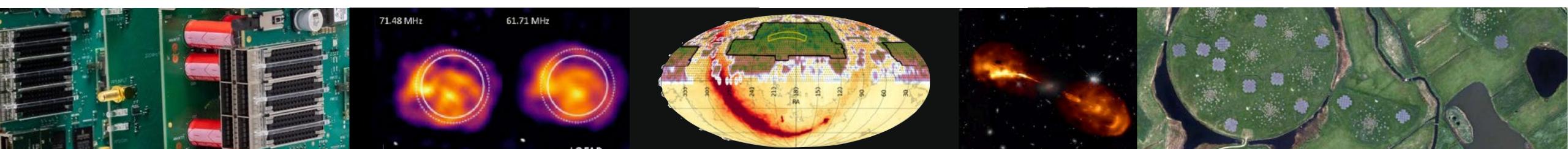
# LOFAR 2.0 - Upgrading the Low Frequency Array A premier low-frequency radio facility for the 2030s and beyond



## **Michiel van Haarlem**

- Director
- LOFAR ERIC
- Radio 2024 Meeting, Erlangen Wednesday 13 November 2024



# Distributed research infrastructure: world-leading low-frequency radio telescope

## Distributed network of antenna stations: condensed in NL, extending >2000 km in Europe

- Central observing operations, peer-reviewed access for the research community

## **Centrally operated data combination**

• GPU-based correlator/beamformer in at University of Groningen (NL)

## **Distributed archive and data analysis centres : >60 PB stored**

- Central operation and open science access for the research community
- Currently 3 nodes: SURF (NL), FZJ (DE), PSNC (PL)



• 52 antenna stations in 8 countries: NL (38), DE (6), PL (3), IE, UK, FR, SE, LV + 2 stations to be constructed in 2025: IT, BG





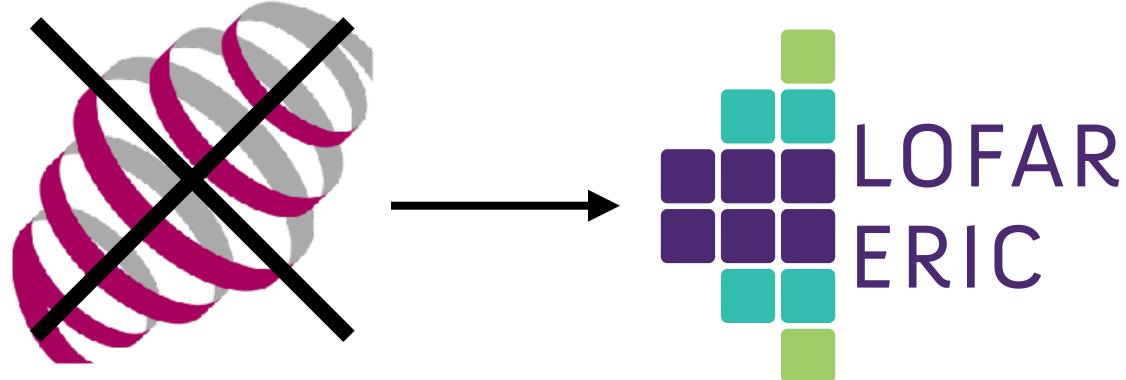
# An ERIC to anchor and further develop the LOFAR distributed RI

## • ILT Foundation $\rightarrow$ Coordinated operation of the LOFAR RI under a joint scientific policy

- Participants: National consortia of partners across Europe (NL, DE, PL, UK, FR, SE, IE, LV, IT, BG) + ASTRON
- Partners own their LOFAR station(s) and commit these to joint operations
- ASTRON provides operational coordination

## • LOFAR ERIC $\rightarrow$ More robust governance to anchor and expand LOFAR partnership

- Partner participation at national level, aligned to common long-term strategy and vision
- Joint funding, steering, and implementation of major projects (e.g., LOFAR2.0) financial advantages
- Increase scientific impact through continued development better recognition e.g. at EC
- Officially established by EC on 20 December 2023





# **LOFAR Stations**

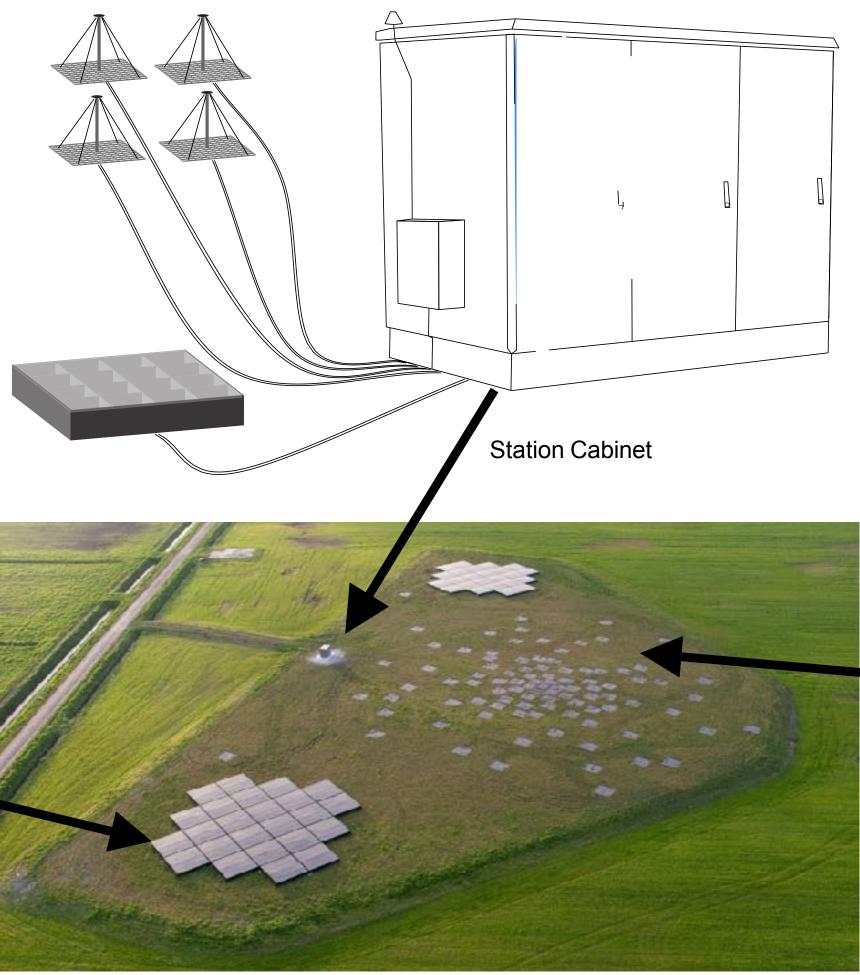
## **Current LOFAR capabilities**

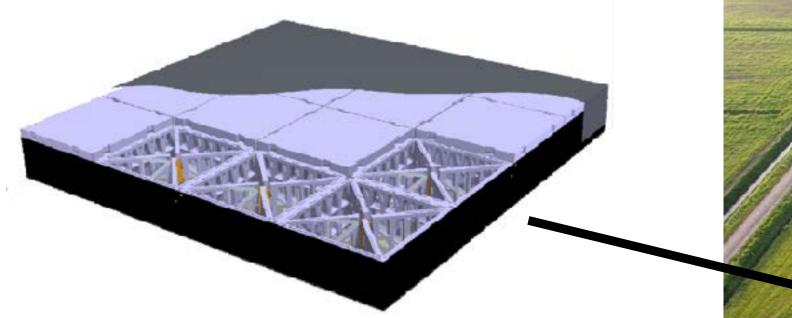
## International Stations

• 96 LBA and 96 HBA

## NL Stations

- 96 LBA and 48 HBA
- only 48 antennas can be used at one time





# **High-Band Antennas**

Frequency = 110-240 MHz Wavelength = 1-3 metres

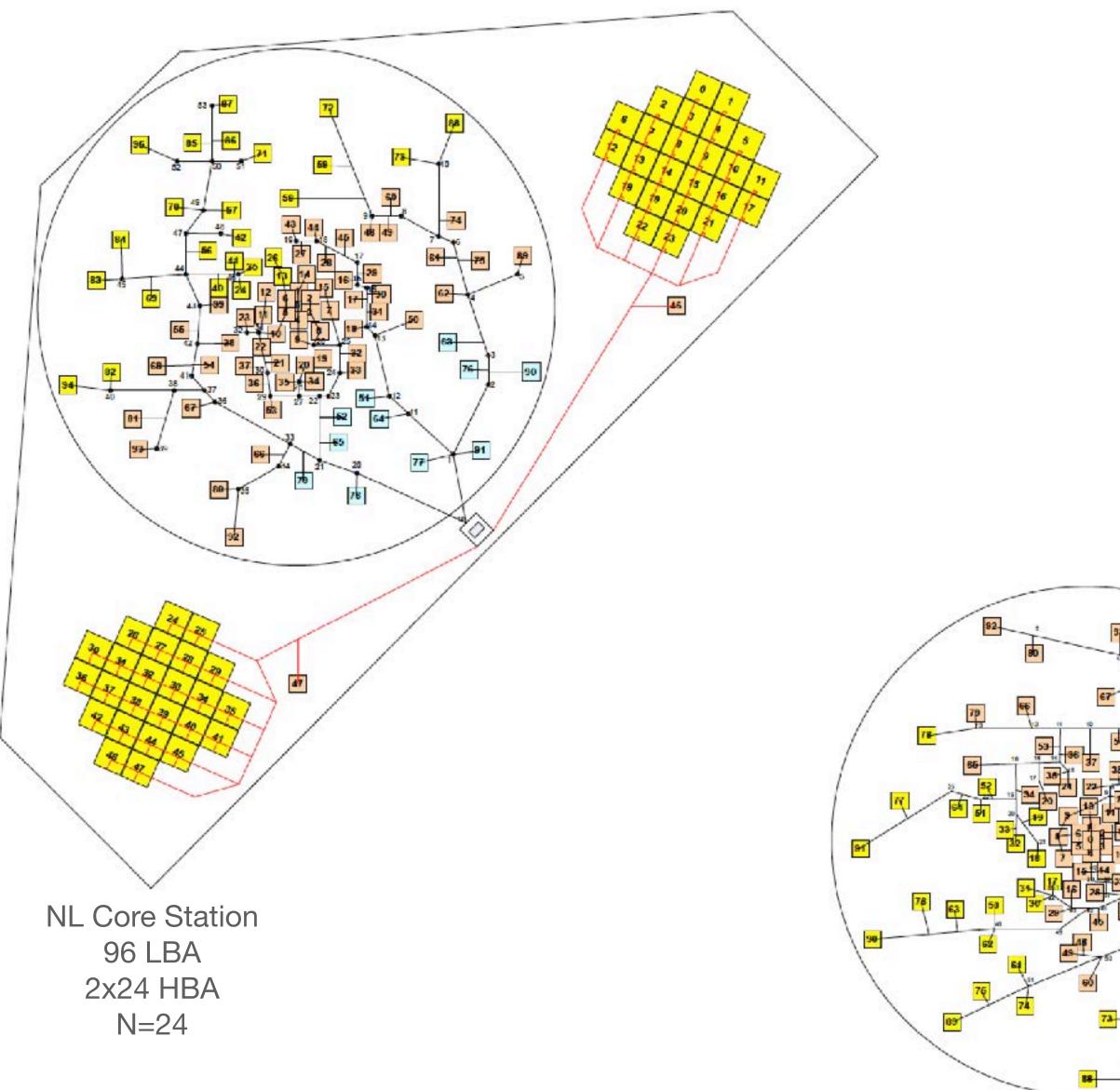




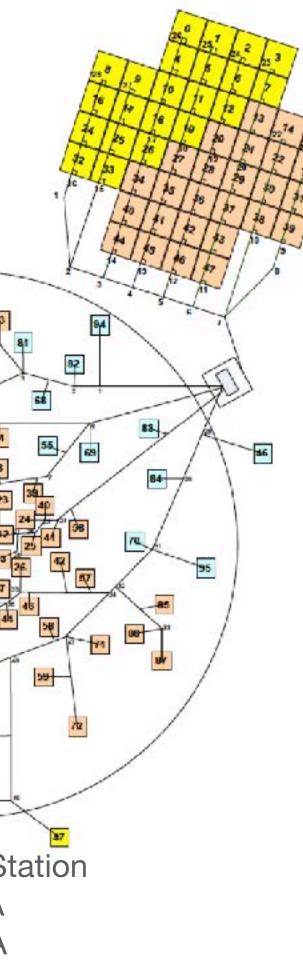
# **Low-Band Antennas**

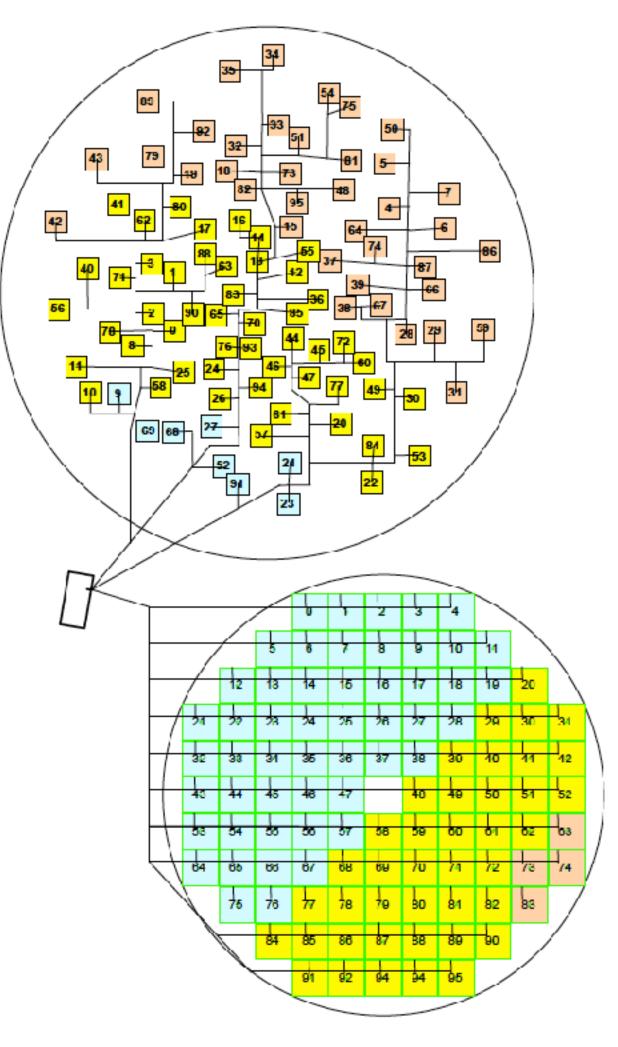
Frequency = 10-90 MHz Wavelength = 3-30 metres





