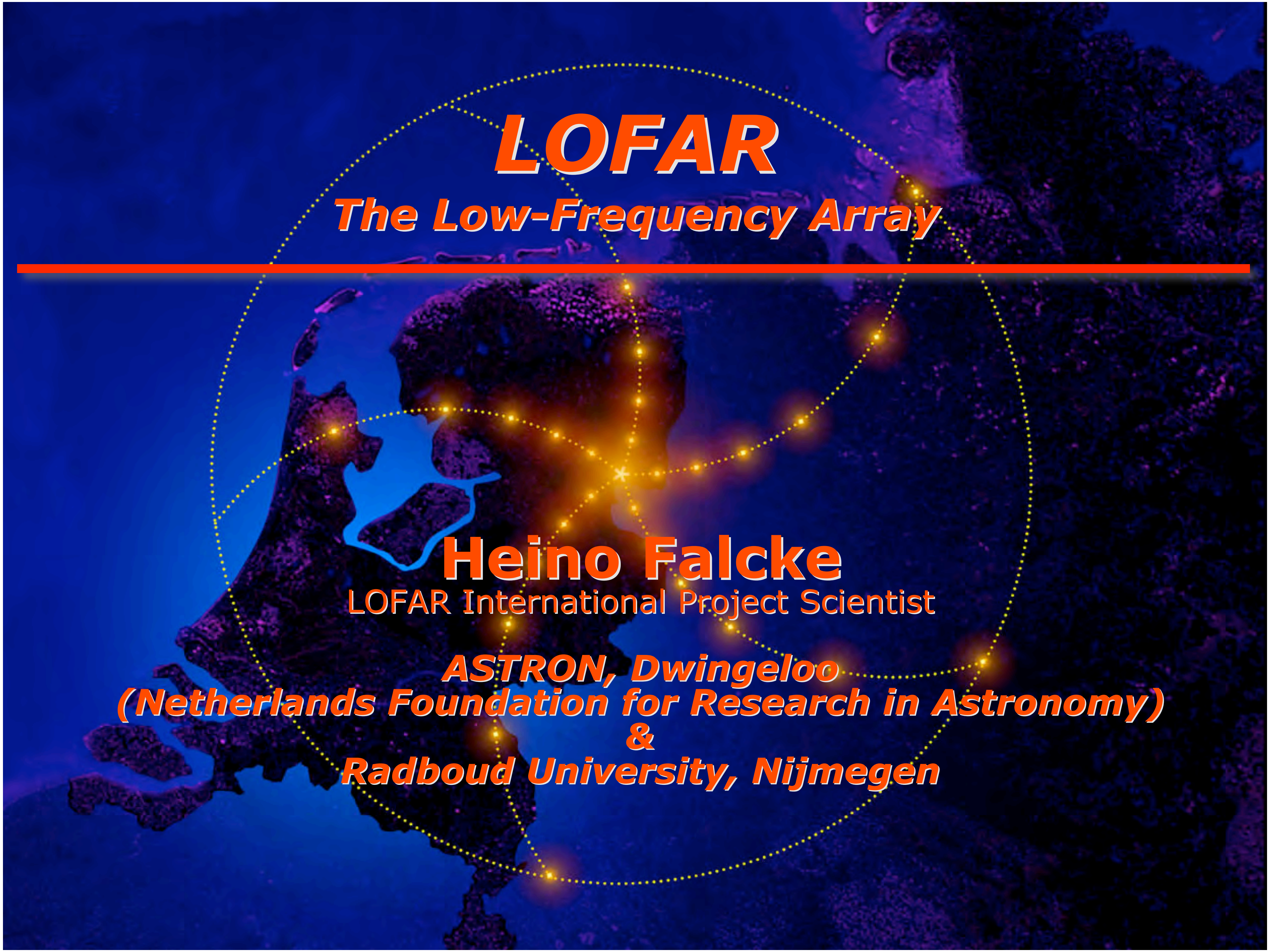


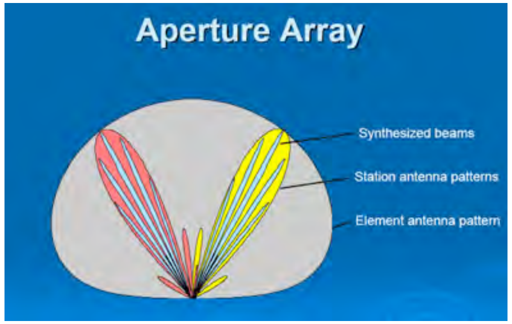
LOFAR

The Low-Frequency Array

Heino Falcke

LOFAR International Project Scientist

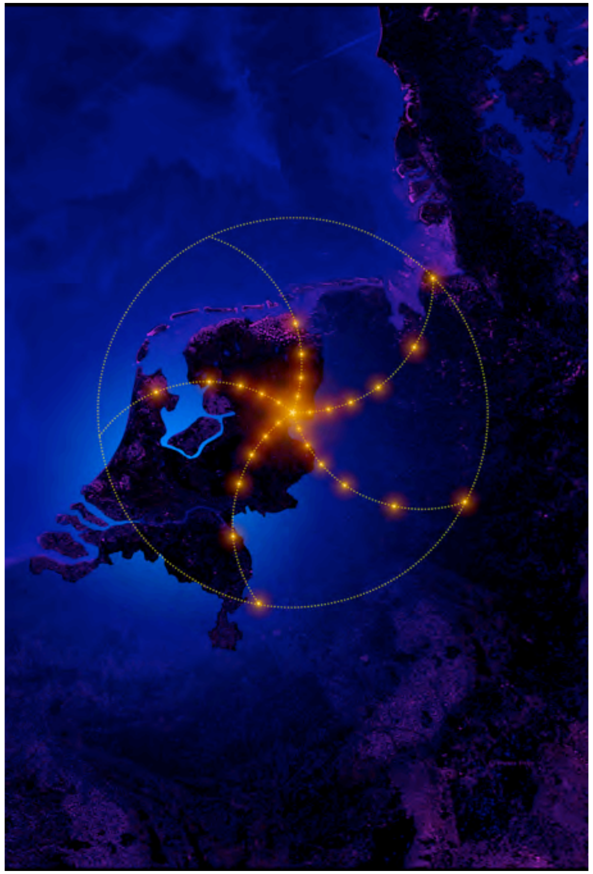
ASTRON, Dwingeloo
(Netherlands Foundation for Research in Astronomy)
&
Radboud University, Nijmegen



Next generation radio telescope

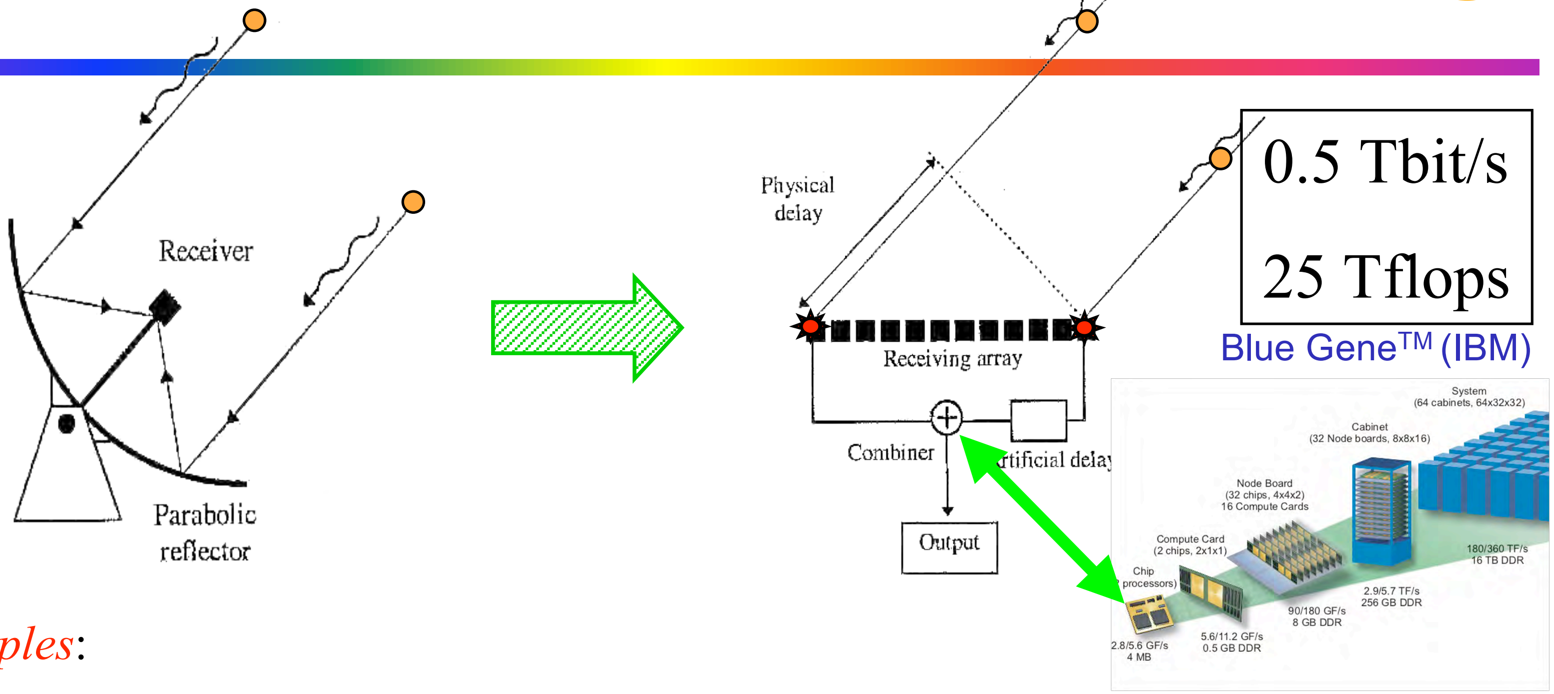
- Telescope the size of the Netherlands plus Germany
- Frequencies: 30 - 240 MHz
- 10% Square Kilometer Array (SKA) prototype at low-frequencies
- Interferometer baselines: 100 km
  - European Expansion to 1000 km
- Aperture array: Replace big dishes by many cheap dipoles
  - 100 stations of 100 dipole antennas + extra sensors (geo+meteo)
  - No moving parts: electronic beam steering
  - supercomputer synthesizes giant dish
- Current Funding: 74 M€
- Two orders of magnitude improvement in resolution and sensitivity
- Science applications: Big bang, astroparticles and the unknown

