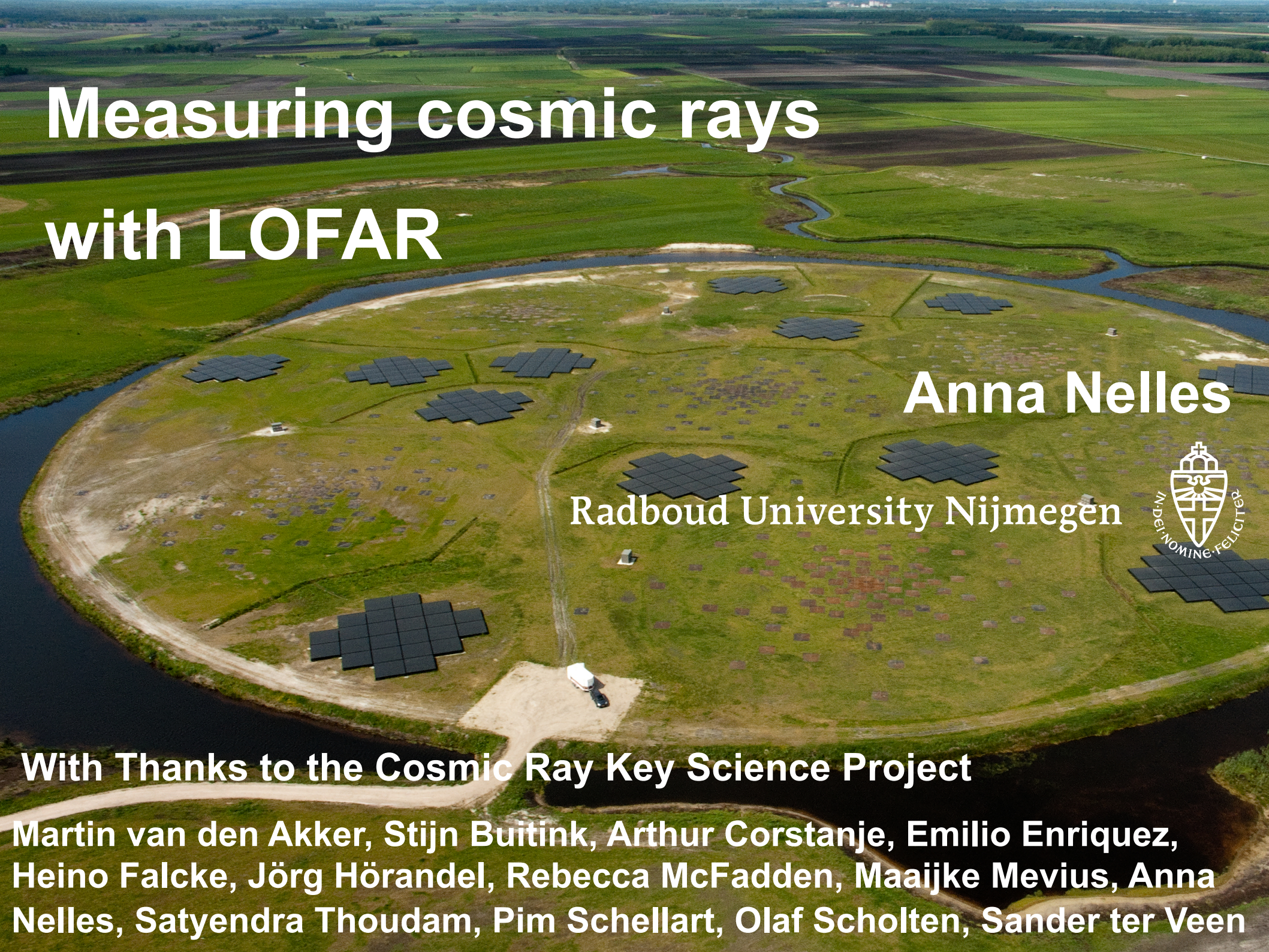
Measuring cosmic rays with LOFAR



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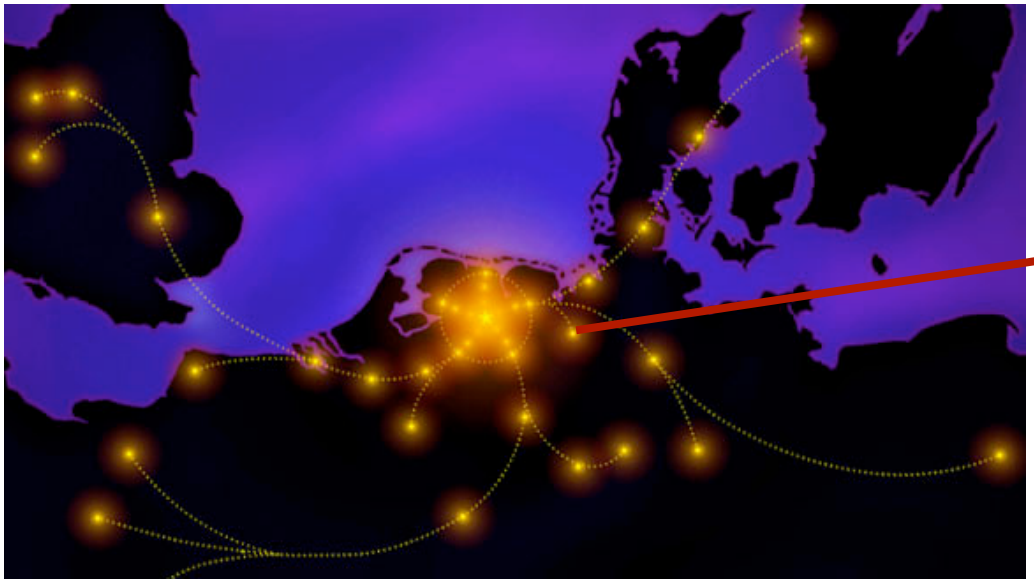
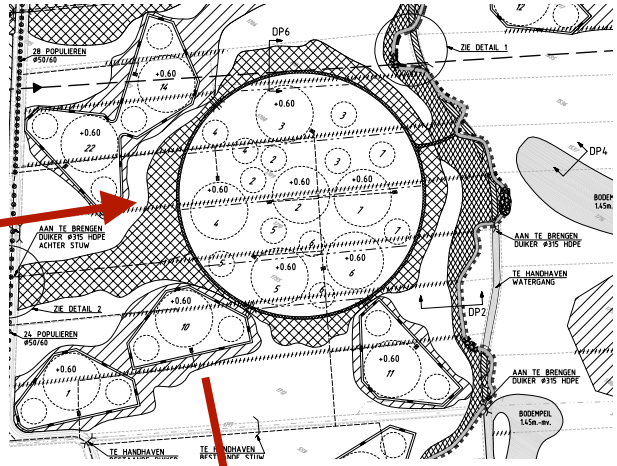
With Thanks to the Cosmic Ray Key Science Project

Martin van den Akker, Stijn Buitink, Arthur Corstanje, Emilio Enriquez, Heino Falcke, Jörg Hörandel, Rebecca McFadden, Maaijke Mevius, Anna Nelles, Satyendra Thoudam, Pim Schellart, Olaf Scholten, Sander ter Veen

LOFAR - Low Frequency Array



LOFAR with core in the Netherlands

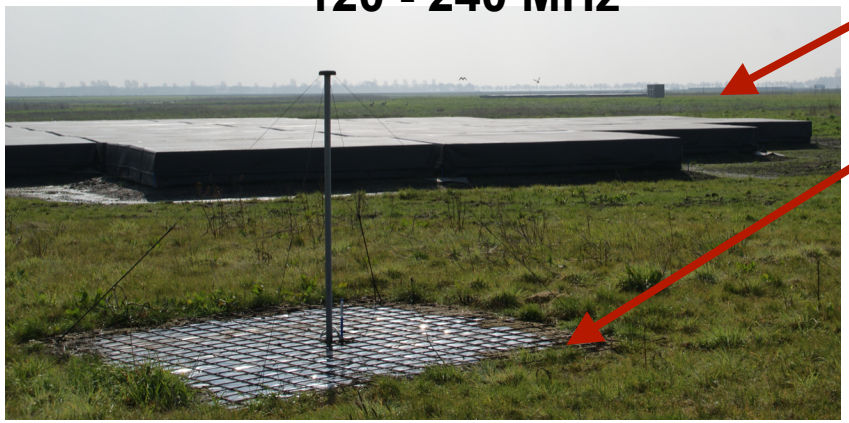


LOFAR core

Core Station

- 96 LBAs per station
- 48 HBAs per station
- 24 core stations
- 9 + 7 remote stations

High Band Antenna
120 - 240 MHz

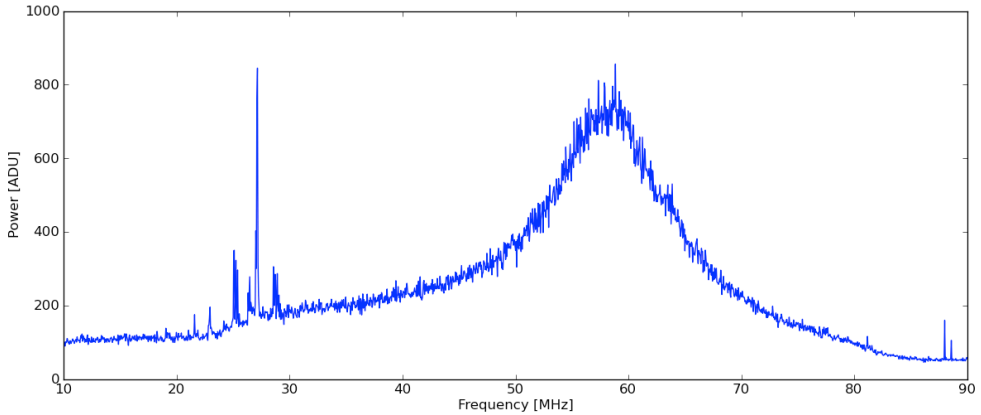


Low Band Antenna
30 - 80 MHz

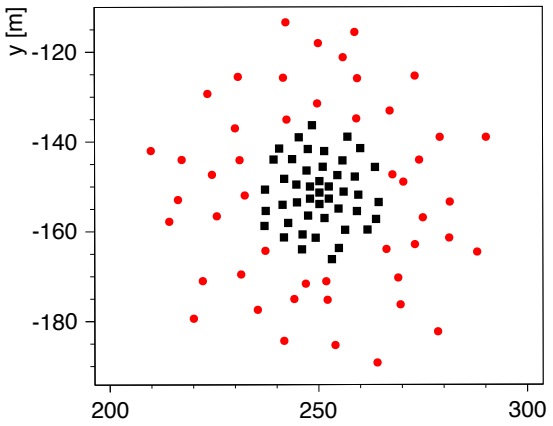
LOFAR

Low Band Antennas (LBA)

- Dual Dipole Antenna with Bandpass resonant at 58 MHz
- Sensitive: 30 - 80 MHz (Filter 10 - 30 MHz optional)
- Sampling: 200 MHz
- Spacing in core: 2 - 50 m
- Clusters of 96 antennas
- available for cosmic ray detection :
- ~ 1000 antennas on ~ 2 km^2

