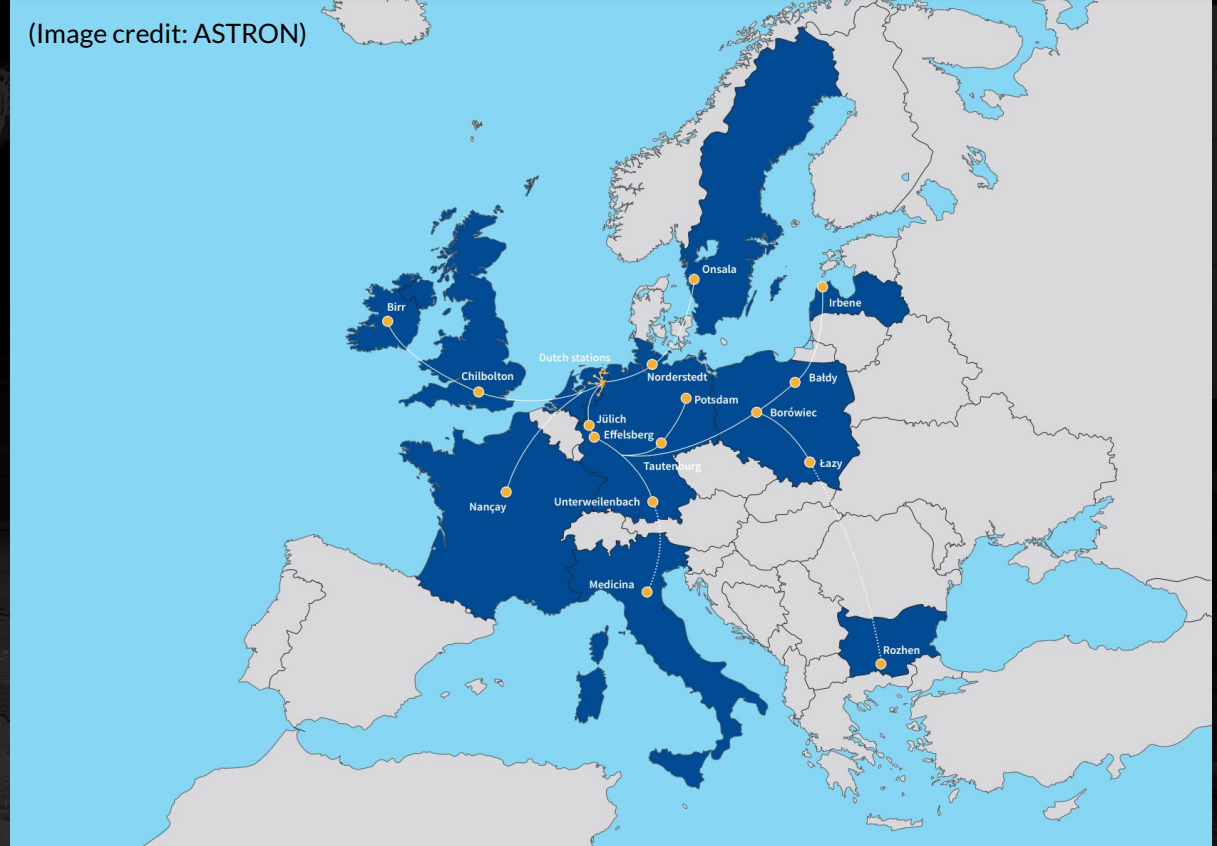

Low-frequency VLBI with the International LOFAR Telescope



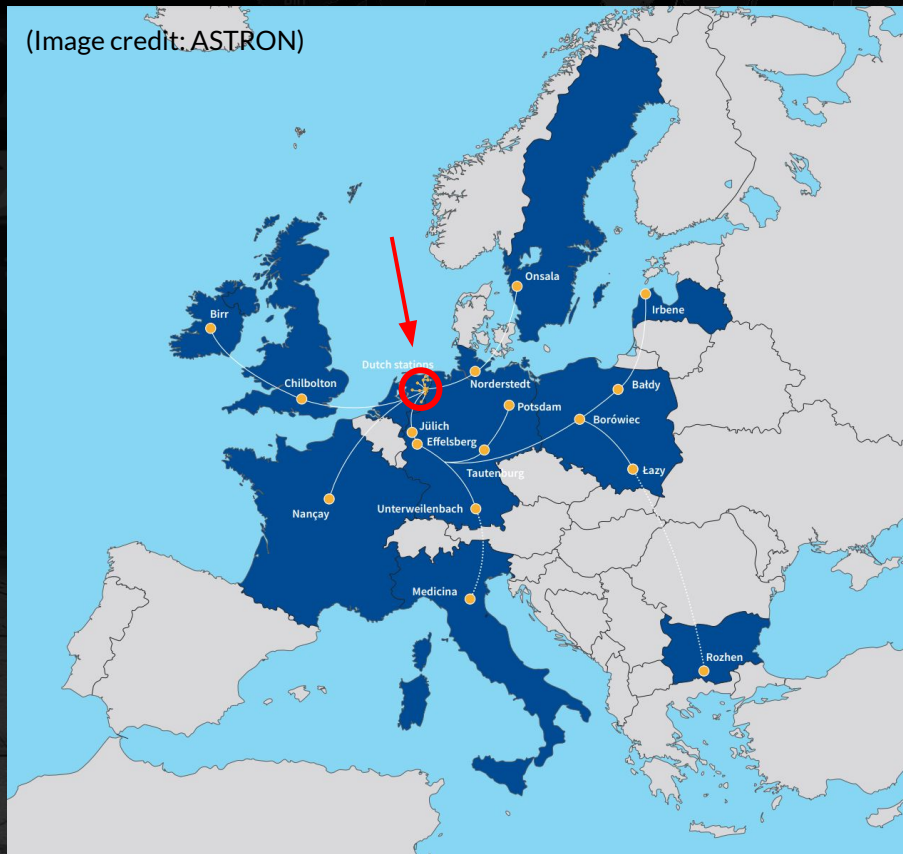
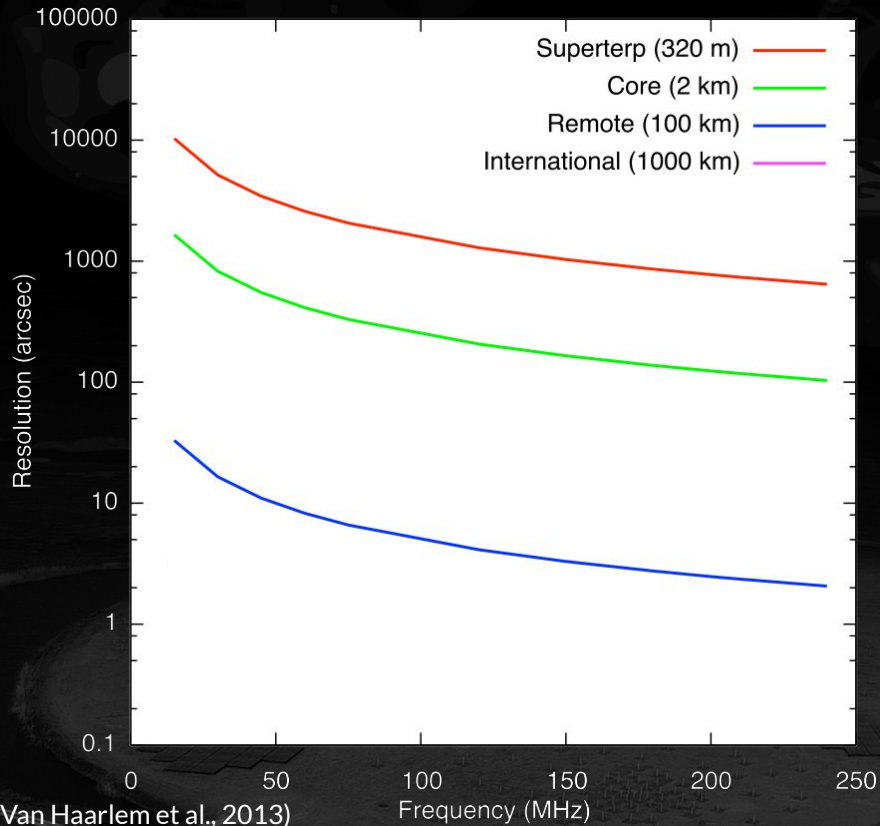
Durham
University

The International LOFAR Telescope

- Low-frequency phased array
 - LBA: 10-90 MHz
 - HBA: 110-240 MHz
- Baselines from 68 m to ~1890 km (soon even more!)
- Total of **52** stations
- Multi-beam observing capabilities
- Wide field of view (several deg²)
- Sky coverage: above Dec. 0°
- LOFAR 2.0 upgrade incoming!
 - Expansion to **Italy** and **Bulgaria**

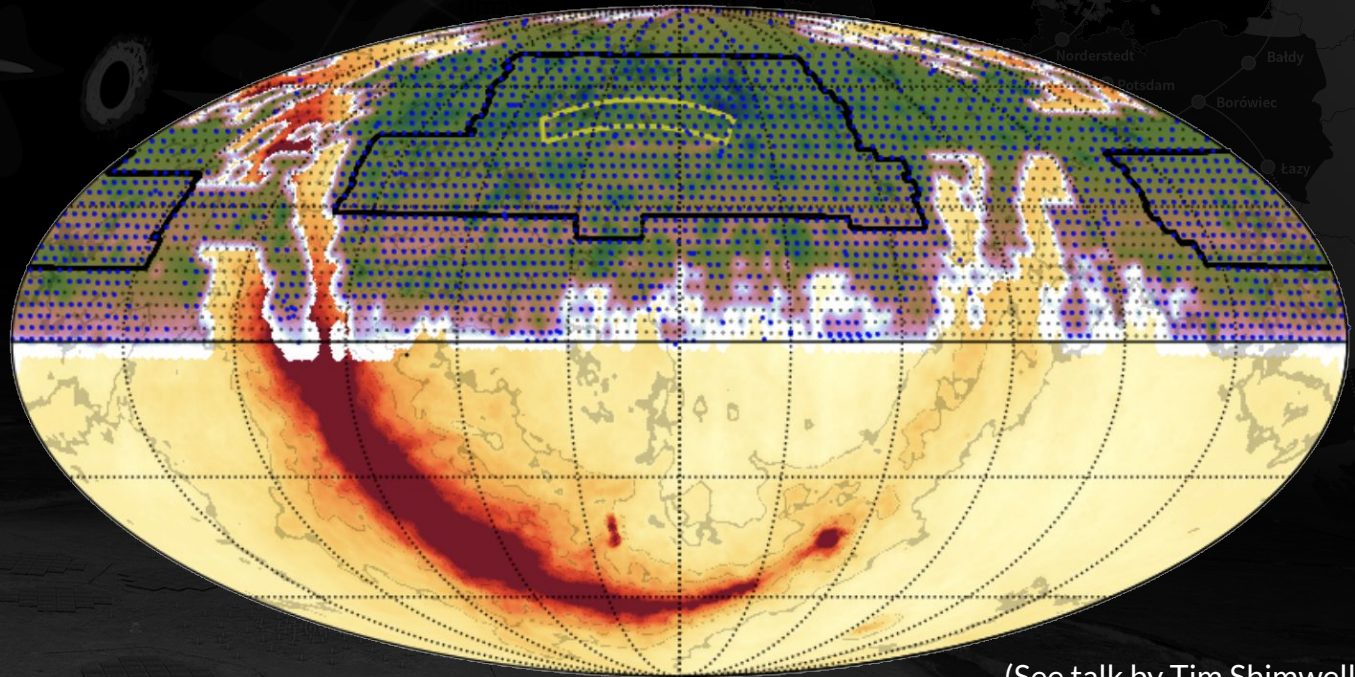


The International LOFAR Telescope



LoTSS: The LOFAR Two-Metre Sky Survey

- 15,000 hours (currently)
- 2013 - Present
- Primarily Northern sky
- 20 PB of data
- 120-168 MHz
- 6" angular resolution
- 80 μ Jy/beam sensitivity
- 10 million sources (92% unresolved)
- International stations recorded but not processed



