Forschungszentrum Karlsruhe
in der Helmholtzgemeinschaft

EAS Radio Detection with LOPES

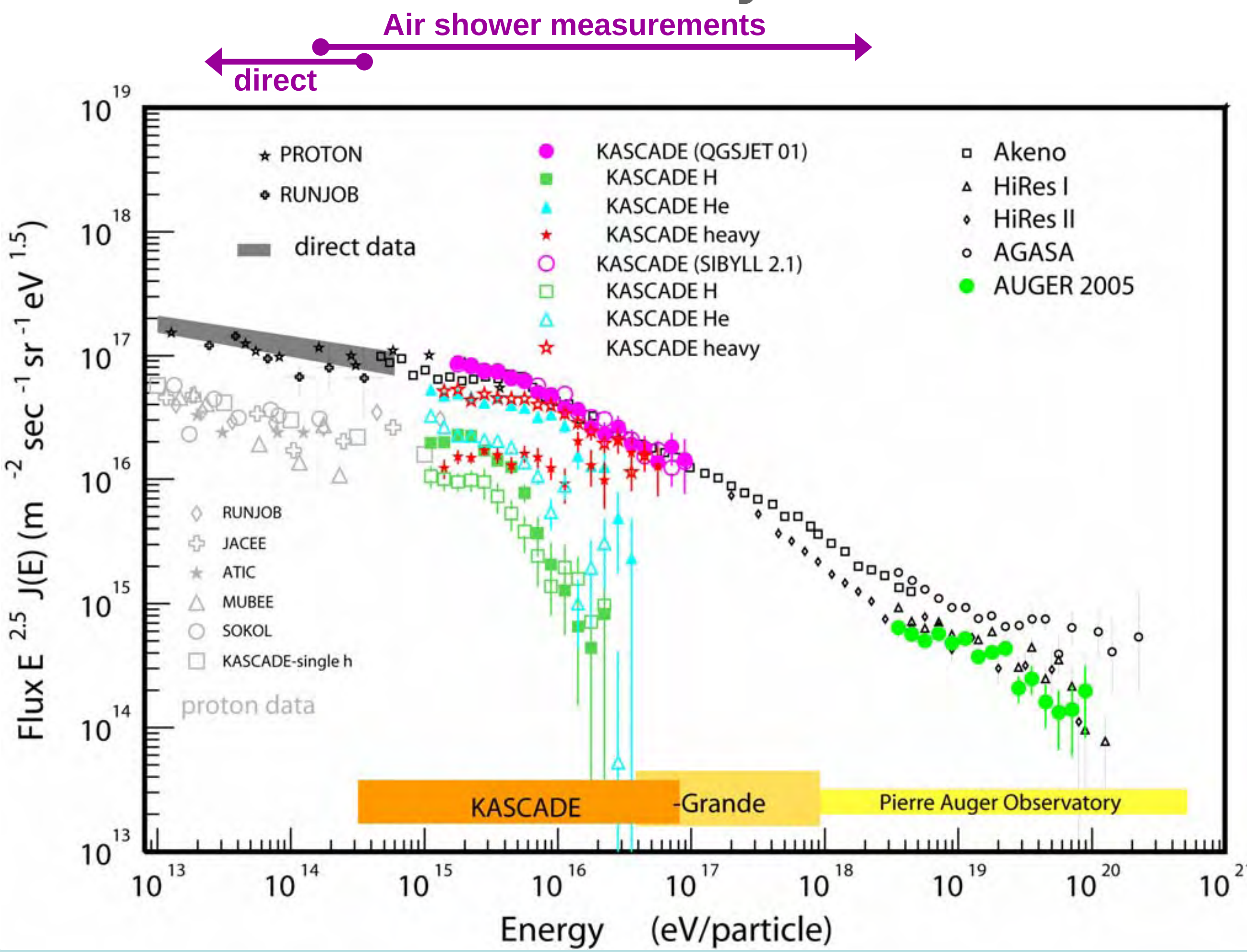
Frontier Objects in Astrophysics and Particle Physics

Isola Vulcano May 2006

Andreas Haungs

haungs@ik.fzk.de

Cosmic Rays



- The cosmic ray energy spectrum is not fully understood
- Above 10^{14}eV primary energy: only air-shower measurements possible

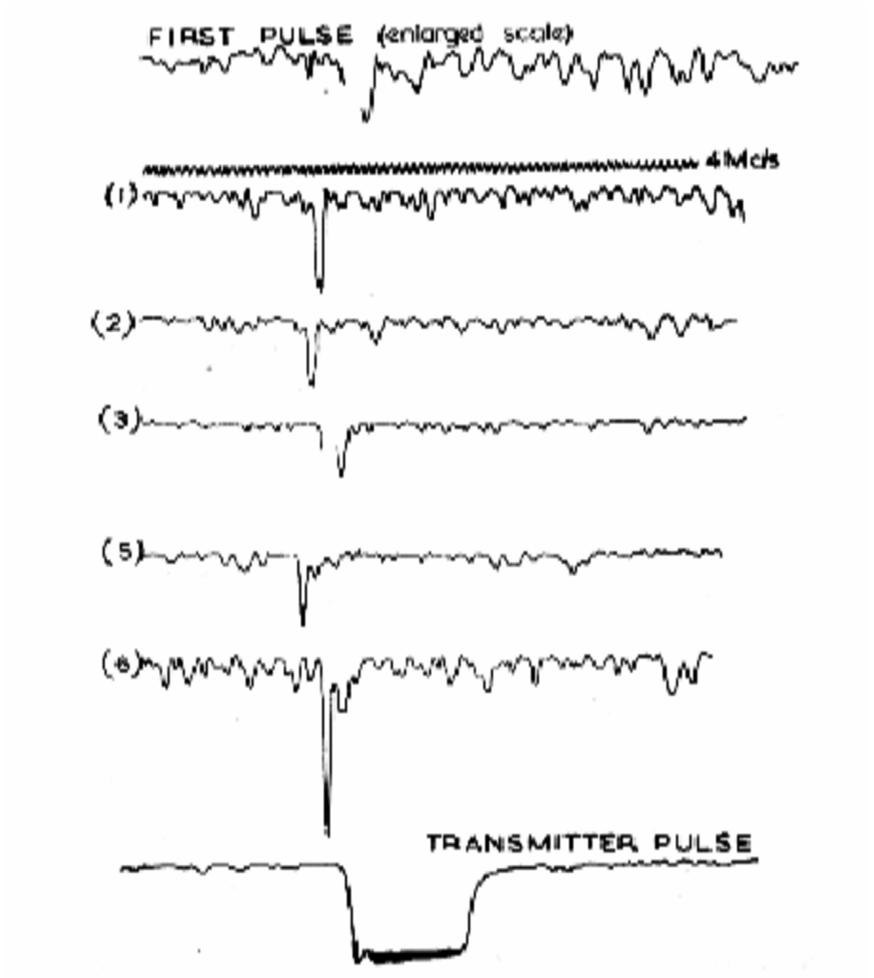
➔ More and better experiments needed: new detection techniques ?

History of Cosmic Ray Radio Detection

- **radio pulses from Extensive Air Showers predicted by Askaryan (1962)**

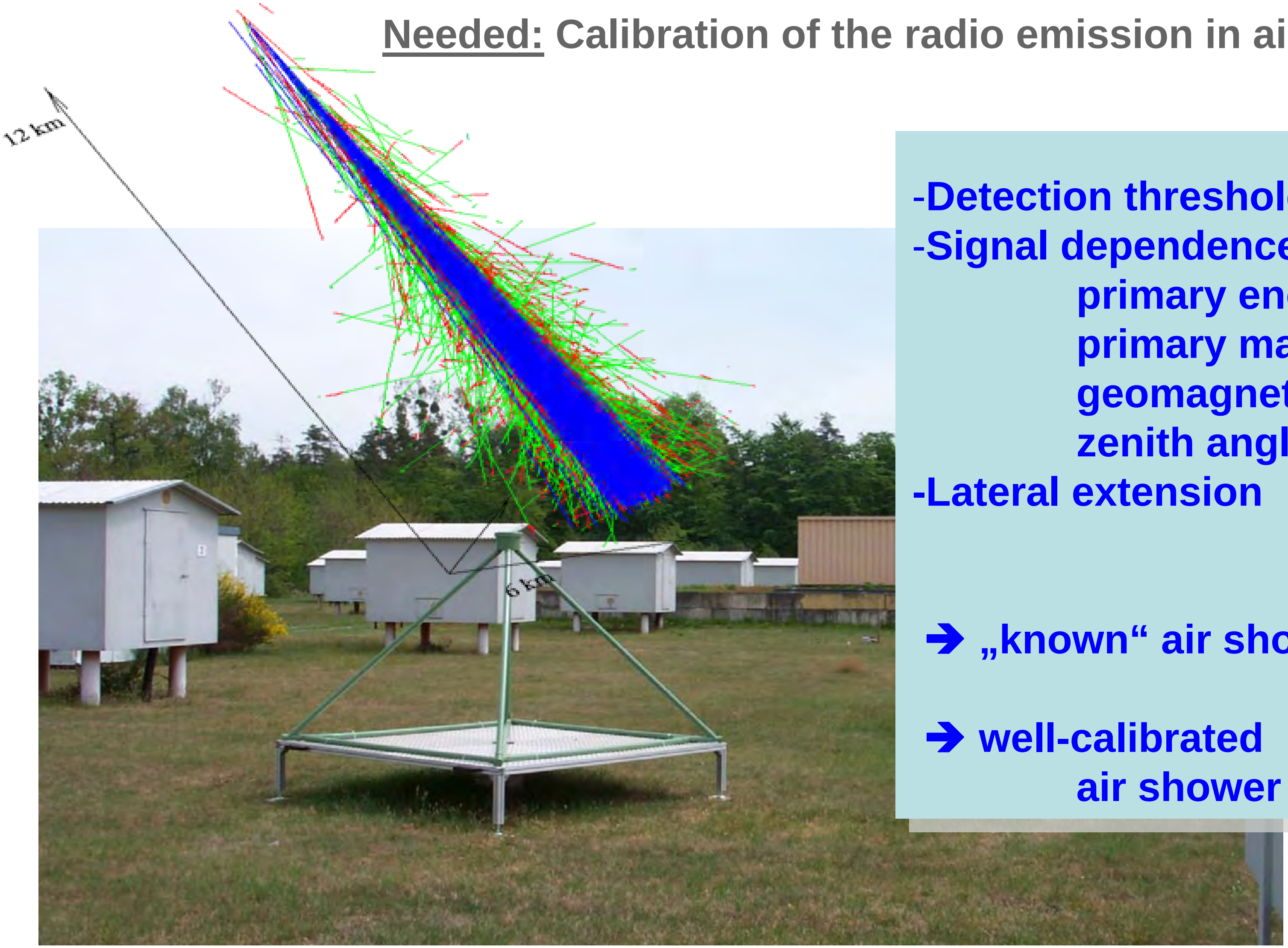
- **first detected by Jelley et al. (1965) at 44 MHz**

- **work ceased in early 1970's due to technical difficulties:**
  - **few antennas**
  - **limited bandwidth**
  - **pure analogue technique (photographing oscilloscopes)**
  - **interpretation problems**
  - **success of other techniques**



LOPES = LOfar PrototypE Station

Questions: LOFAR as Cosmic Ray Detector ?
AUGER enhancement with radio measurements?
Needed: Calibration of the radio emission in air showers !



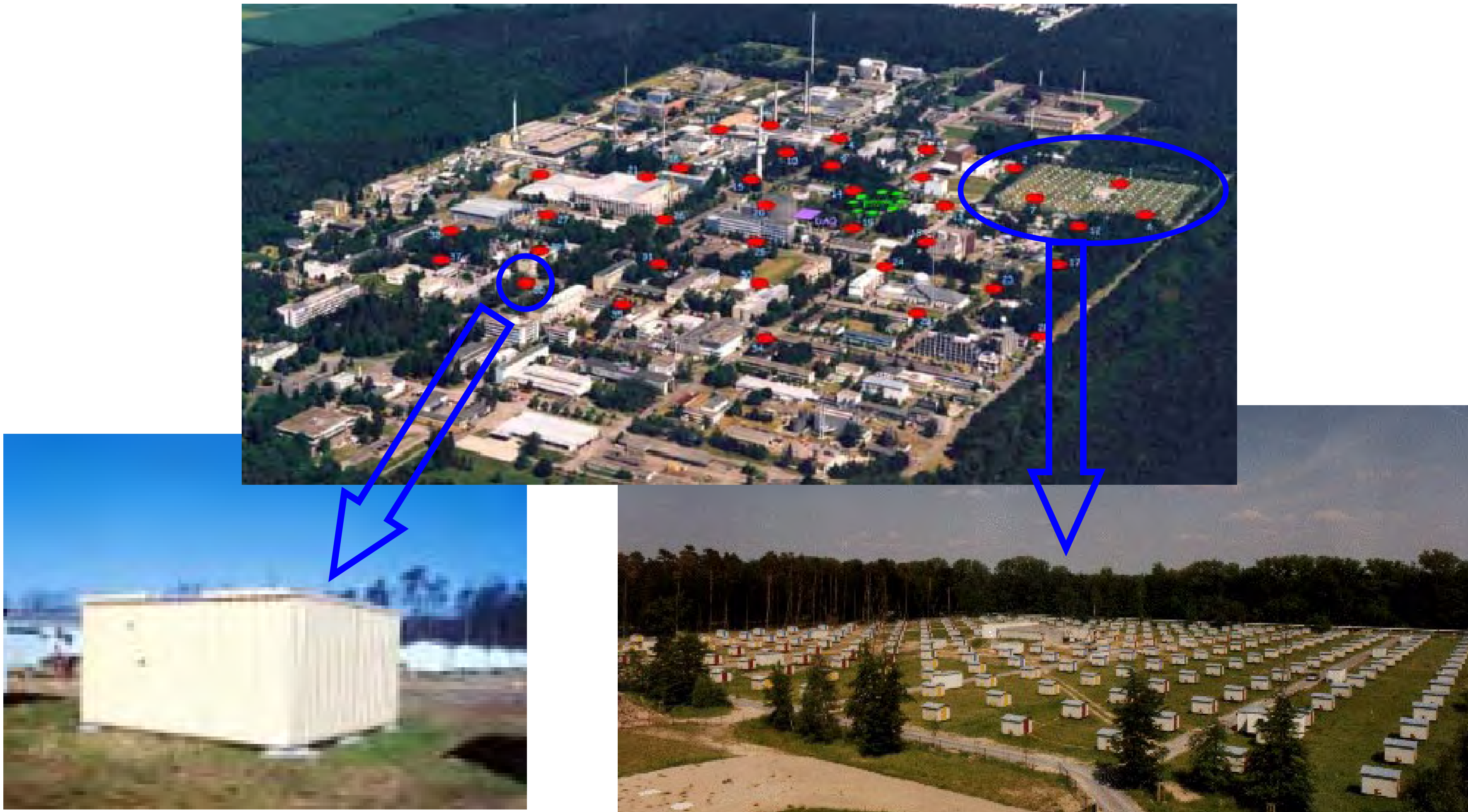
- -Detection threshold
- -Signal dependence on
  - primary energy
  - primary mass
  - geomagnetic angle
  - zenith angle
- -Lateral extension

