LOFAR

More than just a radio telescope …

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&

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Radio Astronomy - Great Discoveries

- quasars – the universe is large,
- discovery of HI and finding of dark matter,
- organic molecules – the fabric of life,
- superluminal motion – jets from black holes, sources of high-energy emission,
- magnetic fields,
- fundamental coordinate reference frame,
- and …

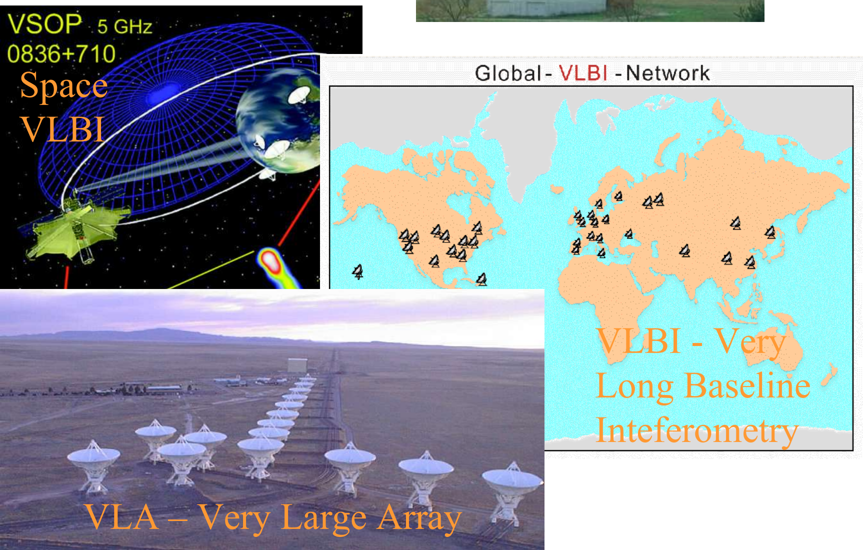
Nobel Prizes in Astronomy/Astrophysics

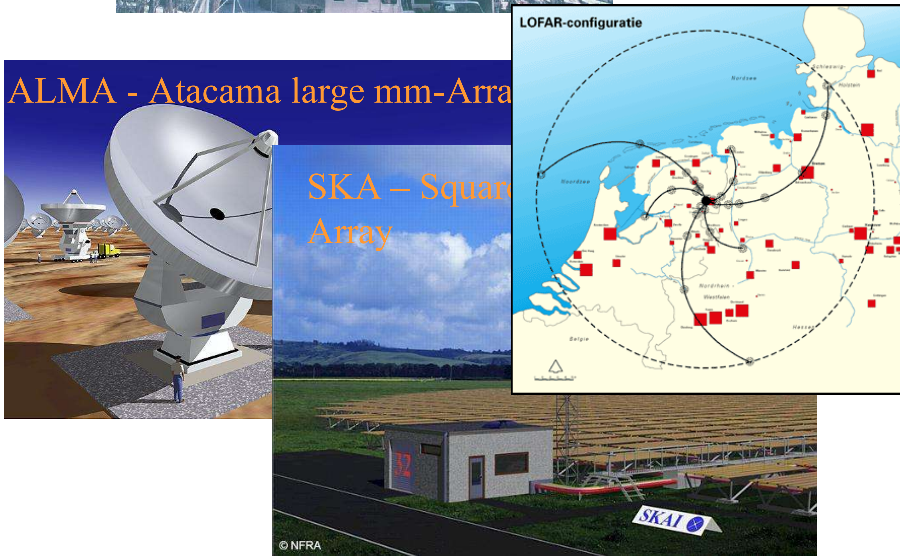
- 1993: **RUSSELL A. HULSE** and **JOSEPH H. TAYLO**
  Pulsars and Gravitational Waves.
- **1983: SUBRAMANYAN CHANDRASEKHAR** *theory*
  WILLIAM A. FOWLER *chemical elements in the unive*
- **1978: ARNO A. PENZIAS** and **ROBERT W. WILSON**
  background radiation.
- **1974: SIR MARTIN RYLE aperture synthesis techniq**
  ANTONY HEWISH pulsars.
- **1967: HANS ALBRECHT BETHE** *theory of nuclear reactions, c*
  the energy production in stars.

Most observational Nobel prizes in astrophysics are in radio astronomy.

All have lived up to their promises!

Great Radio Telescopes





Development Paths in Radio Astronomy

Improvements	Telescopes

1) Resolution.

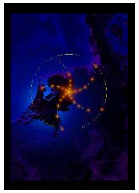
2) Sensitivity.

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

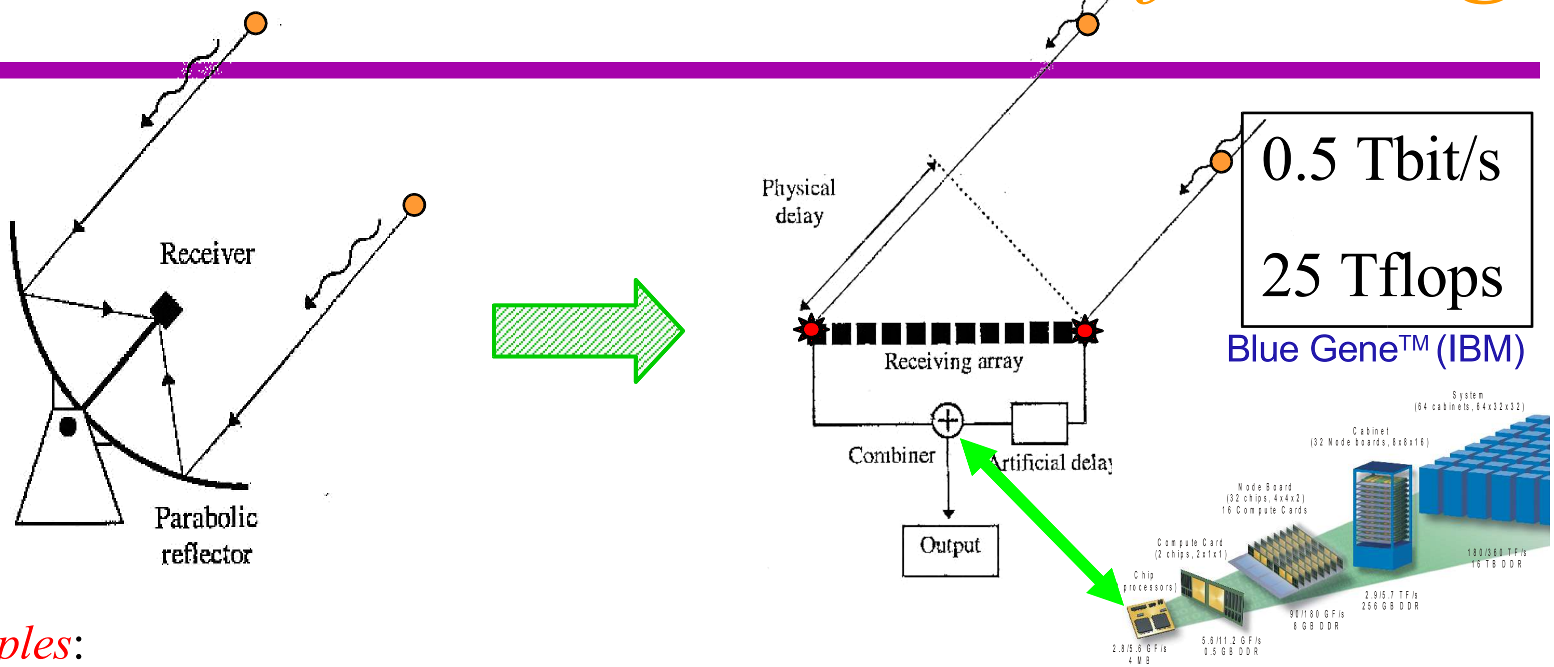
2012-2015: SKA

- 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.

Extreme Flexibility: Electronic Beamforming



Principles:

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

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

Consequences:

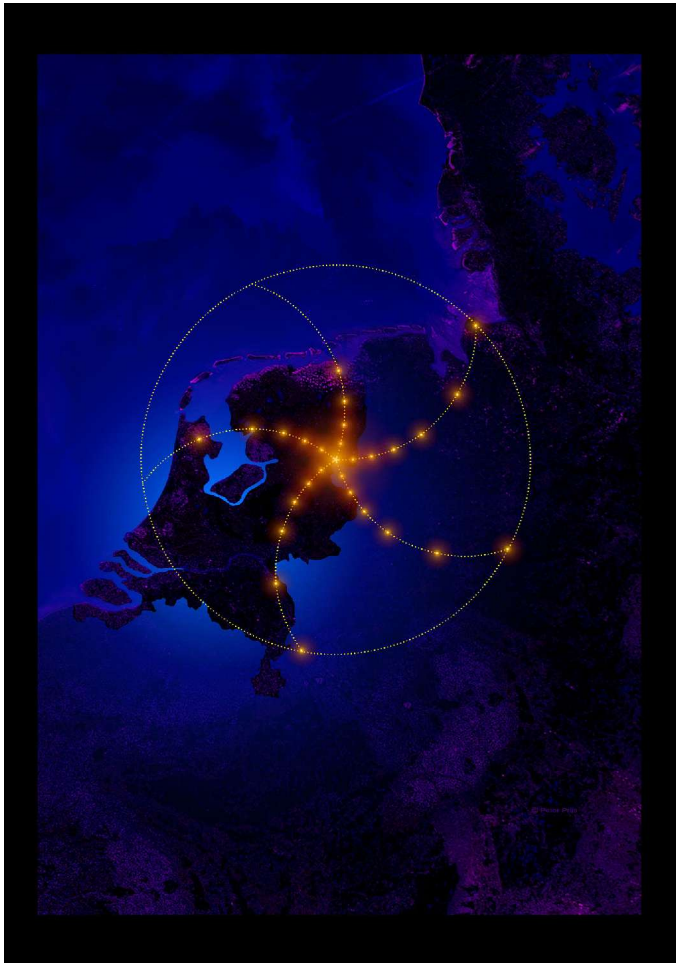
e) Can replace <u>mechanical</u> beam forming by <u>electronic</u> signal processing

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

g) Also: multiple, independent beams become possible

LOFAR

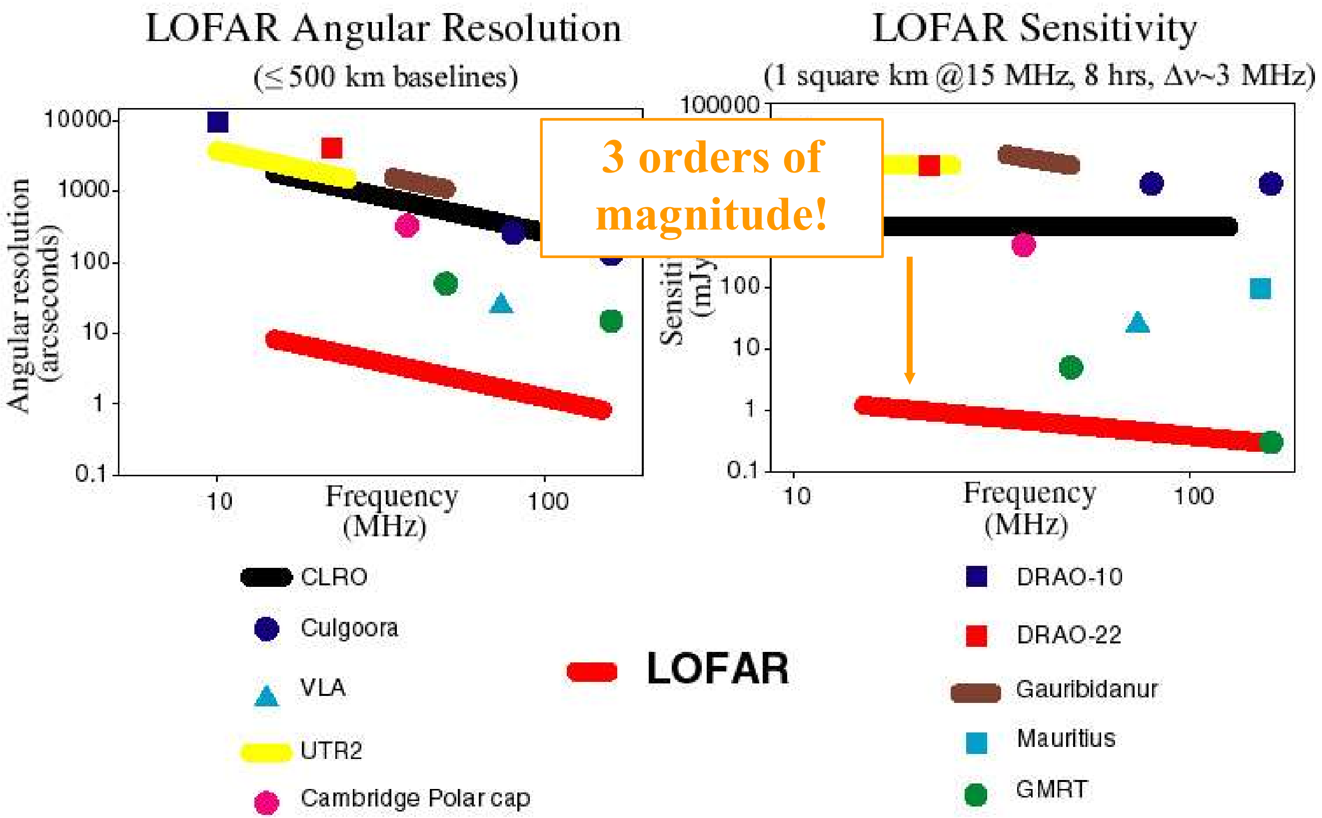
- interferometer for the frequency range of 10 - 200 MHz
- array of 100 stations of 100 dipole antennas
- baselines of 10m to 400 km
- baselines up to 100 km are funded with 52 M€ by Dutch cabinet
- core near Dwingeloo (Borger Odoorn/Exloo) and German boarder
- IBM Blue Gene/L supercomputer in Groningen: now
- Antenna roll-out: end 2006
- Ideal science applications:
  - Large surveys of the universe
  - Transients (cosmic and local)



