Particle Physics with LOFAR

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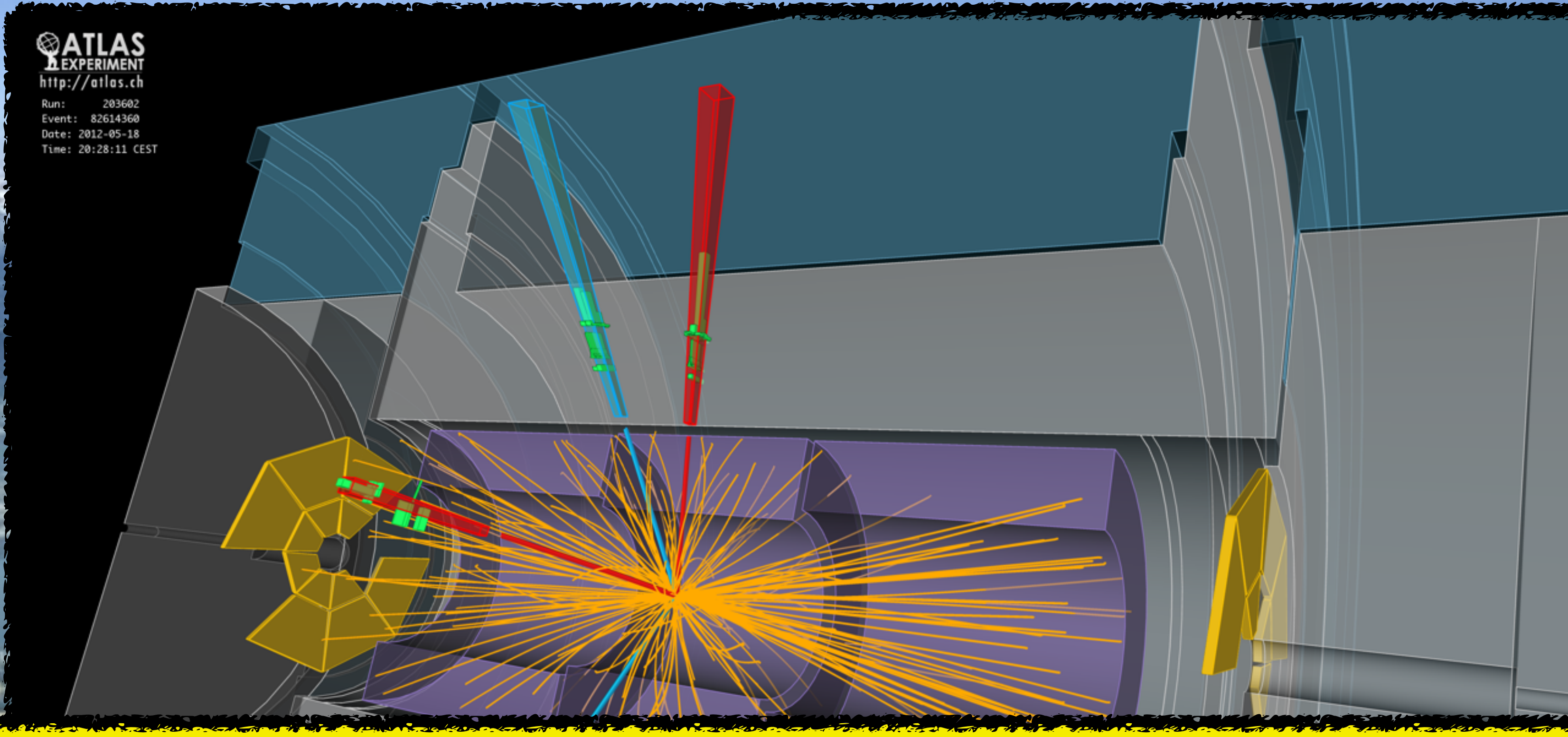
LOFAR Data School 21-11-2014

many thanks to Pim Schellart, Anna Nelles, Arthur Corstanje for plots, pictures, etc.!

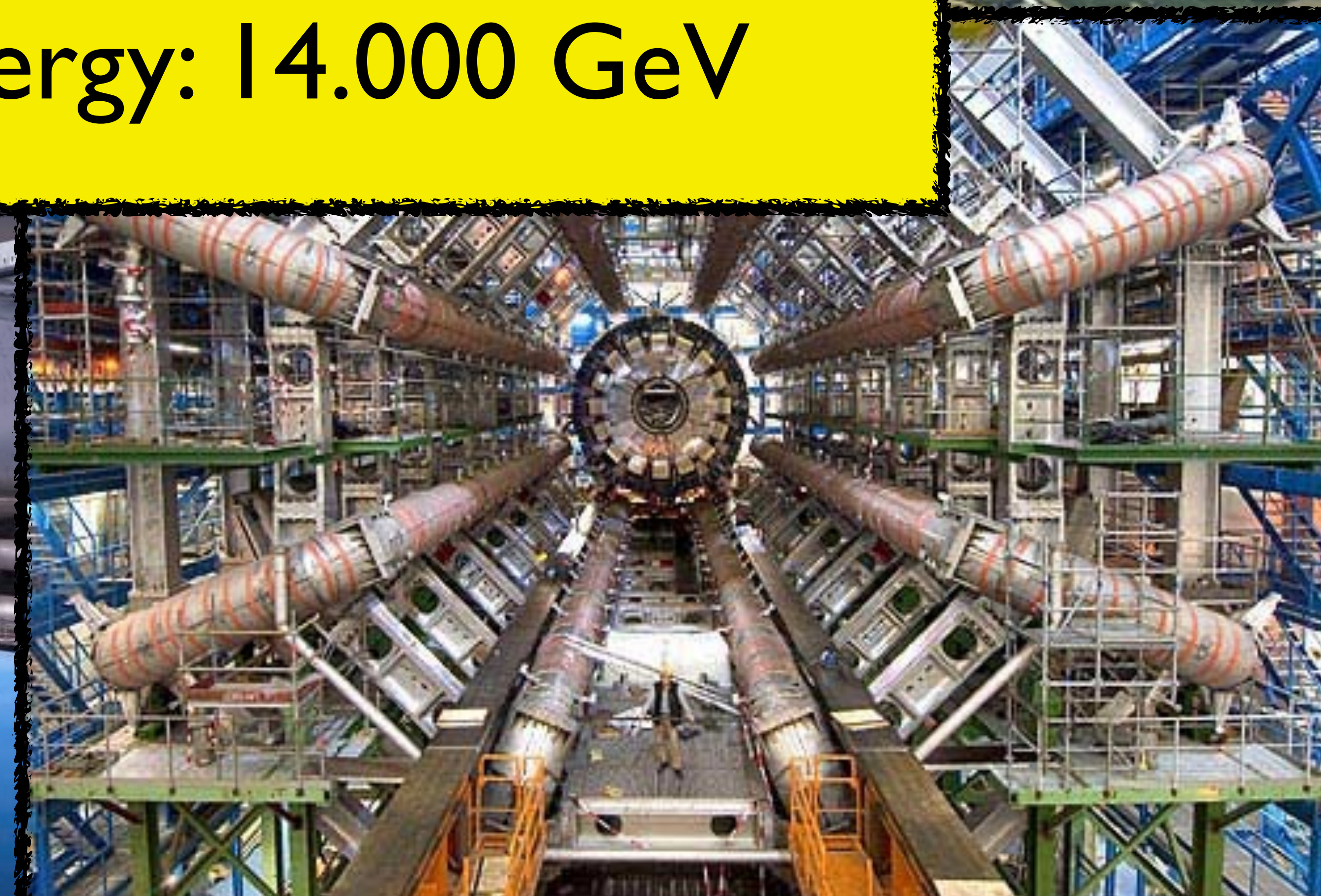
Content

- Particle physics with a radio telescope?
- Working with data from the Buffer Boards
- Analysis techniques for timeseries data
- Introduction to LOFAR cosmic-ray analysis

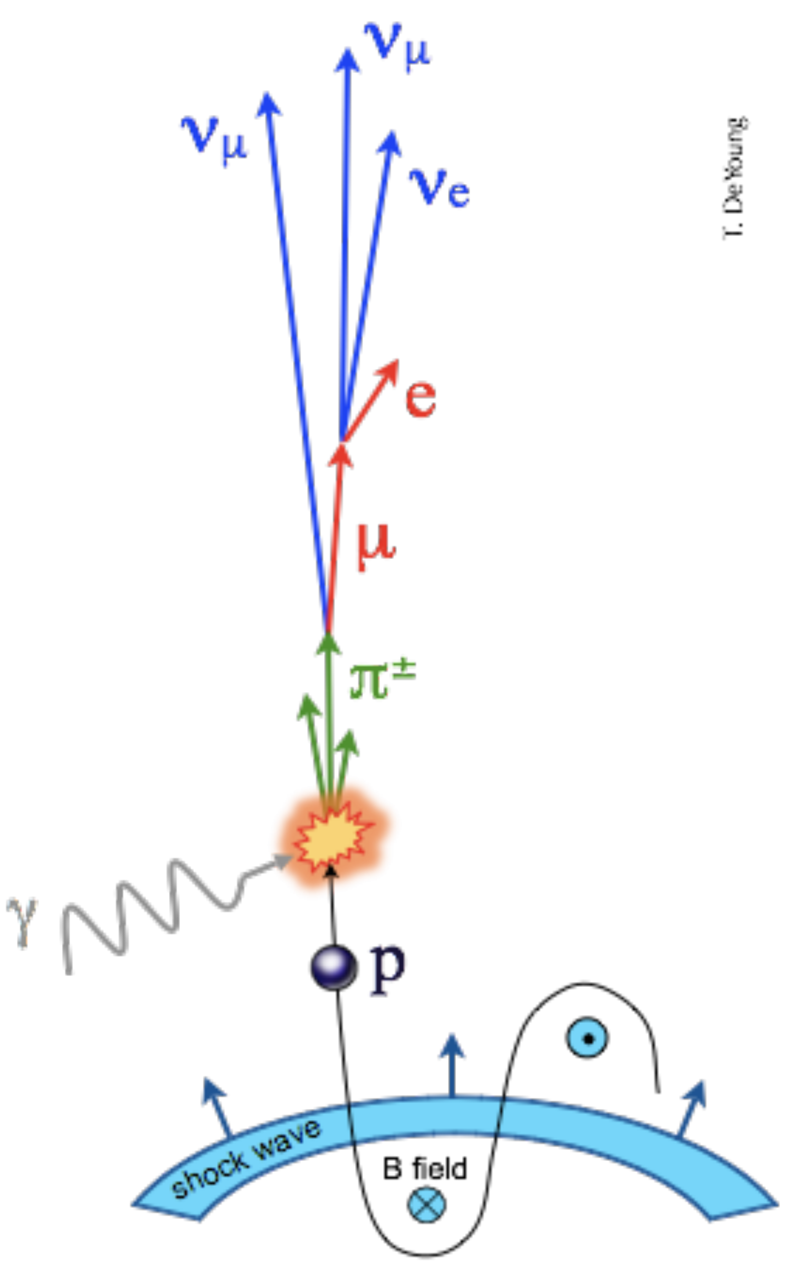
…and some other cool stuff!



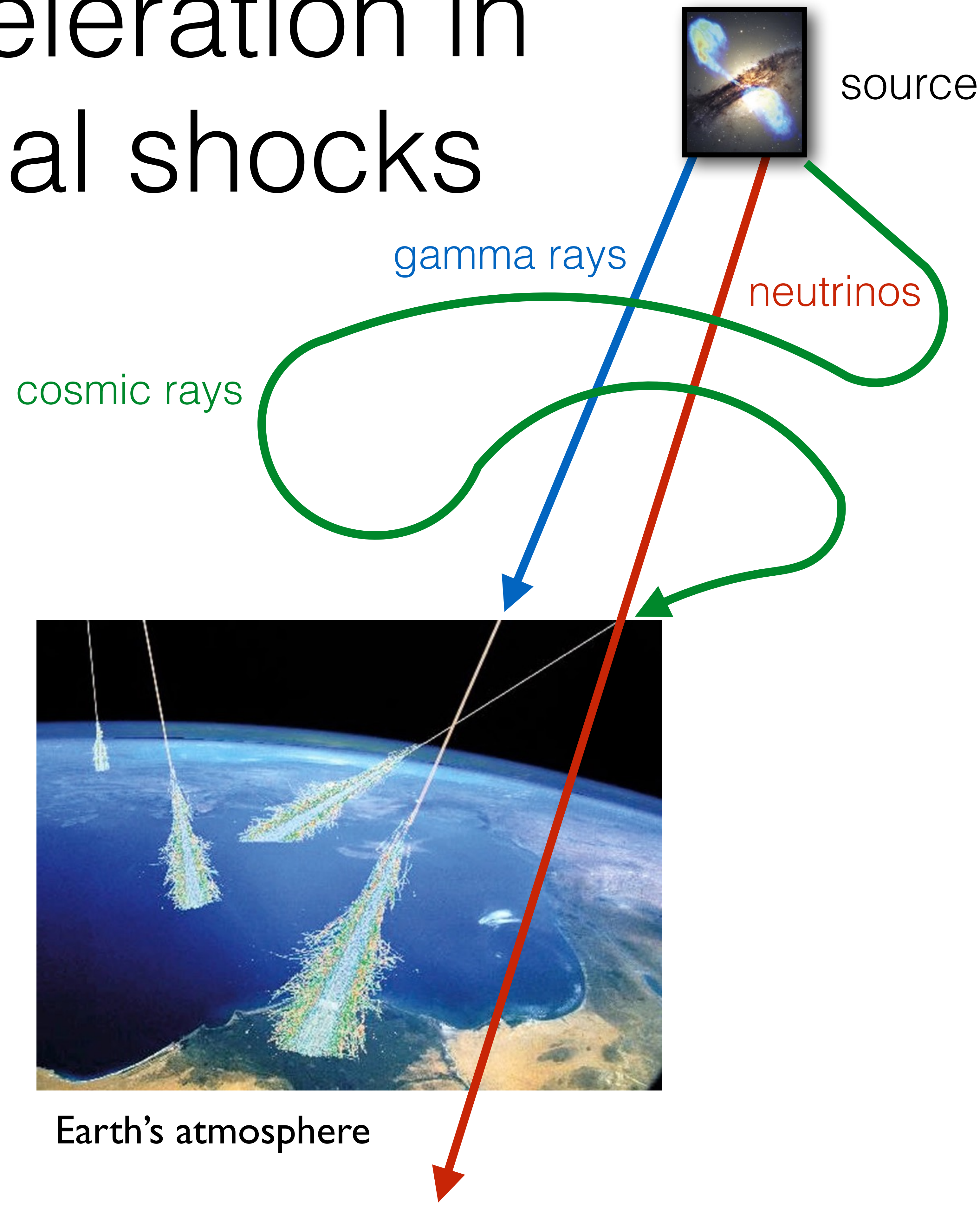
LHC collision energy: 14.000 GeV



Particle acceleration in astrophysical shocks



supernovae, AGNs, GRBs, ...