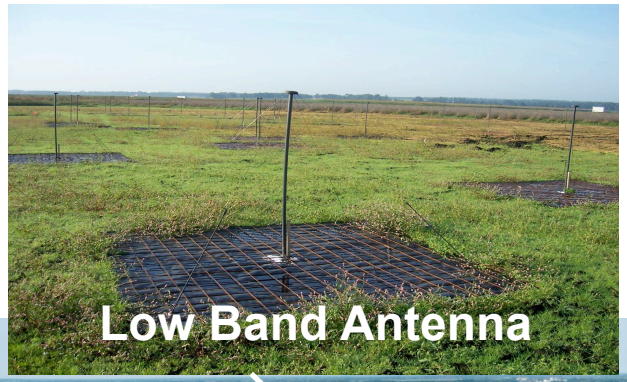


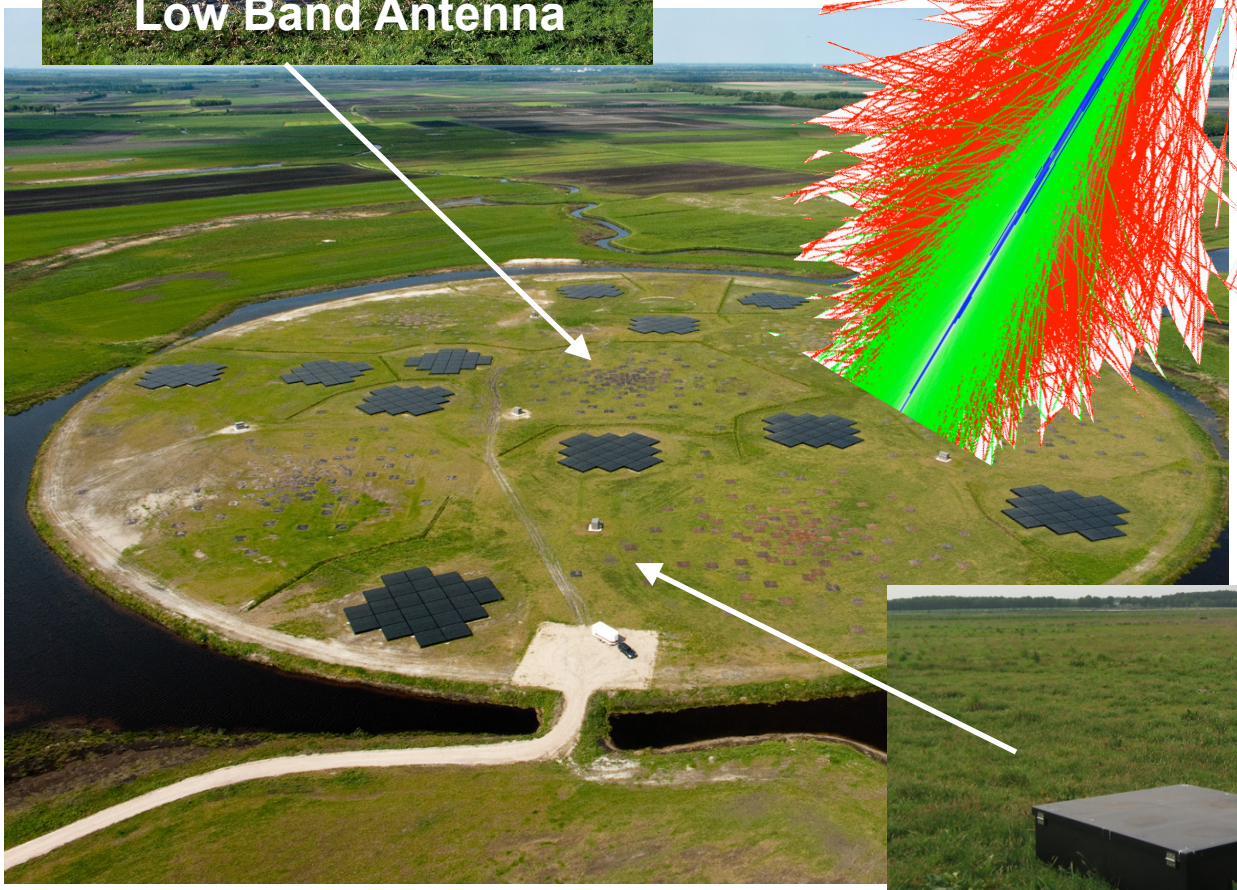
LBA spectrum

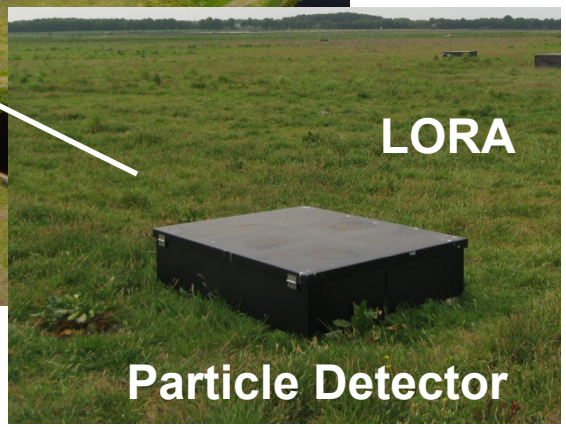


Layout of LBAs in one station

Triggering of Cosmic Rays







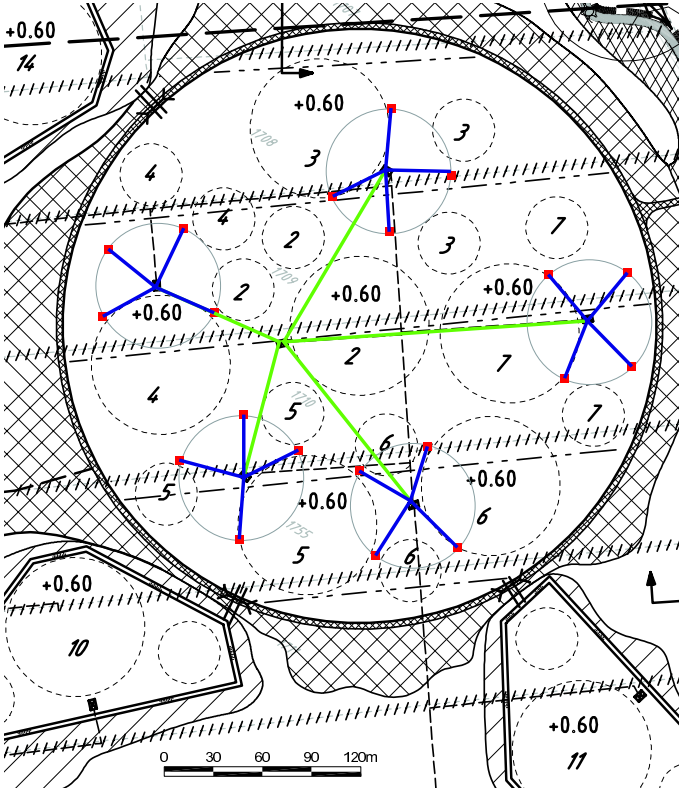
Self-Trigger
Antenna electronics identify pulse and trigger

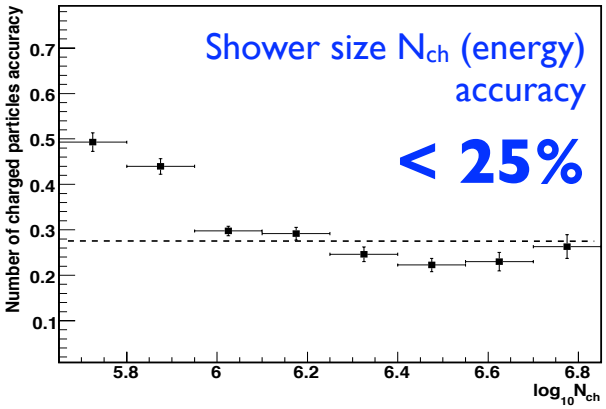
Problem:
- RFI can look like cosmic ray
- Trigger has to be "smart"
- Training-set needed

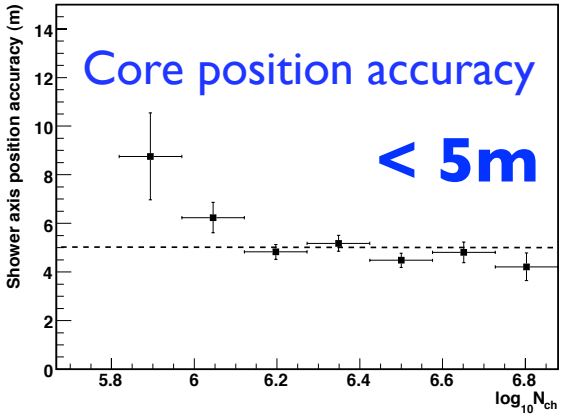
External trigger from LORA

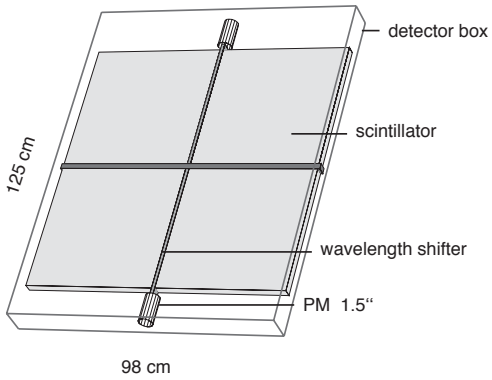
Coincidence of more than one detector = air shower

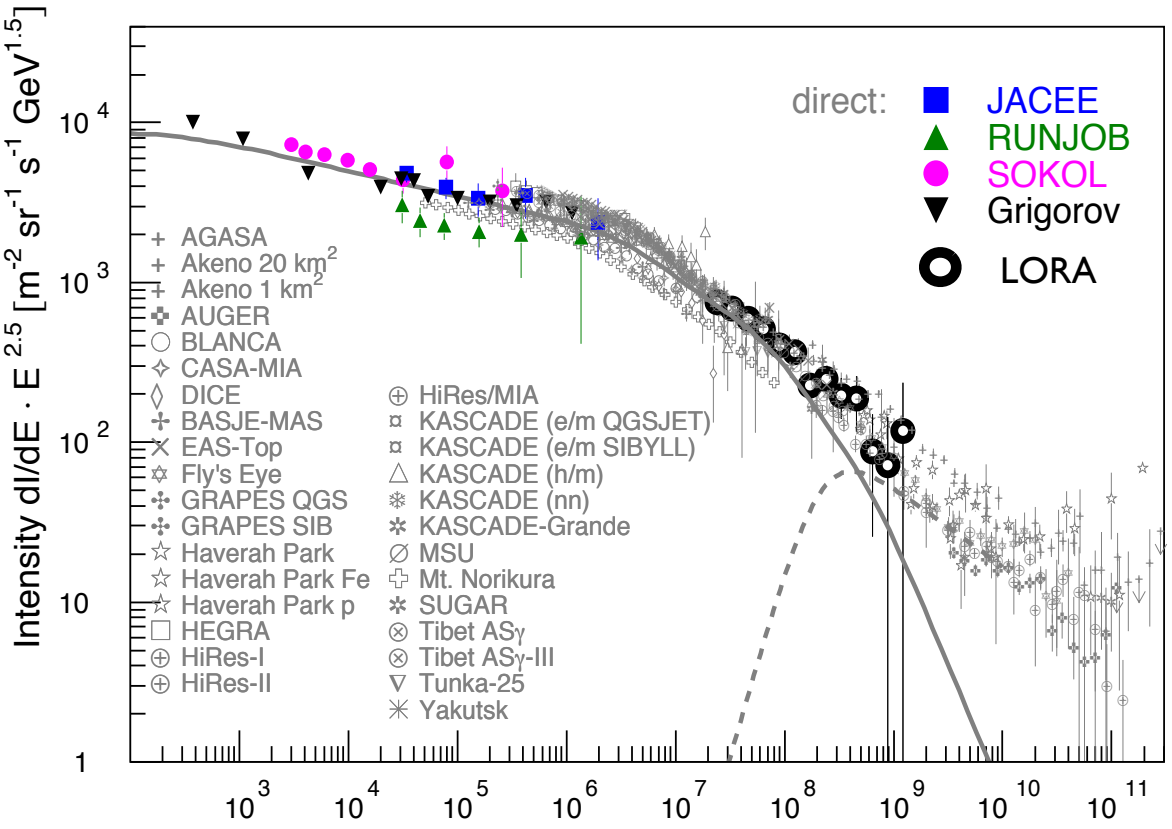
LOFAR Radboud Air Shower Array











Hörandel 2003,APh, 19, 193

Data Taking at a Radio Telescope

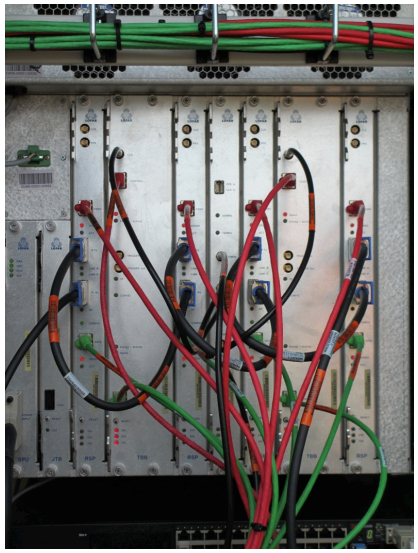
Data is taken in parallel to ongoing observations

