Physics Master's Degree, University of Torino

Radio analysis techniques for EAS measurements with the KIT hybrid engineering array

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KIT
Karlsruher Institut für Technologie


KIT - Campus North


IceCube Group

SUMMARY

- Brief introduction to EAS detection using the **RADIO TECHNIQUE** and overview on the radio extension of IceCube

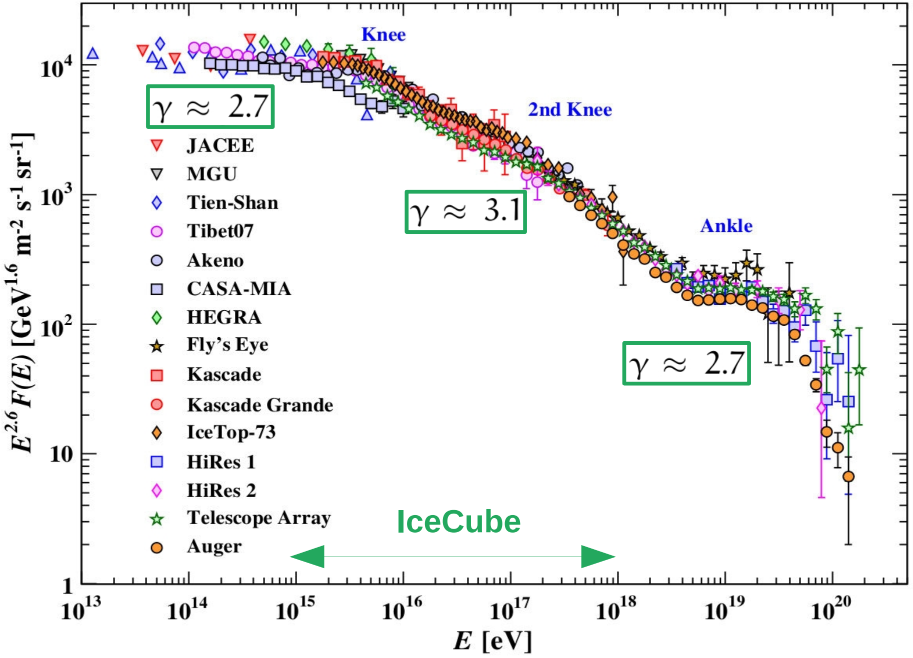
- Characterization of the scintillators of the **KIT hybrid engineering array**

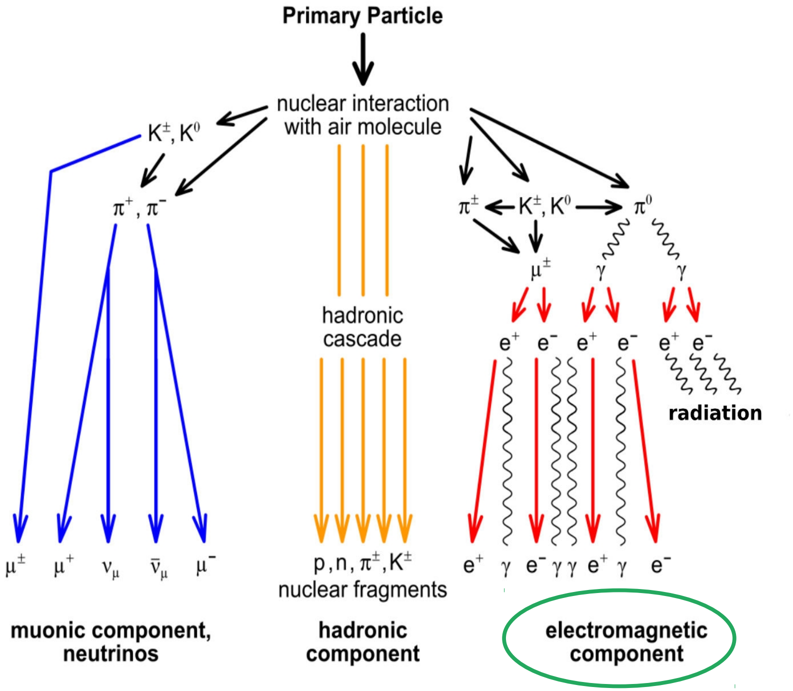
- Radio background and signals analysis

Cosmic Rays and Extensive Air Showers (EAS)

Nuclei originated in astrophysical sources covering about 10 energy orders. The energy spectrum is described by a power-law. Starting from 10^{15} eV the flux is too low for direct measurements and the extensive air showers are detected.

Differential flux od cosmic rays $\frac{dN}{dE} \sim E^{-\gamma}$

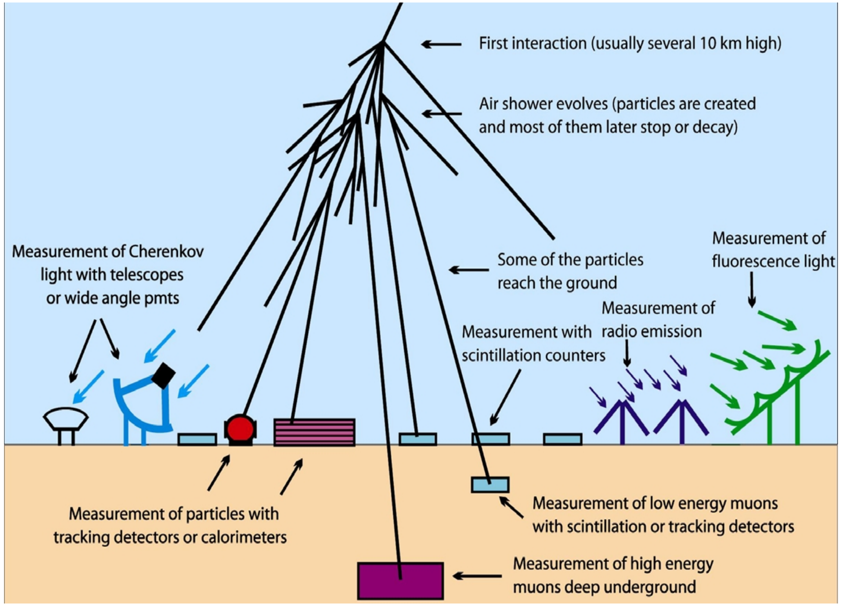




Most of the primary energy belongs to the EM component

EAS Detection

- Several detection techniques are available for EAS observation, such as surface array of particle detectors or telescopes to detect fluorescence and Cherenkov light.
- Analog epoch of **radio detection** in 1960 – 70’s characterized by less accuracy compared to the established techniques
- Revival of the technique in the digital epoch starting from 2000’s thanks to the technology development and the full comprehension of radio simulations.
- Many EAS experiments exploit(ed) radio antennas



LOPES

AERA

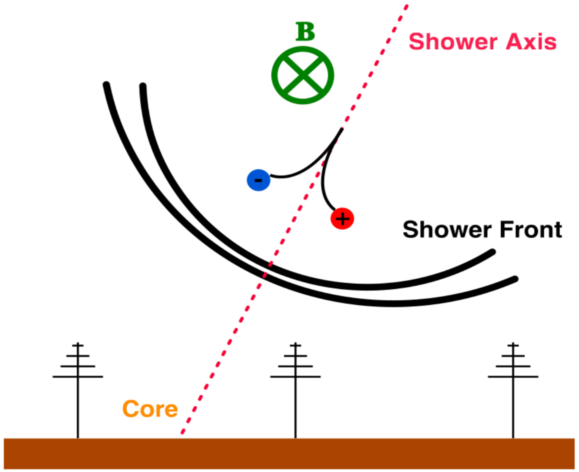
LOFAR

EAS – Radio Emission

Measured signal given by the interference given by two mechanisms:

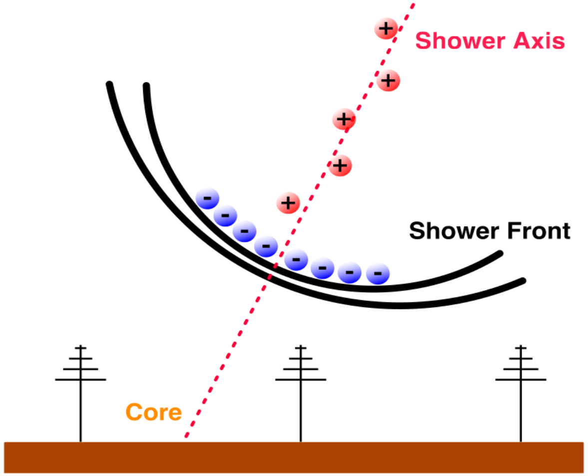
Geomagnetic Effect

- Dominant mechanism
- Deflection of the electrons and positrons by the geomagnetic field B
- Transverse drift current varying in time
- Amplitude proportional to the local value of B and the geomagnetic angle



Askaryan Effect

- Theoretically predicted in 1962 by Askaryan
- Weaker contribution (5-10% of the total)
- Net negative-charge excess
- Ionized positive-charged plasma left behind and current varying in time

