LOFAR

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Air Shower Measurements with LOFAR

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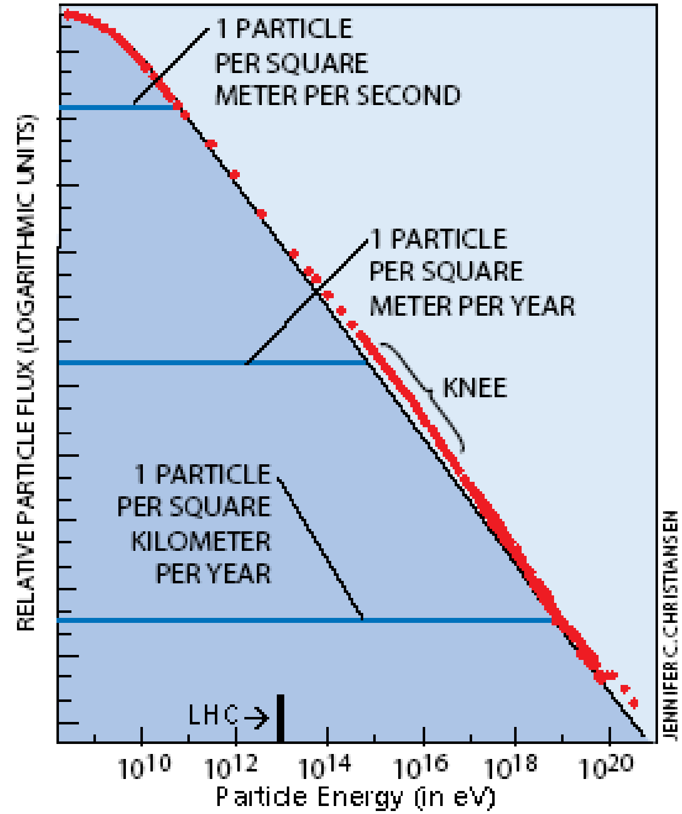
for the Cosmic Ray KSP

Outline

- Cosmic rays and air showers
- Measurement with LOFAR
- Results from LOPES
- Direction determination
- Summary

Cosmic Rays

- 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

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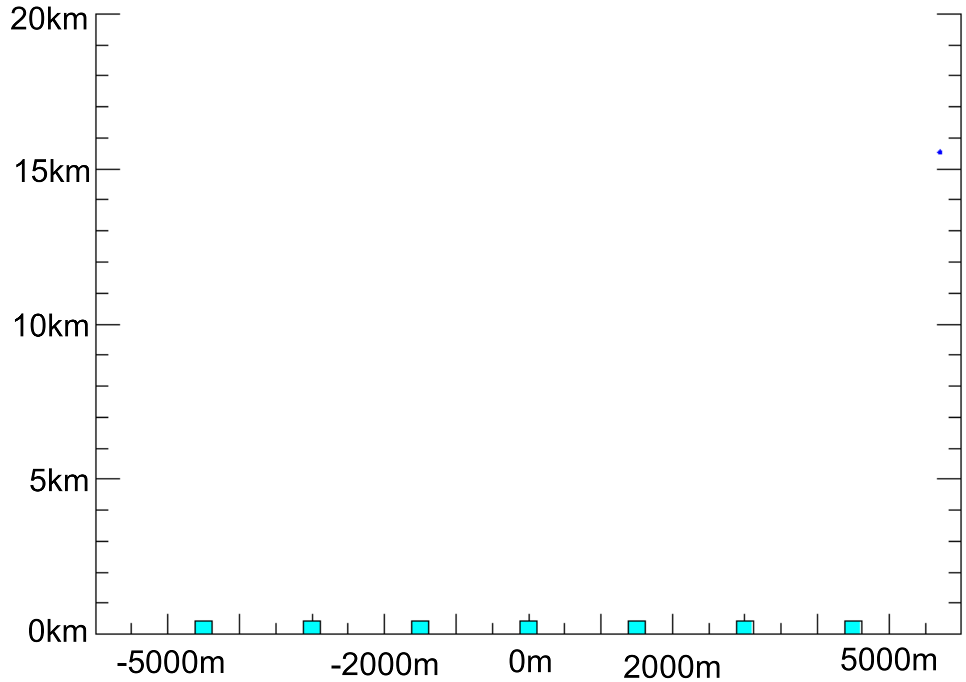
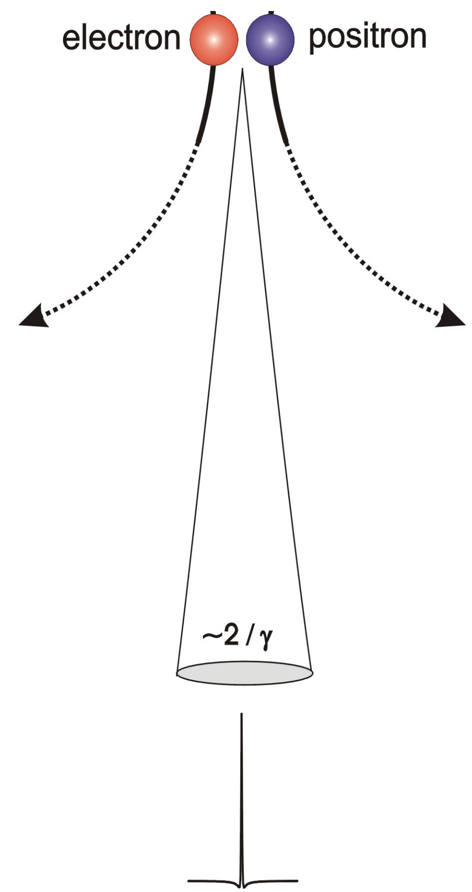
- High energetic cosmic rays interact with nuclei in the atmosphere
- In a cascade lots of secondary particles emerge
- A “pancake” of particles



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

Radio Emission from Air Showers

- Air showers emit short, intense radio pulses, beamed into the forward direction
- Radiation due to geomagnetic emission process e.g. geosynchrotron
- Coherent emission at low frequencies
- Measuring the radio emission from air showers could give several benefits:
  - Higher duty cycle than fluorescence telescopes
  - Effective RFI suppression allows measuring in polluted (populated) areas
  - Data integrated over the shower evolution, can be complementary to particle detectors
  - High angular resolution possible



LOFAR for Cosmic Rays

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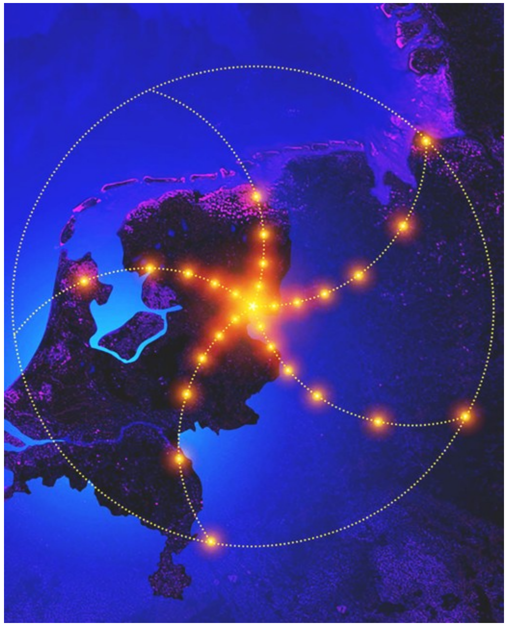
- Designed as an astronomical telescope not an air shower detector:
  - “small” stations with lots of antennas in a small area
  - different baselines between stations
- Consequences:
  - low effective area for the number of antennas
  - **high sensitivity**
  - **very good calibration**
- This makes LOFAR an unique tool to study air showers:
  - Develop the method (triggering, reconstruction)
  - Understand the emission process
  - Air shower physics (new particles?)
  - Change galactic→extragalactic cosmic rays