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

LOFAR Stations

Low Band Antennas

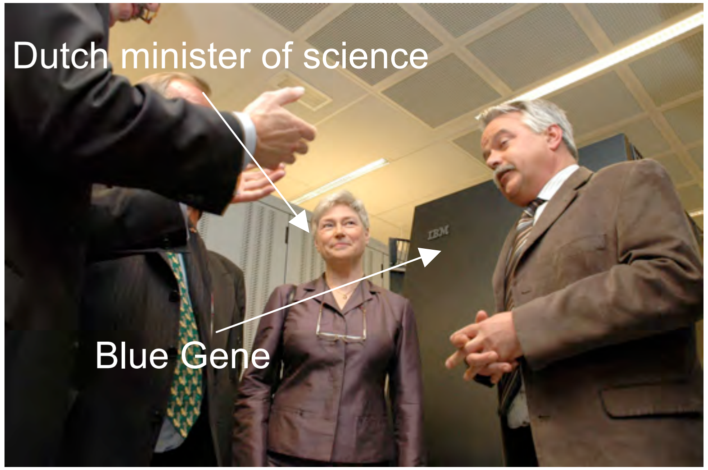
High Band Antennas

- 96 Low Band Antenna's
- Distributed over ~60 m
- Optimized for 30-80 MHz

- 96 High Band Tiles
- 4x4 antenna's
- Disitributed over ~50m
- Optimized ~115-240 MHz

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

- 27,4 Tflop
- ~ 12000 PCs
- Occupying 6 m^2
- 150 KW power consumption
- 0,5 Tbit/s input
- Now operational



List for

TOP500 SUPERCOMPUTER SITES

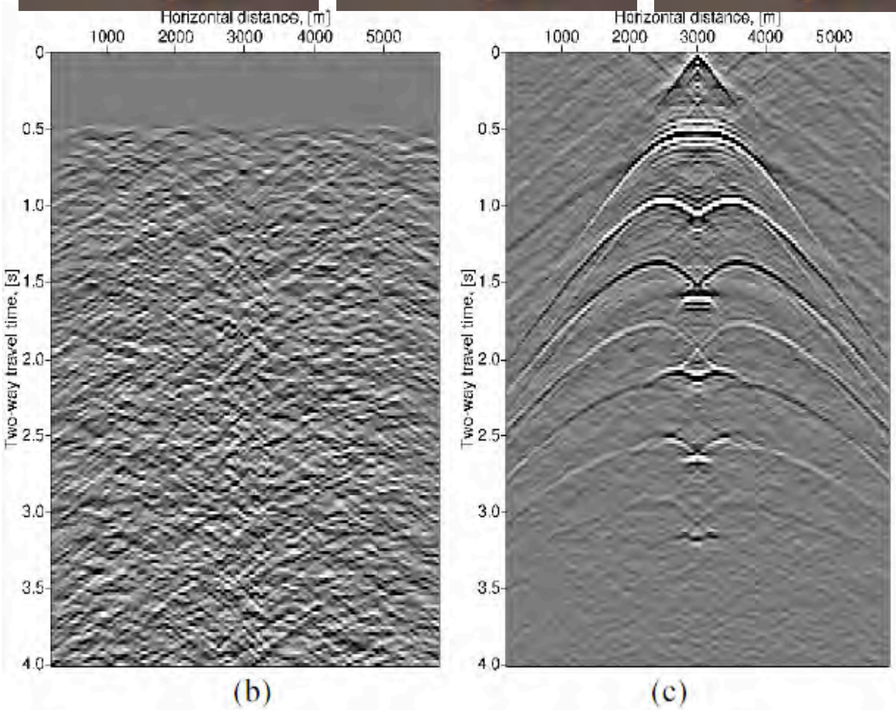
DETAILS | EXPLANATION OF THE FIELDS

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

~1.7% slower than #1 in Europe

LOFAR Network with Geophones + Infrasound



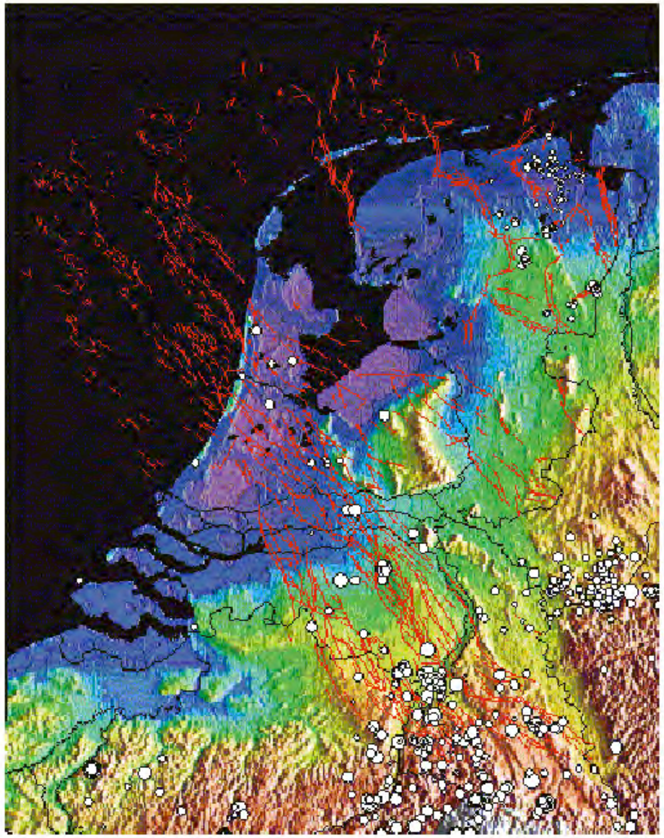
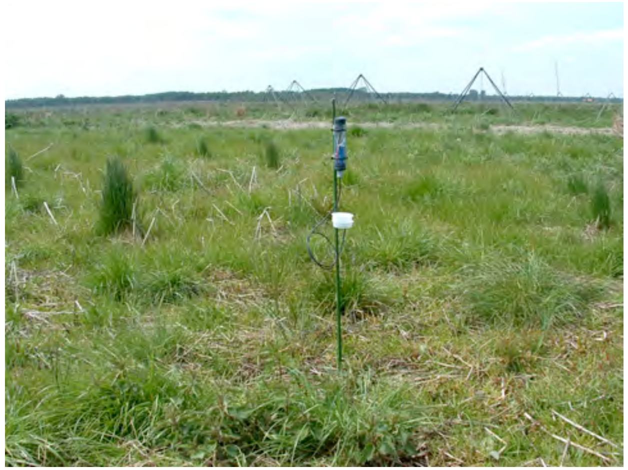


Figure 3.2 Geologic Netherlands. White circles are earthquake epi-centres.

Precision Agriculture

- Use LOFAR infrastructure as testbed for sensor networks in agriculture
- Test case: *Phytophthora* disease in potatoes
- Measure humidity in test fields
- Model spread of diseases in computer

þ Give farmer precise information on usage of pesticides, avoiding unnecessary spraying of chemicals.

