LOFAR2.0: Building on the LOFAR Infrastructure to Create a Unique Low-Frequency Telescope for the Coming Decade

Jason Hessels
(ASTRON/U. of Amsterdam)

LOFAR officially opened June 12th, 2010 by her Majesty Queen Beatrix

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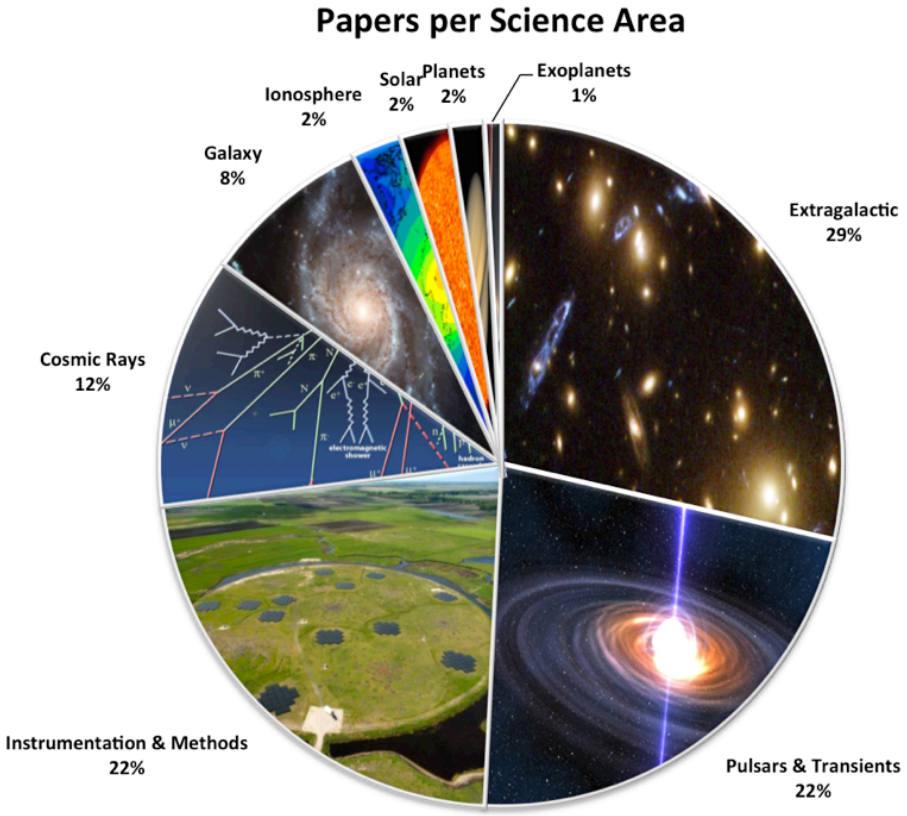
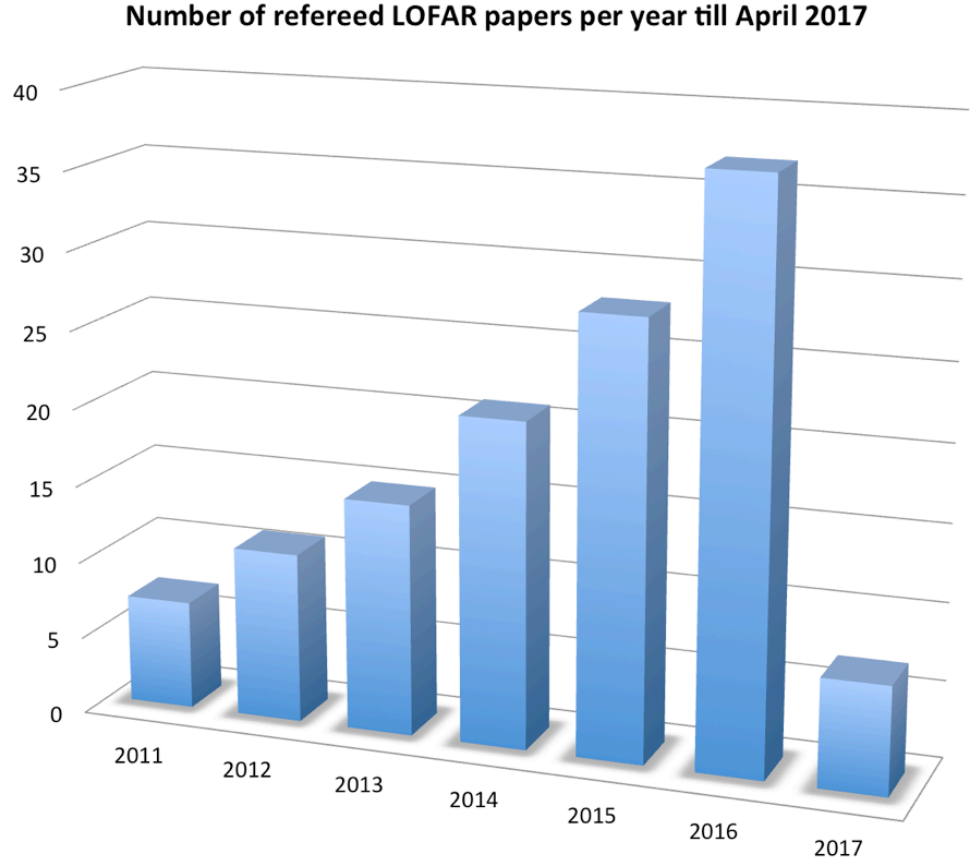
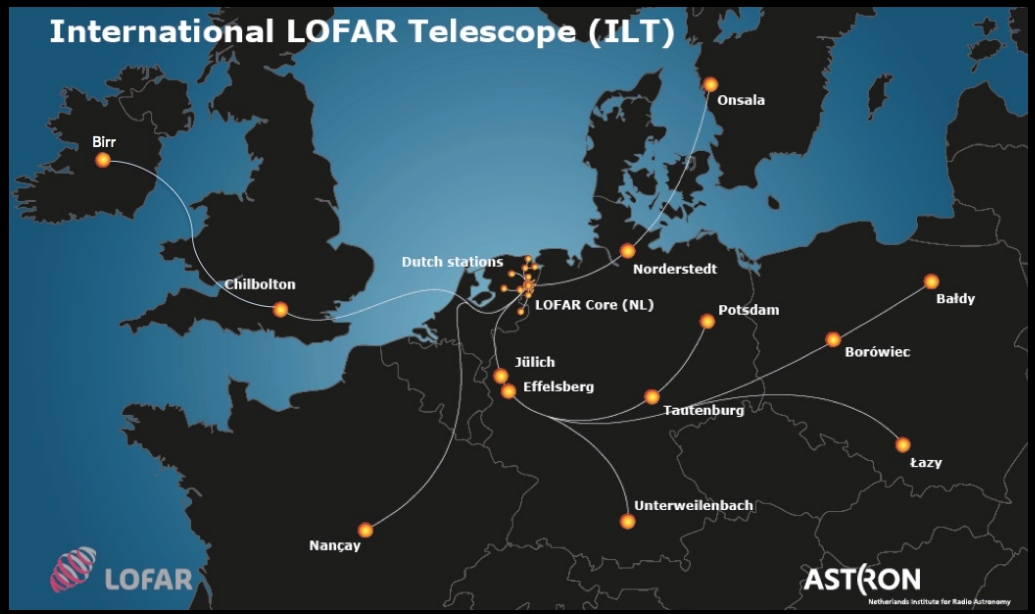
True story…