LOFAR-CR
Energy Ranges

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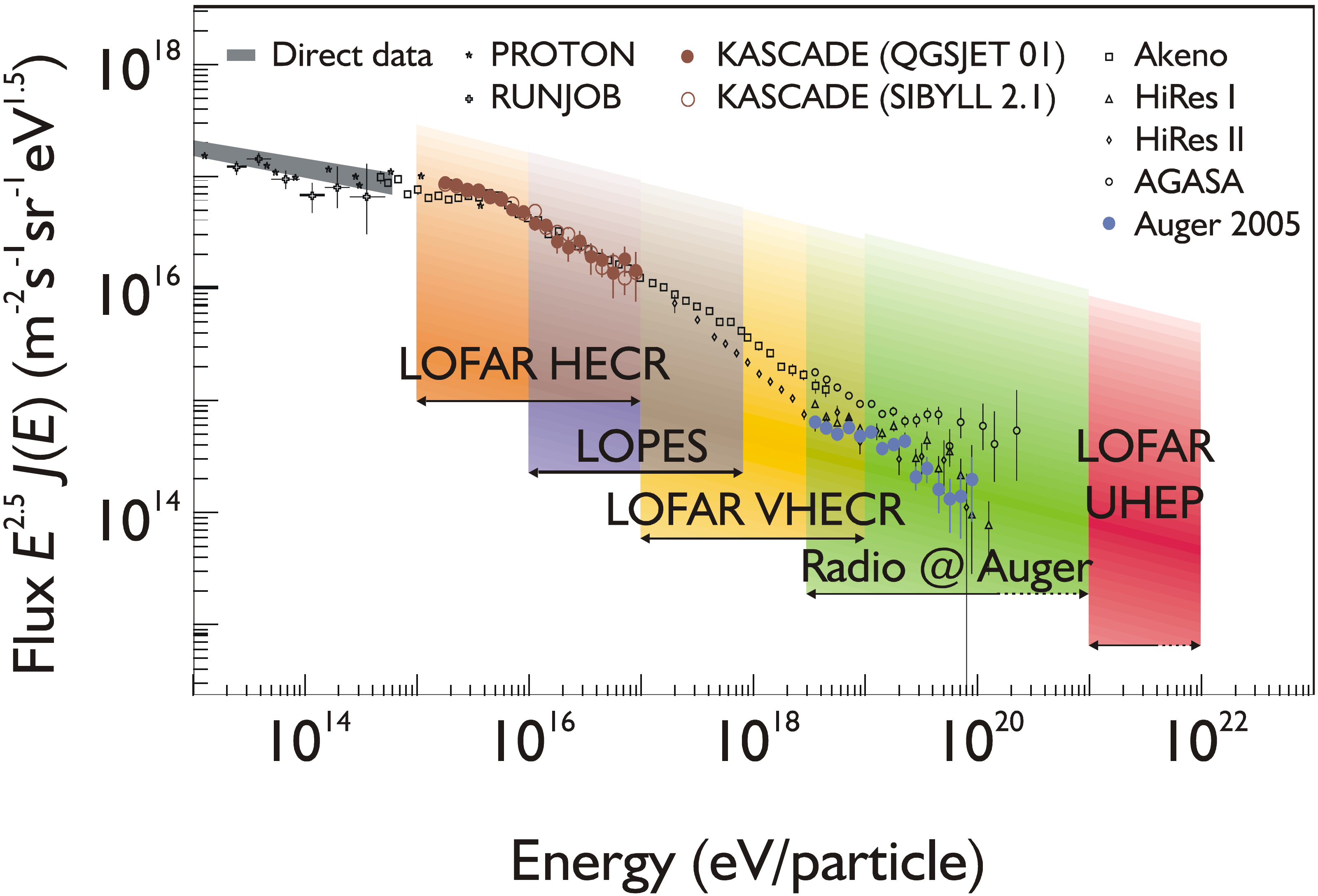

LOFAR VHECR-Triggering

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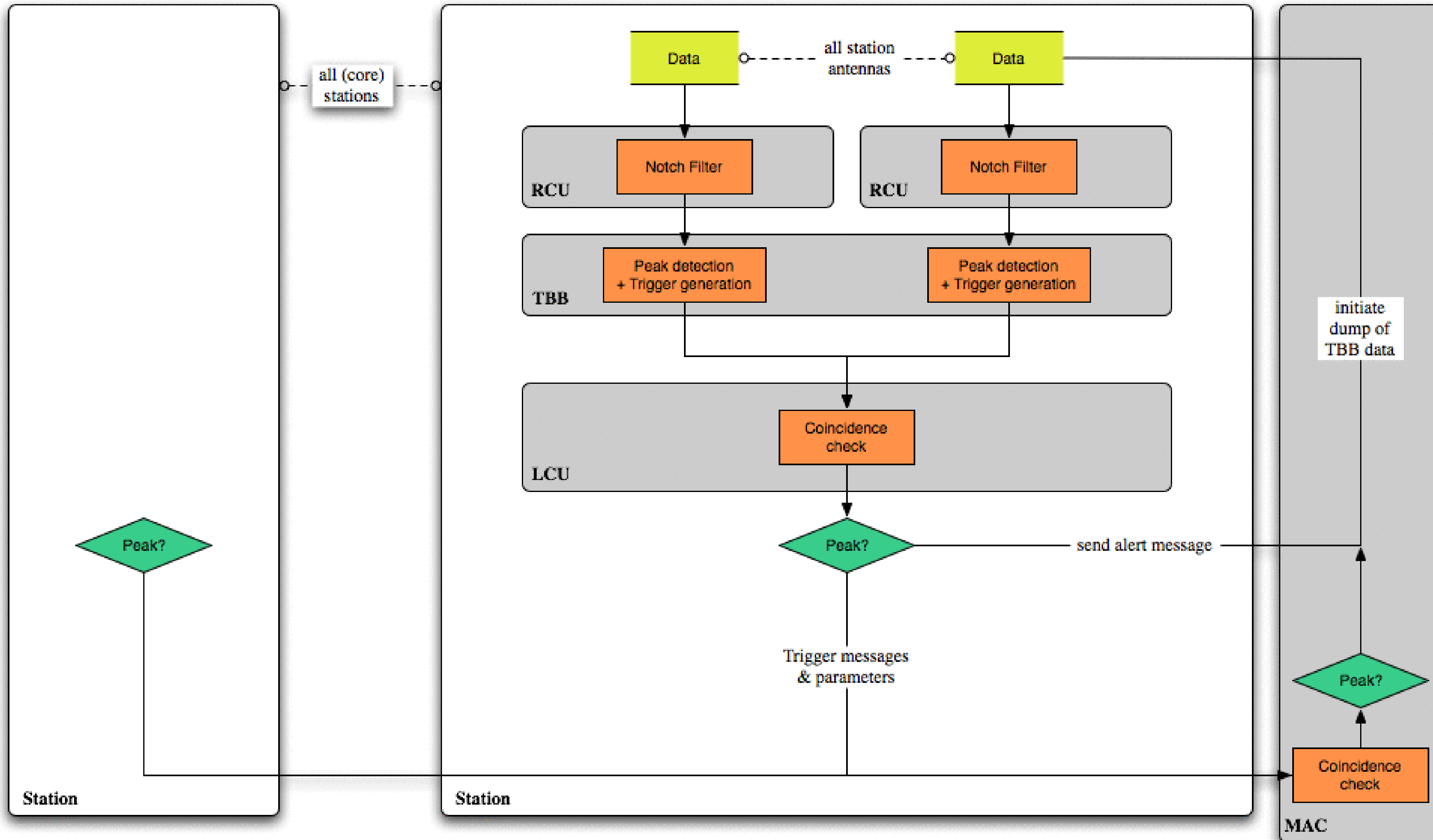