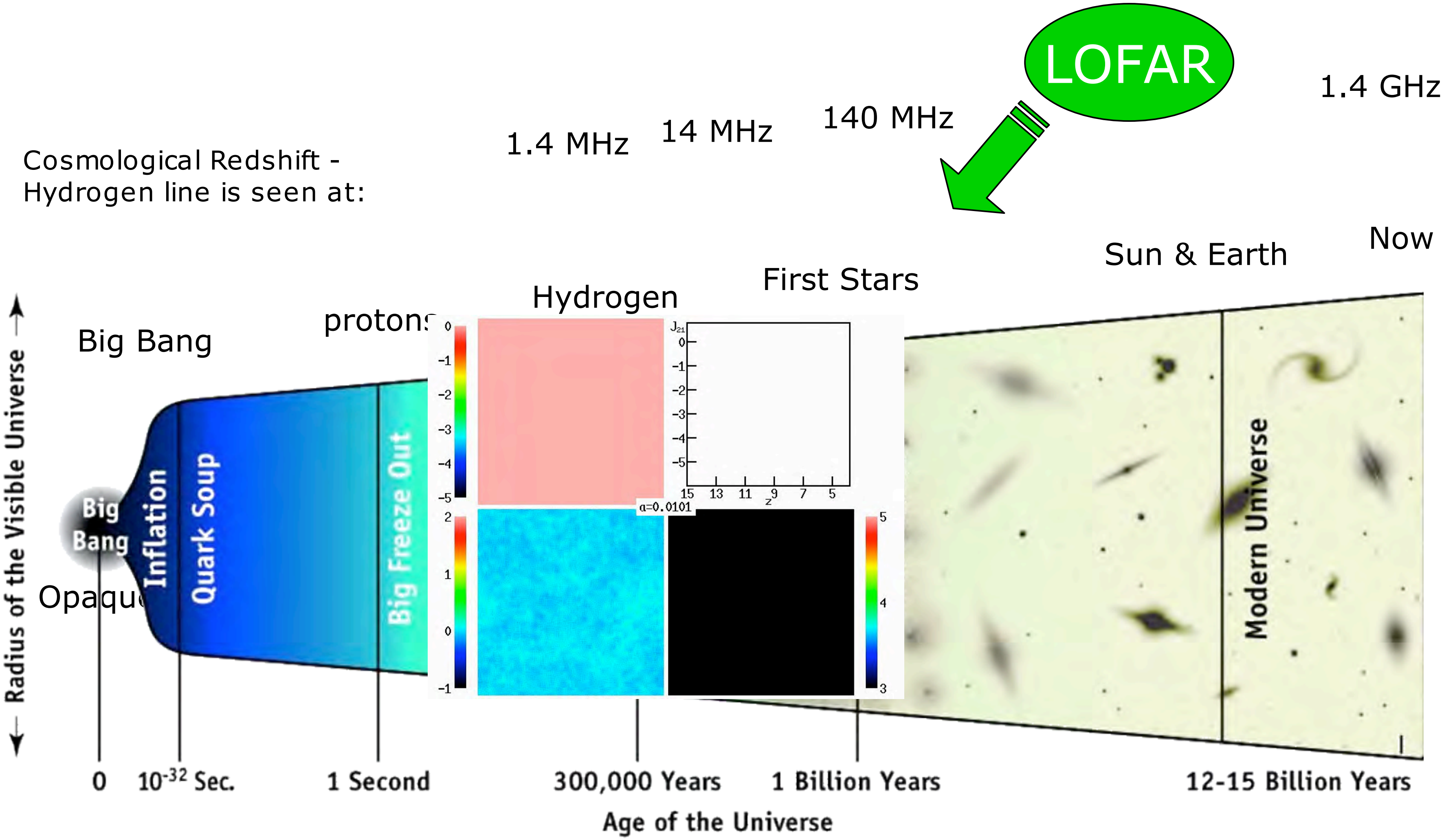


LOFAR Key Science Programs

- Cosmology (Groningen: deBruyn)
  - Epoch of Reionization, first stars in the universe
- Surveys (Leiden: Miley/Rottgering)
  - Star forming galaxies, AGN, Clusters, etc.
- Transient detection (Amsterdam: Wijers)
  - Everything that bursts and varies
- Astroparticle Physics (Nijmegen: Kuijpers/Falcke)
  - Direct detection of cosmic rays
  - Cosmic rays & neutrinos impacting the moon

History of the Universe

(condensed version)



Main science goals of LOFAR – EoR observations

- **Determine Epoch (or Era) of Reionization**
  → **115 MHz → z = 11.4** **(WMAP 3 years: z~11-6)**
  → **180 MHz → z = 6.9**

- **Infer sources of reionization (modeling)**
  → **hot (massive) stars in forming galaxies: photons with l < 912 Angstrom**
  → **Black Holes in (forming) galaxies: photons up to X-ray energies**

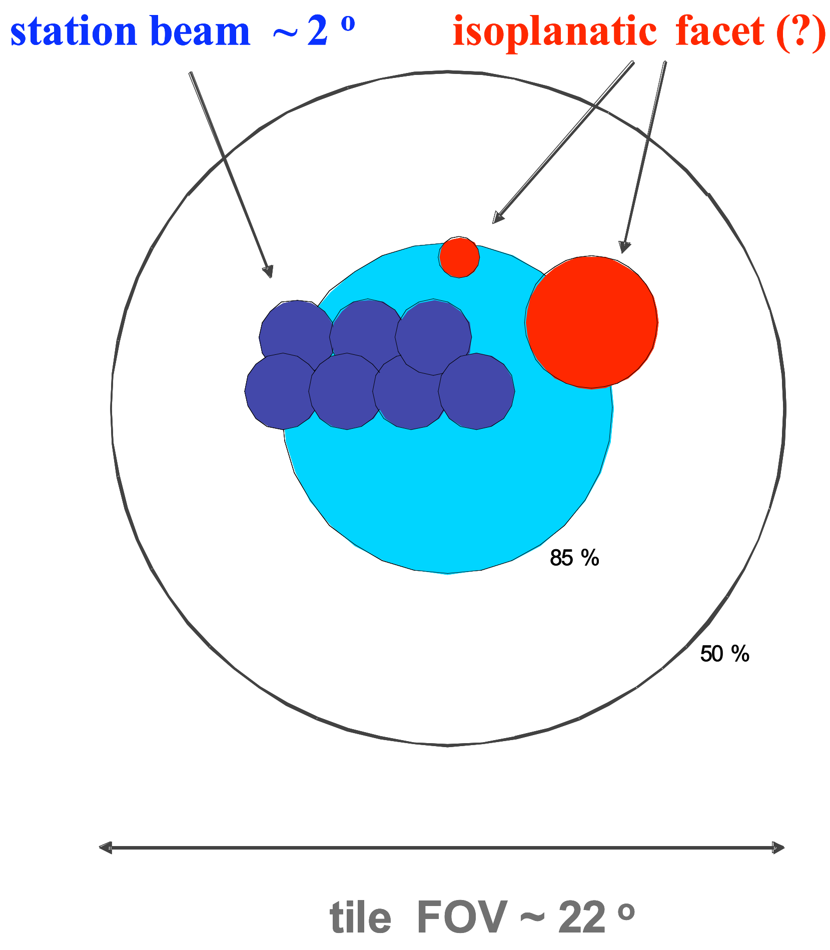
- **Measure power spectrum of fluctuations as function of redshift**
  → **on angular scales from 1′ - 1°**
  → **on frequency scales from 0.1 - 10 MHz**

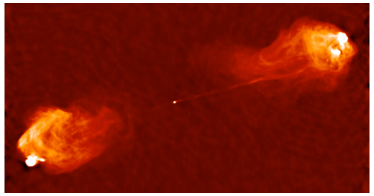
- **Search for giant Stromgren holes around luminous QSO's**

- **Search for 21cm line forest in high z radio sources**

EoR observing program (tentative)

- 3 EoR windows in Galactic halo (tile beam 20-25°)
- Use 24 beams of Δν=32 MHz
- Sept – May season, night time
- Total amount of observing time: 3x70x6h = 1260h (~2 month)
- Total data volume : ~ 1 Petabyte (10s , 10 kHz)
- Extensive reprocessing
- Noise per pixel: 10 - 15 mK for 1.3 km array (5′ , 150 MHz)

