LOFAR: OPERATING THE WORLD'S LARGEST RADIO TELESCOPE

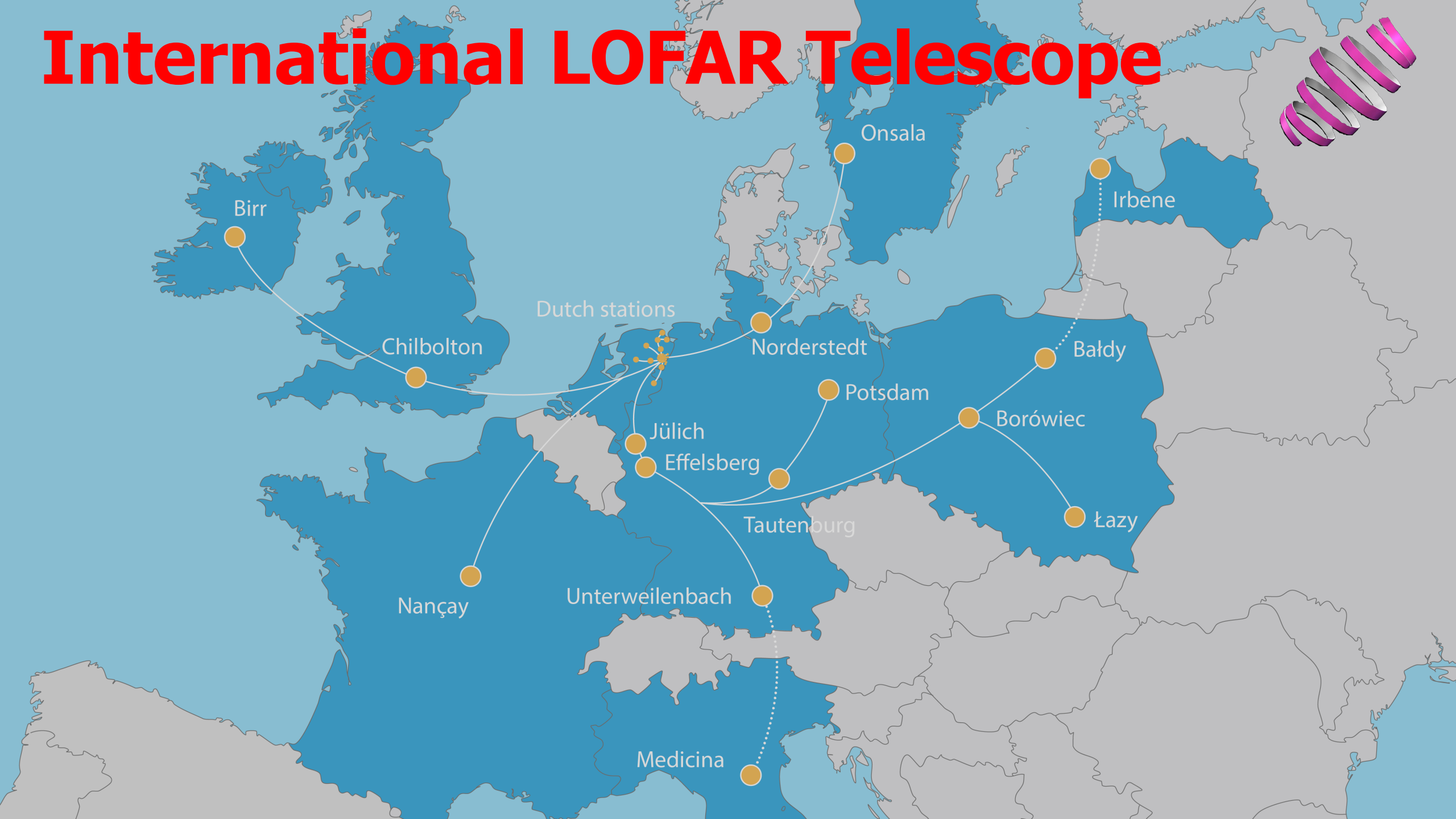
R. F. Pizzo

Head Science Operations & Support

ASTRON
Netherlands Institute for Radio Astronomy

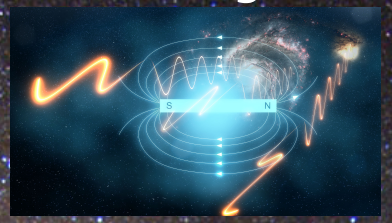
LOFAR

International LOFAR Telescope



LOFAR/ILT Science

Cosmic magnetism



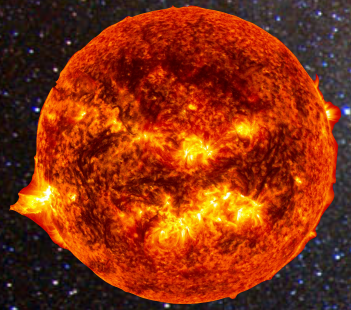
Supermassive black holes

Early Universe

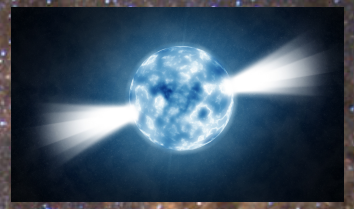
Supernovae

Galaxy clusters

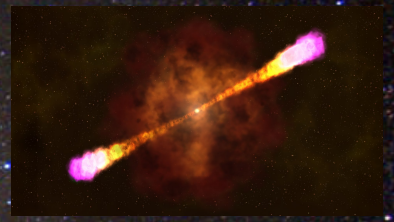
Sun



Pulsars



Gravitational wave events

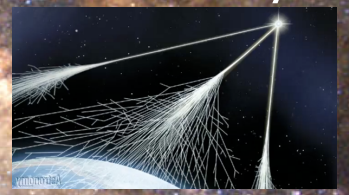


Solar System Planets

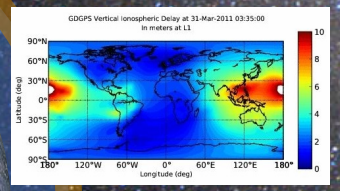
Meteors

Nearby galaxies

Cosmic rays



Ionosphere



Interstellar medium

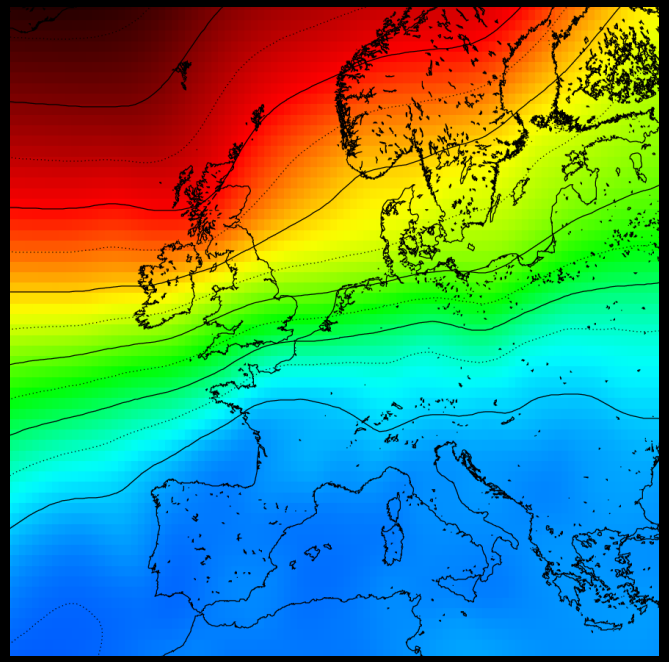
Lightning

Space weather

LOFAR BEYOND RADIO ASTRONOMY

Lightning

Ionosphere



Space weather

THE LOW FREQUENCY ARRAY – KEY FACTS

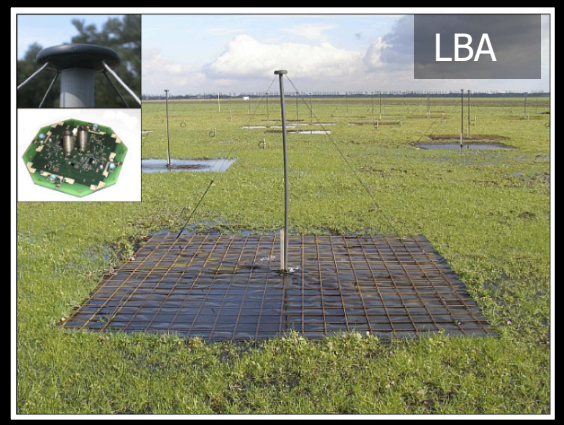
- Array of 52 dipole antenna stations distributed across EU ~2000 km baseline max
- Dense NL core (Exloo)