Transient Buffer Boards (TBBs):
1.3 s of data 0.5 GB of RAM
(will be increased to 2 GB)

Regular measurements scheduled by observatory

FPGA not optimized for cosmic ray trigger (yet)

Allowed trigger-rate: ~ 1/h



At a Radio Telescope:

~ 1000 antennas

Not aligned to magnetic north (45˚)

Astronomical calibration methods available

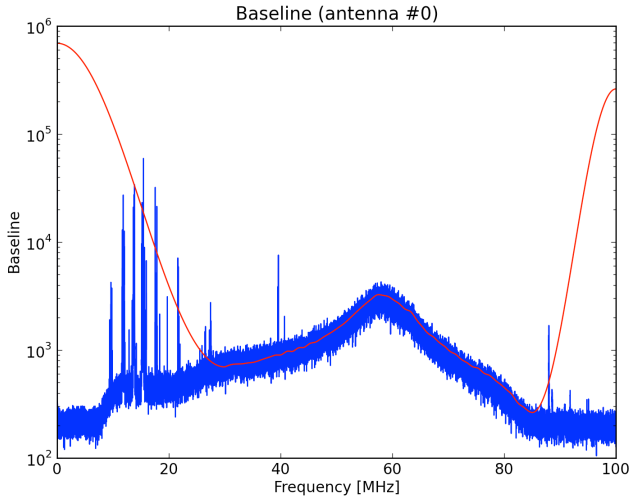
Very low RFI levels

Phase calibration beacon not allowed

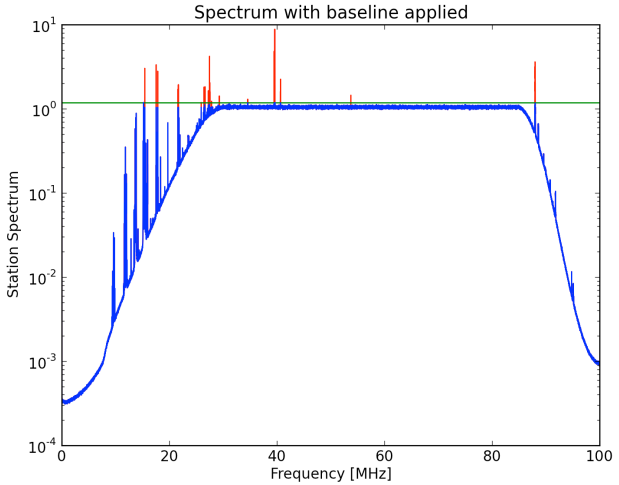
Cooperation in antenna model and hardware properties

Infrastructure available, technical support, data-taking support

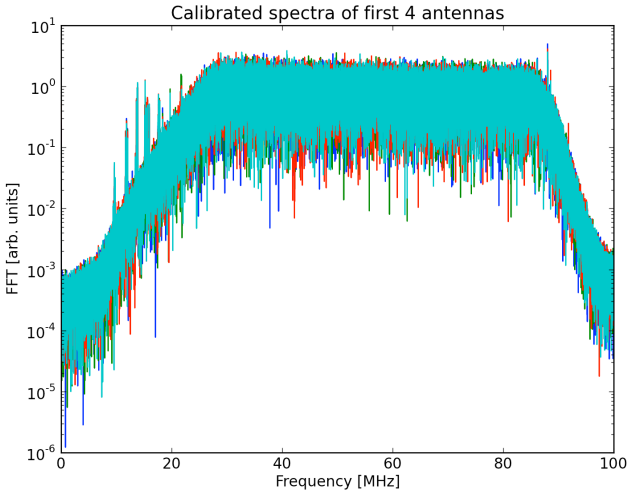
Identifying Cosmic Rays



Fitting baseline of the spectrum



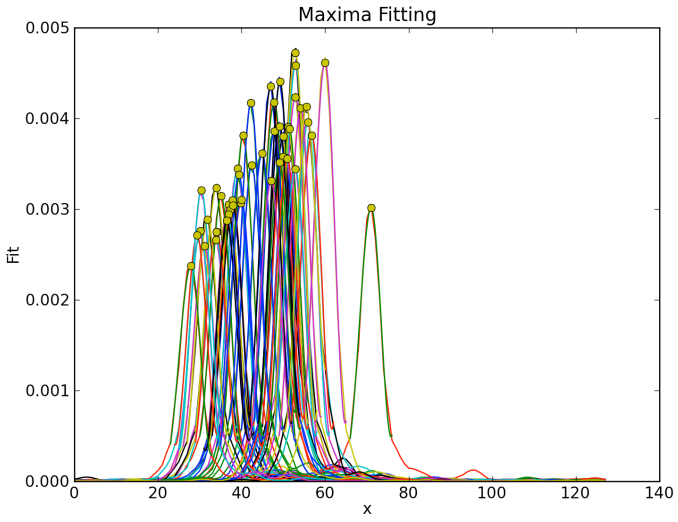
Applying baseline, cutting RFI

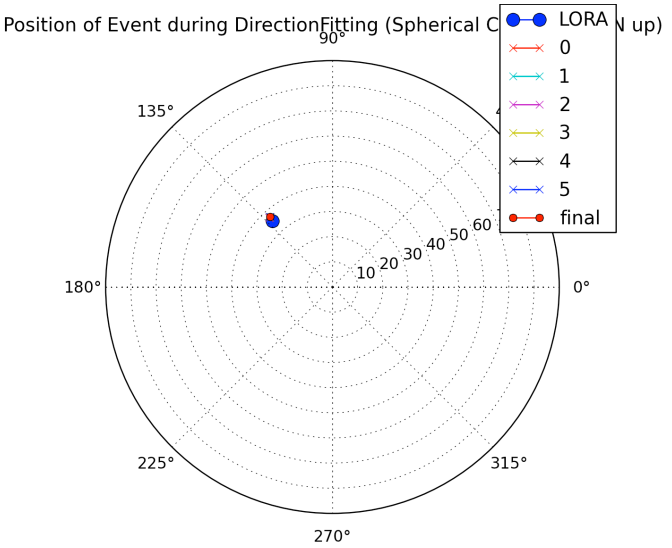


Calibrate to galactic noise

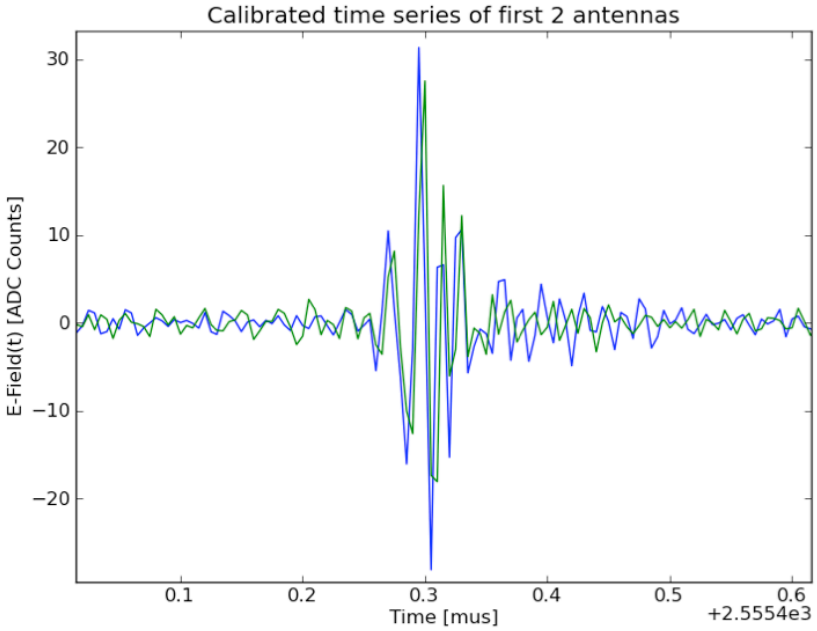
Fit maxima and
fit direction of air shower