➔ „known“ air showers

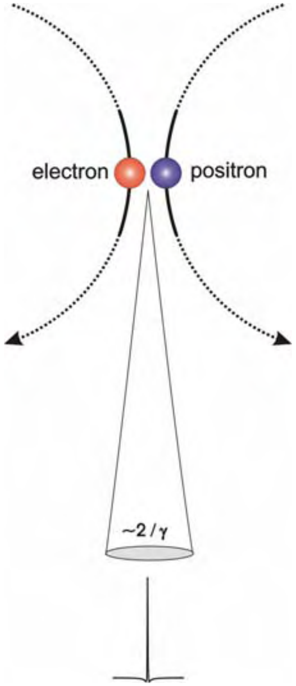
➔ well-calibrated air shower experiment

KASCADE-Grande
= KArlsruhe Shower Core and Array DEtector + Grande

Measurements of air showers in the energy range E_0 = 100 TeV - 1 EeV

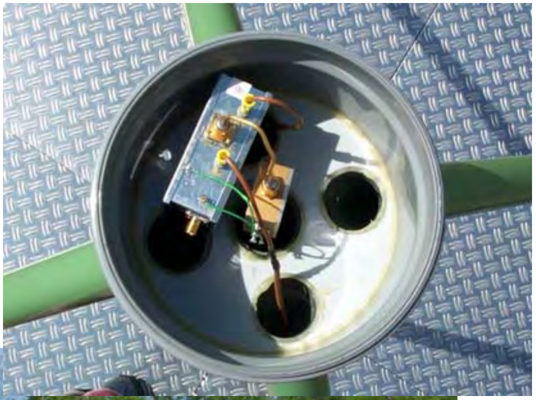


LOPES :
Radio shower detection



•deflection of electron-positron pairs in the Earth's magnetic field
➔coherent emission at low frequencies

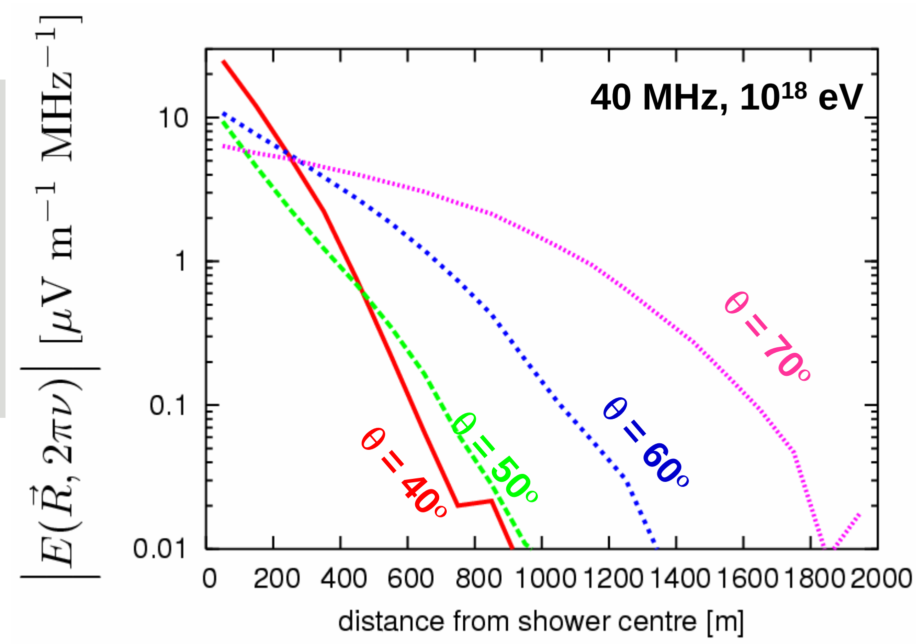
•with radio detection
➔ see shower development
➔ observe 24 hrs/day

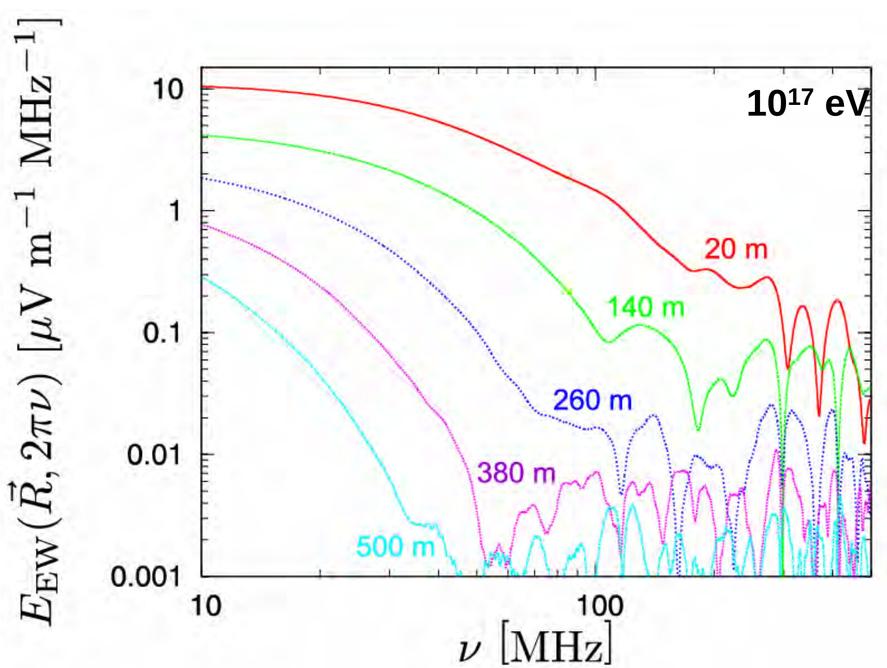


- 30 dipole antennas at KASCADE-Grande
- calibration of radio emission
- theory of radio emission and implementation in CORSIKA
- improvement/optimisation hardware (for application in Auger/LOFAR)

Radio shower detection: Simulations

1. **analytical calculation of emission processes**
2. **Monte Carlo simulations of radio signals**
3. **implementation in CORSIKA**



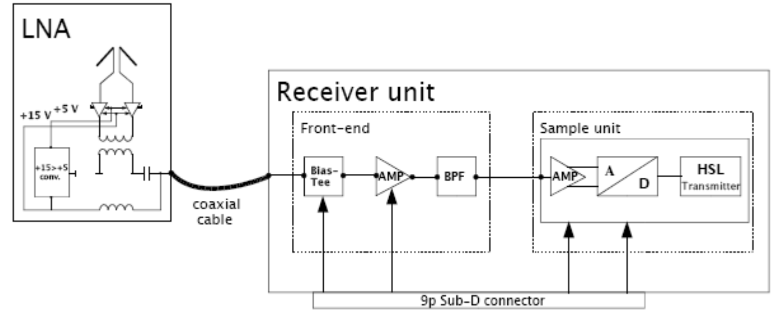


- **expectations on**
- ➔ **frequency spectrum**
- ➔ **lateral distribution**
- ➔ **polarization**
- ➔ **…**

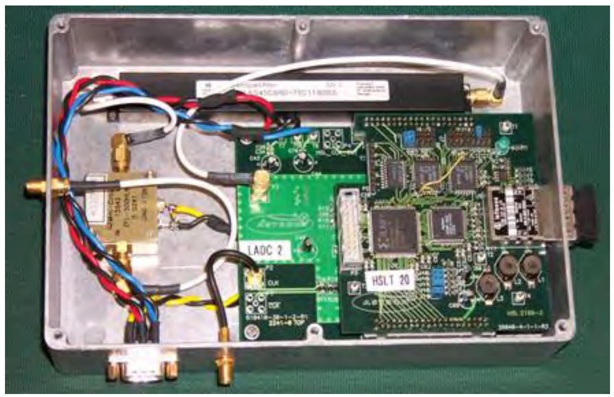
T. Huege & H. Falcke
Astrop. Phys. 24 (2005) 116

Hardware of LOPES:

LOPES-Antenna
Receiver Module
Memory Buffer
Clock and Trigger Board



- short dipole
- beam width 80°-120° (parallel/ perpendicular to dipole)

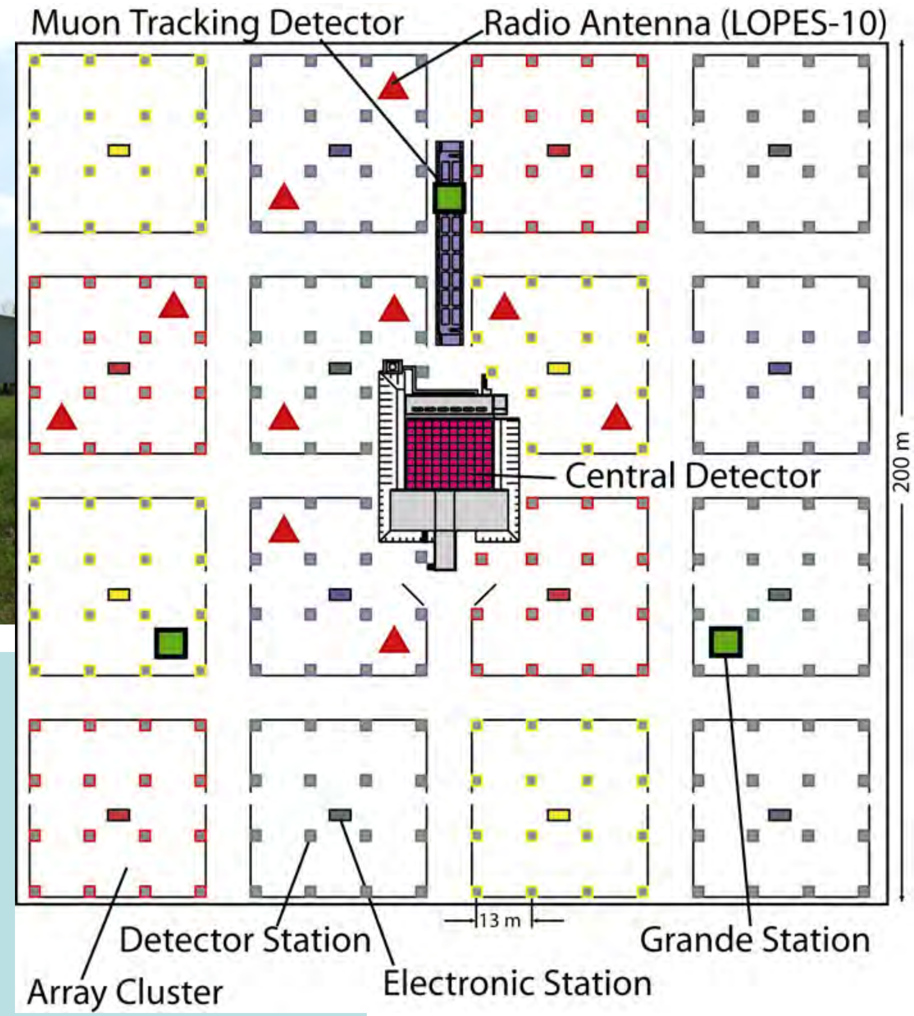


- direct sampling with minimal analog parts: amplifier, filter, AD-converter
- sampling with 80MSPS in the 2nd Nyquist domain of the ADC

- uses PC133-type memory
- up to 6.1 s per channel
- pre- and post-trigger capability

- generates and distributes clock and accepts and distributes trigger

LOPES : First step: 10 antennas at KASCADE (2004)



- 10 antennas at KASCADE array
- frequency band 40-80 MHz
- trigger: >10/16 cluster of KASCADE
  ($E_0 > 10^{16}$ eV)
- 2004: 7 months runtime
- ~630.000 triggered events
  (and correlated EAS information)

➔ sufficient sample of events for detailed analyses

LOPES 10 :

Calibration of radio emission in air showers:
🡐Check or improvement of Allan‘s parametrisation of the early measurements
🡐 quantification of dependencies

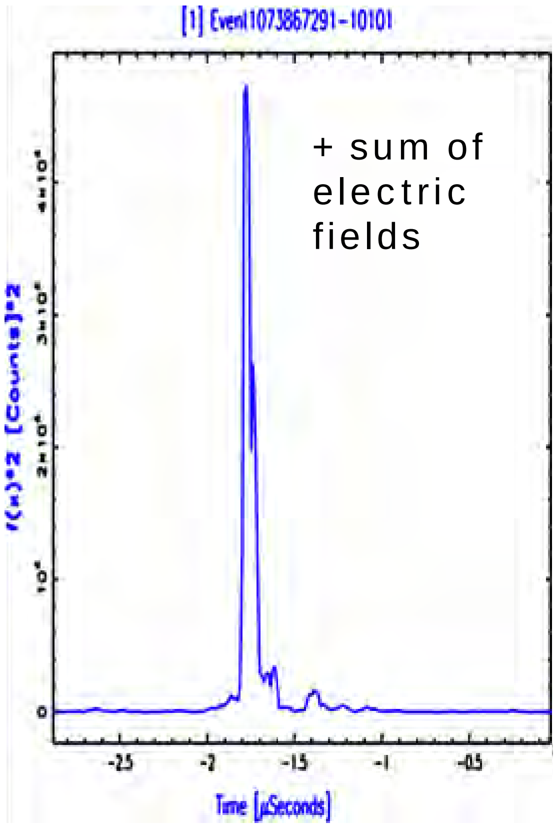
$$\varepsilon_\nu = 20 \cdot (E / 10^{17} \mathrm{eV}) \cdot \sin\alpha \cdot \cos\theta \cdot \exp(- R / R_0(\nu,\theta))$$

[μV / m MHz]

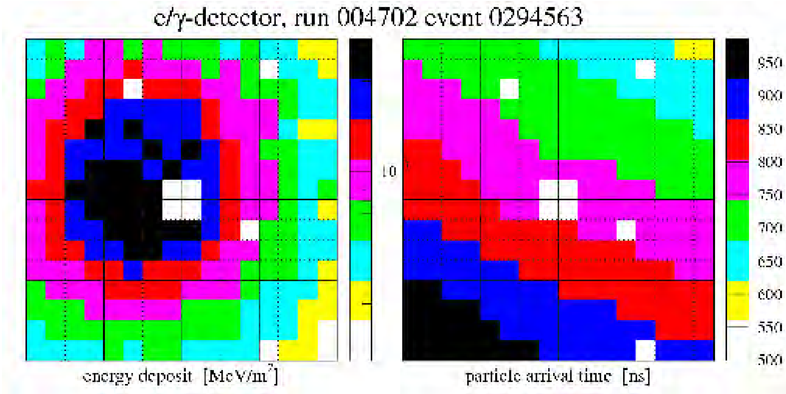
ε_ν	**– radio pulse amplitude per unit bandwith**
E	**– primary energy**
α	**– angle to geomagnetic field**
θ	**– zenith angle**
R	**– distance to shower axis**
R_0	**– scaling radius (110 m at 55 MHz)**

