LOFAR - the Low Frequency Array

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

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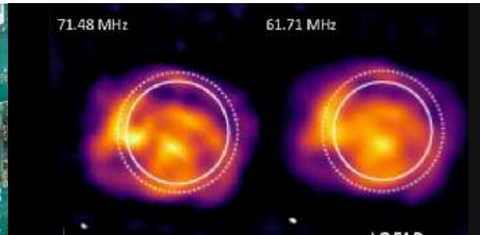
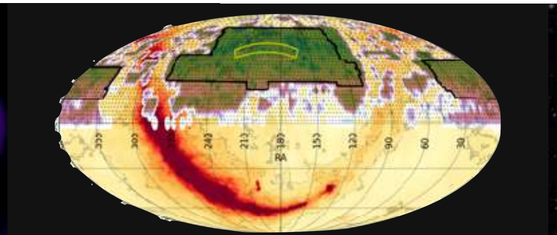
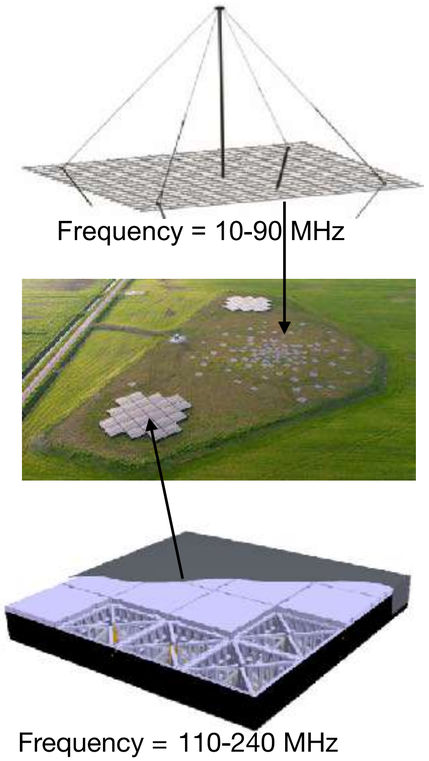
Recovery Plan for Ukrainian Astronomy
Leiden, 10-11 June 2025

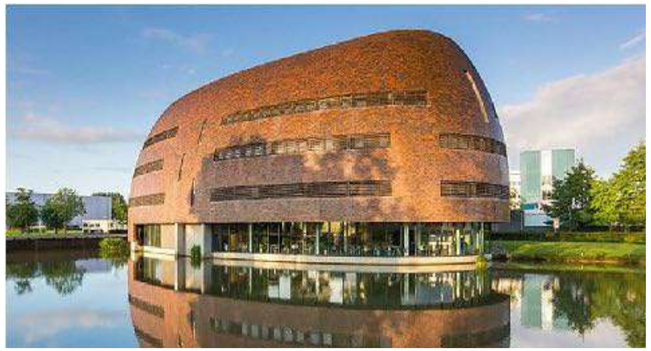





Distributed research infrastructure: world-leading low-frequency radio telescope

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

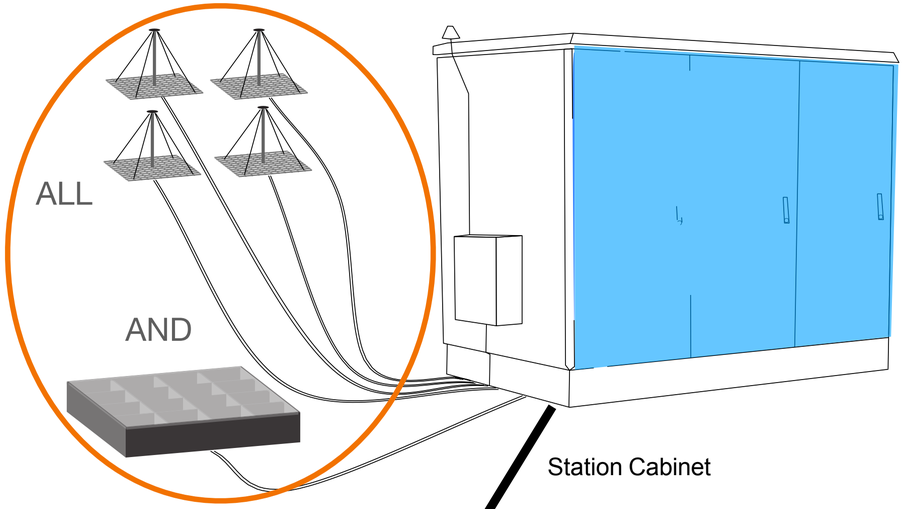




LOFAR Stations

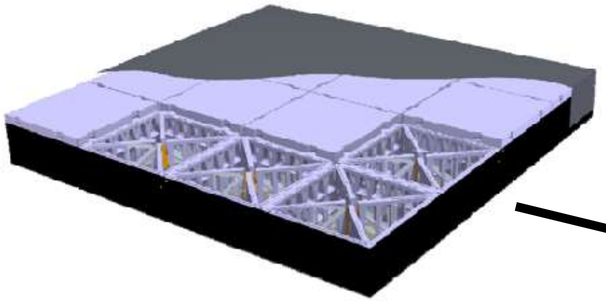
LOFAR 1.0 capabilities

- **International Stations**
  - 96 LBA and 96 HBA
- **NL Stations**
  - 96 LBA and 48 HBA
  - only 48 antennas can be used at one time



LOFAR 2.0 capabilities

- **International Stations**
  - 96 LBA and 96 HBA simultaneously
- **NL Stations**
  - 96 LBA and 96 HBA
  - all antennas can be used simultaneously



High-Band Antennas

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

Low-Band Antennas

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

The LOFAR system - Data flow

Long Term Archives

SURF in the Netherlands
FZJ in Germany
PSNC in Poland
+ more to come

Science processing

Clusters across Europe

Correlation & Beamforming

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

~200 Gb/s

10s Gb/s

10 PB/yr

Data repositories

Station-level processing

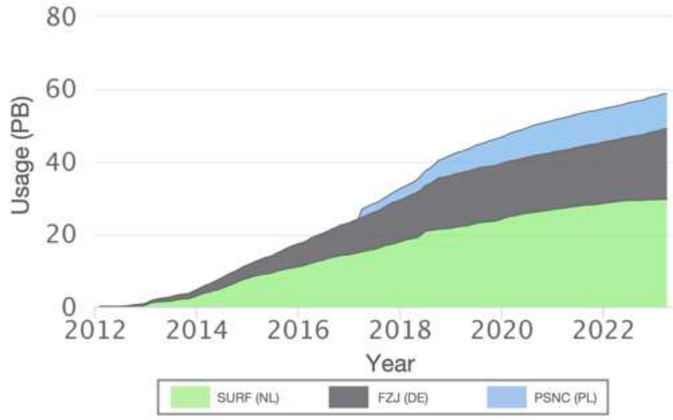
(e.g., amplification, filtering, digitisation, beam-forming)