...and the science output is still ramping up





What is LOFAR2.0?



+ Latvia!

- A staged expansion of the scientific and technical capabilities of LOFAR.
- Enable a state of the art and highly productive telescope from 2020-2030.
- Path to SKA2-Low (like LOFAR was for SKA1-Low).

LOFAR2.0 Science Case

Epoch of Reionization

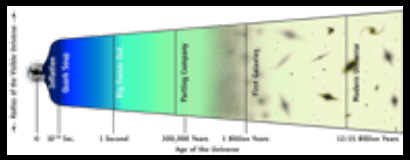
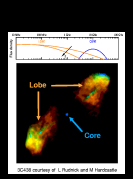
Surveys

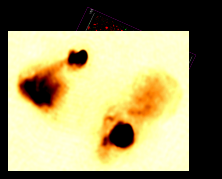
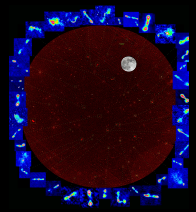
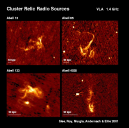
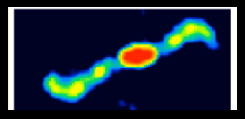
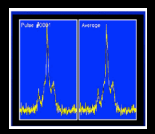
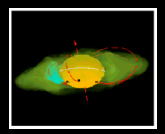
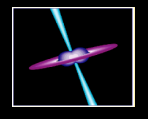
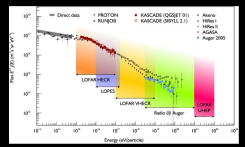
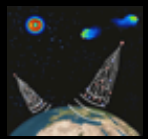
Transients & Pulsars

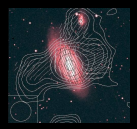
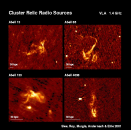
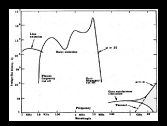
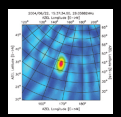
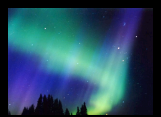
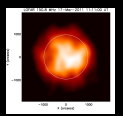
Cosmic Rays

Magnetism

Sun & Space Weather

LOFAR2.0 Boundary Conditions

- Leverage existing investment: in hardware, software, algorithms/pipelines and the **community's collected brain power**
- Remain *unique* and scientifically *impactful*. In the SKA-era this naturally means **lowest frequencies and longest baselines**.
- Strong community support.
- Financially and technically feasible on a 3-10 year timescale.
- **Do not interfere with SKA aspirations, complement.**

Proposals & Activities to Date

LOFAR2.0 Community Consultation

- Mar 24th, 2015: LOFAR2.0 Brainstorm at ASTRON.
- June 1st, 2015: presentation of the various options at LOFAR Users Meeting.
- Nov 19th, 2015: presentation of the various options at LOFAR PIs meeting.
- April 4th, 2016: update and consultation at LOFAR Users Meeting.
- February 23rd, 2017: LOFAR short and long-term science goals meeting at Schiphol.
- **June, 2017: low-freq conference in Bologna.**

NWO-M: COBALT2.0

Application form

Investment Grant NWO Medium

2016/2017

Sub-mode	Stations	Data product	Output Data rate	Science goals
Imaging 1	20CS+14RM+12INT	Visibilities for 2 station beams	2.5GB/s	All-sky imaging survey
Imaging 2	4CS+14RM	Visibilities and incoherent beam	200MB/s	Bright targets of opportunity
Beam-formed 1	6CS (Superterp)	182 Stokes I tied-array beams (high time-res)	4.1GB/s	Pulsar and fast transient survey
Beam-formed 2	20CS	469 Stokes I tied-array beams (high freq-res)	0.35Gb/s	Recombination lines
Beam-formed 3	20CS	16 CV tied-array beams	0.36GB/s	Pulsar timing and RM monitoring
Beam-formed 4	24CS+14RM+12INT	Station auto-correlations	0.7MB/s	Ionospheric scintillation

Tab. 1: ***The LOFAR Mega Mode***. Notes: Each of these imaging and beam-formed modes has a specific time/frequency resolution and bandwidth appropriate for the science goals, but we do not specify this level of detail, giving instead only the total data rate per sub-mode. The total data rate of LMM as a whole is ~8GB/s (roughly 1.5x LOFAR's current maximum data rate, but providing a *lot* more scientific information per bit) assuming 32-bit data samples for imaging, 8-bit samples for pulsar timing, and 4-bit samples for pulsar survey data. Abbreviations: CS = Core Station, RM = Remote Station, INT = International Station, CV = Complex Voltage mode.

- Enable massively parallel observing ("LOFAR Mega Mode") and higher data rate modes.
- Applicants: Hessels, Haverkorn, McKean, Röttgering, Rowlinson.
- COBALT2.0 team: 12 person team from ASTRON AG, RO & R&D + Dutch Universities.

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Funded!

KNAW Grootschalig Infrastructuur

- Roadmap for major Dutch scientific infrastructure on the ~2025 timescale.
- Submitted on Jan 11th, 2016.
- LOFAR2.0 appears in KNAW report and brochure.
- One of 13 projects selected out of a pool of ~50.
- Will be useful for leveraging future funding for LOFAR2.0.

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Selected!

