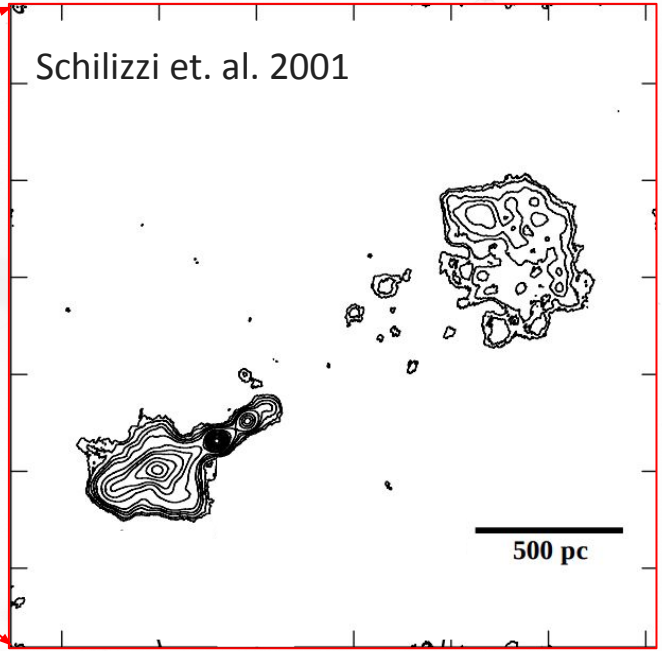
3C 236 : Evidence for a compact, restarted radio structure



3C 236 : Evidence for a compact, restarted radio structure



Mini “inner double” at sub kpc scale



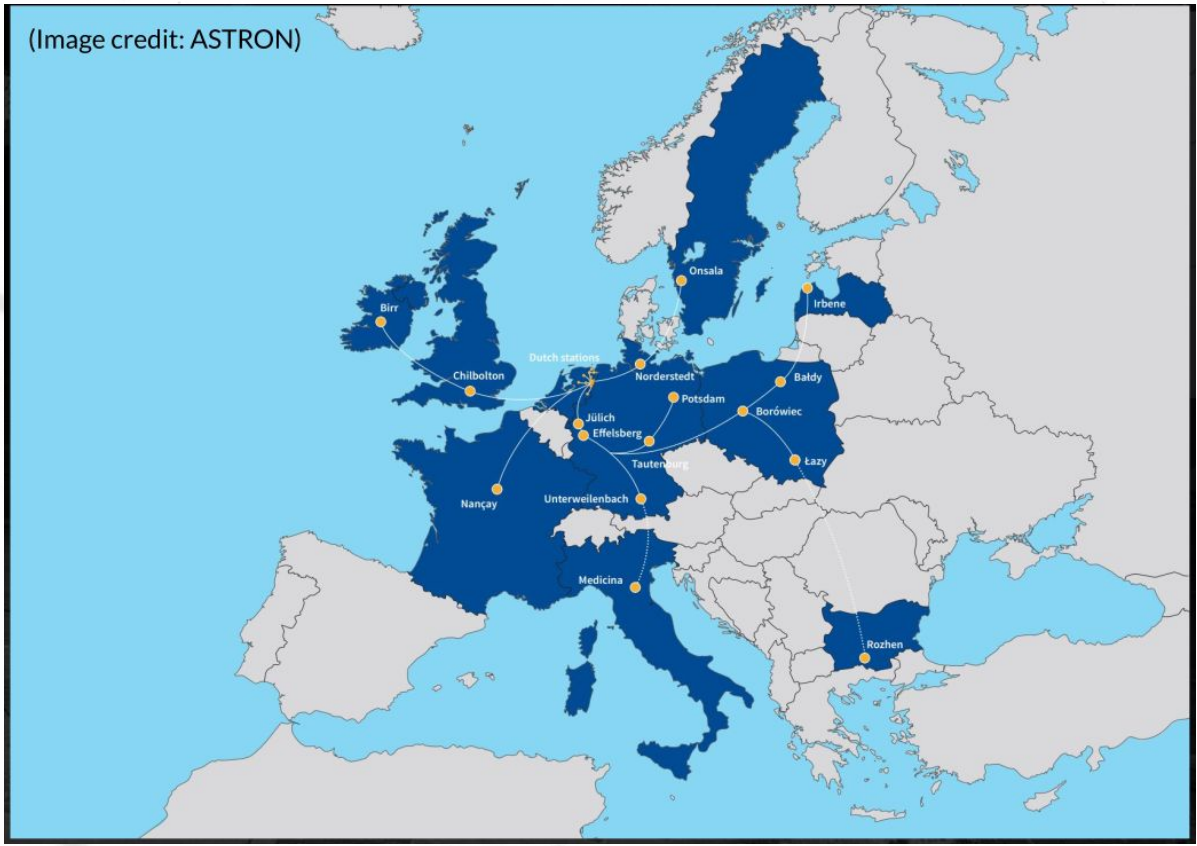
LOFAR: Sensitive to faint, diffuse radio emission

LBA: 10-90 MHz

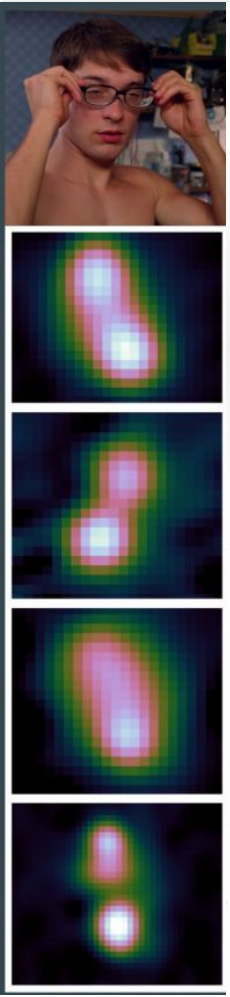
HBA: 110-240 MHz

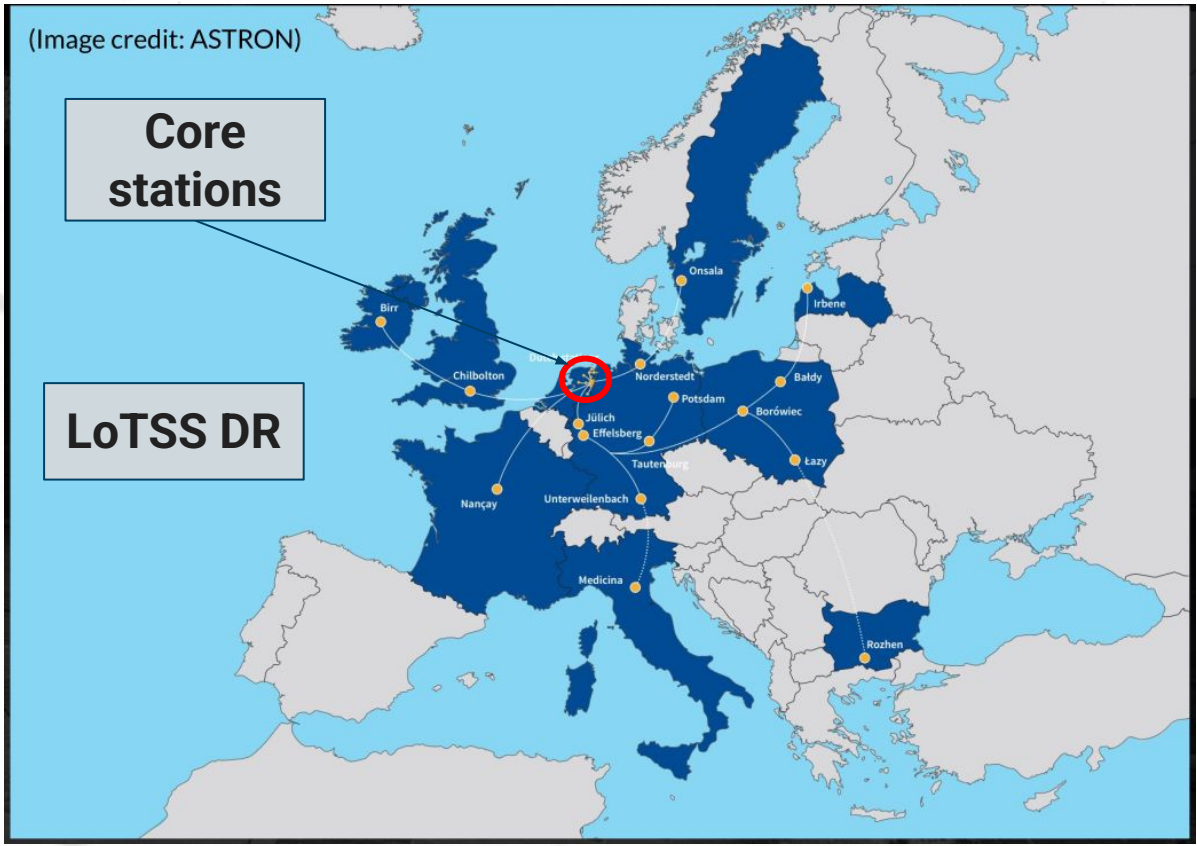
52 stations.

≥ 144 Antenna per station.