NL Remote Station 96 LBA 48 HBA N=14





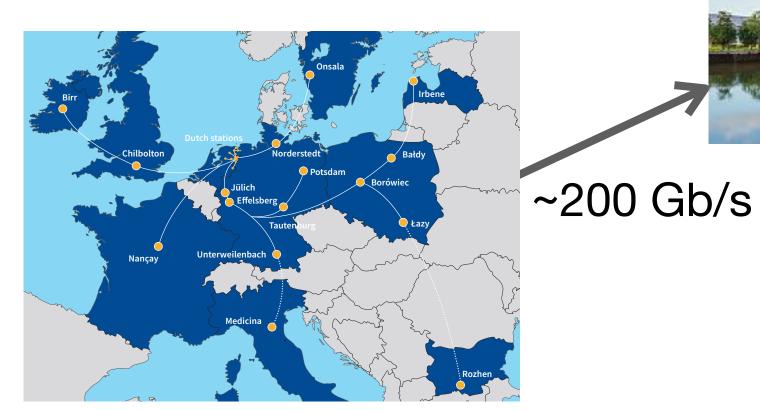
International Station 96 LBA 96 HBA N=14+2



# The LOFAR1 system - Data flow

### **Correlation & Beamforming**

GPU-based system at RuG360 Tflops compute power2 TB temporary storage



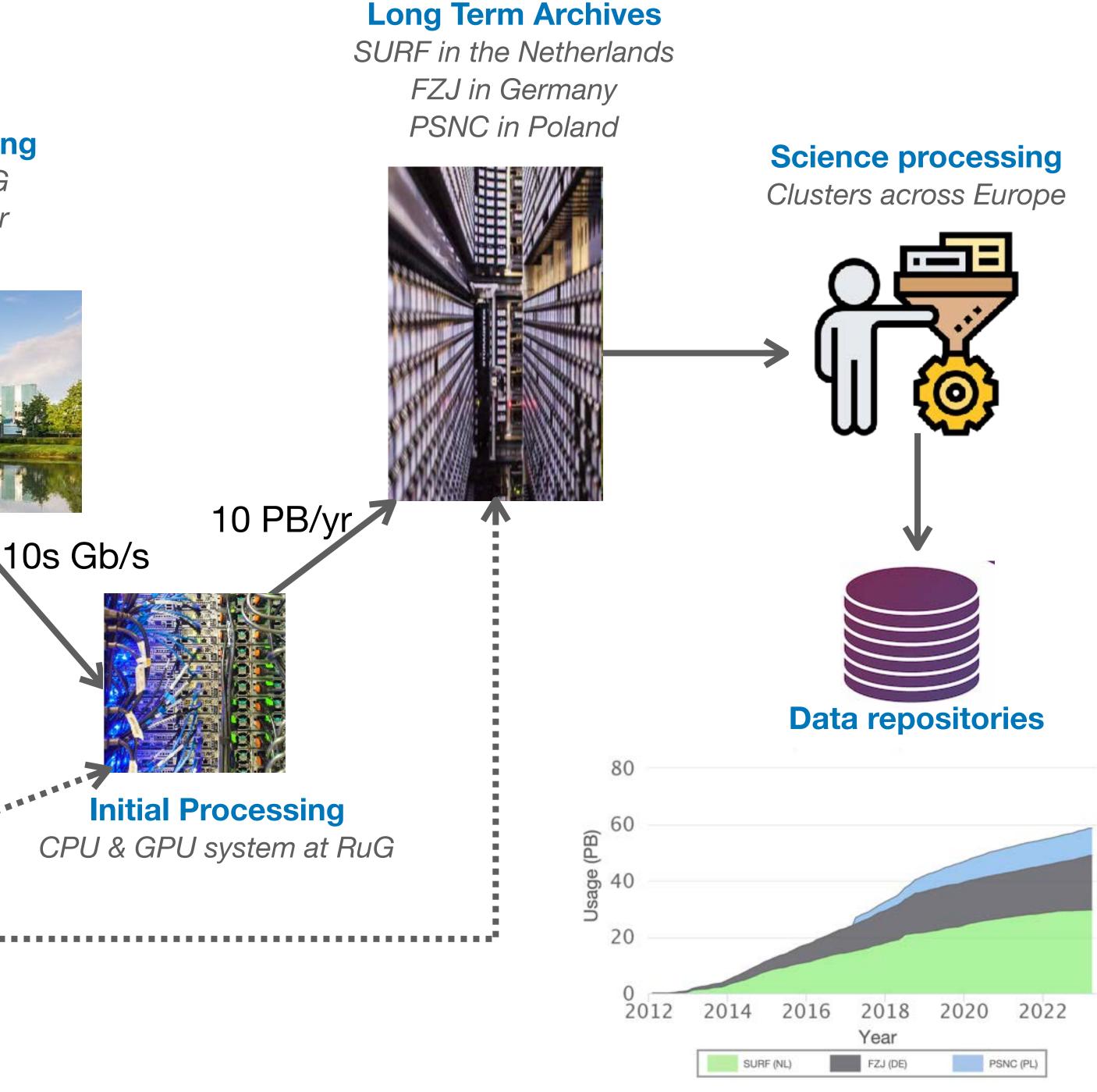
# Station-level processing

(e.g., amplification, filtering, digitisation, beam-forming)