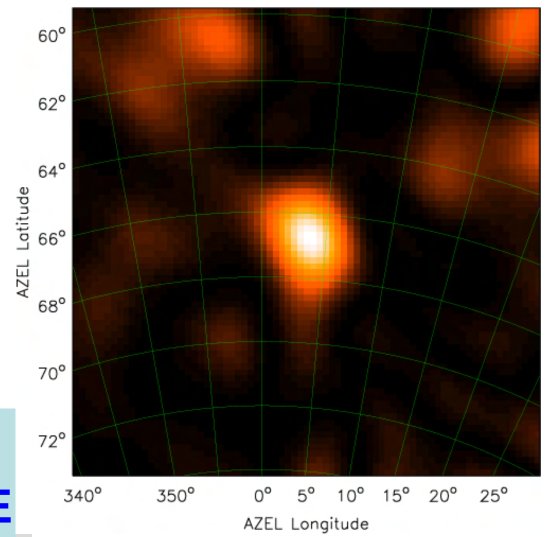
H.R. Allan, review 1971, p.269

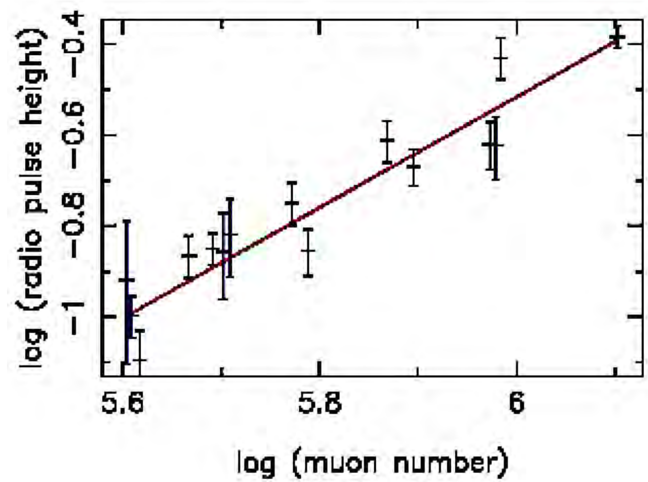
LOPES 10 Analysis : Results
Proof of Principle



- **energy ≈ 10^{17} eV**
- **EAS core inside antennas**
- **Θ = 25.5°, Φ = 42.5°**
- **signal is coherent**







data analyses:

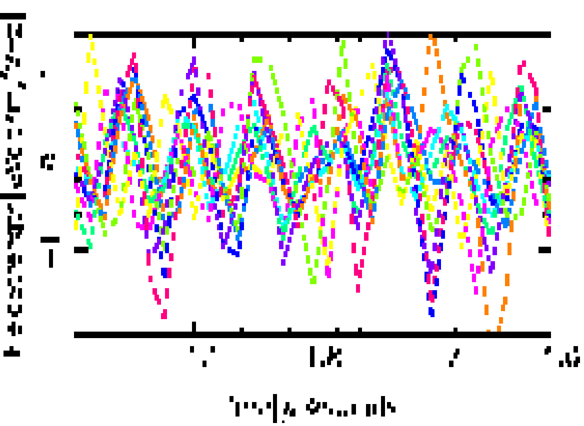
- **EAS analyses KASCADE**
- **radio signal analyses**
- **sky mapping**

LOPES collaboration, Nature 425 (2005) 313

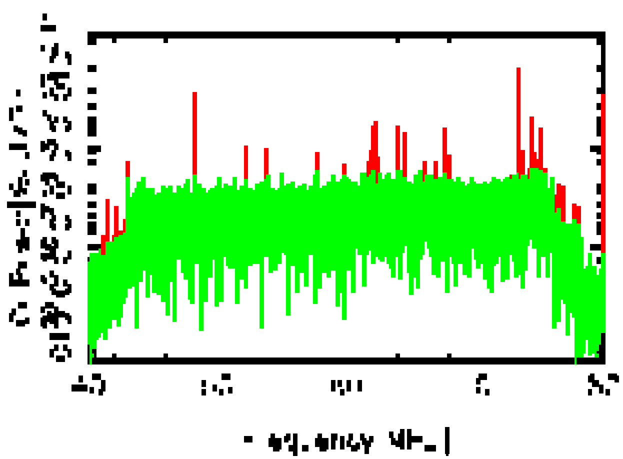
LOPES: Data Processing

1. instrumental delay correction from TV-phases
2. frequency dependent gain correction
3. filtering of narrow band interference
4. flagging of antennas
5. correction of trigger & instrumental delay
6. beam forming in the direction of the air shower
7. optimizing radius of curvature
8. quantification of peak parameters

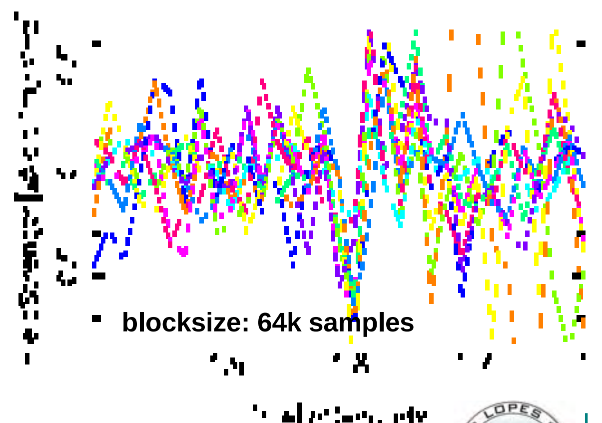
raw data:



power spectrum:

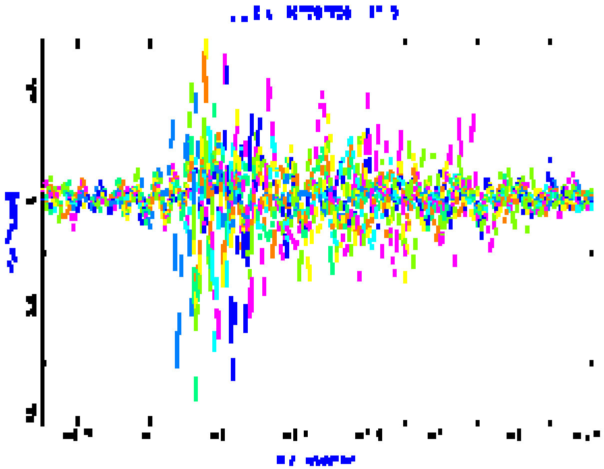


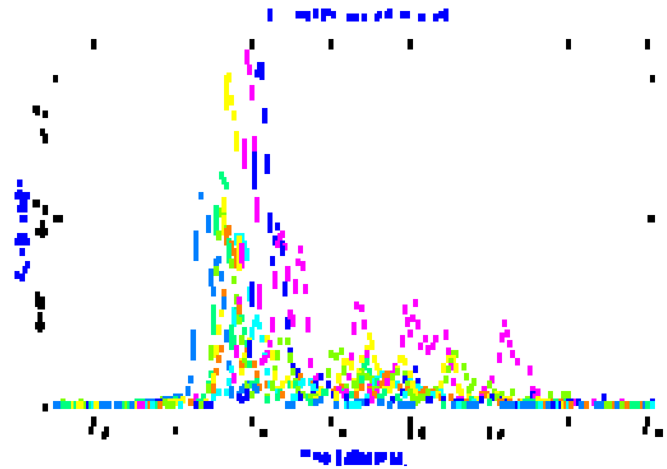
filtered data:



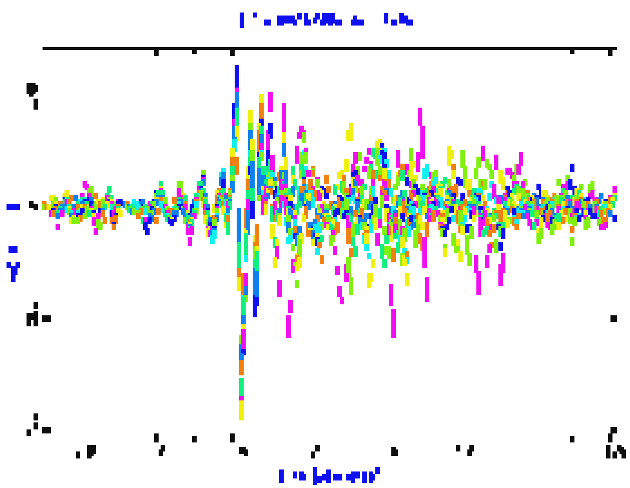
LOPES: Data Processing
Beamforming

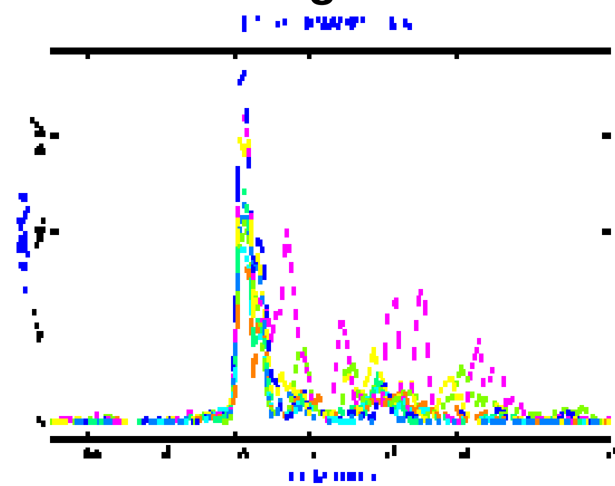
Electric field and power before time shifting:





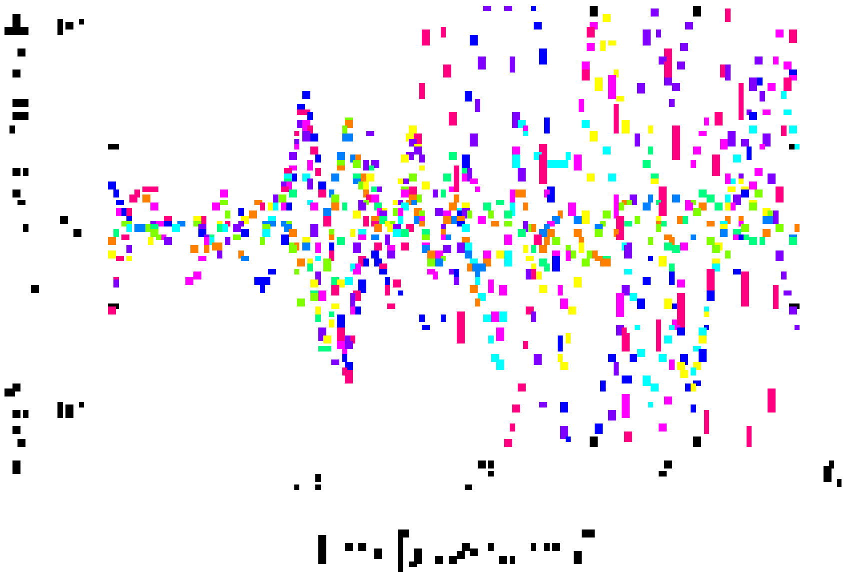
Electric field and power after time shifting:



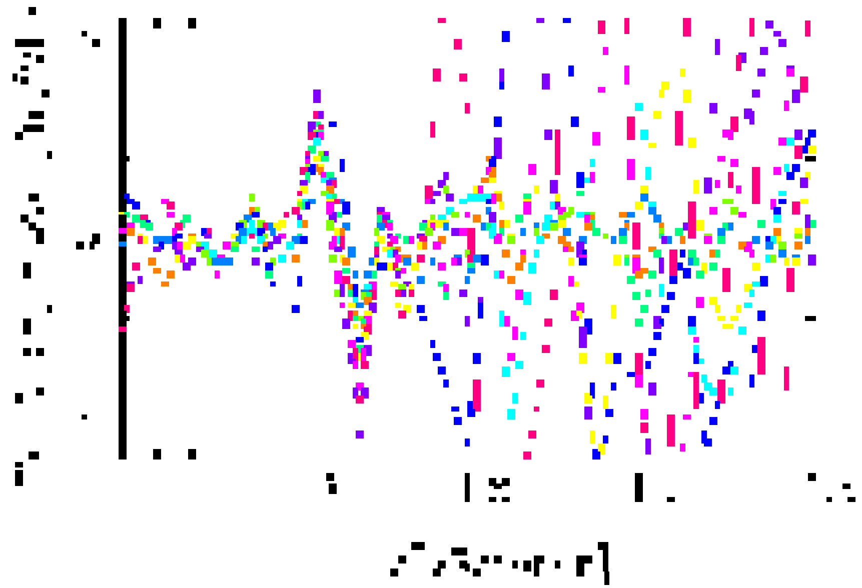


LOPES: Data Processing
Radius of Curvature

Plane wave:



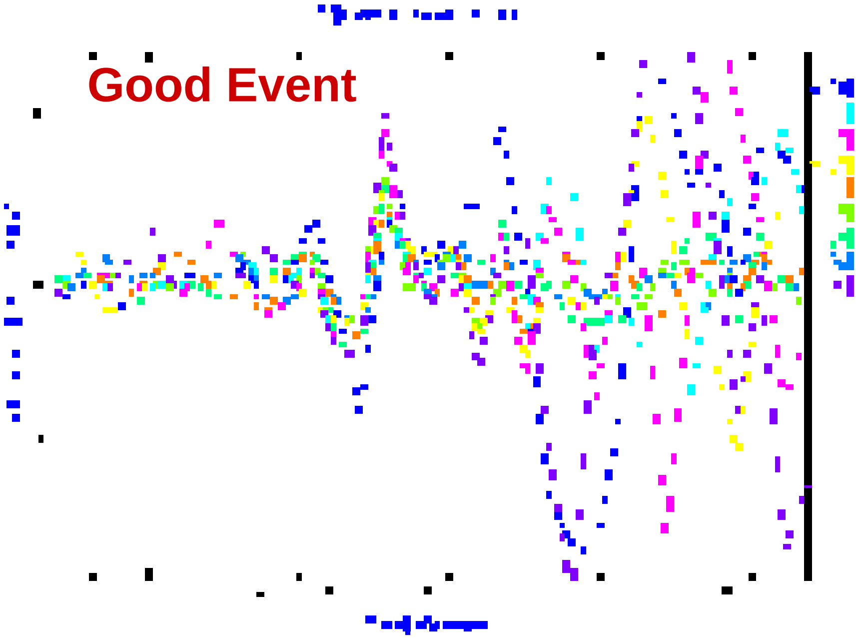
Sphere:

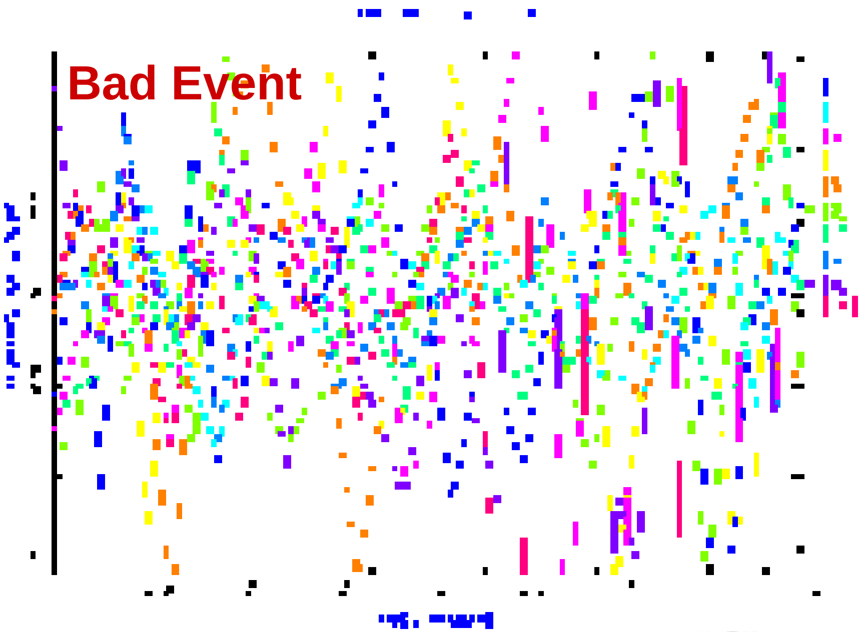


- **plane wave doesn't fit the data**
- **sphere with finite radius of curvature is better**
- **makes radio data sensitive to position of shower center**

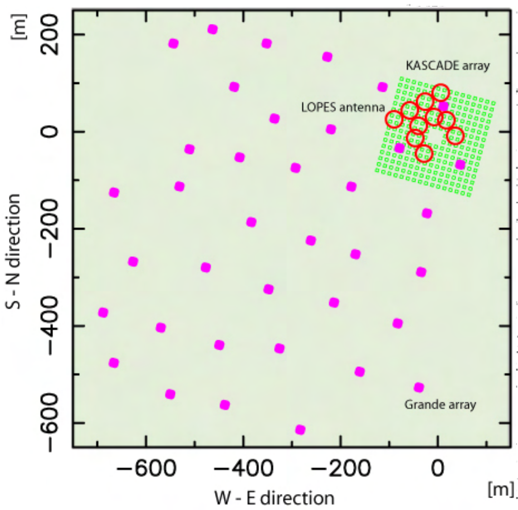
LOPES: Data Processing
Event Discrimination

- criteria for “good” events:
  - existence of a coherent pulse
  - position in time of pulse
  - uniform pulse height in all antennas
- selection currently done manually





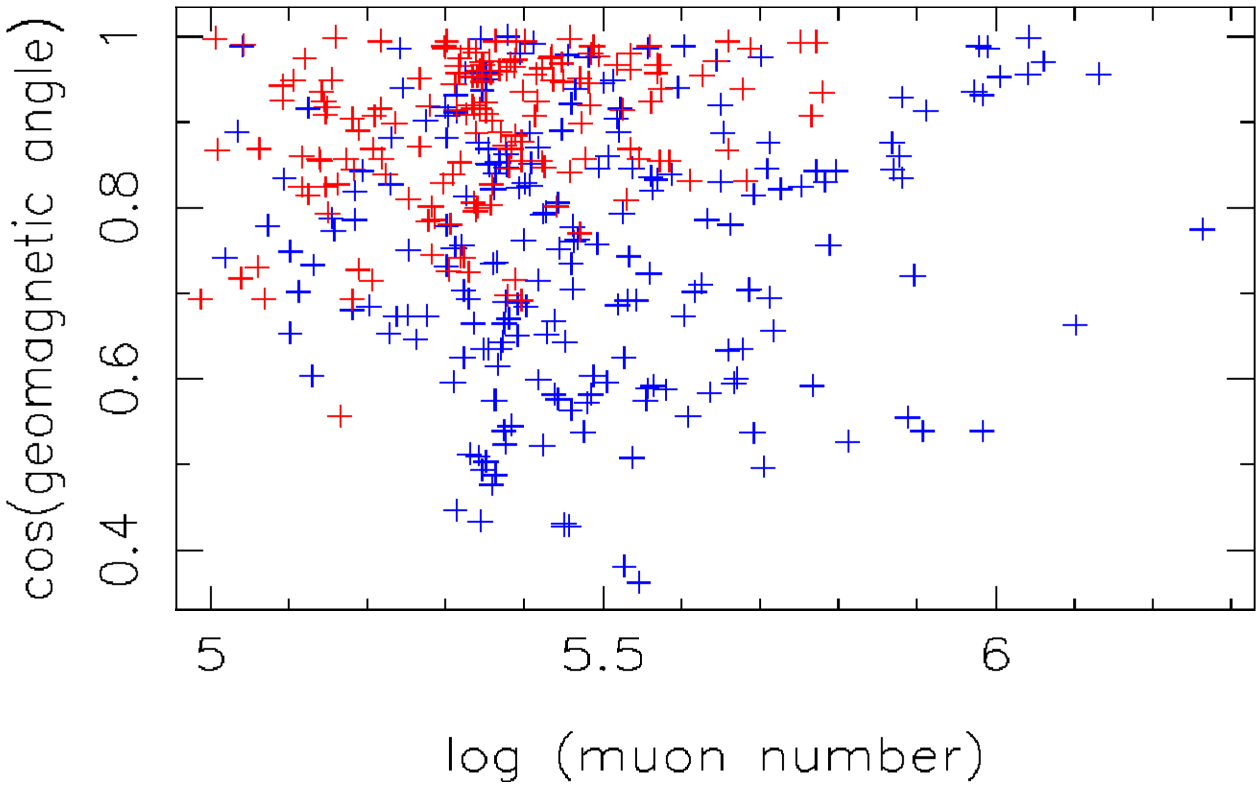
LOPES 10 :
Analysis of central, distant, and inclined events



Showers trigger LOPES with KASCADE:
➔ central event **➔ basic dependencies**
But most have also trigger in Grande
➔higher energies **➔larger distances (lateral extension)**

LOPES 10 Analysis : Results
Central events

- **228 out of 412 events considered good**
- **Fraction of "good" to "bad" events increases with increasing muon number and increasing geomagnetic angle**
- **fraction also increases with zenith angle**



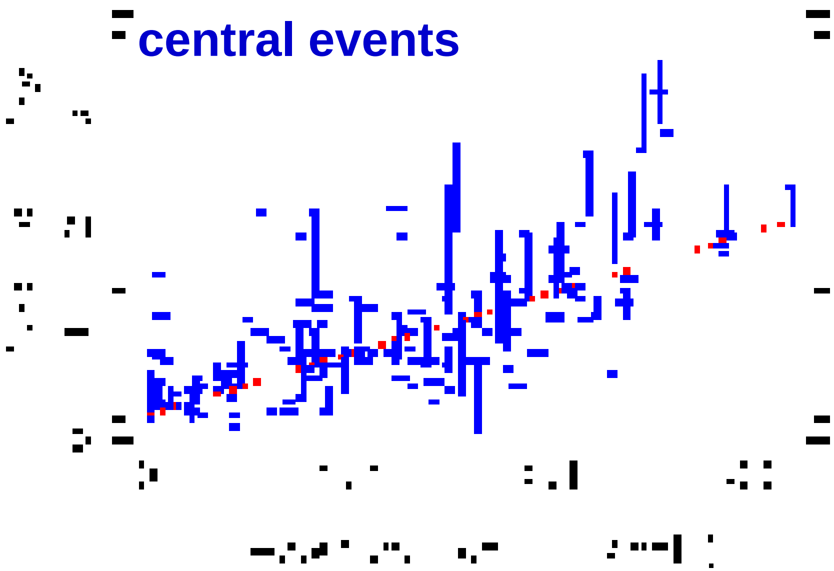
Horneffer et al. – LOPES collaboration, 29th ICRC, Pune, 2005

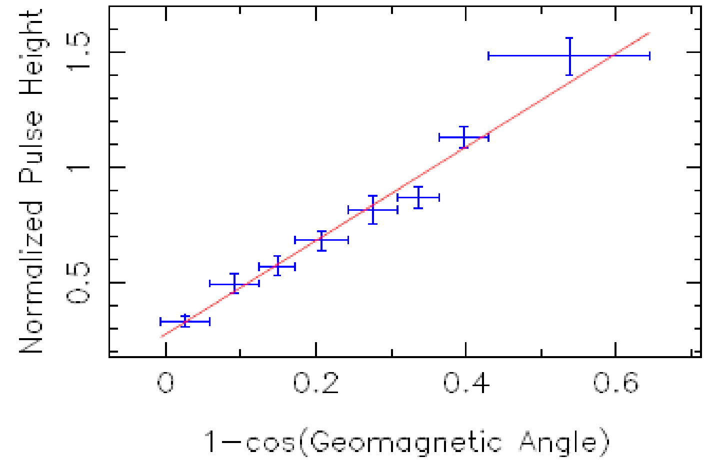
LOPES 10 Analysis : Results
Central Events

Signal dependencies from shower parameters in respect of Allan‘s idea:

$$\varepsilon_\nu = 20 \cdot (E / 10^{17}\text{eV}) \cdot \sin\alpha \cdot \cos\theta \cdot \exp(- R / R_0(\nu,\theta))$$

[µV / m MHz]





Radio signal scales with geomagnetic field:

$\varepsilon_\nu \sim \cos\alpha$

Horneffer et al. – LOPES collaboration, 29th ICRC, Pune, 2005

LOPES 10 Analysis : Results
angle dependencies vs. simulations

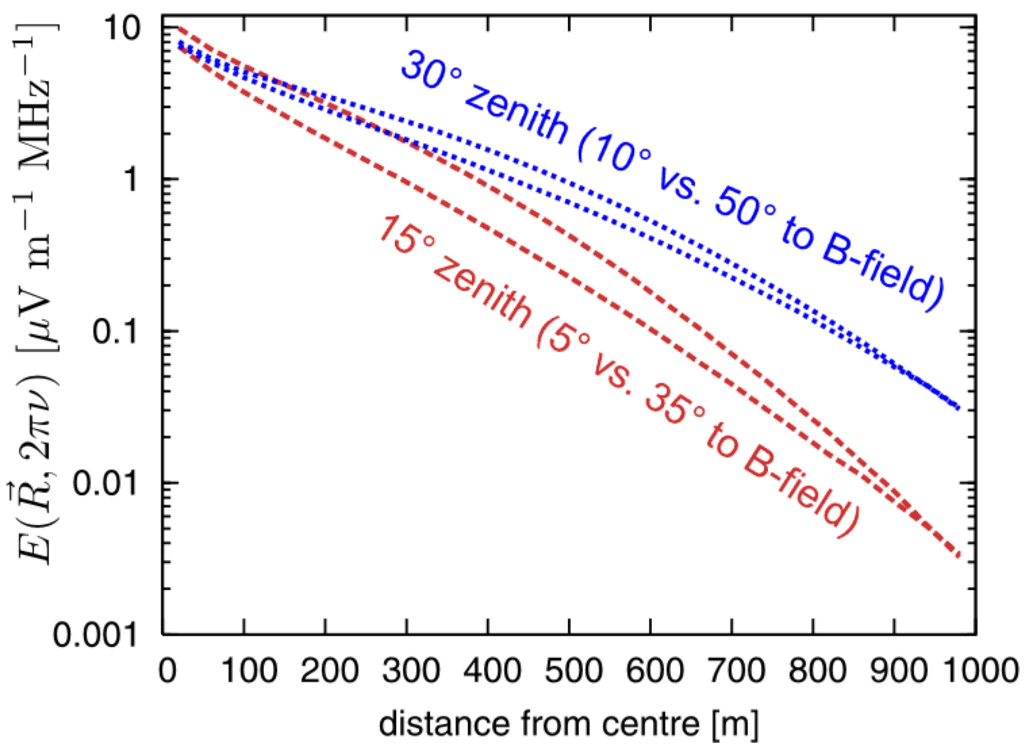
Radio signal scales with geomagnetic field:

$\varepsilon_\nu \sim \cos \alpha$

Monte Carlo Simulations:
separate dependence expected

- **on geomagnetic (Earth magnetic field)**
- **on zenith (footprint broadening & elongation)**
- **and azimuth (polarization effects)**

➔ leads to rather complex predicted behaviour in angle dependencies



Tim Huege, 29th ICRC, Pune, 2005

LOPES 10 Analysis : Distant Events
Interplay of radio and shower particle analysis

Grande Event:

$\Phi = 302.18^o$ $\theta = 41.01^o$

$\alpha = 57.91^o$

$X_c = -142.85$ m $Y_c = 40.27$ m

lg(E/eV) = 17.73 ln(A) = 3.16

curvature = 3250 m

rence

8º

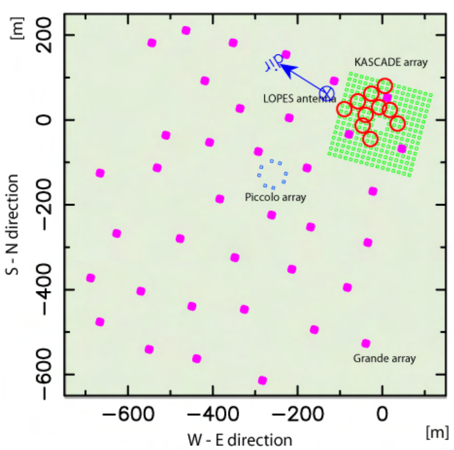
º

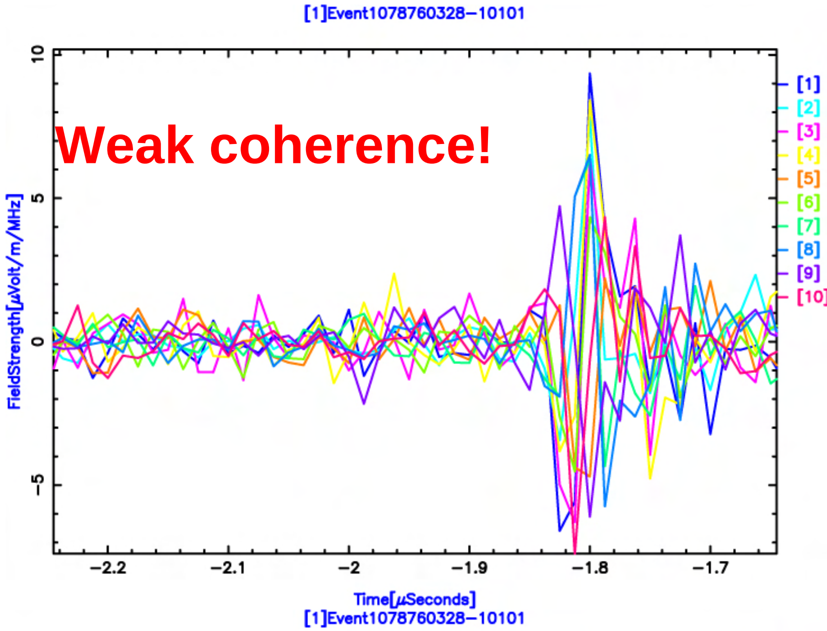
85 m

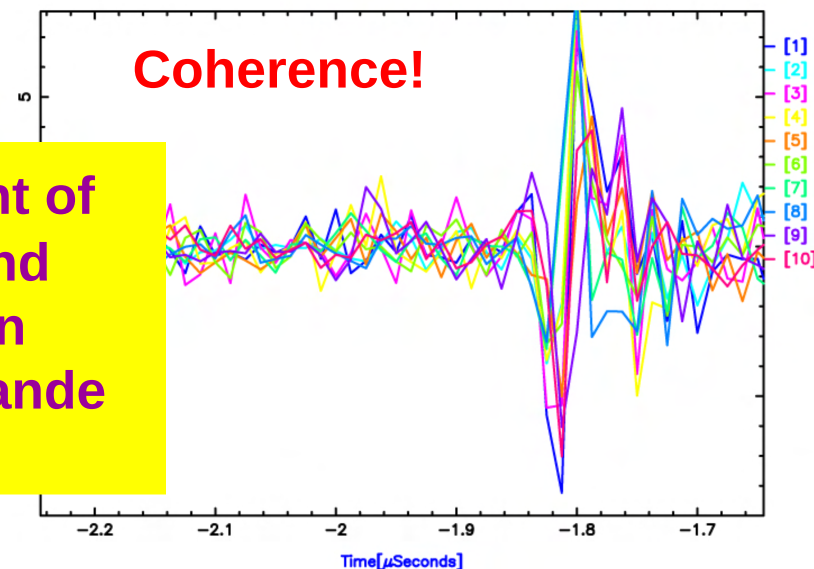
m

ln(A) = 3.16

curvature = 3250 m = 4250 m







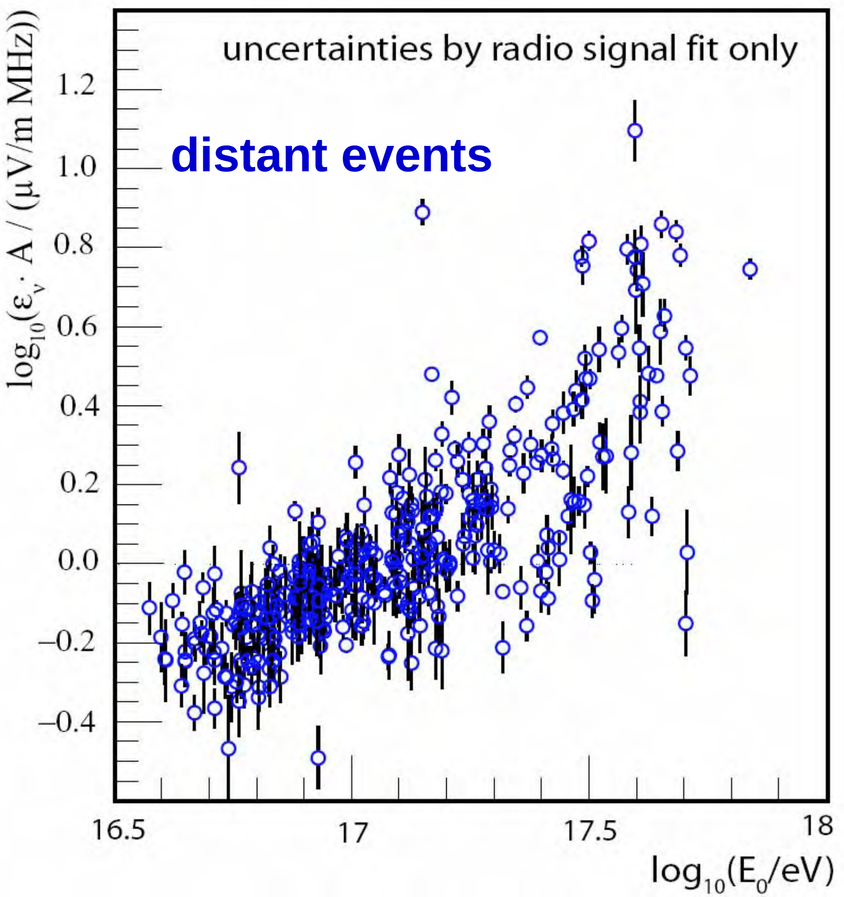
➔Improvement of shower core and arrival direction estimate in Grande by LOPES !

LOPES 10 Analysis : Results
energy dependence of radio signal

Signal dependencies from shower parameters in respect of Allan's idea:

$$\varepsilon_\nu = 20 \cdot (E / 10^{17} eV) \cdot \sin\alpha \cdot \cos\theta \cdot \exp(- R / R_0(\nu,\theta))$$

[μV / m MHz]



Radio signal (electric field) scales with primary energy:

$\varepsilon_\nu \sim E_0$

➔ **Power of electric field scales quadratically with primary energy !**

Apel et al. – LOPES collaboration, Astrop.Phys. (2006) submitted

LOPES 10 Analysis : Results
energy dependence of radio signal

Signal dependencies from shower parameters in respect of Allan's idea:

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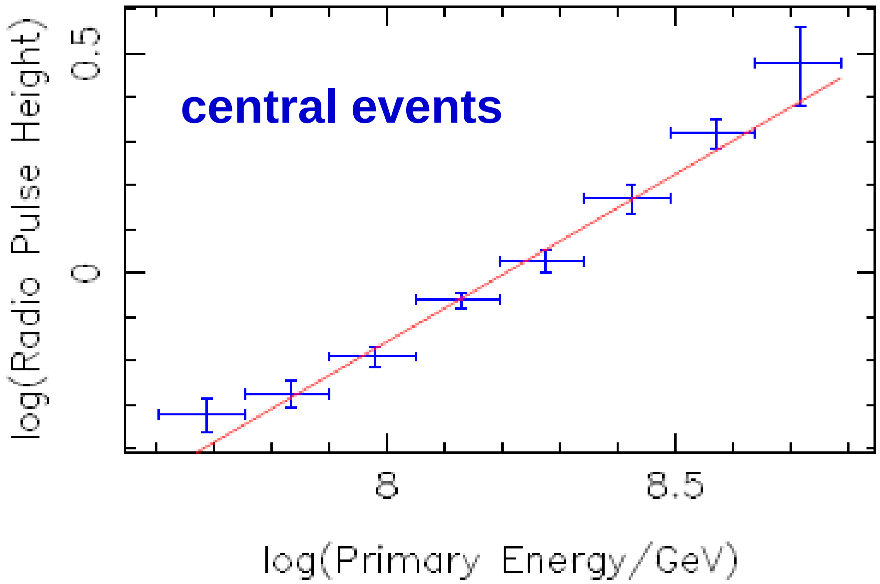
[μV / m MHz]



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➔ Power of electric field scales quadratically with primary energy !

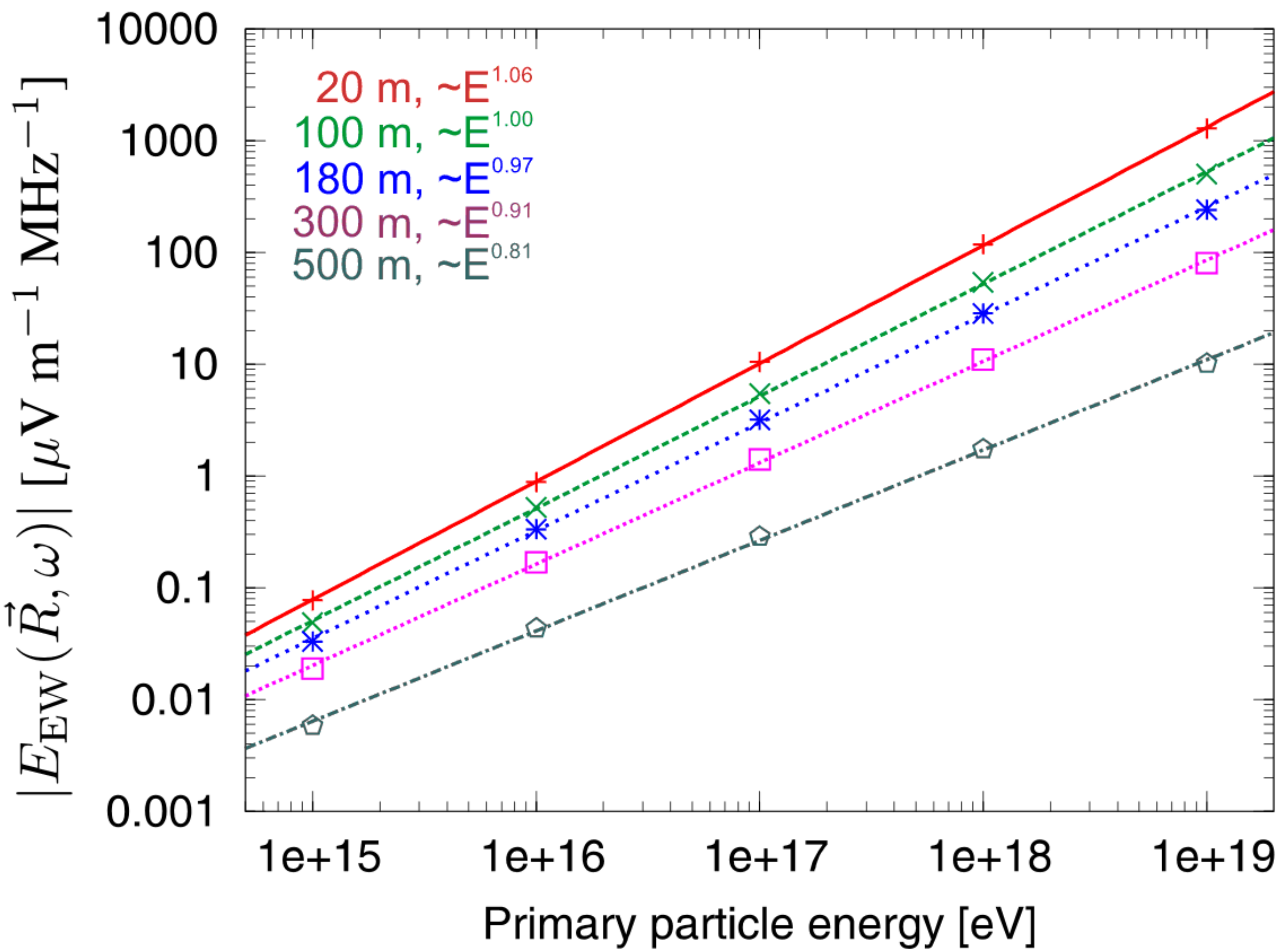
Horneffer et al. – LOPES collaboration, 29th ICRC, Pune, 2005

LOPES 10 Analysis : Results
signal dependency vs. simulations

Radio signal (electric field) scales with primary energy:
$\varepsilon_\nu \sim E_0$

Monte Carlo Simulations:

E-field scales approx. linearly with E_0
➔ proof of coherence



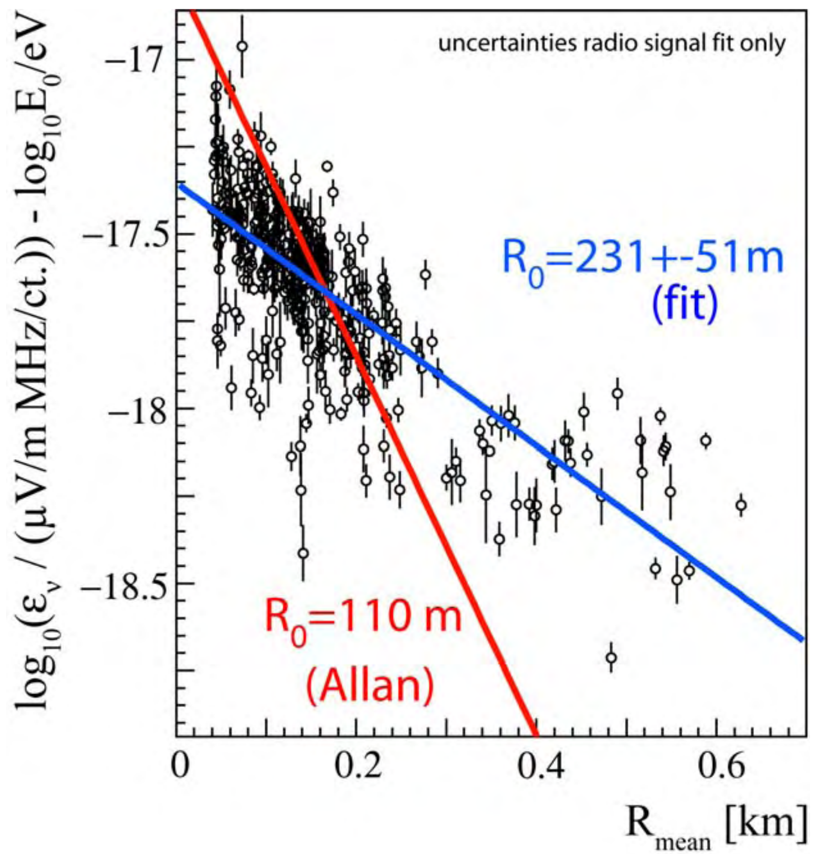
Tim Huege, 29th ICRC, Pune, 2005

LOPES 10 Analysis : Results
lateral profile of radio signal

Signal dependencies from shower parameters in respect of Allan's idea:

$$\varepsilon_\nu = 20 \cdot (E / 10^{17} eV) \cdot \sin\alpha \cdot \cos\theta \cdot \exp(- R / R_0(\nu,\theta))$$

[μV / m MHz]



Radio signal scales with core distance:
$\varepsilon_\nu \sim \exp(-R)$

Apel et al. – LOPES collaboration, Astrop.Phys. (2006) submitted

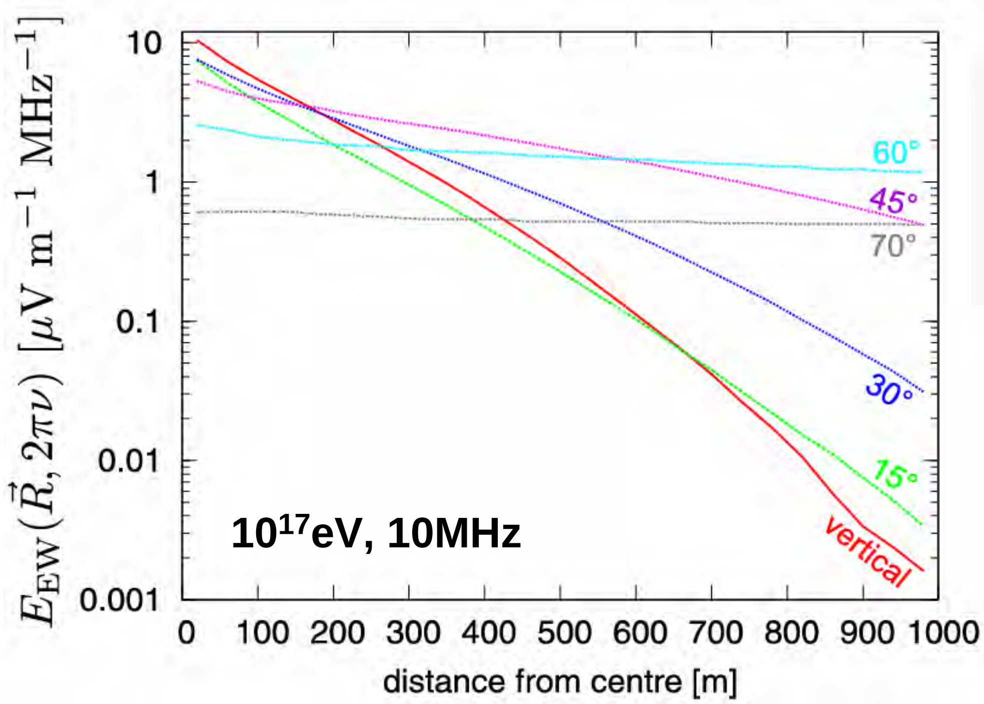
LOPES 10 Analysis : Results
lateral profile vs. simulations