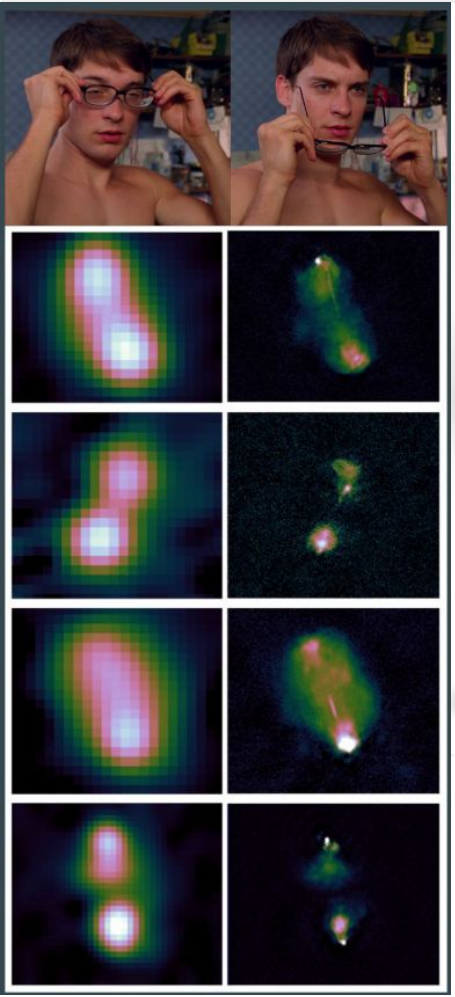
LOFAR Dutch array: arcsecond-scale imaging





de Jong, J. M. G. H. J., et al.: A&A, 689, A80 (2024)

International LOFAR: longer baselines



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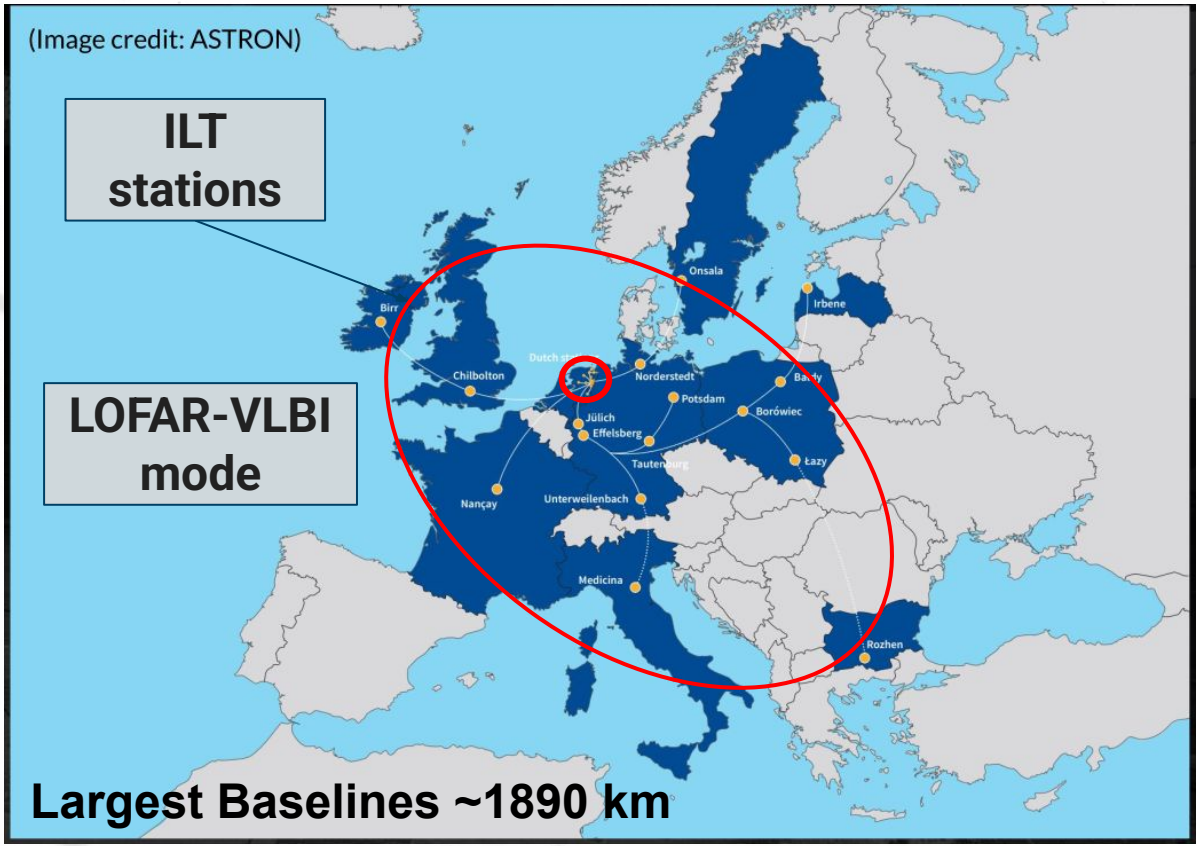

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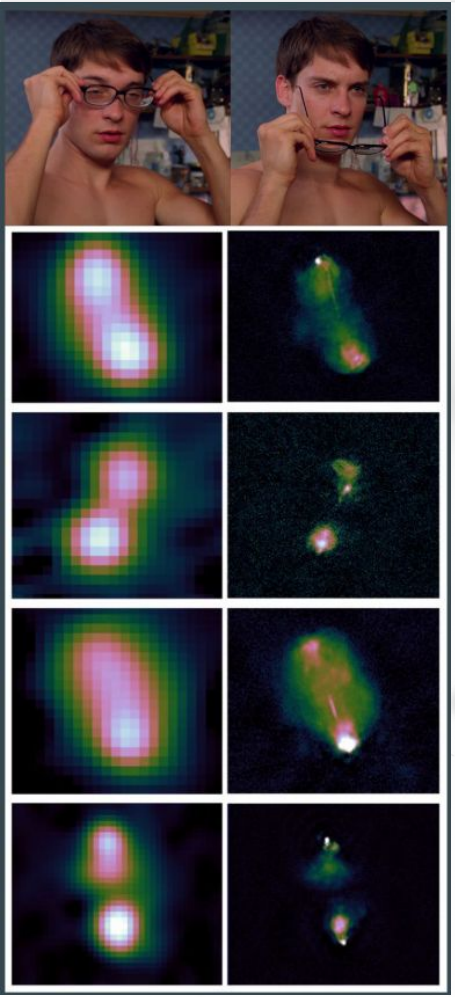

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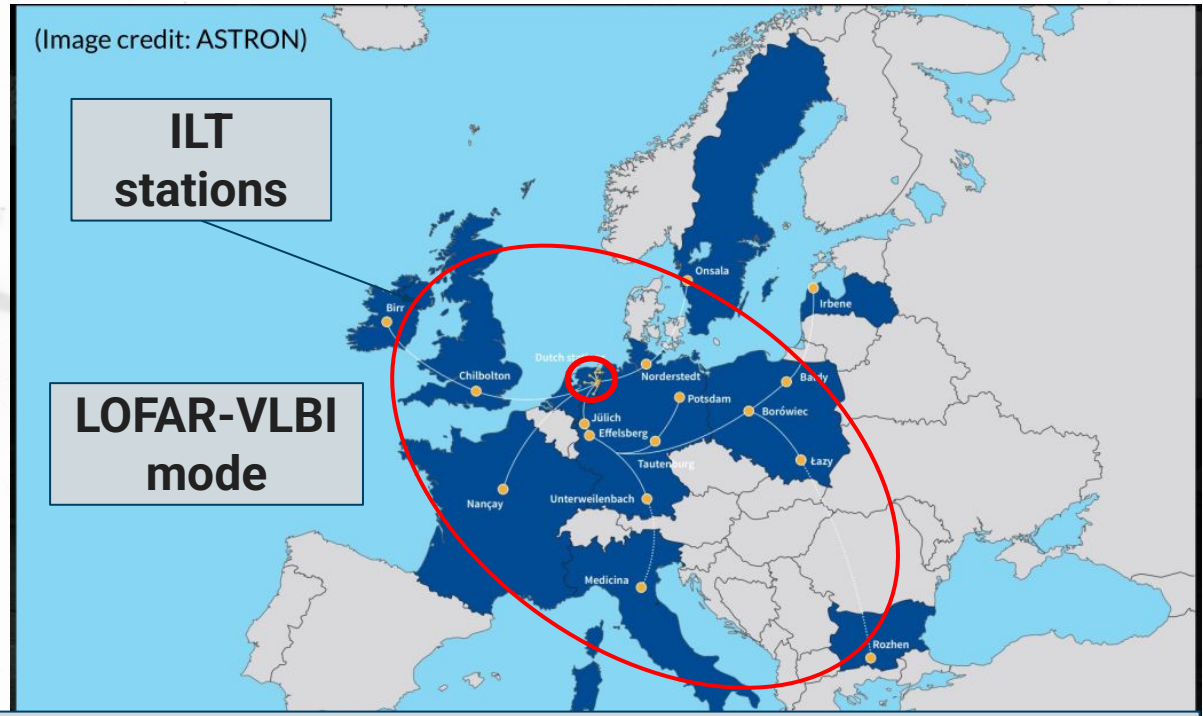
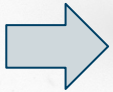


International stations enable sub-arcsecond imaging with LOFAR-VLBI

Why LOFAR-VLBI, any advantage ?

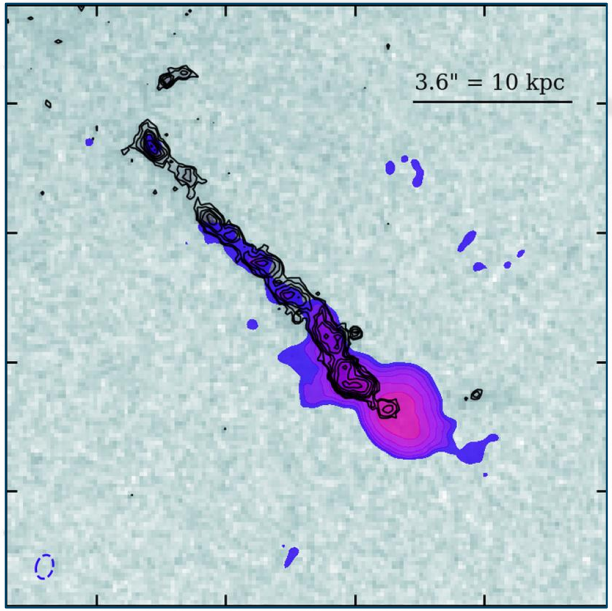
Mpc-scale radio lobes preserve the history of jet activity.



LOFAR-VLBI probes the compact end of that history.

