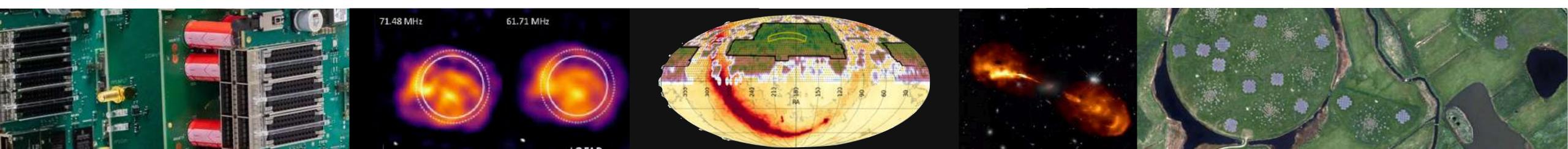
LOFAR - the Low Frequency Array A premier low-frequency radio facility for the 2030s and beyond



Michiel van Haarlem

- Director
- LOFAR ERIC
- irector@lofar.eu
- Recovery Plan for Ukrainian Astronomy Leiden, 10-11 June 2025



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

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

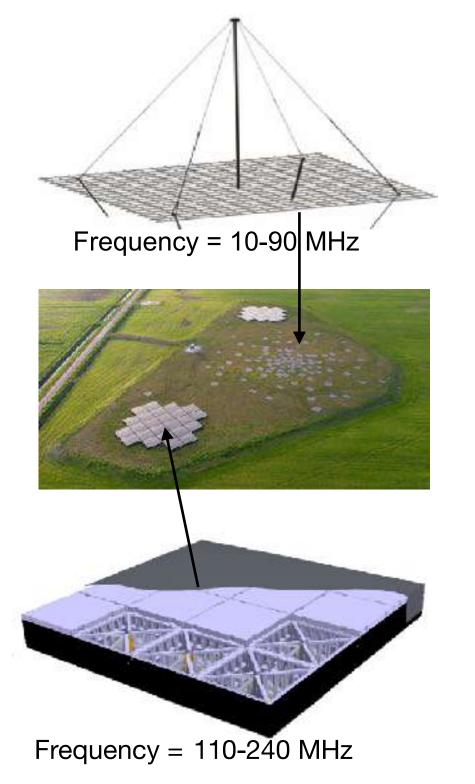
- Central observing operations, peer-reviewed access for the research community

Centrally operated data combination

• GPU-based correlator/beamformer and Central Processing compute cluster at University of Groningen (NL)

Distributed archive and data analysis centres : >50 PB stored

- Central operation and open science access for the research community
- Currently 3 nodes: Amsterdam (NL), Jülich (DE), Poznan (PL)





• 52 antenna stations in 8 countries: NL (38), DE (6), PL (3), IE, UK, FR, SE, LV + 2 stations to be constructed in 2026: IT, BG



LOFAR Stations

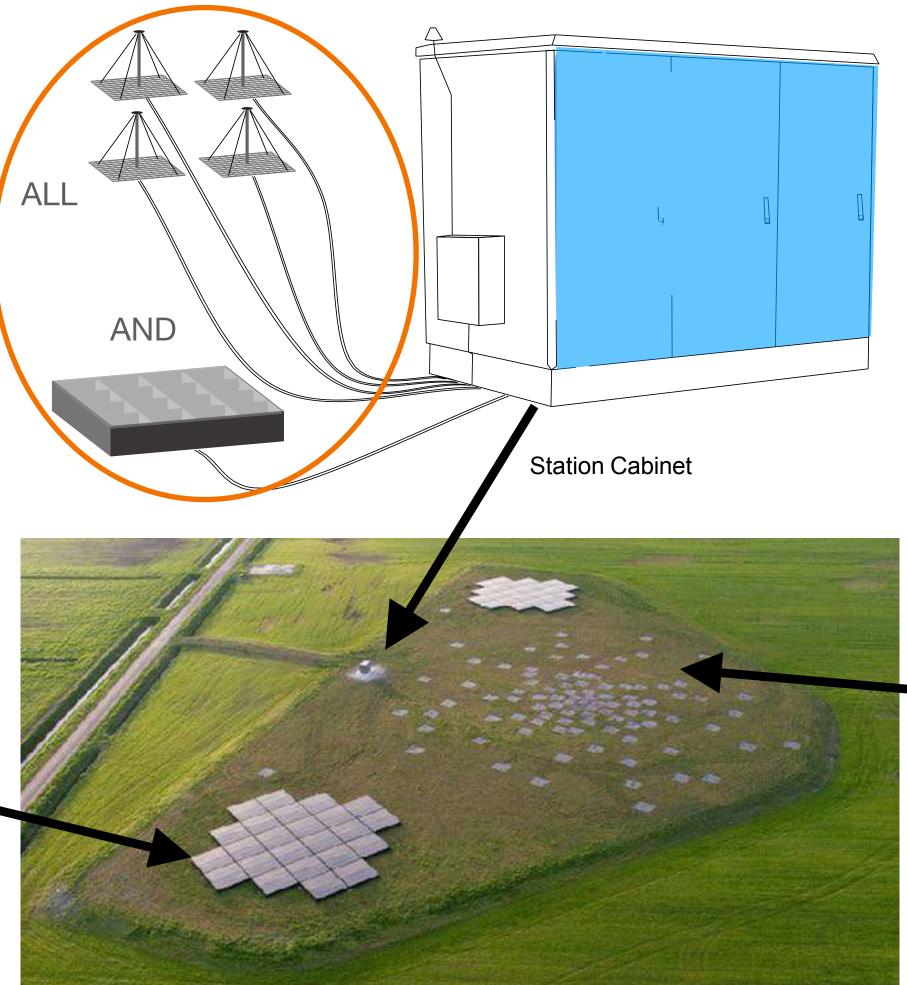
LOFAR 1.0 capabilities

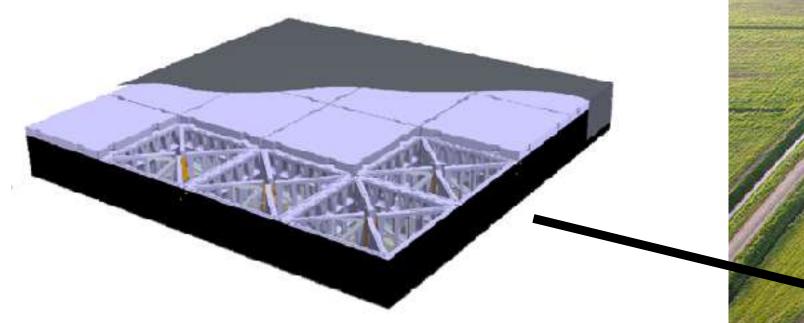
International Stations

• 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

LOFAR 2.0 capabilities

- **International Stations** \bullet
 - 96 LBA and 96 HBA simultaneously

• NL Stations

- 96 LBA and 96 HBA
- simultaneously



Low-Band Antennas

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

The LOFAR system - Data flow

Correlation & Beamforming

GPU-based system in Groningen (RuG) 360 Tflops compute power 2 TB temporary storage



