Low frequency radio astronomy and the LOFAR telescope

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Frontend research at low radio frequency Radio Astronomy:
Science and technical challenges

3 – 7 April 2023
Lecture given 4 April 2023

Lecture Overview: LOFAR past, present, and future

- A bit of low frequency radio astronomy history – motivation for the design of LOFAR

- The basics of LOFAR technology – what makes it unique and cutting-edge

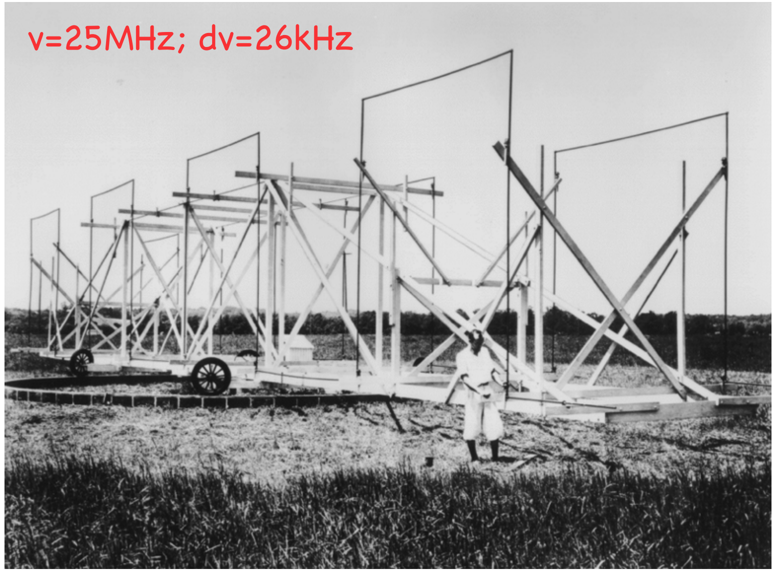
- LOFAR ERIC; continuing to be unique and successful in the SKA era

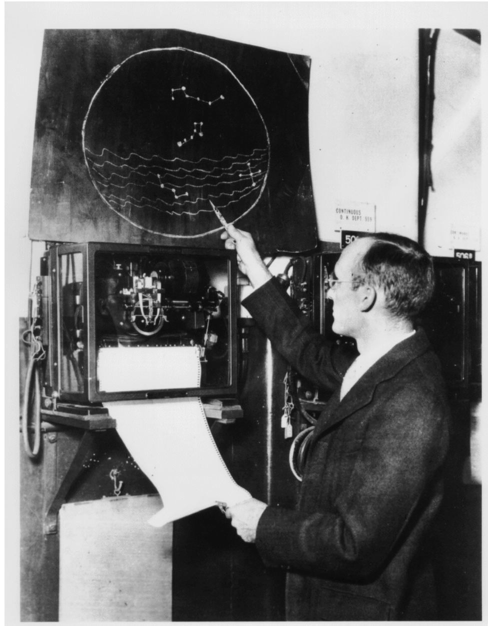
- An incomplete selection of recent LOFAR science highlights

- Summary of the ongoing LOFAR2.0 upgrade: why and what

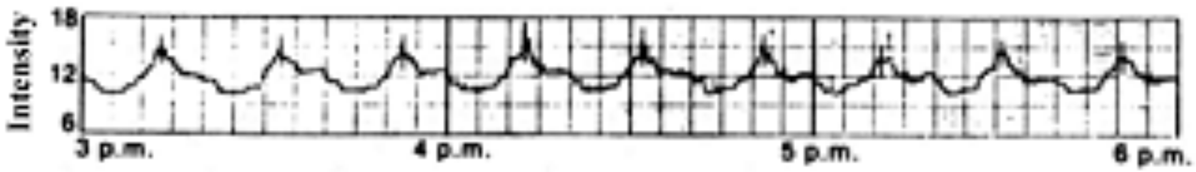
The start of radio astronomy – at LOFAR frequencies!

- Discovery of cosmic radio waves - Karl Jansky, 1932

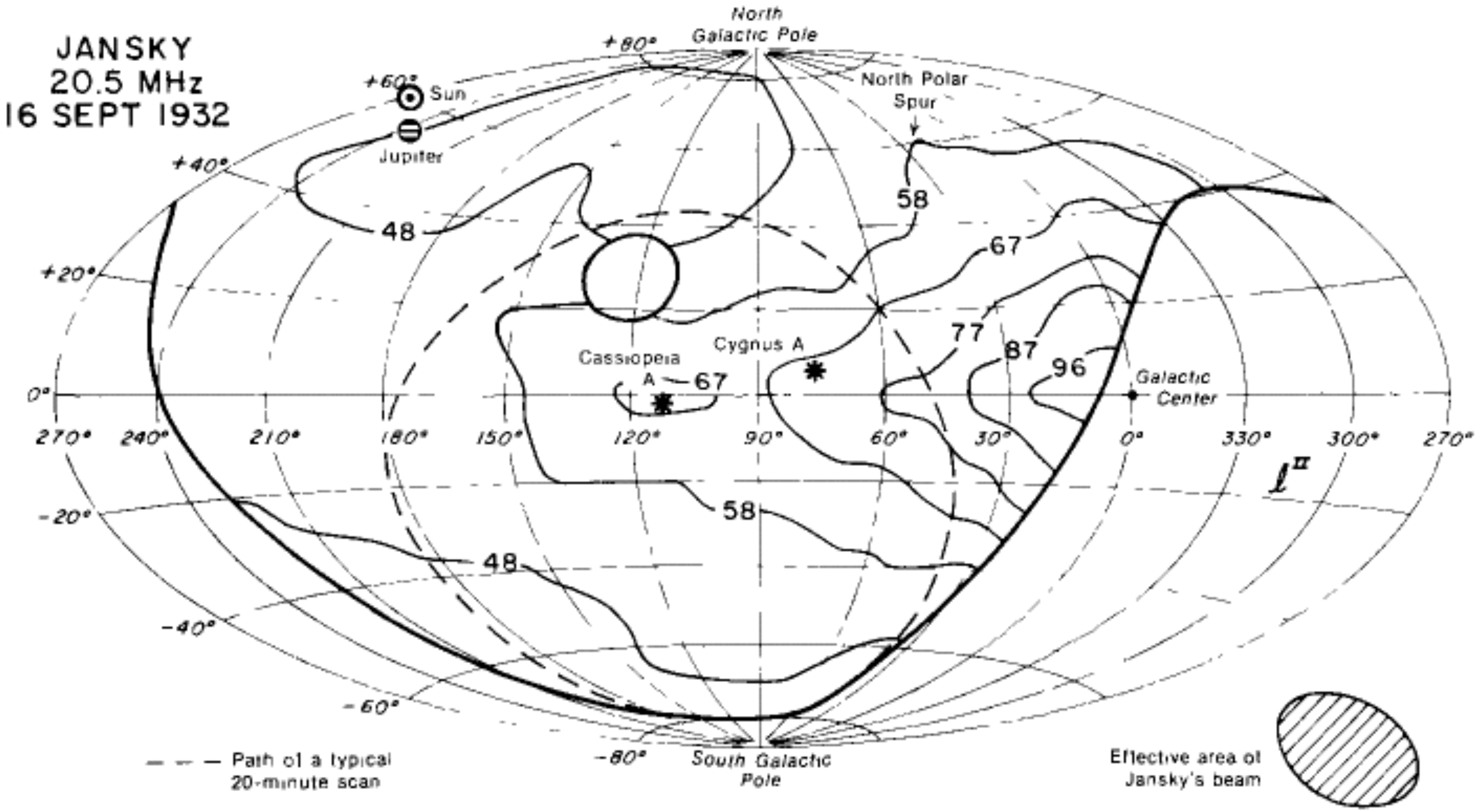




20.5 MHz Recording 16 Sept 1932



The start of radio astronomy – at LOFAR frequencies!

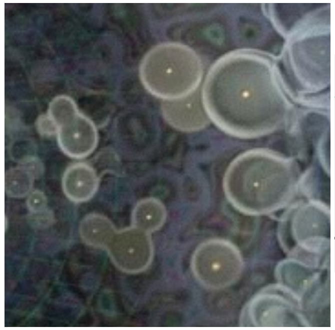


Historical Overview of Low Frequency Radio Astronomy

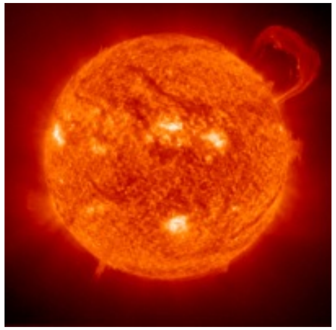
1931-35	Discovery of cosmic radio waves, **birth of radio astronomy** (Jansky)
1935-40	**Discovery of nonthermal emission** (Reber, Heneye, Keenan)
1942	Discovery of solar radio emisson (Hey)
1946	**First 2 element interferometer** (Ryle)
1946-50	**Discovery of discrete cosmic radio sources** (Ryle)
1946-51	Discovery of radio galaxies & SNRs (Ryle et al.)
1955	First all-sky surveys (Kraus, Mills, Baldwin, others)
1955	**First detection of planetary radio emission** (Burke, Franklin, Shain)
1962-63	First widely used radio catalogue (Bennett - 3C)
1963	**Discovery of quasars** (Hazard, Schmidt, Sandage, Greenstein, others)
1967	First VLBI fringes
1968	**Discovery of pulsars**

From: Kassim & Polisensky 2005

By about 1970 several (not all) low frequency science topics had emerged … that in >2000 drove the design and science motivation of LOFAR!