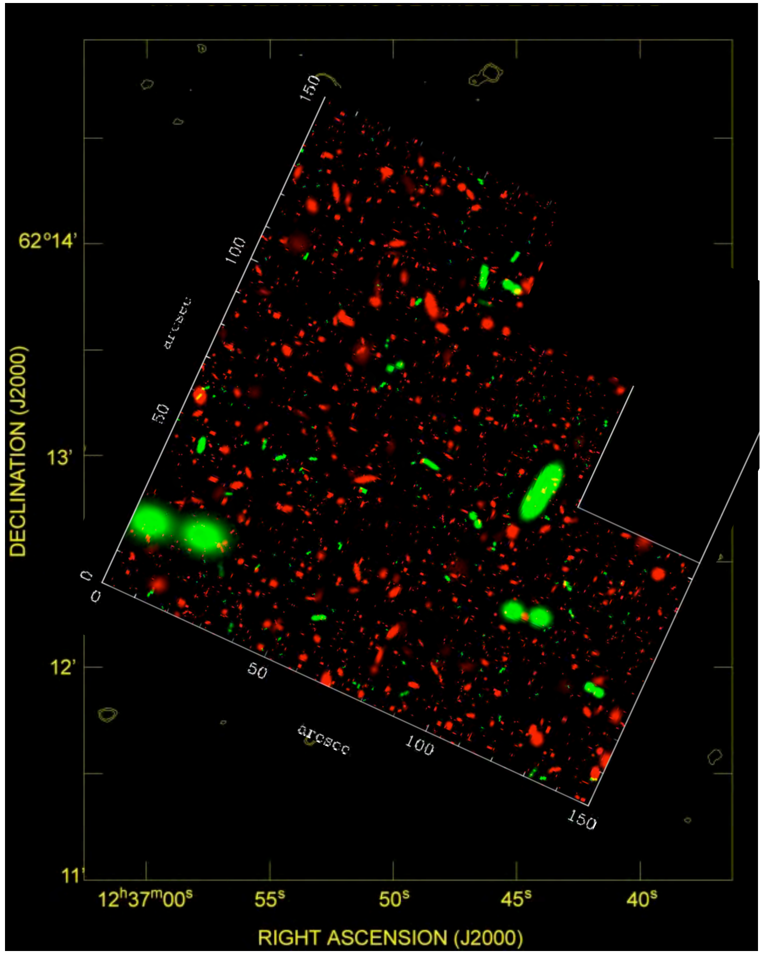




Radio image of
giant radio galaxy

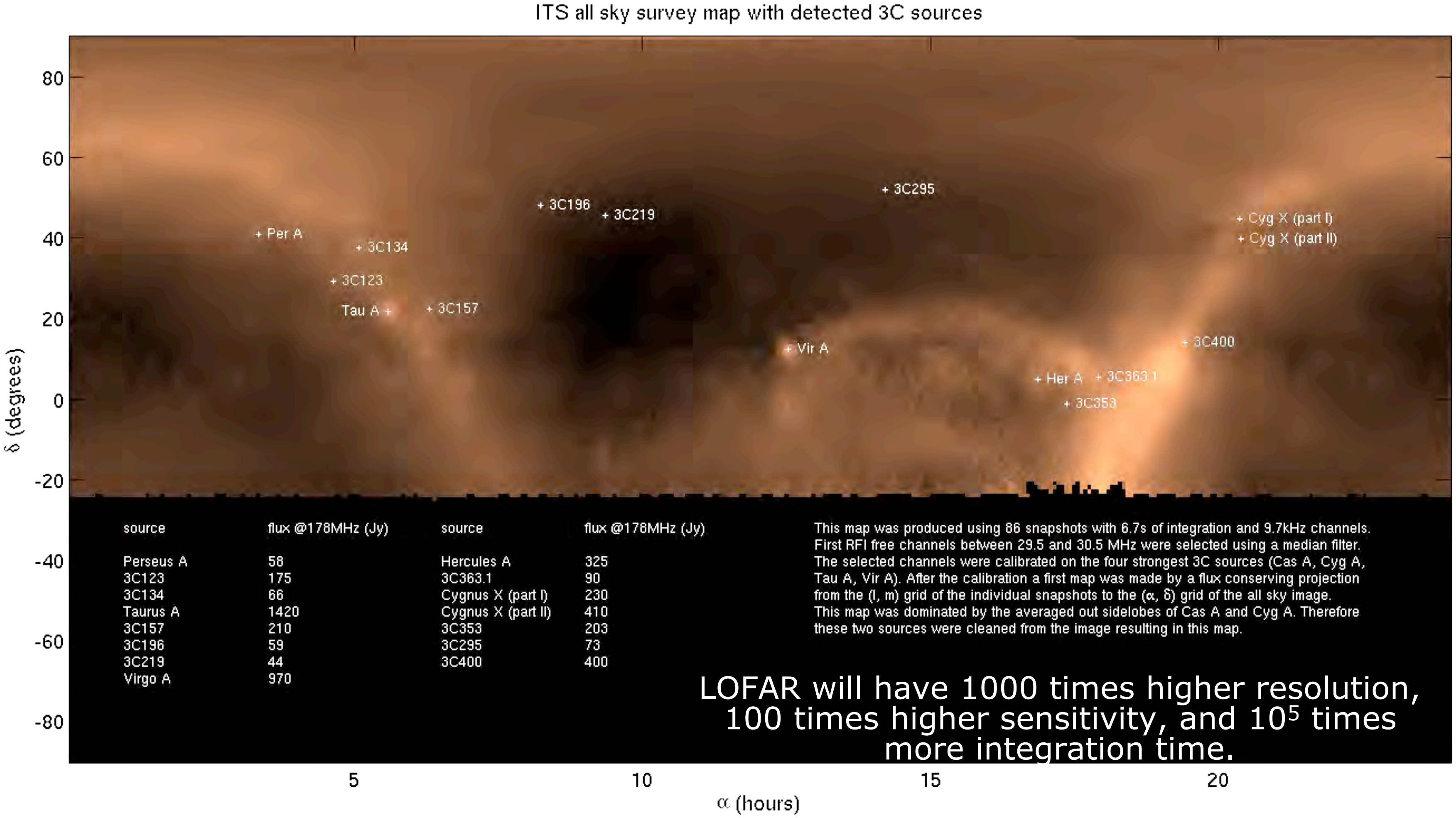
LOFAR Deep fields
Billions of new sources

- LOFAR has a very large field of view and be an ideal survey telescope.
- LOFAR will be an all-sky monitor for detecting bursting (transient) radio sources.
- We expect to find > 100 Million new sources:
  - stars & planets
  - star forming galaxies
  - active black holes
  - first objects in the universe
  - ???



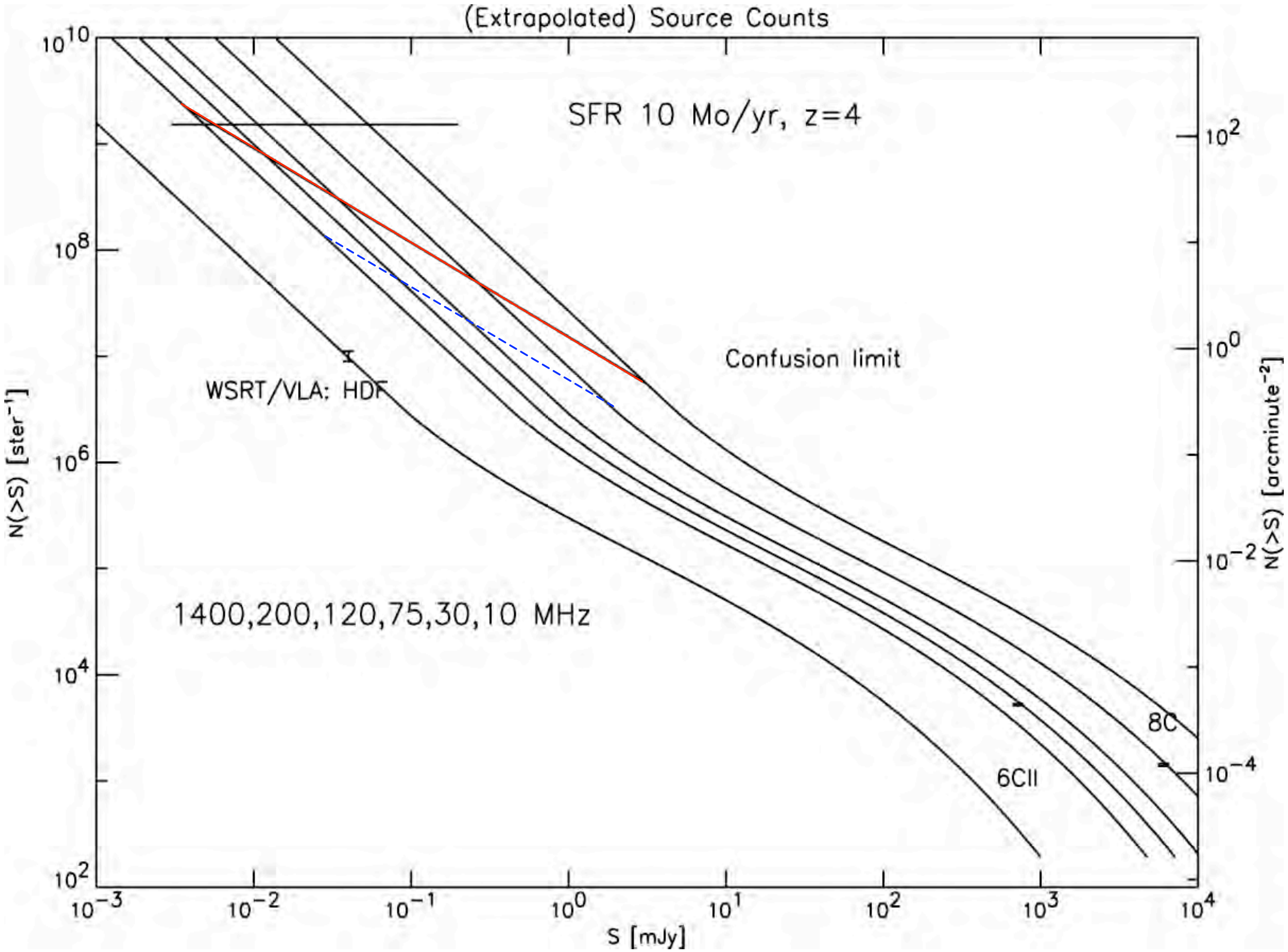
Simulated radio deep field.

