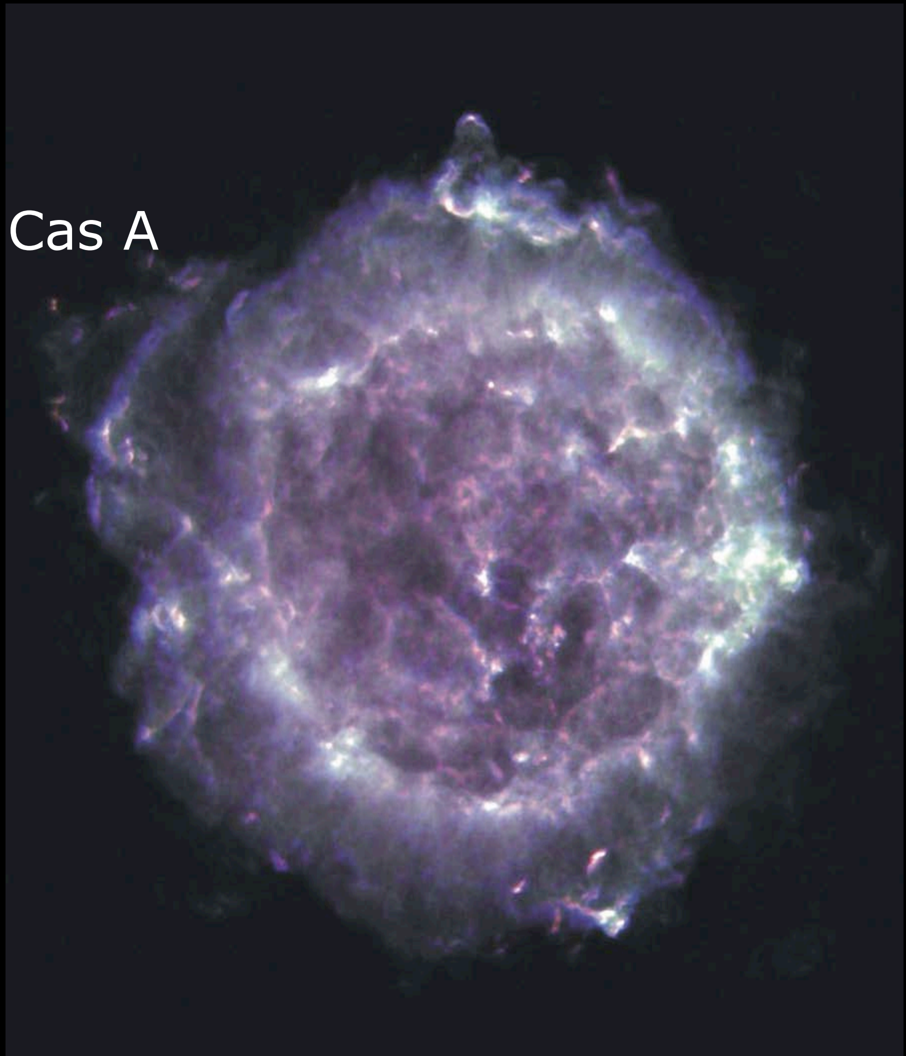
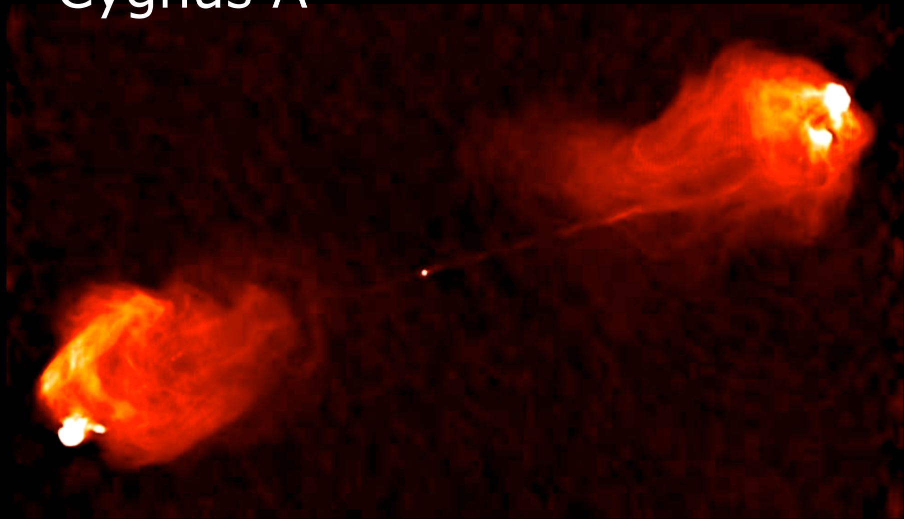
# Radio Images of Cosmic Accelerators

at 1.4 , 5, & 8.4 GHz




Cygnus A



NRAO/AUI

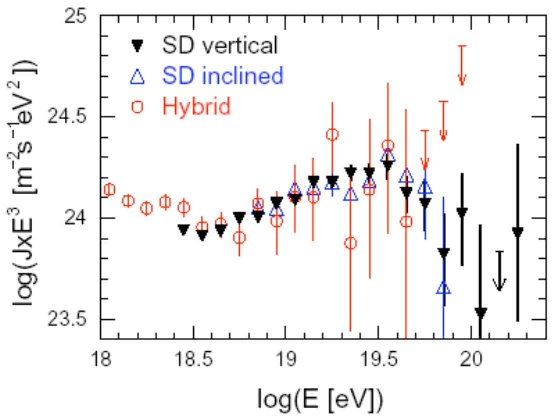
... is there anything else that radio images may offer

# Radio Detection of Ultra High Energy Cosmic Rays

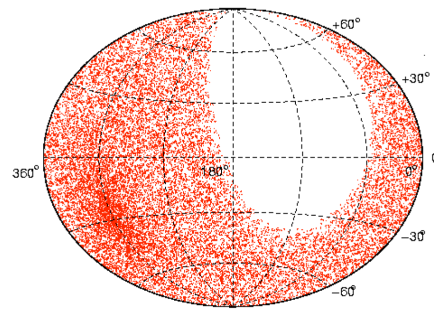
Hartmut Gemmeke on behalf of LOPES and Auger Collaboration
at 13th Lomonosov Conf. 2007

**Goals** for detection of UHECRs:

1. Understand the high energy part of the spectra
2. Find the sources or accelerators in the universe



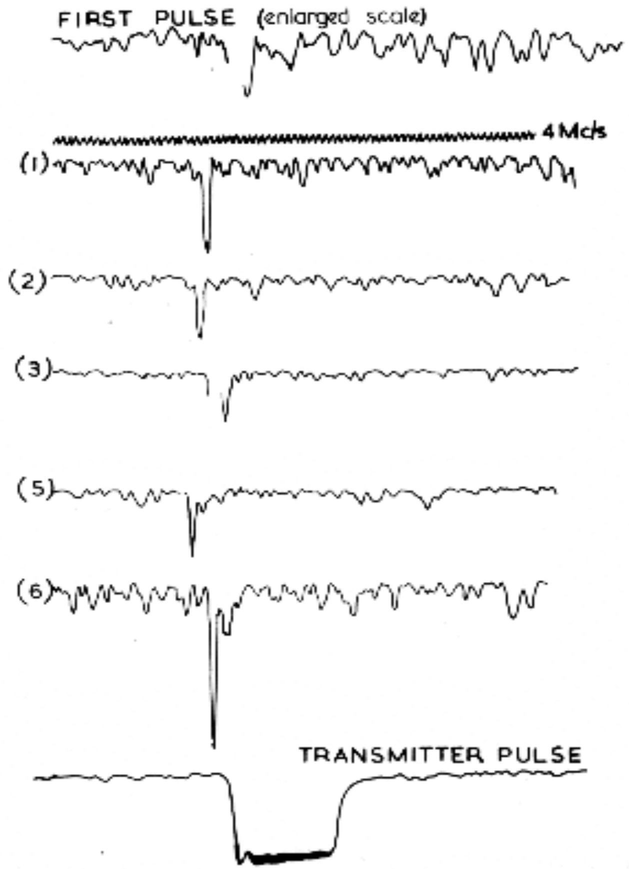

Therefore any new tool to fix **energy scale** and allow good **pointing** is welcome



# Radio Emission from Air Showers:
## A Very Brief History

- **Prediction of Cherenkov-like radio emission process (Askaryan 1962).**
- **Radio pulse discovered at Jodrell Bank at 44 MHz (Jelley et al. 1965, thesis of Weekes).**
- **Colgate makes 1967 first transverse current theory based on geo-synchrotron effect in air with dominating non-Cerenkov radio emission**
- **1970ies various experiments testing the geomagnetic origin, but problems with data acquisition (oscilloscopes!) and interference.**
- **1971 H.R. Allan, Progress in Elementary Particle Cosmic Ray Physics 10(1971)169-302**
- **1990ies upper limits at CASA-MIA and EAS-TOP with single antenna**
- **Revival through digital radio techniques & prediction of "geo-synchrotron" (Falcke & Gorham 2003)**

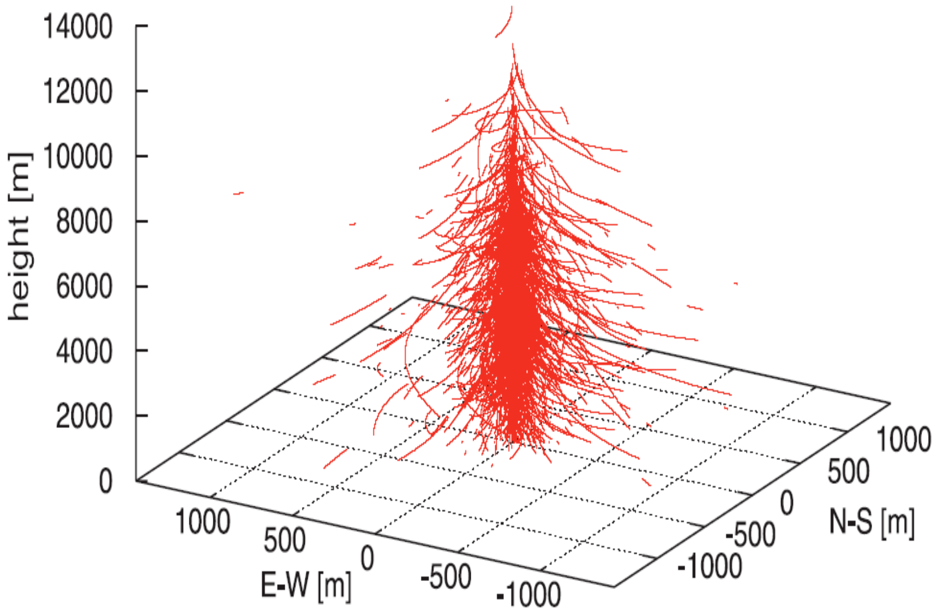
**Oscilloscope traces of CR radio pulses**



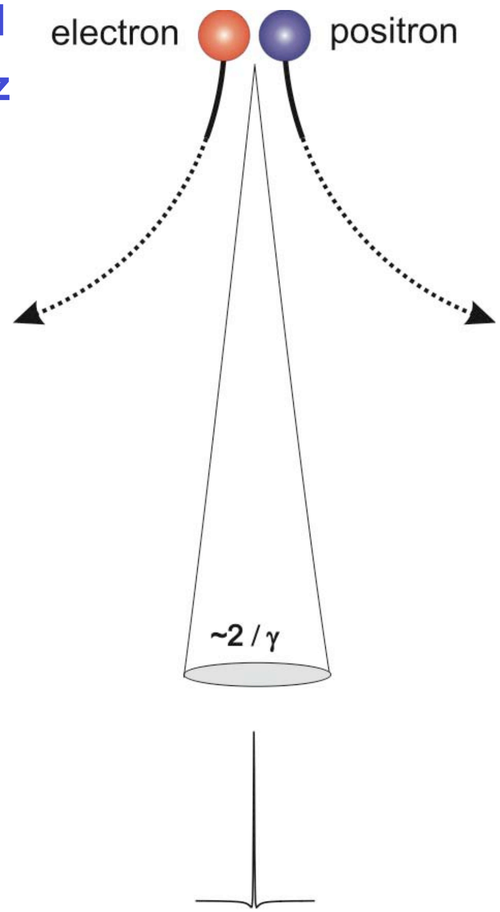

Thesis of T.C. Weekes & Jelley et al. (1965)