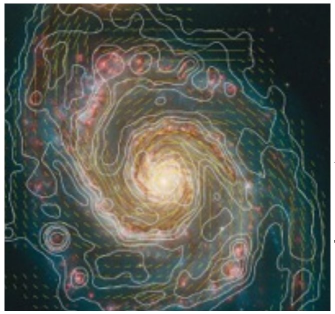
Epoch of Reionization (EoR)
Detection and statistical characterization of the reionization of the IGM by the first stars & galaxies.



Solar & Space Weather
Characterization of the Sun at low radio frequency, detection and study of CMEs and solar wind.

Surveys (SKSP)
Detection of high-z RGs, deep surveys of the radio sky at low frequency. Synergy with high frequency!

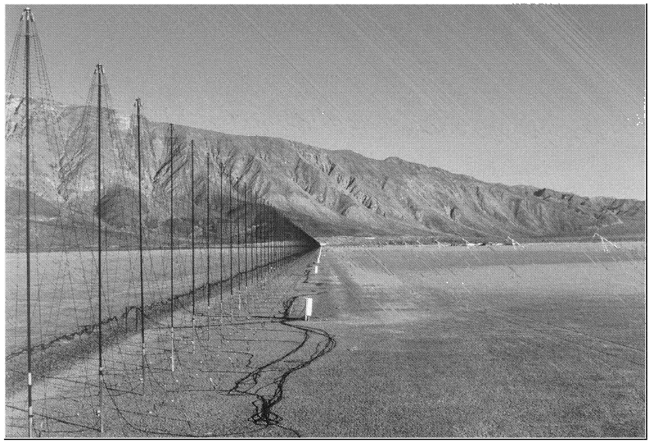
Ultra high energy cosmicrays
Detection of cosmic ray showers, characterization of particle mass and origin. Also particle detection.



Cosmic magnetism (MKSP)
Study of magnetic fields in various astrophysical objects, e.g. galaxies, and possibly the IGM.

Transients (TKP)
Search for fast transients (e.g. Lorimer bursts, pulsars) and slow transients (e.g. supernovae).

The intermediate era of low frequency radio astronomy



Clark Lake (1959 – 1986); USA

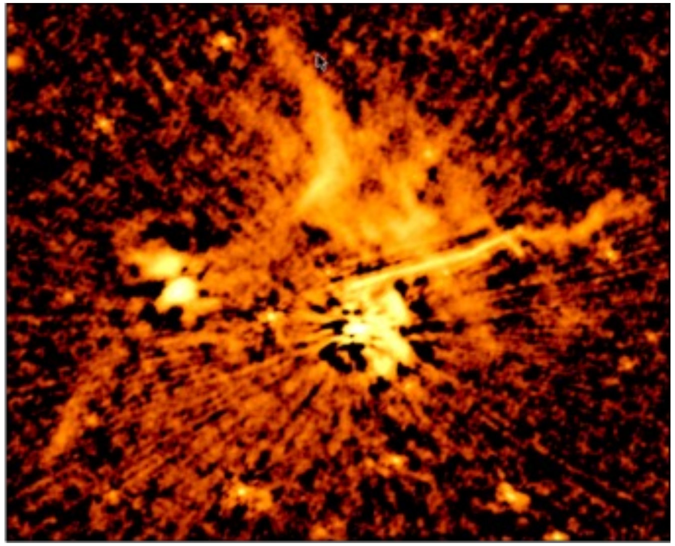
UTR-2 (1972 – present
currently damaged by war);
Ukraine

GMRT (1996; now uGMRT); India

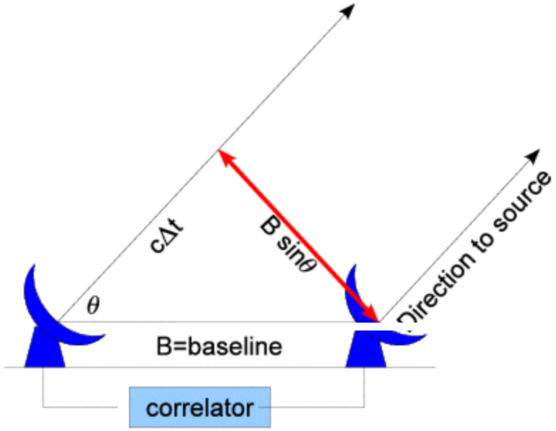
VLA 74 MHz (1997 – 2007); USA

The challenge: atmospheric scintillation, small “seeing” cells

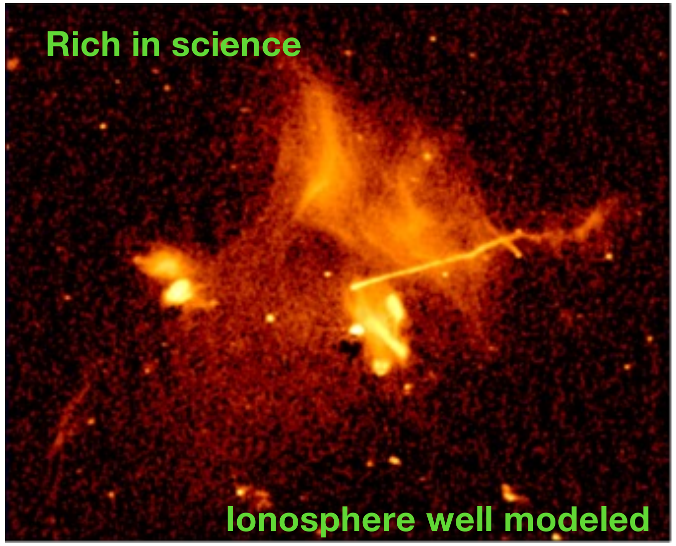
Scientifically limited



No ionospheric correction



$$\text{Angular resolution } \Theta \approx \frac{\lambda}{B_{\max}}$$

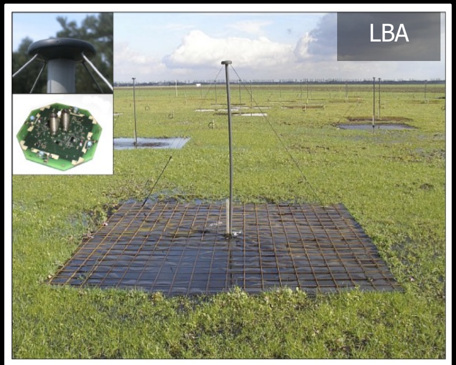


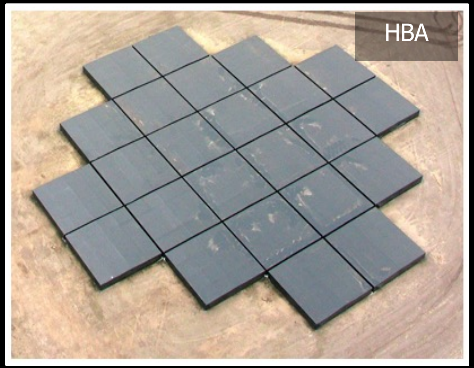
Solutions in the digital domain using HPC:

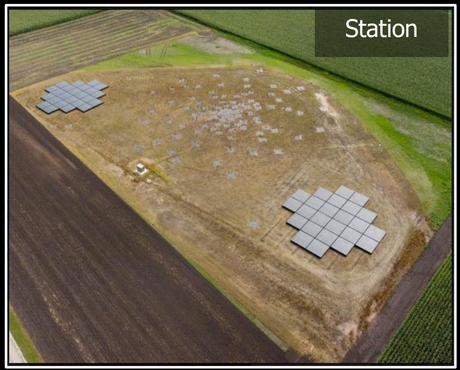
- Interferometry: high spatial resolution, tomography
- Wide bandwidth: phase delay solutions
- Direction-dependent calibration

LOFAR: KEY FACTS

- Array of 52 (soon 54) dipole antenna stations concentrated in NL and distributed across Europe (sub-arcsec resolution)
- 10-250 MHz: 96 Low Band Antennas (LBA; 10-90 MHz); 48/96 High Band Antenna 4x4 Tiles (HBA; 110-240 MHz)
- On-station data processing includes (in)coherent adding & (multiple) beam forming, cyclic data buffering & readout
- Central data processing includes correlation/imaging and in(coherent) adding/beam forming modes
- Responsive telescope generation of and response to triggers
- Pathfinder: technology, data intensive astronomy (7 PB/yr)