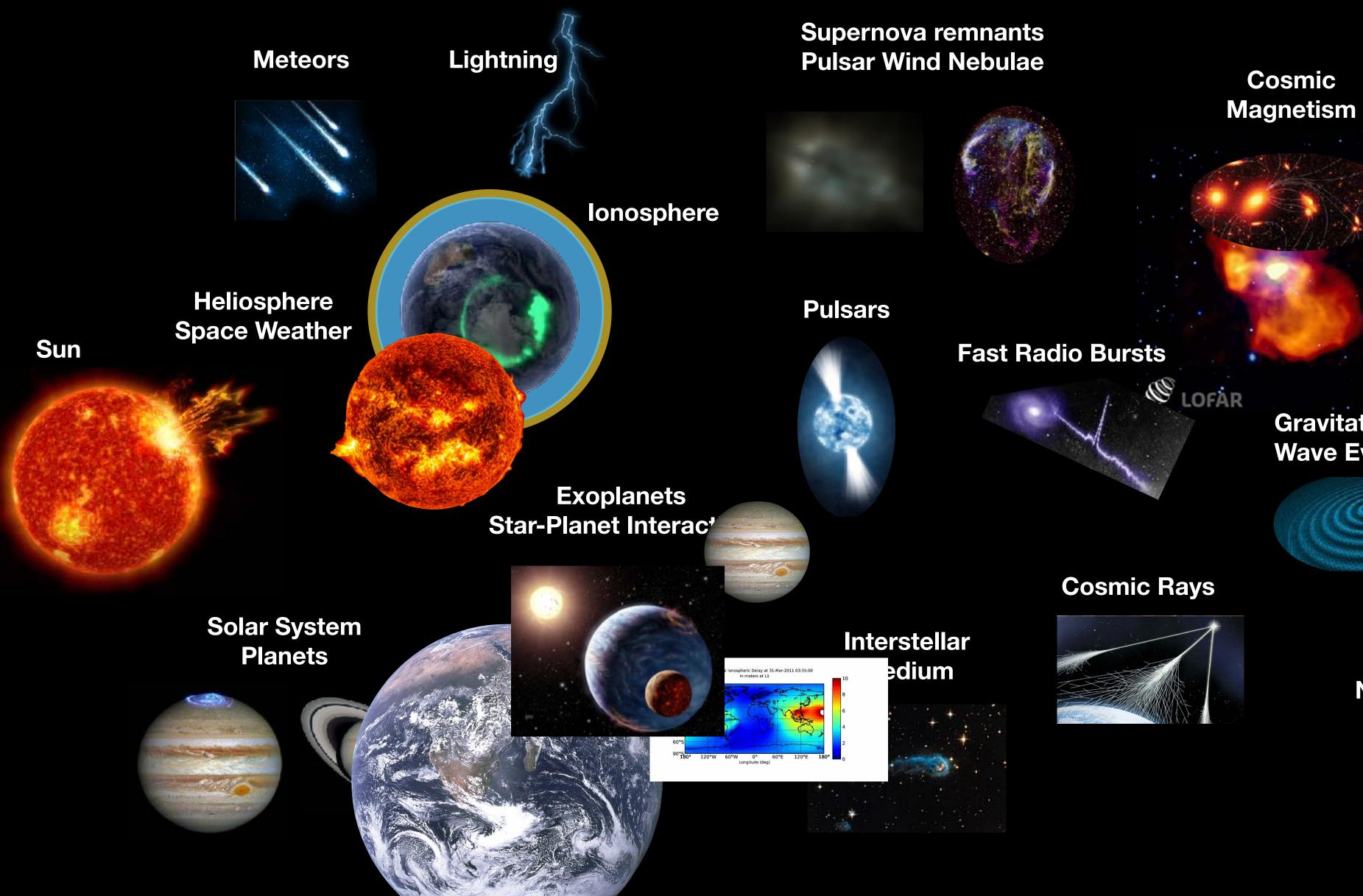
13 PB/s sampling



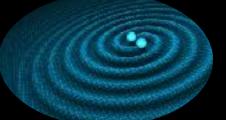
### **Central operation**



# LOFAR's broad science case



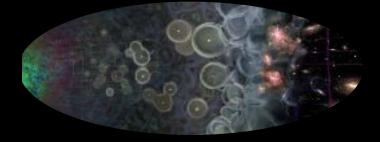
### Gravitational **Wave Events**



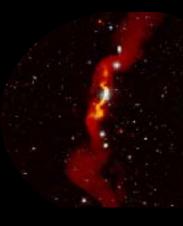
### Clusters



#### **Early Universe Cosmic Dawn**



### **AGN** physics

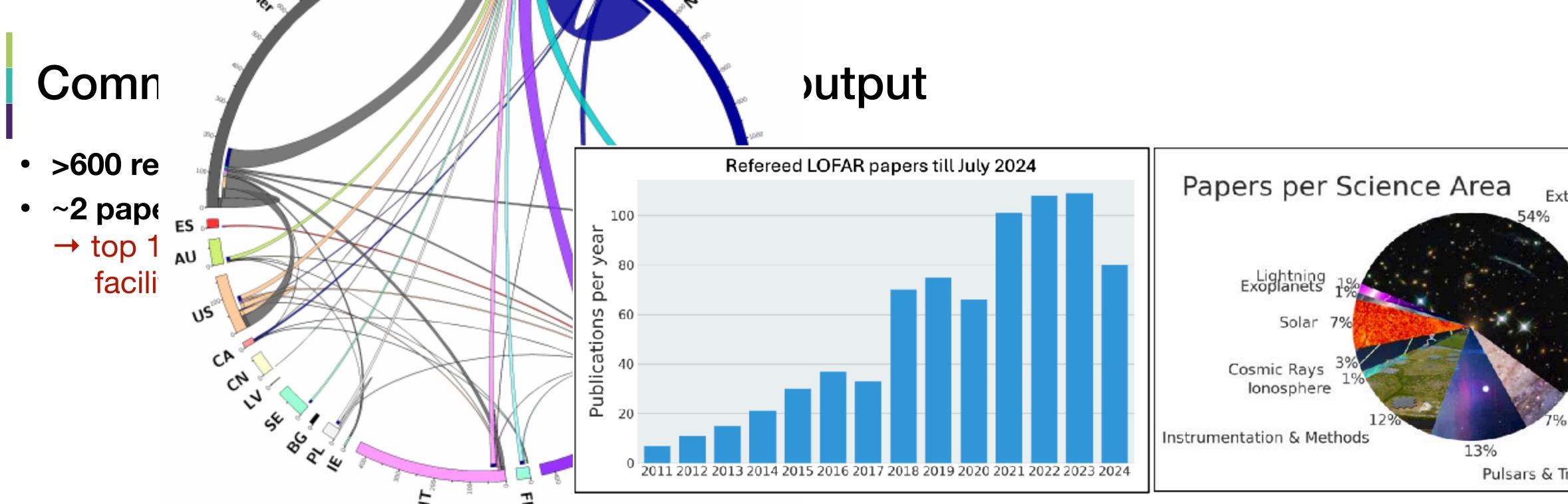


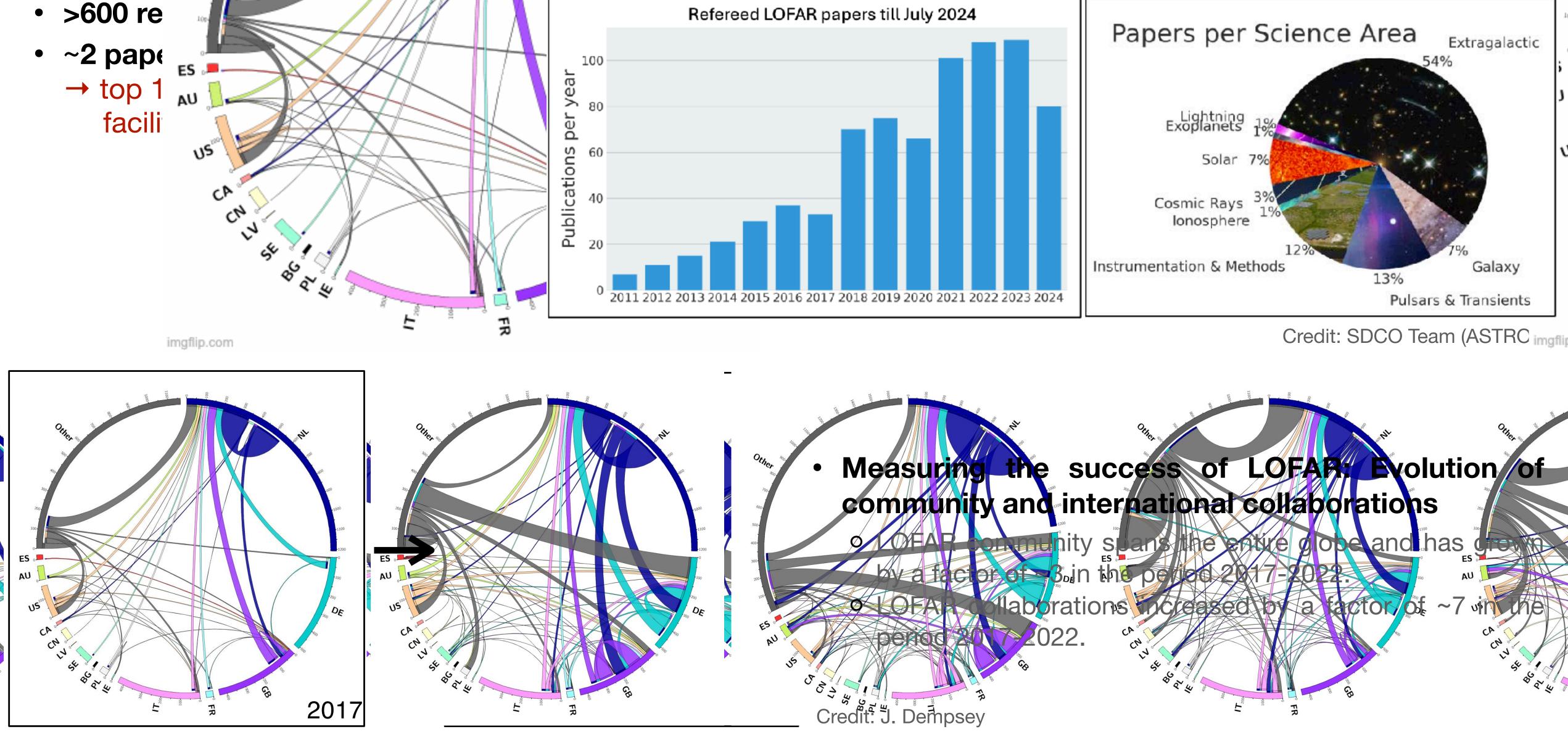
### **Nearby Galaxies**







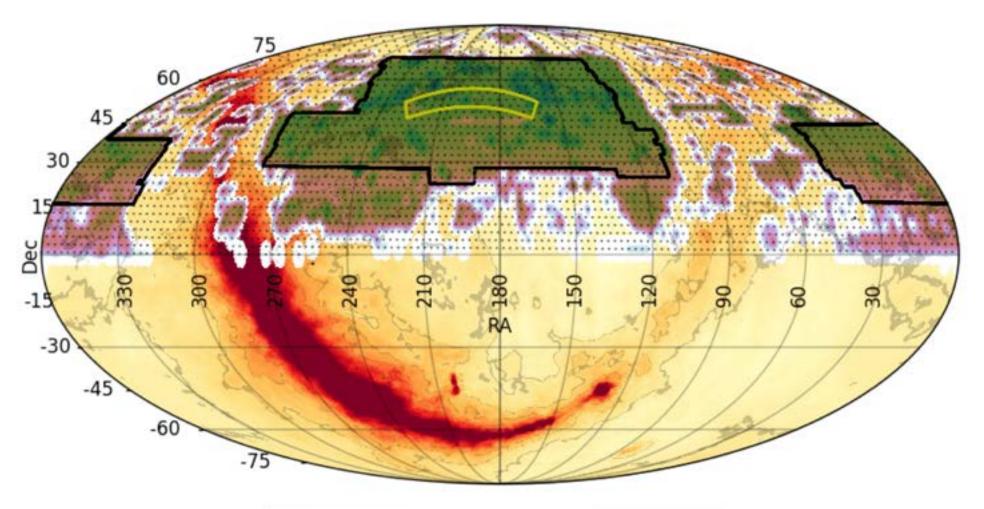




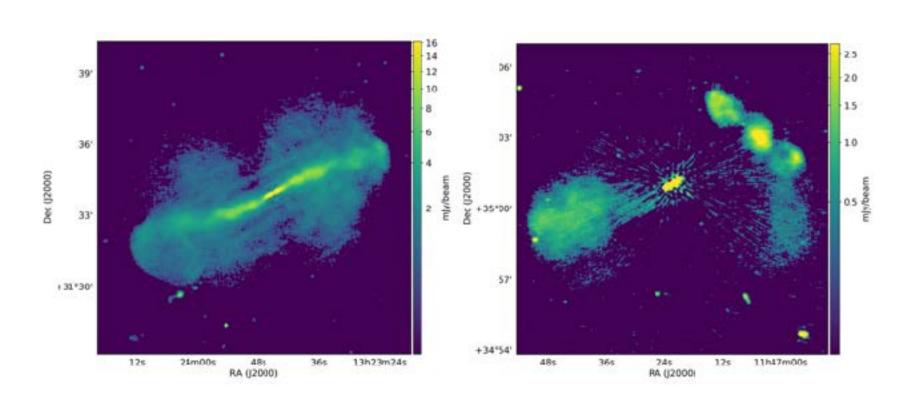
# Surveying: huge area, huge object samples LoTSS: LOFAR Two-Metre Sky Survey (Shimwell-

- Mapped ~27% of Northern sky at 120-168 MHz
- Detailed radio image of 4.4 million objects
- Resolution 6"

0.04



Shimwell+22



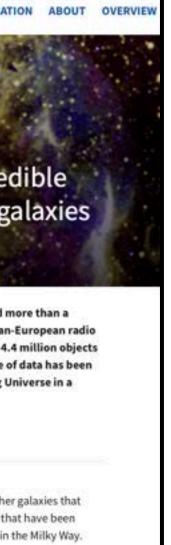
mJy/beam

0.15

### PHYS

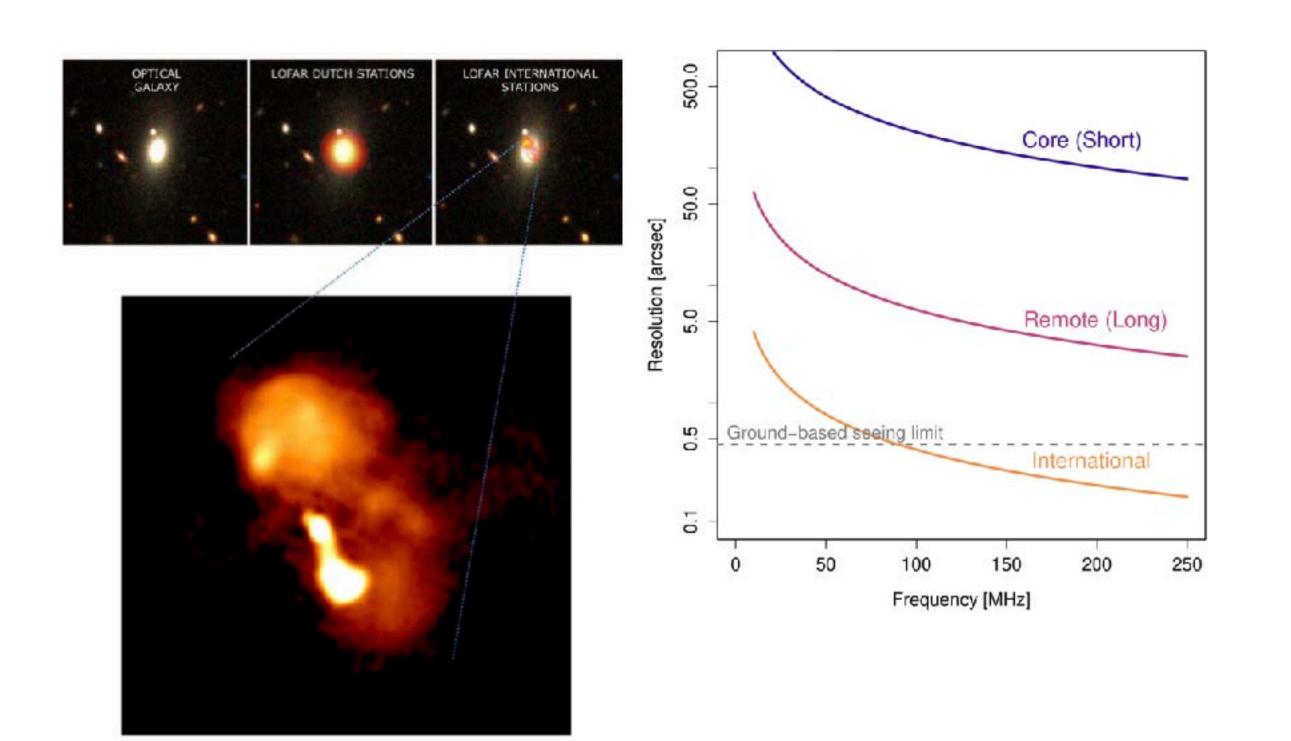
Array (LOFAR), a pan-European radio telescope.