Advantage of LOFAR-VLBI for studying restarted activity in GRGs

1. Sub-arcsecond resolution



3C 273, 144 MHz ILT + HST (Harwood et al.,2022)

Advantage of LOFAR-VLBI for studying restarted activity in GRGs

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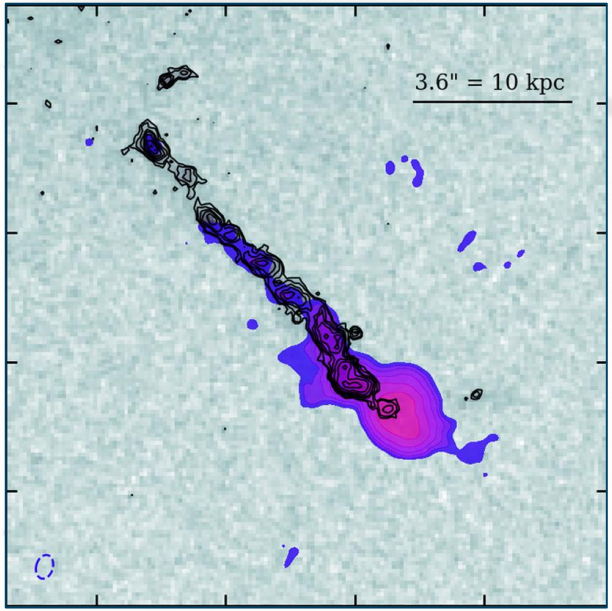
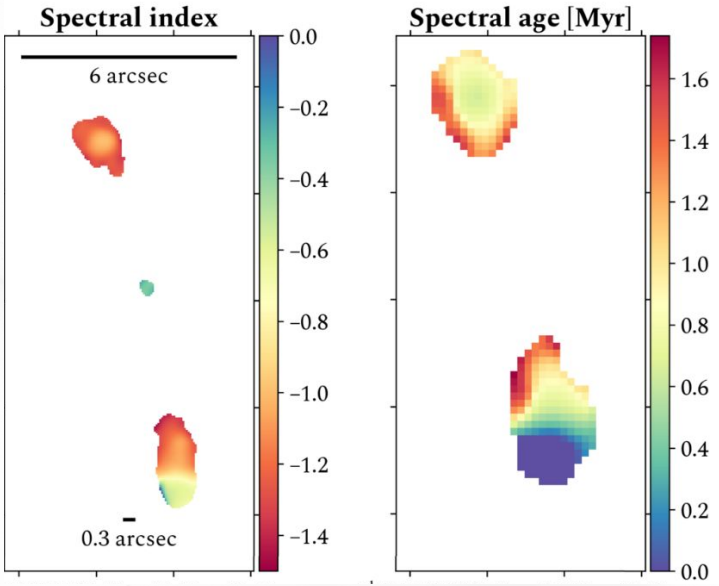


3C 273, 144 MHz ILT + HST (Harwood et al.,2022)

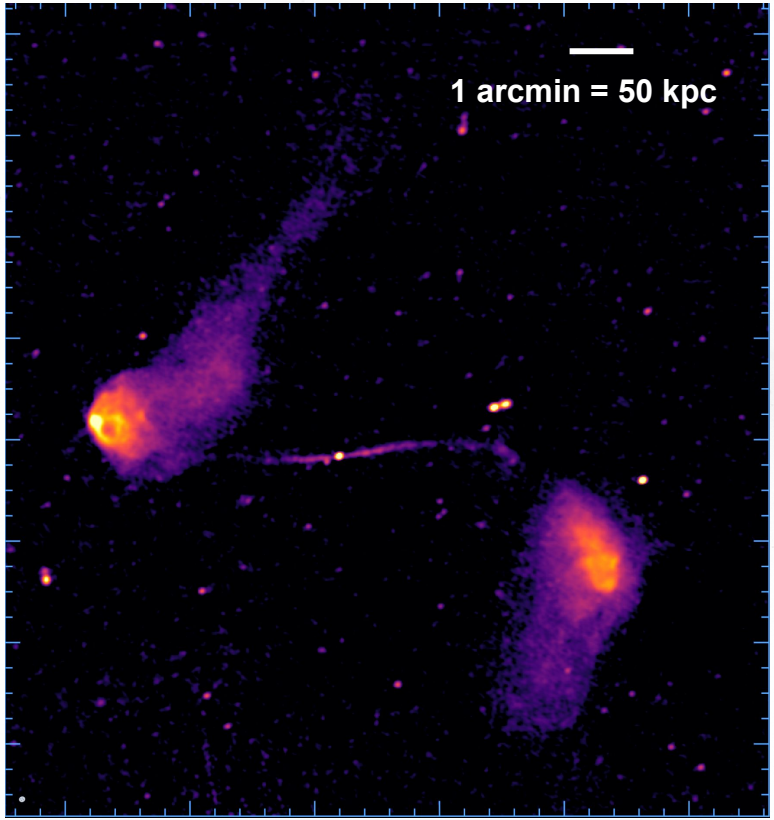
2. Resolve spectral structure on sub-arcsecond scale



Spatially resolved spectral indices and ages of 4C 43.15 (Sweijen et al. 2022)

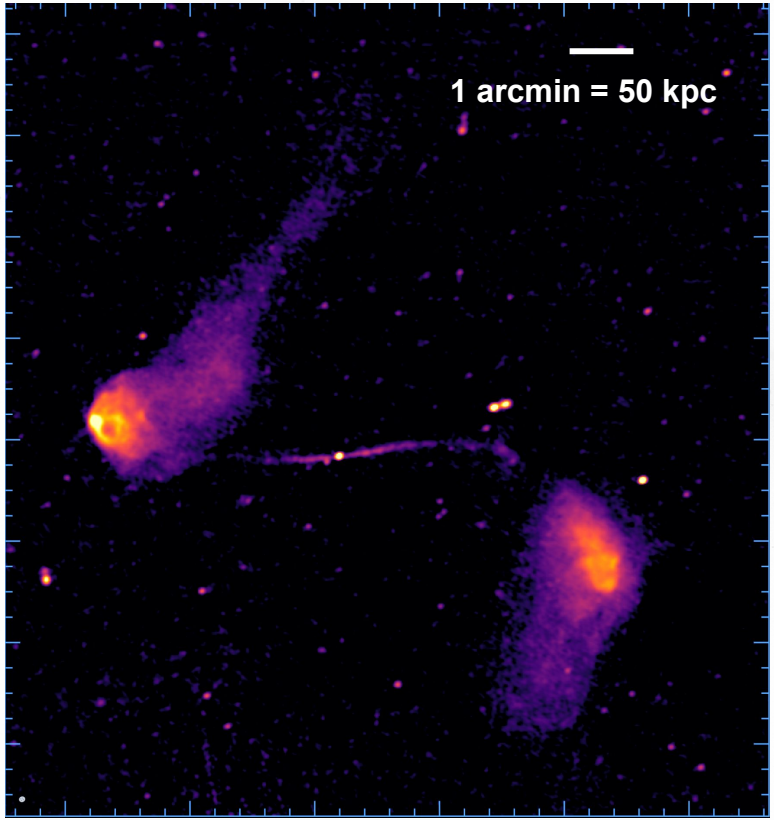
J0644+1043: S-shaped GRG

J0644+1043



uGMRT 650 MHz observation (Sethi et al 2024, ApJ)

J0644+1043



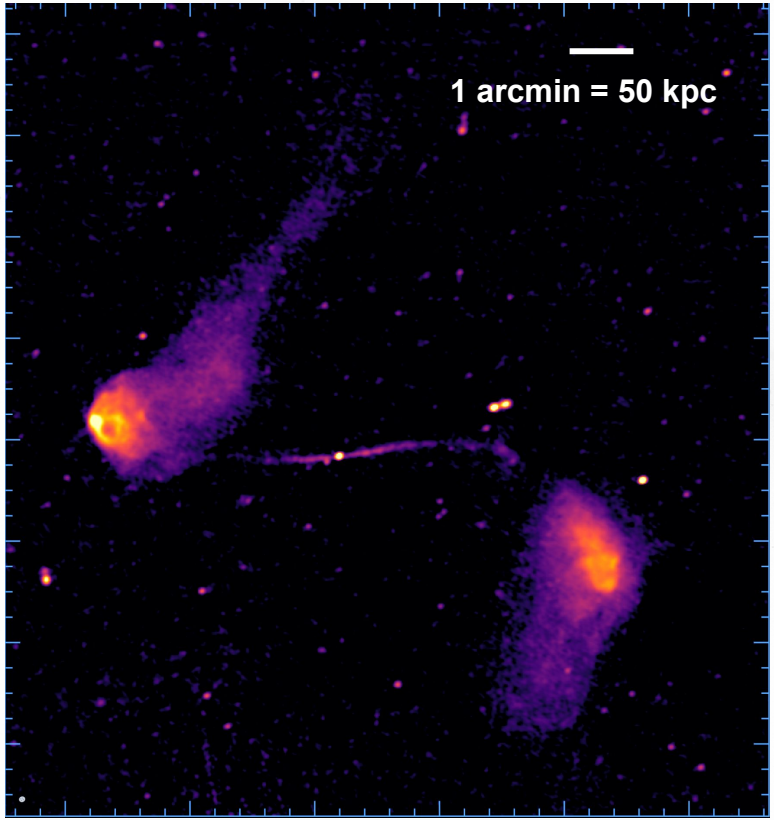
20 arcmin

uGMRT 650 MHz observation (Sethi et al 2024, ApJ)