LOFAR simple station prototype: 500 Second All-Sky Map



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

LOFAR Survey Source Counts



Surveys: Strategy and Storage Requirements

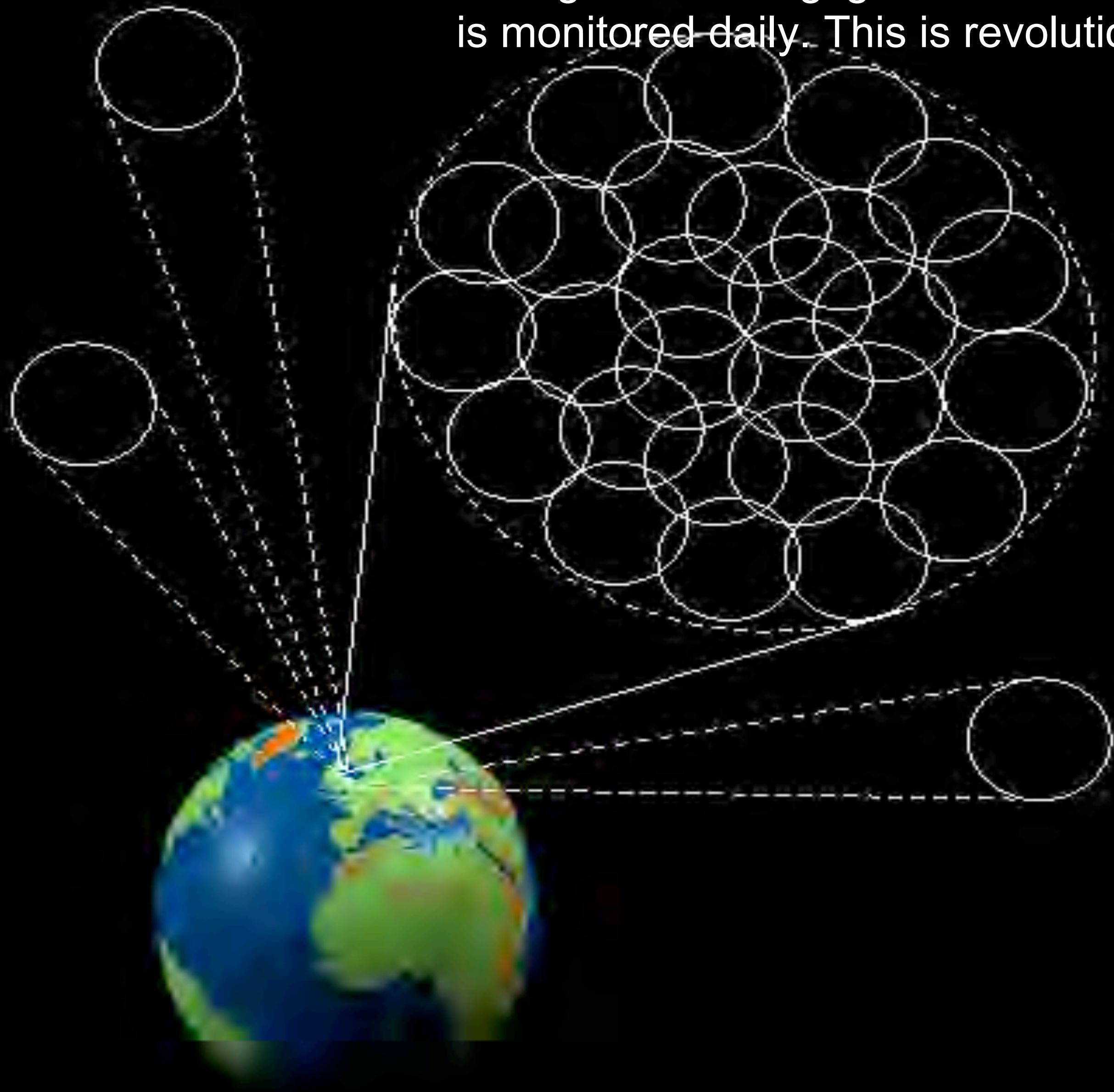
Table 9. Proposed LOFAR surveys

ν MHz (1)	Flux density mJy (2)	Area	Source density $\min^{-2}$ (3)	Number Sources (4)	Int. time 1 beam hour (5)	Total 4 beam years (6)	Main aim
15	4.745	2π sr	0.2	1.3e+07	48	0.07	Serendipity
30	0.969	2π sr	0.7	5.4e+07	38	0.22	$z \sim 6$ radio galaxies
75	0.124	250 $\deg^2$	4.5	4.2e+06	991	0.44	Spectral information
120	0.043	2π sr	11.6	8.6e+08	23	2.17	Distant halos in clusters $z \sim 6$ radio galaxies
200	0.006	250 $\deg^2$	32.2	3.0e+07	1000	2.29	Distant starbursts $z \sim 6$ 21-cm absorbers

Table 10. Storage requirements for proposed LOFAR surveys

ν MHz (1)	Number of pixels (2)	Amount of data continuum maps Gbyte (3)	Amount of data spectral data cubes at full polarization Tbyte (4)
15	4.2e+08	1.7	27
30	1.7e+09	6.8	108
75	1.3e+08	0.5	8
120	2.7e+10	108	1729
200	9.4e+08	3.8	60

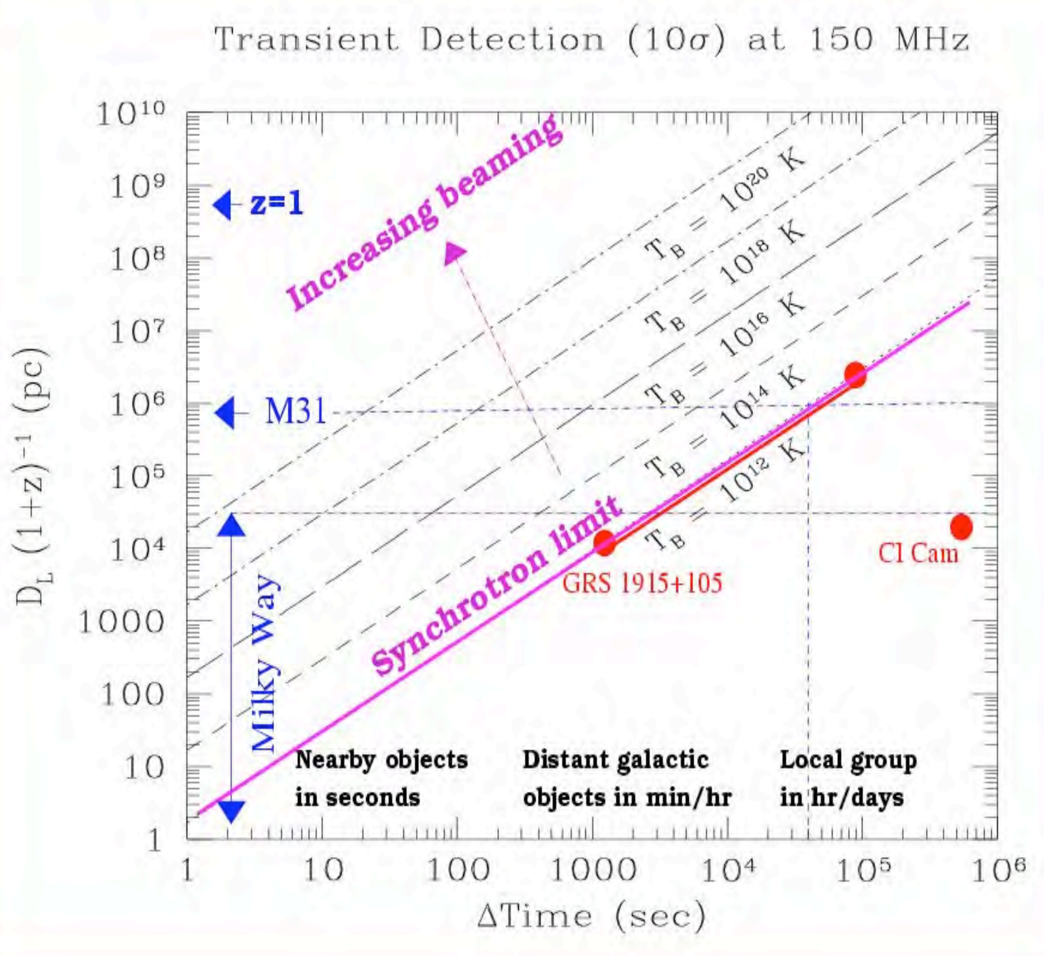
Multiple (up to 24) station beams tile out a significant fraction of the entire compound element beam. Sky passes through monitoring ‘grid’ and in this way a large fraction of it is monitored daily. This is revolutionary, and achievable.



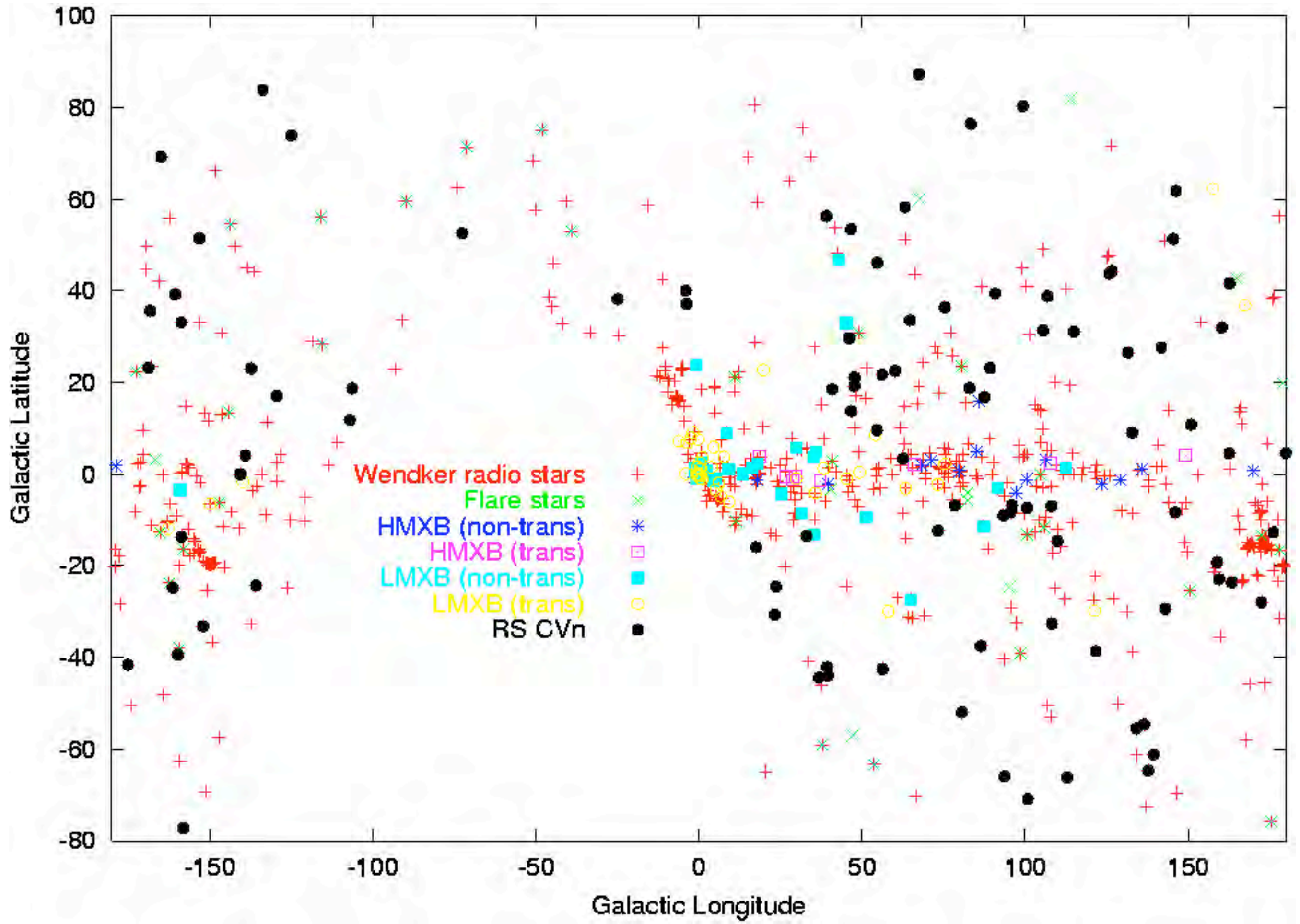
In addition, we will ‘piggyback’ on other observations, examining data for rapid transients and comparing with last time field was imaged