Iteratively also fitting
cable delays as hardware
check

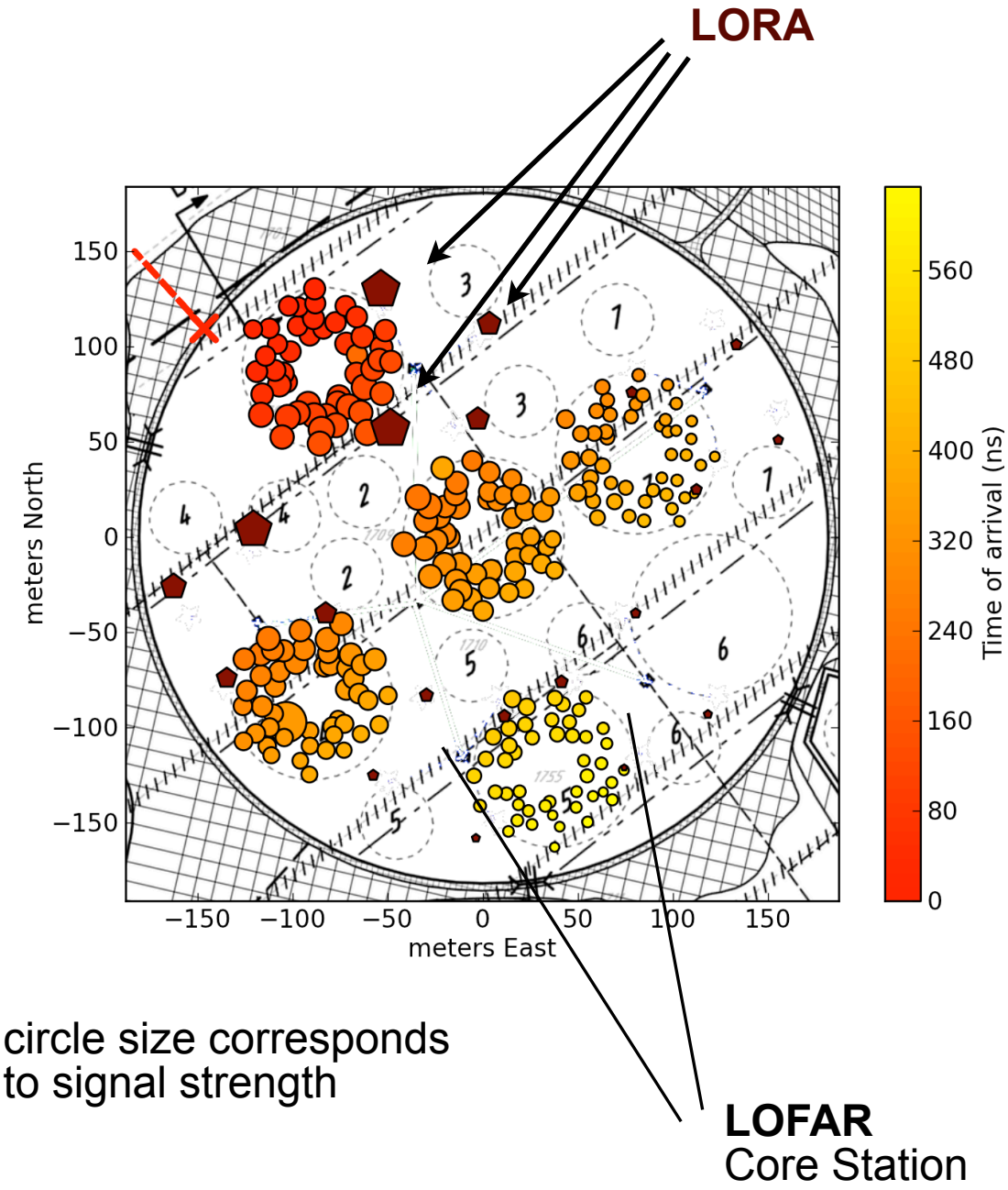




Cosmic Ray Data



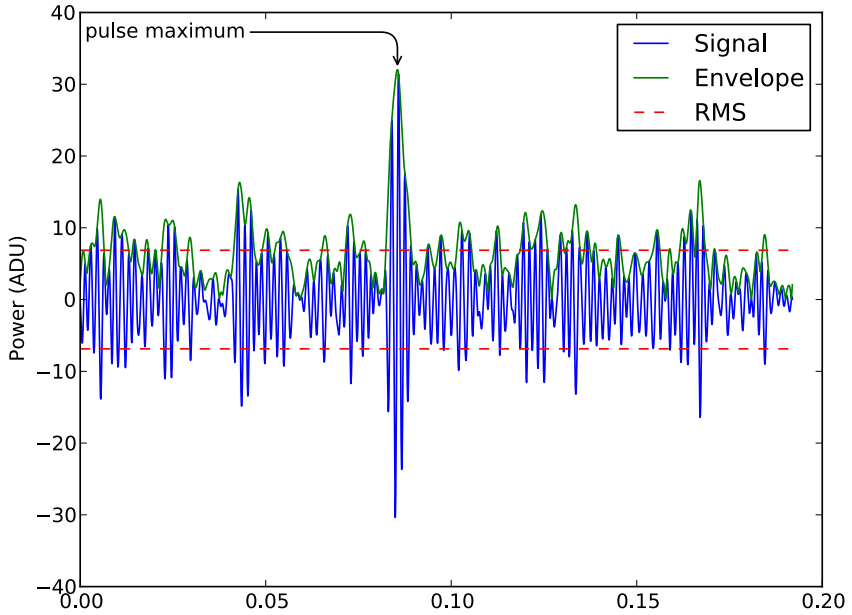
Pulse from cosmic ray air shower

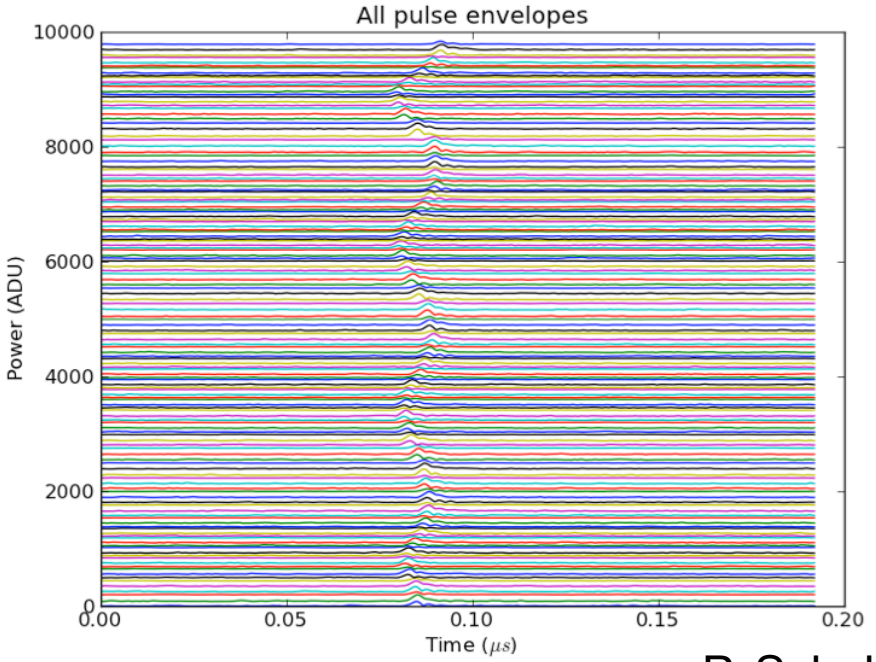


Event Processing

- Combination of polarizations (per station)
- Correction of gain variations to galactic noise
- Identification of pulse
- Iterative:
  - Unfolding of antenna pattern

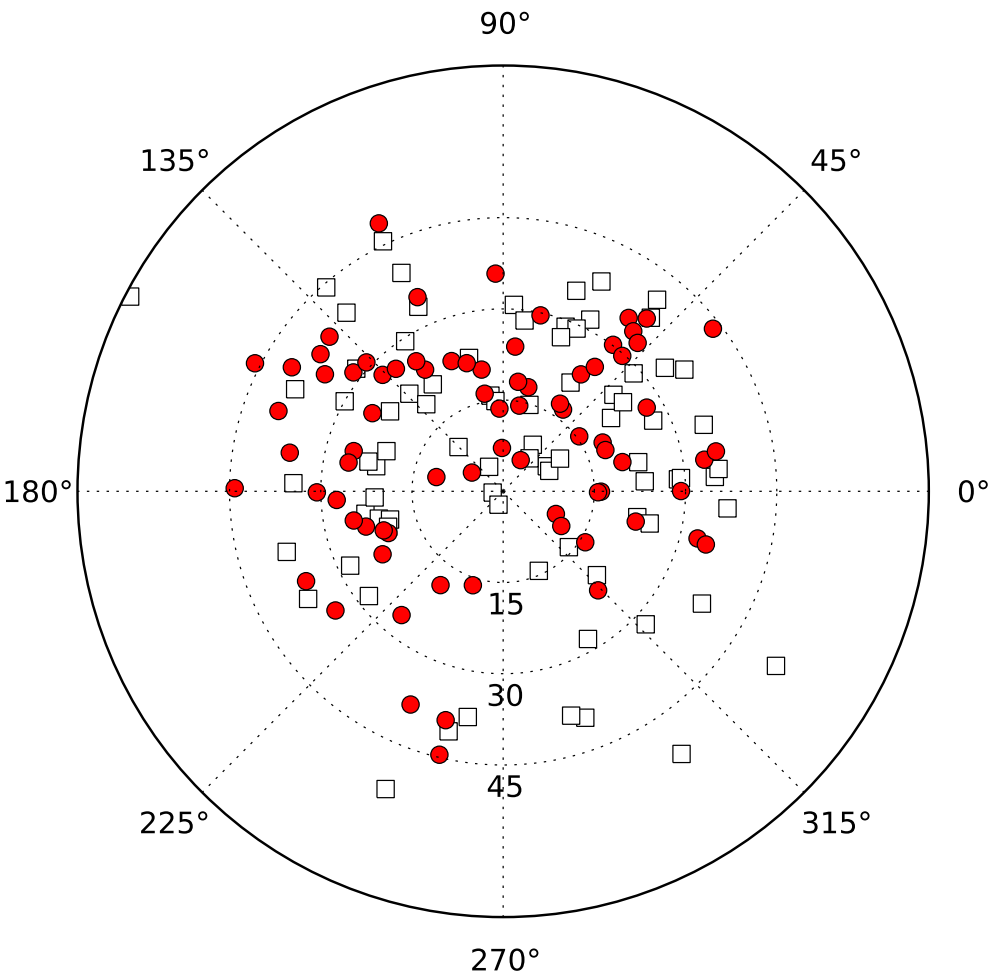
    (still under discussion with astronomy colleagues)
  - Direction fit (plane-wave)
- Projection of on-sky polarization in x-y-z polarization
- Combination of all stations for further analysis





P. Schellart

Event Set



Events that contained pulse

Red: High-quality information from particle detector

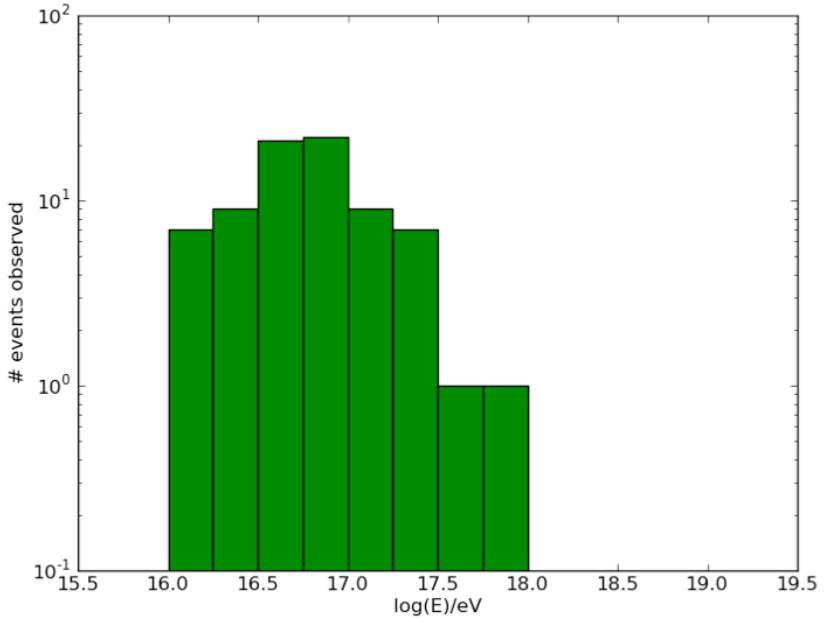
North-South Asymmetry

Events with pulse observed:

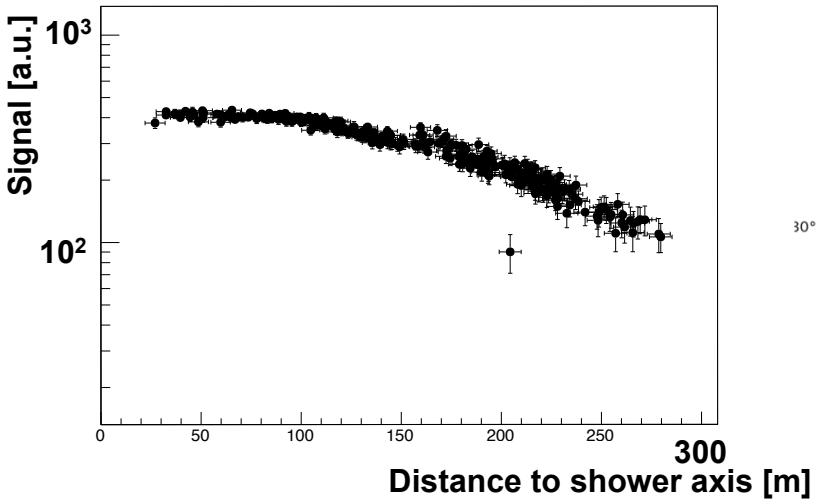
p(North) = 0.690 +/- 0.037
p(South) = 0.310 +/- 0.037

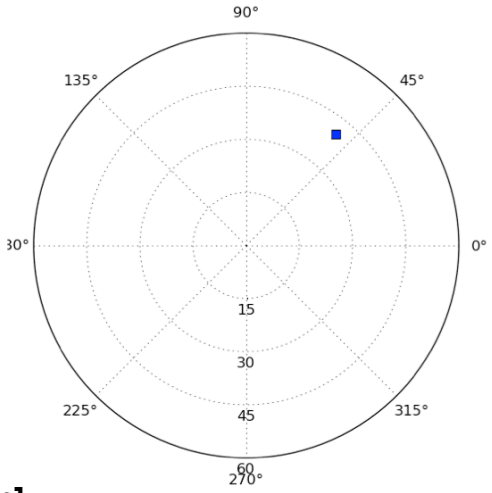
Events with no pulse observed:
(dominated by low energy events)