LOFAR VHECR-Triggering

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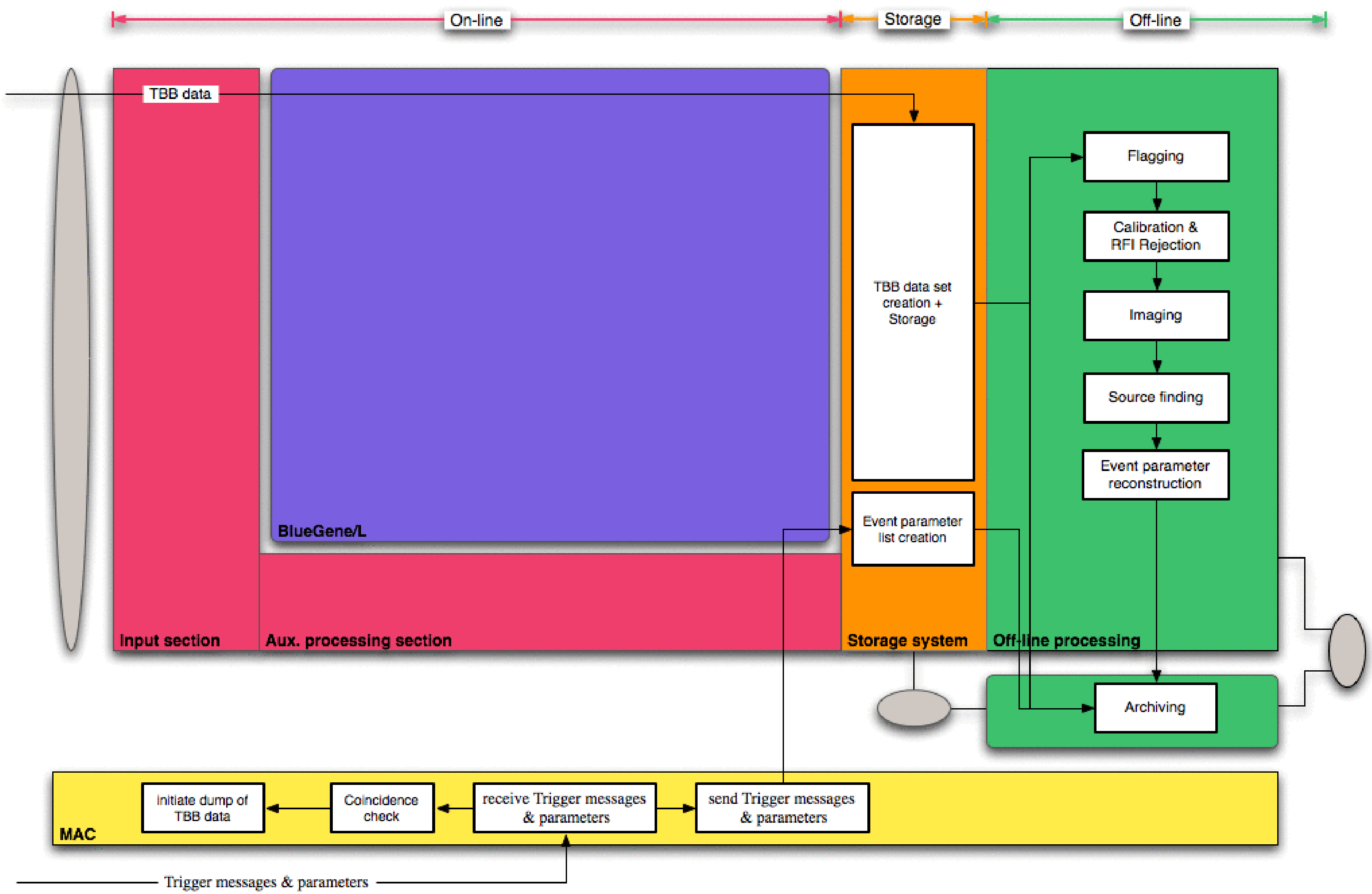

HECR-Triggering

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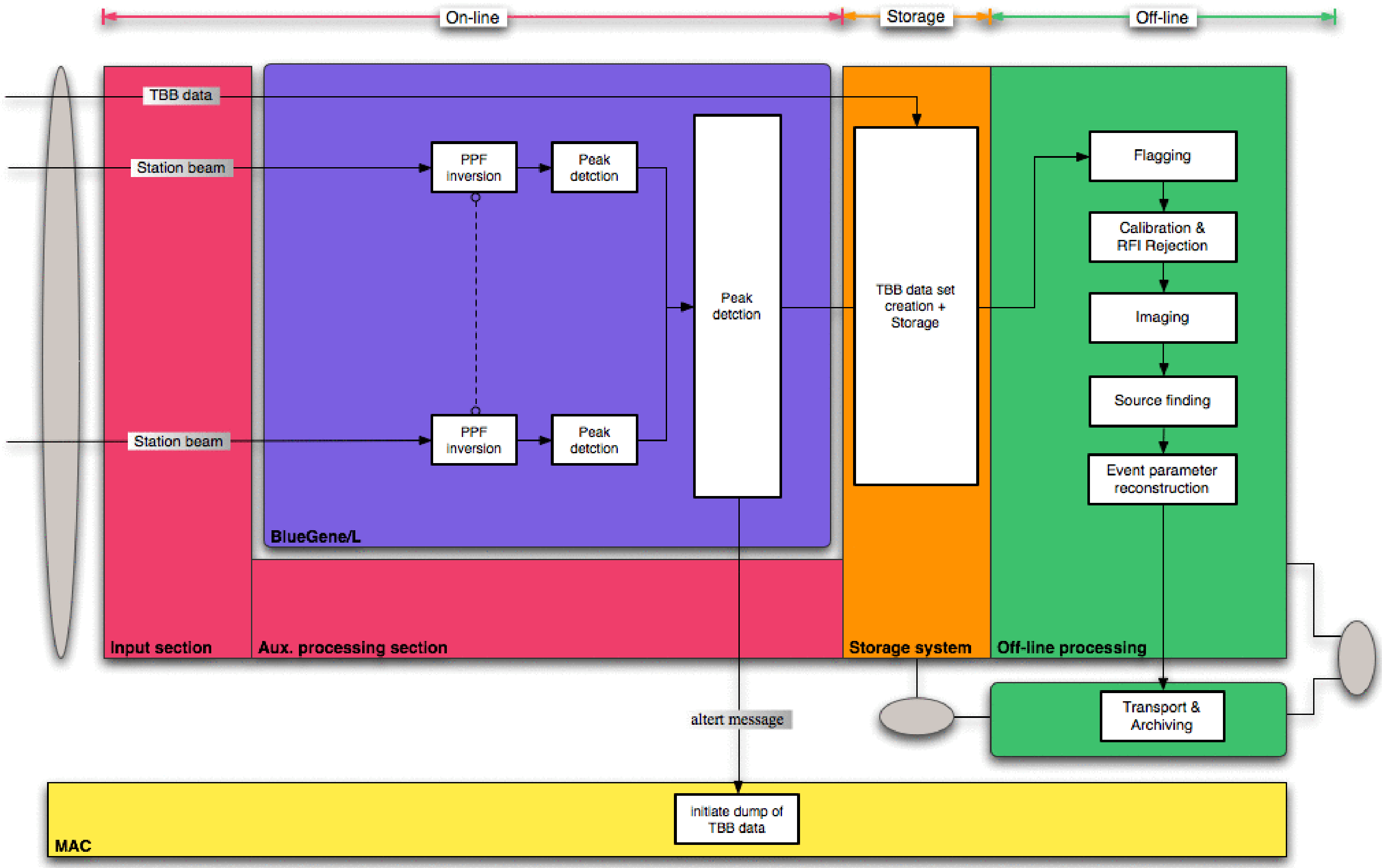

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- **Results from LOPES**
- Direction determination
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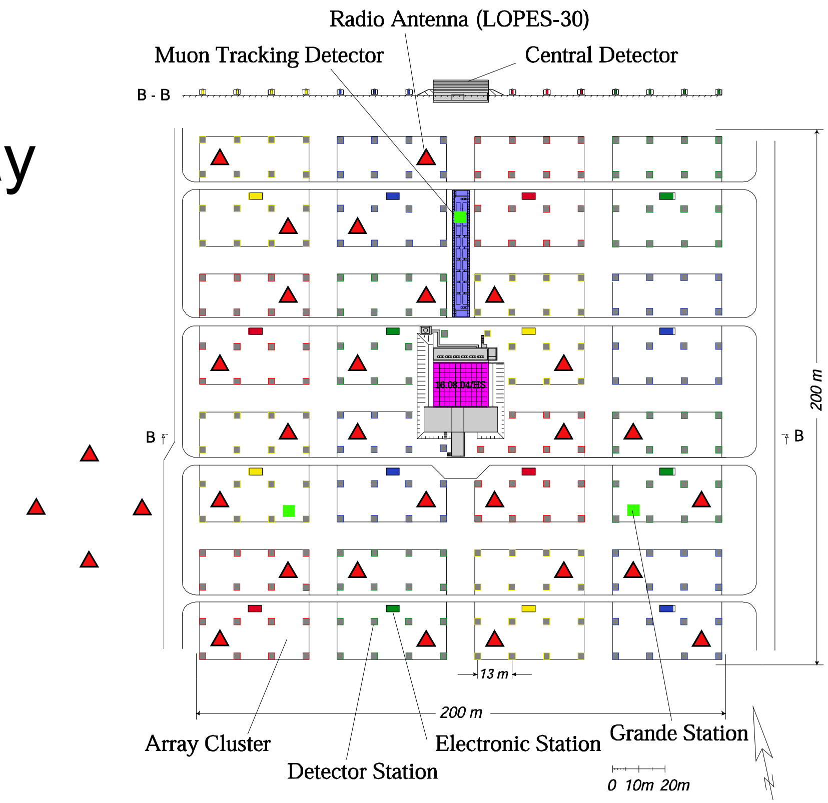
LOPES
(**LO**FAR **P**rototyp**e** **S**tation)

