German LOFAR – a new era in radio astronomy

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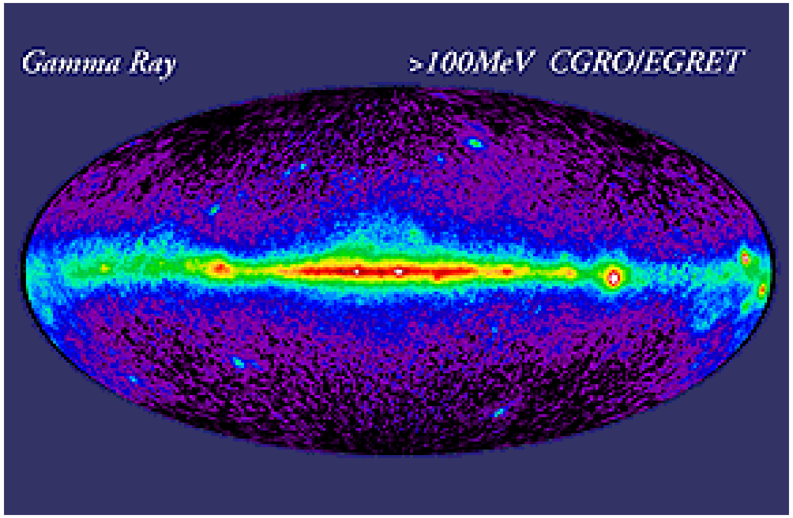
Outline