The LOFAR antennas

Low-band antenna
10 - 80 MHz
96 antennas per station

High-band tiles
120 - 240 MHz
48/96 tiles per station
4x4 antennas per tile

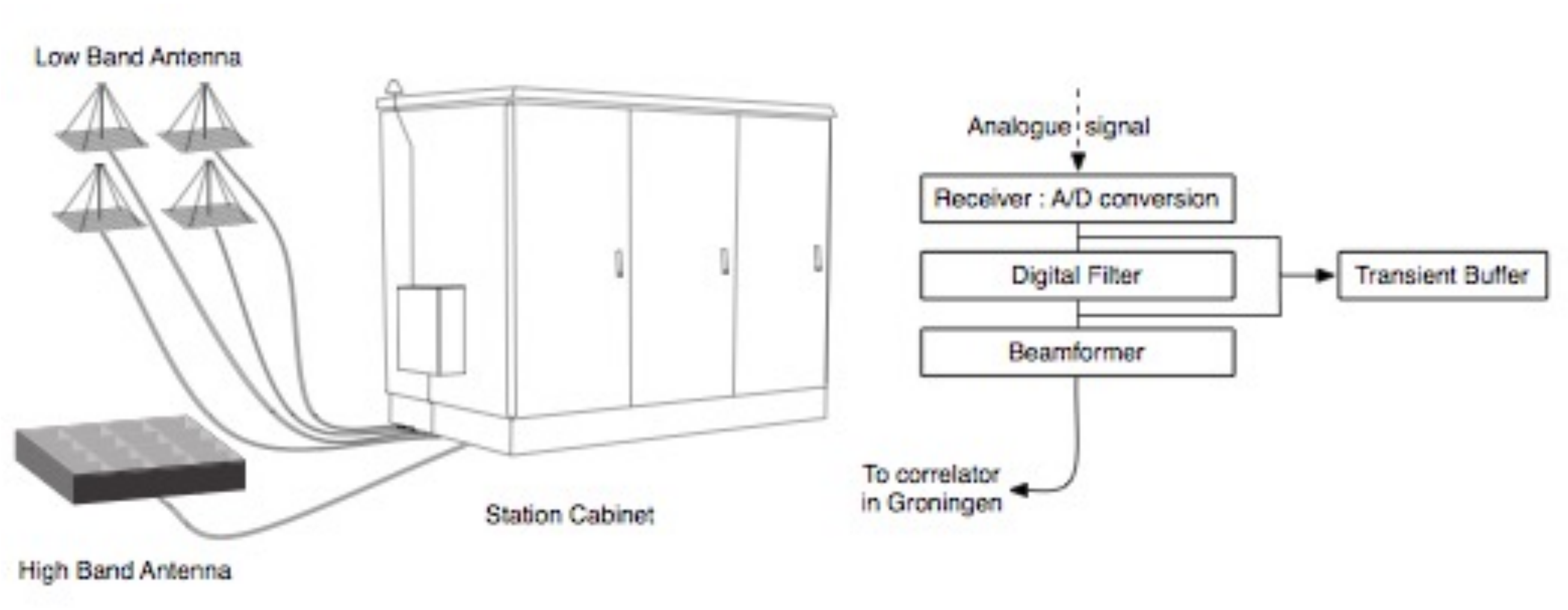
Replace big dishes by many cheap dipoles.
No moving parts: electronic beam steering.
Flexible digital beam forming


The LOFAR core
24 stations within radius of 2 km located in Exloo (NL)

The principle: Analogue + Digital beam-forming

Dipole   Station   Tied-array

LOFAR station data flow

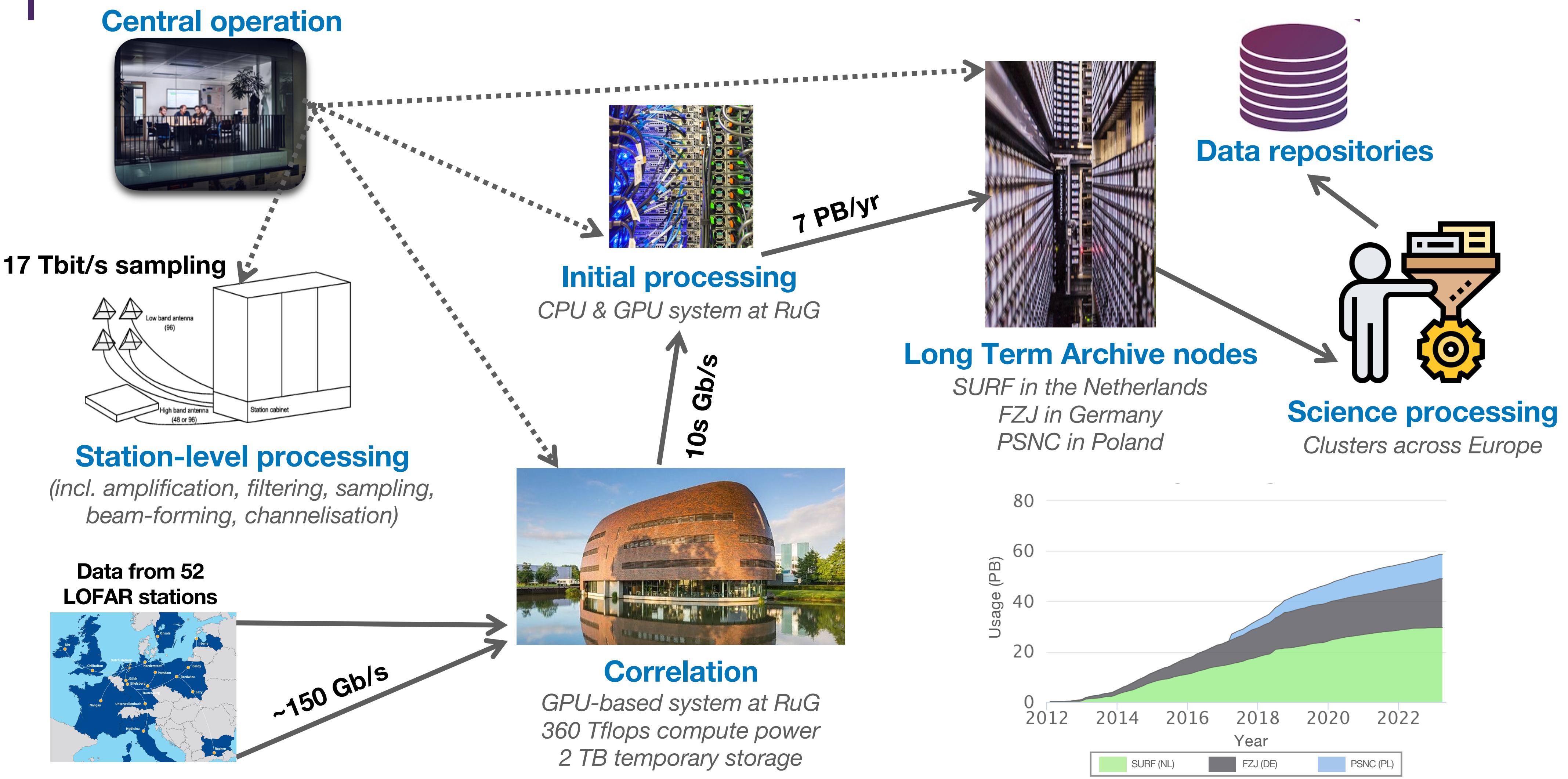


Station level processing: Amplification, digitisation, filtering, beam-forming, transient ram buffers
Central Processing: Delay compensation, correlation, calibration, data reduction, pipelines

Van Haarlem et al. 2013

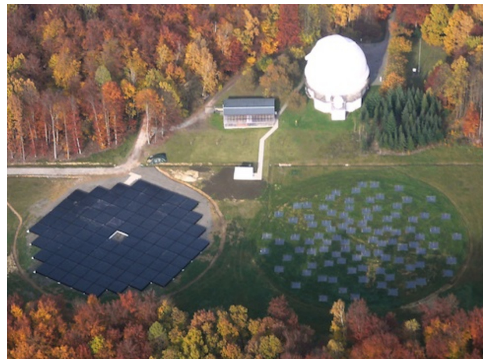
150 Gbps sustained data inflow

The LOFAR system - Data flow



Cutting-edge Distributed Research Infrastructure in the European ecosystem

- World's largest and most sensitive low-frequency radio telescope
- Distributed antenna stations: condensed in NL & extending >2000 km in Europe; dedicated light paths
  - 52 operating LOFAR stations in 8 countries: NL (38), DE (6), PL (3), FR, IE, LV, SE, UK
  - 2 new stations funded: IT and BG; further prospects being explored.
- SKA pathfinder: science areas, calibration & processing algorithms/pipelines, scale of data flow/storage,