# How works the Geo-Synchrotron Effect

- Cosmic Rays produce a particle cascade in air containing also $e^-$ and $e^+$

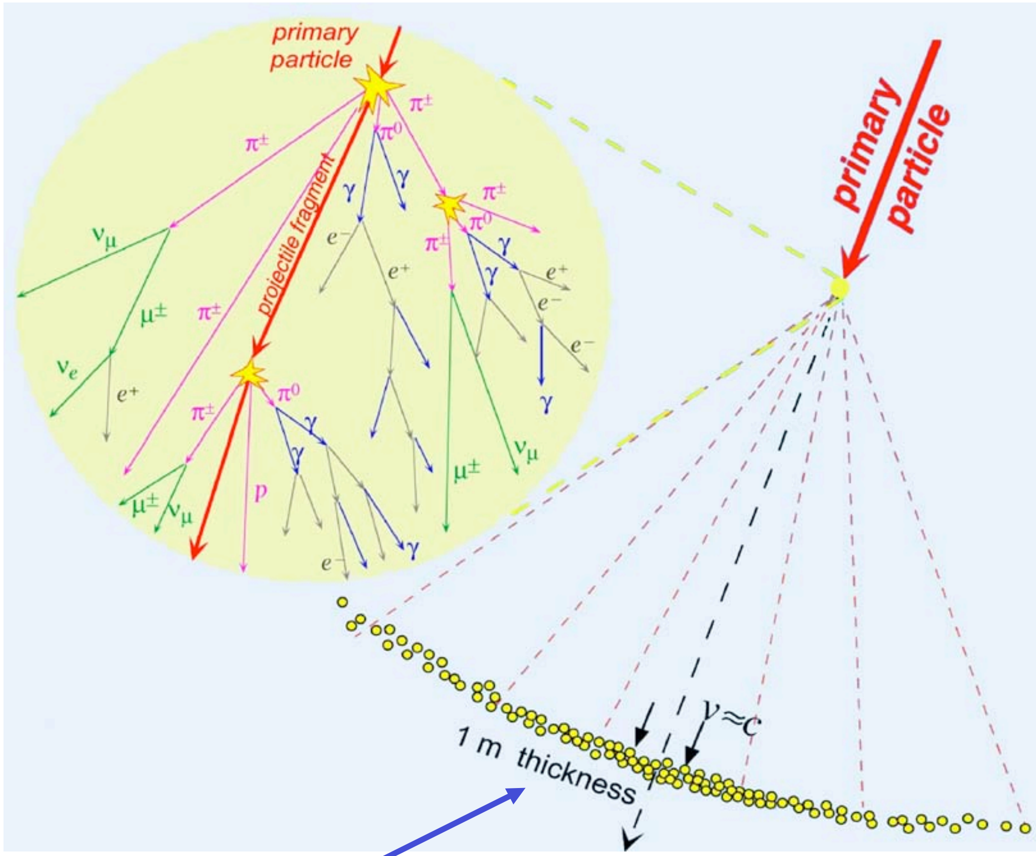



- $e^-$ and $e^+$ gyrate in the geomagnetic field of the earth
  - ⇒ **acceleration**
  - ⇒ **Geo-Synchrotron Radiation** in forward direction
  - ⇒ $\Delta\alpha \approx 2/\gamma$ and
  - ⇒ $f < 100$ MHz



# Properties of Radio Emission from Air Showers

- *Practical **no attenuation** in air* therefore
  - *Good for distant and inclined showers*
  - *Bolometric* measurement
- **"cheap" detector and easy to deploy**
- ***Coherence* gives quadratic dependence on energy**
- **Also useable for neutrino induced showers**
- ***Detection* limited by galactical radio noise to $E_p \geq 10^{16.5}$ eV**
- ***High duty cycle* (day & night) in comparison to FD**

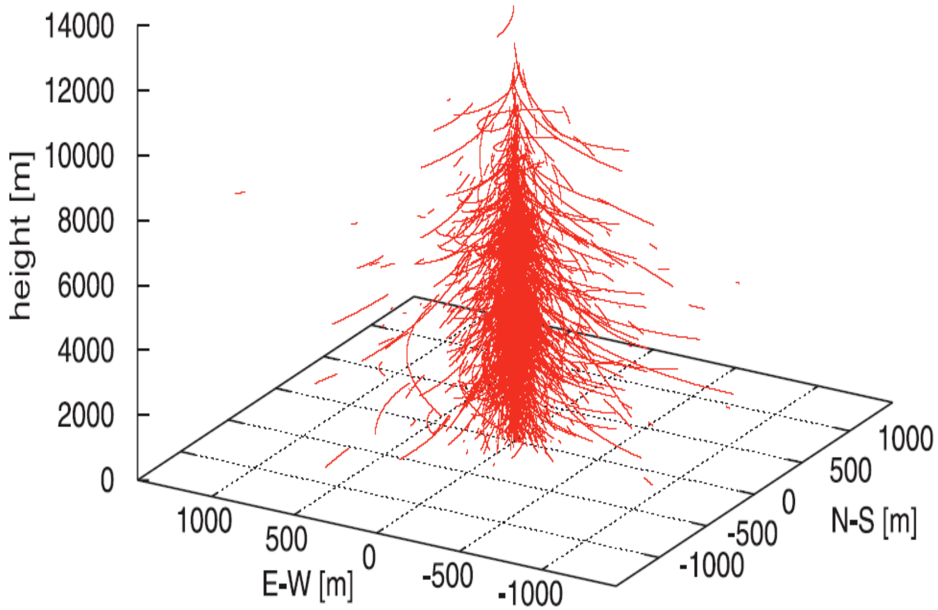



delivers coherence

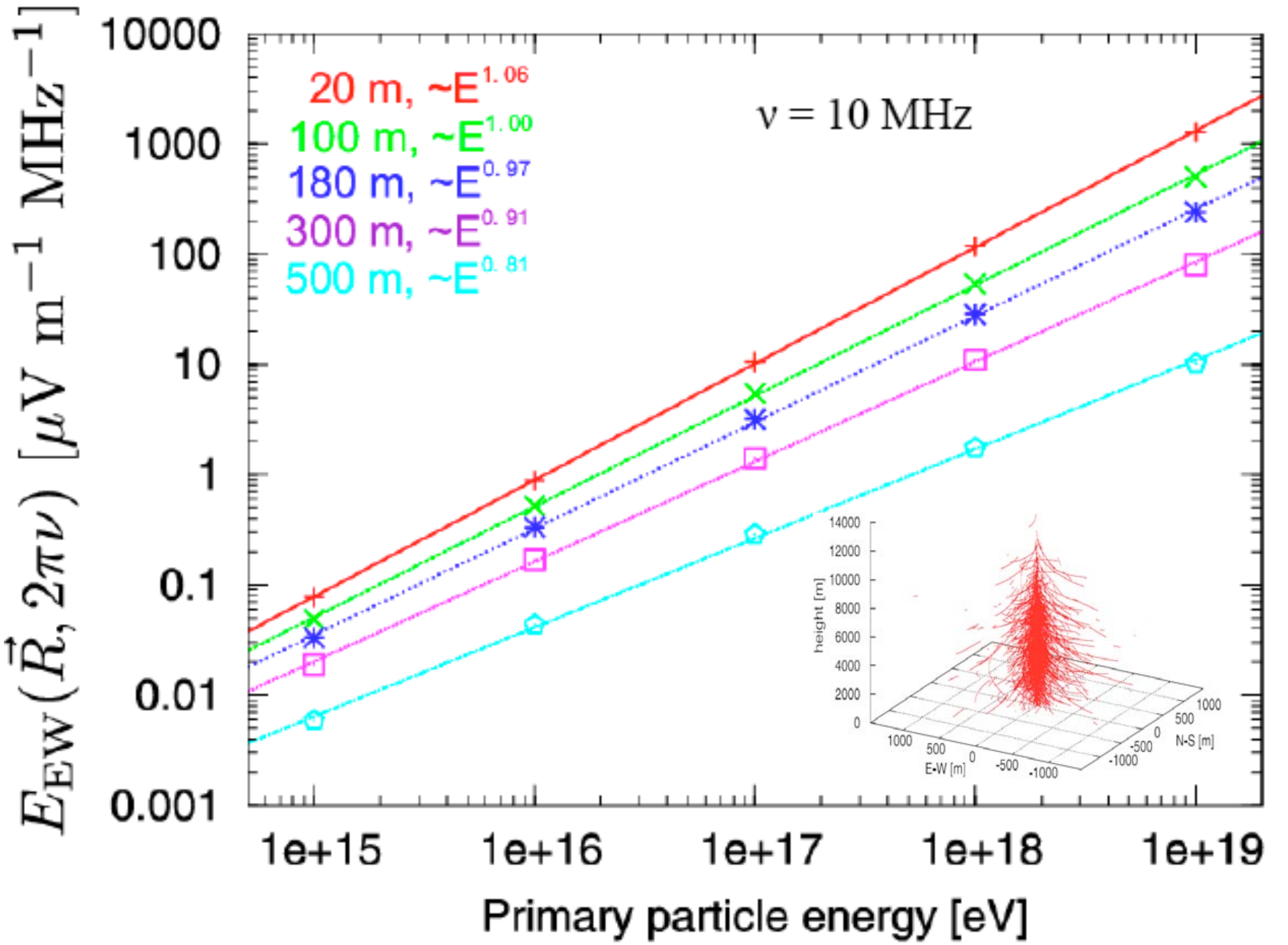
# Simulation of Radio Emission from Cosmic Rays

- **2005: Monte Carlo simulations based on parameterized air showers**

- **2006: full Monte Carlo simulations based on CORSIKA by histogramming (T. Huege Reas2), includes**
  - longitudinal & lateral particle distributions
  - particle track length & energy distributions
  - air shower and magnetic field geometry