J0644+1043

Redshift = 0.0489

Size = 711 kpc



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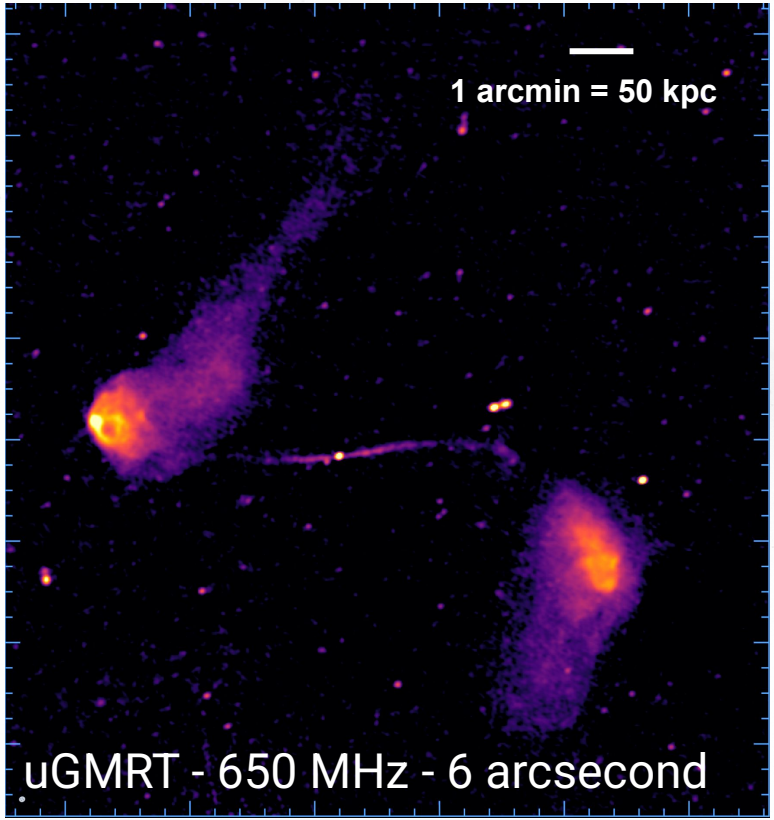
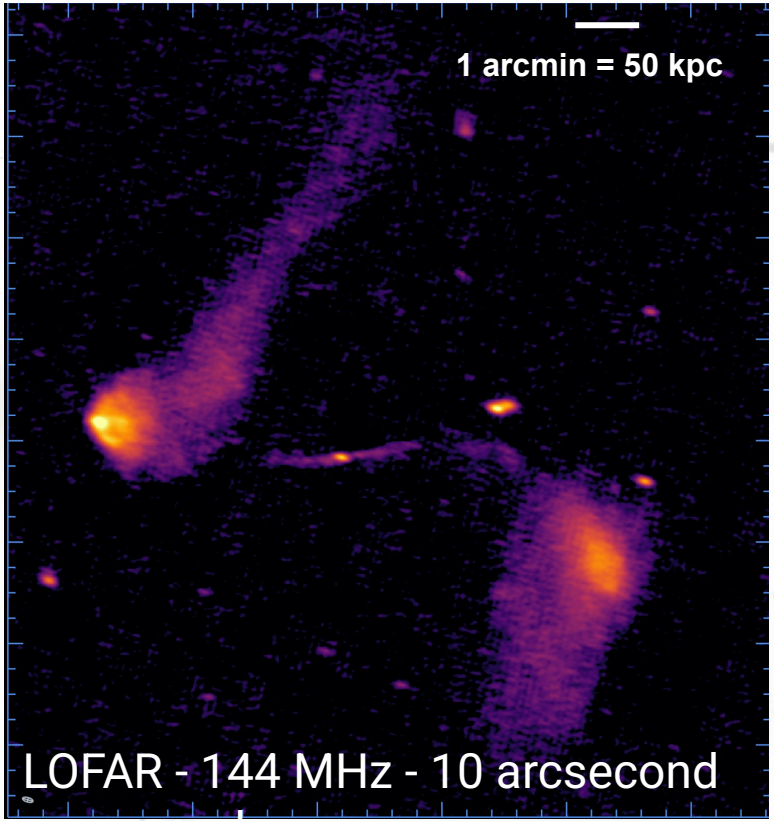


20 arcmin



uGMRT 650 MHz observation (Sethi et al 2024, ApJ)

Dedicated LOFAR observation (PI: Sagar Sethi)

Mixed FR-I/FR-II morphology

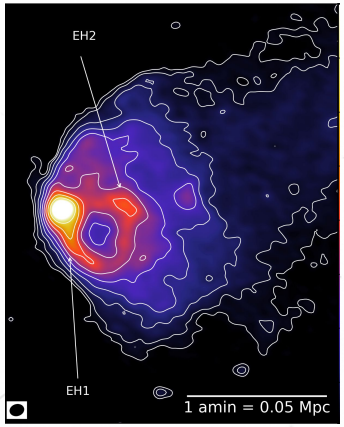
(Sethi et al 2024, ApJ)

FR-I-like properties in SGRG:

- Total radio power (1.4 GHz) ~ **5.92×10^{24} W/Hz**
- Kinetic jet power (150 MHz) ~ **2.01×10^{42} erg/sec**

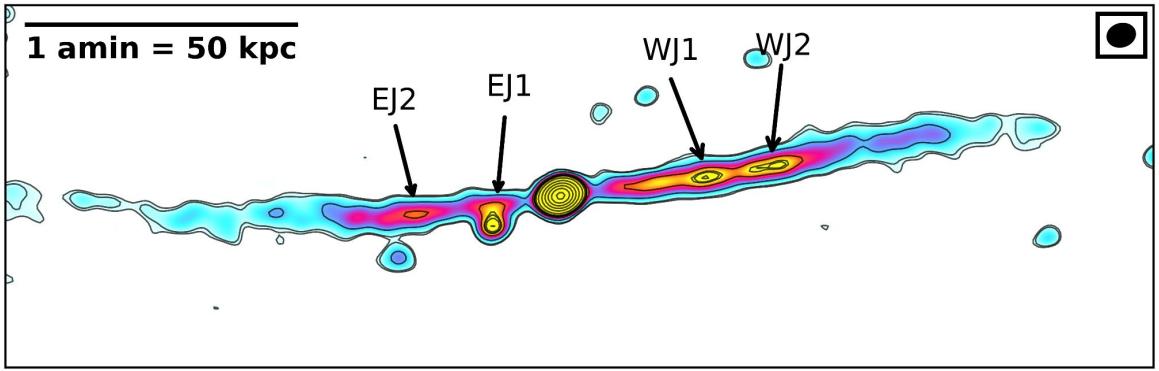
FR-II-like morphology in SGRG:

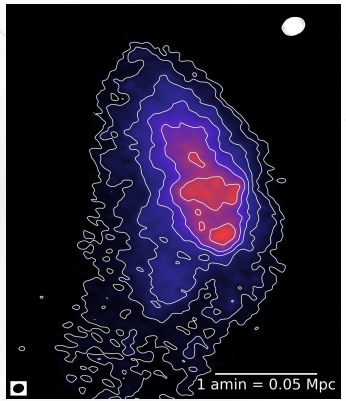
- Collimated narrow jet and counter jet
- Eastern hotspot
- Jet knots



Eastern hotspot region

Key feature→ a ~100 kpc twin jet.

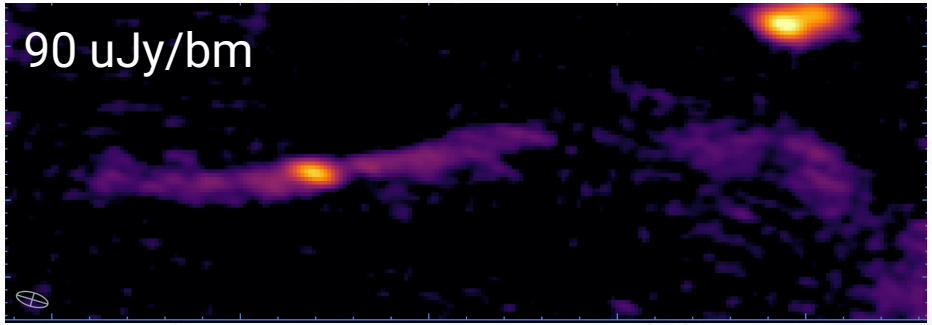




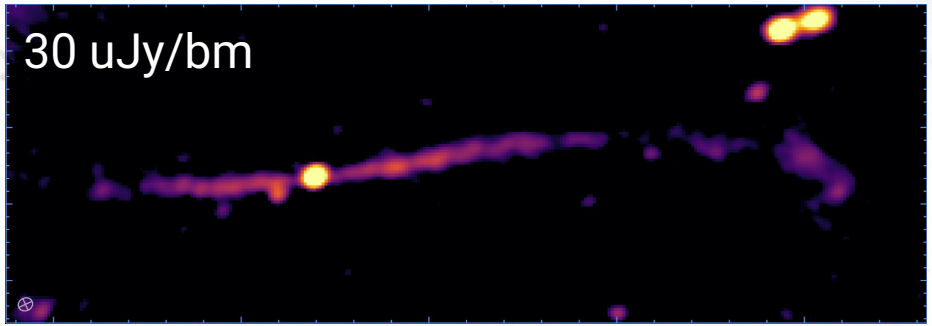
Western plateau region

100 kpc twin jet

Dedicated Low frequency observations



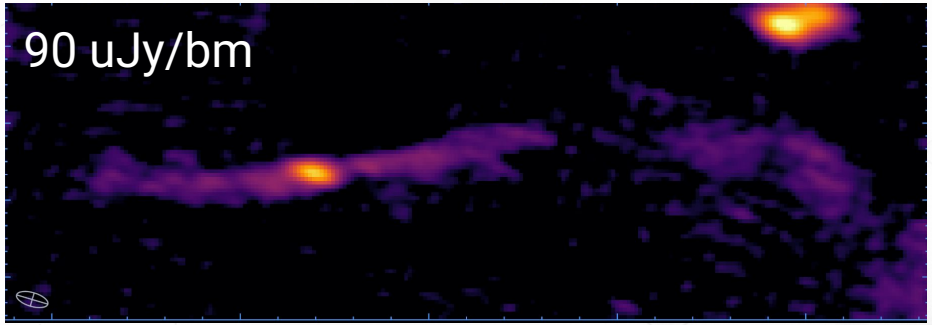
LOFAR 144 MHz HBA (10 arcsec)



uGMRT 650 (6 arcsec)