- Why LOFAR?
- What is happening with LOFAR?
- Why LOFAR in Germany?
- Outlook

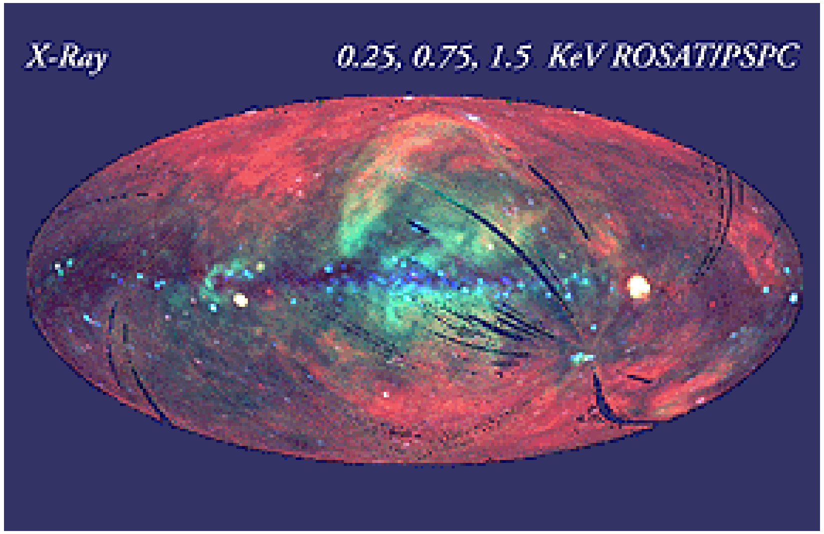
10^{23}-10^{20} Hz

10^{19}-10^{17} Hz

Compton Gamma-Ray Observatory



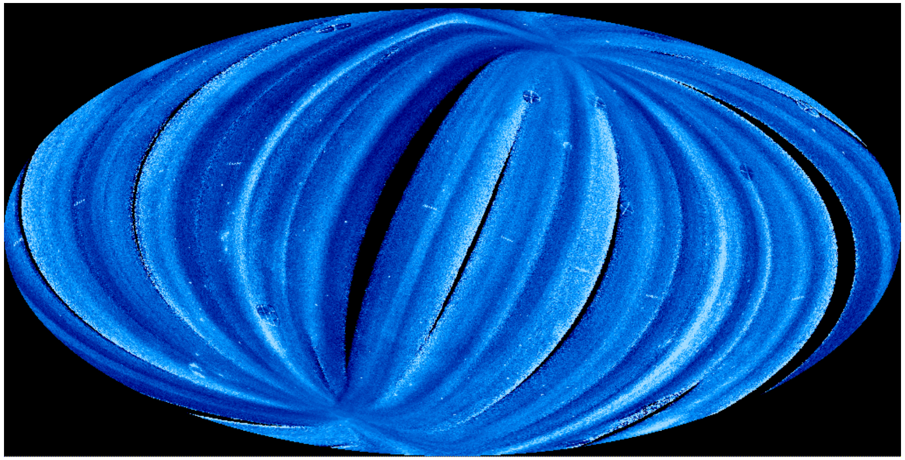
ROSAT



10^{16}-10^{15} Hz

10^{14} Hz

Extreme Ultraviolet Explorer

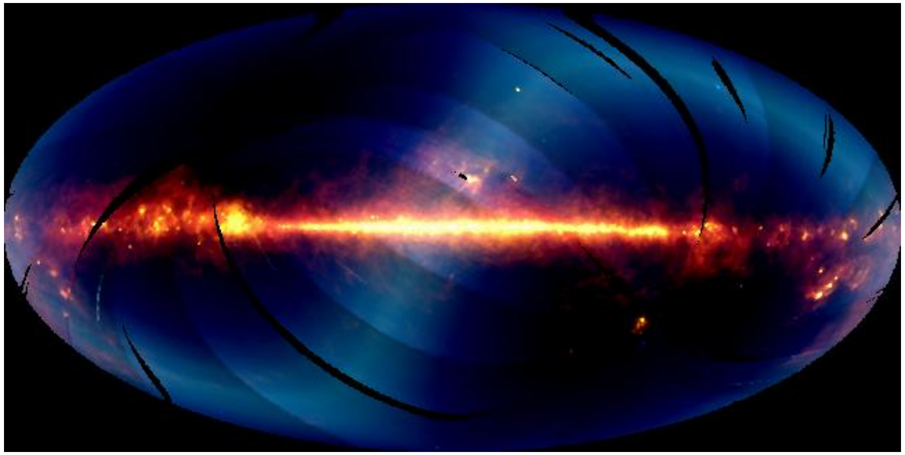


Hubble Space Telescope

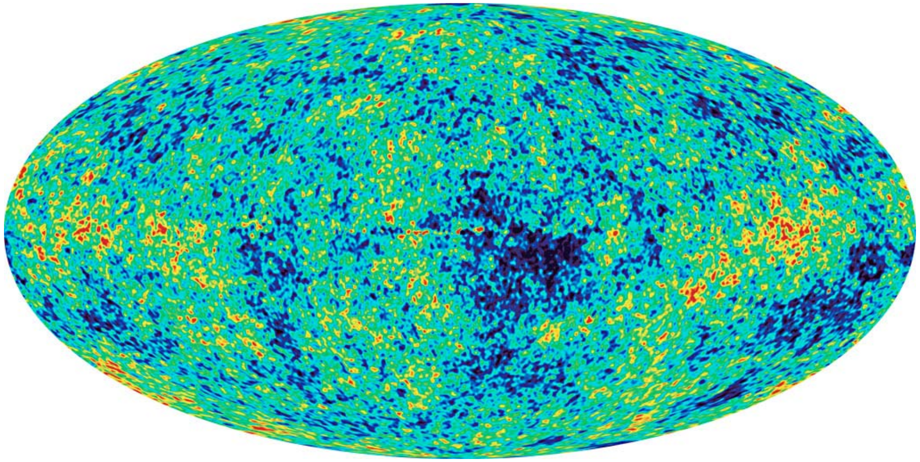
10^{13}-10^{12} Hz

10^{11}-10^{10} Hz

Infrared Astronomical Satellite

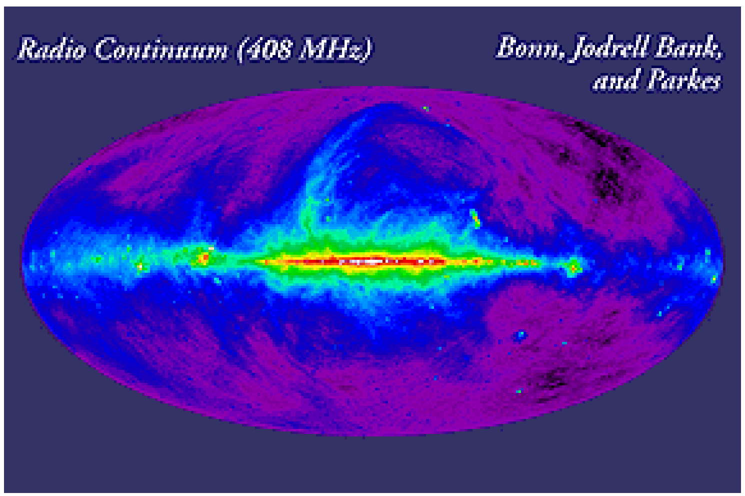


Wilkinson Microwave Anisotropy Probe



10^9-10^8 Hz

Radio



10^8-10^7 Hz

Low-frequency

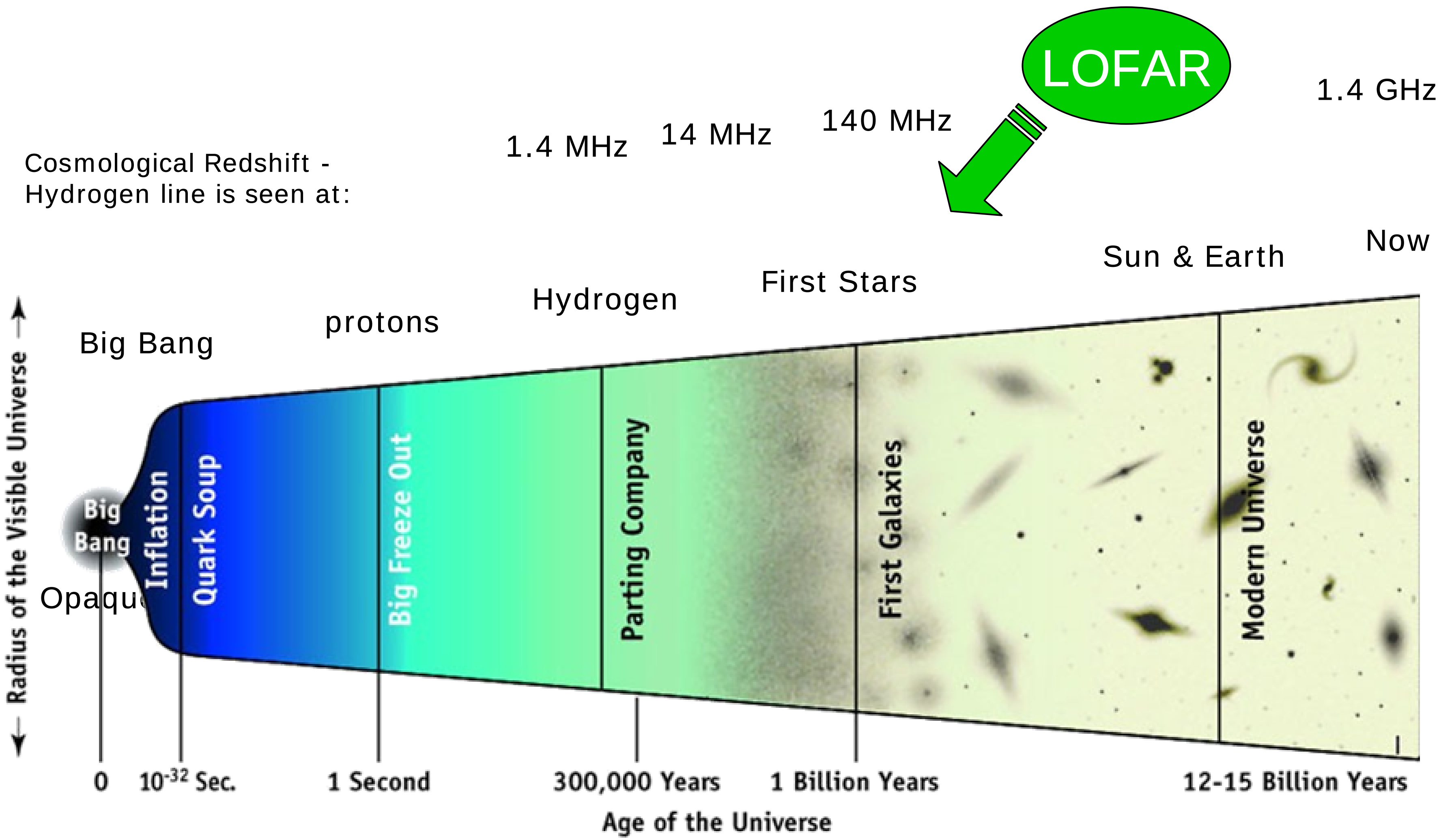
?

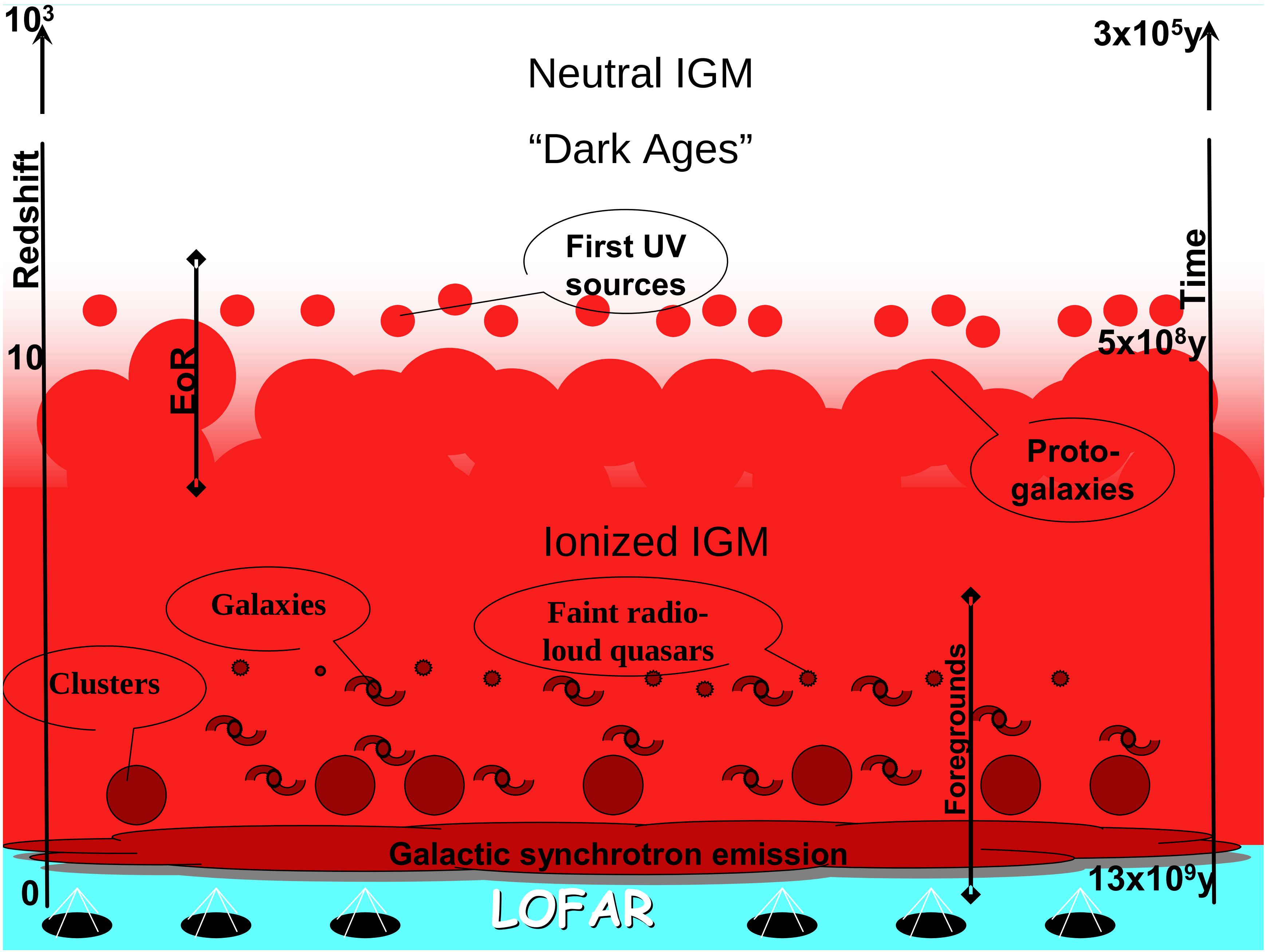
Why is the low-frequency regime still unexplored?