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KNAW Grootschalig Infrastructuur

- Written with help from KSP leaders.
- Identified 4 key enhancements.

VOORSTEL 12
RADIO 2025, RADIOSIGNALEN UIT HET VERRE VERLEDEN MET LOFAR 2.0

Radio 2025

Radioastronomie gebruikt radiogolven uit het heelal om informatie te vergaren over de fysica van sterren, zwarte gaten, kosmische straling, sterrenstelsels en het materiaal ertussenin. Nederland is vanaf de jaren veertig van de vorige eeuw een wereldleider op dit gebied. Rond 2025 zal een grotendeels in Nederland gebaseerde radiotelescoop verdere successen voor de Nederlandse radioastronomie mogelijk maken: LOFAR2.0, een brede innovatie van de bestaande *Low-Frequency Array* telescoop die zijn zwaartepunt in Drenthe heeft. LOFAR2.0 kan de scherpst mogelijke beelden maken van het heelal op de langste golflengten die hier op aarde zichtbaar zijn.

Werking

LOFAR, ontwikkeld en geëxploiteerd door ASTRON (Nederlands Instituut voor Radioastronomie) in samenwerking met de Nederlands sterrenkundige instituten en internationale partners, is opgebouwd uit tienduizenden kleine antennes verspreid over een groot geografisch gebied. Al deze sensoren zijn geclusterd in verschillende stations, die via snelle glasvezelkabels zijn verbonden met een centrale supercomputer. Op deze manier vormen de antennes samen een reuzentelescoop die vergelijkbaar is met

De LOFAR 'Superterp', het centrale deel van de array in Drenth tratie antennes zijn. Foto: Aerophoto Eelde.

ASTRON Netherlands Institute for Radio Astronomy LOFAR Low-Frequency Array

KNAW-Agenda Grootschalige Onderzoeksfaciliteiten

I. VOORSTEL ALGEMEEN

Acroniem	LOFAR2.0
Naam van de infrastructuur	Low-Frequency Array 2.0
Hoofdindiener	Rene Vermeulen
Organisatie	ASTRON
Functie	Director Radio Observatory; Director International LOFAR Telescope
Adres	Oude Hoogeveensedijk 4, 7991 PD Dwingeloo
Telefoon	(+31) (0)521595772
Email	rvermeulen@astron.nl
Mede indiener(s)	Heino Falcke (U. Nijmegen); Michiel van Haarlem (ASTRON); Leon Koopmans (U. Groningen); Huub Röttgering (Leiden); Ralph Wijers (UvA)
Naam contactpersoon/mede-indiener	Jason Hessels
Organisatie	ASTRON/UvA
Functie	Universitair hoofddocent
Adres	Oude Hoogeveensedijk 4, 7991 PD Dwingeloo
Telefoon	(+31) (0)521595769
Email	hessels@astron.nl

Samenvatting *Geeft korte samenvatting van deze faciliteit in termen van werking, wetenschappelijke voordelen etc. (max 350 woorden).*

We present LOFAR2.0, a major radio astronomy infrastructure for the Netherlands on the timescale leading up to 2025, and beyond. Astronomical radio sources are found as nearby as the Solar System, and reach back out as far as the first stars and galaxies formed in the Universe. Radio telescopes observe astronomical radio waves, which give unique information about the physics of planets, stars, galaxies, and the material between them. For example, astronomical radio signals allow us to probe elementary particle acceleration, magnetic fields, and the motion of interstellar material in ways that are impossible with other instruments.

On the timescale of 2025, LOFAR2.0, primarily located in the Netherlands, will be a major international radio telescope driving Dutch astronomy; this facility will leverage the current infrastructure of the Dutch-led Low-Frequency Array (LOFAR), which is constructed and operated by ASTRON – the Netherlands Institute for Radio Astronomy. LOFAR2.0 will be a unique telescope that will complement Phase 1 of the Square Kilometre Array (SKA), which is already planned for construction between 2018-2023. LOFAR2.0's unique strengths lie in its ability to make the sharpest possible images of the sky using the longest-wavelength radio waves we can see from Earth. It will detect the birth of the first generation of stars, map the evolution of galaxies, and elucidate the pivotal role of magnetic fields in shaping the Universe.