~200 Gb/s

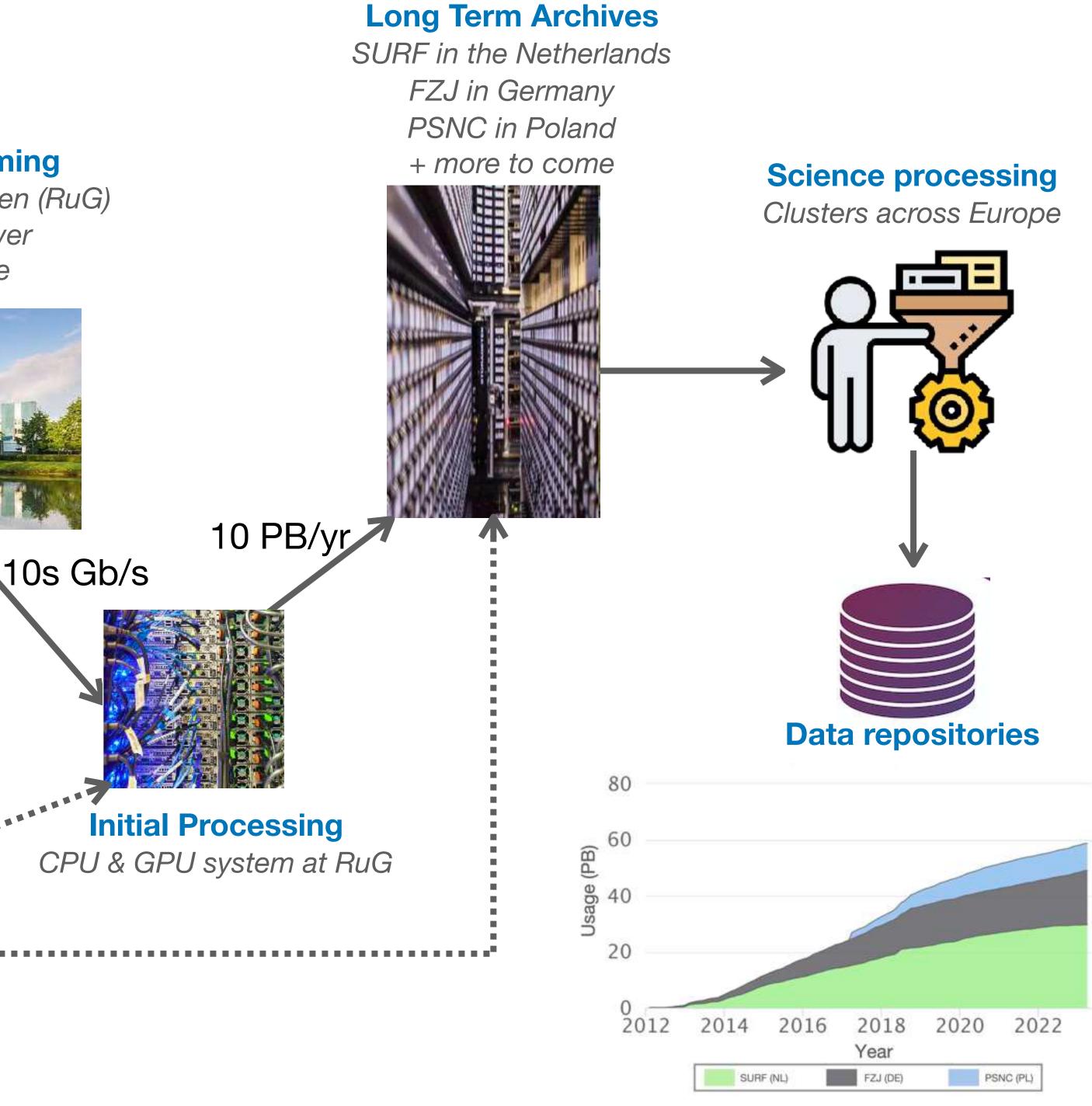
Station-level processing

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

13 PB/s sampling



Central operation



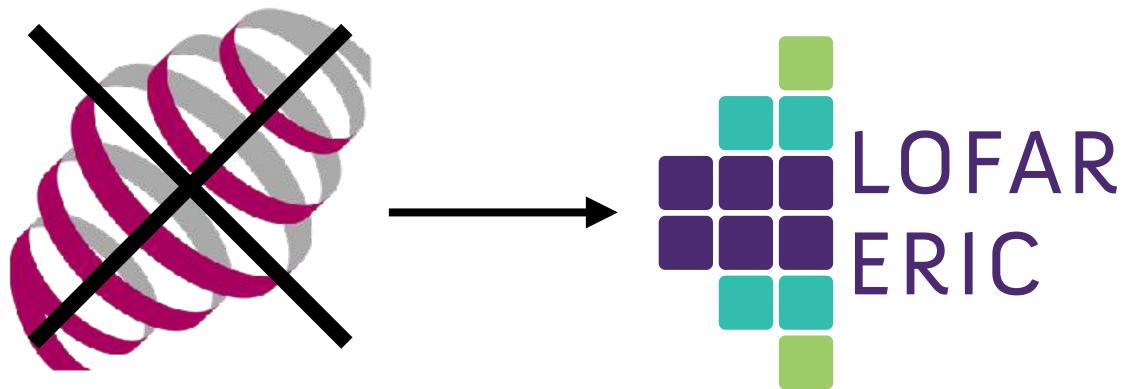
An ERIC to anchor and further develop the LOFAR distributed RI

• 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

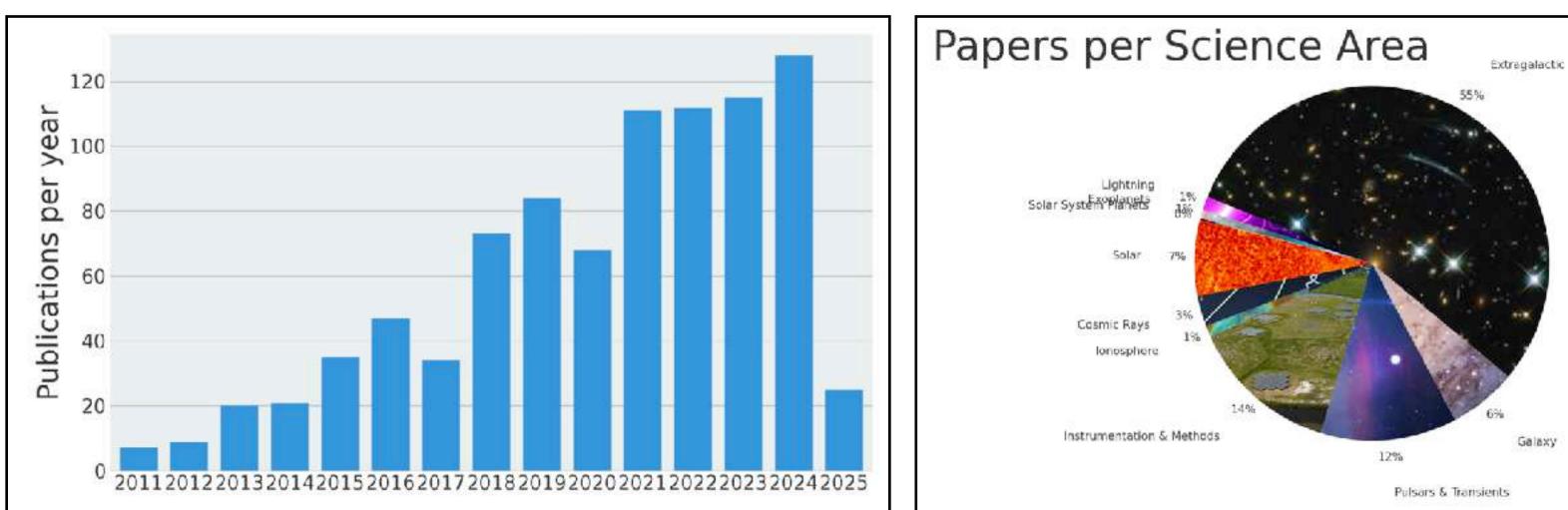
- Partner participation at national level, aligned to common long-term strategy and vision
- Joint funding, steering, and implementation of major projects (e.g., LOFAR2.0) financial advantages
- Increase scientific impact through continued development better recognition e.g. at EC
- Officially established by EC on 20 December 2023
- Current Members: NL, DE, PL, BG, IE, IT, SE, UK
- Collaborating Organisations: FR, LV

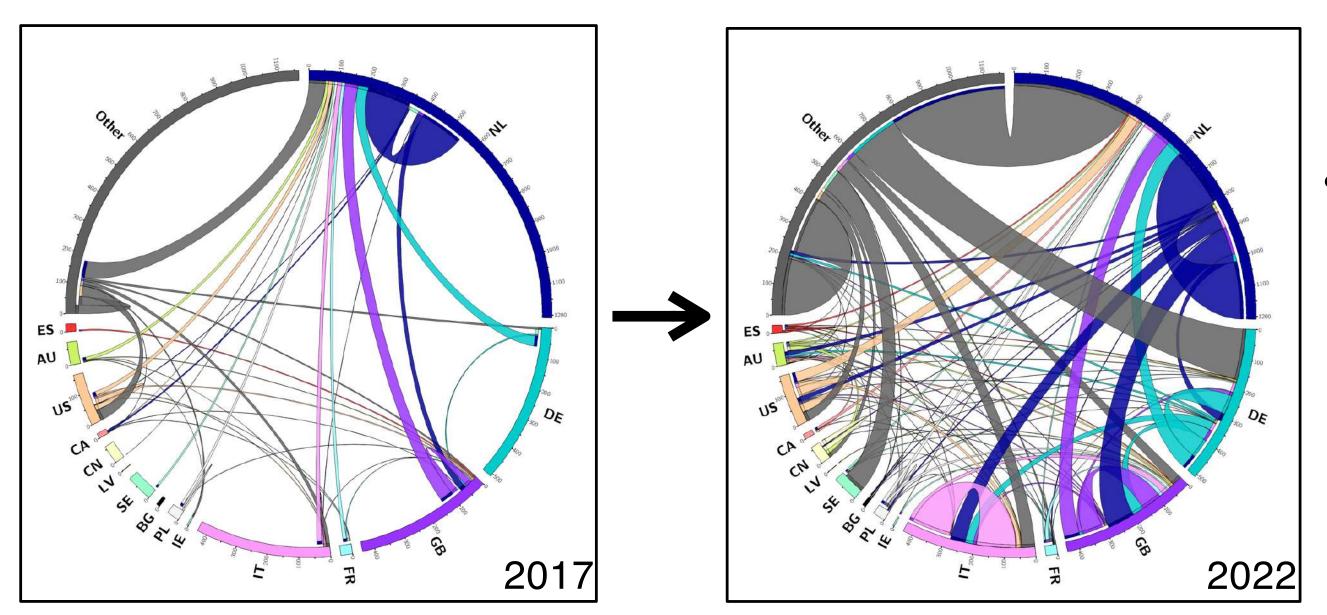




Community evolution and science output

- **889 refereed publications** (2011-Feb 2025)
 - \rightarrow top 10% of all astronomical facilities

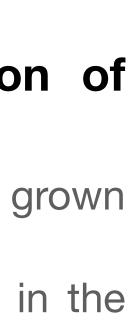


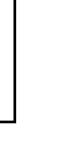


Credit: SDCO Team (ASTRON)

Measuring the success of LOFAR: Evolution of lacksquarecommunity 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.































































































































































Only scratching the surface of LOFAR science results!