- RFI mitigation
- Ionospheric transients

History of the Universe

(condensed version)

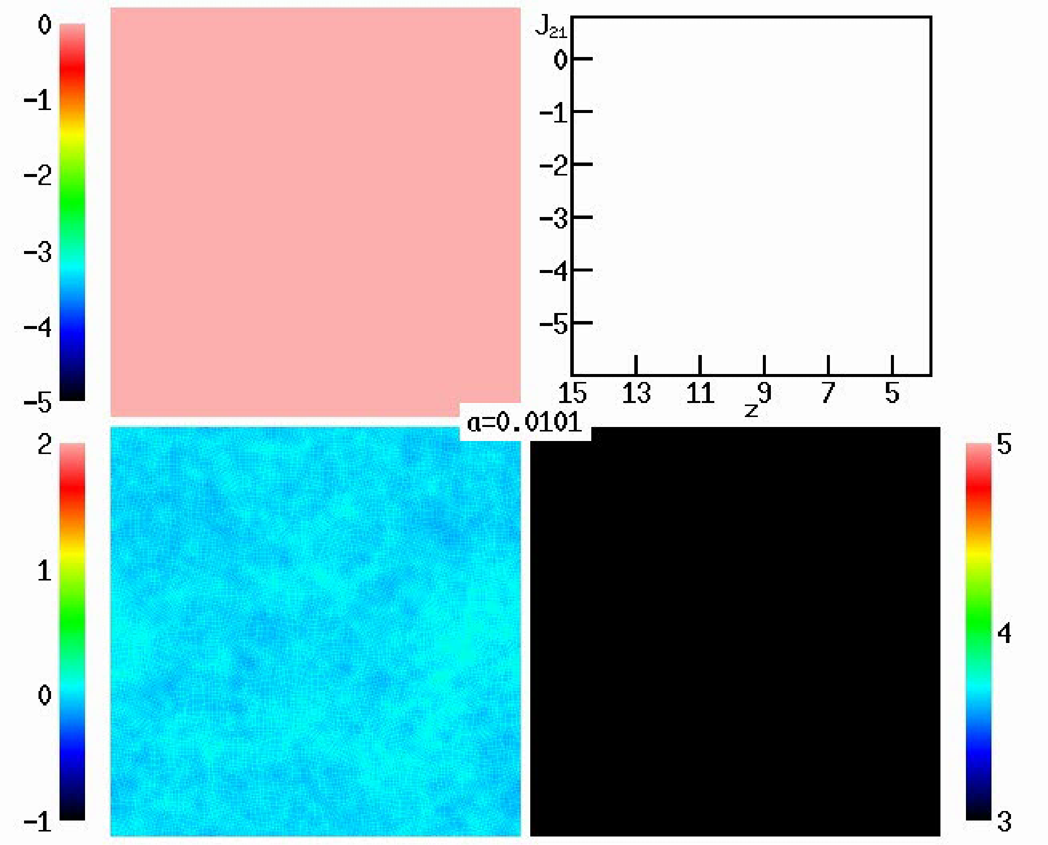




10^3
3x10^5y
Neutral IGM
"Dark Ages"
Redshift
First UV sources
Time
10
5x10^8y
EoR
Proto-galaxies
Ionized IGM
Galaxies
Faint radio-loud quasars
Clusters
Foregrounds
Galactic synchrotron emission
0
13x10^9y
LOFAR

Re-Ionization of the Universe

- A key science goal of LOFAR is to map the epoch of re-ionization
- After the big bang and recombination of elements the universe was neutral
- Stars and quasars must have started to re-ionize the universe
- We expect clumpy neutral hydrogen emission from primordial matter at z~6-12.
- 21cm line shifted to 200 MHz

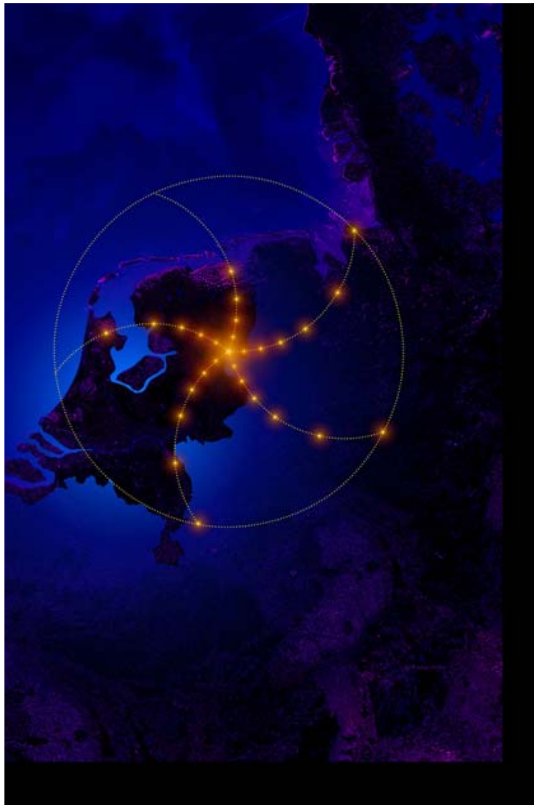


Gnedin (1999)