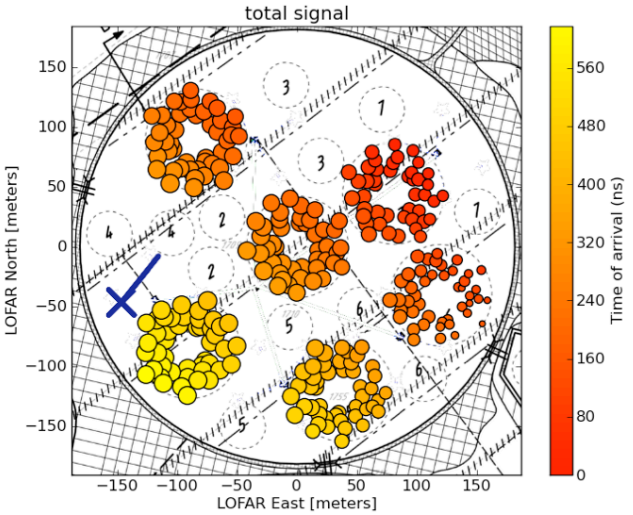
p(North) = 0.479 +/- 0.017
p(South) = 0.521 +/- 0.017



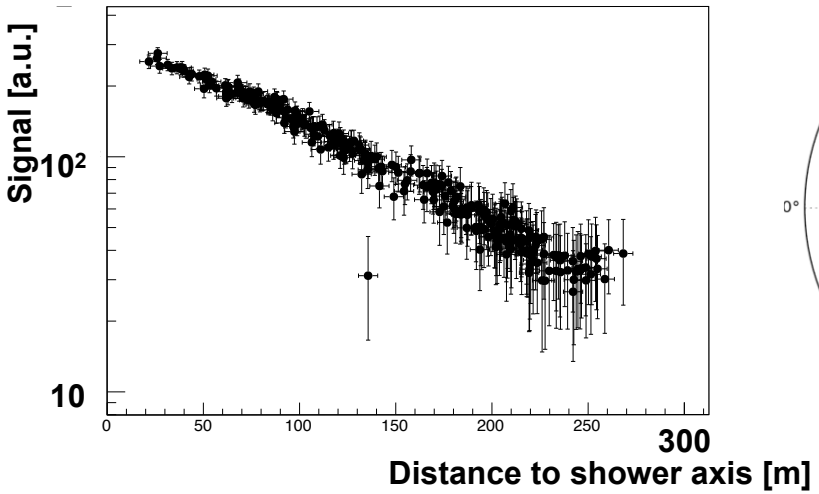
Event Data

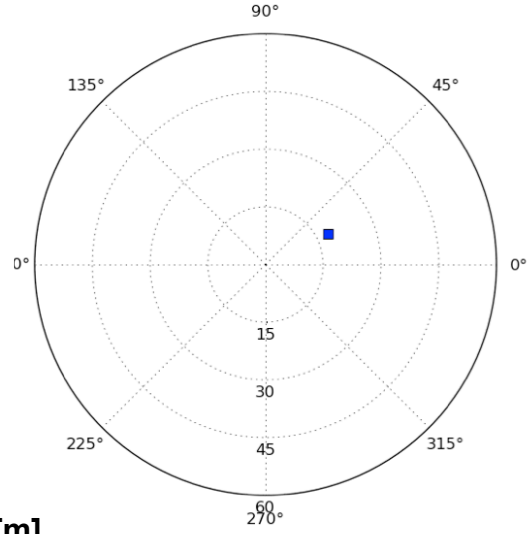


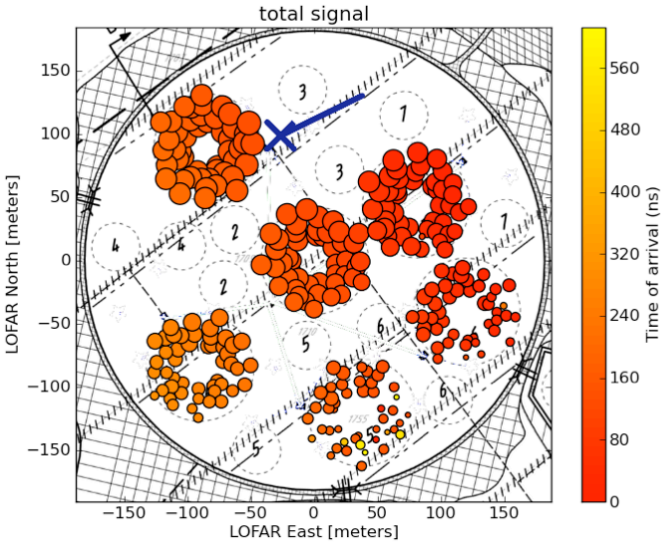




Energy: 2.7 x 10^{16} eV



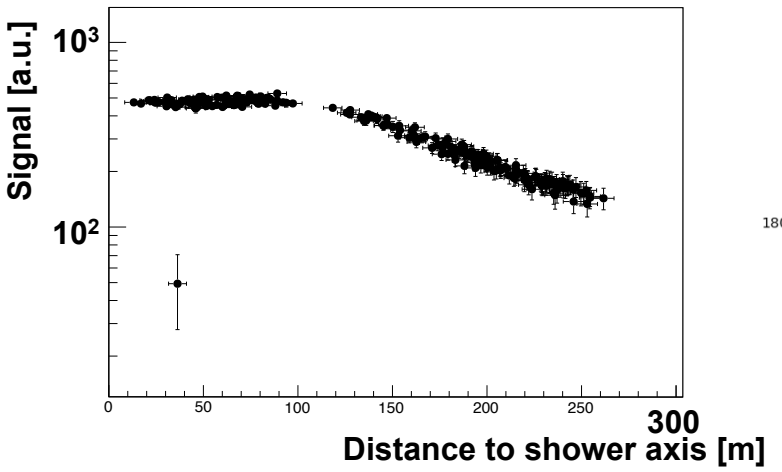


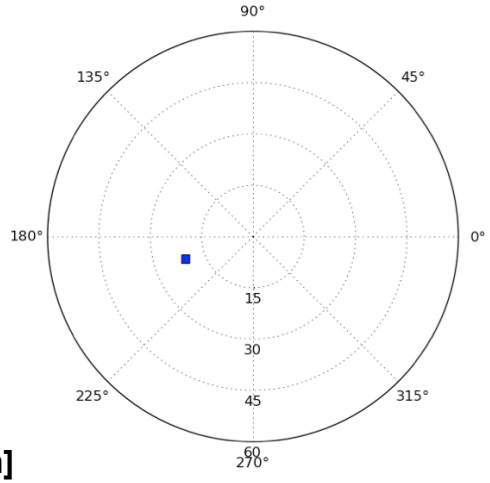


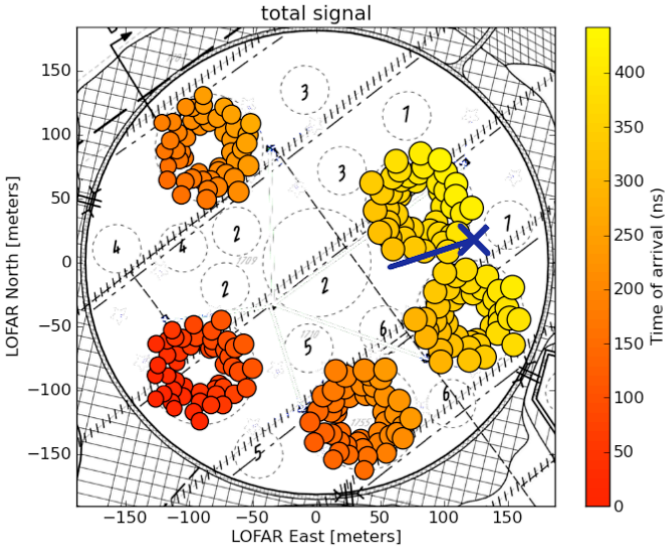
Energy: 2.0 x 10^{17} eV

Energy uncertainty from LORA: ~ 30% per event

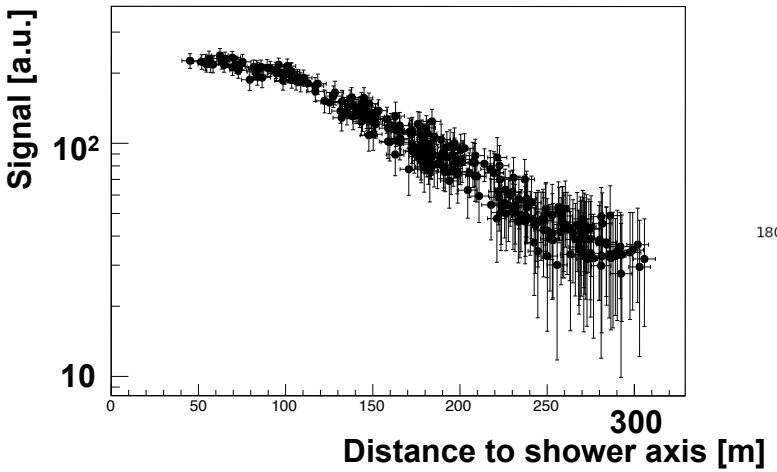
Event Data

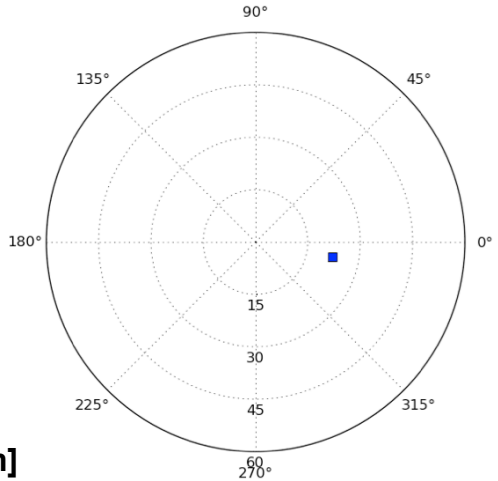


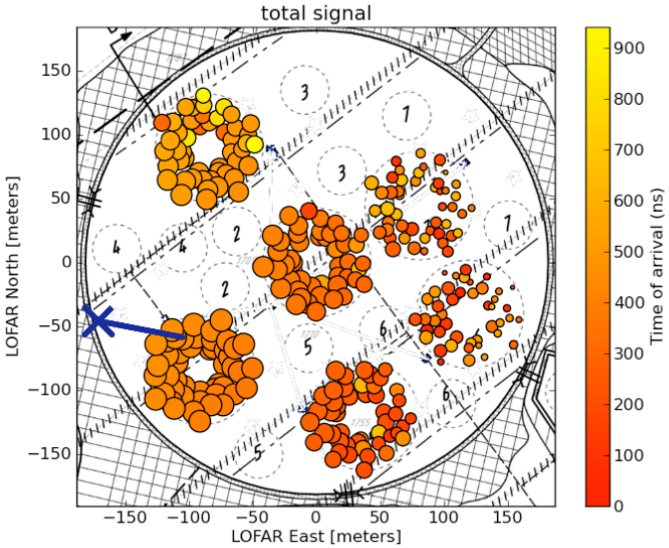




Energy: 1.2 x 10^{17} eV



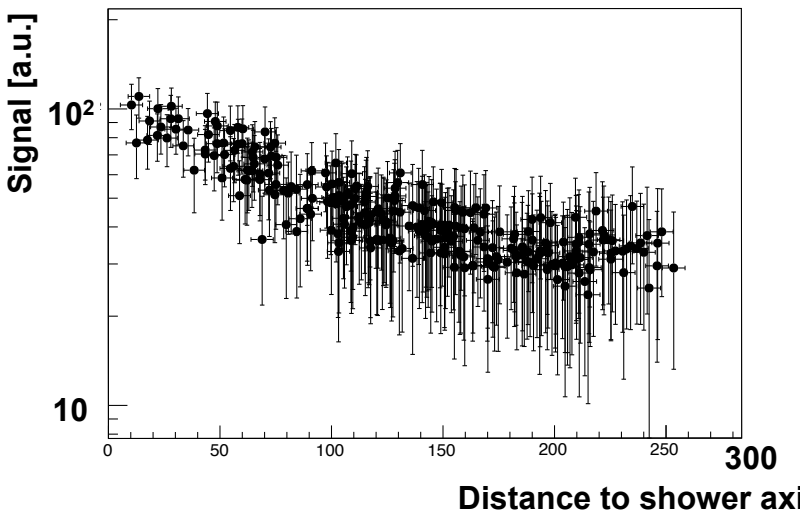


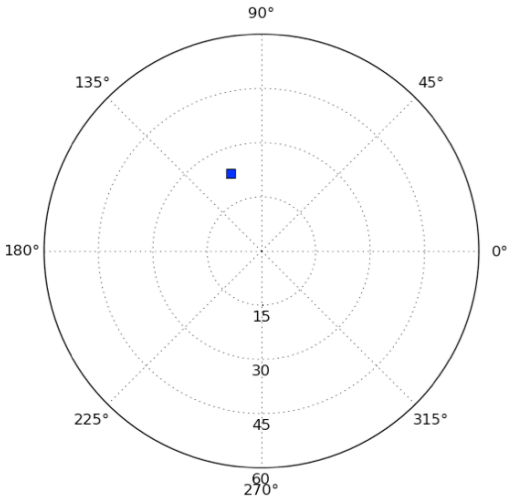


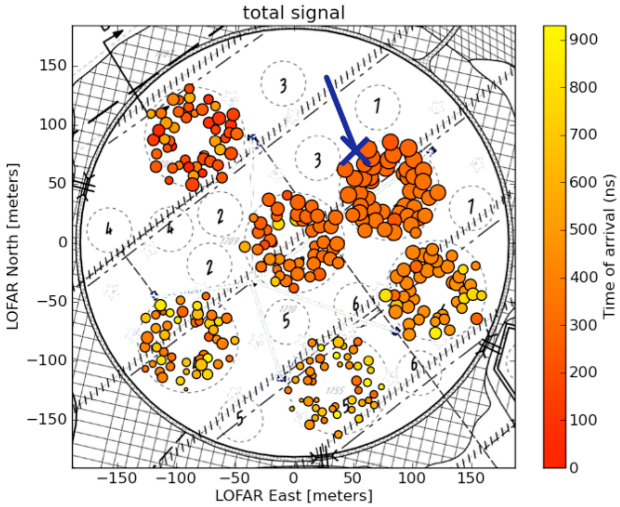
Energy: 3.5 x 10^{16} eV

Energy uncertainty from LORA: ~ 30% per event