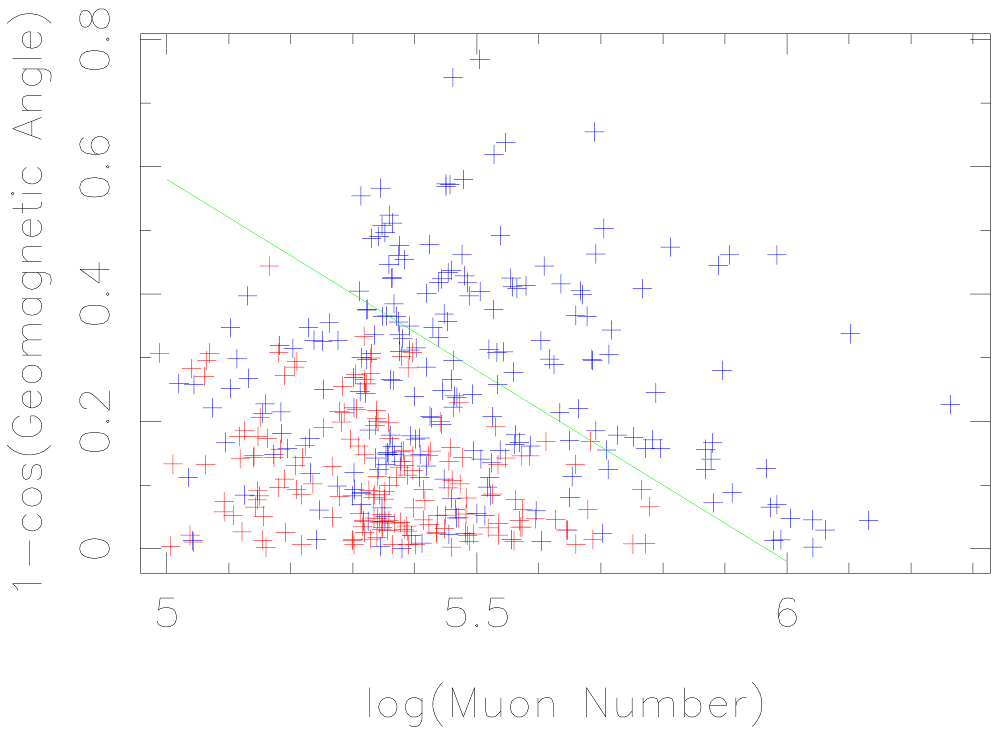
- Prototype of a LOFAR station
- Set up inside an air shower array
- Frequency range of 40–80 MHz
- Triggered by particle detectors
- Detection of air showers with LOFAR technology



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

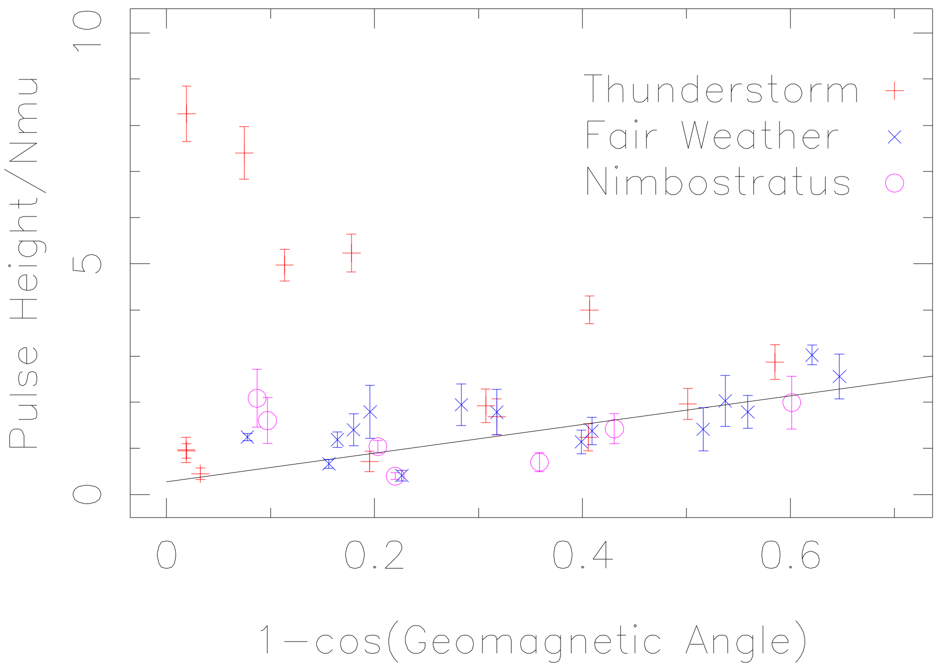
Detected Events

- Not all triggered events have a detectable radio pulse
- Fraction of “good” to “bad” events increases with increasing shower size and increasing geomagnetic angle
- Suitable cuts give 100% detection efficiency



Thunderstorm Events

- Does the electric field of the atmosphere influence CR radio signal?
- Increased pulse height during thunderstorms.
- No other effects seen.



Buitink et al. (LOPES coll.) 2007, A&A (in print)

Parametrization

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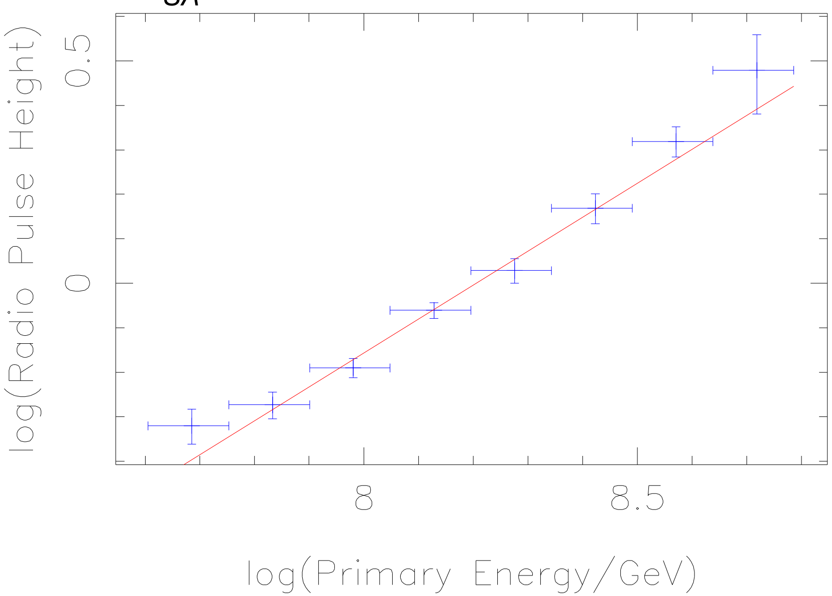
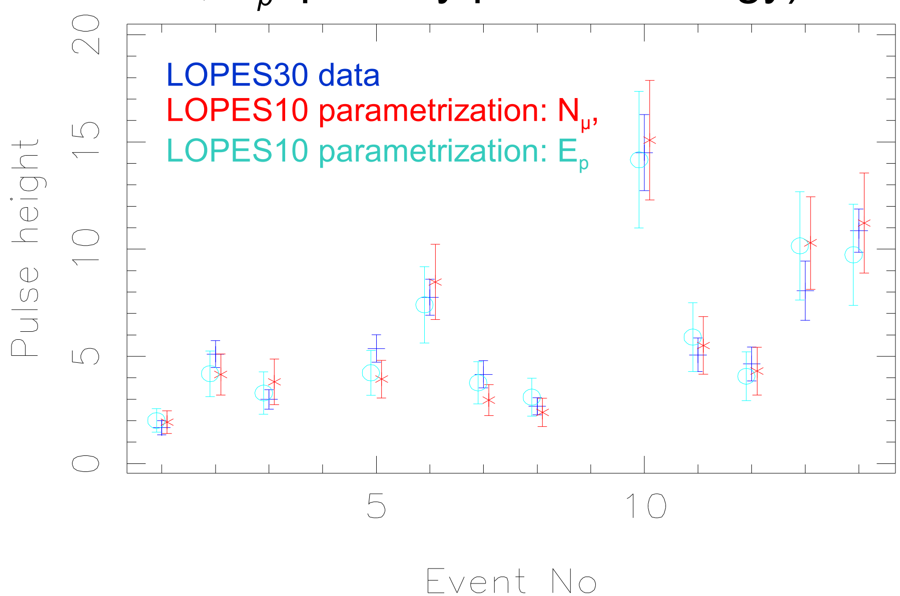
$$\varepsilon_{est,E_p} = (12 \pm 1.8)\left[\frac{\mu V}{m\ MHz}\right]\left(1 + (0.1 \pm 0.03) - \cos(\alpha)\right)\cos(\theta)$$

$$\times \exp\left(\frac{-R_{SA}}{(200 \pm 45)m}\right)\left(\frac{E_p}{10^{17}\,eV}\right)^{(0.91 \pm 0.07)}$$

