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Cosmic Rays with LOFAR

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for the LOFAR-CR Team

Cosmic Rays

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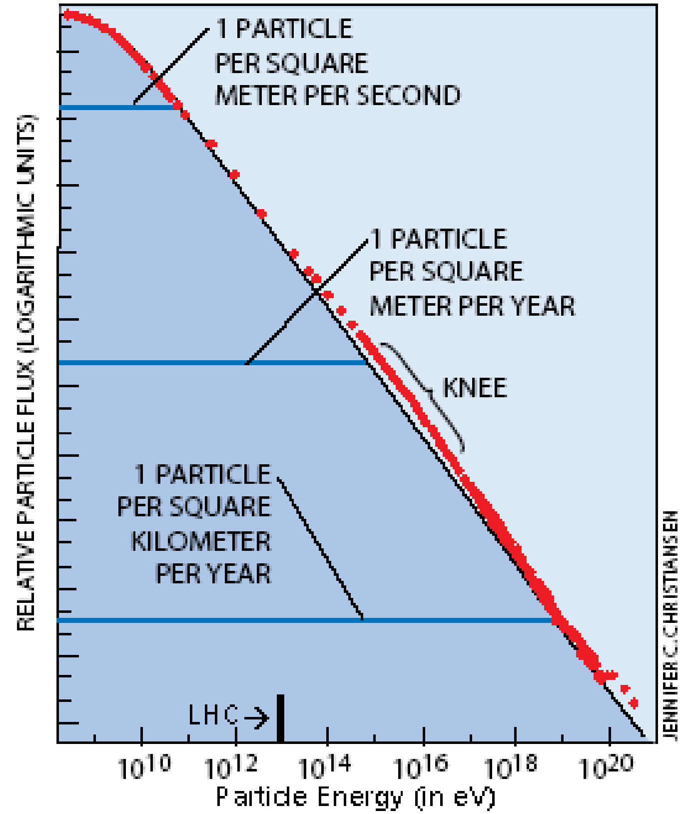
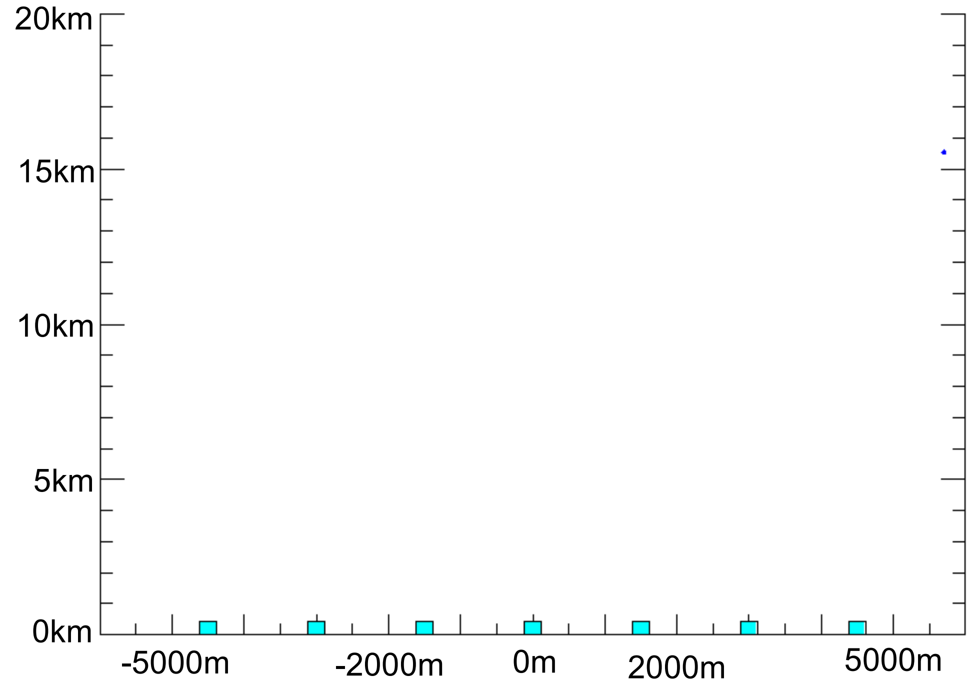
- High energy particles
- Dominated by hadrons (atomic nuclei)
- Similar in composition to solar system
- Broad range in flux and energy
- Different energy regimes:

<10^7 eV	Modulated by solar wind
<5*10^14 eV	Direct detection possible
> 5*10^14 eV	Indirect detection (air showers)



Air Showers

- High energetic cosmic rays interact with nuclei in the atmosphere
- In a cascade lots of secondary particles emerge
- A “pancake” of particles



- Established detection methods:
  - Air-Fluorescence: Detection of fluorescence light
  - Particle Detector Arrays: Particles that reach the ground
- New: Radio Detection

LOPES
(LOFAR Prototype Station)

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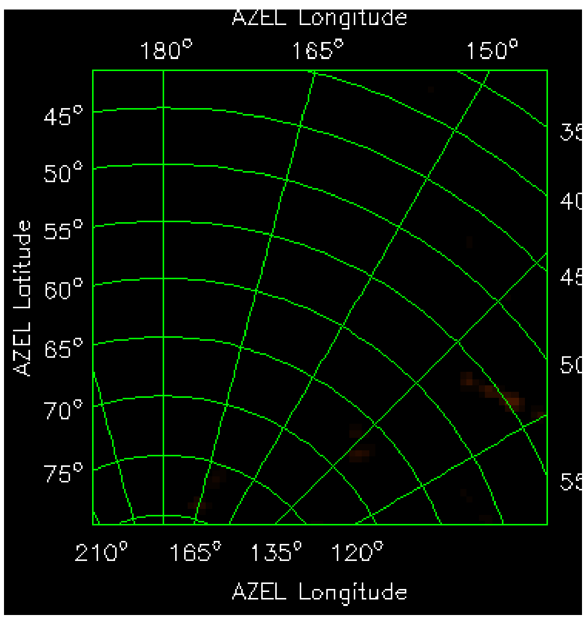
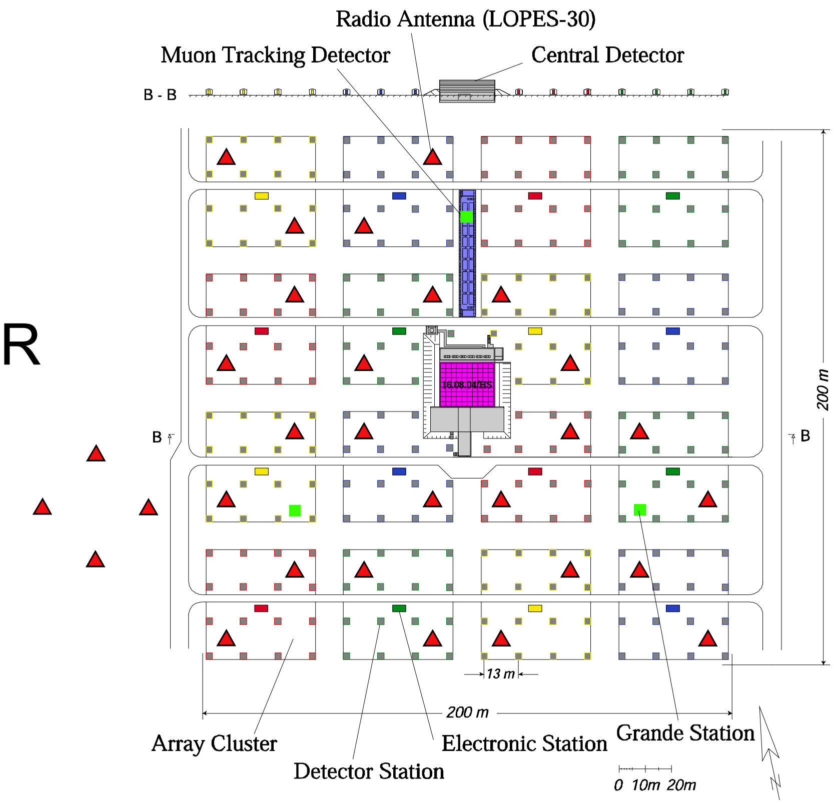
- Prototype of a LOFAR station
- Set up inside an air shower array
- Frequency range of 40–80 MHz
- Triggered by particle detectors
- Detection of air showers with LOFAR technology