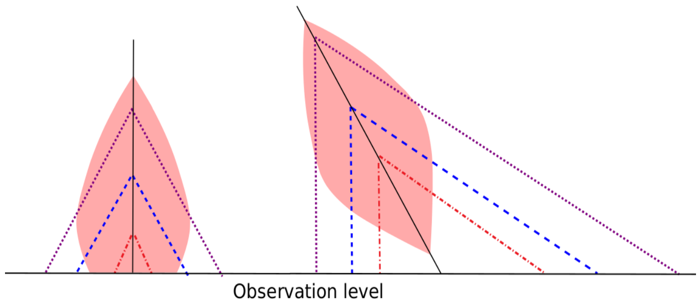


EAS – Radio Detection

The technique is especially effective if **combined with particle detectors**:

PRO

- Increased accuracy on the mass composition and the energy estimation
- Electric field strength of the signal proportional to the number of electrons, hence to the primary energy
  $\longrightarrow$ direct and universal energy indicator
- Atmosphere absorption neglectable
- Highly **inclined showers** detection
- High duty cycle compared to other radiation techniques

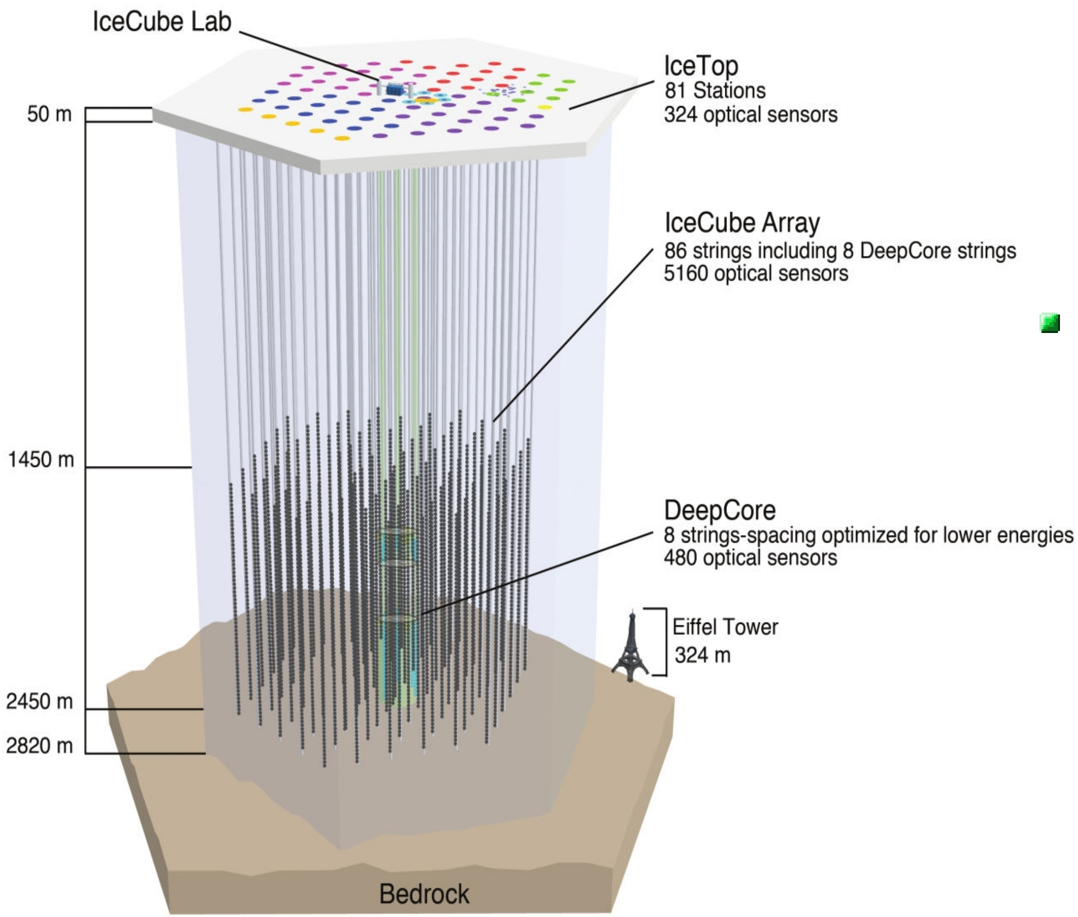


Footprint of vertical and inclined showers

CONS

- Duty-cycle limited by thunderstorms
- **Human-made noise** strongly affects the measurements (radio-quiet sites are needed)
- The **energy threshold** is about 10^{17} eV

The IceCube Neutrino Observatory



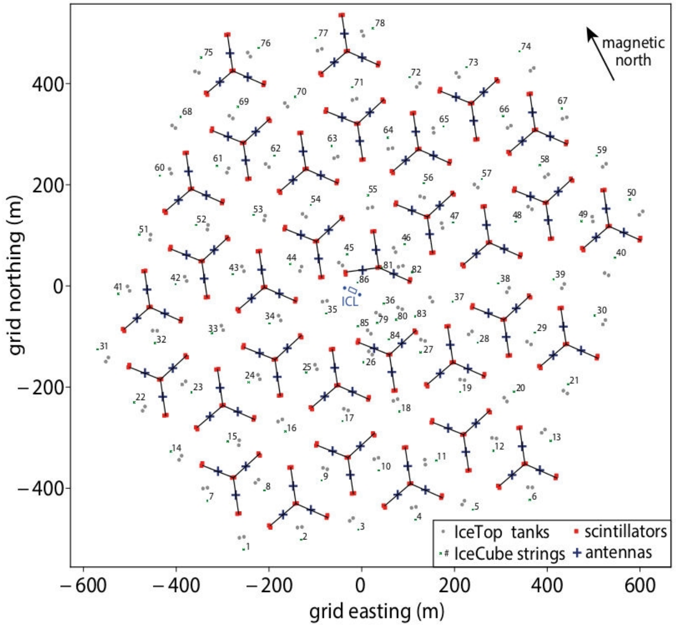
- **In-ice detector** made of PMTs to measure Cherenkov light for the detection of astrophysical neutrinos

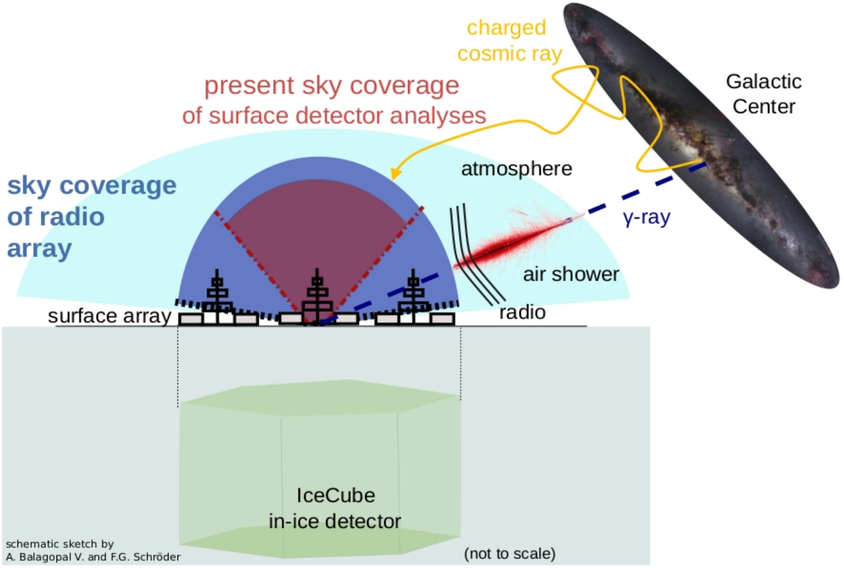
- **Surface array (IceTop)** made of 81 stations of ice-Cherenkov tank-pairs in order to:
  - *Veto for the in-ice detector*
  - *Calibrate*
  - *Air-showers measurements*

IceCube – The IceTop Enhancement

Additional 32 stations deployment foreseen in 2021-2022.
Each station equipped with:

- Four pairs of scintillators
- Three **radio antennas**





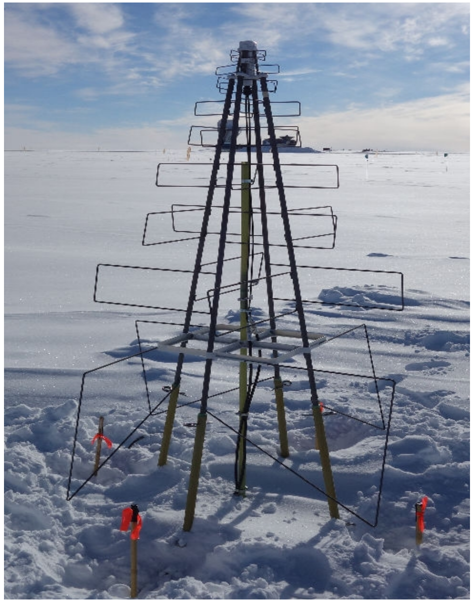
BENEFITS OF INCLUDING ANTENNAS

- Improve the general accuracy of IceTop and the calibration and veto capabilities
- Increase the **sky coverage** to detect more inclined showers and gamma-rays coming from the Galactic Center (61°)