(ε_{est}: EW-pol field strength per unit bandwidth, α: geomagnetic angle, θ: zenith angle, R_{SA}: mean distance antennas ↔ shower axis, E_p: primary particle energy)





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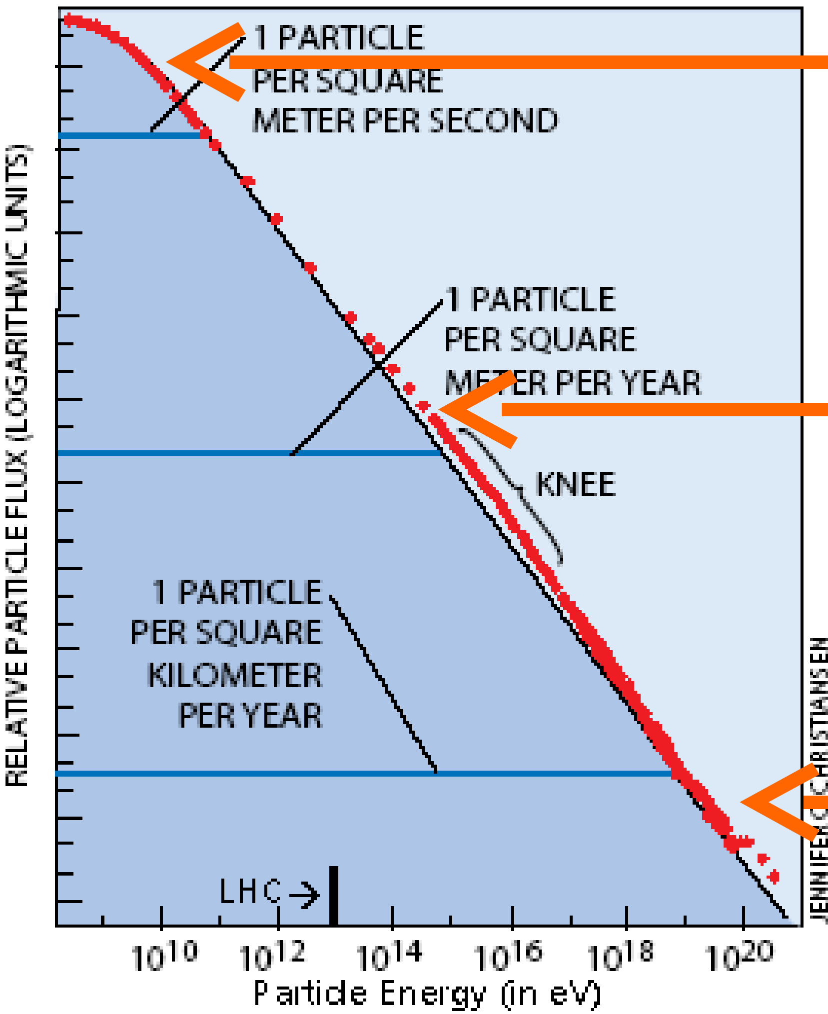
Sources of Cosmic Rays

Scientific American, (c) 1998



New Physics?

Finding Sources of Ultra High Energy Cosmic Rays

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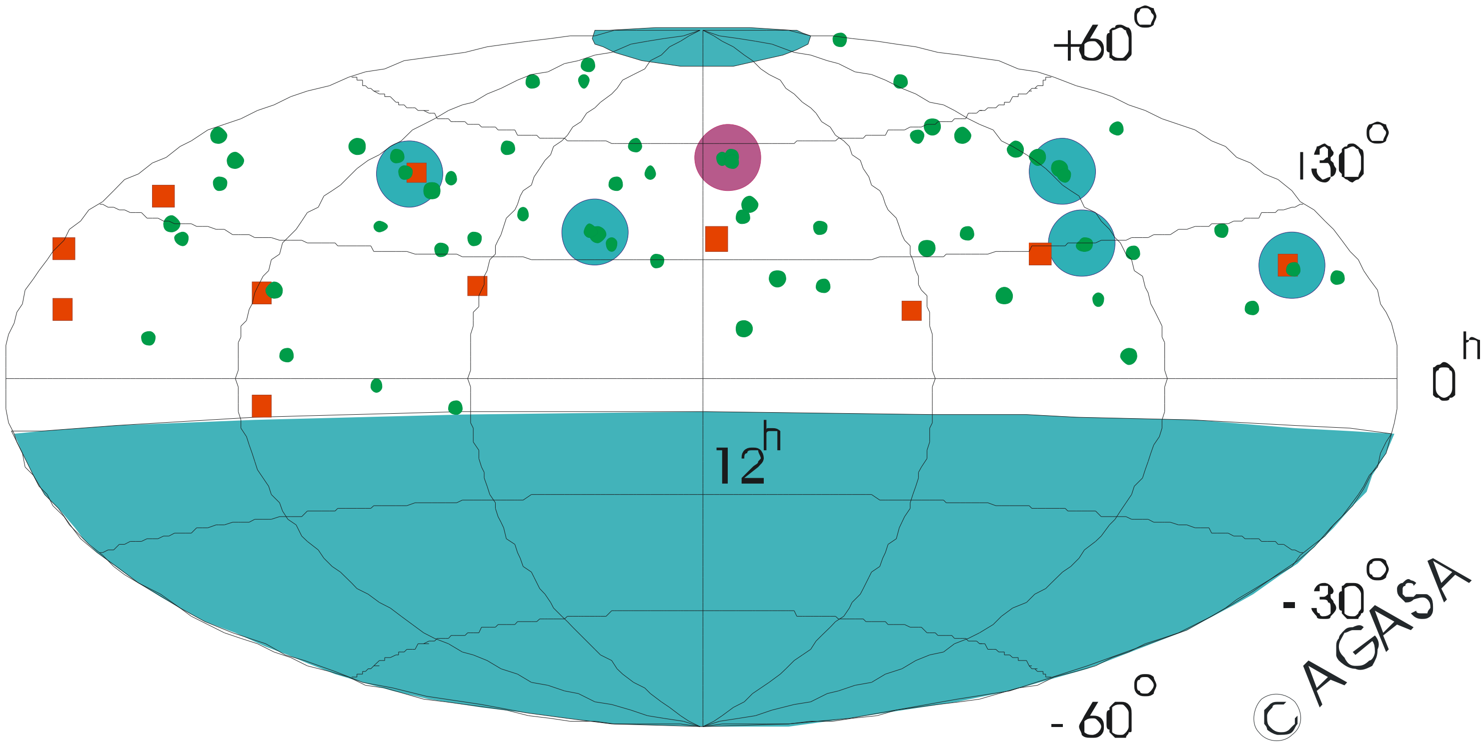
- Limited by statistics and angular resolution



→Need large detectors with good angular resolution!

Large detectors are being built, need angular resolution.