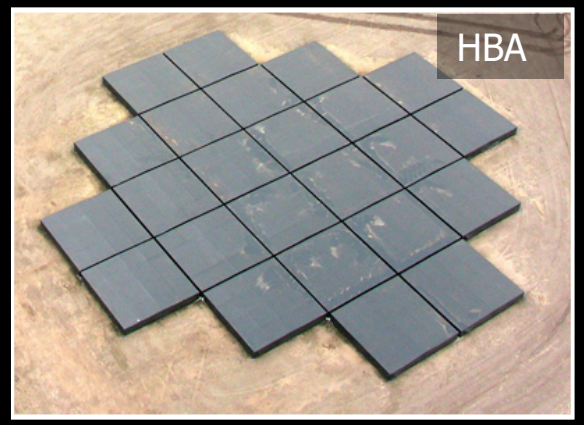
- Low band antenna (LBA; 4800 dipole pairs, 96 LBA per station, Area ~ 75200 m^2; 10-90 MHz)

- High Band Antenna (HBA; 47616 dipole pairs, 48/96 tiles per station in NL/EU, Area ~ 57000 m^2; 110-250 MHz)

- Several observing modes @ 96 MHz bandwidth (multi-beam option)

- 7 years of operations - > 40,000 hours of science delivered





THE LOFAR SYSTEM: DATA FLOW

Data from all stations (HBA or LBA)

COBALT2: correlation

CEP4 compute cluster

flag, demix (remove A-team sources from visibilities), average and compress

ingest into Long-term archive (NL, D, PL)

- Transport, processing and storage of large amounts of data :
  - Data flow from all antennas combined: 1.7 Tbyte/s
  - To COBALT from station after beamforming: 28 Gbyte/s
  - Correlator output to disk: between 2-10 Gbyte/s
  - Data storage challenge: ~ 80 TB/h