100 kpc twin jet

Dedicated Low frequency observations



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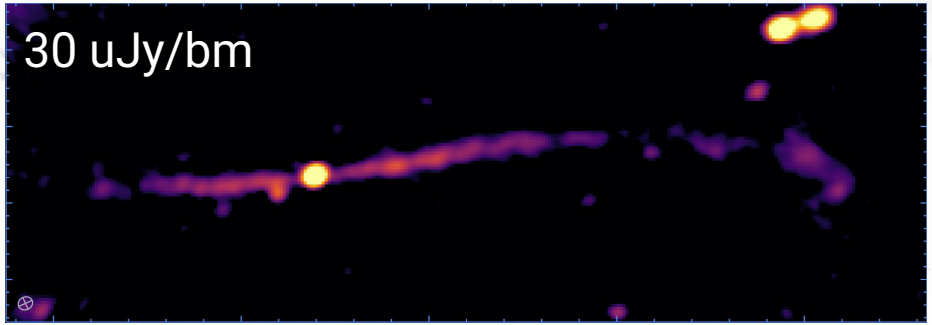
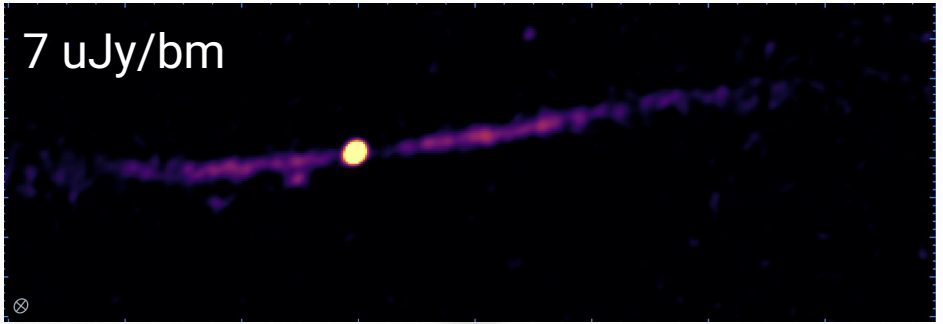
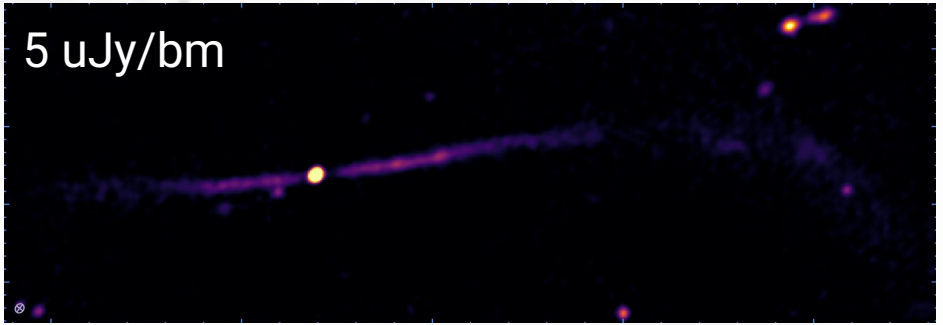


uGMRT 650 (6 arcsec)

Dedicated VLA observations



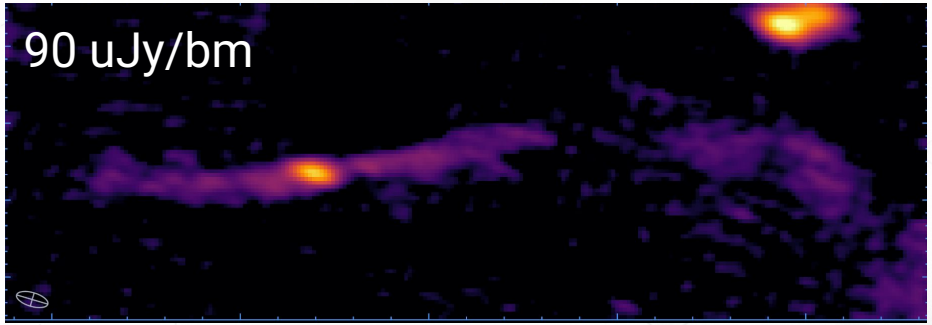
VLA B-Array, S-band, 3 GHz (3 arcsec)



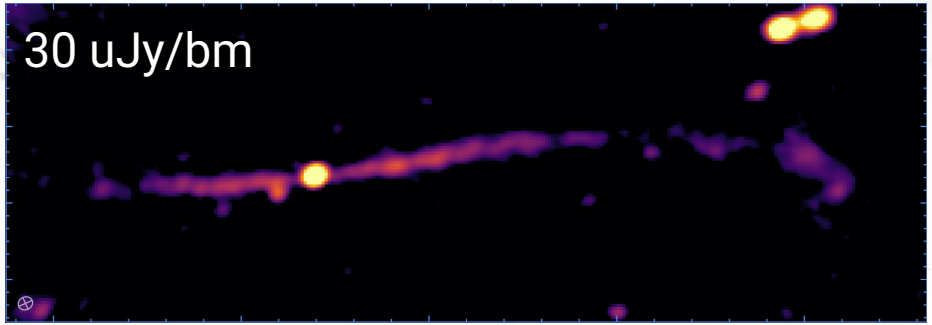
VLA B-Array, C-band, 5 GHz (0.7 arcsec)

100 kpc twin jet

Dedicated Low frequency observations

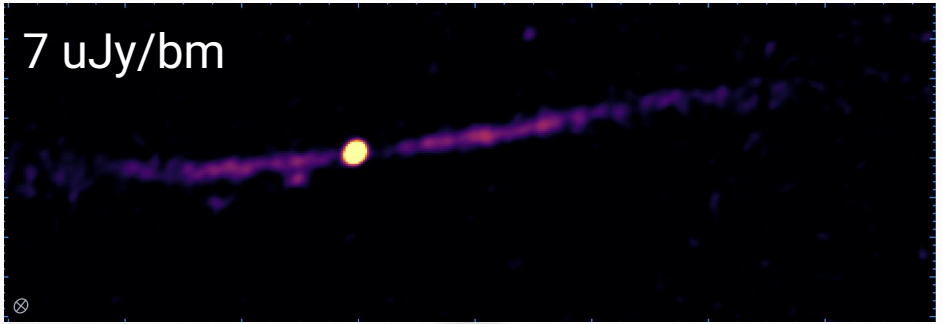


LOFAR 144 MHz HBA (10 arcsec)

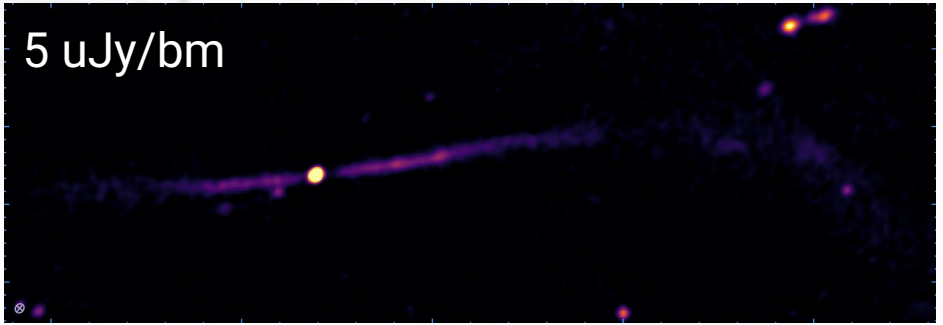


uGMRT 650 (6 arcsec)

Dedicated VLA observations



VLA B-Array, S-band, 3 GHz (3 arcsec)



VLA B-Array, C-band, 5 GHz (0.7 arcsec)

LOFAR-VLBI

LOFAR-VLBI observation & data reduction

OBSERVATION

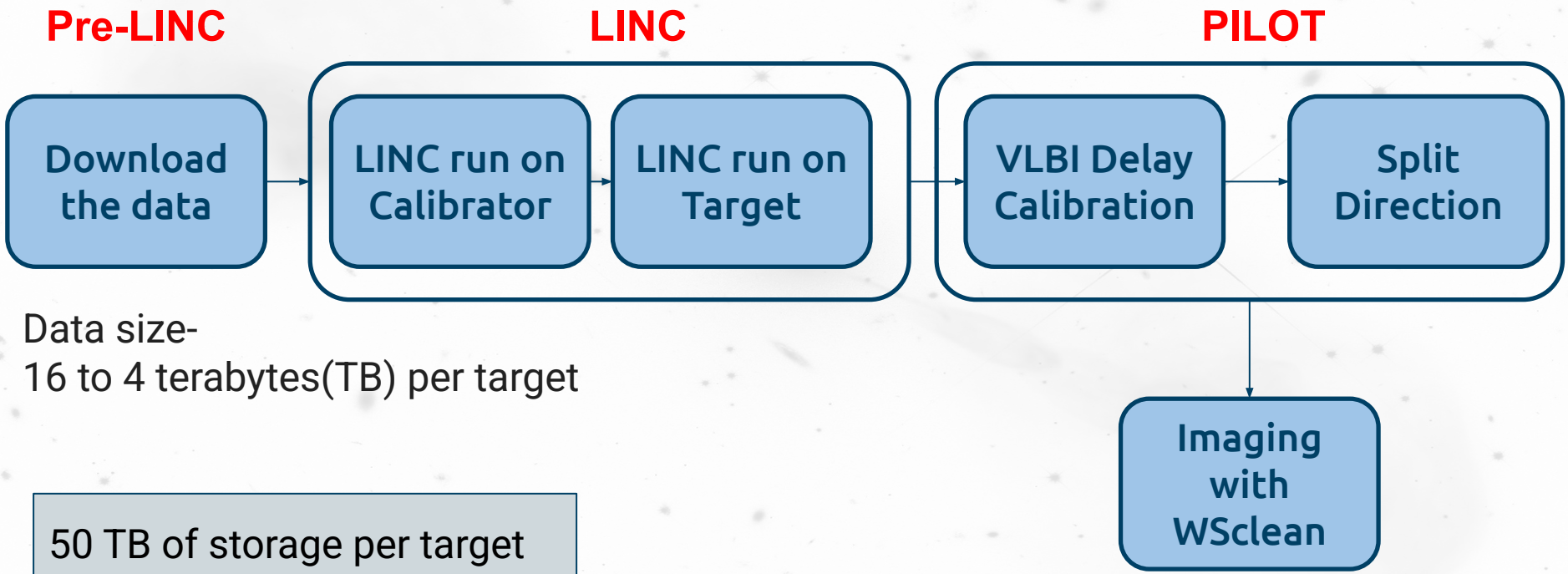
- **Dedicated** LOFAR-VLBI proposal
  PI: **Sagar Sethi**
- **16** hours total
- **4** hrs (international stations)
- Total station - **49**
- Calibrators- **3C48, 3C295**

DATA reduction with HPC

- Pipeline- **FLoCS**
- Computing resource →
  - **LOFAR-VLBI cluster**
    in UWM, Olsztyn, Poland
  - **PLgrid HPC grant**
    Cyfronet, Krakow.