The International LOFAR Telescope (ILT) Foundation

- **Foundation under Dutch law established in 2010**
  - Board establishes the policies
  - Participants: National consortia of institutional partners + ASTRON
    - 10 partners across Europe: NL, DE, PL, UK, FR, SE, IE, LV, IT, BG
- **Jointly exploits the LOFAR Resarch Infrastructure**
  - Partners individually own / arrange observing, data processing and storage facilities
    - Central operations and most of the development carried out by/at ASTRON on behalf of ILT
- **On the way to become a European Research Infrastructure Consortium: LOFAR ERIC**

European Commission

LOFAR ERIC

LOFAR ERIC will serve the research community by coordinating the world's most powerful very-low frequency radio telescope during the next decade and beyond. The ERIC governance model lends itself to:

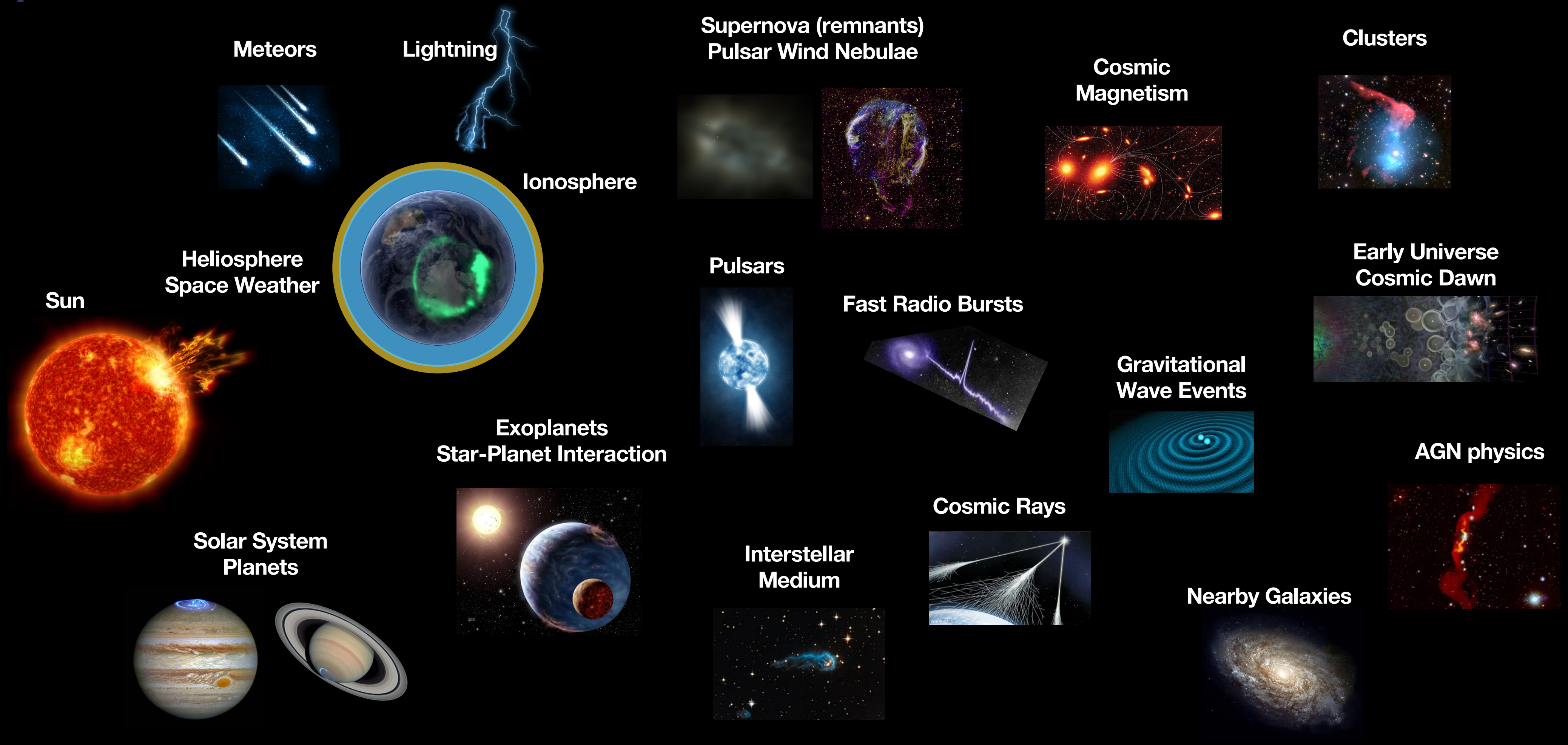
- Robust coordination and efficient joint operation of the distributed LOFAR infrastructure
- Community-wide access to LOFAR data & wide range of science services
- Financial Plan: member contributions coupled to operations & development priorities

  Strategic joint fundraising
- Partner in science policy dialogue at national, European, and global levels
- Consolidation of multi-national collaborations, attracting new partners
- Role in coherence of European research community

  Advanced technologies, contributing to the vitality of the European research landscape

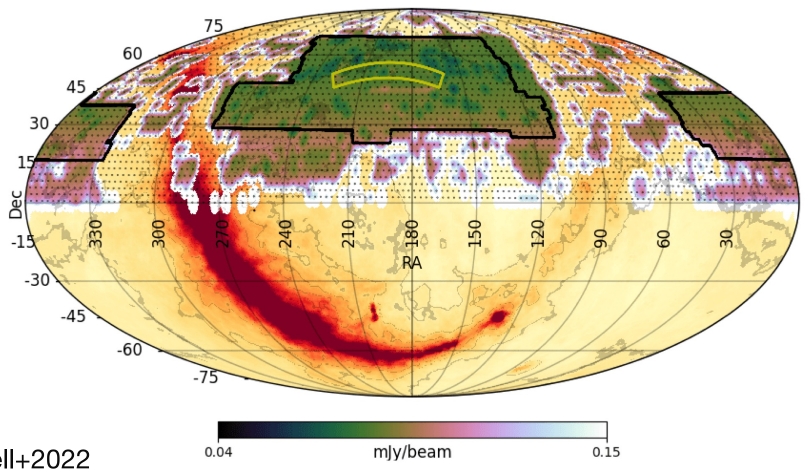
Step-2 submitted to the EC at the end of January; aim is to form LOFAR ERIC in 2023

LOFAR’s broad science case

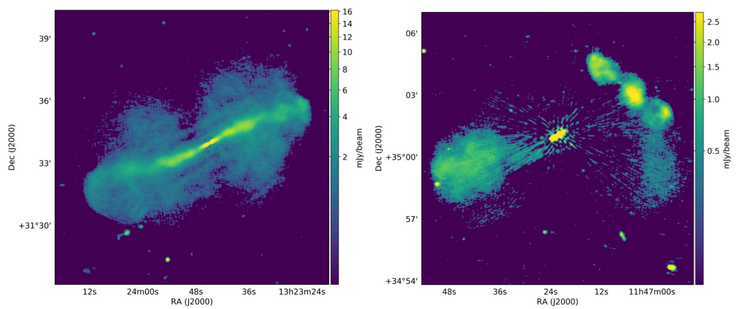


LOFAR science highlights

- **Massive LoTSS data release** **(Shimwell+2022)**
  - LoTSS: LOFAR Two-Metre Sky Survey (120-168 MHz)
  - Mapped of ~25% of Northern sky
  - Detailed radio image of 4.4 million objects



Shimwell+2022



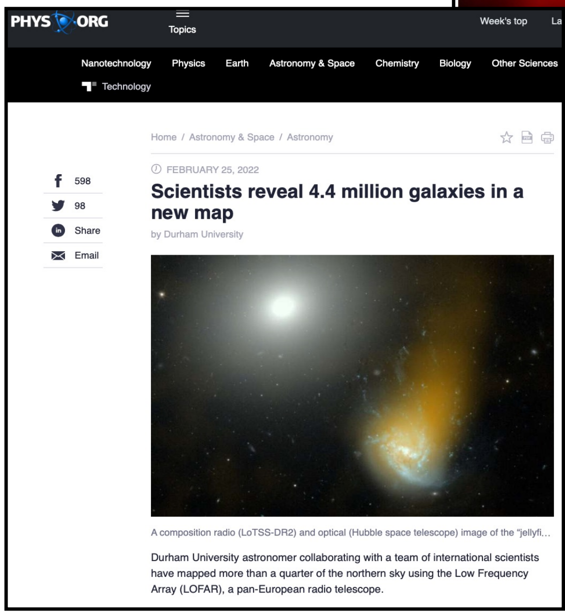

World Africa Americas Asia Australia China Europe India Middle East United Kingdom

New map of the night sky reveals 4.4 million galaxies and other space objects

By Katie Hunt, CNN
Published 5:00 AM EST, Fri February 25, 2022

Annalisa Bonafede

...and infrared (white) image depicts the Coma cluster, which is over 300 million light-years from ...er 1,000 individual galaxies. The radio image shows radiation from highly energetic particles between the galaxies.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FEBRUARY 25, 2022

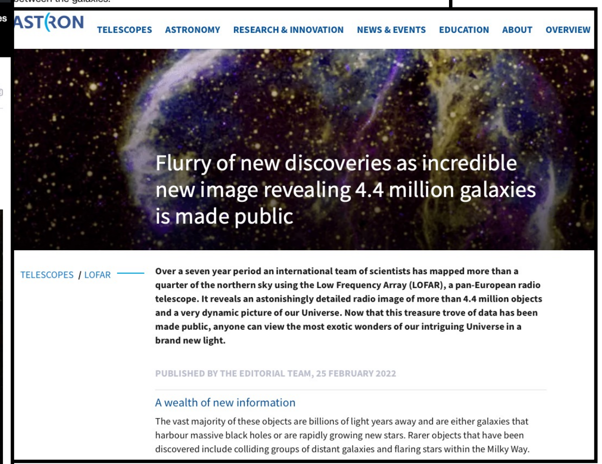
Scientists reveal 4.4 million galaxies in a new map

by Durham University

598 98 Share Email

A composition 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.