LOFAR – the next generation radio telescope

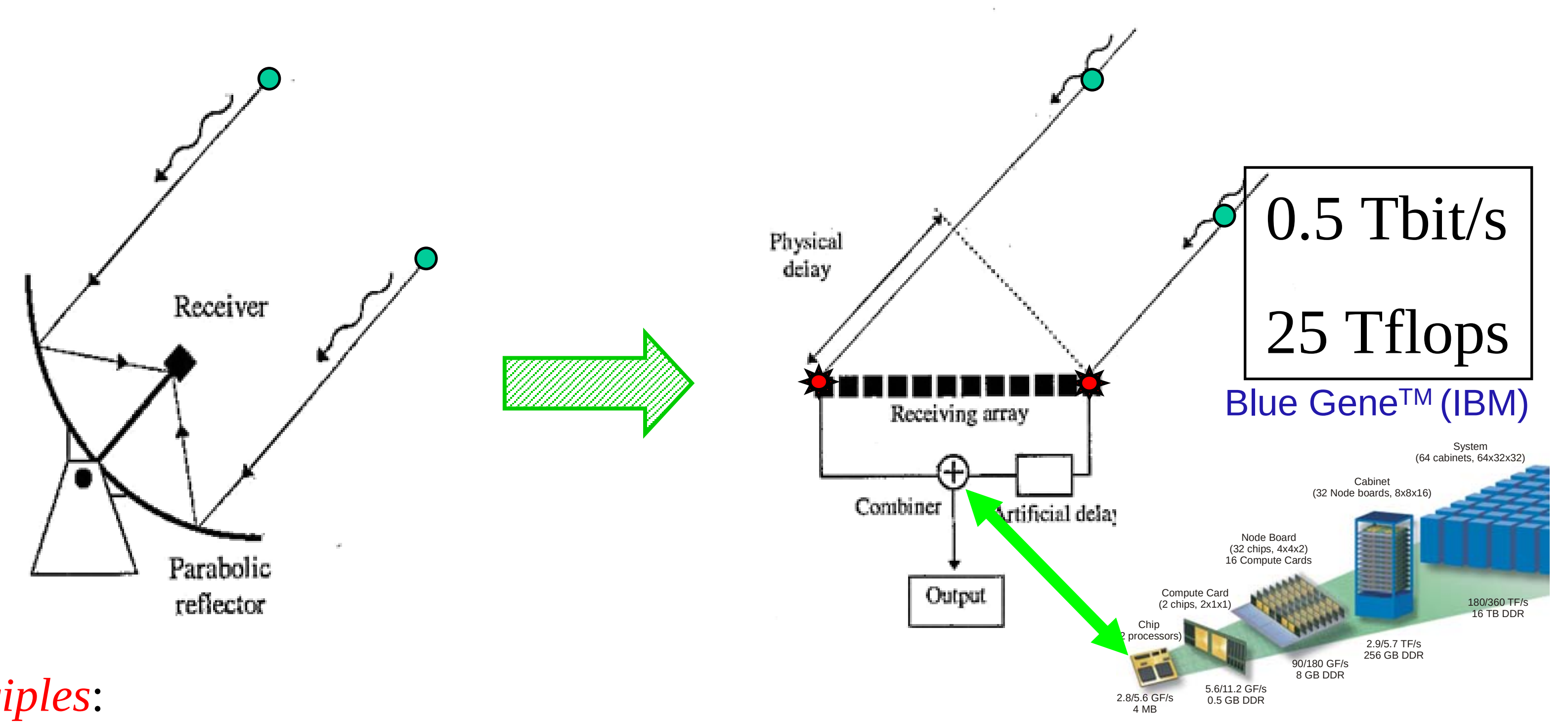
- Telescope the size of the Netherlands plus Germany
- Frequencies: 30 - 240 MHz
- Replace a few big expensive antennas by many cheap ones
- No moving parts: purely electronic beam steering
- Current Funding: 74 M€

LOFAR - phased array telescope



construction: 2006-2007

Extreme Flexibility: Electronic Beamforming



Principles:

a) **E** is detected, interference can be performed (off-line) in computer

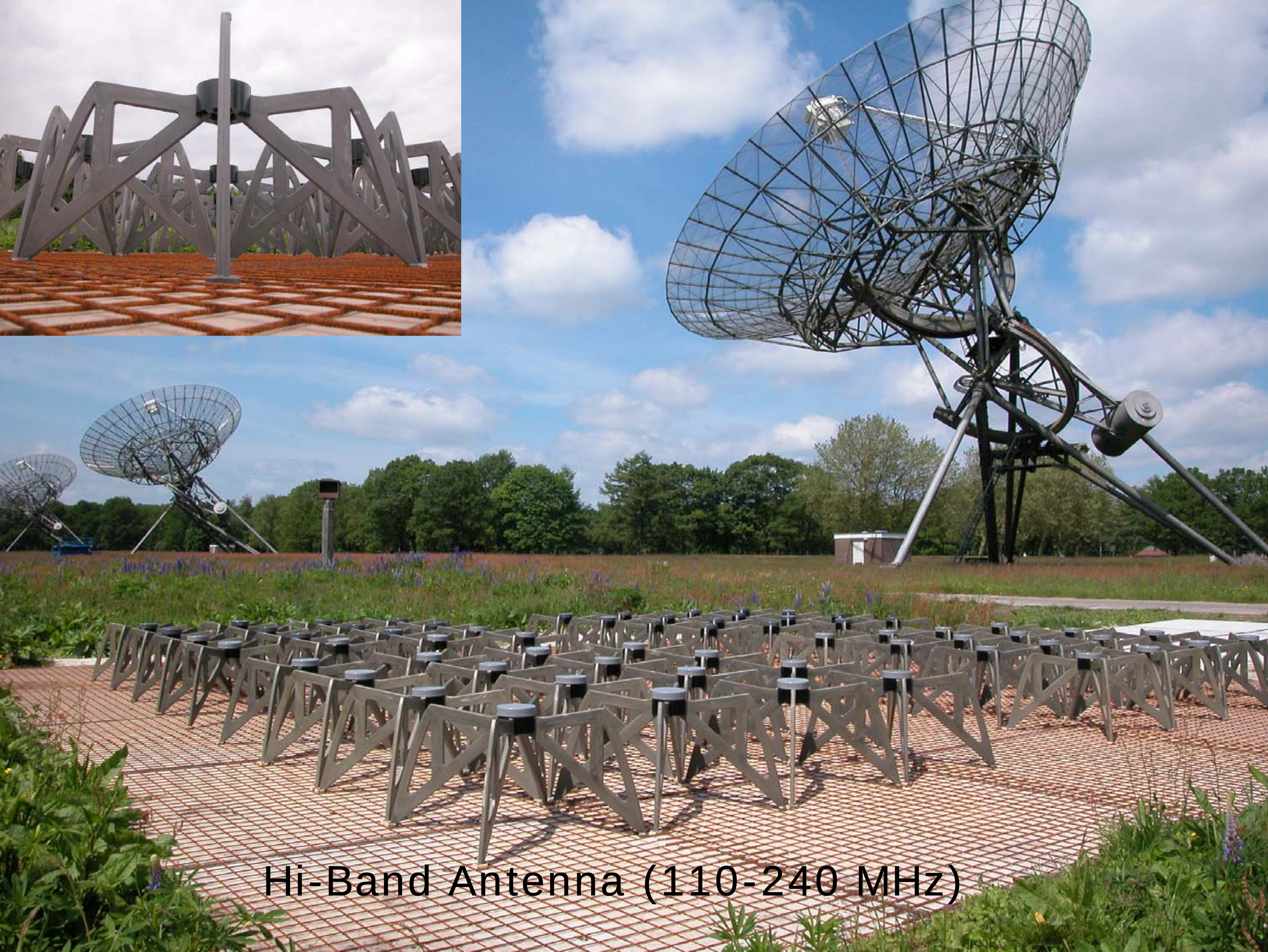
b) No quantum shot noise: extra copies of the signal are free!