# Simulation: Scaling with $E_{pp}$(vertical shower)




- Nearly **linear scaling**

  $|\vec{E}_{EW}| \propto E_{pp}$

  -> $E_{EW} \propto E_{pp}^2$

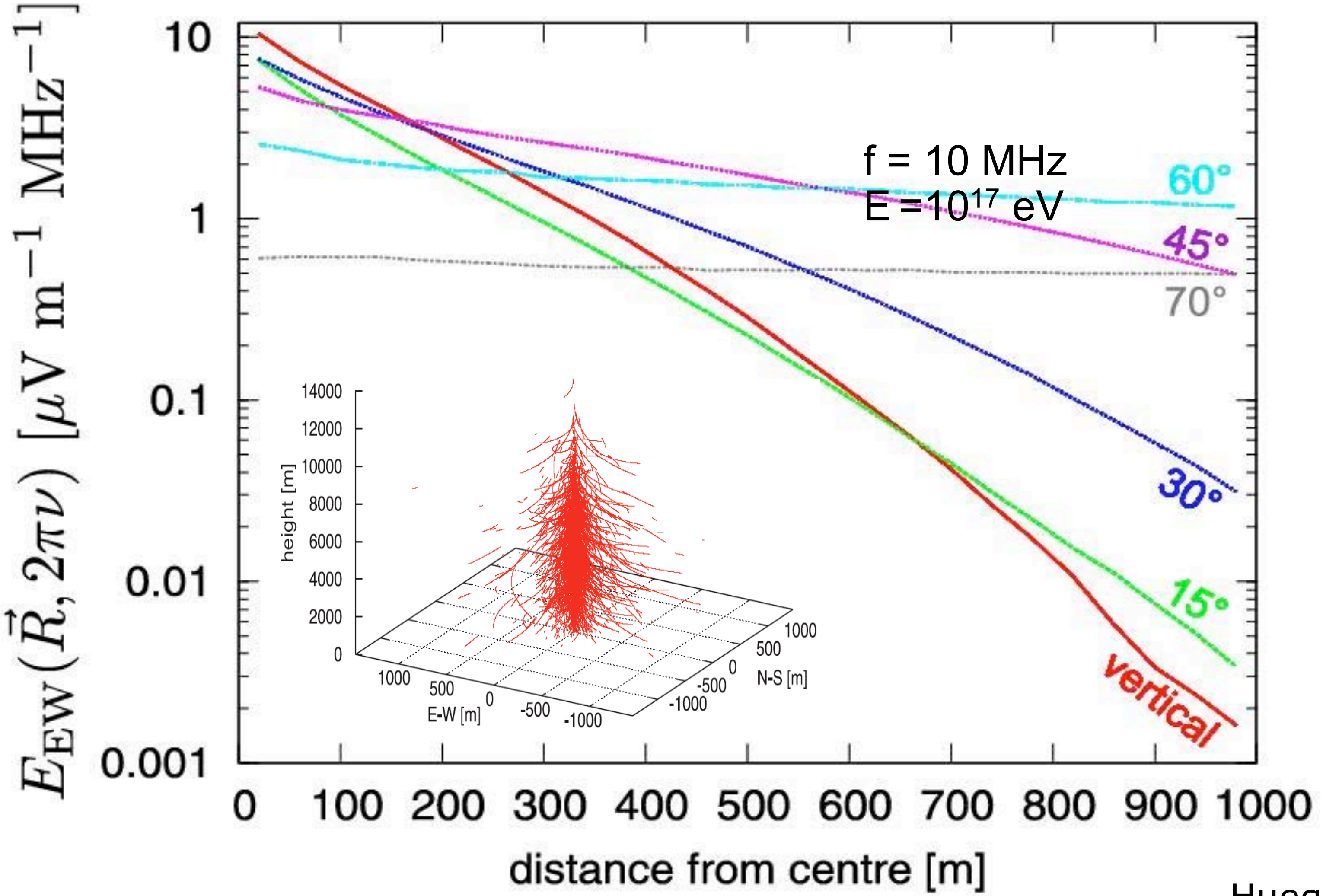
  **coherent** effect

- Radio is **bolometric**: atmosphere for h < 8 km transparent

- Flattening with increasing distance

**T.Huege, Thesis**

# Simulation: lateral profiles




**flattening** with increasing zenith angle

approx. **exponential scaling**

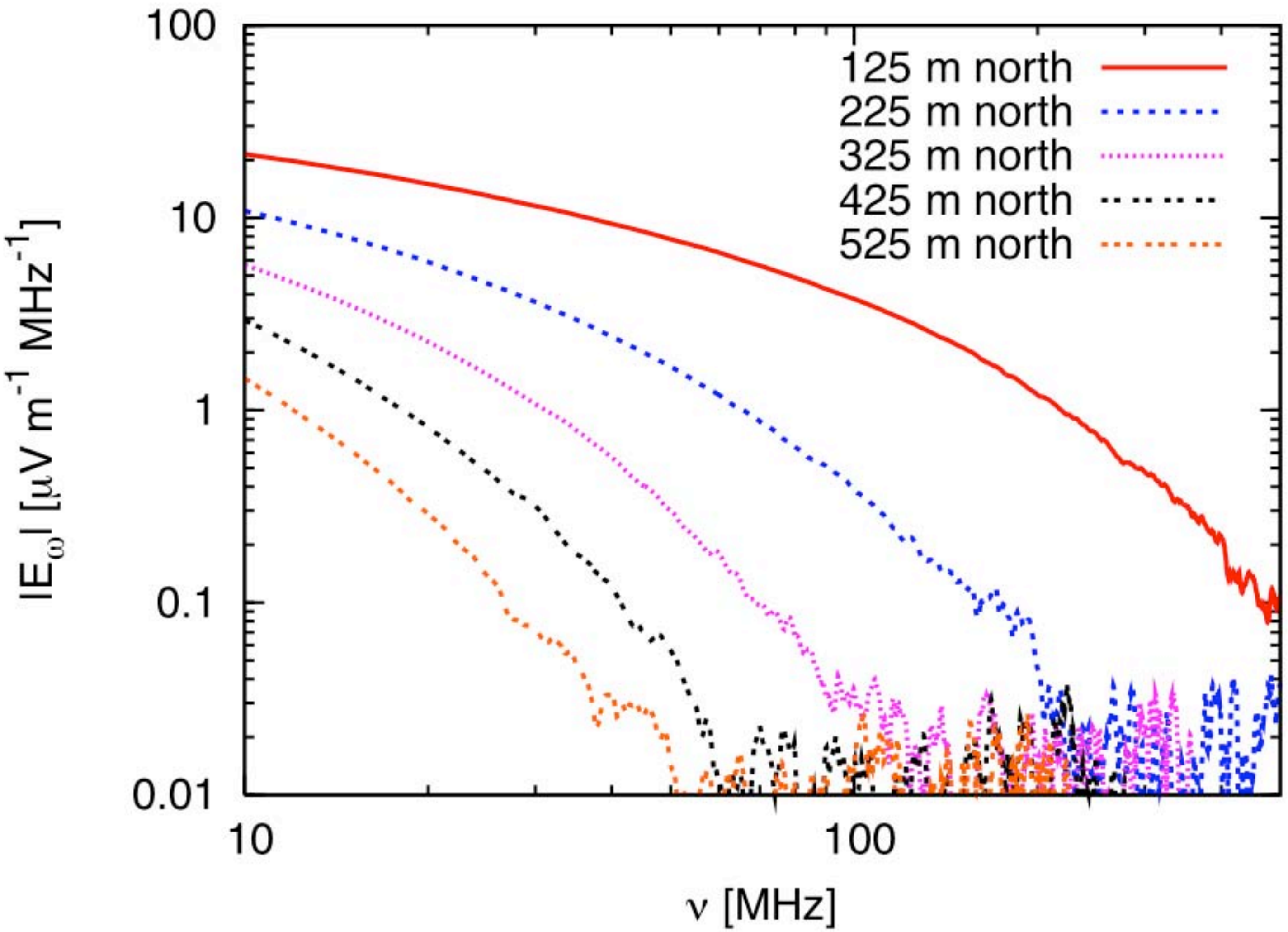
**$R_0$ = 100 ... 800 m**

⇒ **Inclined showers can be seen at large distances**

Huege & Falcke (2005)

# Frequency dependance of radio signal

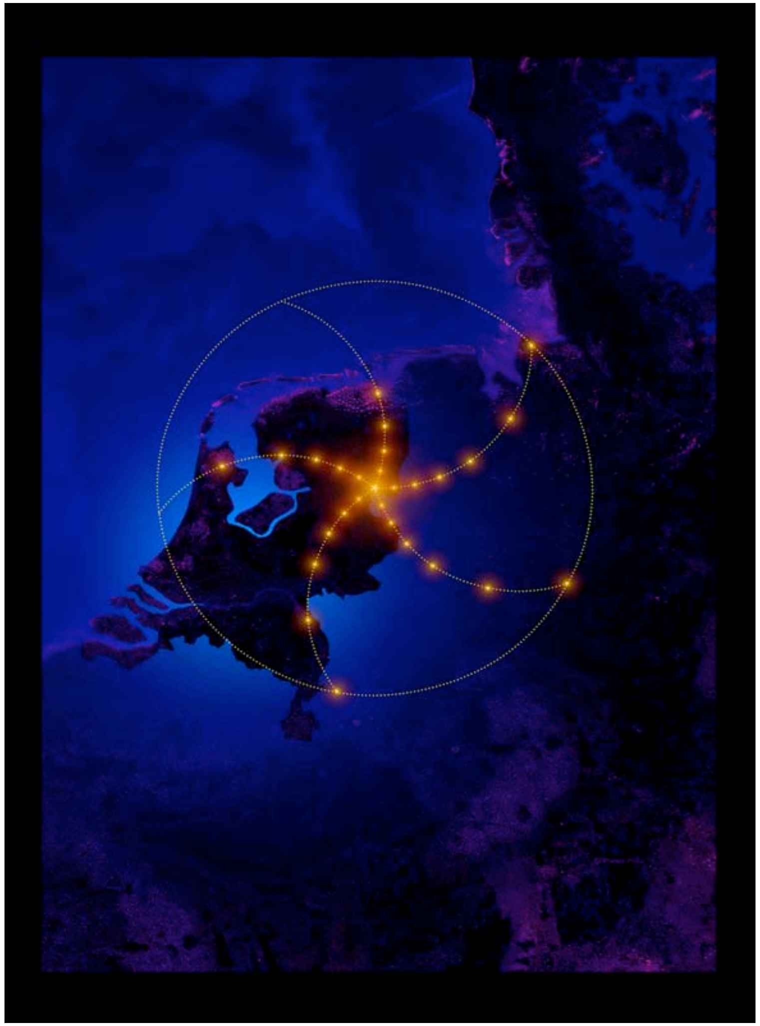
**zenith angle 30°, $E_{pp} = 10^{18}$ eV**




- **spectra steeper at higher distances**
- **low frequencies better for large grid spacings**

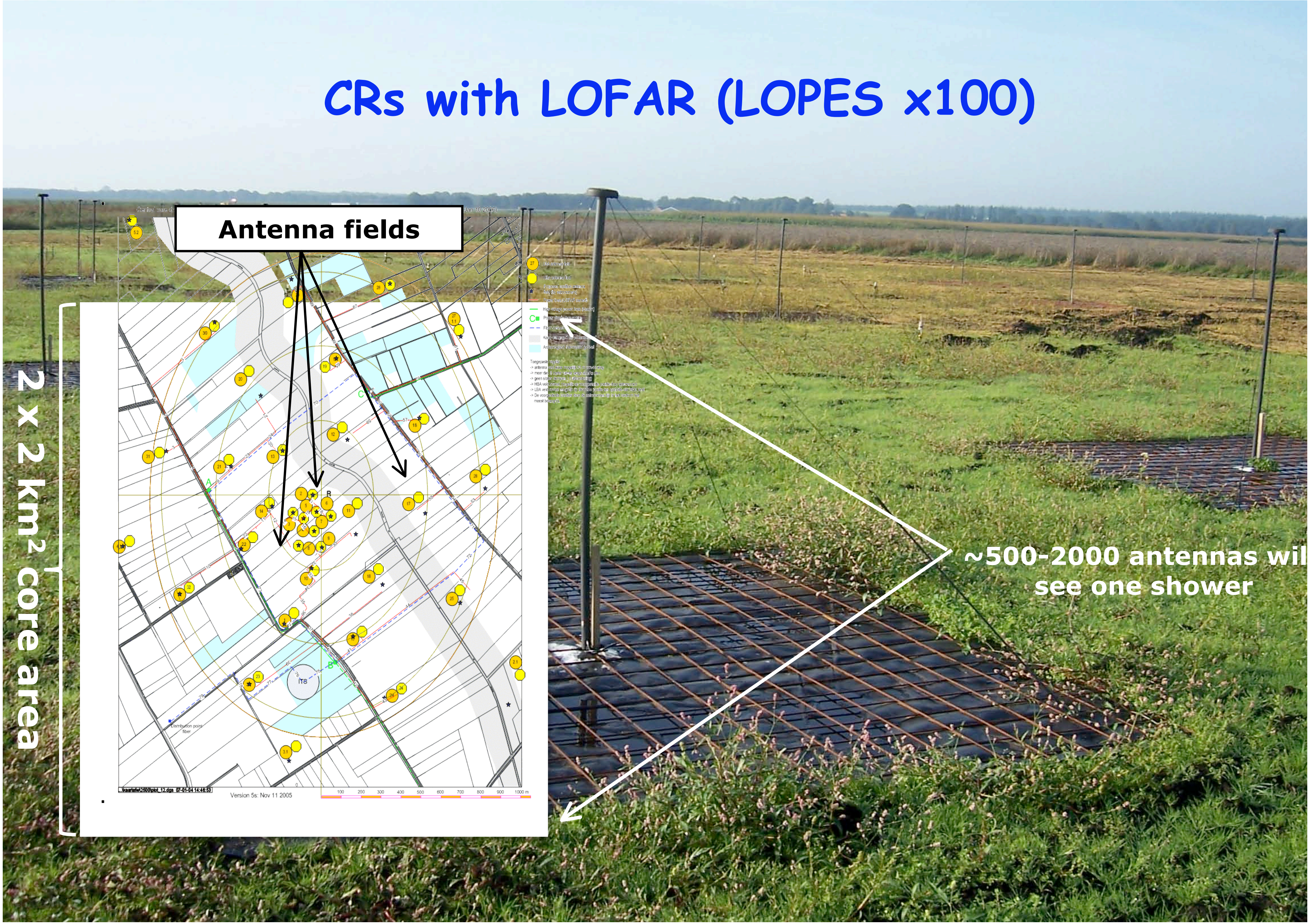
T. Huege 2006

# Experiments: LOw Frequency ARray LOFAR



- ≥ 4 000 antennas
- with 2 000 antennas (10-90 MHz and 110-240 MHz) in 4 km$^2$ core area
  - remote stations out to 2-3 hundred kilometers
  - connected by high-speed internet
- applications:
  - Cosmology,
  - bursting universe,
  - Cosmic Rays & Neutrinos above $10^{18}$ eV
- $1_{st}$ station operational 2007/8