<b>I+22</b> )	New map of galaxies and O <sup>By Katle Hunt, CNN</sup> Published 5:00 AM EST, F	Americas Asia Australia China Europe India Middle East United Kingdom the night sky reveals 4.4 million other space objects
	betwee	Annalisa Bonafede rared (white) image depicts the Coma cluster, which is over 300 million light-years from 0 individual galaxies. The radio image shows radiation from highly energetic particles in the galaxies.
f 598 98 Share Email	Home / Astronomy & Space / Astronomy	YELESCOPES   ASTRONOMY   RESEARCH & INNOVATION   NEWS & EVENTS   EDUCATION     Fluery of new discoveries as increating the service of the public of the public, anyone can view the most exotic wonders of our intriguing UP brand new light.   Over a server year period an international team of scientists has mapped in quarter of the northern sky using the Low Frequency Array (LOFAR), a pantelescope. It reveals an astonishingly detailed radio image of more than 4.4 and a very dynamic picture of our Universe. Now that this treasure trove of made public, anyone can view the most exotic wonders of our intriguing UP brand new light.     PUBLISHED BY THE EDITORIAL TEAM, 25 FEBRUARY 2022   A wealth of new information     The vast majority of these objects are billions of light years away and are either harbour massive black holes or are rapidly growing new stars. Rarer objects tha discovered include colliding groups of distant galaxies and flaring stars within the starsour provement on the start galaxies and flaring stars within the start galaxies and flaring stars within the start of the start provement on the start galaxies and flaring stars within the start of the start provement on the start galaxies and flaring stars within the start of the start provement on the start galaxies and flaring stars within the start of the start provement of the start galaxies and flaring stars within the start of the start provement on the start galaxies and flaring stars within the start of the start provement on the start galaxies and flaring stars within the start of the start provement on the start galaxies and flaring stars within the start of the start provement on the start galaxies and flaring stars within the stare start provement on the start provement on the start provement o

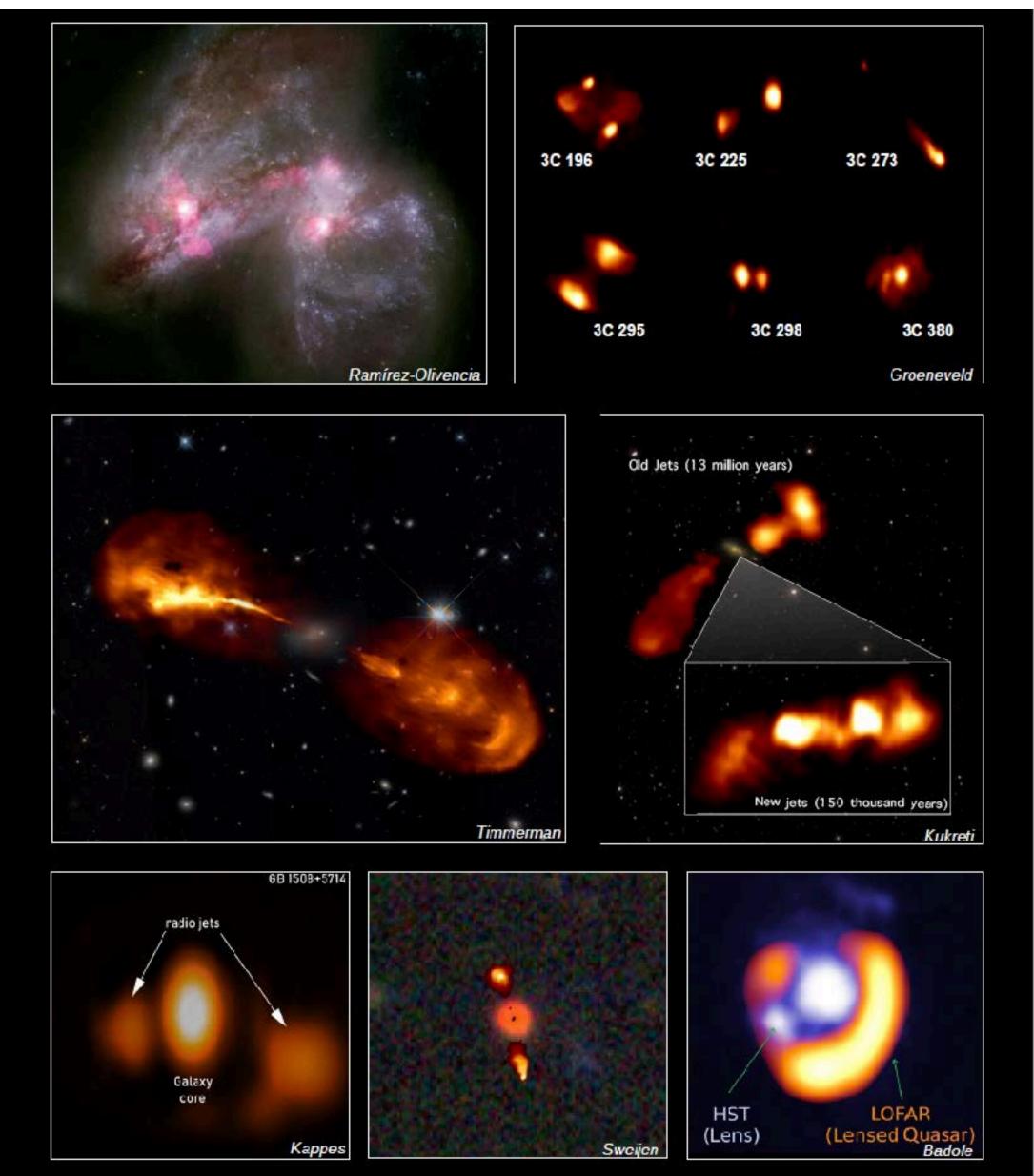


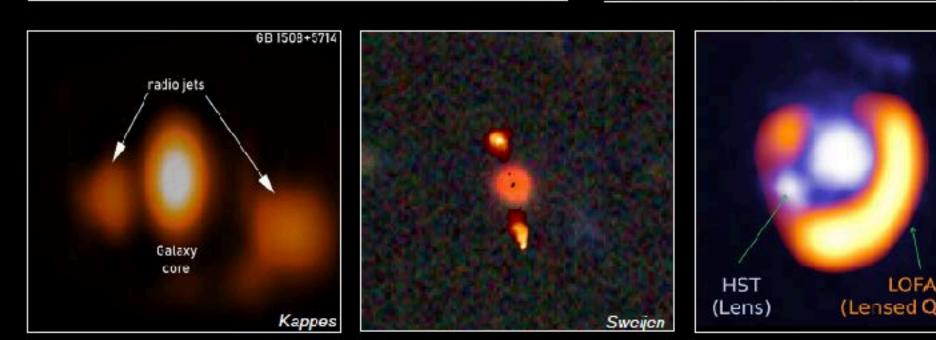
#### Most detailed images of galaxies at 150 MHz ullet

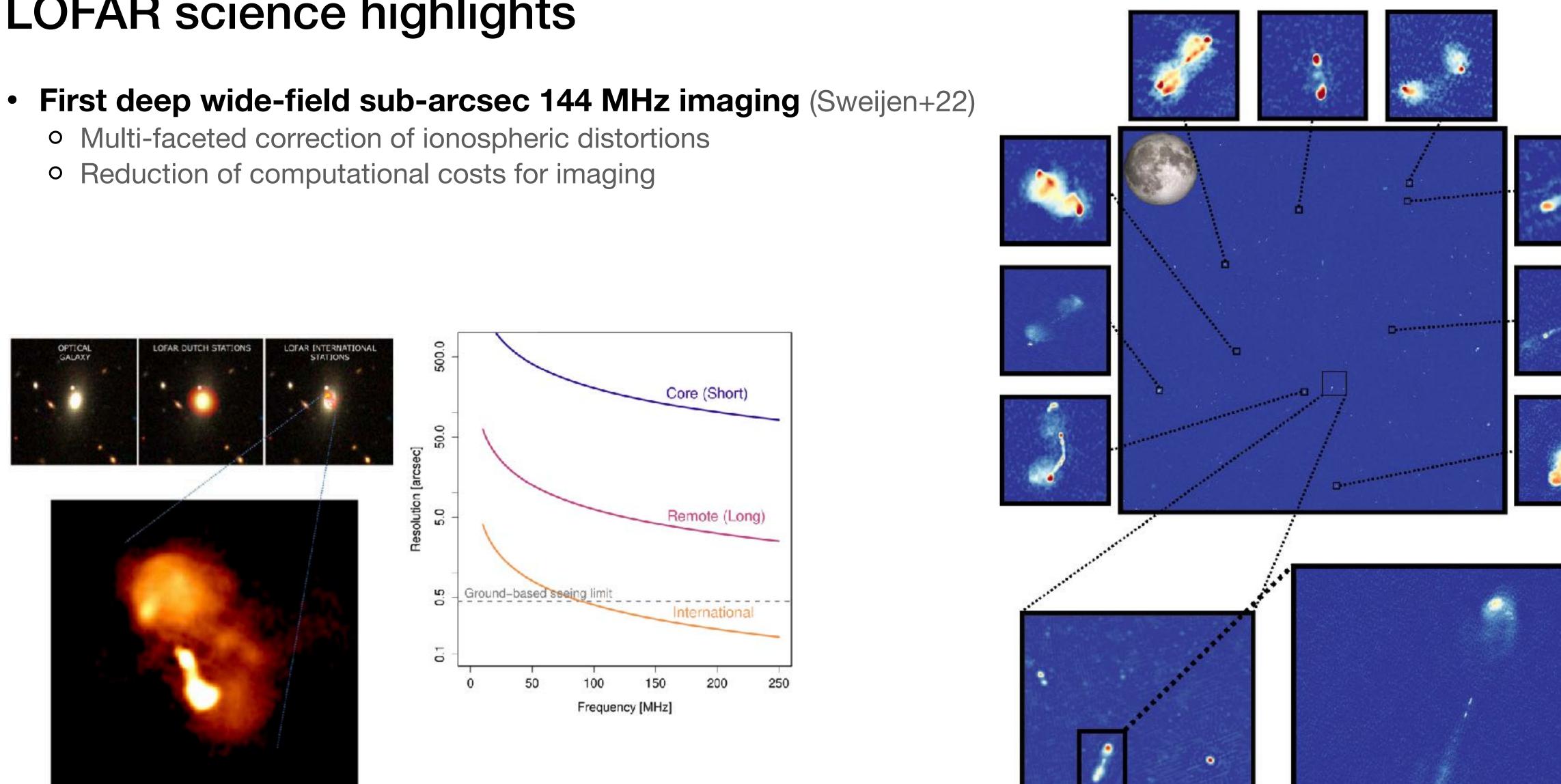
- Data release and 10 research publications (A&A), doubling the number of scientific results using LOFAR sub-arcsec resolution
- Possible thanks to LOFAR's international baselines (>2000 km)
- Images 20x higher resolution than NL-only LOFAR images