13 PB/s sampling

Initial Processing

CPU & GPU system at RuG

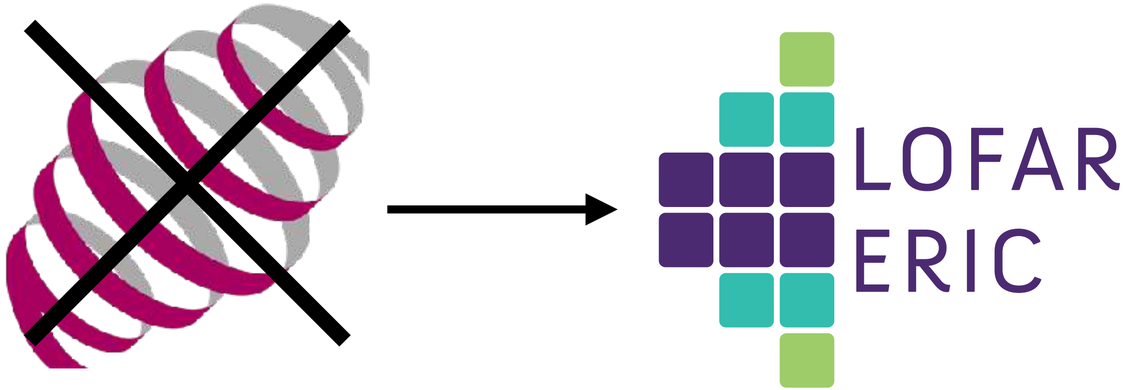
Central operation



An ERIC to anchor and further develop the LOFAR distributed RI

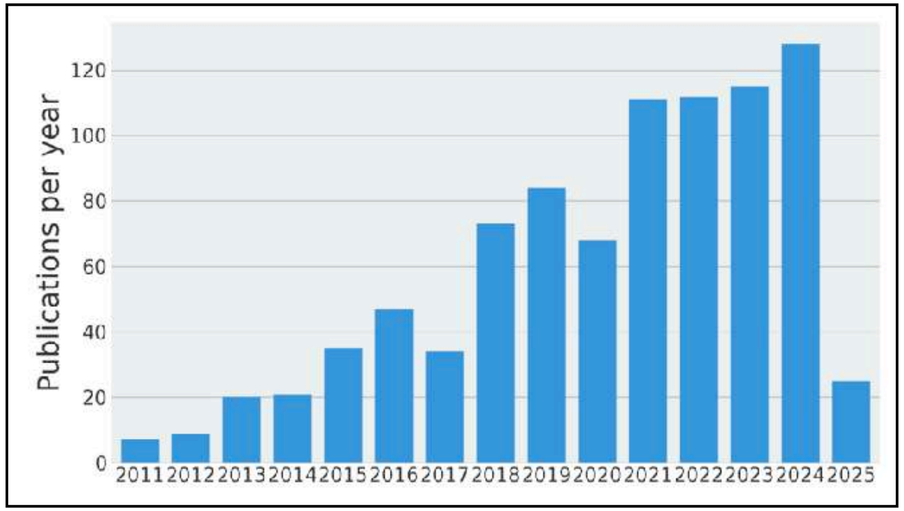
- **ILT Foundation → Coordinated operation of the LOFAR RI under a joint scientific policy**
  - Participants: National consortia of partners across Europe (NL, DE, PL, UK, FR, SE, IE, LV, IT, BG) + ASTRON
  - Partners own their LOFAR station(s) and commit these to joint operations
  - ASTRON provides operational coordination

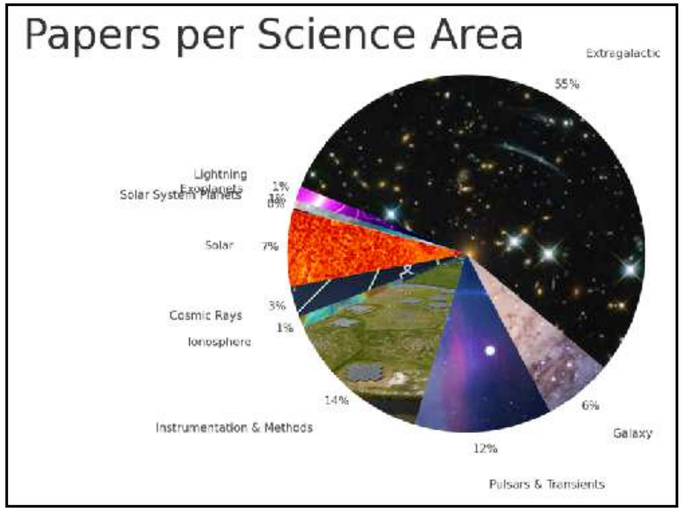
- **LOFAR ERIC → More robust governance to anchor and expand LOFAR partnership**
  - Partner participation at national level, aligned to common long-term strategy and vision
  - Joint funding, steering, and implementation of major projects (e.g., LOFAR2.0) - financial advantages
  - Increase scientific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



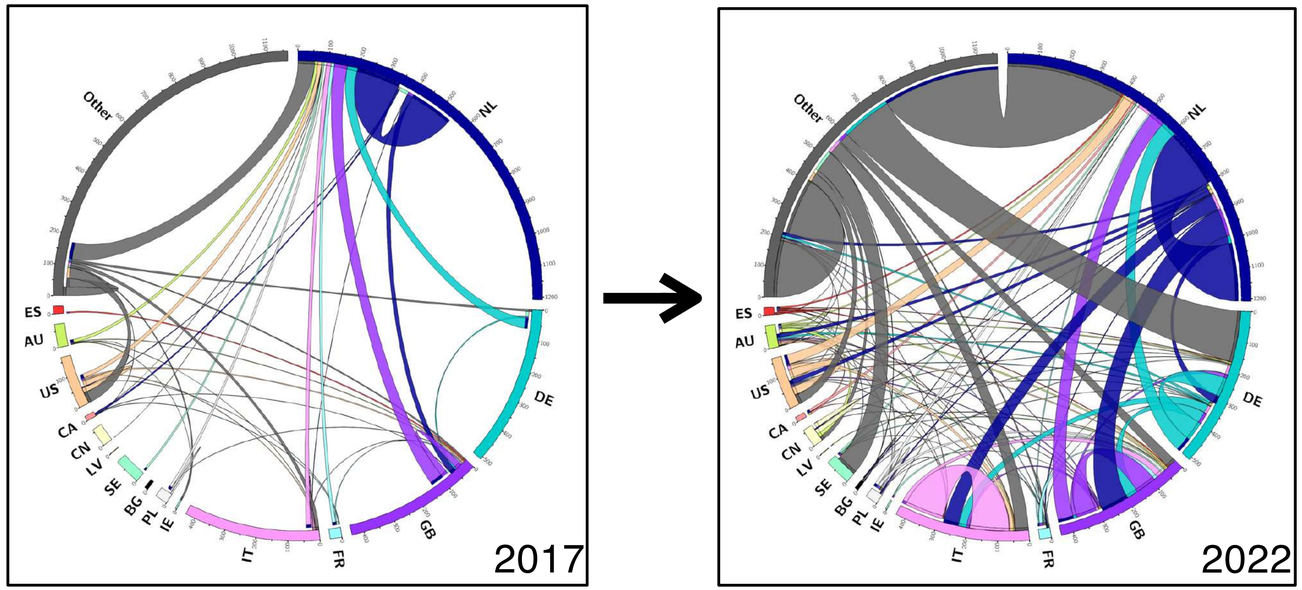
Community evolution and science output

- **889 refereed publications (2011-Feb 2025)**
  → **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

Only scratching the surface of LOFAR science results!

LOFAR Family Meeting 2023 (Olsztyn, Poland)

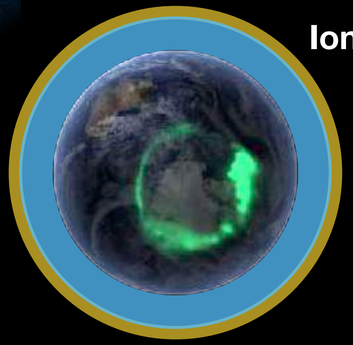
LOFAR Family Meeting 2024 (Leiden, The Netherlands)