LOFAR2.0 will leverage ongoing research and development initiatives at ASTRON, as well as an ASTRON-hosted Science Data Centre that will serve the data to astronomical users. LOFAR2.0 presents "Big Data" as well as "Complex Data" challenges that are matched in scale by few other scientific projects (e.g., the SKA), and which will also drive ICT and High-Performance Computing advances in collaboration with well-established partners in industry and at academic institutes.

Kernwoorden *Geef maximaal 8 kernwoorden die de faciliteit typeren.*
Radio Astronomy, Astrophysics, Cosmology, Interferometry, Big Data, Complex Data, Science Data Centre

Won't Discuss Improvements to...

- General system monitor and control.
- Long-term archive.
- Responsiveness.
- Calibration and algorithms
- etc.

...these can all be big science drivers, but are not the primary drivers of large investment grants.

LOFAR2.0 Hardware Upgrades

Enhancement I

Double or triple station electronics

- Use all 96 LBAs.
- Simultaneous LBA+HBA for ionospheric calibration.
- Simultaneous LBA+HBA but on different fields.
- Correlator and data transport need to grow proportionately.

LOFAR2.0 Hardware Upgrades

Enhancement II

Replace LBA dipoles with new design

- Achieve much better response at 30-50MHz.
- Need to prove the potential in Enhancement I?

LOFAR2.0 Hardware Upgrades

Enhancement III

Build ~6 new stations

- Strategically chosen to augment 10-100km baselines?
- Fill in Superterp too?

LOFAR2.0 Hardware Upgrades

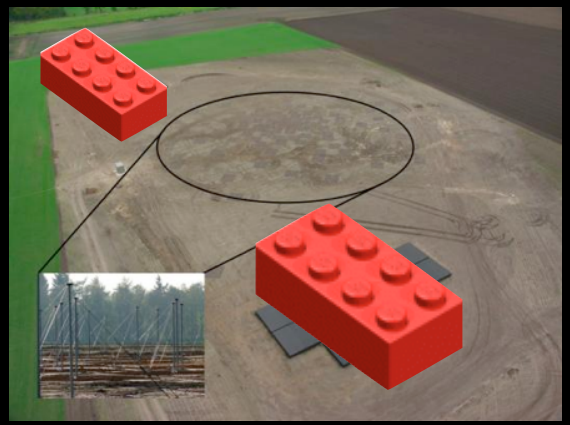
Stage IV

Build ~6 new international stations

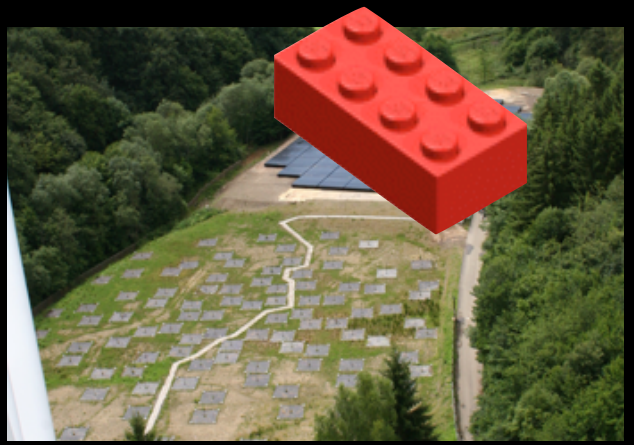
- Strategically chosen to augment 200-1000km baselines.