- 2003 Netherland-German Collaboration LOPES = LOFAR PrototypE Station at Karlsruhe

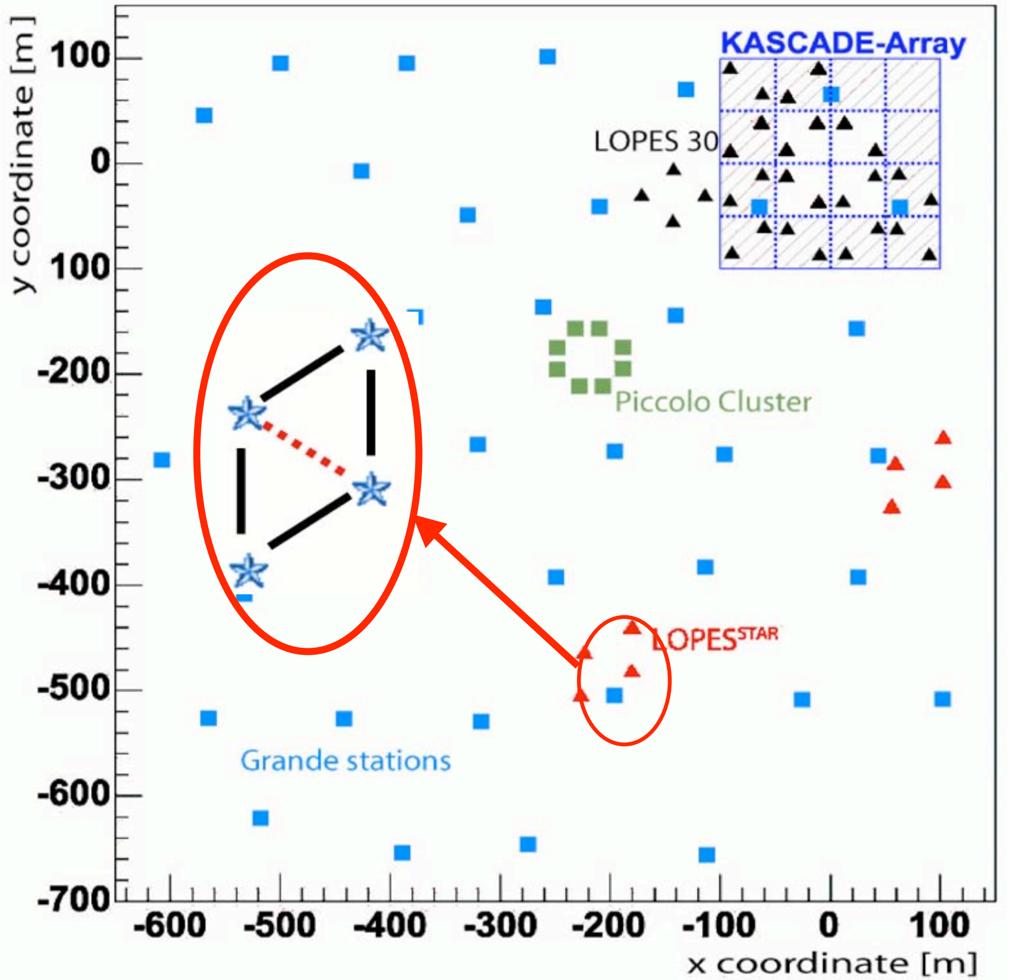

CRs with LOFAR (LOPES x100)
Antenna fields
2 x 2 km² core area
~500-2000 antennas wil
see one shower
Version 5s: Nov 11 2005
Distribution point fiber
100 200 300 400 500 600 700 800 900 1000 m

# KASCADE-Grande the Test-Bed for LOPES

## LOPES10,30 ⇒ LOPES$^{STAR}$

**Lofar PrototypE Station** **Self-Triggered Array of Radio detectors**

**Plan of Site: KASCADE-Grande (Karlsruhe)**



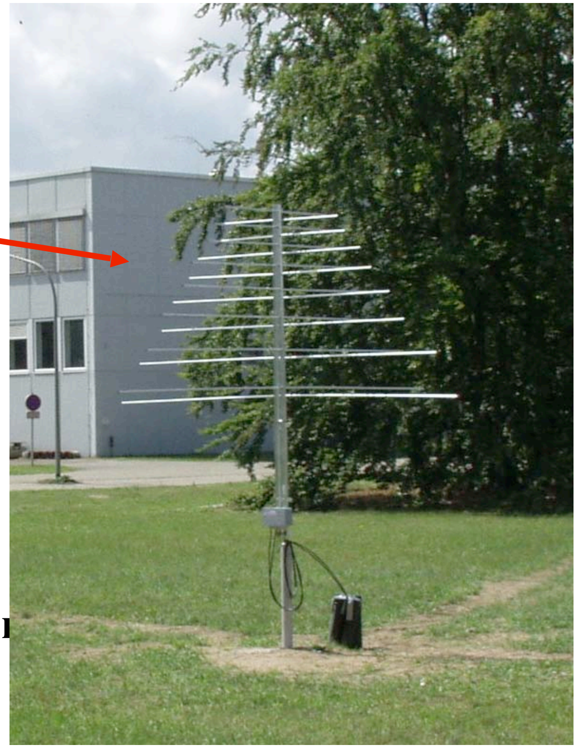

V-Dipole (LOPES30) &

Logarithmic Periodically Dipole-Antenna (LPDA)

both observe radio emission between 40 – 80 MHz

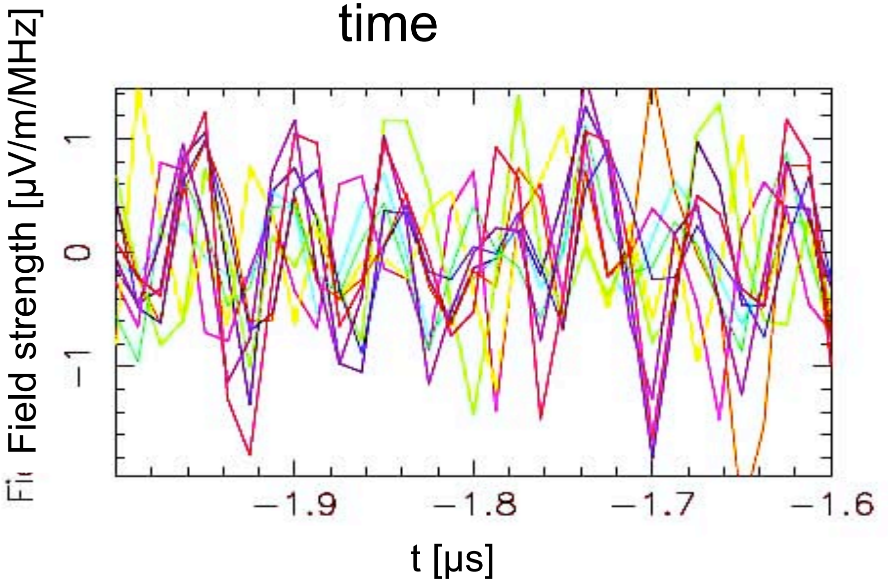
dual-polarisation (North/South & East/West )

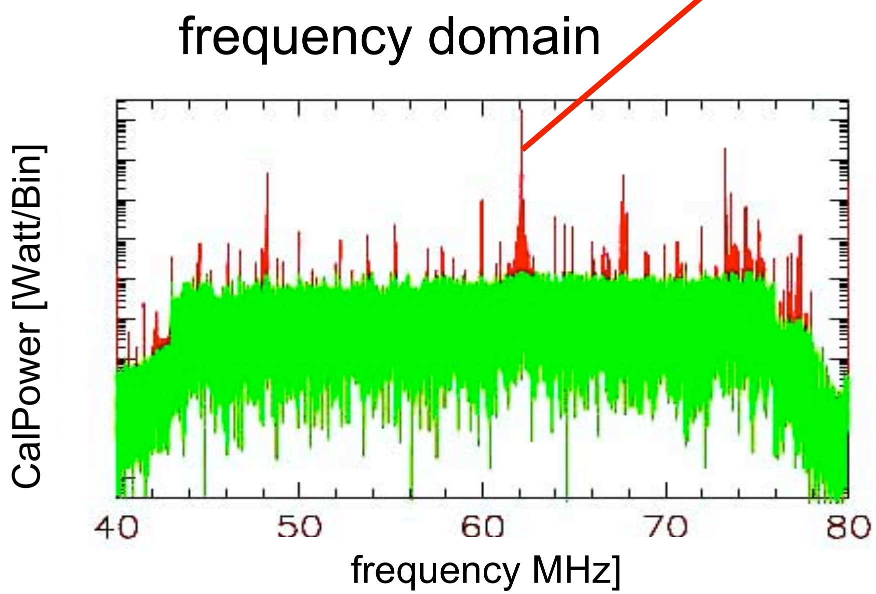
LOPES$^{STAR}$ has triangular trigger structure

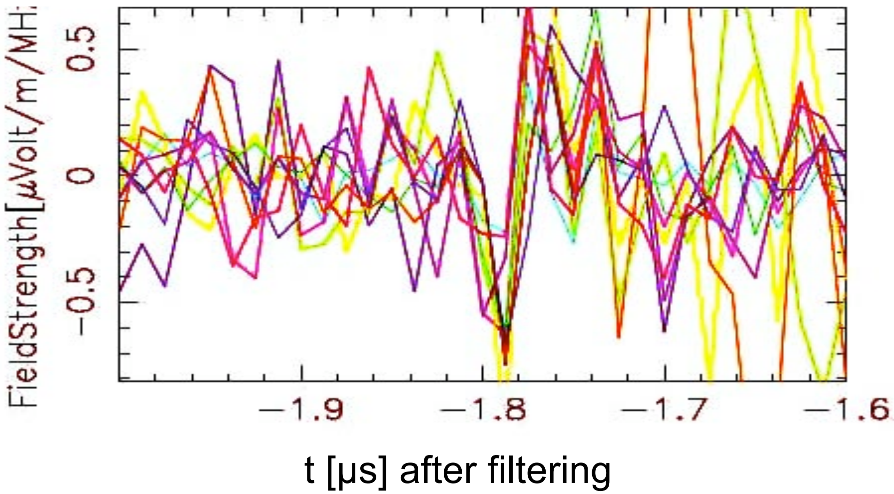


# RFI Filtering LOPES

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




- **Unfiltered data** **A.Horneffer 2006, Thesis**
- **Fourier transformation and filter**
- **Filtered data**