Falcke et al. (LOPES collaboration), Nature, 435, 313, 2005

Radio Signature of Air Showers

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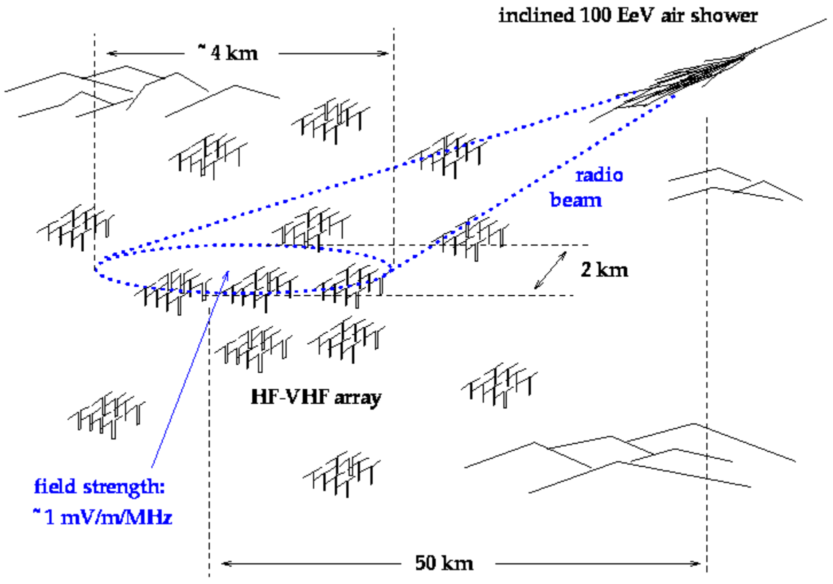
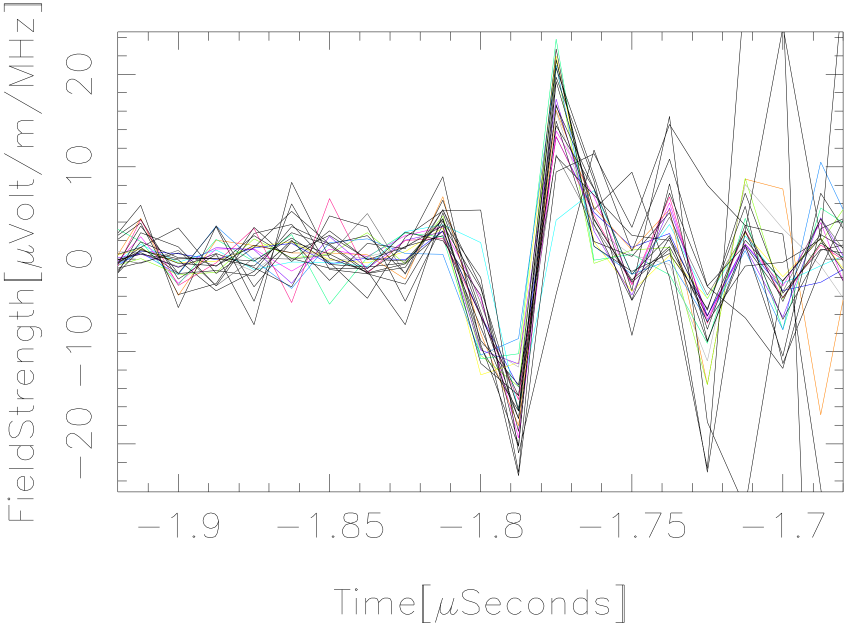
- random arrival times and directions
  - can ignore (man made) pulses from the horizon
- broad-band, short time pulse (~10ns)
- limited illuminated area on the ground
  - depending on primary energy
- curvature of radio front
  - similar (but not identical) to point source in few km height
- coincident with other air shower signs
  - e.g. particle front