Direction determination with detector arrays

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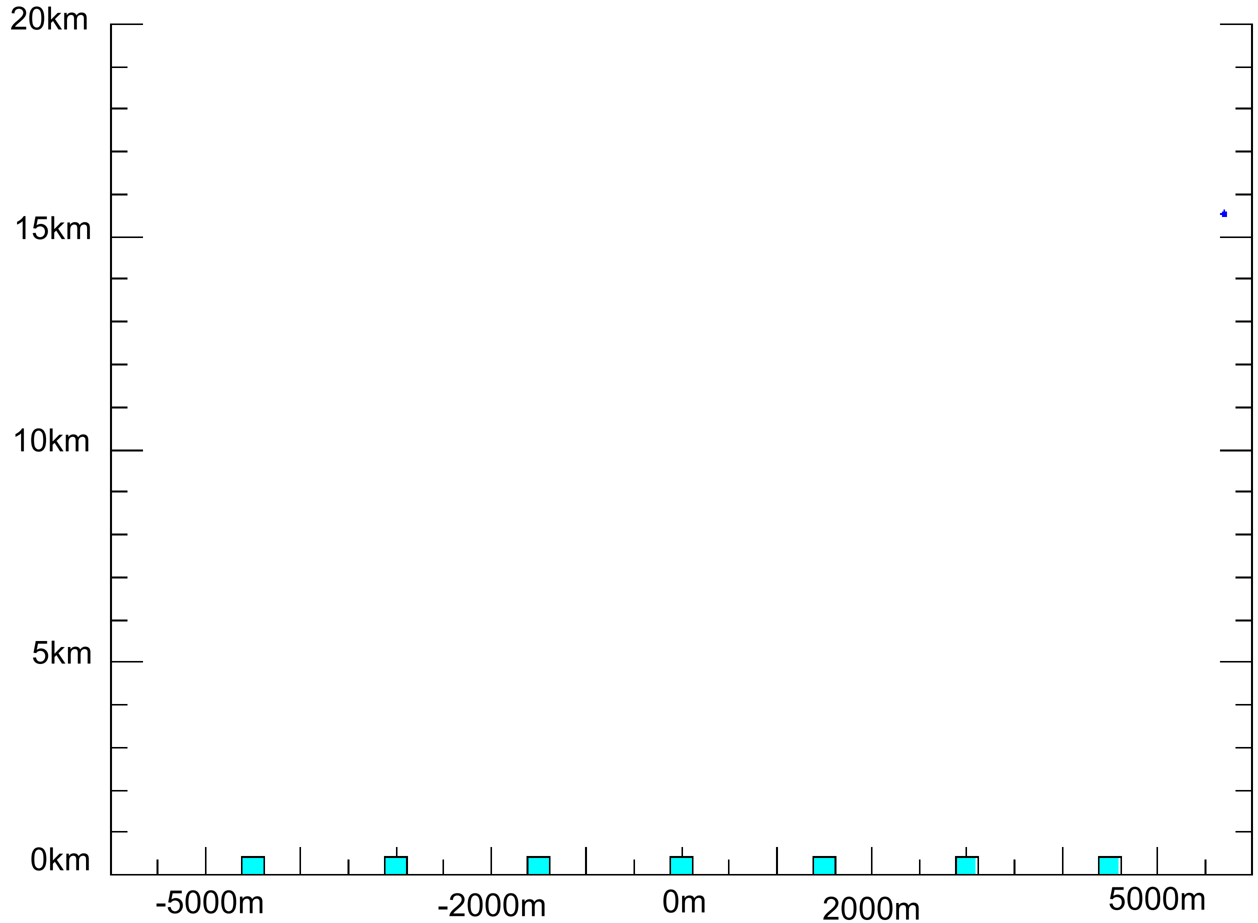
- Measure the arrival time at different positions on the ground
- The relative times gives the direction



Direction Determination

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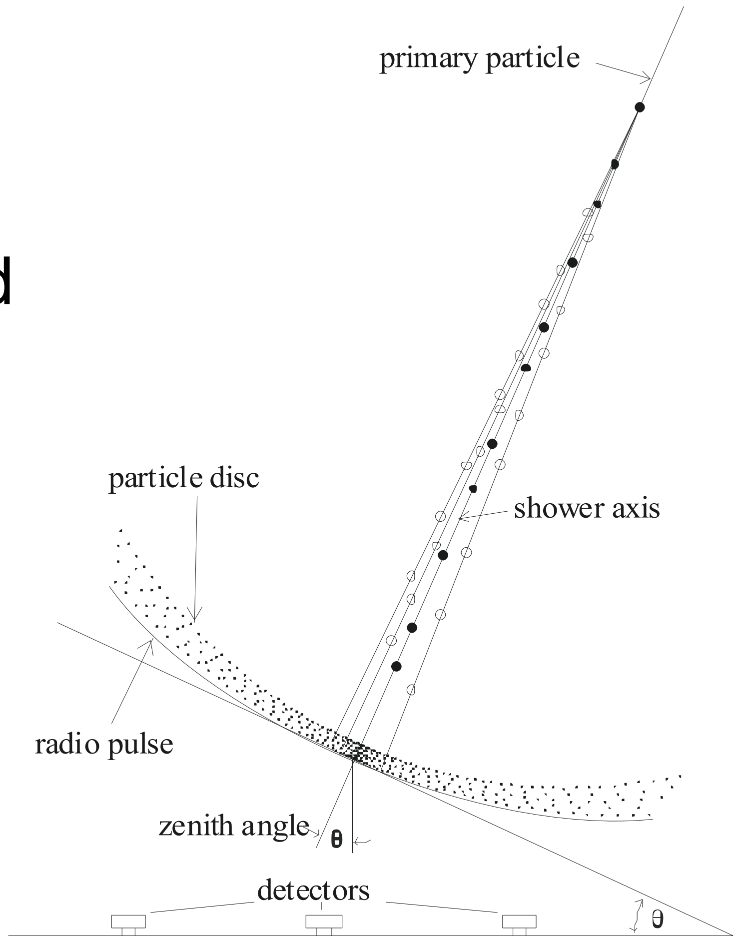
- Current resolution: ~0.5° limited by costs (pixel size) and/or physics (quantization)
- Radio signal is smooth, not quantized
- Good timing (phase) calibration of radio antennas possible
- Radio can increase angular resolution from ~0.5° to <0.1°
- Needed work:
  - Study shape of radio pulse front
  - (Timing calibration for large antenna fields)

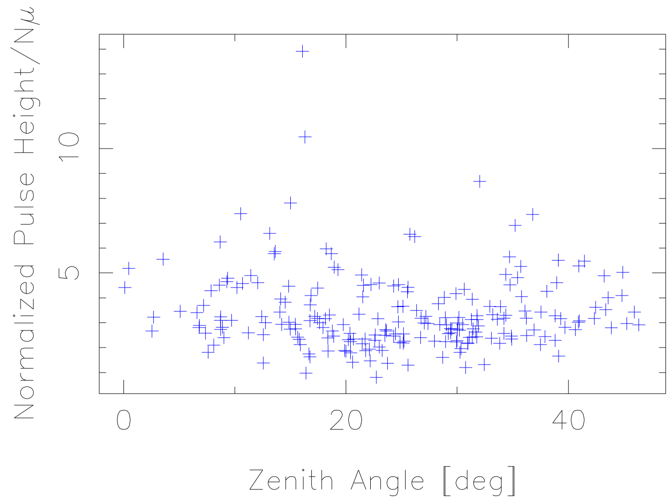


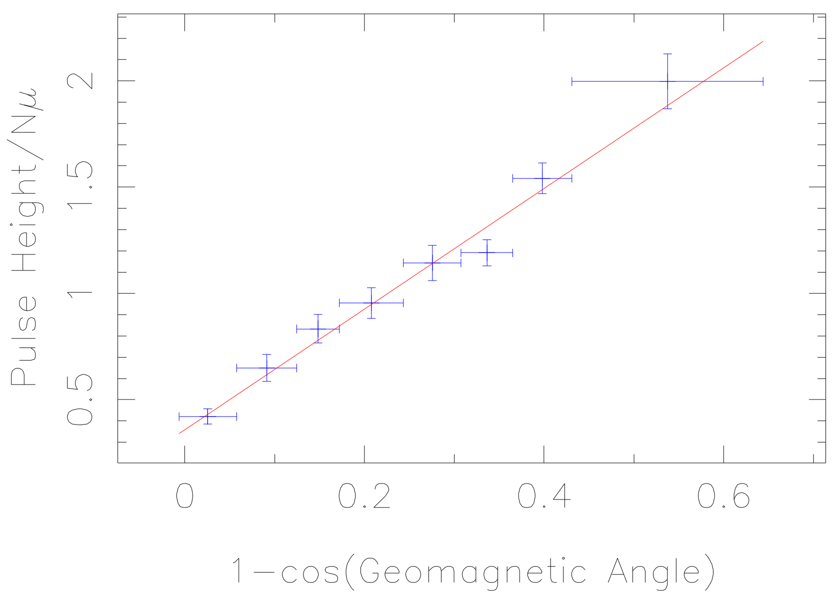
Summary

- LOPES has proven that LOFAR can measure air showers
- LOFAR is an unique tool for this measurement
  - High sensitivity
  - Excellent calibration
- Interesting new physics
  - Understand the emission process
  - Air shower physics (new particles?)
  - Change galactic→extragalactic cosmic rays
  - Direction resolution → particle astronomy