ASTRON TELESCOPES ASTRONOMY RESEARCH & INNOVATION NEWS & EVENTS EDUCATION ABOUT OVERVIEW

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.

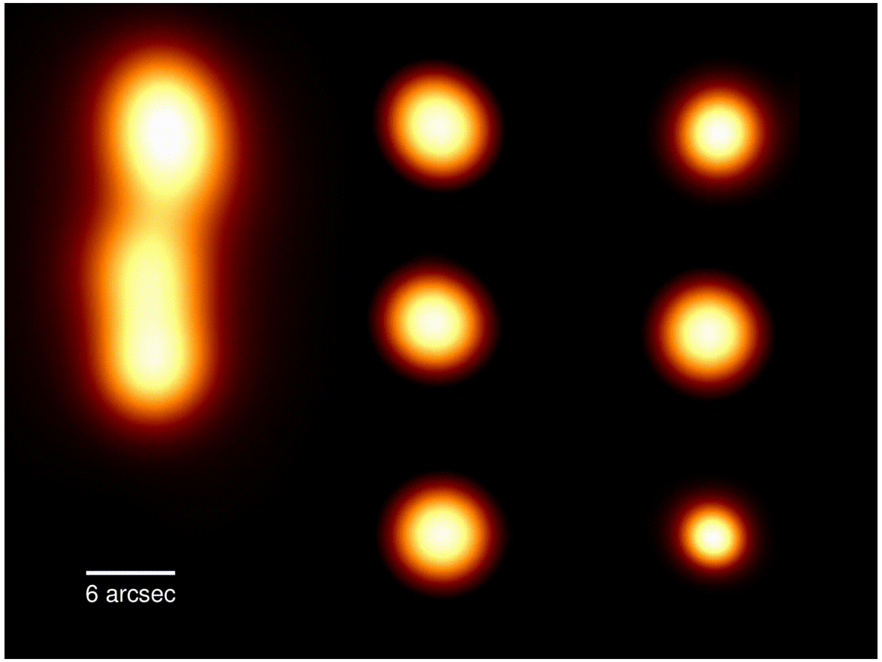
PUBLISHED BY THE EDITORIAL TEAM, 25 FEBRUARY 2022

A wealth of new information

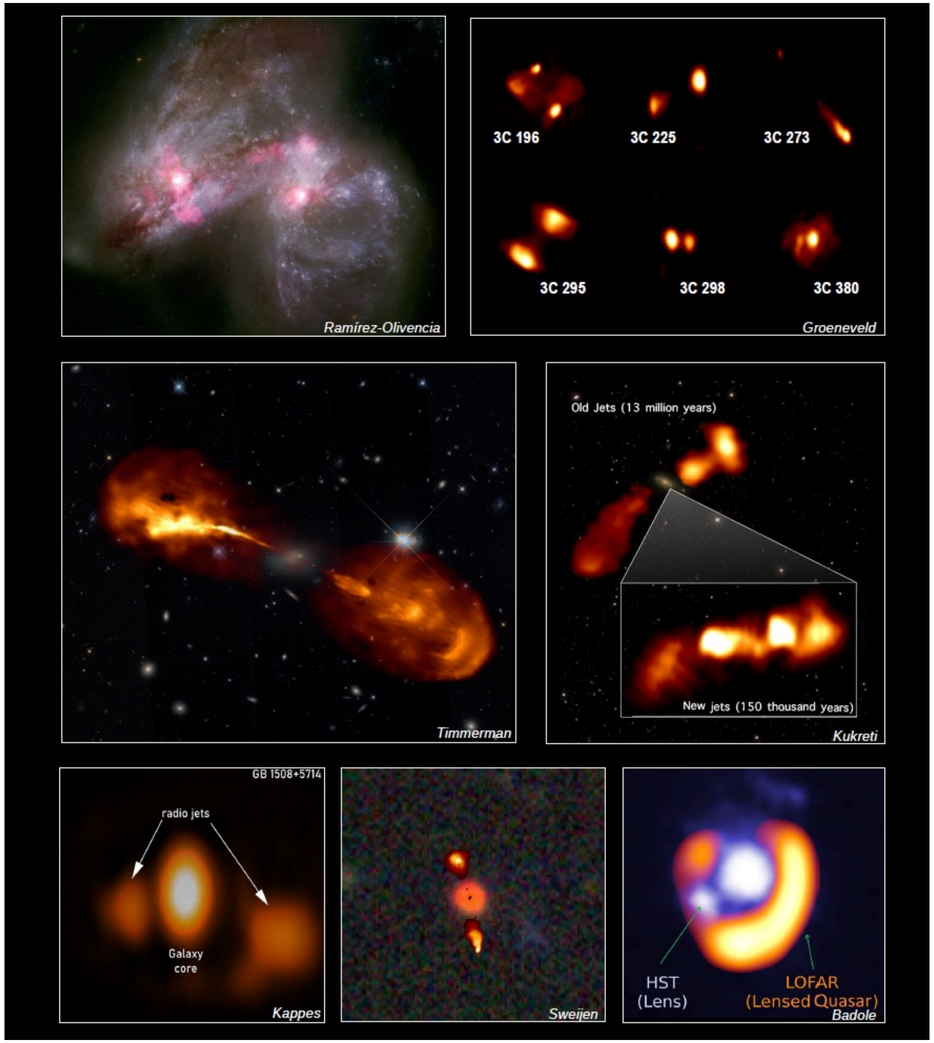
The vast majority of these objects are billions of light years away and are either galaxies that harbour massive black holes or are rapidly growing new stars. Rarer objects that have been discovered include colliding groups of distant galaxies and flaring stars within the Milky Way.

LOFAR science highlights

- **Data release and 11 research publications (A&A), revealing the most detailed-ever images of galaxies**
  - Images 20x higher resolution than NL-only LOFAR images
  - Possible thanks to the international baselines to 2000 km.