  **⇒ Correlation appears**

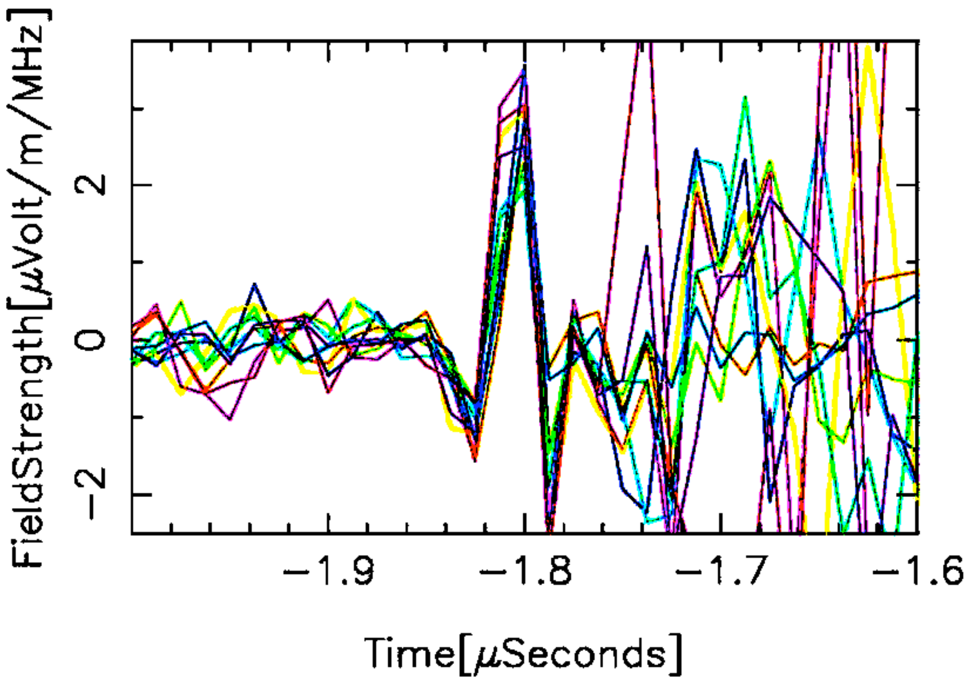
- **LOPES prepares an online Filter in a FPGA**

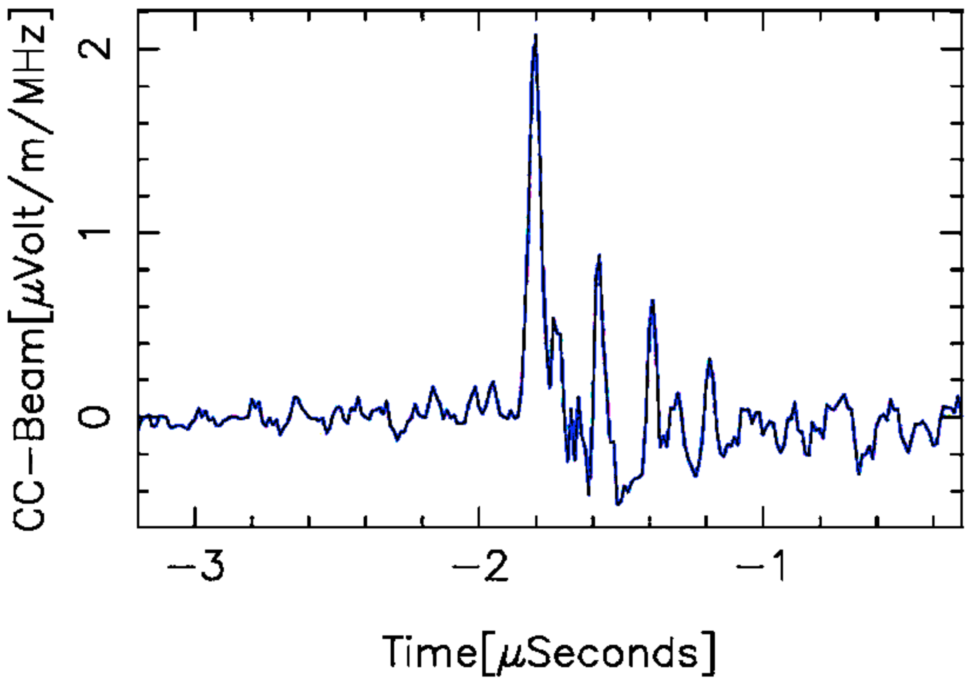
# KASCADE-Grande Triggered Pulse Detection

Electric field for each dipole after correcting for instrumental and geometric delays.

Block-averaged, radio emission as a function of time after beam-forming

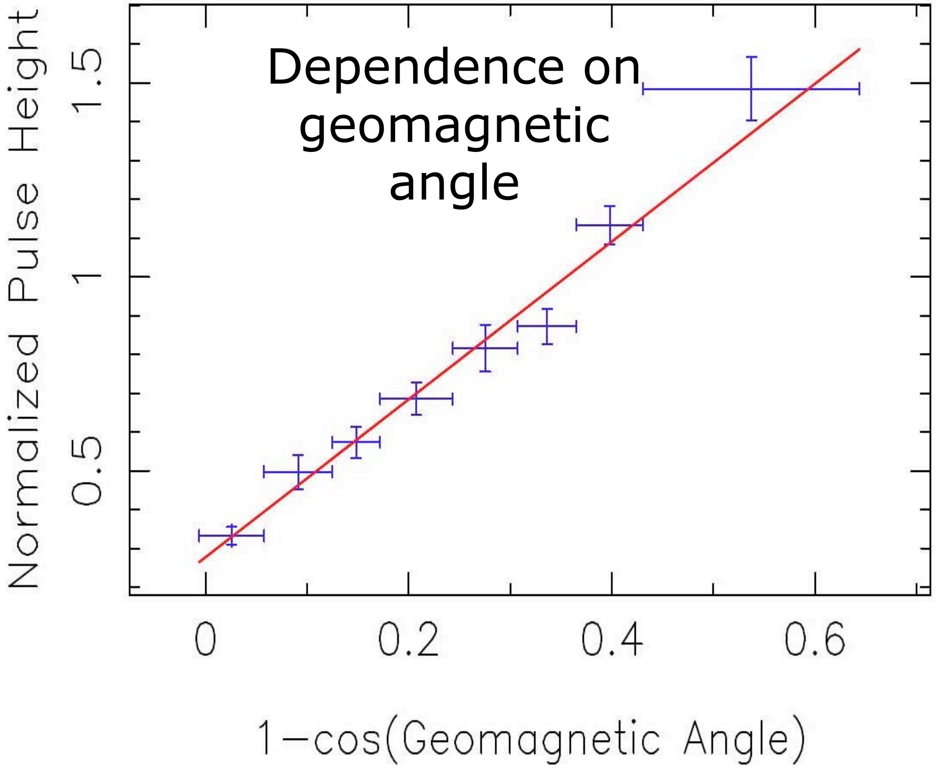
(Correlation analysis)

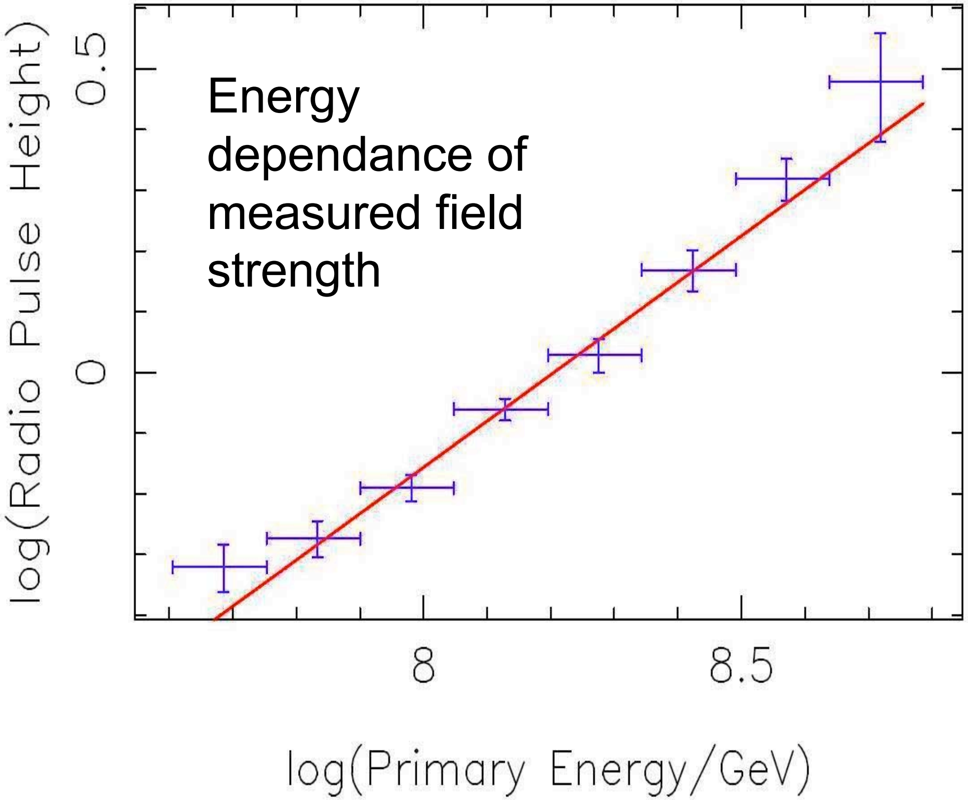



Nature 2005 and A.Horneffer 2006, Thesis

# Calibration of CR Radio Signal with LOPES




1. **Proof** of geo-synchrotron effect
2. Threshold at Karlsruhe 7*$10^{16}$ eV
3. Radio signal is a **good scale for energy**
4. Emission is **coherent**: m ≈ 2.0

**Nature 435, 313 (2005)**

**A.Horneffer 2006, Thesis**

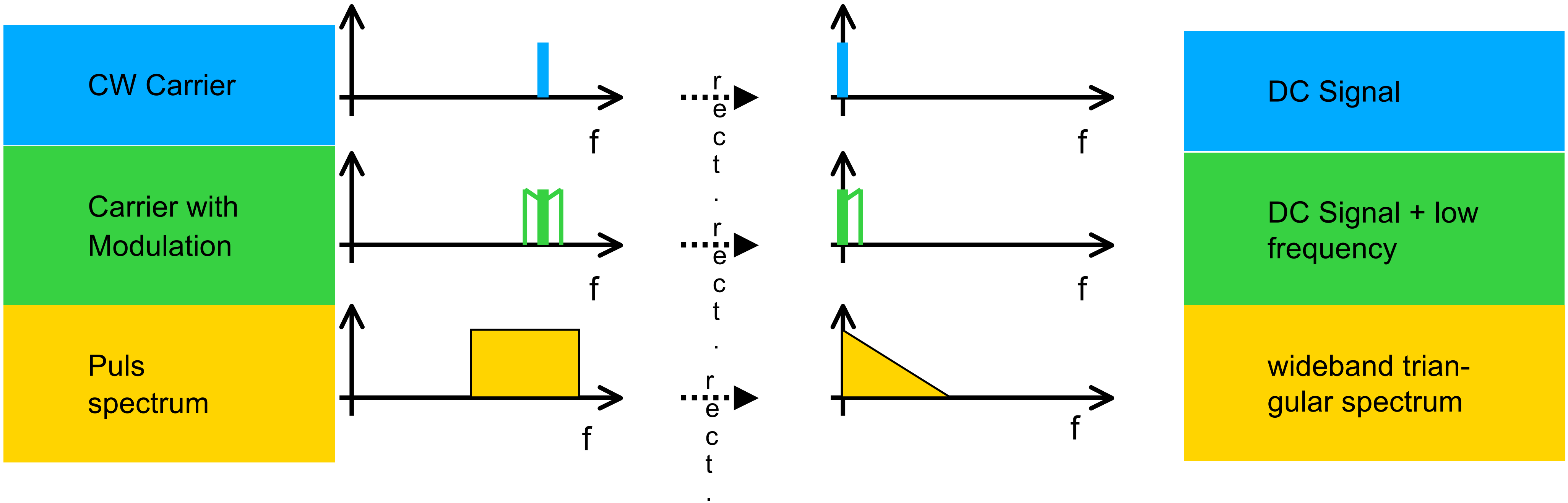
# Transformation to Envelope at LOPES$^{STAR}$ as further trick for background suppression