LOFAR OPERATIONS & COORDINATION

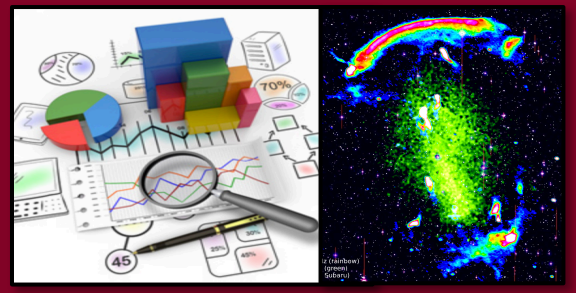
O&M

Operations & maintenance

- Hardware maintenance
- System monitoring

SOS

Science Operations & Support

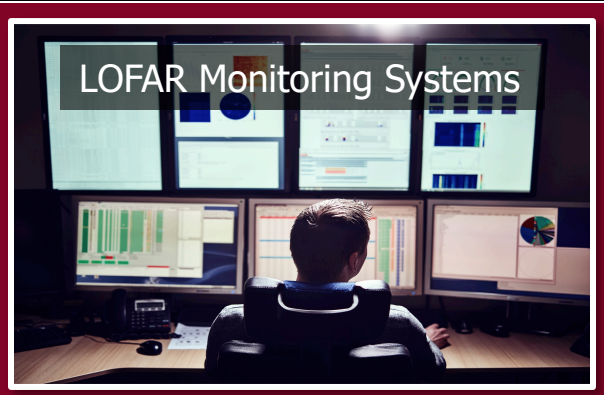


- Link to community
- Data quality assurance
- Commissioning & research

SDOS

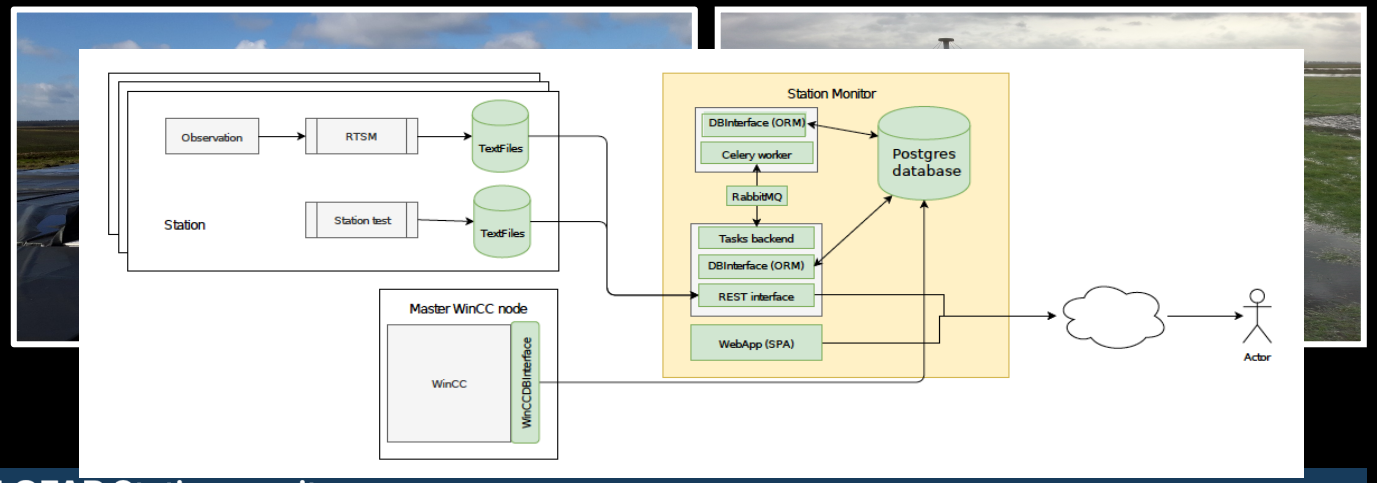
Software Operational Support

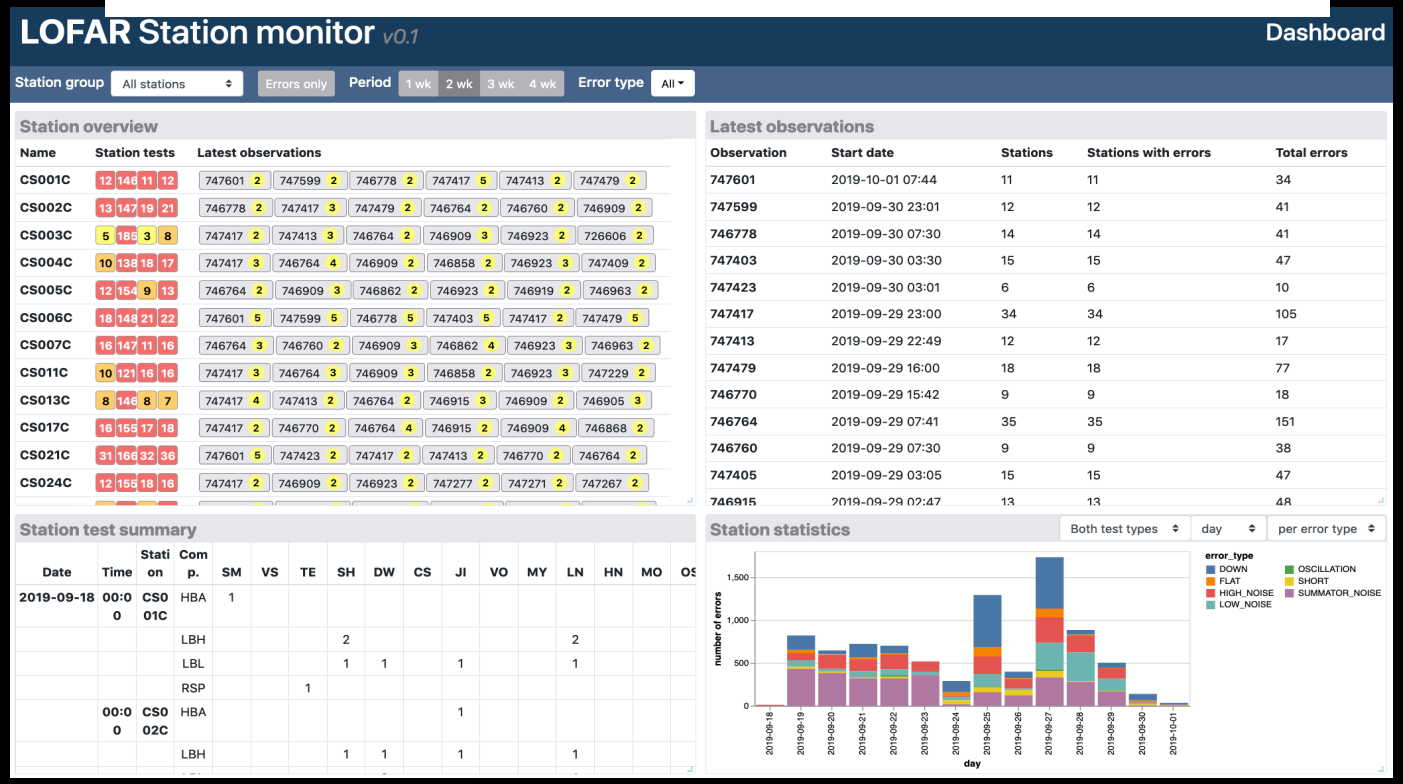
- Maintenance of software and compute clusters



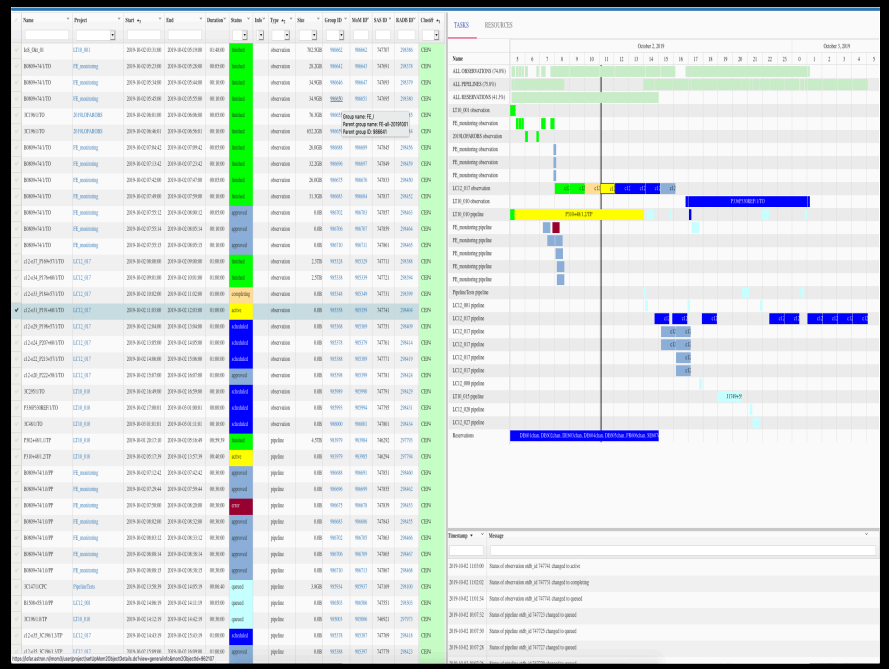
LOFAR HARDWARE HEALTH

- Ongoing hardware maintenance -> Maintenance Management Information System (MMIS)
- StationMonitor: database of system performance data: REST API and a web user interface
- Challenge: comprehensive assessment of 100's of datapoints
- *towards* automatic enabling/disabling of elements

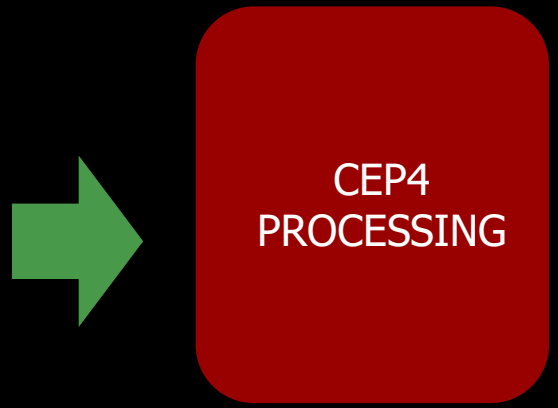




RESOURCE MANAGEMENT



SCHEDULING:
RESOURCE ASSIGNER



- Maintain steady data flow across the LOFAR system
  ~50 PB raw data + 7 PB data products
- Balance load across LOFAR's available resources
- Pipeline queue handled automatically: SLURM
- Automatic data cleanup after ingest into CEP4
- Manual ingest into LTA after data quality is assessed

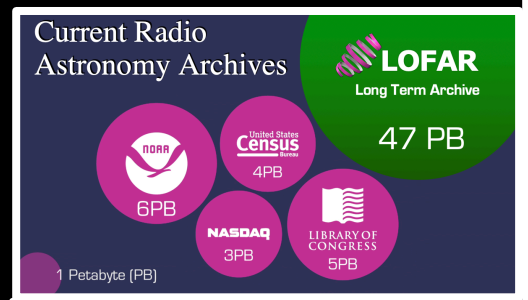
OPERATIONAL ACHIEVEMENTS

- 12 operational Cycles completed
> 40,000 hours of science delivered

- Upgraded capabilities
  - Responsive Telescope (5 min)
  - COBALT2.0
  - Dysco – visibilities compression tool