Credit: L.K. Morabito; LOFAR Surveys KSP



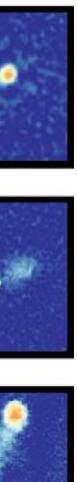




Credit: L.K. Morabito; LOFAR Surveys KSP

Sweijen+22

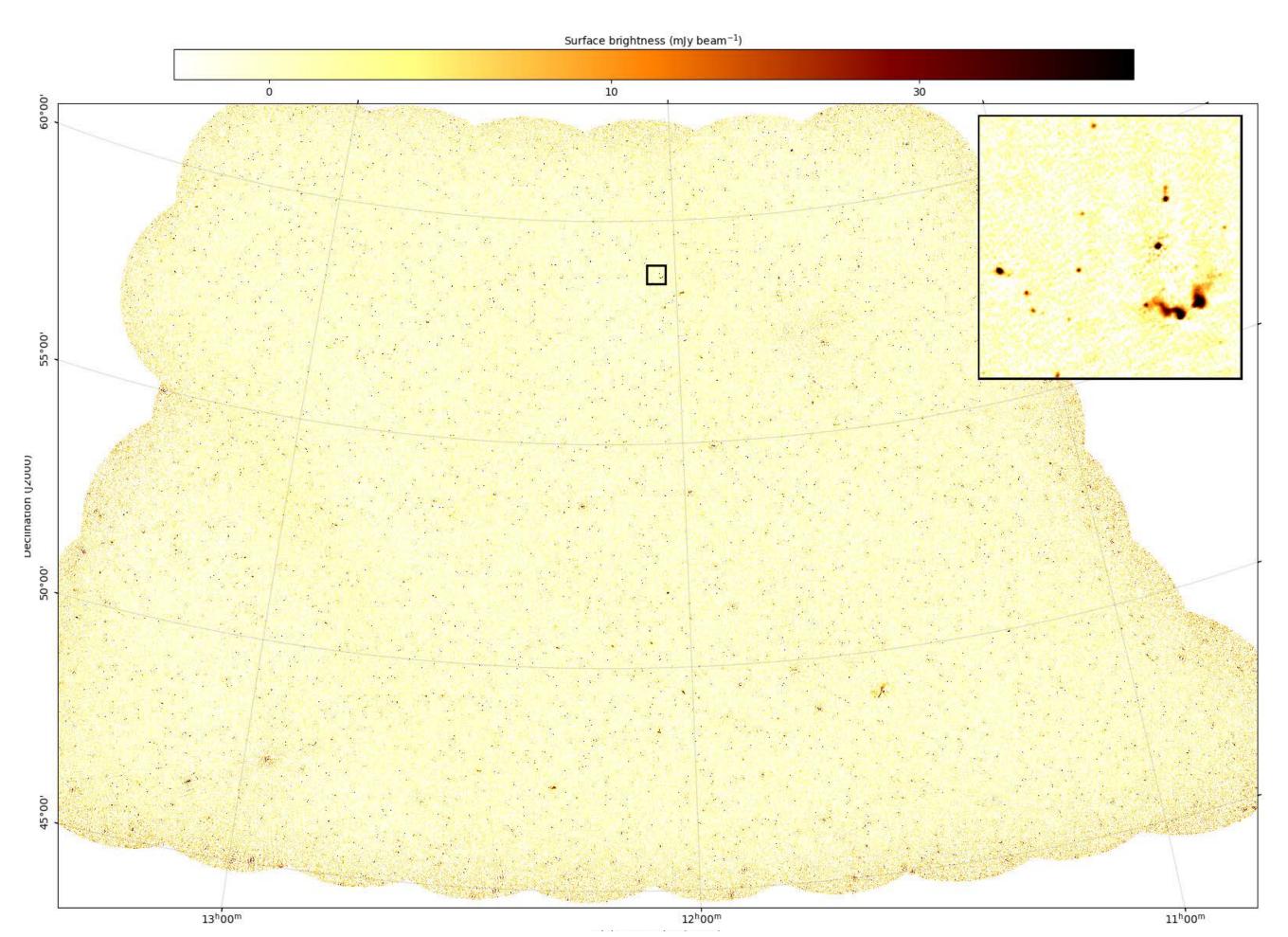
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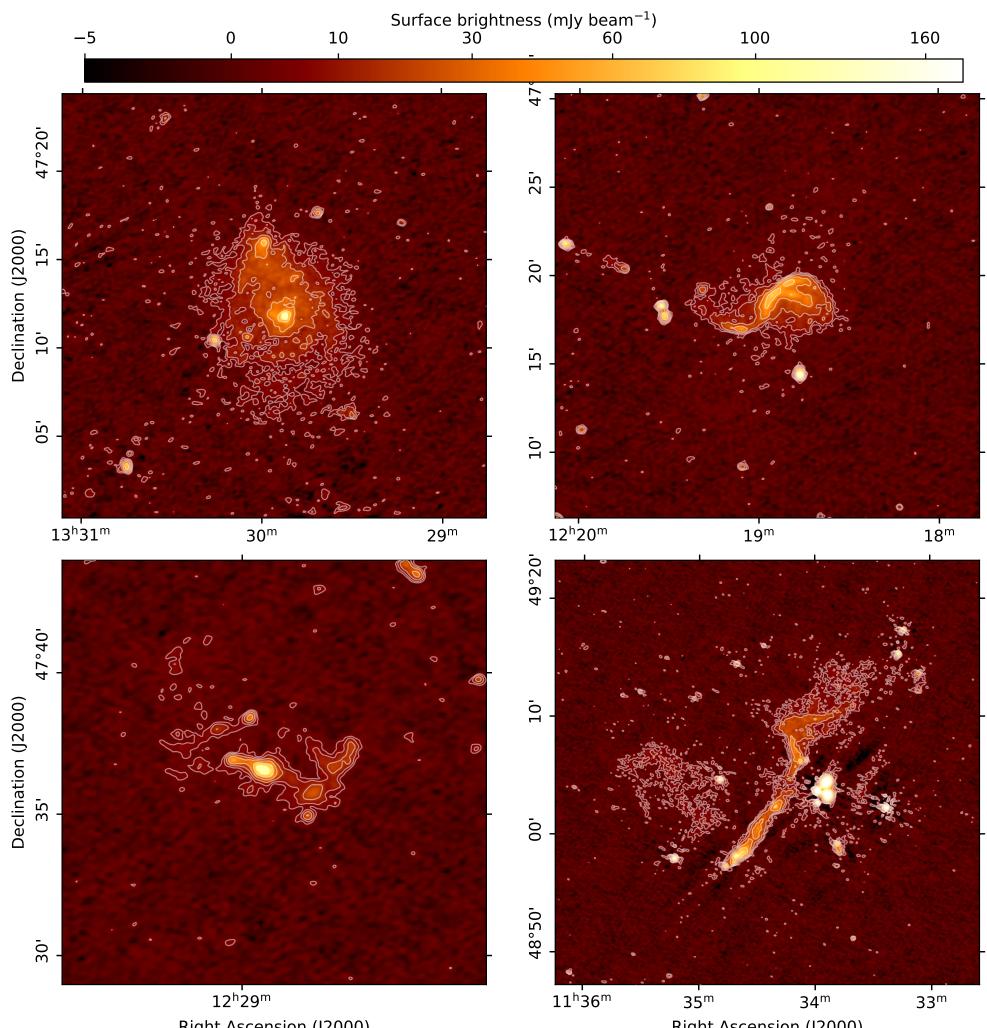




## • LoLSS: Deepest, highest resolution wide-area survey <100 MHz ever (de Gasperin+23)

- Sensitive wide-area survey at 42-66 MHz (LBA)
- More than 40,000 radio sources detected





Right Ascension (J2000)

Right Ascension (J2000)

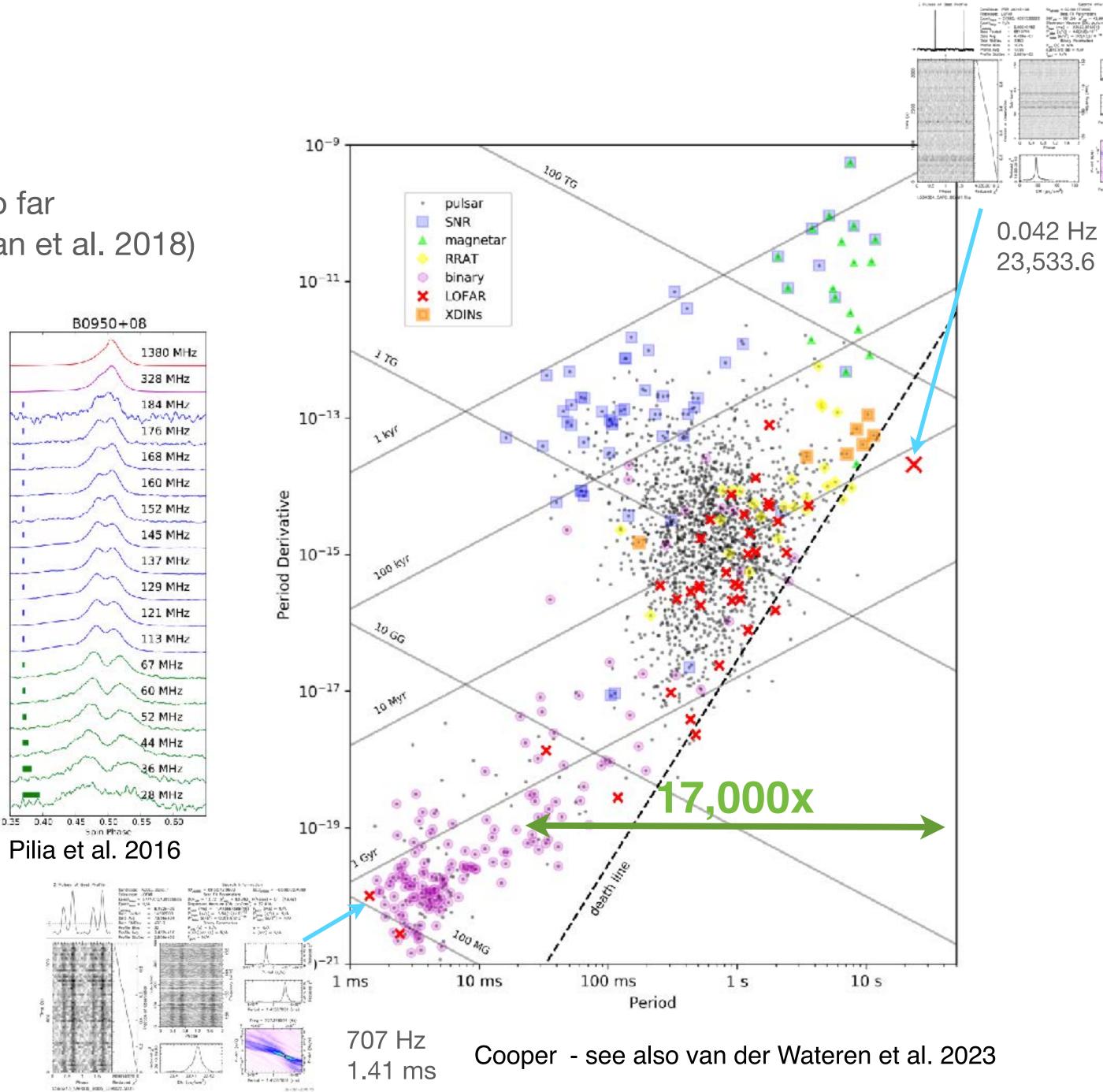
de Gasperin+23

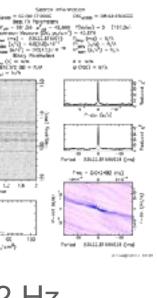
## **LOFAR Pulsar Census**

- LOFAR has detected more than 300 pulsars so far
- including a super-slow (23.5 second) pulsar (Tan et al. 2018) and a 1.4 ms (707 Hz) pulsar

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Bilous et al. 2016

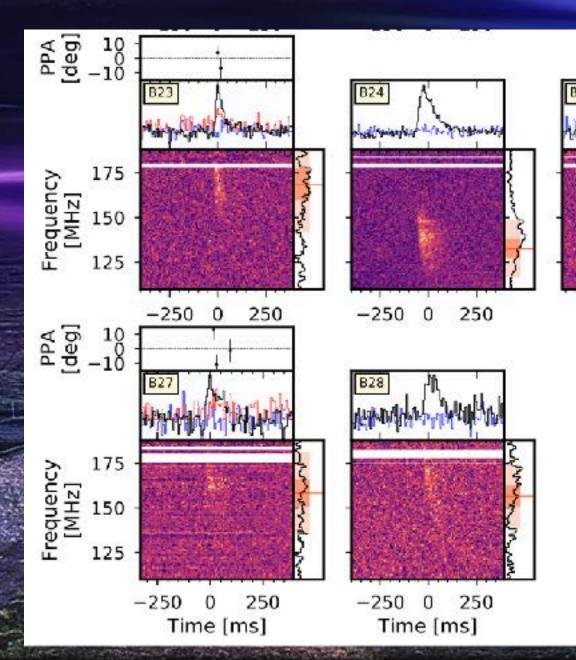






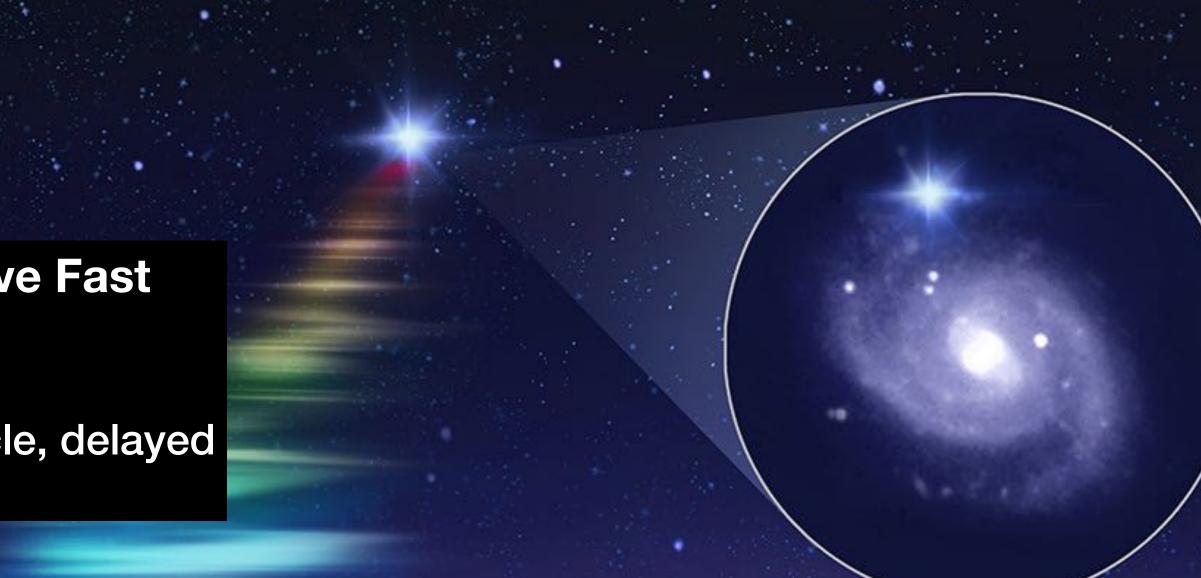
## LOFAR long-term monitoring of the periodically active Fast Radio Burst source 20180916B (Gopinath+24)

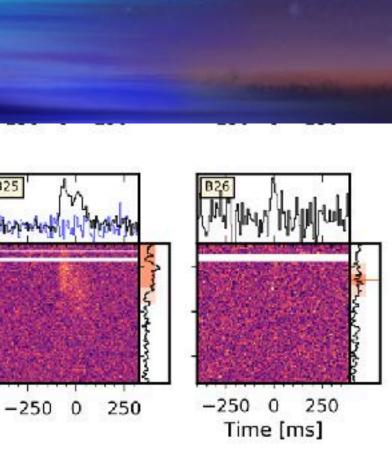
- Multi-year monitoring campaign with HBA
- 11 new bursts detected, strictly periodic 16.3 day cycle, delayed several days after CHIME