**The rectifier is a squaring device:** $r(t) = s(t) \cdot s(t) \rightarrow R(j\omega) = S(j\omega) * S(j\omega)$

s(t) → ( )$^2$ → r(t)

multiplication → Convolution

(time domain) (frequency domain)




Rectifier output: Man made RFI turns into DC or low frequency and may be separated from pulse spectrum by high-pass filtering

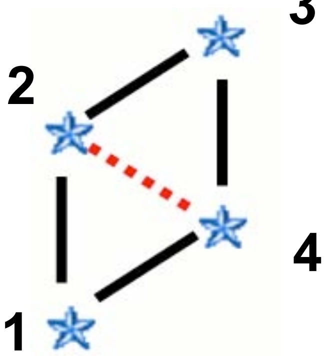
**Use of a high pass filter at 500 kHz after squaring reduces background at Ka by 30% whilst the loss in signal is < 2.5%**

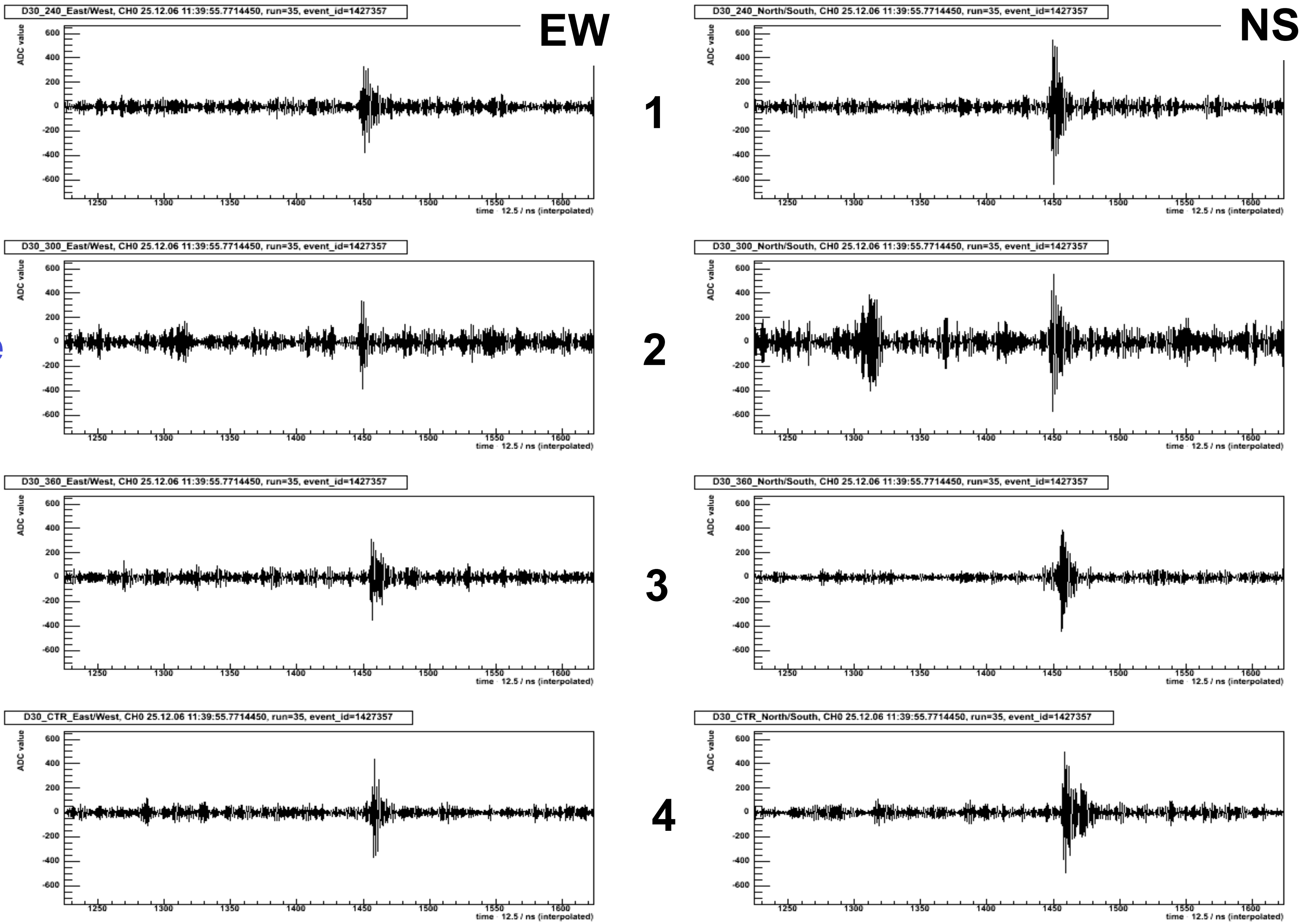
# LOPES$^{STAR}$ event reconstruction

**fixed scaling**

**LOPES$^{STAR}$**
**Azimuth φ = 293°**
**Zenith θ = 48°**

**KASCADE-Grande**
**Azimuth φ = 295°**
**Zenith θ = 44°**
**E ≈ 6 · 10$^{17}$eV**



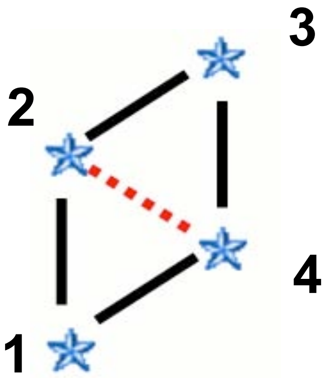



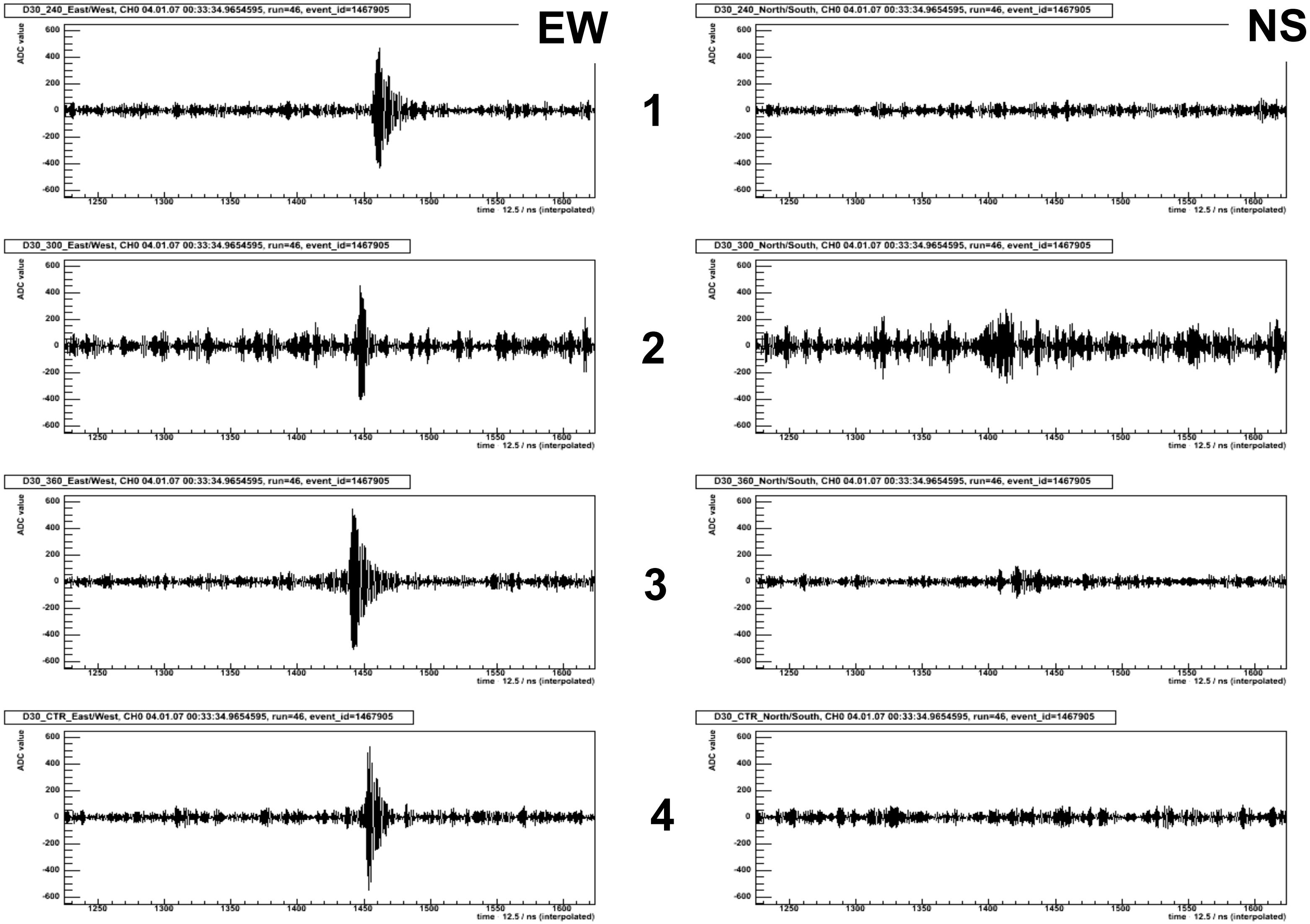
# LOPES$^{STAR}$ event with strong Polarisation

**fixed scaling**

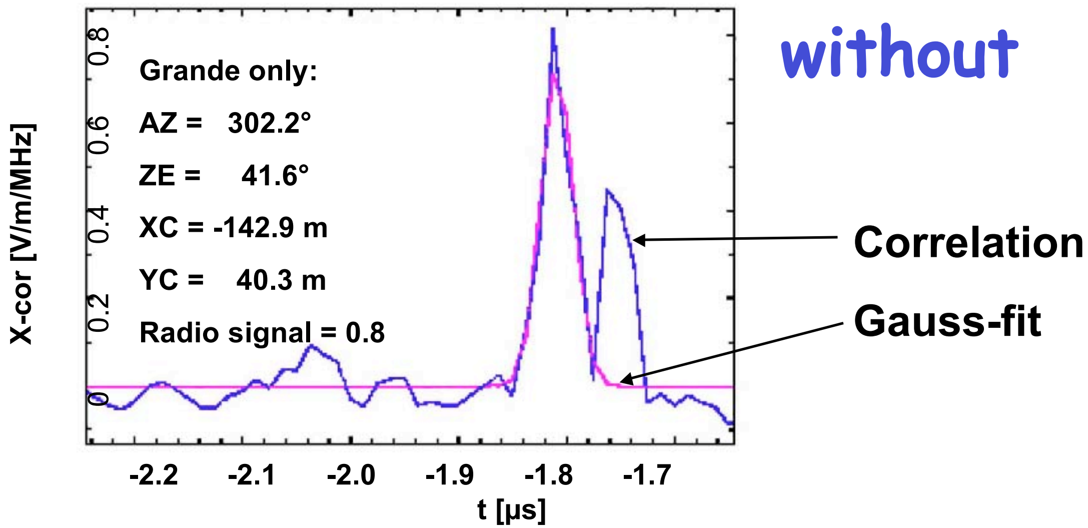
**LOPES$^{STAR}$**
**Azimuth φ = 24°**
**Zenith θ = 66°**