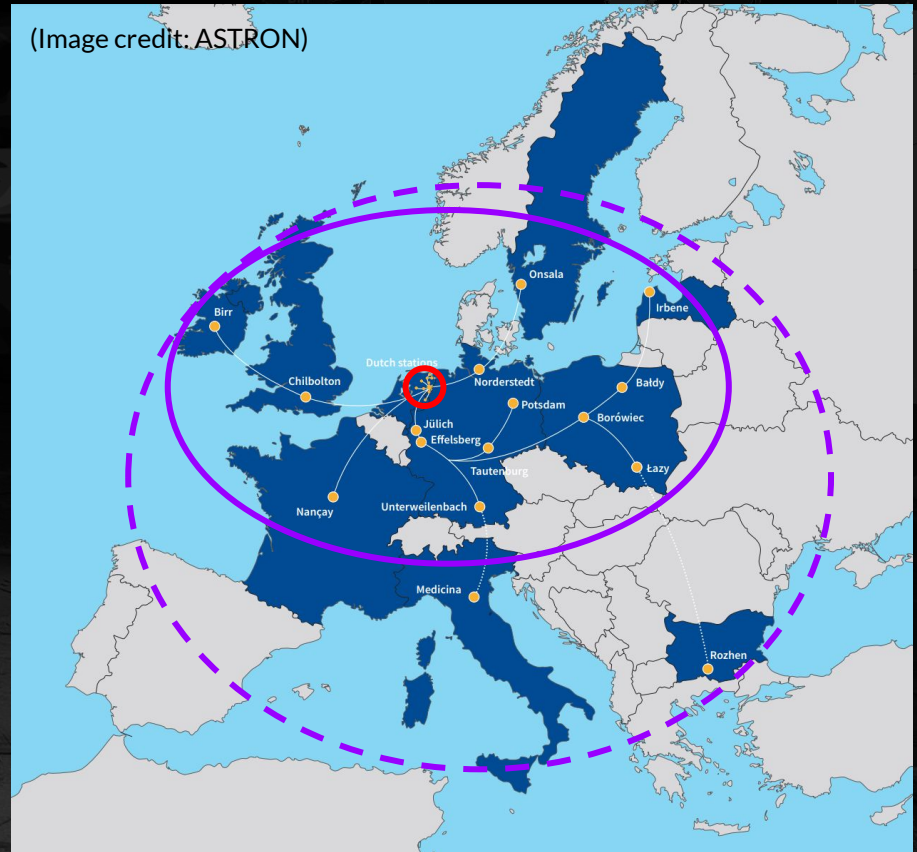
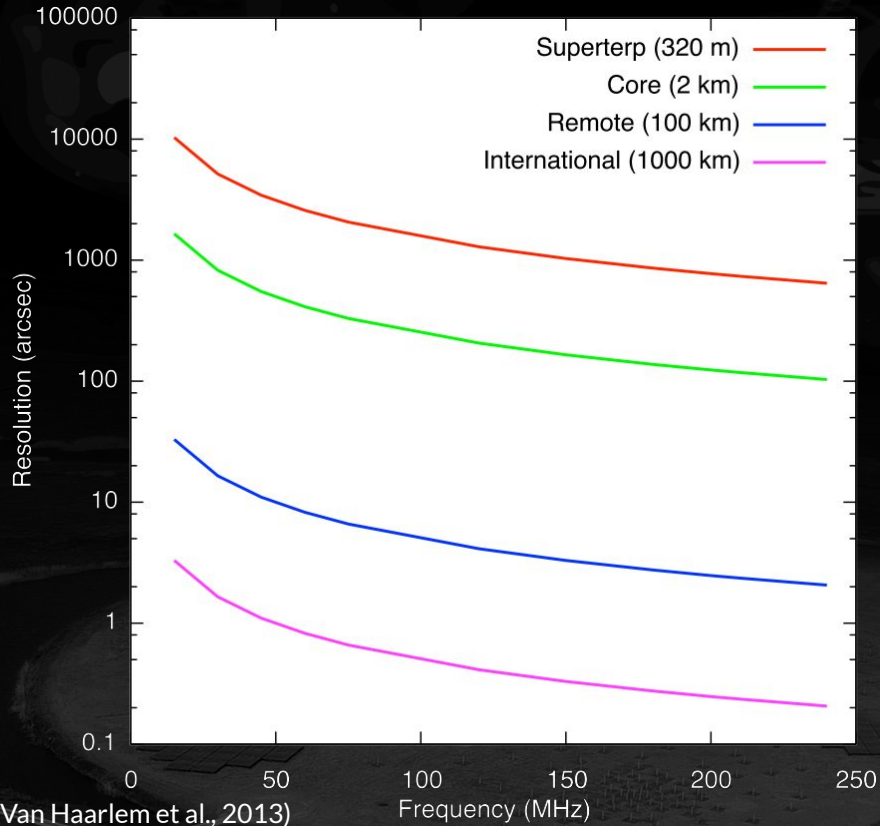
(See talk by Tim Shimwell)

0.04

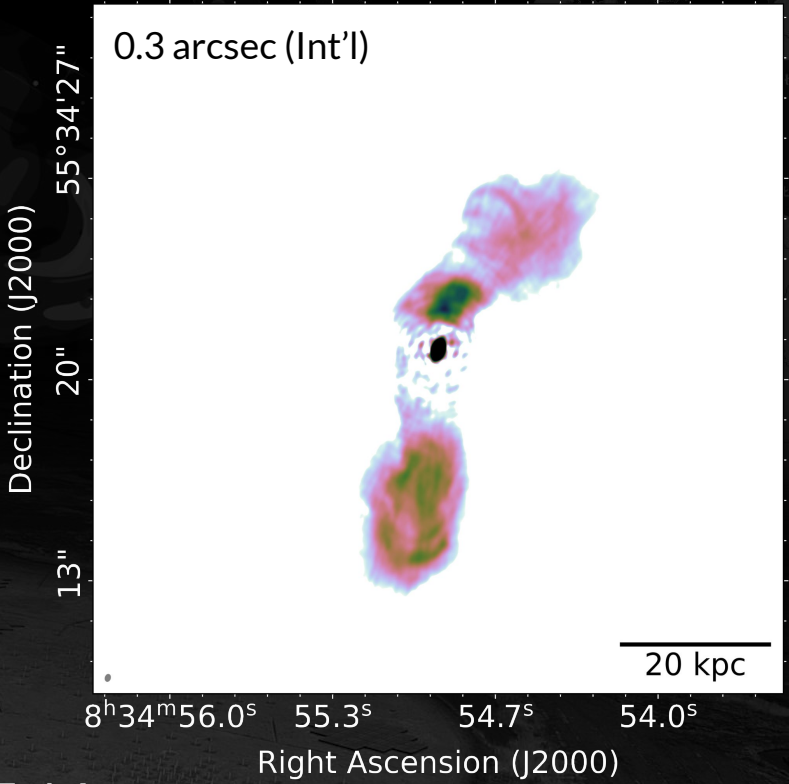
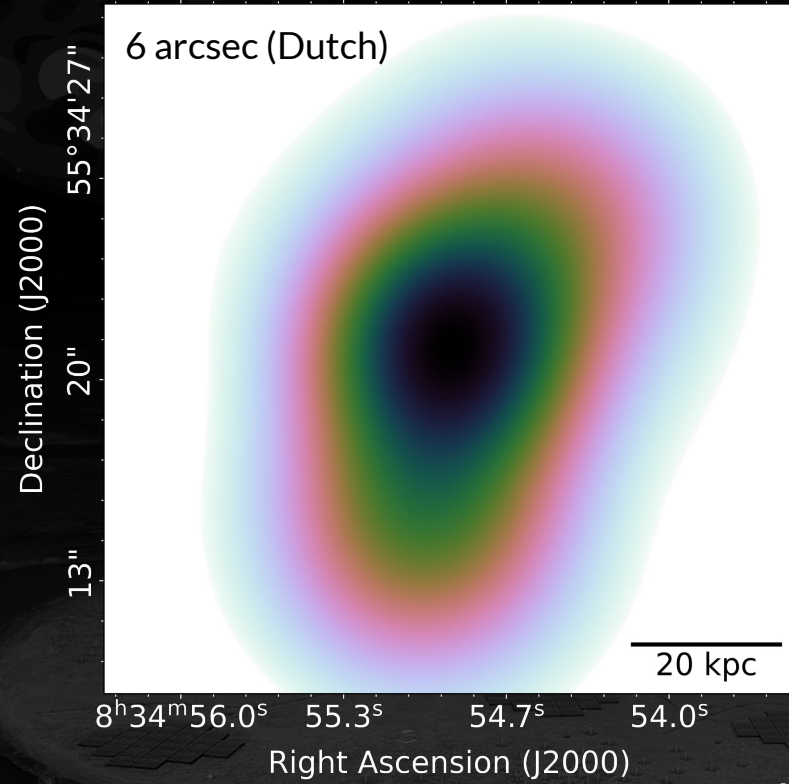
mJy/beam

0.15

The International LOFAR Telescope

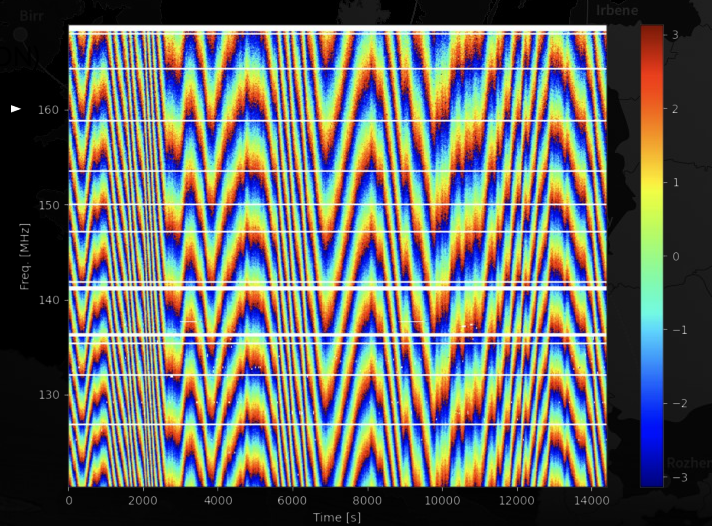
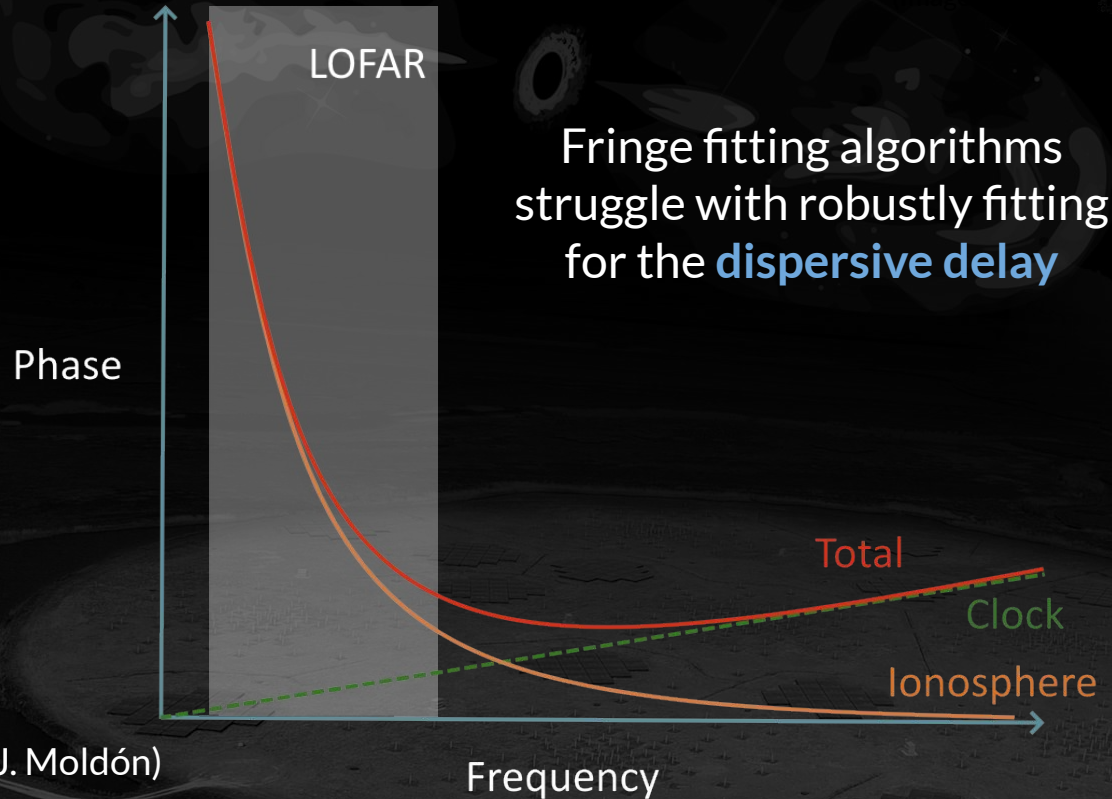


