LOFAR

a novel new radio observatory

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[+] on behalf of the LOFAR collaboration

ASTRON, Dwingeloo & Kapteyn Institute, Groningen

The Netherlands

IPMU, Tokyo, 24 February 2009

Outline

— Renaissance of low frequency radio astronomy

— LOFAR array: dipoles, tiles and stations

— RFI and frequency selection

— Science drivers : Key Science Programmes (KSP)

— Pilot facility results: the *learning* phase

— Images from Rollout: started July 2008

— Calibration issues: Ionosphere !!

— Conclusions and web info

A renaissance of low frequency radio astronomy

Existing arrays:

WSRT (NL)	1984 (2004)	3 km	270 - 400 and 110-180 MHz	
VLA (USA)	1995	30 km	74 MHz	
GMRT (India)	1999	25 km	(50),150, 230, 330, 610 MHz	

New arrays:

LOFAR	(NL, Europe)	2009	100-1000 km	20-240 MHz
MWA	(Australia)	2010	1.5 km	70-300 MHz
LWA	(USA)	>2012	~ 400 km ?	20-80 MHz

Why? There are many reasons but foremost are:

Search for redshifted HI (EoR) (1420/(1+z) ⇒ ~100-180 MHz , see prof Zaroubi's talk)

Transients sources (high T_b), Clusters-Relics-SS, high- z AGN, polarimetry

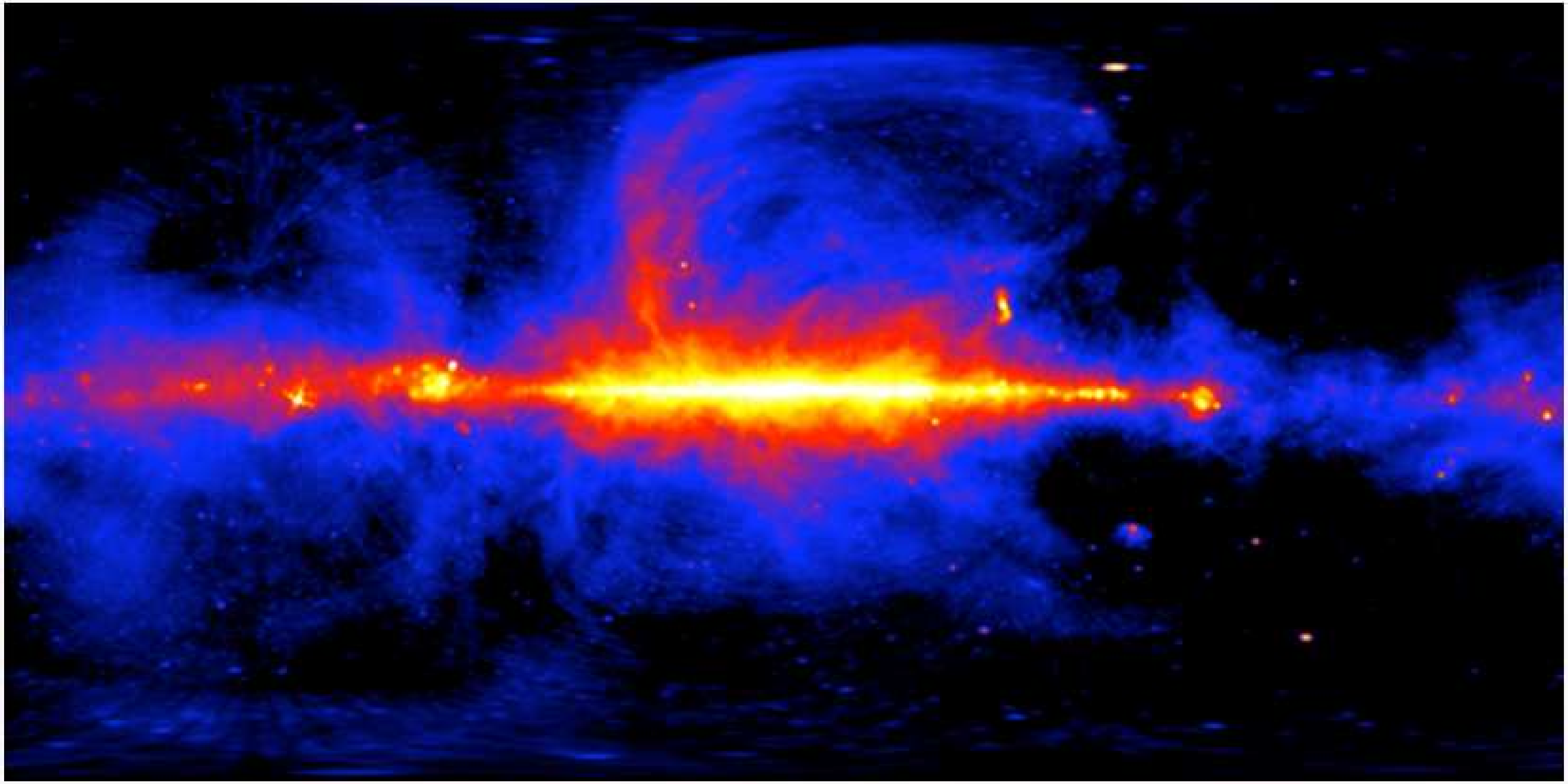
and ……..radio astronomy is good at winning (Nobel) prizes

Giant radio telescopes of the world

- 1957 76m Jodrell Bank, UK
- ~1970 64-70m Parkes, Australia
- ~1970 100m Effelsberg, Germany
- ~1970 300m Arecibo, Puerto Rico
- ~2000 100m GreenBank Telescope, USA

HPBW at 300 MHz ~ 0.5 - 2°

All-sky image at 408 MHz (~ 1° PSF)



Galactic longitude

Haslam etal (1981)

Reflectors (single feed/FPA) versus Aperture Arrays

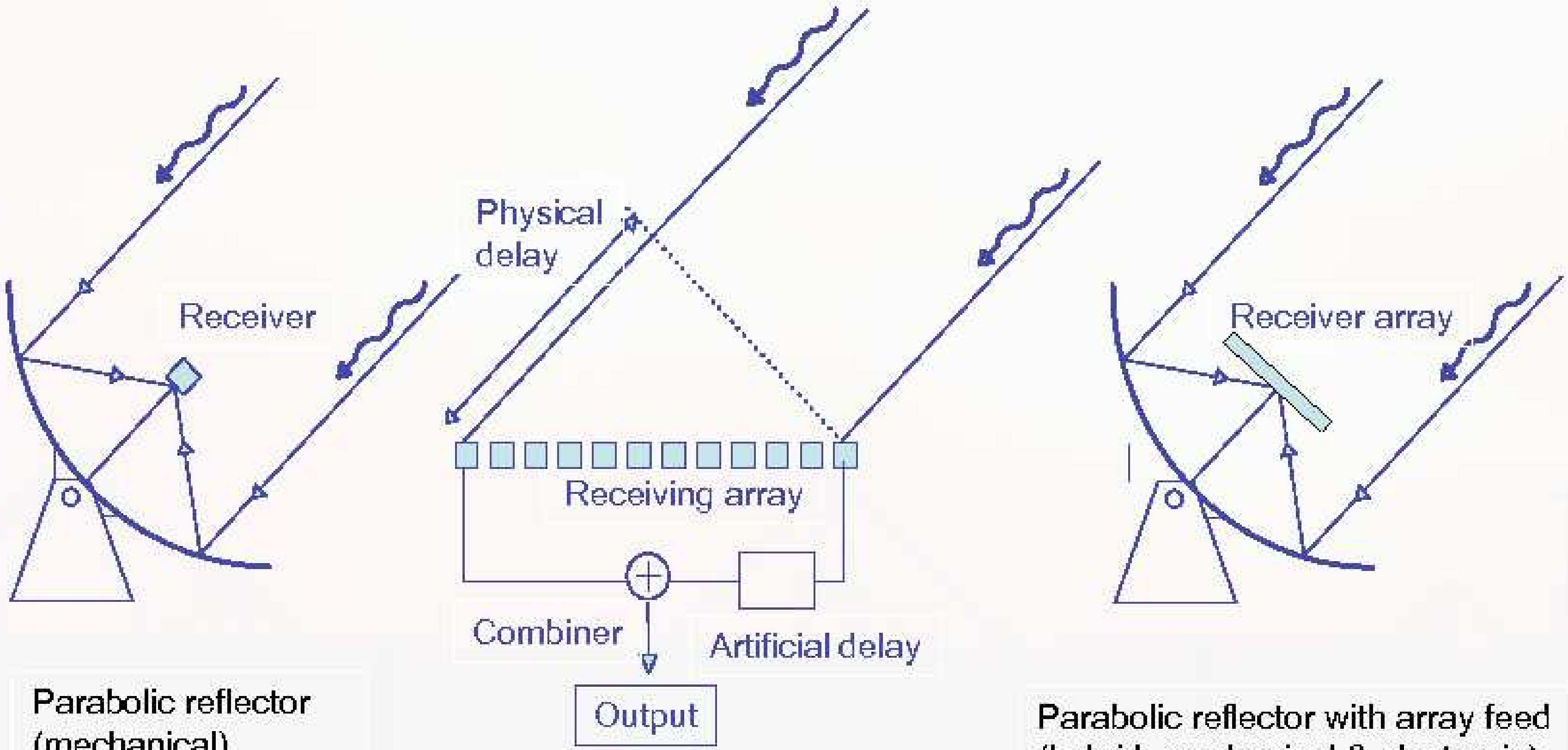
e.g. WSRT, VLA, ATCA

GMRT, ALMA

LOFAR

WSRT

ASKAP



Parabolic reflector (mechanical)

Aperture Array (electronic)

Parabolic reflector with array feed (hybrid: mechanical & electronic)

The LOFAR observatory

LBA (10) 30 - 80 MHz
isolated dipoles

HBA 115 - 240 MHz
tiles (4x4 dipoles)

Core	2 km	18+ stations
NL	80 km	18+ stations
Europe	>1000 km	8+ stations

A station will have 24 - 96 antennas / tiles:
FOV: dipole ~100°, tile ~20°, station ~5°

Principle of **Aperture Synthesis**
Array resolution: sub-arcsec to degrees

Sensitivity (after 4 h, 4 MHz, ~ 50 stations)
@ 60 MHz ~ 3 mJy
@ 150 MHz ~ 0.1 mJy

Up to 8 simultaneous 4 MHz beams (or 'users') possible

LBA antenna station (48 dipoles, Feb 2007)

LBA-antenna (4 wires, 2 pol) + ground plane

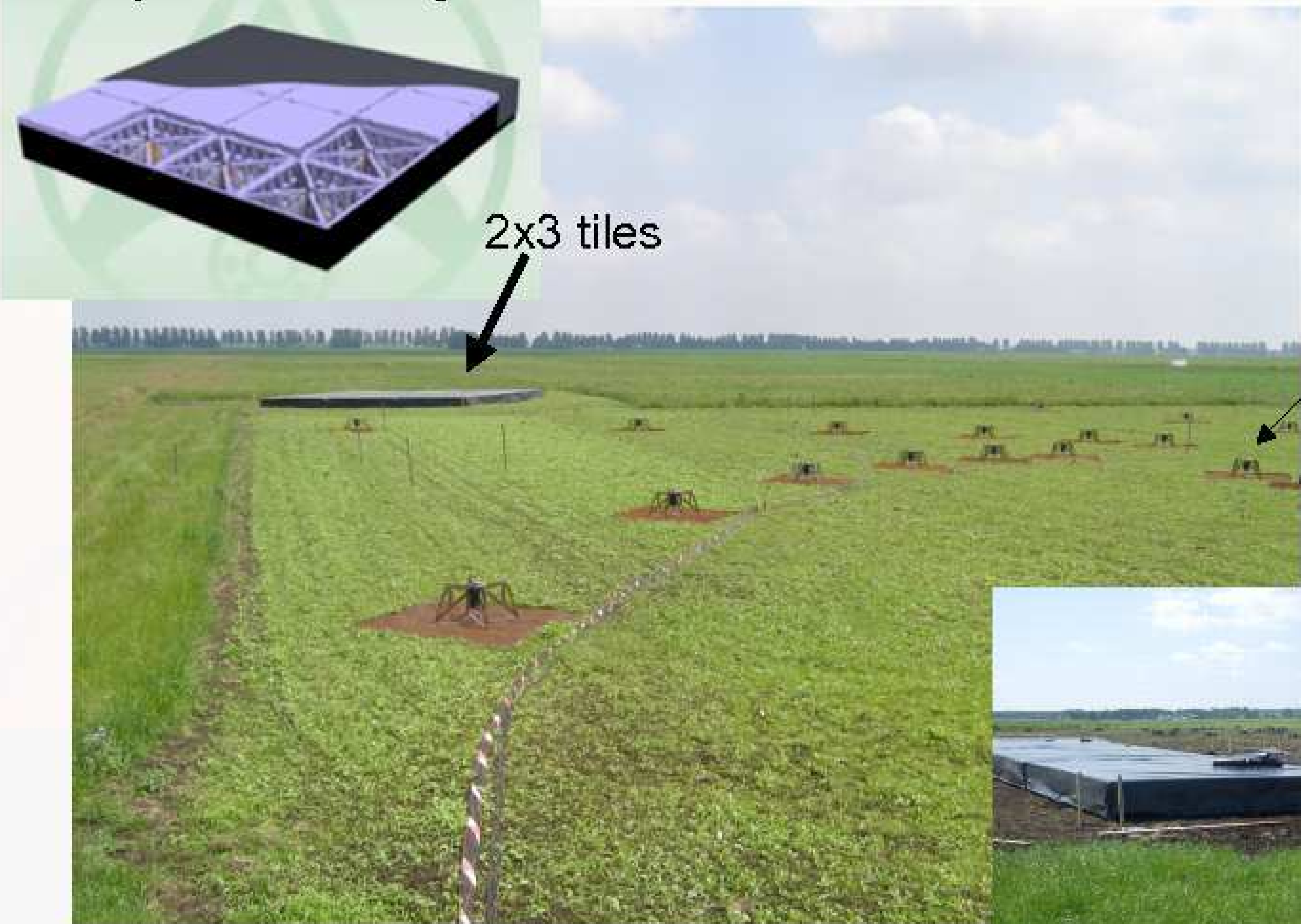
Field of LBA dipoles in the summer of 2007

HBA initial test configuration

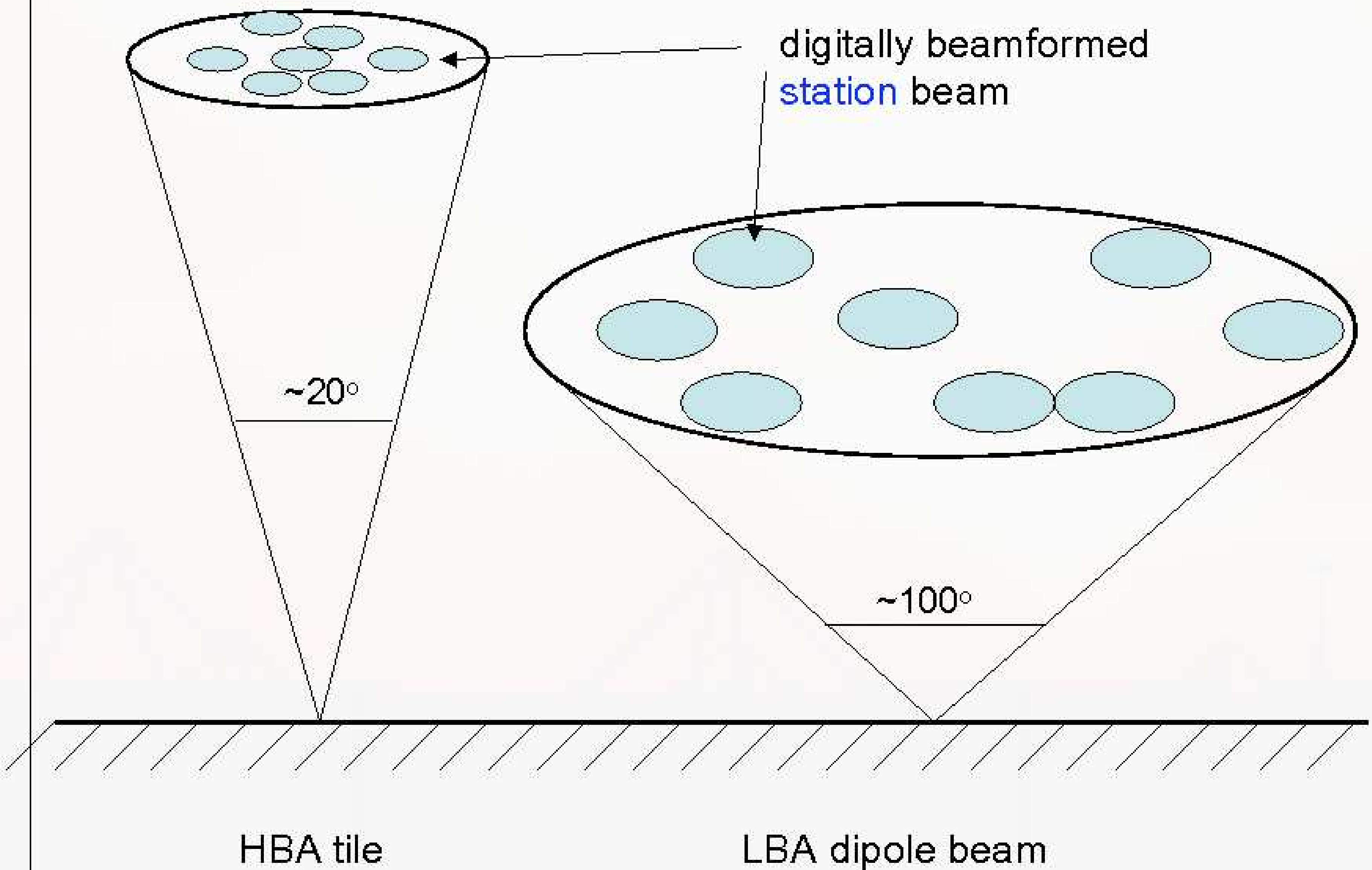
Tile with 4x4 dipoles (5x5 meter)
with Styrofoam backing structure

2x3 tiles

individual HBA
dipoles ('spider')



LOFAR has an extremely wide Field-of-View



A wide FOV is both good and bad

Good because of sensitivity to most of the visible hemisphere

— transients science, serendipity

— very rapid electronic (re)pointing (< 1 second)

— multi-user capability (up to 8 independent users: surveys, monitoring, TOO,..)

Bad because of the complications in calibration:

— interferometers measure the all-sky integral of the source coherencies

— station beam and ionospheric non-isoplanaticity cause errors to be spatially varying

⇒ standard selfcalibration fails

I will return to this calibration challenge at the end of the talk

Radio astronomy and Radio Frequency Interference

RFI is an issue for all radio arrays, but especially at low frequencies :

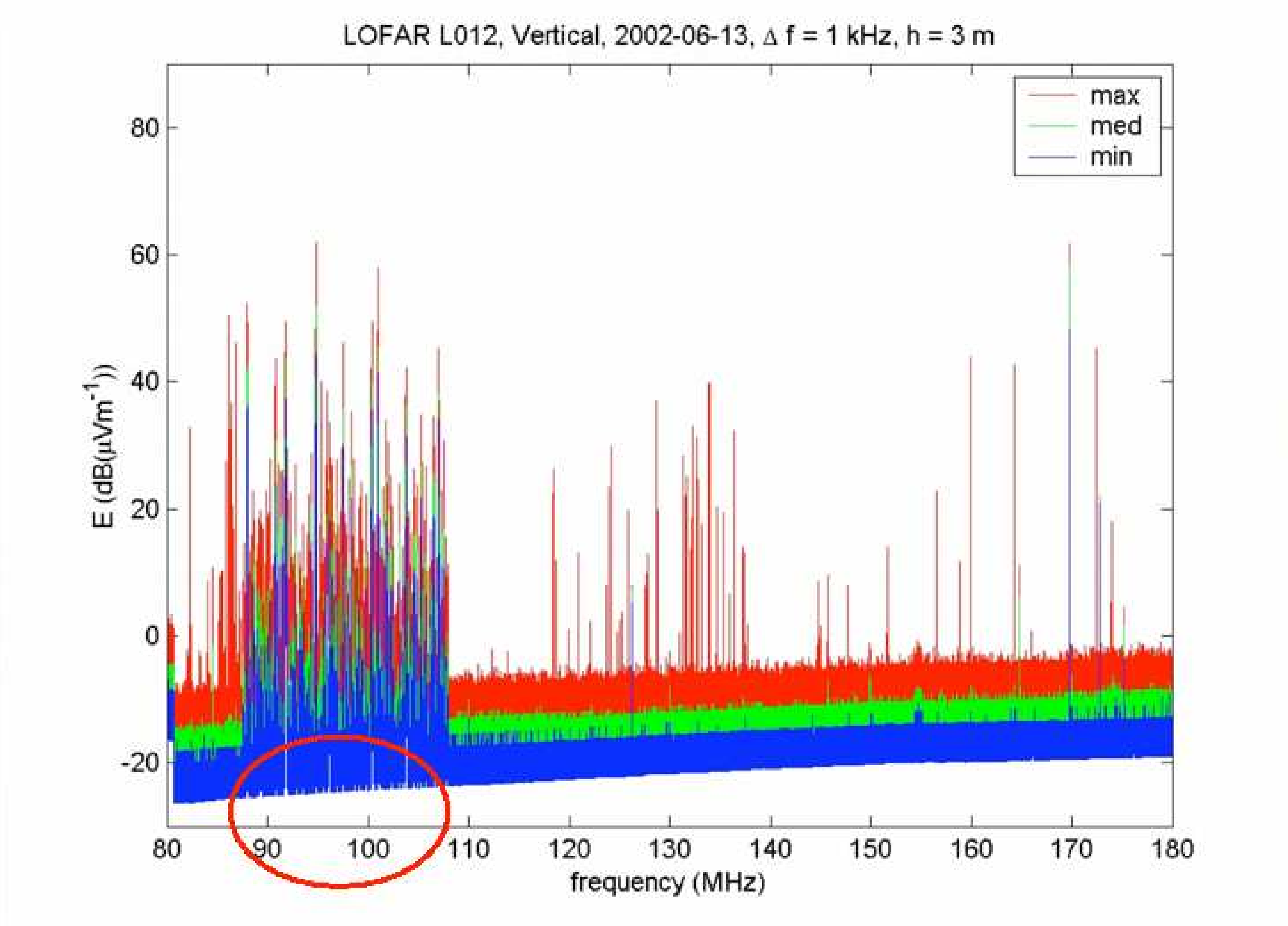
1) Levels of RFI are high $\Rightarrow$ non-linearity $\Rightarrow$ 12-bit sampling needed

2) Time-frequency occupancy is key issue

3) Many strong signals are broadcast from space satellites (you can not hide) !

But remember that most science is continuum science and not all frequencies are always needed !