**KASCADE-Grande**
**Azimuth φ = 17°**
**Zenith θ = 63°**
**E ≈ 2 · $10^{17}$eV**



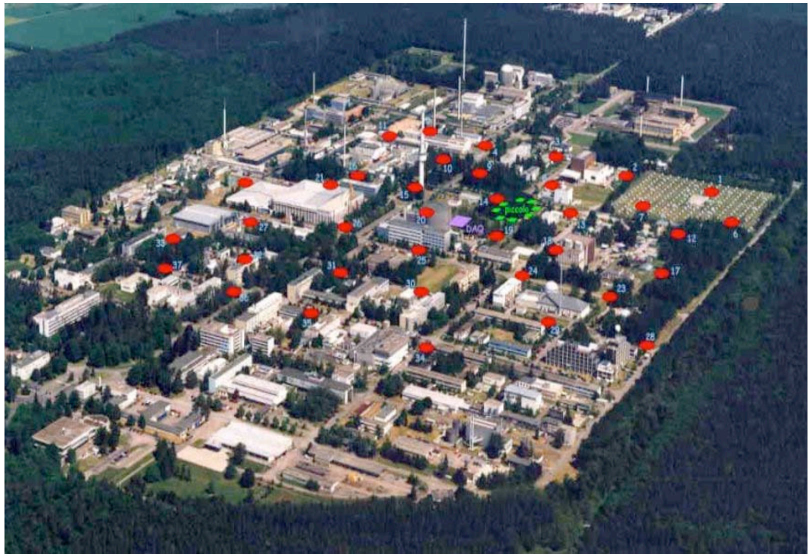



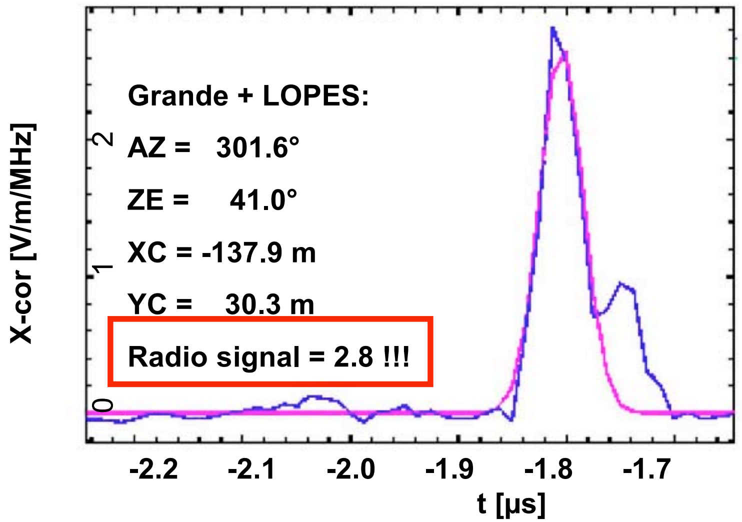
# Reconstruction of KASCADE-Grande events without and with LOPES




## without

Red points





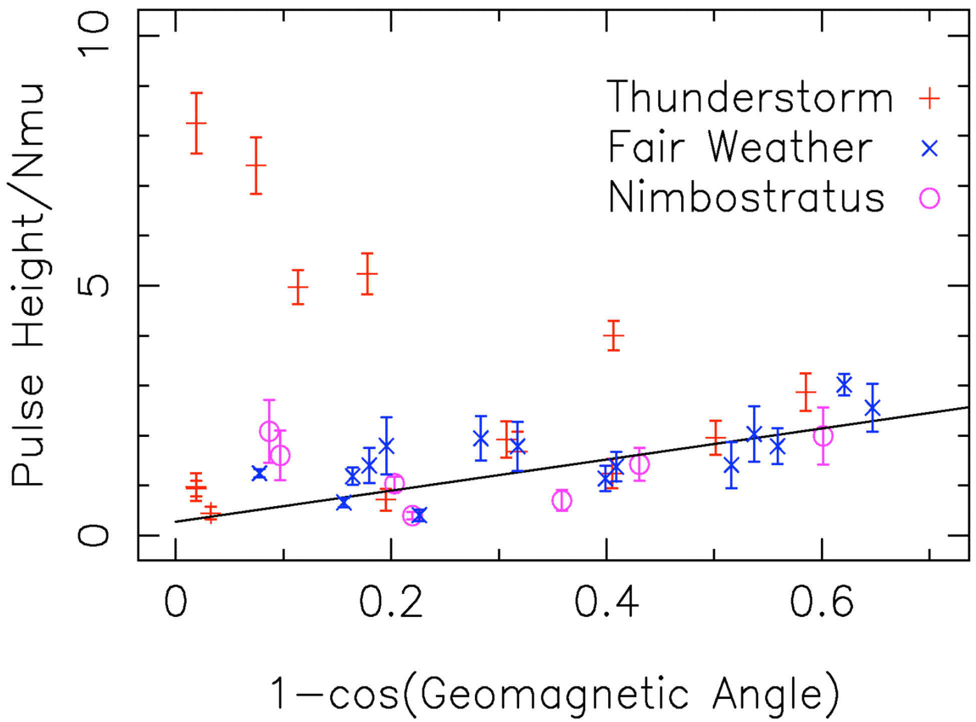

## with LOPES

**Optimized correlation**

**⇒ indication for improvement in precision of direction and core position !?**

# Influence of Thunderstorm on radio signals

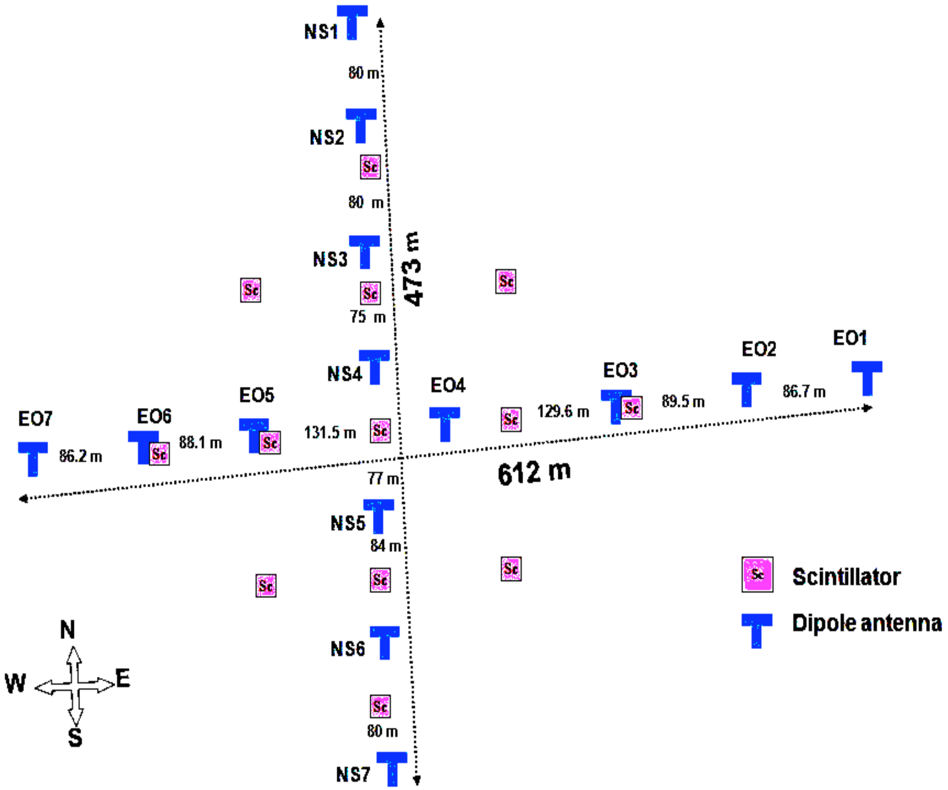
- **Does the Electric field of the atmosphere influence CR radio signal?**
- **For E>10 kV/m E-field force dominates B-field:**
  - **Fair weather: E ≈ 100 V/m**
  - **Thunderstorms: E ≈ 100 kV/m**
- **Select thunderstorm periods from meteorological data:**
  - **⇒ Clear radio excess during thunder storms**
  - **⇒ B-field effect dominates under normal conditions**
  - **⇒ > 90% duty cycle possible**