Building on LOFAR

48
Dutch Core
Sub-Stations



14
Dutch Remote
Stations



12+2
International
Stations

ASTRON LEGO Project

ASTRON

Project Management Plan

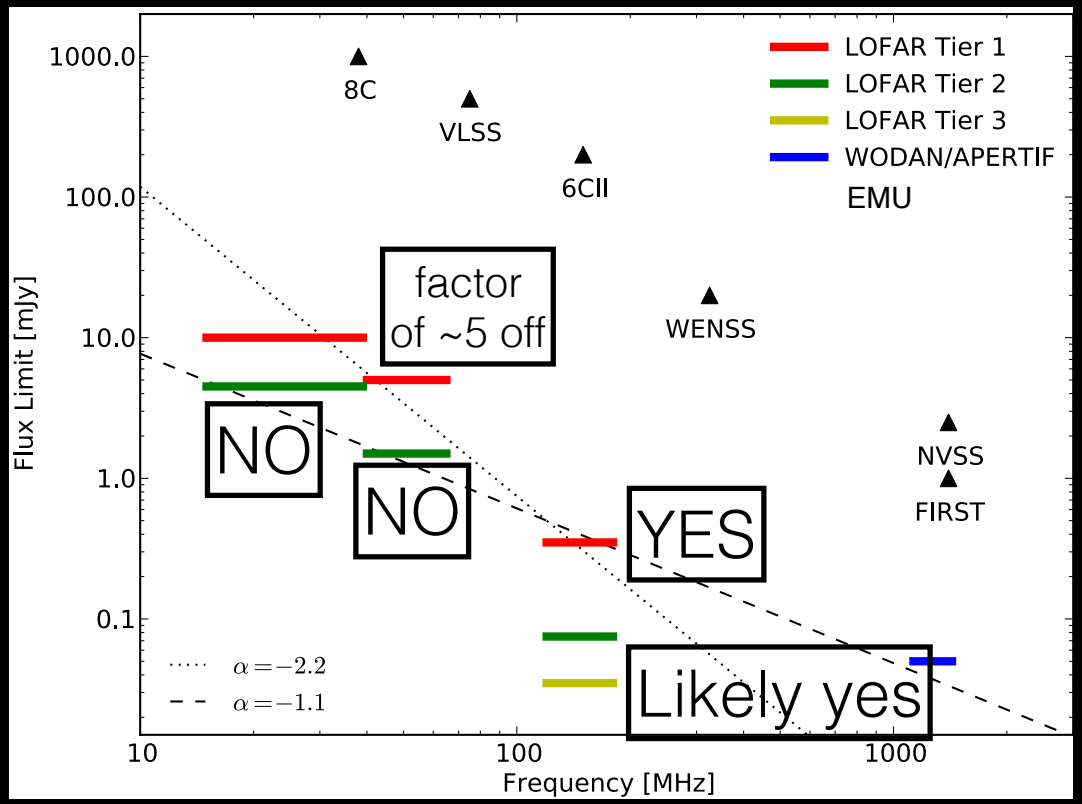
LOFAR2.0

LOFAR Enhanced Generation & Operation

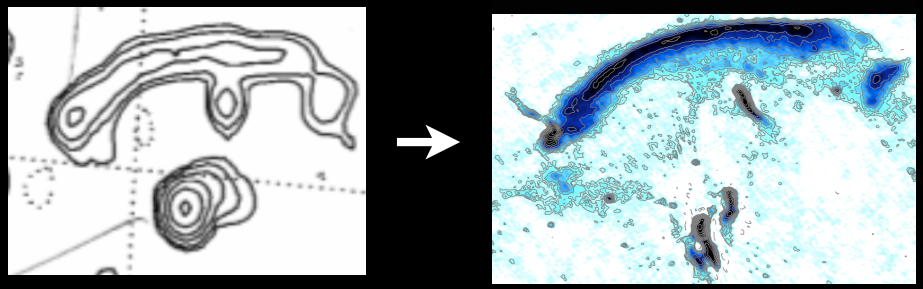
	Organisatie / Organization	Datum / Date
Auteur(s) / Author(s): N. Ebbendorf	ASTRON	
Controle / Checked:	ASTRON	
Goedkeuring / Approval:	ASTRON	
Autorisatie / Authorisation:	ASTRON	

- Team of 15 from ASTRON AG, RO & R&D + LOFAR2.0 Calibration Group (incl. also Leiden)
- Nico Ebbendorf: Project Manager.
- Jason Hessels: Project Scientist.
- Weekly meetings (yey!!!)