I have established an end-to-end HPC setup for
LOFAR-VLBI reduction at UWM, Olsztyn and PLgrid Cyfronet, Krakow

LOFAR-VLBI reduction workflow



Data size-
16 to 4 terabytes(TB) per target

50 TB of storage per target
20 000 to 30 000 cpu hours

Challenges with VLBI-delay calibration for this field

1. Manually I ran **pybdsf** on my LOFAR image.
2. I tried out **2 nearby compact sources** and **manually ran VLBI delay**.

But the phase scores are completely unreliable.

1st one

```
Source_id = ILTJ064310.6+112546
Total_flux = 759.3
Peak_flux  = 689.8
Distance   = 0.73 deg
```

Phase score reliability: 0.3 %

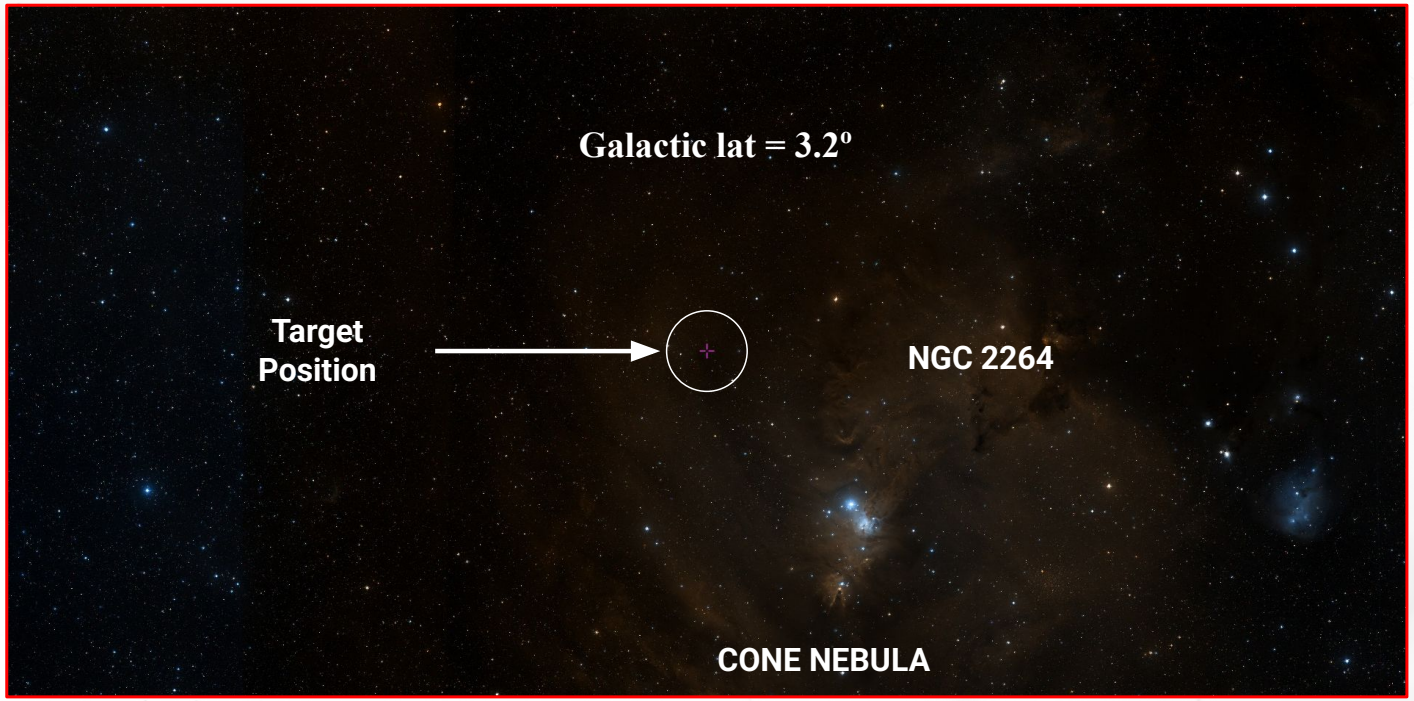
2nd

```
Source_id  = ILTJ064448.74+105121.7
Total_flux = 283.4 mJy
Peak_flux  = 225.2 mJy
Distance     = 0.21 deg
```

Phase_score reliability: 1 %

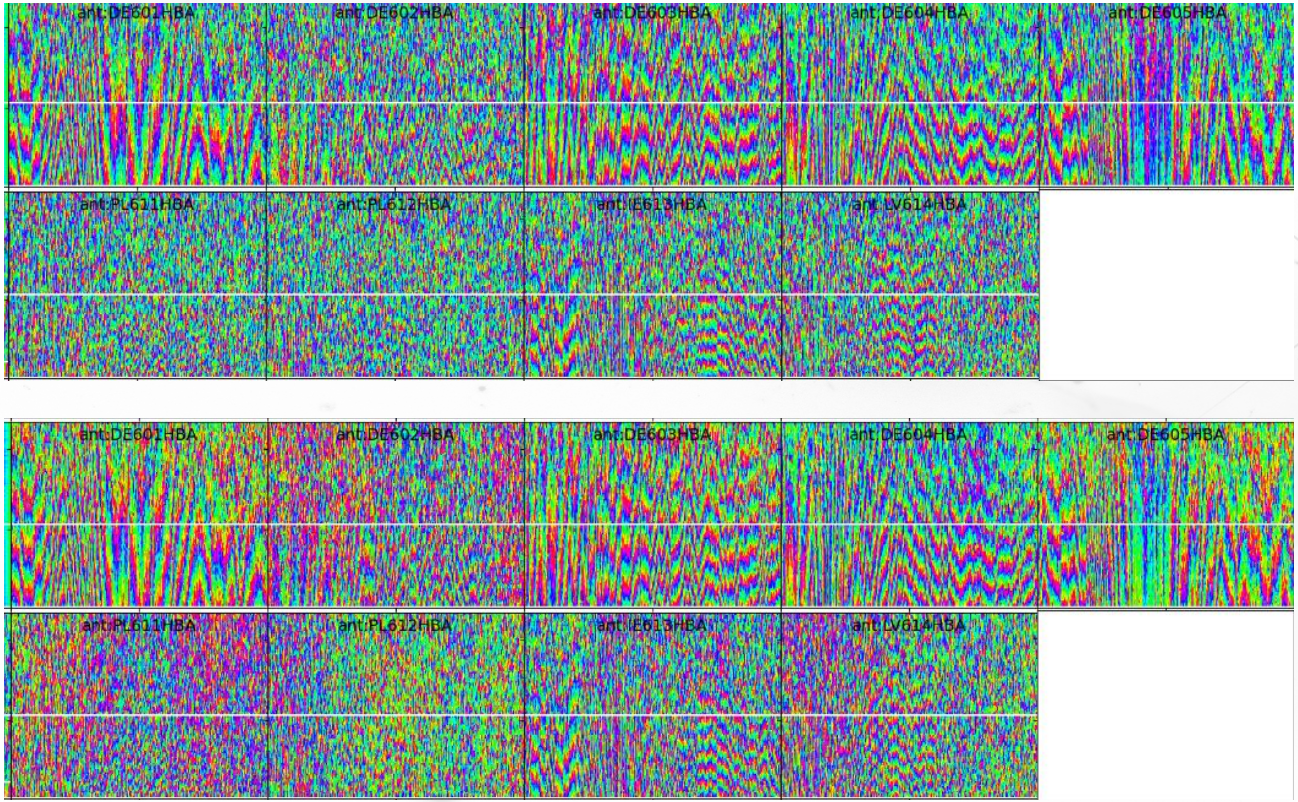
VLBI-delay calibration near galactic plane

The source is present in a crowded region of the galactic centre (zone of avoidance).