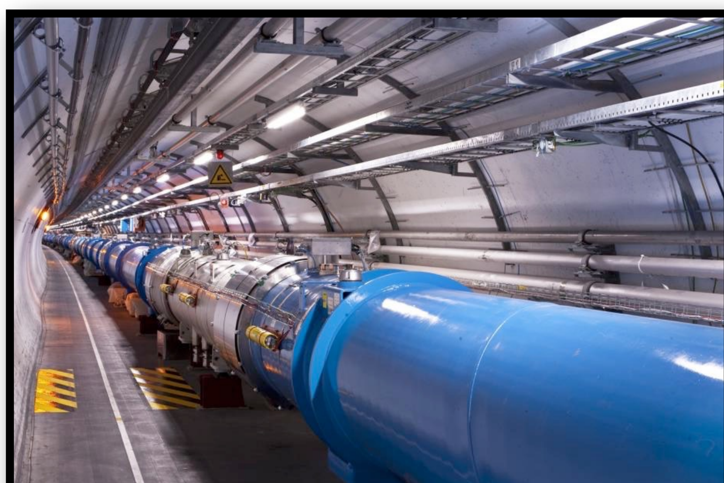
Cosmic energy scale

Detected:
Cosmic rays up to 10^{20} eV
Neutrinos at 10^{14} -10^{15} eV
Gamma rays up to 10^{14} eV

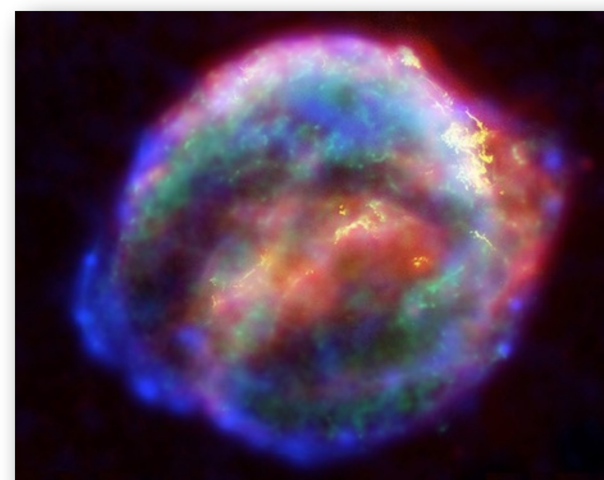
AGN

solar flares

LHC



Supernovae

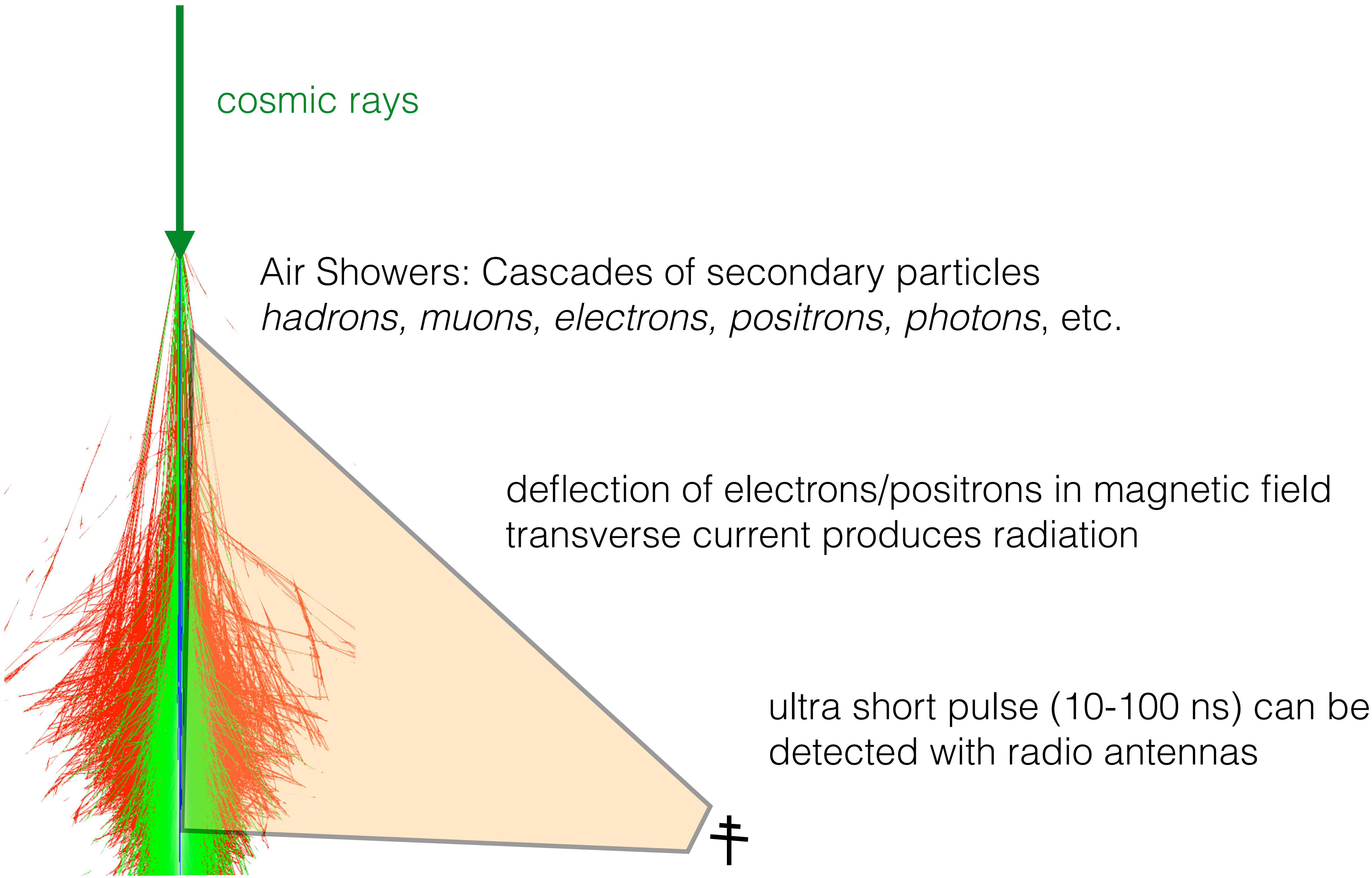


GRB

or...?

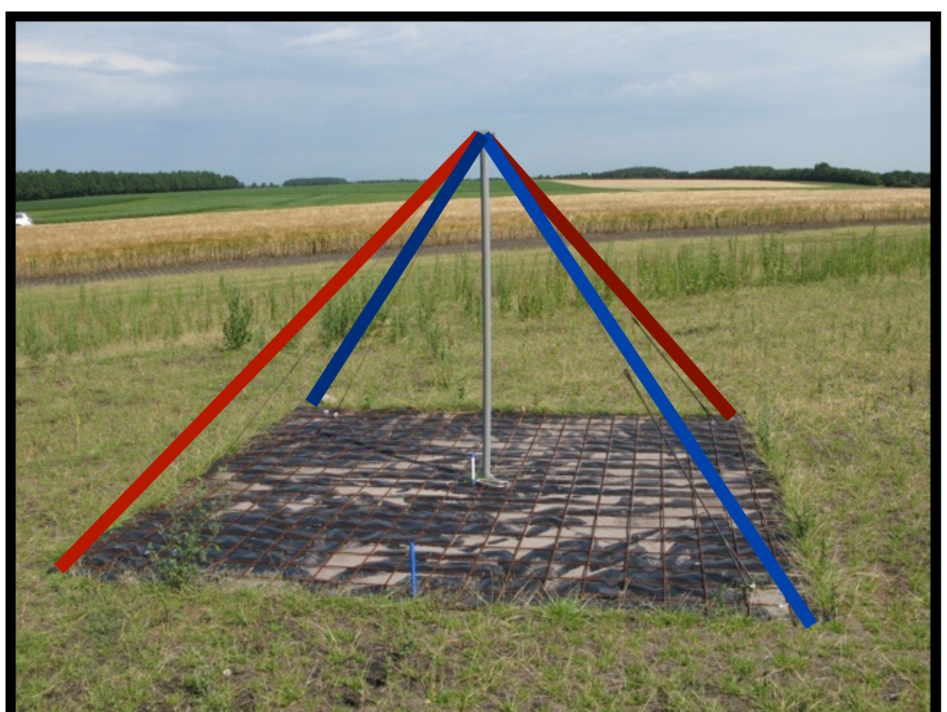
10^{10} eV 10^{12} eV 10^{15} eV 10^{20} eV

Cosmic-ray air showers



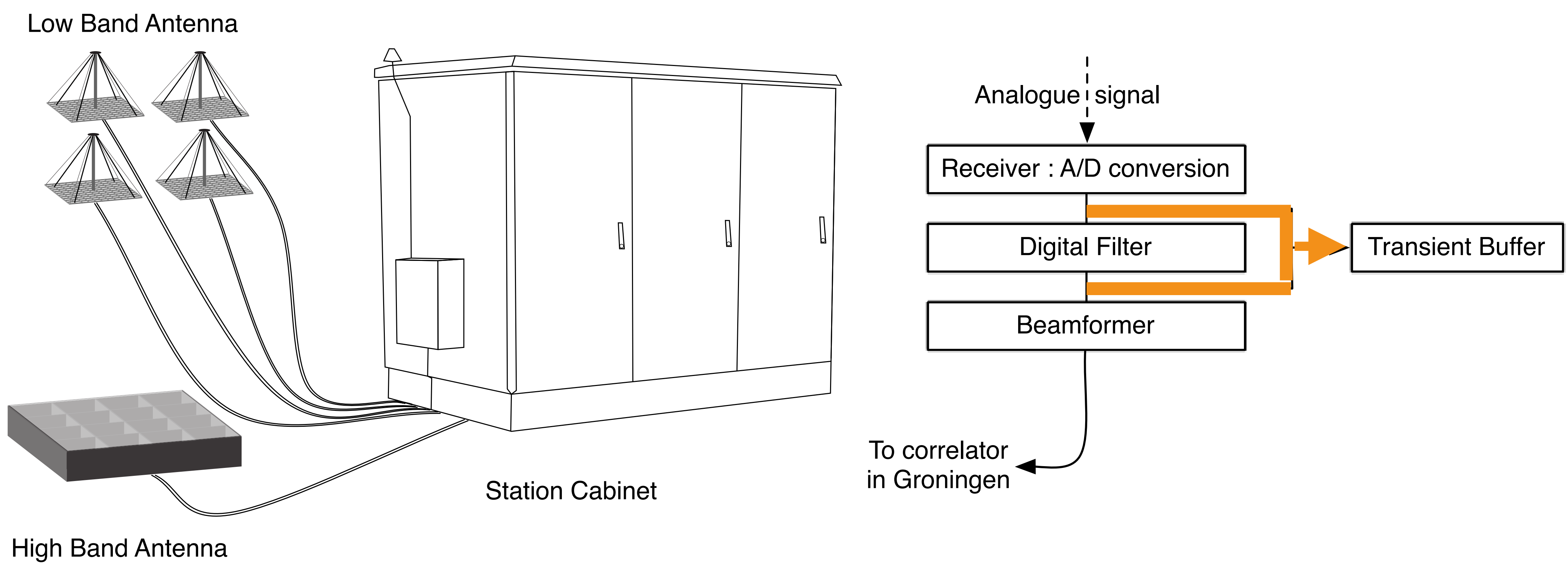
Air showers detection with LOFAR

<u>Goal:</u>
understand origin of CRs around 10^{17} eV
disentangle Galactic & extragalactic component



<u>Challenge:</u>
ultra-short signals (10-100 ns)
random arrival time & direction
complicated radiation mechanism

Transient Buffer Boards (TBBs)

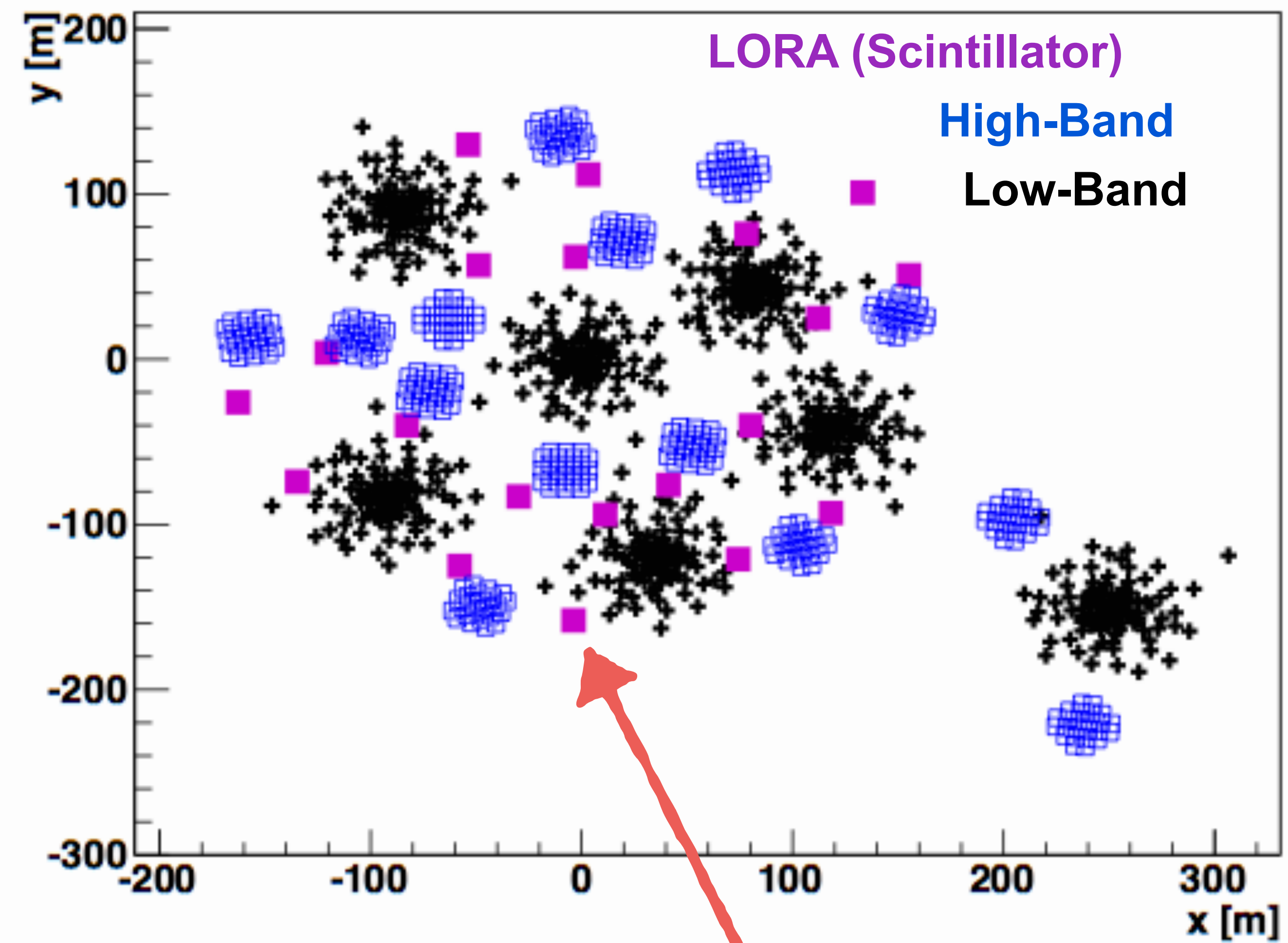


- raw LOFAR data can be accessed via TBBs
- 5 seconds of data stored on ring buffer for each active antenna
- raw timeseries data or sub-band data
- 12 bit

Reading out TBBs

Trigger strategies

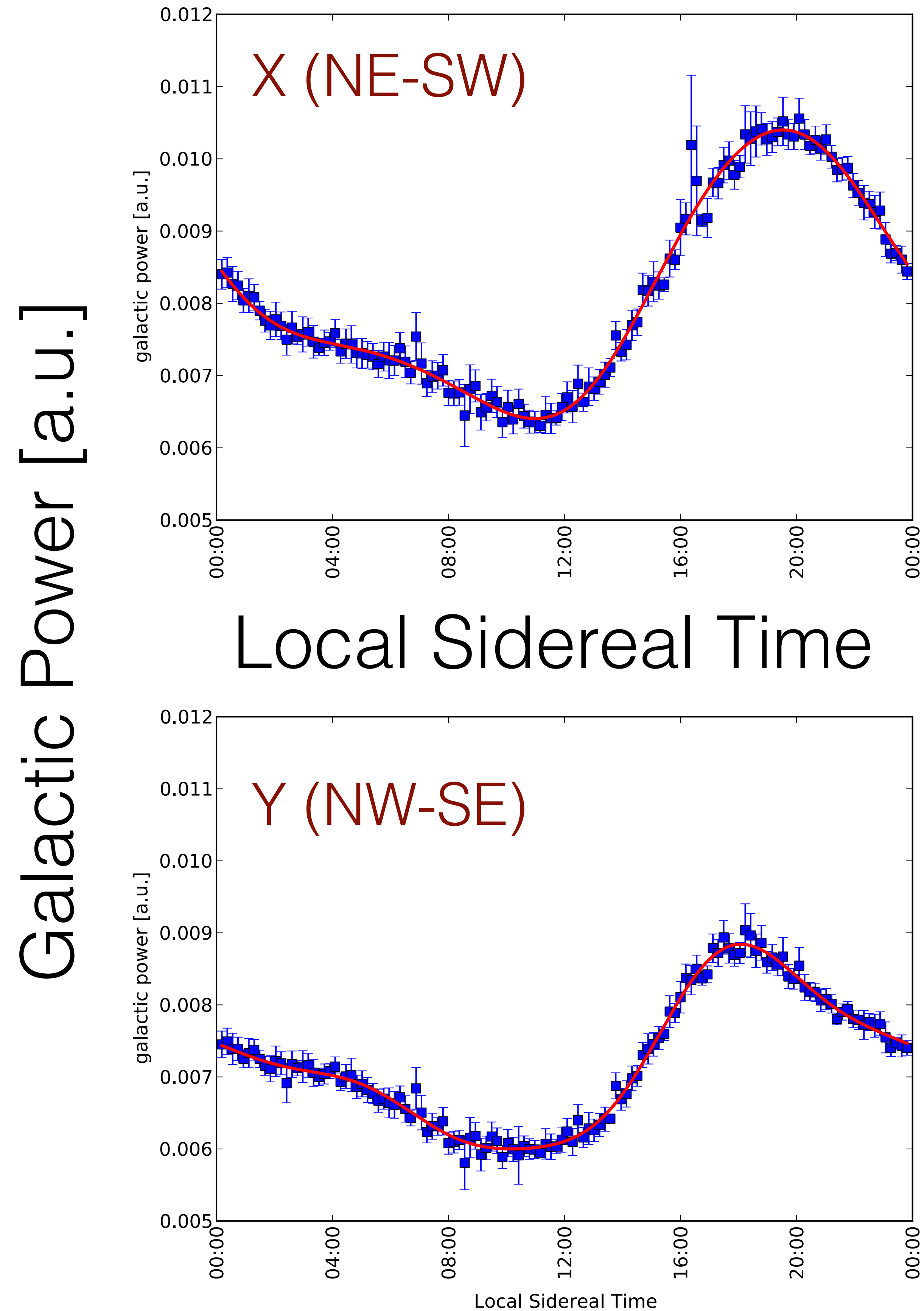
- Manual trigger
- External trigger
- Local station trigger
- Central trigger