LOFAR Family Meeting 2023 (Olsztyn, Poland)

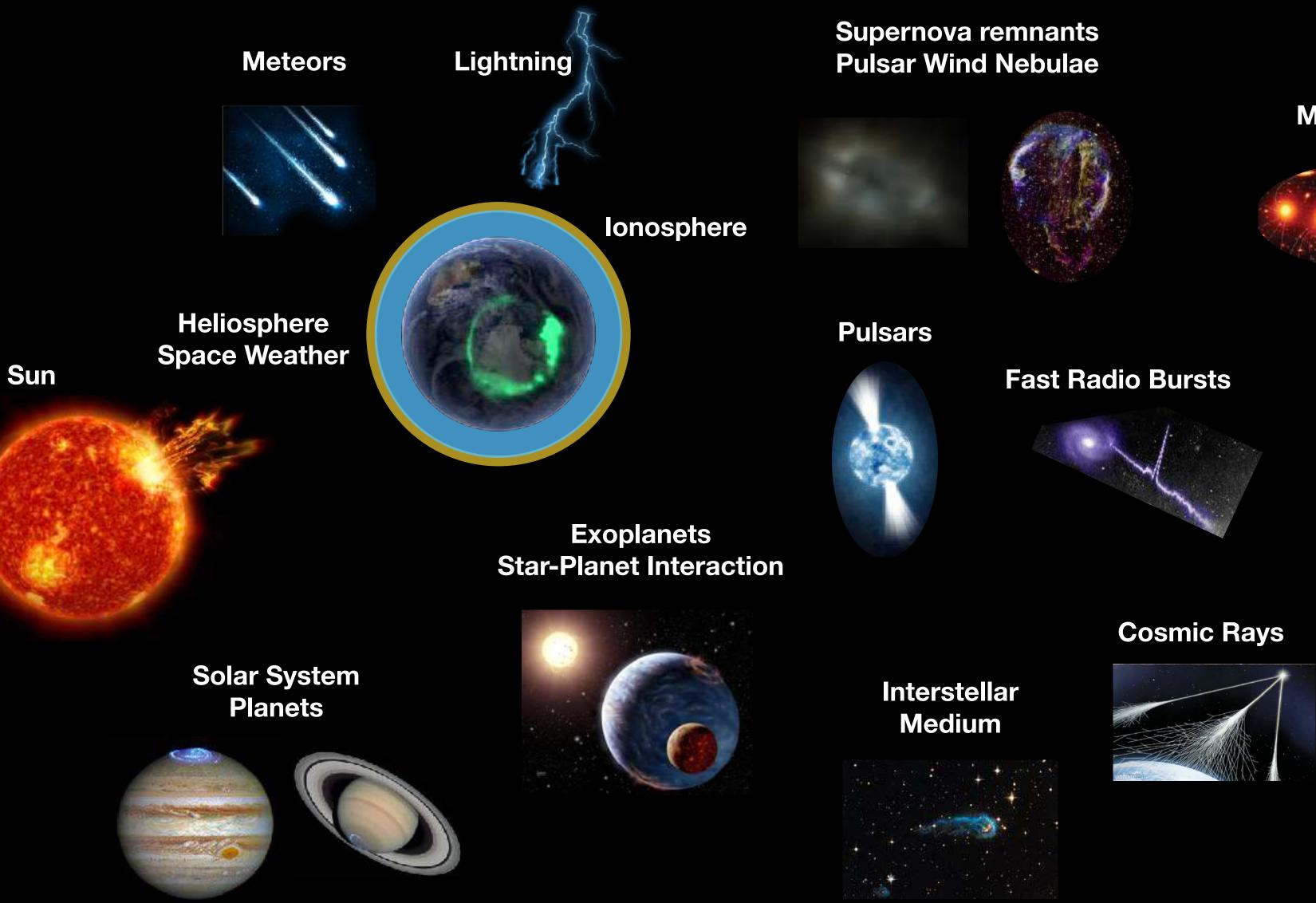




LOFAR Family Meeting 2024 (Leiden, The Netherlands)



LOFAR's broad science case



Cosmic Magnetism

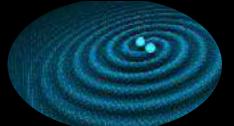


Clusters



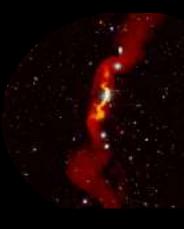
Early Universe Cosmic Dawn

Gravitational Wave Events





AGN physics



Nearby Galaxies





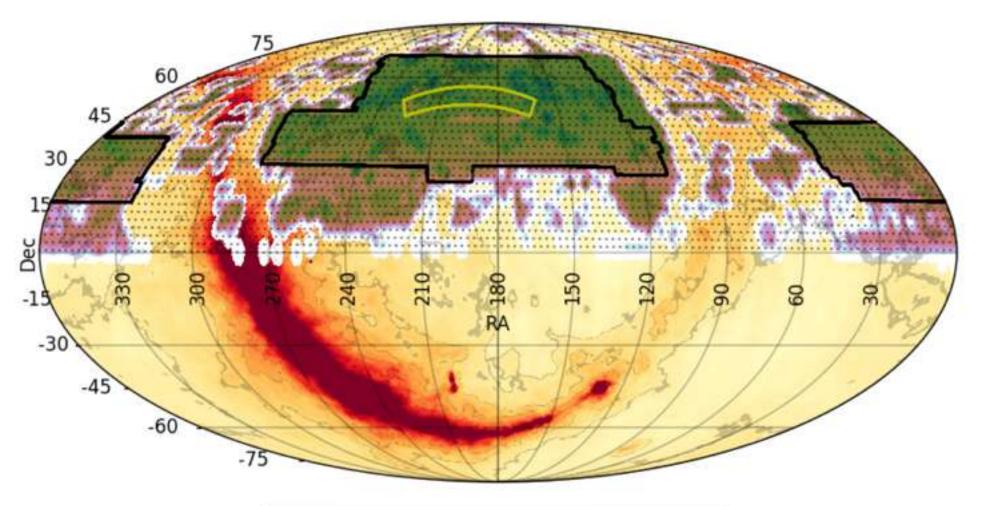


LOFAR science highlights - HBA Surveys

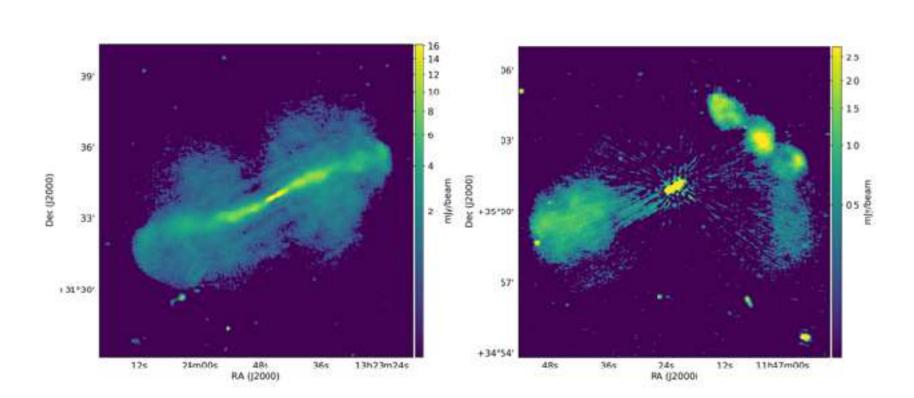
• Surveying: huge area, huge object samples O Lots: LOFAR Two-Metre Sky Survey (Shimwell+22)

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

0.04



Shimwell+22



mJy/beam

0.15

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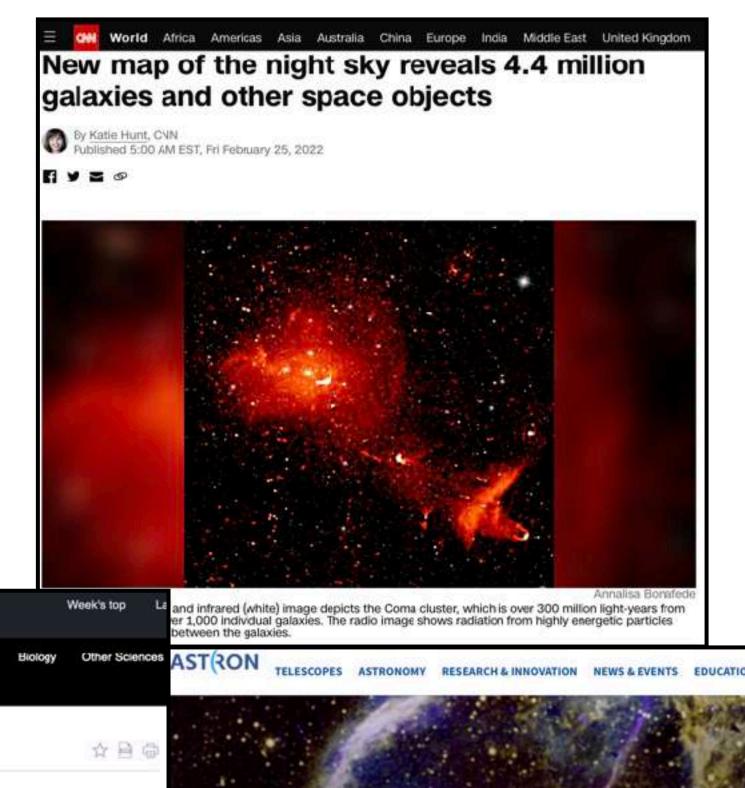
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Hame / Astronomy & Space / Astronomy

⑦ FEBRUARY 25, 2022

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Scientists reveal 4.4 million galaxies in a new map

by Durham University



Acomposition radio (LoTSS-DR2) and optical (Hubble space telescope) image of the "jellyfi...