DSS2 colored image of the area near the target

Bad phase solutions of LOFAR international stations for S-shaped GRG



At this moment LOFAR-VLBI team also do not have solution to this

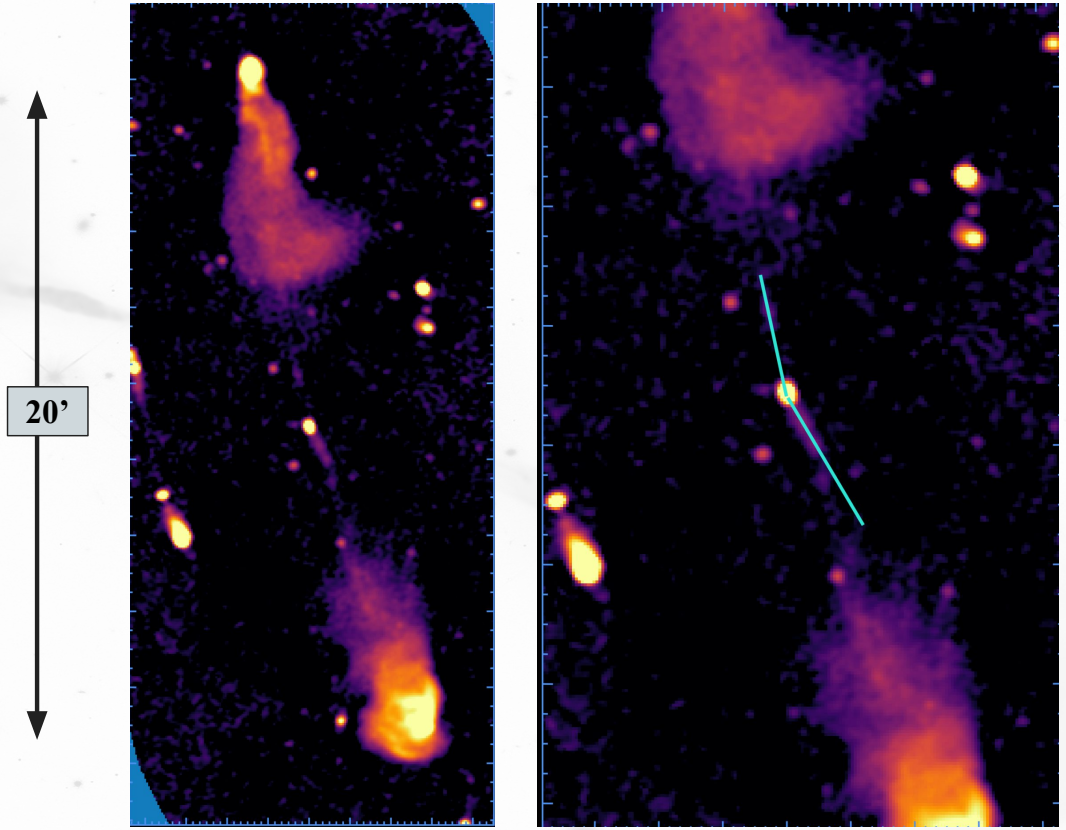
J2145+81: GRG with size 3 Mpc

J2145+81

Spec z = 0.146

Size = 20 amin

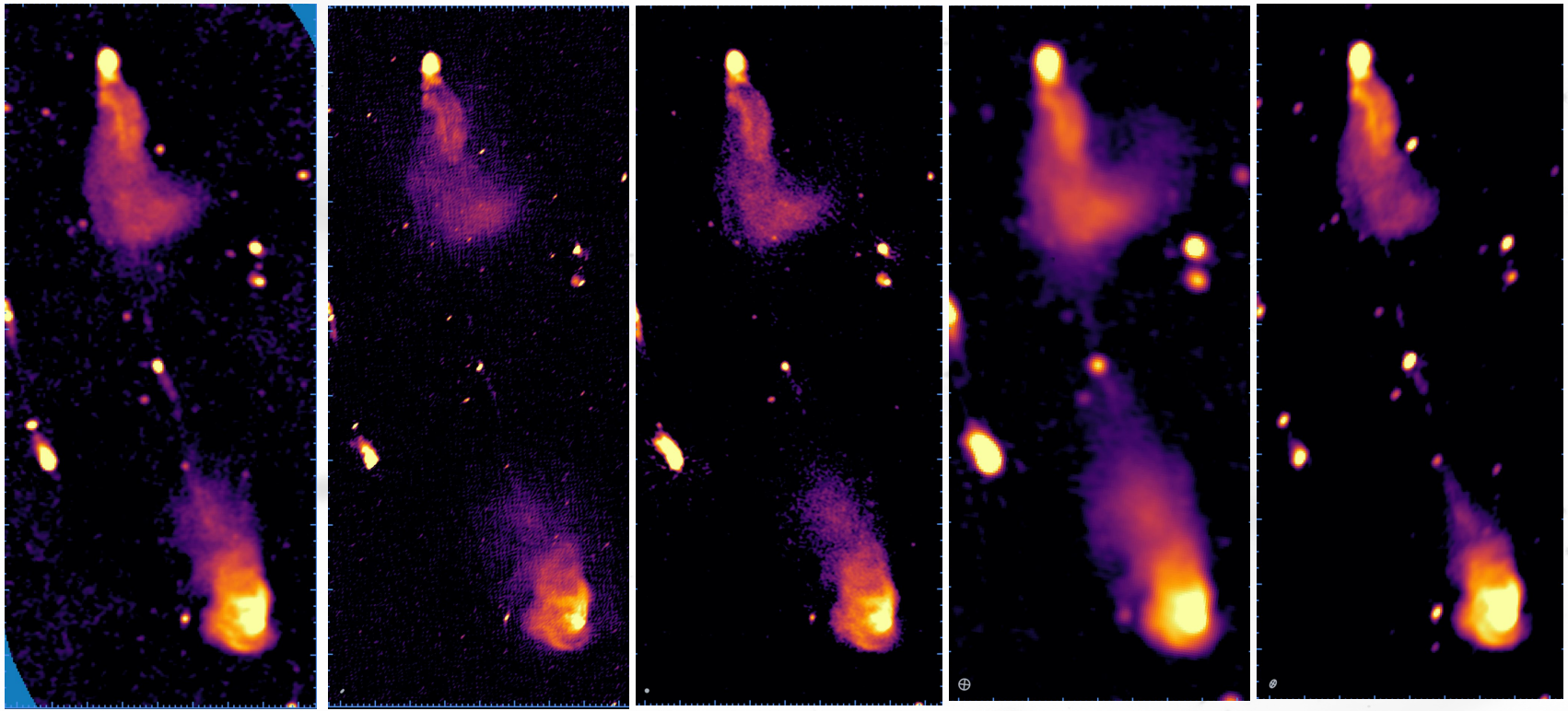
Size ~ 3Mpc



VLA1.4 GHz (Palma et. al. 2000)

Multi-frequency view of the 3-Mpc radio structure

Sethi et. al. in prep



(Palma et. al. 2000) uGMRT 650 MHz LOFAR 6” LOFAR 20” VLA 5GHz, 15”

LOFAR-VLBI data reduction

LOFAR- VLBI Observation(PI- Sagar Sethi)

- 8 hours
- Total international stations - 51
- Calibrators used during observation
  3C48 + 3C295

LOFAR-VLBI data reduction

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- Total international stations - 51
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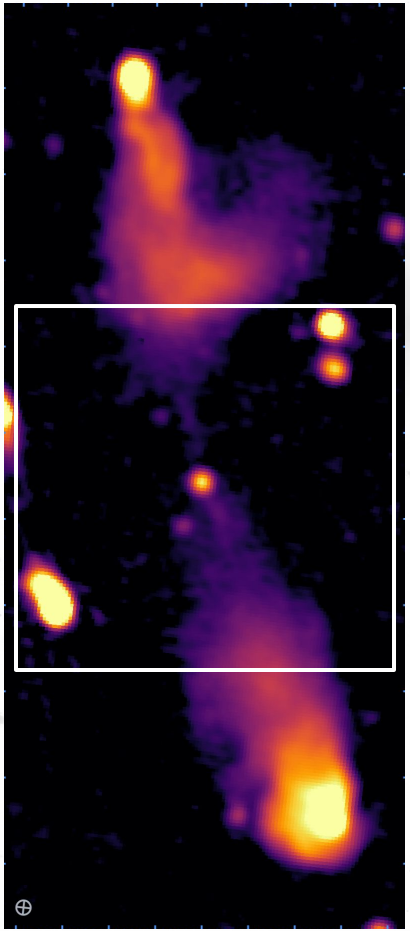
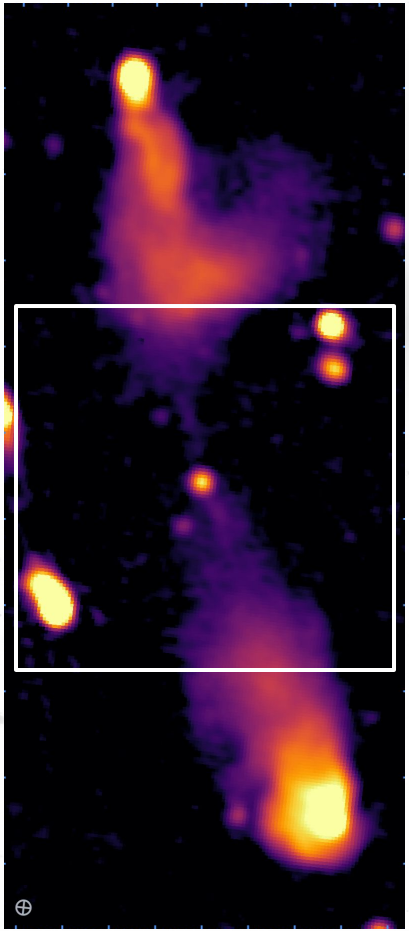
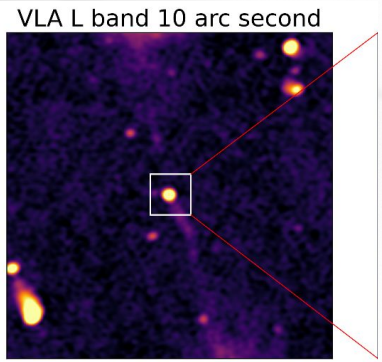
VLBI-delay calibration is successful
Phase score reliability: 97 %