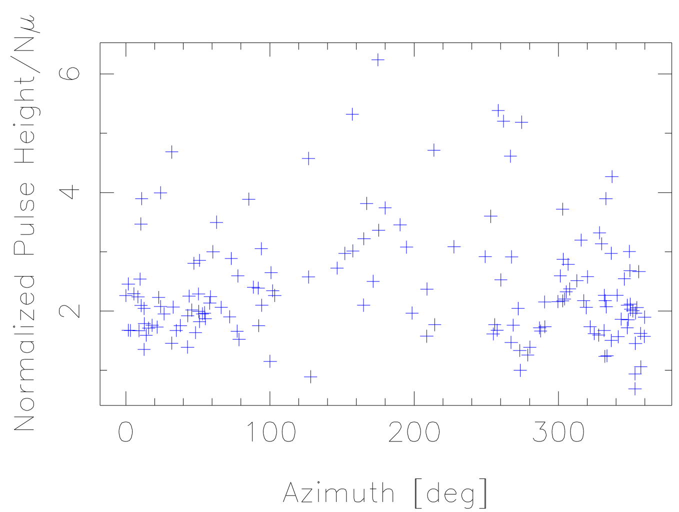
Angular dependence

- Pulse height depends on the geomagnetic angle
- After normalization no further dependence on zenith or azimuth angle





(events with ZE>17 degree)



Dependencies: Size, $N\mu_{trunc}$ and Energy

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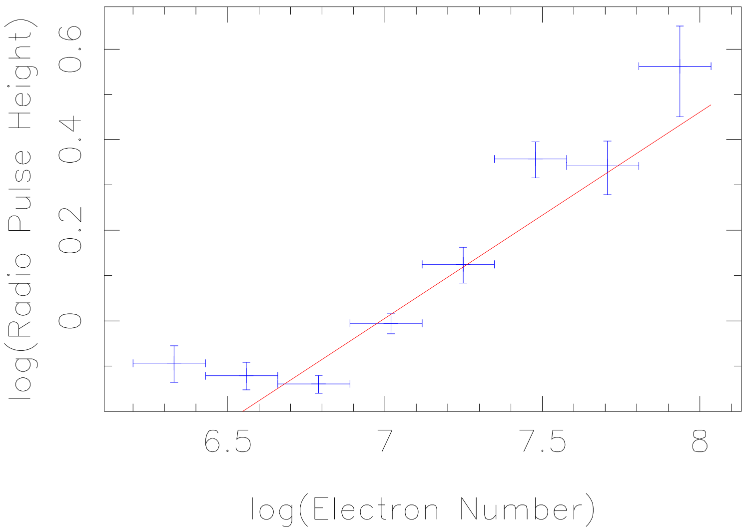
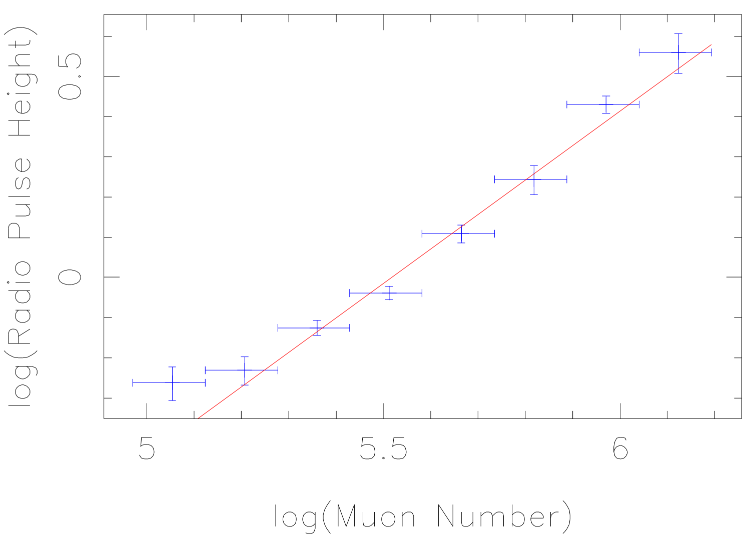
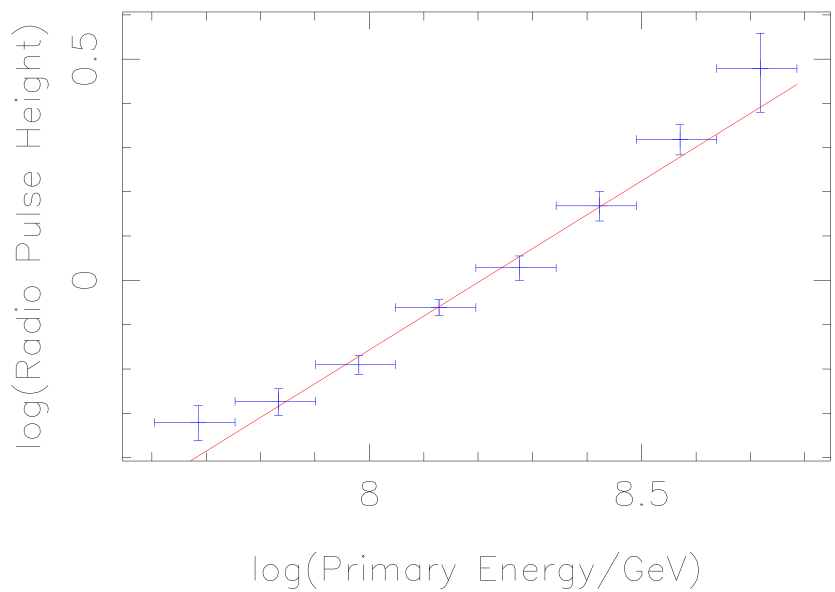
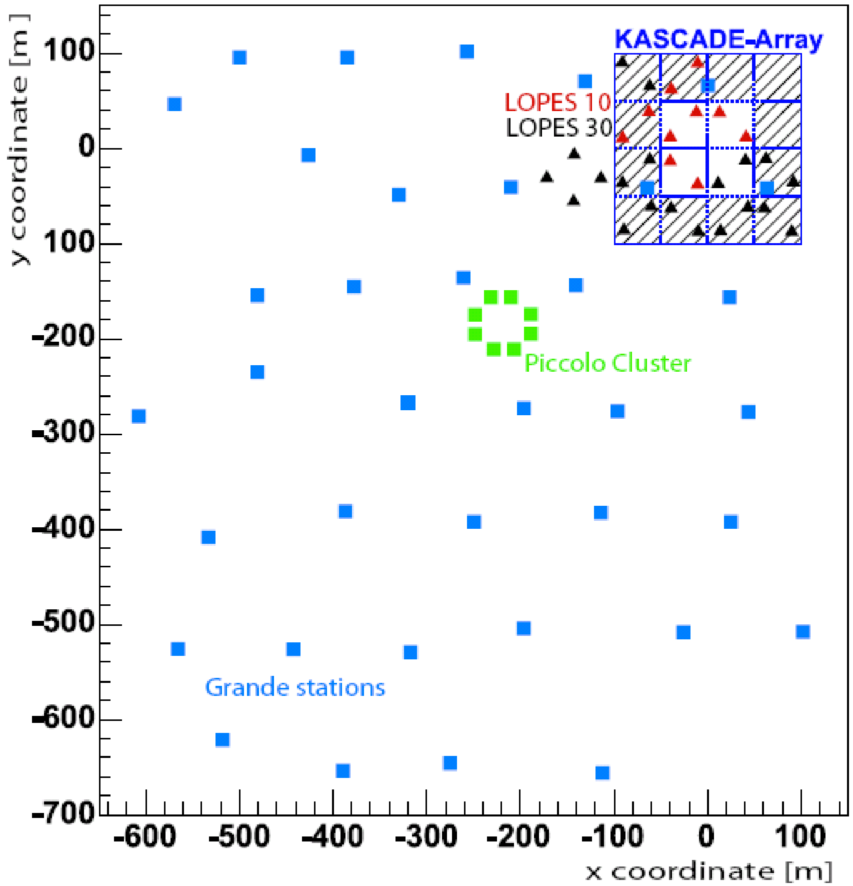
- Only little dependency on electron number
- Power law is a good fit for muon number and energy