Durham University astronomer collaborating with a team of international scientists have mapped more than a quarter of the northern sky using the Low Frequency Array (LOFAR), a pan-European radio telescope.

Flurry of new discoveries as incredible new image revealing 4.4 million galaxies is made public

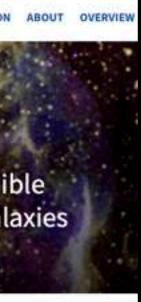
TELESCOPES / LOFAR -

Over a seven year period an international team of scientists has mapped more than a quarter of the northern sky using the Low Frequency Array (LOFAR), a pan-European radio telescope. It reveals an astonishingly detailed radio image of more than 4.4 million objects and a very dynamic picture of our Universe. Now that this treasure trove of data has been made public, anyone can view the most exotic wonders of our intriguing Universe in a brand new light

PUBLISHED BY THE EDITORIAL TEAM, 25 FEBRUARY 2022

A wealth of new information

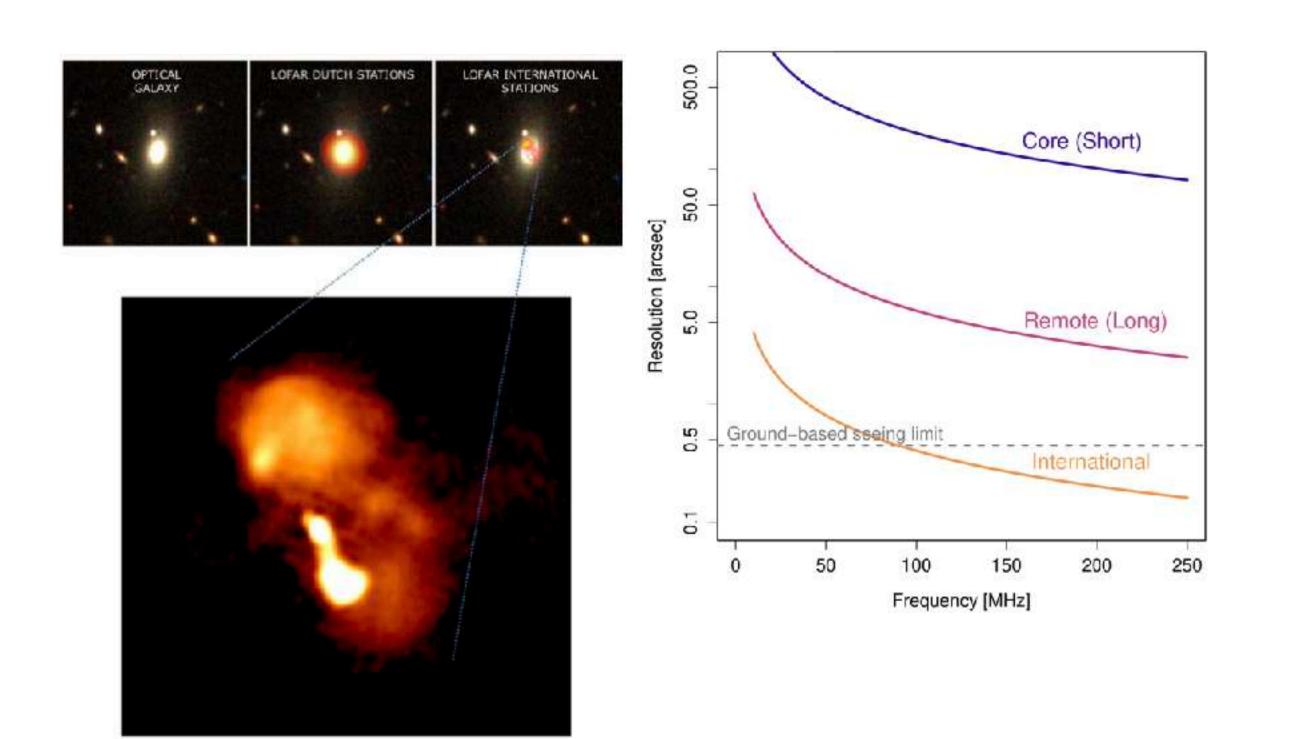
The vast majority of these objects are billions of light years away and are either galaxies that harbour massive black holes or are rapidly growing new stars. Rarer objects that have been discovered include colliding groups of distant galaxies and flaring stars within the Milky Way.



LOFAR science highlights - HBA Surveys - International Baselines

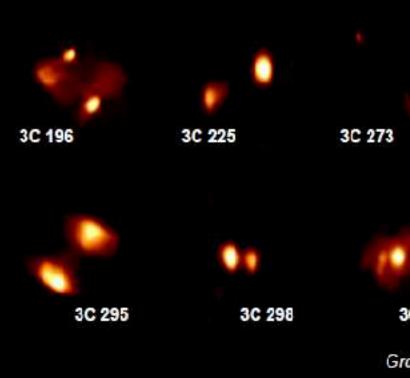
Most detailed images of galaxies at 150 MHz ullet

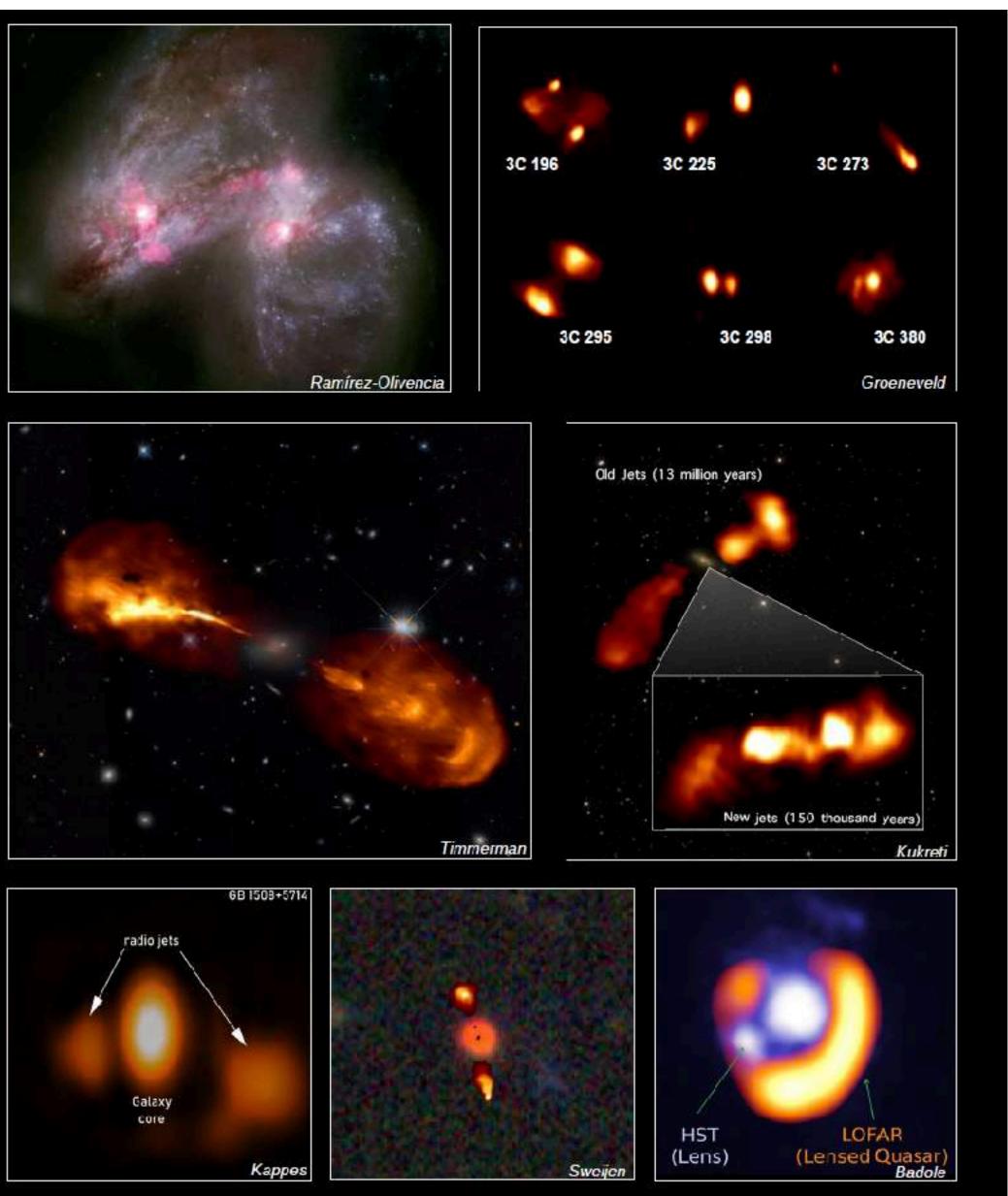
- Data release and 10 research publications (A&A), doubling the number of scientific results using LOFAR sub-arcsec resolution
- Possible thanks to LOFAR's international baselines (>2000 km)
- Images 20x higher resolution than NL-only LOFAR images