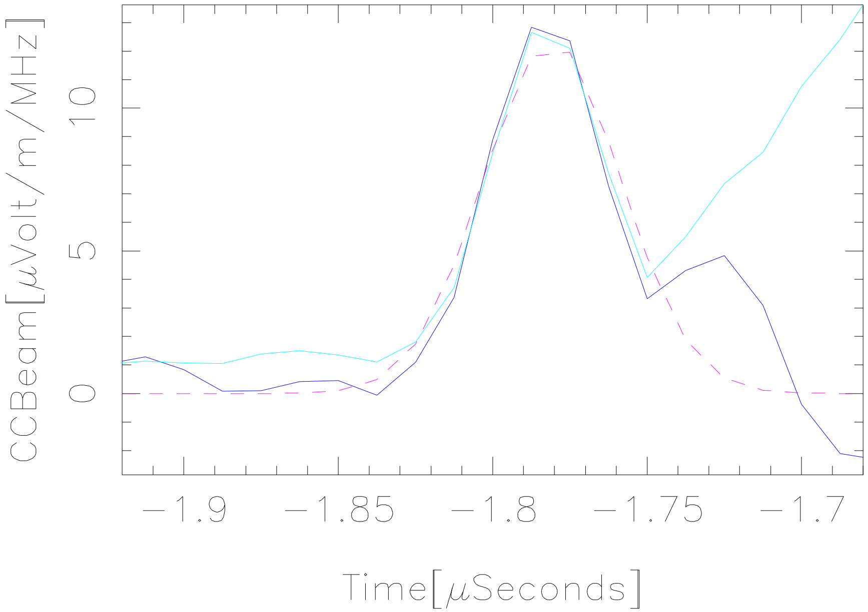


Example Event

single antenna traces



after beam-forming



LOFAR-CR Energy Ranges

LOFAR

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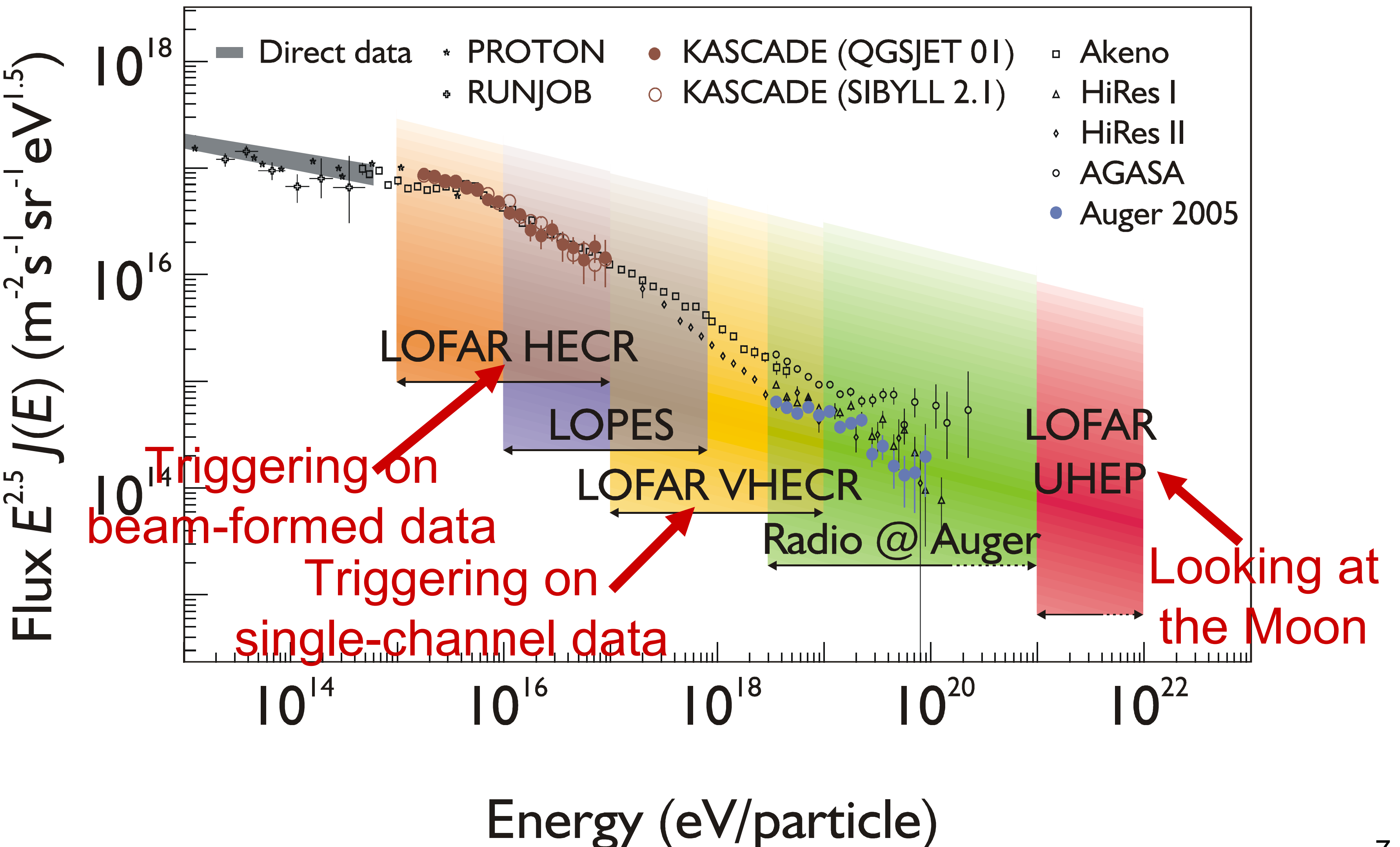

UHEP Detection-Principle

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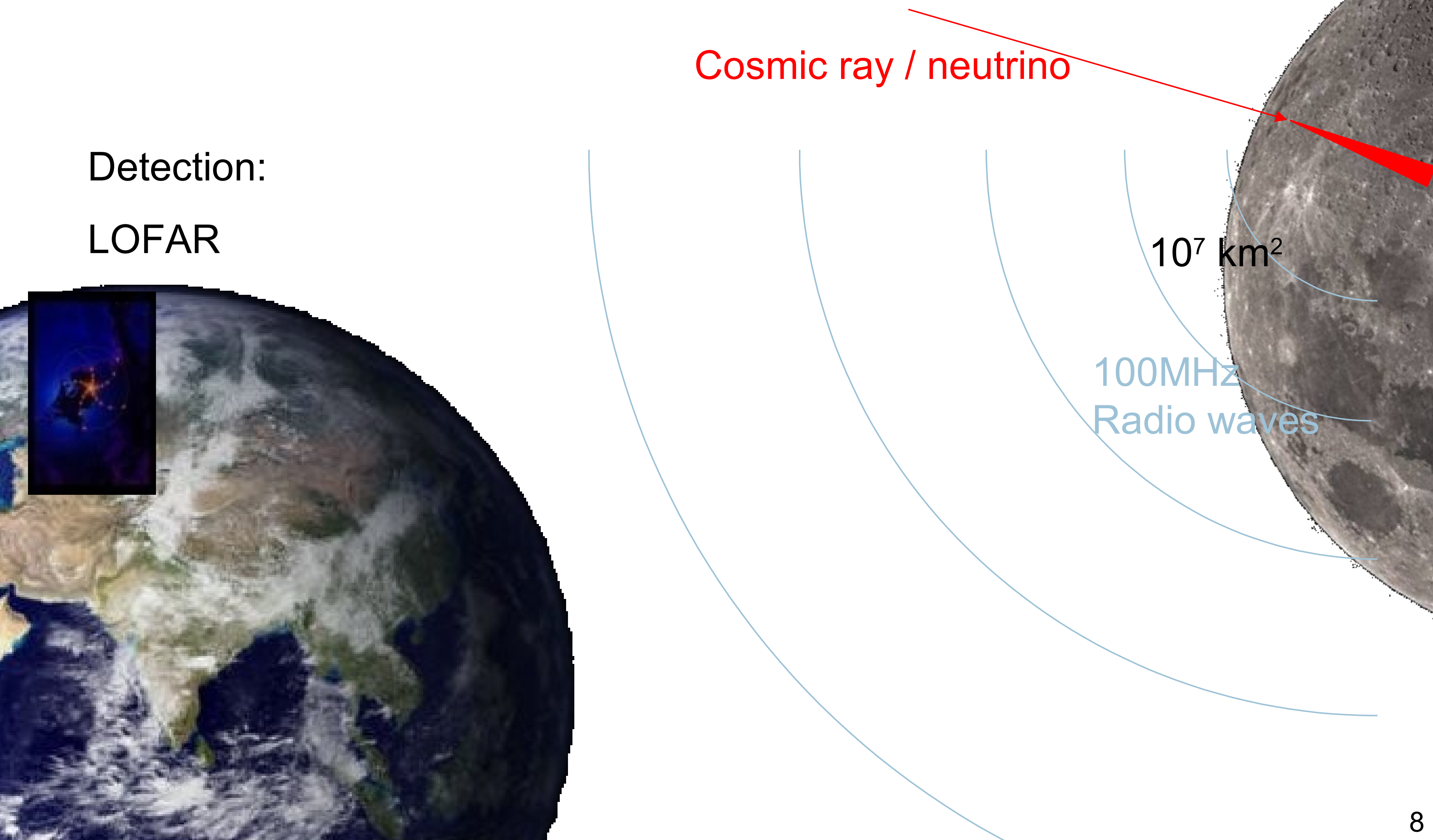
Detection:

LOFAR



VHECR-Triggering
Central Processor View

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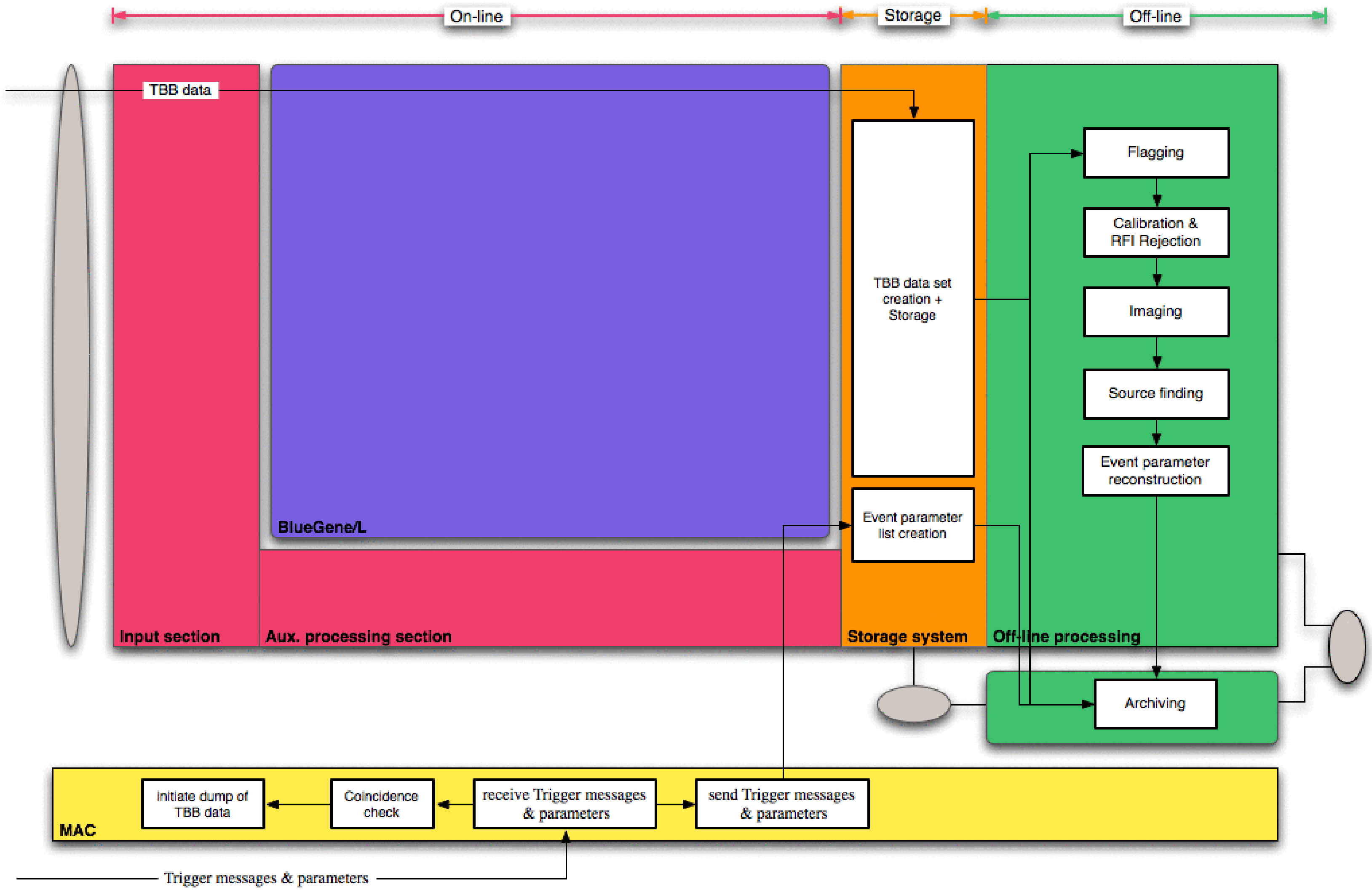

HECR-Triggering
Central Processor View

LOFAR

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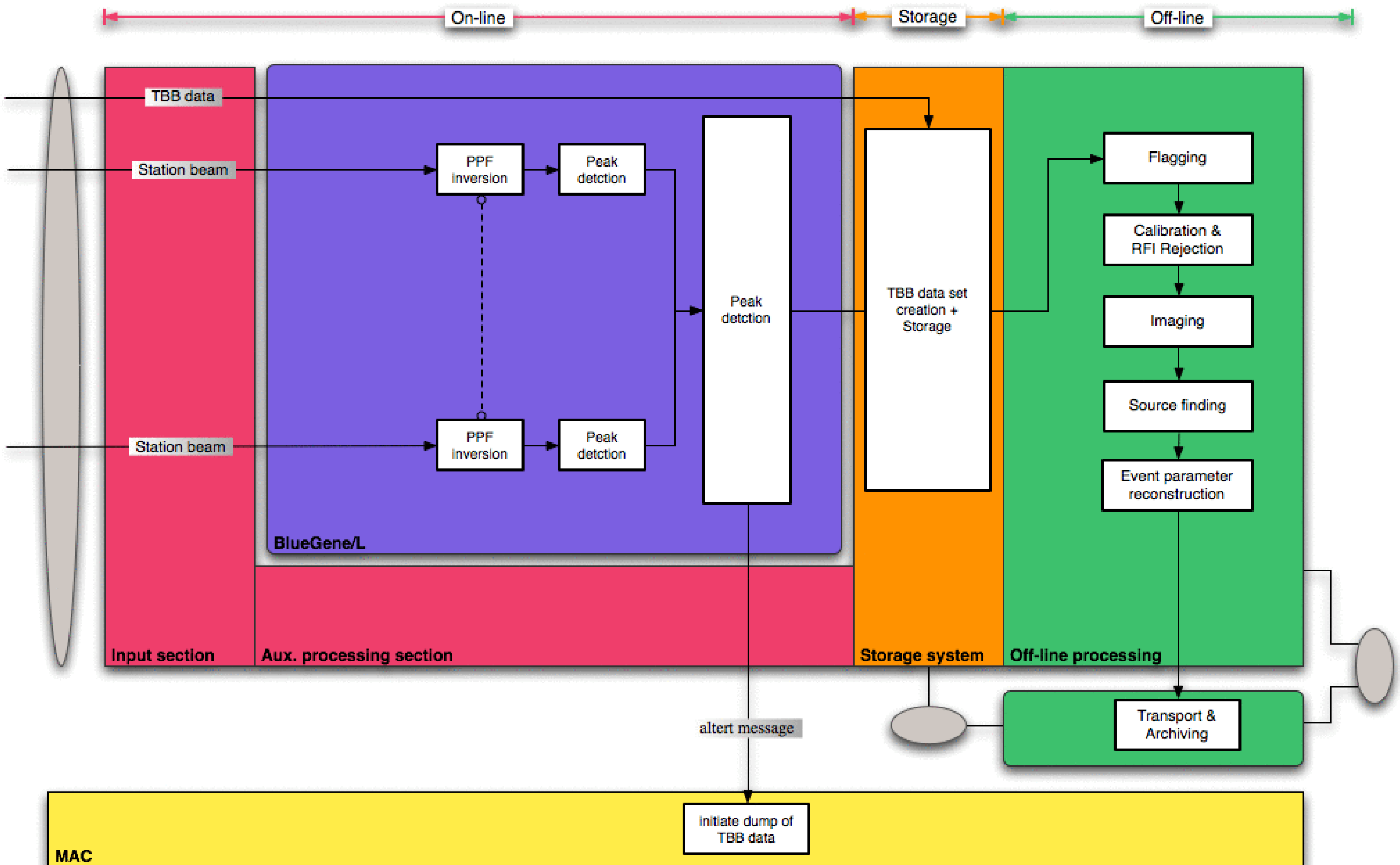