LOFAR 20 asec

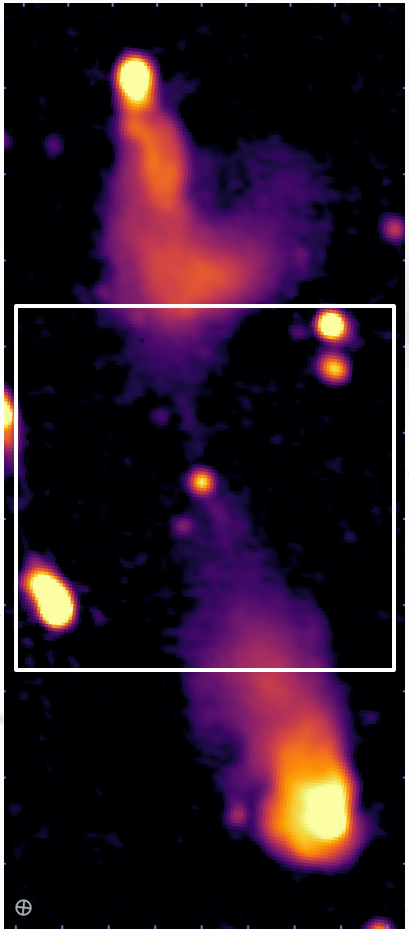


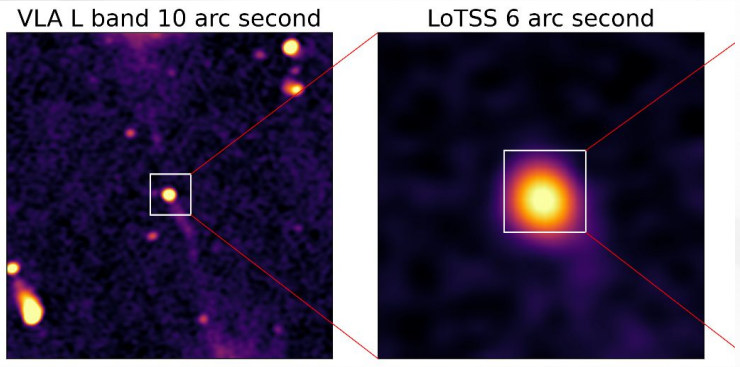
LOFAR 20 asec



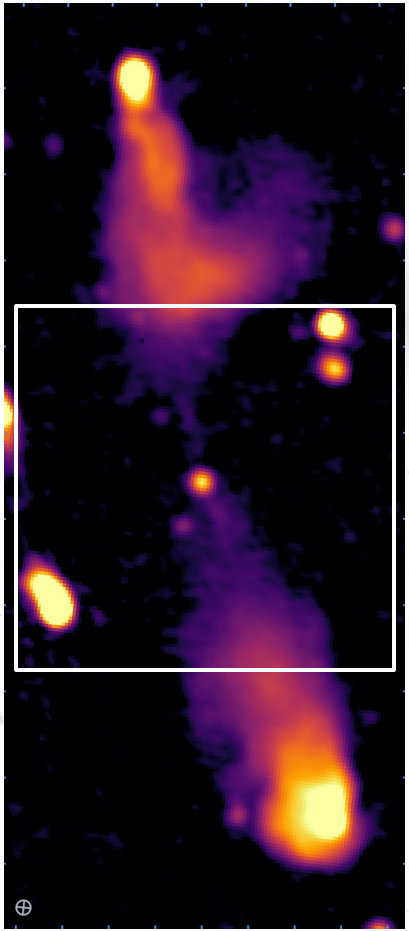


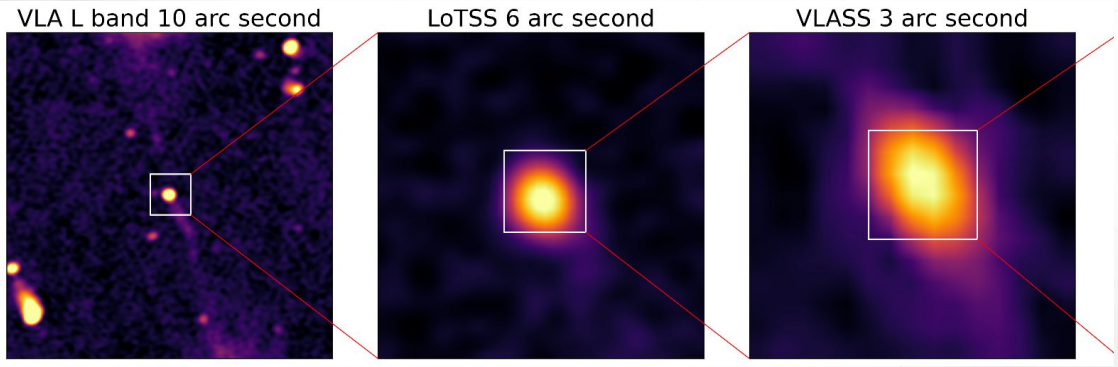
LOFAR 20 asec



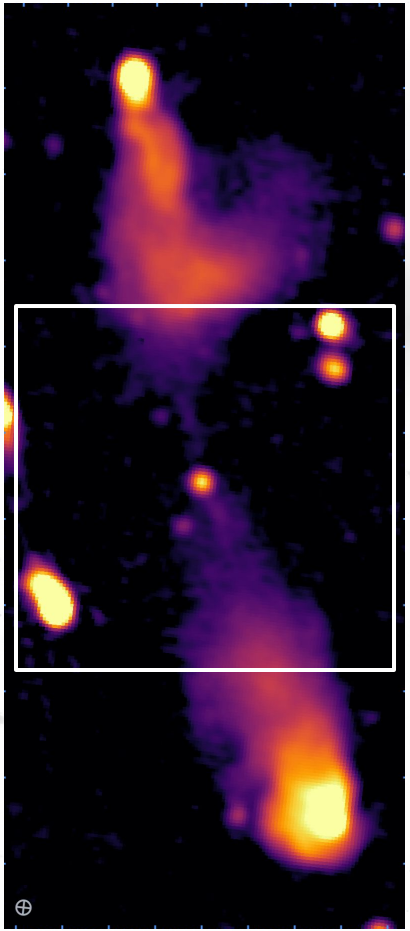


LOFAR 20 asec

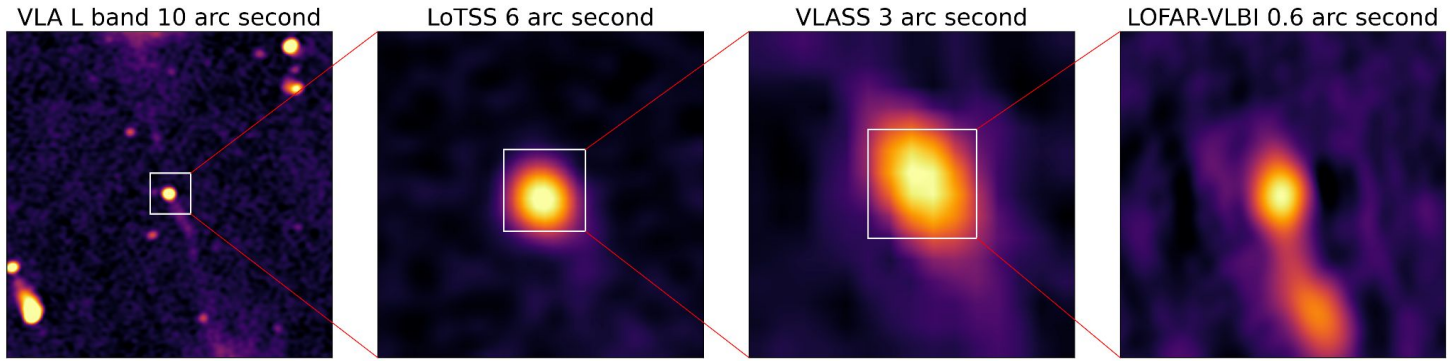




LOFAR 20 asec



The first LOFAR-VLBI image of a GRG, to our knowledge



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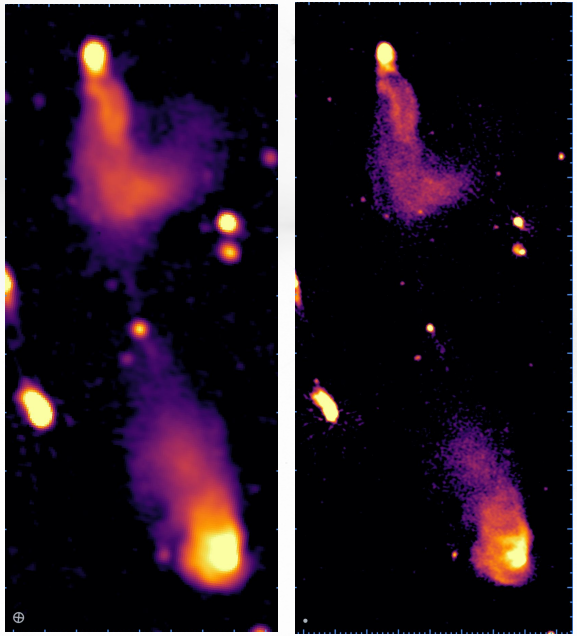
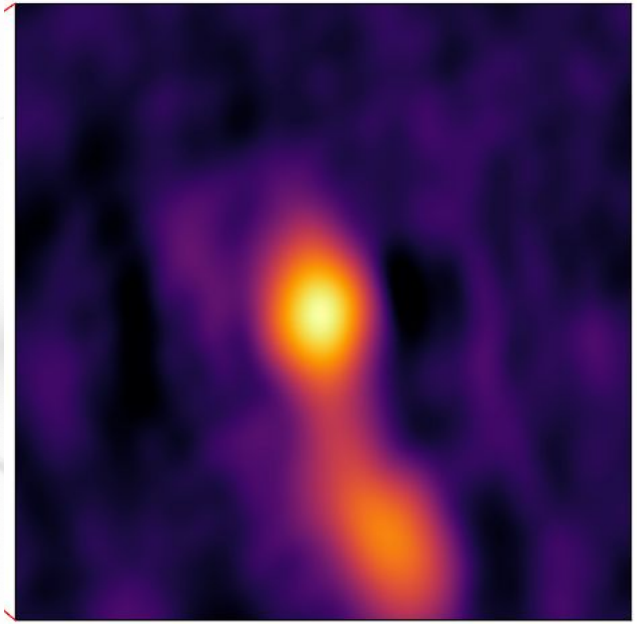
Connecting Mpc to sub-kpc scales

LOFAR 6 and 20 arcsecond images



LOFAR traces large-scale histrory

LOFAR-VLBI 0.6 arc second



LOFAR-VLBI reveals compact central structure

Together they connect the current compact sub-kpc scale jet to long-term history recorded by Mpc scale jet for this GRG.

Future directions

- Complete LOFAR-VLBI calibration of J0644+1043
- Sub-arcsecond VLA C-band imaging of J2145+8154
- Extend the analysis to a well-selected GRG sample
- Constrain jet recurrence and duty cycles
- Develop wide-field LOFAR-VLBI imaging

Final scientific takeaway

From Mpc to sub-kpc: connecting the history and present activity of SMBH jets

LOFAR → large-scale radio history

LOFAR-VLBI → compact jet/core

Together → a view of SMBH jet activity across scales

Thank you

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