LOFAR’s broad science case

Meteors

Lightning

Ionosphere



Heliosphere
Space Weather

Sun

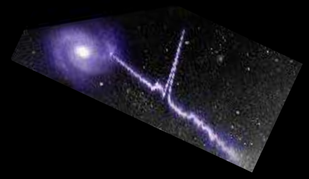
Supernova remnants
Pulsar Wind Nebulae

Cosmic
Magnetism

Clusters

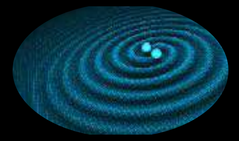
Pulsars

Fast Radio Bursts

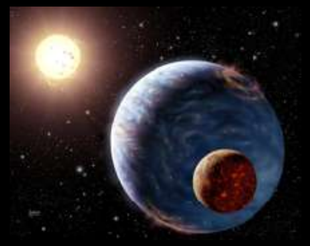


Early Universe
Cosmic Dawn

Gravitational
Wave Events



Exoplanets
Star-Planet Interaction

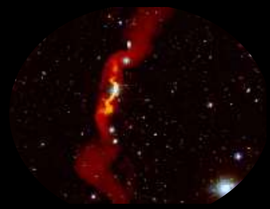


Solar System
Planets

Interstellar
Medium

Cosmic Rays

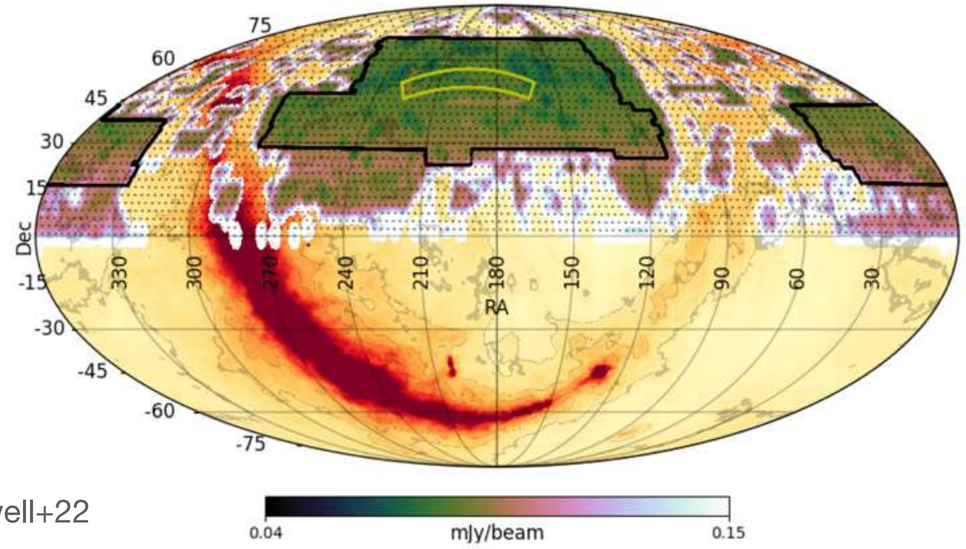
AGN physics



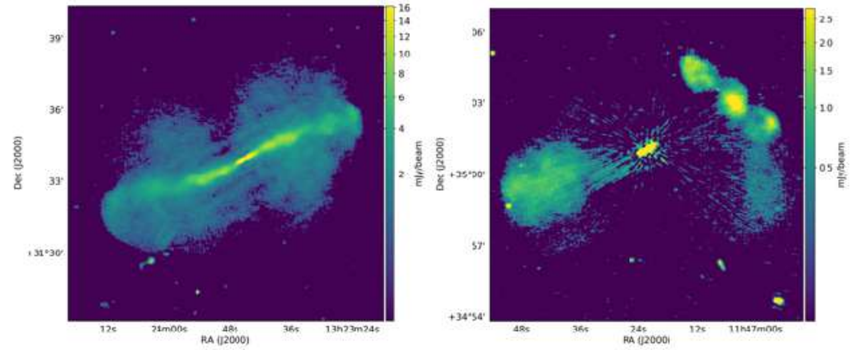
Nearby Galaxies

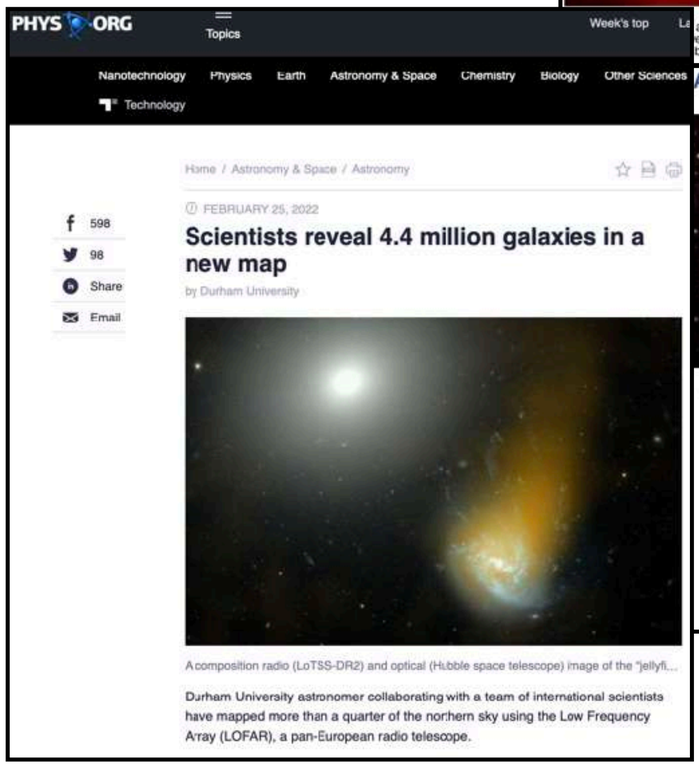
LOFAR science highlights - HBA Surveys

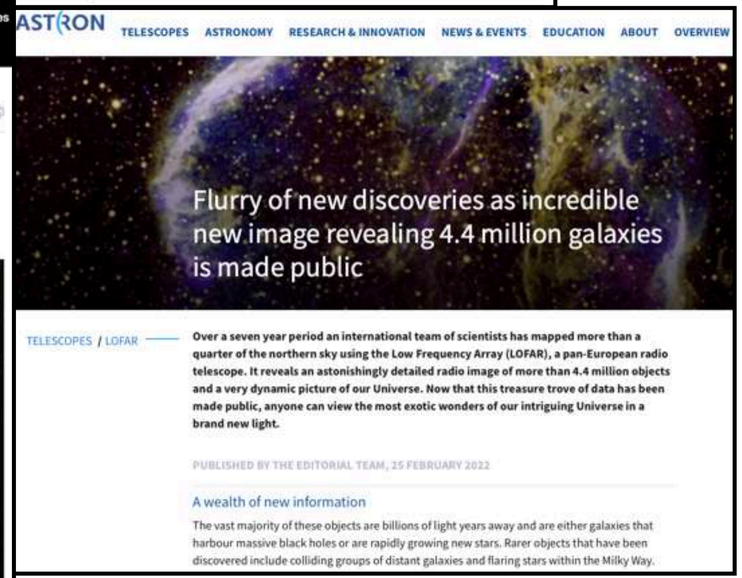
- **Surveying: huge area, huge object samples**
  - **LoTSS: LOFAR Two-Metre Sky Survey (Shimwell+22)**
    - Mapped ~27% of Northern sky at 120-168 MHz
    - Detailed radio image of 4.4 million objects
    - Resolution 6”



