LOFAR 2.0 - Upgrading the Low Frequency Array

A premier low-frequency radio facility for the 2030s and beyond

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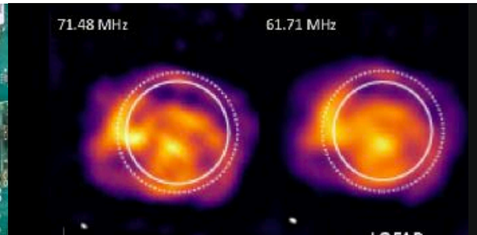
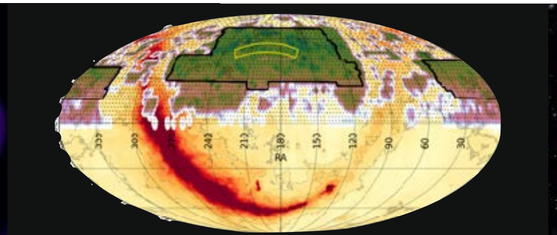
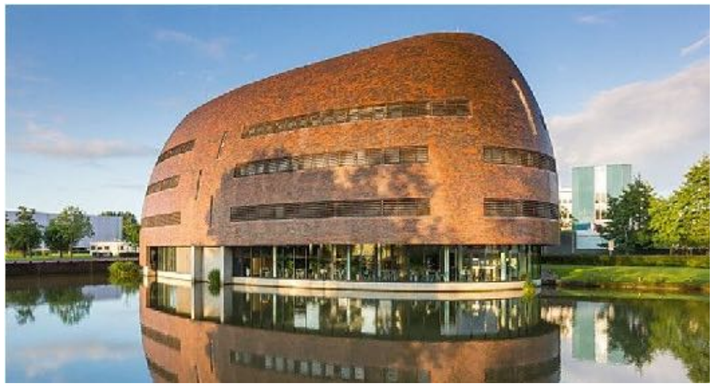




Distributed research infrastructure: world-leading low-frequency radio telescope

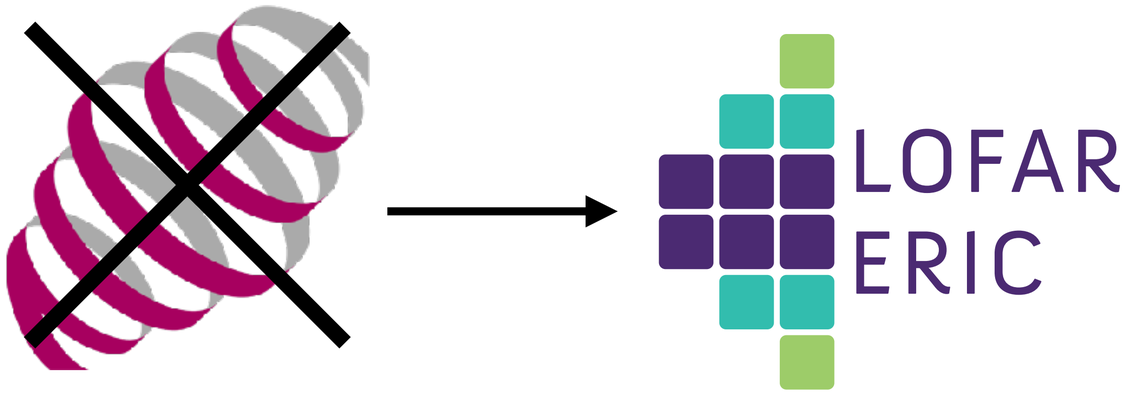
- **Distributed network of antenna stations: condensed in NL, extending >2000 km in Europe**
  - 52 antenna stations in 8 countries: NL (38), DE (6), PL (3), IE, UK, FR, SE, LV + 2 stations to be constructed in 2025: IT, BG
  - Central observing operations, peer-reviewed access for the research community
- **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)



An ERIC to anchor and further develop the LOFAR distributed RI

- **ILT Foundation → 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

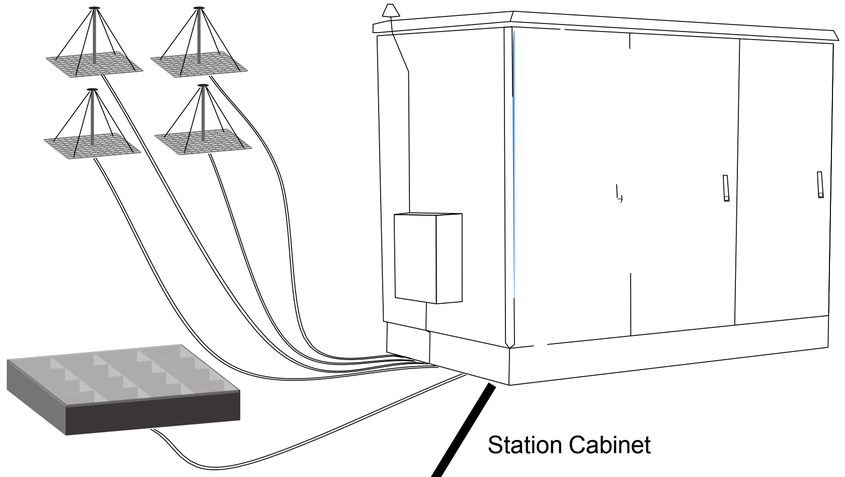
- **LOFAR ERIC → More robust governance to anchor and expand LOFAR partnership**
  - Partner participation at national level, aligned to common long-term strategy and vision
  - Joint funding, steering, and implementation of major projects (e.g., LOFAR2.0) - financial advantages
  - Increase scientific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

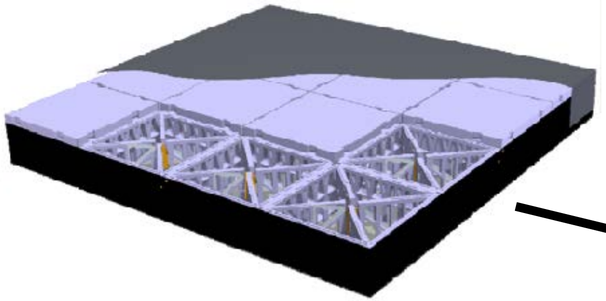


LOFAR Stations

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



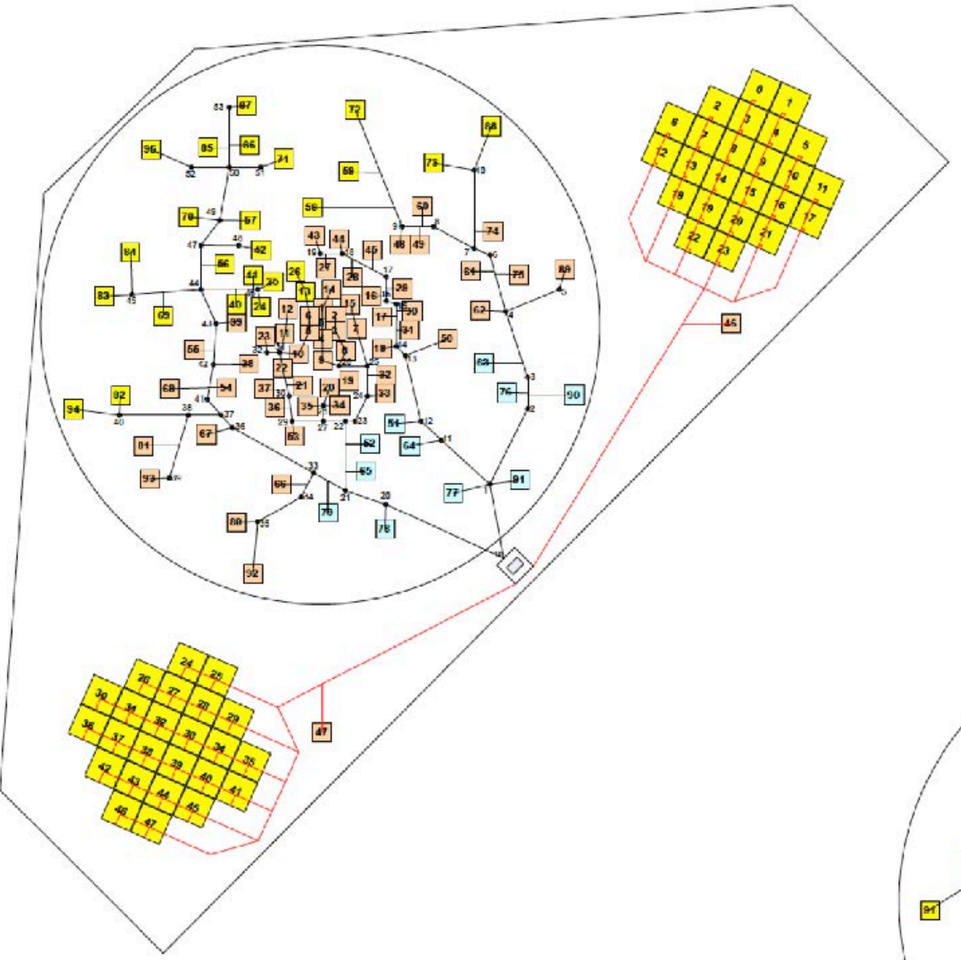


High-Band Antennas

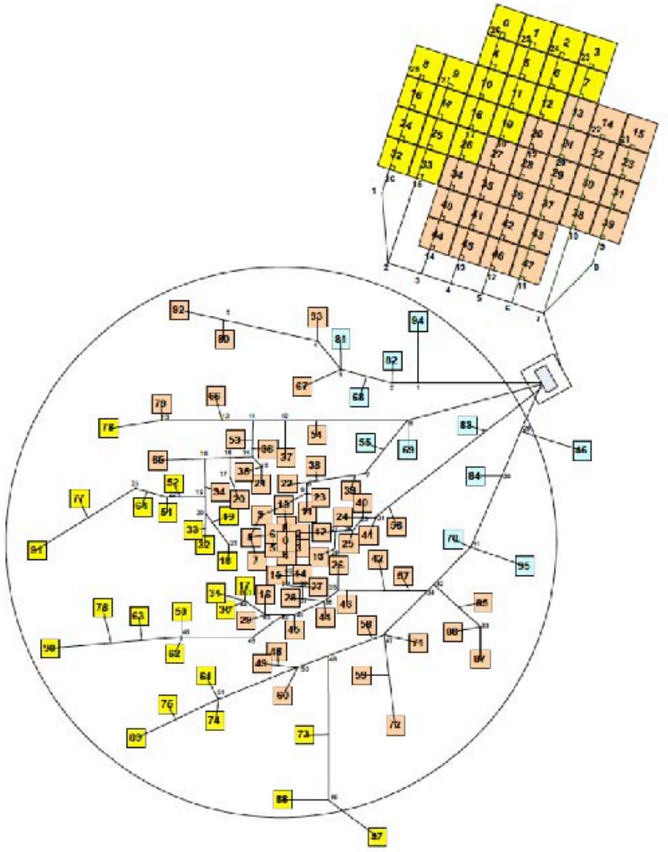
Frequency = 110-240 MHz
Wavelength = 1-3 metres