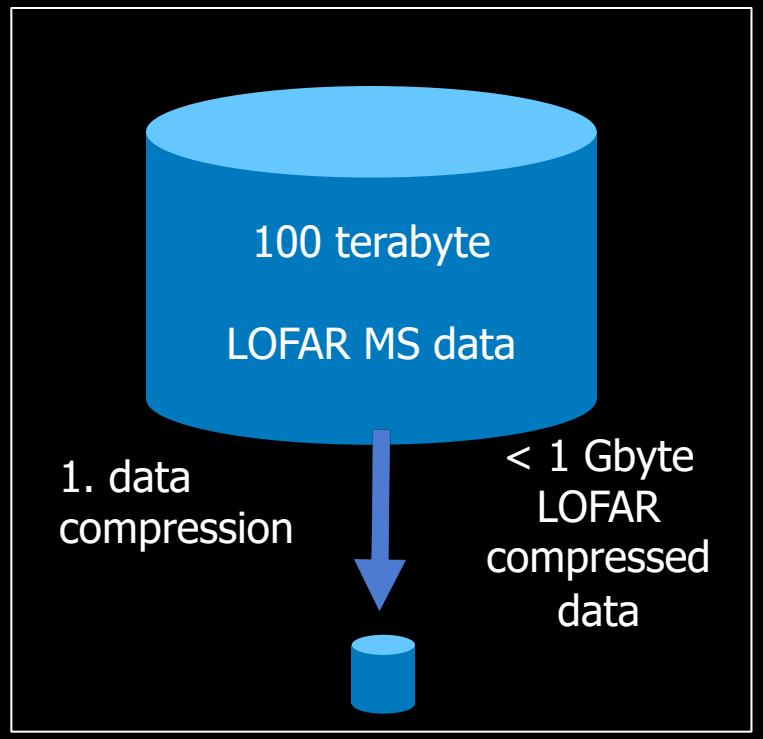
- 47 PB in the LTA: distributed (NL, DE, PL)

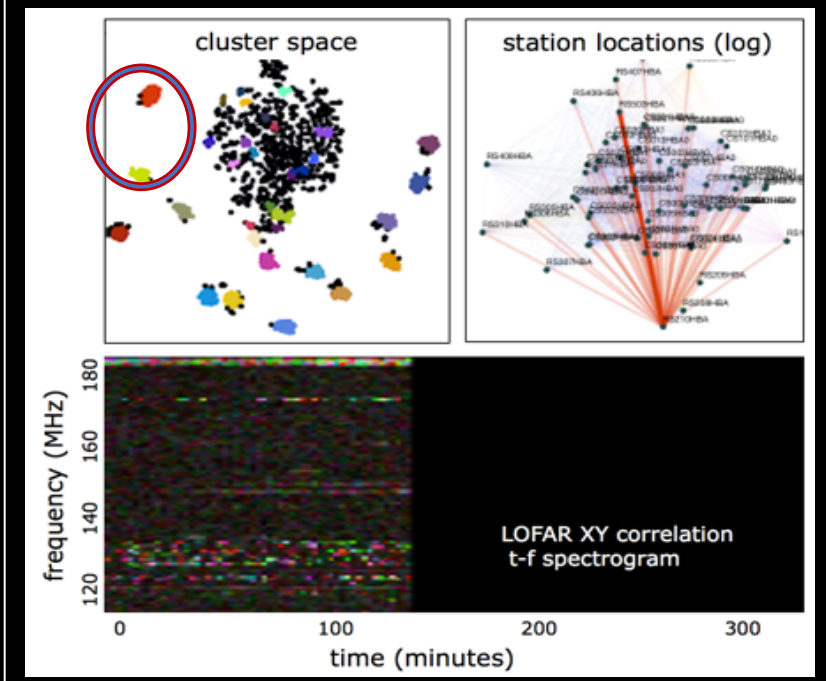
- LOFAR Schools (250+ participants)
- Traineeship – 'Science Operations with Massive Arrays'



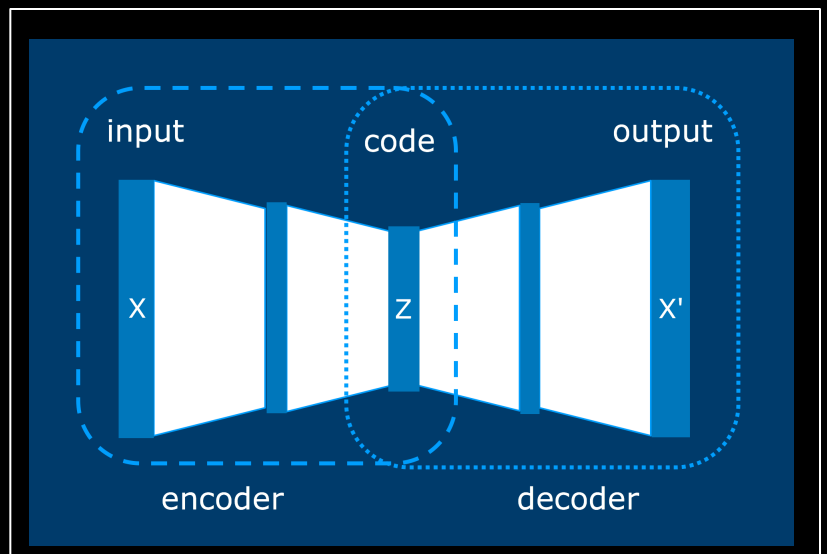
DATA QUALITY ASSESSMENT

- 6000+ validation plots automatically generated: visual inspection impossible!
- AI analyses now adopted: Dynamic spectrum plots grouped per cluster ("ADDER")
- In training – goal is automatic observation reports