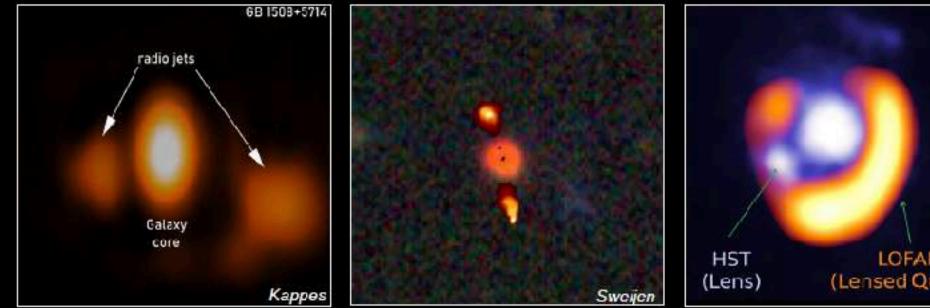


Credit: L.K. Morabito; LOFAR Surveys KSP





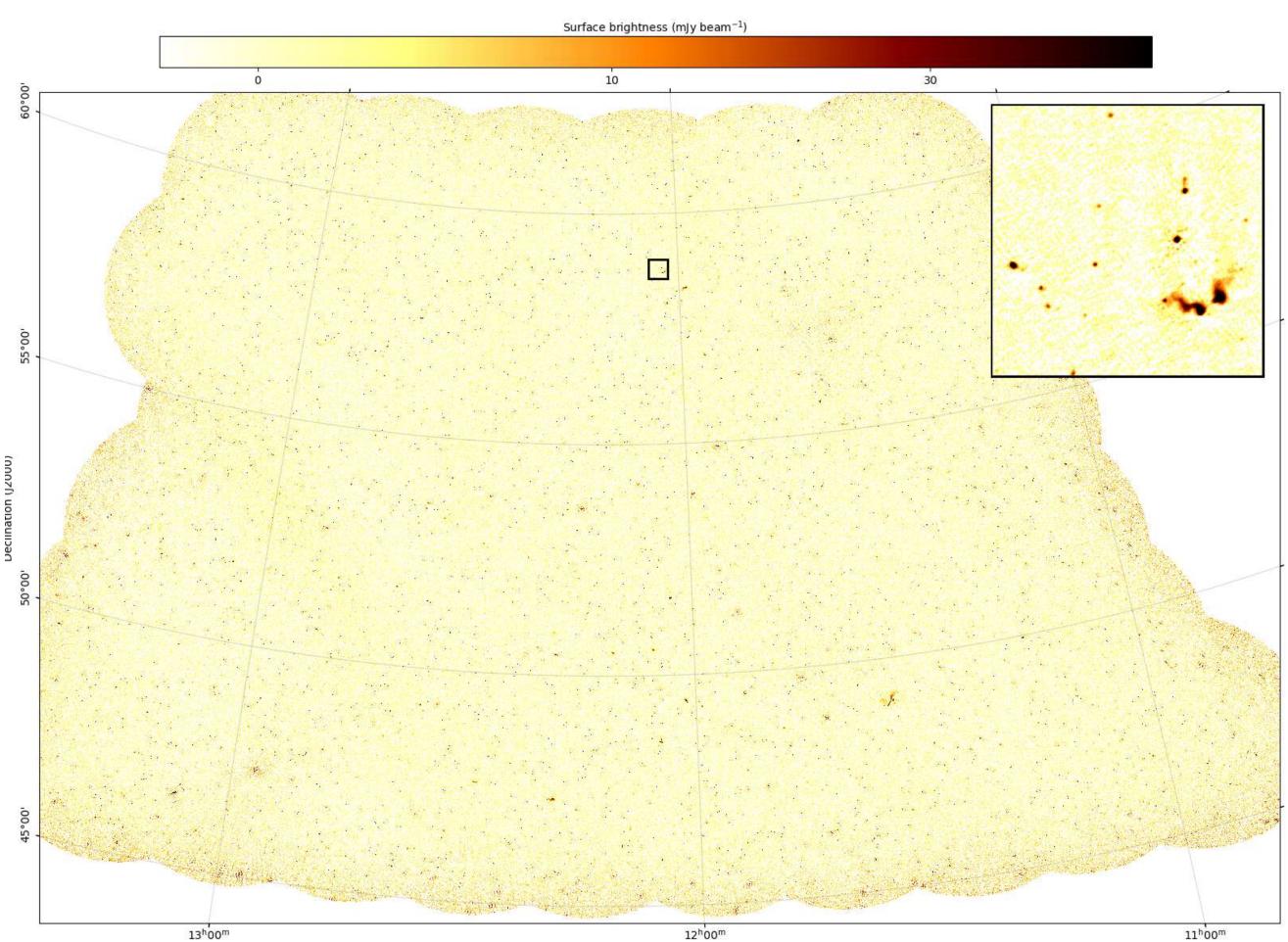




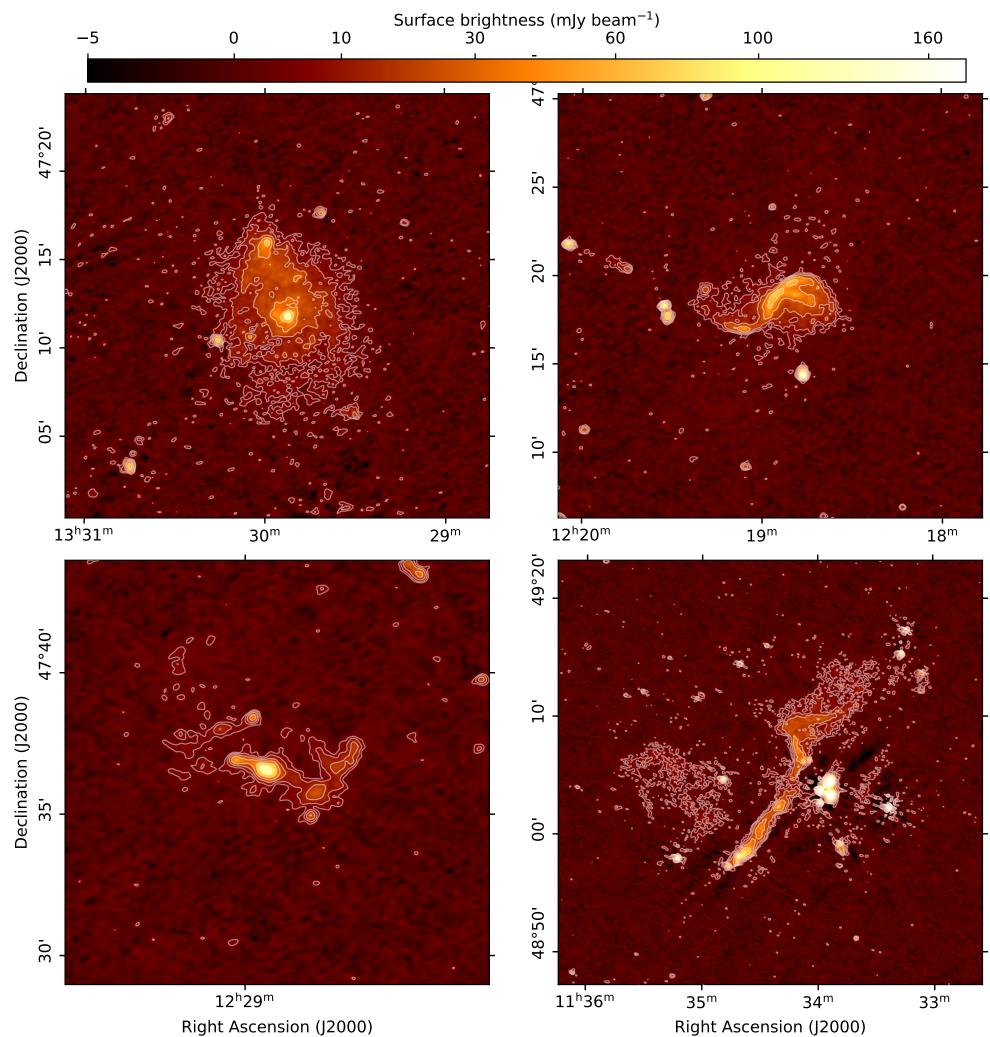
LOFAR science highlights - LBA Surveys

• 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



13^h00^m



de Gasperin+23