Low-Band Antennas

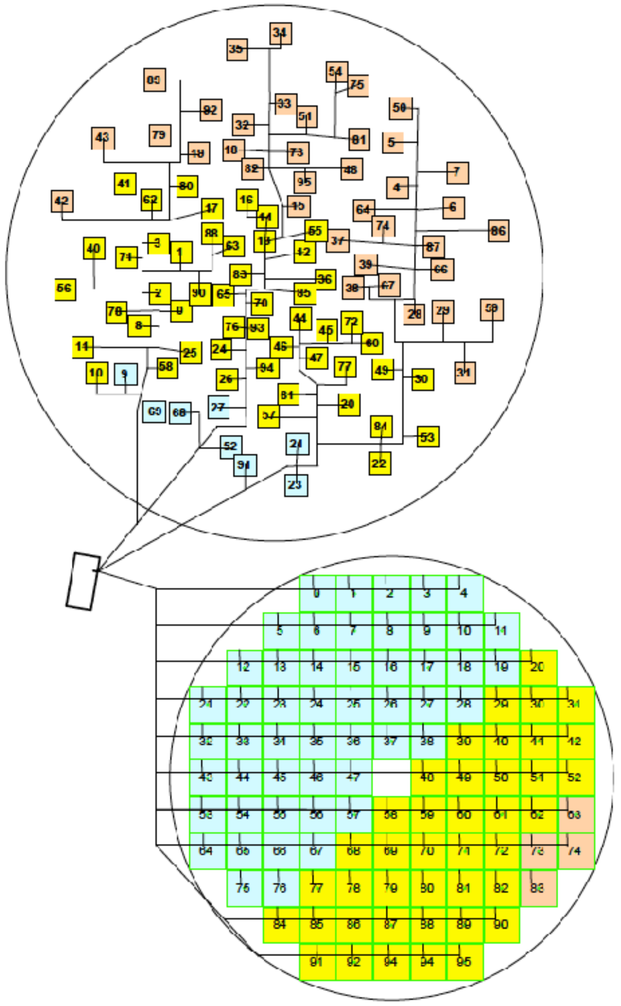
Frequency = 10-90 MHz
Wavelength = 3-30 metres



NL Core Station
96 LBA
2x24 HBA
N=24



NL Remote Station
96 LBA
48 HBA
N=14



International Station
96 LBA
96 HBA
N=14+2

The LOFAR1 system - Data flow

Long Term Archives
SURF in the Netherlands
FZJ in Germany
PSNC in Poland

Science processing
Clusters across Europe

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

~200 Gb/s

10s Gb/s

10 PB/yr

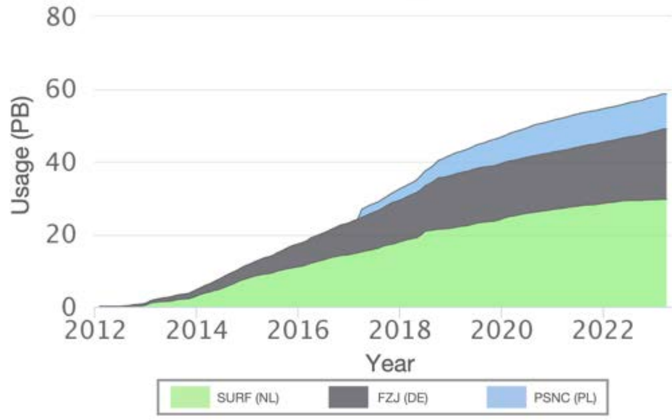
Station-level processing
(e.g., amplification, filtering, digitisation, beam-forming)

13 PB/s sampling

Initial Processing
CPU & GPU system at RuG

Central operation

Data repositories

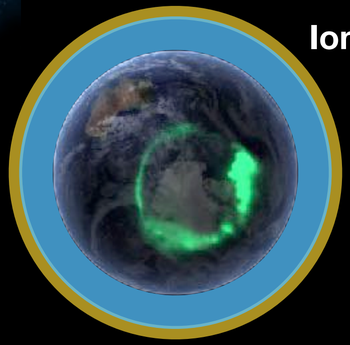


LOFAR’s broad science case

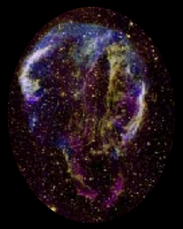
Meteors

Lightning

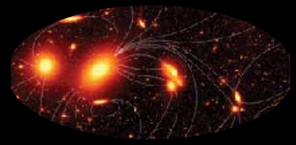
Ionosphere



Supernova remnants
Pulsar Wind Nebulae



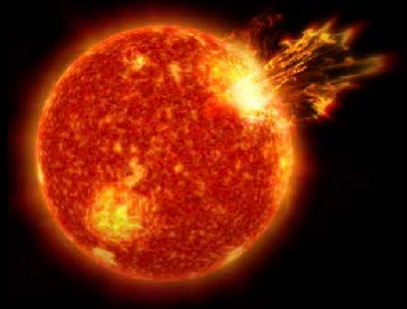
Cosmic
Magnetism



Clusters

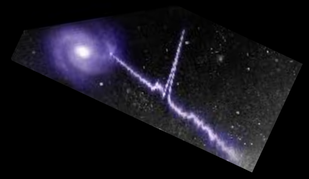
Heliosphere
Space Weather

Sun

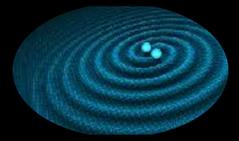


Pulsars

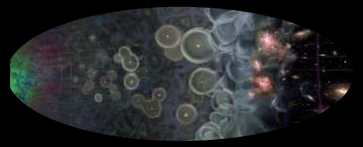
Fast Radio Bursts



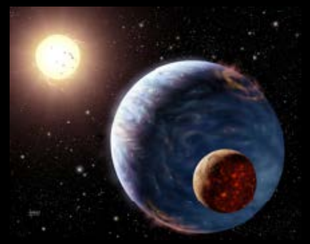
Gravitational
Wave Events



Early Universe
Cosmic Dawn



Exoplanets
Star-Planet Interaction

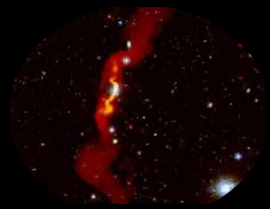


Solar System
Planets

Interstellar
Medium

Cosmic Rays

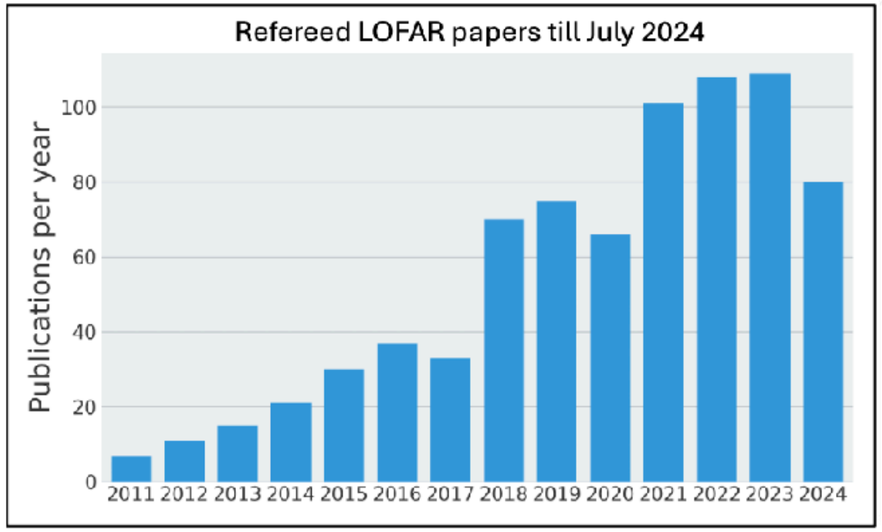
AGN physics

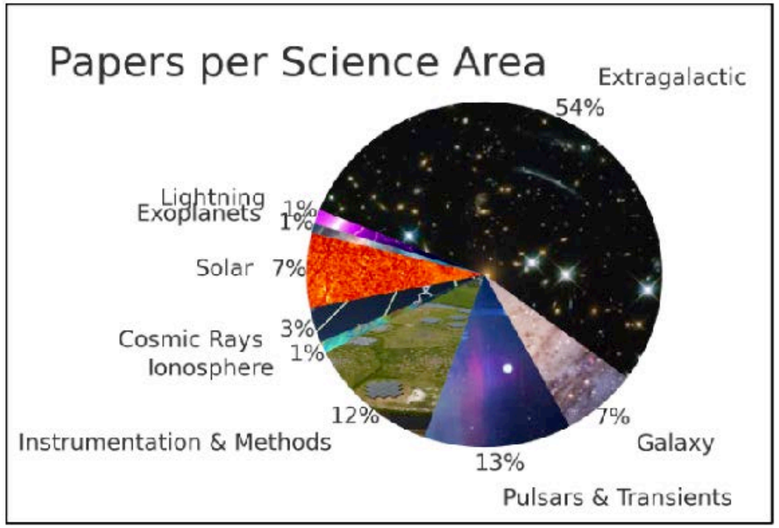


Nearby Galaxies

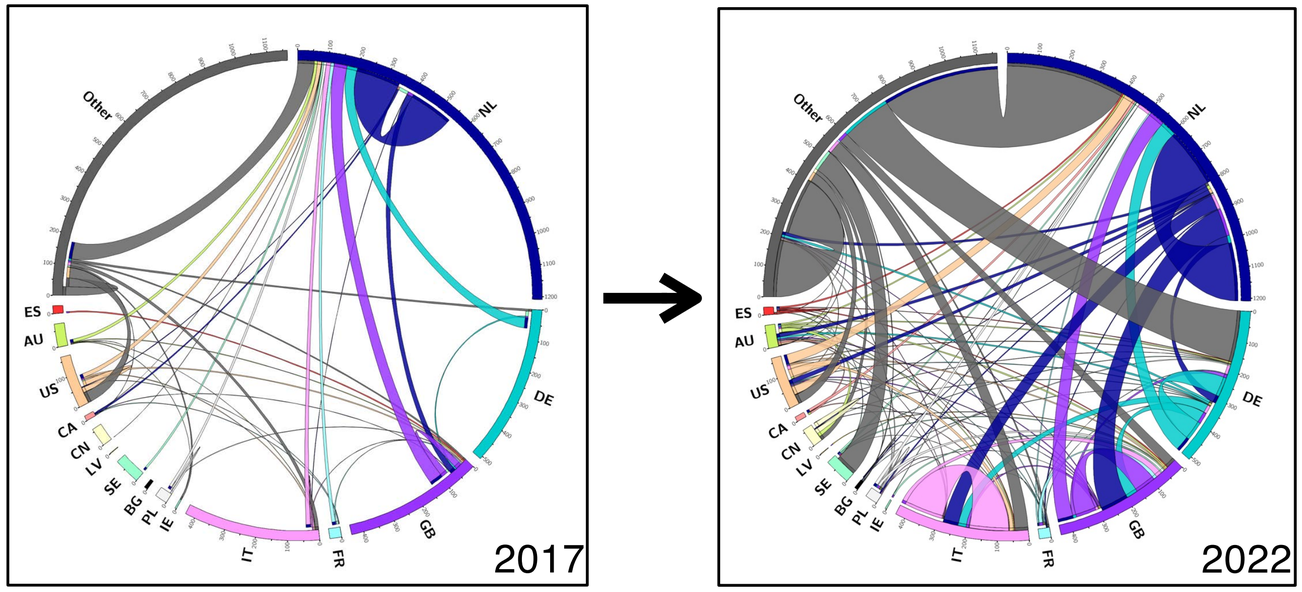
Community evolution and science output

- **>600 refereed publications**
- **~2 papers per week**
  → top 10% of all astronomical facilities





Credit: SDCO Team (ASTRON)

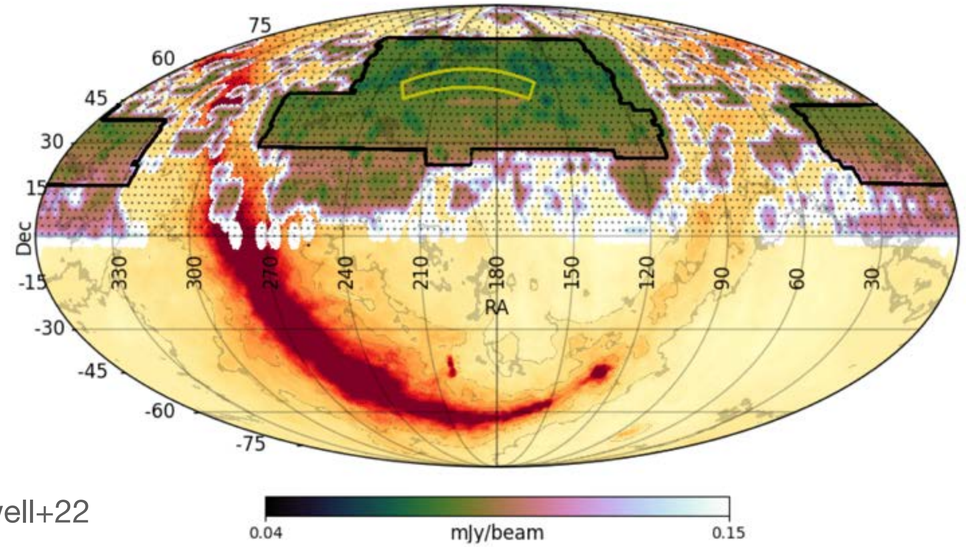


- **Measuring the success of LOFAR: Evolution of community and international collaborations**
  - LOFAR community spans the entire globe and has grown by a factor of ~3 in the period 2017-2022.
  - LOFAR collaborations increased by a factor of ~7 in the period 2017-2022.