UHEP-Triggering

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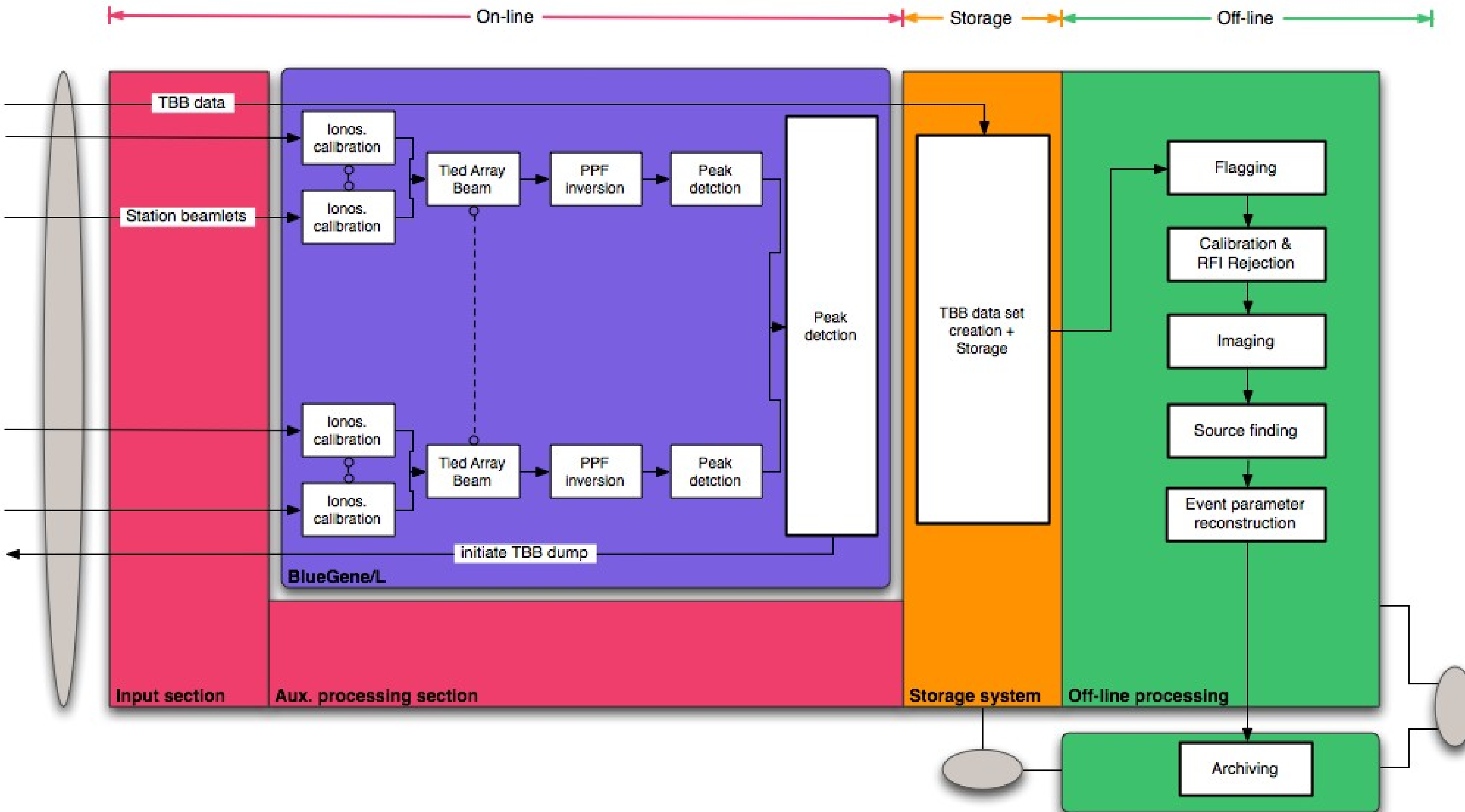

VHECR Trigger I

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- runs on the FPGAs of the TBBs
- pulse detection for single channels
  1. digital Filtering of some RFI (IIR-filters)
  2. peak detection
  3. calculation of pulse parameters (position, height, width, sum, avg. before, avg. after)
- peak detected if:

$$|x_i| > \mu_i + k_1\sigma_i$$

- can be simplified to:

$$|x_i| > k_2\mu_i$$

Transient Buffer Boards

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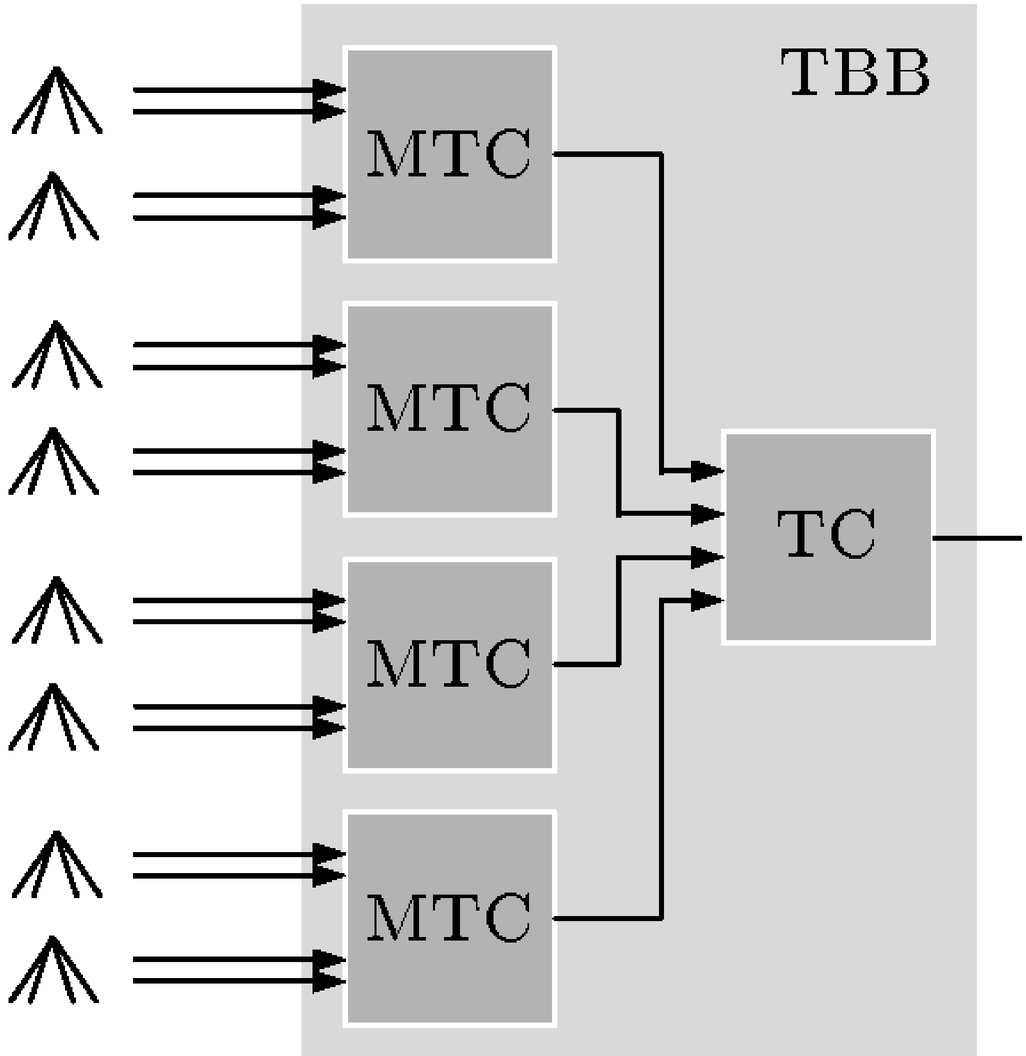
- one TBB for 16 channels
- one FPGA for 4 channels
- larger FPGA allows 3 IIR filters plus peak detection per channel



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VHECR Trigger II

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- TBBs send “trigger messages” to station LCU
- coincidence trigger at station level
  - filtering of “bad” pulses
  - coincidence detection
  - (direction fit)
  - data dump if pulse is found
- stations send messages to CEP
  - dump more (all) stations for large events
- after trigger: dump 1ms worth of data
  (1kHz frequency resolution)

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CR-Radio Analysis Software

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- Not reinvent the wheel!
  Which wheel???

$\longrightarrow$ So we need to write our own software.

- Three Versions:

1. Original Glish-based
   - Slow, ugly, **not supported anymore!**
2. Plain C++
   - Fast, but only “batch-mode”
3. Python/C++ based
   - Interactive analysis + GUI
   - Not ready yet.