High-resolution imaging at low frequencies



4C+55.16

Calibration challenges



Dispersive delays can reach **$\sim 1 \mu\text{s}$** in LOFAR's LBA and are strongly **direction-dependent!**

(J. Moldón)

Calibration challenges

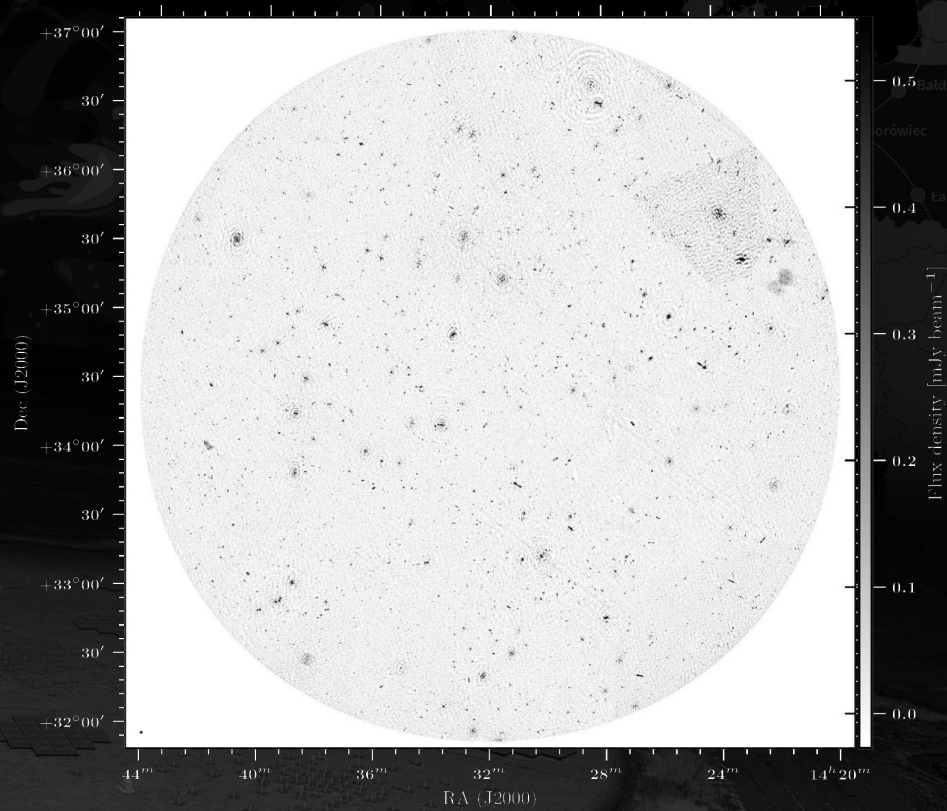
Large field of view of several degrees
(depending on the station type)

→ Field of view contains **several thousand sources** at all times

→ Isolating the source and any calibration source is difficult

Interference from “**A-team**” sources
up to 30 degrees away:

Cas A, Cyg A, Herc A, Vir A, Tau A



(Retana-Montenegro et al., 2018)

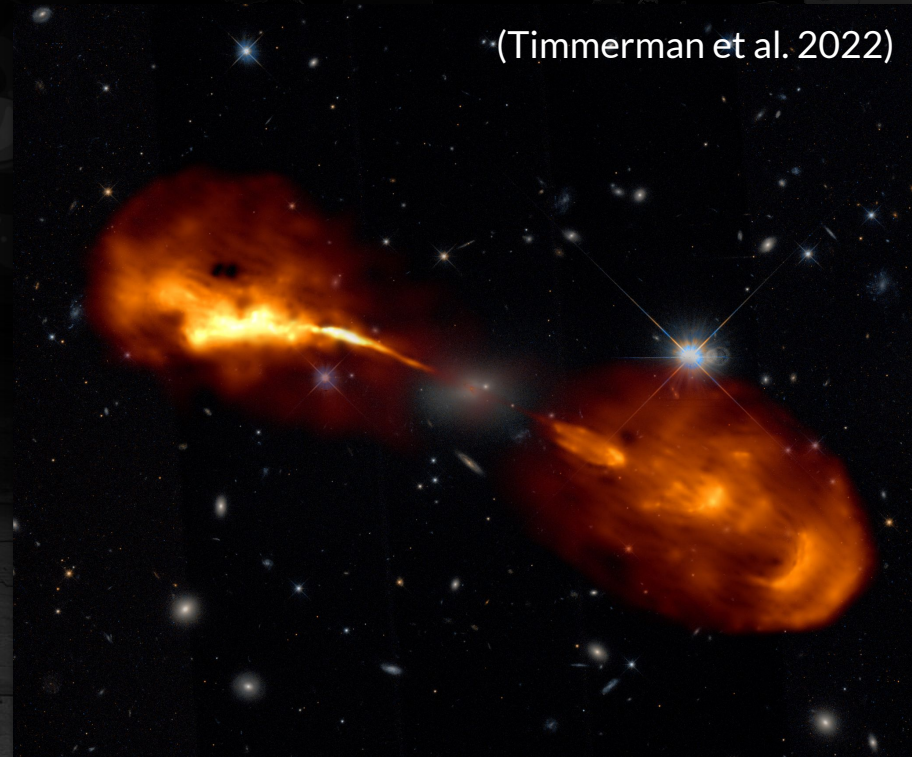
Calibration challenges

Sources tend to show **complex source structure** at low frequencies

High sensitivity to **steep-spectrum emission** such as found in radio jets and lobes, haloes and SFR

→ Only few sources are both **bright** and **compact** at 0.3'' angular resolution at low radio frequencies

→ Finding a suitable calibrator source near the science target can be difficult



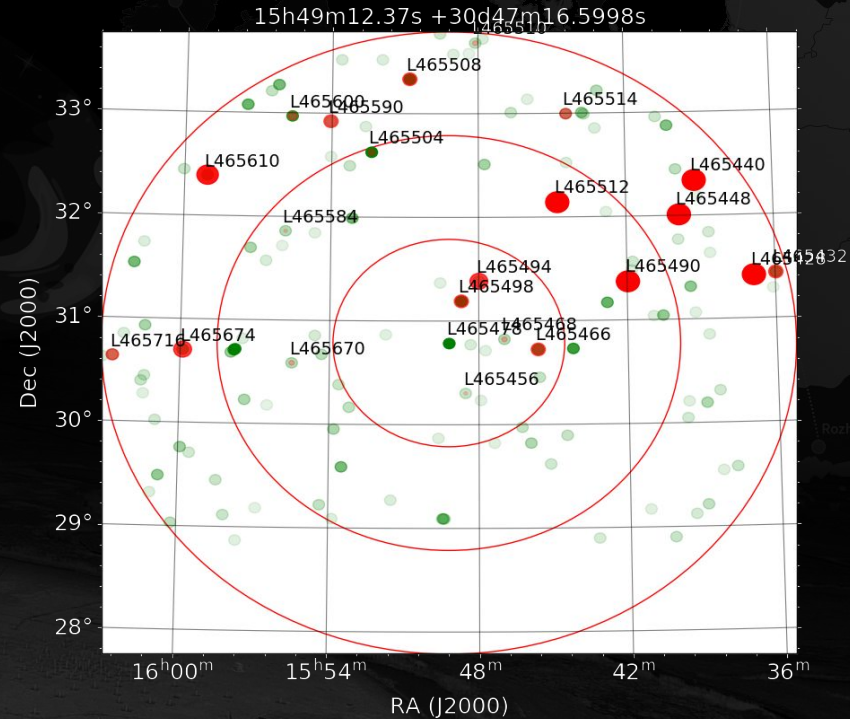
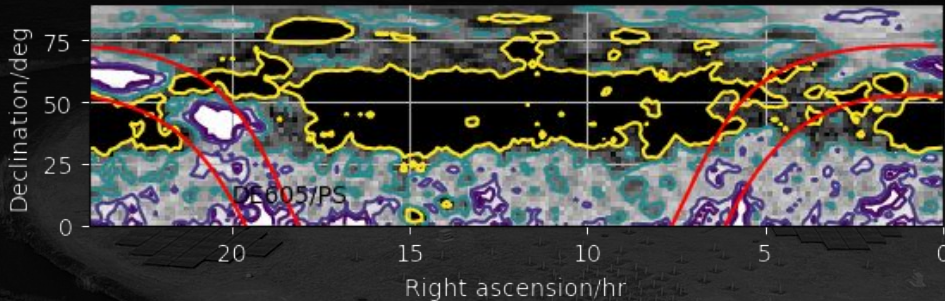
(Timmerman et al. 2022)

The Long Baseline Calibrator Survey

Most low-frequency radio sources show **complex source structure**

LBCS catalog provides list of known **bright** and **compact** sources for calibration

→ Approximately **24000** sources detected (average ~1 per square degree)

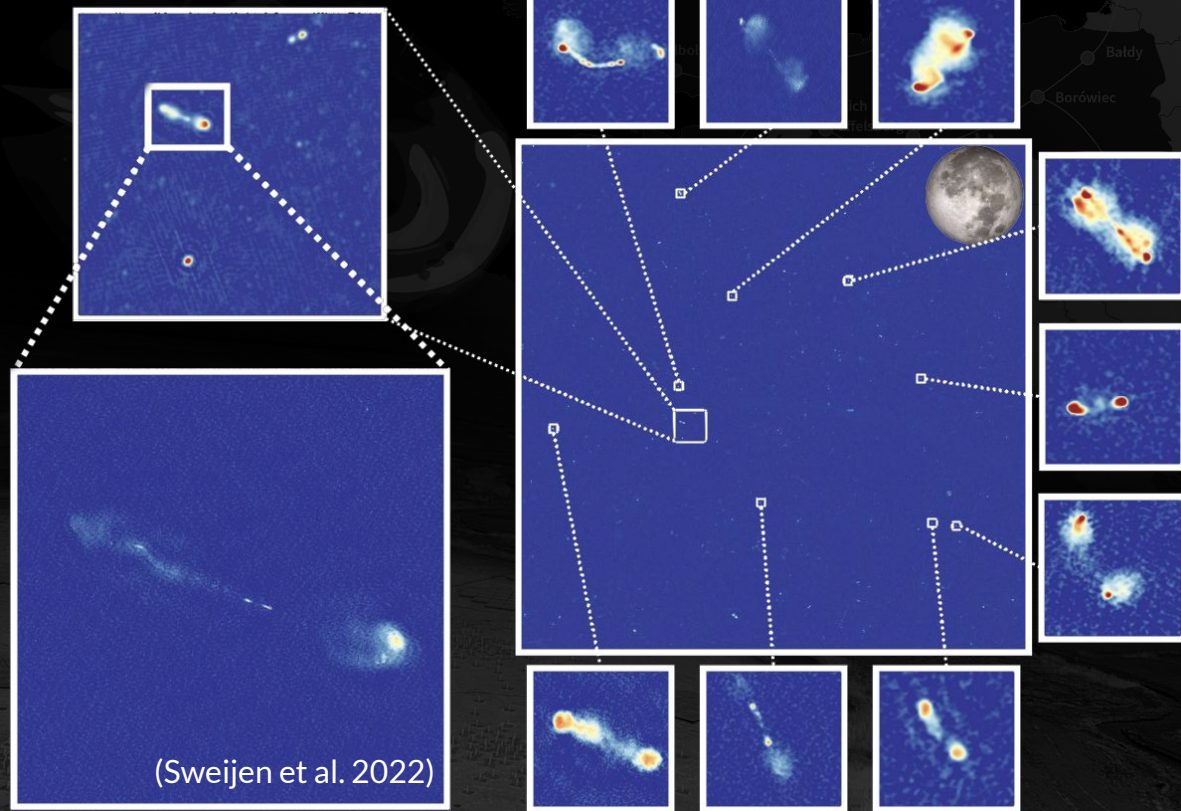


(Jackson et al., 2022)