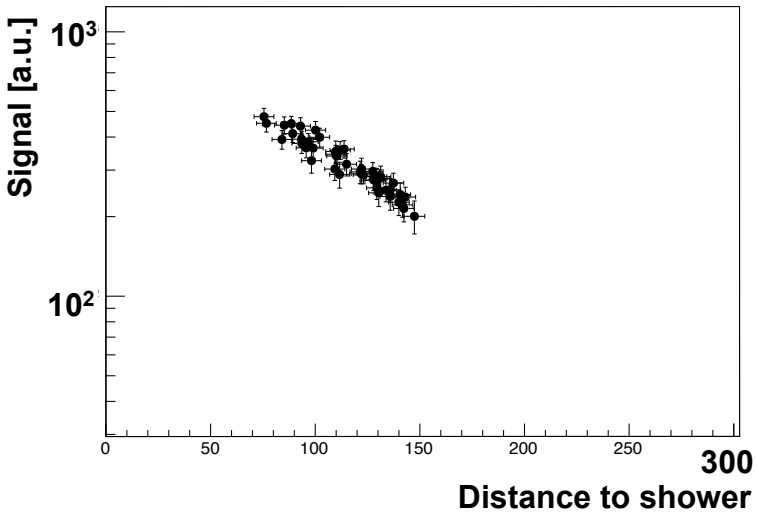
Event Data

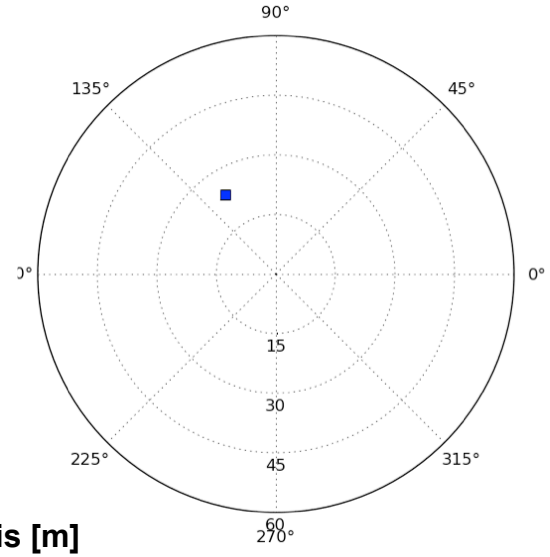


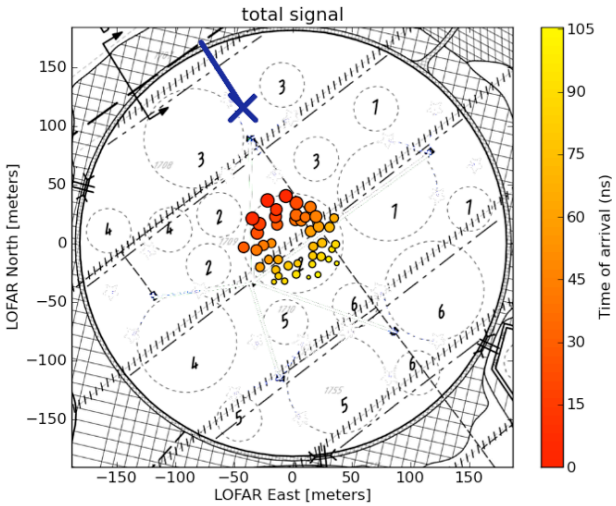




Energy: 1.2 x 10^{17} eV







Energy: 2.8 x 10^{17} eV

Energy uncertainty from LORA: ~ 30% per event

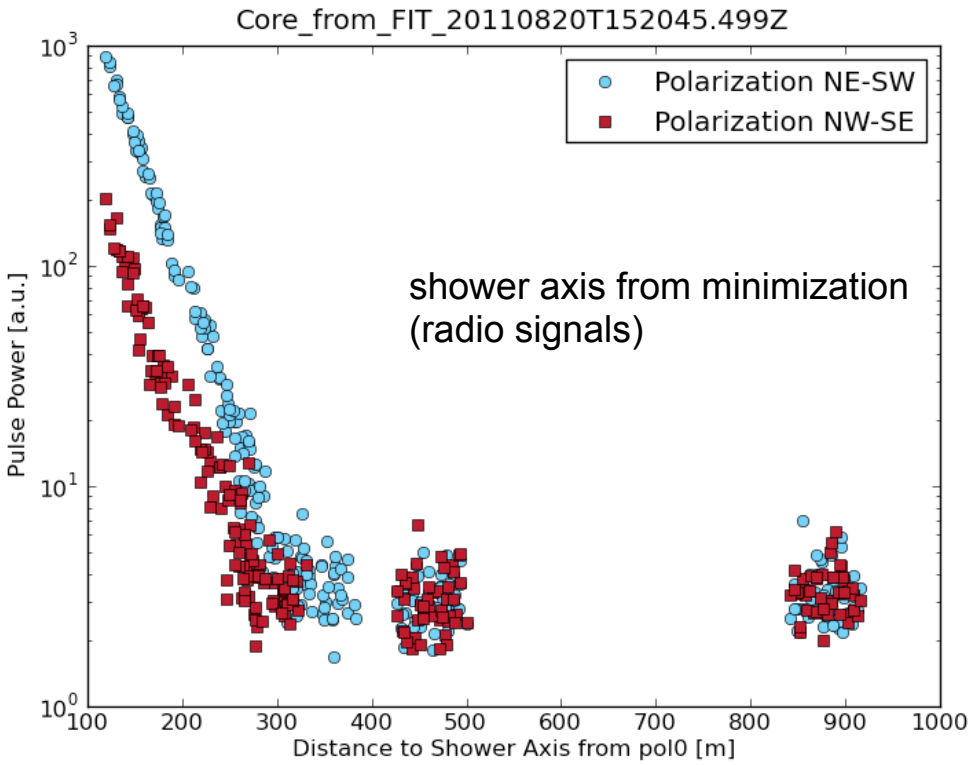
Event Data

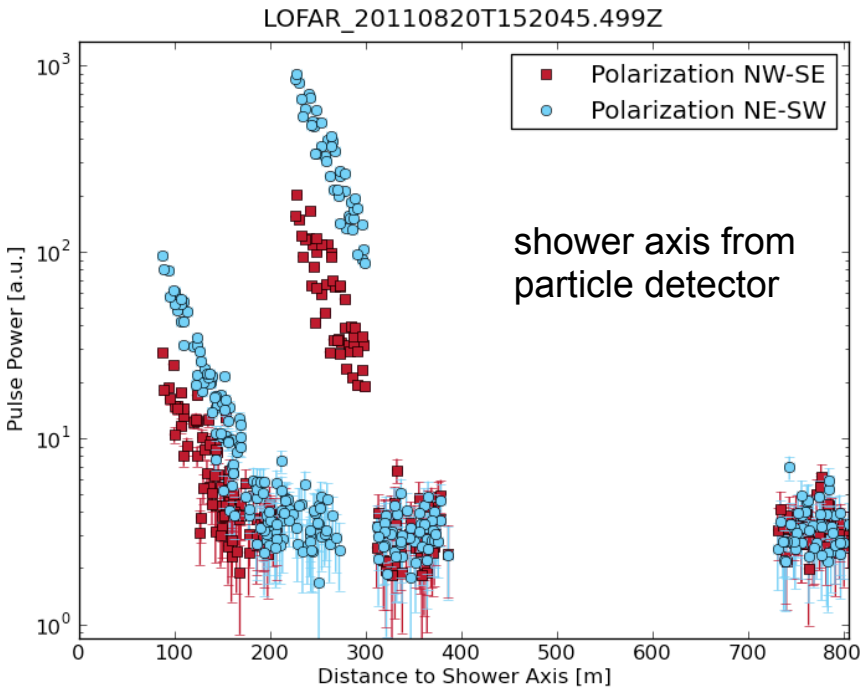
- Almost all events (95 %) show **flattening within 100m** distance to shower axis
- Almost all events (95%) show **steep (exponential) fall off**, starting at distances larger than 100m
- Signal strength shows **dependence on angle to magnetic field and primary energy**
- Signal in individual polarization shows promising features
- Hint at behavior of signal, which is not symmetrical around shower axis
- Detailed investigation will follow as soon as antenna model is completed