Shimwell+22

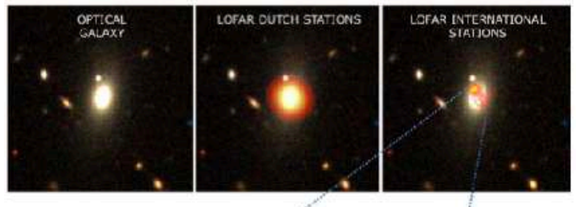


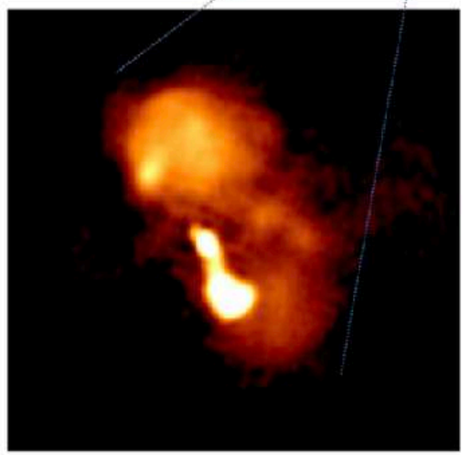


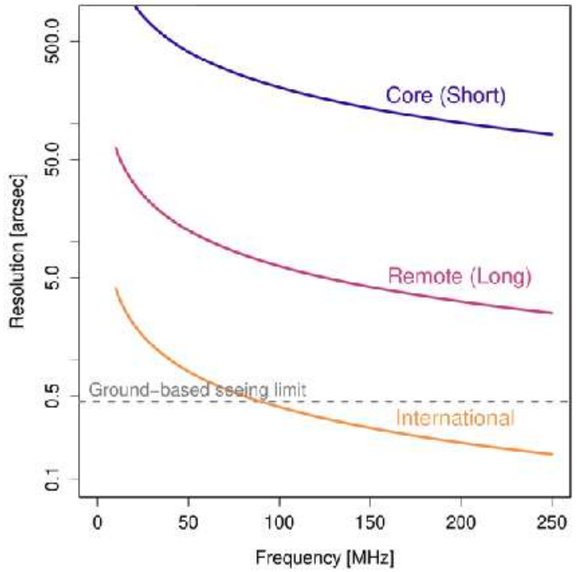


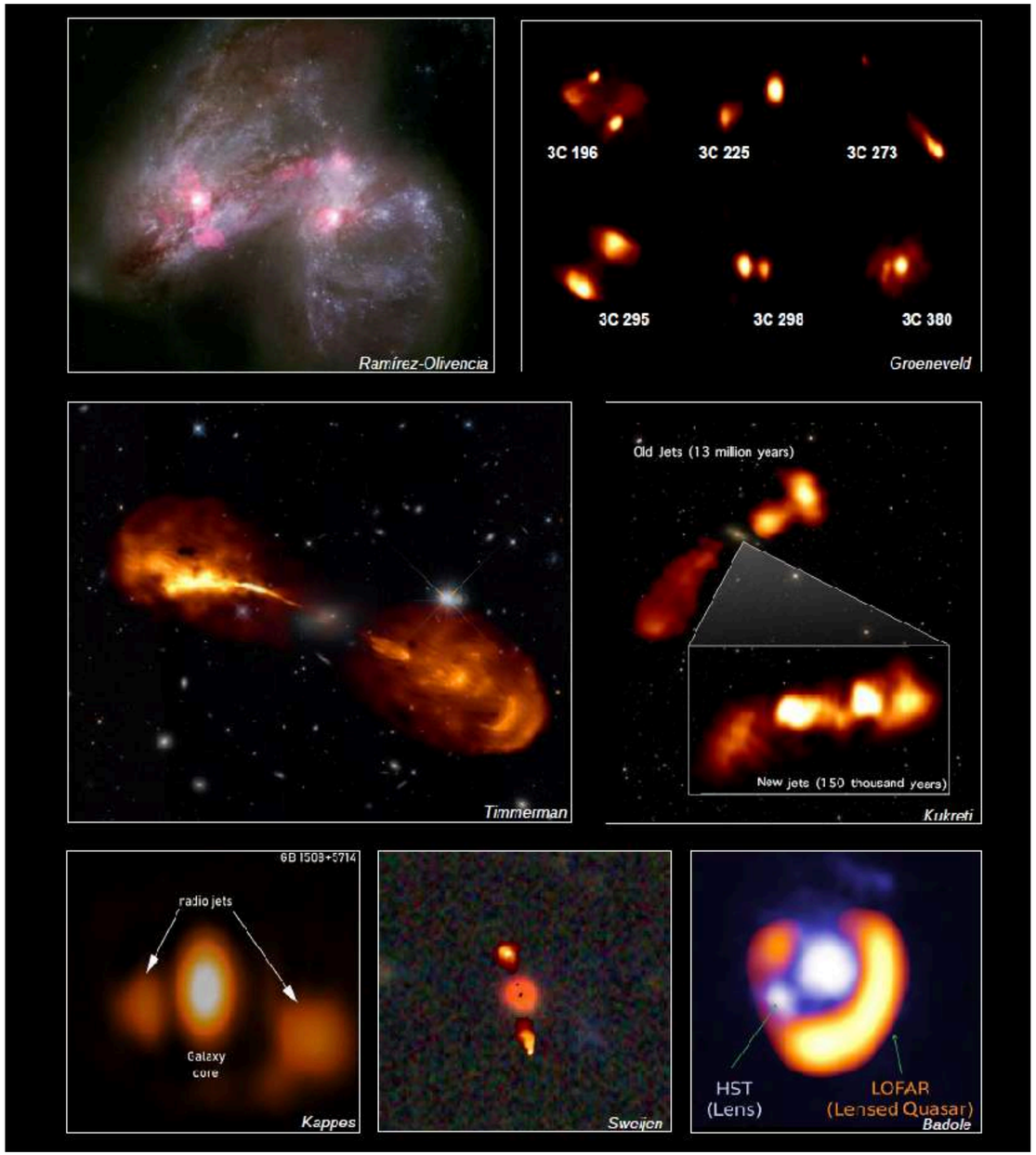
LOFAR science highlights - HBA Surveys - International Baselines