High-resolution imaging at low frequencies

From postage stamp images to wide fields

- Single 8-hour pointing
- 6.6 deg^2 area map at 144 MHz
- $0.38'' \times 0.30''$ angular resolution
- 2483(!) sources detected
- **7 billion pixels**
- **250,000 CPU hours**



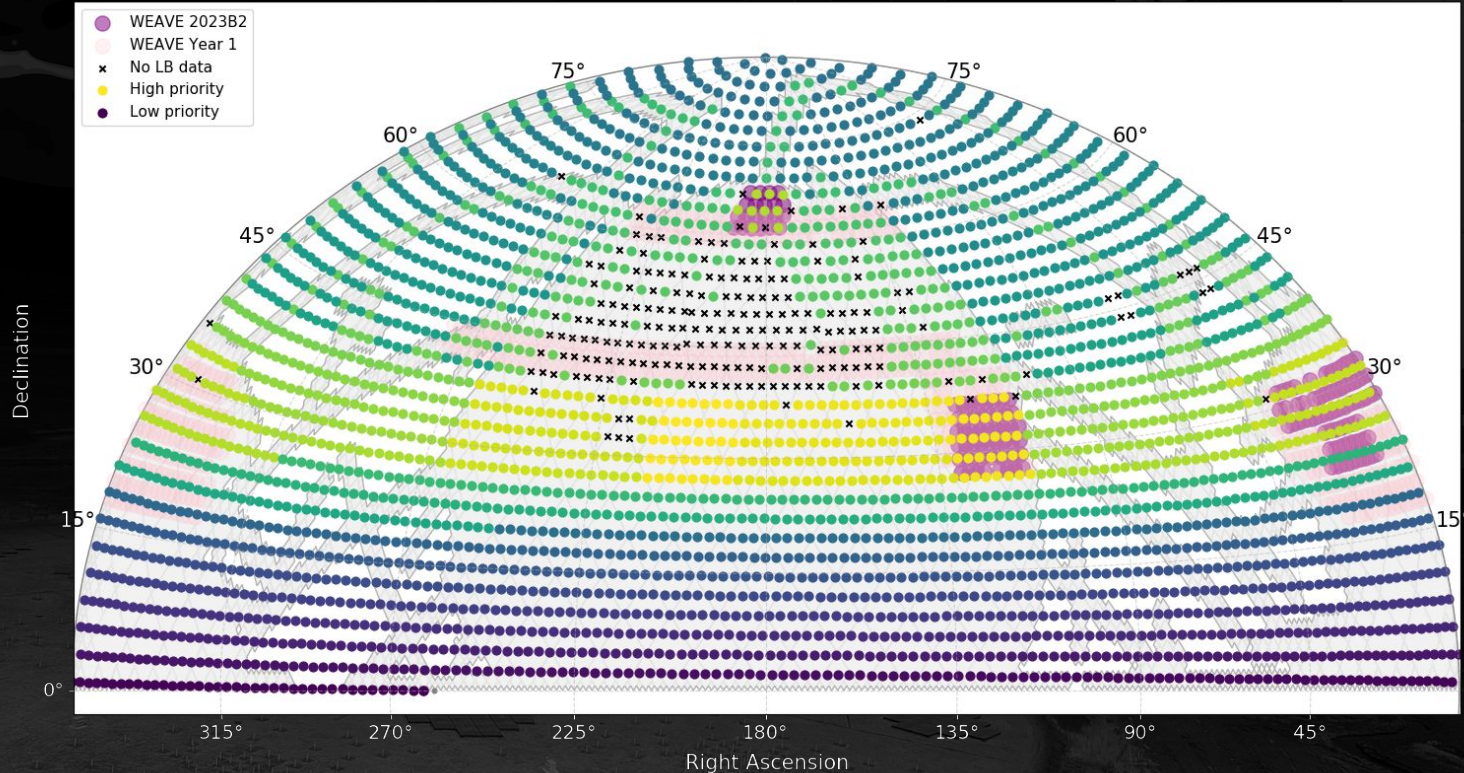
LoTSS-HR: The High Resolution LoTSS

Reprocessing all of LoTSS using the full international array

Postage stamp imaging of all sources >10 mJy in the field of view (~100 sources per field)

Both 0.3" and 1.2" imaging products to be published

Data products stored for possible widefield follow-up



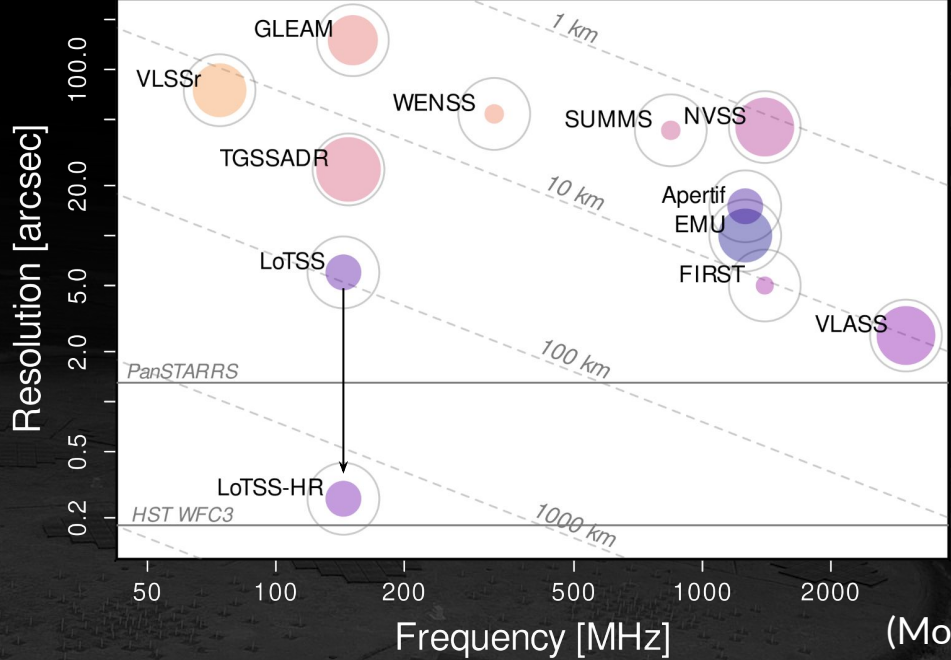
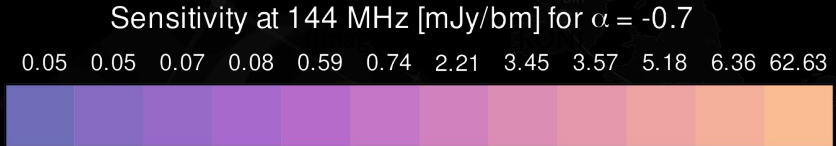
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Sky coverage



(Morabito et al., 2022)

The upgrade: LOFAR 2.0

Expansion of the array to Italy and Bulgaria!

All Dutch stations on the same **clock** (<100 ps error)

Upgraded correlator (COBALT 2.0)

→ **Simultaneous LBA & HBA** observations

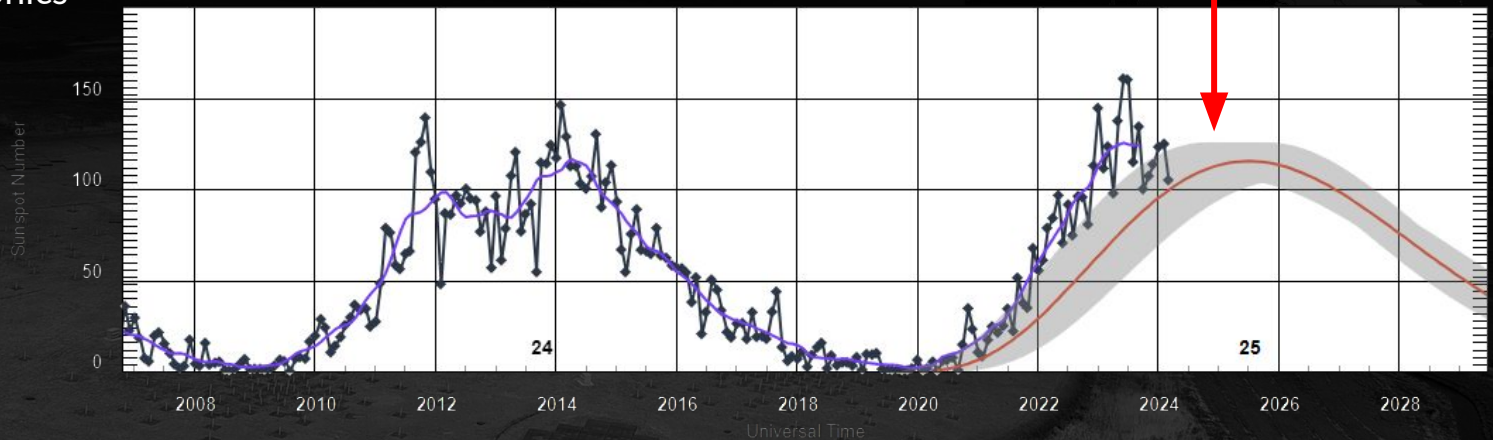
Reduced **RFI** environment

Upgraded electronics

Much more!



LOFAR upgrade time
(now)



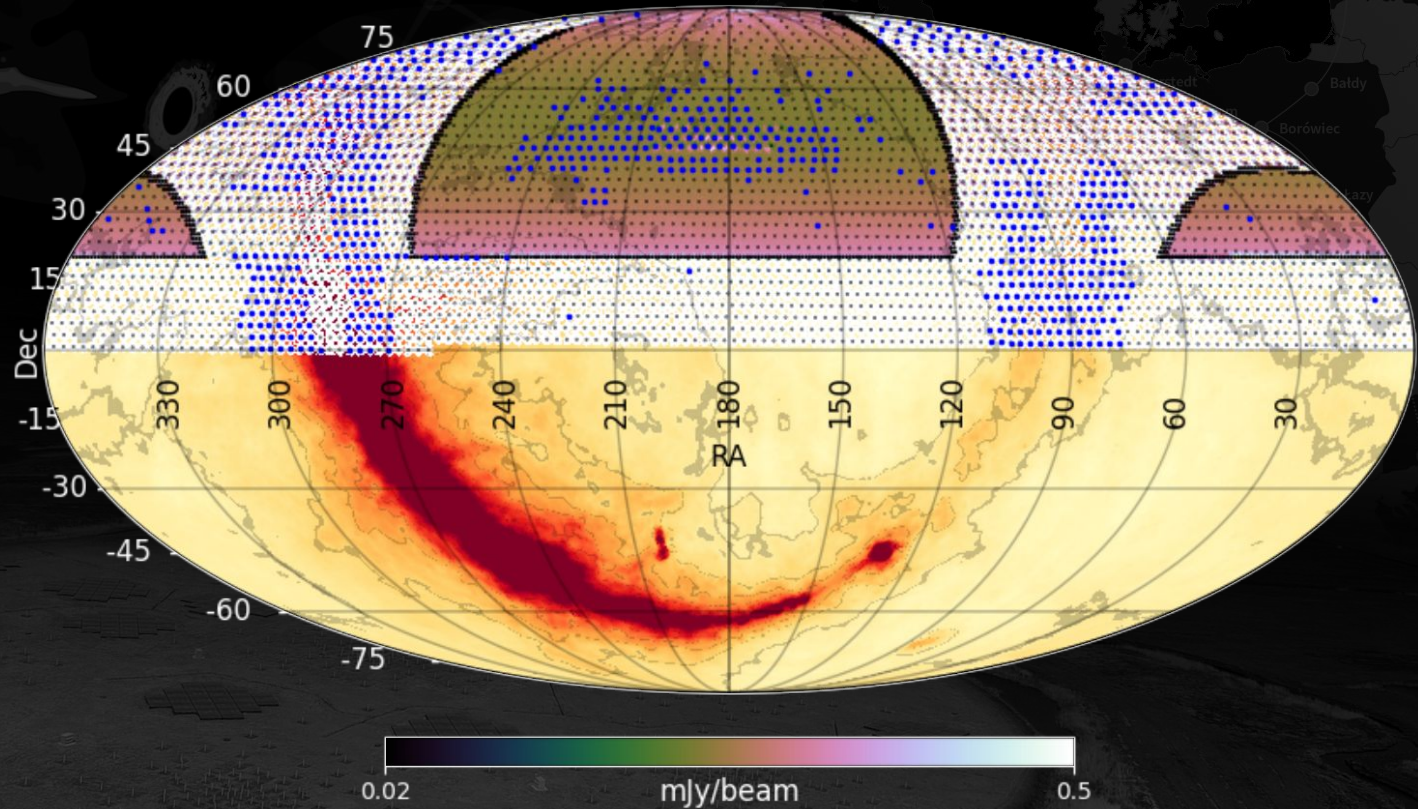
iLoTSS: International LoTSS

(See talk by Tim Shimwell later)