3. Cluster spectrograms

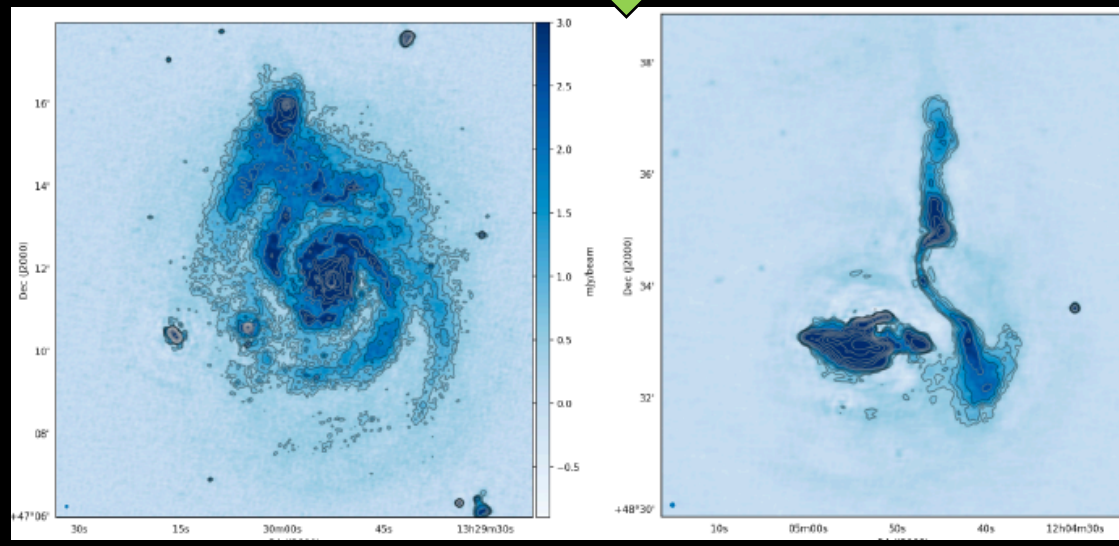


2. Neural network

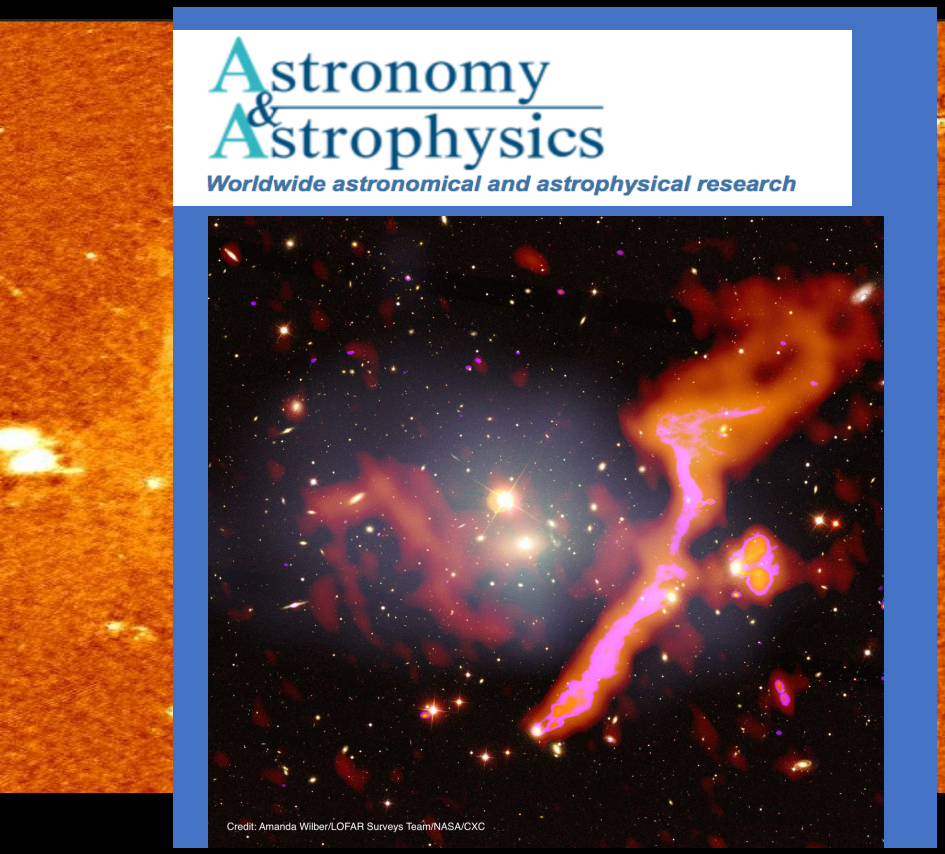
Collaboration with eScience center

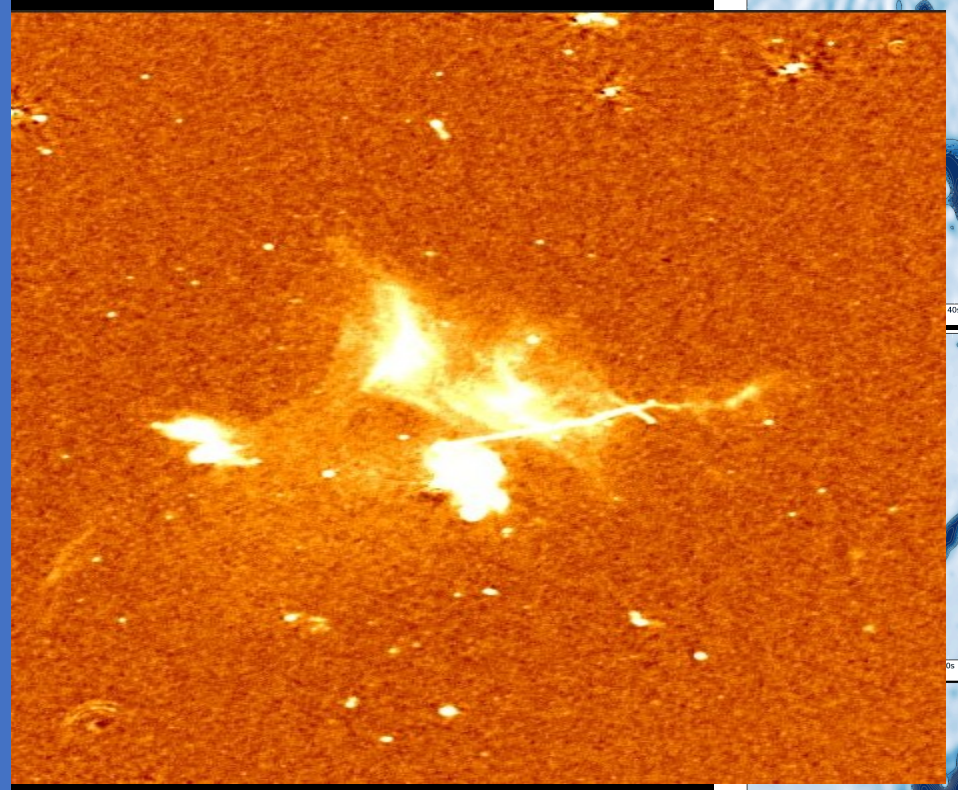
DELIVERING SCIENCE-READY DATA

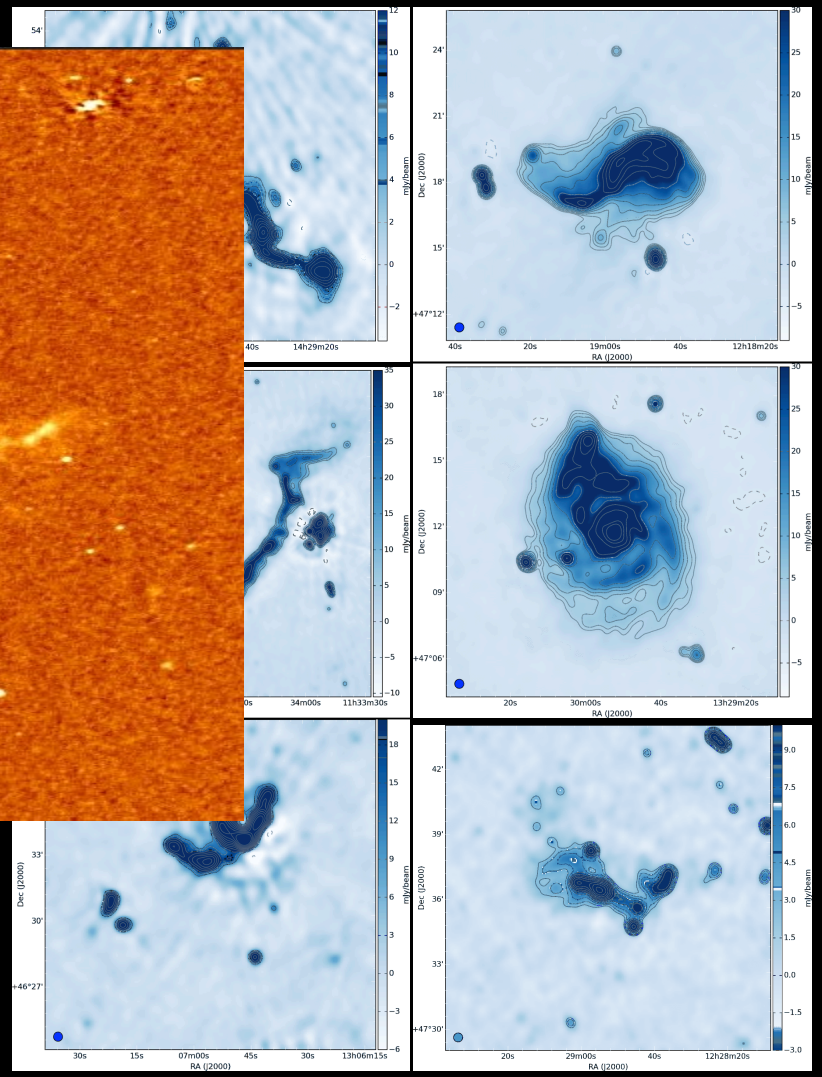
- Goal: Make LOFAR data accessible to a much wider community
- Deliver high level data products ready for scientific exploitation
- Method:
  - Implement advanced reduction pipelines, accessible by community
  - Scientific exploitation of data *from archive*
  - *Available from H1 2020*
  - *Issue: resources & cost of processing*