LOFAR Radboud Array (LORA)
external cosmic-ray trigger

Calibration I

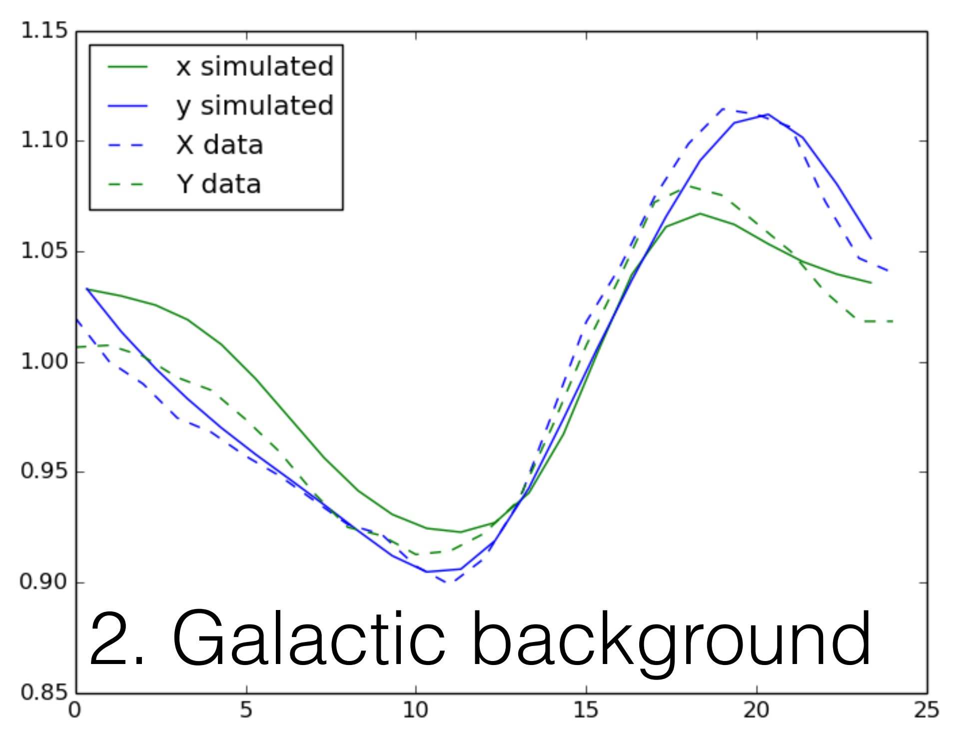
- Time scale too short to calibrate on single source
- Noise dominated by galactic background
- Noise curve measured for specific reference antenna
- All antennas are calibrated relative to reference antenna



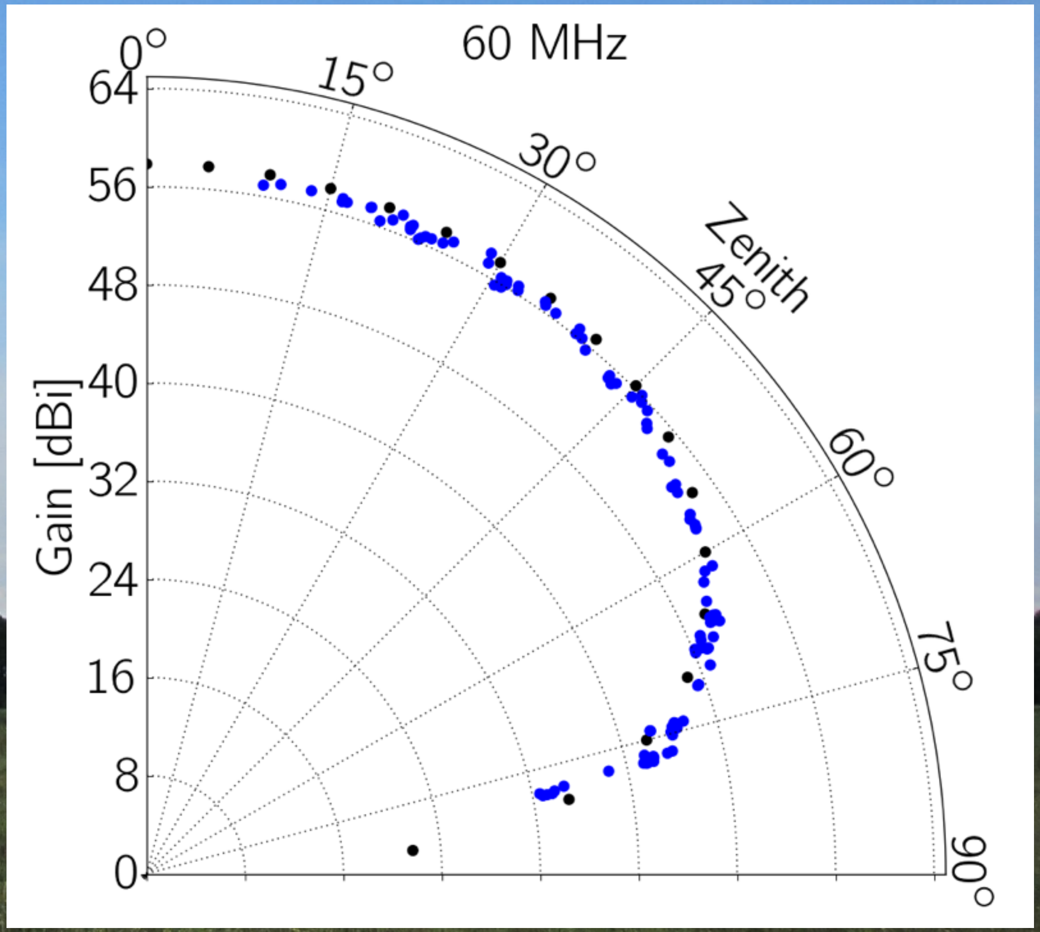
Calibration II

Absolute calibration strategies

1.Octocopter



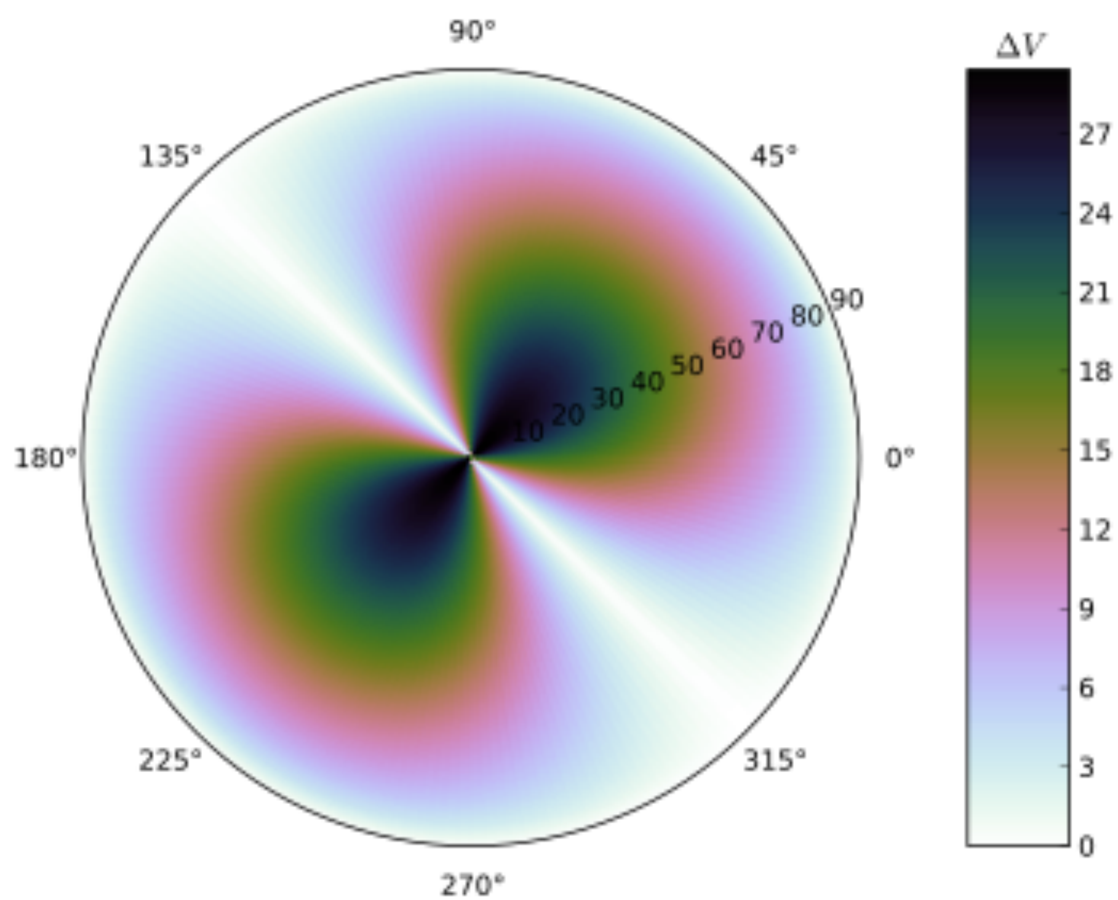
2. Galactic background

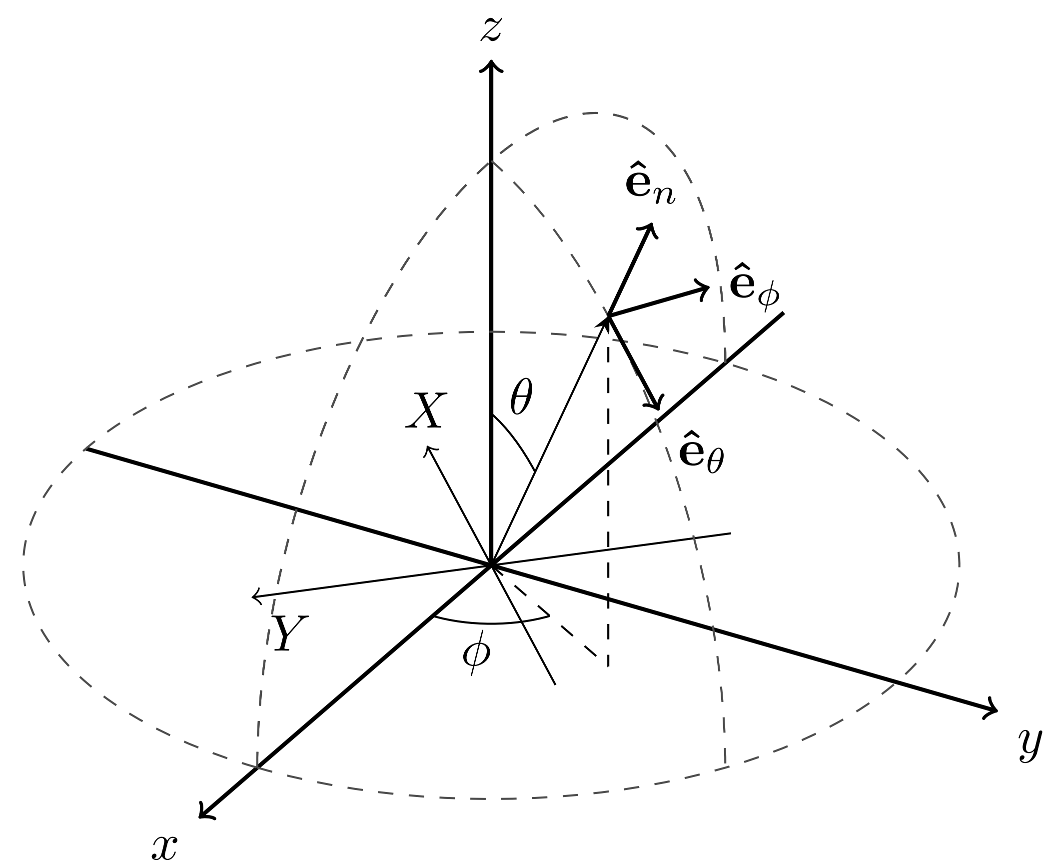


3. Reference antenna on crane

Absolute gain, antenna pattern, bandpass… in progress

The antenna model



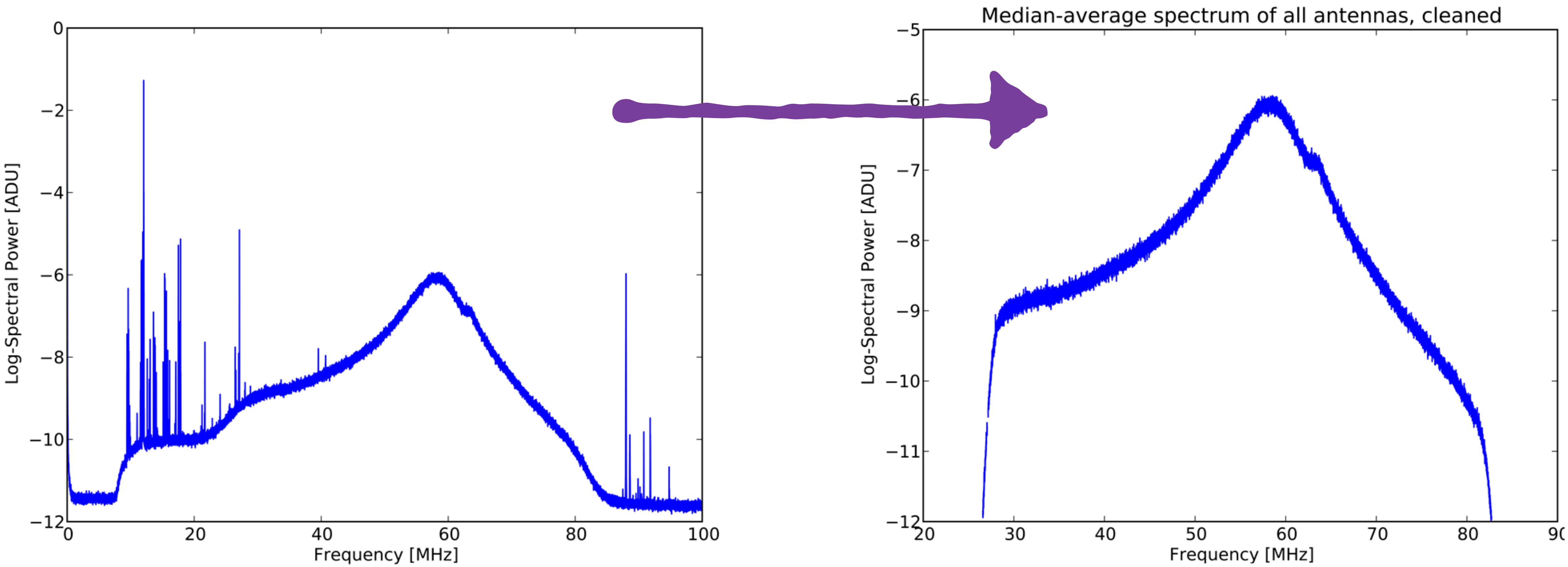


$$\begin{pmatrix} V_X \\ V_Y \end{pmatrix} = \begin{pmatrix} J_{X\theta} & J_{X\phi} \\ J_{Y\theta} & J_{Y_\phi} \end{pmatrix} \begin{pmatrix} E_\theta \\ E_\phi \end{pmatrix}$$

Jones Matrix

- simulated with WIPL-D package
- complex response to incoming wave
- depends on direction, polarisation, frequency