Consequences:

a) Can replace mechanical beam forming by electronic signal processing

b) Put the technology of radio telescopes on *favorable cost curve*

c) Also: multiple, independent beams become possible



Hi-Band Antenna (110-240 MHz)


Lo-Band Antenna (30-80 MHz)

LOFAR Correlator

List for

R_{max} and ... ails about
other fiel... on of the
Fields"

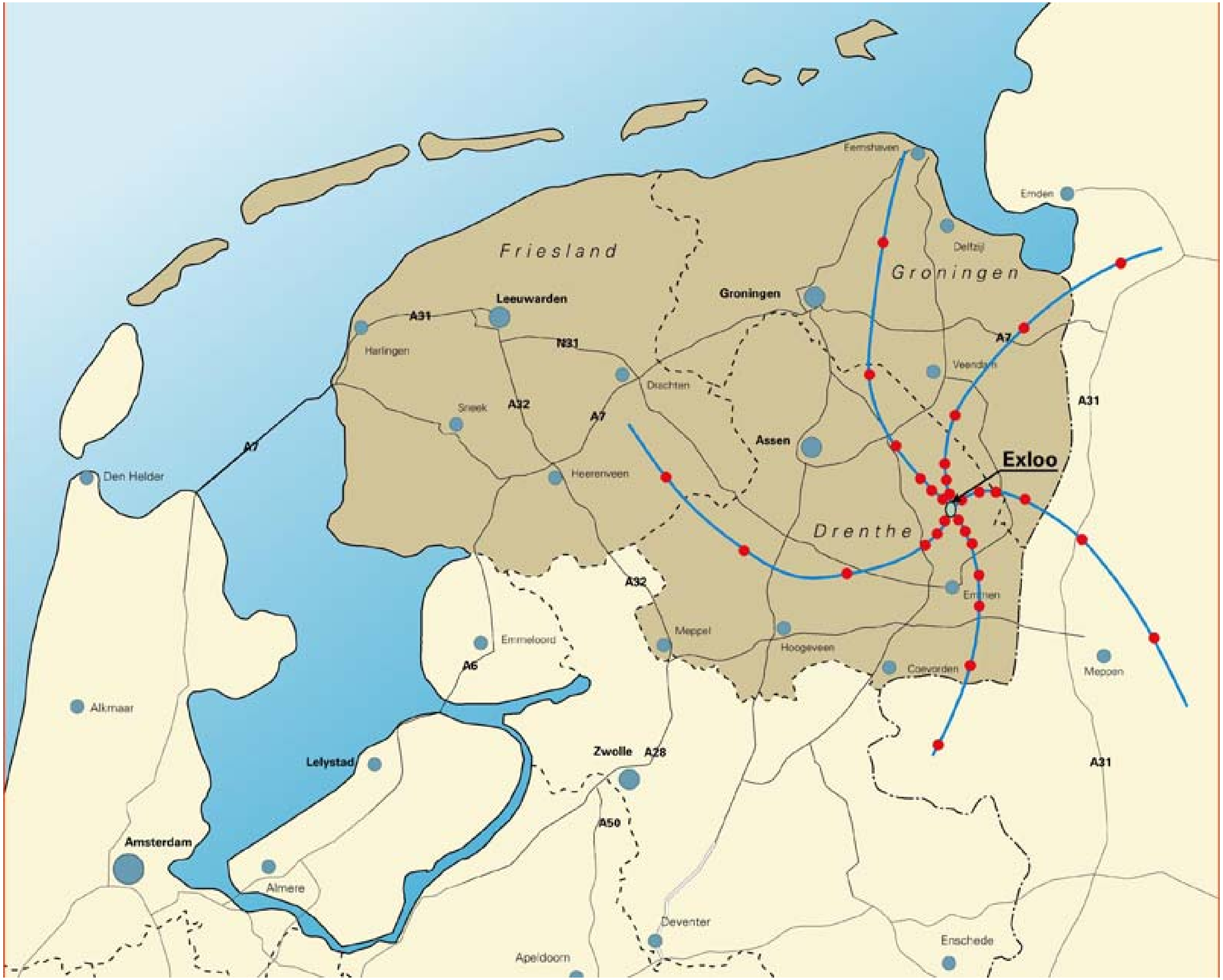
TOP500® SUPERCOMPUTER SITES

DETAILS — EXPLANATION OF THE FIELDS

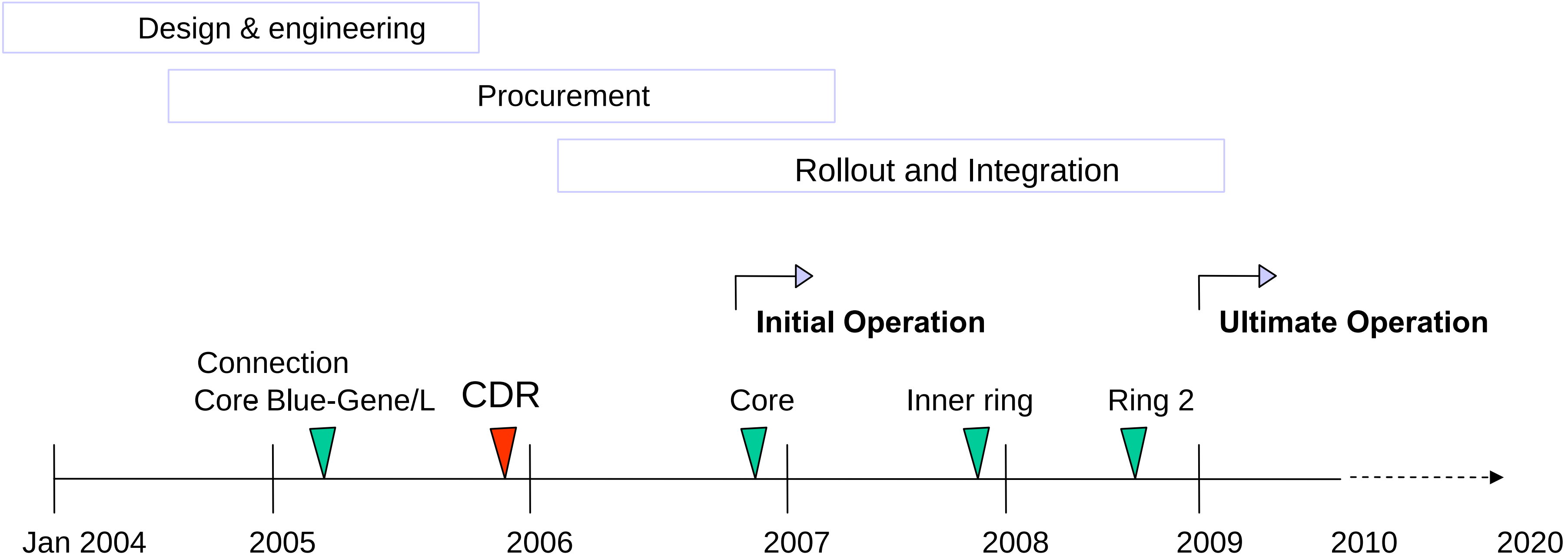
1-100 | 101-200 | 201-300 | 301-400 | 401-500

Rank	Site Country/Year	Computer / Processors Manufacturer	R_{max} R_{peak}
1	DOE/NNSA/LLNL United States/2005	*BlueGene/L* **eServer Blue Gene Solution** / 65536 IBM	136800 183500
2	IBM Thomas J. Watson Research Center United States/2005	*BGW* **eServer Blue Gene Solution** / 40960 IBM	91290 114688
3	NASA/Ames Research Center/NAS United States/2004	*Columbia* **SGI Altix 1.5 GHz, Voltaire Infiniband** / 10160 SGI	51870 60960
4	The Earth Simulator Center Japan/2002	**Earth-Simulator** / 5120 NEC	35860 40960
5	Barcelona Supercomputer ...	*MareNostrum* **JS20 Cluster, PPC 970, 2.2** ...	27910 42144
6	ASTRON/University Groningen Netherlands/2005	**eServer Blue Gene Solution** / 12288 IBM	27450 34406.4