IceTop Enhancement – Prototype Antenna SKALA

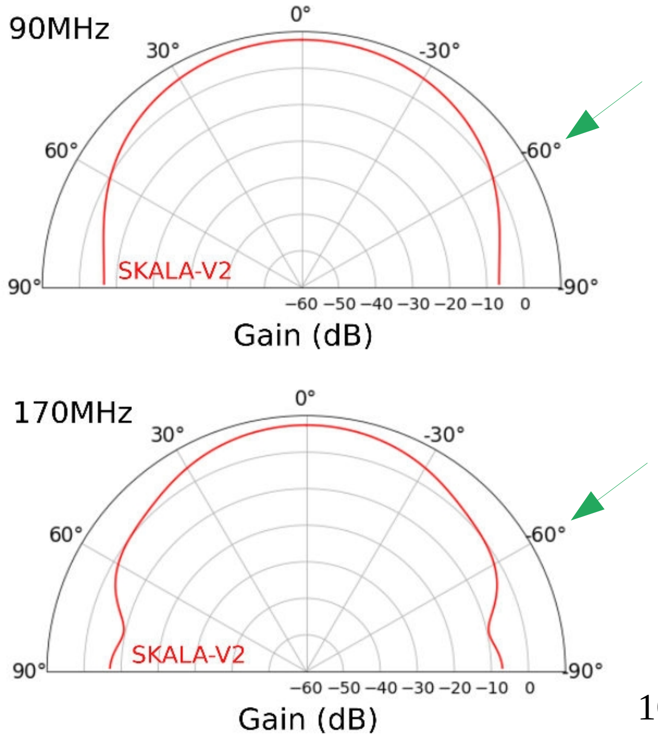
The prototype version of the so-called **SKALA** antenna was tested with the **KIT hybrid engineering array** and successfully deployed at South Pole in 2019 to perform further tests.

KIT hybrid engineering array

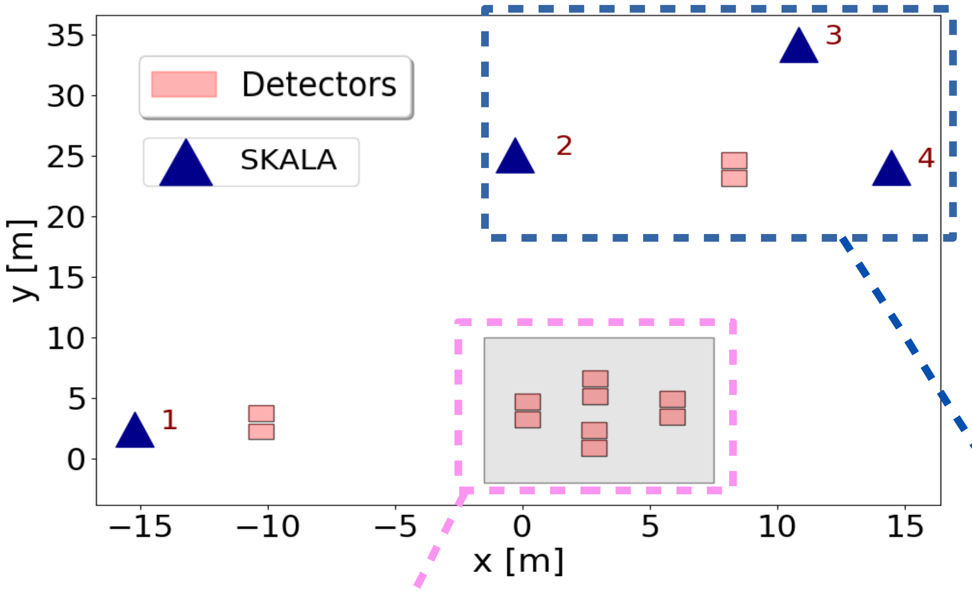


Deployment at South Pole

Directive patterns

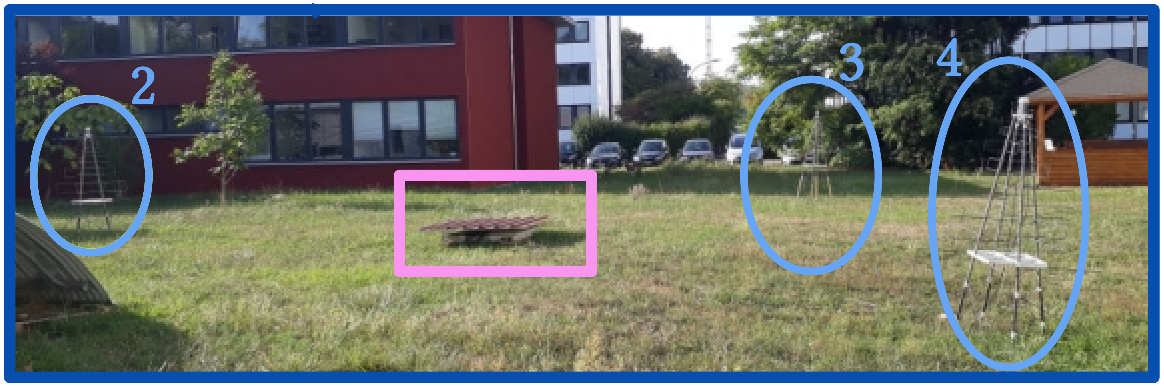


KIT Hybrid Engineering Array



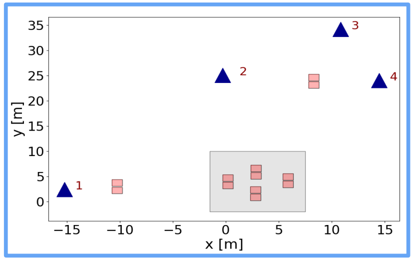
The array is composed by:

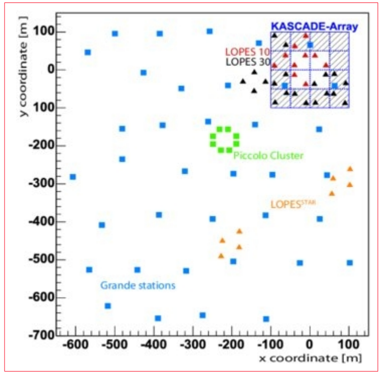
- 4 SKALA antennas
- 6 pairs of Mini-KASCADE scintillation detectors, 4 of which located inside an array building hosting the DAQ

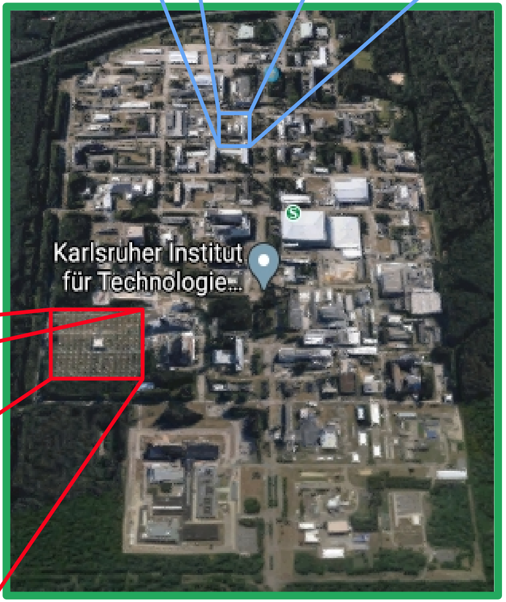


KIT Hybrid Engineering Array vs LOPES/KASCADE-Grande

KIT hybrid engineering array







KASCADE-Grande & LOPES

- **KASCADE-Grande** starting from 2000's was extended with **LOPES**.
- The experiments successfully verified the feasibility of the radio technique, publishing several relevant papers.

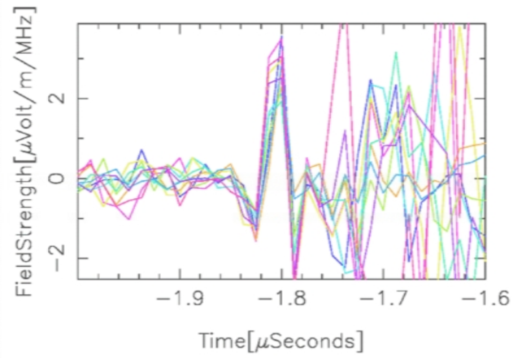


Figure from *H.Falcke, et al. (LOPES Collaboration), Nature 435 (2005) 313*

- Compared to the hybrid engineering array (built for test purposes):
  - Larger and more quiet area
  - Larger number of antennas (10-30)
  - Antennas co-located with 37 scintillators stations used for the trigger

KIT Hybrid Engineering Array vs LOPES/KASCADE-Grande

KIT hybrid engineering array

Geometric area: $28 \cdot 32\,\text{m}^2 \sim 1000\,\text{m}^2$

DATA	Trigger	Events
Radio	Mini-K	5935

12 days of acquisition

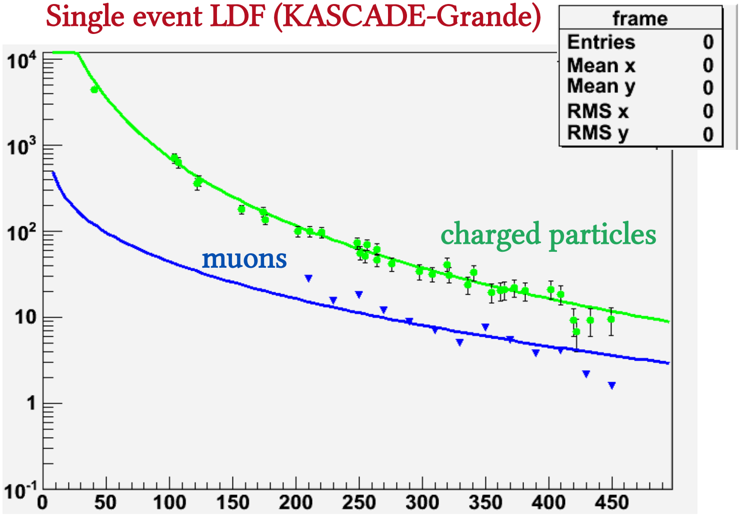
Expect number of events above the knee $\frac{1\,\text{particle}}{\text{yr m}^2} \rightarrow \frac{12\,\text{d} \cdot 1000\,\text{m}^2}{365\,\text{d}} \sim 33$