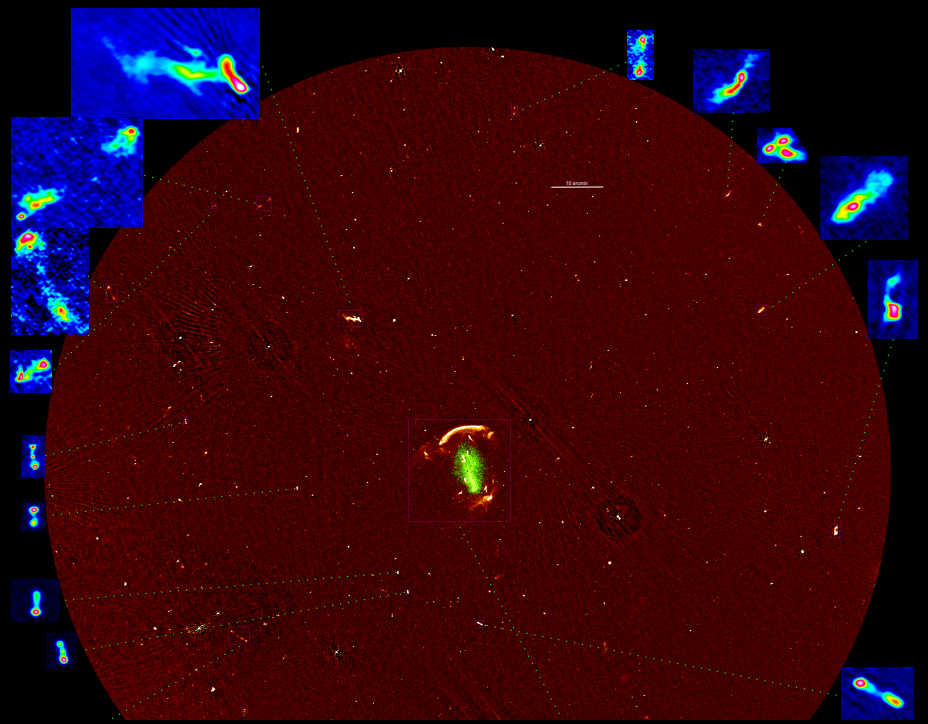
The surveys dream is being realized in the HBA