Radio signal scales with core distance:
ε_ν ~ exp (-R) (R$_0$~230m)

Monte Carlo Simulations:

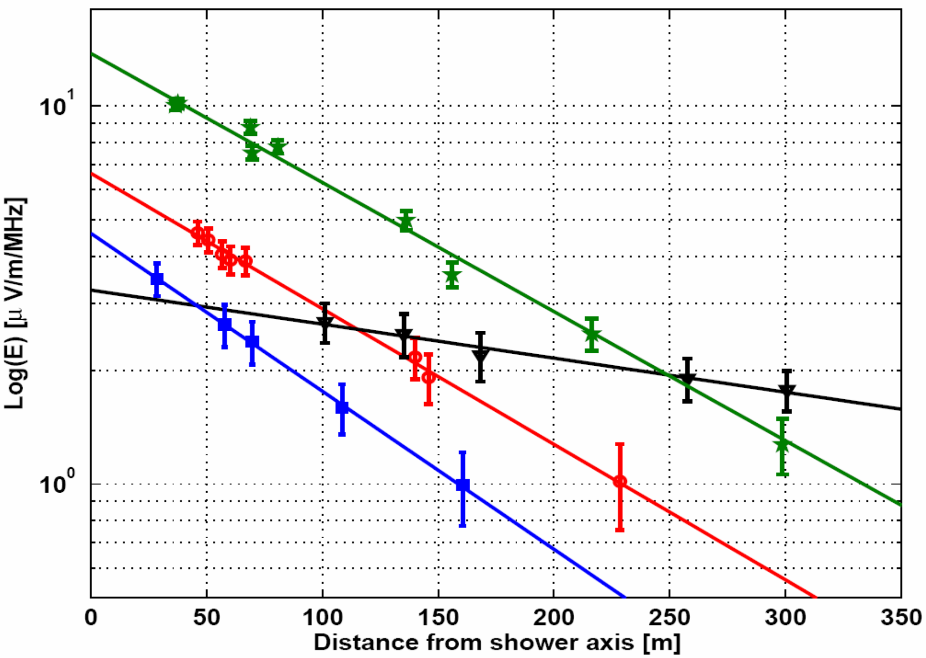
flattening with zenith angle

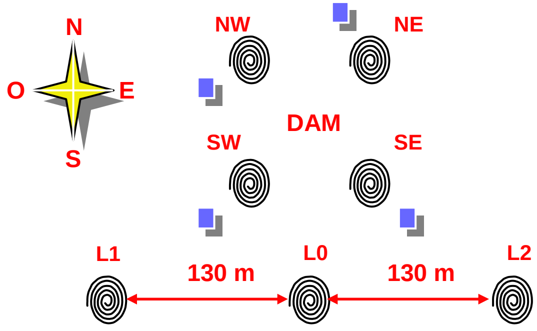
approx. exponential scaling R$_0$ ~ 100 to 800 m



Tim Huege, 29th ICRC, Pune, 2005

CODALEMA experiment : Results
lateral profile of radio signal in individual events

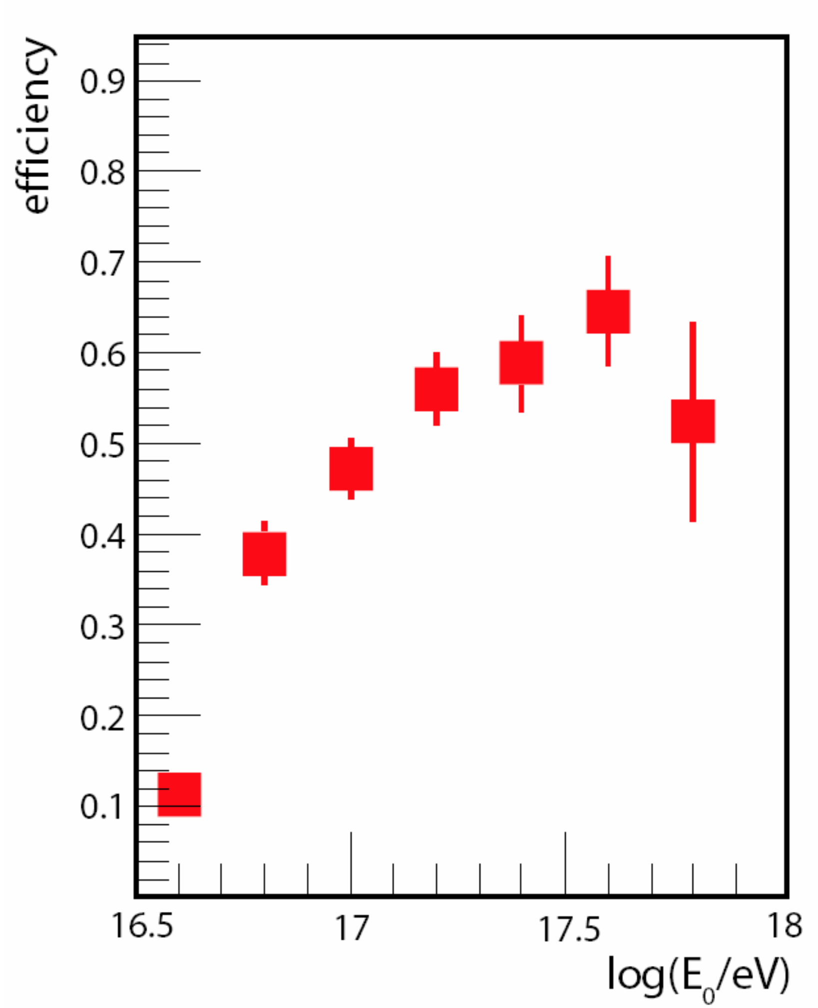




Radio signal scales with core distance:
$\varepsilon_\nu \sim \exp(-R)$

Ardouin et al., astro-ph/0510170

LOPES 10 Analysis : distant events efficiency



detection threshold at
$E_0 \sim 10^{17}$eV

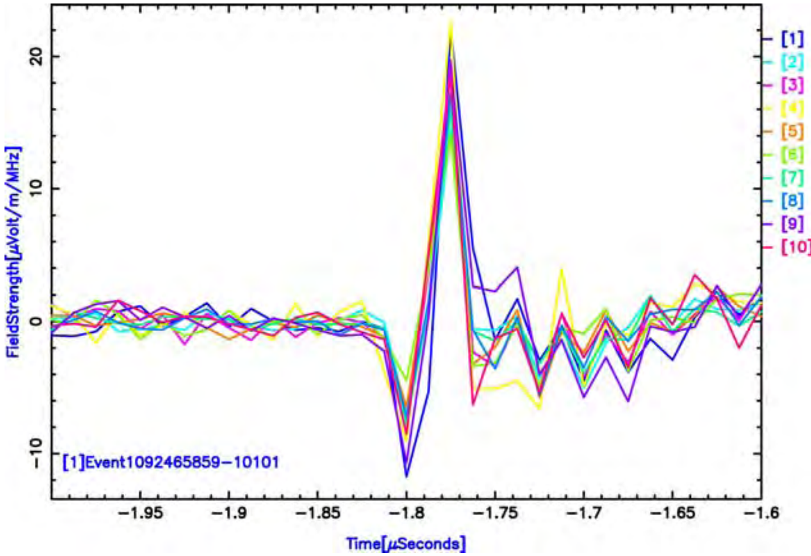
Missing efficiency due to
- polarization
- geomagnetic angle

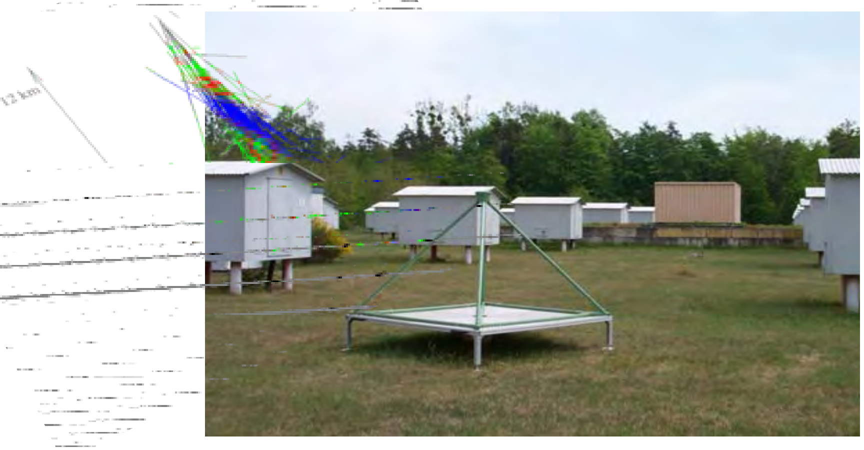
Apel et al. – LOPES collaboration, Astrop.Phys. (2006) submitted

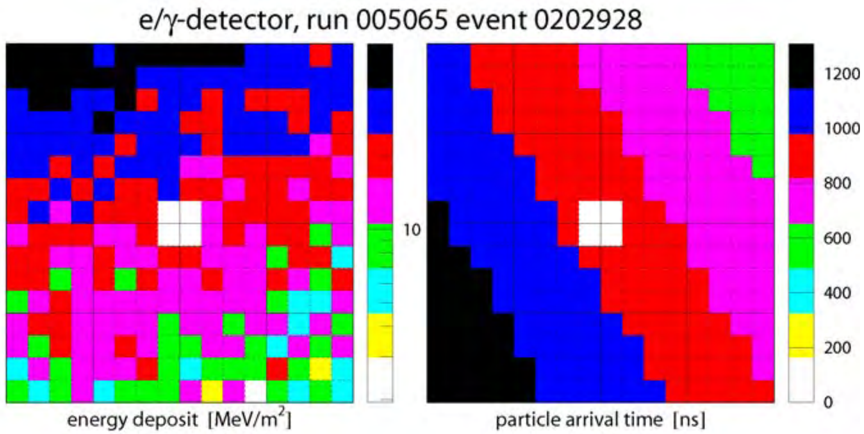
LOPES 10 : Analyses of inclined events

Event:
Φ = 74,4° θ = 68°
core = outside
lg(N_e) ~ 6 ? lg(N_μ) ~ 5.7 ?
but clear radio signal !!

-reconstruction of shower by particle detectors difficult
-clear radio signals seen







Petrovic et al. – LOPES collaboration, 29th ICRC, Pune, 2005

LOPES 10 Analysis : Results
inclined events vs. simulations

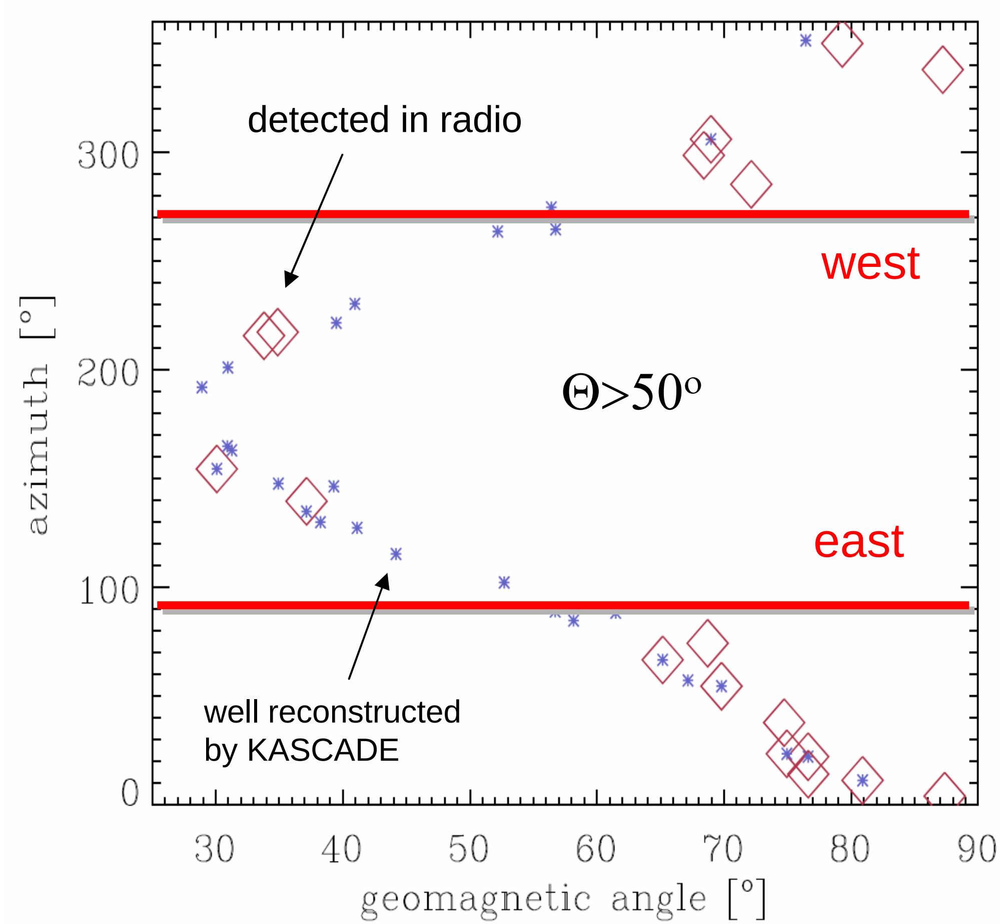
no radio events from east or west

north-south asymmetry in radio events

Monte Carlo Simulations:

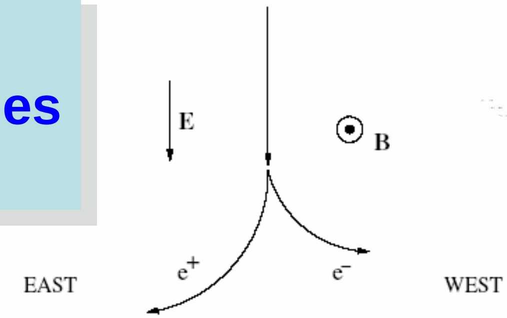
east-west ←→ north-south asymmetries expected due to polarization, antenna gain and geomagnetic effects