IBM Blue Gene/L "Stella" – the heart of LOFAR

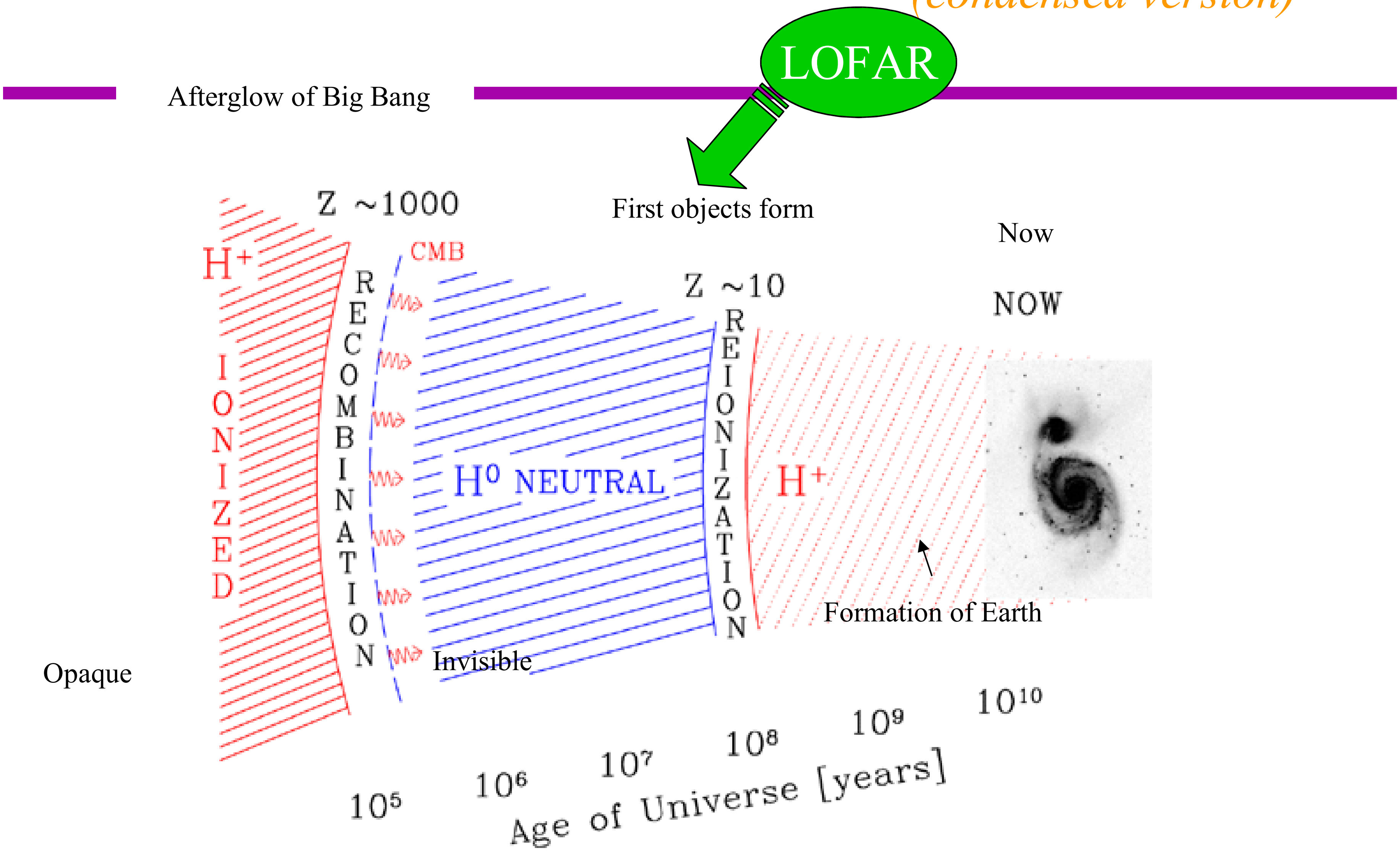
- 27,4 Tflop
- equivalent to 12000 PCs
- Occupying 6 m^2
- 150 KW power consuption
- 0,8 Tbit/s streaming data
- operational since 04/2005

LOFAR Performance



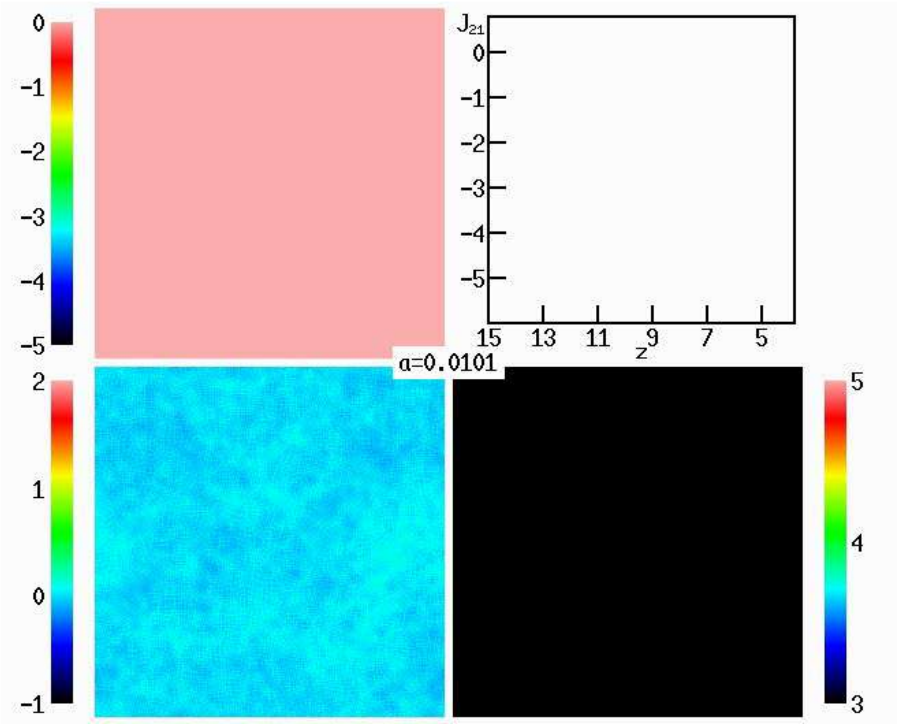
History of the Universe

(condensed version)



Re-Ionization of the Universe

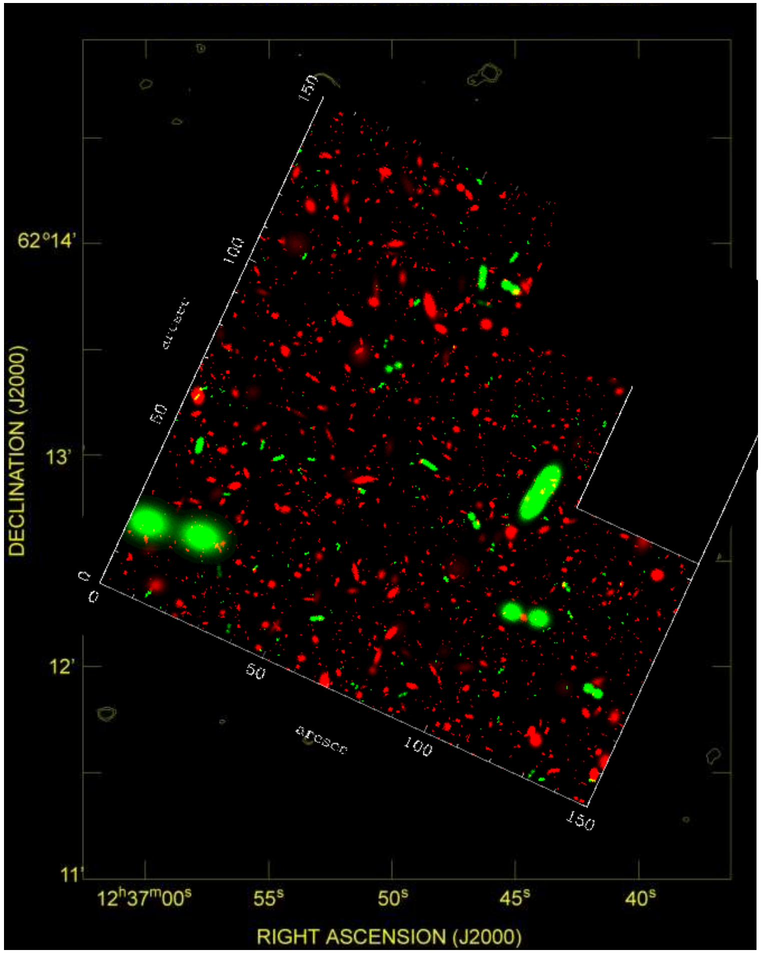
- A main science goal of LOFAR is to map the epoch of re-ionization!
- After the big bang and recombination of elements the universe was neutral!
- Stars and quasars must have started to re-ionize the universe.
- We expect clumpy neutral hydrogen emission from primordial matter at z~6-10.
- 21cm line shifted to 200 MHz.



Gnedin (1999)

Deep fields

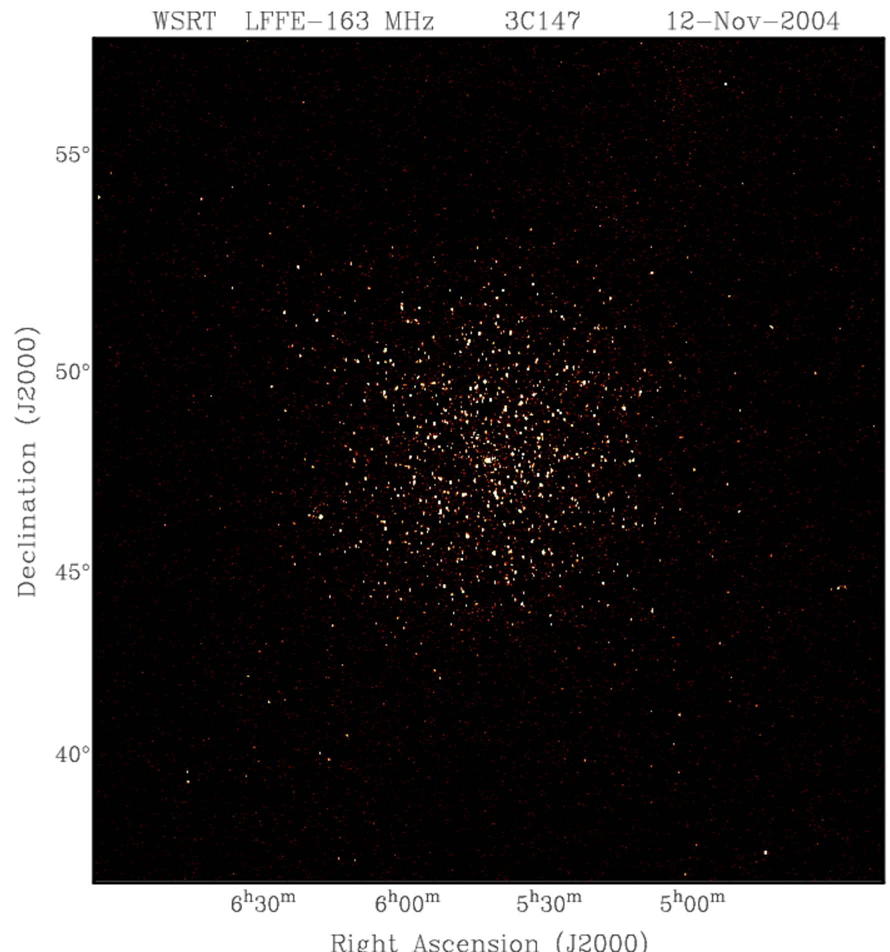
- Black holes and galaxies are strong radio sources. Next generation radio telescopes (LOFAR & SKA) will be the premier way to find them.
- LOFAR will find many new galaxies and black holes.
- We expect to find about $\sim 10^8$ new sources.
- This gives the largest unbiased survey of the universe.



Simulated radio deep field.

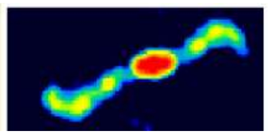
Tests with new digital low-frequency receivers installed at Westerbork

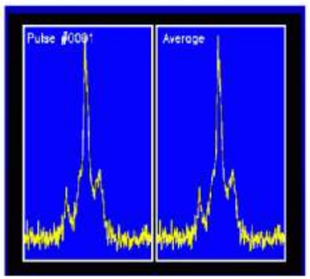
3C147 with Westerbork
Frequency: 163 MHz
Field of View: 20° x 20°
Integration: 12 hrs

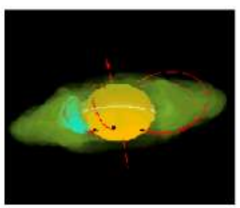


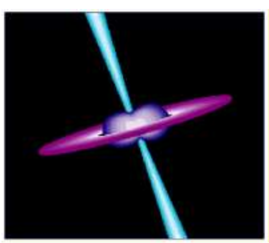
de Bruyn & Brentjens (2005)

Transient Sources







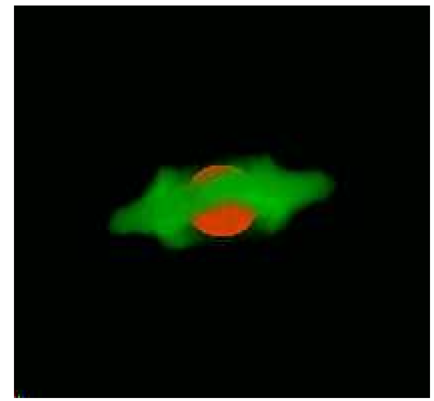


- X-ray Binaries (stellar mass black holes)
- AGN (supermassive black holes)
- Pulsars (neutron stars)
- CV's/Flare Stars
- LIGO Events (merging neutron stars)
- Supernovae
- Jupiter-like Planets
- Gamma-Ray Bursts (prompt emission and afterglows)
- Cosmic Rays & Neutrinos
- Meterorites
- … New sources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

For the first time we will have an (almost) all-sky monitor of the radio sky!