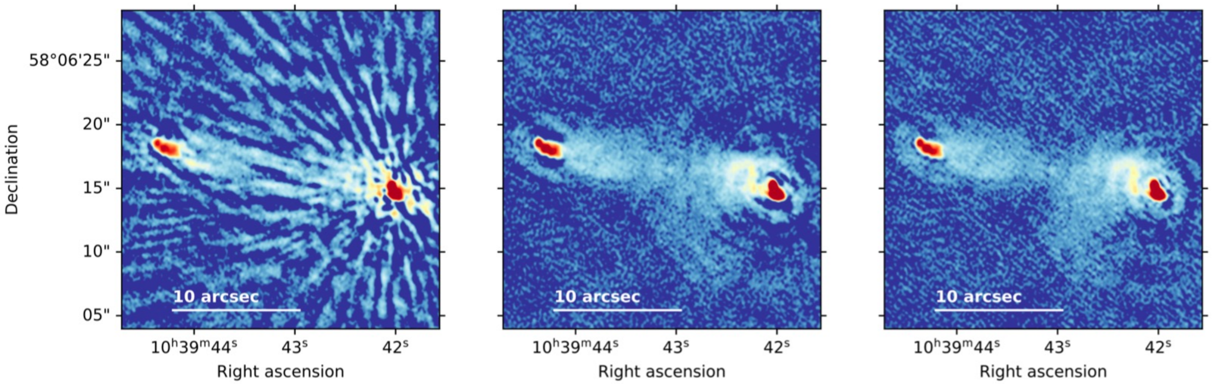


Credit: L.K. Morabito; LOFAR Surveys KSP

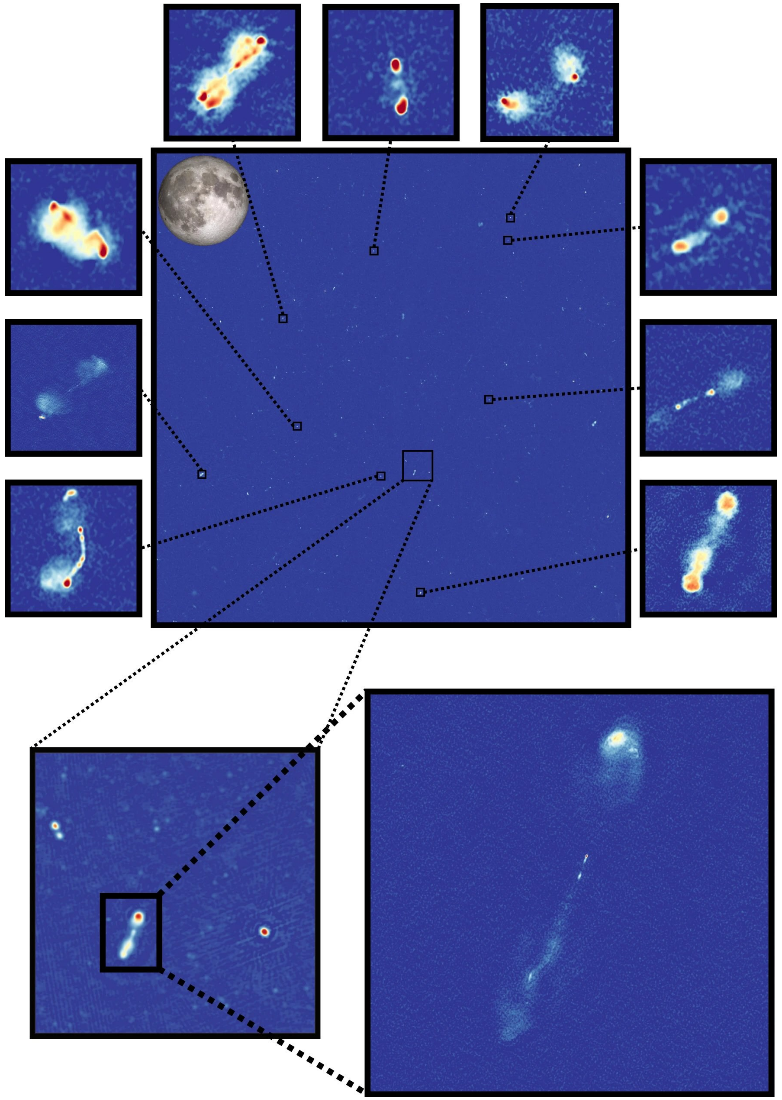


LOFAR science highlights

- **First deep widefield sub-arcsecond imaging at low radio frequencies (144 MHz), thanks to new algorithms and supercomputers** (Sweijen+2022)
    - Correction of ionospheric signal disturbances
    - Reduction of computational cost for imaging
- <u>**Next step**</u>: Map the entire northern low-frequency sky to sub-arcsecond resolution

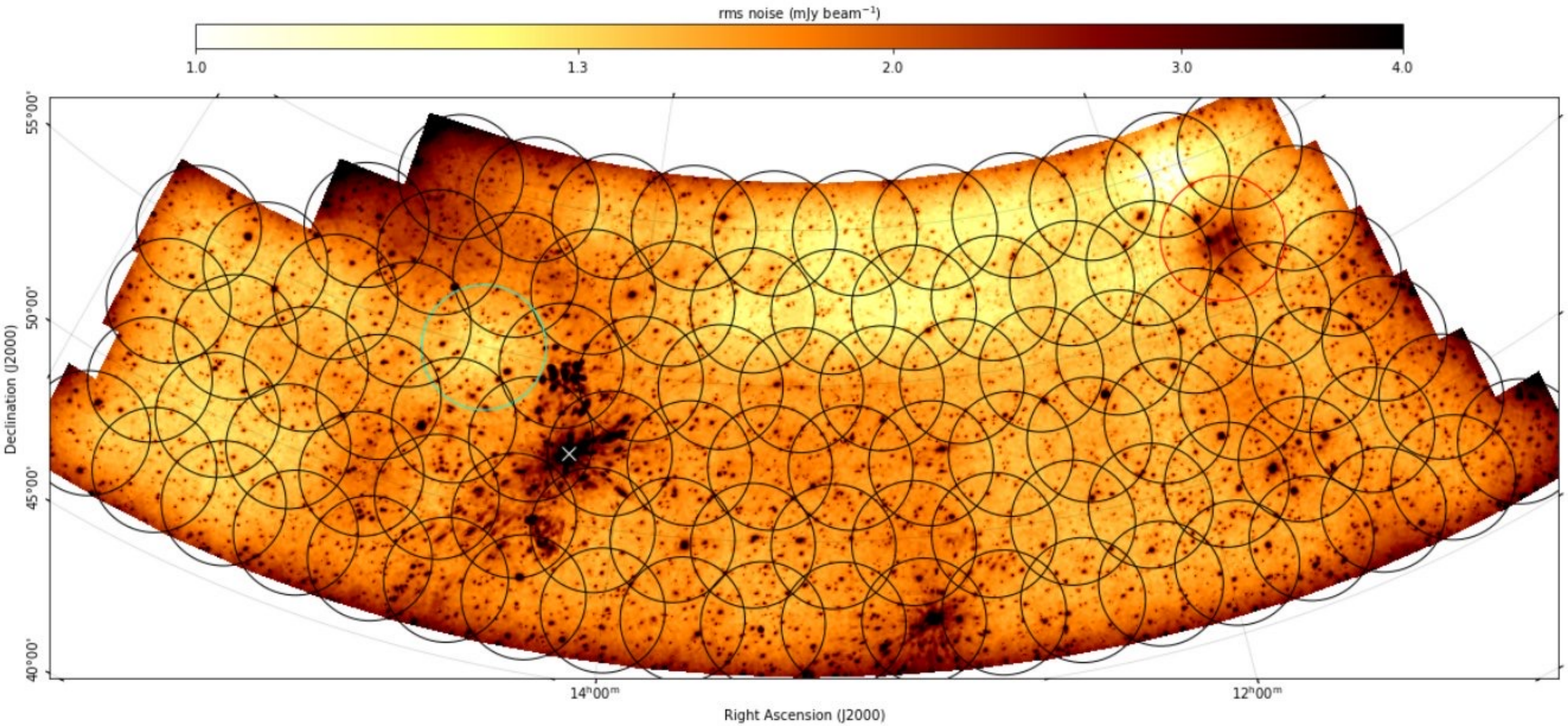


Sweijen+2022, Nat. Astron.

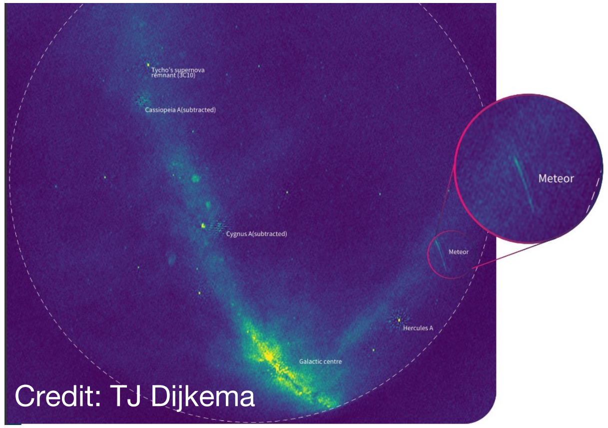


LOFAR science highlights - LoLSS data release

- **First data release of LoLSS** **(de Gasperin+2023)**
  - LoLSS: LOFAR LBA Sky Survey → Sensitive wide-area survey at 41-66 MHz
  - More than 40,000 radio sources detected

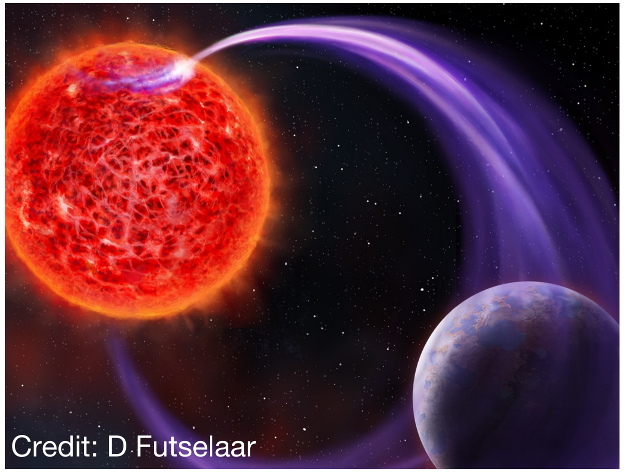


Sampling other LOFAR science highlights



Credit: TJ Dijkema

- **Transients**
  - Meteors
    - First image of radio emission from Perseid meteor showers
    - Persisting radio trails after the disappearance of optical meteors
  - Pulsars
    - Discovery of both record-breaking slow (23.5 *s*) and fast (1.41 ms) pulsars **(Bassa+2017; Tan+2018)**