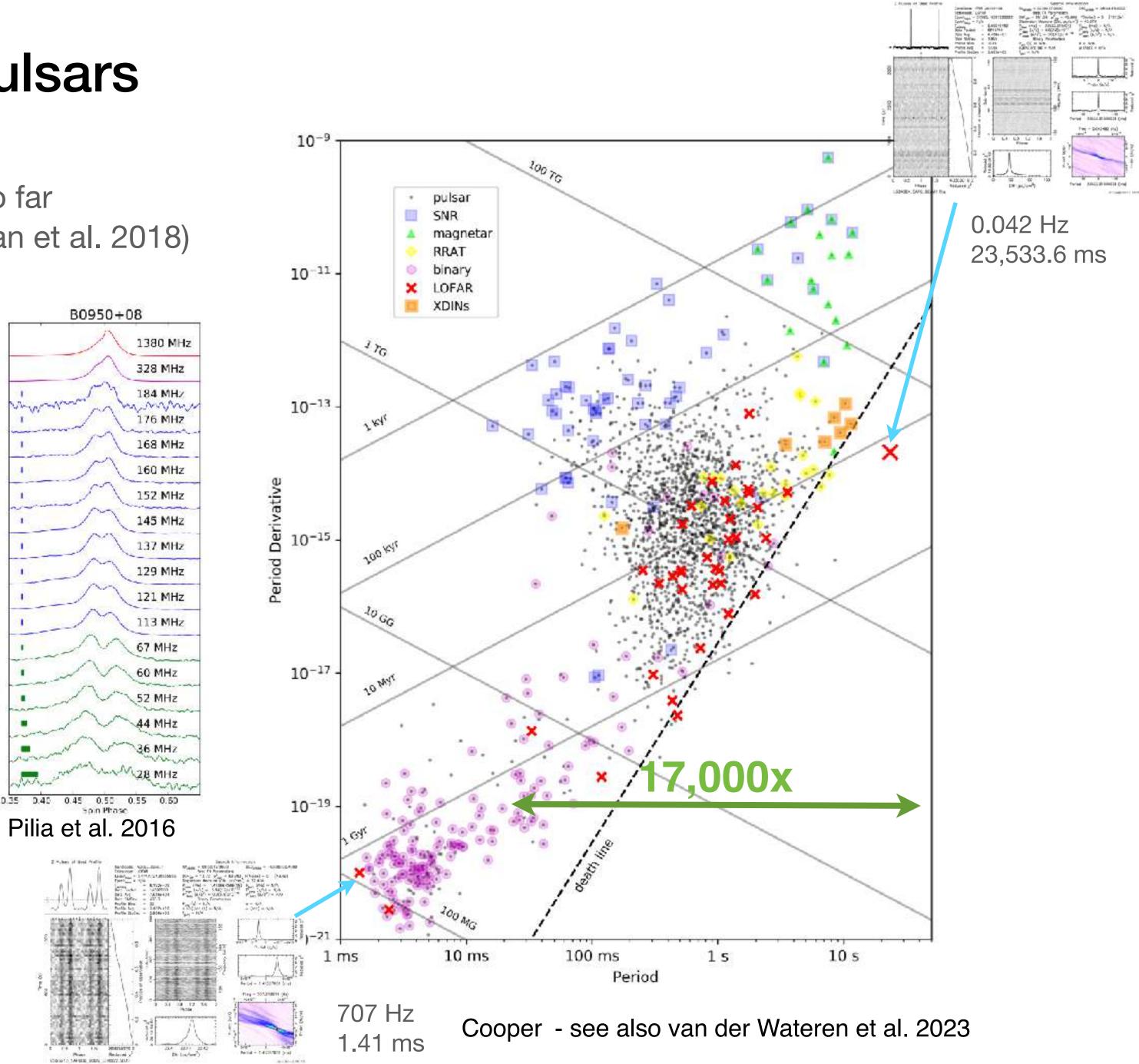
LOFAR science highlights - Pulsars

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

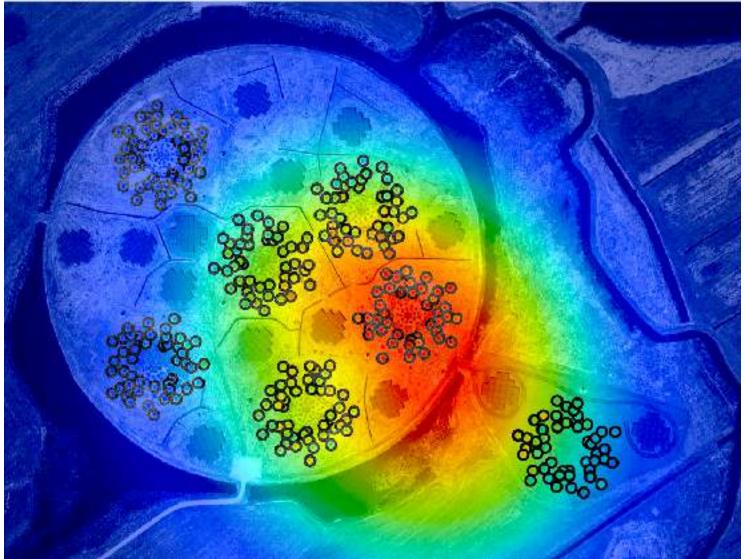
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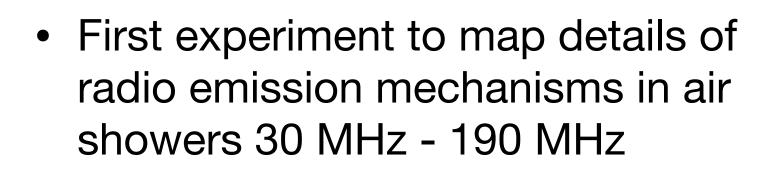
Bilous et al. 2016