LOFAR Studies of the Solar System: Planets and Planet Search

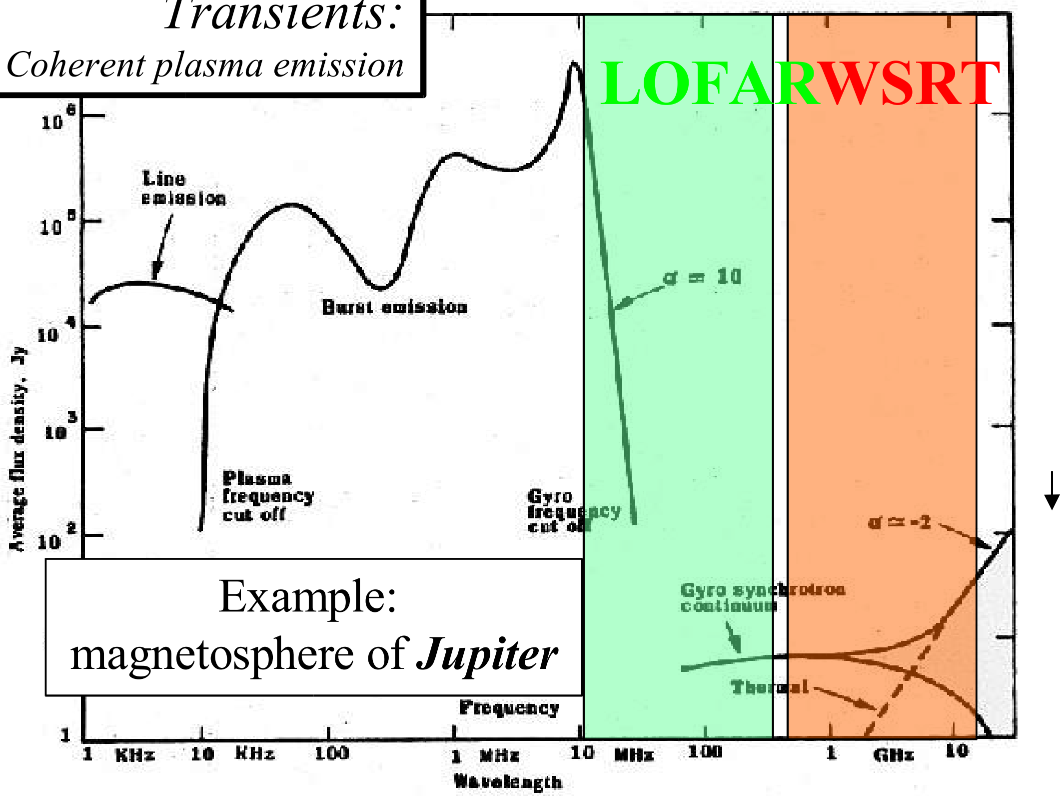
1.4 GHz radio emission of Jupiter



polarized emission

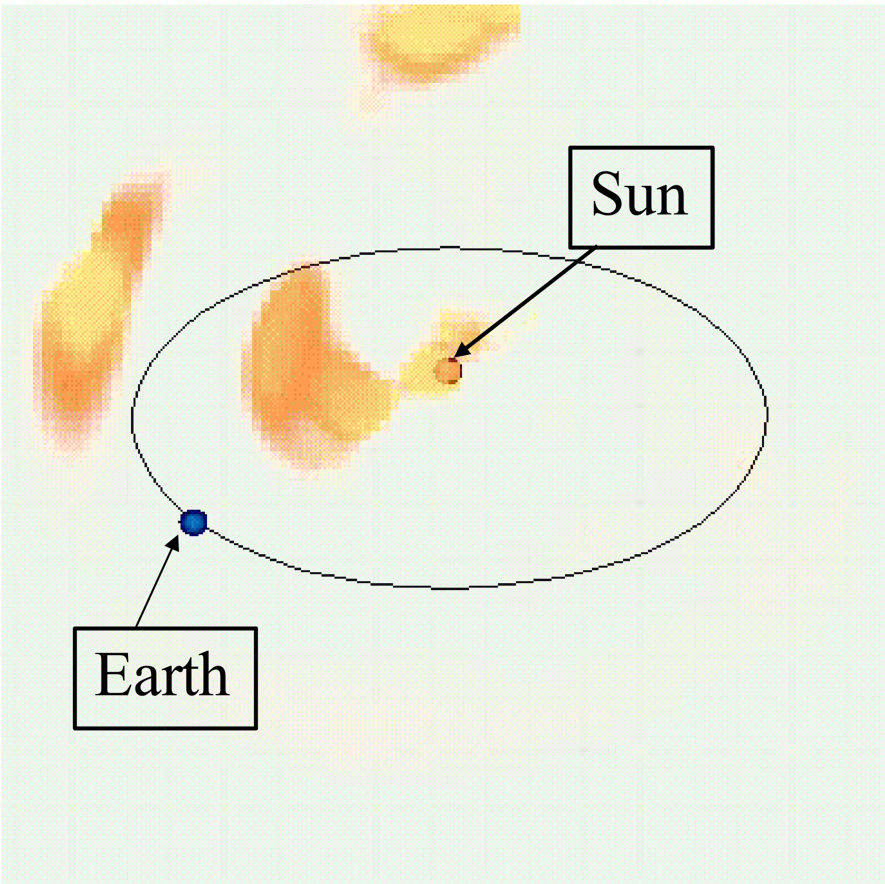
Sault (ATNF)

Transients:
Coherent plasma emission

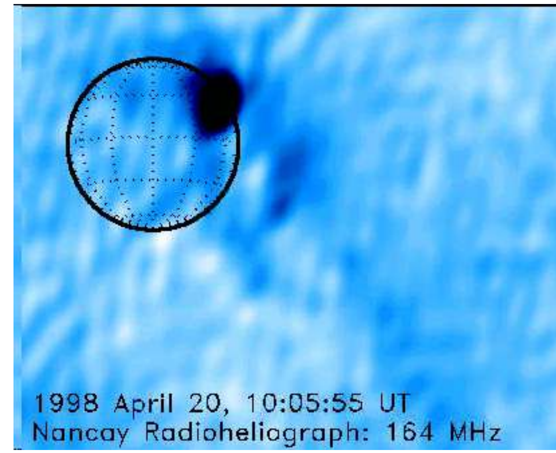


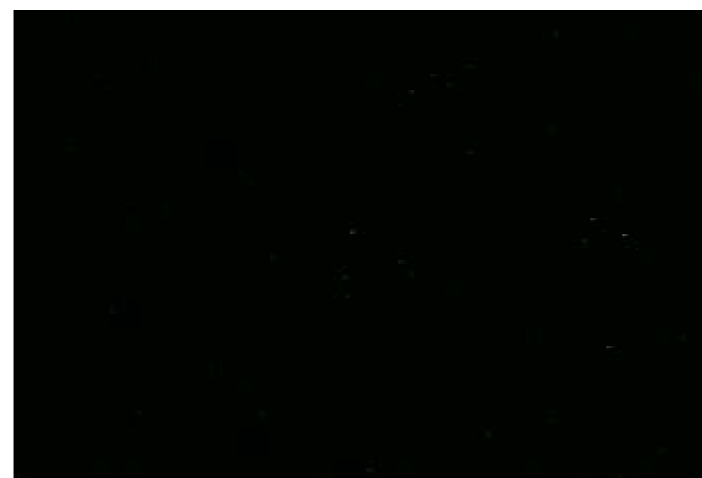
Example:
magnetosphere of ***Jupiter***

LOFAR Studies of the Solar System: Space Weather



Solar Wind
observed via Radio Source Scintillation

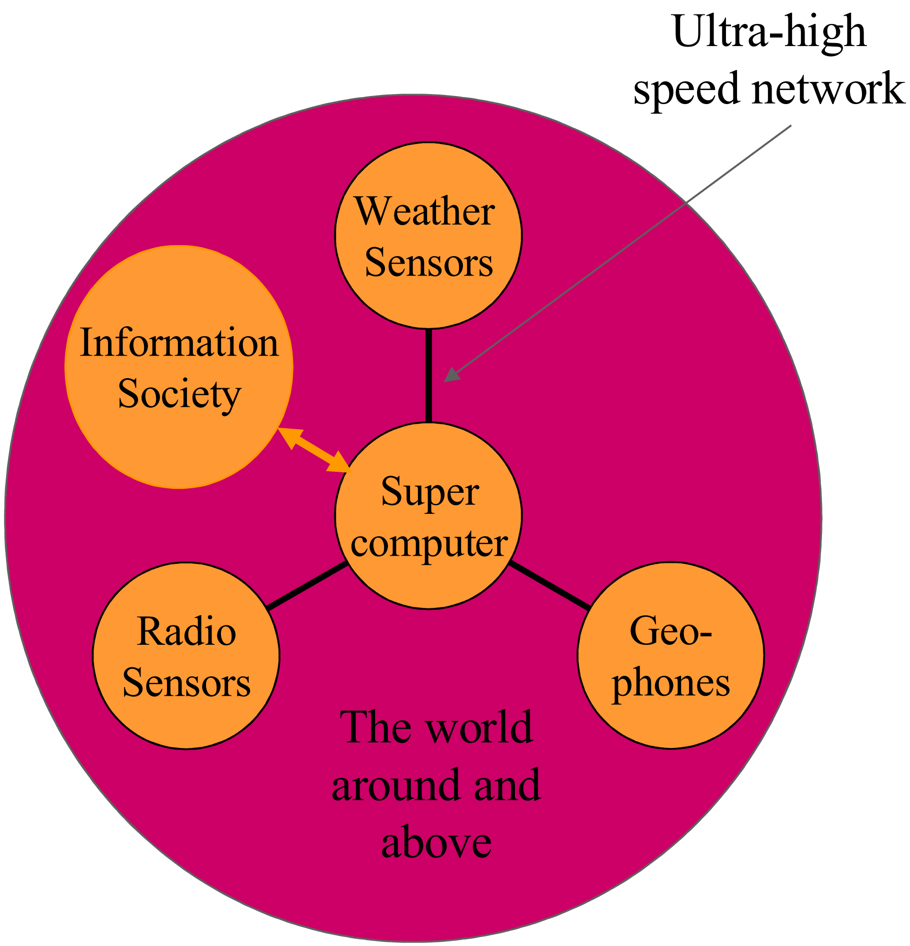




Animation

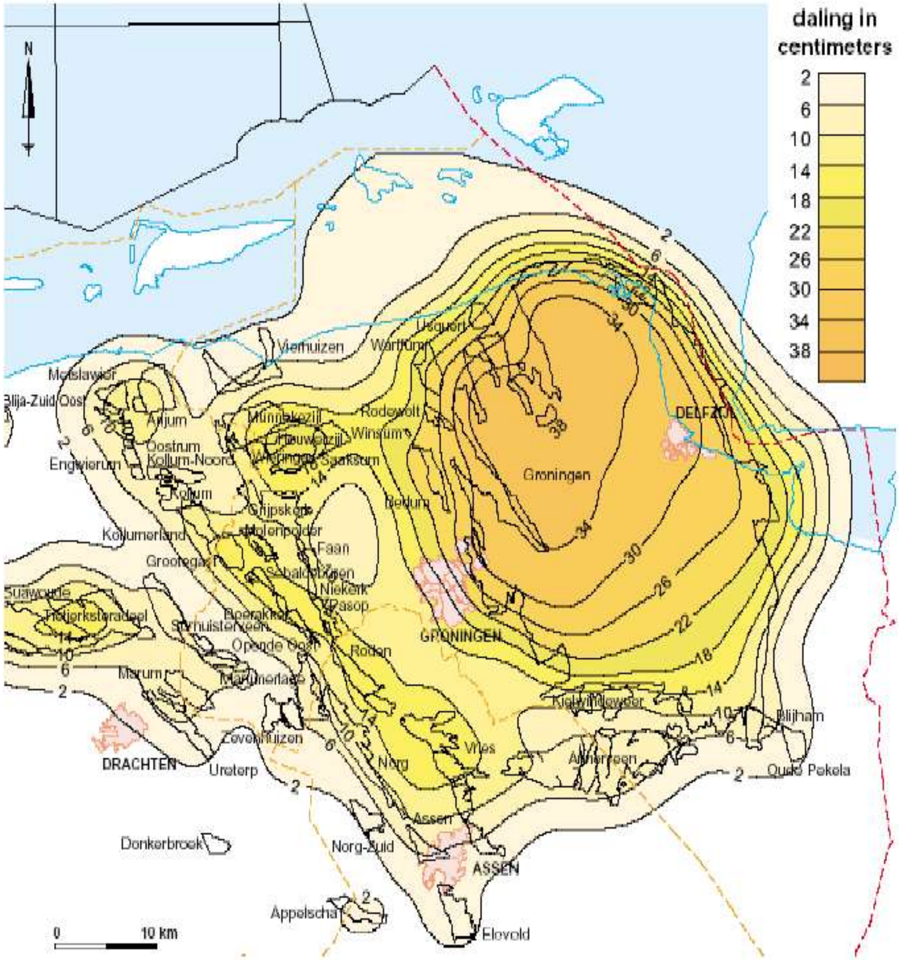
LOFAR as a Wide Area Sensor Network

- LOFAR is a sensor network.
- The Earth breathes, changes, and lives
- The changing world around and above us provides an enormous amount of information that
  - can be measured through a distributed network of sensors, providing a continuous data stream
  - needs to be channeled to central data bases and monitoring and control units
  - needs to be processed for our information society to understand, predict, and shape our environment.
- This has demands beyond traditional high-bandwidth networks

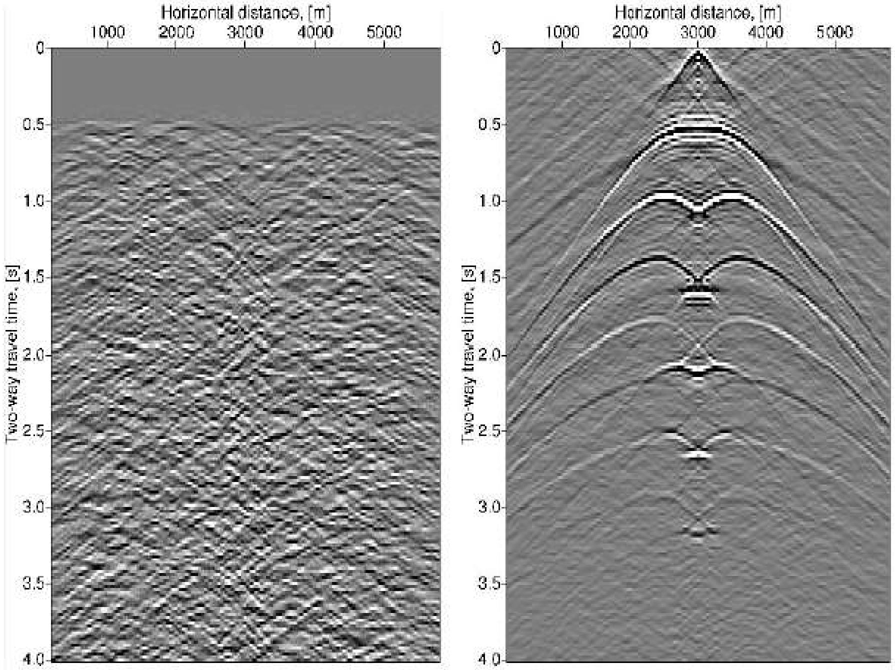


LOFAR Network with Geophones

- LOFAR is a Wide-Area-Sensor Network and can work with different sensors.
- Geophones can be added as additional sensors.
- Micro-Earthquakes can be used to “image” the Earth
- Can be used to monitor ground water level or subsidence due to oil and gas drilling.