Above 10^{16} eV *geometric area* $\rightarrow \sim 3.3$

Above 10^{17} eV (*LOPES threshold*) *sensitive area:* $0.1\,\text{km}^2 \rightarrow \sim 3.3$; $1\,\text{km}^2 \rightarrow \sim 33$

Low statistics BUT: detection of showers with core outside the geometric area having larger footprint (see LDF)

Single event LDF (KASCADE-Grande)



KASCADE-Grande

Geometric area: $\sim 0.5\,\text{km}^2$

(*Trigger above 10^{16} eV*)

Mini-KASCADE Detectors Characterization

The antennas of the hybrid engineering array are **triggered** by the Mini-KASCADE detectors (*full-coincidence*) $\longrightarrow$ combined analysis makes easier the unfolding of the useful information from radio signals $\longrightarrow$ *energy and arrival direction from scintillators*

Characterization of the scintillators before performing the radio analysis in order to study the **detectors performance**.

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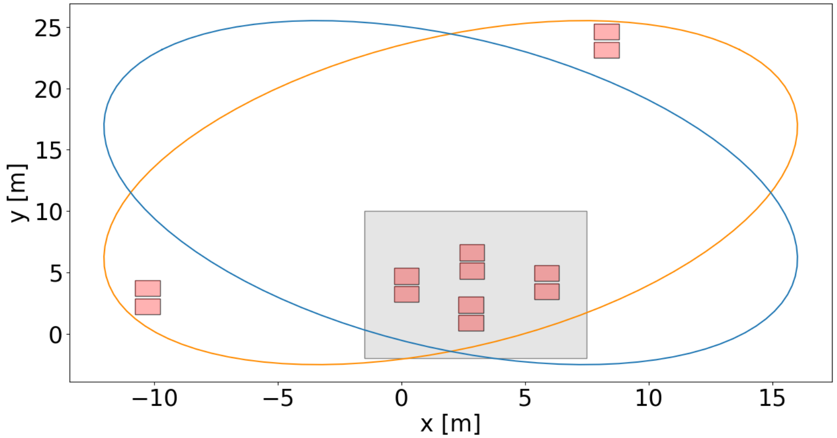
DATA SET

Acquisition Time	Trigger	Events
$\sim$ 1167 hours	12/12	29049

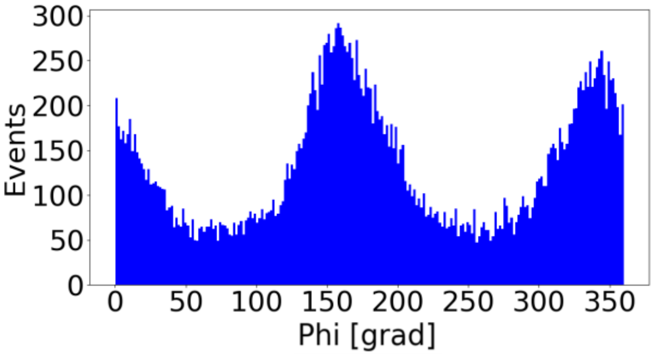
Example of full coincidence for inclined shower



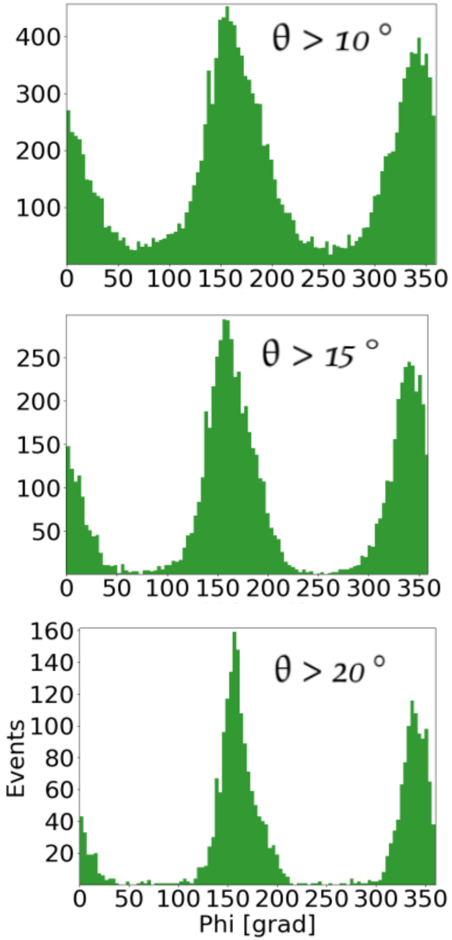
The cosmic-rays flux is strongly isotropic, but an **anisotropy** of the reconstructed arrival directions from the TOFs of the measured particles is expected due to the asymmetrical layout of the array and the Mini-KASCADE software

Mini-KASCADE Detectors Characterization - Angles Distribution

Lack of events for **azimuth** angles in the ranges 30-130° and 200-320°

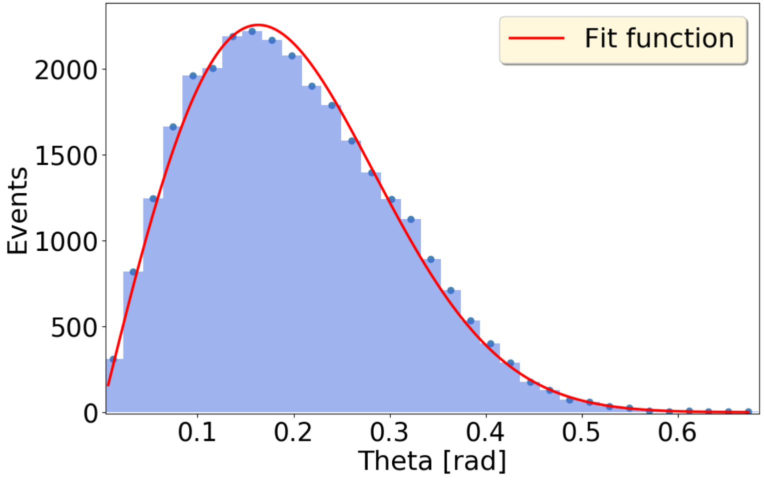


Changing threshold



Stronger anisotropy for increasing zenith angle threshold (selection of highly inclined showers)

Peak **zenith** angle distribution: θ ≈ 10°



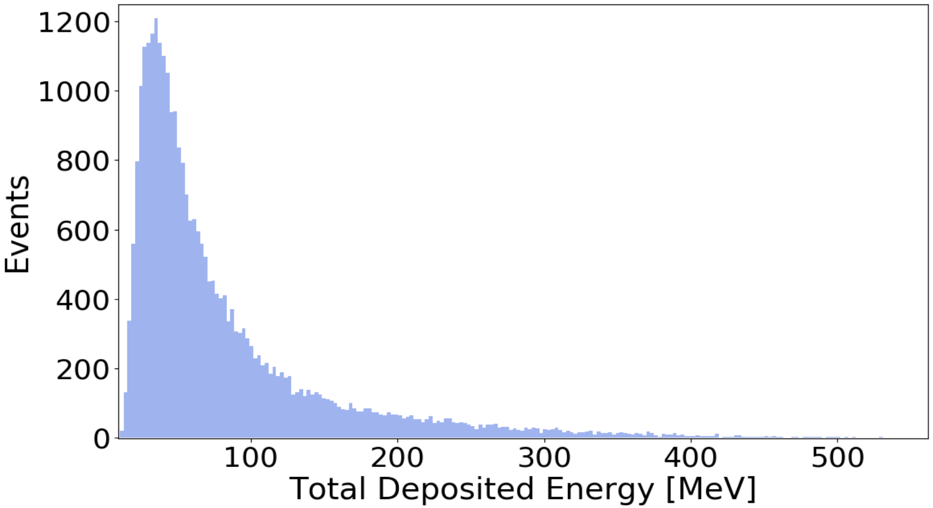
$$g(\theta) = \alpha(\theta)e^{-\beta(\theta)}$$

$$\alpha(\theta) = p_0 \cos(\theta)\sin(\theta)$$

$$\beta(\theta) = p_1/\cos(\theta)$$

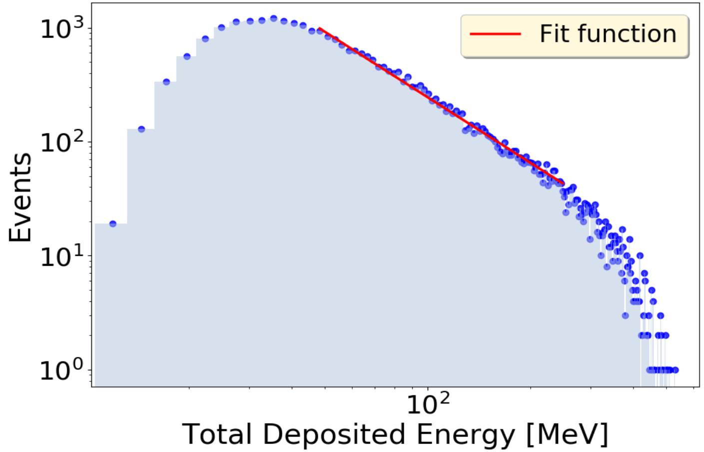
Mini-KASCADE Detectors Characterization – Deposited Energy

Max Energy	Energy Peak
~ 531 MeV	~ 35 MeV



Note that on the x-axis there is the total energy deposited in the scintillators.
To reconstruct the primary energy one would need simulation tools.