Initial RFI campagne ('02) in NL at 1 kHz resolution



FM band

LOFAR has superb frequency resolution to deal with RFI

Two 12-bit ADC sampling modes: 160 or 200 MHz clock

Frequency filtering done in two digital (Poly-Phase-Filter) stages:
- at station ⇒ 512 subbands (either 156 or 195 kHz)
- at CEP (BG/P) ⇒ 256 channels for ~ each of 200 subbands (~ 30 MHz total)

~ 50,000 channels
of 0.6 - 0.8 kHz !!

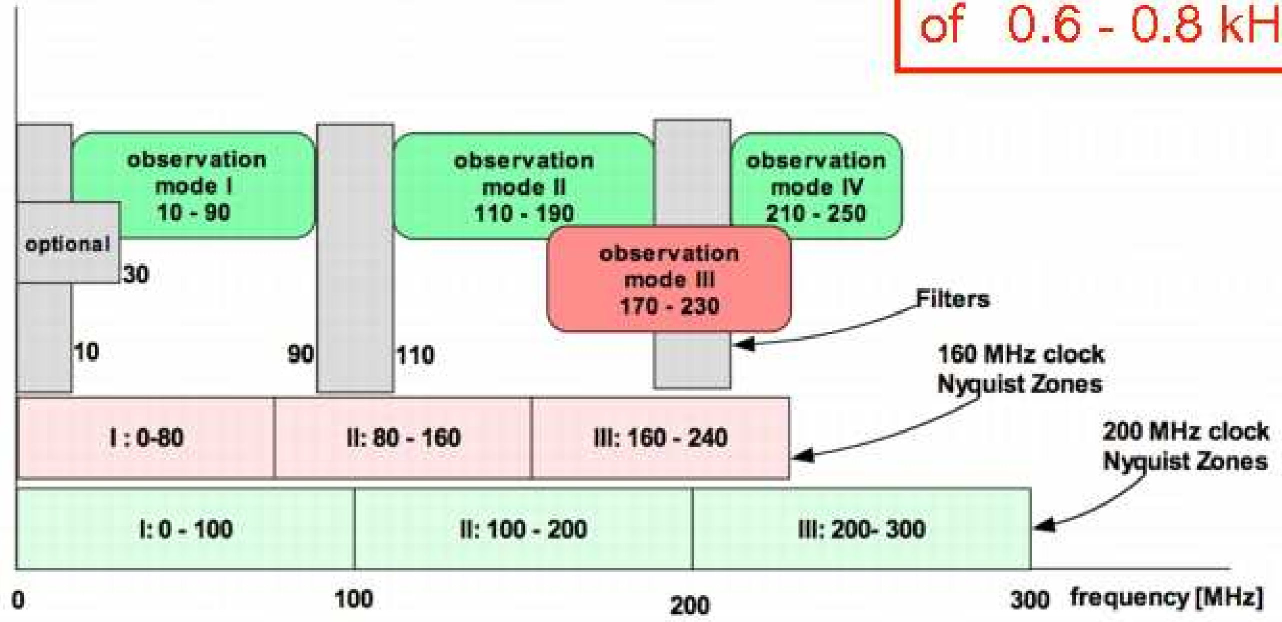
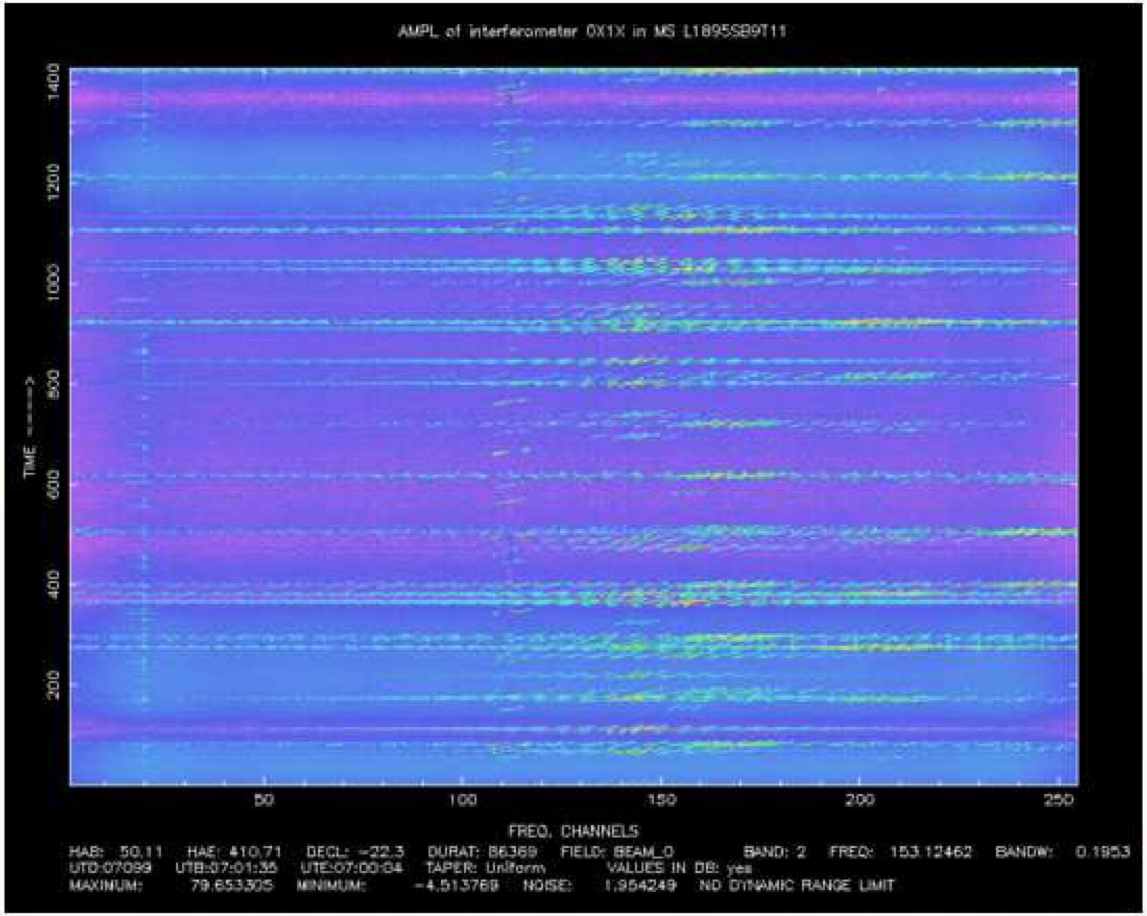


Figure 10 *Selection of Nyquist zones is used to select the observed band in the station.*

Dynamic spectrum at ~147 MHz (9apr07)

24h



~ 84 dB intensity range !!

(equivalent to ~20^m in optical!)

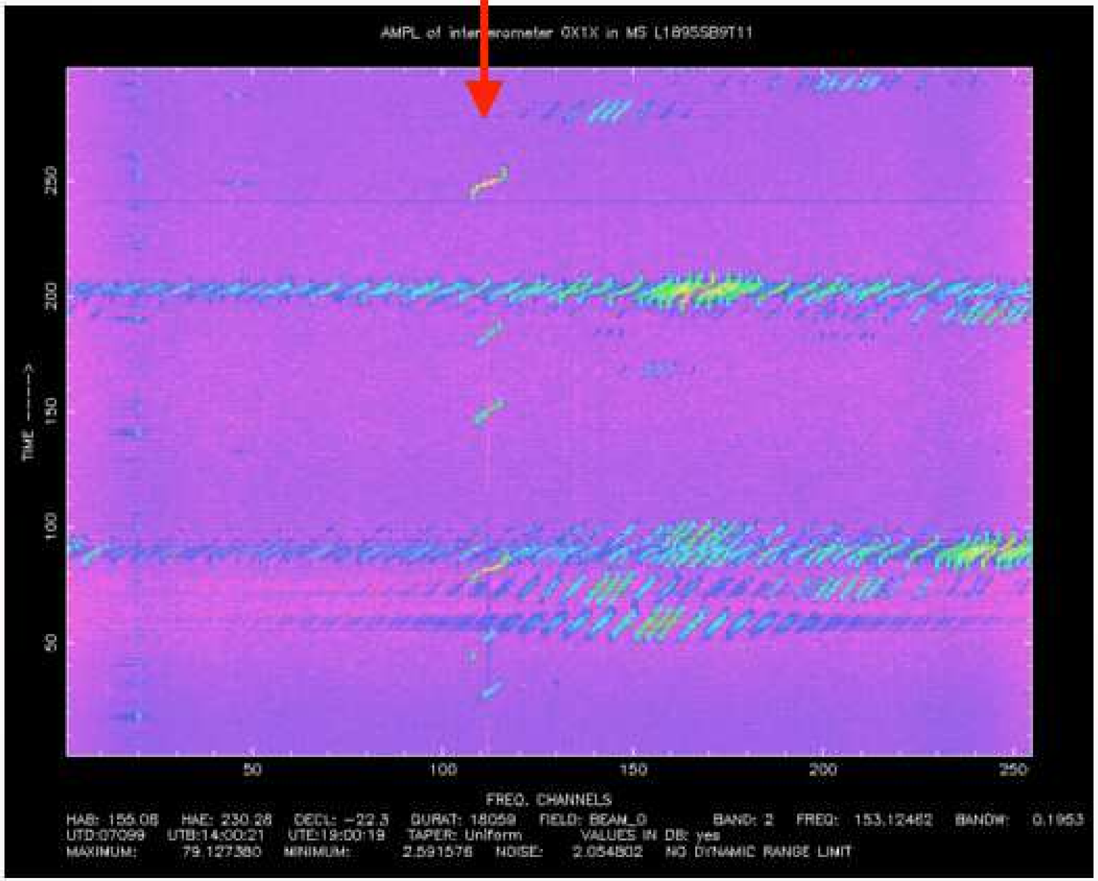
156 kHz in 256 channels

Drifting signals from LEO satellites at 147 MHz

exquisite spectral resolution !

8 kHz Doppler shift in 5-10m

time



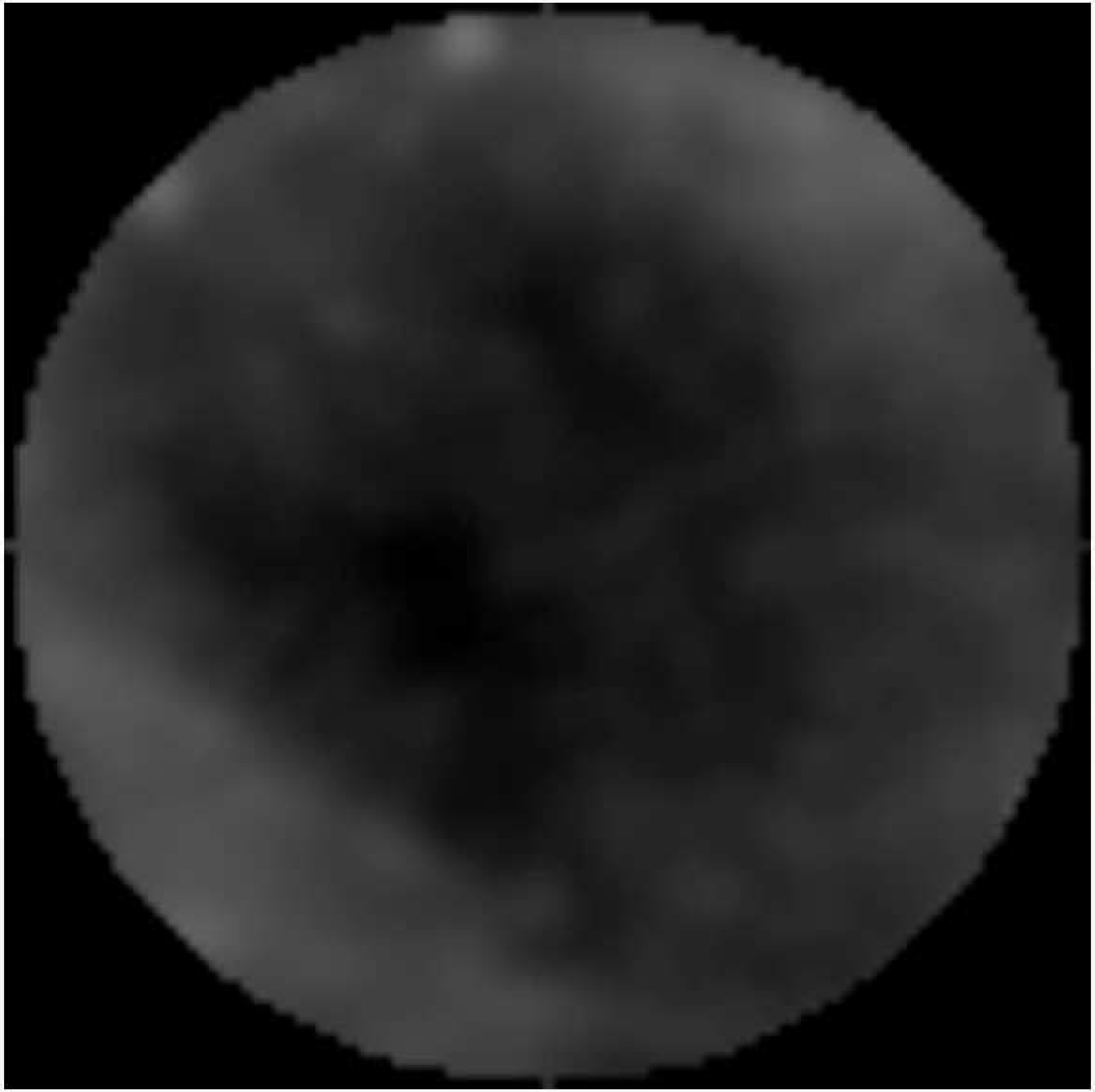
frequency

Movie from a LOFAR station at ~ 50 MHz

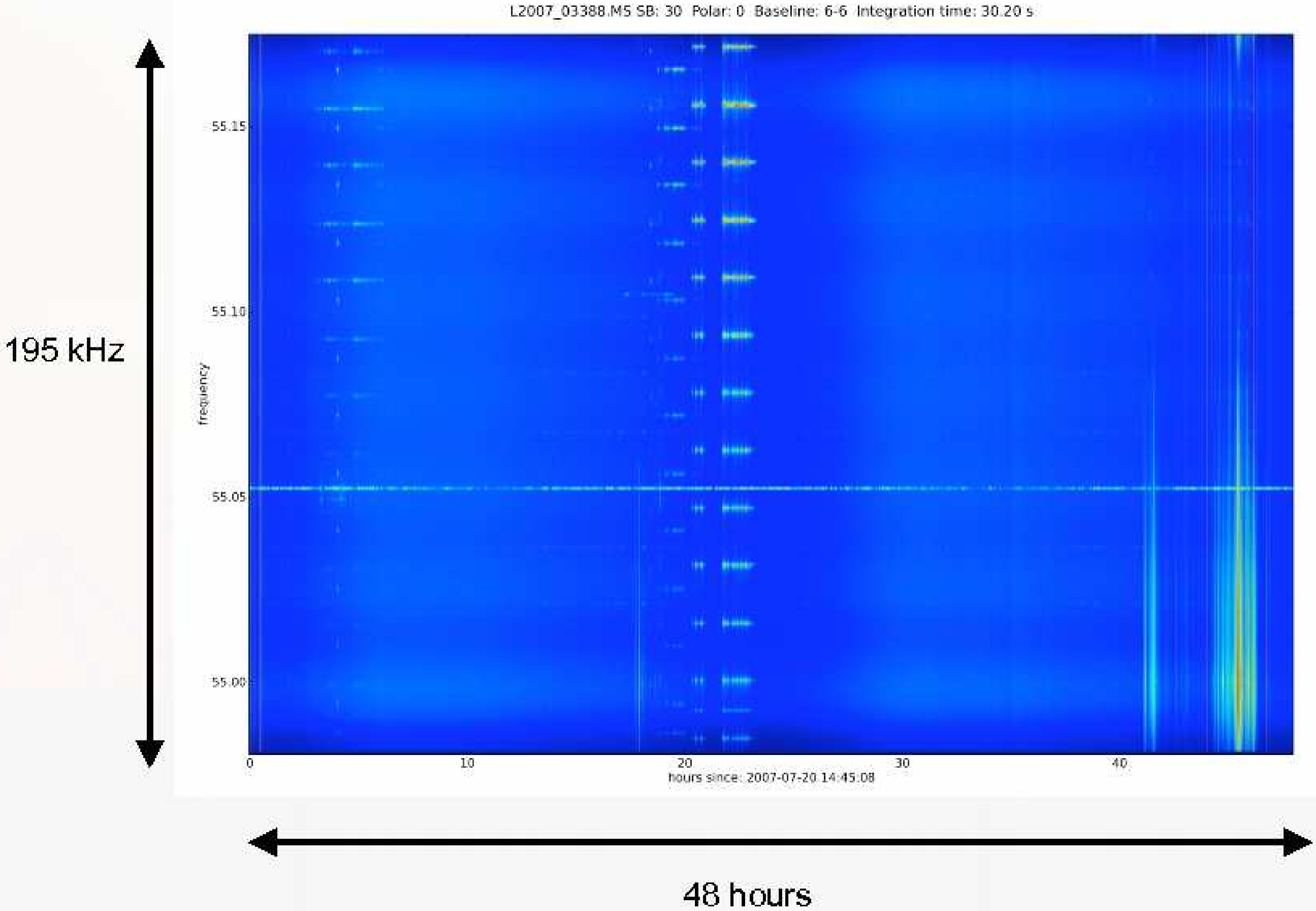
24 h

resolution 5°

M. Brentjens, 2008



Tracking airplanes at 55.05 MHz with LOFAR



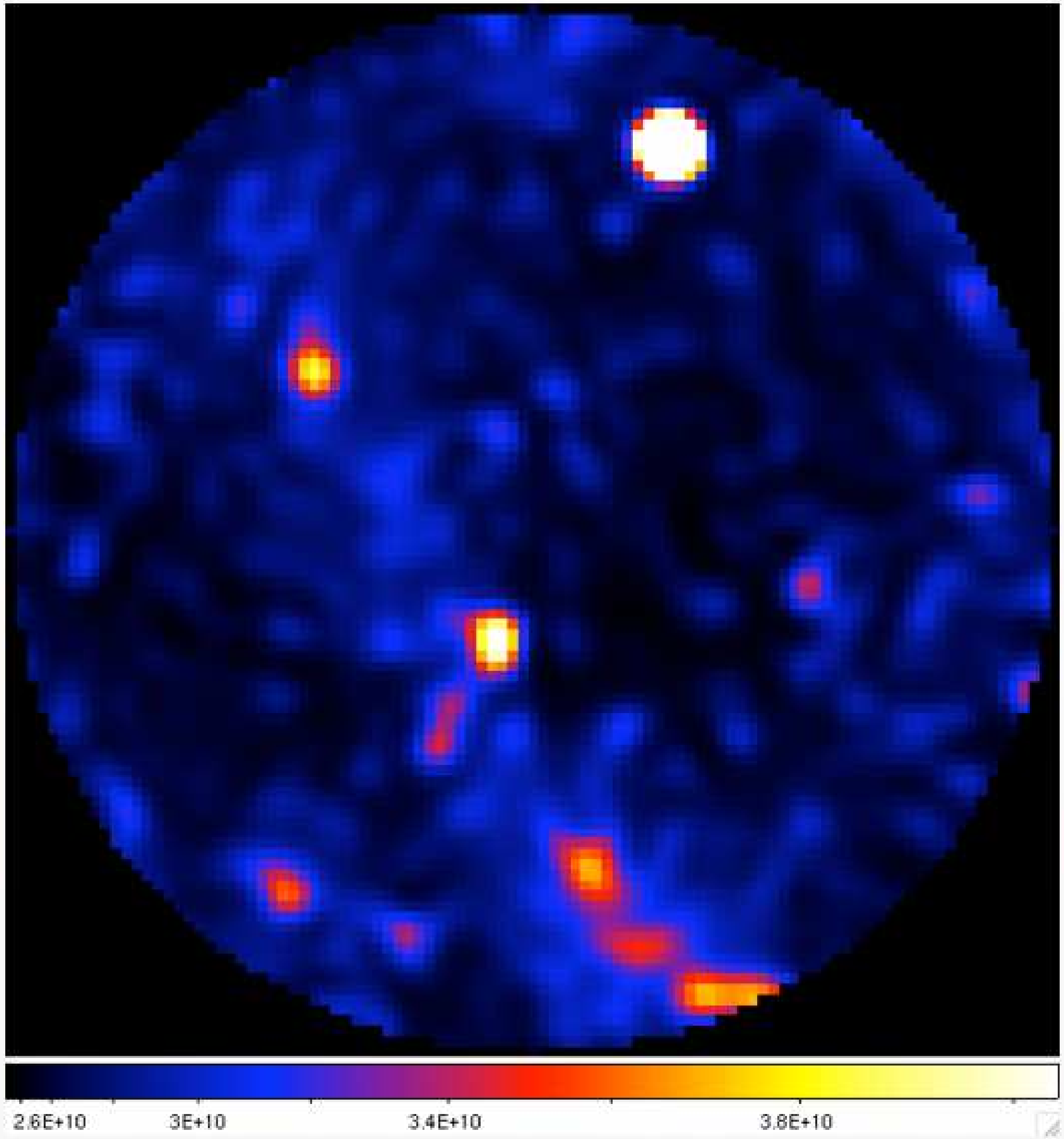
Airplane movie with LOFAR CS010 (25 Feb 2008)

Movie using 60 x 1s snapshot all-sky images using the LOFAR CS10 stationcorrelator at a frequency of about 55 MHz.

It contains the emission from the Milky Way, CasA and CygA, as well as a moving airplane illuminated by reflected emission from a 55.05 MHz Danish TV transmitter (~ 400km NE from Exloo)

Note drifting sidelobe patterns of the airplane reflected signal !