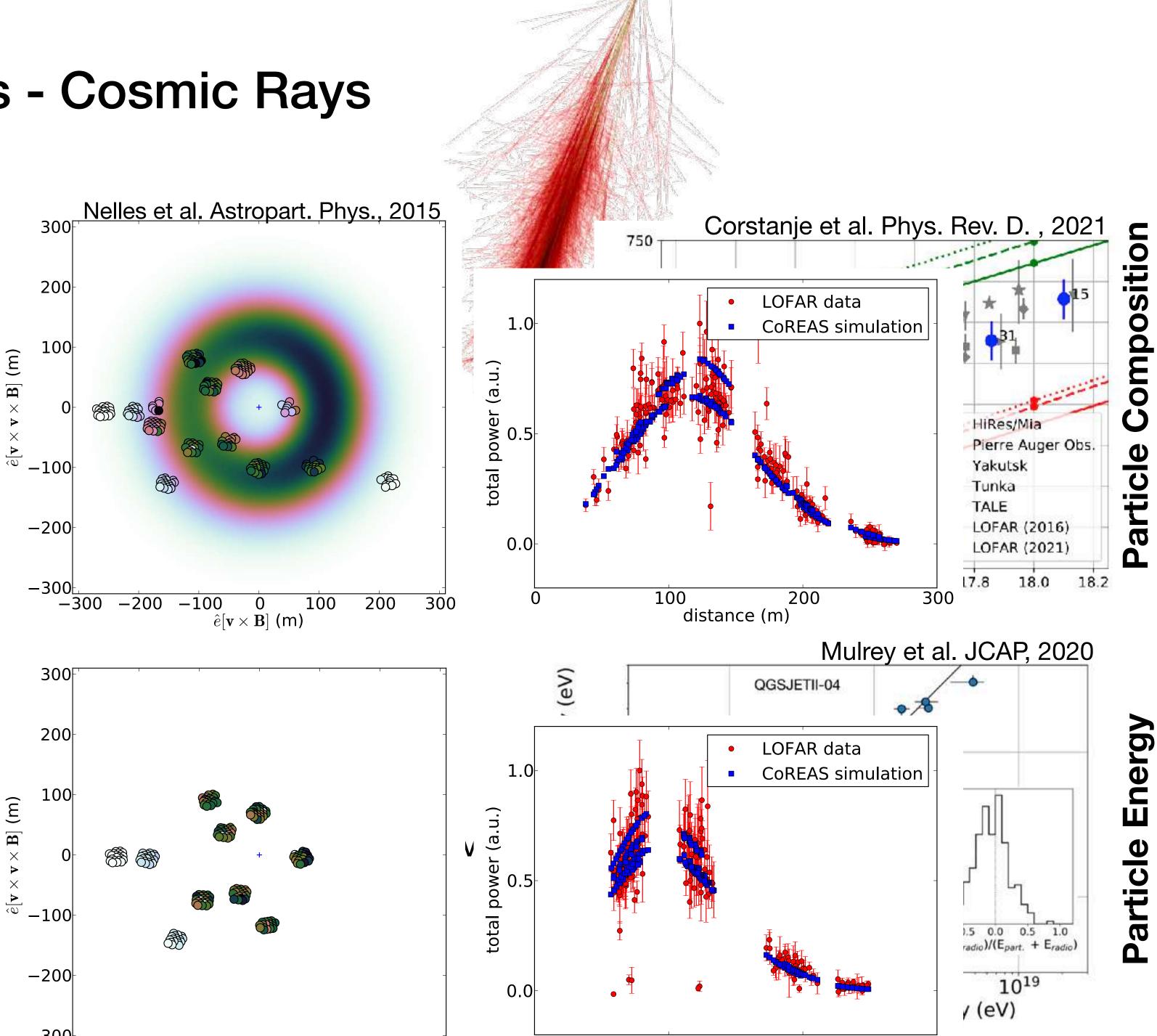
LOFAR science highlights - Cosmic Rays

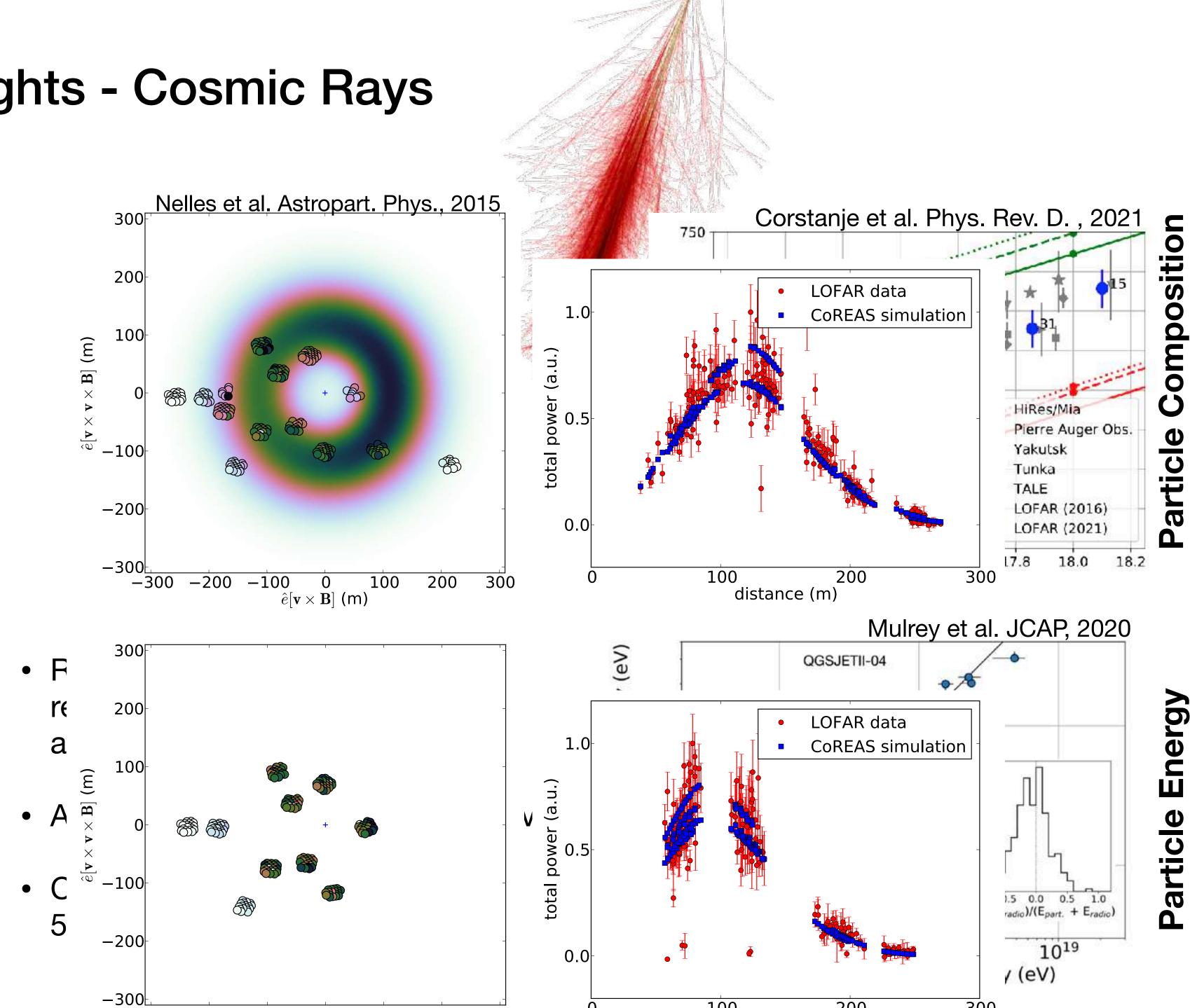
Buitink et al. Nature, 2016





- Superior timing = wavefront shape
- Demonstration of circular polarization





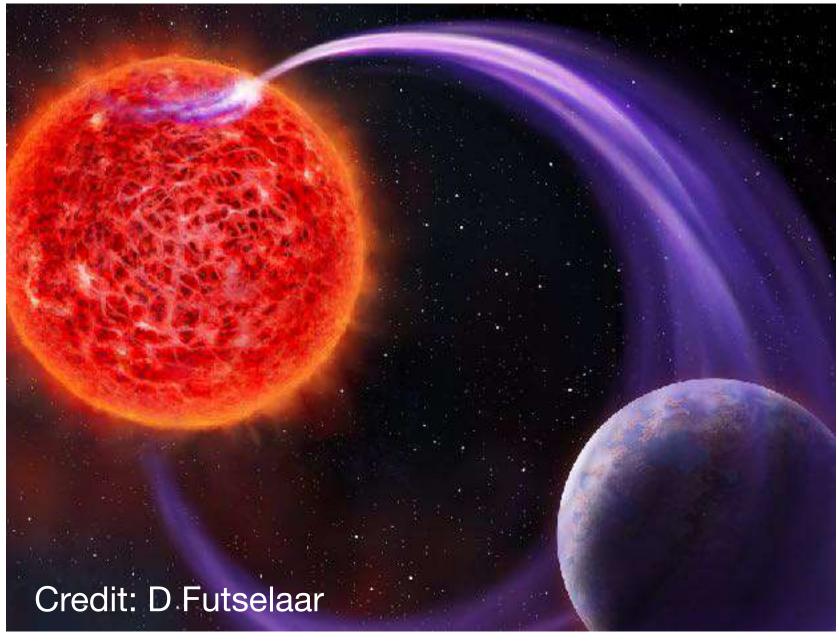
Sampling other LOFAR science highlights

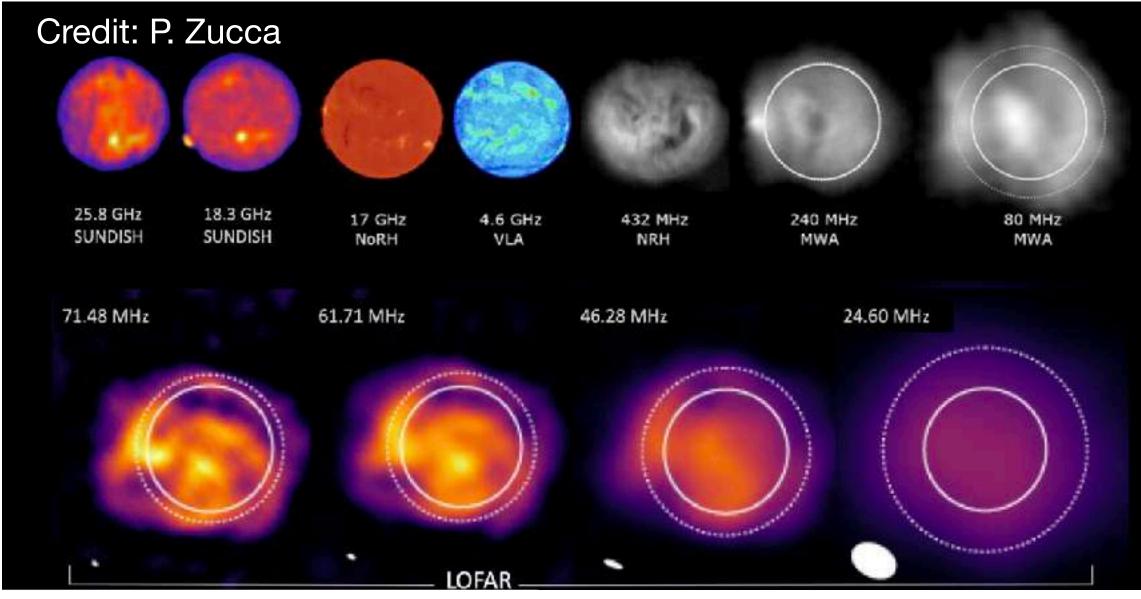
- **Lightning** (e.g., Hare+19, Hare+20)
 - Discovery of sub-structures (needles) explaining repeated discharge on the ground

• 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







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 (lower frequencies and longer baselines)
- 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)

New Capabilities

- Simultaneous LBA and HBA observations higher LBA sensitivity (NL)
- Simultaneous imaging and beamformed (pulsar) observations
- Better Linearity
- New Correlator, integration of NenuFAR
- New Proposal Tool

LOFAR2.0 status

- Hardware production and assembly almost complete
- Planned station upgrades 2025-2026, initial operations in 2026
- Capability will grow throughout 2026 and later years



Credit: W. van Cappellen

LOFAR 2.0 Large Programmes

- 5-year programme (2026-2030)
 - 1 commissioning year + 4 years of operations
 - Portfolio
 - Smaller, PI-led projects of more limited scope will run in parallel in later years.
 - see <u>https://www.lofar.eu/call-for-lofar2-0-large-programmes/</u>
- Deadline: 12 October 2023
 - 15 proposals received
 - 22 astronomers from Ukraine involved in L2LP proposals
 - focus on deep field HBA survey and low band survey
 - technical evaluation and preliminary scientific ranking completed
 - final allocation of projects ~mid 2026
 - first projects expected to start in the second half of 2026



• Major part of net observing time (about 17,500-20,000 hours) devoted to Large Programme

• observing, compute and data storage requests exceed capacity by a factor of <u>2.4-2.7x</u>