Follow-up of the
LoTSS survey in the
LOFAR2.0 era
including the **int'l**
stations

Aims to cover the
northern
extragalactic sky

Increase the density
of pointings
compared to LoTSS to
fill in the gaps



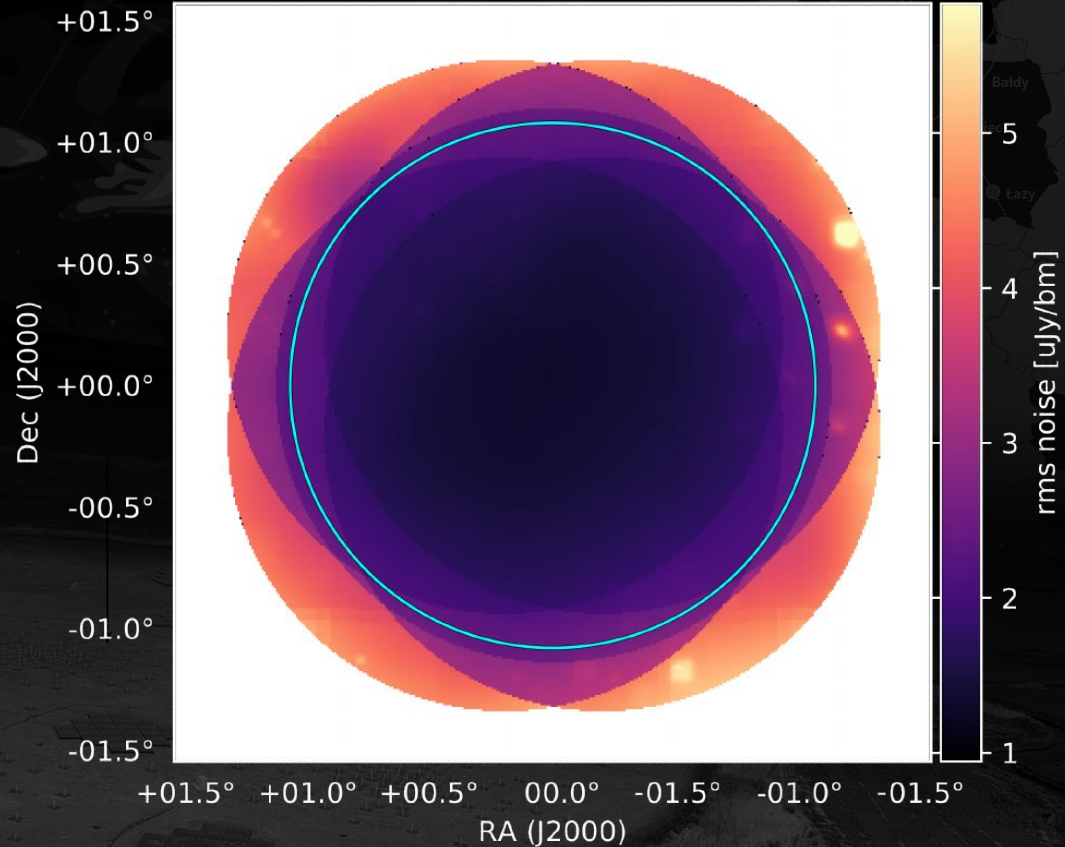
LUDO: LOFAR2.0 Ultra Deep Observation

Single deep field using the **LOFAR2.0** HBA system, including the **int'l** stations

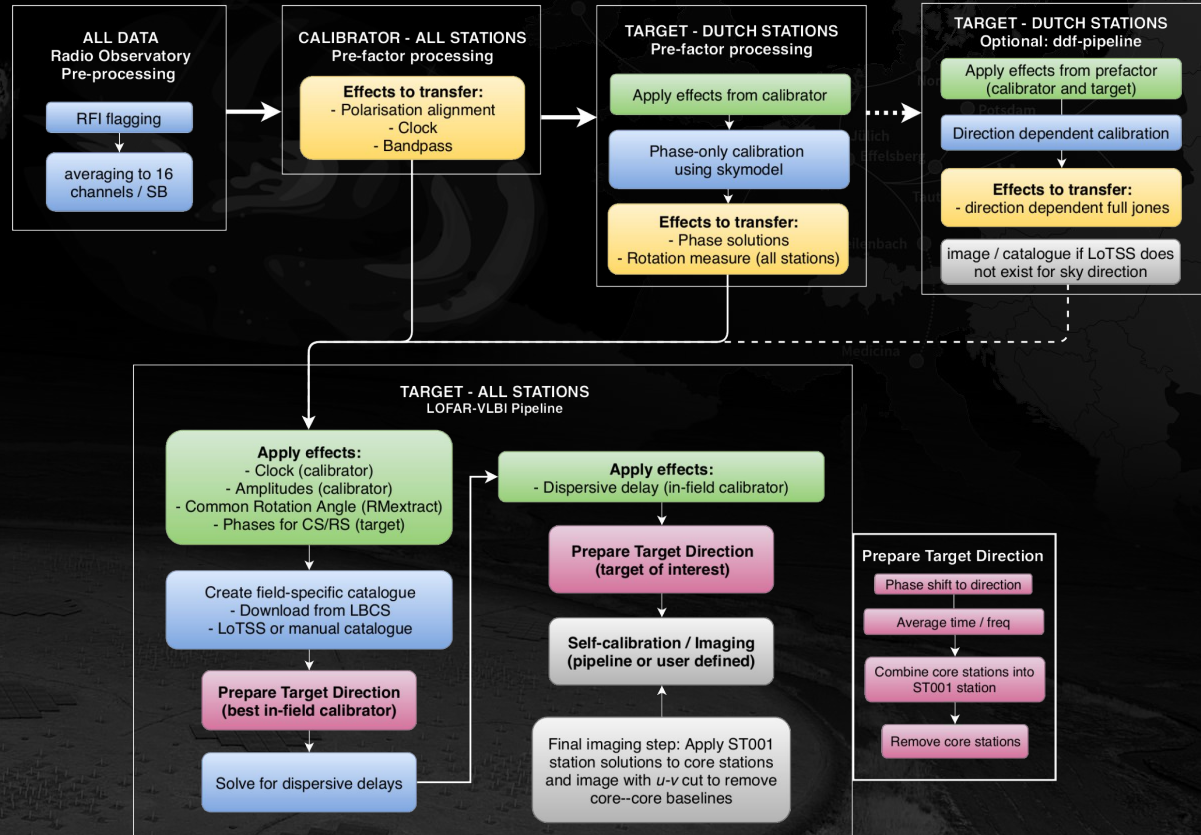
Aims to probe the **Euclid Deep Field North** and reach a noise level of only **2 $\mu\text{Jy}/\text{beam}$** at **0.3''**

Full **widefield** imaging

Estimated detection of **$\sim 75,000$** sources per deg^2

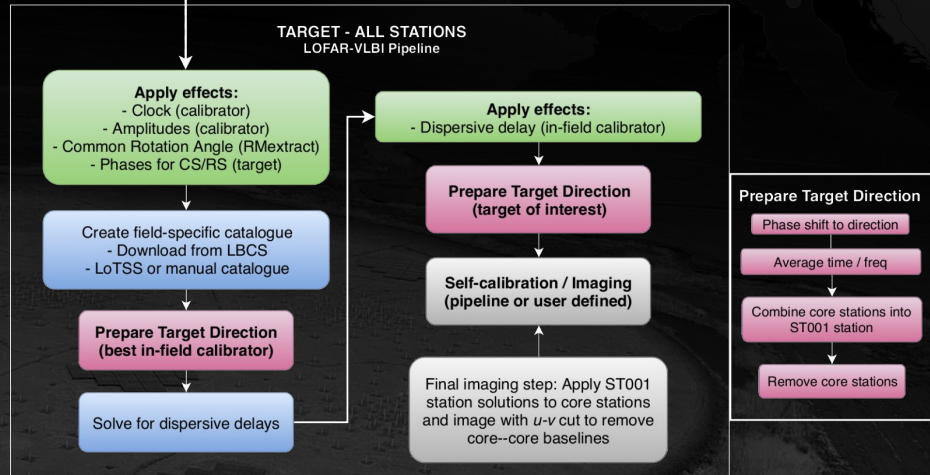
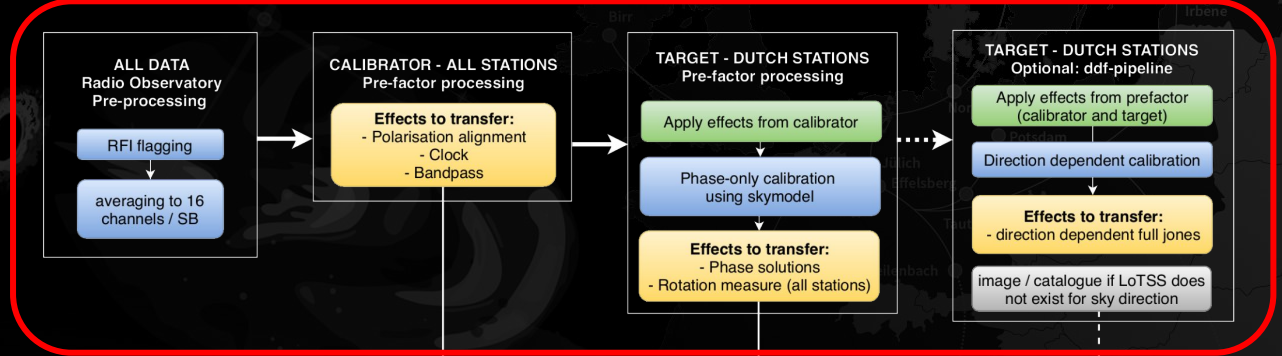