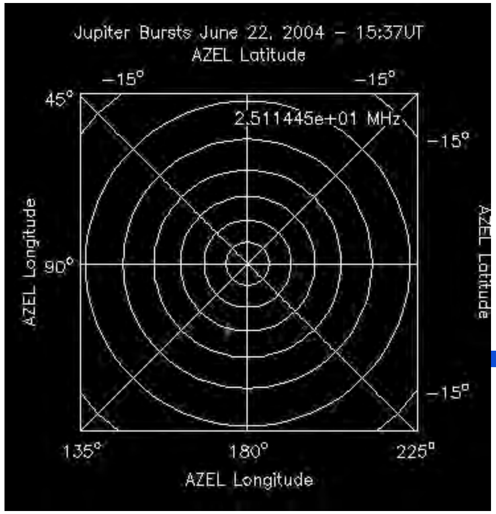
Transients with LOFAR

- Compact Synchrotron Sources
  - AGN, X-ray binaries, GRBs
- Cyclotron & Coherent Processes
  - stars & planets
- Scintillation
  - All compact sources



Galactic Transients with LOFAR

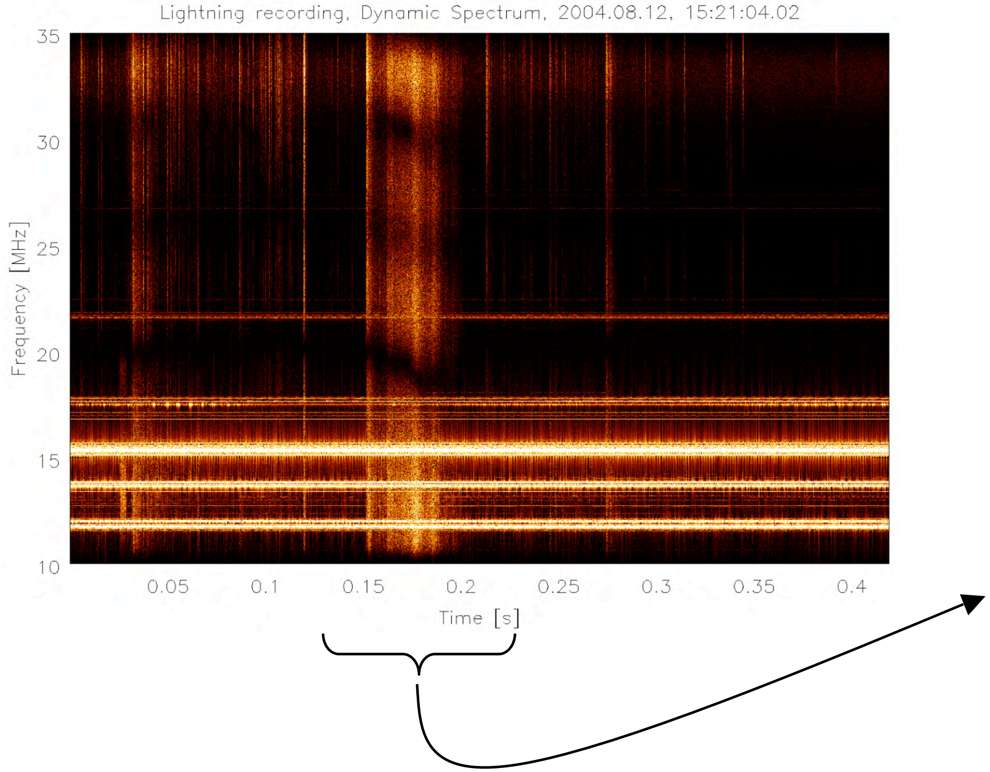


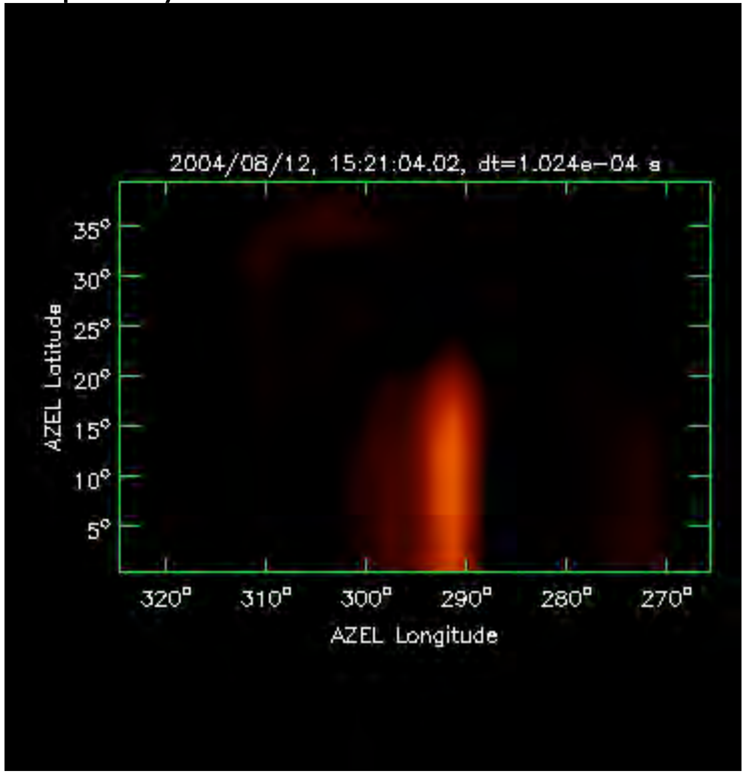


Transients with LOFAR-ITS: Jupiter and Lightning

Movie: 25 ms, 0.1ms/frame
Playing time: 31 sec
Frequency: 23-26 MHz

Dynamic Spectrum

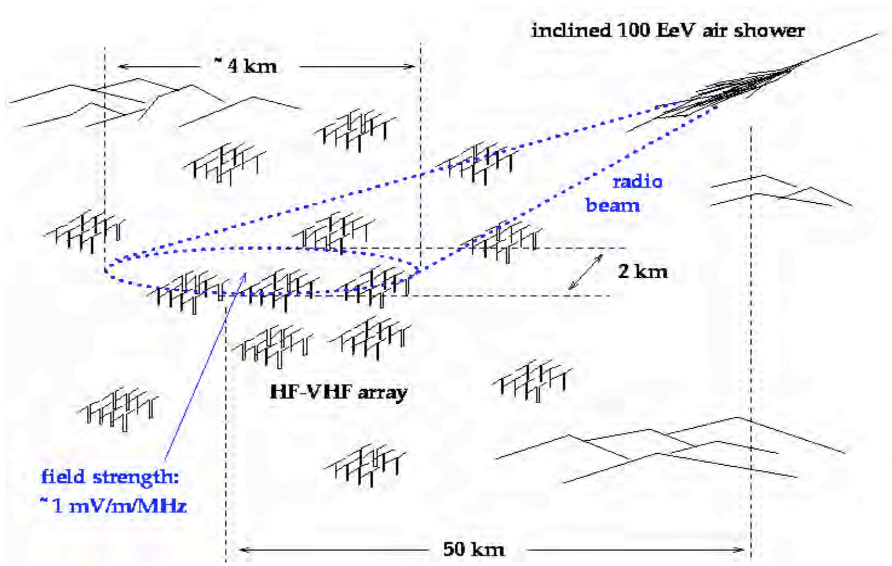




L. Bähren (ASTRON)

Astroparticle Physics: Radio Emission from Air Showers

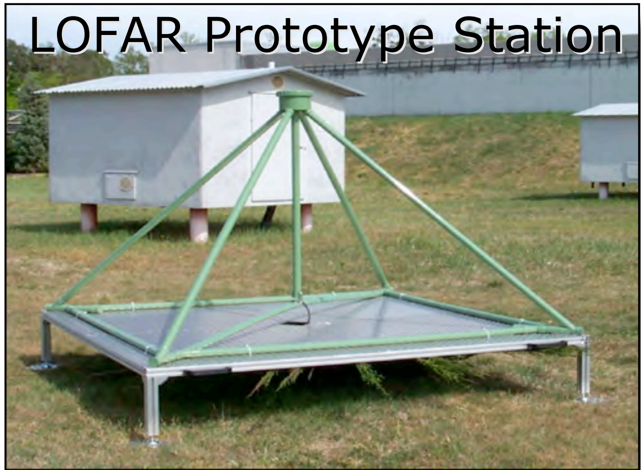
- Leptons in extensive air showers produce geosynchrotron emission
- þ Cheap detectors
- þ High duty cycle (24 hours/day minus thunderstorms)
- þ Low attenuation (can see also distant and inclined showers)
- þ Bolometric measurement (integral over shower evolution)
- þ Very interesting for neutrinos and UHECRs