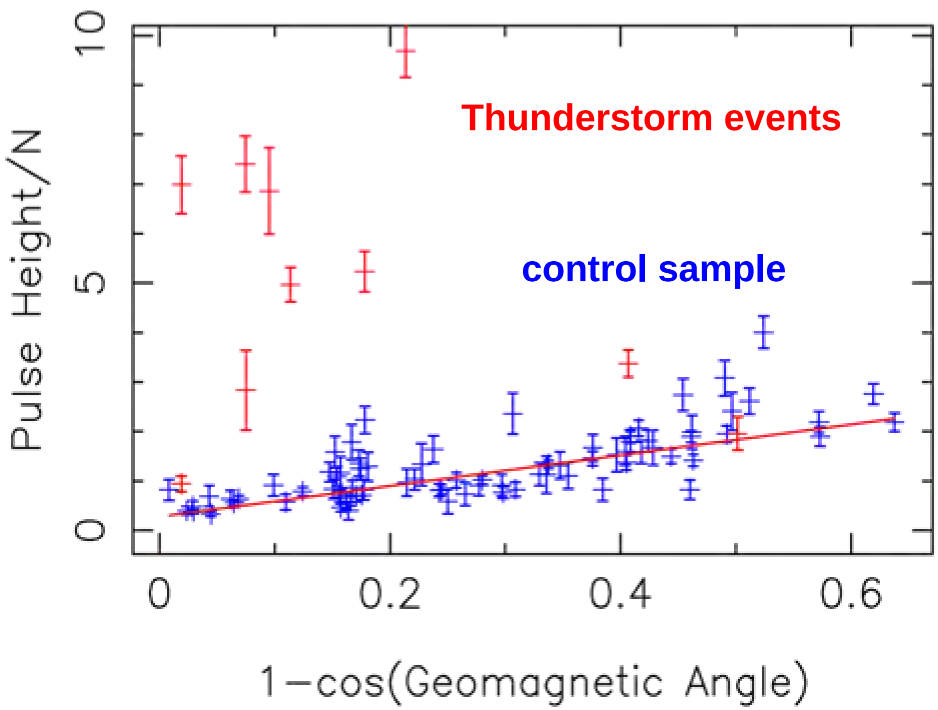
first measurements consistent with simulation but difficult situation



LOPES 10 : Analyses of events during thunderstorms

Downward electric field
→Asymmetry in trajectories
→Radio emission



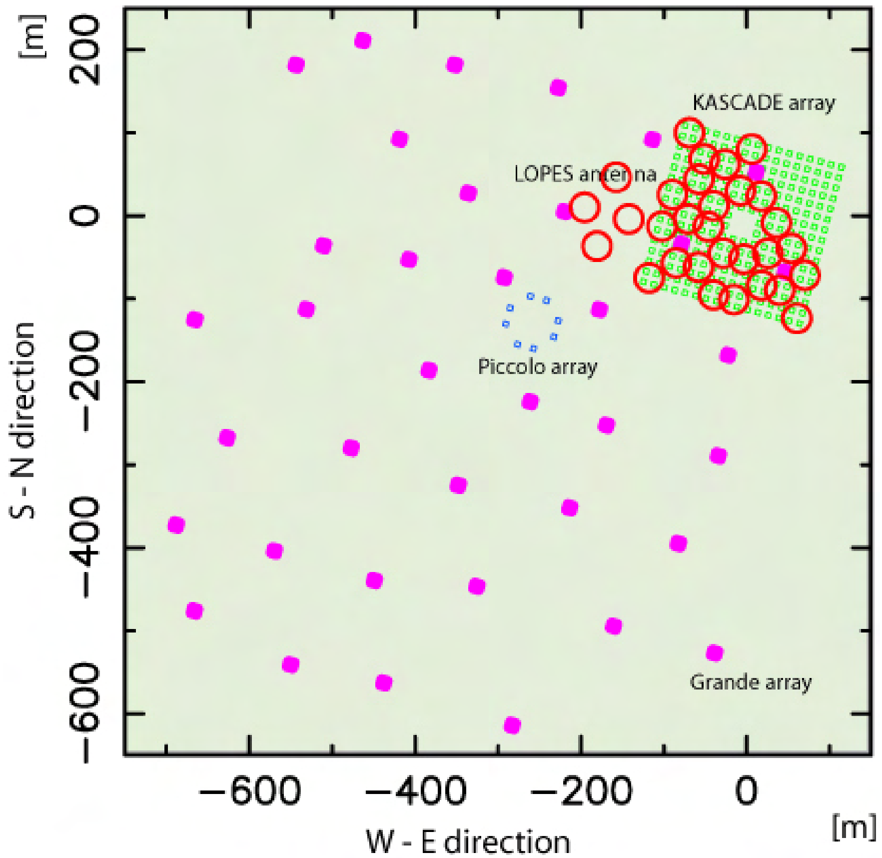


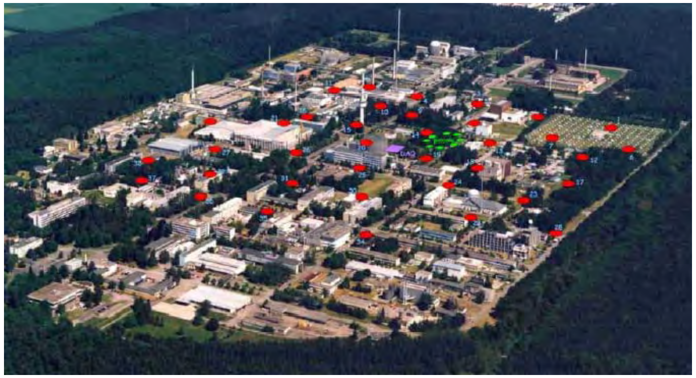
For E>100 V/cm:
E-field force dominates B-field:
Fair weather: E=0,1 V/cm
Thunderstorms: E=1 kV/cm

Buitink et al. – LOPES collaboration, 29th ICRC, Pune, 2005

LOPES 30: Extension: 30 antenna at KASCADE-Grande

- **30 antennas at KASCADE-Grande**
- **Maximum baseline: ~300 m**
- **Trigger: KASCADE <u>and</u> KASCADE-Grande**
- **Absolute Calibration**
- **Environmental monitoring**

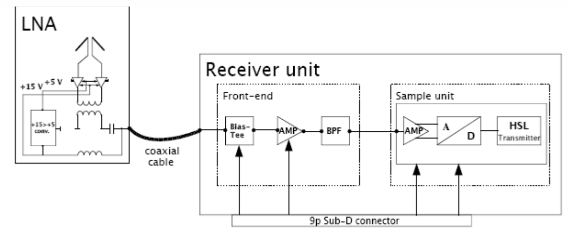




LOPES 30: absolute calibration

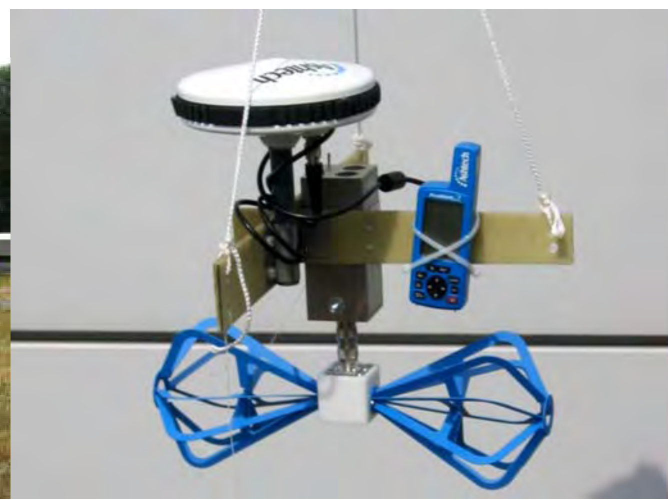
measured power $P_{DAQ}(\nu)$ of each antenna compared with received power $P_{rec}(\nu)$ from reference radio source

$$V(\nu)=\frac{P_{DAQ}(\nu)}{P_{rec}(\nu)}=\frac{P_{DAQ}(\nu)}{\frac{E^2(\nu)}{Z_0}\cdot r^2 G(\nu)\cdot\frac{1}{4\pi}\left(\frac{c}{\nu d}\right)^2}$$



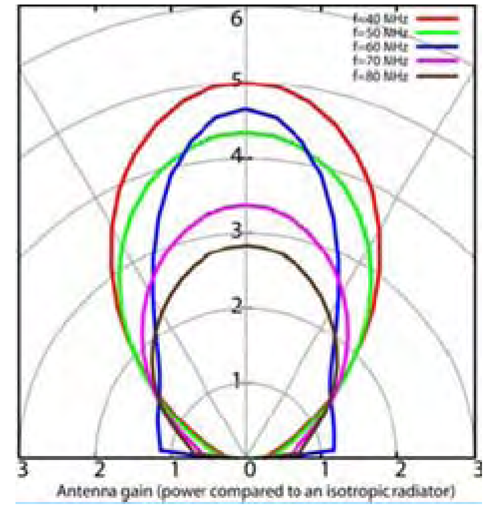
- amplification factor V per antenna obtained with external commercial calibrated reference antenna

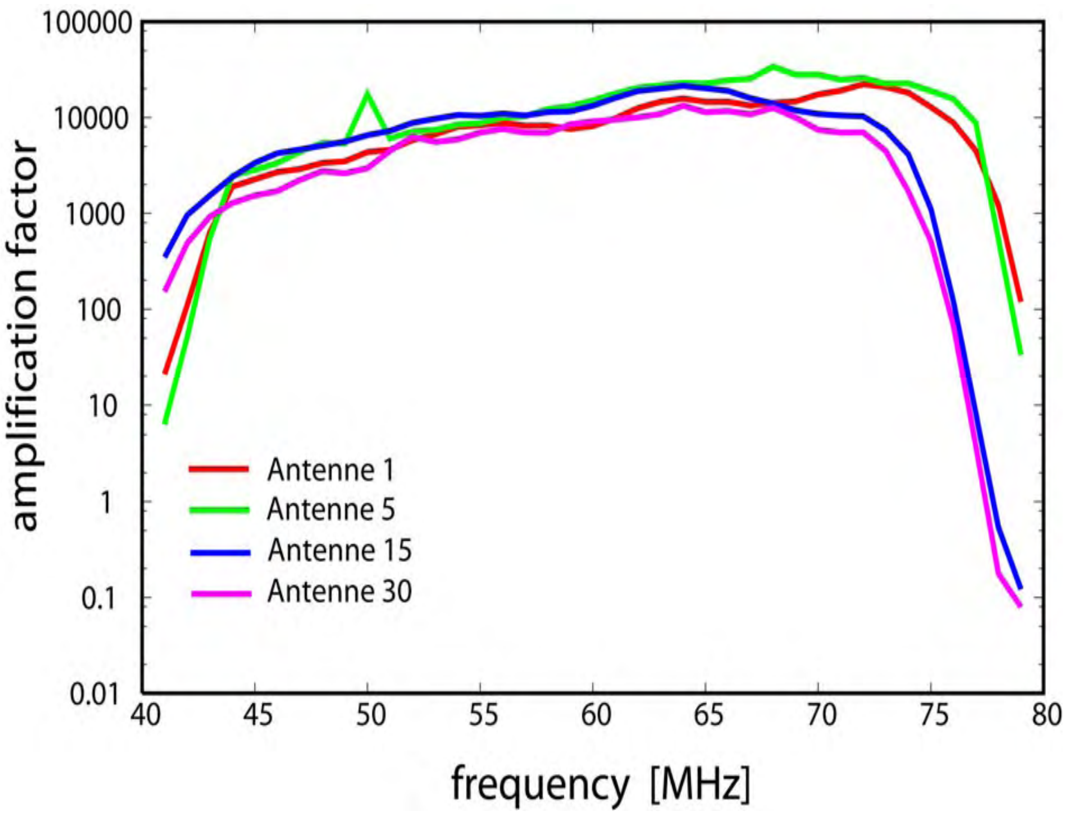
➔ correction factor dependent on
  - antenna
  - frequence
  - weather conditions
  - angle