Credit: D Futselaar

- **Star-planet interactions, Exoplanets (Vedantham+2020a/b; Turner+2021)**
  - First compelling evidence for radio emission from star-planet interaction
  - First discovery of a sub-stellar object using radio data alone
  - Tentative detection of cyclotron emission from an exoplanet

- **Lightning (Hare+2019, 2020)**
  - Radio emission reveals unique features of lightning
  - Discovery of sub-structures (needles) explaining repeated discharge on the ground


Credit: ASTRON

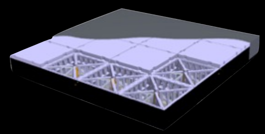
Towards LOFAR in the SKA era: LOFAR2.0

- Major science capability upgrades and expansions to keep LOFAR cutting-edge in SKA era
  - All ILT partners share development costs, joint hardware procurement
  - Managed and mostly developed by ASTRON, with other partners developer contributions

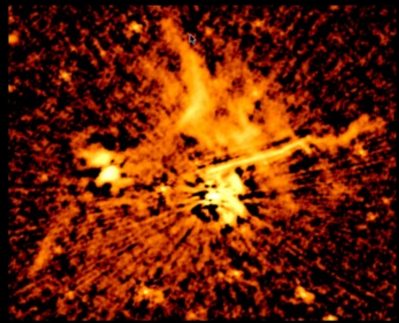
- 5x more sensitive, well-calibrated high-resolution in LBA (10-90 MHz) + HBA (110-240 MHz)
  - 1 to 5 mJy/beam r.m.s. @ 60 to 30 MHz after 8 hrs with 0.5” resolution over 12 deg^2 FOV
  - 0.03 mJy/beam r.m.s. @ 150 MHz after 8 hrs with 0.2” resolution

The solutions of LOFAR

High-Band



Scientifically limited



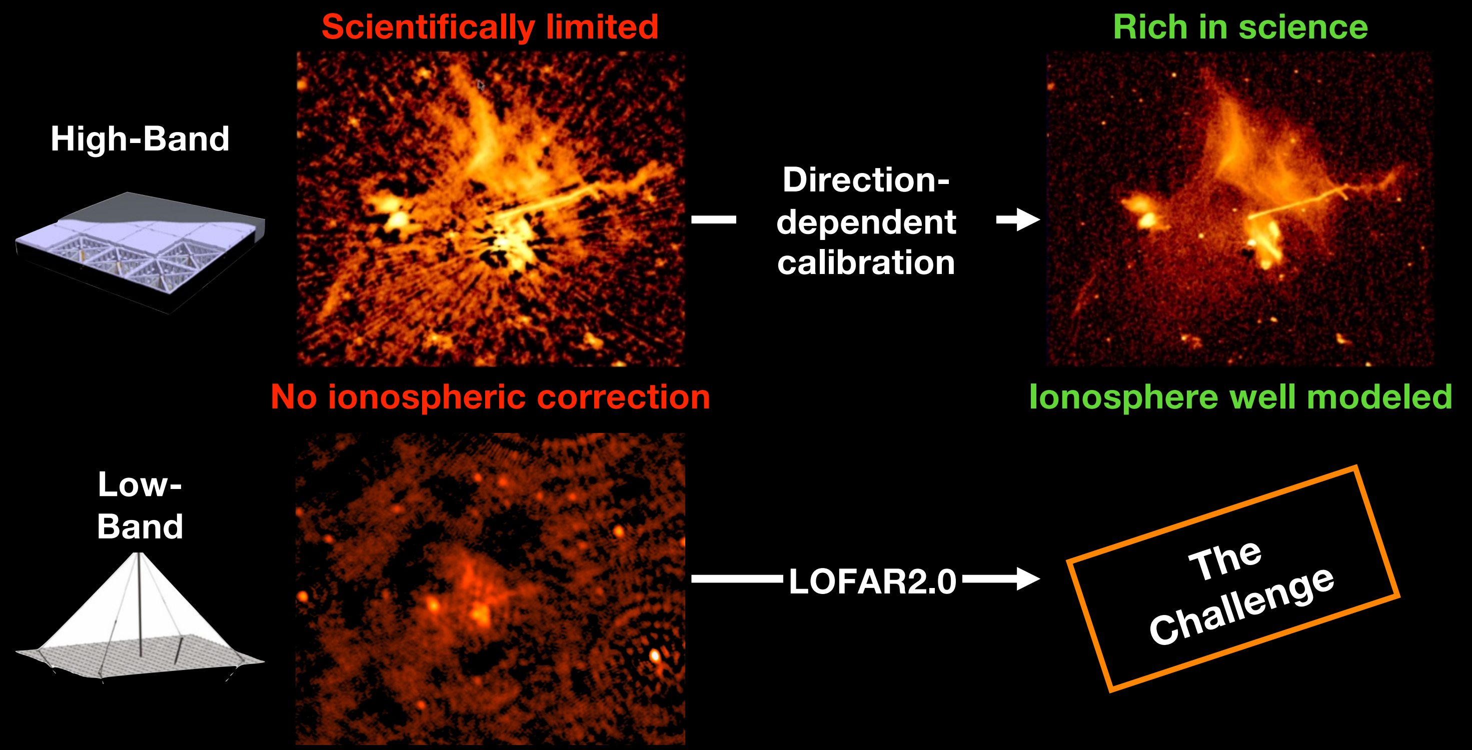
No ionospheric correction

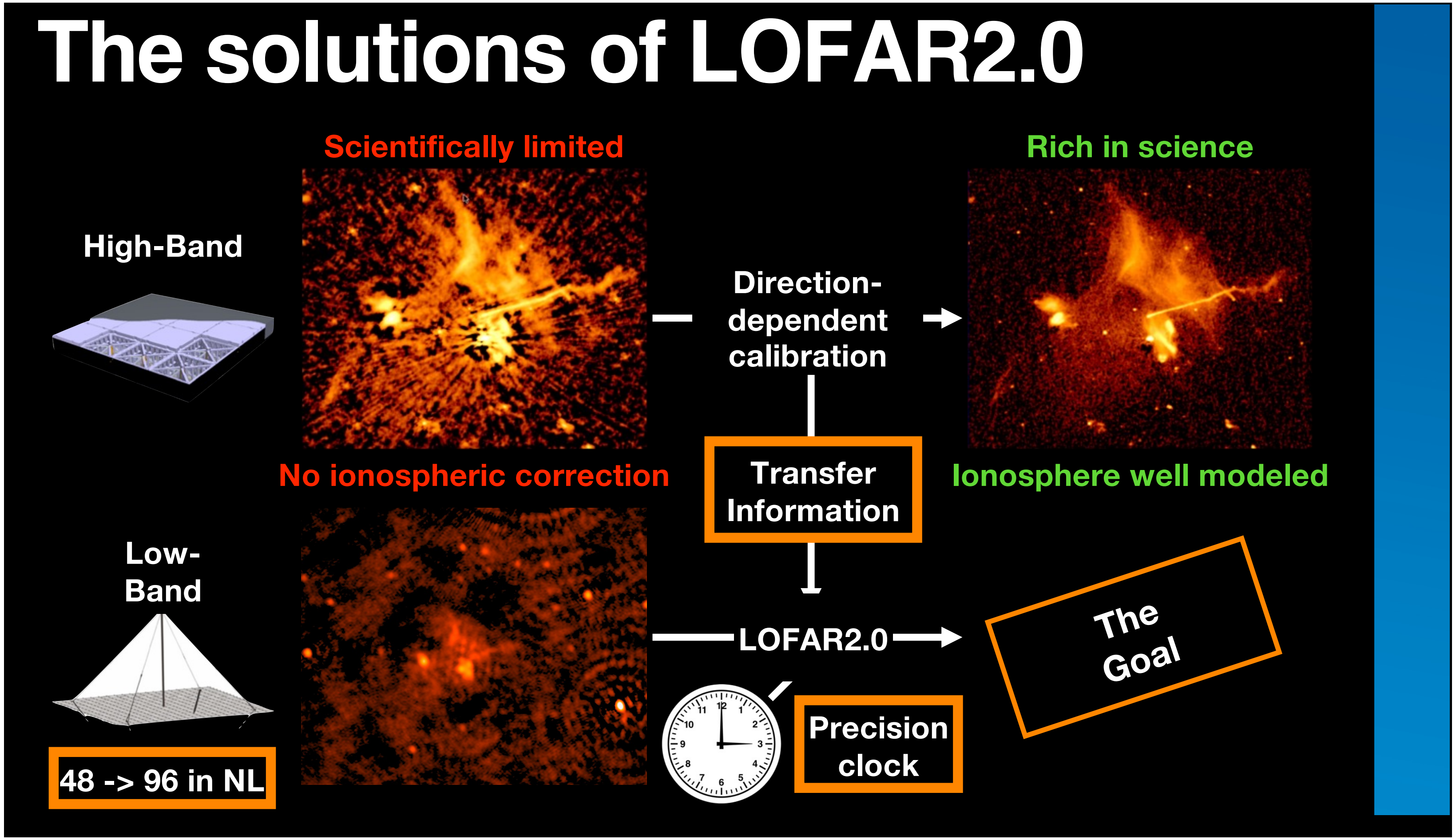
Direction-dependent calibration

Rich in science

Ionosphere well modeled

The solutions of LOFAR2.0

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Low-
Band
LOFAR2.0
The
Goal
Precision
clock
48 -> 96 in NL