- **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





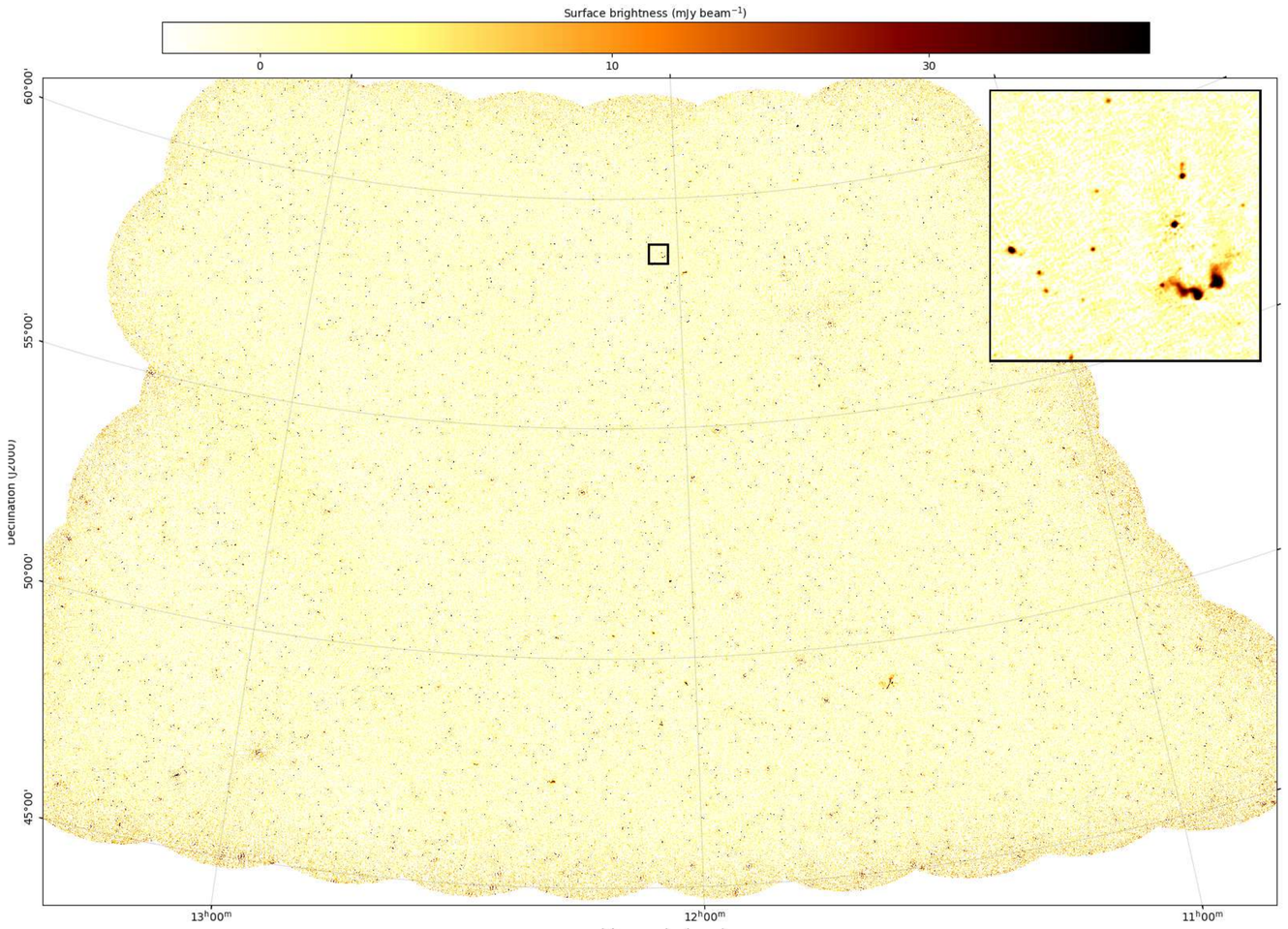


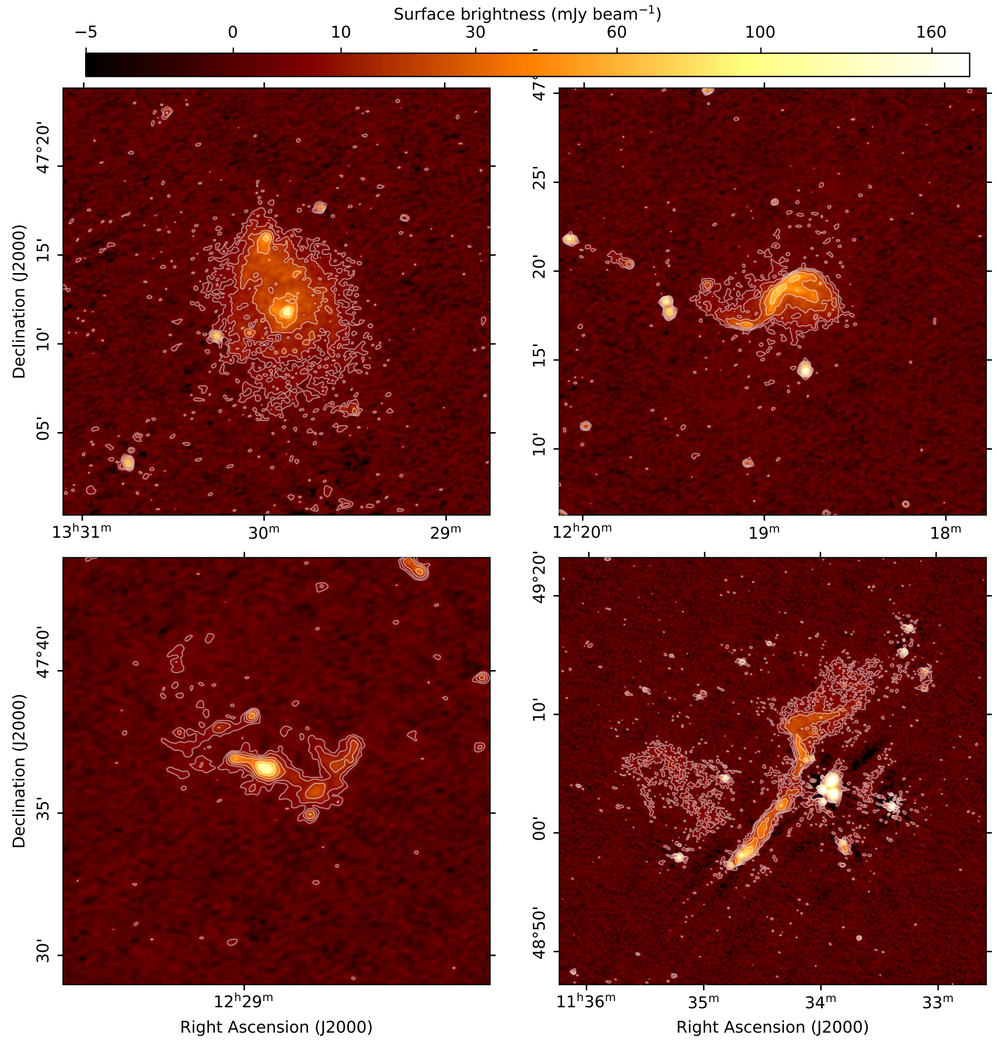


Credit: L.K. Morabito; LOFAR Surveys KSP

LOFAR science highlights - 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

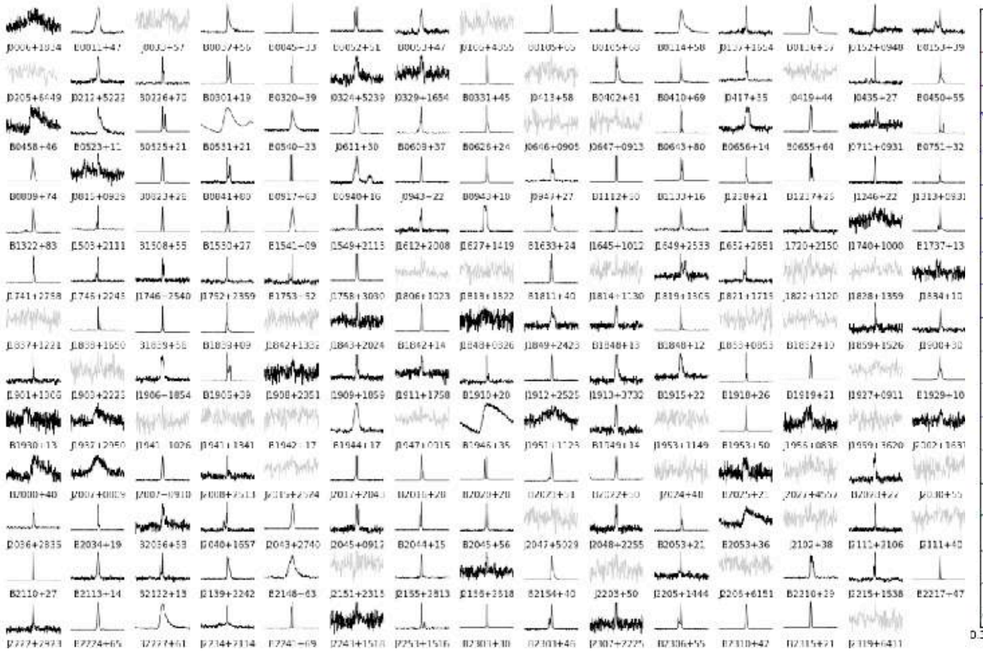




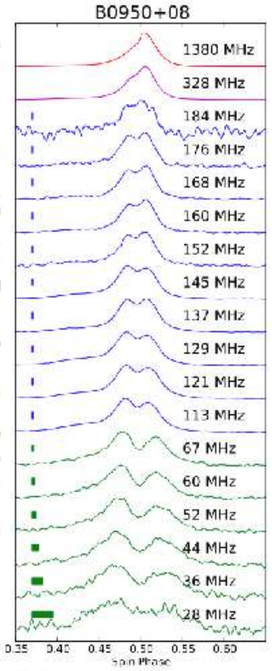
de Gasperin+23

LOFAR science highlights - Pulsars

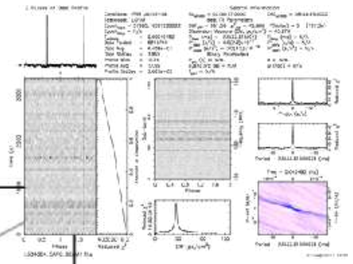
- **LOFAR Pulsar Census**
  - LOFAR has detected more than 300 pulsars so far
  - including a super-slow (23.5 second) pulsar (Tan et al. 2018) and a 1.4 ms (707 Hz) pulsar