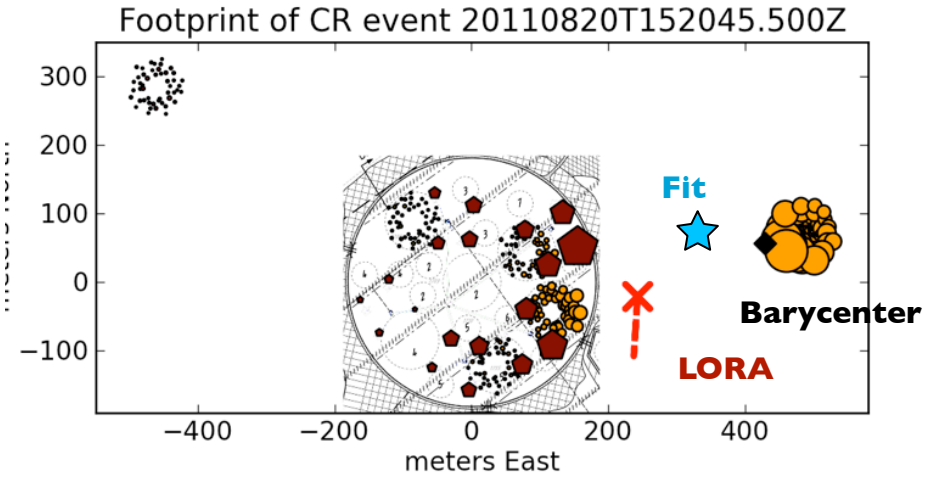
Air shower properties: Core

Problem: If position of core is outside particle array, core cannot be reconstructed by LORA

Idea: Use radio LDF and minimize jumps in it to identify correct core position, use only smoothness, no specific model







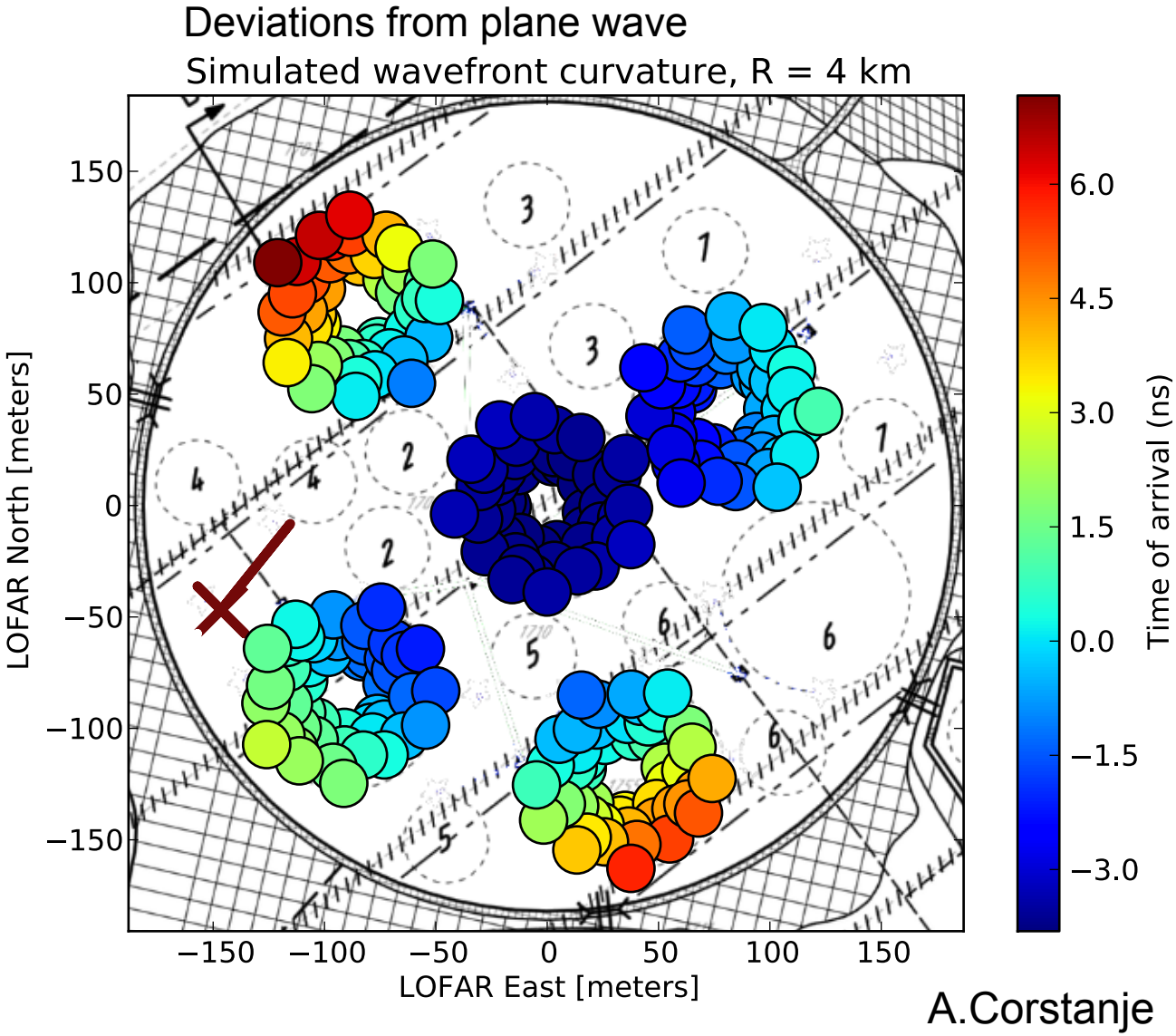
Air shower properties: shower front

Ability of LOFAR to measure shape of shower front

LOFAR can resolve 2 ns
(no additional phase calibration)

Simulated spherical shower front for measured air shower signals

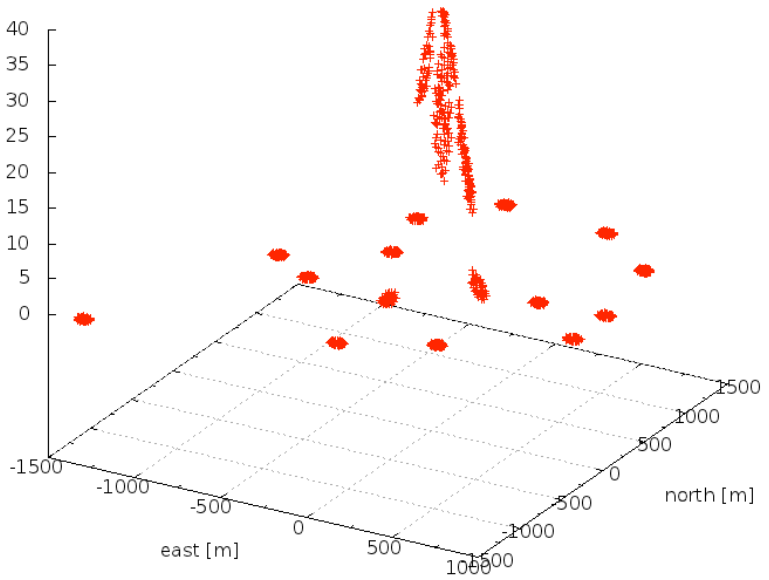
Differences in time with respect to plane wave are resolvable



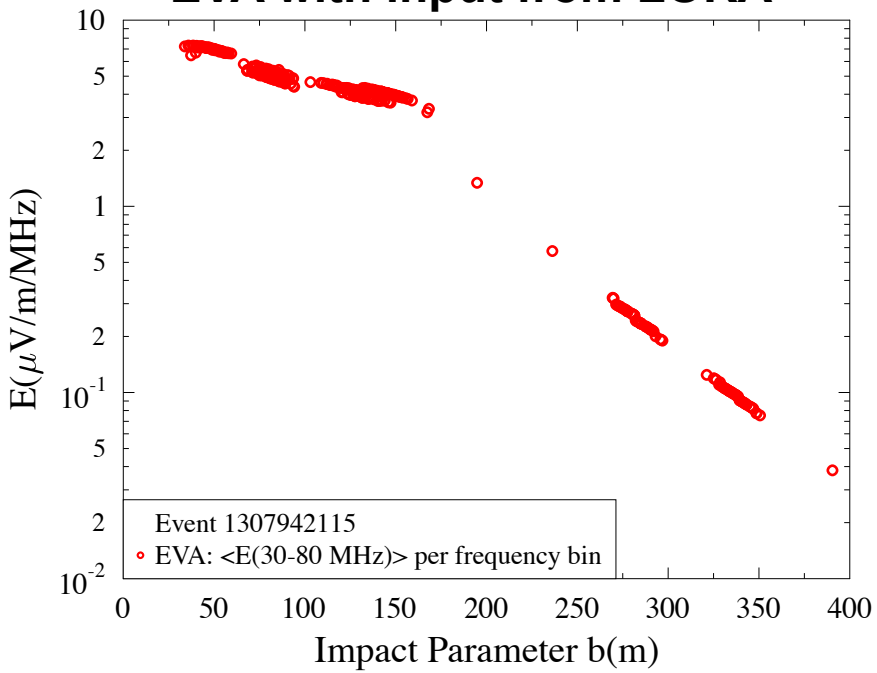
Simulations

Extensive simulations are planned to take advantage of high antenna density at LOFAR

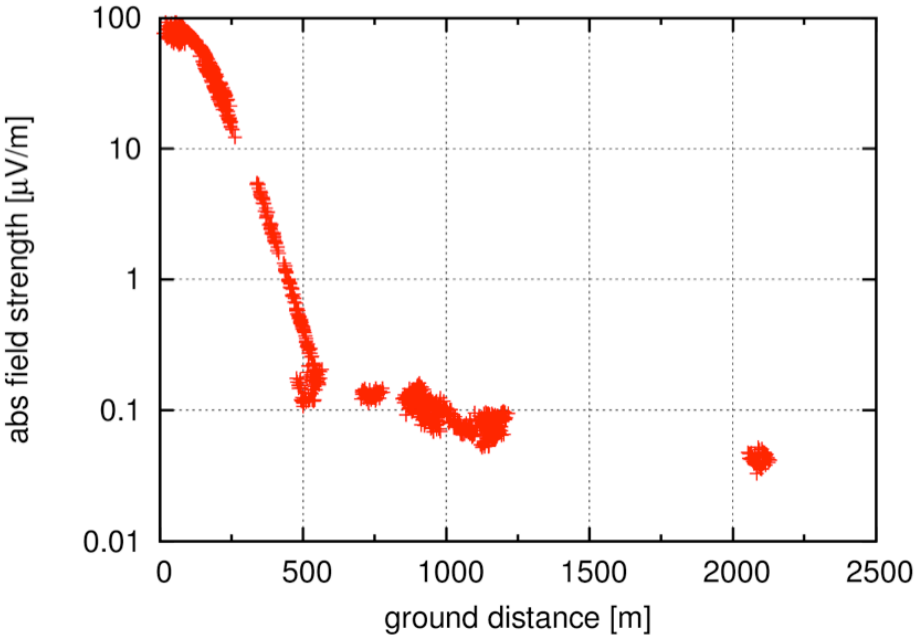
First glimpse:



EVA with input from LORA



CoREAS with input from LORA



Conclusions and Outlook

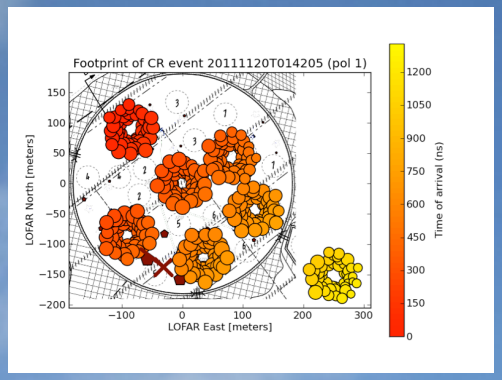
- LOFAR is steadily taking data, having currently detected ~ 160 cosmic ray events of good quality

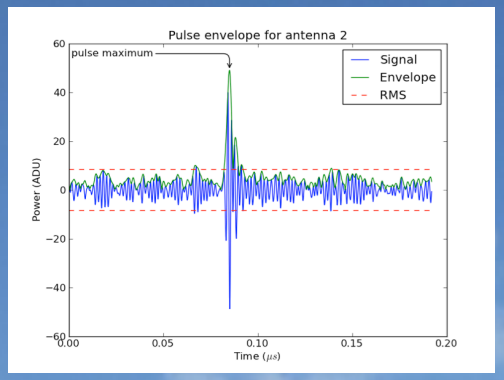
- LOFAR has the highest density of antennas of any air shower experiment for radio detection