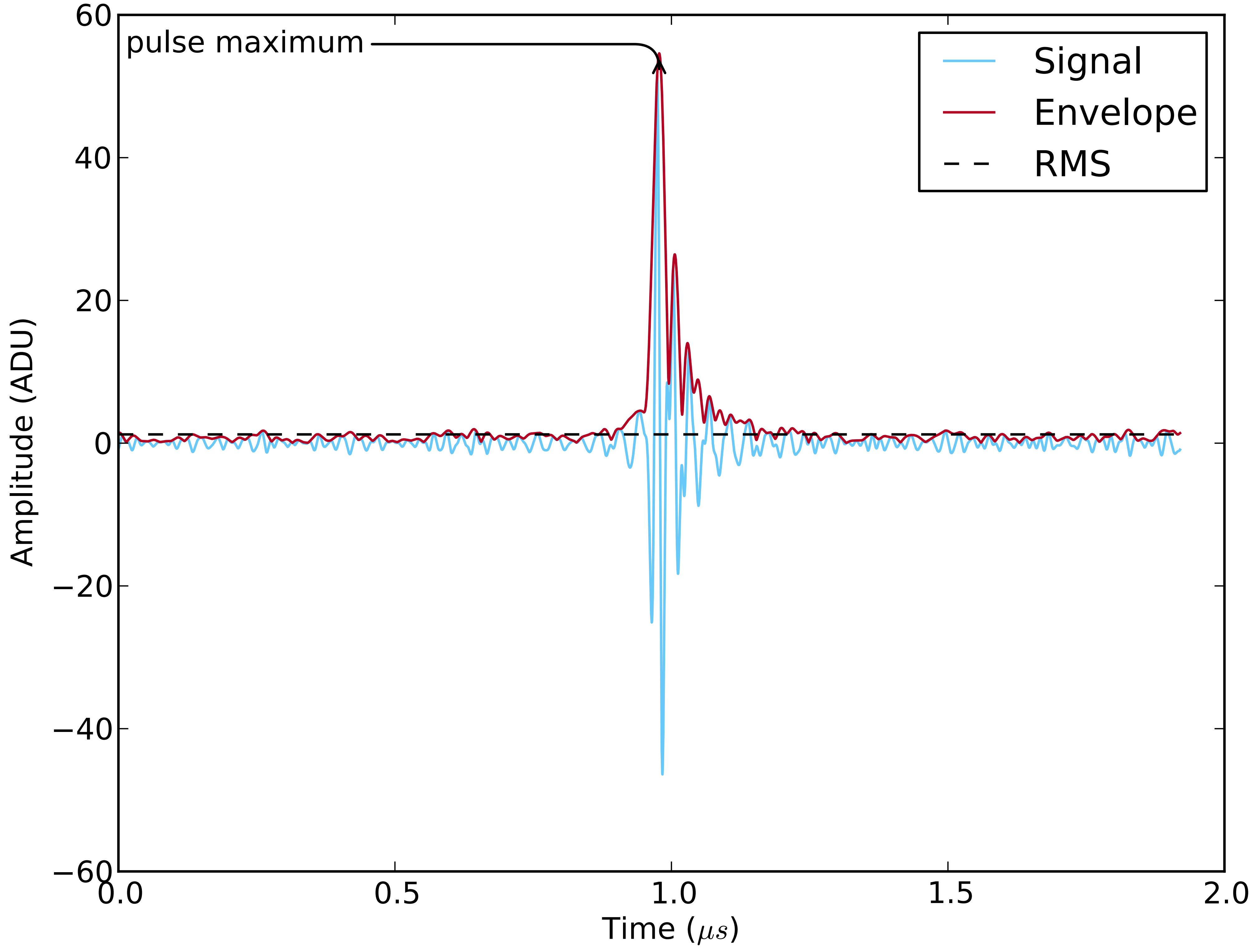
Cleaning RFI



Average of multiple block FFTs
e.g. 2^{16} samples/block = 33 ms = 3 kHz resolution
multiple blocks to reduce noise

line identification:
- polynomial fit to baseline
- phase stability

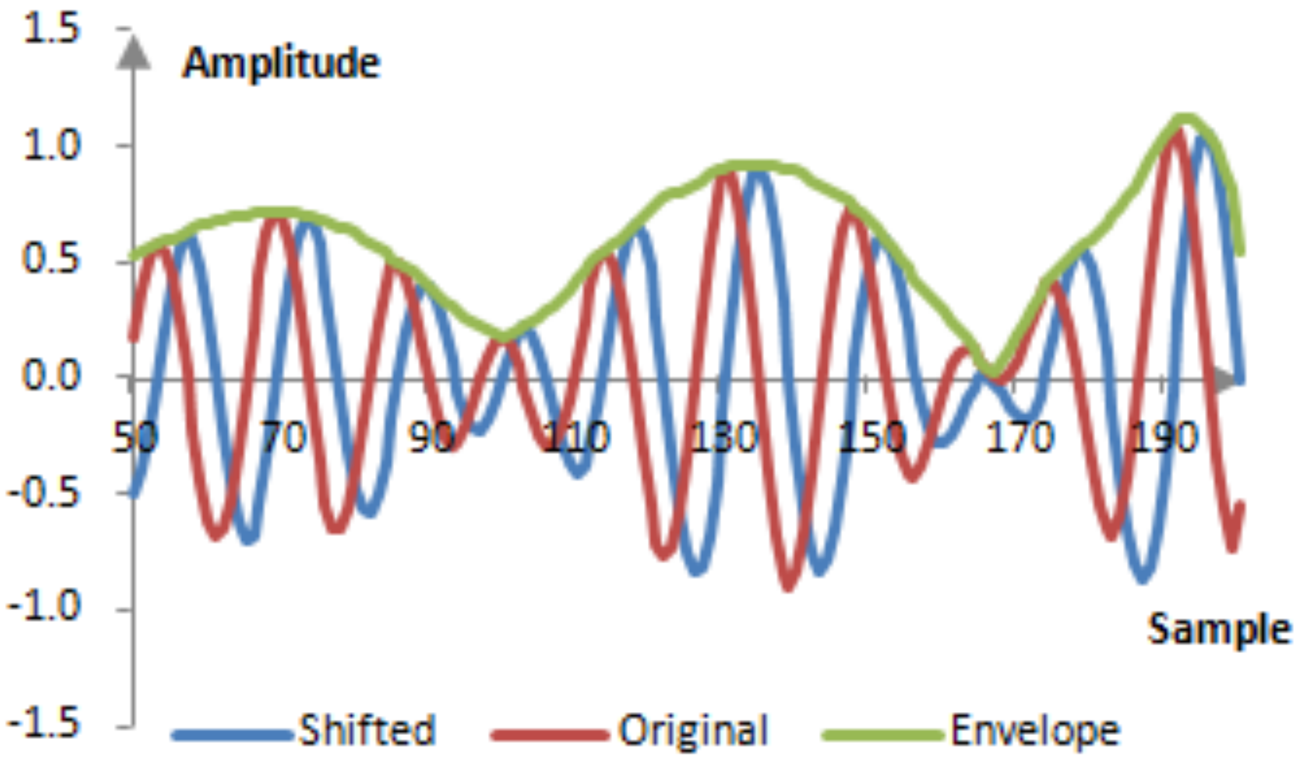
Pulse finding



Hilbert Envelope

Hilbert transform

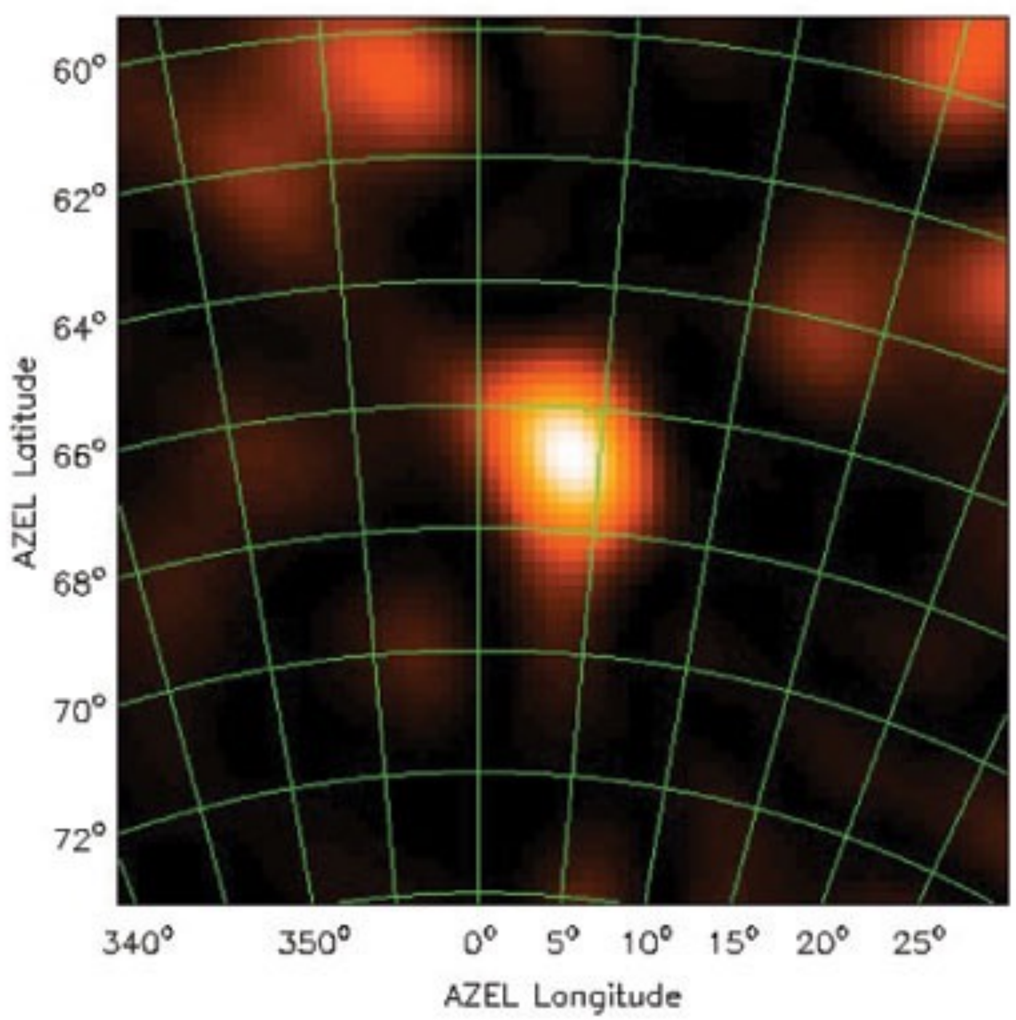
$$\mathscr{F}(\hat{x}(t))(\omega) = -i \cdot \operatorname{sgn}(\omega) \cdot \mathscr{F}(x(t))(\omega)$$

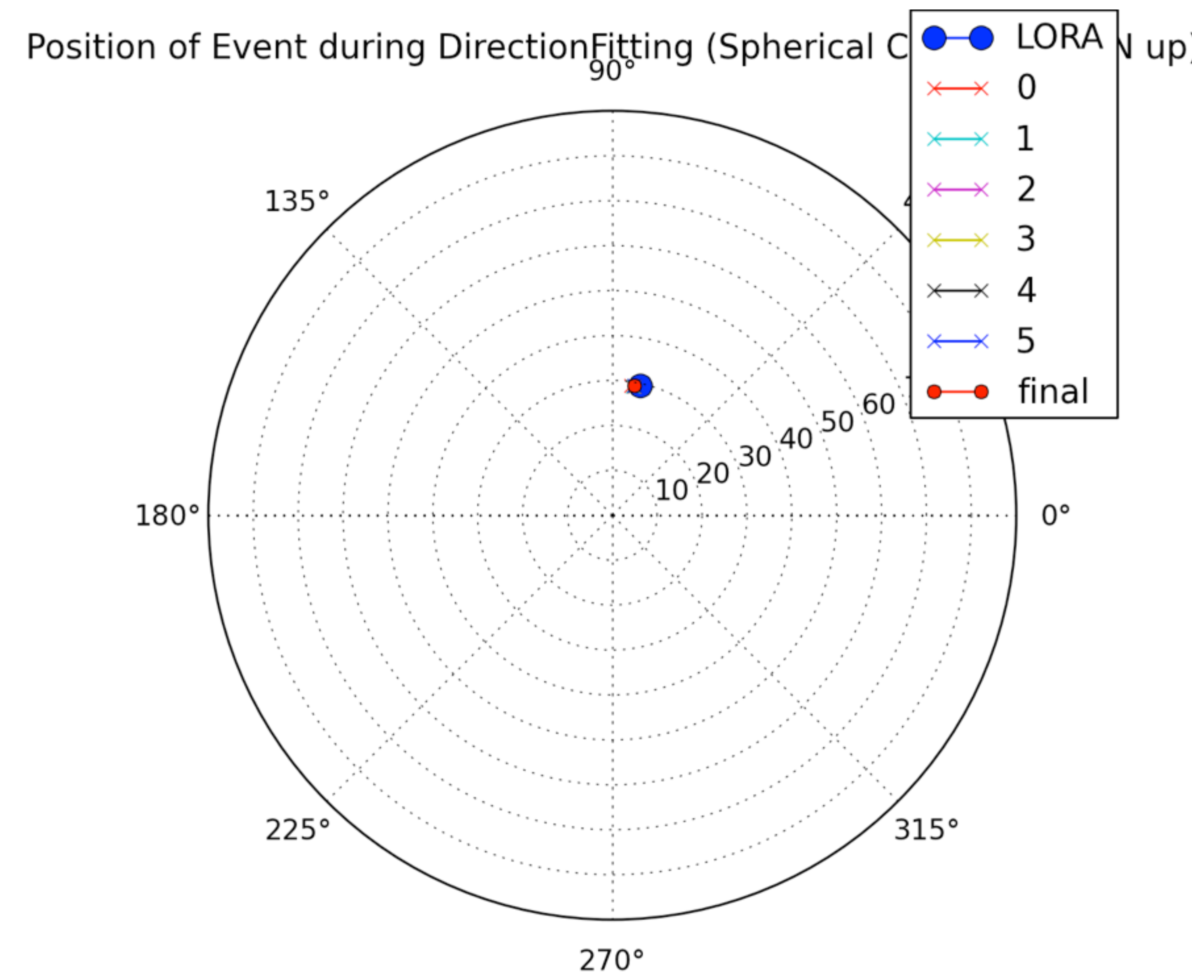


Envelope

$$A(t) = \sqrt{x^2(t) + \hat{x}^2(t)}.$$

Pulse arrival direction





Beamforming

very sensitive

many local minima (side-lobes)

Plane wave fit (using pulse arrival time)

less sensitive

more stable

Pulse polarization

$$I = \frac{1}{n}\sum_{i=0}^{n-1}(E_{i,x}^2 + \hat{E}_{i,x}^2 + E_{i,y}^2 + \hat{E}_{i,y}^2),$$

$$Q = \frac{1}{n}\sum_{i=0}^{n-1}(E_{i,x}^2 + \hat{E}_{i,x}^2 - E_{i,y}^2 - \hat{E}_{i,y}^2),$$

$$U = \frac{2}{n}\sum_{i=0}^{n-1}(E_{i,x}E_{i,y} + \hat{E}_{i,x}E_{i,y}),$$

$$V = \frac{2}{n}\sum_{i=0}^{n-1}(\hat{E}_{i,x}E_{i,y} - E_{i,x}E_{i,y}).$$

Integrate Stokes parameters over bins containing pulse

angle of semi-major axis:

$$\psi = \frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right).$$

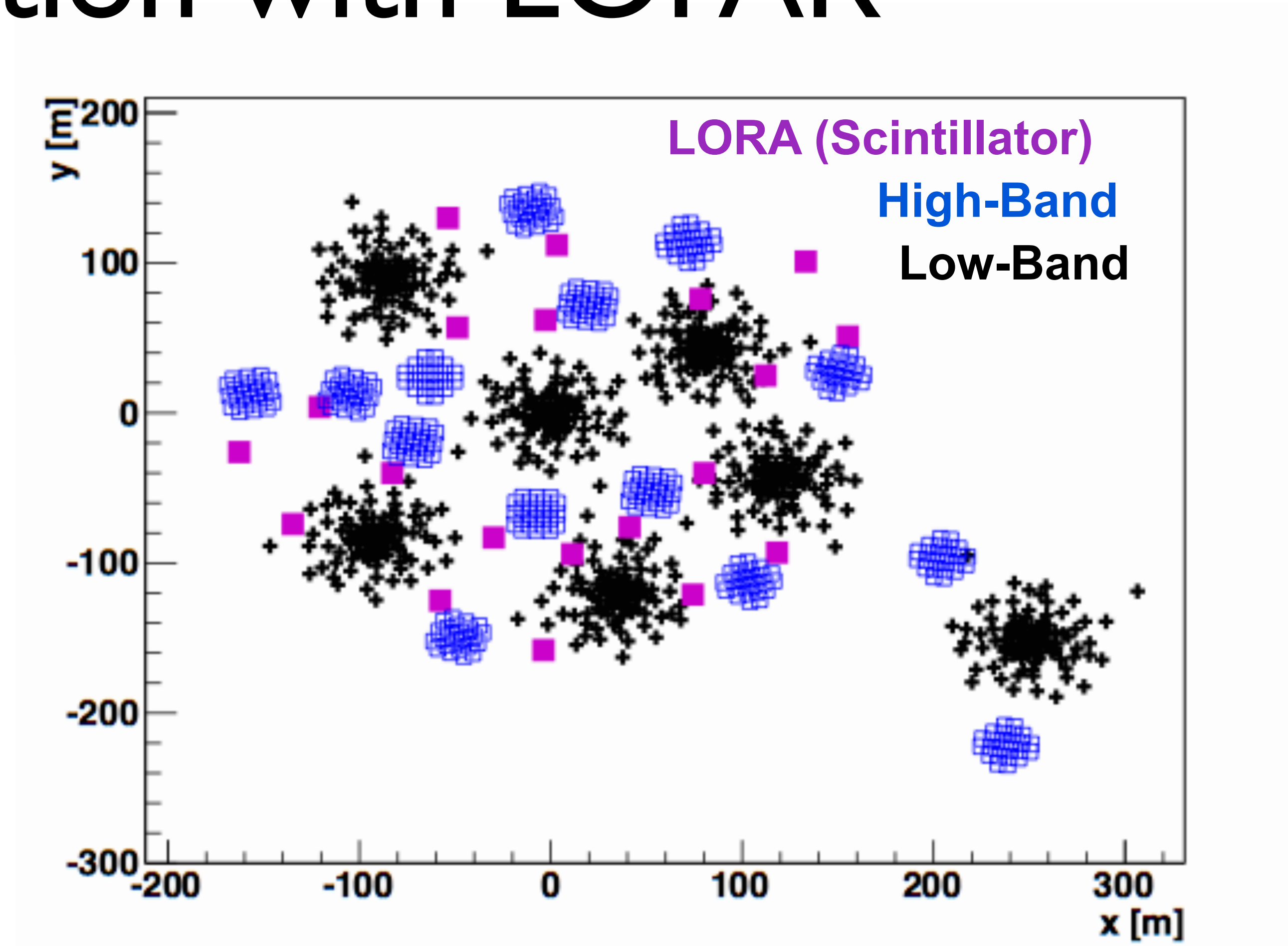
degree of polarization:

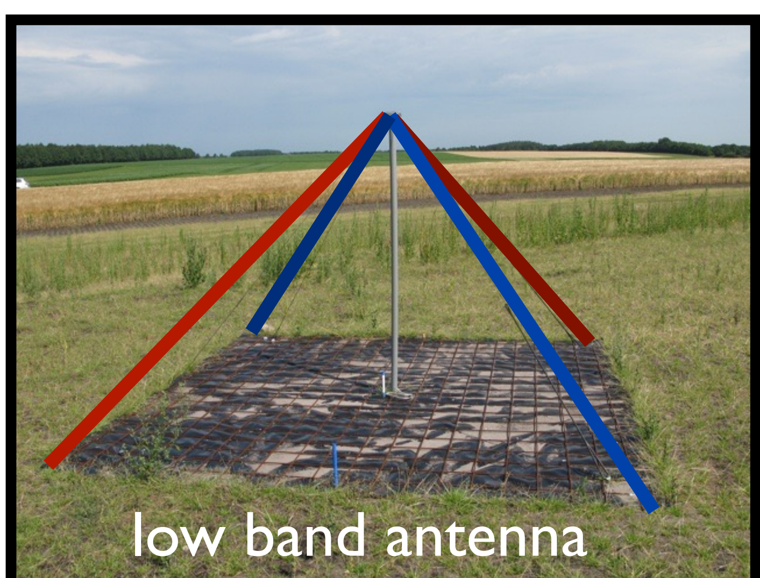
$$p = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}.$$

Air shower detection with LOFAR

LORA
LOFAR Radboud Array
scintillator detectors

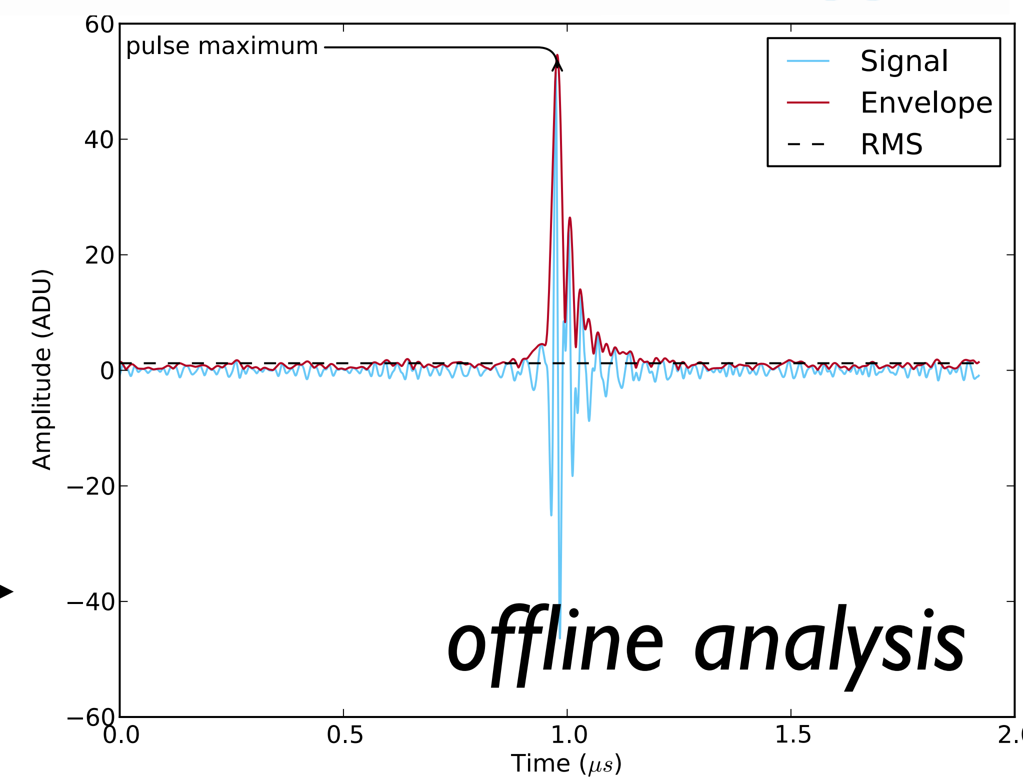
trigger





TBBs

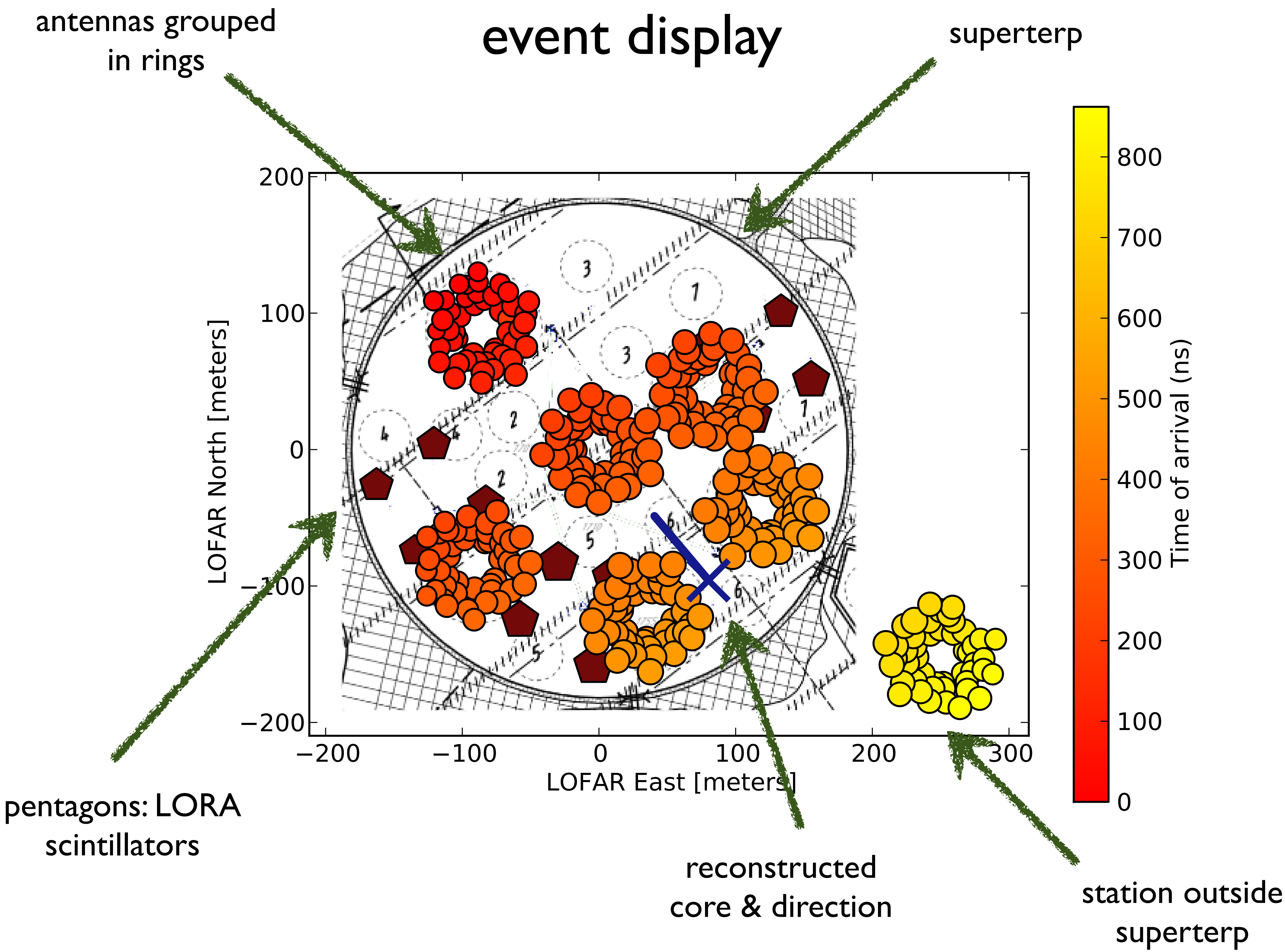
2 ms read-out



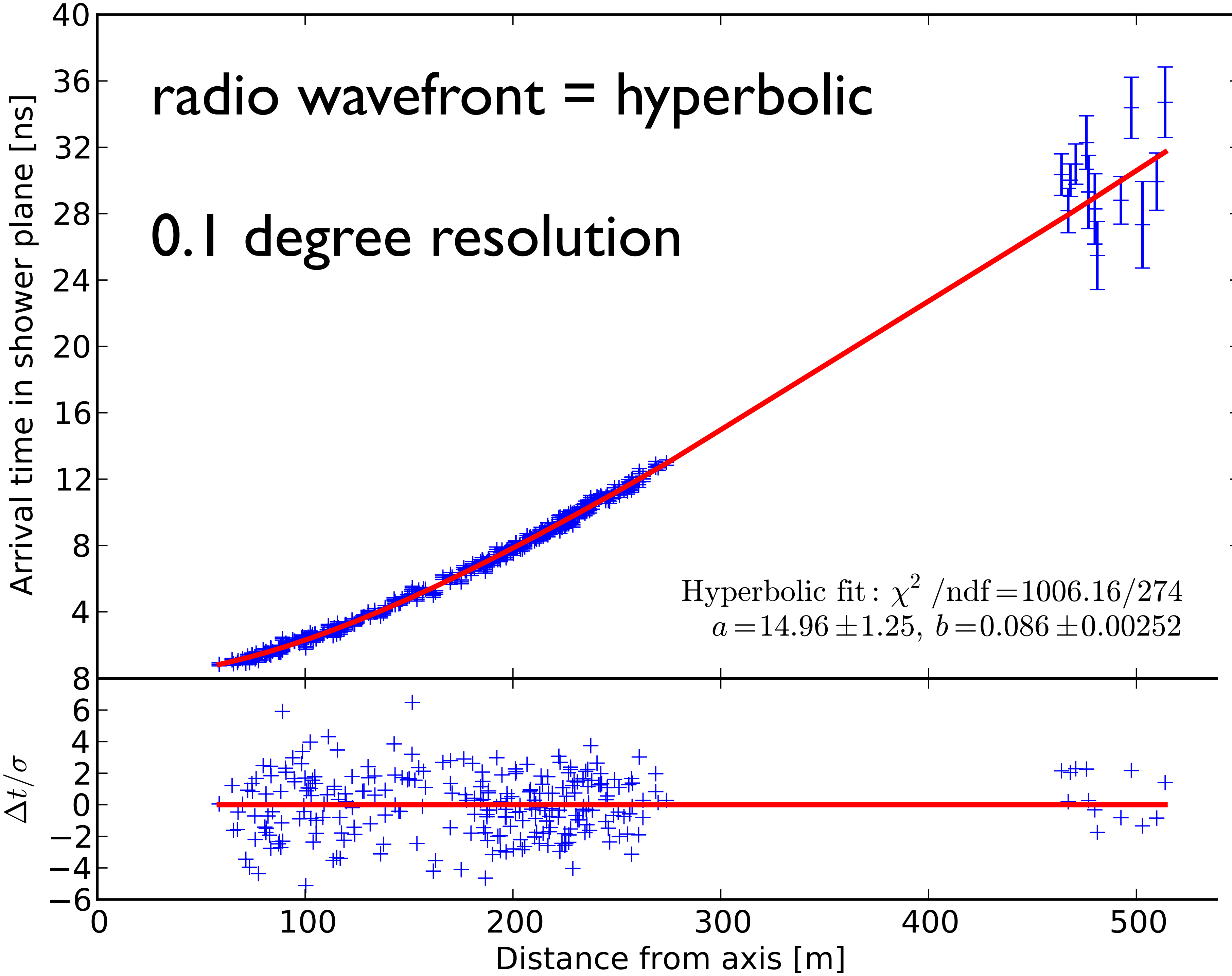
offline analysis

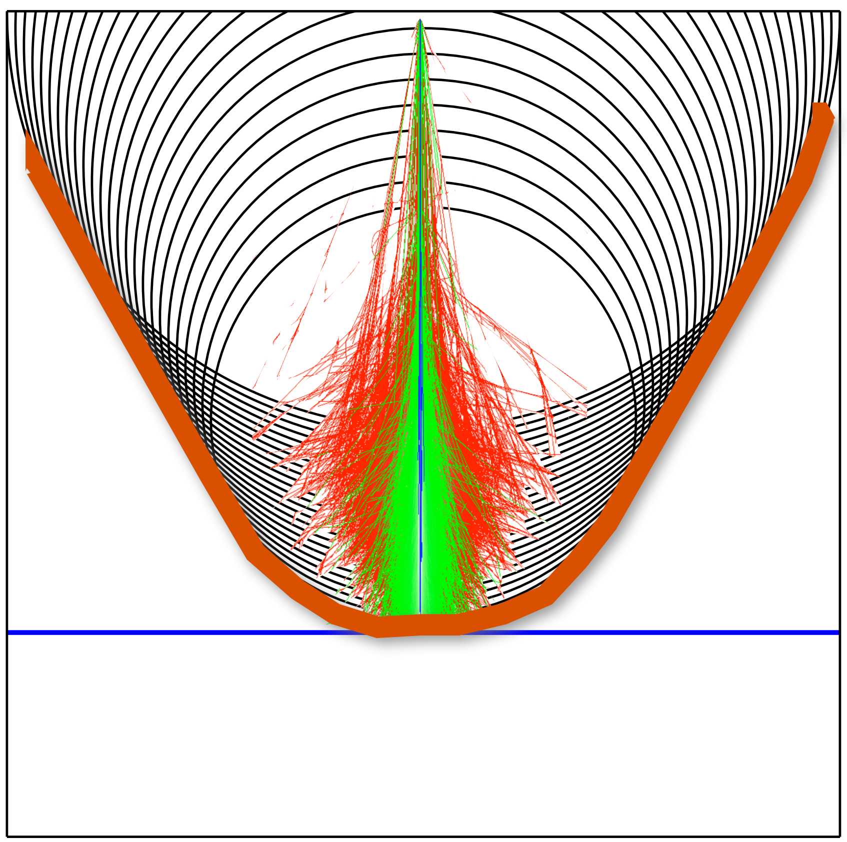
Pim Schellart et al., A&A 560, 98 (2013)