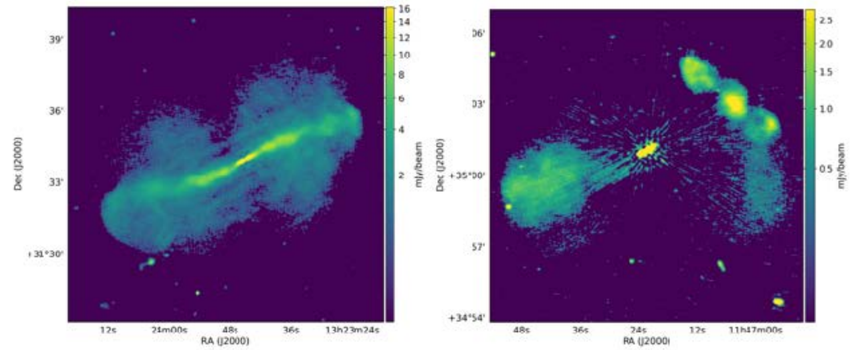
Credit: J. Dempsey

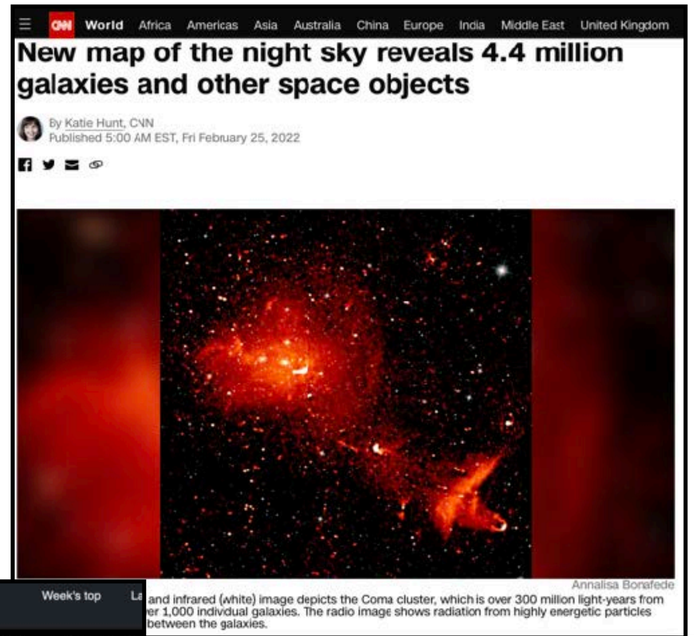
LOFAR science highlights

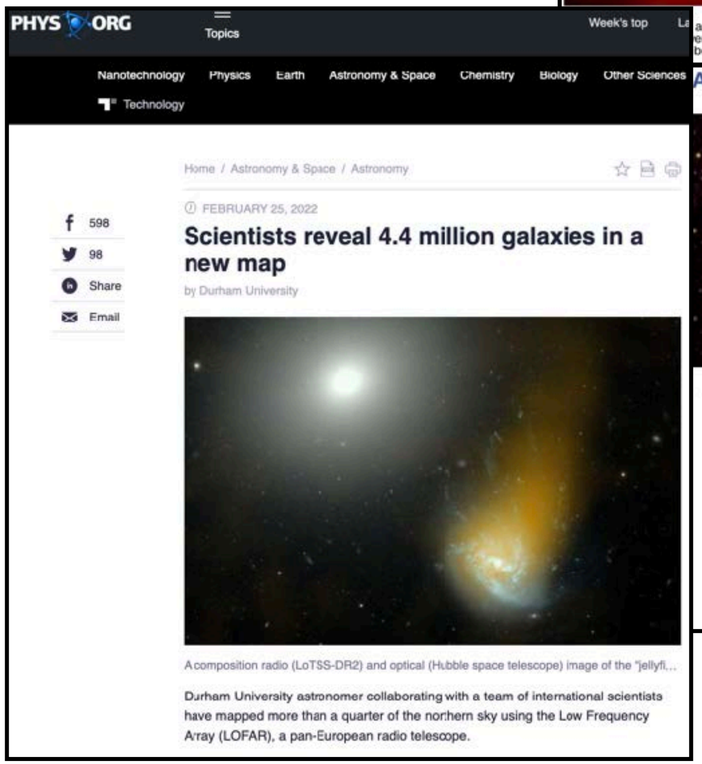
- **Surveying: huge area, huge object samples**
  - **LoTSS: LOFAR Two-Metre Sky Survey (Shimwell+22)**
    - Mapped ~27% of Northern sky at 120-168 MHz
    - Detailed radio image of 4.4 million objects
    - Resolution 6”

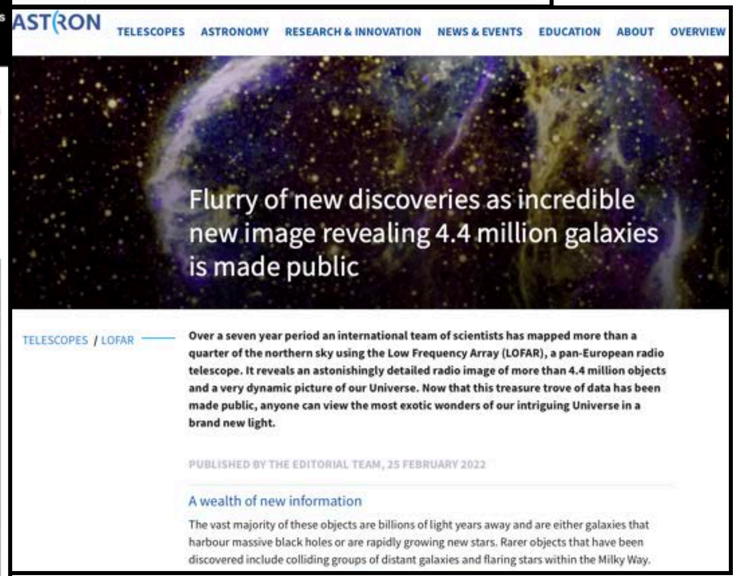


Shimwell+22



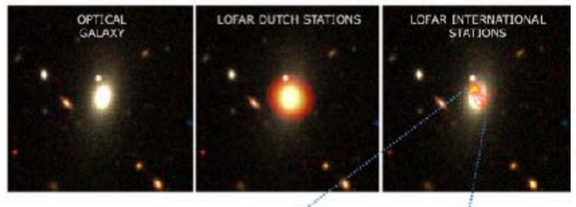


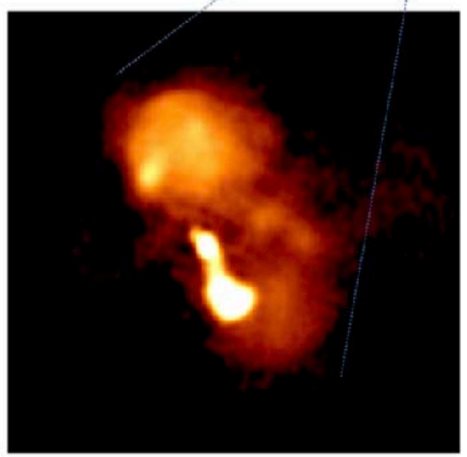


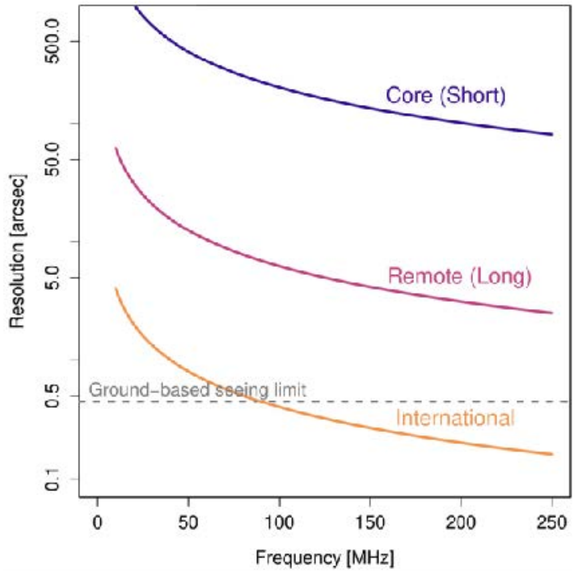


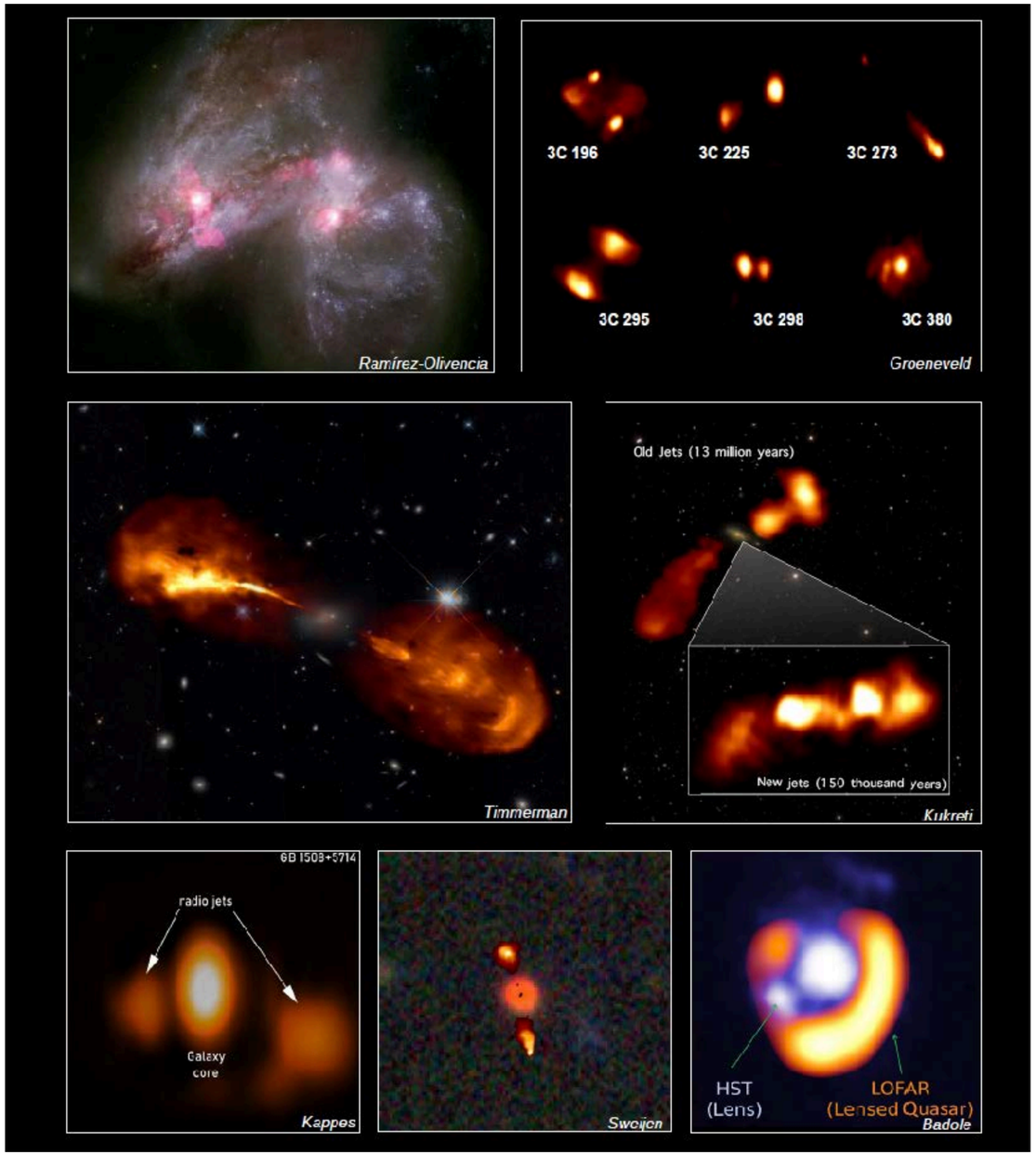
LOFAR science highlights

- **Most detailed images of galaxies at 150 MHz**
  - 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