LOFAR Network with Geophones



(b) (c)

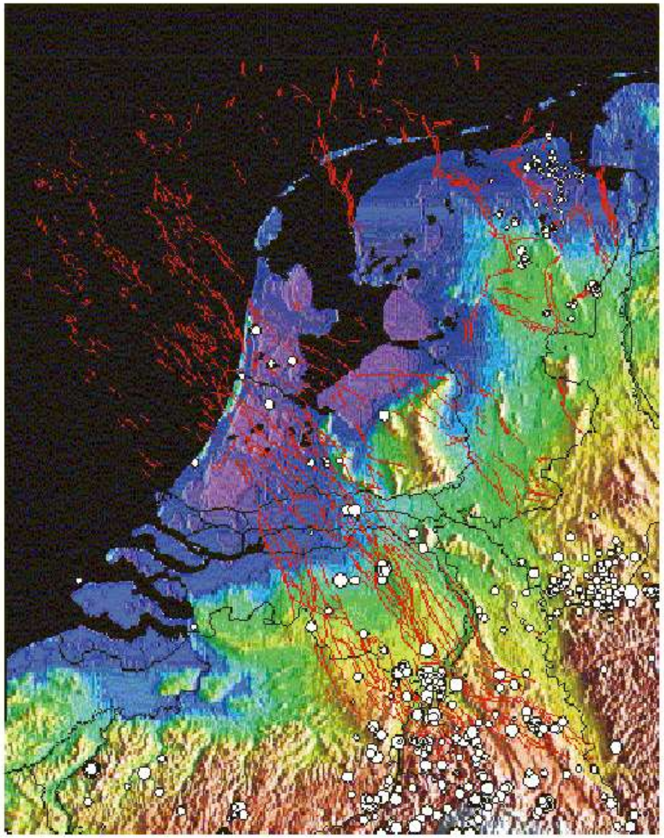
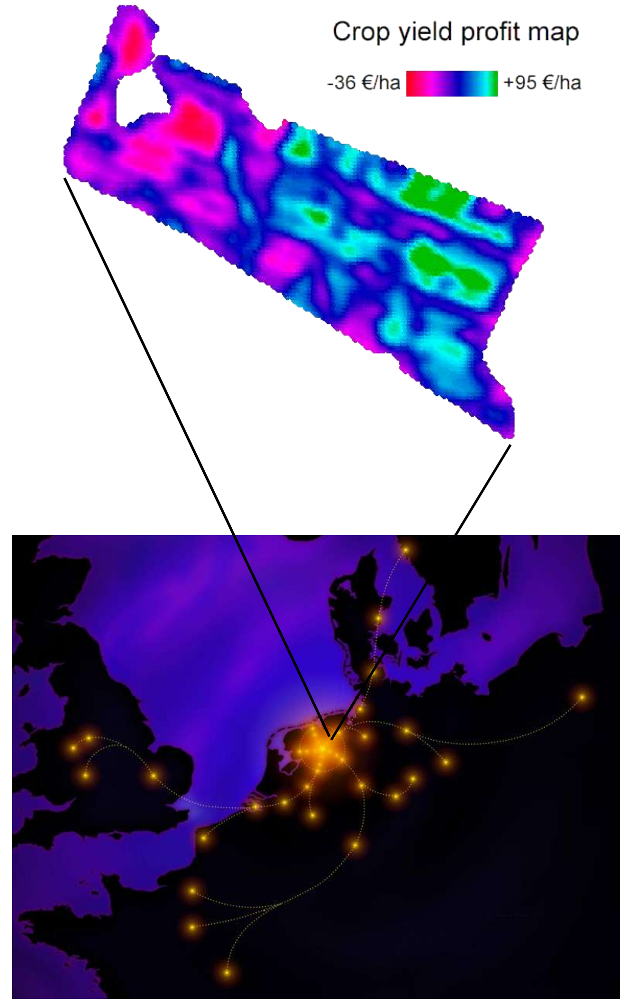
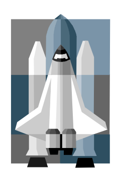


Figure 3.2 Geologic Netherlands. White circles are earthquake epi-centres.

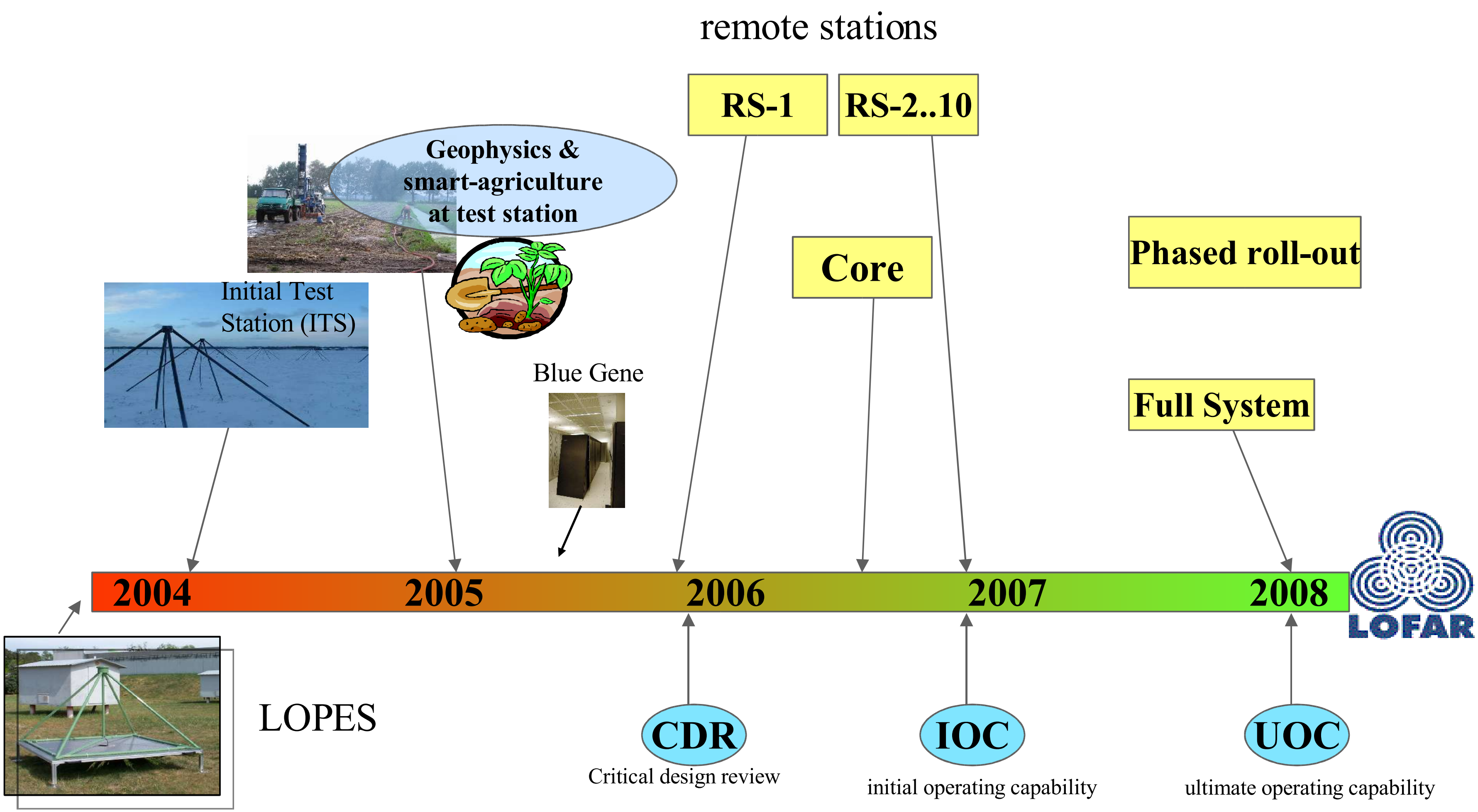
Precision Agriculture Weather Monitoring & GMES

- Distributed Sensor networks can be used in a variety of disciplines
- For a site near Dwingeloo agriculture is an obvious issue.
- Crop yields depend quite sensitively on many parameters (water, temperature, soil, etc.) which can fluctuate strongly in time and location.
- Weather sensors can be used to investigate small-scale weather patterns
- Distributed sensor network can complement satellite data (i.e., within ESA's GMES program).





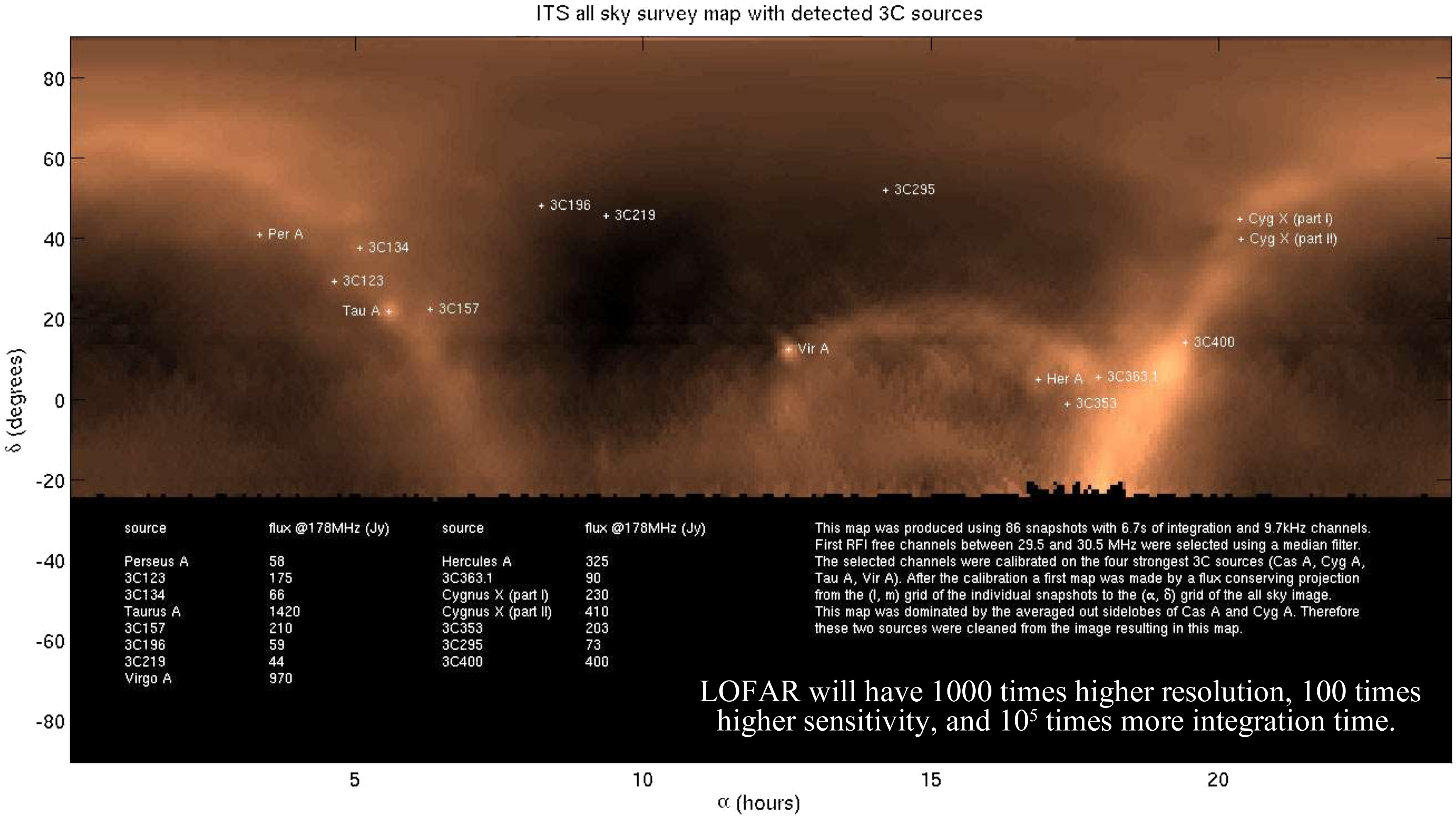
Development Plan



Current Prototyping Activities: ITS

- Initital Test Station for engineering purposes
  - 60 Antennas
  - Cluster of 15 PCs
  - 80 MHz ADC per channel, 1 GB RAM
  - 10-30 MHz
  - All-sky viewing, access to full bandwidth and time information
  - Max 6.7 seconds per observation (60 GB) data set
  - Triggered observations are possible (3 seconds look-back capability)