LOFAR Two-metre Sky Survey

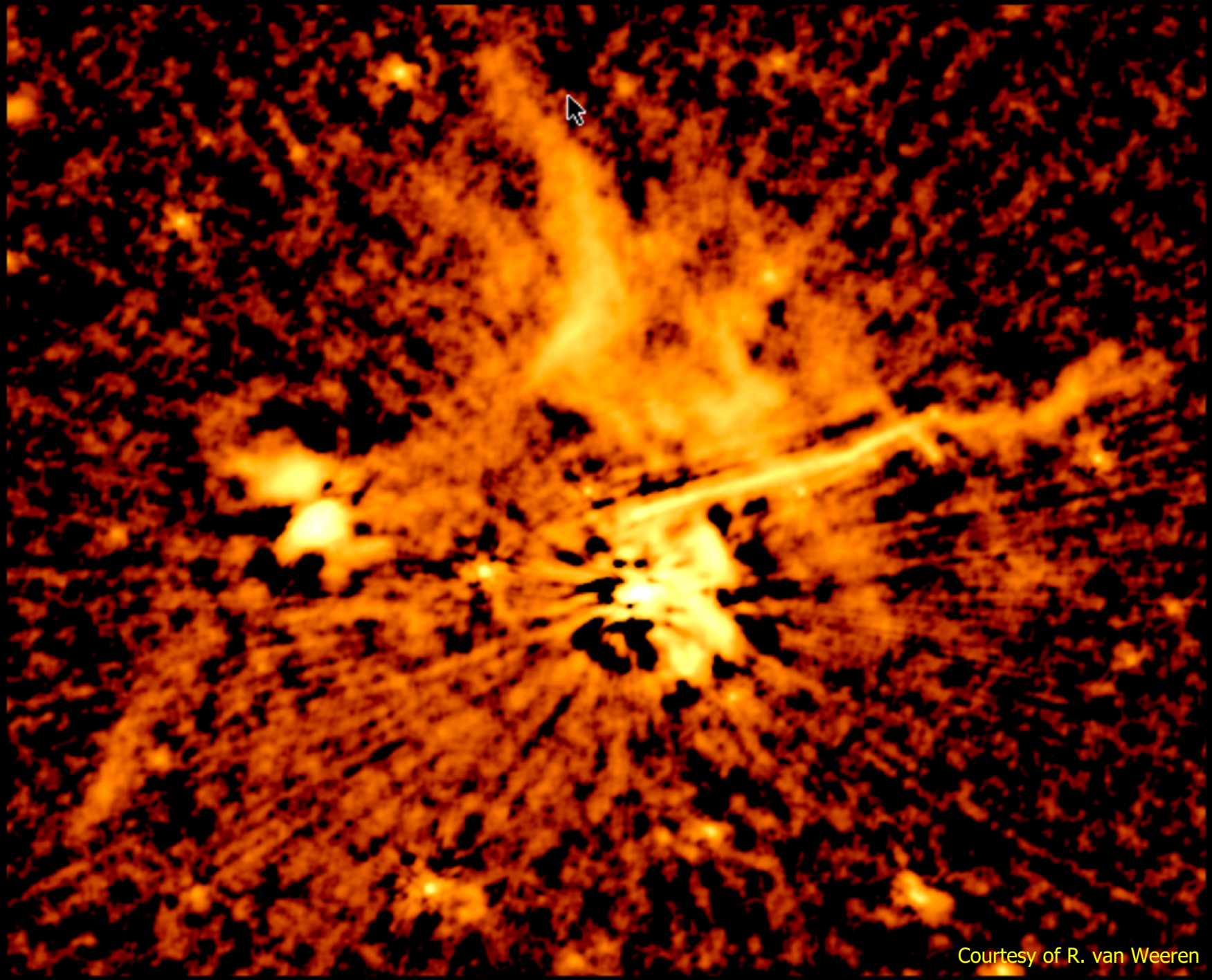




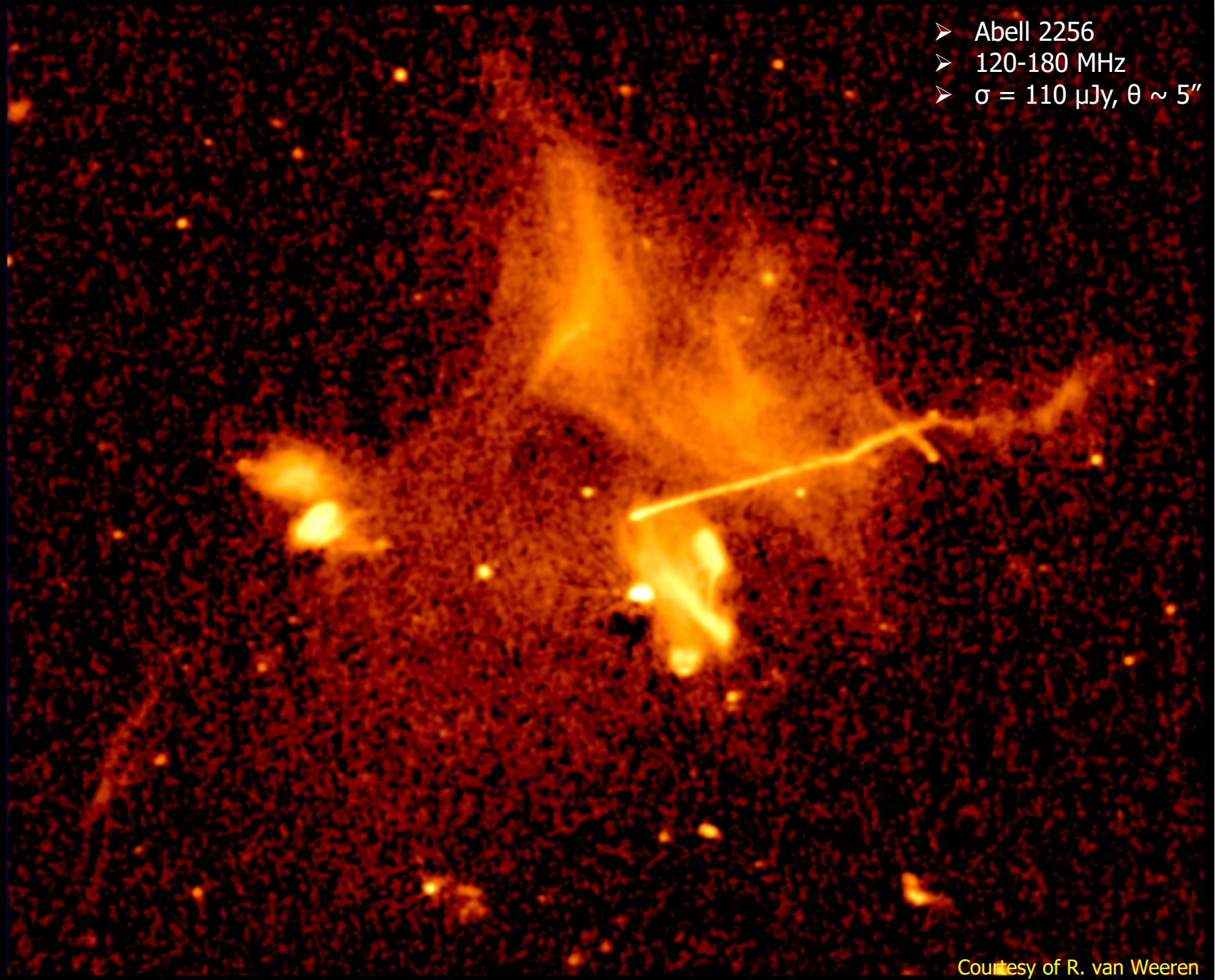


A&A February 2019, volume 622
"LOFAR surveys – A new window on the Universe"
26 papers (LOTSS) (Shimwell & many other authors)