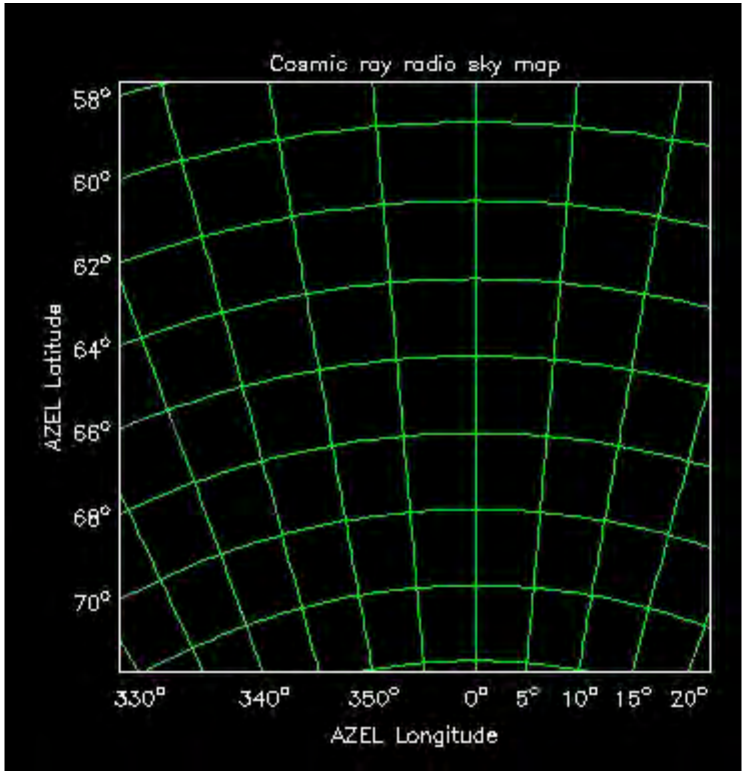
Falcke & Gorham (2003)

LOFAR Prototype Station (LOPES):

detection of nanosecond radio flashes from ultra-high energy elementary particles

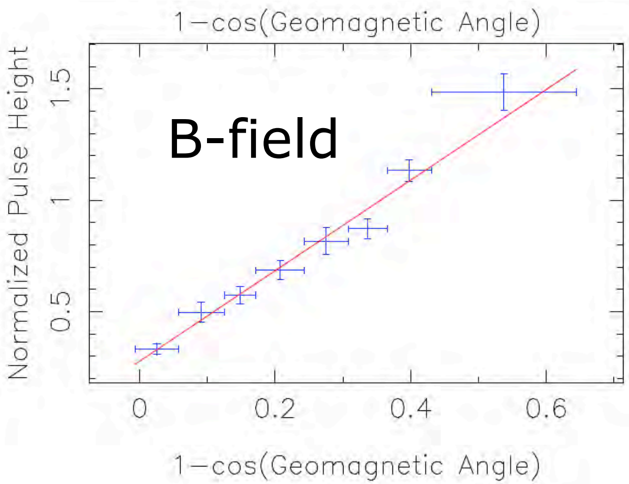


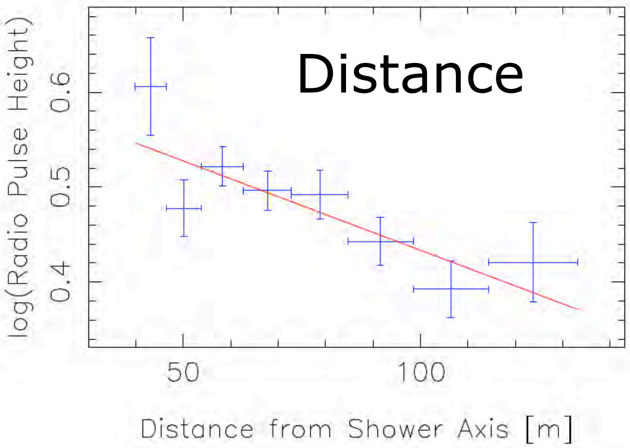
LOPES All-Sky Movie of Radio Flash:
200 ns duration (repeating)



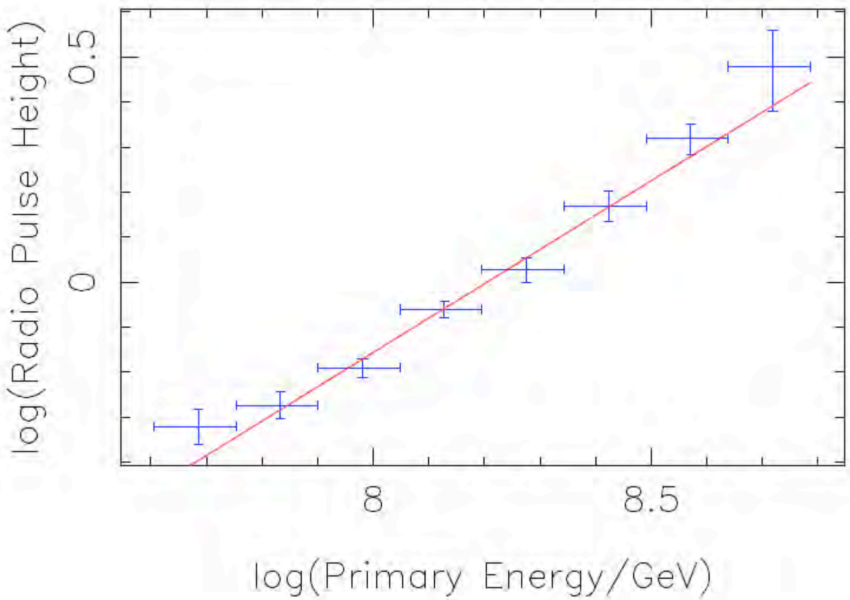
Falcke et al. (2005), *Nature*, Vol. 435, p. 313

Calibration of CR Radio Signal with LOPES





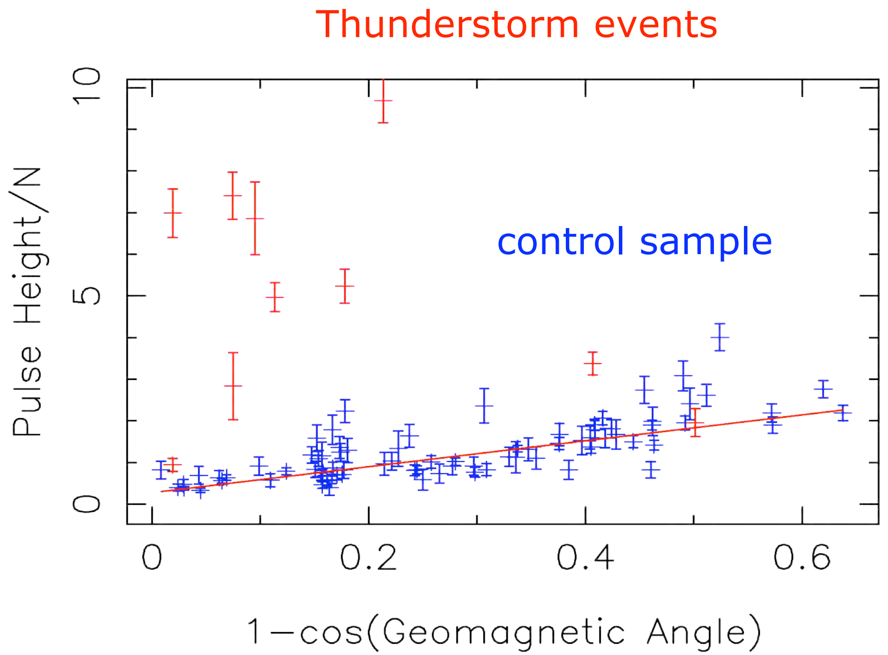
UHECR Particle Energy



Horneffer 2006, PhD

Thunderstorm Events

- Does the Electric field of the atmosphere influence CR radio signal?
- For E>100 V/cm E-field force dominates B-field:
  - Fair weather: E=1 V/cm
  - Thunderstorms: E=1 kV/cm
- Select thunderstorm periods from meteorological data:
  - Þ Clear radio excess during thunder storms
  - Þ B-field effect dominates under normal conditions
  - Þ >90% duty cycle possible



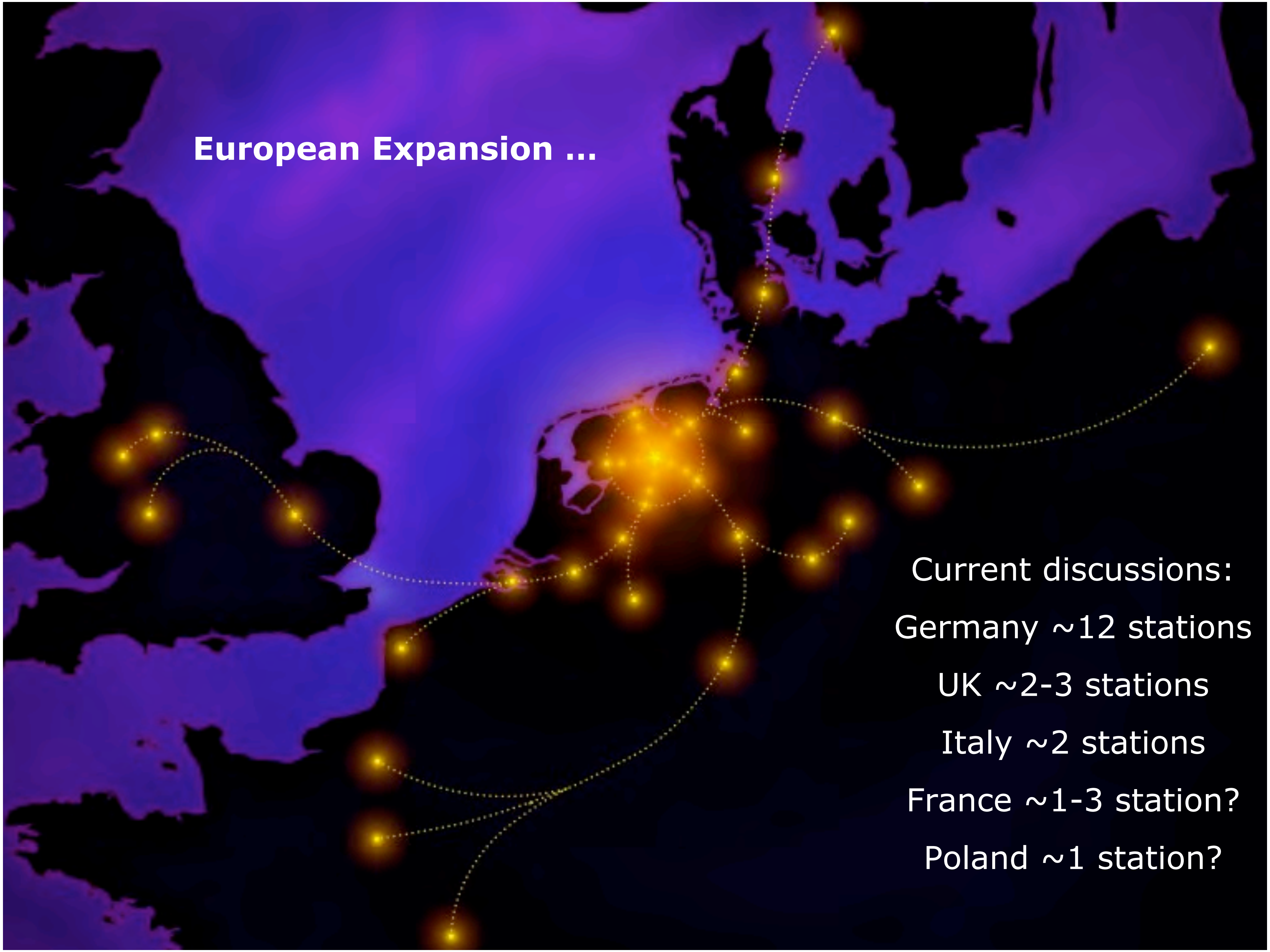
Buitink et al. (LOPES coll.) 2005 & 2006 in prep.