event display



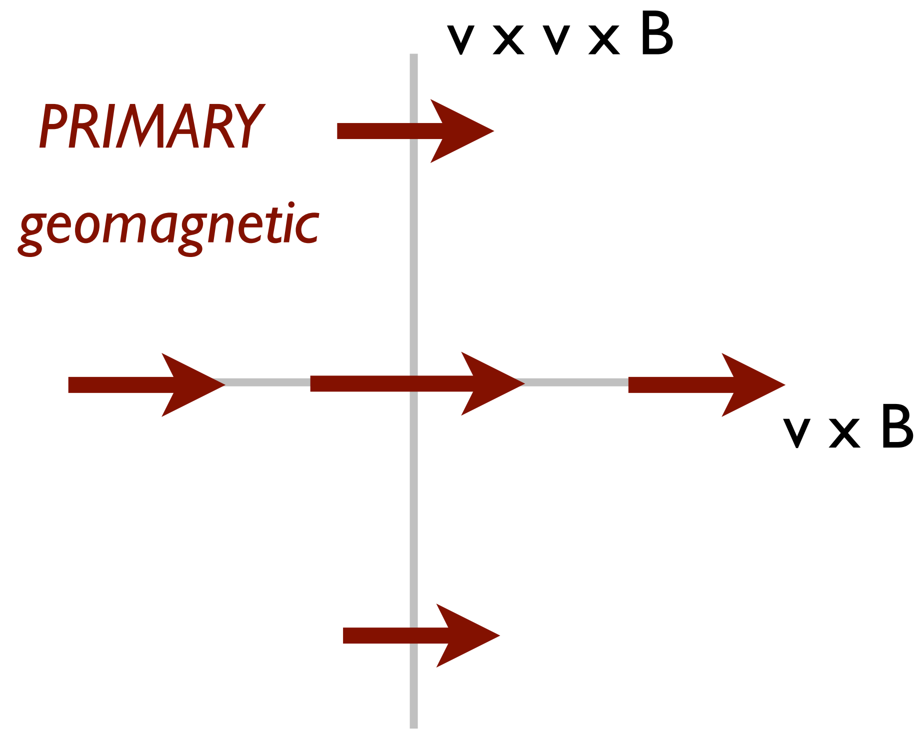
Nanosecond timing precision

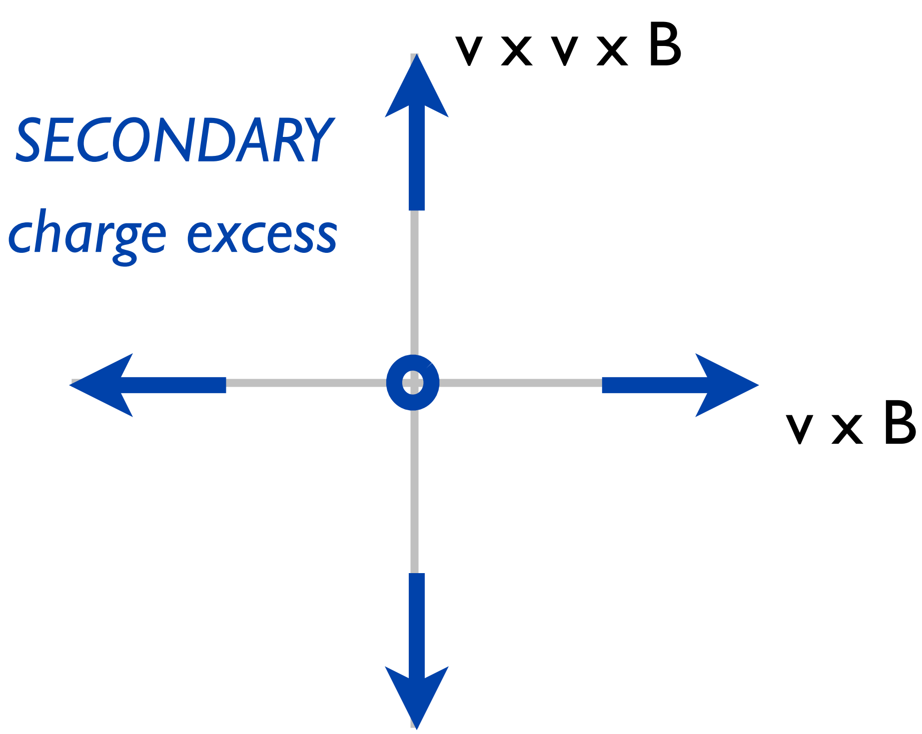


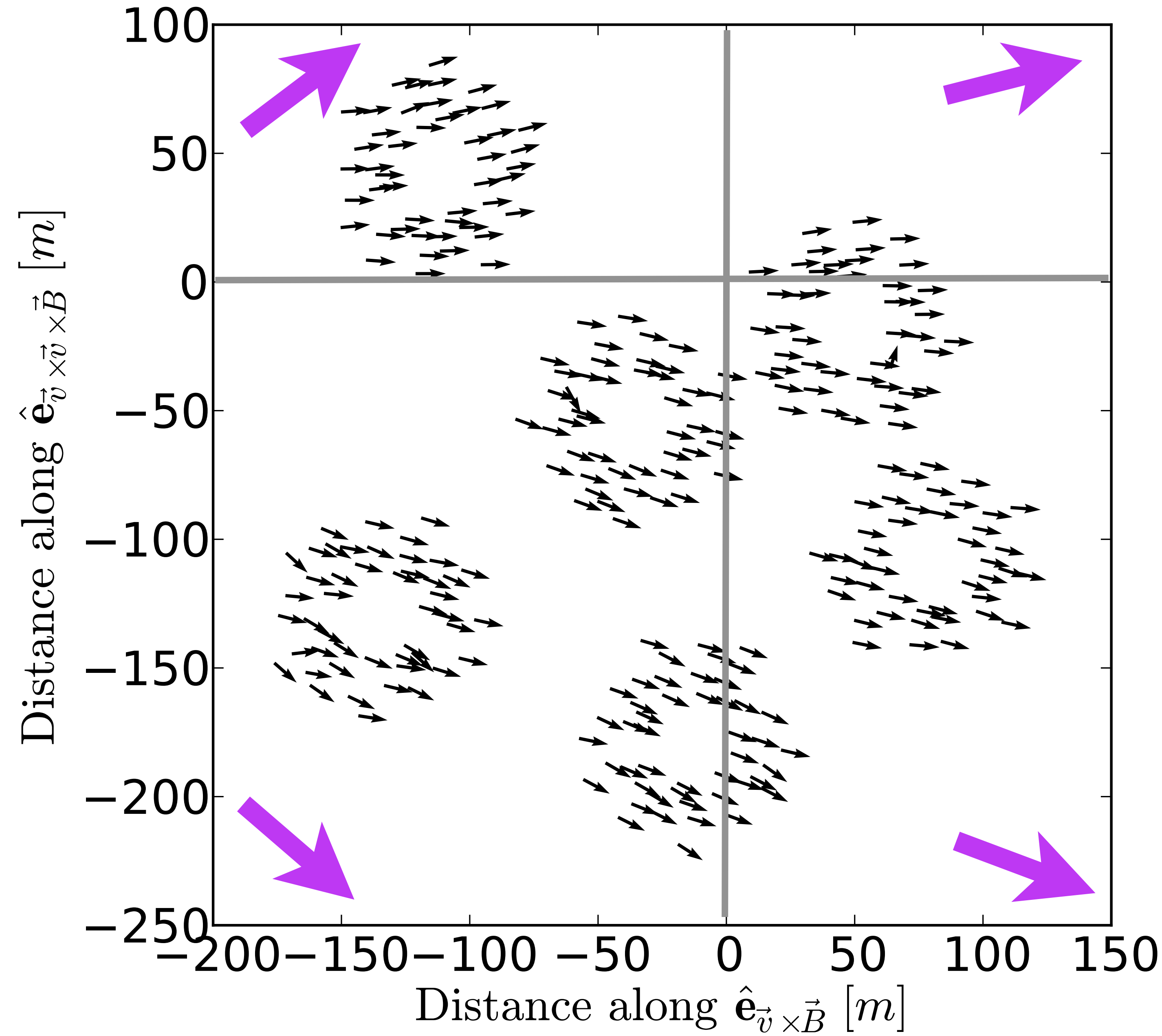


Arthur Corstanje et al., *Astropart. Phys.* **61** 22 (2015)

Understanding the polarization

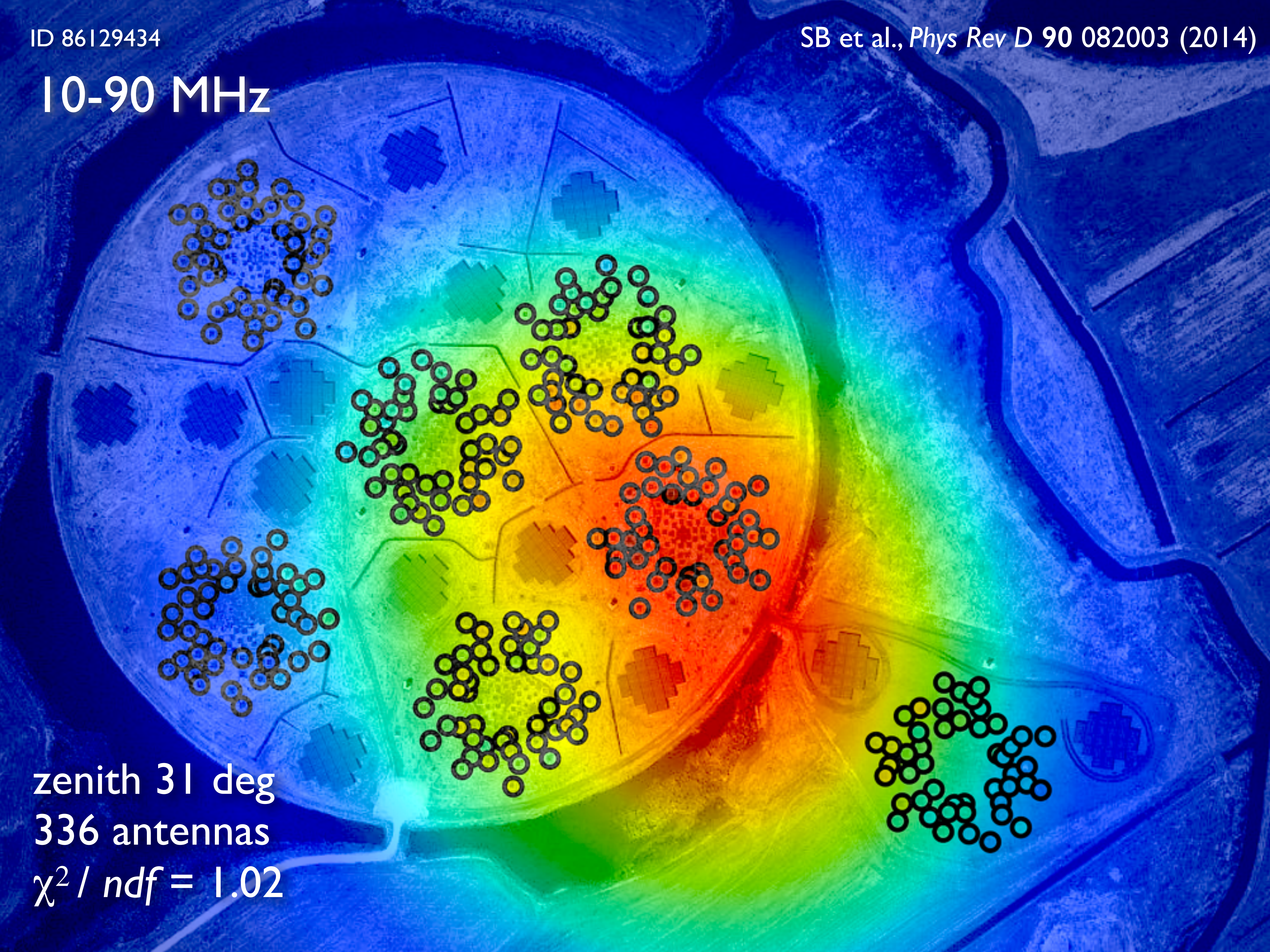


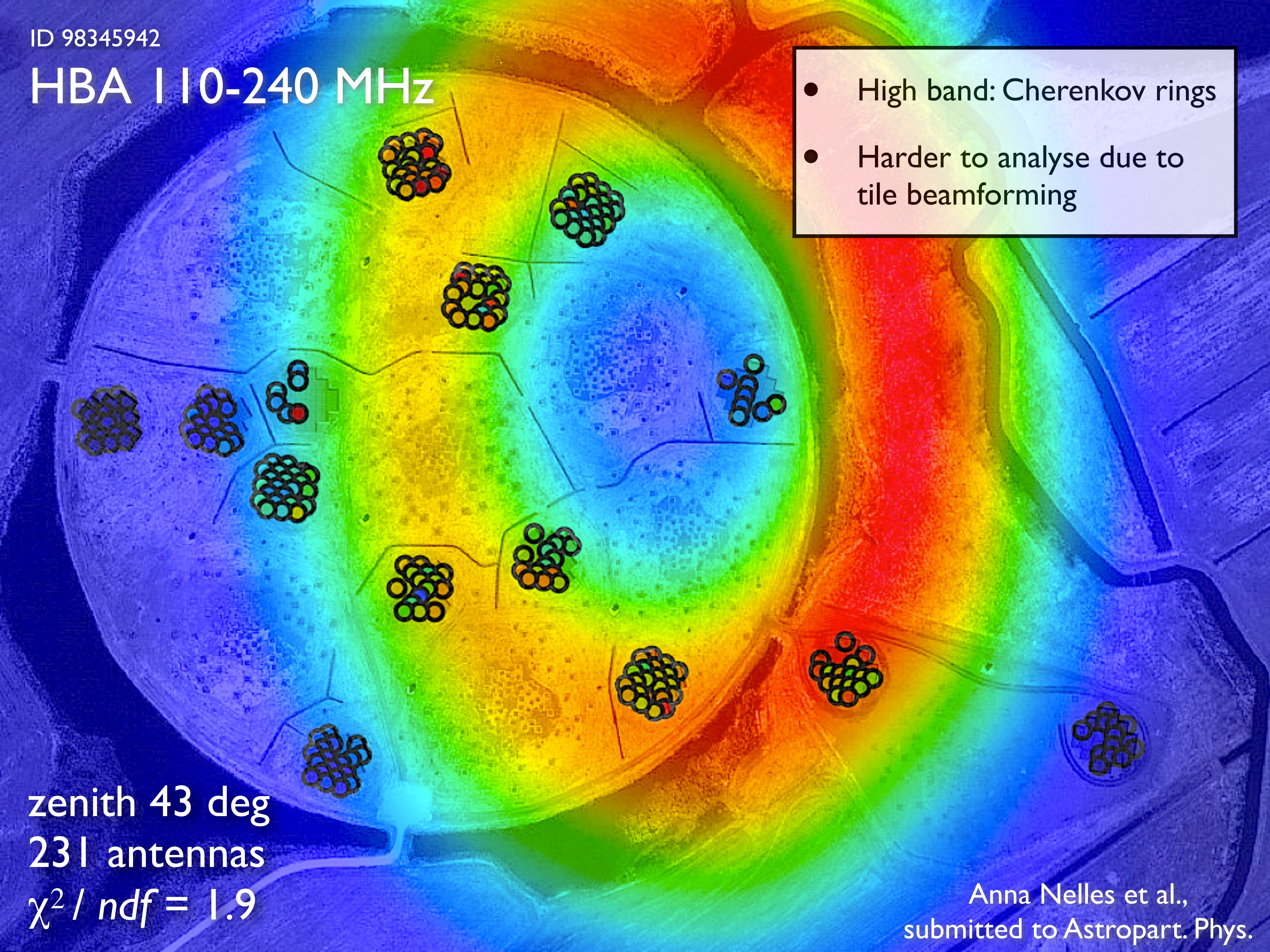




Interference: emission pattern = asymmetric

Pim Schellart et al., *JCAP* **10** 14 (2014)


ID 86129434
SB et al., *Phys Rev D* **90** 082003 (2014)
10-90 MHz
zenith 31 deg
336 antennas
$\chi^2 / ndf = 1.02$



ID 98345942

HBA 110-240 MHz

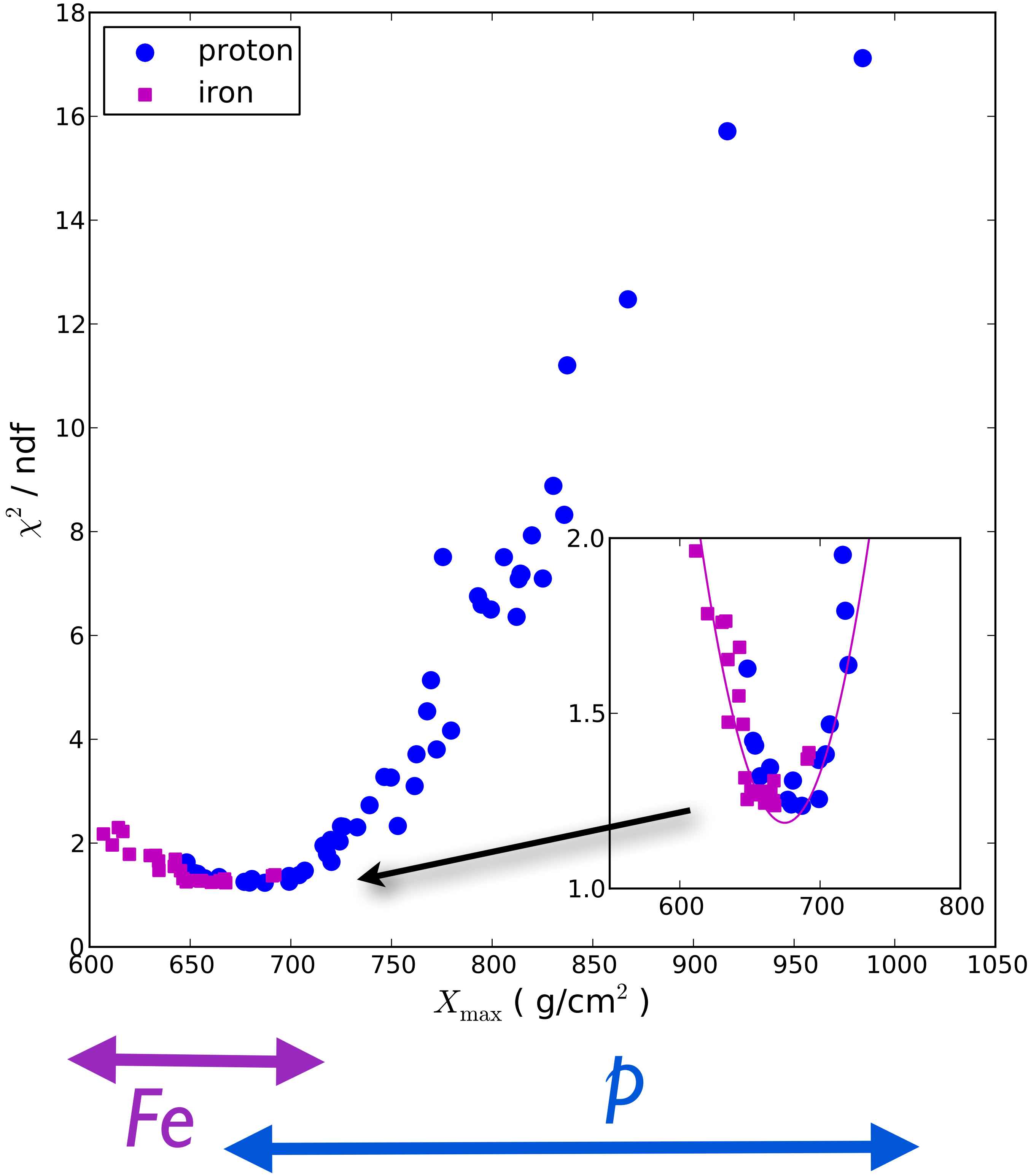
- High band: Cherenkov rings
- Harder to analyse due to tile beamforming

zenith 43 deg
231 antennas
$\chi^2 / ndf = 1.9$

Anna Nelles et al.,
submitted to Astropart. Phys.