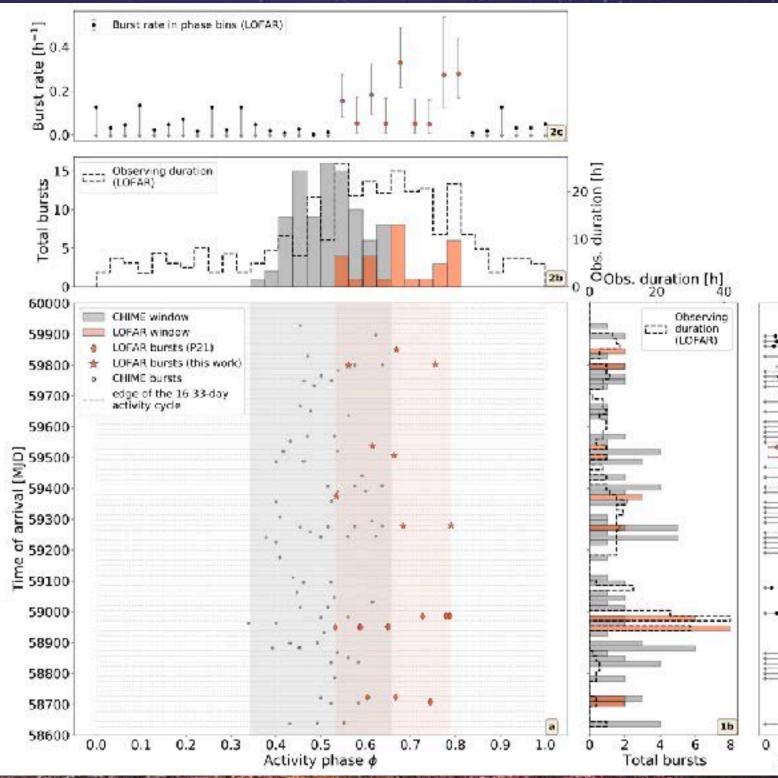


Futselaar / ASTRON

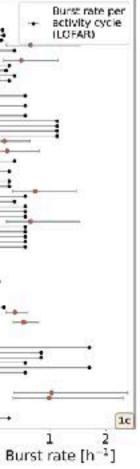
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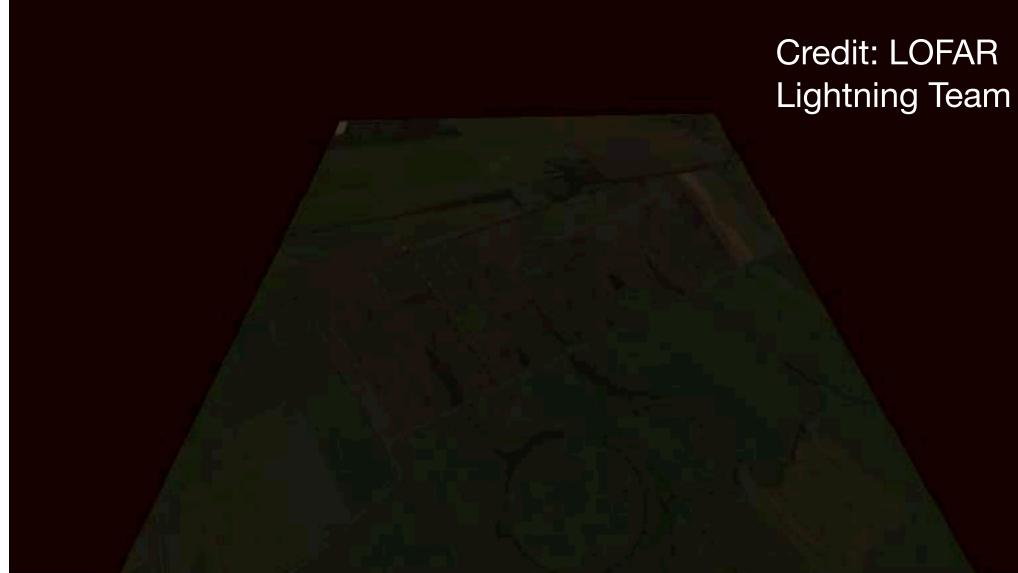


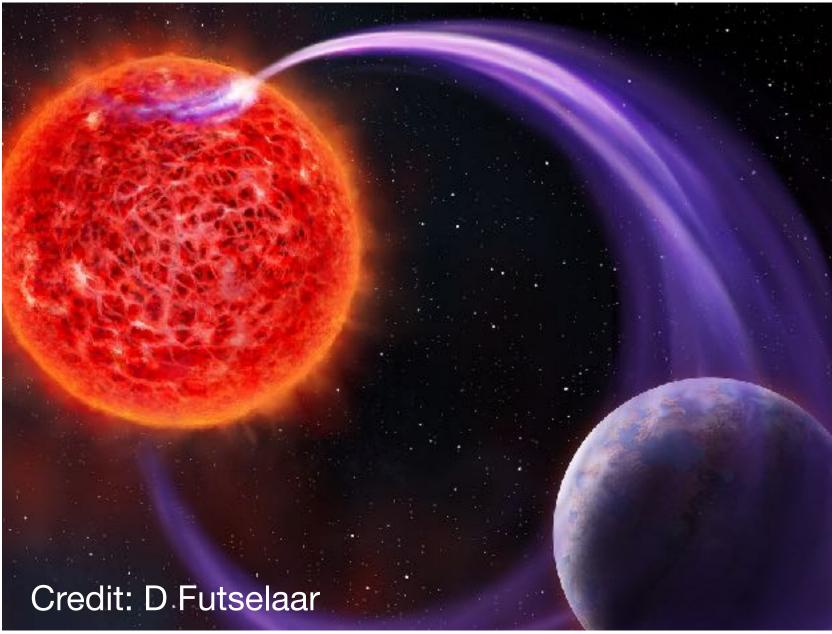
# Sampling other LOFAR science highlights

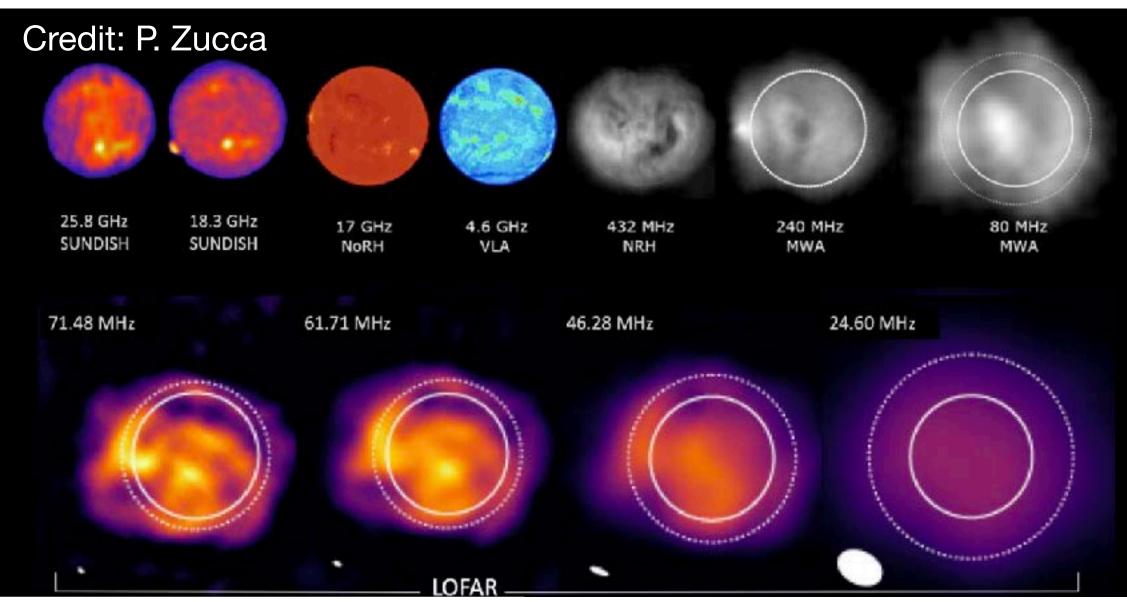
- Lightning (e.g., Hare+19, Hare+20)
  - Discovery of sub-structures (needles) explaining repeated discharge on the ground

## • Star-planet interactions, Exoplanets (e.g., Vedantham+20; Callingham+21)

- First compelling evidence for radio emissions from star-planet interaction
- Solar physics, Space Weather (e.g., Zhang+22) lacksquare
  - High quality interferometric imaging spectroscopy observations of quiet Sun coronal emission at frequencies <90 MHz







## Major science capability upgrades and expansions

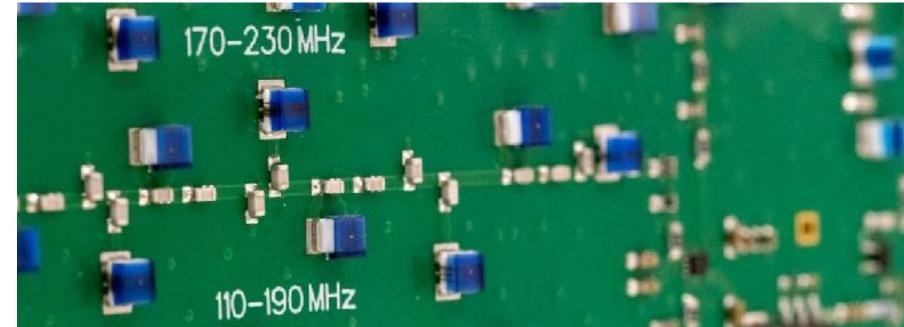
- Build on existing investments by enhancing distributed and central hardware & software components
- Remain unique and scientifically impactful in the SKA era
- Make LOFAR & its data more accessible to non-experts

## Enabling Technologies

- 3x higher level of integration of electronics
- 3x more powerful realtime processing in the same cabinets
- Central clock distribution to all NL stations (White Rabbit)
- Higher dynamic range (from 12 to 14 bits ADC)
- Improved thermal design
- Modernised monitoring and control (TANGO, OPC-UA)

## LOFAR2.0 status

- Hardware production and assembly ongoing
- Verification of LOFAR2.0 test station completed
- Planned station upgrades 2024-2025, first general science 2026









# What's new with LOFAR2.0?

0.3

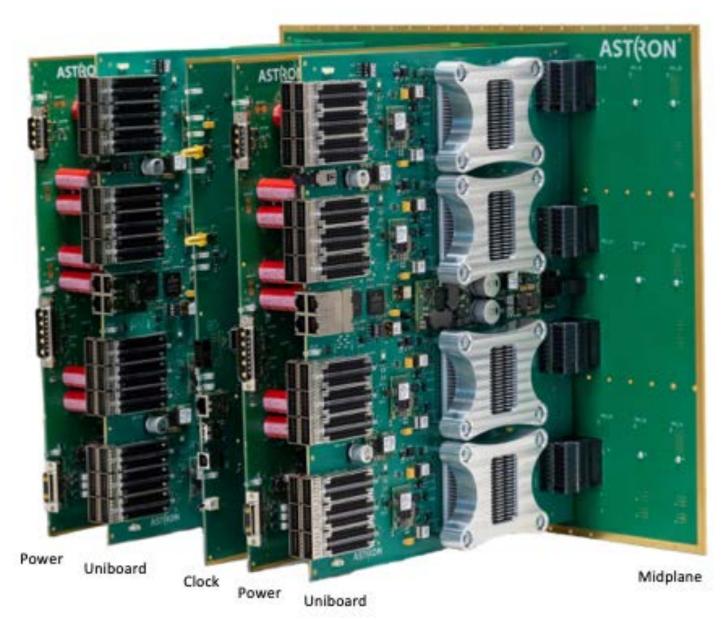
€ 0.0

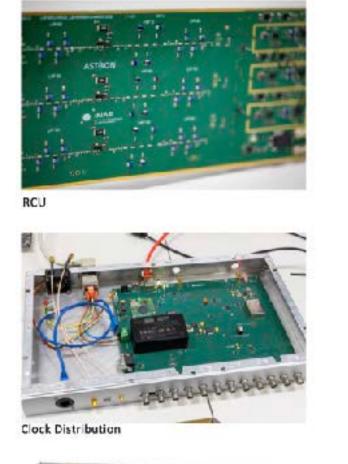
## Station cabinet hardware upgrades

More receivers and processing capacity

- Simultaneous LBA-HBA observing
- Double number of active LBA antennas (NL only)
- **Central clock to NL stations**
- **Better linearity**
- **Transient buffer & trigger mechanism 24/7**