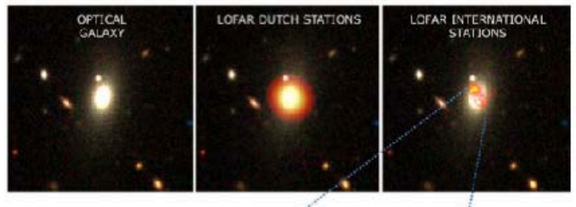


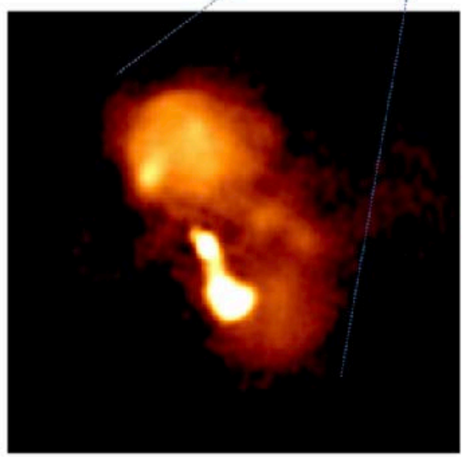


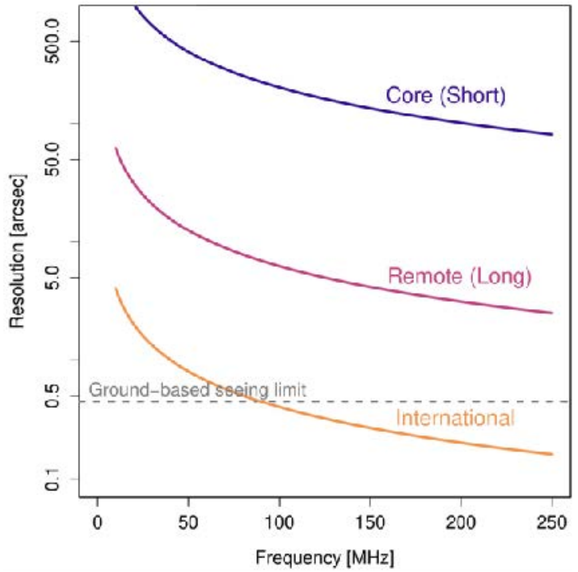
Credit: L.K. Morabito; LOFAR Surveys KSP

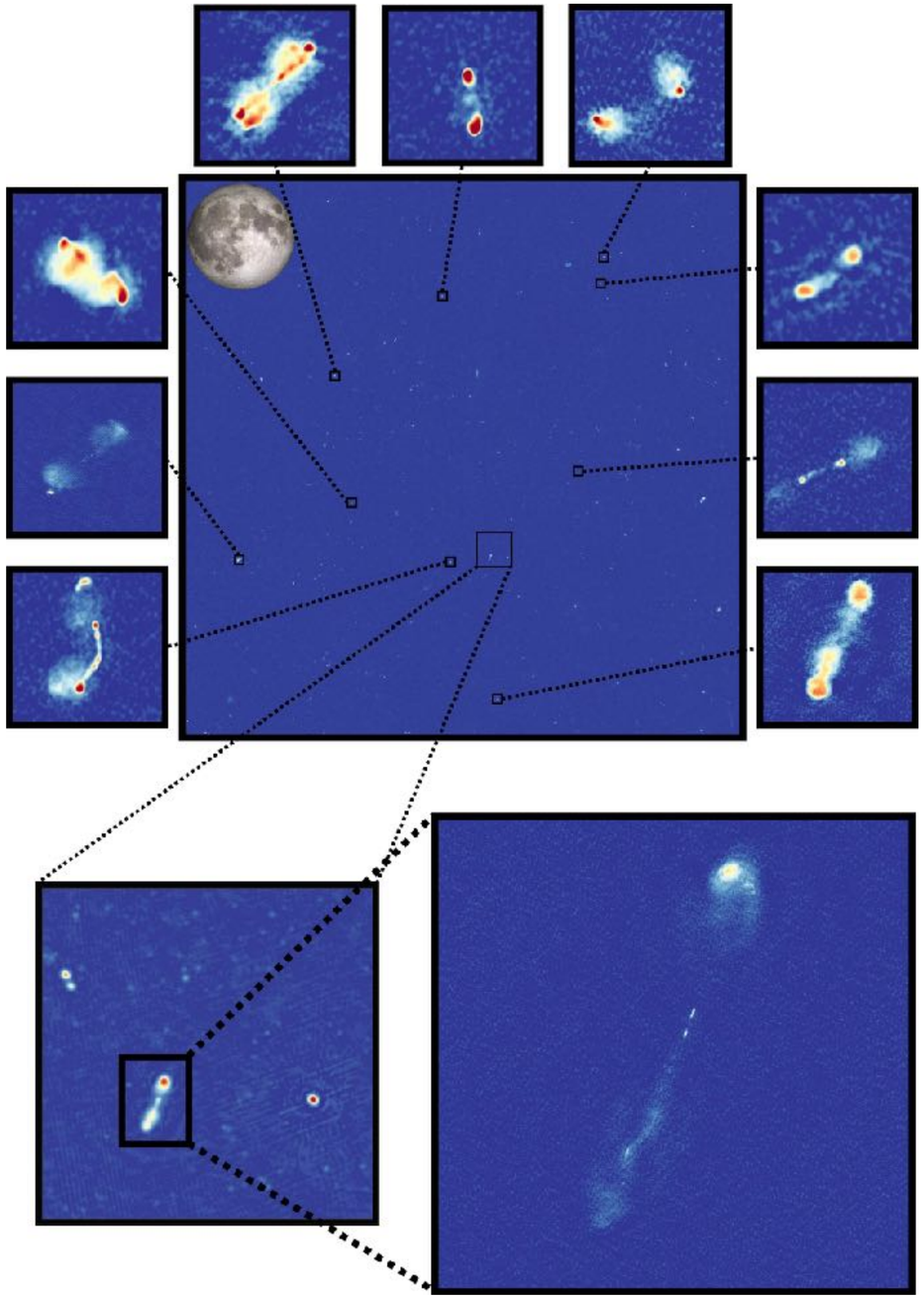
LOFAR science highlights

- **First deep wide-field sub-arcsec 144 MHz imaging** (Sweijen+22)
  - Multi-faceted correction of ionospheric distortions
  - Reduction of computational costs for imaging