Fit function $f(E) = AE^{-\gamma}$



Interpolation hypothesis accepted with a significance of 5%

$$\gamma_{\mathrm{int}} = 1.91 \pm 0.02$$

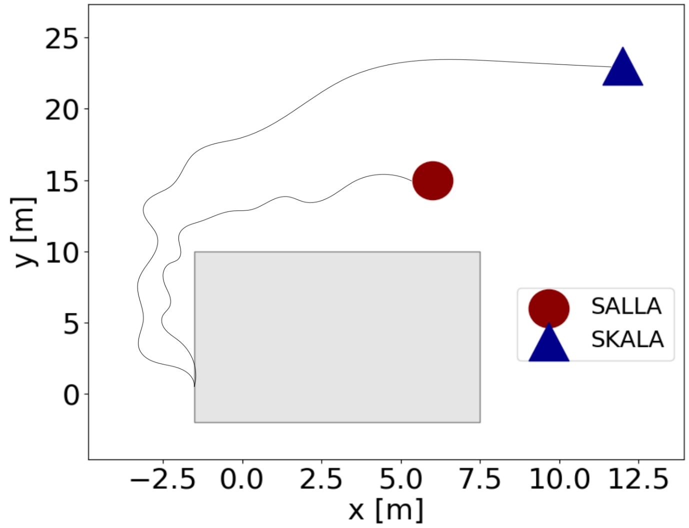
$$\rightarrow \gamma_{\mathrm{diff}} = 2.91$$

Radio Background Measurements – SALLA Deployment

Several measurement periods over different months analyzed (SKALA antennas).

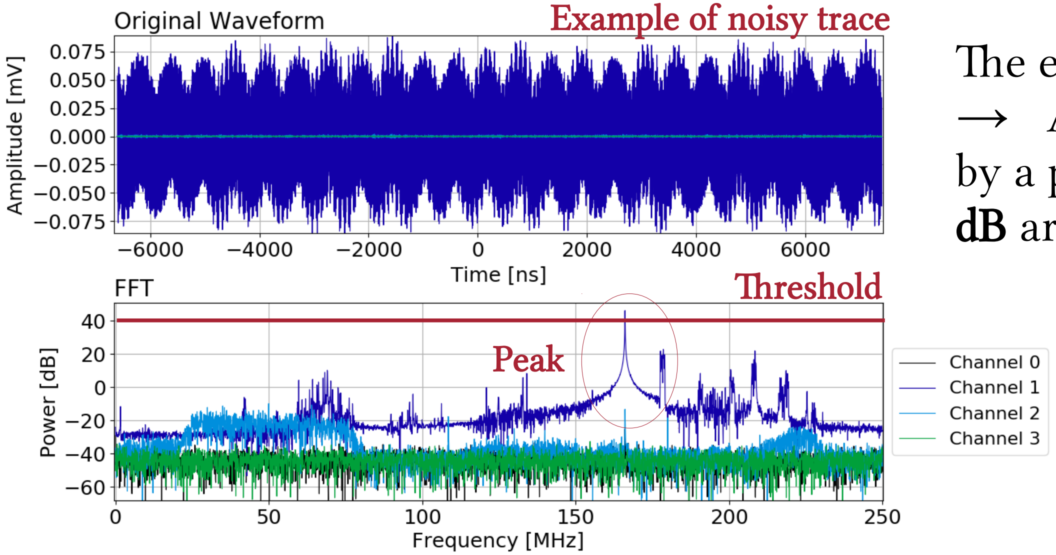
Deployment of a SALLA antenna in order to perform further background measurements to achieve better sensitivity on low frequencies (30-70 MHz).

Background measurements setup with SALLA



Radio Background – Sources

- The ***human-made noise*** can be broad or narrow-band (RFI easier to suppress) and depending on the location can be dominant or not.
- The strenght of the ***Galactic noise*** depends on the Earth location and decreases with increasing frequencies.
- At higher frequencies, the noise produced by the ***antenna electronics*** becomes the dominant component of background.



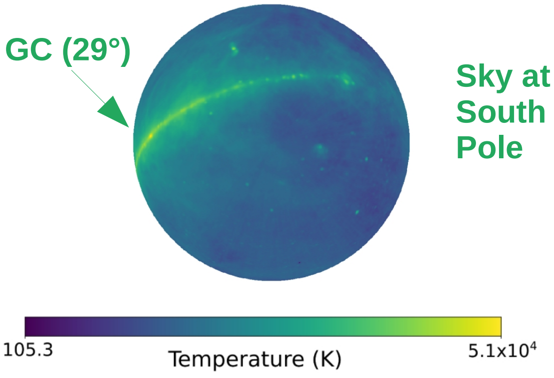
The electronics used can produce internal noise $\longrightarrow$ All the events having traces characterized by a power peak with amplitude higher than **40 dB** are excluded from the analysis.

$$P[k] = 20 \cdot \log_{10}(|F[k]|)$$

F[k] is the fast Fourier Transform of the recorded waveform

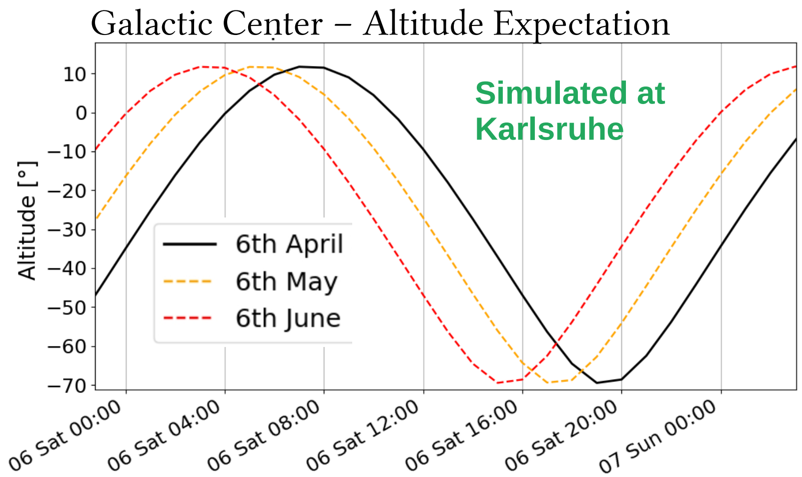
Radio Background – Galactic Noise

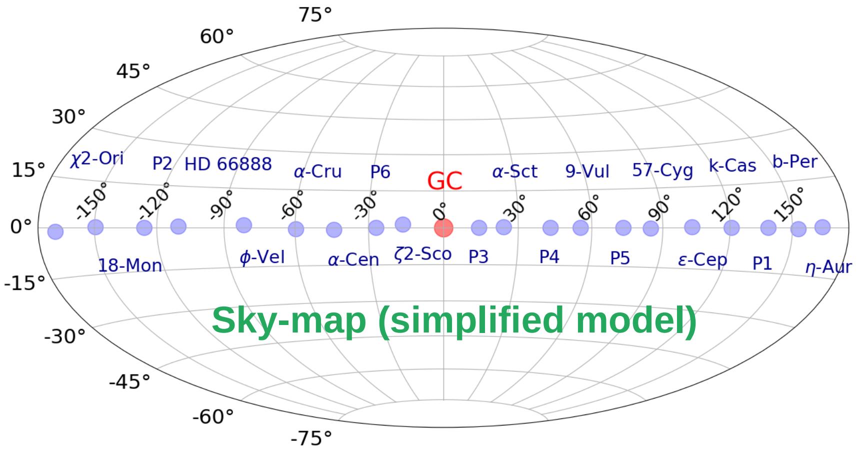
- **Galactic noise** is made of thermal radio emissions from sources in our Galaxy. The brightest source is the **Galactic Center** (GC).
- At South Pole the GC is always above the horizon and, because of its relative motion, a **sinusoidal** variation in time of the measured signal amplitude is expected.
- Due to the rotation period of the Earth, a **shift** in time of the curve is predicted (about 2 hours per month).