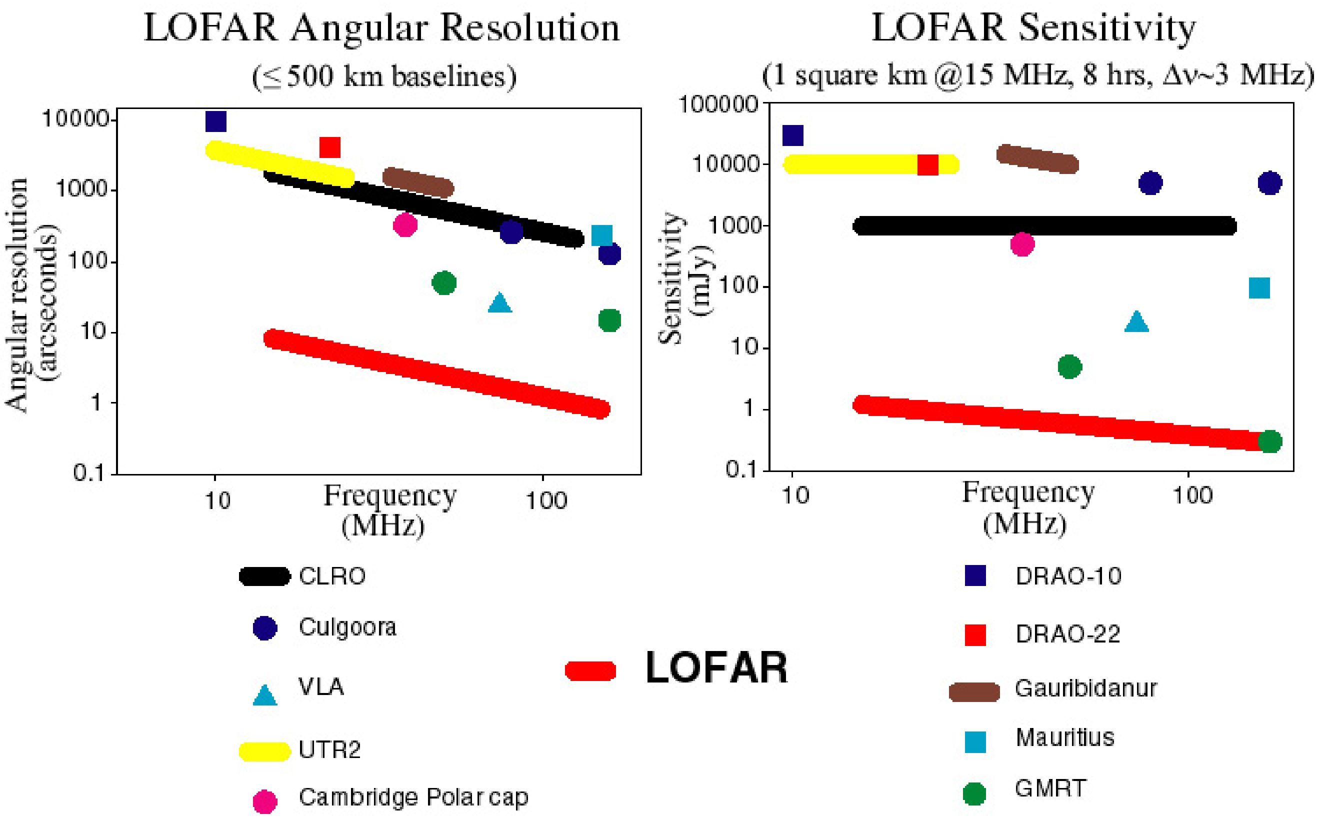
LOFAR Configuration



LOFAR Planning



LOFAR Performance



3 orders of magnitude!

The EoR with LOFAR

LOFAR will measure, with ~ 3’ resolution, several data-cubes with ~10°x10° spatial dimensions and one frequency dimension (redshift ~6-11.5).

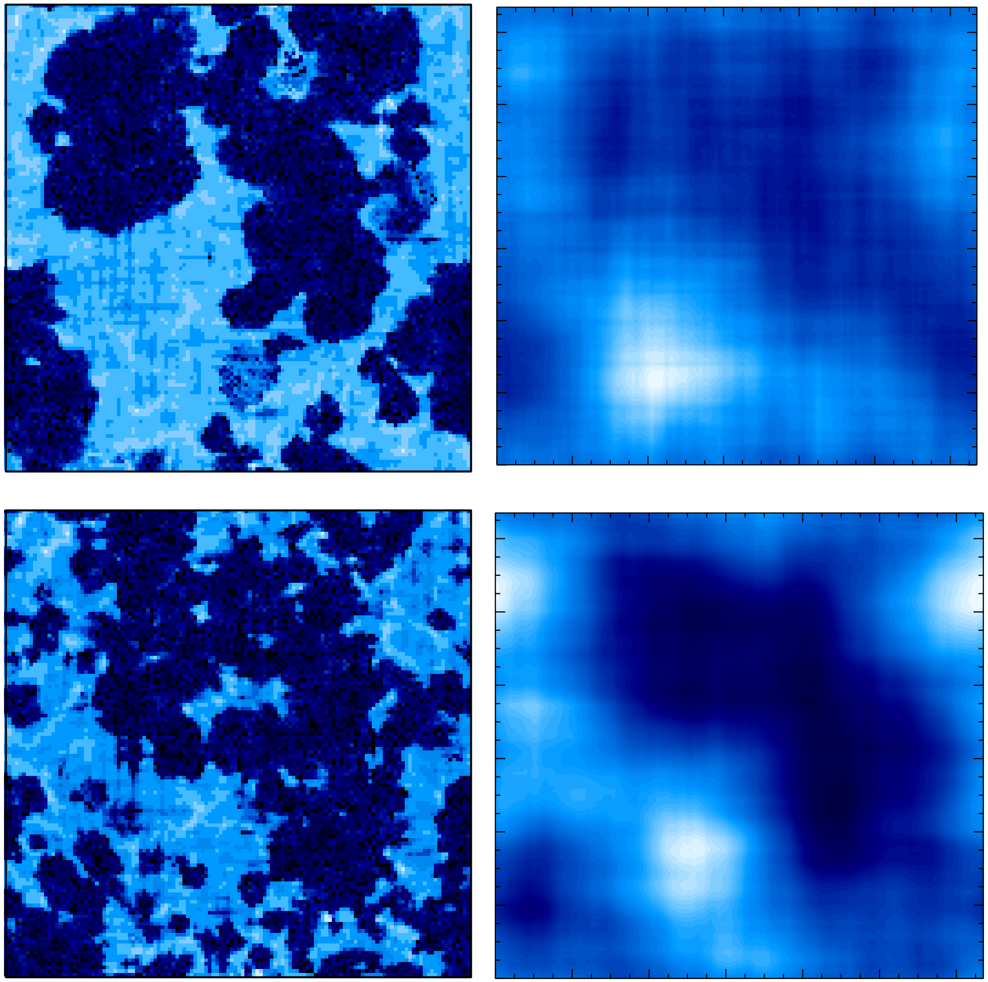
The main scientific goals are:

- The global EoR signal
- Statistical analysis will be used in order to extract the principal structural measures of the reionisation signal from the noisy and foreground contaminated data
- EoR map reconstruction: The ultimate goal is to reconstruct a large-sky maps of the EoR signal.