LOFAR Basic Properties

Frequency dependent Array Performance (Initial array)

Frequency	Point Source Sensitivity[b]		Effective Collecting Area		Beam Size	
	VC	Full Array	VC	Full Array	VC	Full Array
30 MHz	4.8 mJy	2.0 mJy	7.9×10^4 m^2	1.9×10^5 m^2	21′	25″
75 MHz	3.3 mJy	1.3 mJy	1.2×10^4 m^2	3.0×10^4 m^2	8.3′	10″
120 MHz	0.17 mJy	0.07 mJy	7.9×10^4 m^2	1.9×10^5 m^2	5.2′	6.0″
200 MHz	0.15 mJy	0.06 mJy	2.9×10^4 m^2	6.9×10^4 m^2	3.1′	3.5″

[b] Sensitivity quoted for 1 hour integration time, 2 polarizations and 4 MHz bandwidth


European Expansion ...
Current discussions:
Germany ~12 stations
UK ~2-3 stations
Italy ~2 stations
France ~1-3 station?
Poland ~1 station?

GLOW – German Long Wavelength Consortium

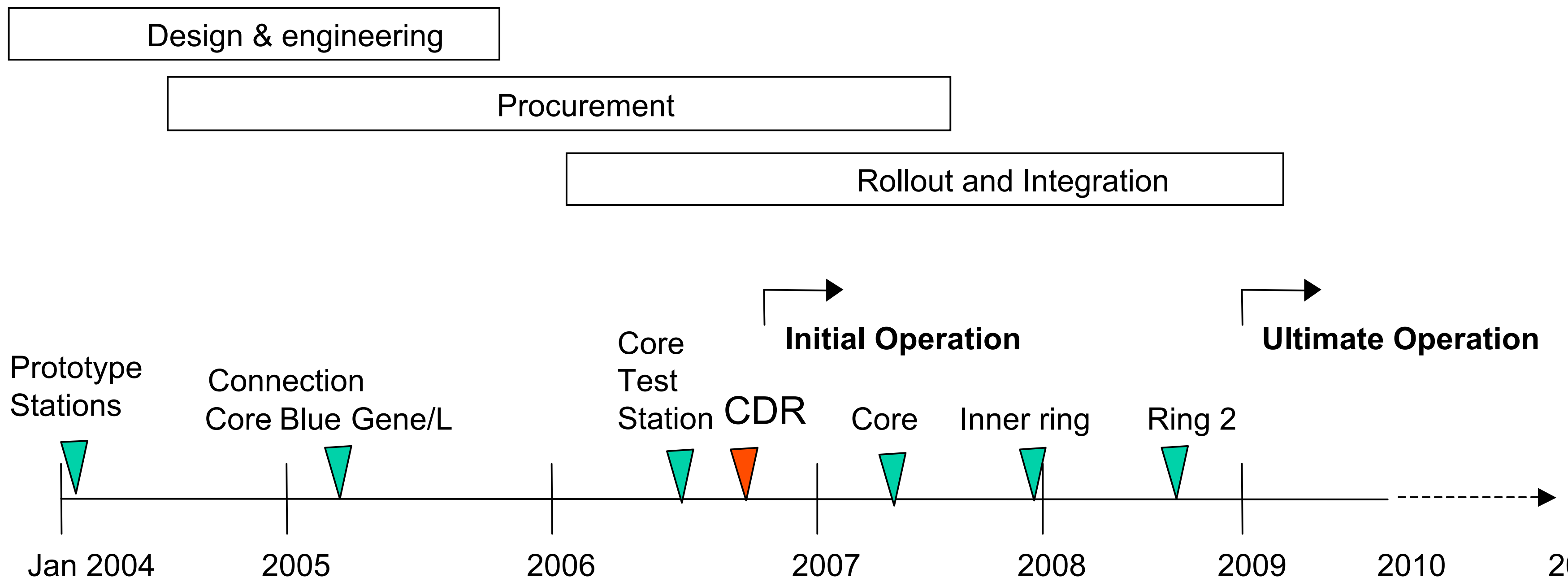
German Roadmap

- Informal discussions with a group of universities (twice per year)
- Writing of a German LOFAR White Paper
- Presentation of WP to German Community
- Individual grant applications by some institutes for stations (two already honored)
- Effelsberg will get first remote station this summer
- Formulation of German Key Science Interests
- Memorandum of Understanding to create German Long Wavelength (GLOW) consortium
  - We strongly encourage formation of one consortium per country
  - Later integrate with EU RadioNet and form int. consortium
- Presentation of plan to German ministries
- Basic documents describing data rights and access, involvement of German institutes are being developed
- Discussions with German supercomputing center (Jülich) about support for German community (LOFAR science center)

Cost

- LOFAR total cost: ~150 MEuro
- Cost of one station: ~0.5 MEuro
- Operations cost per station
  - Electricity: 20-40 kEuro; 15 kW
  - Maintenance: tbd (no operator needed, self-diagnosing, graceful degradation)
  - Network connection: tbd (3Gbit/sec into Geant)
  - Contribution to operations center(s): tbd

LOFAR Schedule

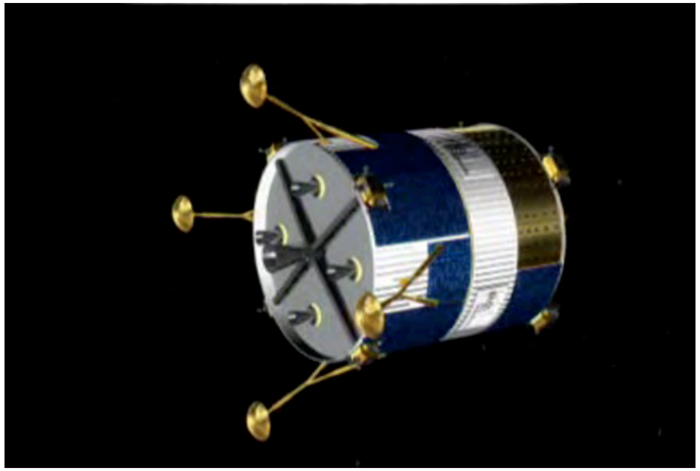


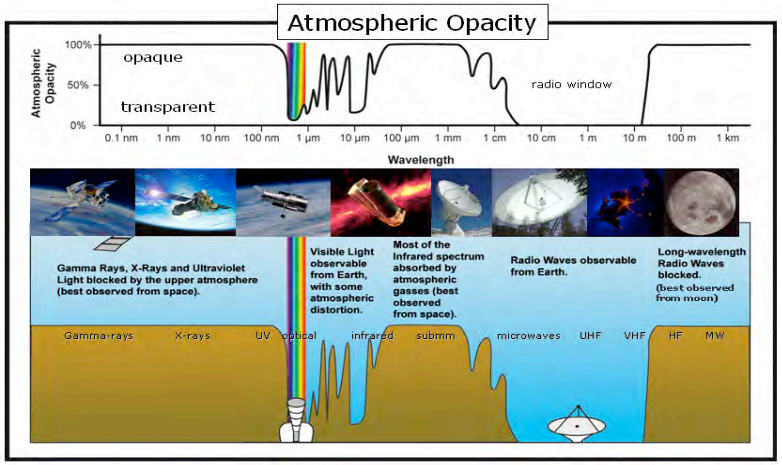
Future Directions: Low-Frequency antennas at AUGER

Future directions: LOFAR on the Moon

EADS/ASTRON study

- Below 10 MHz the atmosphere blocks radio emission.
- Man-made interference completely swamps all signals.
- No astronomy has ever been done in this long-wavelength regime.
- The only location where this can be explored is the far-side of the moon.
- A single Ariane V could bring a ~300m LOFAR telescope to the moon!
- Cooperation with EADS Space Transportation.





Summary

- LOFAR is well on track, first science already
- It is the first serious aperture array and digital software telescope in astronomy – excellent preparation for SKA
- Current Science: Cosmology, Transients, Astroparticles
- It will open up an almost forgotten frequency range and improve by two orders of magnitude
- Future:
  - European expansion
  - put LOFAR antennas near AUGER – the world largest cosmic ray detector in Argentina
  - there should be a southern LOFAR eventually …
  - put LOFAR on the moon …