LOFAR 2.0 Data and Computing Challenges

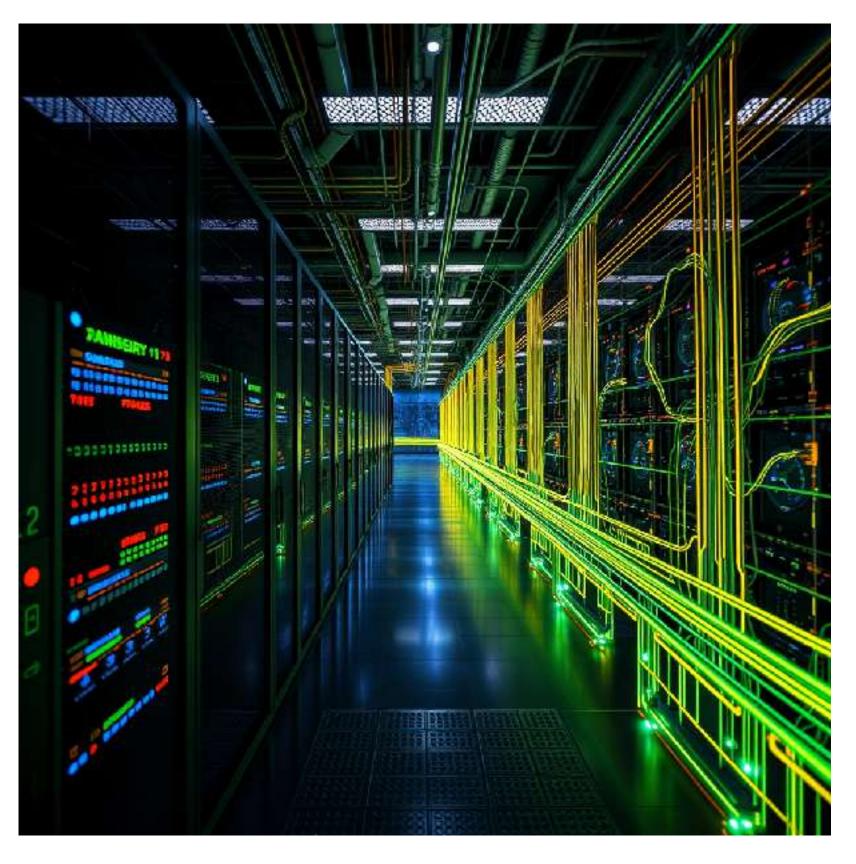
Historical context:

- In the LOFAR 1.0 era, data processing couldn't keep up with acquisition
- Result: 62 PB archived, mostly raw data reduced by compression and deletion of early LOFAR data (2012-2026)
- This approach cannot be sustained for LOFAR 2.0 raw data retained for ~18 months
- Data processing must keep pace with data gathering

Challenges facing us...

- Secure storage and compute commitments to carry out LOFAR 2.0 Large Programmes
- Discussions ongoing with members to provide sufficient resources •
- Data Processing Pipelines still under development especially for long baselines and low frequencies





Components in production are delivered weekly



A dedicated team is working on integration



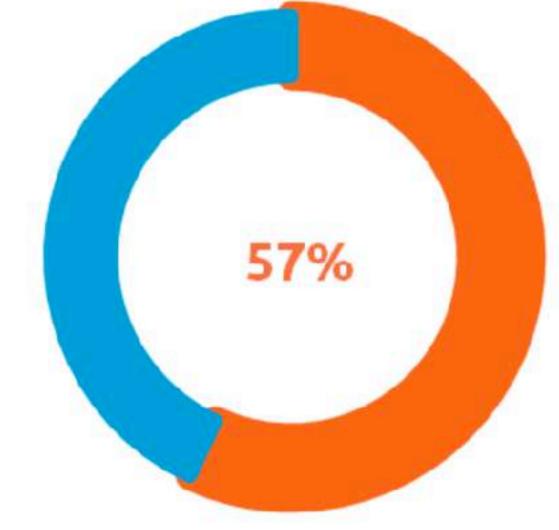
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Subrack integration











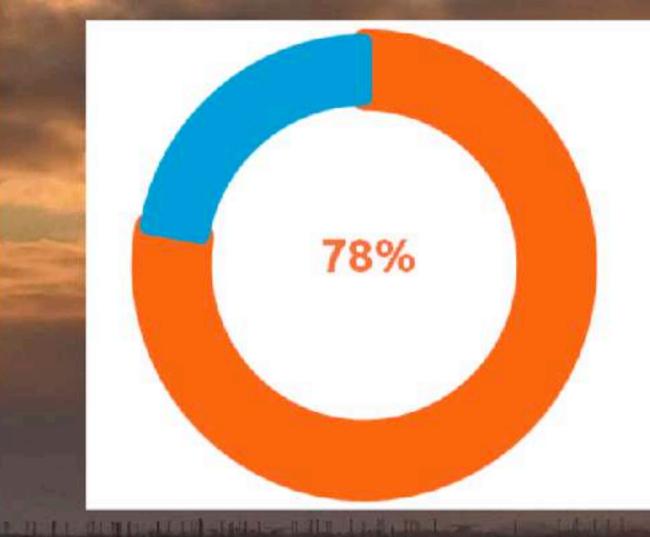


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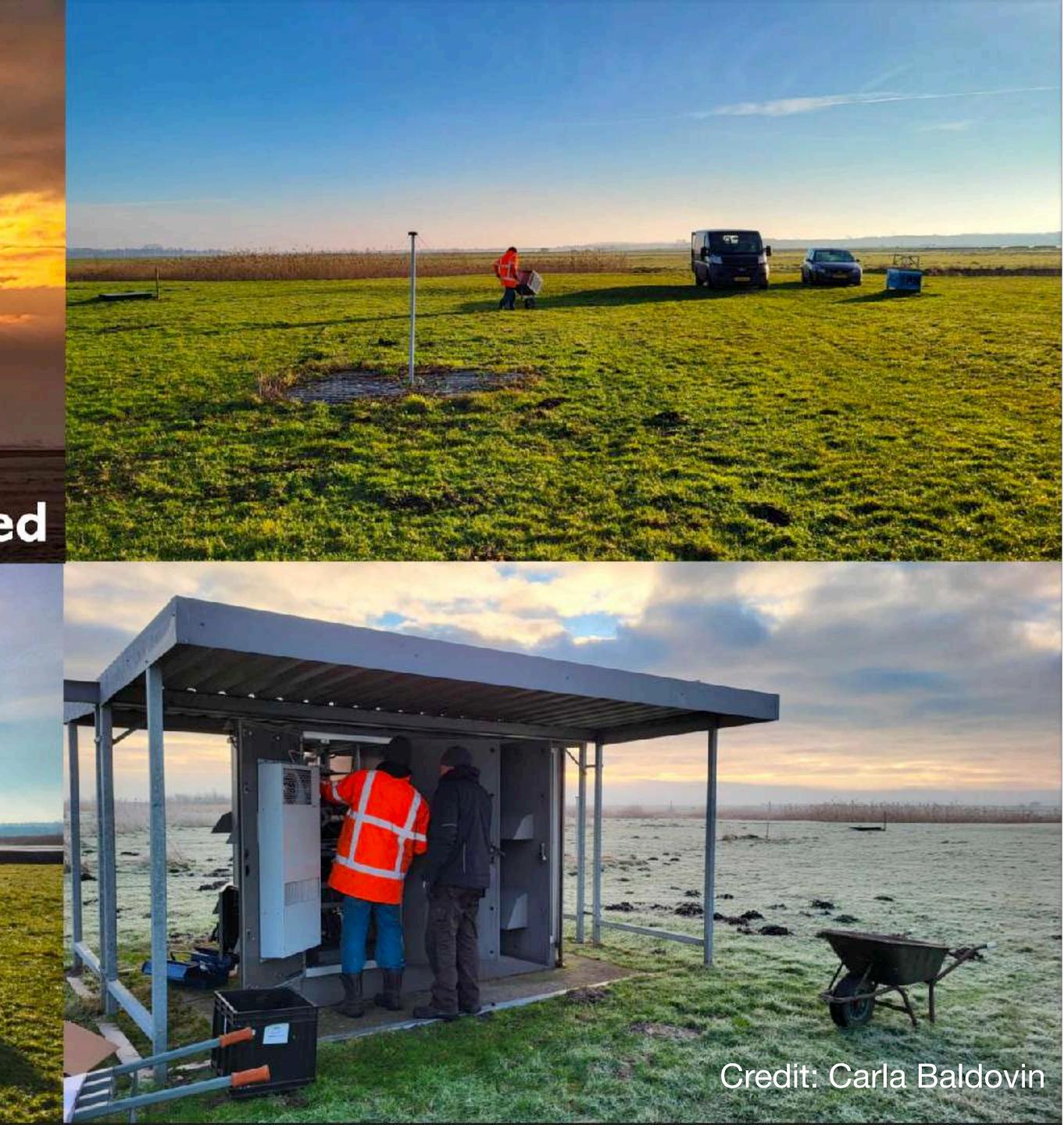






Dismantling of LOFAR1 in NL started

28/36 Stations dismantled





Delivery of CEP6 hardware





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

Future Development Opportunities

- New Members, Building new LOFAR stations
- Increased network bandwidth between stations and correlator (10 to 100 Gbps)
- LBA redesign in future possibly 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





Thank you