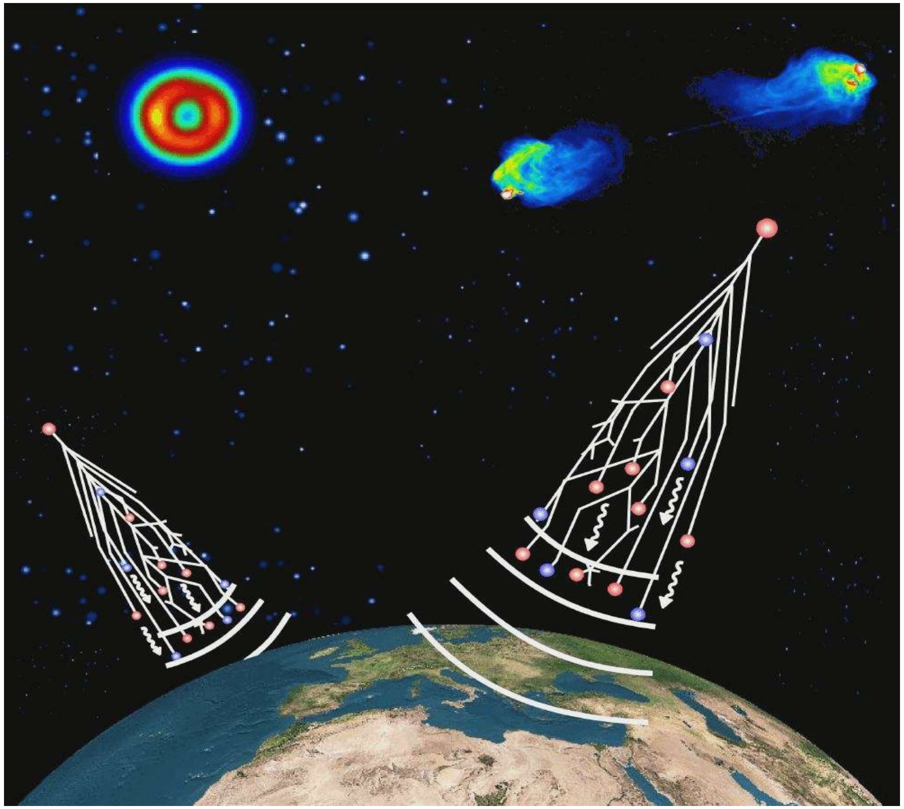
LOFAR-ITS: 500 Second All-Sky Map



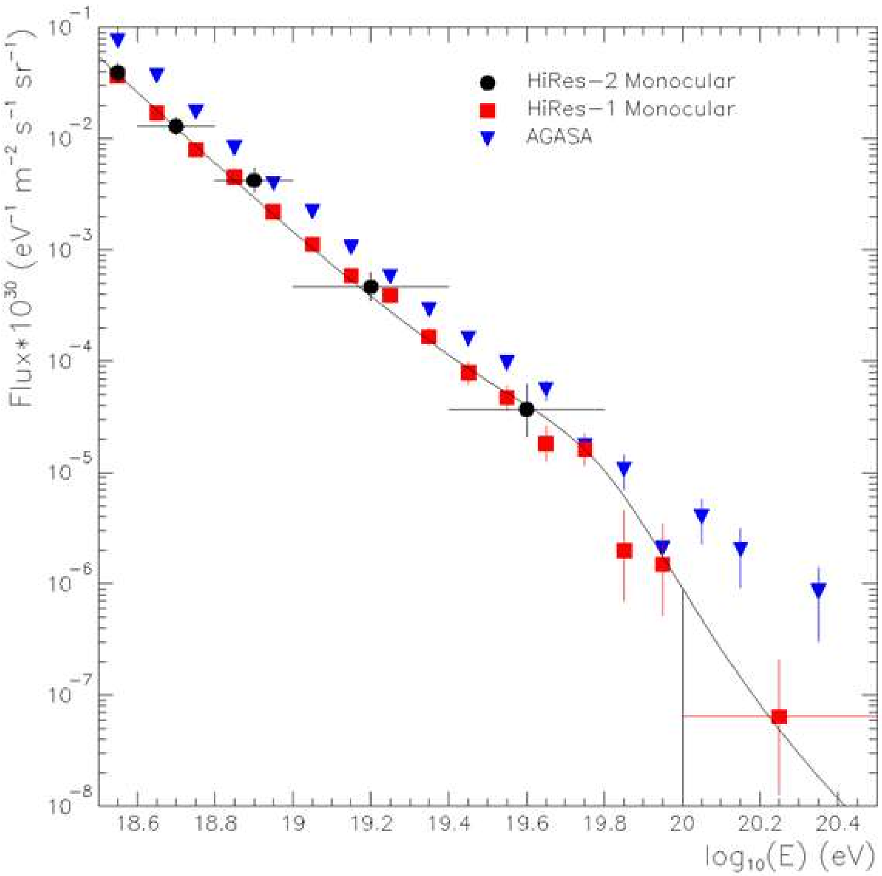
LOFAR will have 1000 times higher resolution, 100 times higher sensitivity, and 10^5 times more integration time.

Astroparticle Physics with LOFAR

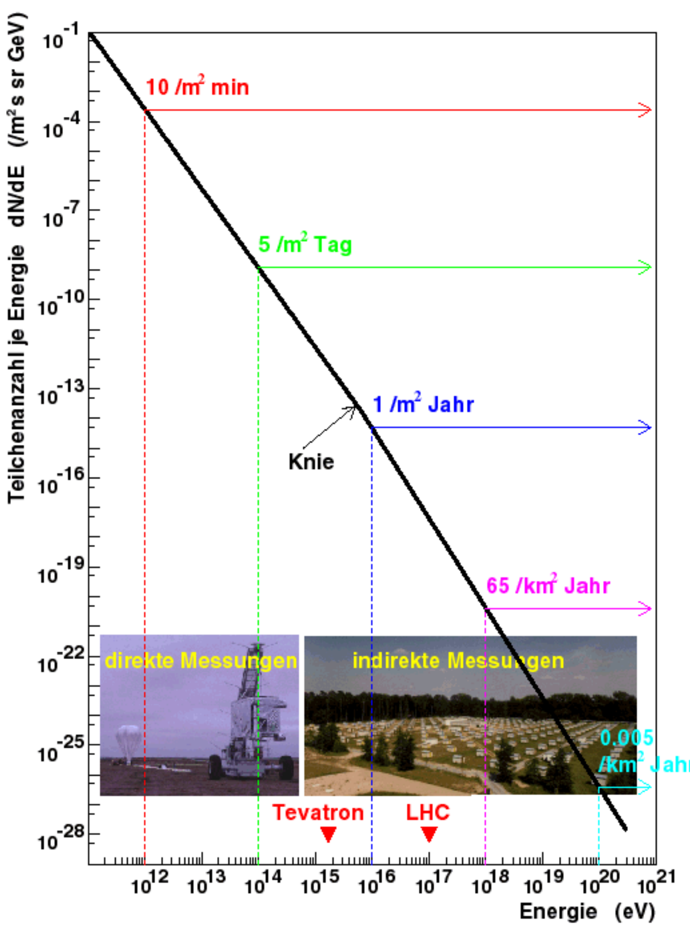
- Cosmic Ray Air Showers produce radio pulses as electrons rush through the geomagnetic field.
- LOFAR will detect these pulses (“for free”) and become an interesting CR array in the energy range around 10^{18} eV.
- Test this with LOPES
- Interesting extensions also for AUGER.



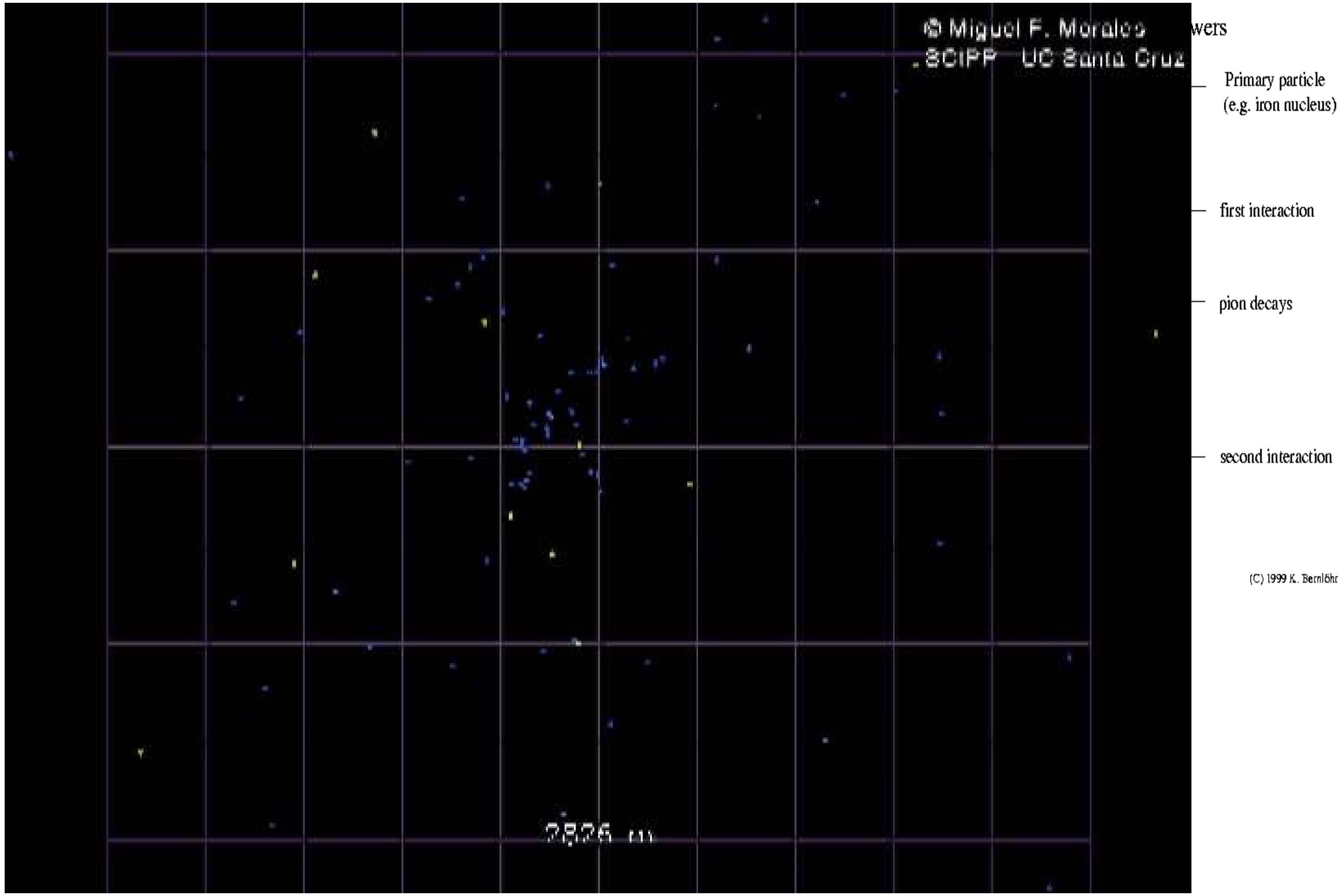
Cosmic Ray Energy Spectrum



Energiespektrum der kosmischen Strahlung



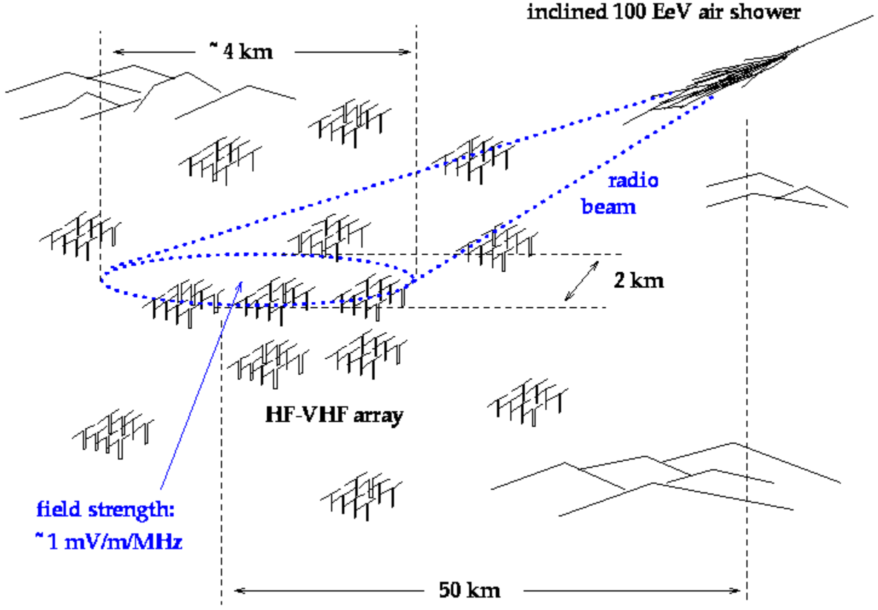
A (very) Brief History of Cosmic Rays



- 1960's: Cosmic rays with energies of $>10^{19}$ eV detected - how are they made??
- Greisen, Zatsepin, Kuzmin (GZK): there should be a limit at $\sim 5 \times 10^{19}$ eV

Radio Emission from Ultrahigh-Energy Cosmic Particles

- Advantages:
  - Cheap detectors, easy to deploy
  - High duty cycle (24 hours/day)
  - Low attenuation (can see also distant and inclined showers)
  - Bolometric measurement (integral over shower evolution)
  - Very interesting for neutrinos
- History:
  - 1960ies prediction of Cherenkov-like radio emission (Ashkaryan)
  - 1960ies/70ies experimental verification of CR/radio link (Jelley et al. 1965, Allan 1971) – but effect not really understood.
  - Analog radio technique too cumbersome
  - SLAC verification of radio emission from showers in sand (Saltzberg et al. 1999)
  - Proposal of geosynchrotron mechanism and use of LOFAR (Falcke & Gorham 2003)
  - Monte Carlo code (Huege & Falcke 2004)
  - LOPES …



LOFAR Prototype Station (LOPES): FZ Karlsruhe / KASCADE-Grande

Max-Planck-Institut für Radioastronomie

EHEF K.U. NIJMEGEN

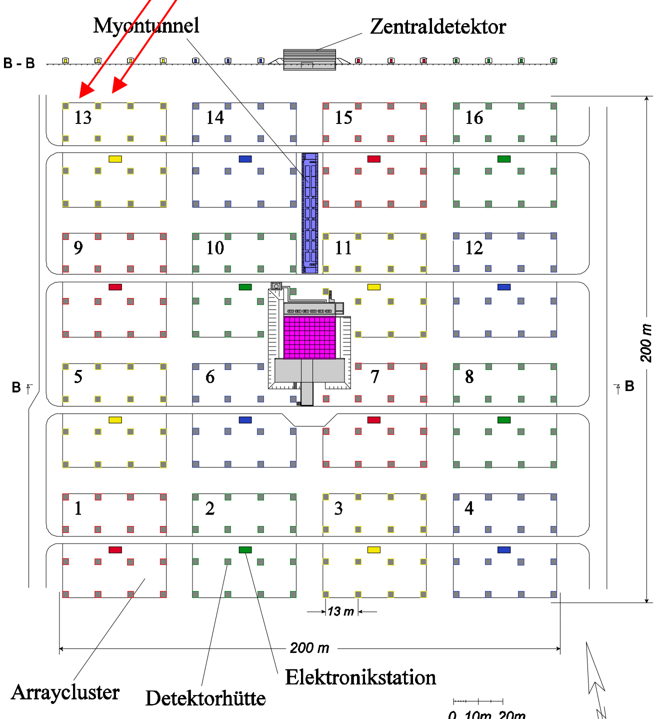
UNIVERSITÄT KARLSRUHE (TH)

bmb+f - Förderschwerpunkt
Astro-Teilchenphysik
Großgeräte der physikalischen Grundlagenforschung

ASTRON

...