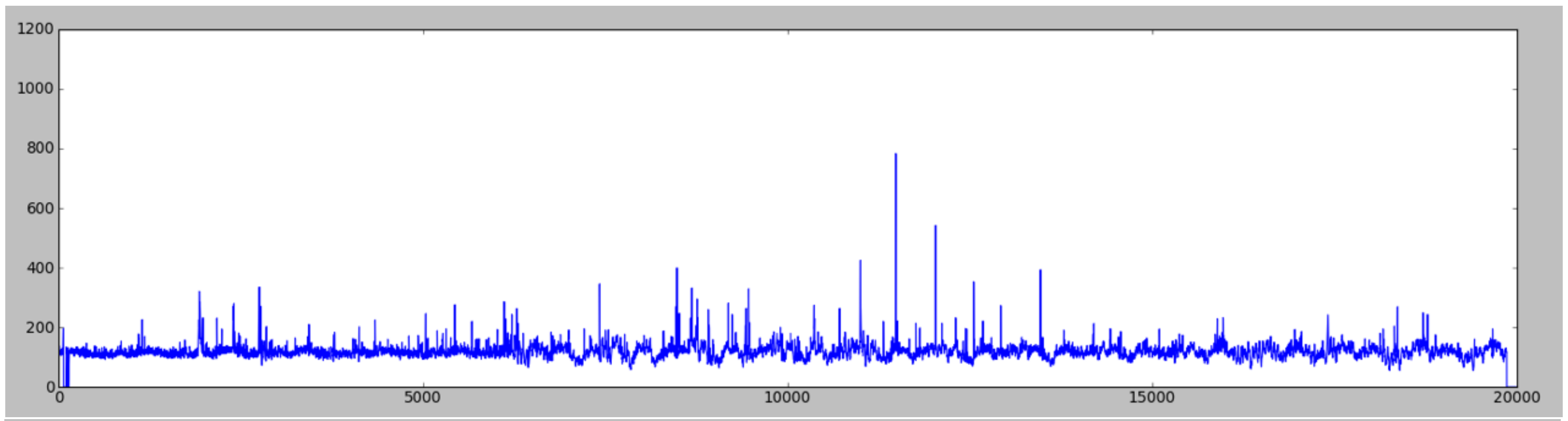
CR mass composition

proton penetrate deeper than iron nuclei

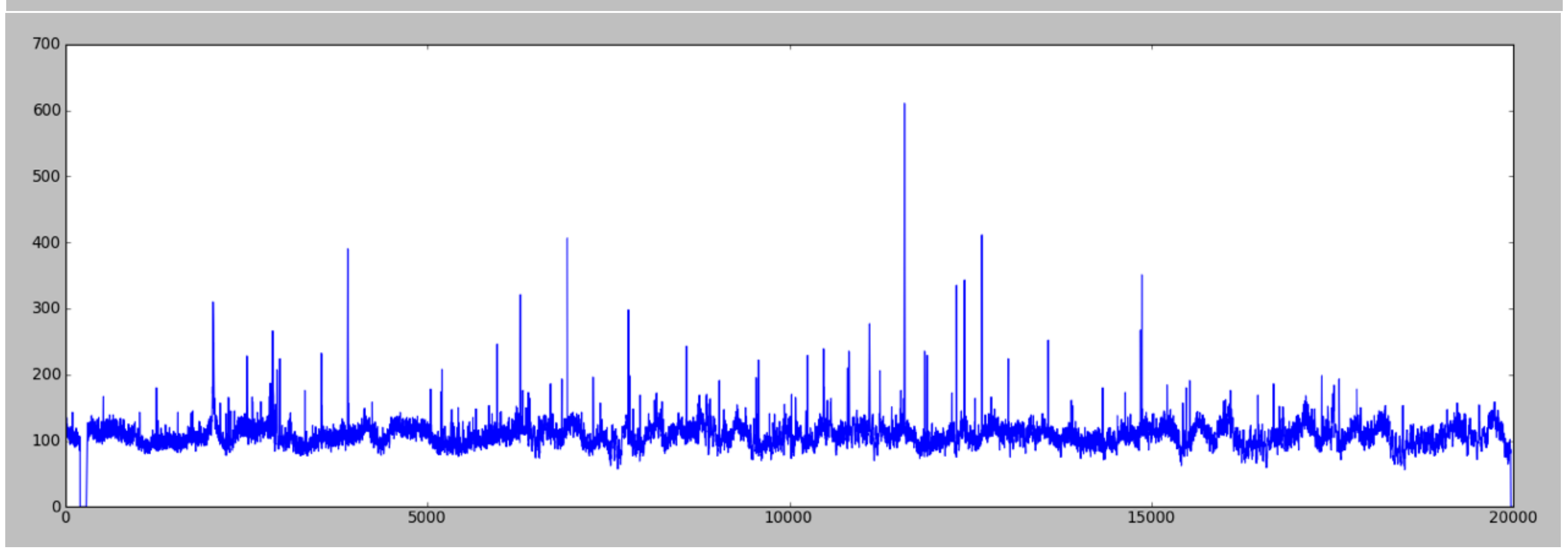


- In its first years of operation LOFAR has “solved” the radiation mechanism
- Now: astrophysics!
- Comparison to simulation gives mass composition of CR flux
- Changes in mass as a function of energy hint at different source component
- Searching for the transition Galactic/extragalactic sources

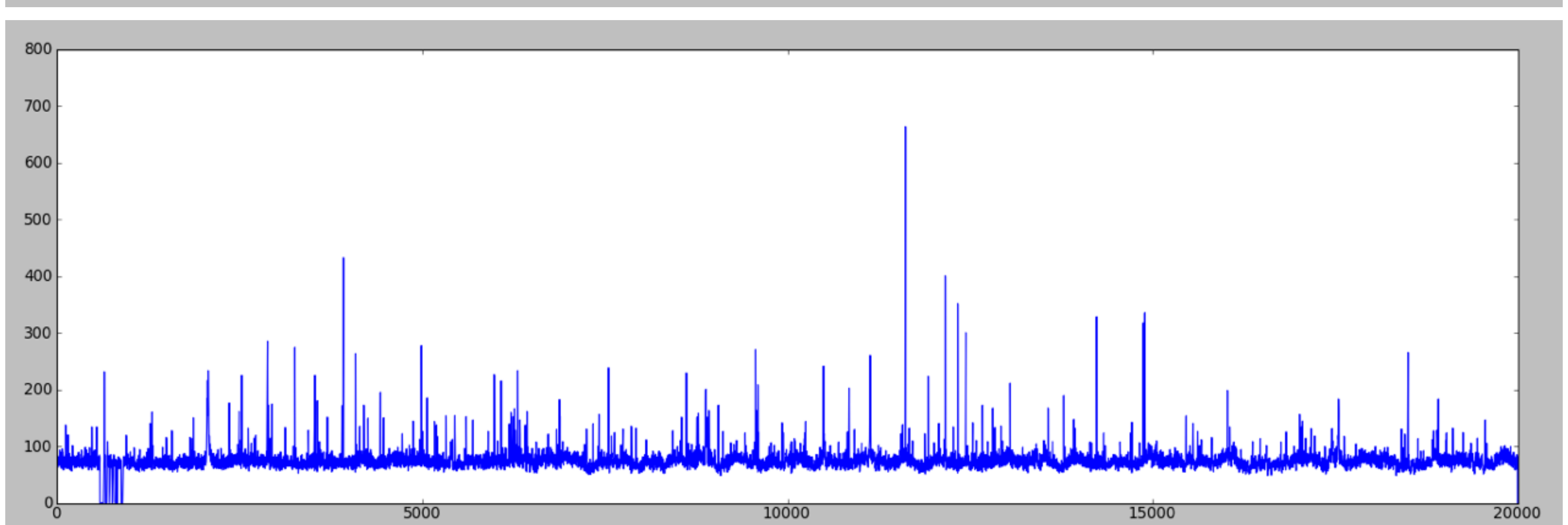
What else can we see…?