Another airplane, as well as a meteorite show up briefly at the end of the movie



LOFAR science

The specifications and capabilities of LOFAR were mainly driven by

6 Key Science Projects (KSP)

1) Surveys of the (northern) sky
2) Transients, Pulsars, (exo-)Planets
3) Epoch of Reionization
4) Cosmic Rays
5) Cosmic Magnetism (polarimetry)
6) Sun and Solar system science

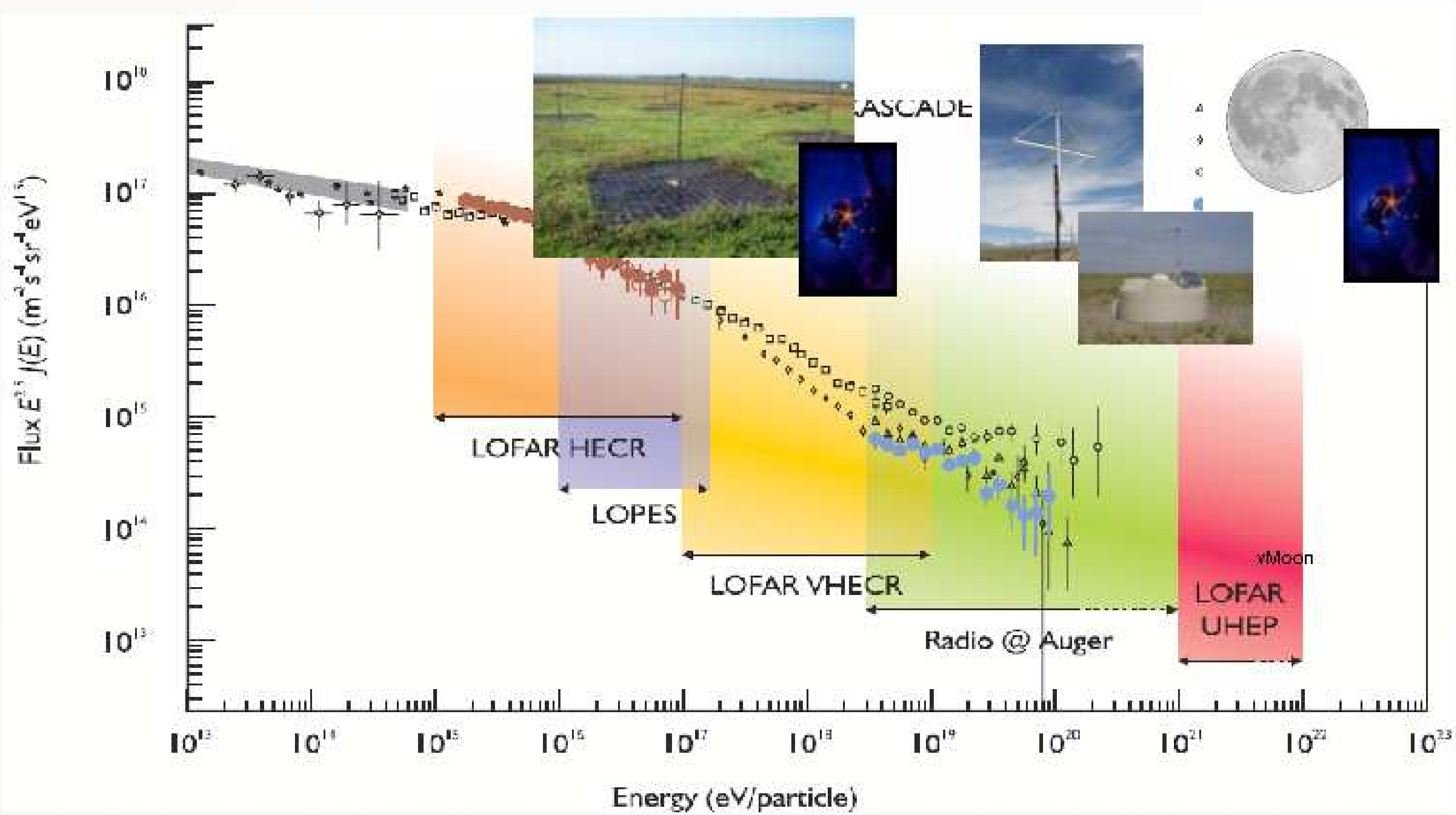
\+ other science applications still coming in…

All science done under ‘umbrellas’ of International Key Science Project teams, based at Leiden, Amsterdam, Groningen, Nijmegen (all NL) Bonn, Potsdam (Germany) Total more than 100 scientists involved. For their efforts they will be rewarded with guaranteed observing time (a fraction declining over a 5 year period)

(UHE) Cosmic Rays

KSP collaboration centered at
Radboud University Nijmegen

Cosmic Rays in the Radio

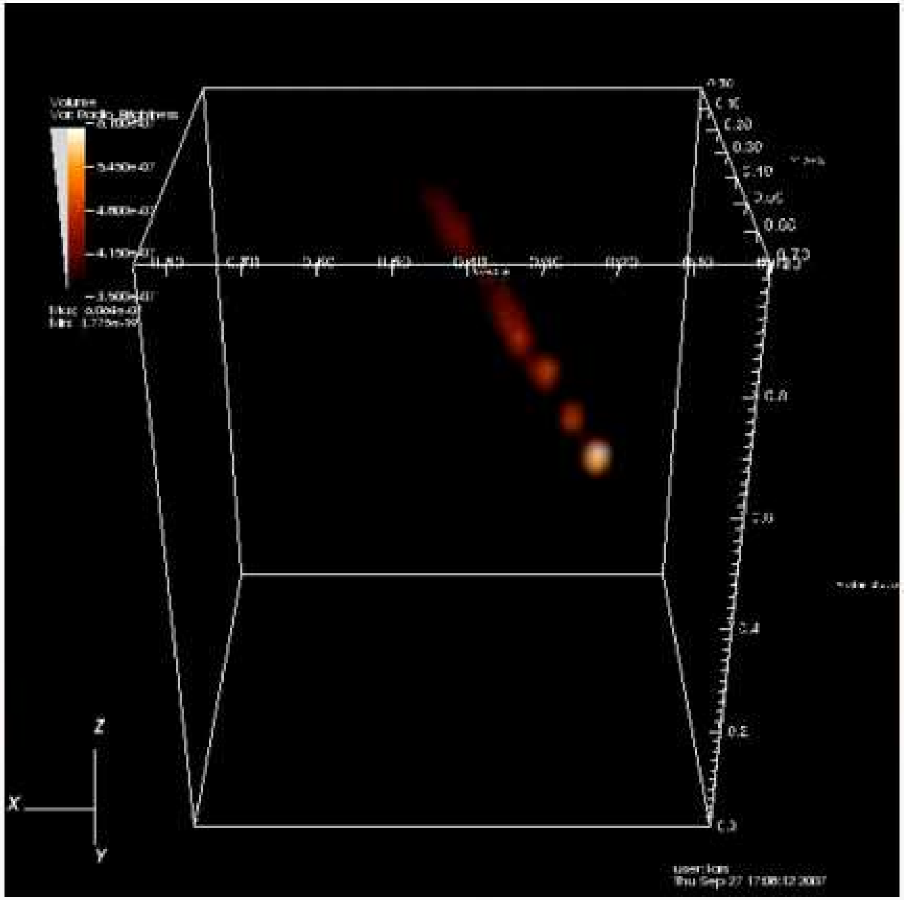


S. Lafebre

Nanosecond Radio Imaging in 3D

- Off-line correlation of radio waves captured in buffer memory
- We can map out a 5D image cube:
  - 3D: space
  - 2D: frequency & time
- Image shows brightest part of a radio airshower in a 3D volume at $t=t_{max}$ and all freq.
- Curved wavefront: Resolution in depth < 1km ?

Actual 3D radio mapping of a CR burst
No simulation!



Bähren, Horneffer, Falcke et al. (RU Nijmegen)

Memory Requirements for CR KSP

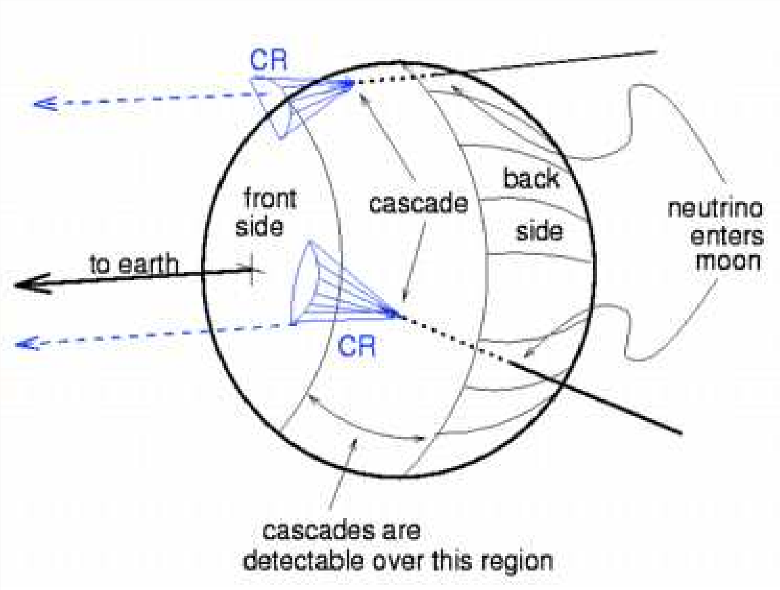
Various buffering mechanisms:

- Antenna buffers
  - Transient Buffer Boards:
  - ~0.5 GB per antenna
  - 1s full BW, 16 min (200 KHz)
  - 1TB full core dump (for 1 sec full BW)
  - ⇒ One Second All Sky Survey (OSASS): All sky in one sec and all frequencies
- Station beam buffer
  - Needs 0.87 TB per station per hour
  - Needs 15 TB per hours for core, 36 Gb/s data rate
  - ⇒ 40 squaredeg for hours, 500 hours to survey entire sky, need in total 7.5 PB for 1 h per pointing
- Incoherent Station beam
  - 1.9 TB per hour, 2Gb/s data rate, in piggy-back mode
  - 40 deg° continuously for 500 hours needs 1 PB
- Tied array beam
  - Needs 1.8 TB per hour
  - 30 beams to cover moon, need 200 Tb for 4 hour run.

Ultra-High Energy (Super-GZK) Neutrino Detections

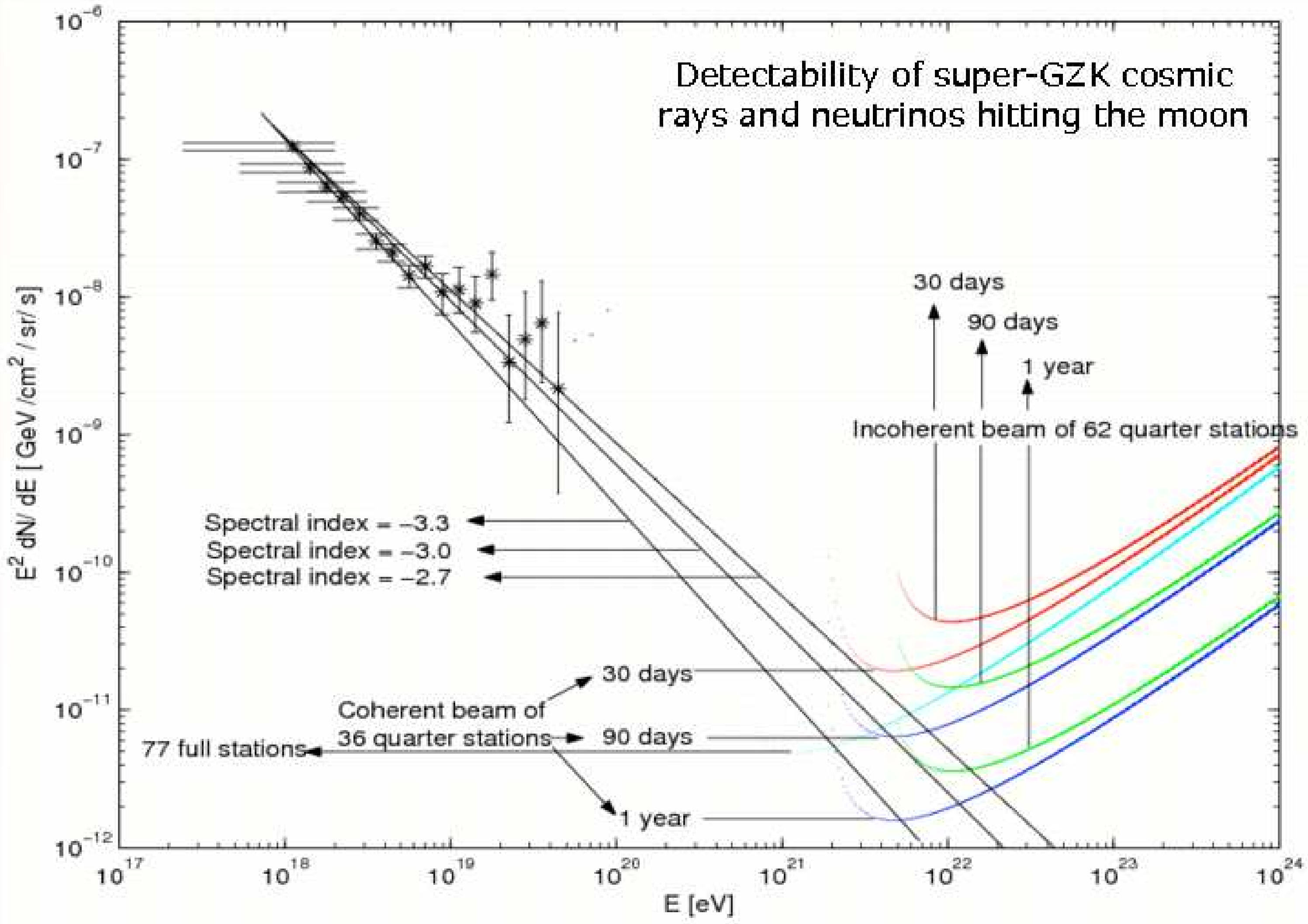
- Ultra-high energy particle showers hitting the moon produce radio Cherenkov emission (Zas, Alvarez-Muniz, Gorham, ...).
- This provides the largest and cleanest particle detector available for direct detections at the very highest energies.
- In the forward direction (Cherenkov cone) the maximum of the emission is in the GHz range.
- However at lower frequencies the radio emission is much more isotropic and count rates are higher.

radioflashes from neutrinos hitting the moon



from Gorham et al. (2000)

WSRT/LOFAR NuMoon experiment Scholten et al, 2008)



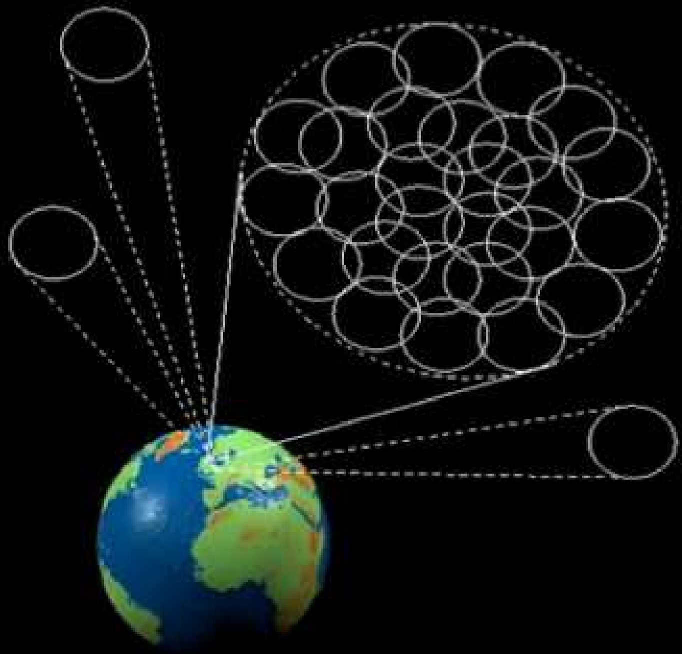
Transient KSP

collaboration centered at
Amsterdam, NL

Transient science overview

Transients with LOFAR

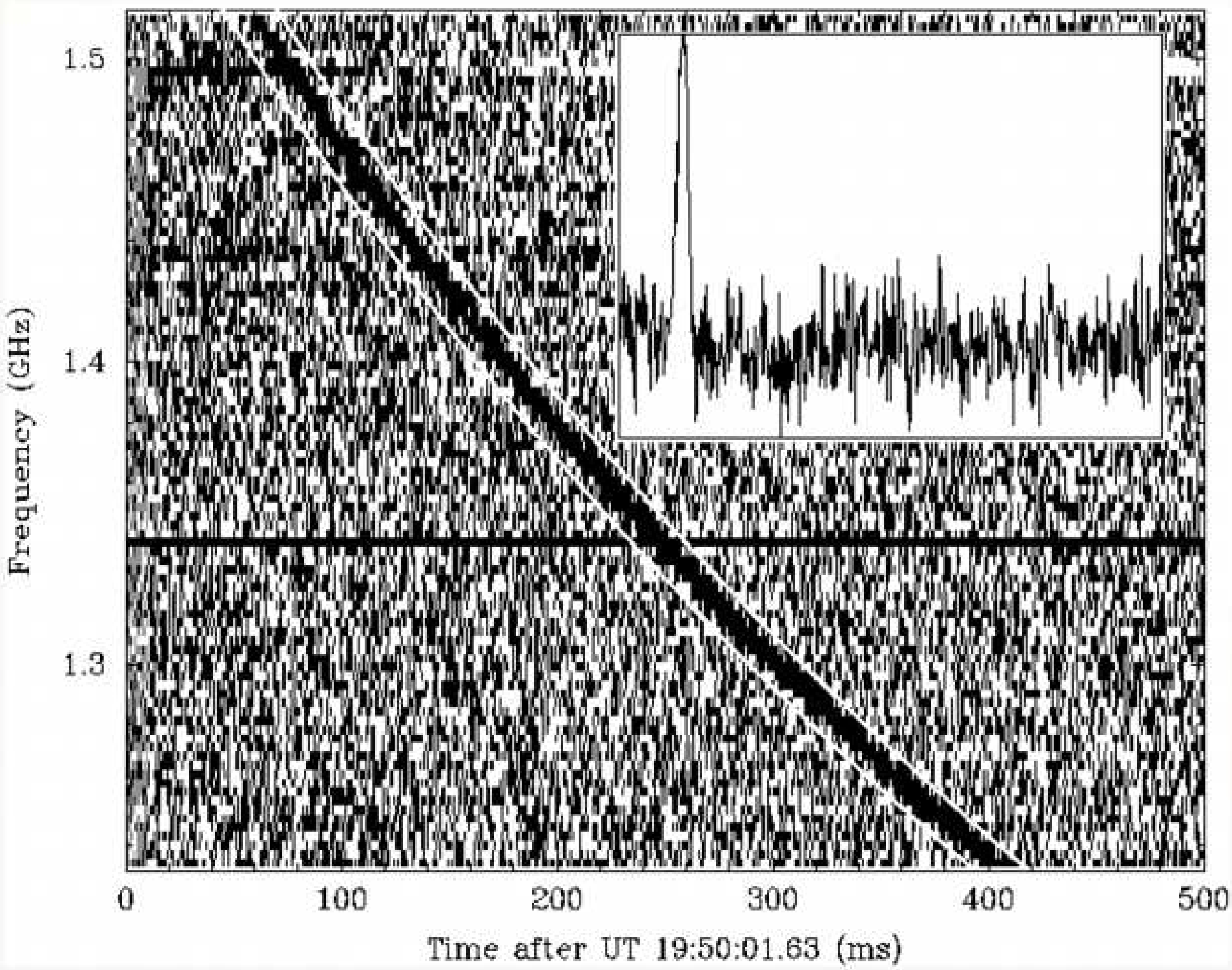
LOFAR will provide the first **Radio Sky Monitor** monitoring **all transient and variable radio phenomena**



- Accreting black holes / neutron stars / GRB afterglows
- Pulsars : LOFAR will at least double the number of known pulsars
- Extrasolar planets, active flare stars
- Counterparts to GW sources – tests of gravity on cosmological scales
- Serendipity, SETI ....

Fender et al, dec 2008 (www.transientskp.org/workshop)

The Lorimer transient: a strange new source?



S = 30 Jy

5 ms

dispersion -->
DM=375 !

--> cosmological !?

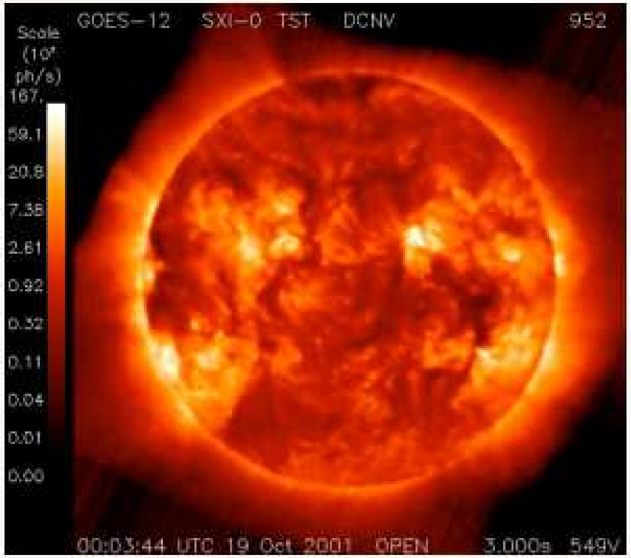
Lorimer et al, Science , Sep2007

Solar and Solar System KSP

collaboration centered at Potsdam, Germany

Objectives of solar observations

Mann & Vocks, 2008



Long-term evolution:

- Development of solar active regions
- Changes preceding a solar flare

Radio burst studies:

- Rapid evolution of the source
- External or internal triggering
- Development of the burst in the corona
- Space Weather connections

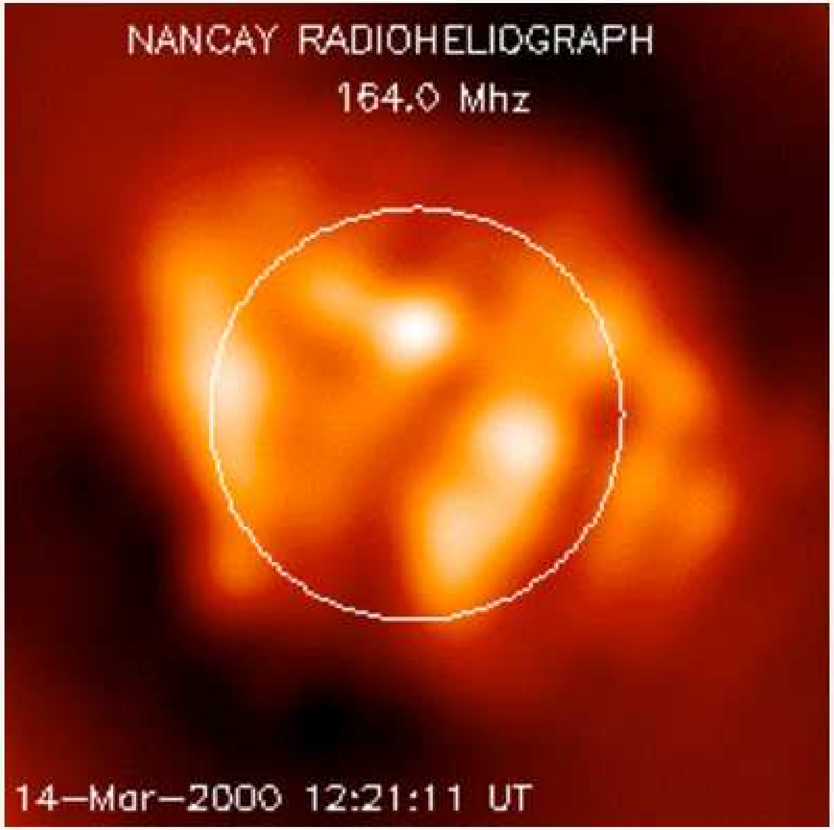
Dedicated observation campaigns:

- Complementary to e.g. X-ray, EUV, optical

These objectives rely on LOFAR's imaging capability

LOFAR imaging of the Sun

Mann & Vocks, 2008



LOFAR's imaging capability:

- Theoretical limit: <1"

Solar corona:

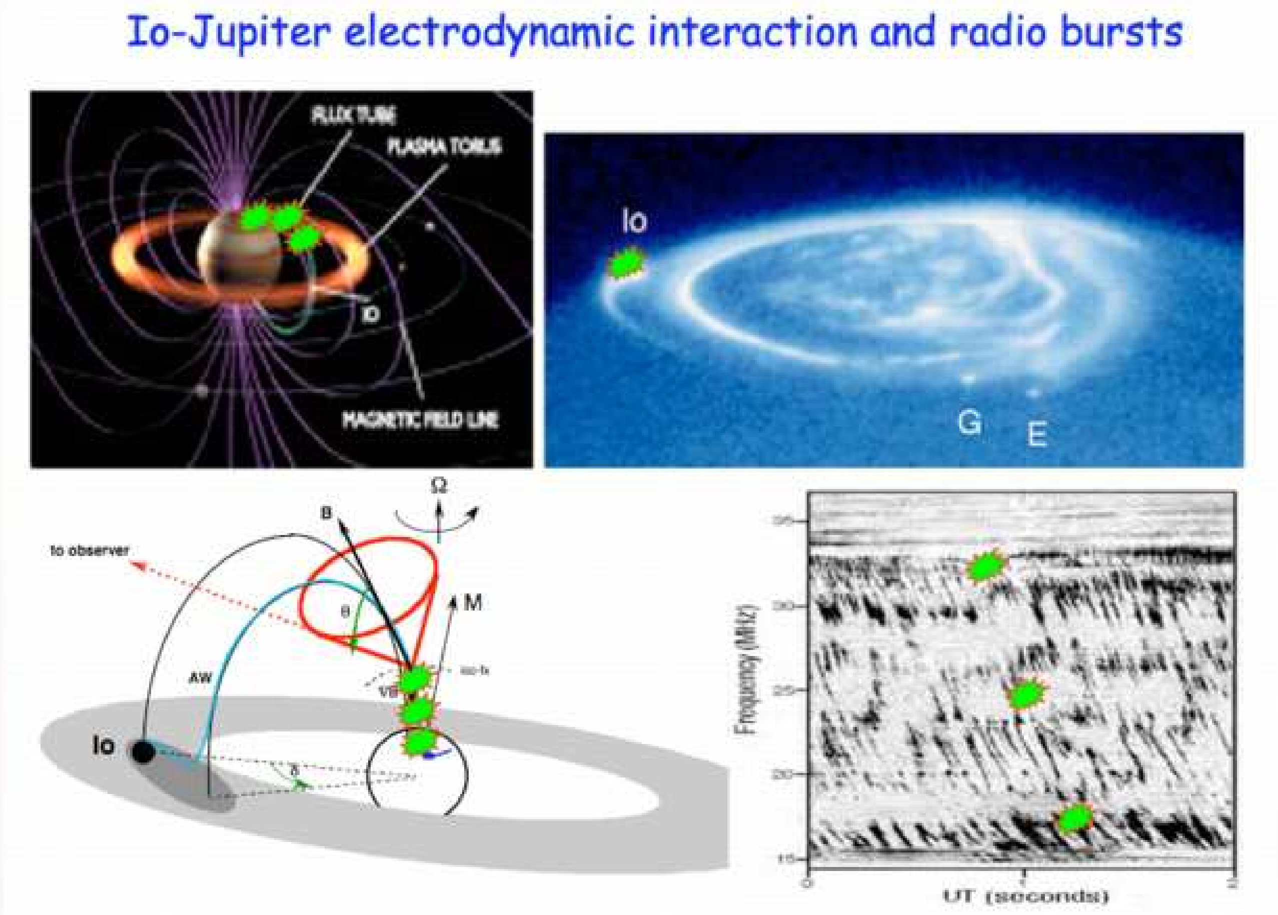
- Scattering of radio waves
- Resolution 40-60"

LOFAR will provide radio images of the middle and upper solar corona.