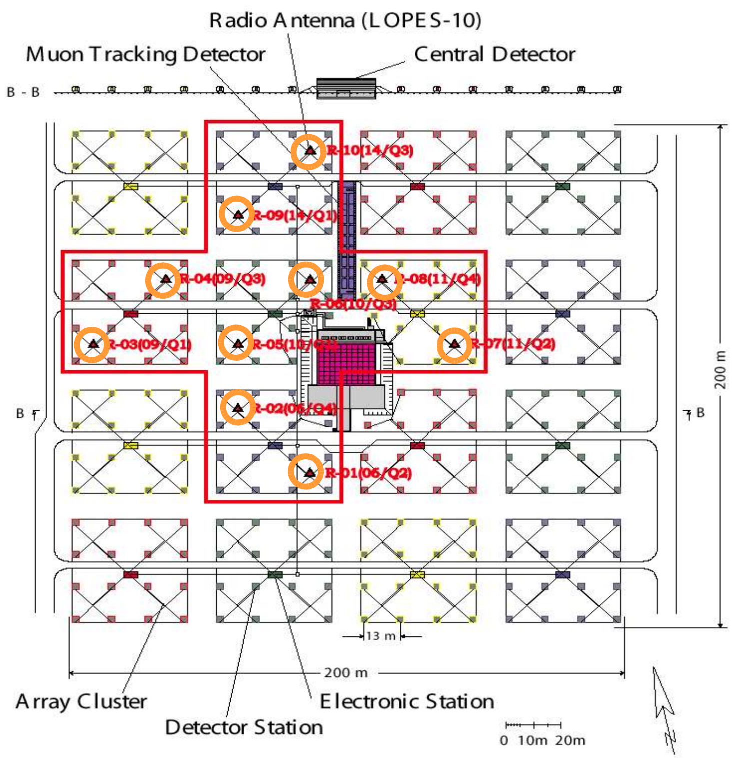
KASCADE

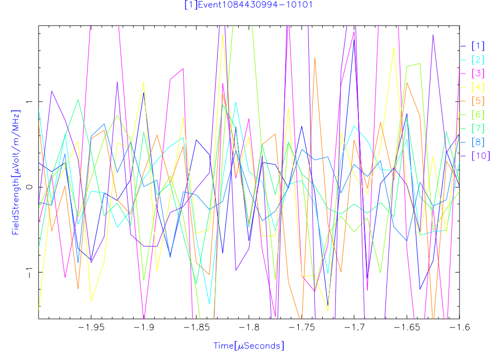


KASCADE Grande

LOFAR Prototyping: LOPES

10 Antennas · 45-75 MHz · 0.8ms radio data snippets · triggered by KASCADE · project began 2002 · in operation since Jan. 2004



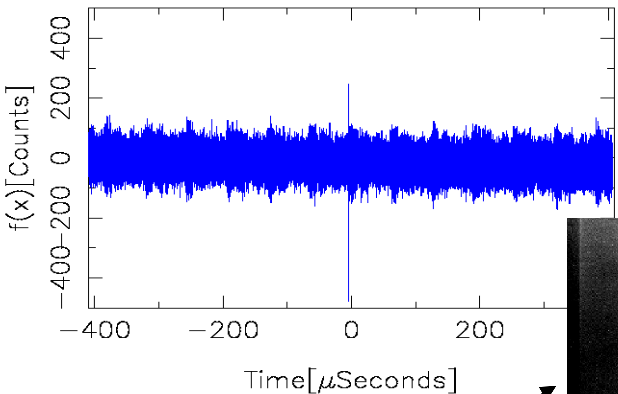


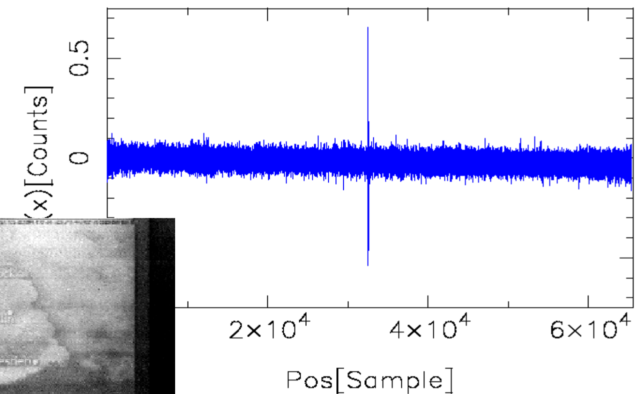
Digital Filtering

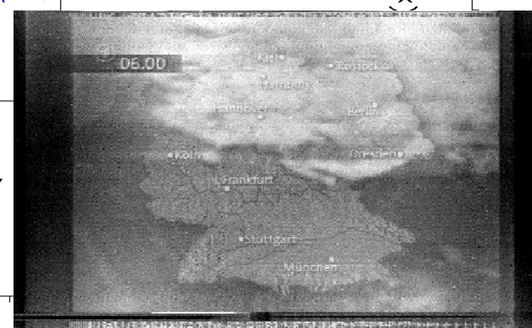
raw data

filtered data

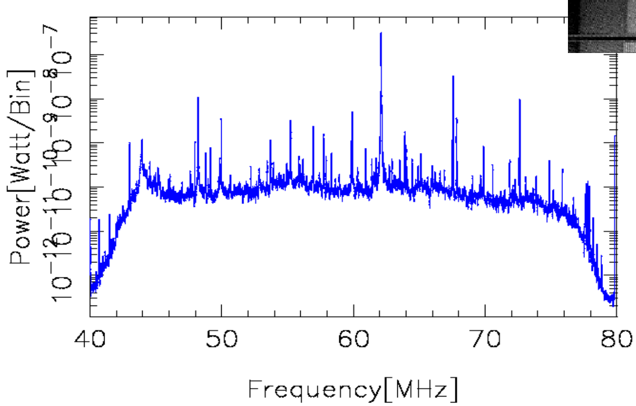
time domain

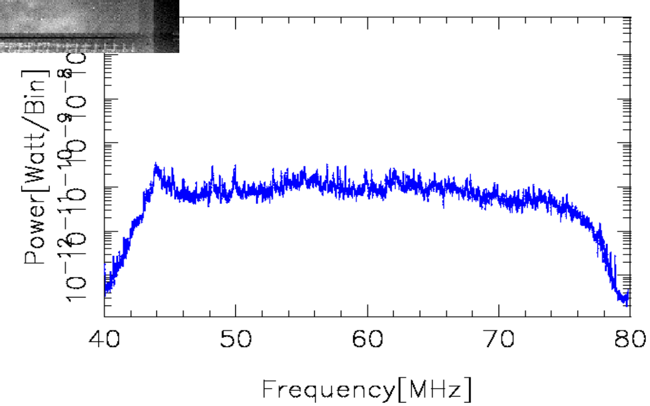






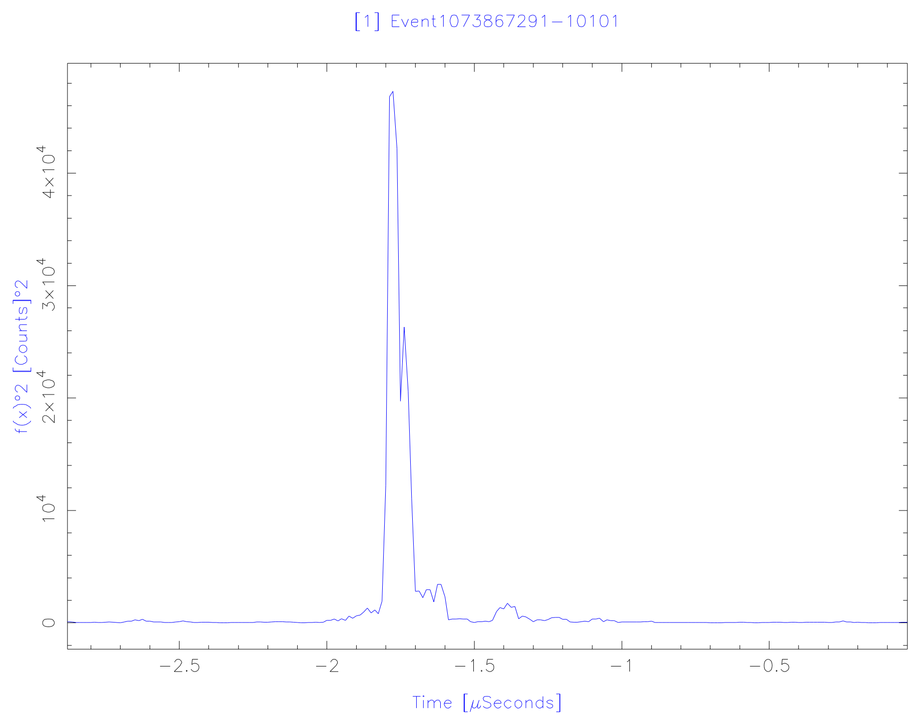
frequency domain



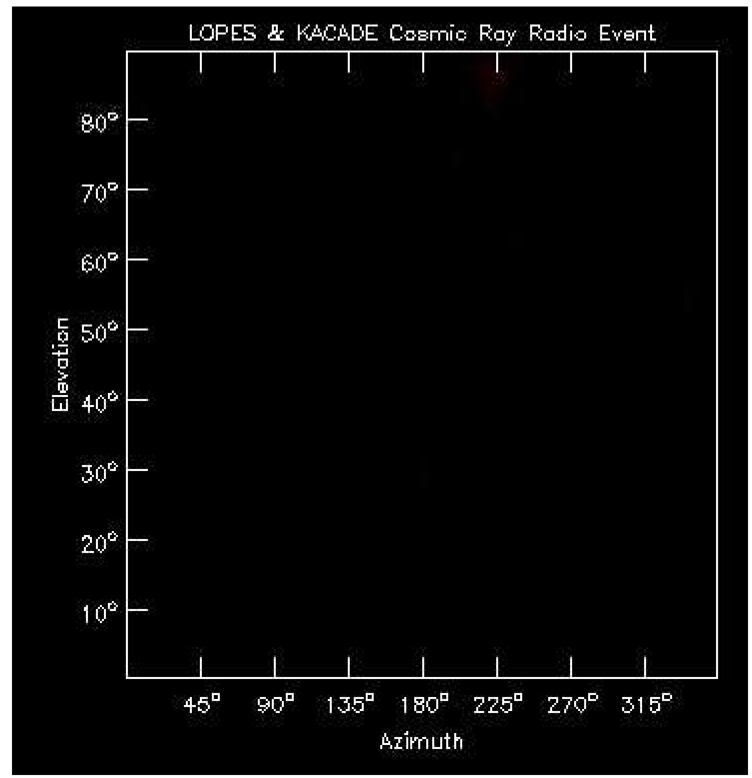


Jan 18, 2004: The first event!