The LOFAR-VLBI pipeline



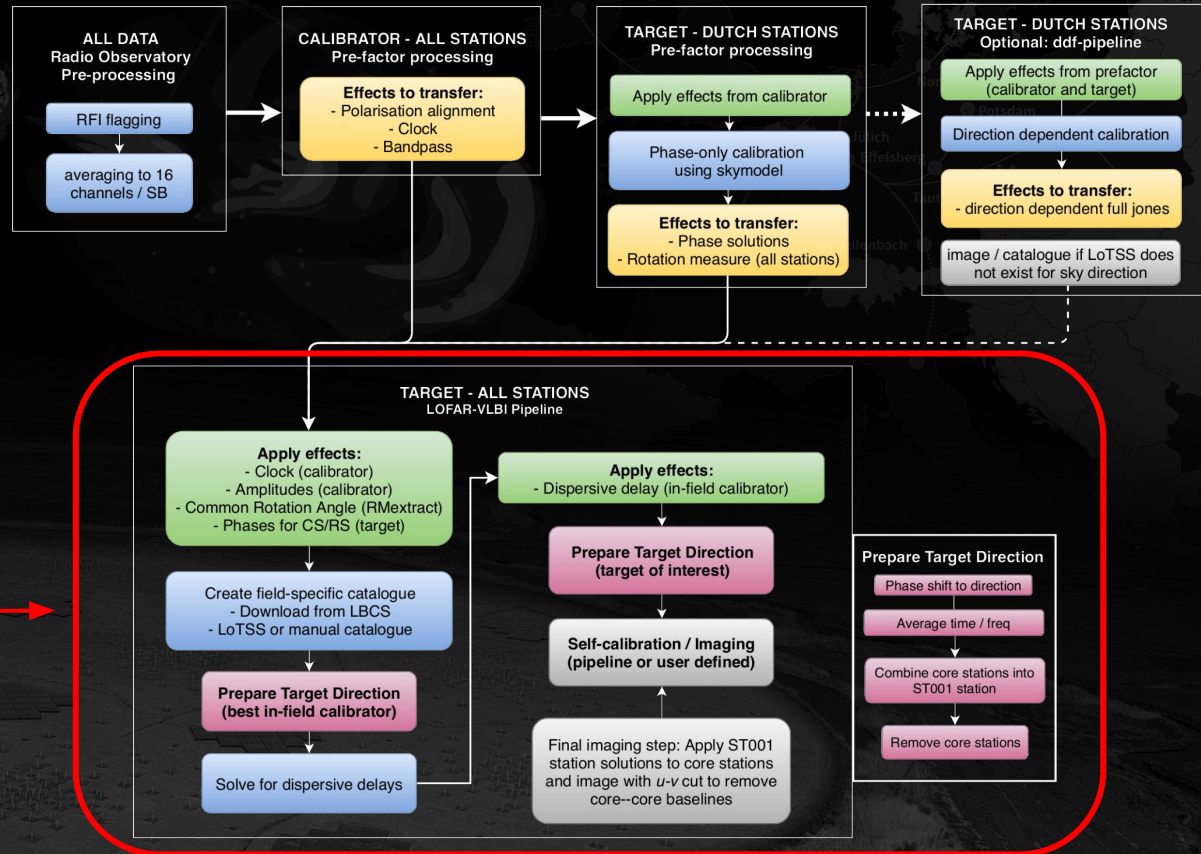
The LOFAR-VLBI pipeline

Standard Dutch
array processing



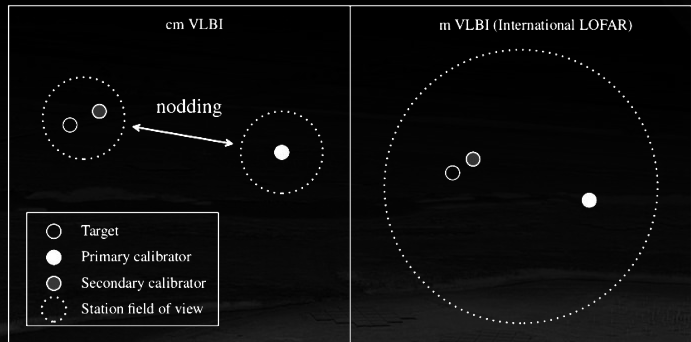
The LOFAR-VLBI pipeline

LOFAR-VLBI Pipeline →

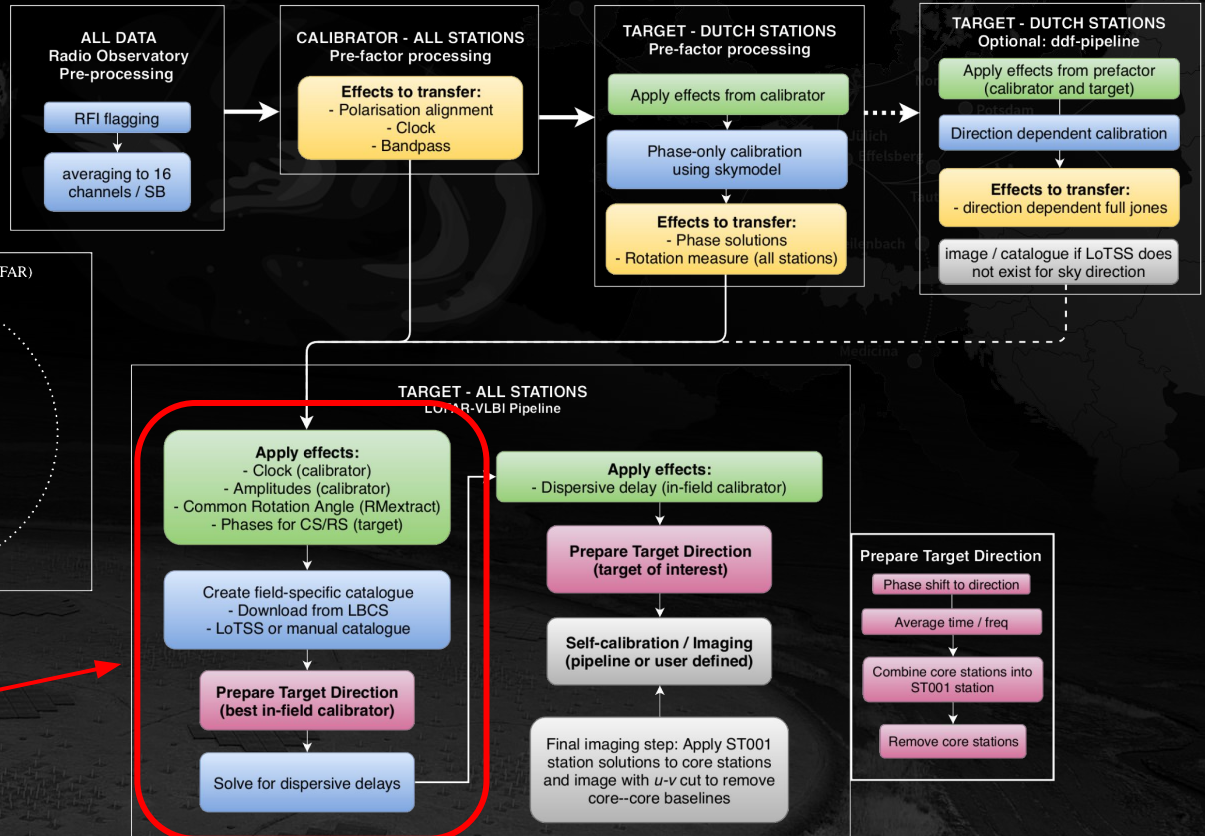


The LOFAR-VLBI pipeline

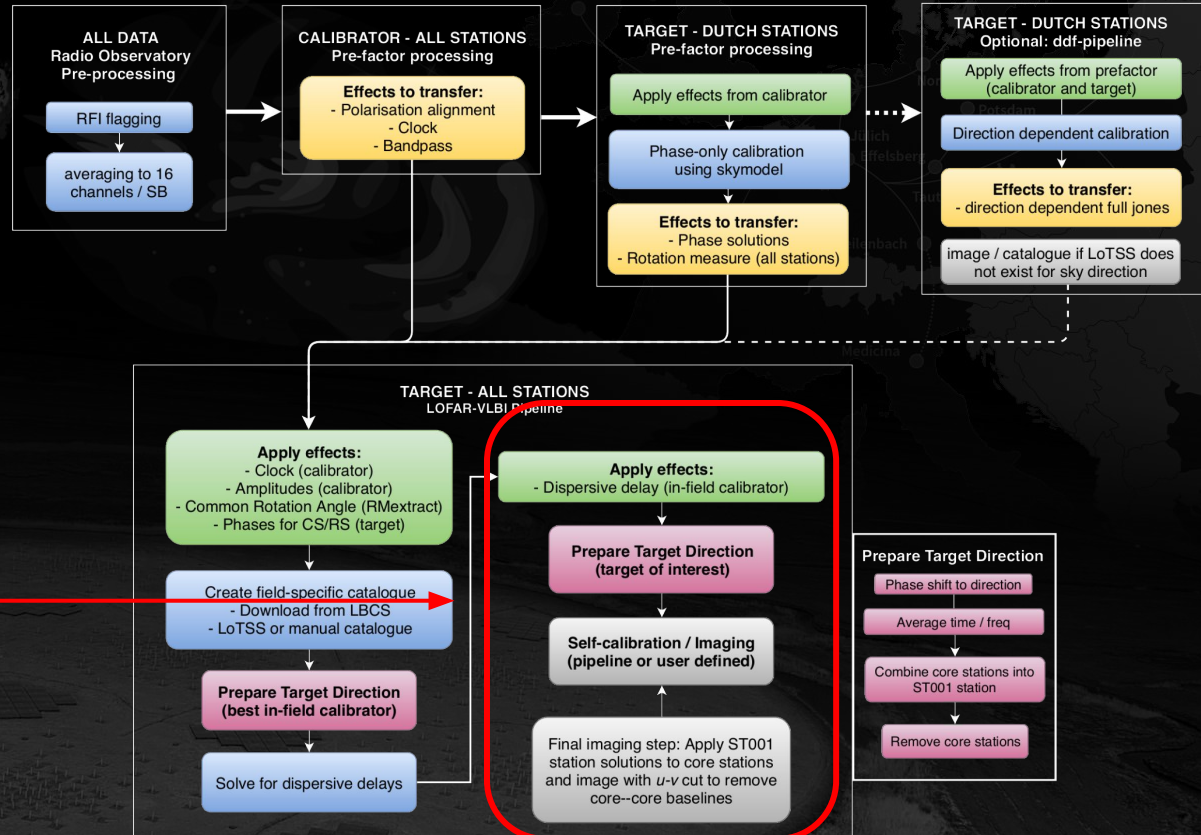
(J. Moldon)



Solve for dispersive delays using in-field calibrator source



The LOFAR-VLBI pipeline



Apply solutions and perform final self-calibration on target

Science with LOFAR-VLBI

VLBI at the LFM: 2022: **3** talks

2023: **7** talks

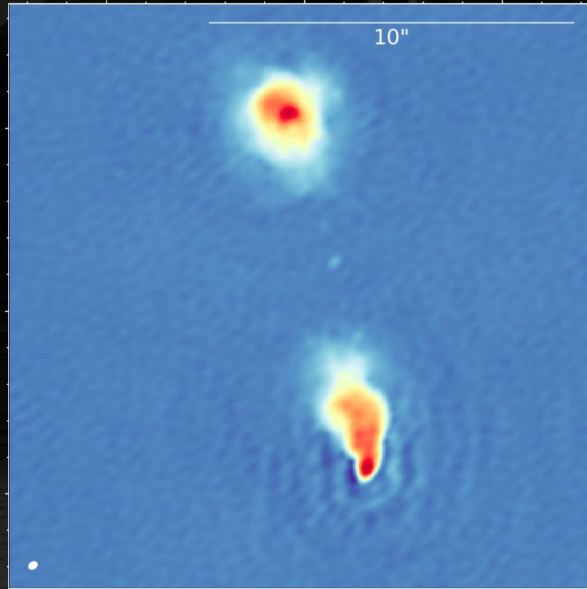
2024: **8** talks

1. **Eleni Vardoulaki** - The high-resolution COSMOS: peering into the unknown with LOFAR and JWST observations
2. **Jurjen de Jong** - Into the Depths: Unveiling ELAIS-N1 with LOFAR's deepest sub-arcsecond wide-field images
3. **Nadia Biava** - The high resolution view of radio phoenixes
4. **Maria Arias** - The Crab Nebula
5. **Gabriella Di Gennaro** - A view on cluster-scale diffuse radio emission at high redshift
6. **Emmy Escott** - AGN through the eyes of the LOw Frequency ARray
7. **Hrishikesh Shetgaonkar** - High-resolution low-frequency probes of X-ray emitting knots in blazar jets
8. **Emanuele De Rubeis** - Revealing the sub-arcsecond nature of radio galaxies in Abell 2255