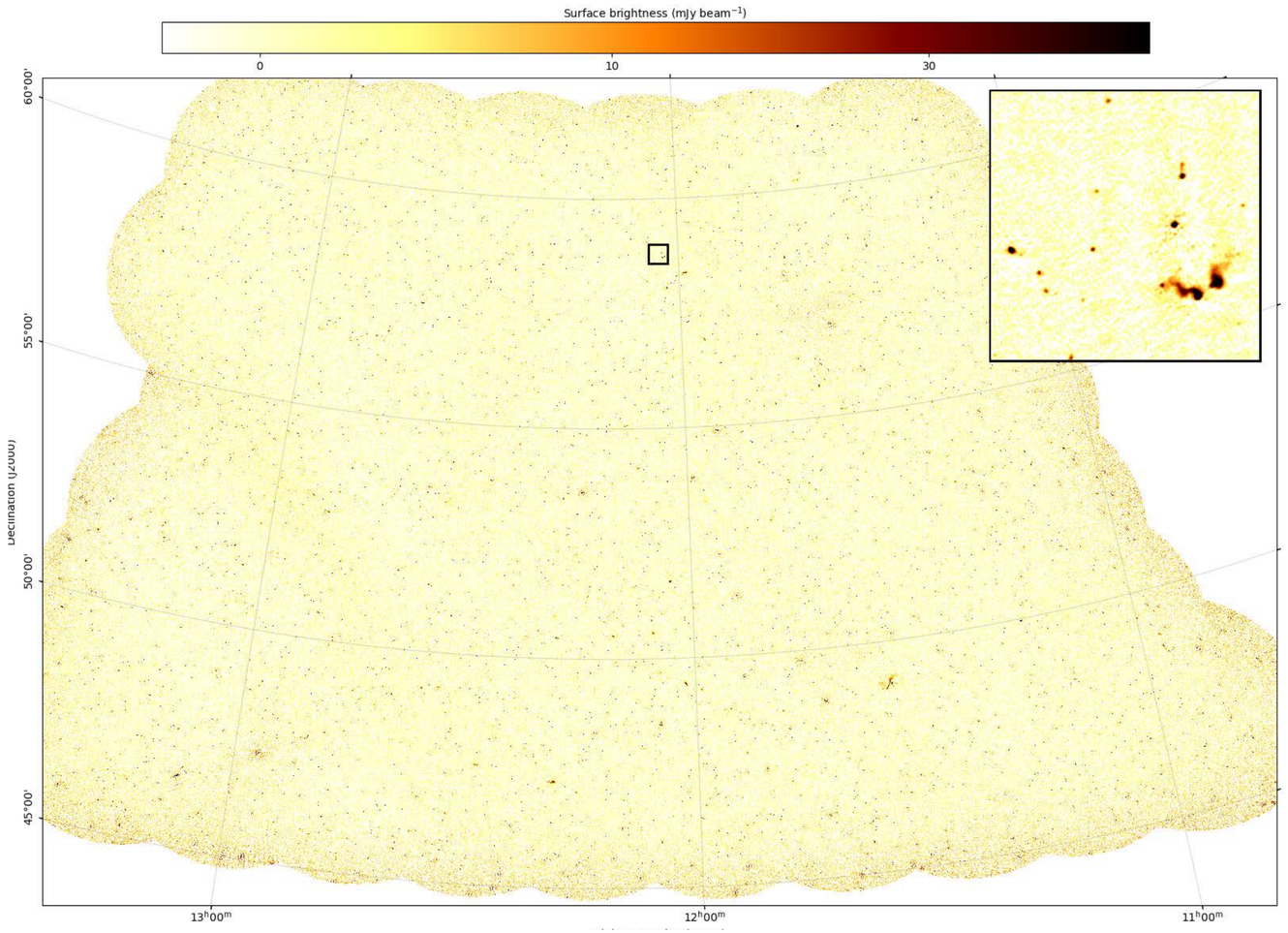


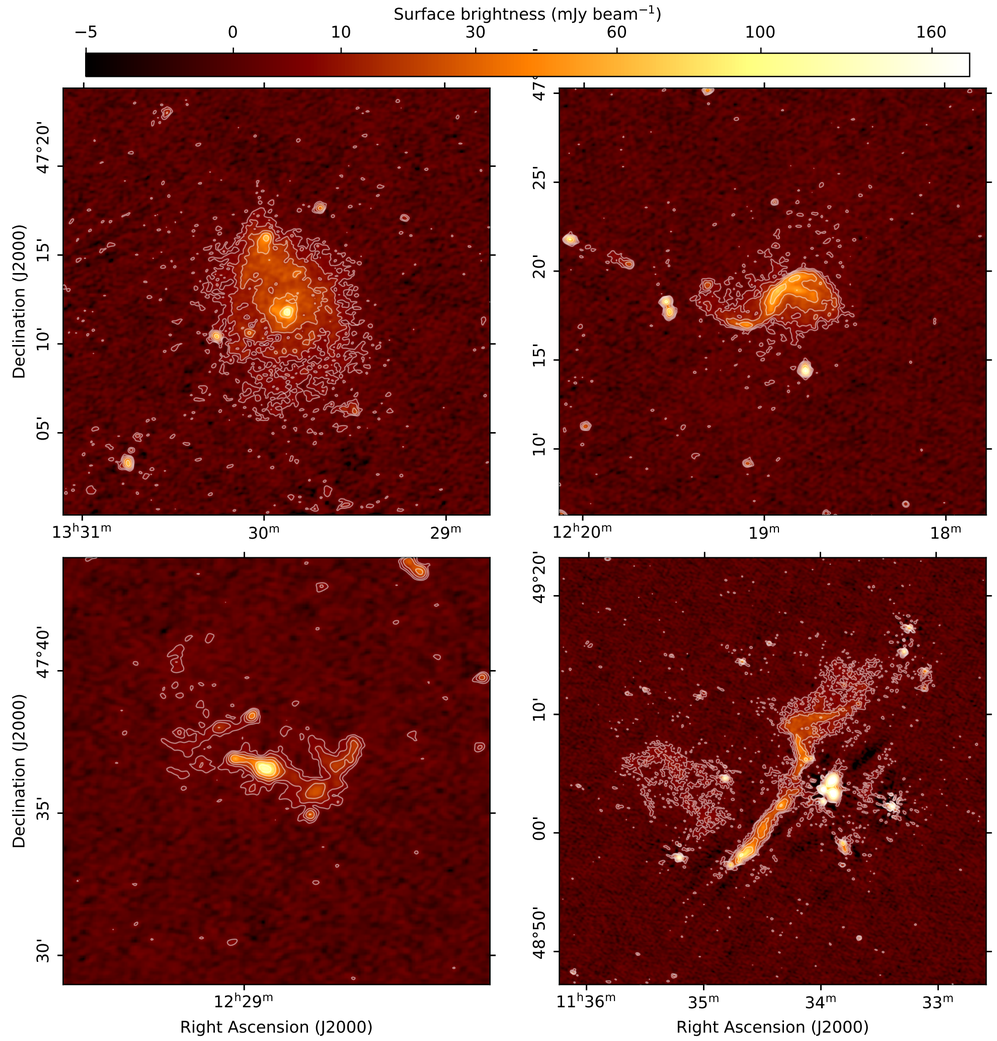
Credit: L.K. Morabito; LOFAR Surveys KSP

Sweijen+22

LOFAR science highlights

- **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

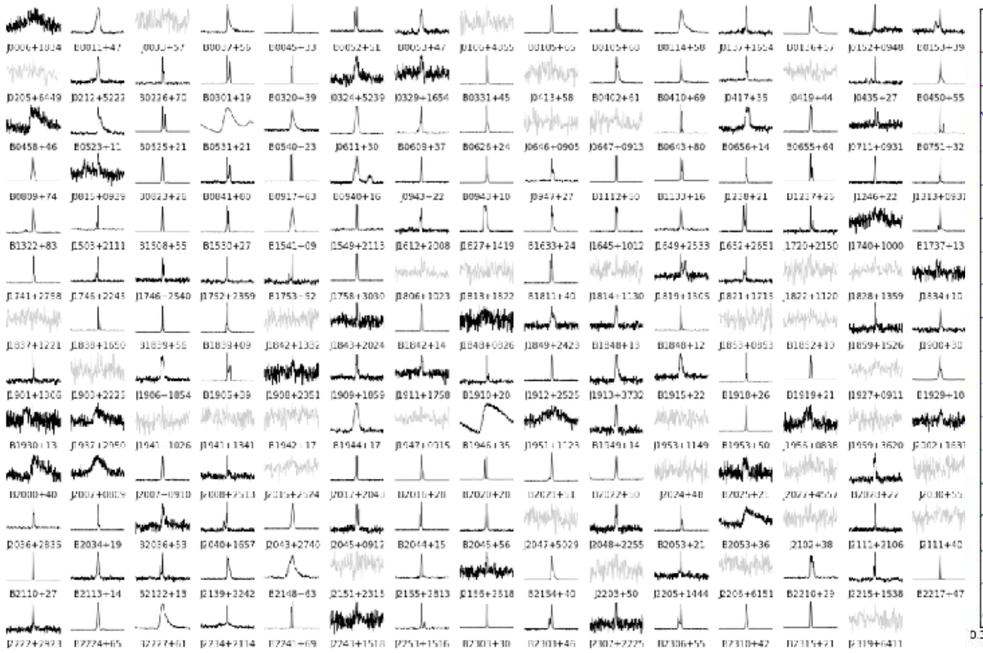




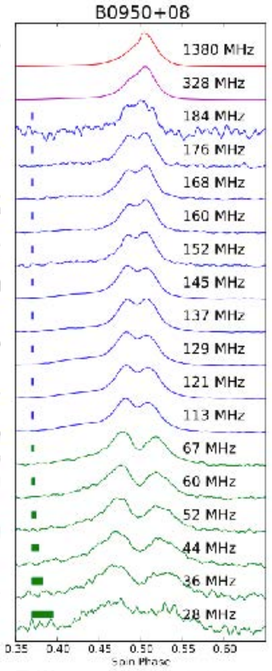
de Gasperin+23

LOFAR science highlights

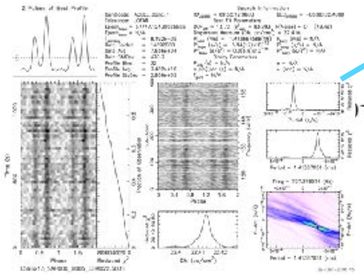
- **LOFAR Pulsar Census**
  - LOFAR has detected more than 300 pulsars so far
  - including a super-slow (23.5 second) pulsar (Tan et al. 2018) and a 1.4 ms (707 Hz) pulsar