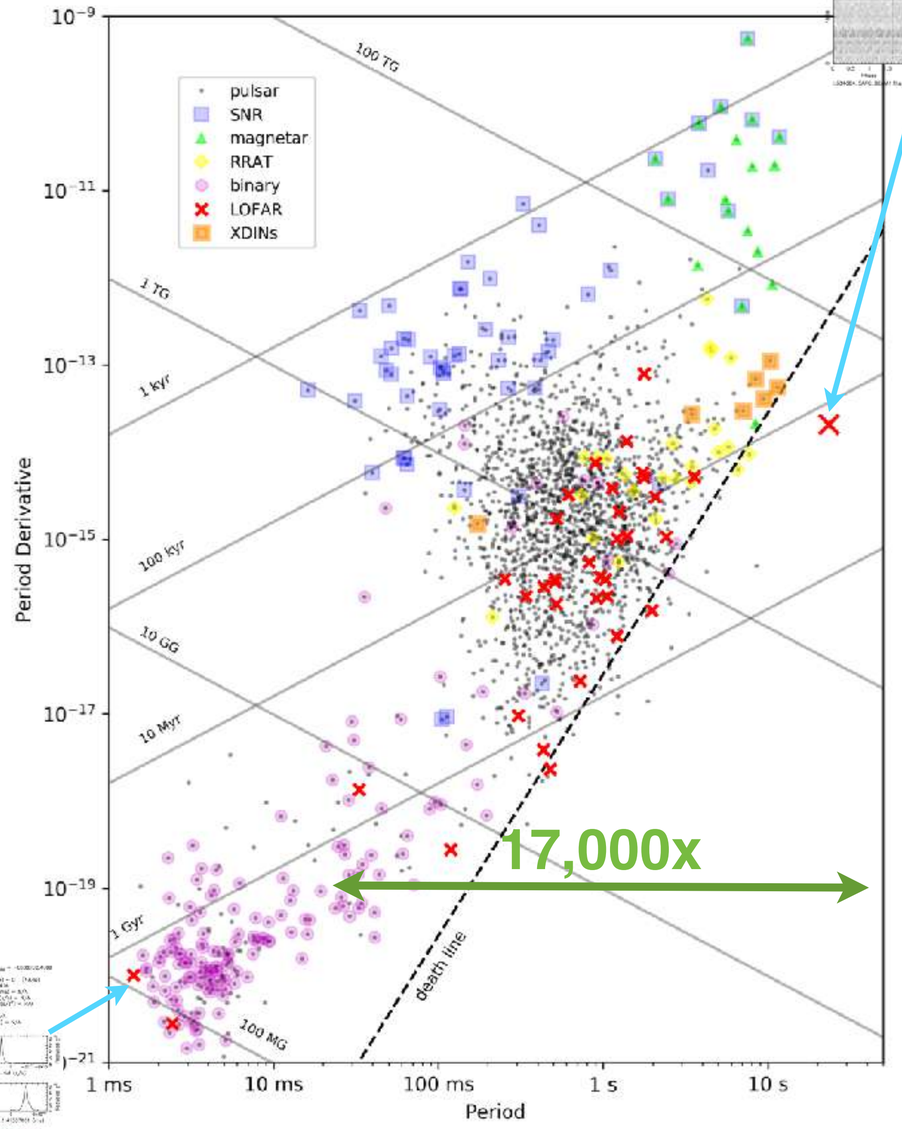
Bilous et al. 2016

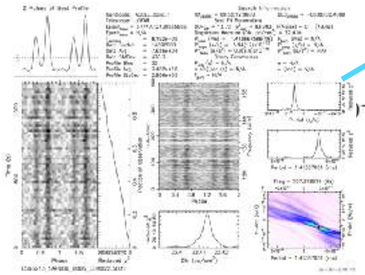


Pilia et al. 2016



0.042 Hz
23,533.6 ms



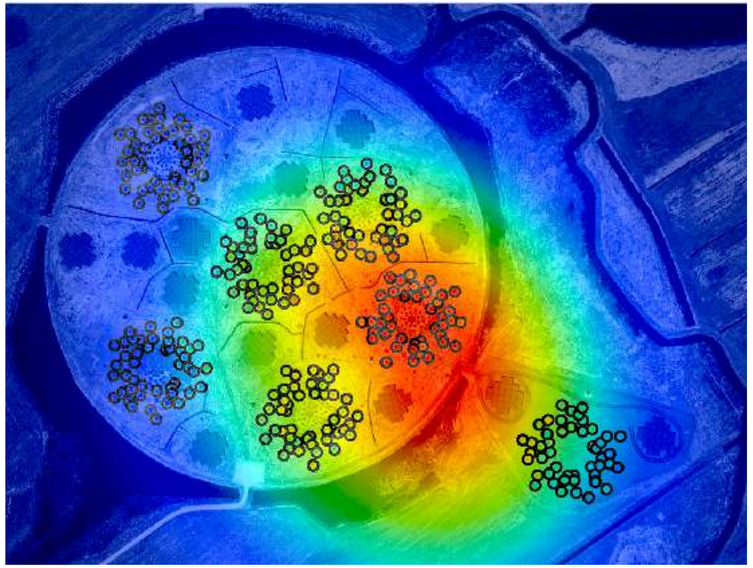


707 Hz
1.41 ms

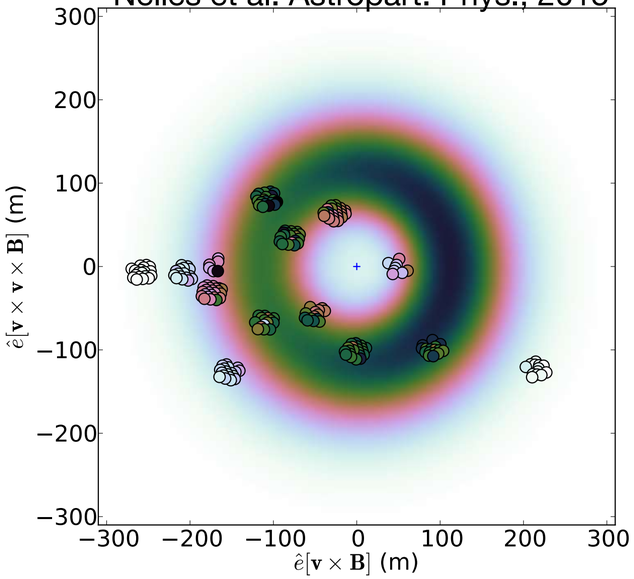
Cooper - see also van der Wateren et al. 2023