(Technical talks excluded)

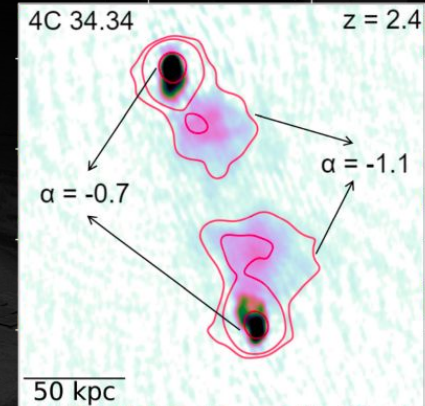
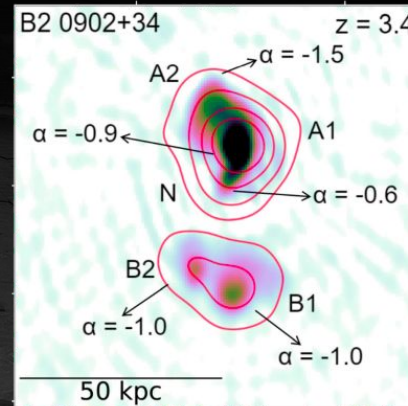
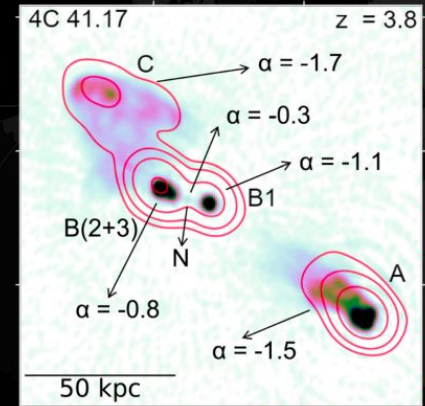
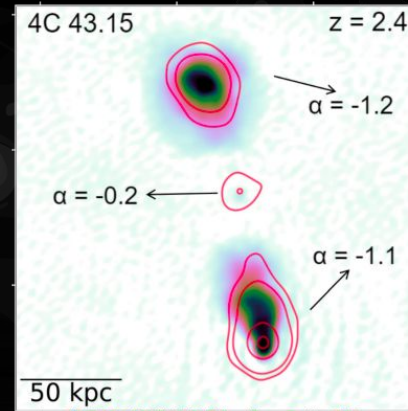
Science with LOFAR-VLBI

AGNs at high redshifts! ($z > 2$)



(Sweijen et al., 2022)

(Cordun et al., 2023)



Science with LOFAR-VLBI

Detailed (sub-)structure in nearby AGNs!

- Correlations with emission-line and X-ray maps
- Insight into the duty cycle of AGNs
- Strong filamentary structures in radio lobes

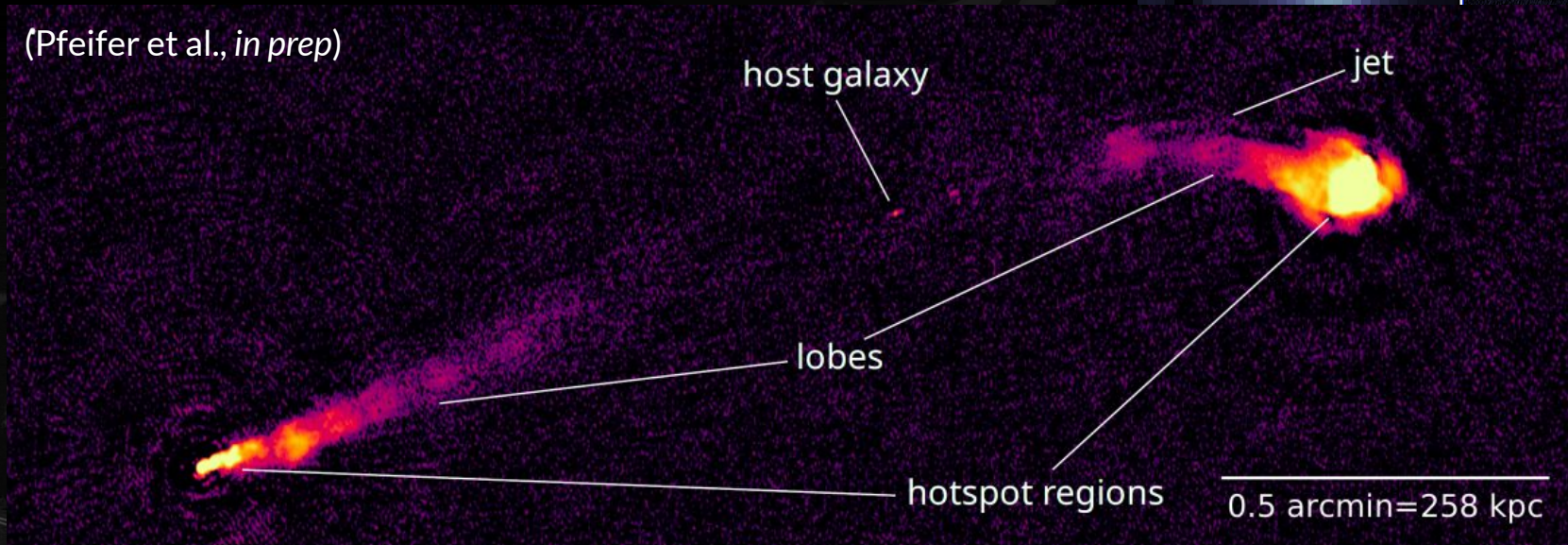
LoTSS 6"



iLoTSS 0.3"
R. Timmerman



(Pfeifer et al., *in prep*)



ABELL 2029

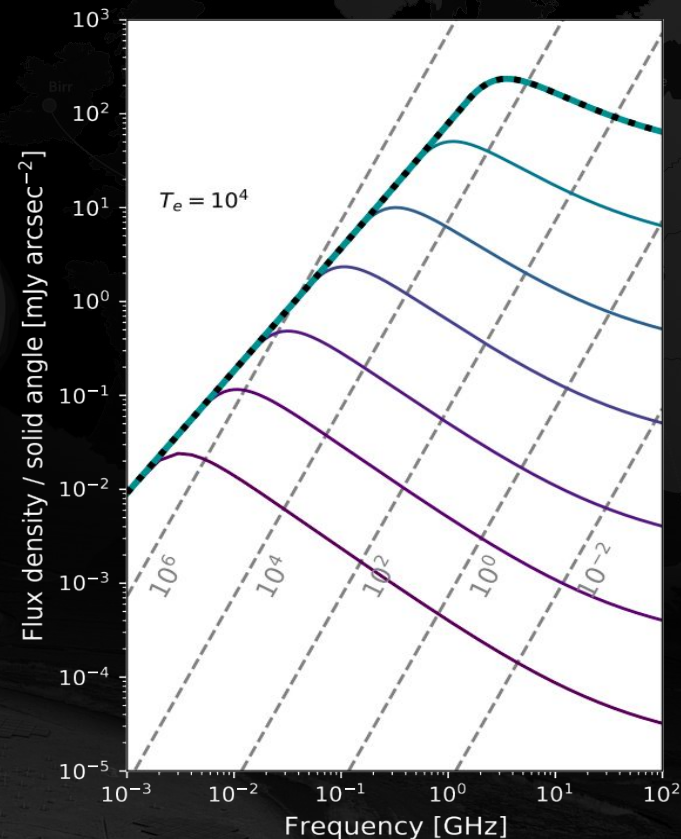
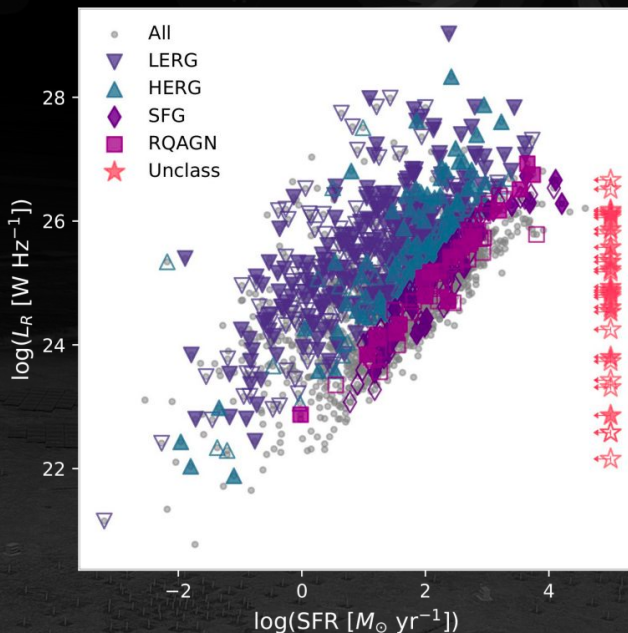
Rozhen

Science with LOFAR-VLBI

Much stronger constraints on
brightness temperatures!

Identification of
940 AGNs in the
Lockman Hole
(160 new identifications)

- HERGS: 68%
- LERGS: 57%
- RQAGN: 32%
- SFG: 20%



(Morabito et al., 2022)

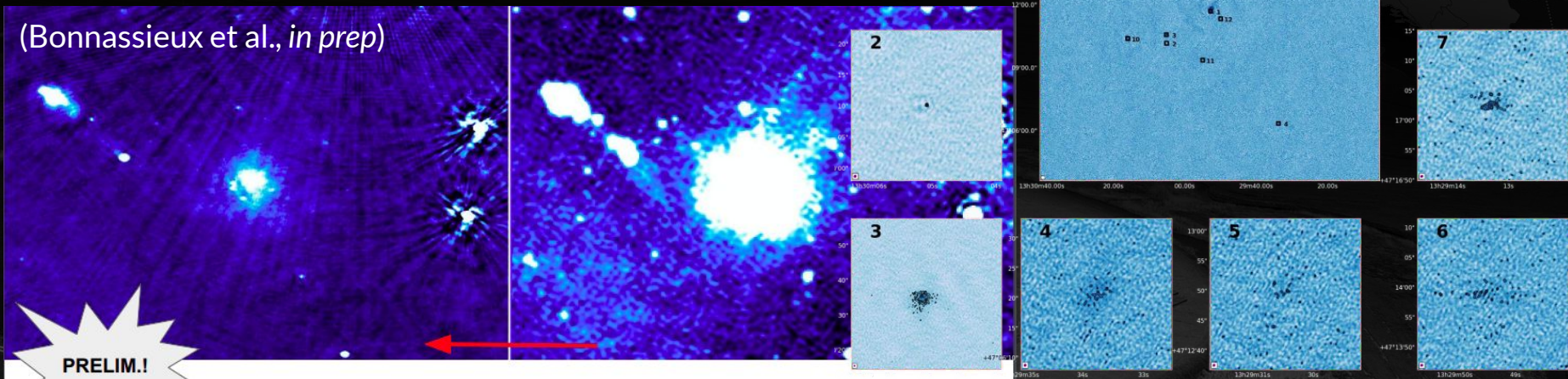
Science with LOFAR-VLBI

(Venkattu et al., 2023)

Detecting **supernovae** in galaxies!


- Disentangling the diffuse galactic emission from compact SN
- Low-frequency absorption constraints!