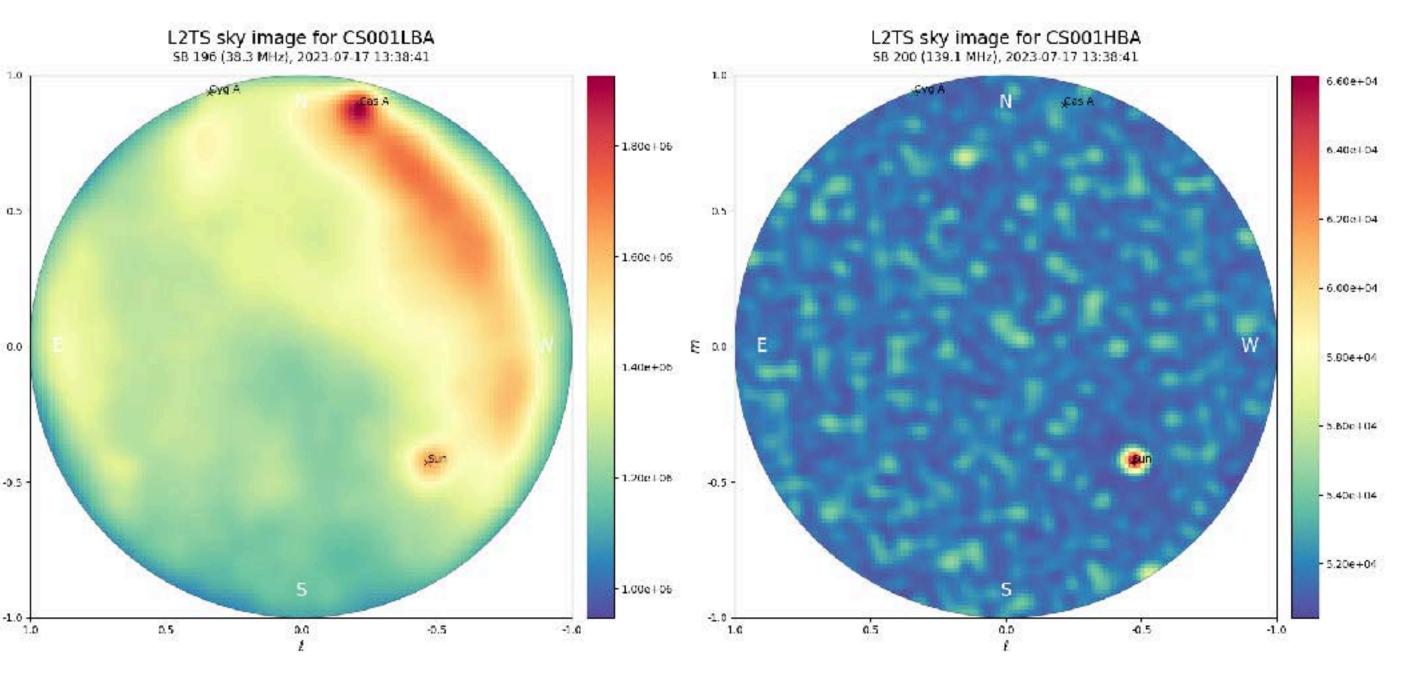
#### LOFAR2.0 Test Station hardware







## First simultaneous LBA+HBA all-sky images with LOFAR2.0!





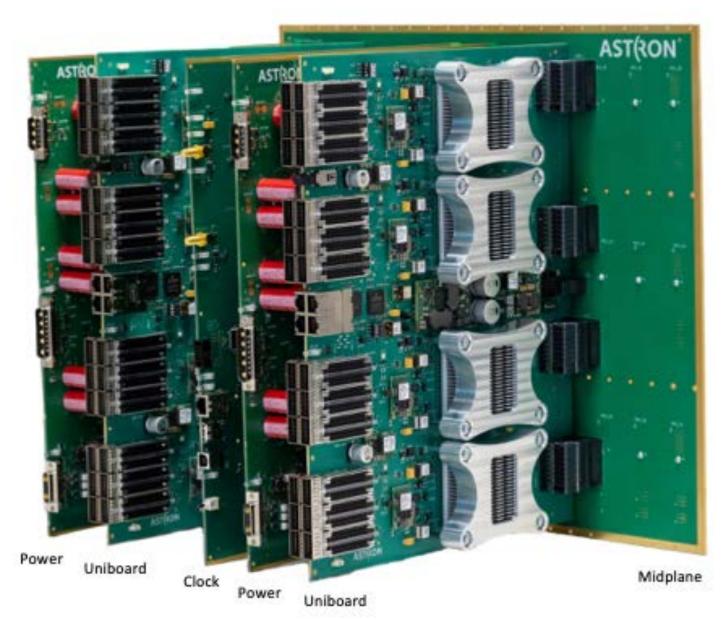
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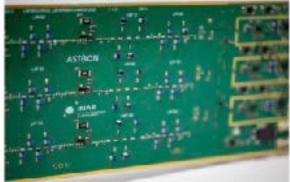
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#### LOFAR2.0 Test Station hardware









# Other developments

- **Correlation of NenuFAR Tied Array with LOFAR**
- New correlator, central processor, network ullet
  - Megamode simultaneous interferometric and beamformed observations
- New telescope management & scheduling system lacksquare
- New standard imaging (& other) pipelines
- **New-generation HBA front-end boards**
- LOFAR carbon footprint and energy consumption



Time in UTC on 2023-06-01



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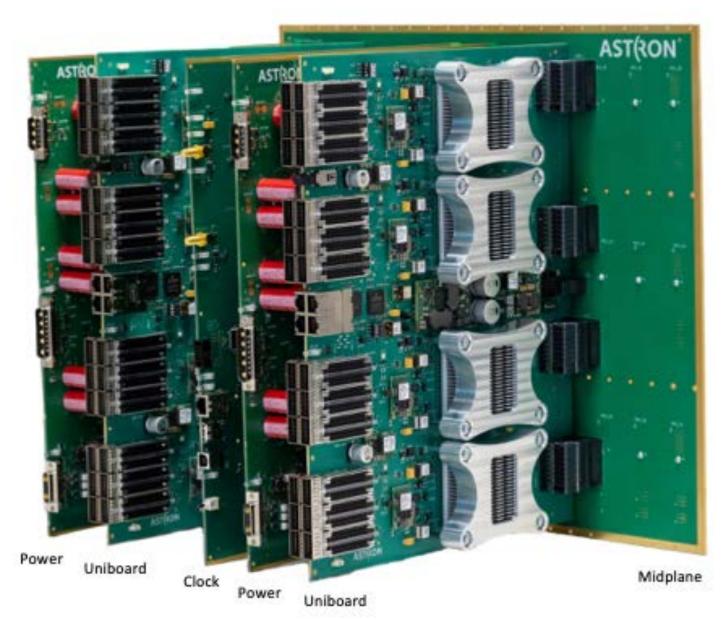
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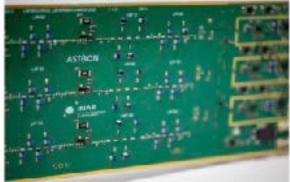
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#### LOFAR2.0 Test Station hardware





RCU

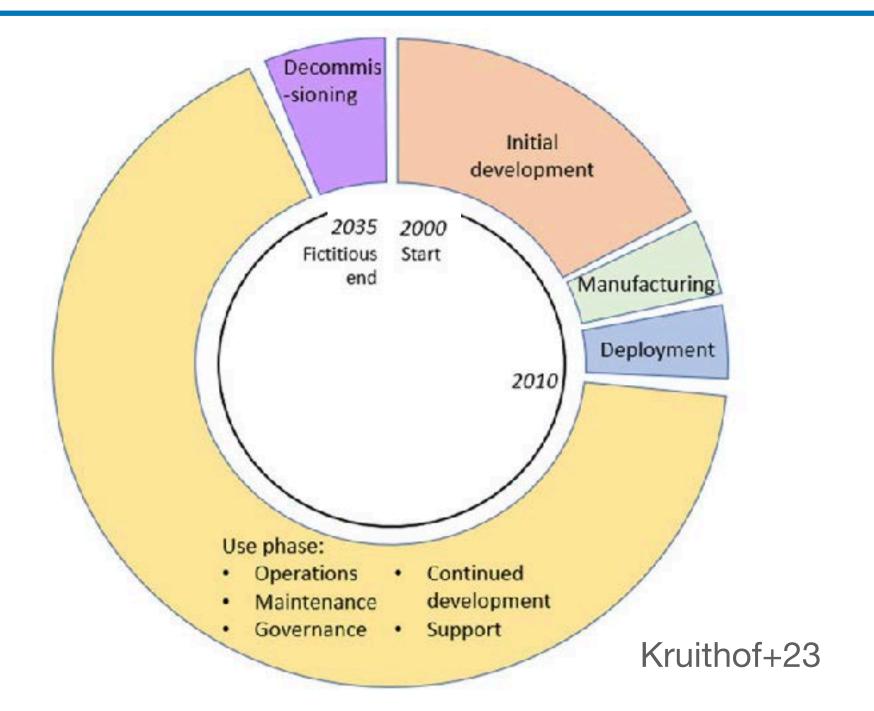


**Clock Distribution** 



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- New standard imaging (& other) pipelines
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- LOFAR carbon footprint and energy consumption





# LOFAR 2.0 roll-out

• Staged delivery - 5 Array Releases

	AR-A	AR-B	AR-C	AR-D	AR-E
Approximate date	Q2 2024	Q4 2024	Q1 2025	H2 2025	2026
LOFAR2.0 stations	1	3	4–38	38 ("Dutch")	54 ("Eur")
Single clock	LOFAR1 RS	LOFAR2	Dutch	Dutch	Dutch
	+LOFAR2				
Central processor	LOFAR1 full	Limited	Limited	Full array	Full array
Network upgrade		LOFAR2 and	Dutch	Dutch	Europe
		most RS			
Station automation	Jupyter	Scripts	Full	Full	Full
Ops automation	N/A	Scripts	Partial	Full	Full
Pipeline integration	R&D	R&D	Manual	Partial	Full

2024			2025			2026					
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2		•••
	Α		В	С		D		E	SV		

# LOFAR 2.0 roll-out - progress

- On 2 September LOFAR 1.0 was switched off! •
- On schedule to start hardware integration in February 2025 and station rollout from March 2025.
- Working on a detailed rollout planning, based on the experience of rolling out the production test stations.





# **Production Test Stations**

Goal: Final verification before releasing designs for series production

# **CS001**











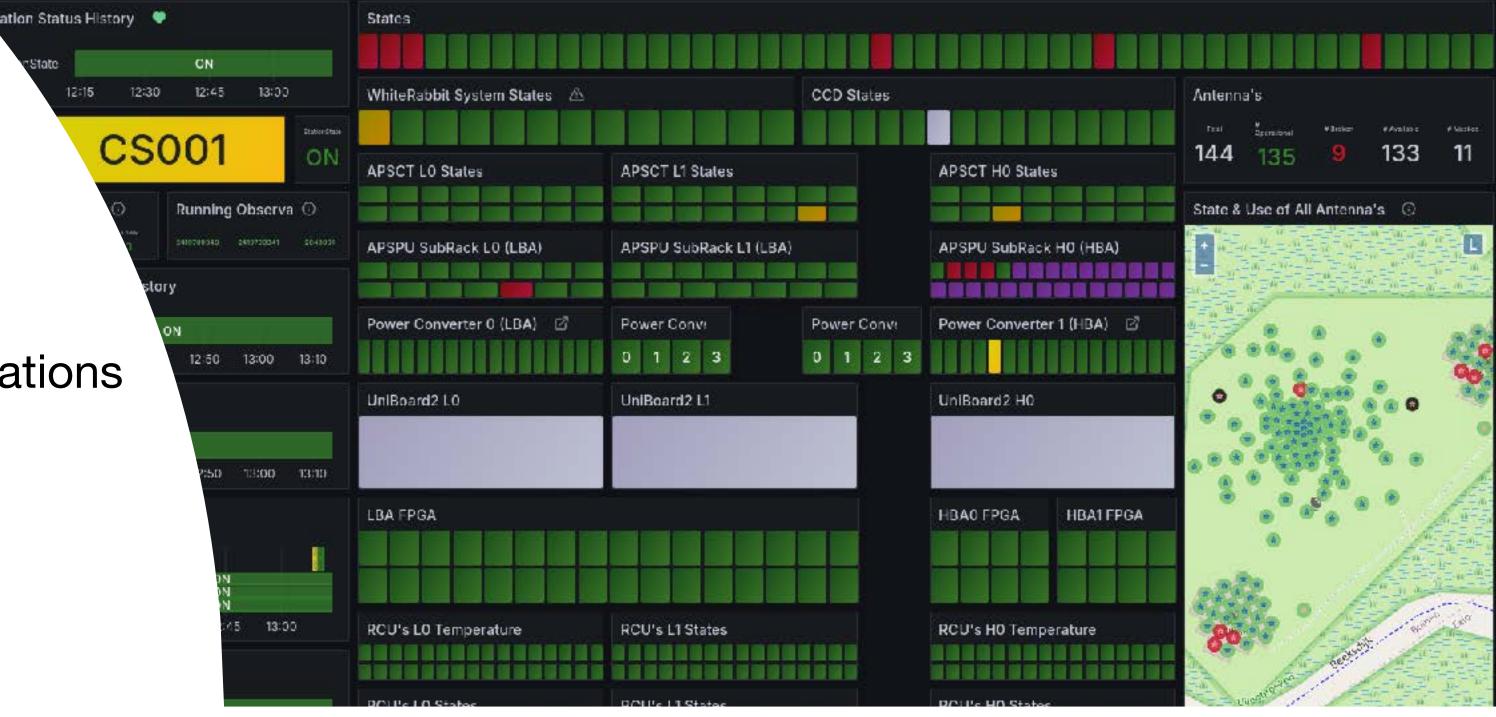
# LOFAR 2.0 Central Systems

- Commissioning of LOFAR MegaMode
  - Observations done
  - Processing ongoing, looking good!
- Correlator (COBALT2) and compute cluster (CEP4) have been reconfigured for LOFAR2.0 commissioning
- New core network switches have been installed
- Procurement of COBALT3 and CEP6 is progressing to plan. Public tender completed. Hardware to arrive in Mar/Apr 2025