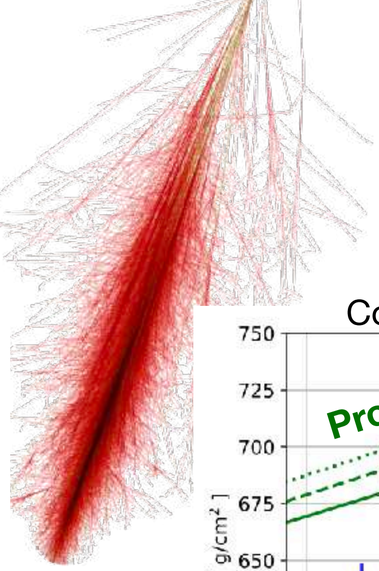
LOFAR science highlights - Cosmic Rays

Buitink et al. Nature, 2016

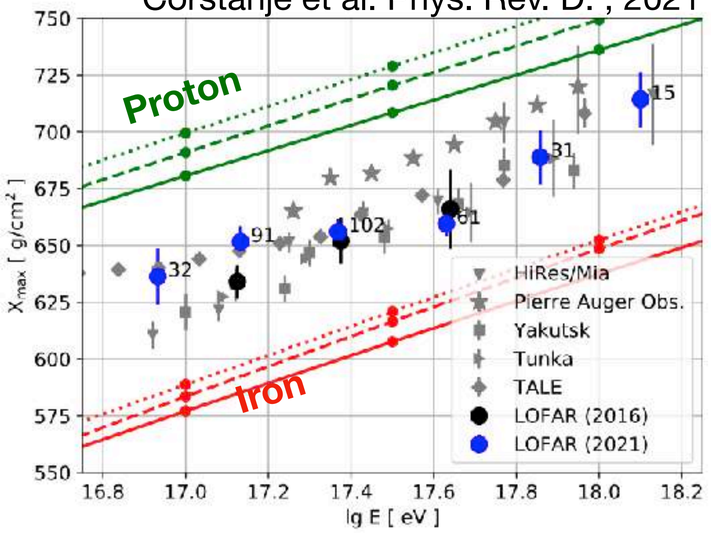


Nelles et al. Astropart. Phys., 2015





Corstanje et al. Phys. Rev. D. , 2021

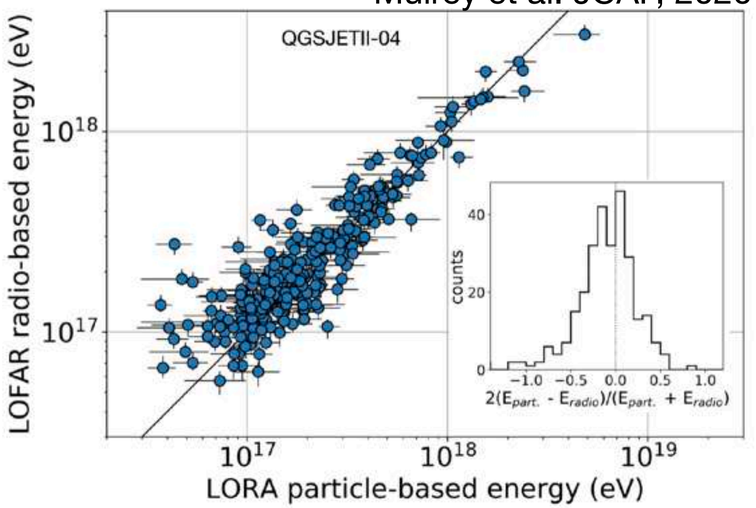


Particle Composition

- First experiment to map details of radio emission mechanisms in air showers 30 MHz - 190 MHz
- Superior timing = wavefront shape
- Demonstration of circular polarization

- Radio-based (energy and X_{max}) reconstruction with world leading accuracy
- Absolute LBA calibration (ADU -> V/m)
- Cosmic ray composition studies in the 50 PeV to 2 EeV energy range