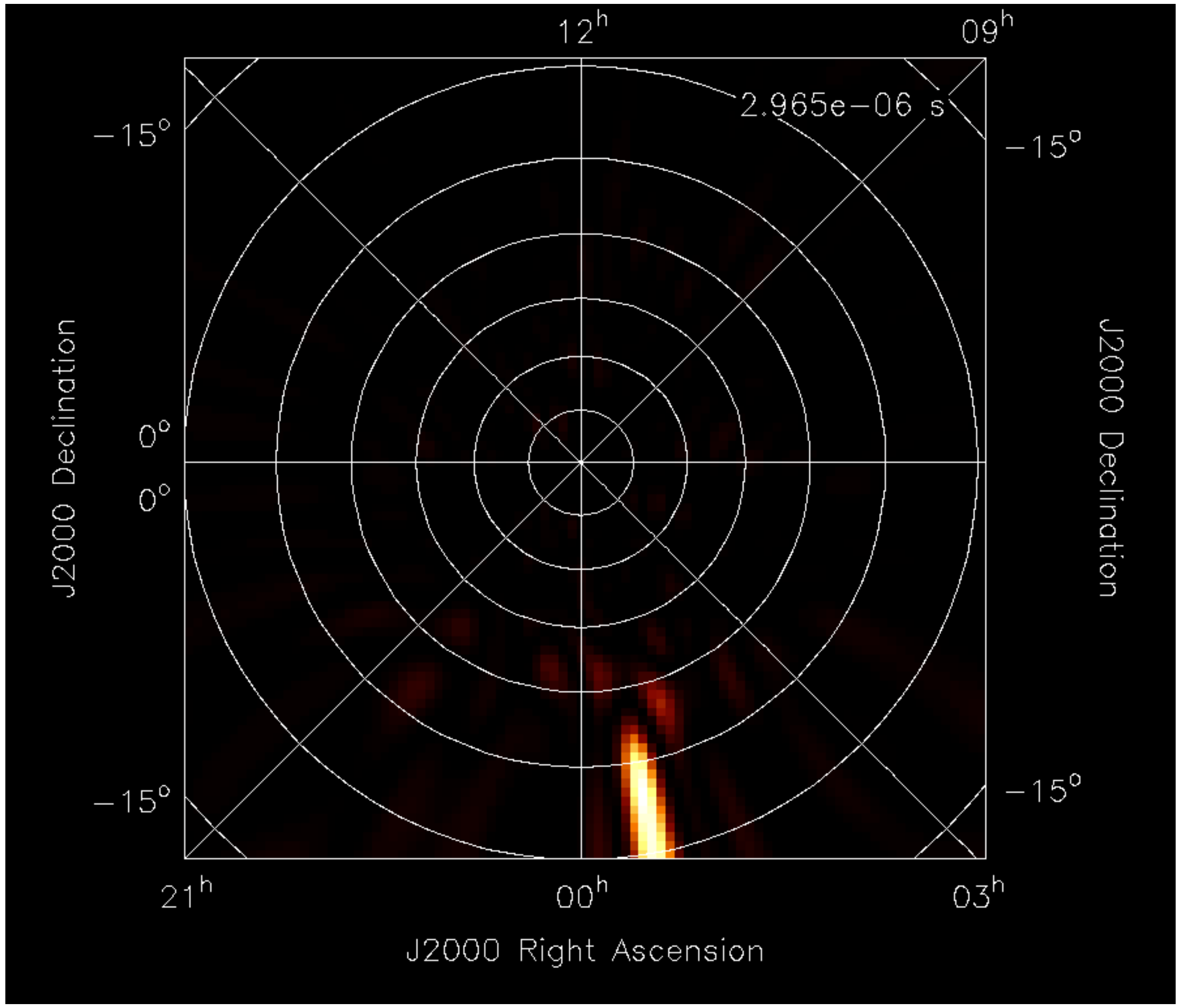
RS503



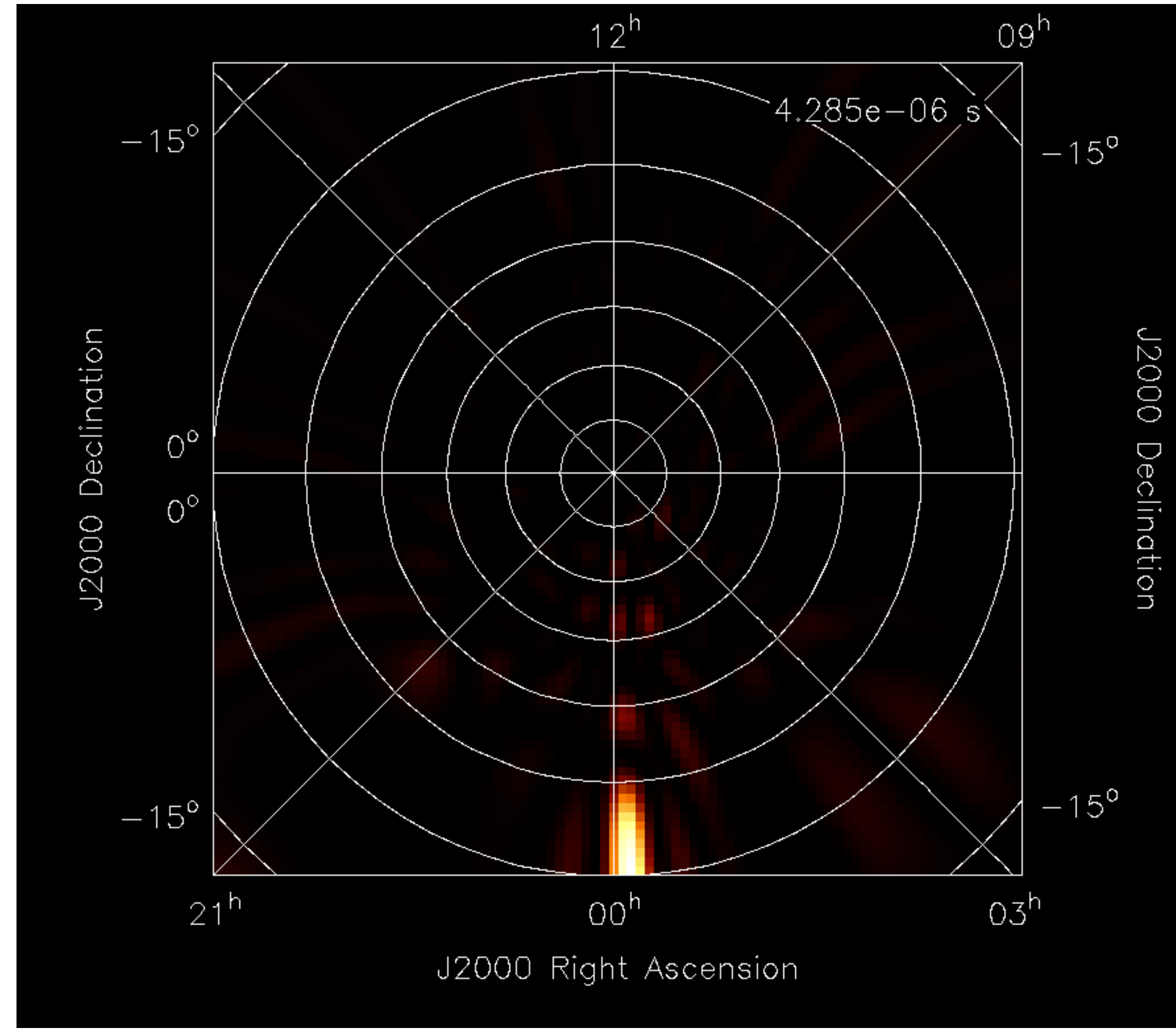
RS106



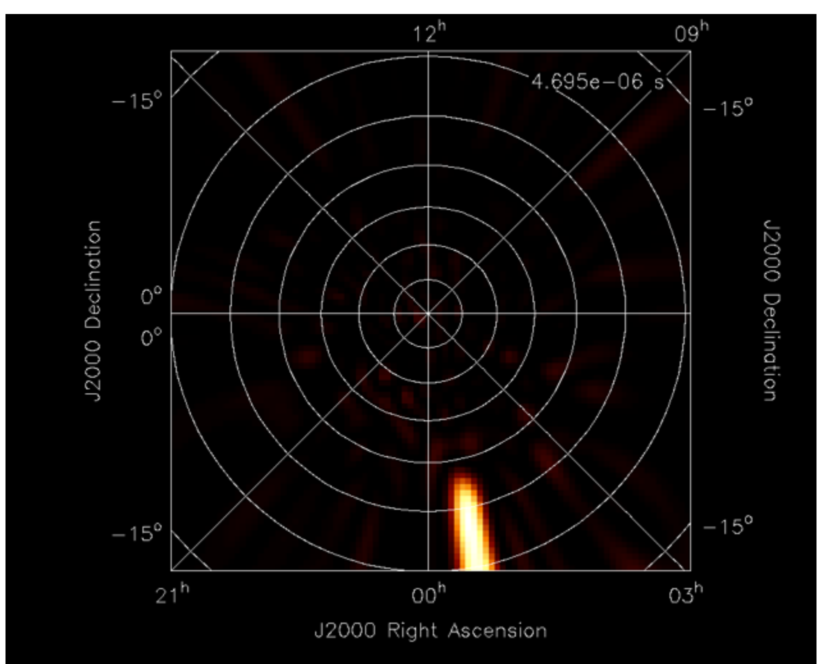
CS002



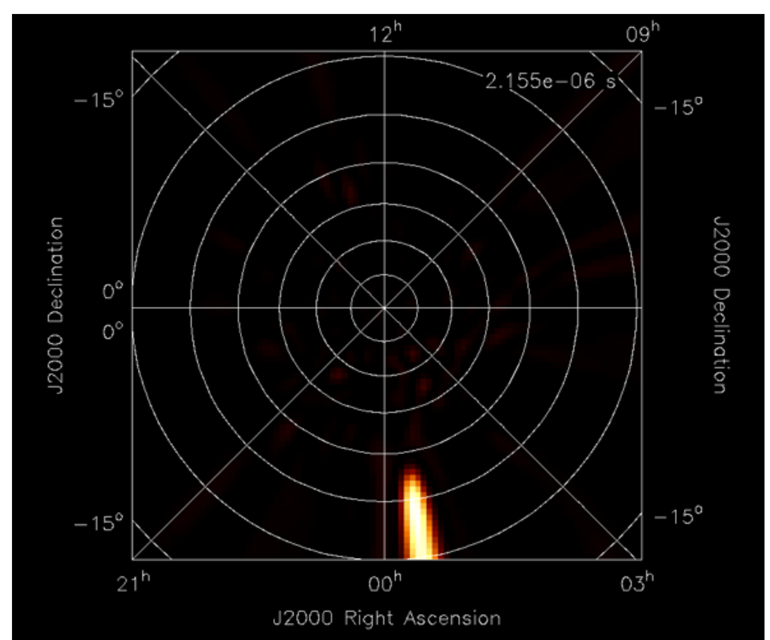
RS503



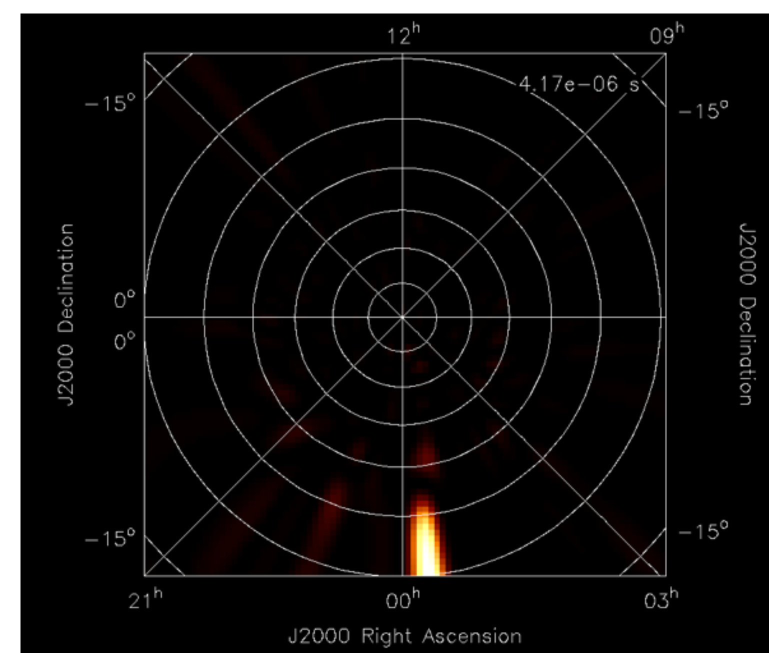
RS106



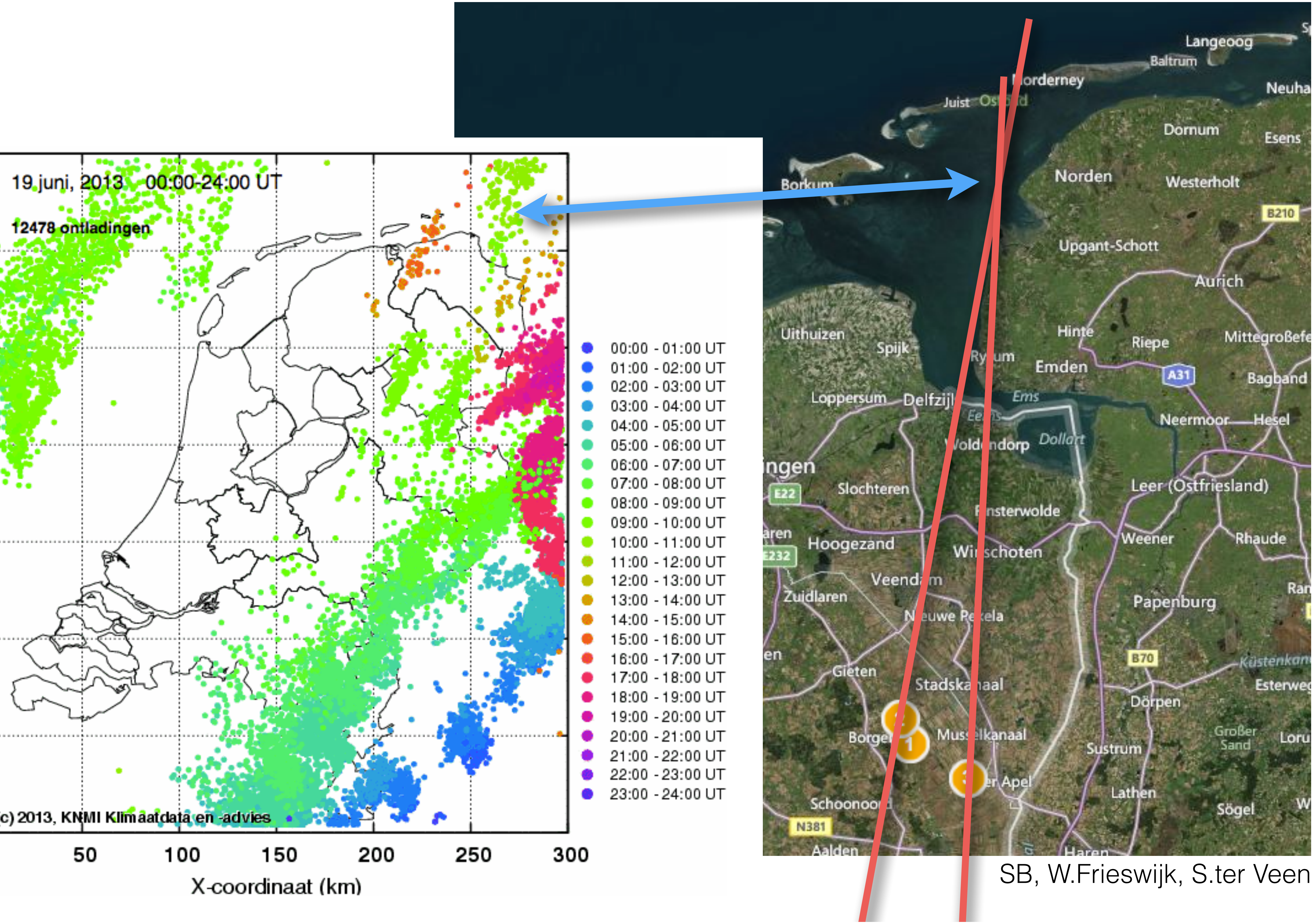
CS002



RS205



RS208



SB, W.Frieswijk, S.ter Veen

Trigger: manual

future: local station trigger?

10^{20} - $10^{??}$ eV: Moon = 10^7 km^2 detector area

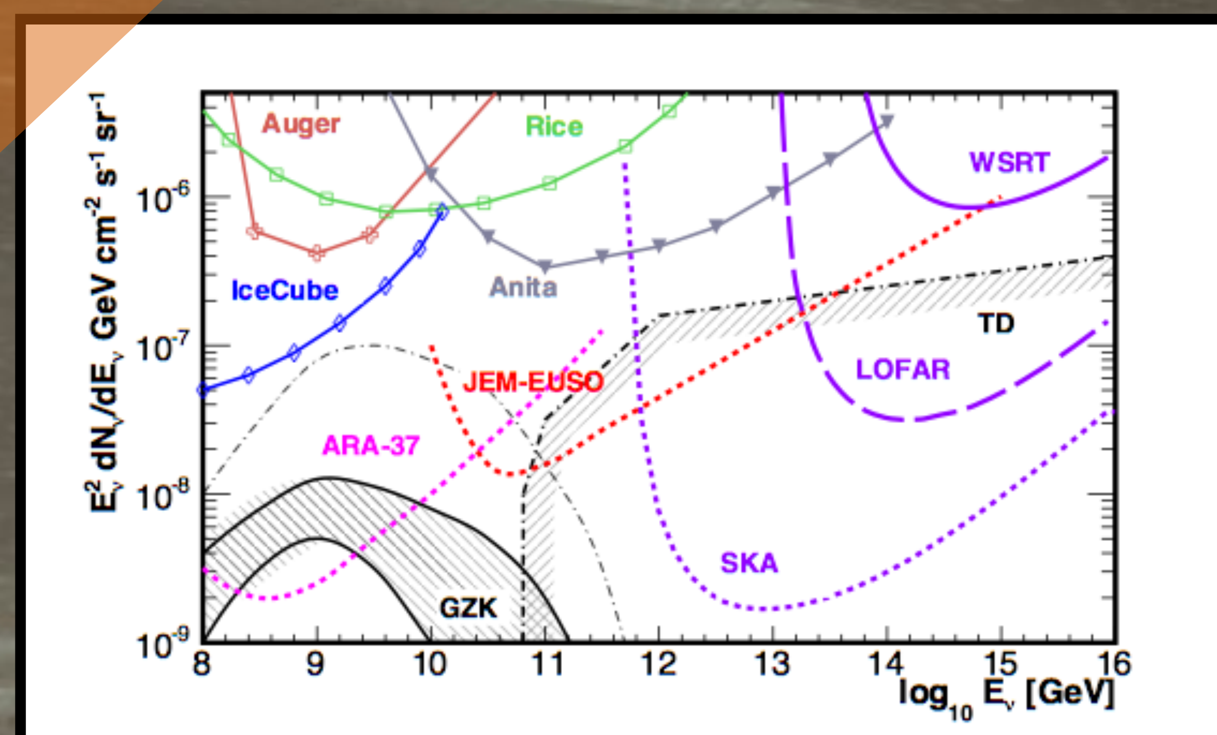
WSRT

LOFAR

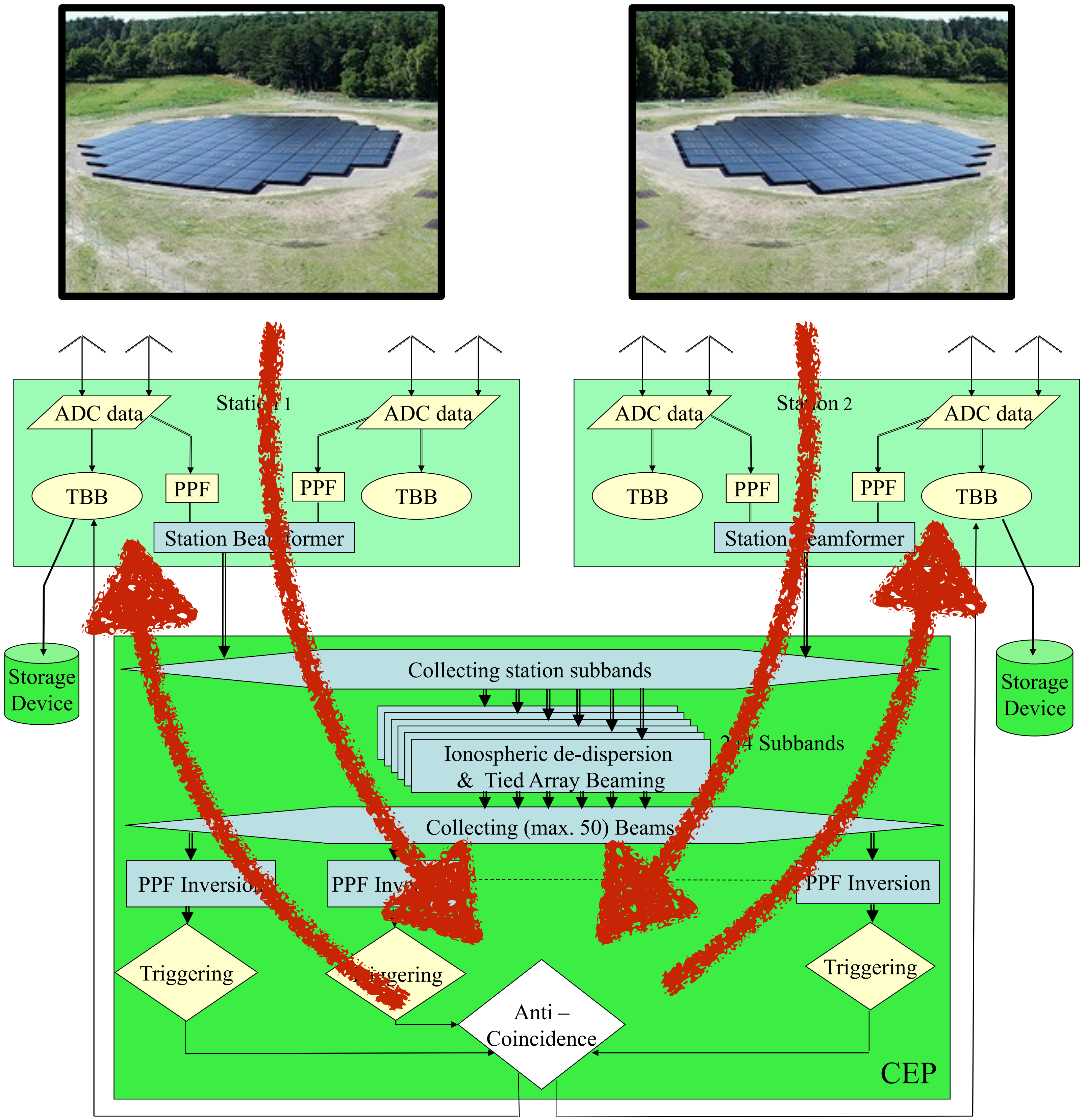
best sensitivity now:
Buitink et al. A&A 521, 47(2010)

radio flash
ns scale!

CR/neutrino



NuMoon: New Observation Mode



best limit @ WSRT
offline analysis

new challenge:
real-time analysis!

signal synthesis
+
trigger decision
+
communication

within 5 seconds

TBBs & you ?

- Transient Buffer Boards (TBBs) store 5 seconds of raw timeseries data
- Many triggering strategies possible
- Full-sky-all-the-time when running in background
- Cosmic rays, neutrinos from the Moon, lightning, fast radio bursts, …

Thanks for your attention!