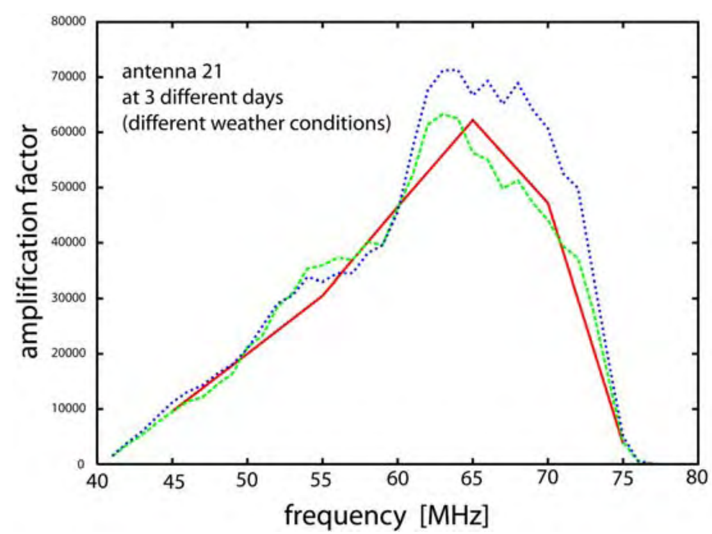


LOPES 30: absolute Calibration

- **antenna gain by simulations**
- **amplification factor from measurements**



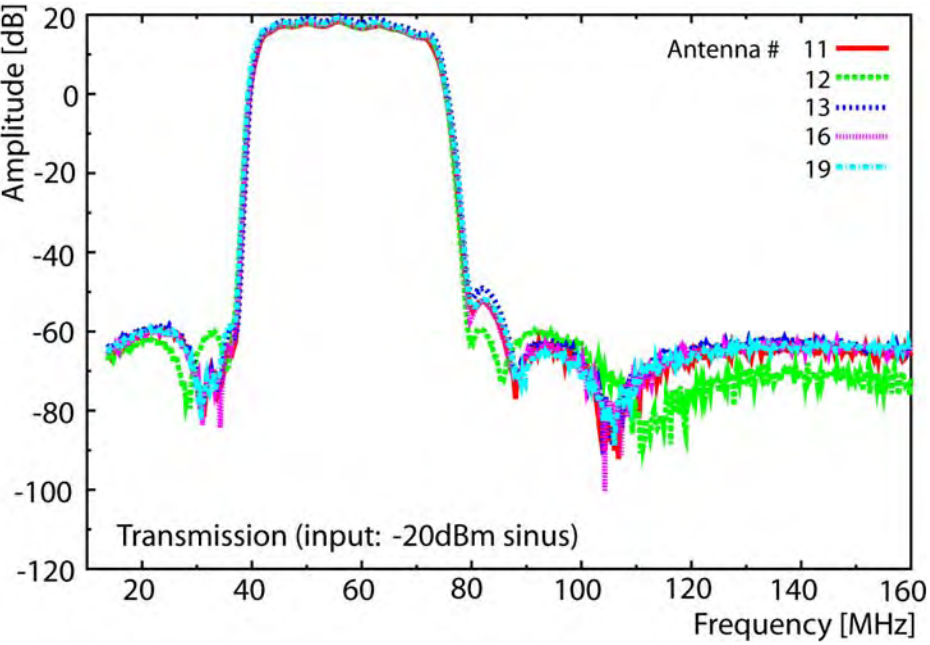


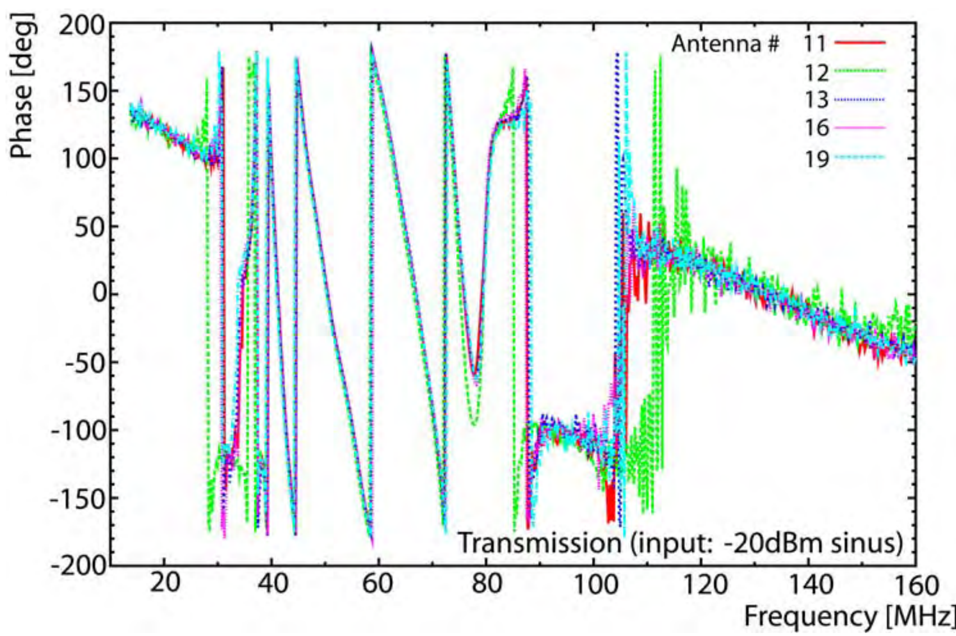


Nehls et al. – LOPES collaboration, 29th ICRC, Pune, 2005

LOPES 30: absolute Calibration

- crosscheck: Lab measurements
- systematic analysis of all LOPES-electronic components
- amplitude and phase measurements to determine system response
- LNA, coaxial cable, Front-end, Sample unit





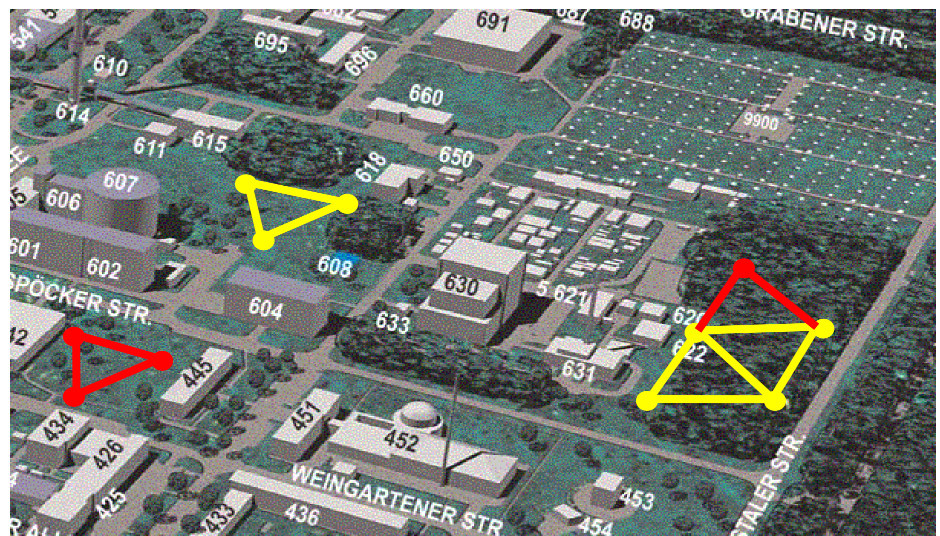
Nehls et al. – LOPES collaboration, 29th ICRC, Pune, 2005

LOPES^{STAR}: large scale application?

- radio technique has great potential for large scale application:
  - LOFAR will measure CRs
  - R&D for use in the Pierre Auger Observatory has started

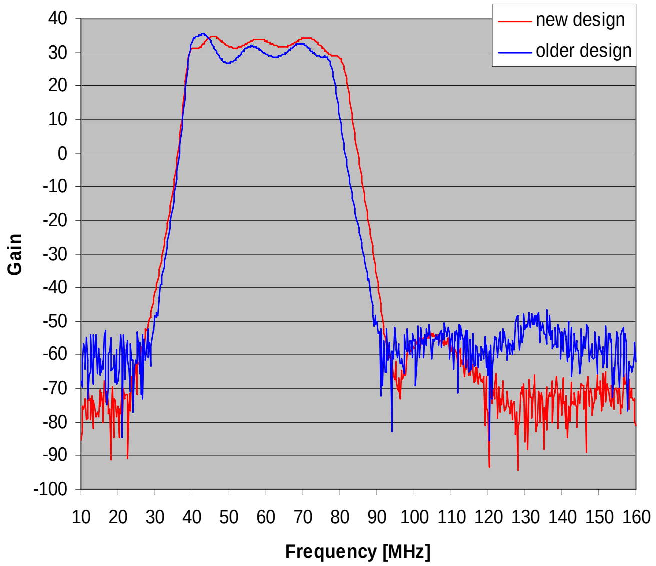
- LOPES continues to contribute experience and physics results

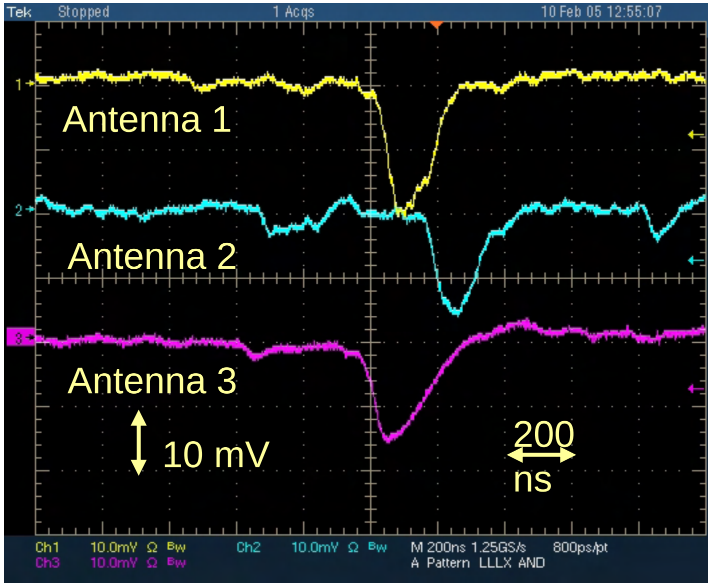
- application in Auger needs a different detector concept:
  - LOPES develops LOPES^{STAR}
  - self-triggered by radio signals only
  - low power consumption
  - decentralized array organization



LOPES^{STAR}

- -crossed logarithmic-periodic dipole antenna (crossed LPDA)
- -dual channel low noise, low power amplifier (0,022 W/Channel)
- -RF mainboard with BIAS-T, 32nd order RF- bandpass filter, limiter, amplifier, envelope rectifier
- - ADC and circular buffer (80 Mhz sampling rate)
- - basic (self)trigger setup by enveloping

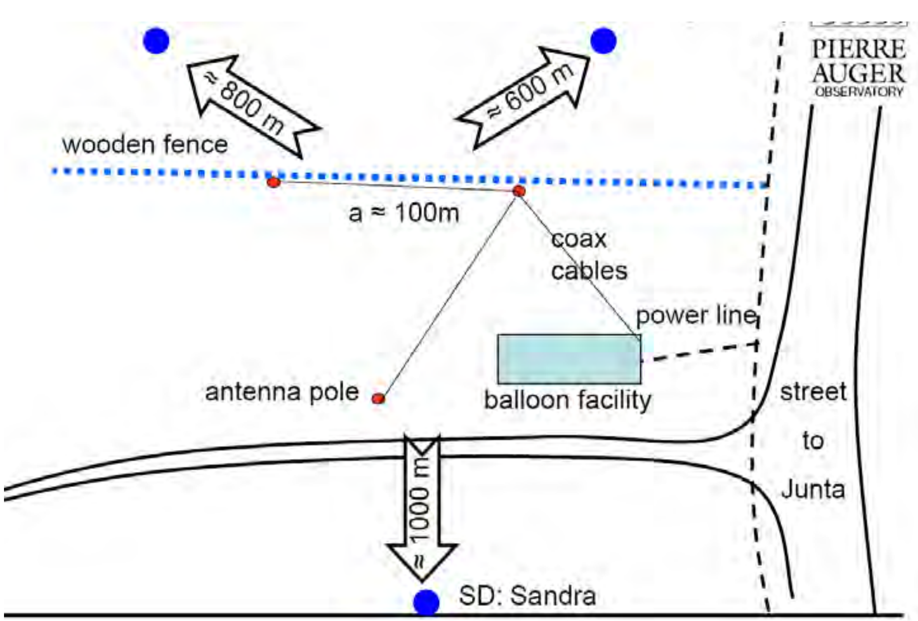


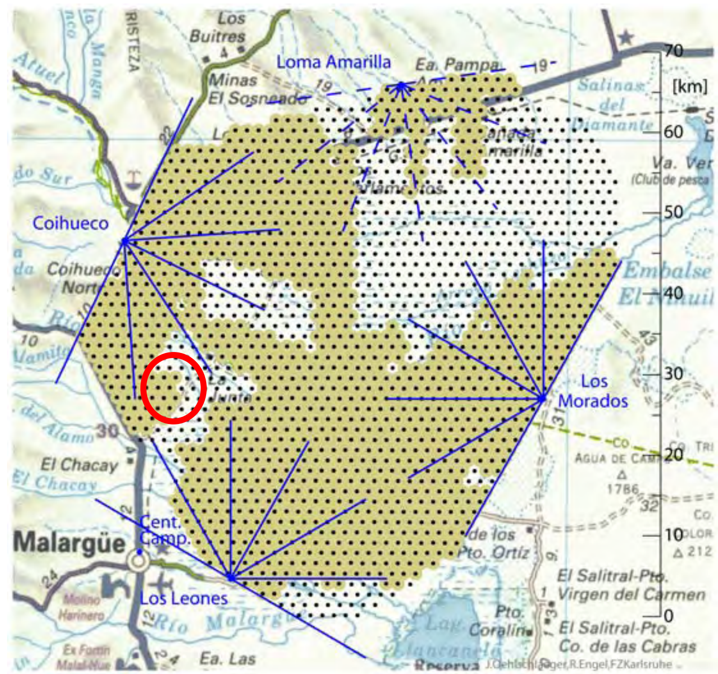


Krömer et al. – LOPES collaboration, SPIE 2005

LOPES^{STAR}: test station at Auger Observatory

- close to Balloon Launching Station
- flexible setup
- define hardware and measure background
- test trigger system
- test hardware
- installation in 2006
- ask for additional tank





LOPES: next steps

LOPES 10

- continuation data analysis

LOPES 30

- continuation absolute calibration LOPES 30
- monitoring environmental conditions
- continuation data taking LOPES 30
- analysis of LOPES 30 data
- polarisation measurements
- comparison with simulations

Simulations

- inclusion in CORSIKA

LOPES^{STAR}

- data taking in Karlsruhe
- tests and improvements hard- and software
- setup in Argentina

Summary : LOPES

- Successful cooperation of Radioastronomy and Astroparticle Physics groups
- LOPES 10:
  - ➔ Large Sample of radio detected showers
  - ➔ Detailed analyses of central events, distant events, inclined showers, thunderstorm events

➔ Proof of Principle

- LOPES 30
  - ➔ absolute calibrated, higher energies, longer maximum baseline
  - ➔ direct comparison of simulations with measurements

➔ Precision measurements for energies up to 10^{18}eV

- LOPES^{STAR}
  - ➔ autonomous system, self-trigger system, test facility for Auger application

➔ Optimization for large scale application

➔ LOPES will calibrate the radio signal in EAS (with all the dependencies on cosmic ray parameters)

LOPES Collaboration

ASTRON, Dwingeloo, The Netherlands
L. Bähren, H. Butcher, G. de Bruyn, C.M. de Vos, H. Falcke, G.W. Kant, Y. Koopman, H.J. Pepping, G. Schoonderbeek, W. van Capellen, S. Wijnholds

Department of Astrophysics, Nijmegen
The Netherlands
S. Buitink, A. Horneffer, J. Kuijpers, S. Lafebre, A. Nigl, J. Petrovic, K. Singh

National Institute of Physics and Nuclear Engineering
Bucharest,Romania
A. Bercuci, I.M. Brancus, B. Mitrica, M. Petcu, O. Sima, G. Toma

Universität Wuppertal, Germany
R. Glasstetter, K.H. Kampert, J. Rauthenberg

Universität Siegen, Germany
M. Brüggemann, P. Buchholz, C. Grupen, Y. Kolotaev, S. Over, W. Walkowiak, D. Zimmermann

Max-Planck-Institut für Radio-
astronomie, Bonn, Germany
P.L. Biermann, J.A. Zensus

Istituto di Fisica dello Spazio
Interplanetario, Torino, Italy
P.L. Ghia, C. Morello, G.C. Trinchero

Soltan Institute for Nuclear Studies, Lodz, Poland
P. Luczak, A. Risse, J. Zabierowski

Institut für Kernphysik,
Forschungszentrum Karlsruhe, Germany
W.D. Apel, A.F. Badea, K. Bekk, J. Blümer, H. Bozdog, F. Cossavella, K. Daumiller, P. Doll, R. Engel, A. Hakenjos, A. Haungs, D. Heck, T. Huege, P.G. Isar, H.J. Mathes, H.J. Mayer, C. Meurer, J. Milke, S. Nehls, R. Obenland, J. Oehlschläger, S. Ostapchenko, T. Pierog, S. Plewnia, H. Rebel, M. Roth, H. Schieler, H. Ulrich, J. van Buren, A. Weindl, J. Wochele

Institut für Prozessdatenver-
arbeitung und Elektronik, FZK, Germany
T. Asch, H. Gemmeke, O. Krömer

Dipartimento di Fisica Generale
dell'Universita, Torino, Italy
M. Bertaina, A. Chiavassa, F. di Pierro, G. Navarra

Institut für Experimentelle
Kernphysik Universität Karlsruhe, Germany
E. Bettini, M. Deutsch, A. Hakenjos, J.R. Hörandel, M. Stümpert