LF planetary radiosources : plasma phenomena

Radio component	Planet	Frequency	Radiation process
Radiation belts	J	<100 MHz - GHz	Synchrotron (incoherent)
Auroral	E J S U N	10's kHz - 10's MHz	Cyclotron Maser (coherent)
Satellite induced	J (I,G,C?) S?	100's kHz - 10's MHz	Cyclotron Maser (coherent)
Lightning	E (J) S U (N)	kHz - 10's MHz	Antenna radiation (current discharge)
VLF e.m. (NTC, nKOM…)	E J S U N	≤10's – 100 kHz	Mode conversion e.s.→ e.m. Instabilities ~f_{pe}, f_{UH} ?

Jupiter-IO interactions at 25 MHz



Resolving Jupiter at 25 MHz takes a ~1000 km array !

Epoch of Reionization KSP

collaboration centered at Groningen,NL

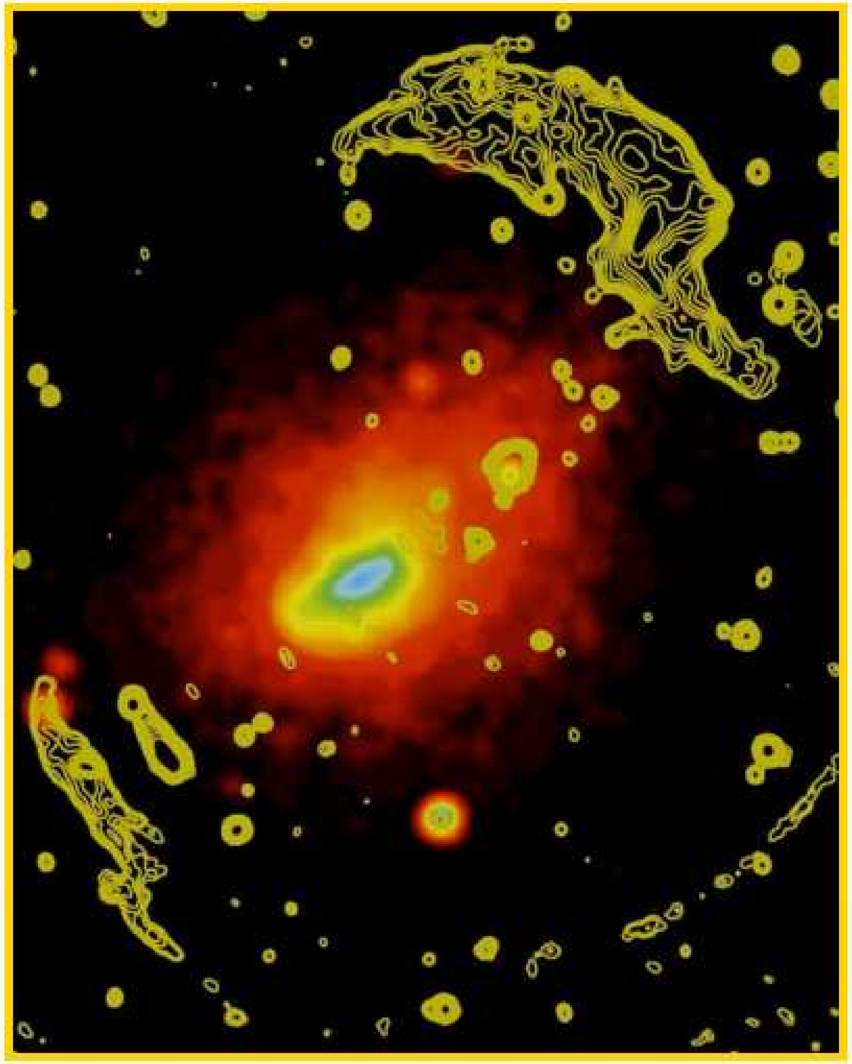
Surveys KSP

collaboration centered at Leiden, NL

Main drivers of LOFAR sky surveys

- 100 z ~ 6 radio galaxies
  - Formation and evolution of massive galaxies, black holes and clusters
- 100 cluster radio sources at z > 0.6
  - dynamics of cluster gas, evolution of cluster wide magnetic fields
- 10 clusters of starbursts starbursts at z>2
  - SFR ~ 10 M_0/yr at z=2-3
- Serendipity
  - << 30 MHz

Diffuse relic/LSS radio emission around clusters



Johnston-Hollitt et al, 2003

Abell 3667

Rottgering et a, 1997l

Magnetism KSP
and
Polarization results at low frequencies

collaboration centered at Bonn

Overview of scientific themes in Magnetism KSP

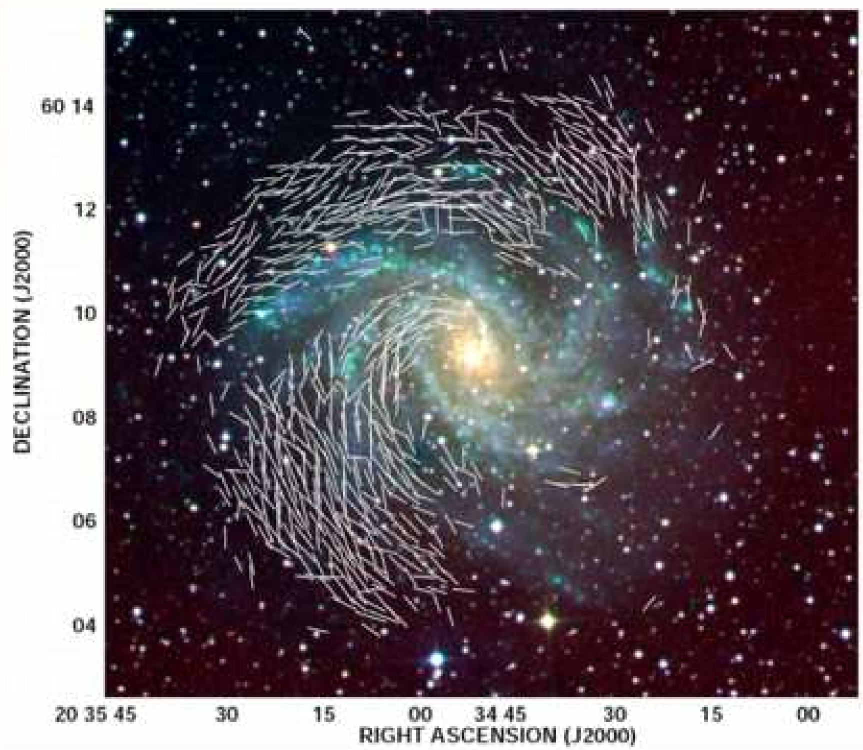
- Solar system: IPM and CME's
- Our Galaxy (SNR)
- Galactic foreground (…EoR nuisance)
- Disk and haloes of spiral Galaxies
- Dwarf galaxies
- AGN and giant radio galaxies (e.g. DDRG)
- Clusters , LSS and Cosmic Web

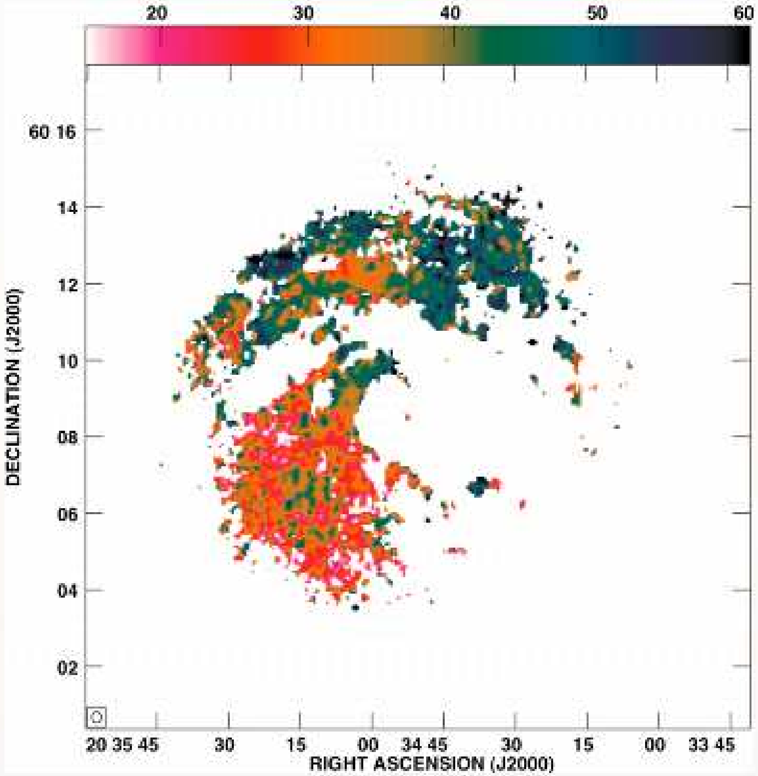
- …anything that is polarized ….

e.g. NGC 6946 Faraday rotation gradient/structure

WSRT data 18+21cm

Heald et al, in prep





Interarm regions have about 3 mJy/30" beam of polarized emission at 150 MHz **IF** not Faraday-thick **and** no beam-depolarization

Important tool : RM synthesis

Brentjens and de Bruyn (2005)

1) Linear polarization vector: $P = Q + iU = p\, I\, e^{2i\chi}$

   where I, Q, U (V) are the Stokes parameters, p = % polarization, and $\chi = 0.5\,\mathrm{atan}(U/Q)$ is the polarization angle

2) When observing the polarized power P at a range of λ^2 we can define:

$$P(\lambda^2) = W(\lambda^2) \int F(\phi) \exp(2i\phi\lambda^2)\, d\phi$$

where $F(\phi)$ is the complex polarized power per unit Faraday depth ϕ first defined by Burn (1966), and $W(\lambda^2)$ is the window function of the instrument

3) This relation can be Fourier inverted to yield $F(\phi)$

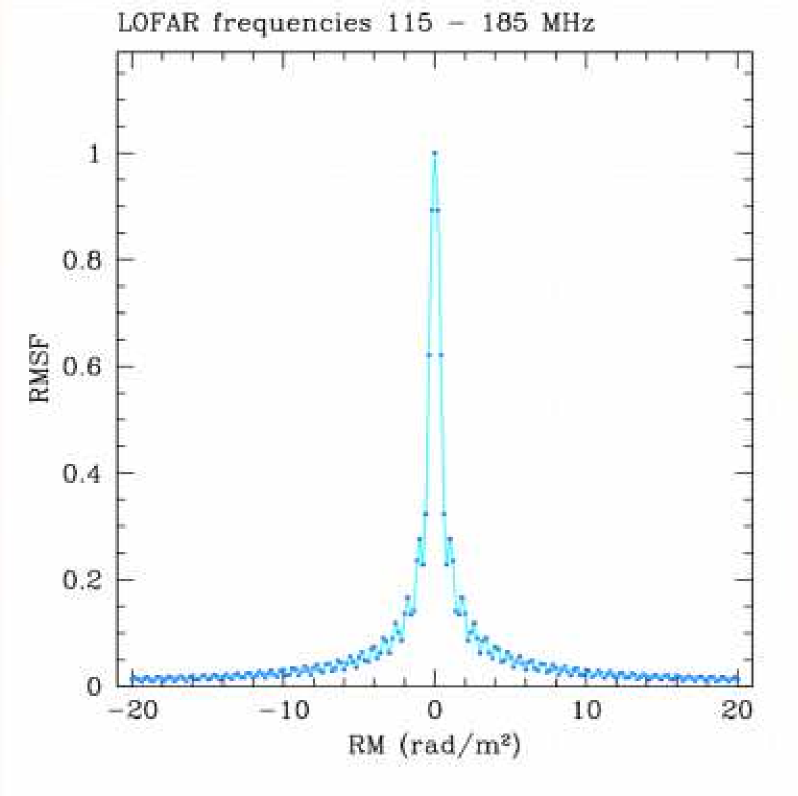
The derived quantity $F(\phi)$, also called the Faraday depth spectrum, is convolved with a response function, the RMSF, which gives the resolution in RM-space. In complex situations, deconvolution is still required. Note that the RMSF is the FT of the window function $W(\lambda^2)$ in λ^2 space.

The output of RM synthesis is a cube of (Q,U) images

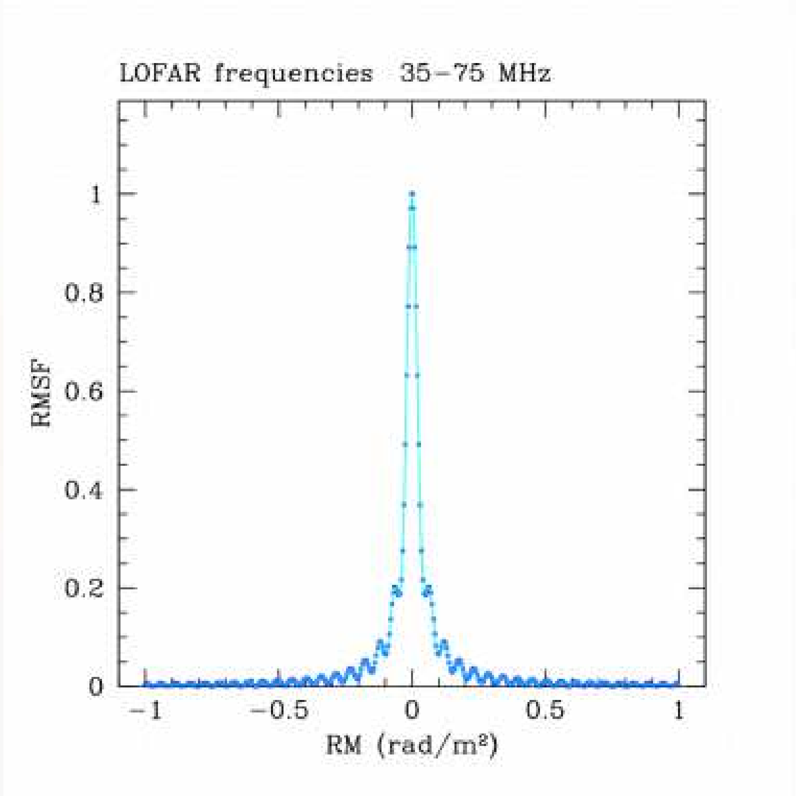
in 'Faraday depth' space.

Exquisite RMSF's at LOFAR - frequencies !

115 - 185 MHz
halfwidth ~ 1.0 rad/m^2

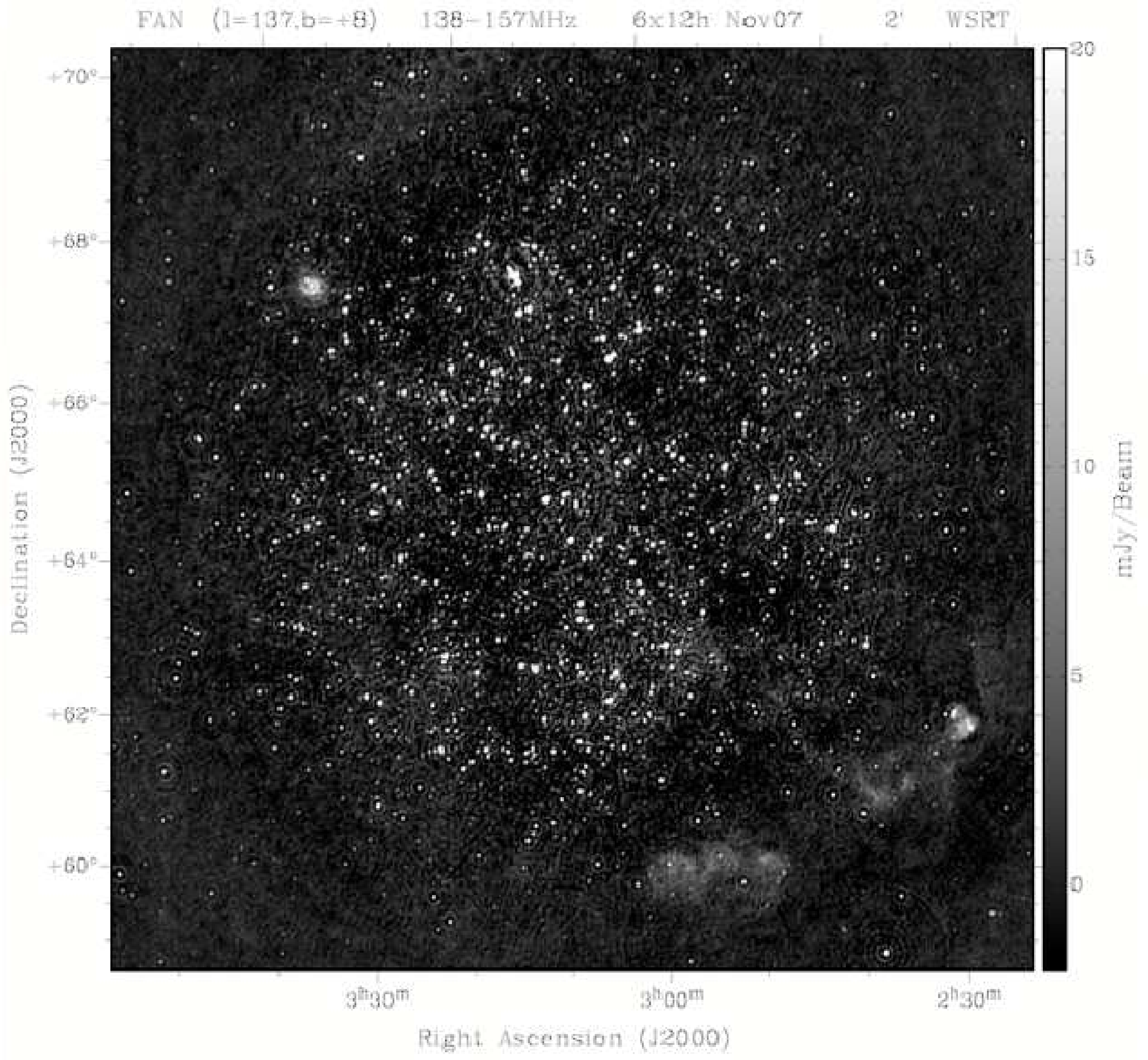


35 - 75 MHz
halfwidth ~ 0.05 rad/m^2



Deepest WSRT 150 MHz image:

Bernardi et al 2009

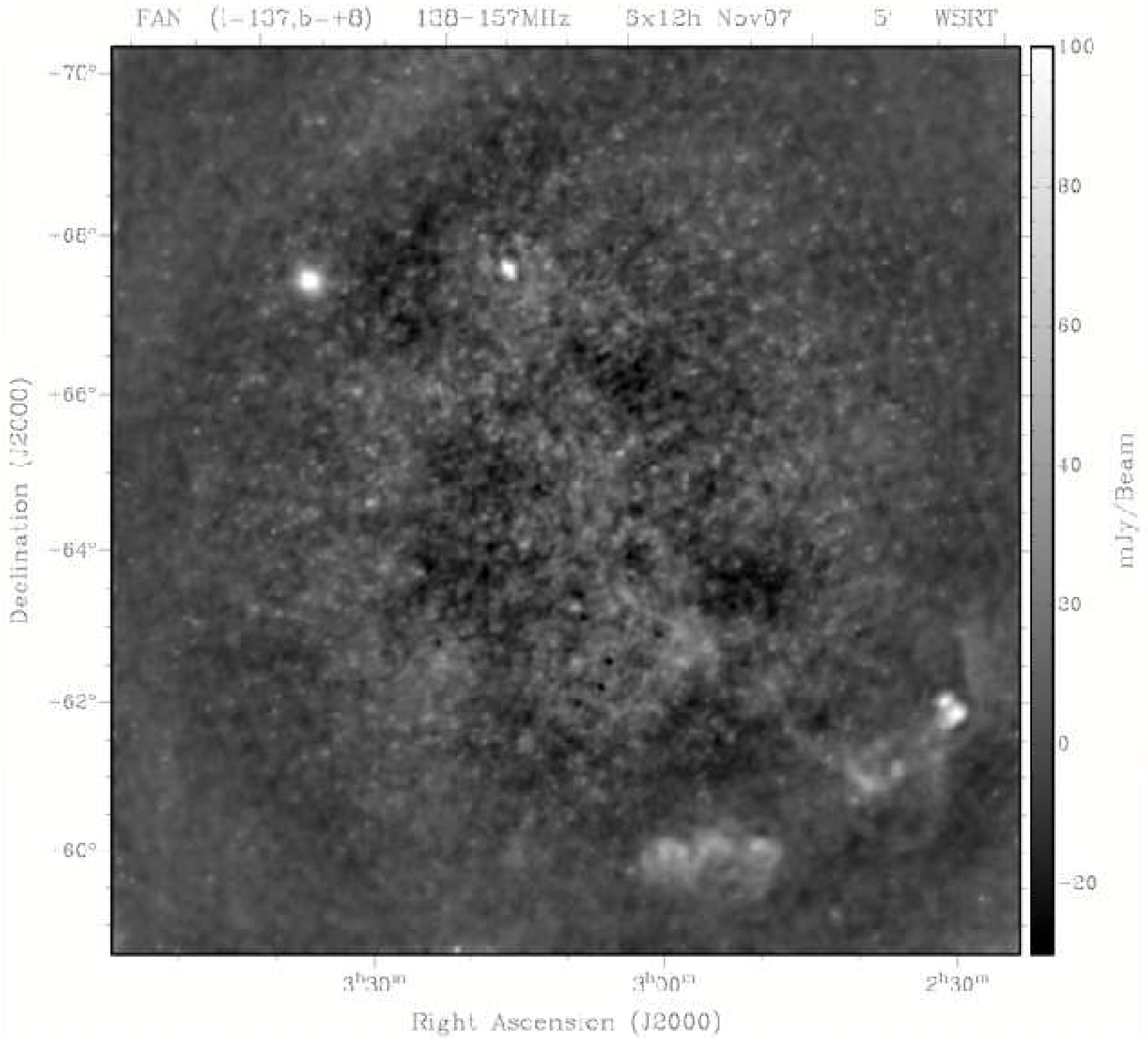


Stokes I

range

-2, 20 mJy

Galactic foreground fluctuations in Stokes I

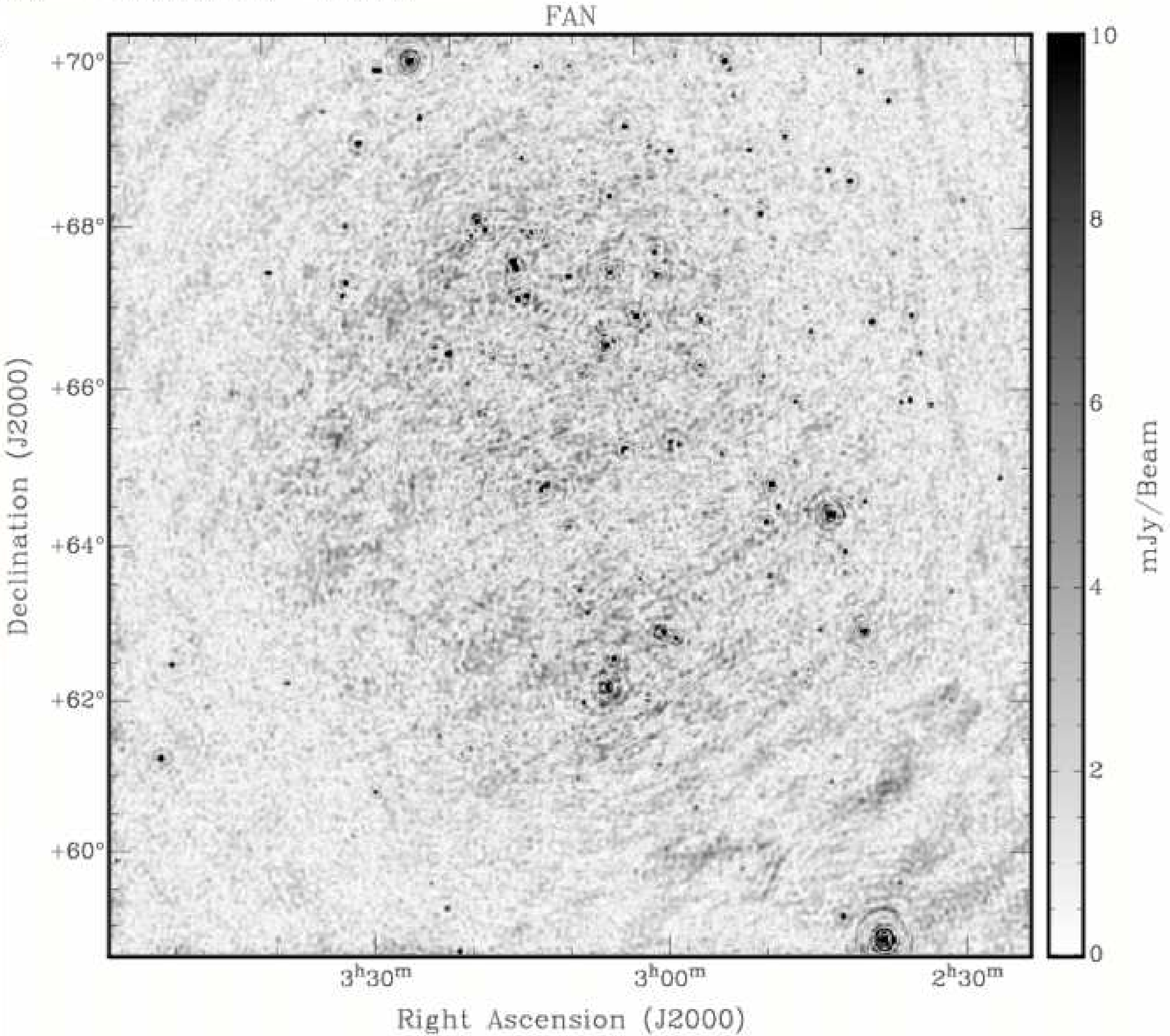


Residual image after subtracting sources to 20 mJy and smoothed to 5'

range

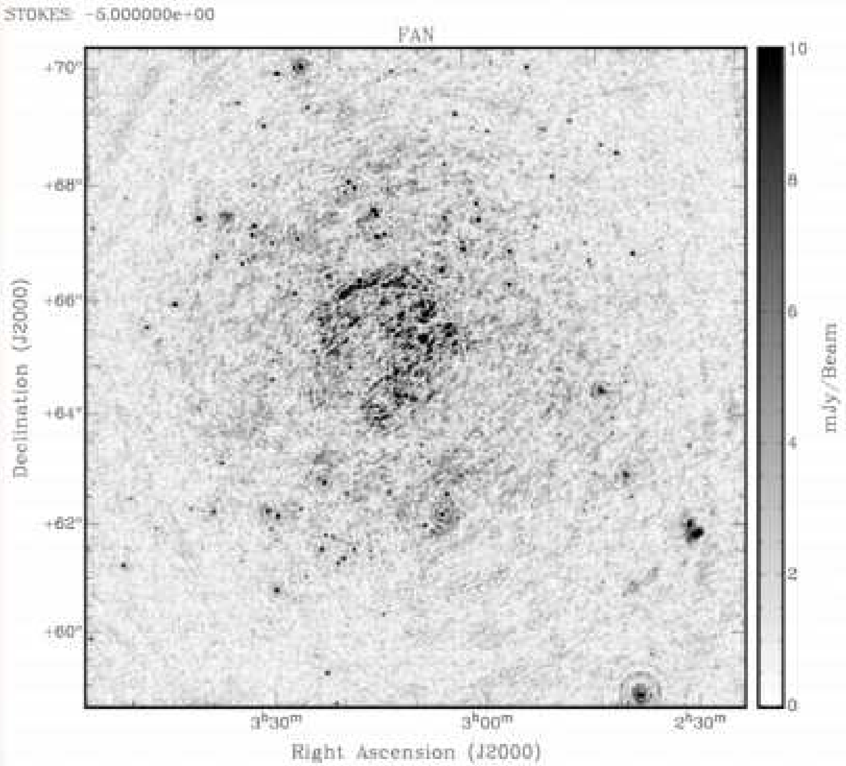
-30,100 mJy

RM= 4.000000e+00 rad/m^2

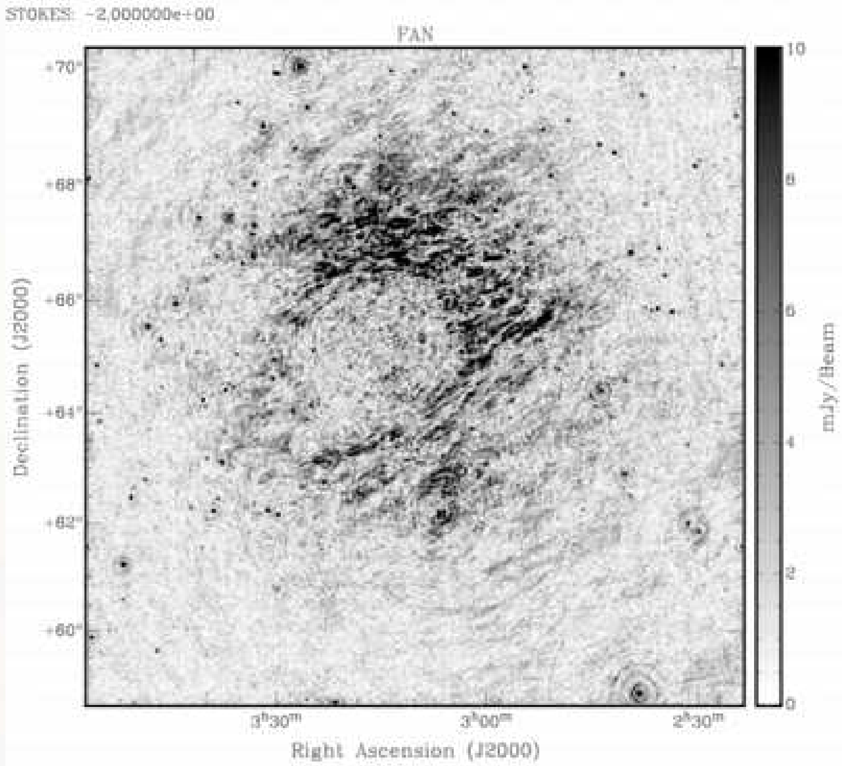


Polarized intensity distributions in/around 'the ring'

RM = - 5 rad/m^2



RM = - 2 rad/m^2

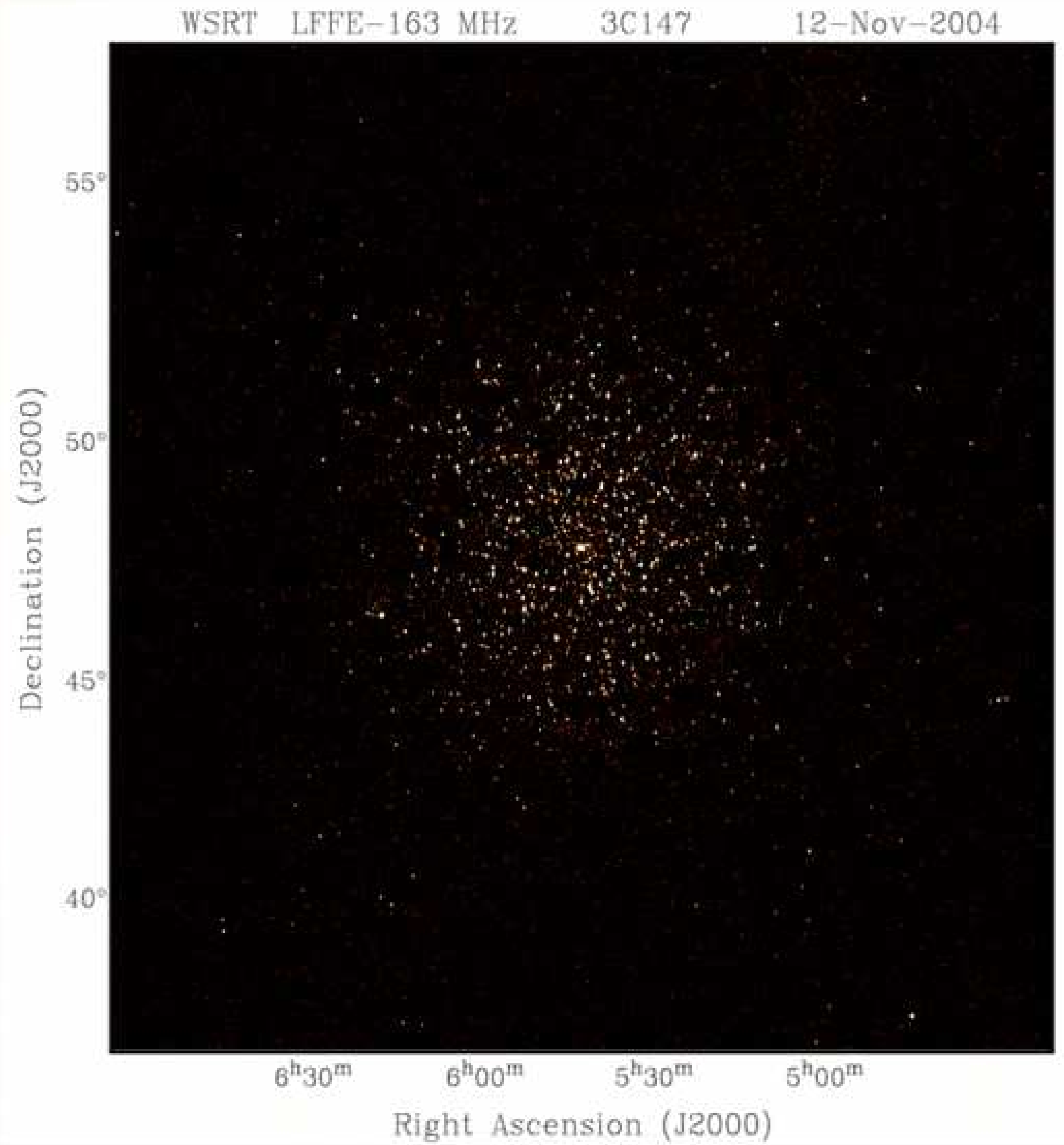


NO enhanced synchrotron emission associated with the ring !

Ring appears to be some sort of 'Faraday bubble'

First results and images from the WSRT at ~150 MHz and a ‘mini’ LOFAR

The first WSRT 150 MHz image (nov 2004)



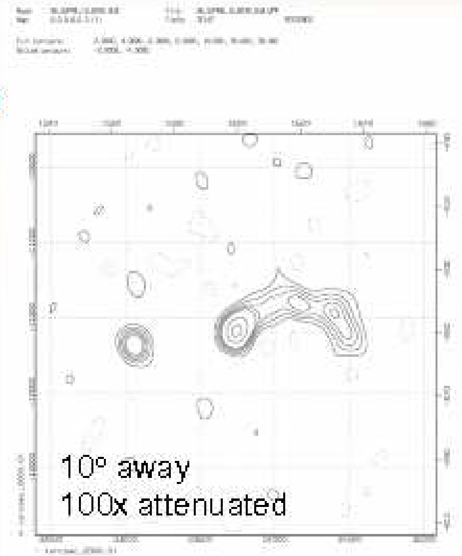
3C147 60 Jy pointsource

rms noise 3-4 mJy

VERY quiet ionosphere

Isoplanatic scale > 20° !!

3C129/129.1



‘mini’-LOFAR configuration: a ‘learning playstation’

Dec 06 --> Jan 09

- hardware distributed across 4 stations:
  - LBA: 96 dipoles (48 + 3x16)
  - HBA: 32 dipoles + 6 tiles
- per station: 4 -12 ‘micro’stations
- digital beamforming (with 4 - 48 dipoles)
- baselines from ~ 10 - 400 meter
- 16-24 ‘micro’stations

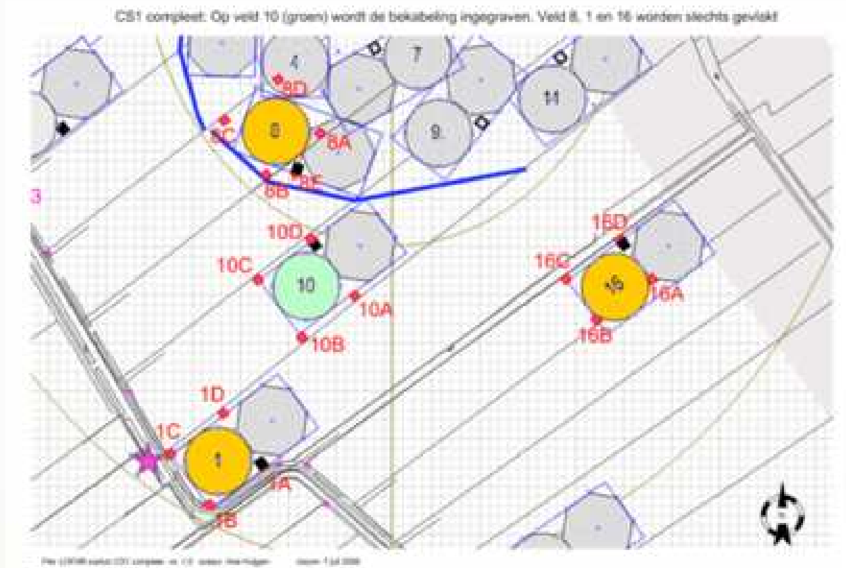


Figure 1: CS1 station locations.

400 m

Confusion limited LOFAR CS-1 image at ~ 50 MHz

Sarod Yatawatta (aug07)

3 x 24h

38 - 59 MHz (B=6 MHz)

Image made from

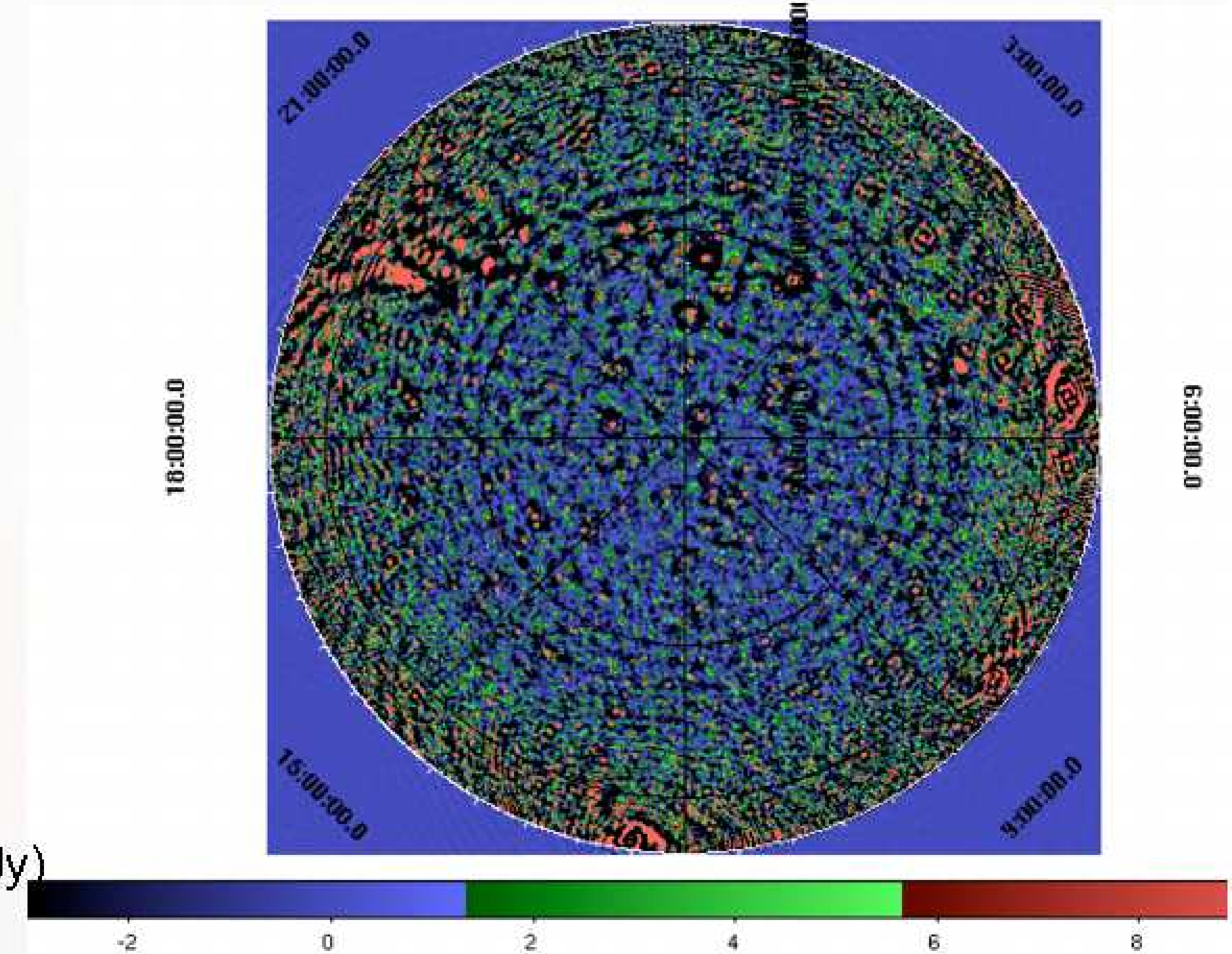
16 dipoles

(~ 70 baselines only)

~ 800 sources !