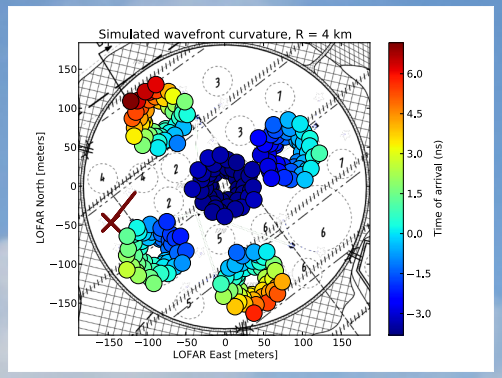
- Implementation of full unfolding of antenna model

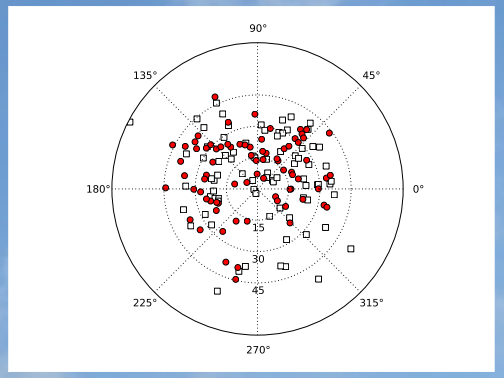
- Gather sufficient statistics to
  - Find parameterization for LDF that allows statistical conclusions
  - Find parameterization for shower front

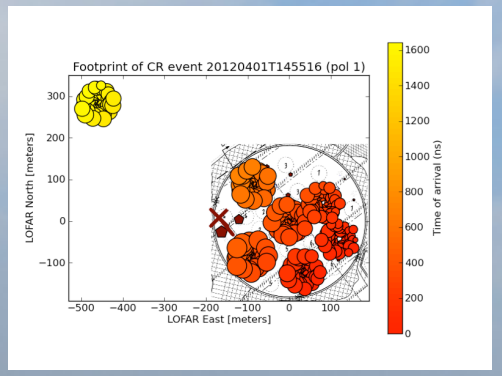
- Do extensive comparisons with air shower simulations

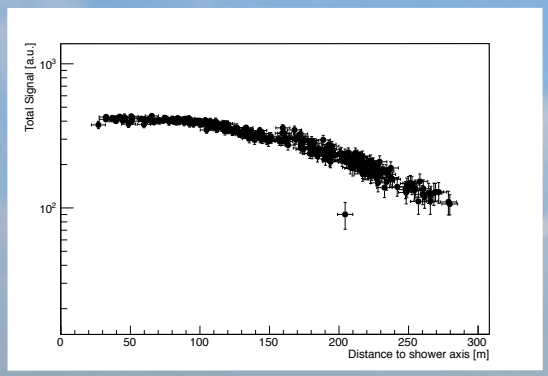












Cosmic Ray Key Science Project

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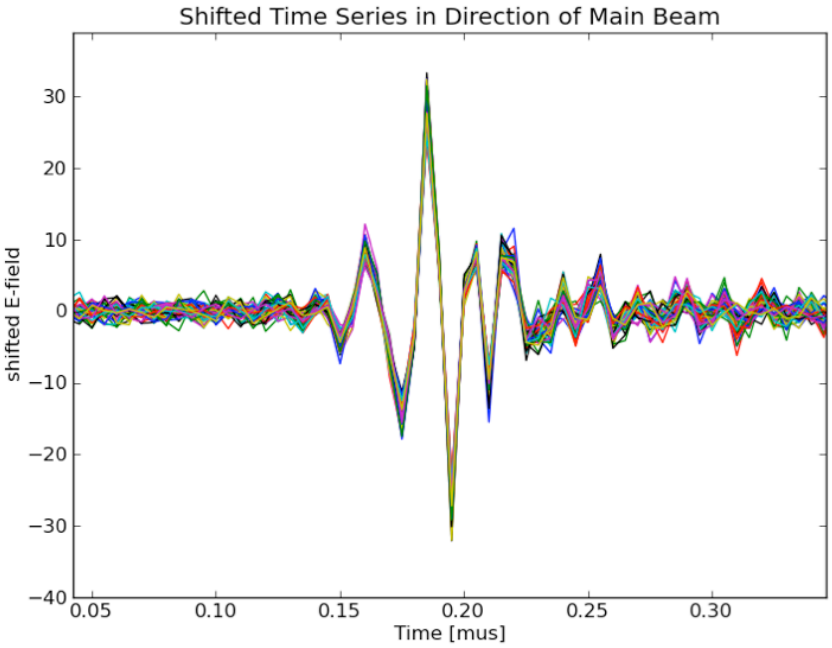
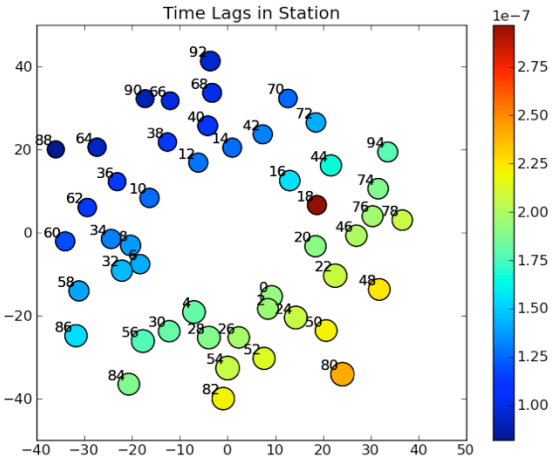
BACK-UP

Processing Cosmic Rays

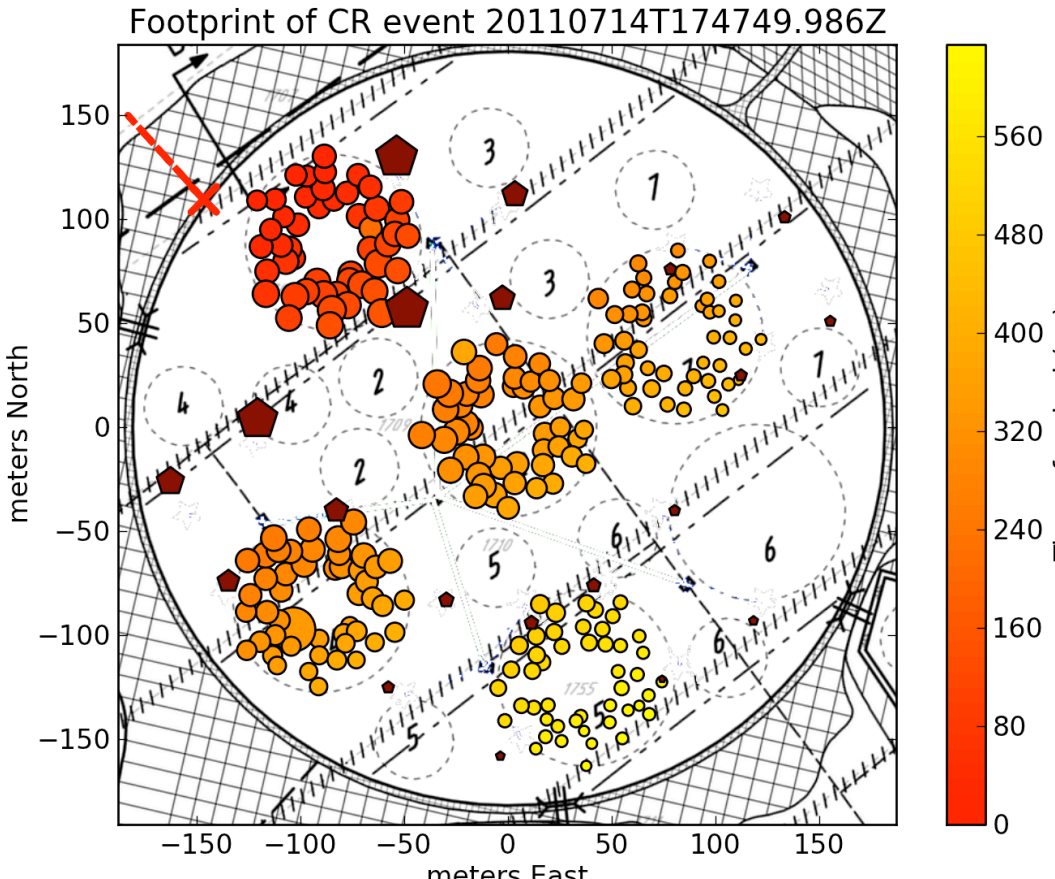


Single station



Results:

- Coherent pulse of all antennas per station
- Overall picture of the Cosmic Rays

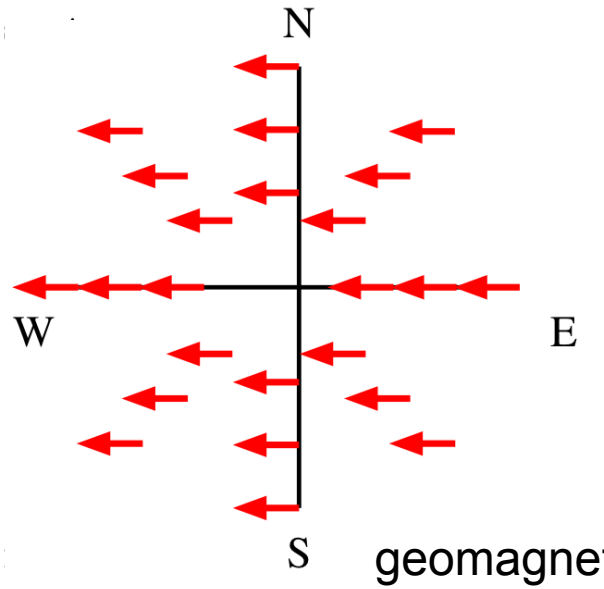


Radio Detection of Cosmic Rays

Geomagnetic Field

- electrons and positrons in shower emit coherent radiation
- Mainly: Charge separation in geomagnetic field, moving dipole

$$\vec{E} \propto \vec{v} \times \vec{B}$$

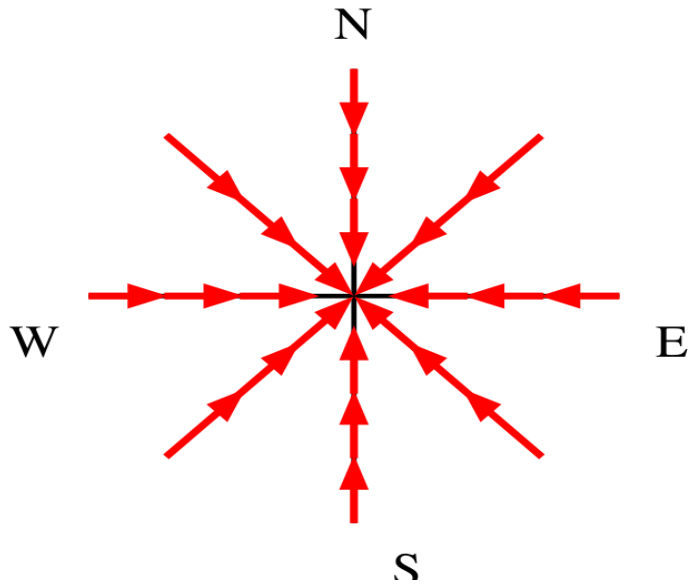


geomagnetic effect

Radio Emission of Cosmic Rays

- But picture not as simple:
- Theory predicts: additional mechanisms
  - charge excess of electrons
  - Cherenkov effects of index of reflection different from 1

- All effects: frequencies in MHz range (up to GHz)
- Dominant in different distances to shower
- Distinguishable by polarization
- Challenge:
  - Disentangle and explain the emission mechanisms
  - correlate characteristics to air shower parameters



charge excess effect