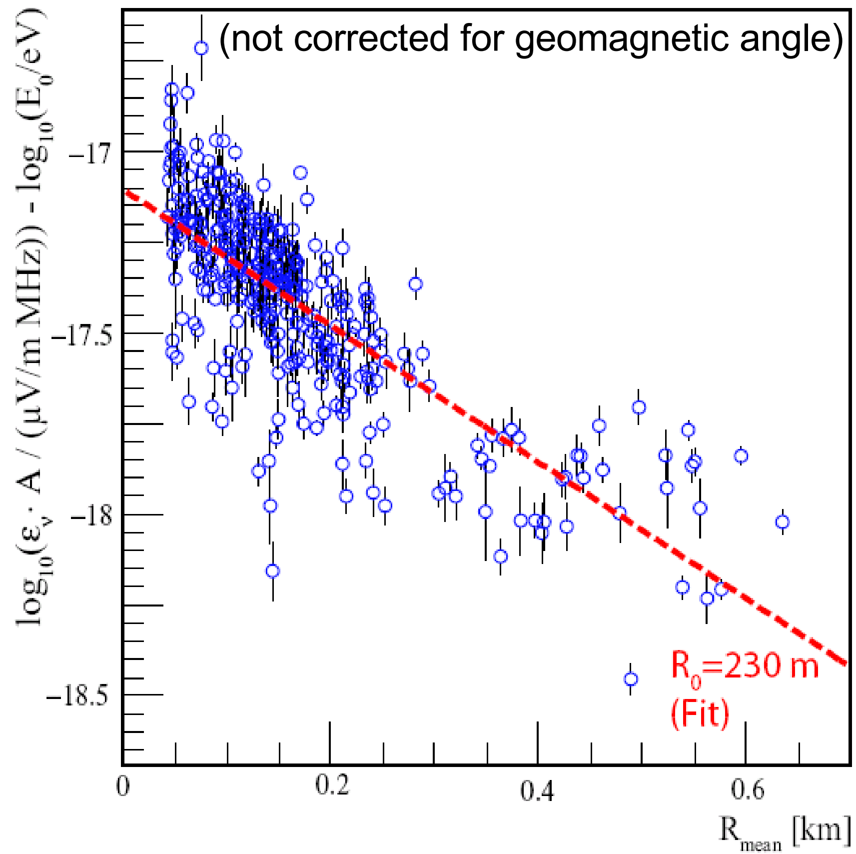






Distant events with KASCADE-Grande





Haungs et al. 2006; Badea et al. 2005; Apel et al. (LOPES coll.), Astropart.Phys. **26** p.332

Inclined Showers
(Θ=50-90°)

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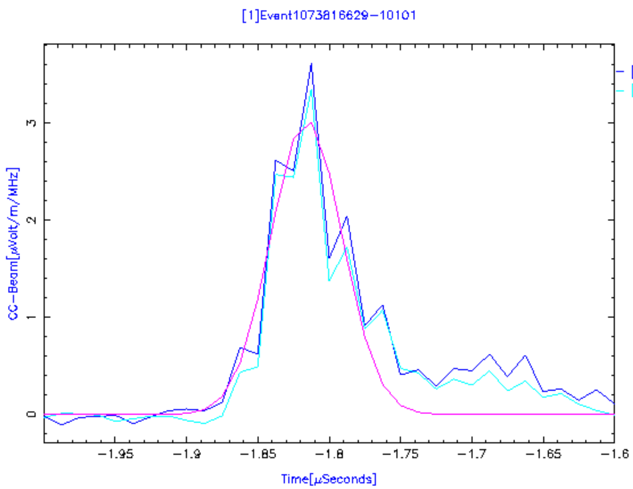

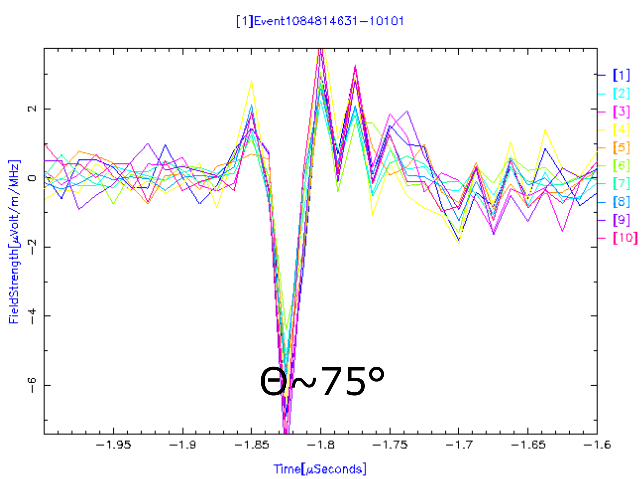

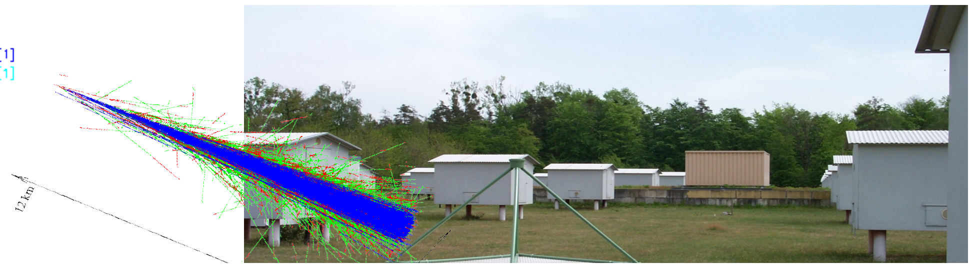

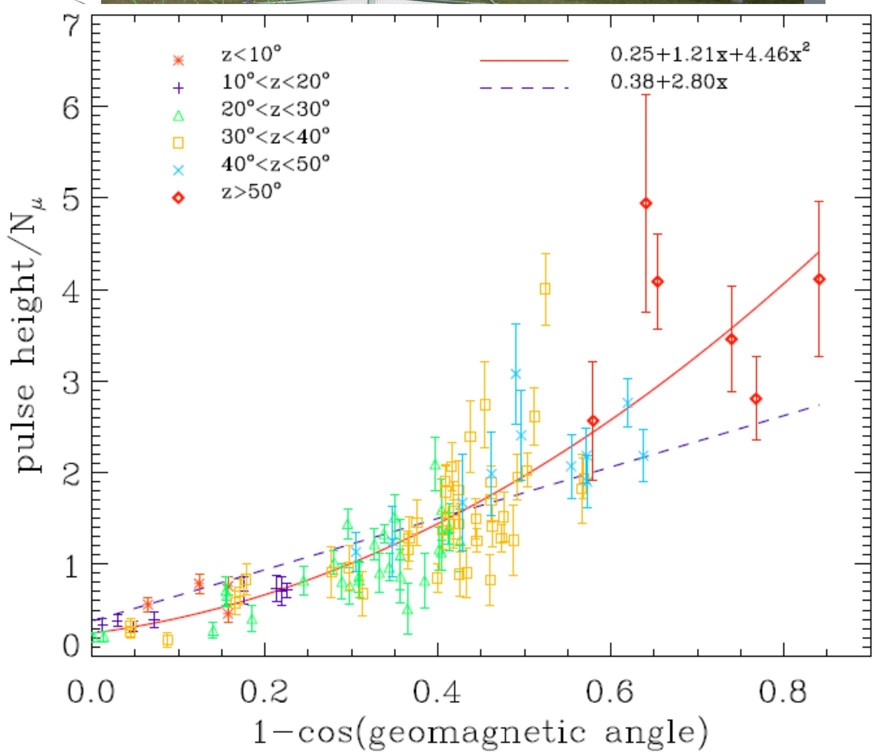

J. Petrovic et al. (LOPES Coll.), A&A 462, p.389