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- **Station cabinet hardware upgrades:**
  - All antennas simultaneously (NL: 96 LBA + 48 HBA)
  - Or double number of beams on-sky

  - Single high-precision clock (first: all NL stations)

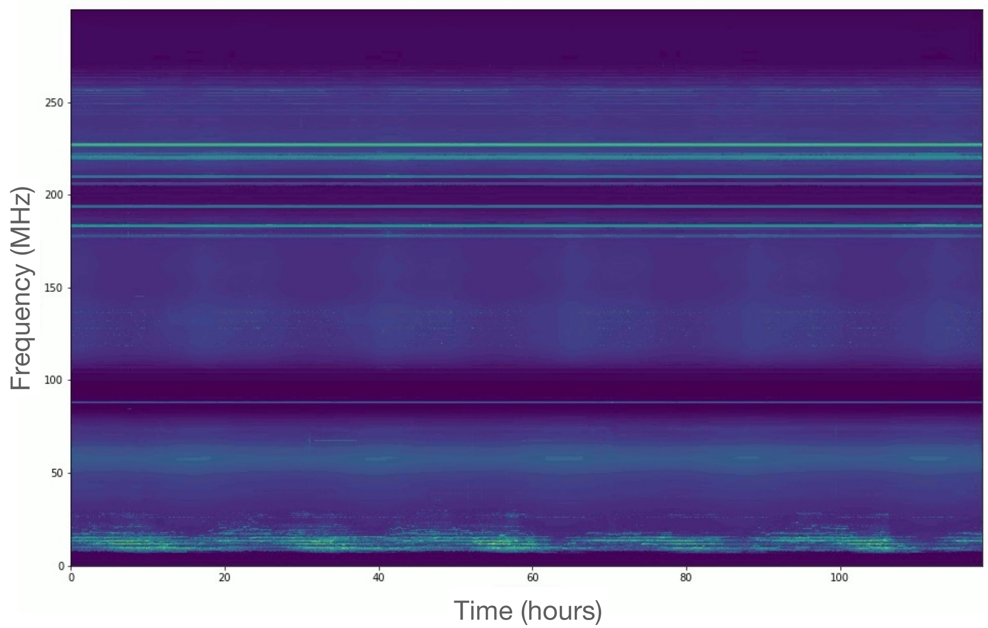
  → Improved correction for ionospheric distortion

  - Greater receiver linearity

  → Improved RFI robustness

  - Commensal Transient Buffer & trigger mechanism

  → Unique monitoring transients, cosmic rays, lightning



Credit: ASTRON

- Hardware rollout 2024-2025, & new stations (Italy, Bulgaria)

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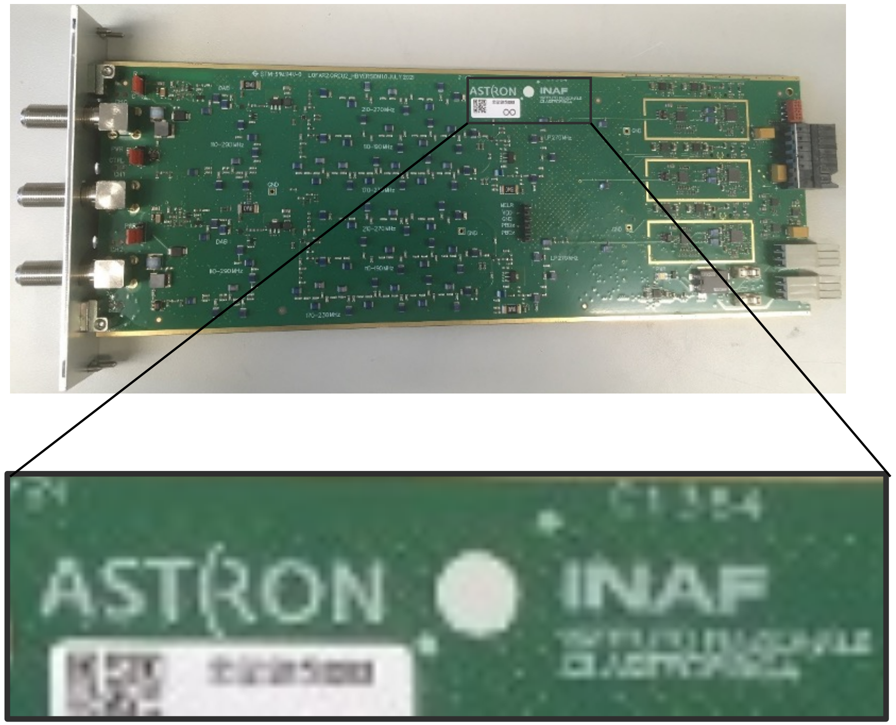

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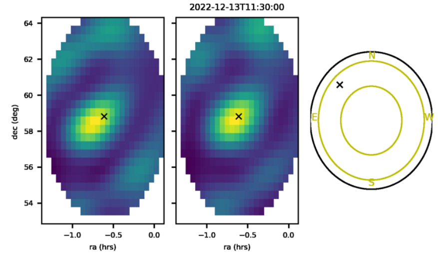
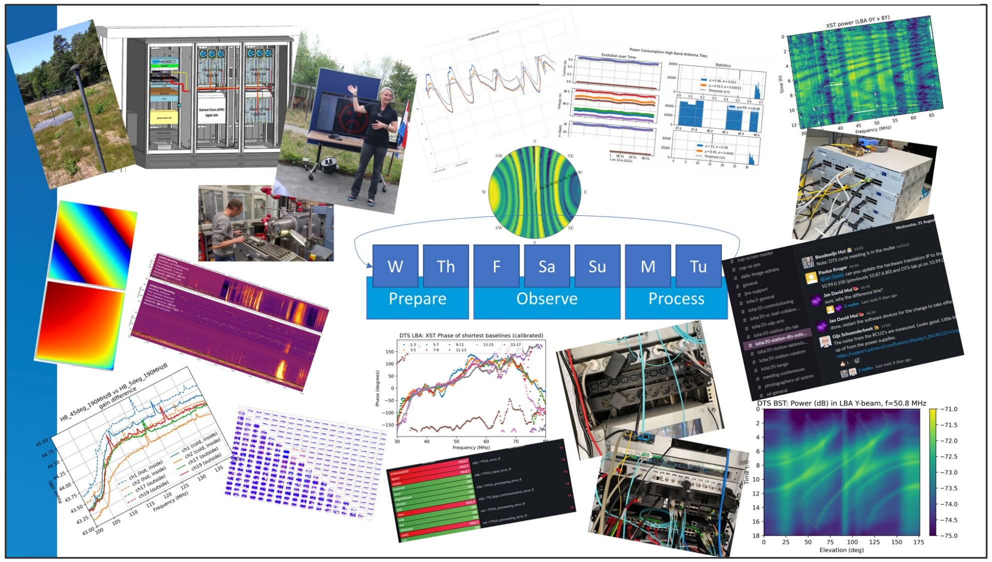


Credit: A. Schoenmakers

- **Ancillary upgrades:**
  - Correlate NenuFAR Tied Array with LOFAR stations
    → Improved sensitivity below 50 MHz
  - New Correlator (COBALT), processor (CEP6), network
    → Order of magnitude increase in compute capacity
  - New Telescope Management & Scheduling System
    → Dynamic scheduling
  - New standard imaging (& other) pipelines
    → Calibration & High-resolution imaging



LOFAR2.0: unique capabilities complementing the SKA

- Frequency coverage down to 10 MHz (and up to 240 MHz)
  - With NenuFAR as added dense superstation
- Very high spatial resolution (0.1-1 arcsec) while sensitive to >arcminute-scale structures
- Standardisation for large-scale, impactful production, coupled to breadth and agility where possible
  - Suite of default observing modes and analysis pipelines to generate products for the community in LOFAR LTA
  - Responsive triggering & Transient Buffer capacity
  - Commensal capabilities continue to be developed
- Dual-beam HBA tiles under design
  - e.g., combined surveying & independent monitoring beam (solar, space weather, transients)
- Intensive collaboration with specialists in the Large Programme Portfolio to ensure continued algorithmic development and high-risk/high-reward science
- Northern hemisphere observing

→ **SKA2 pathfinder**