Data Processing

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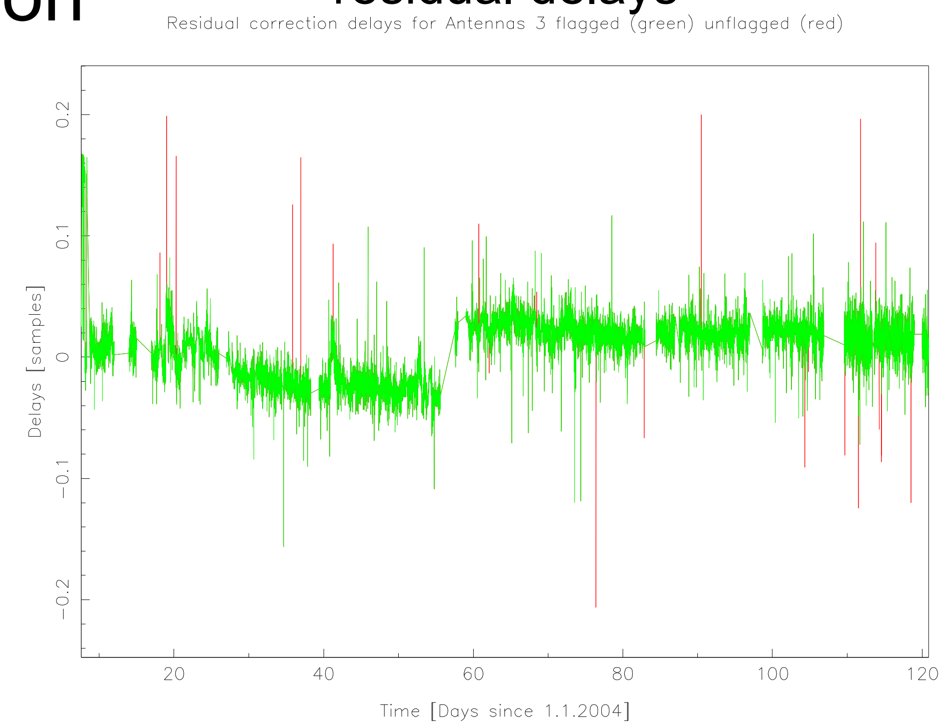
- steps of the data processing:
  1. delay/phase correction
  2. filtering of narrow band Interference
  3. frequency dependent gain correction
  4. flagging of antennas
  5. correction of trigger delay
  6. beam forming in the direction of the air shower
  7. direction fitting
  8. quantification of peak parameters
  9. event discrimination

Delay correction

- At LOPES: Calibrate on relative phases from a TV-transmitter or extra beacon
- At LOFAR: Solutions from standard calibration

residual delays



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Gain Calibration

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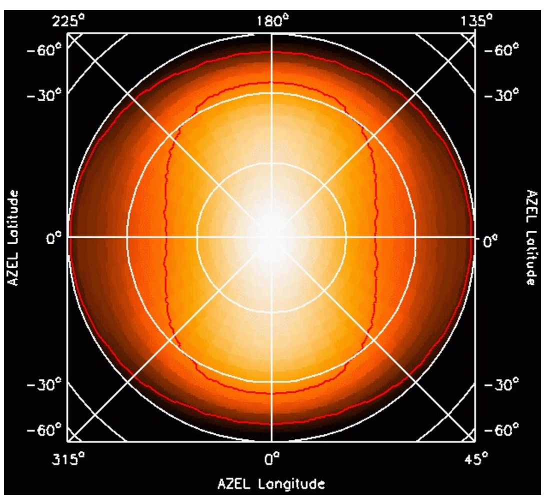
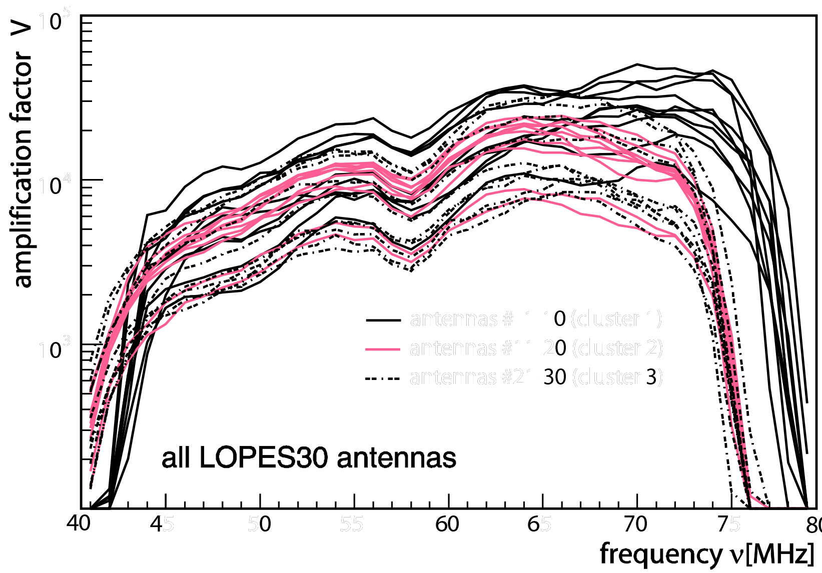
- Convert measured ADC values into field-strength
- At LOPES: Gain measurements with reference source
- At LOFAR: Station calibration

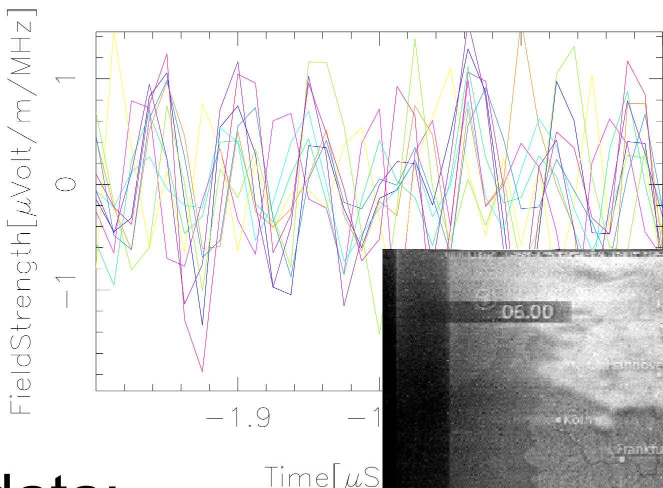
$$\varepsilon = \sqrt{\frac{4\pi \nu \mu_0}{G_{(\theta,\phi,\nu)} c} \frac{1}{A_{ele(\nu)} R_{ADC}}} V_{ADC}$$



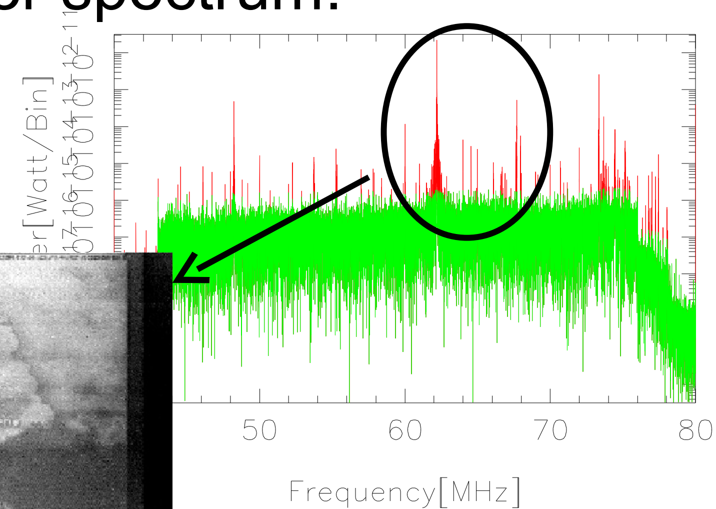


Digital Filtering

raw data:

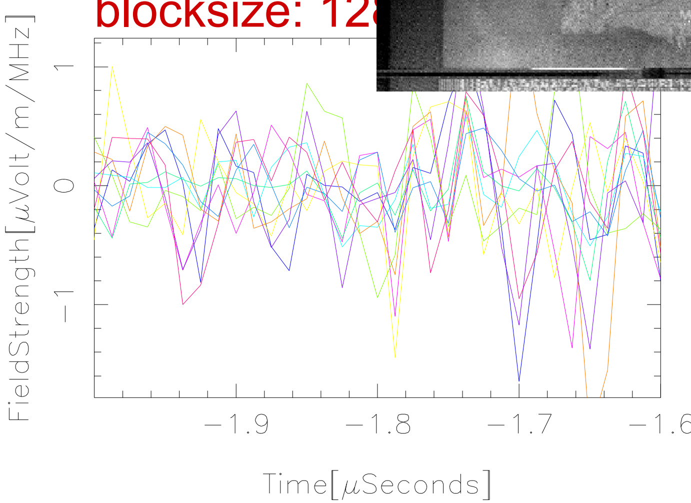


power spectrum:

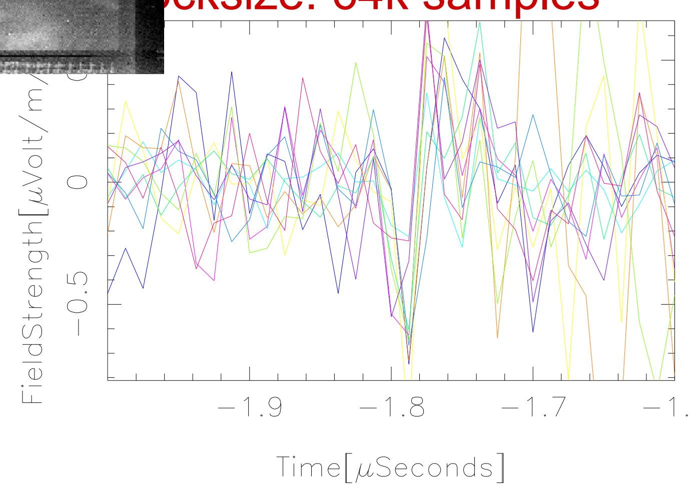


filtered data:

blocksize: 128



ocksize: 64k samples



Beam Forming

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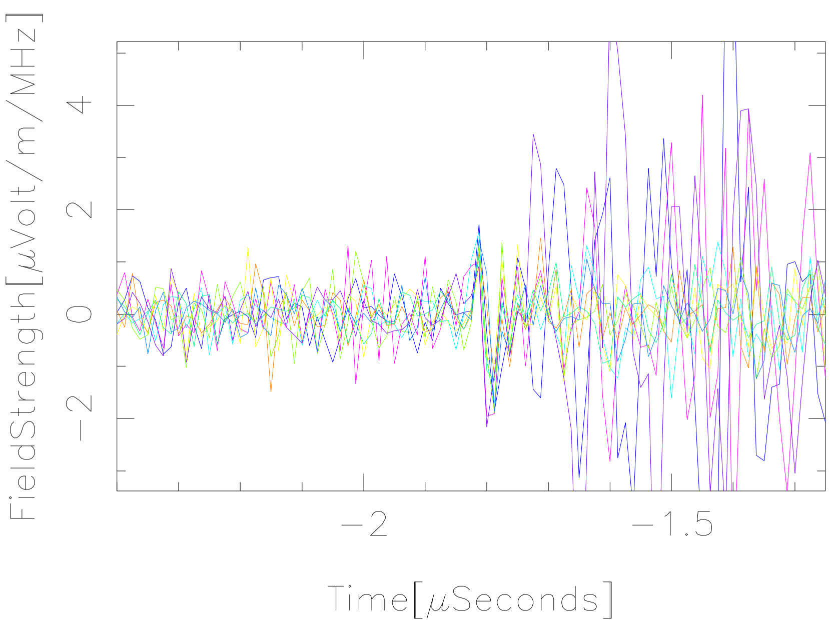
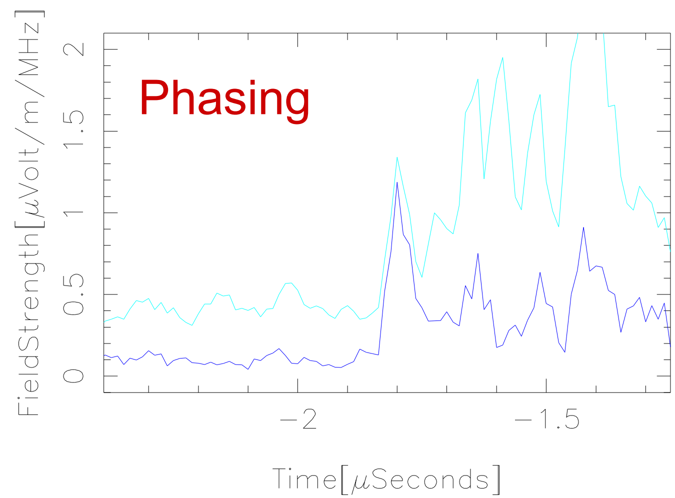
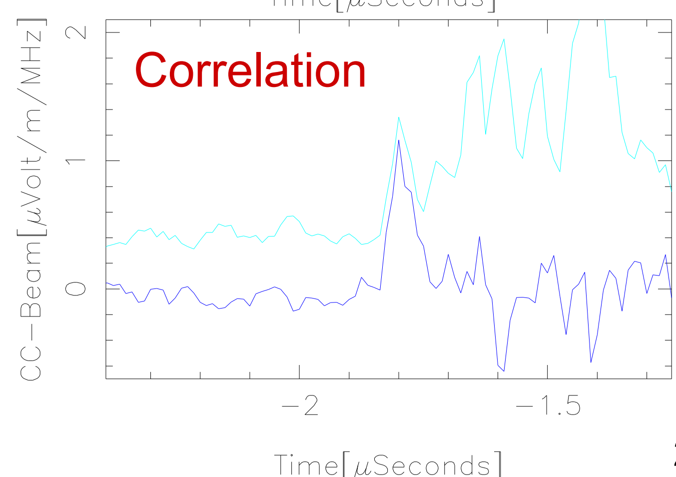
- filtered and time shifted data from single antennas
- beamformed data after correlation of all antennas
  - air shower pulse at -1.8μs
  - particle detector noise from -1.75μs to -1.3μs
  - Phasing ↔ Correlation



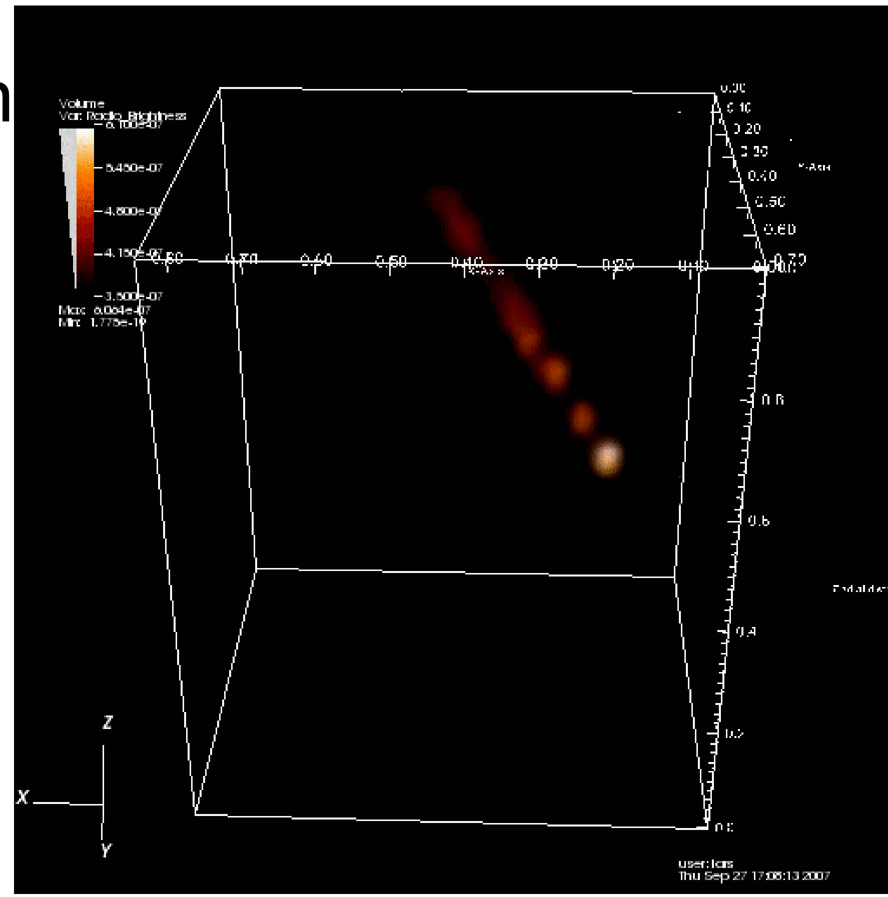




Position Fitting

- find maximum pulse height in 3d space (azimuth, elevation, radius)
- plus: time and position on the ground