(Bonnassieux et al., *in prep*)



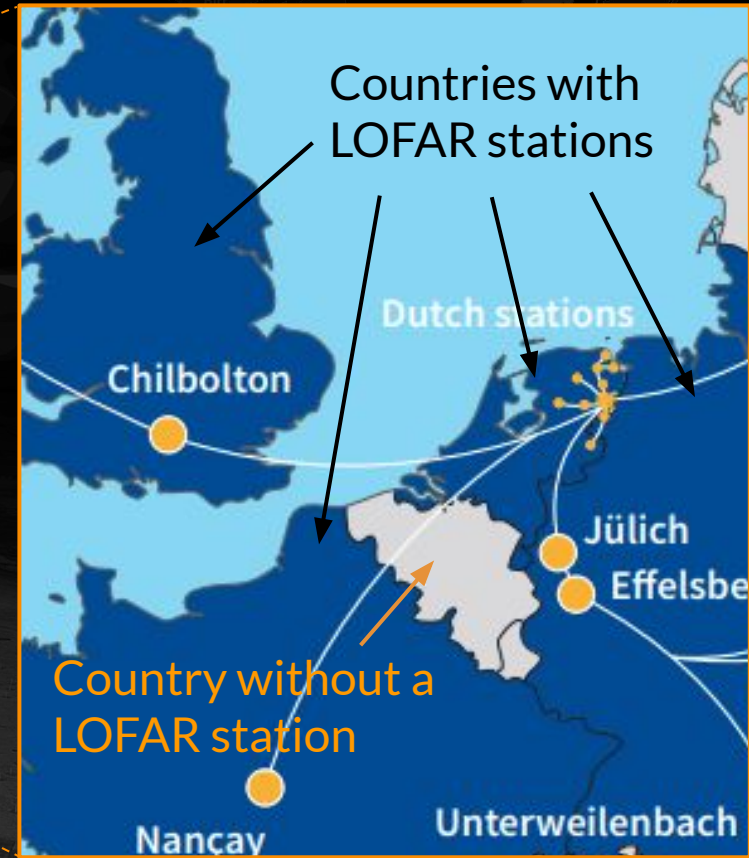
PRELIM.!



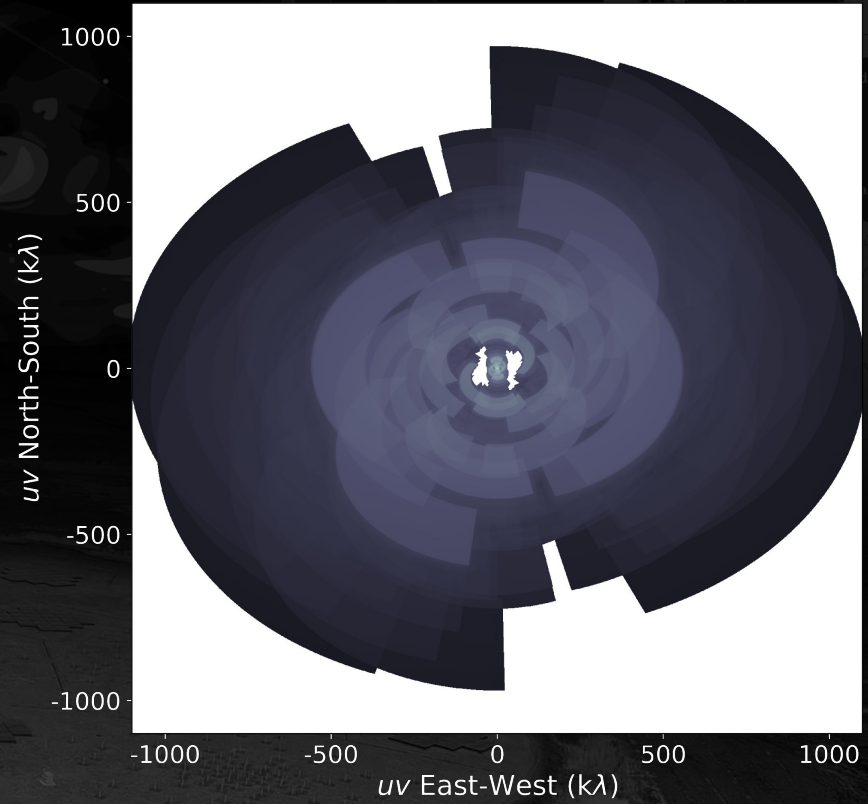


“Next year, I am going to talk about the Belgian Gap”
- Me, one year ago

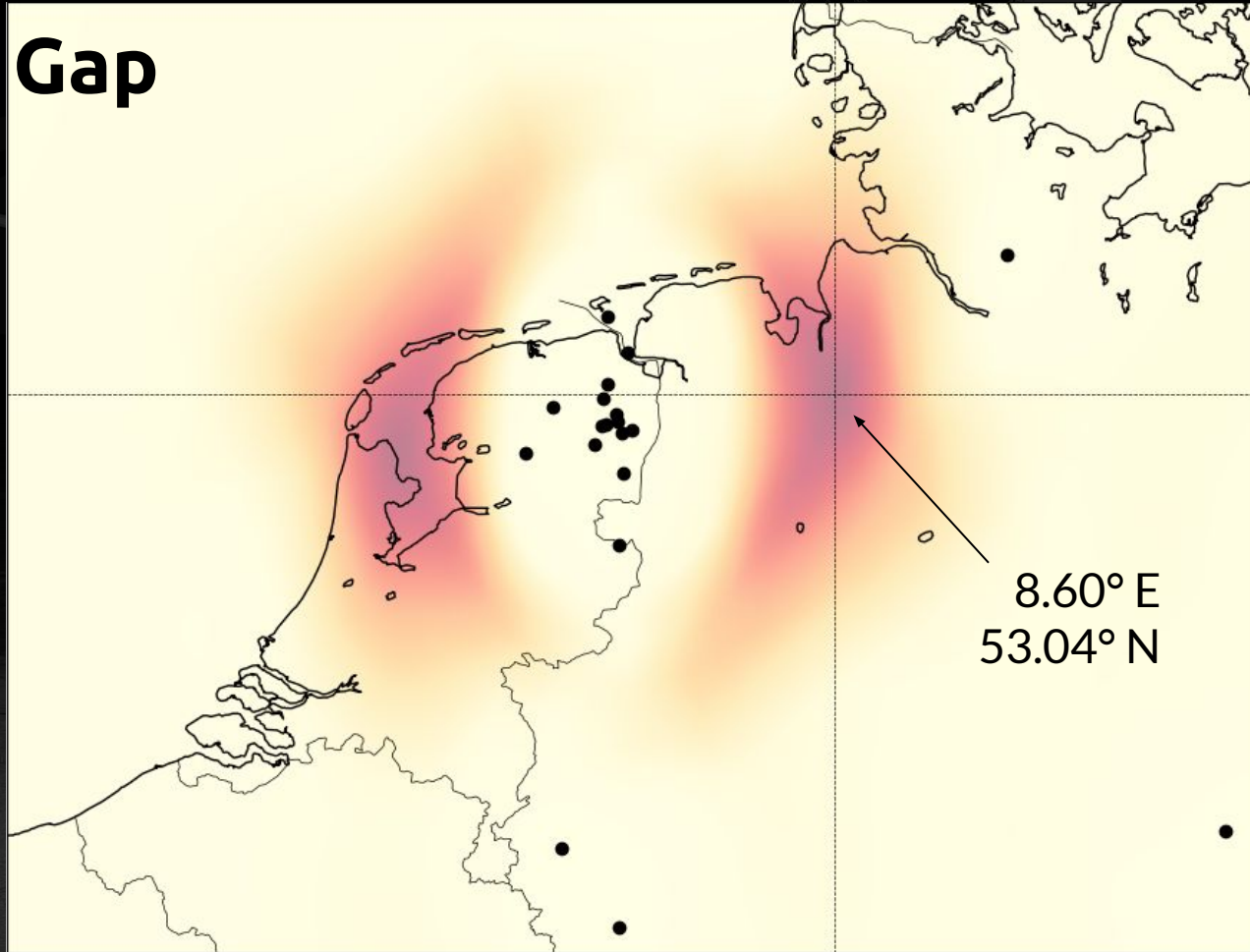
The Belgian Gap



The Belgian Gap

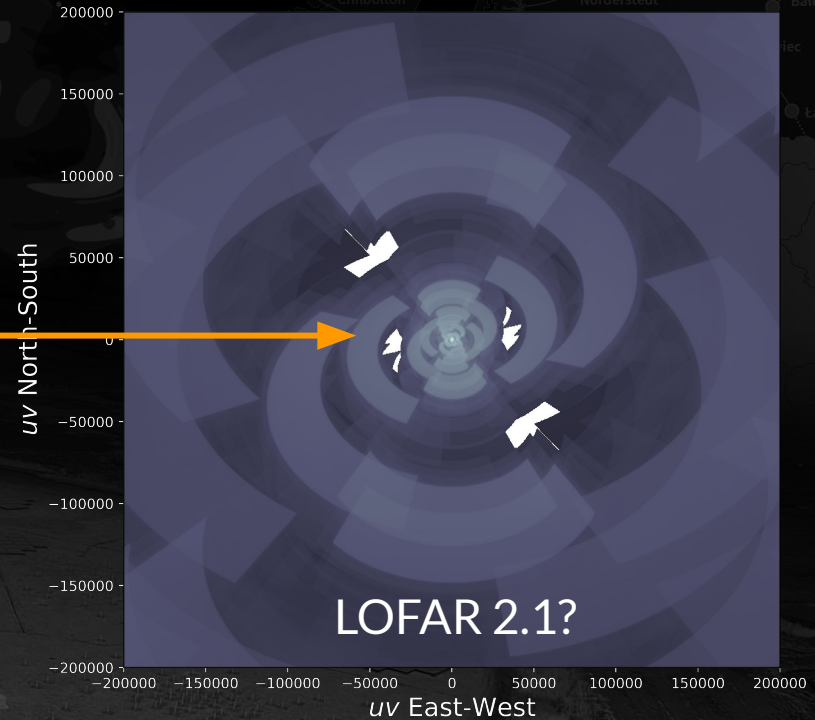
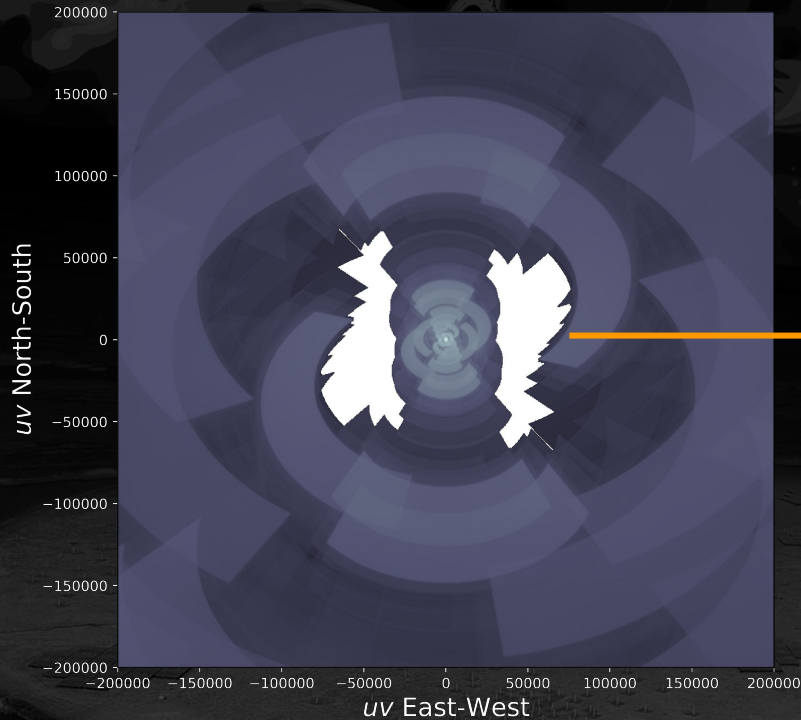


The Belgian Gap



The Belgian Gap

LOFAR should probably not only expand to longer baselines



Take-home messages

1. The current VLBI capabilities of LOFAR provide a unique combination of high angular resolution at low radio frequencies, and will continue to remain unique for the foreseeable future
(Low frequency VLBI and the International LOFAR Telescope are practically synonymous)
2. Low-frequency observations with sub-arcsecond resolution enable a wide variety of new and exciting scientific opportunities
3. With LoTSS-HR, these observations will soon become more accessible than ever before!
4. With the LOFAR2.0 upgrade, the future of high-resolution low-frequency radio astronomy is looking very bright!