Röttgering

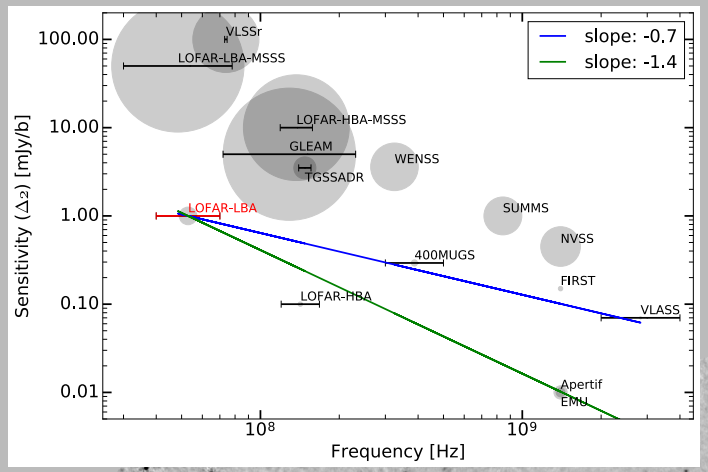


van Weeren



Next LOFAR2.0 step

LBA pilot survey mosaic

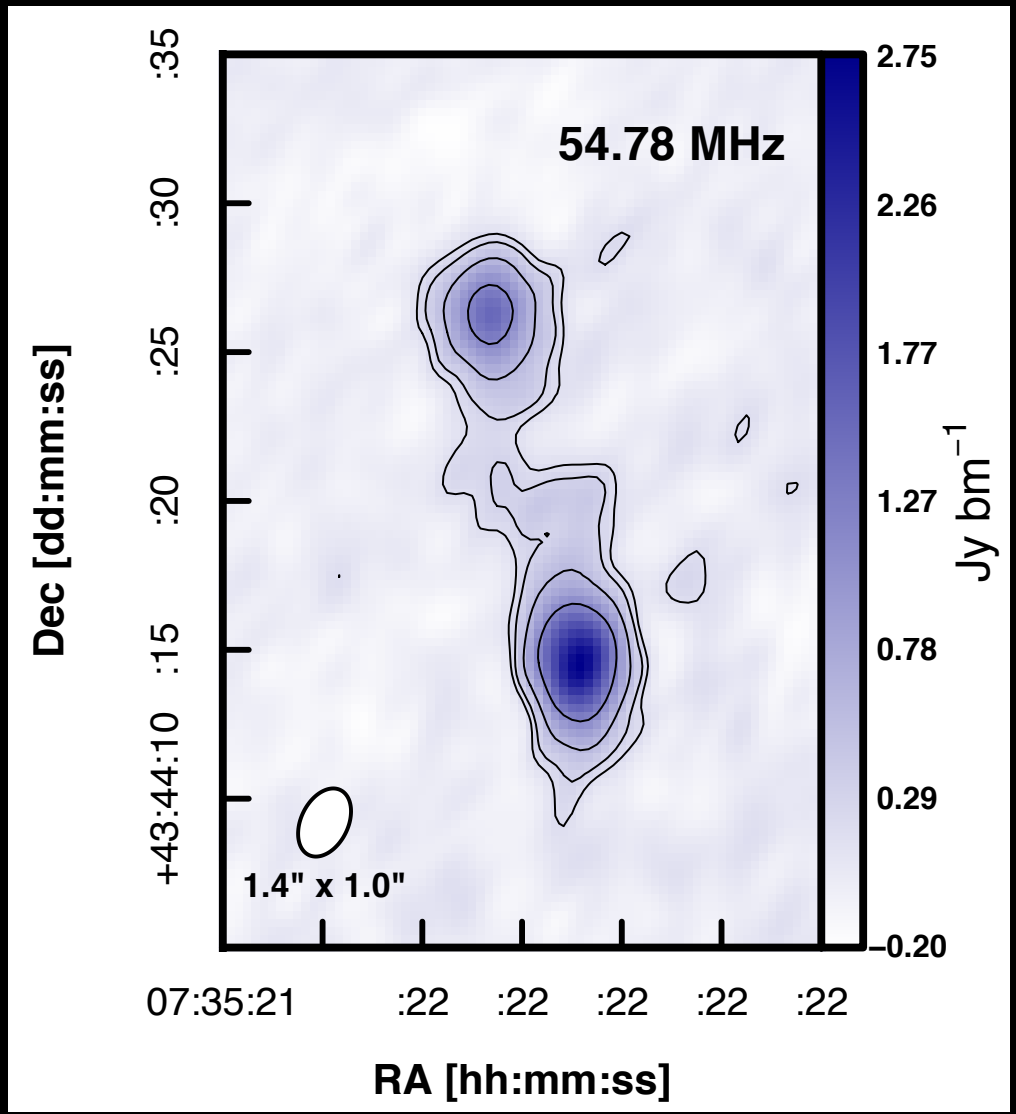


Frequency: 54 MHz
Rms noise: 4 mJy/b
Resolution: 45”
Detections: ~1500

de Gasperin

Next LOFAR2.0 step

First published LBA long-baseline image

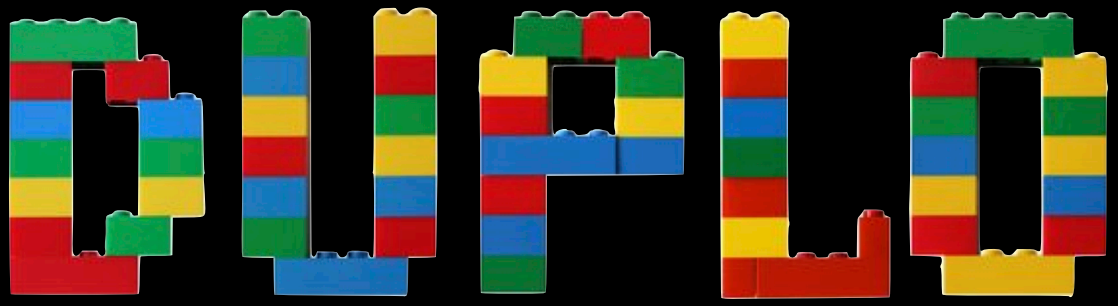


Morabito

Next LOFAR2.0 step

- The time is ripe to make a big leap in our ability to do thermal-noise-limited LBA imaging and an all-sky survey.
- Triple the station electronics in all Dutch stations to enable enough LBA sensitivity for calibration.
- Also provides increased HBA capacity (3x) for deep surveys and in-situ processing for a super-AARTFAAC and space weather.
- Design a DAB-robust HBA frontend.
- Also solves the issue of replacing aging components.
- Surveys typically help (nearly) everyone's science!

Next LOFAR2.0 step



Digital Upgrade for Premier LBA Observing

- NWO-Groot proposal deadline in October this year.
- Build a detailed technical case/design as part of LEGO.
- First tackle station electronics.
- Refine the detailed science case in consultation with the LOFAR community.

Your feedback & ideas welcome!