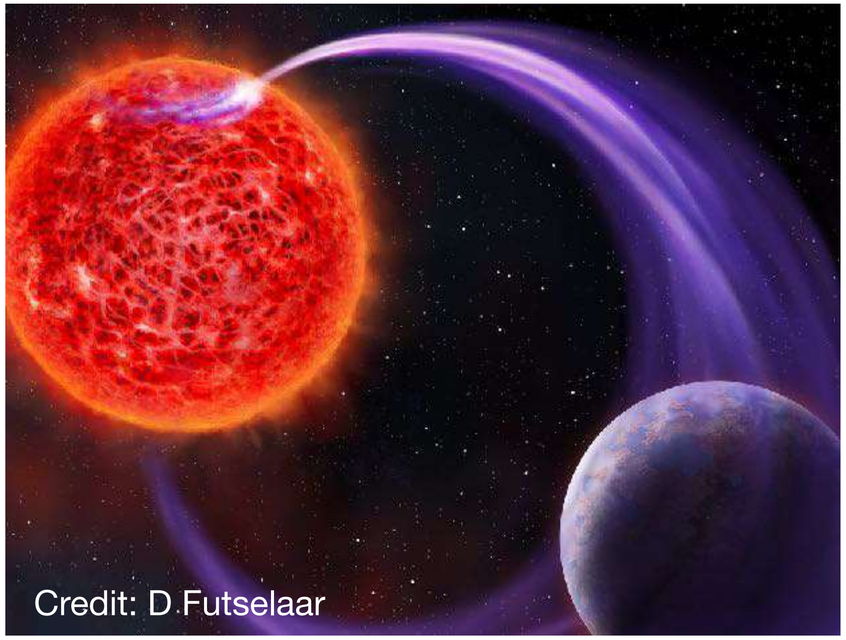
Mulrey et al. JCAP, 2020

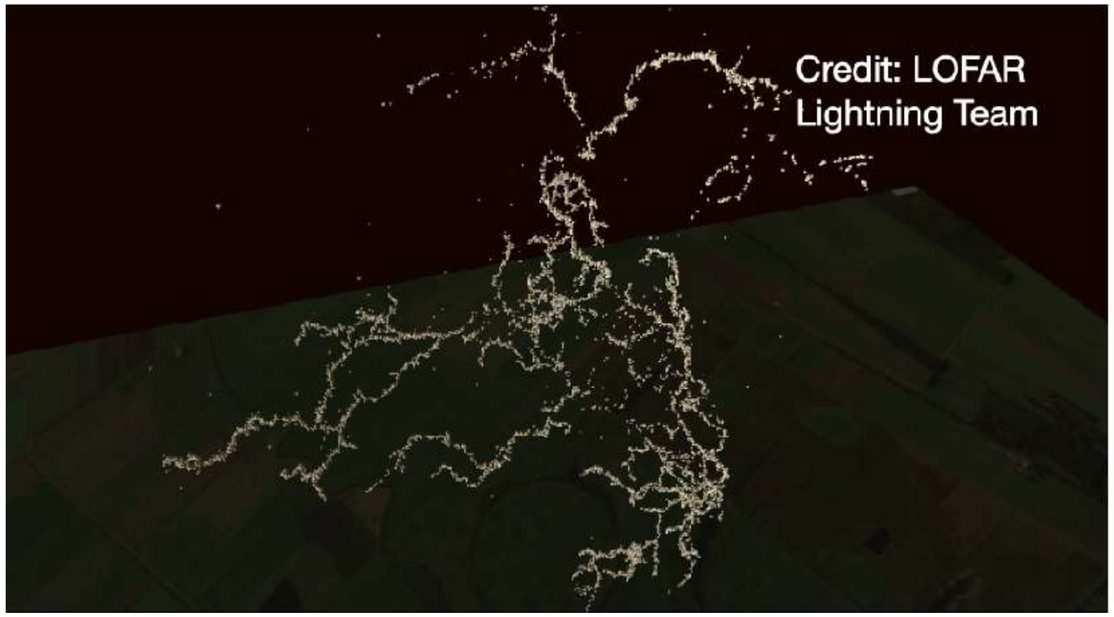


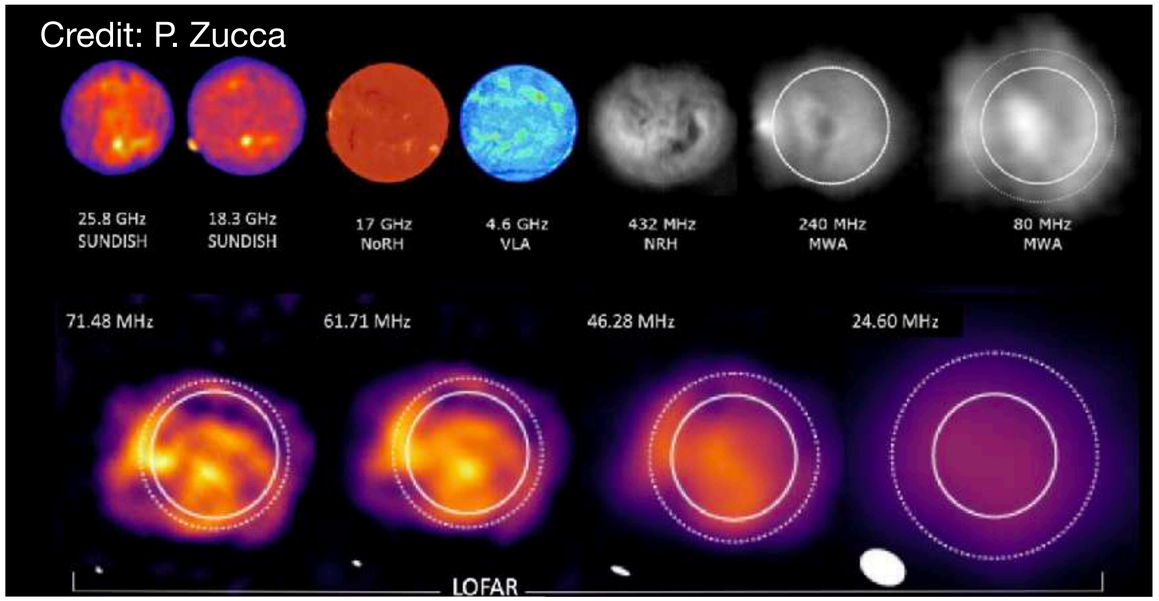
Particle Energy

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 (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

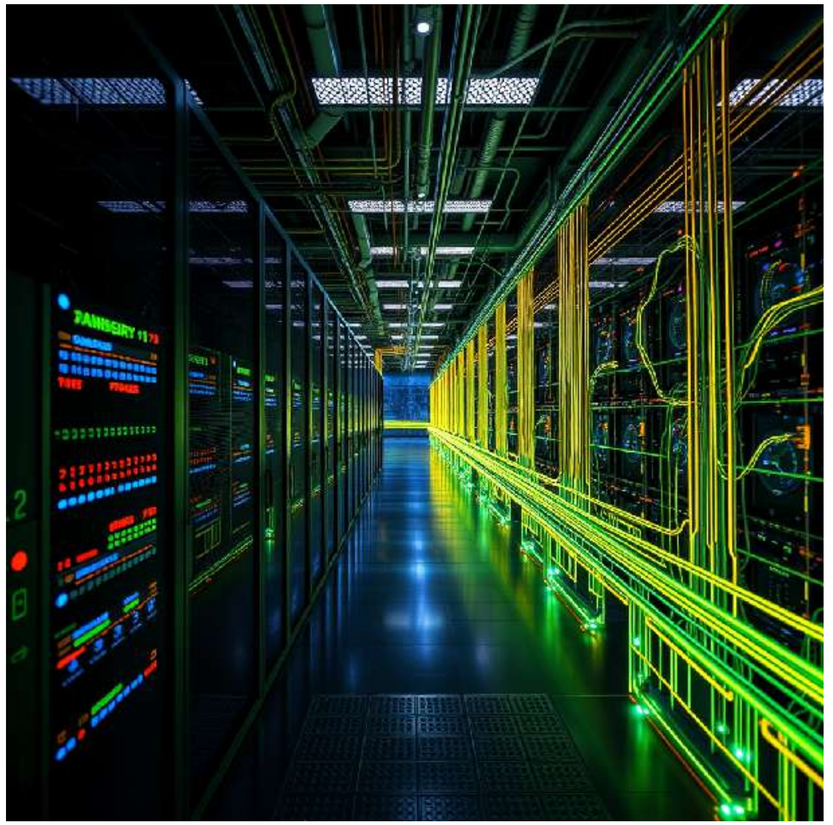
- 5-year programme (2026-2030)
  - 1 commissioning year + 4 years of operations
  - Major part of net observing time (about 17,500-20,000 hours) devoted to Large Programme Portfolio
  - Smaller, PI-led projects of more limited scope will run in parallel in later years.
  - see https://www.lofar.eu/call-for-lofar2-0-large-programmes/

- 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
    - observing, compute and data storage requests exceed capacity by a factor of 2.4-2.7x
  - final allocation of projects ~mid 2026
  - first projects expected to start in the second half of 2026

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

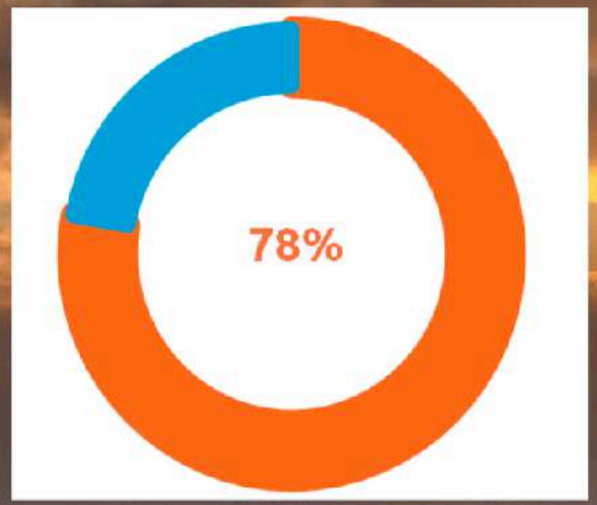

Components in production are delivered weekly

A dedicated team is working on integration

Credit: Carla Baldovin

Placement of LOFAR2.0 subracks in station cabinets started.

Credit: Carla Baldovin



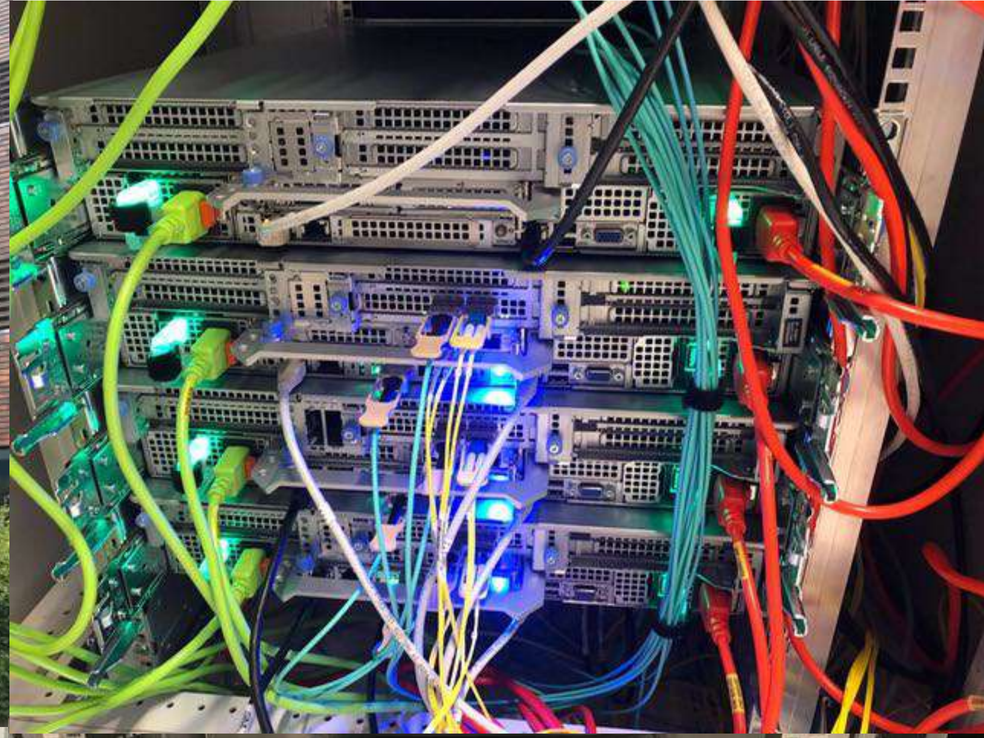
Dismantling of LOFAR1 in NL started

28/36 Stations dismantled

Credit: Carla Baldovin

LOFAR ERIC

Delivery of CEP6 hardware



university of groningen

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

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Thank you