Signal to noise >100
Width: 45 ns (~$1/\Delta\nu$)



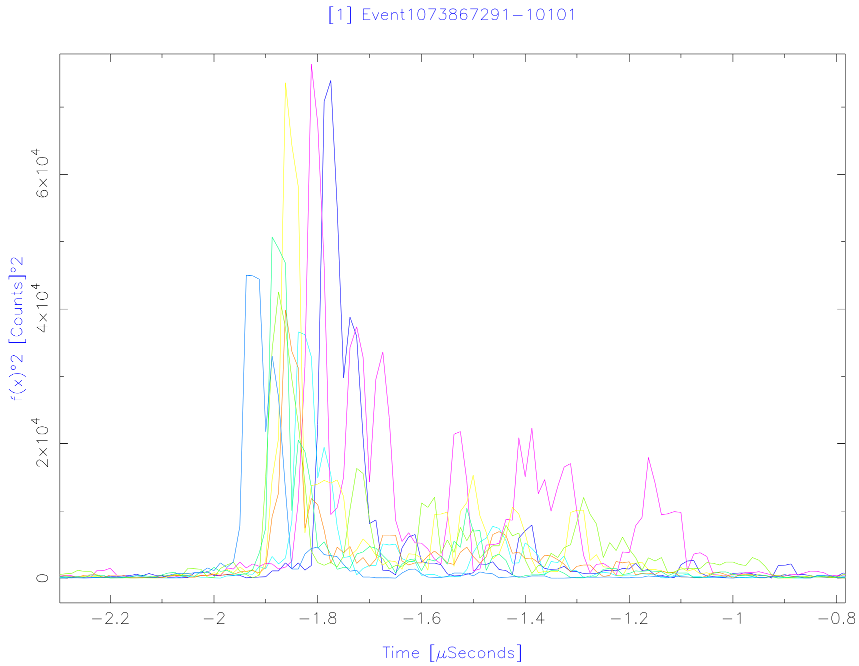
Radio flash coincides within 0.5°
with KASCADE position



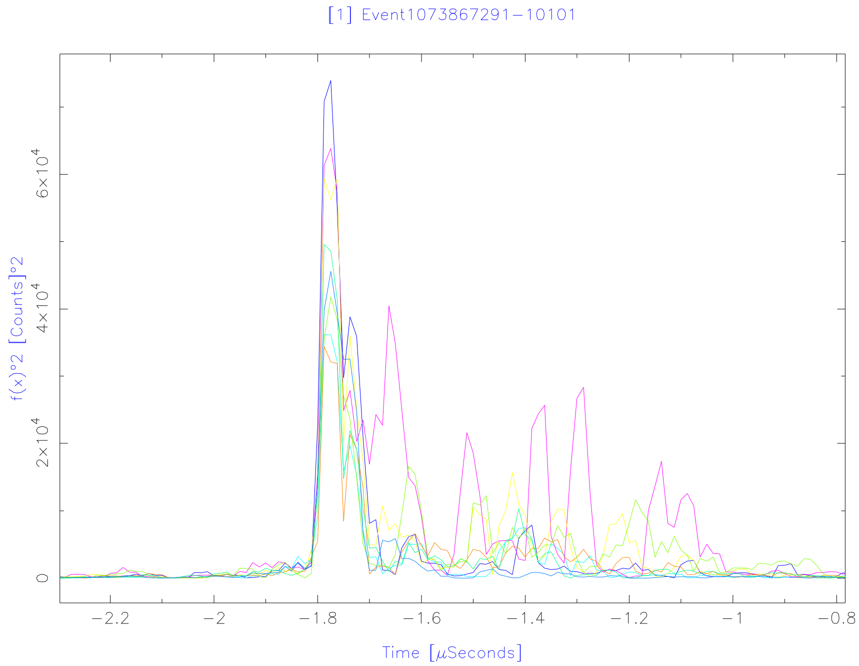
Falcke et al. (LOPES collaboration) 2005, Nature, in press (the usual press embargo …
For details see workshop at DESY-Zeuthen this month

Pulse Detections

power (E-Field squared)
at different antennas

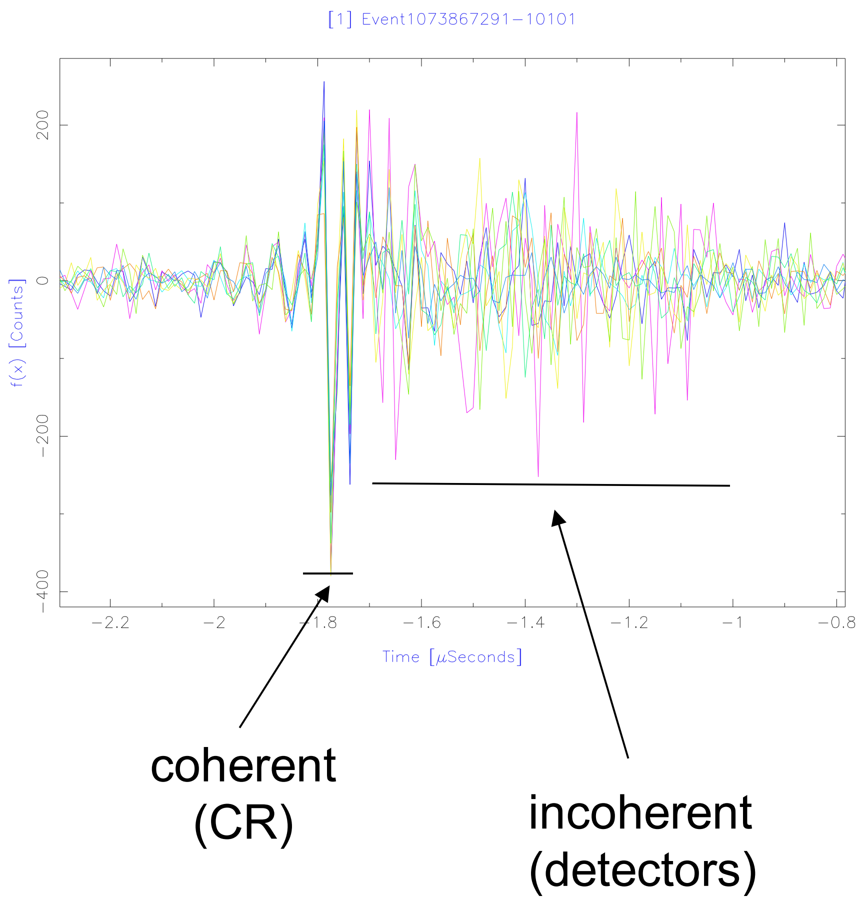


time delay corrected for
arrival direction of CR
(from KASCADE)

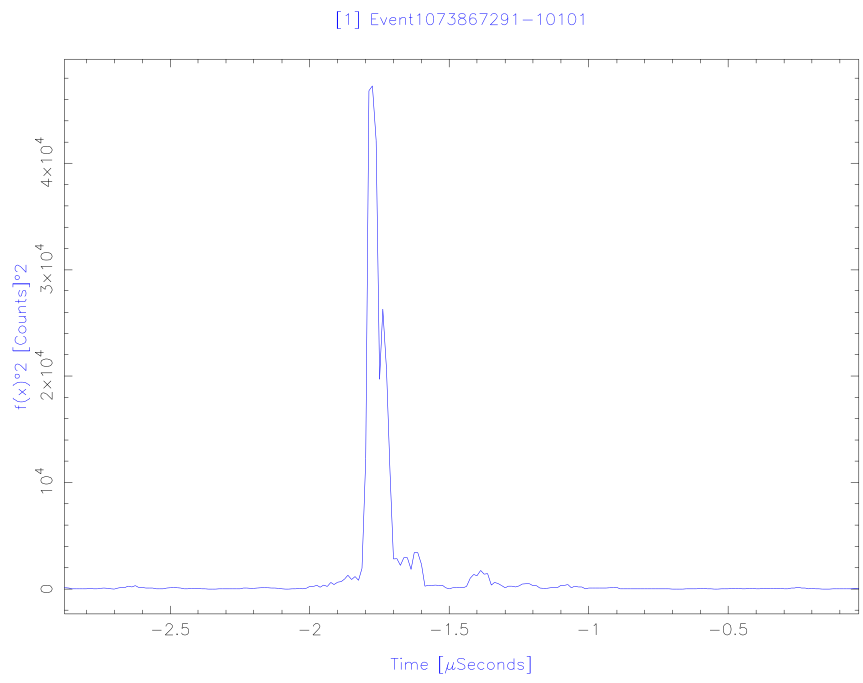


Pulse Detection
Emission is coherent

Electric field at each antenna corrected for arrival direction of CR



Sum of delay-corrected E-field from all antennas, squared

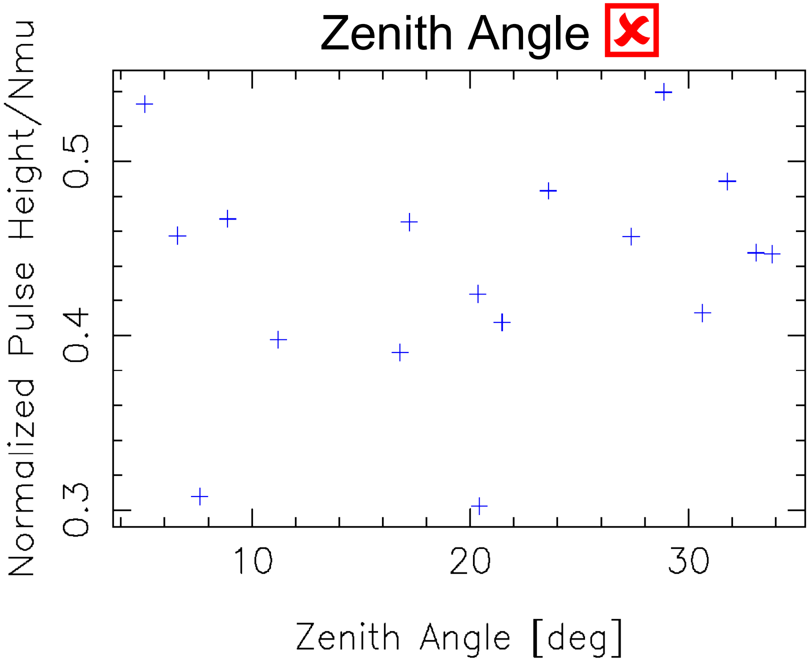


Some statistical results
Geomagnetic vs Zenith Angle!

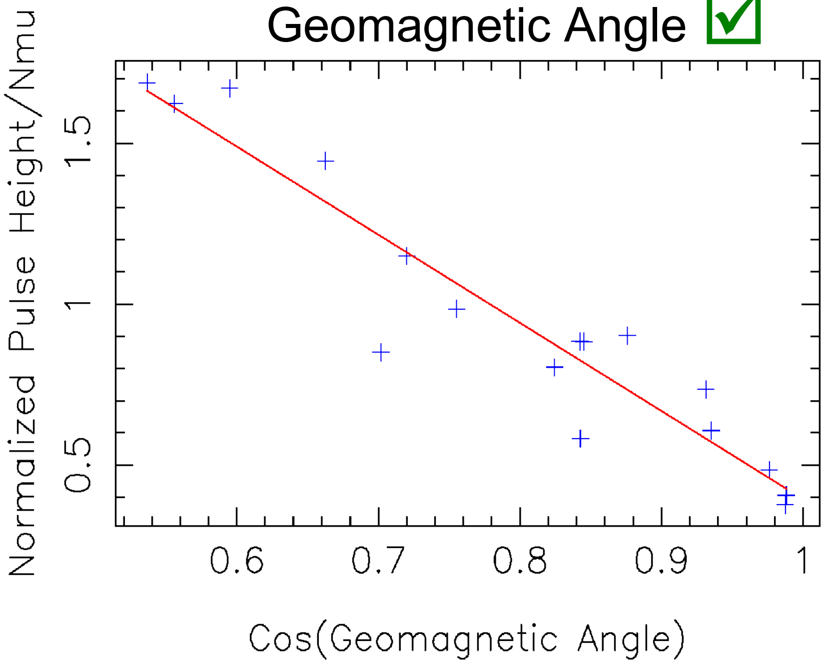
Detected events: >100 events

Select only events with muon number $>4\times10^5$ (to have sure radio detections) and R<70 m (to avoid fiddling with radius effects) → 17 events

Zenith Angle ✗



Geomagnetic Angle ✓



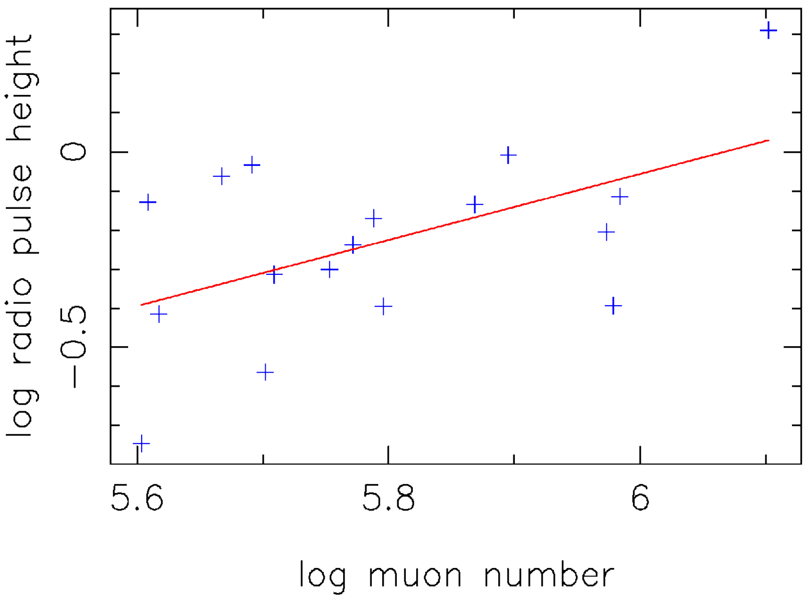
⇒ Dependence on angle to Earth magnetic field is strongest effect!