Self-calibration

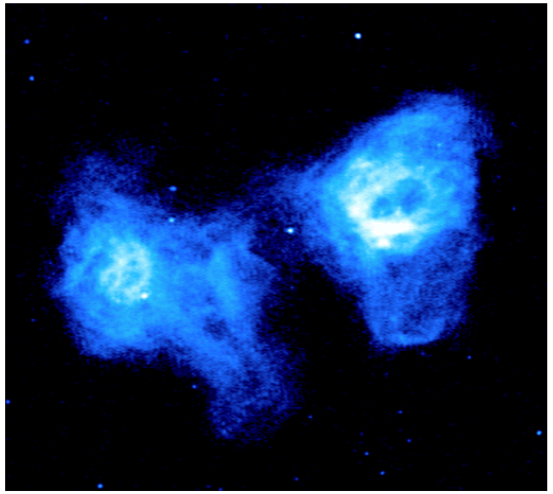


Direction-dependent calibration



LOFAR SURVEYS

Welcome to the LOFAR Surveys website



Performing increasingly sensitive surveys is a fundamental endeavour of astronomy. Over the past 60 years, the depth, fidelity, and resolution of radio surveys has continuously improved. However, new, upgraded and planned instruments are capable of revolutionising this area of research. The International Low-Frequency Array (LOFAR) is one such instrument. LOFAR offers a transformational increase in radio survey speed compared to existing radio telescopes. It also opens up a poorly explored low-frequency region of the electromagnetic spectrum. An important goal that has driven the development of LOFAR since its inception is to conduct wide and deep surveys in order to advance our understanding of the formation and evolution of galaxies, clusters, and active galactic nuclei (AGN).

Explore this website to learn more about the LOFAR surveys and their scientific results.

NEWS: LoTSS DR1 catalogues and images are now available (see releases page).

LOFAR SURVEYS

Data releases

Preliminary

The preliminary LoTSS data release (PDR) is described by Shimwell et al. (2017). It consists of 350 square degrees in the region of the HETDEX Spring field imaged at a resolution of 25 arcsec and a typical noise level less than 0.5 mJy/beam. Over 35,000 sources are detected.

- PDR image archive
- PDR Image Cutout Service
- LoTSS PDR Catalogue Query Service

Data release 1

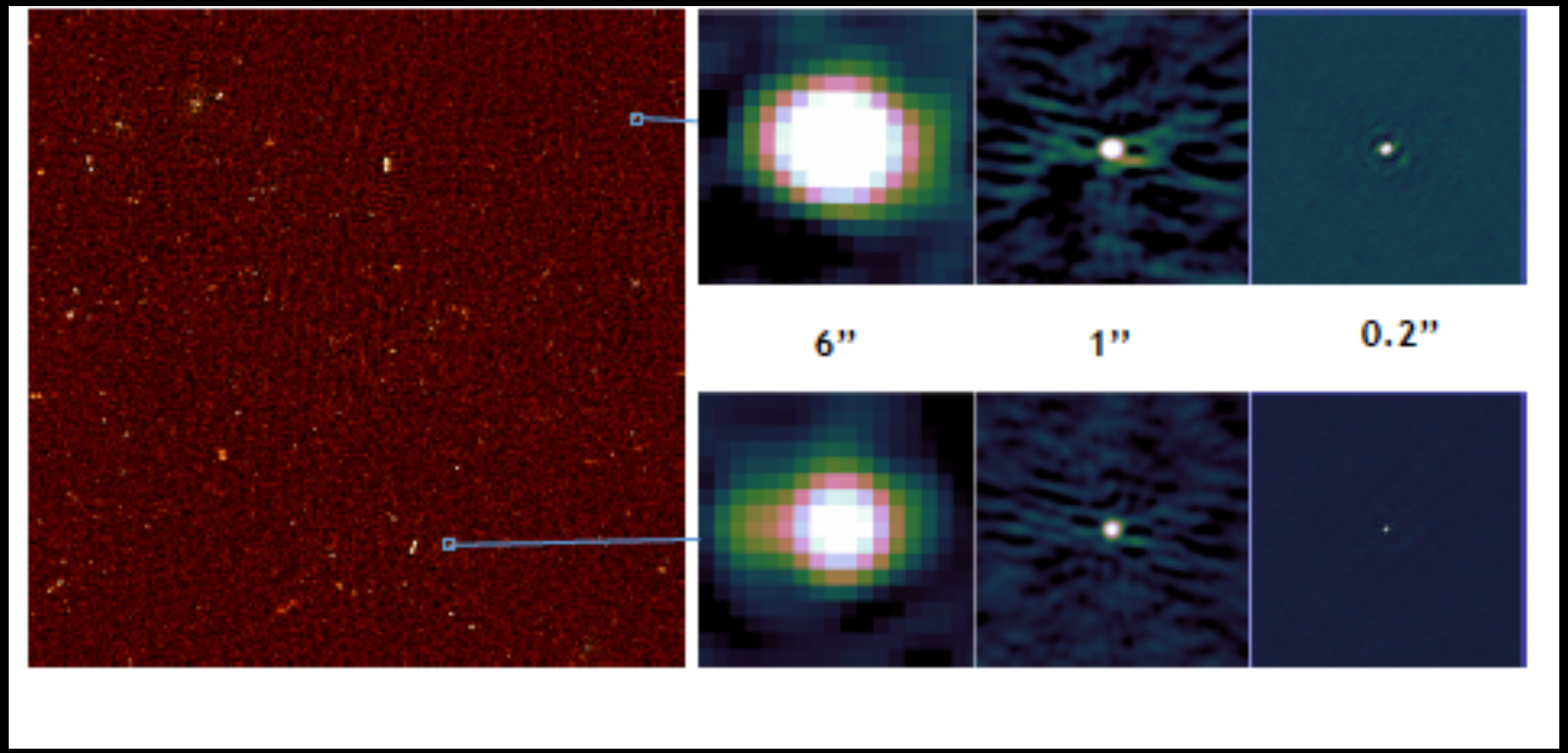
LoTSS data release 1 (DR1) is described by Shimwell et al. (2019). It consists of images at the full resolution (6 arcsec) and sensitivity (better than 0.1 mJy/beam) of Dutch LOFAR over 400 square degrees in the region of the HETDEX Spring field. Over 325,000 sources are detected. The data release includes optical counterparts for 71% of the radio sources (Williams et al. 2019) and photometric redshifts for these sources (Duncan et al. 2019).

- From the ASTRON VO:
  - DR1 image archive
  - DR1 Image Cutout Service
  - LoTSS DR1 radio source catalogue Query Service
  - LoTSS DR1 value-added source catalogue Query Service
- Direct download from this site:
  - Radio source catalogue from Shimwell et al (2019)
  - Catalogue of HETDEX associations and optical IDs and corresponding component catalogue from Williams et al (2019).
  - Value-added catalogue column description
  - Catalogue of morphological classifications and readme file from Mingo et al. (2019).
- Aladin:
  - An interactive Aladin view of the low-resolution and high-resolution DR1 data is available on the surveys status page
  - Desktop Aladin apps can point to the URLs `https://lofar-surveys.org/public/HIPS/low_hips/` and `https://lofar-surveys.org/public/HIPS/high_hips_new/`.

Images available from this site

For small regions of sky please use the cutout servers. For large sky areas, the individual mosaics are available for direct download from the sortable, searchable table below.