# Software Development

- Top priority: support the LOFAR2.0 rollout
  - Central infrastructure to control the new stations
  - Monitoring (temperature protection!)
  - Automated station test
  - Station calibration
  - Data inspection toolkit
- During commissioning, the software will be on the critical path
- Functionality will be enabled step-by-step
- Robustness will take time



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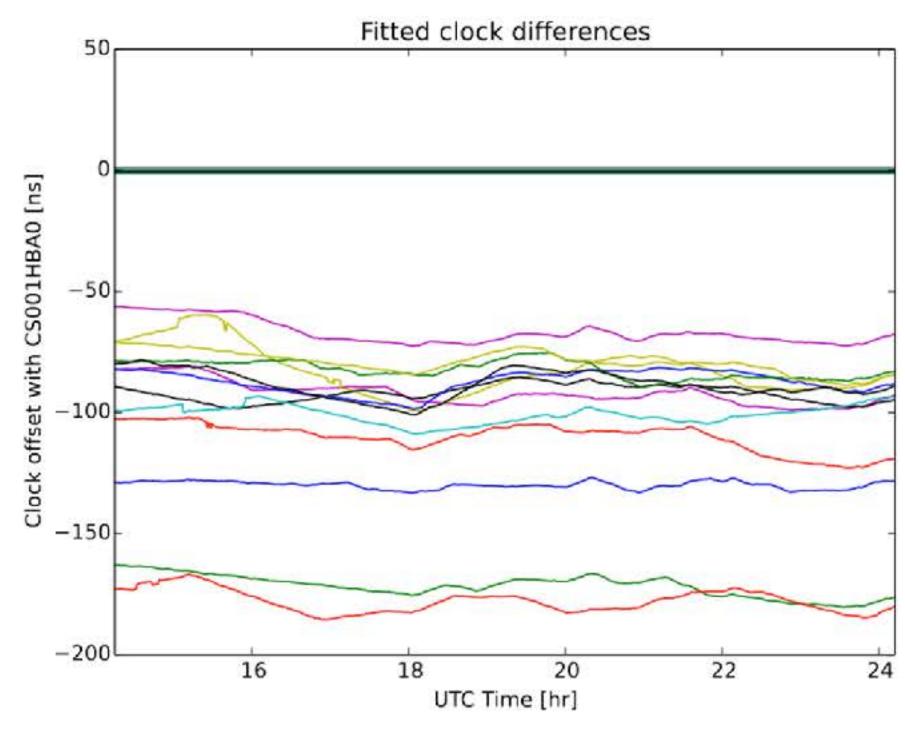
	nily 🖓	member 🖓	state 🖓
	NB2	но	OFF
	NB2	LO	OFF
	JNB2	u	OFF
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/	AFH	HBA1	ON
	TemperatureManag	1	ON
	APSCT	но	ON
	APSCT	LO	CN
	APSCT	L1	CN
	DigitalBeam	HBAO	GN
	DigitalBeam	HBA1	CN
	DigitalBeam	LBA	CN
	StationManager	1	QN
	TileBeam	HBA0	CN





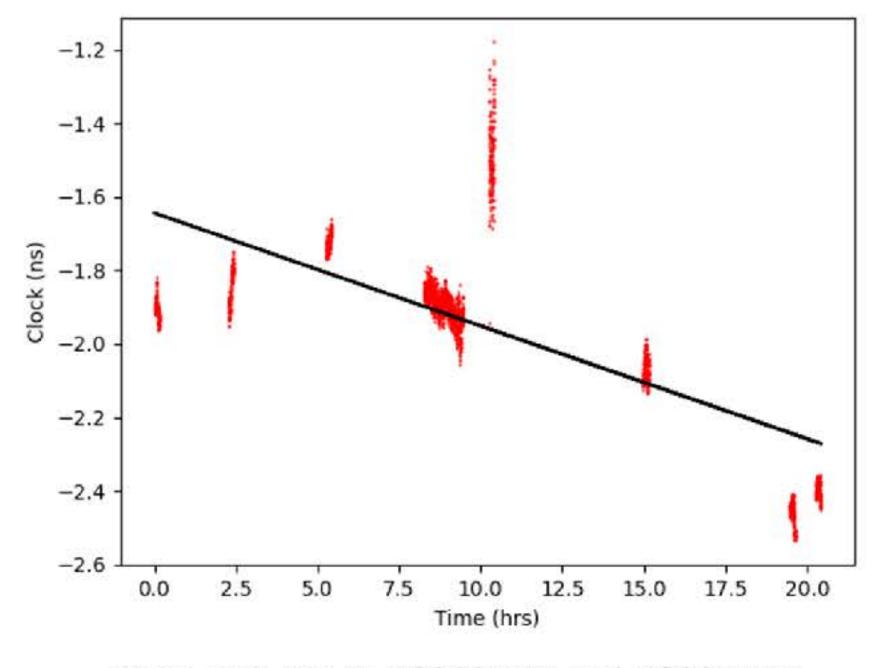
# White Rabbit clock distribution

Current LOFAR clock



Van Weeren et al. 2016

## With White Rabbit



Tests with WR in RS208HBA and RS307HBA. Credits: R. Witvers, J. Morawietz, T. Shimwell

# LOFAR 2.0 Commissioning

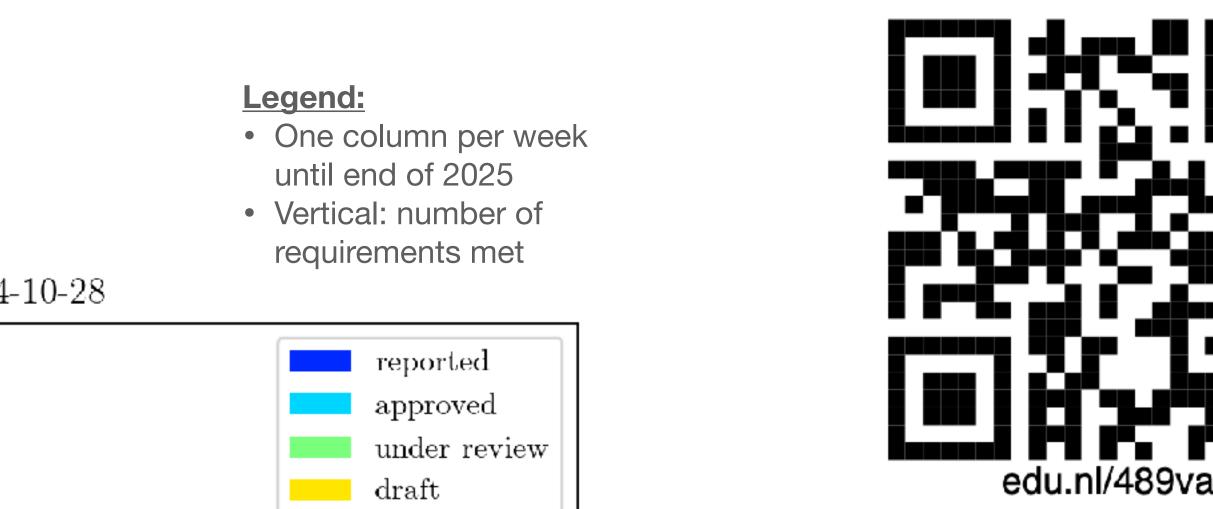
LOFAR-2.0 commissioning progress 2024-10-28



2024-09-02 2024-10-28

## **Progress so far:**

- Last day of LOFAR (1.0) : September 2nd 2024
- Three LOFAR 2.0 stations available for commissioning
- Requirements and telescope functions (almost) fully described (in Polarion)
- L0 requirements assigned to teams and releases • test plans being drafted



**ASTRON Confluence link** Register to get access

## **Stations**

- Can use all LBAs and HBAs simultaneously
- Are reasonably well phase-calibrated

remaining

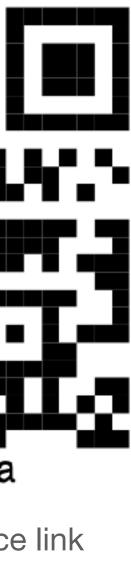
- Are on the new clock system
- Can be controlled and inspected through Jupyter notebooks
- Can be (partially) inspected through Grafana

## CEP

- Network reconfiguration done
- OS upgrade done
- Cobalt (correlator/beamformer) works gain
- CEP4 waiting on global file system config

## **User Facing**

• New proposal tool in initial test use



# LOFAR2.0 Large Programmes

- 5-year programme (2026-2030)
- ~21,000 hours available assuming 70% observing efficiency
  - Deadline: 15 October 2023
  - 15 proposals received
  - SDCO evaluation completed compute and data storage requests exceed capacity
  - Programme Committee evaluation planned for early 2025.





# LUFAK EKIU

Low Frequency Array



INFORMATION FOR SCIENTISTS



# LOFAR 2.0 Large Programme - Data (Processing) Challenges

## **Historical context:**

- In the LOFAR 1.0 era, data processing couldn't keep up with acquisition
- Result: 62.1 PB archived, mostly raw, data reduced to ~56 PB after compression of some data
- This approach cannot be sustained for LOFAR 2.0
- Data processing must keep pace with data gathering
  - Raw & intermediate data products may only be retained for a limited time (1-2 years)

## **Technical Review of Proposals:**

- ~48,000 hours of observing time requested
- Compute requests: at CEP O(10<sup>7</sup> core hours) and at LTA sites (or after CEP) O(10<sup>9</sup> core hours)
- LP storage requirements: 32 PB for final data products (science ready data) stored indefinitely

## Challenges facing us...

- resources as well as processing techniques (pipelines) & expertise.
- Busy week held 21-25 October to discuss challenges with Large Programme PIs
- pipelines to process the data



rising to 87 PB including requests from some PIs to store raw (visibility data)

• Successful execution of LOFAR 2.0 Large Programmes depends on availability of compute, storage & network

• LOFAR ERIC and L2LP Teams working to acquire sufficient resources for storage and processing + develop

# **Opportunities for further development beyond LOFAR 2.0**

#### LOFAR ERIC → More robust governance to anchor and expand LOFAR partnership $\bullet$

- Partner participation at national level, aligned to common long-term strategy and vision
- Joint funding, steering, and implementation of major projects (e.g., LOFAR2.0)
- Increase scientific impact through continued development

## **Potential Future Developments**

- Next generation LBA: Ultra-low-band: 5-50 MHz
- Improved 24/7 all-sky monitor (AARTFAAC)
- Hand-in-hand with investments in LOFAR processing
  - algorithmic enhancement and real-time processing for imaging pipelines
- Upgraded data discovery and access systems



Increased network bandwidth between stations and correlator (10 to 100 Gbps)

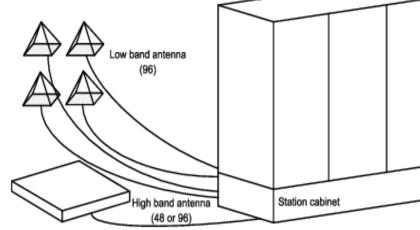


# The LOFAR system - Data flow

## **Central operation**



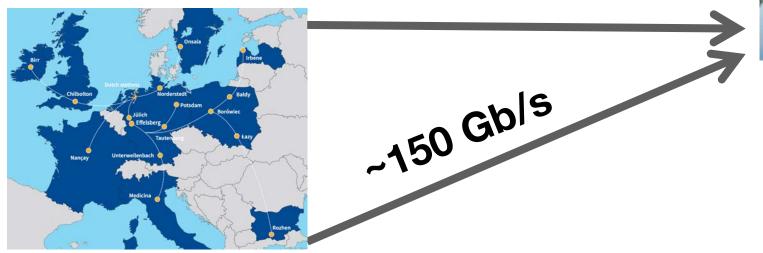
17 Tbit/s sampling

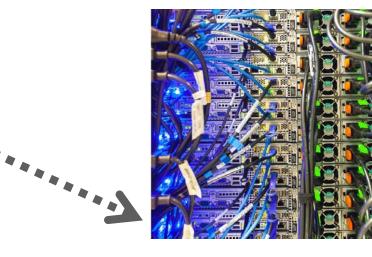


## **Station-level processing**

(incl. amplification, filtering, sampling, beam-forming, channelisation)

Data from 52 LOFAR stations





### Initial processing CPU & GPU system at RuG





## Correlation

GPU-based system at RuG 360 Tflops compute power 2 TB temporary storage