Some statistical results
Scaling with Muon Number

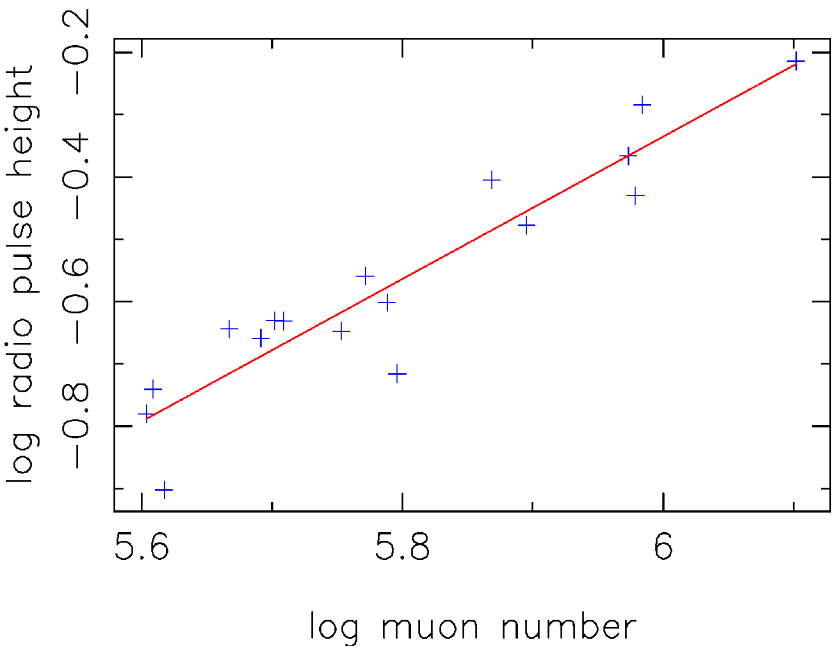
radio vs. muon number:

The muon number scales fairly linearly with energy

without geomagnetic angle correction



with geomagnetic angle correction



The electric field scales linearly with muon number, i.e. the radio power scales quadratically with muon number and energy ⇒ radio signal is coherent emission

LOPES Conclusions and Outlook

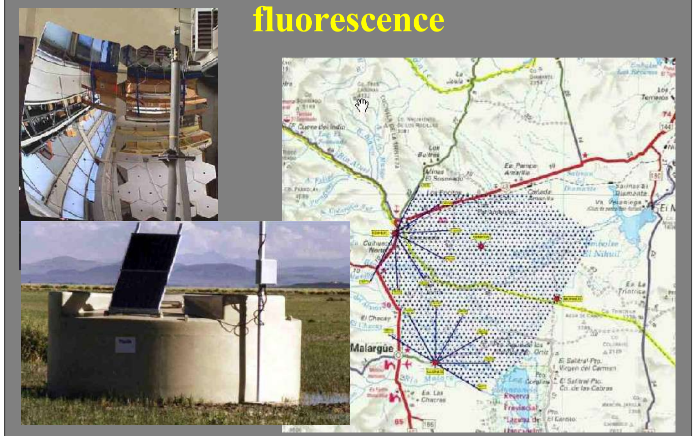
- Radio flashes of cosmic rays are:
  - real
  - coherent emission
  - correlated with geomagnetic field
  - scale with energy and muons (less so with electrons in shower)
  - well-detected for inclined showers

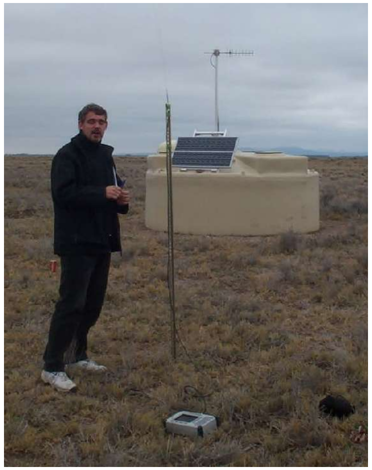
⇒ LOPES has essentially confirmed the geosynchrotron effect.

⇒ LOFAR will be an ideal instrument to measure ultra-short radio pulses from Cosmic rays, neutrinos, thunderstorms, etc...

⇒ Further expansion of this technique at KASCADE (LOPES30) and later with the AUGER array in Argentina.

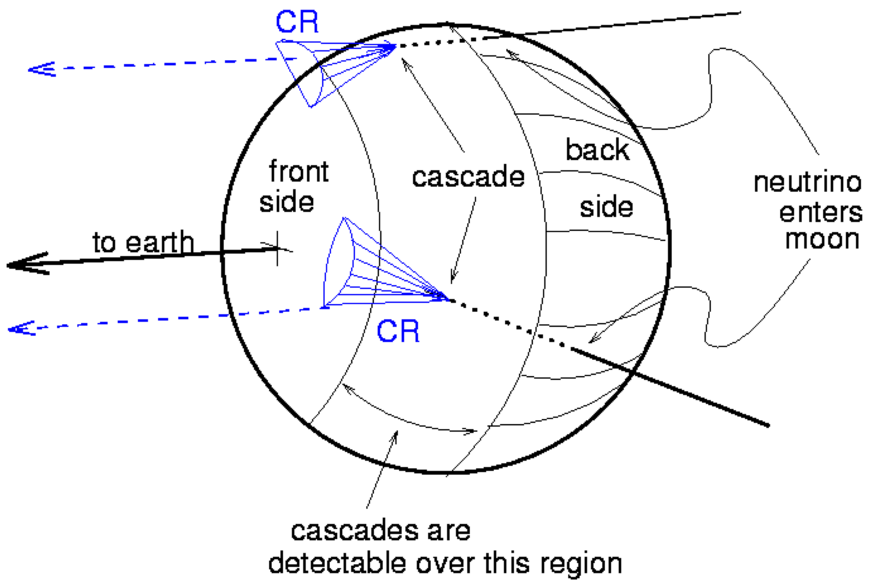
AUGER: 3000 km^2,1600 water tanks & fluorescence



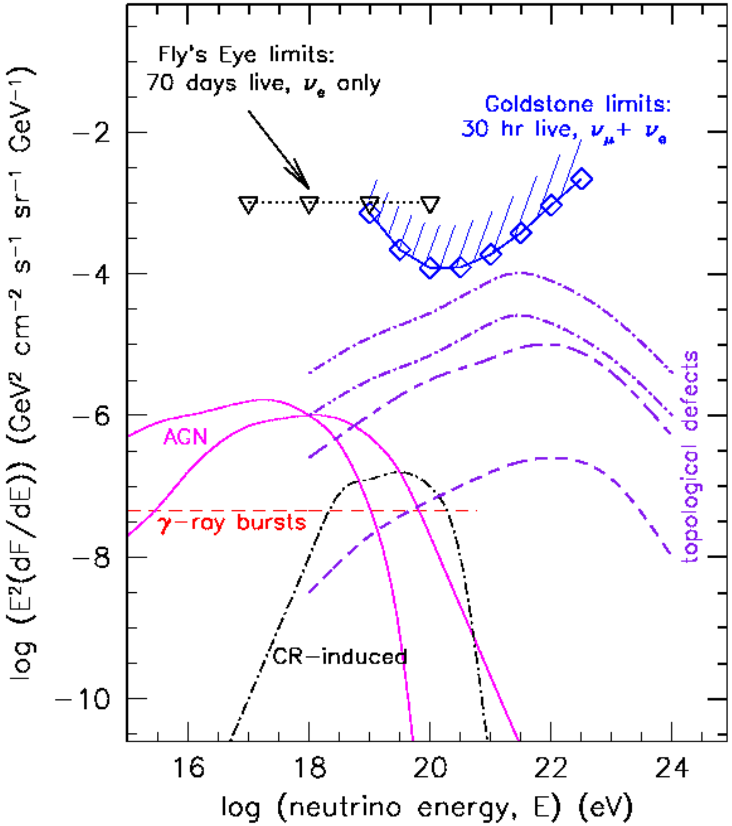


Radio background measurements at AUGER in the Pampa …

Lunar Regolith Interactions & RF Cherenkov radiation



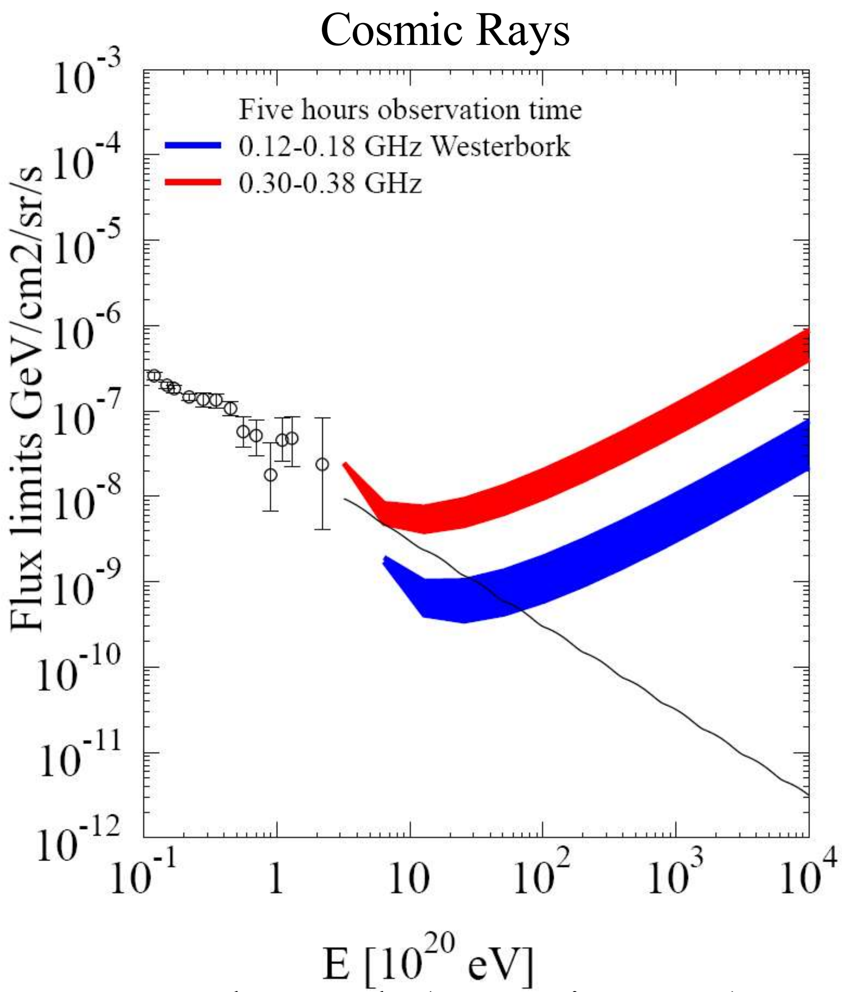
neutrino limits



Gorham et al. (2000)

Low-Frequency Observations of the Moon

- Lunar radio emission is also produced by Cosmic Ray showers impacting on the moon (Zas, Alvarez-Muniz)
- Low Frequencies have longer attenuation lengths and sample larger volume.
- Lunar observations may give best limit on super GZK Cosmic Rays!



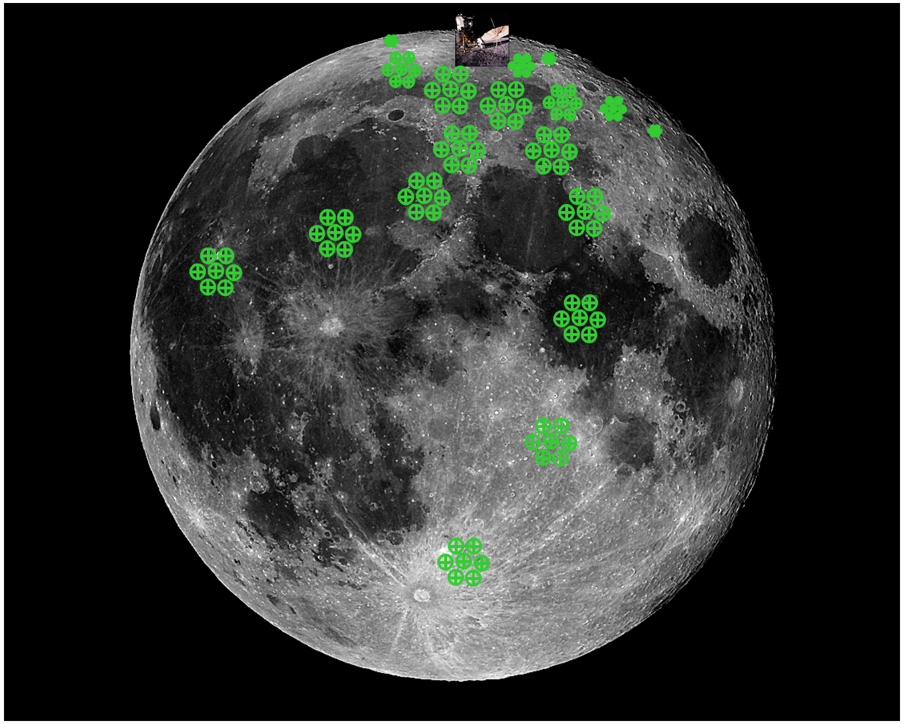
Bacelar et al. (2005, in prep.)

LIFE* on Moon

*Lunar Infrastructure for Exploration
(A proposal for a future European Space Exploration Venture)

Hartmut Müller, EADS ST, Think Tank

The final frontier: LOFAR on the moon



- Very low frequencies (<10 MHz) can only be observed from the moon because of Earth's ionosphere.
- The backside of the moon will also be free of interference.
- There is virtually no imaging information available – the last unexplored frequency range.

⇒ Collaboration with space company (EADS) to explore a Lunar Infrastructure for Exploration (LIFE).

⇒ A giant 300 m telescope can be deployed with a single Ariane V launch with modified components developed for ISS.

⇒ Other experiments may follow (IR and optical telescope, CR detectors)

⇒ Build up lunar research infrastructure

GLOW-Consortium

- German universities have formed the “German Long Wavelength (GLOW) Consortium”
- A white paper has been written
  - Scientific and technological involvement is foreseen as well as the establishment of a/several science (operation) centers – this will be fully grid-based.
  - Key Science areas have been identified (Surveys, Large Scale Structure, Milky Way, Transients, Astroparticle Physics, Solar Physics)

GLOW-Consortium

- Current and interested partners
  - MPIfR Bonn (Surveys, Astroparticle)*
  - IU Bremen (IT-Science, Gamma-Ray bursts)*
  - AIP Potsdam (Solar Physics)*
  - Univ. Hamburg (Quasars, stars)*
  - Univ. Göttingen (Quasars)*
  - Bochum, Köln, Uni Bonn, Karlsruhe
- Several institutes have already offered land for placing of a German station (see *).
- Discussions with T-Systems about the network.

Draft Layout

LOFAR-Layout_NL_D

Animation ….?

Conclusion

- Radioastronomy had a spectacular history and it has a bright future with ALMA, SKA, LOFAR.
- The new generation of software telescopes will revolutionize low-frequency radio astronomy.
- LOFAR will offer the single largest step forward that will be undertaken at any wavelength in the next decade.
- LOFAR is a truly interdisciplinary instrument. It will be a premier instrument from cosmology to climatology and astroparticle physics. It is a research platform for sensor networks.
- Unique chance for D/NL and European cooperation.
- Next steps: Australia (southern hemisphere), Moon (<10 MHz) …
- LOFAR is extremely flexible: a lot is to be discovered!
- … and LOFAR is just pure fun …