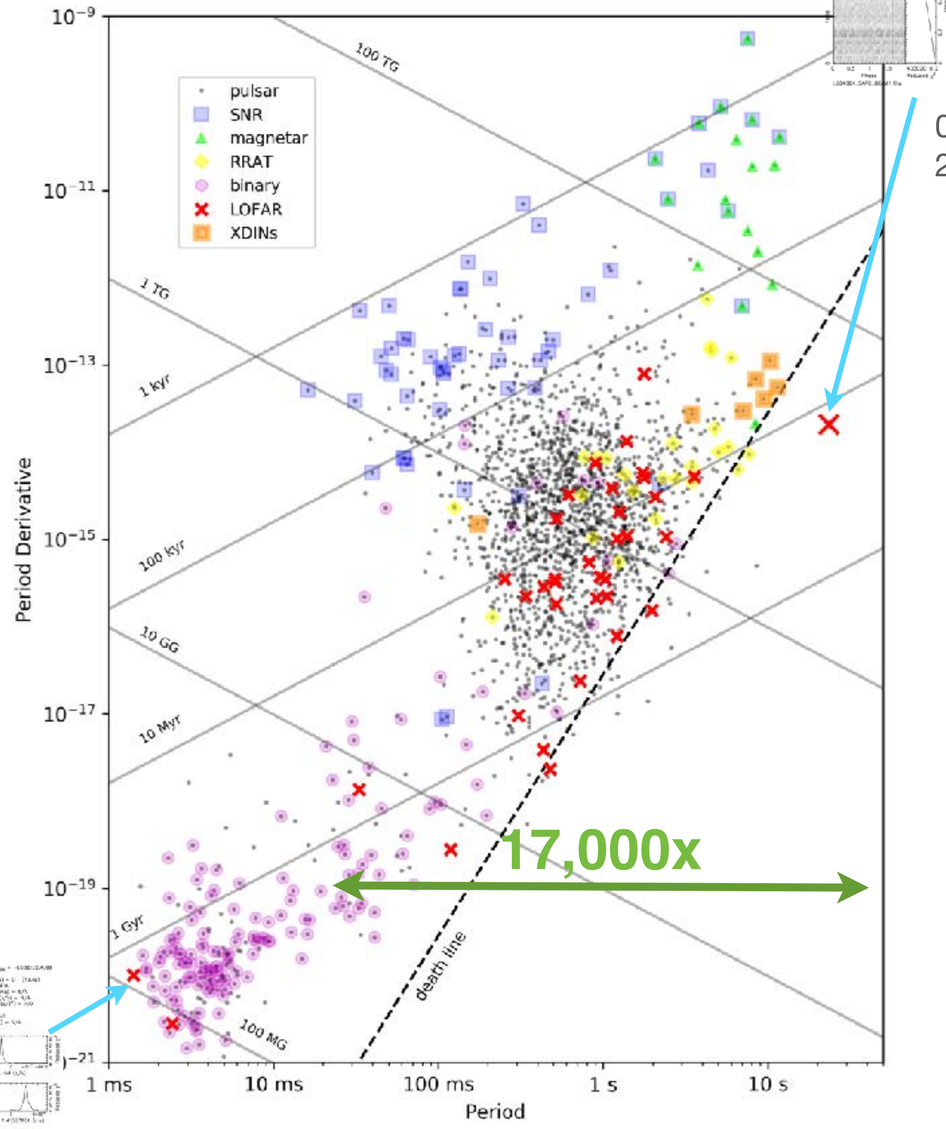
Bilous et al. 2016

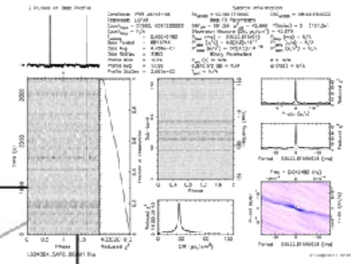


Pilia et al. 2016



707 Hz
1.41 ms





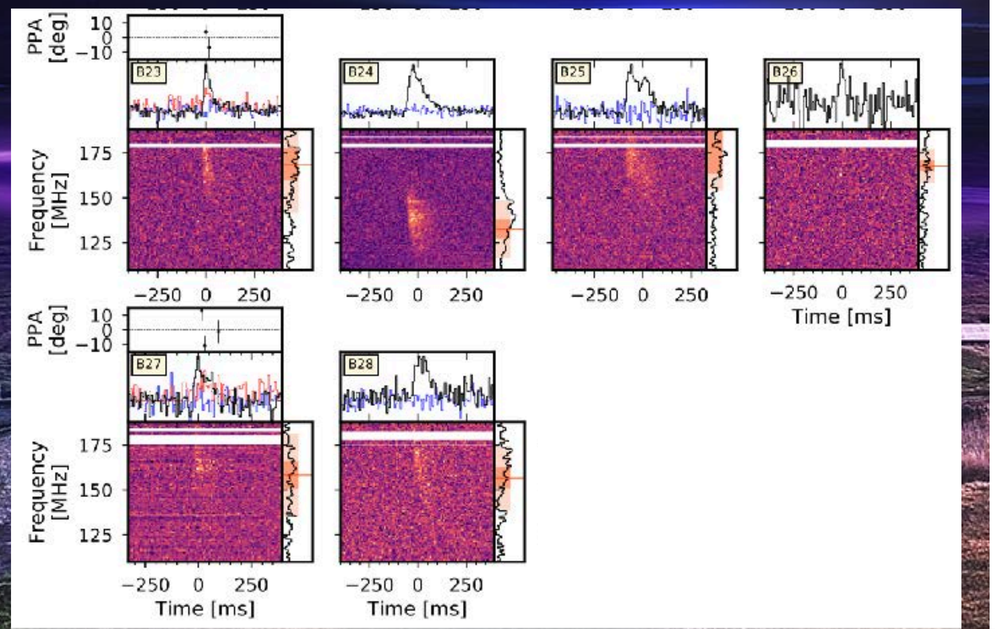
0.042 Hz
23,533.6 ms

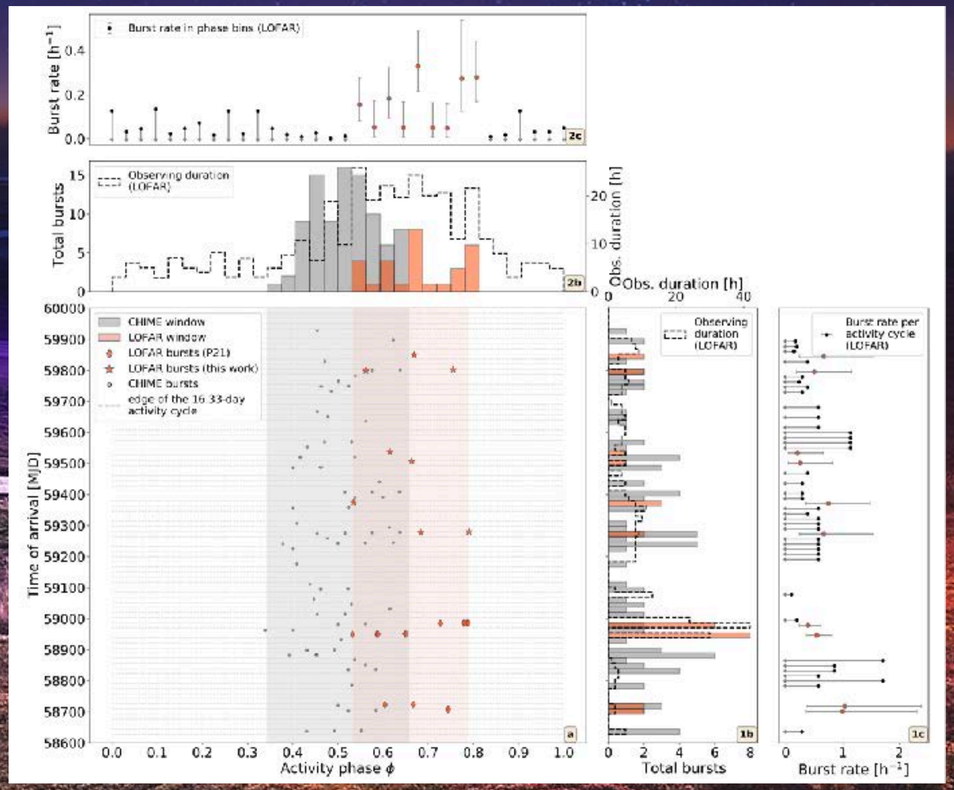
Cooper - see also van der Wateren et al. 2023

LOFAR science highlights

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

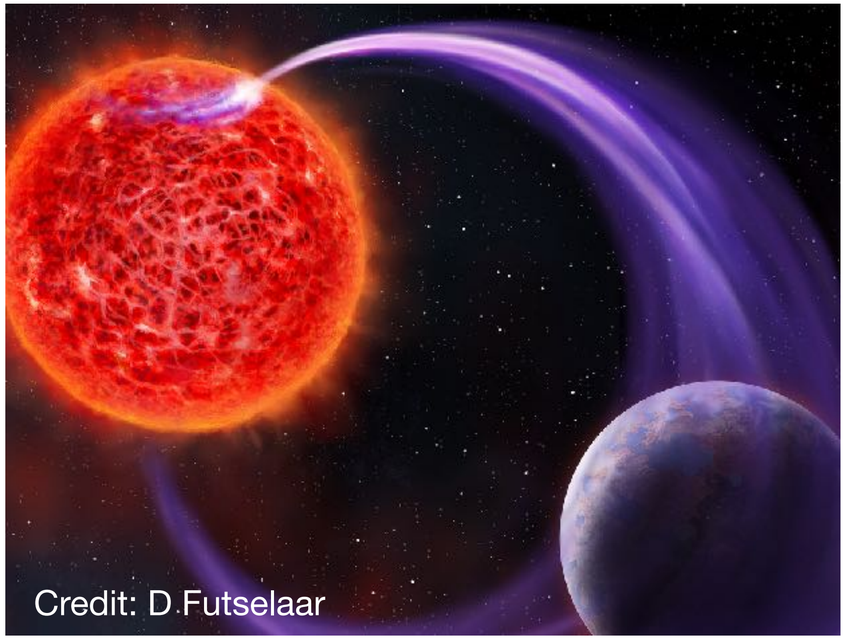


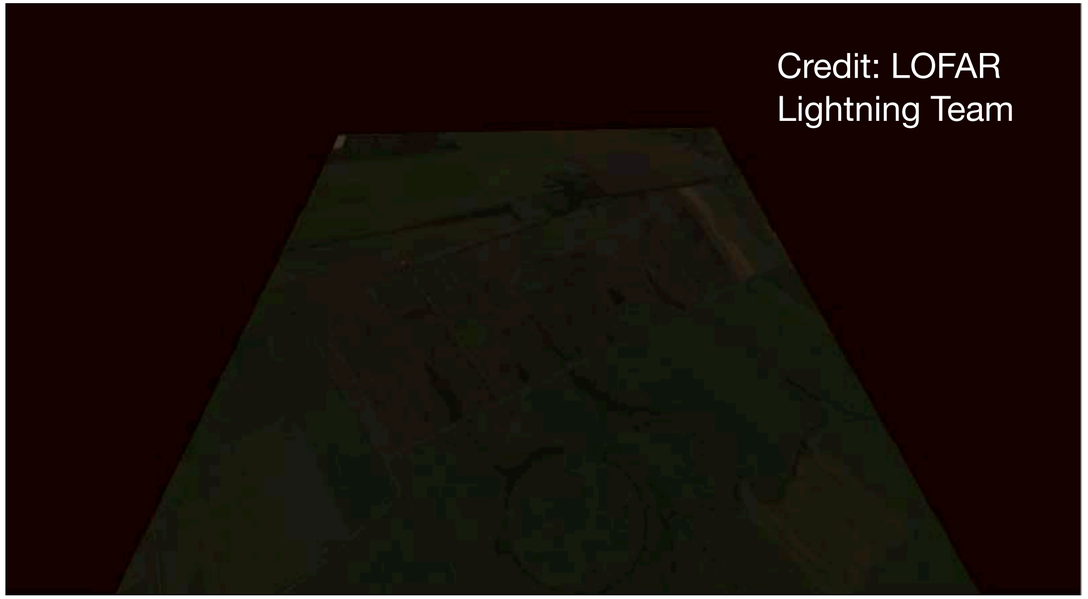


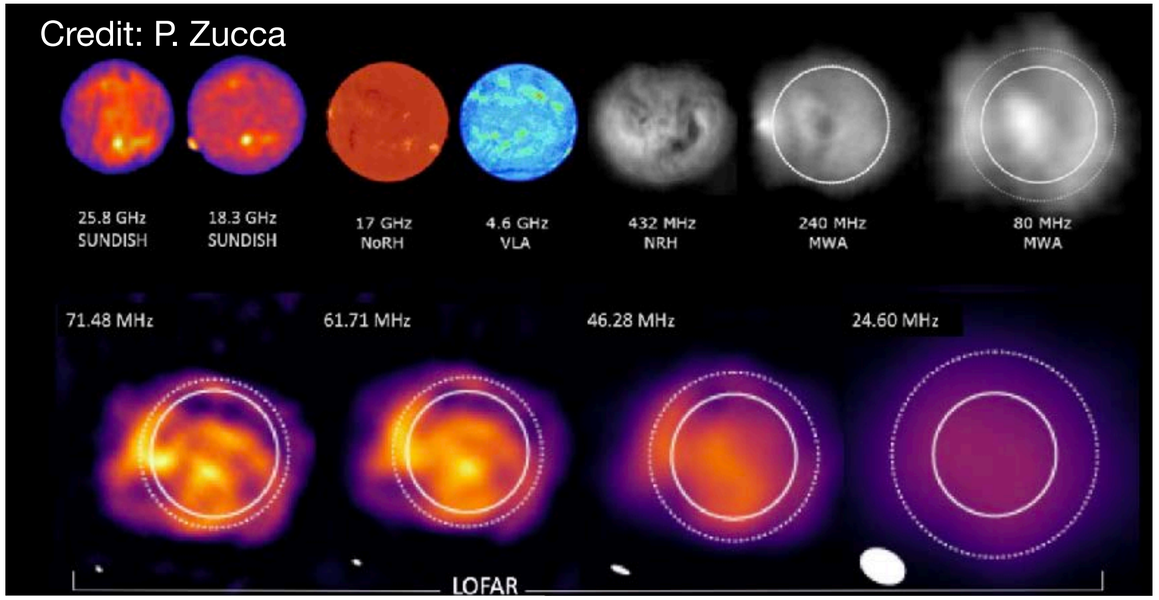
Futselaar / ASTRON

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)
  - High quality interferometric imaging spectroscopy observations of quiet Sun coronal emission at frequencies <90 MHz

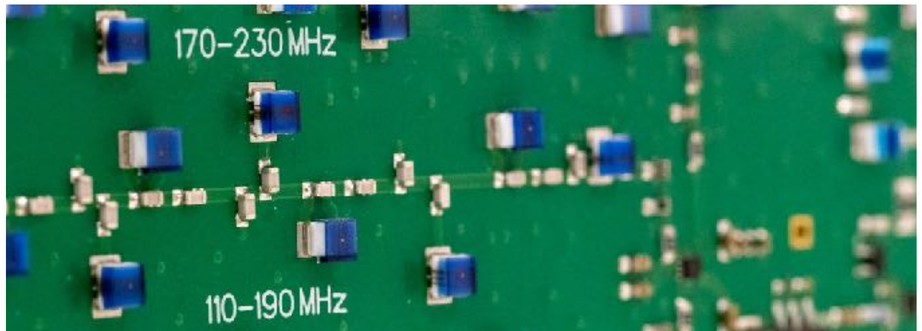






Upgrading: LOFAR2.0 towards 2030 and beyond

- **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



Credit: W. van Cappellen

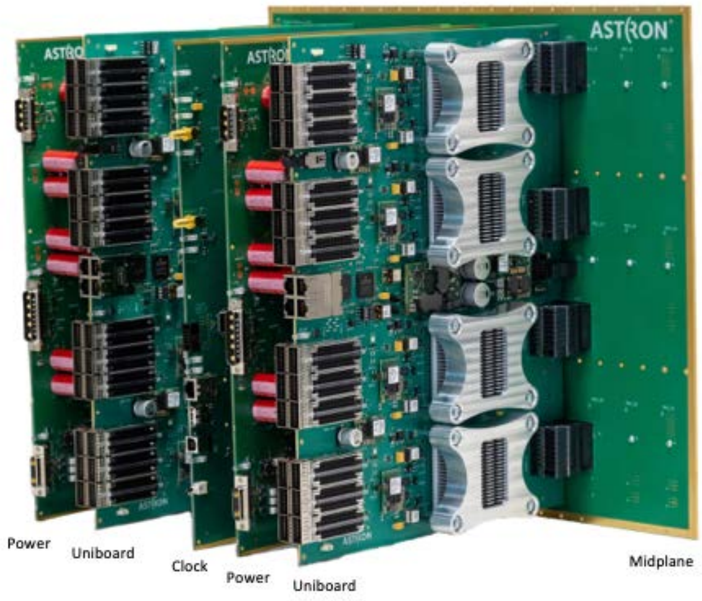
Upgrading: LOFAR2.0 towards 2030 and beyond

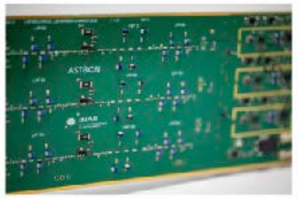
What's new with LOFAR2.0?