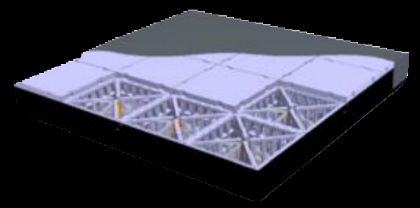
LOFAR LoTSS imaging – from 6 arcsec (NL) res to 0.2 arcsec (ILT) at 155 MHz

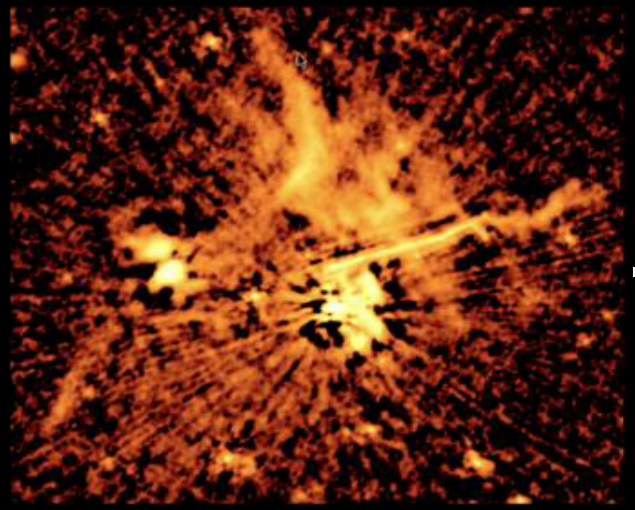


Courtesy of de Gasperin,
R. van Weeren & LoTSS

LOFAR 2.0 upgrade 2018-2023

High-Band





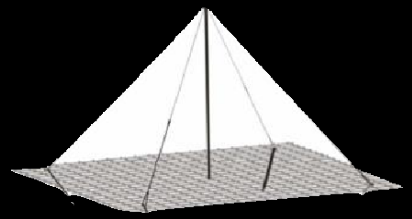
Breakthrough techniques →

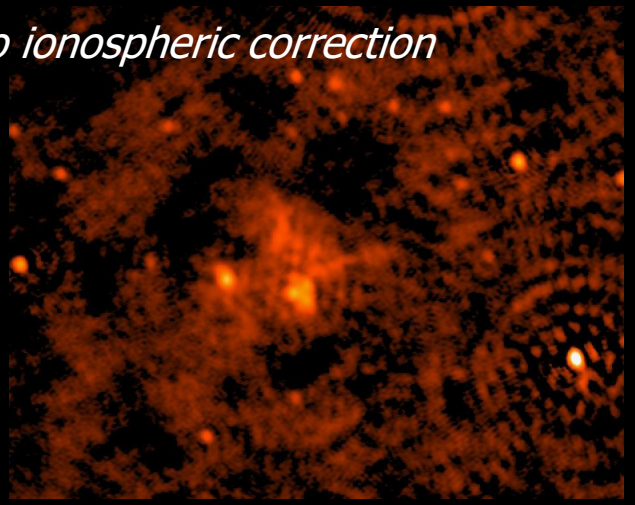
Rich in science

Ionosphere well modeled

No ionospheric correction

Low-Band

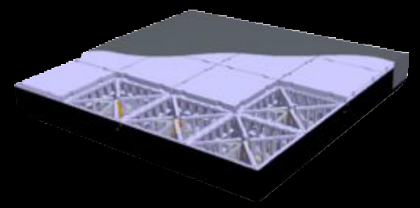


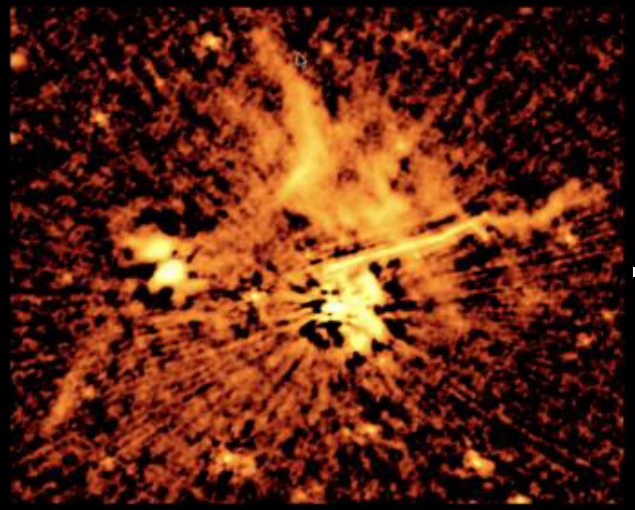


credit: Jason Hessels

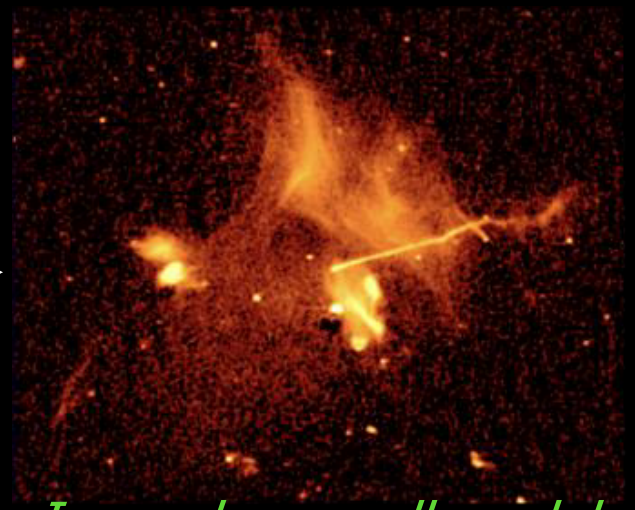
LOFAR 2.0 upgrade 2018-2023

High-Band





Breakthrough techniques

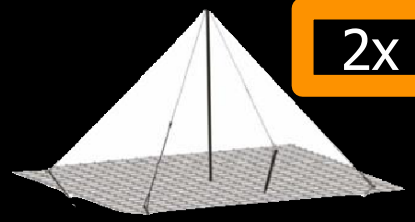


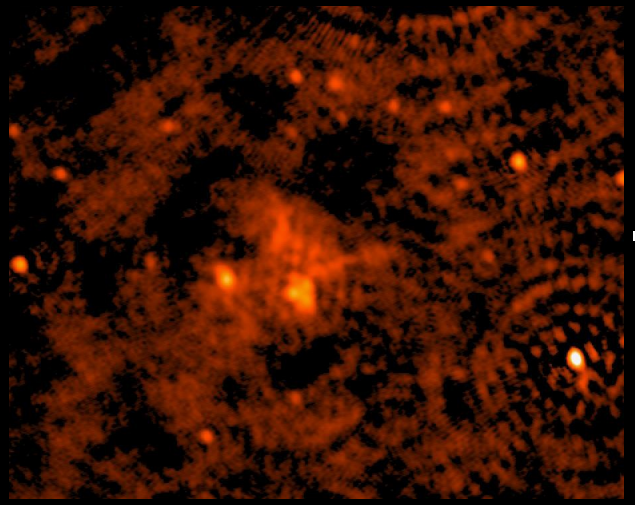
Ionosphere well modeled at both High and Low bands

Transfer Information

Low-Band

2x





DUPLLO

Precision clock

2024+

DUPLLO surveys 55 MHz & 155 MHz on ILT baselines

credit: Jason Hessels

Summary

- LOFAR is a massive, complex system – technological pathfinder for SKA
- System complexity == operational challenges for
  - Hardware maintenance – in the field, trends & monitoring
  - Resource management – load balance observations & processing
  - Maintaining data quality delivery (real-time) to LTA
- LOFAR -> "LOFAR2" = full science plan to at 2030 & beyond (SKA2?)
- LOFAR operational procedures continue to mature & upgrade
- Towards science-ready data & on-demand processing