PSF ~ 0.5°

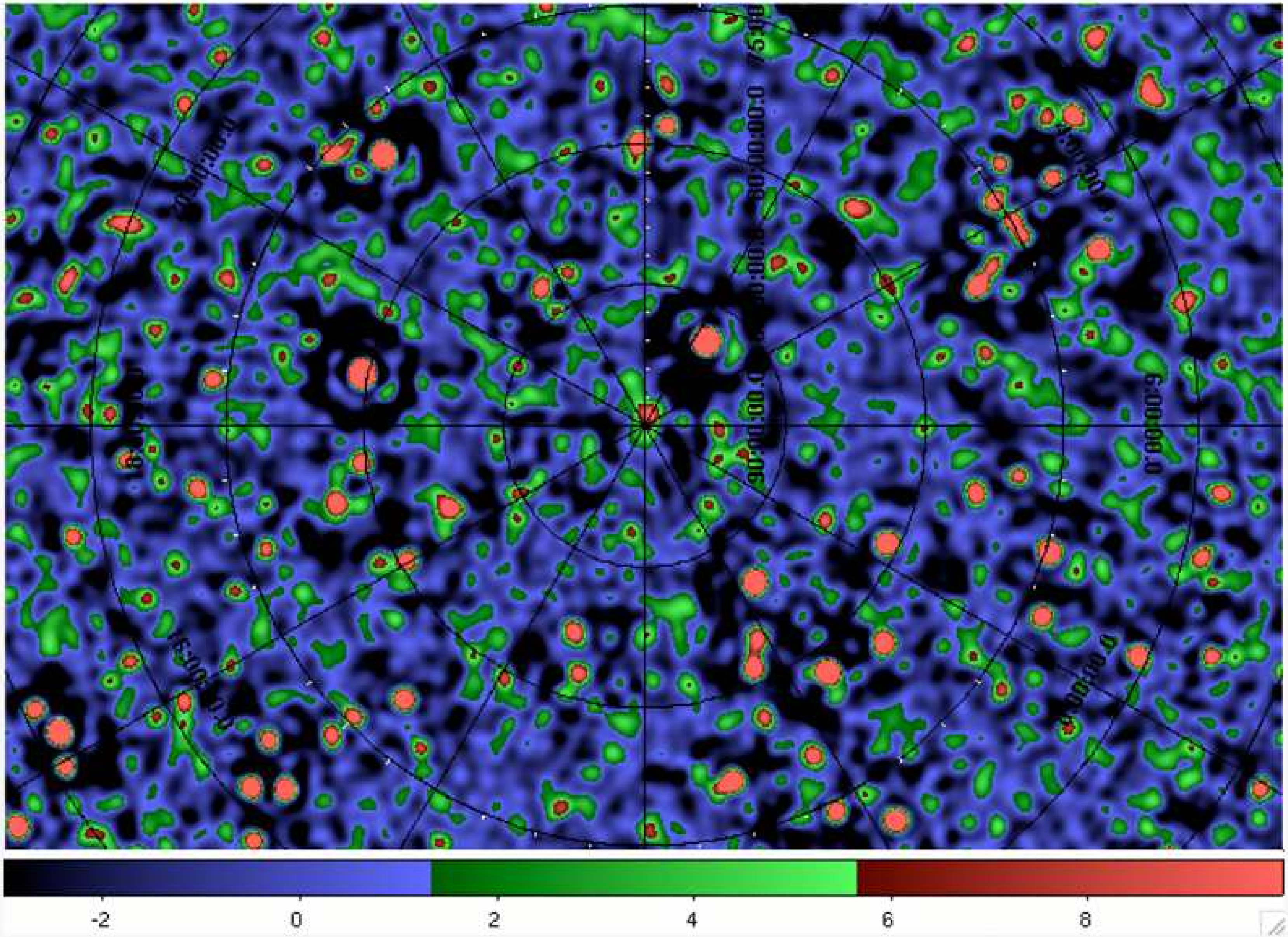
noise ~ 0.5 - 1 Jy



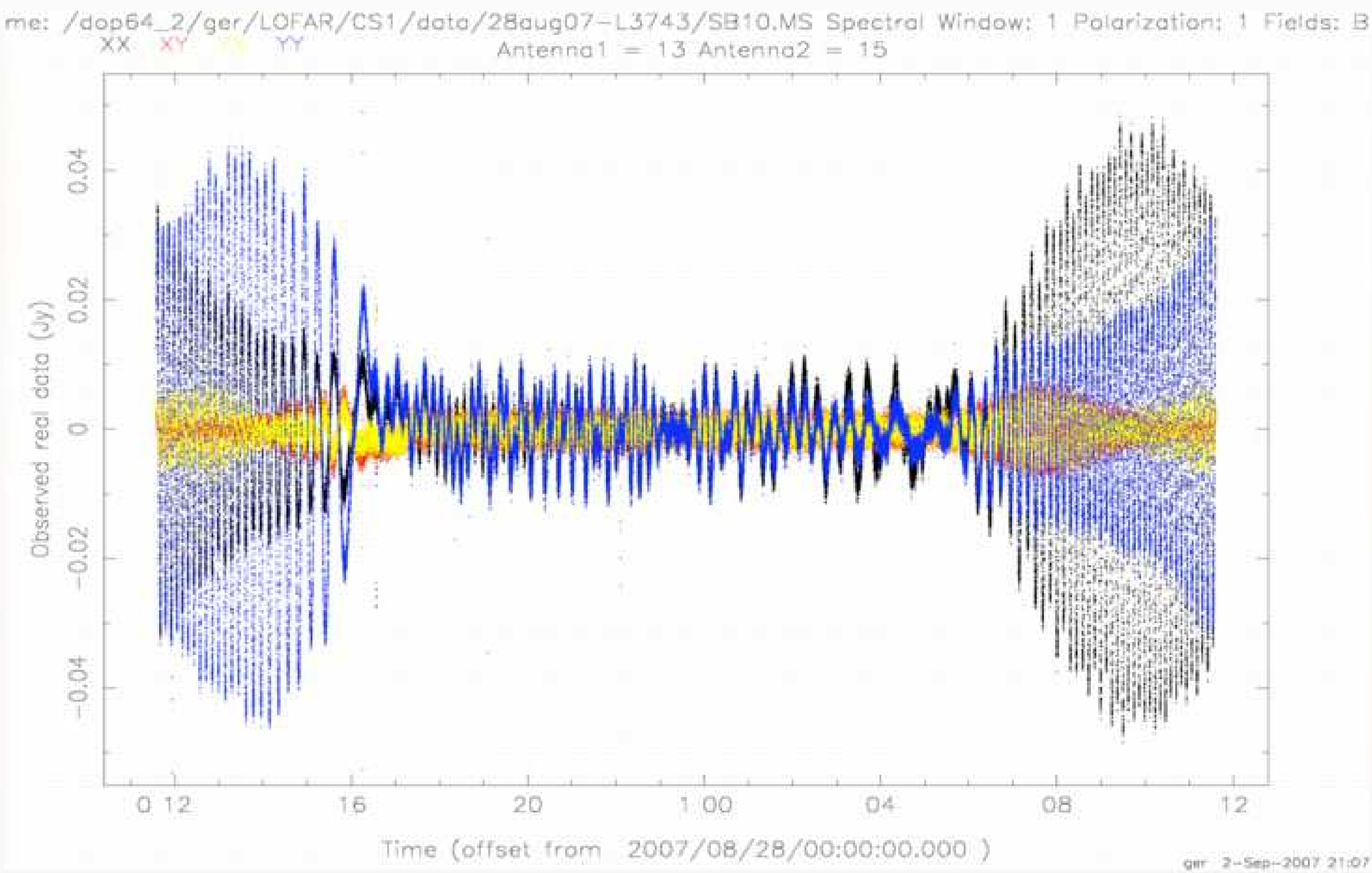
CasA & CygA (~20,000 Jy) subtracted

- dipole beam corrected
- no deconvolution yet

ASTRONs Dec 2007 Xmas card (North Pole)

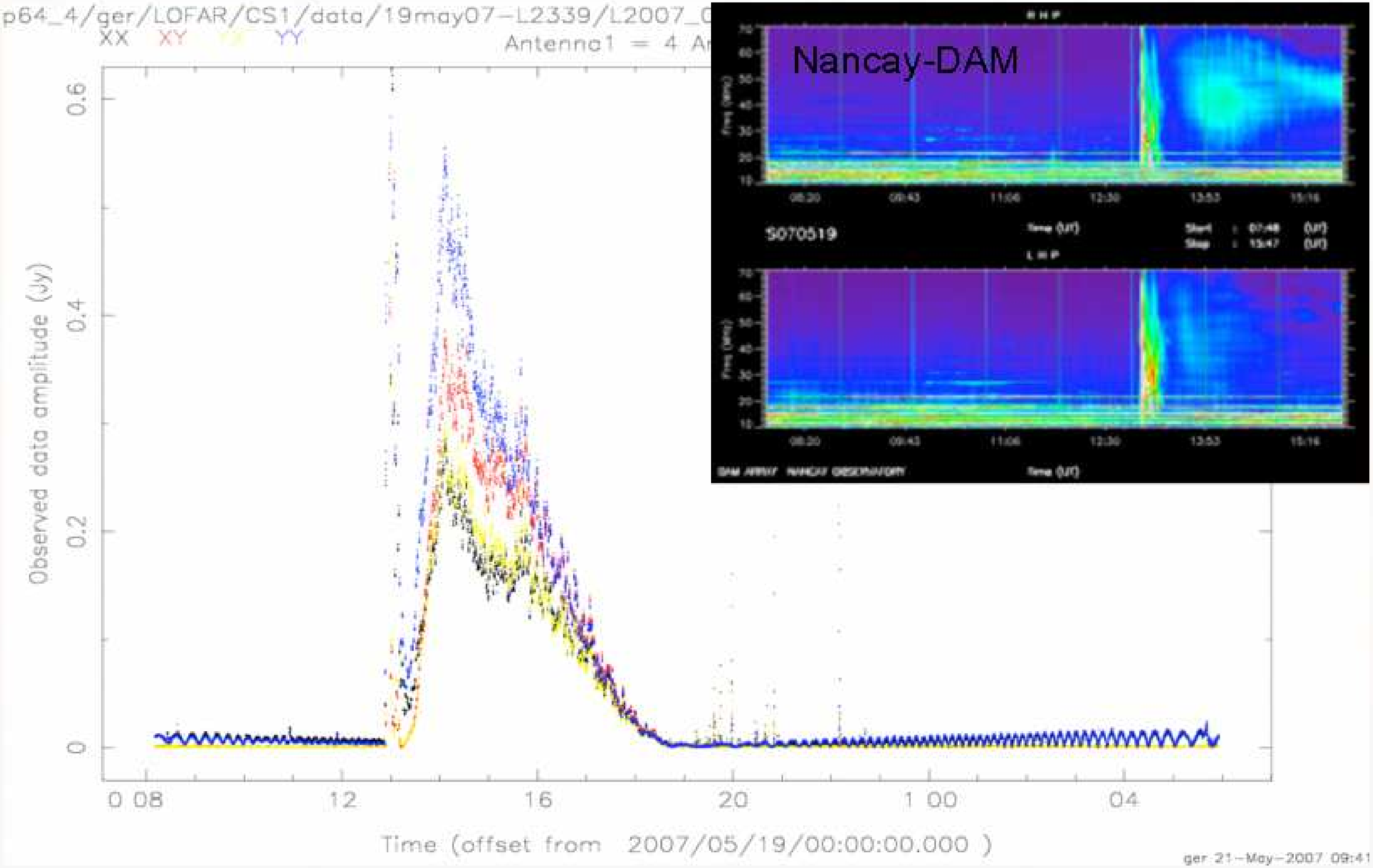


The difference between day and night at 220 MHz

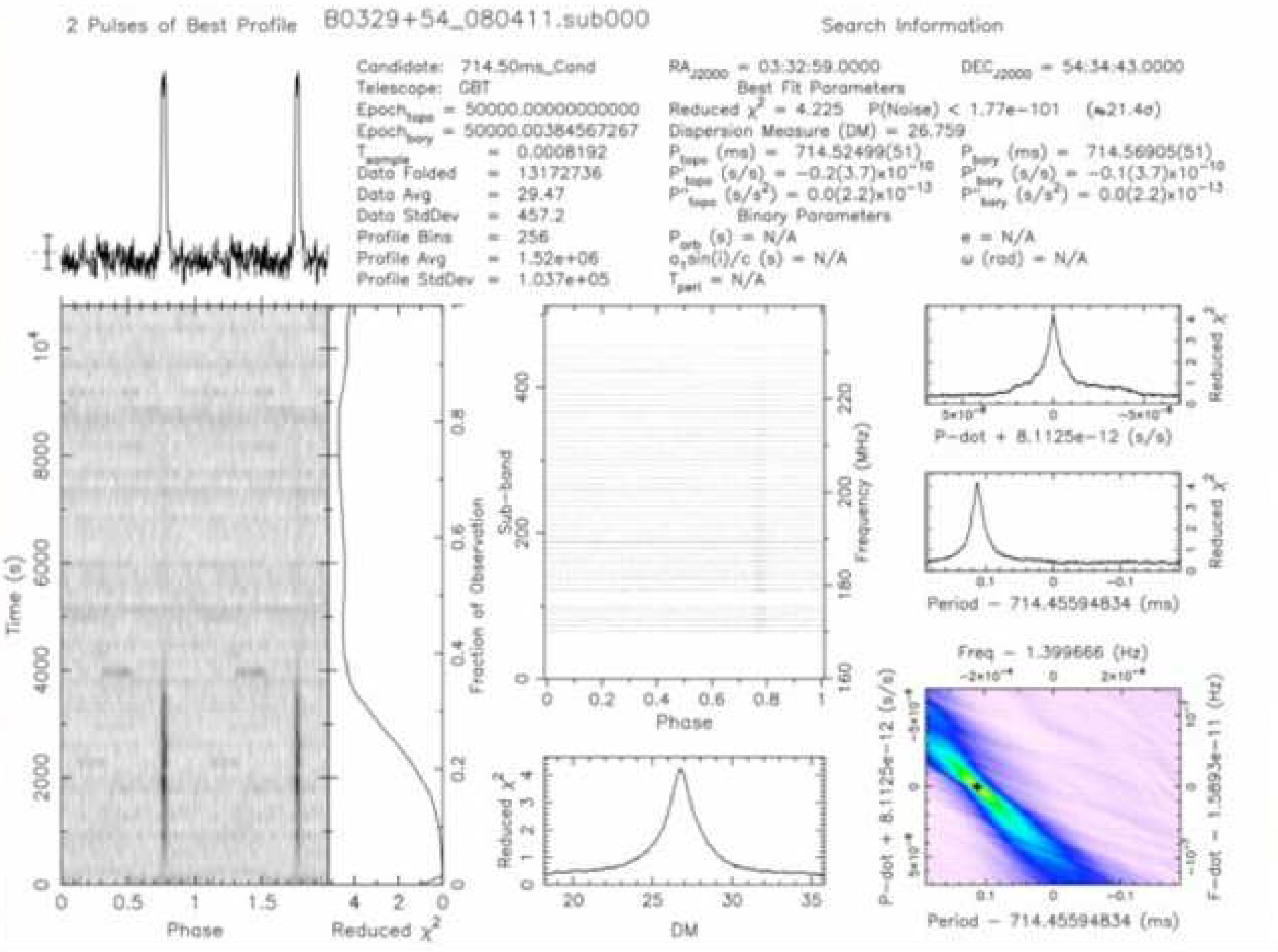


and this is still the ‘quiet’ Sun …

The disturbed Sun ~50 MHz 19May07



First LOFAR pulsar detection



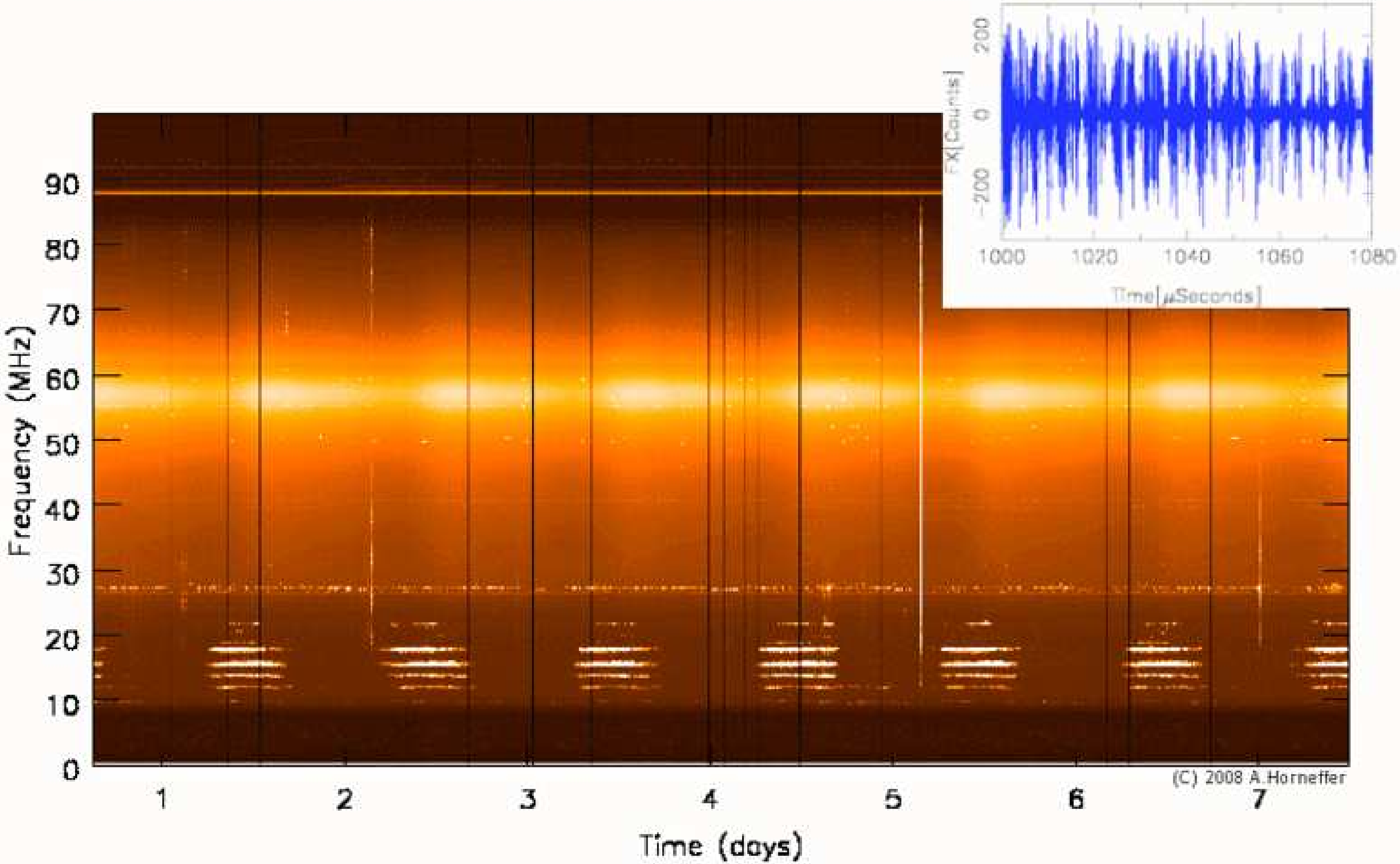
6 tiles coherently added

single pulses seen

Hessels, Stappers, Karuppusamy & Masters AJDI 25Apr08

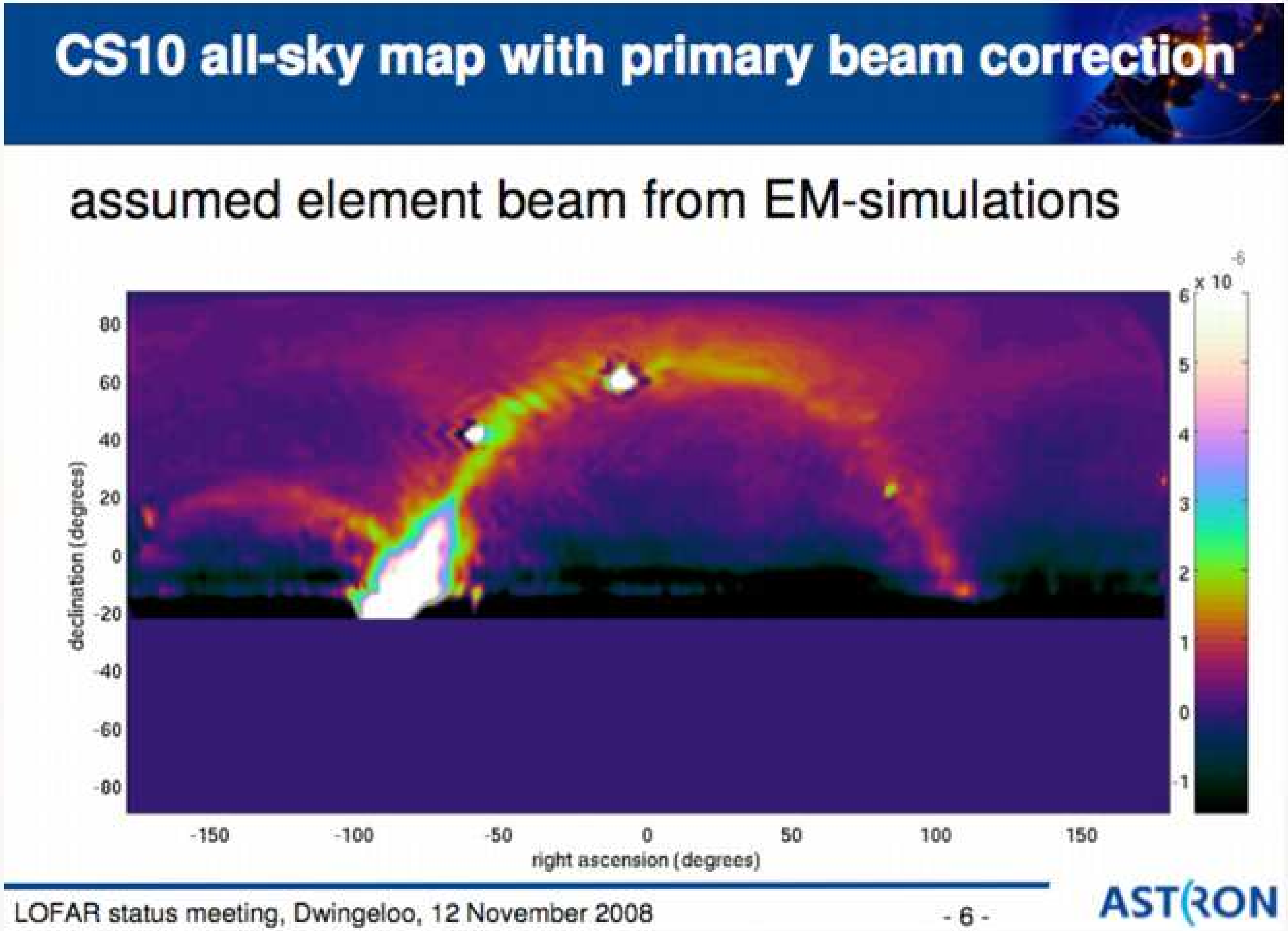
LOFAR TransientBufferBoards: 7 day coverage

baseband data (Δt=5ns): 10ms - every 5min - for 7 days



Horneffer, 12mar08 (AJDI)

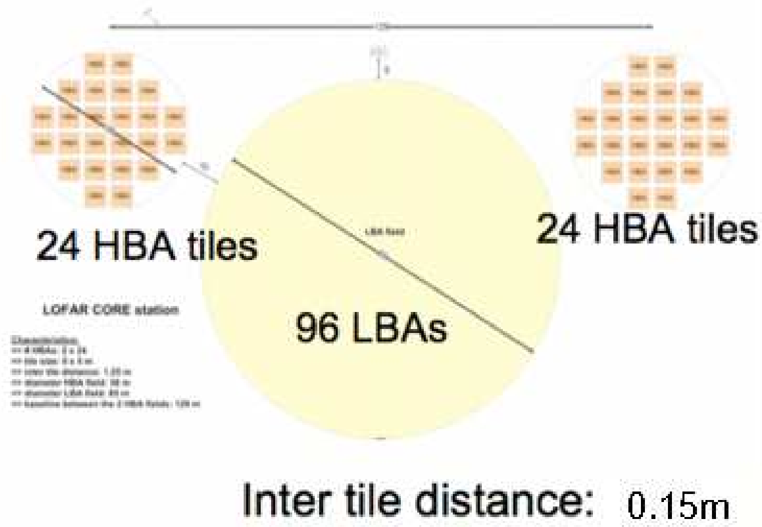
A real-time ML-image from the 48-dipole station correlator