LOFAR expected response

(Valdes et al. , in prep)

L20 @ z~14.5 (~90 MHz)



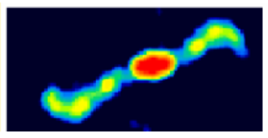
S5 @ z~10 (~130 MHz)

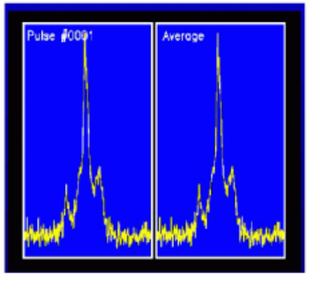
- Instrument sampling
- Gaussian noise
- Convolution with a Gaussian beam (σ=3 arcmin)

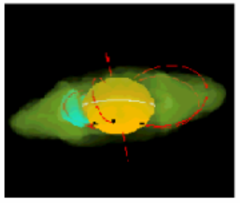
It will be possible to map the reionization history, especially its latest stages

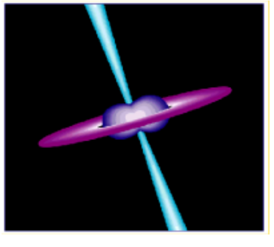
Courtesy of Benedetta Ciardi (MPA)

Transient Sources



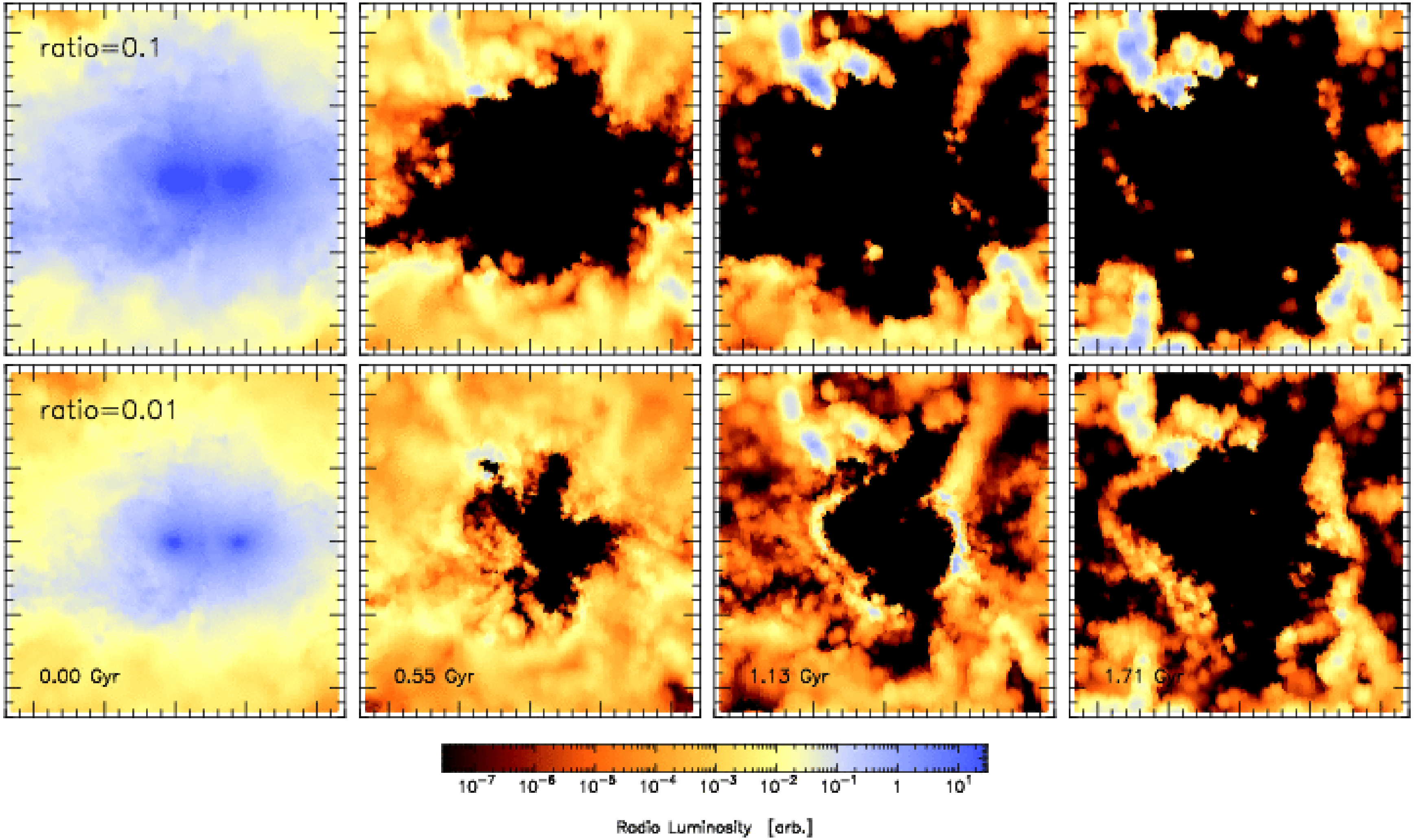






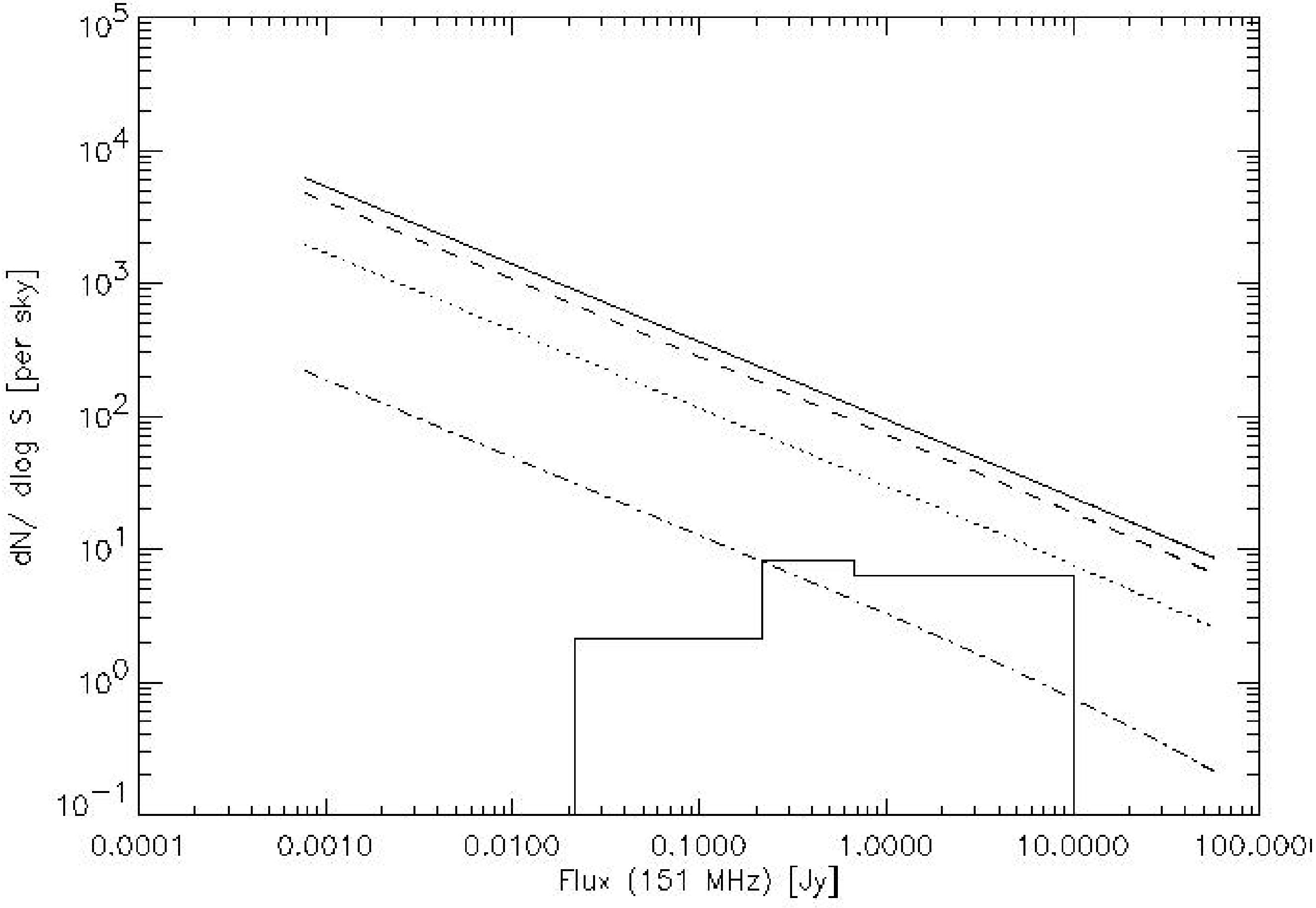
- X-ray Binaries (stellar mass black holes)
- AGN (supermassive black holes)
- Pulsars (neutron stars)
- CV's/Flare Stars
- LIGO Events (merging neutron stars)
- Supernovae
- Jupiter-like Planets
- Gamma-Ray Bursts (prompt emission and afterglows)
- Cosmic Rays & Neutrinos
- Meterorites
- … New sources …
  - Aliens, Airplanes, etc.