At Karlsruhe, the GC stays below the horizon many hours per day

→ other Galactic objects contribution needs to be taken into account

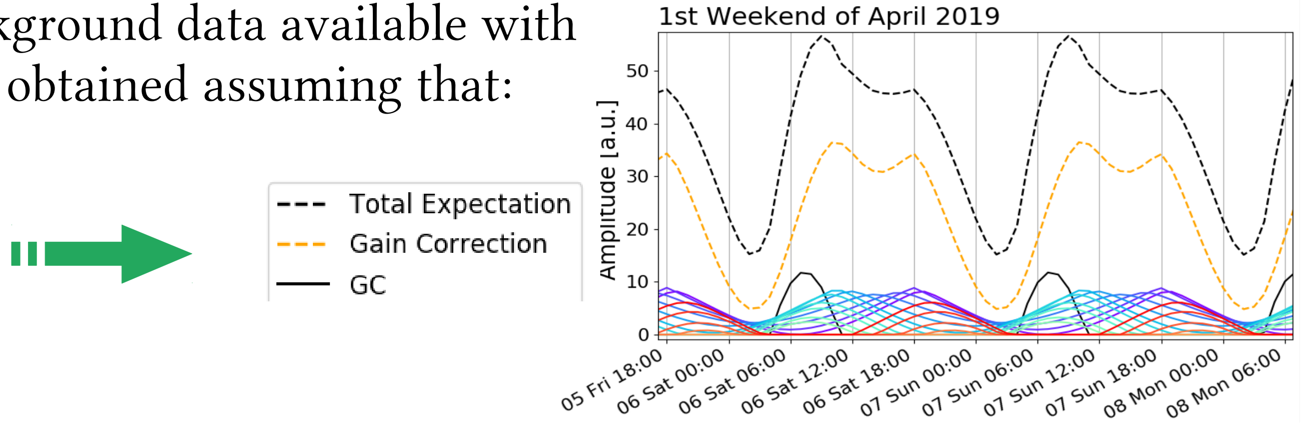




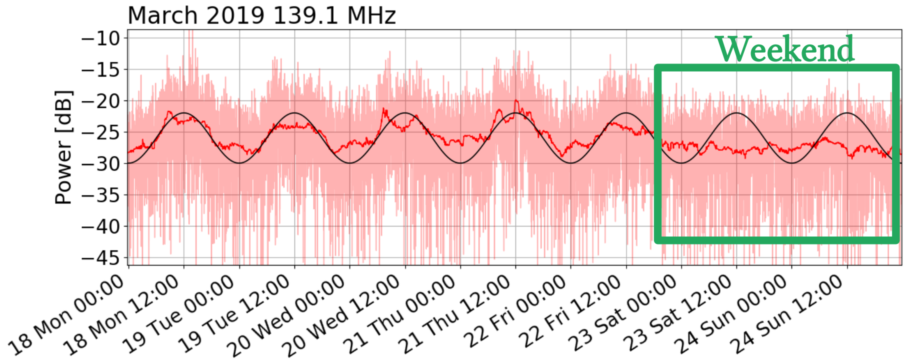
Radio Background – Analysis

The goal is to compare the background data available with the **Galactic noise expectation**, obtained assuming that:

- The temperature of the sky-map objects is 10 times smaller of the GC one
- The gain is is linearly decreasing with the altitude



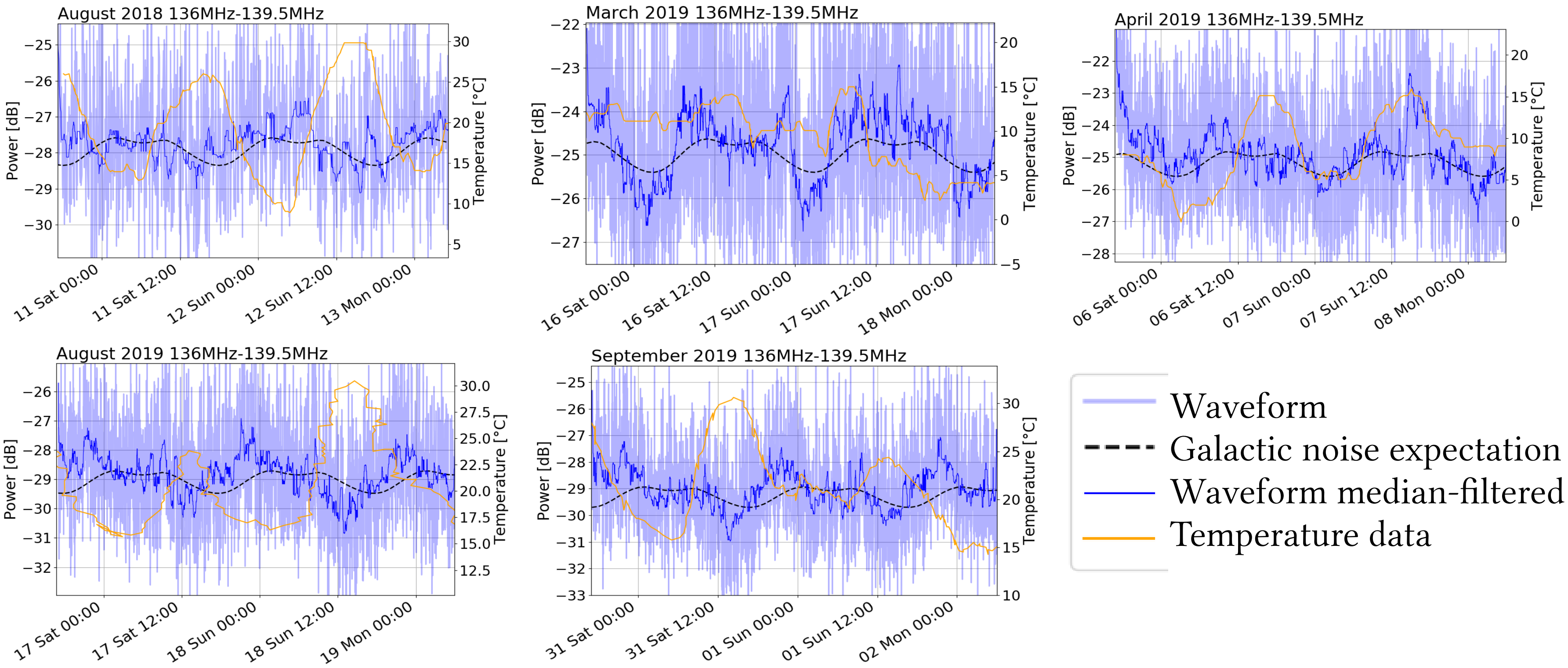
To reduce the human-made component only the **weekends** data are analyzed. Furthermore, small frequencies bandwidth excluding the **RFI peaks** are considered



The data are also compared to the **temperature** in Karlsruhe to check any correlation with: the thermal noise of the antenna, the cables and the electronics; the thermal radiation of the surrounding environment; the LNA temperature dependency.

Radio Background – Results

SKALA: freq. Bandwidth 136-139.5 MHz over the weekends of several measurement periods



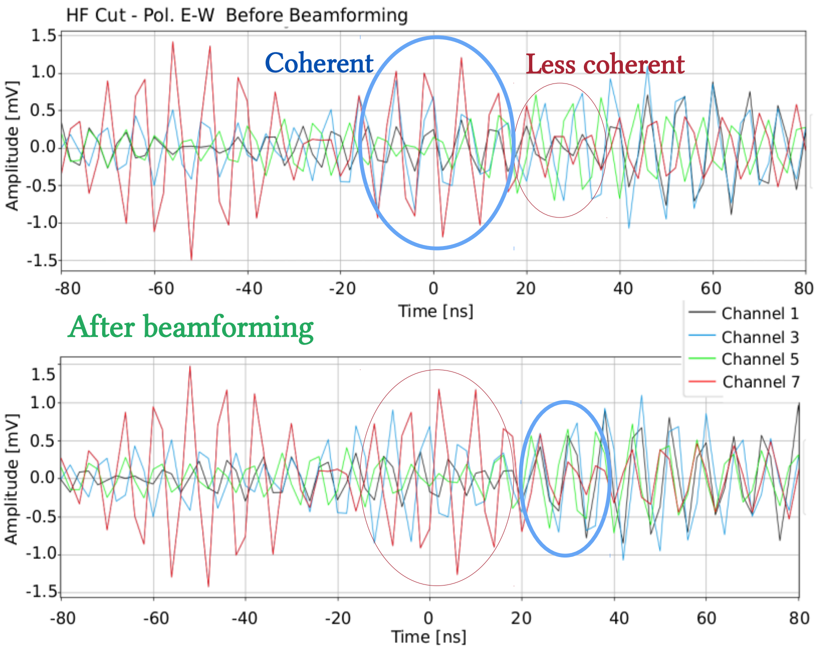
The results point toward a correlation with the Galactic noise in the bandwidths
<u>122.4-124.7 MHz, 125.3-130.8 MHz and 136-139.5</u> measured by SKALAs.
No evidence of correlation with the temperature neither for SKALA nor SALLA measurements.