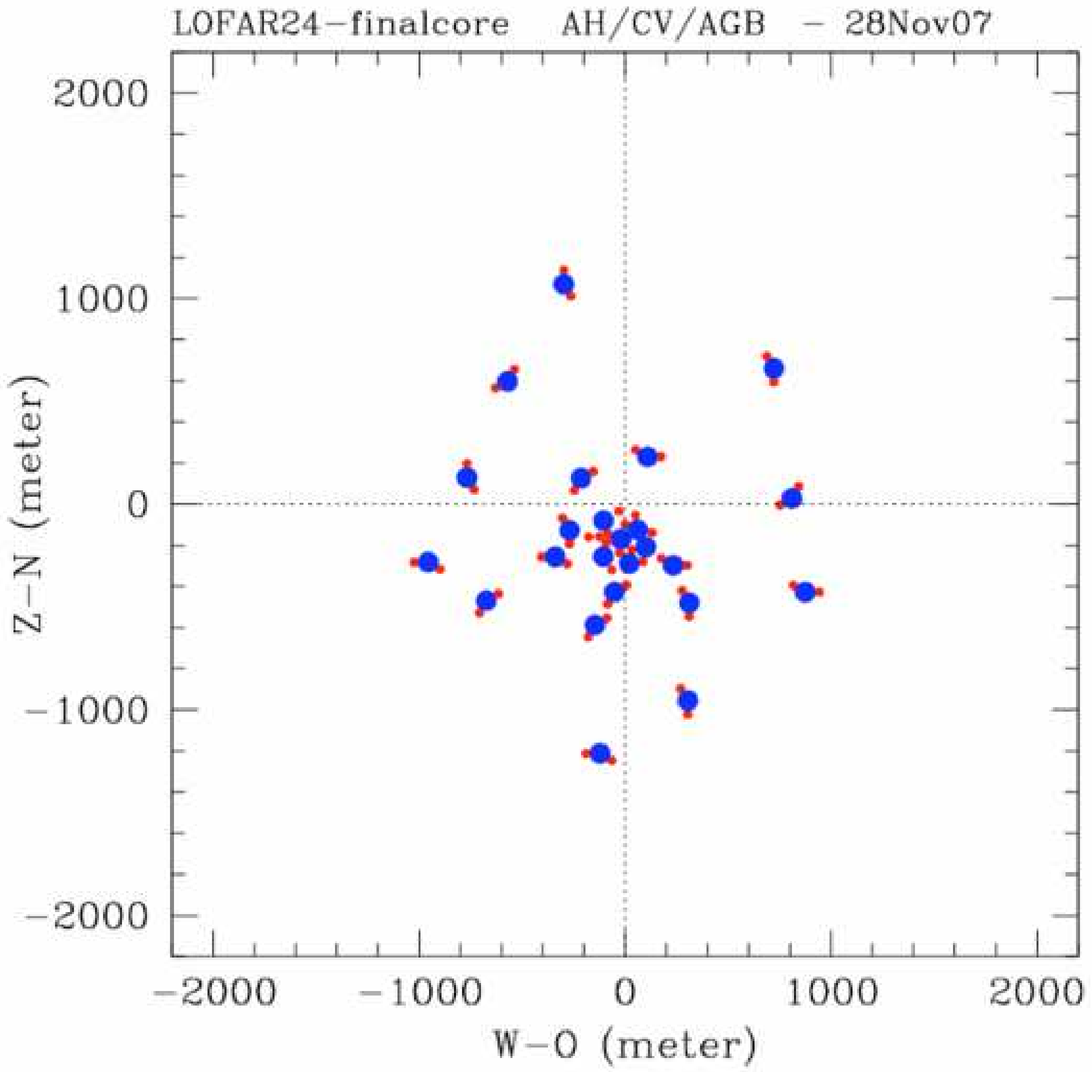
36 subbands: 45-67 MHz, 10s int: real time calibration Stefan Wijnholds, nov 08

Rollout status in December 2008

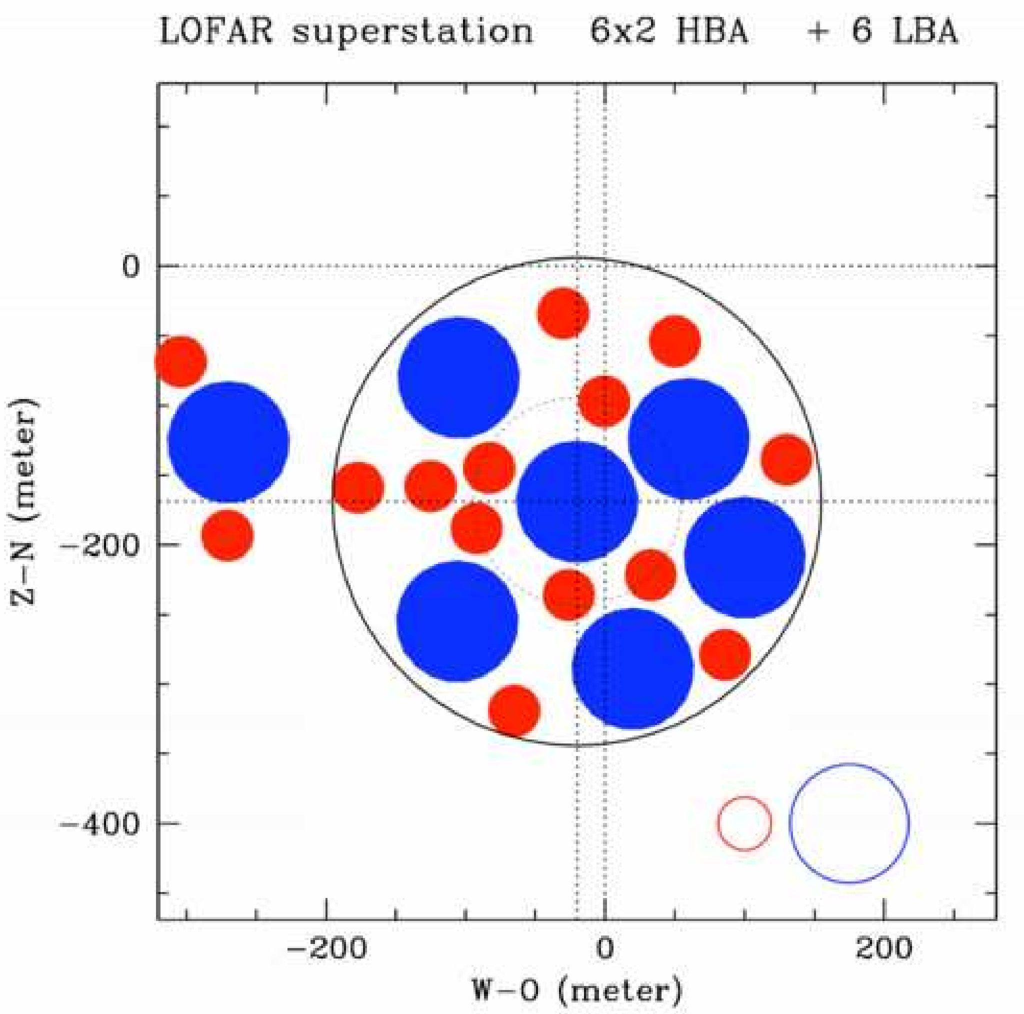
LOFAR core configuration (18, 24, 32 stations)



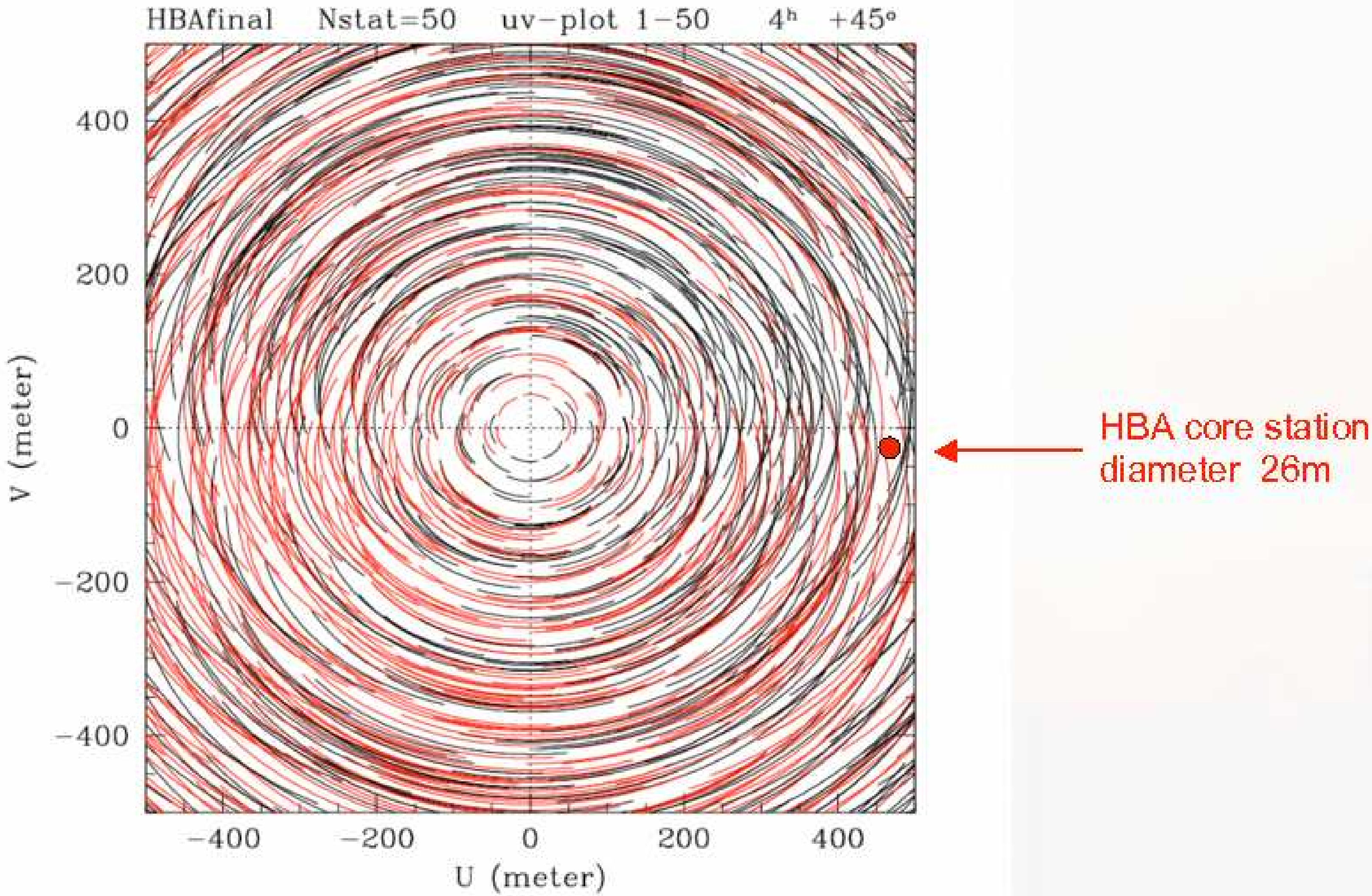
The LOFAR24(x2) core configuration



The ‘superstation’ in the core: 6 LBA and 6x2 HBA



LOFAR24(x2) inner uv-cov for +45° after 4^h



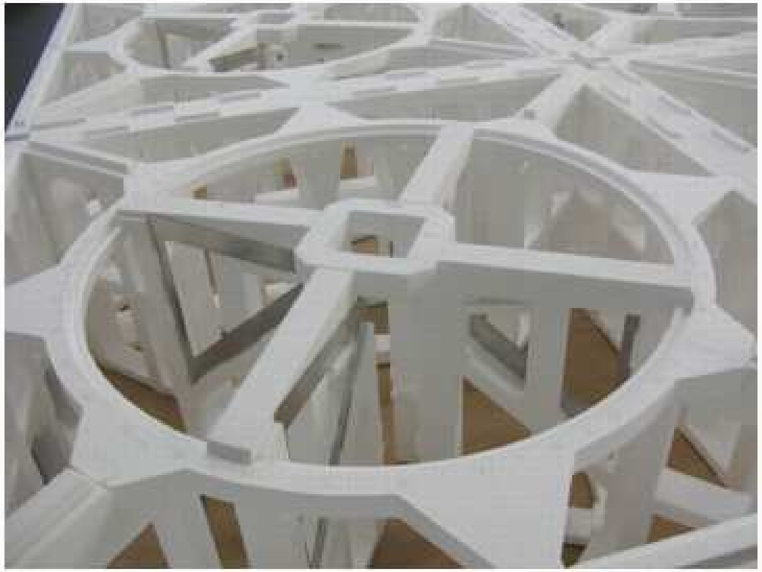
A small river flows through the 2 km core: connected to wetlands

The 'superstation': on a 350 m diameter 'island'

The projected location of 6 LBA and 6x2 HBA stations

In the foreground-right the current CS-1 dipoles and electronics huts.

HBA tiles: what is inside….



Each LOFAR station will have a unique orientation ⇒ scrambling of distant sidelobes

But to keep parallel dipoles antenna rotation within styrofoam HBA-tile structure is required.

HBA-tiles (5x5m) will be integrated and folded within assembly hall near Exloo

HBA assembly in Exloo

Updated hardware roll-out and Planning

Stations delivery:

- Apr 09 2 stations
- Sep 09 20 stations + (2 - 7) in Europe

CEntral Processor (BG/L ⇒ BG/P transition) Aug 08

Off line cluster (5 Tflops) + 500 TB storage May 09

Technical/Software commissioning: Oct08 - Jul 09

Software integration: Scheduling / Monitoring /
On-line applications /Off-line processing

Creation Global Sky Model (GSM): Summer/Autumn 09

Some calibration challenges for LOFAR

— Varying primary beams (e.g. projection issues)

— Full polarization treatment required using matrix Measurement Equation (Hamaker et al, 1996) using 2x2 Jones matrices for each instrumental effect (Ionosphere, Faraday rotation, beam, bandpass,…)

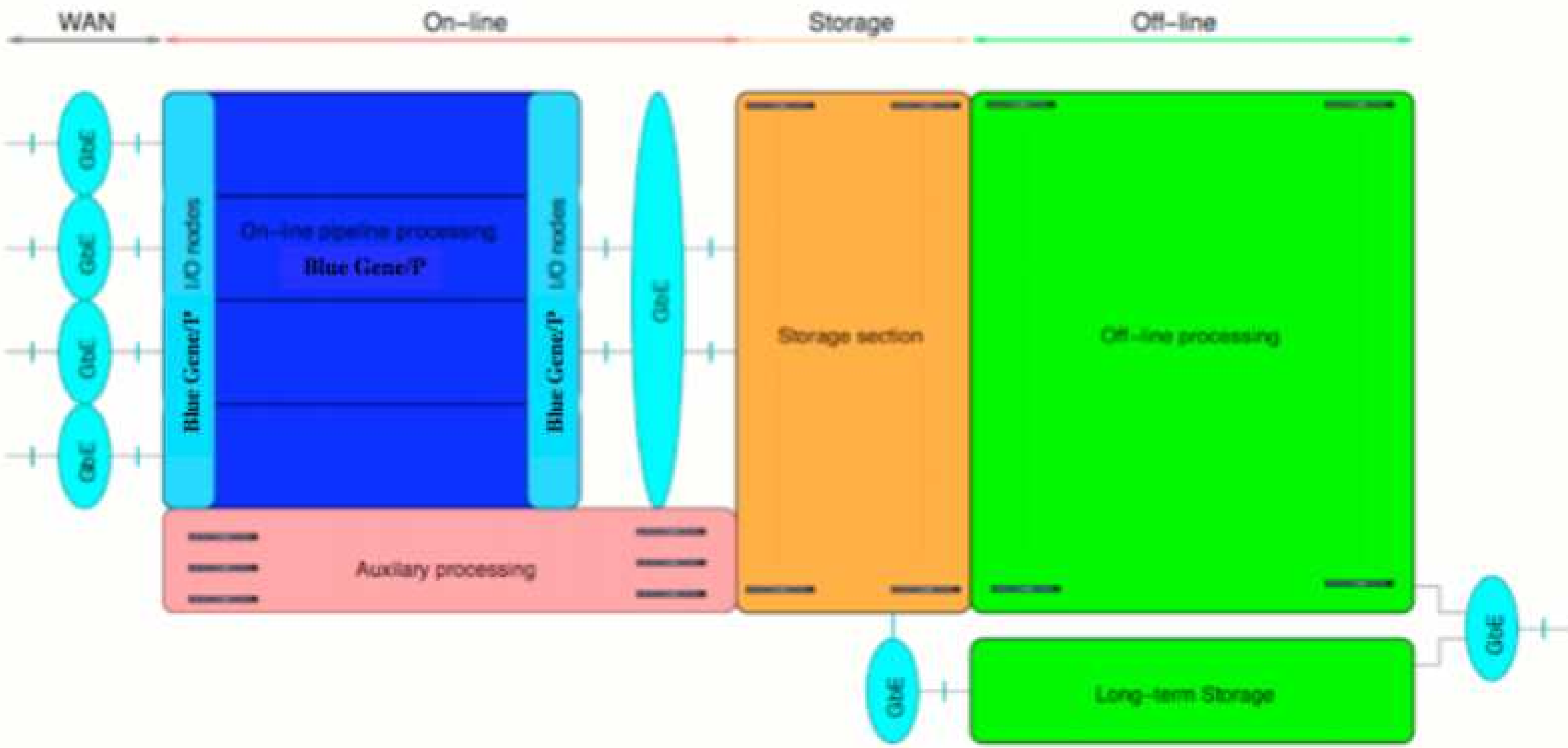
— Rapidly changing ionospheric phase corruptions and small isoplanatic patches. Therefore (self)calibration is required in many different directions ! Hence most corrections are not uv-plane but image-plane based. Solve for instrumental errors towards each bright source separately and 'peel it off'

— Many simultaneous users…

— Data processing: many hundreds of Terabytes per day (compression!)

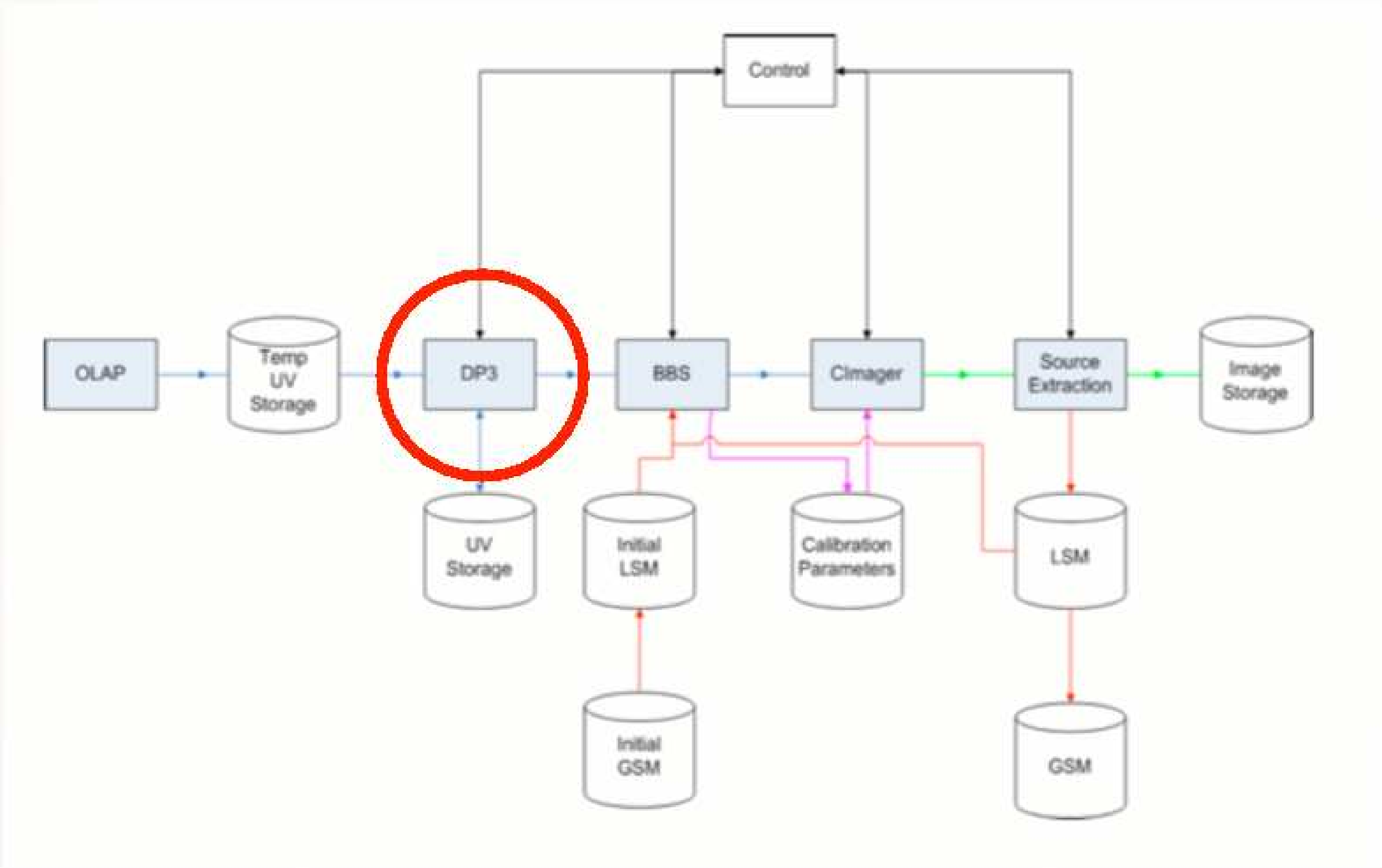
— Real time processing (transients, TBB, …