The fossil Universe: Radio relics and halos

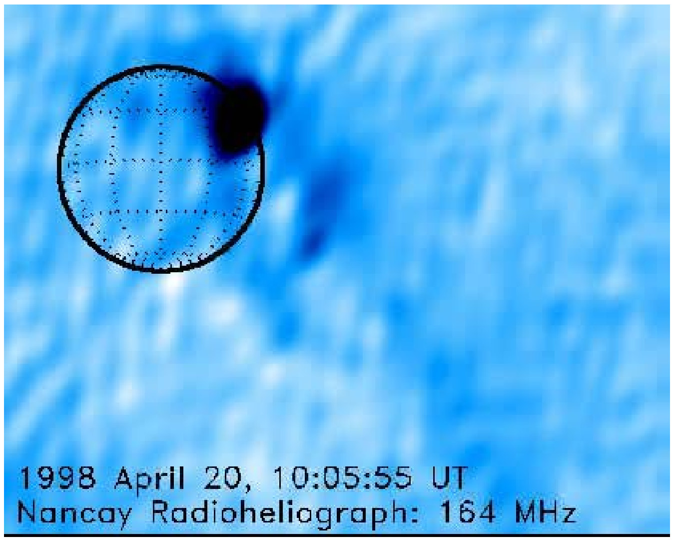


Hoeft, Brüggen, Yepes 2003

Radio Relic Luminosity Function



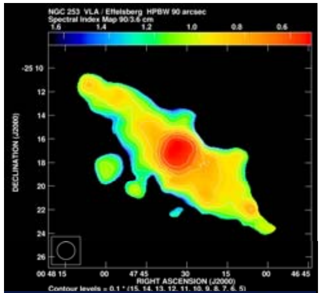
LOFAR Studies of the Solar System: Space Weather



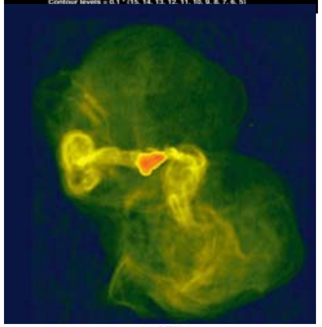
Solar Wind

observed via Radio Source Scintillation

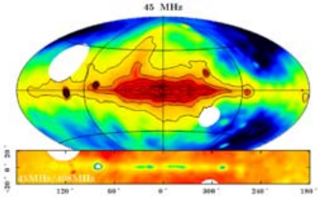
Other LOFAR Science Drivers



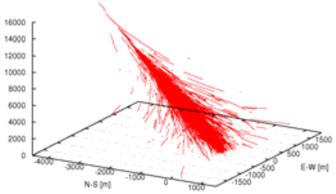
• Structure and Evolution of Galaxies (cosmic rays, magnetic fields)



• Evolution of AGN, Jets & Radio Lobes



• Galactic astronomy (magnetic field, ISM, SNR, surveys)



• Astroparticle physics (neutrinos, cosmic rays)

European Expansion …

The White Paper describes a German participation in LOFAR.

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German contribution

- Six LOFAR remote stations in Phase I (2006-2009)

  planned locations: Bremen, Effelsberg-Bonn, Garching, Hamburg, Jülich, Tremsdorf-Potsdam, and possibly Göttingen
- LOFAR Science network
- Another six stations in Phase II (2009-2012)


Germany
DENMARK
SWEDEN
Baltic Sea
North Sea
NETHERLANDS
POLAND
BELGIUM
CZECH REPUBLIC
FRANCE
AUSTRIA
SWITZERLAND
Hamburg
Bremen
Dwingeloo
Tremsdorf
Göttingen
Jülich
Effelsberg
Garching

Key benefit of German contribution: **long baselines** (> 100 km)

Science Network

Based on the existing expertise in Germany, the foci of the science network could be the following areas:

- Galaxies
- Polarization, Galactic astronomy, AGNs
- Large-scale structures
- Cosmology & Epoch of Reionisation
- Surveys
- Solar physics

Development Paths in Radio Astronomy

Improvements	Telescopes

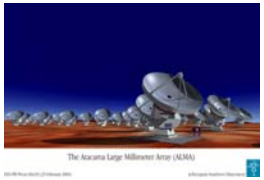
1) Resolution.
2) Sensitivity.
3) Frequency.
4) Flexibility!

2006-2010: LOFAR

- "new" frequency windows
- 100 times more resolution
- 100 times more sensitivity
- very flexible digital beam forming

2007-2011: ALMA

- new frequency window
- 10-100 times more sensitivity
- 10-100 times more resolution



2012-2015: SKA

- 100 times more sensitive
- very flexible beam forming
- extreme frequency agility

NOW: → eVLBI

Factor 100 improvement in **all** areas within a decade over 5 decades of frequency!
This will be the largest step radio astronomy has ever made.

Conclusions

- LOFAR is a novel radio telescope that will observe a largely unexplored part of the spectrum
- As a result exciting new discoveries loom in the low frequency regime
- LOFAR is the first instrument to map the re-ionisation of the Universe
- Almost all branches of astronomy are served by LOFAR
- A German participation with the provision of long baselines is essential

LOFAR Performance

Frequency (MHz)	A_{eff} (m^2)	T_{sys} (in K)	δS in 1s (mJy)	δS in 10h (mJy)	δS in 100h (mJy)
30	3.3×10^5	23k	68	0.35	0.11
75	5.2×10^4	2450	46	0.24	0.07
120	3.3×10^5	820	2.4	0.013	0.004

Approximate sensitivity per beam, with 4 MHz BW and for a single polarization

LOFAR Key Science Programmes

- Cosmology
  - Epoch of Reionization
- All-Sky Surveys
  - Star forming galaxies, AGN, Clusters, etc.
- Transient detection
  - Everything that bursts and varies
- Astroparticle Phyiscs
  - Direct detection of cosmic rays
  - Cosmic rays & neutrinos impacting the moon

Costs for 2006-2009 (Phase I)

Initial investment per station	**€ 686,000**
Two engineers to be in charge of the six statio	**€ 100,000/year**

Excluding the costs for the data connection and land we envisage for a period of 3 years a total investment of ~ € 5 Million.