Radio Signal Processing – Beamforming

Processing of radio signals:

- Hann window function to reduce the alisiang phenomenon
- **Beamforming** in the arrival direction reconstructed from the scintillators data assuming the radio wavefront to be spherical

Introduction of a geometrical time delay referring to a fixed antenna to align the signals: r_i / c



Tansformation matrix

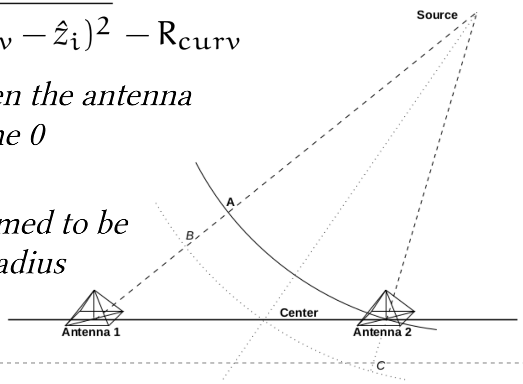
$$\begin{pmatrix} \hat{x}_i \\ \hat{y}_i \\ \hat{z}_i \end{pmatrix} = \begin{pmatrix} -\sin\phi & \cos\phi & 0 \\ \sin\theta\cos\phi & \sin\theta\sin\phi & -\cos\theta \\ \cos\theta\cos\phi & \cos\theta\sin\phi & \sin\theta \end{pmatrix} \cdot \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}$$

Antennas coordinates in the shower system

$$r_i = \sqrt{\hat{x}_i^2 + \hat{y}_i^2 + (R_{curv} - \hat{z}_i)^2} - R_{curv}$$

Relative distance between the antenna and the wavefront at time 0

Wavefront assumed to be spherical with radius of 2250 m



Radio Signal Processing – Digital Filters

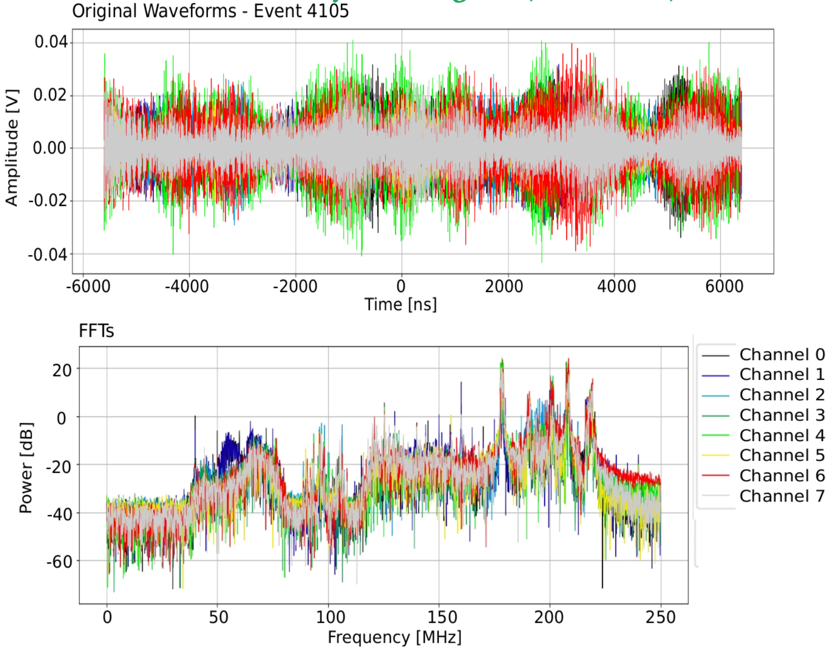
Off-line **digital filtering** in order to:
- study HF and LF separately
- smooth the signal
- reduce RFI pollution

4 types of filters tested on the candidate event 4105

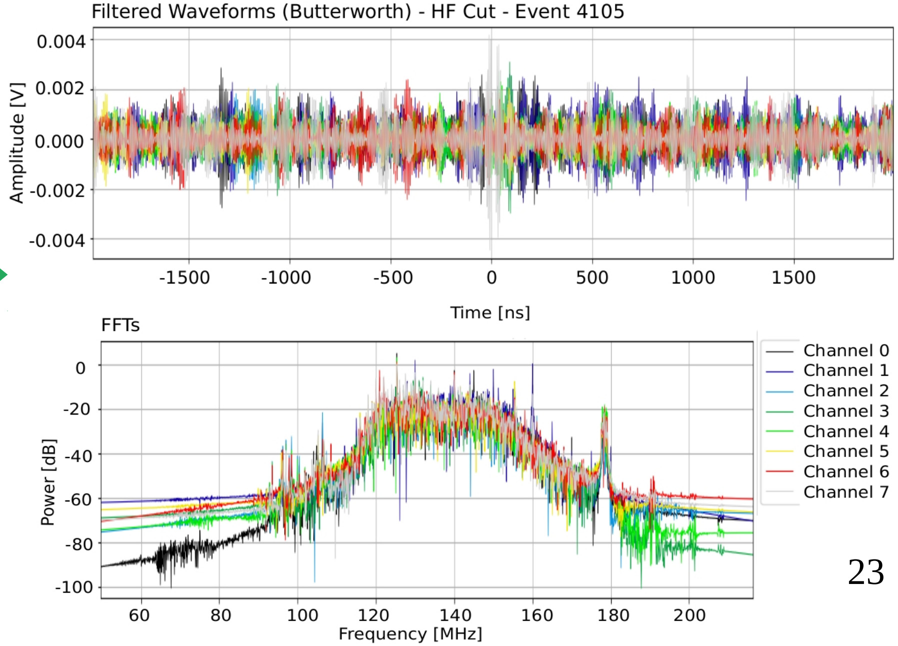
BUTTERWORTH-based

Filter Cut	LP Threshold [MHz]	HP Threshold [MHz]
HF	150	120
LF	70	40

Candidate cosmic-ray radio-signal (event 4105)



HF filter cut

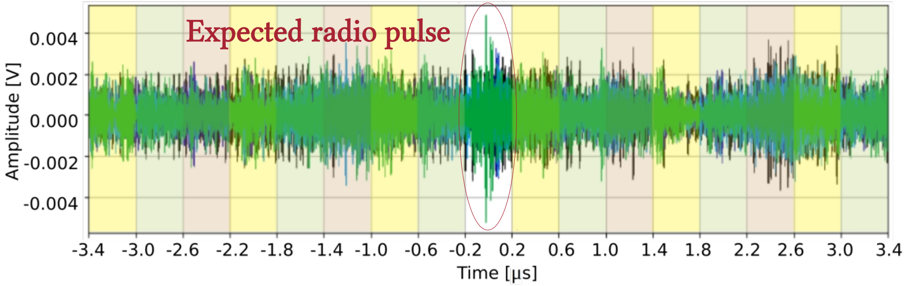


Radio Signals Analysis: Time Range

The goal is the analysis of the radio signals on a large scale *without using radio simulations,* searching for candidate cosmic-ray events of high energy.

- Set a **high-energy threshold** from the scintillators data
- Divide the trace in time-range bins of 400 ns
- Selection of the signals setting ***RADIO CONSTRAINS*** in each bin
- Expected cosmic-ray signal centered in 0 μs
  $\longrightarrow$ expected peak of the histogram centered in [-200,+200] ns bin

Example of division in time-range bins of 400 ns

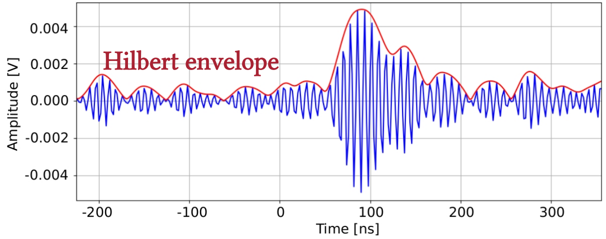


Radio Signals Analysis - Results

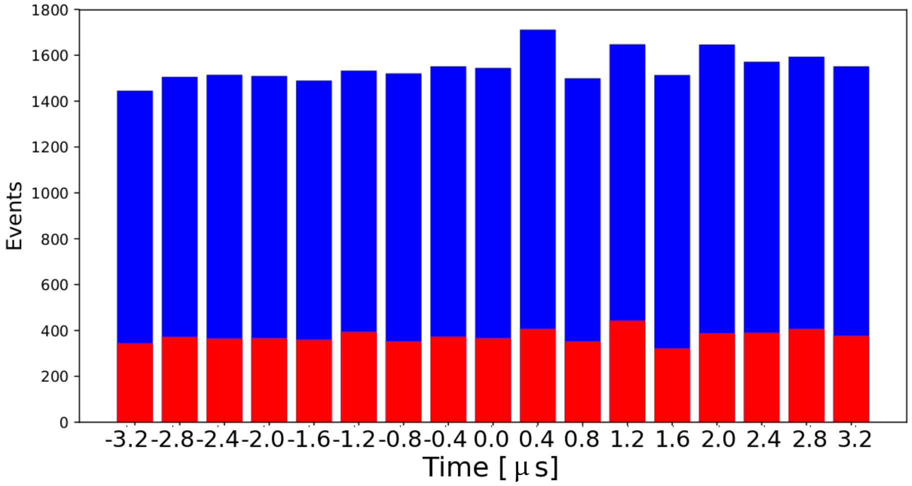
Analysis repeated studying **HF and LF** and the **East-West and North-South** polarizations of the antenna separately with changing energy threshold and constrain on the signals.