Station cabinet hardware upgrades

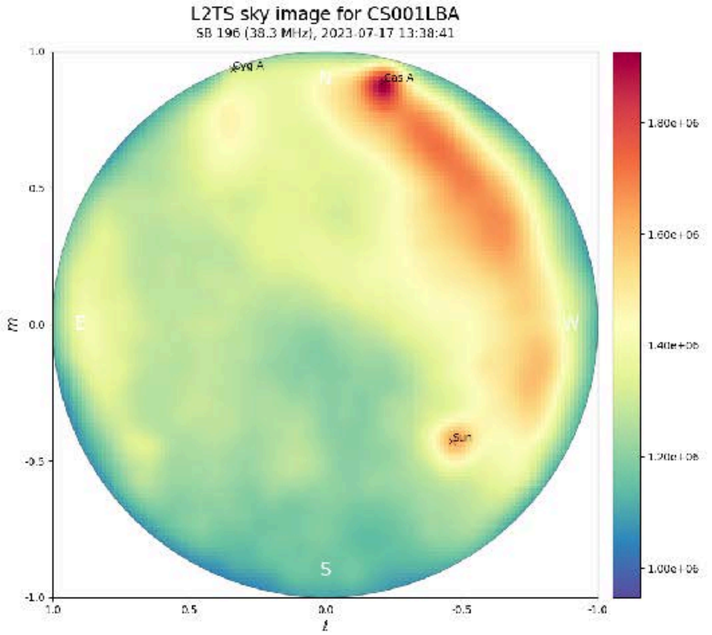
- **More receivers and processing capacity**
  - Simultaneous LBA-HBA observing
  - Double number of active LBA antennas (NL only)
- **Central clock to NL stations**
- **Better linearity**
- **Transient buffer & trigger mechanism 24/7**

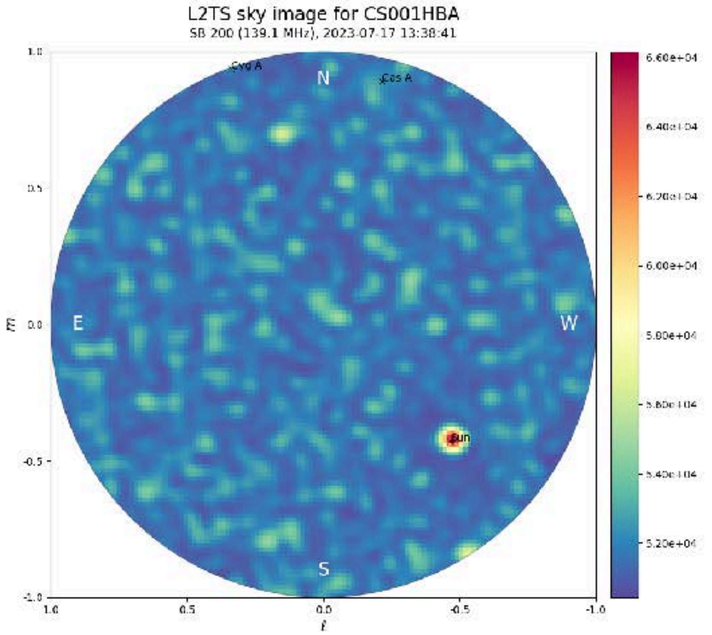
LOFAR2.0 Test Station hardware





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





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- **New standard imaging (& other) pipelines**
- **New-generation HBA front-end boards**
- **LOFAR carbon footprint and energy consumption**

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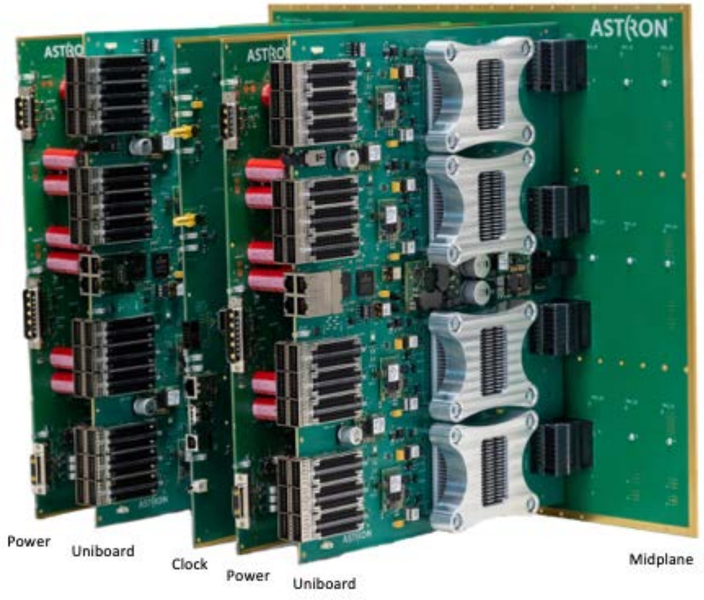

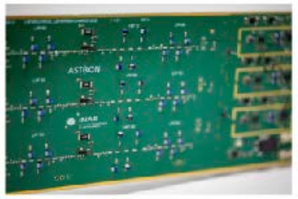

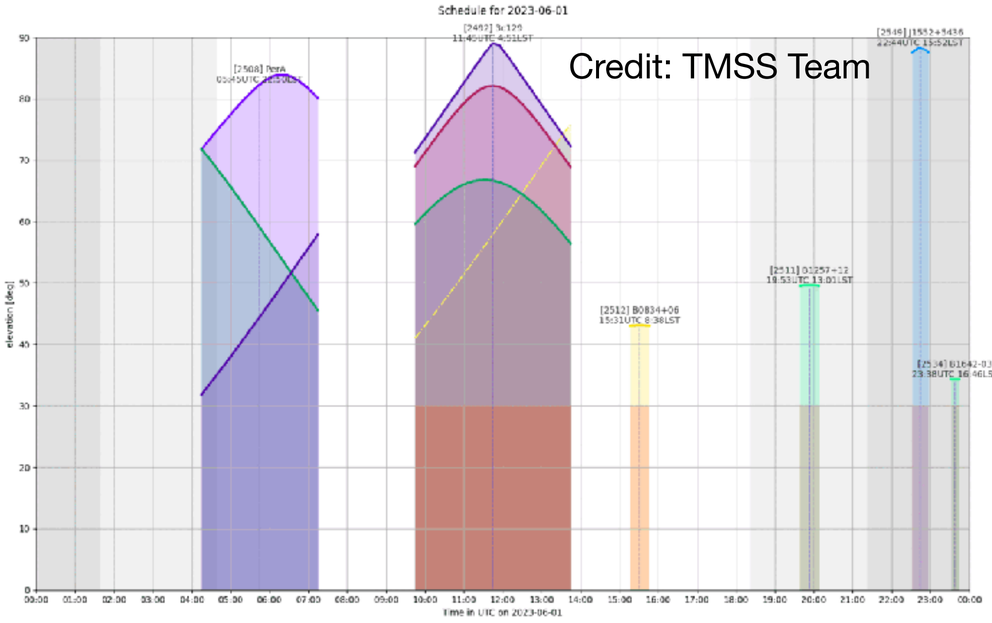

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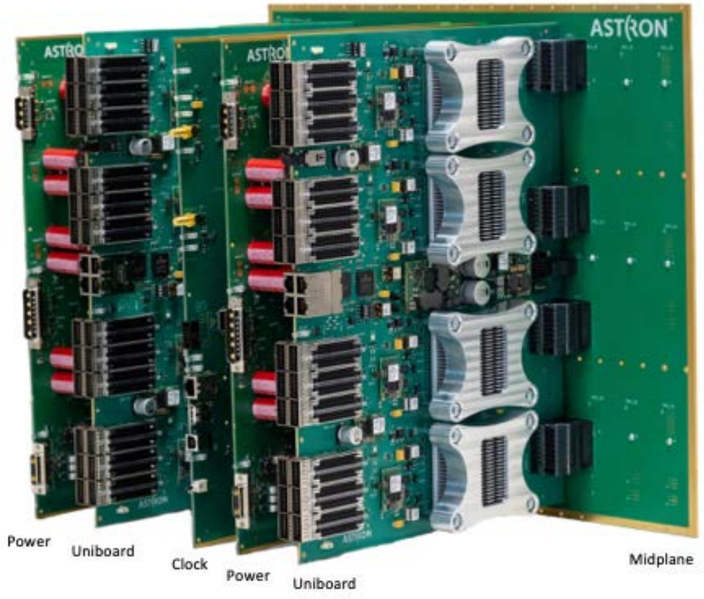
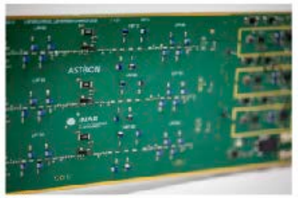
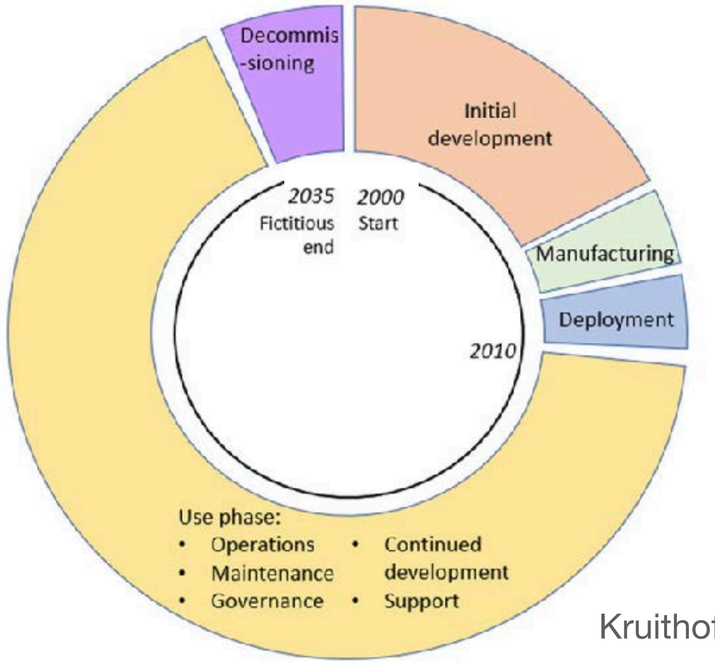






Kruithof+23

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	LOFAR2	Dutch	Dutch	Dutch
Central processor	LOFAR1 full	Limited	Limited	Full array	Full array
Network upgrade		LOFAR2 and most RS	Dutch	Dutch	Europe
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	…	…
	A		B	C		D		E	SV	…	…