LOFAR data flow and correlation overview

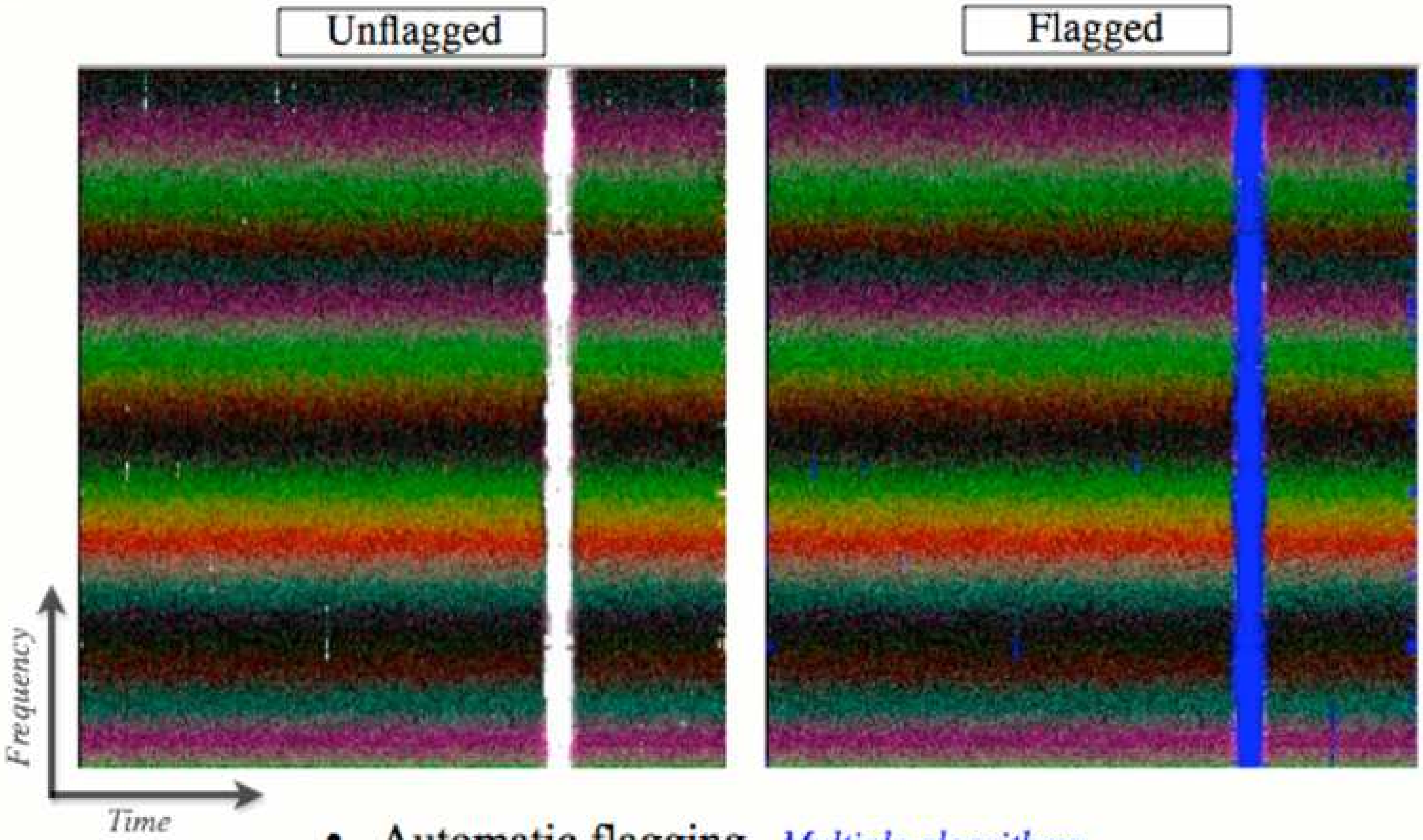


- BG/P *Data reception, transpose, correlation, beam-forming, de-dispersion*
  - Storage system *Short term storage of data, ~1 PByte, >100Gbps I/O*
    - Offline cluster *Calibration, data products, off-line analysis, ~10 TFLOPS*

The automated calibration and imaging pipeline

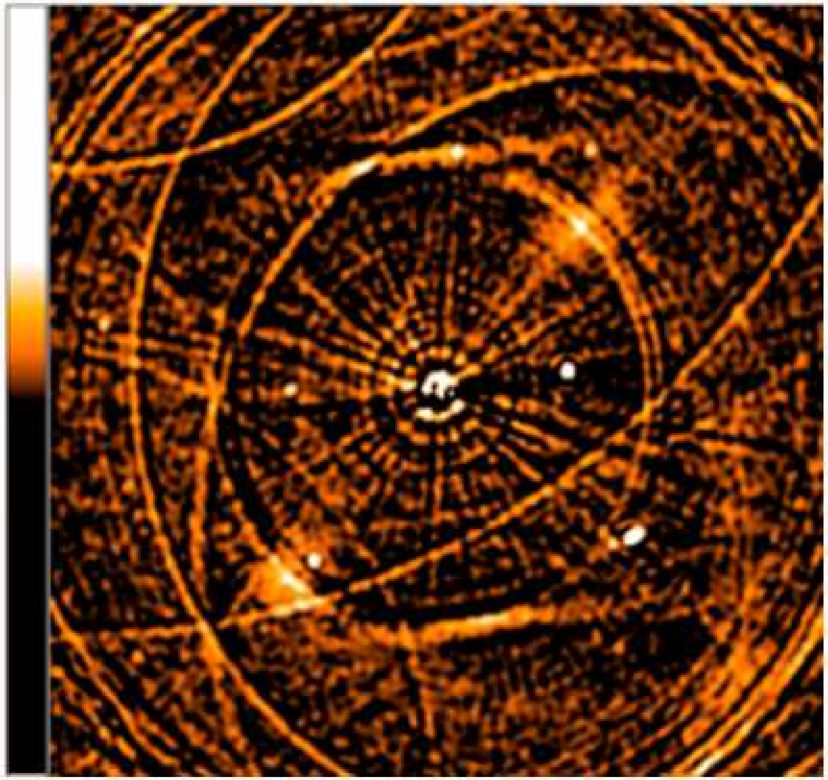


The pre-processing of visibilities

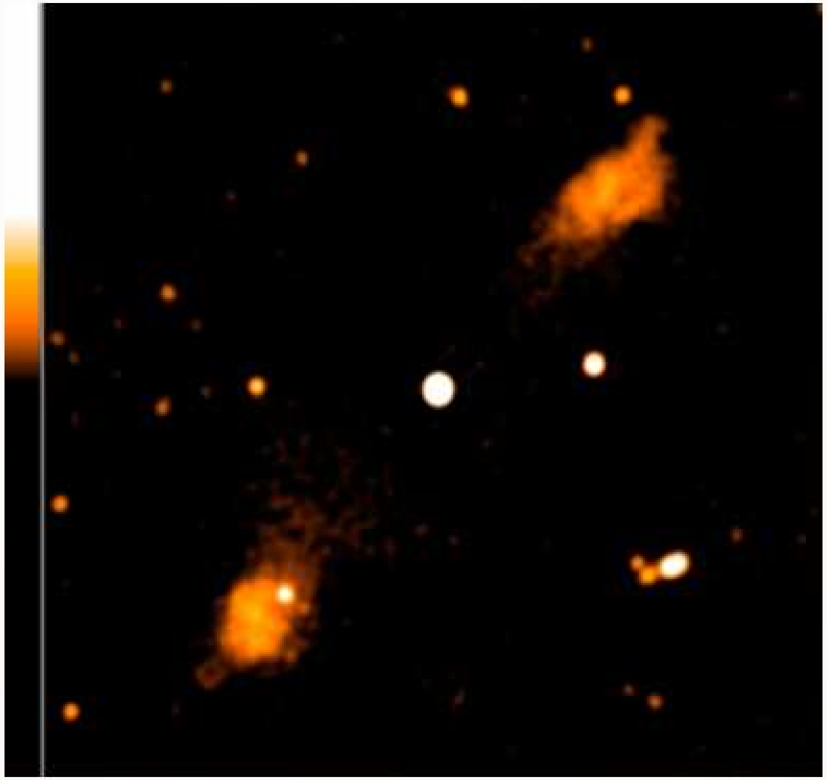


- Automatic flagging *Multiple algorithms*
  - Data compression *Time and frequency averaging*
    - Simple cal. corrections *Clock phases, A-team subtraction*

Traditional, simple, selfcalibration



Raw image



Selfcalibrated image

LOFAR calibration issues and overview:

Calibrating dipole-station arrays at low frequency §

— Sky or Global Sky Model (= GSM)

— Station beampattern: (position, frequency, polar) dependent

— Ionospheric phase screen

In the next year our knowledge will increase rapidly:

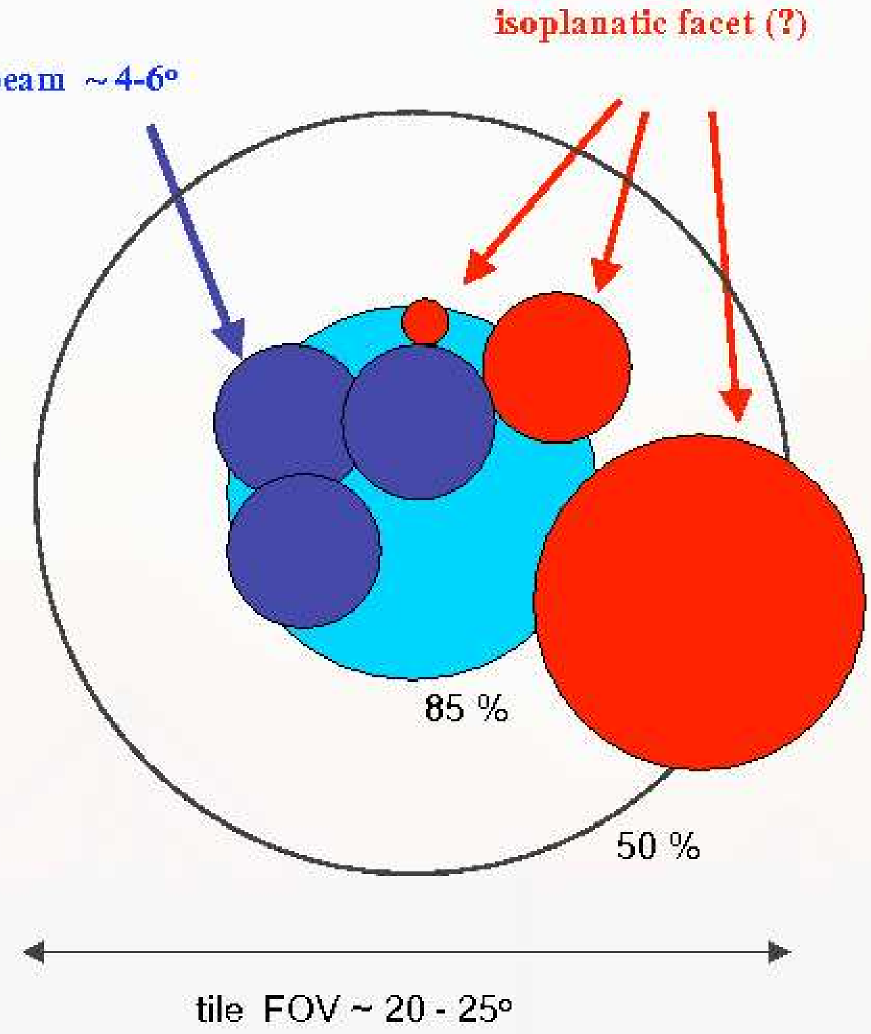
1. After some time we will know the GSM: I,Q,U,V (RA,Dec, freq, (time))
2. We expect (hope) that beampatterns (=Jones matrices) are 'stable'
3. Hence real challenge (every 10s again) is solving phase-screen (possibly in 3-D !)

but we still wonder whether

1. There are enough constraints to fit for all source/ionosphere/beam parameters
2. It can be done with the available processing time /resources?

A cartoon of the ionospheric calibration problem

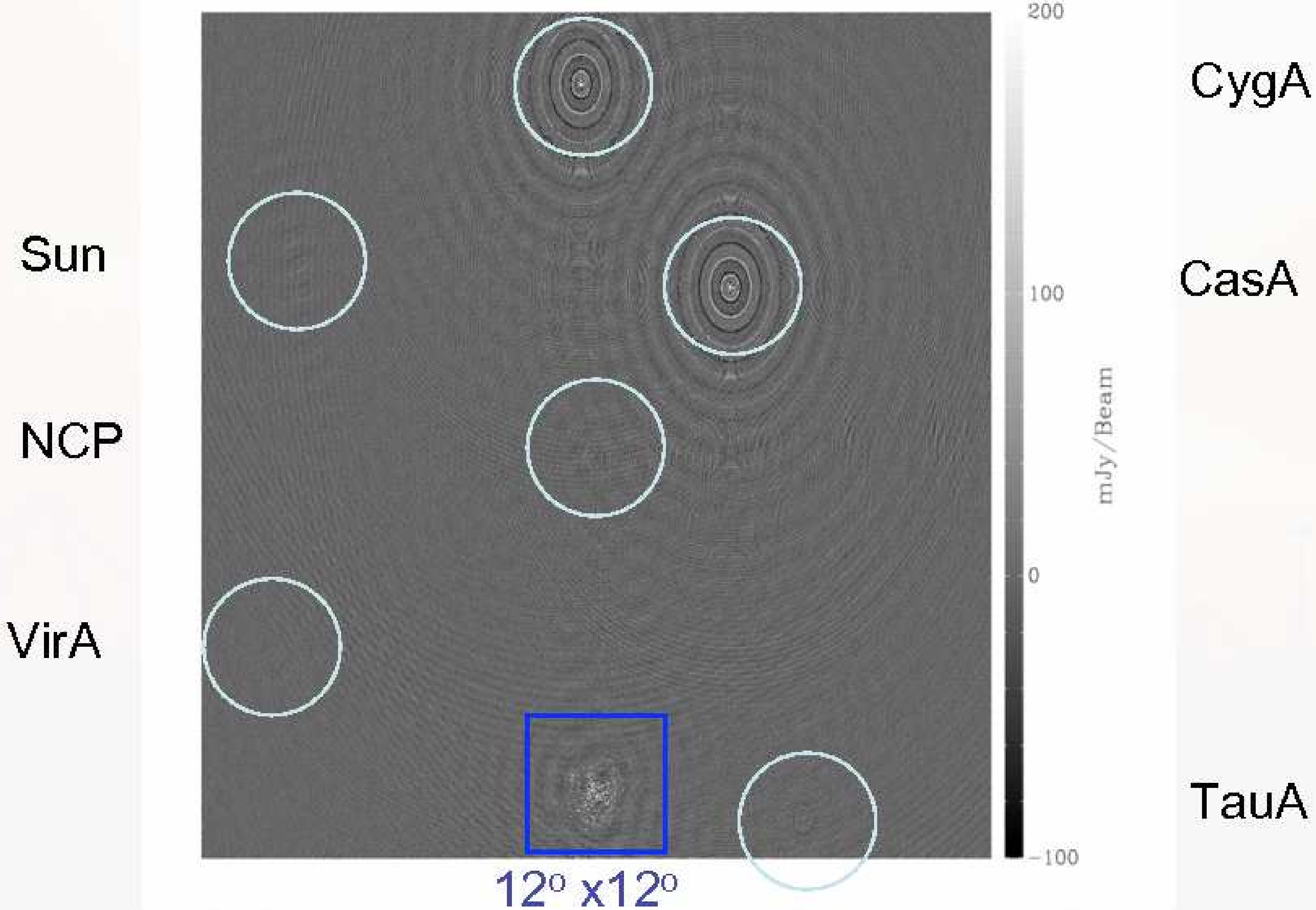
HBA angular scales
(24 tiles/station)



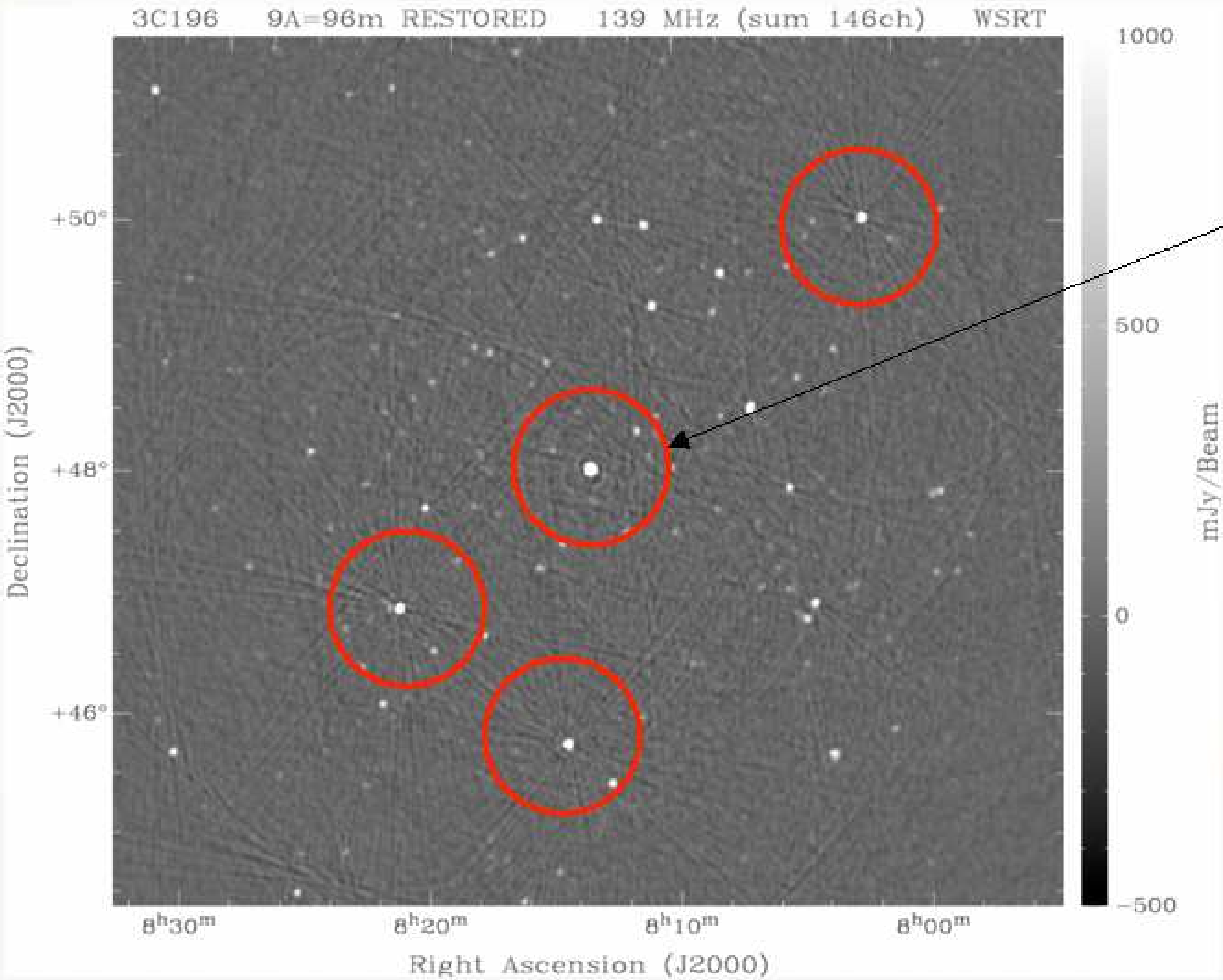
Note:

All scales are frequency dependent but in different - timevariable - ways

WSRT 150 MHz image of 3C196: 'all-sky imaging needed !'



3C196 in one night: serious nonisoplanaticity !!



3C196

80 Jy

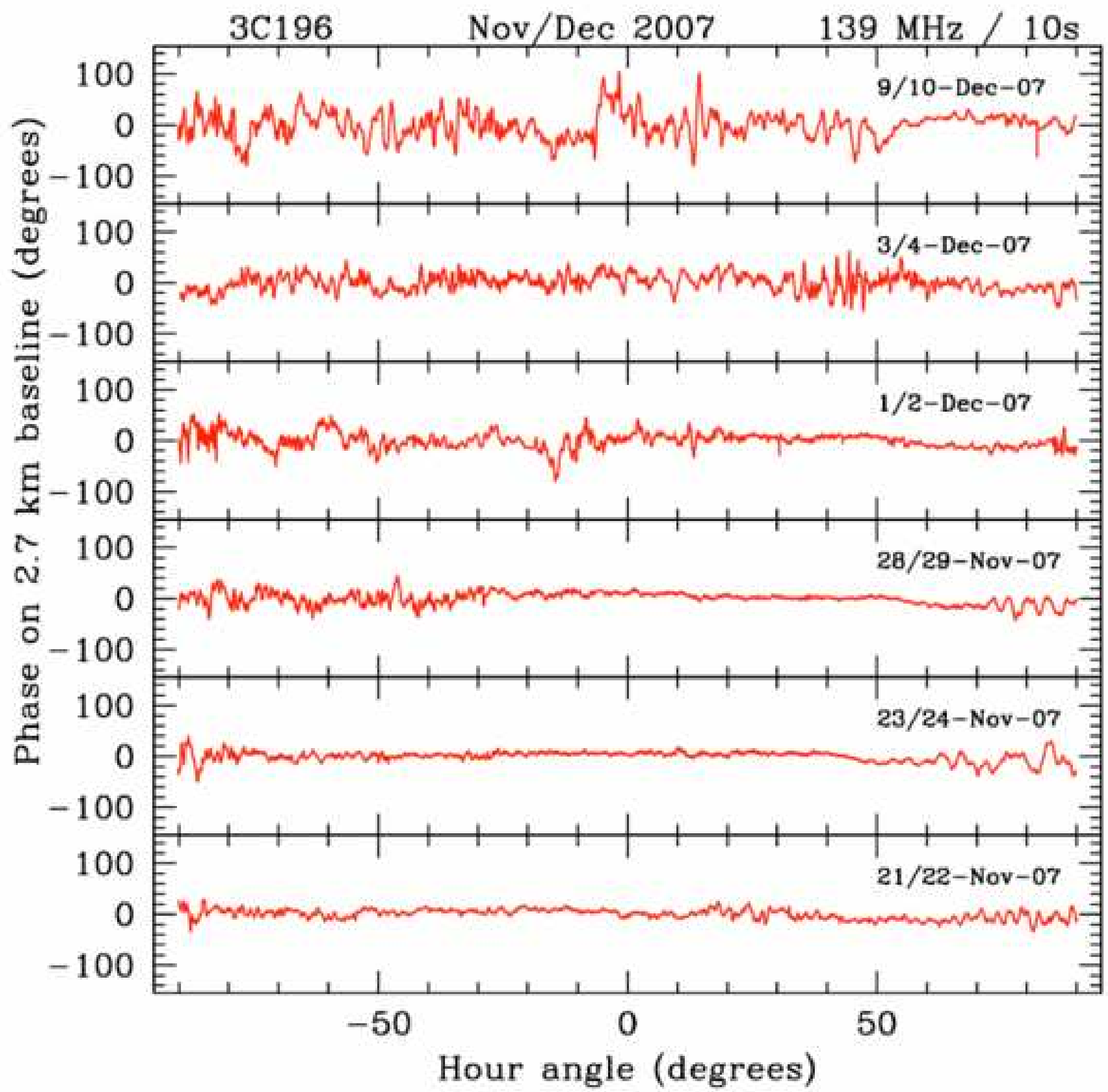
3 other sources

6-8 Jy

All sources need to be 'peeled off'

Works !

3C196 - selfcal phase solutions



6 x12h

Note the variation in the ionosphere from night-to-night

Conclusions

- LOFAR will address many new themes in radio science of the Universe
- Will have arcsec and sub-mJy imaging at very low frequencies
- PetaByte storage and ~10-30 Tflops processing required
- Rollout has begun: ~ 20 stations in late September 2009
- Initial results with pilot facilities are very promising !
- Still many calibration challenges !
- Stay tuned !

For more info

http:/www.astron.nl/

http://www.lofar.org/operations (new web portal in March 2009)

plus various KSP homepages

Latest science workshop ('Astrophysics with E-LOFAR', Sep 2008)
http://www.hs.unihamburg.de/DE/Ins/Lofar/Lofar_workshop/index.html

Thank You for your attention !