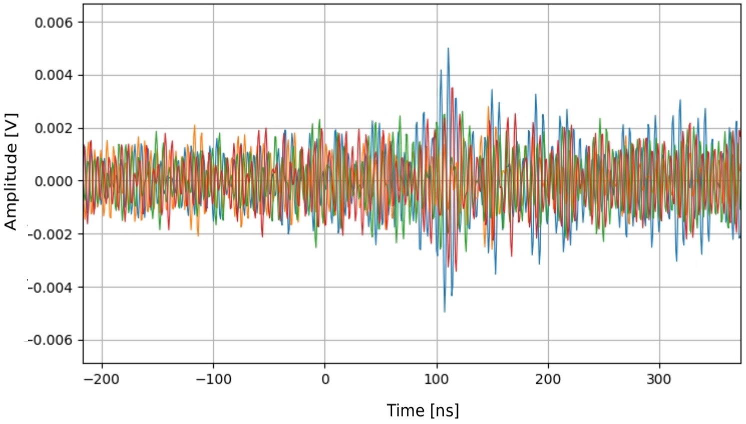
RADIO CONSTRAIN
There is at least a local maximum in the time bin considered for one of the four traces

Local maximum: peak above the Hilbert-envelope mean value in the bin plus 3σ



All the events High-energy events: 25%





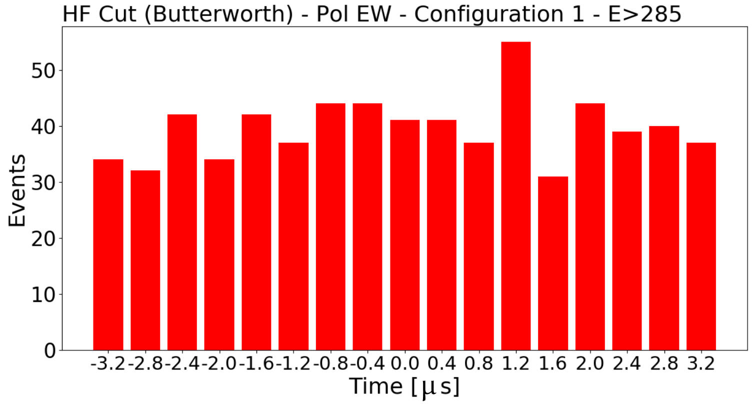
Several candidate events found

Radio Signals Analysis - Results

Analysis repeated studying **HF and LF** and the **East-West and North-South** polarizations of the antenna separately with changing energy threshold and constrain on the signals.

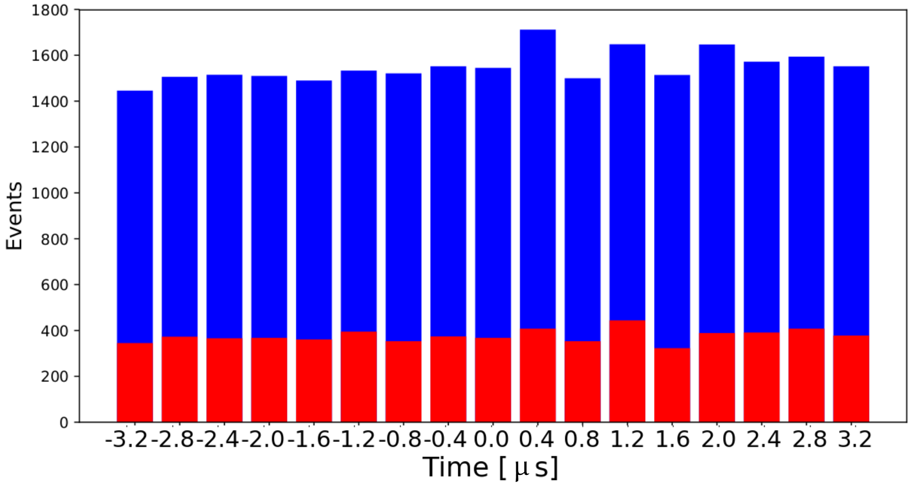
RADIO CONSTRAIN
There is at least a local maximum in the time bin considered for one of the four traces

High-energy events: 2.5%

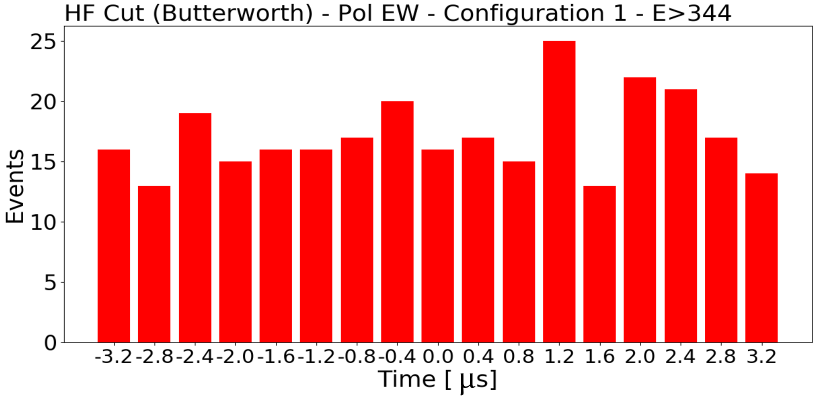


All the events

High-energy events: 25%



High-energy events: 1%

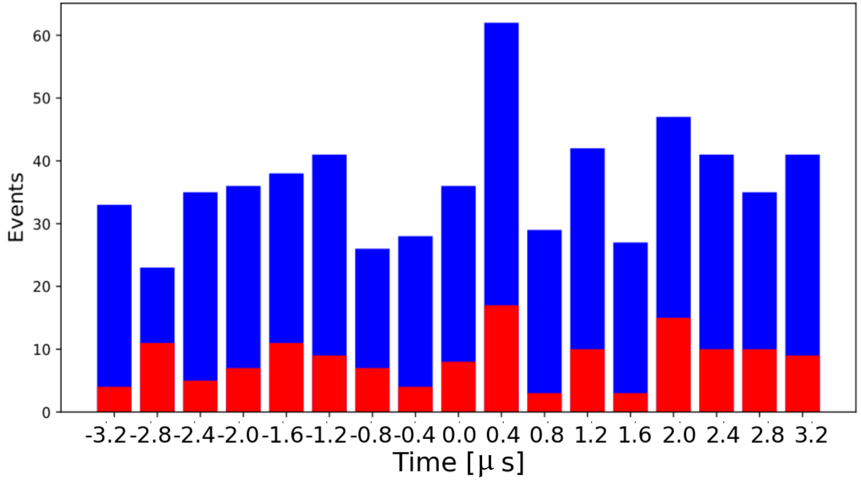


Radio Signals Analysis - Results

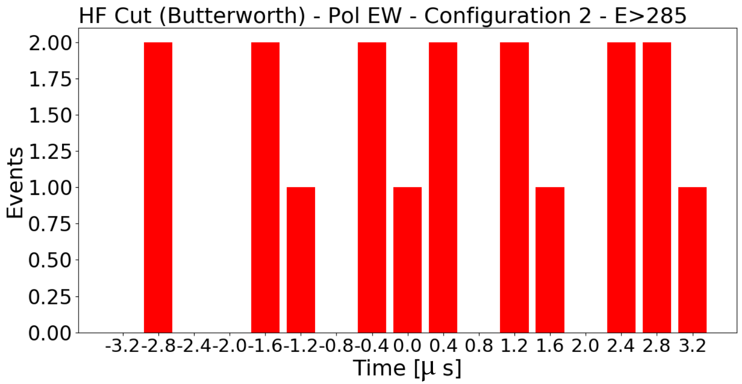
Analysis repeated studying **HF and LF** and the **East-West and North-South** polarizations of the antenna separately with changing energy threshold.

> *RADIO CONSTRAIN*
> All the four traces have a **local maximum** in the time bin considered

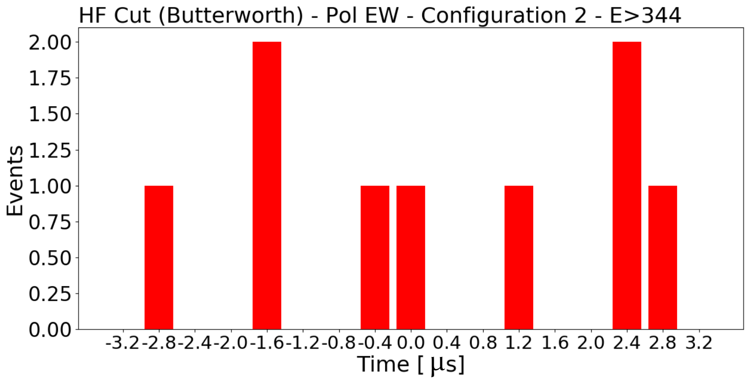
All the events   High-energy events: 25%



High-energy events: 2.5%



High-energy events: 1%



Outlooks and Conclusions

Radio Background Analysis

- Verified functionality of the experimental setup
- No evidence of correlation with the electronics thermal noise (temperature data from weather station and weather forecast website)
- Additional investigations needed (due to the approximations adopted)
  - $\longrightarrow$ For further analysis and measurements, temperature sensors on top of the antenna are suggested

Radio Signals Analysis

- Several candidate cosmic-rays events found, but not conclusive evidence
- Too low statistics (high deposited energy of low energy showers with core inside the geometrical area)
  - $\longrightarrow$ Repeat the analysis with a higher acquisition time
  - $\longrightarrow$ Make the array layout symmetrical
  - $\longrightarrow$ Additional GPS sensor to measure the antennas positions
  - $\longrightarrow$ (Comparison with radio simulations)

Accuracy of the beamforming process

Thank you for your attention!

Vielen Dank!