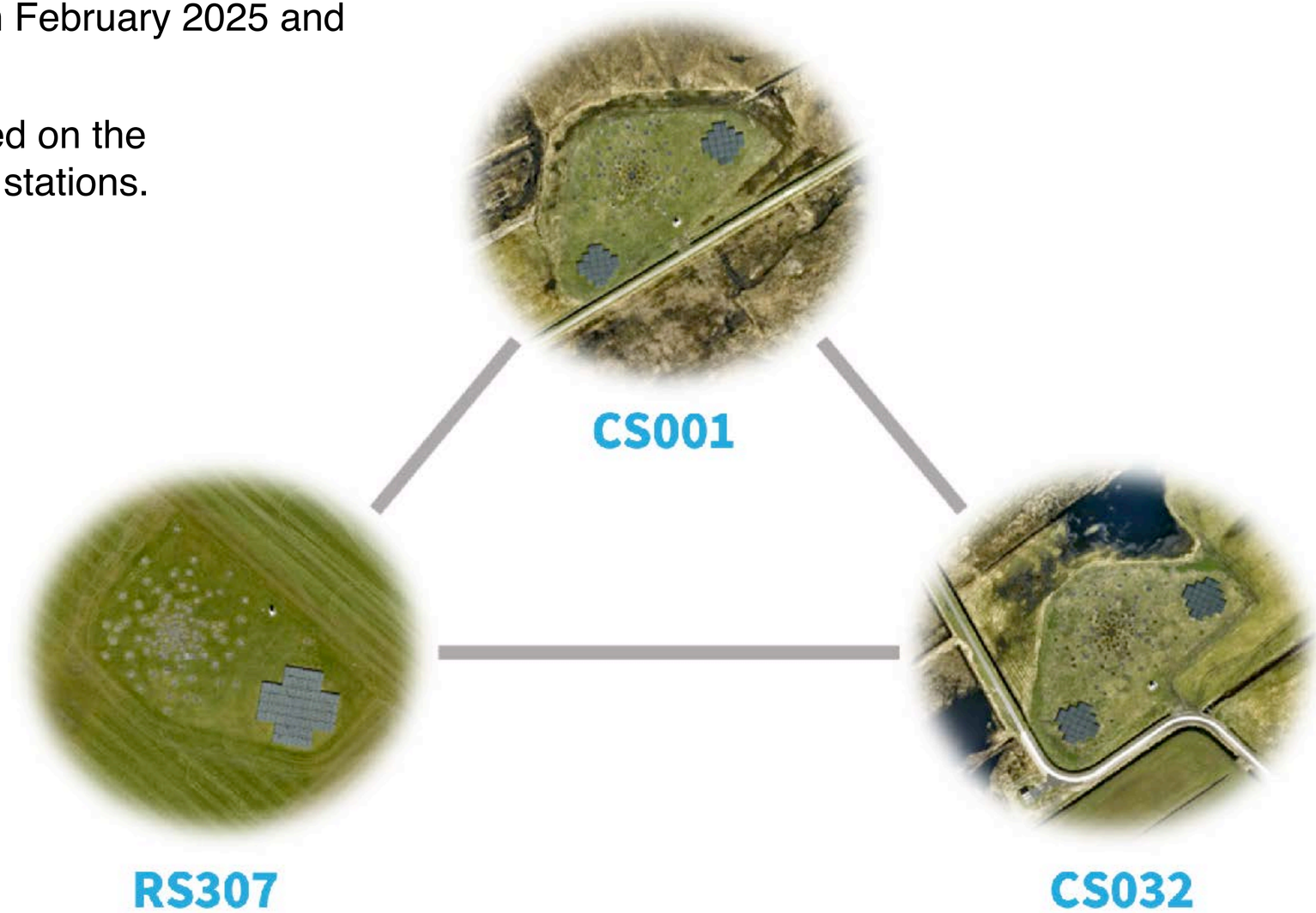
LOFAR 2.0 roll-out - progress

- 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



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

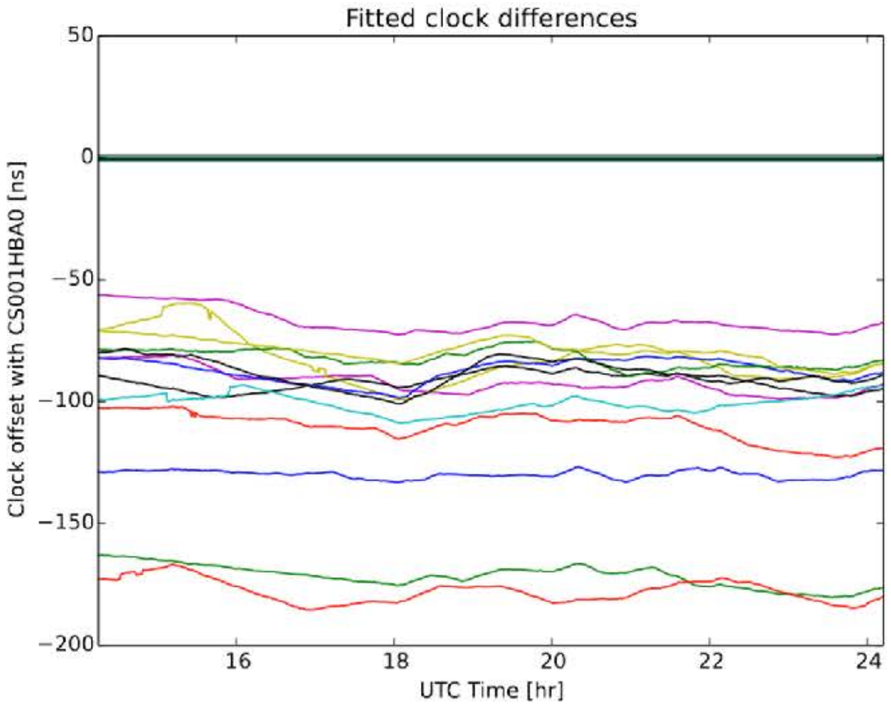
Software Development

- 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

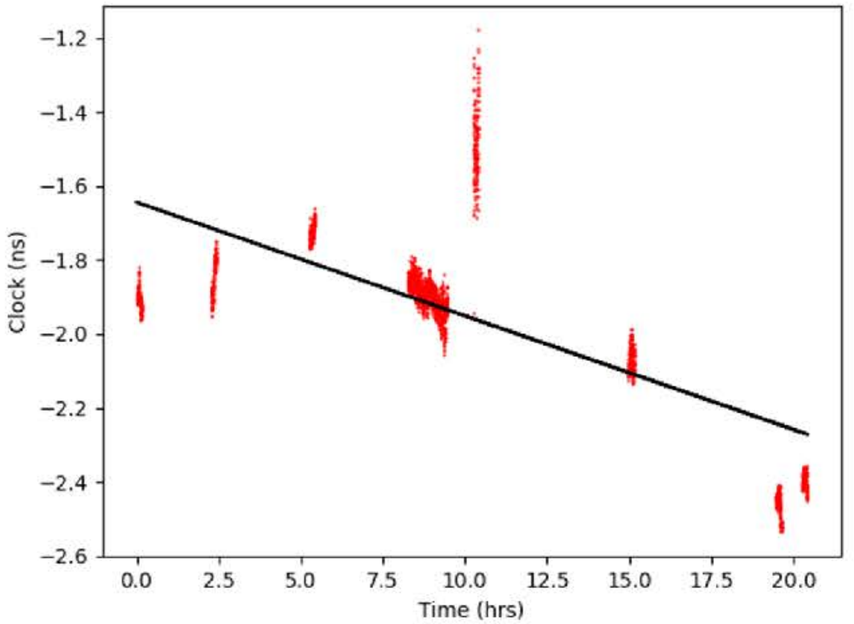
White Rabbit clock distribution

Current LOFAR clock



Van Weeren et al. 2016

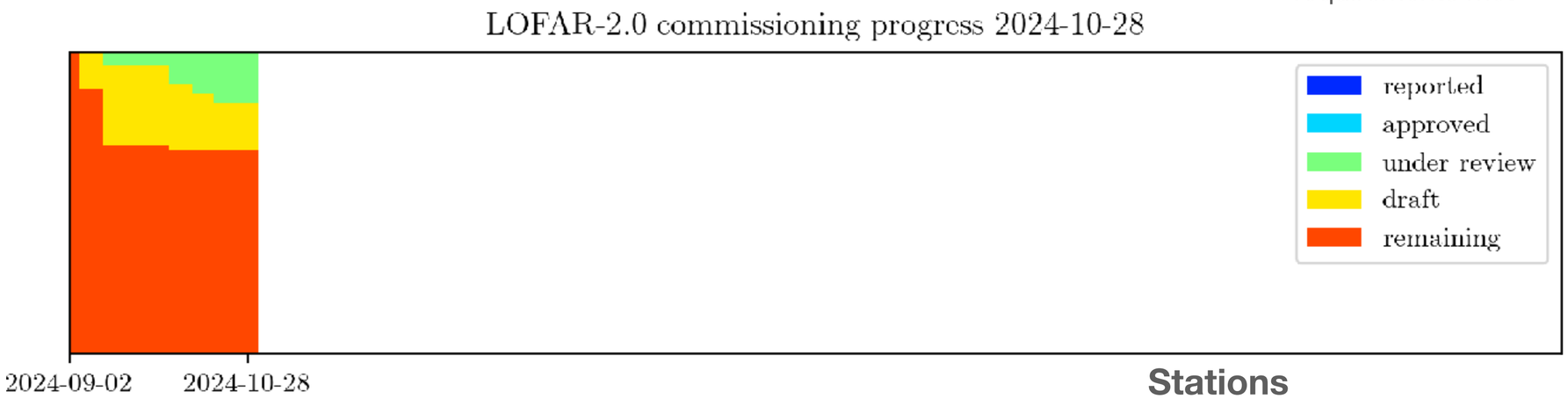
With White Rabbit



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

LOFAR 2.0 Commissioning

Legend:
- One column per week until end of 2025
- Vertical: number of requirements met



edu.nl/489va

ASTRON Confluence link
Register to get access

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

Stations

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

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(10^7 core hours) and at LTA sites (or after CEP) O(10^9 core hours)
- LP storage requirements: 32 PB for final data products (science ready data) - stored indefinitely
  rising to 87 PB including requests from some PIs to store raw (visibility data)

Challenges facing us…

- Successful execution of LOFAR 2.0 Large Programmes depends on availability of compute, storage & network resources as well as processing techniques (pipelines) & expertise.
- Busy week held 21-25 October to discuss challenges with Large Programme PIs
- LOFAR ERIC and L2LP Teams working to acquire sufficient resources for storage and processing + develop pipelines to process the data

Opportunities for further development beyond LOFAR 2.0

- **LOFAR ERIC → 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)
  - Increase scientific impact through continued development

Potential Future Developments

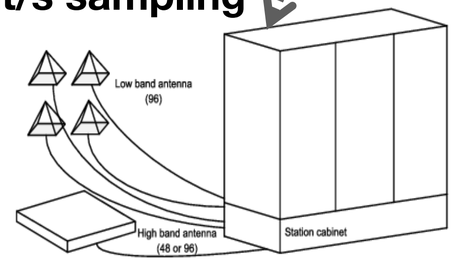
- Increased network bandwidth between stations and correlator (10 to 100 Gbps)
- Next generation LBA: Ultra-low-band: 5-50 MHz
- Improved 24/7 all-sky monitor (AARTFAAC)
- Hand-in-hand with investments in LOFAR processing
  - algorithmic enhancement and real-time processing for imaging pipelines
- Upgraded data discovery and access systems

LOFAR ERIC

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

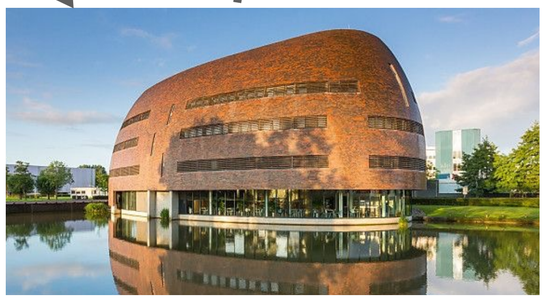
~150 Gb/s

Initial processing

CPU & GPU system at RuG

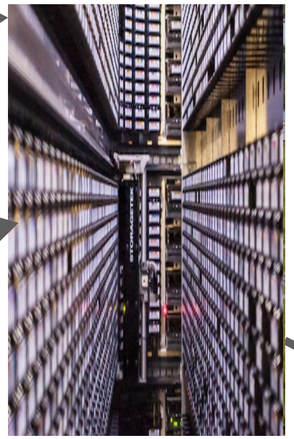
7 PB/yr

10s Gb/s



Correlation

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



Long Term Archive nodes

SURF in the Netherlands
FZJ in Germany
PSNC in Poland

Data repositories

Science processing

Clusters across Europe