1. start with image cube (around KASCADE values of of the full sky)
2. do a fit around the maximum of the cube



Event Discrimination

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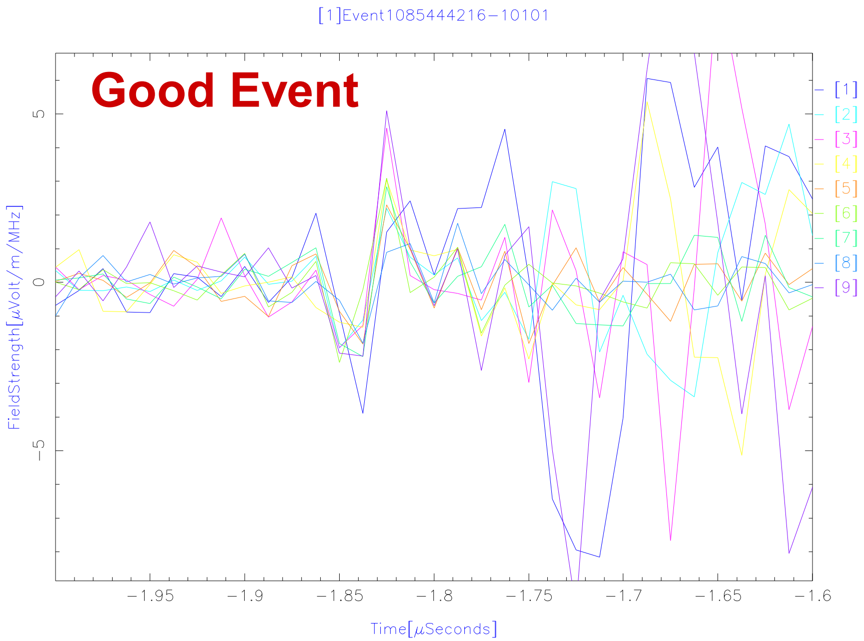
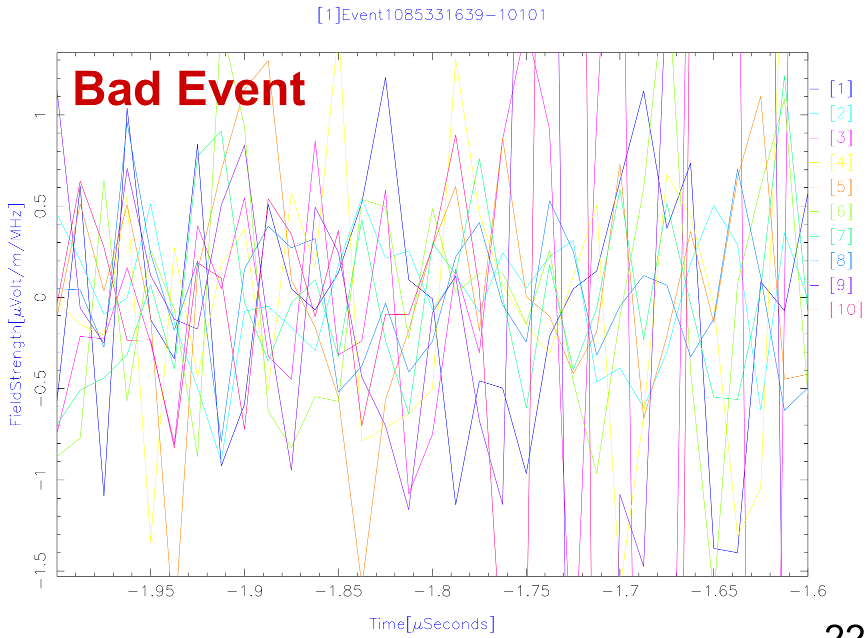
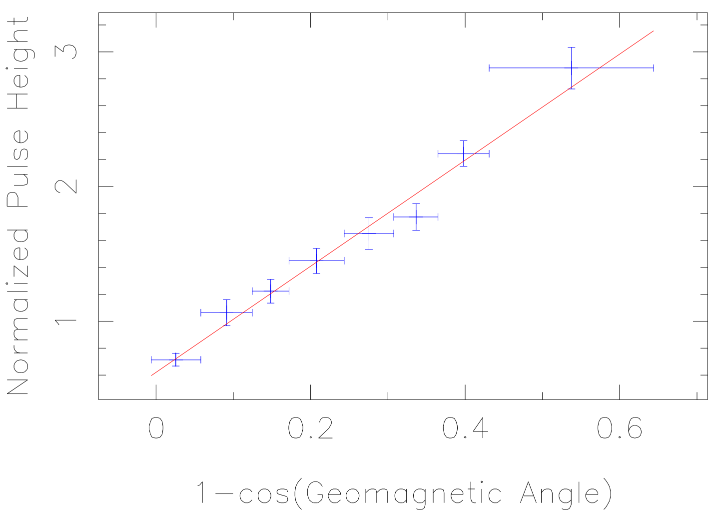
- criteria for “good” events:
  - existence of a coherent pulse
  - lateral distribution of pulse height in the antennas
  - position in time of pulse (only LOPES)
- selection currently done manually

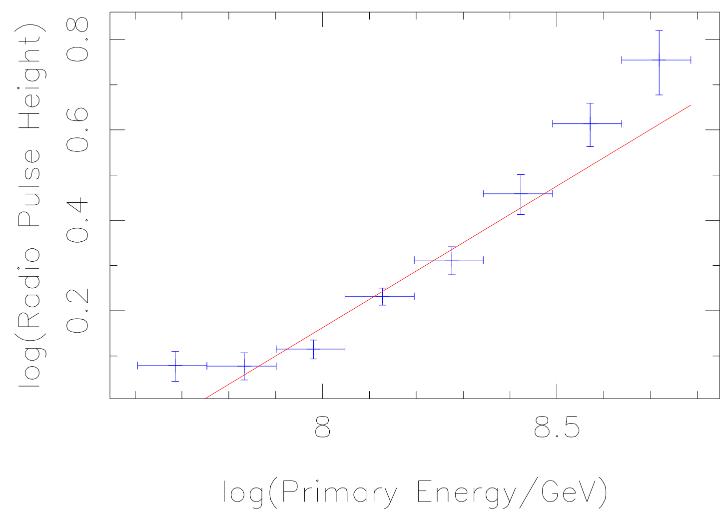




Statistical Analysis

- the output of the processing pipeline is a list of events and their parameters
- these are then analyzed to determine properties of the radio emission or the cosmic ray spectrum, composition etc.





LOFAR

Summary

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- pulses with ns timescales, so need full time resolution of the ADCs → raw ADC data
- cosmic rays come at unpredictable times and directions → triggering of events
- “batch-mode” software for LOPES already in production, adaptation fir LOFAR and interactive version soon