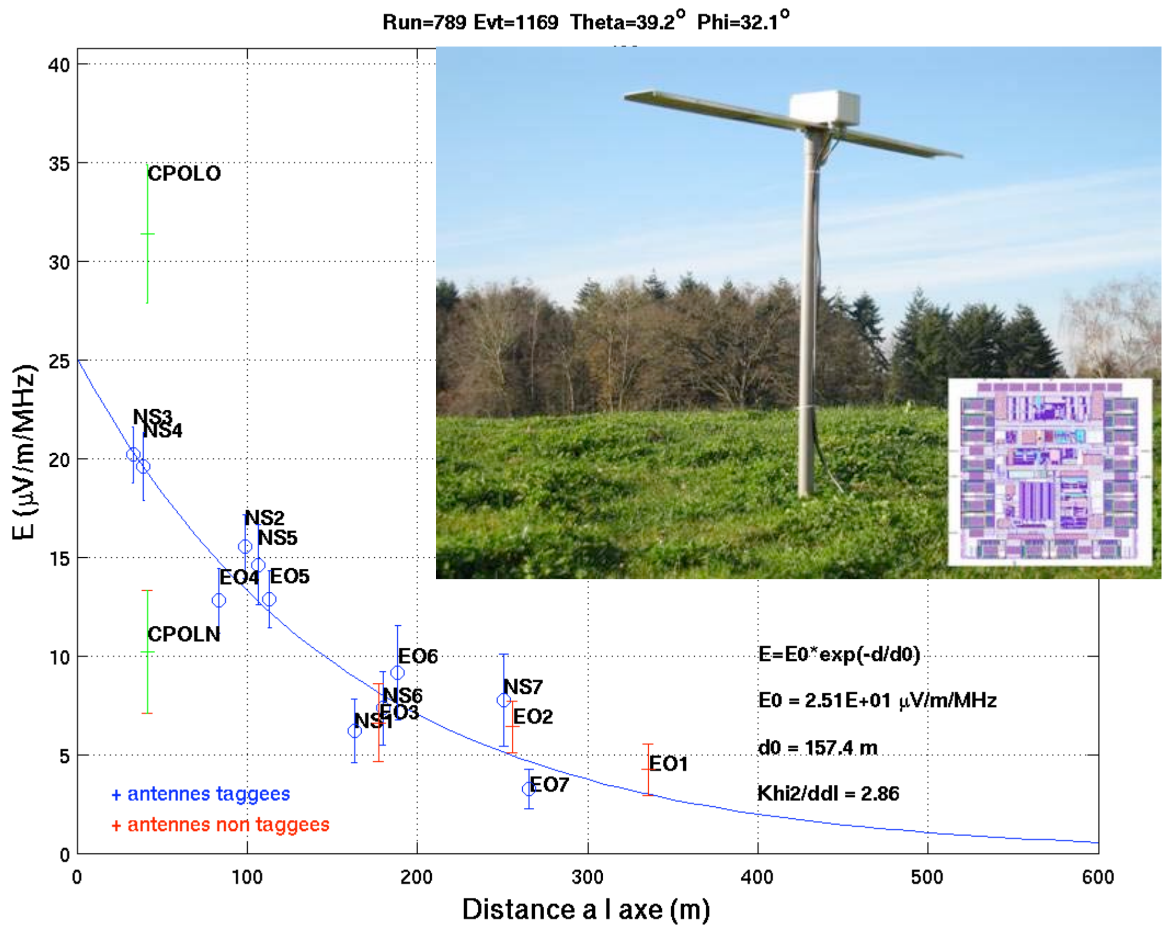

Buitink et al. (LOPES coll.) 2007, A&A

# CODALEMA - Nancay Observatory

Cosmic ray Detection Array with Linear Electro-Magnetic Antennas

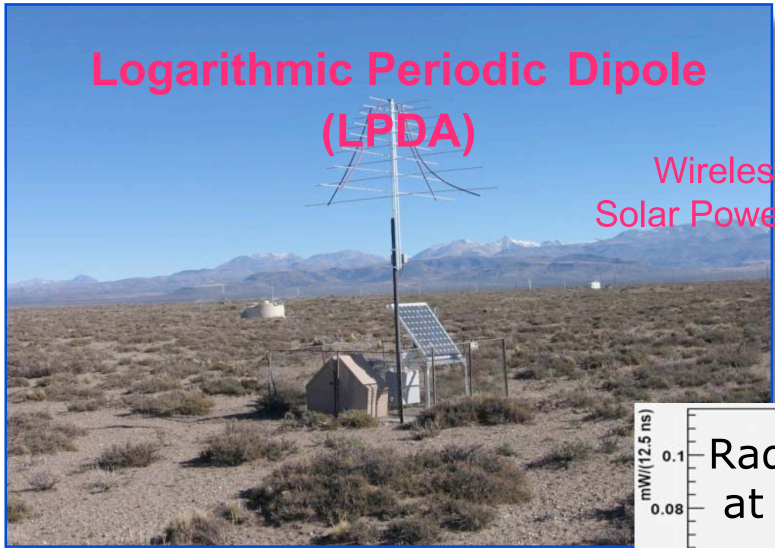


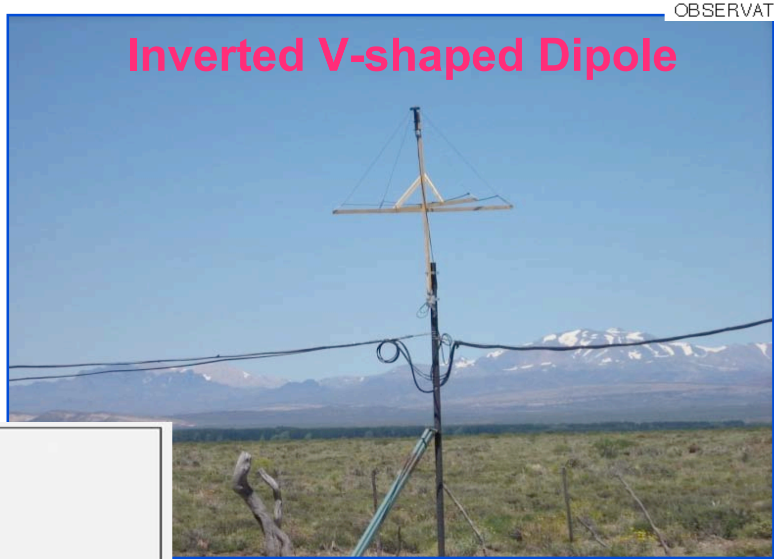

CODALEMA @ Nançay

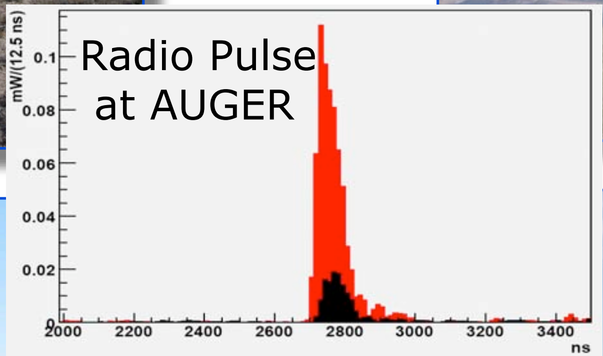


# Radio R&D at Auger

van den Berg & AUGER Collaboration (2007, ICRC)



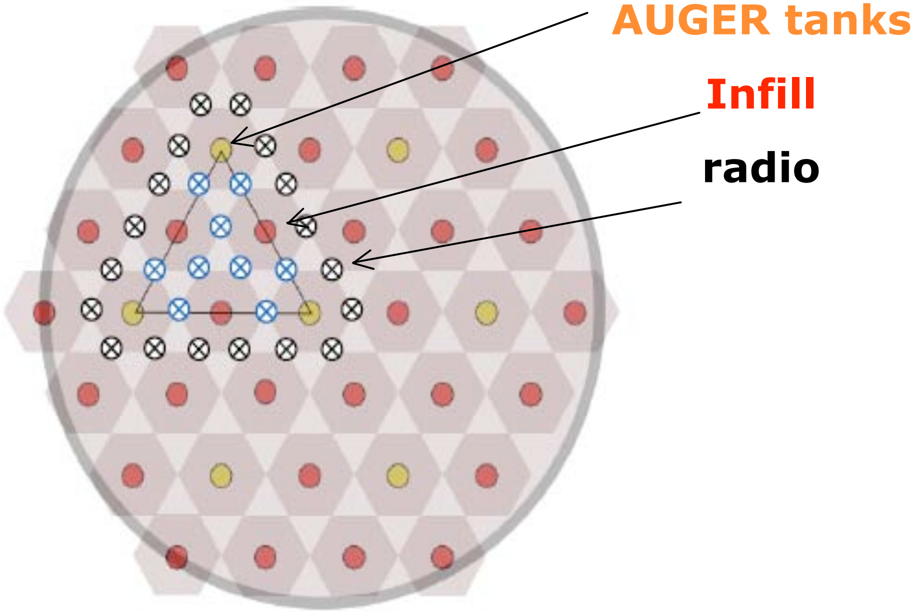





# Radio at Auger …

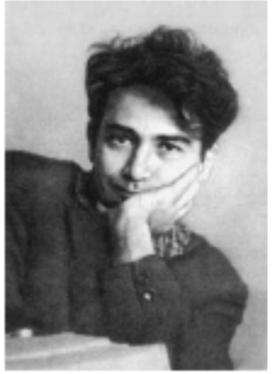
- Proposal: build a 10 - 20 km² self-triggering radio array
- Radio will allow triple-detection (radio, fluorescence, particles) to nail down energy scale at $E > 5 \cdot 10^{18}$ eV over 24 h a day
- Questions to be answered:
  - Maximal lateral extent and shape on km scale?
  - Composition with ~100% duty cycle possible?
  - < 0.1° angular resolution?
  - Self-trigger?



# Askaryan-effect

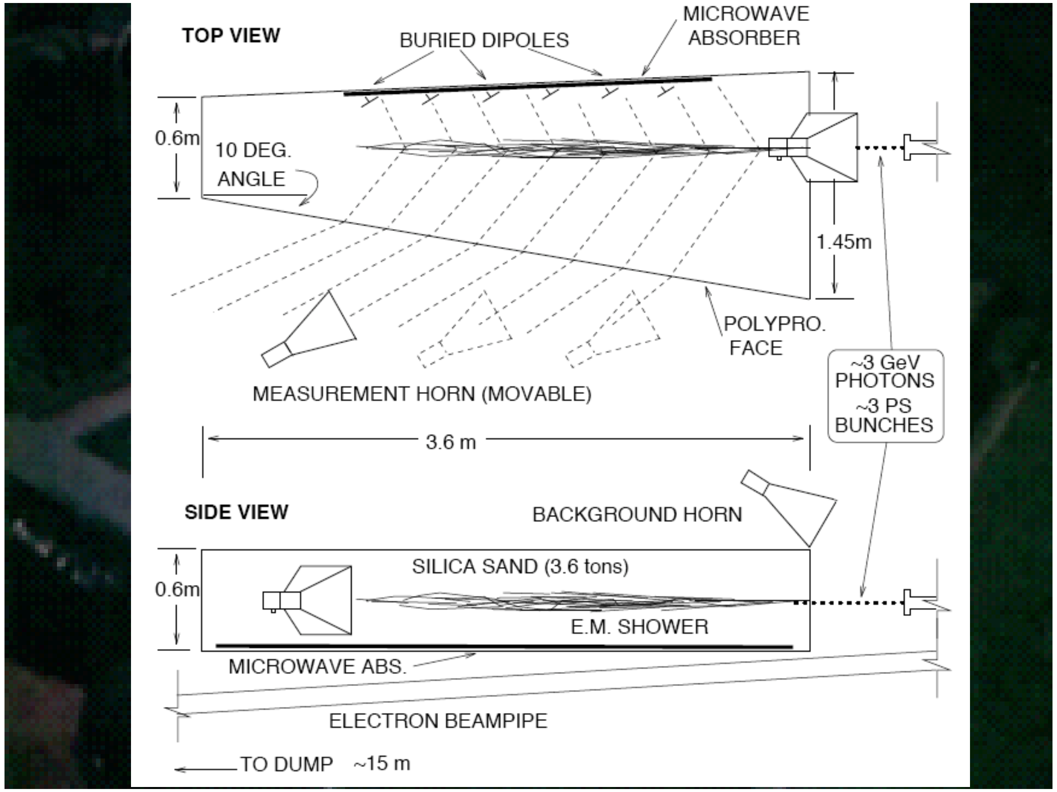
Soviet Phys. JETP 14(1962)441

- Cherenkov emission for neutrinos or UHECR induced showers in ice, salt, lunar regolith, sand
- Reason: $e^-$ charge excess in $\nu$ or CR induced shower
- Proof of effect in sand and now for ANITA also in ice:
- D. Saltzberg et al. at SLAC, 2005 arXiv:hep-ex/0011001
- No theoretical prediction in air
- Growing number of experiments plan to use this effect for $\nu$'s and CR's:
  - ANITA, GLUE, FORTE, RICE, LOFAR, $\nu$Moon Westerbork (E > $10^{21}$eV)

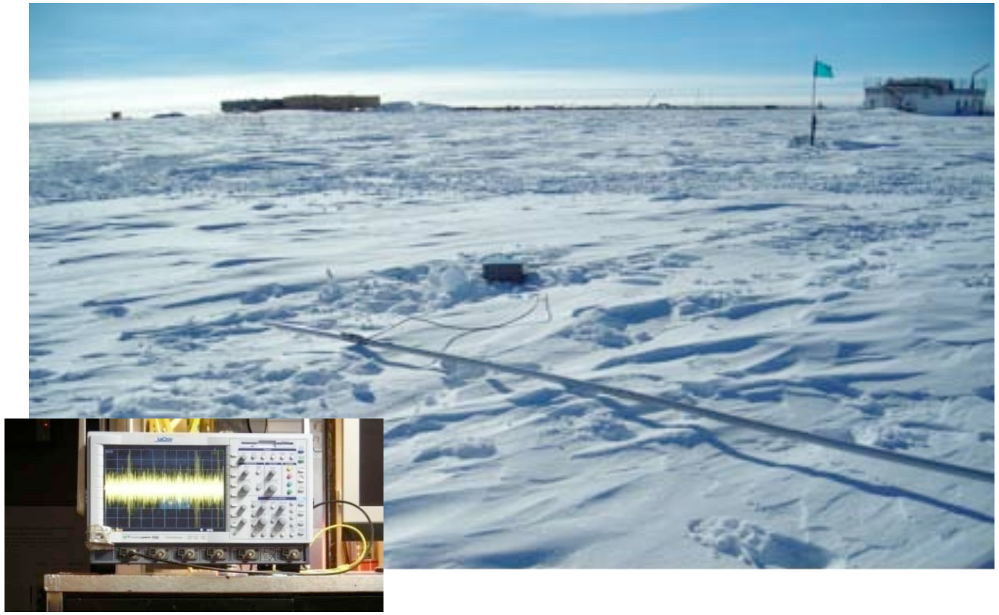


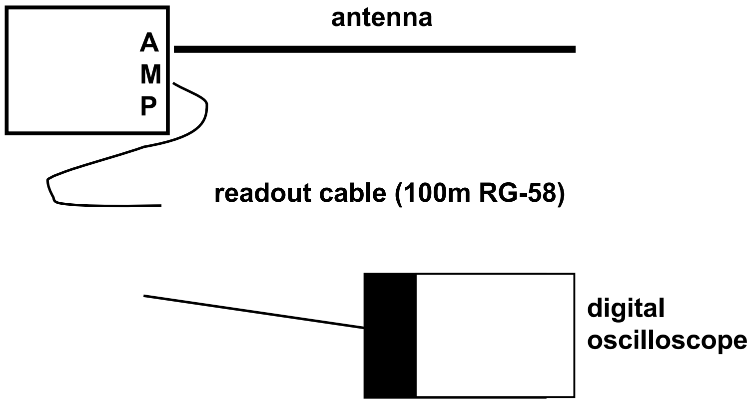
Gurgen Askaryan

1928-1997



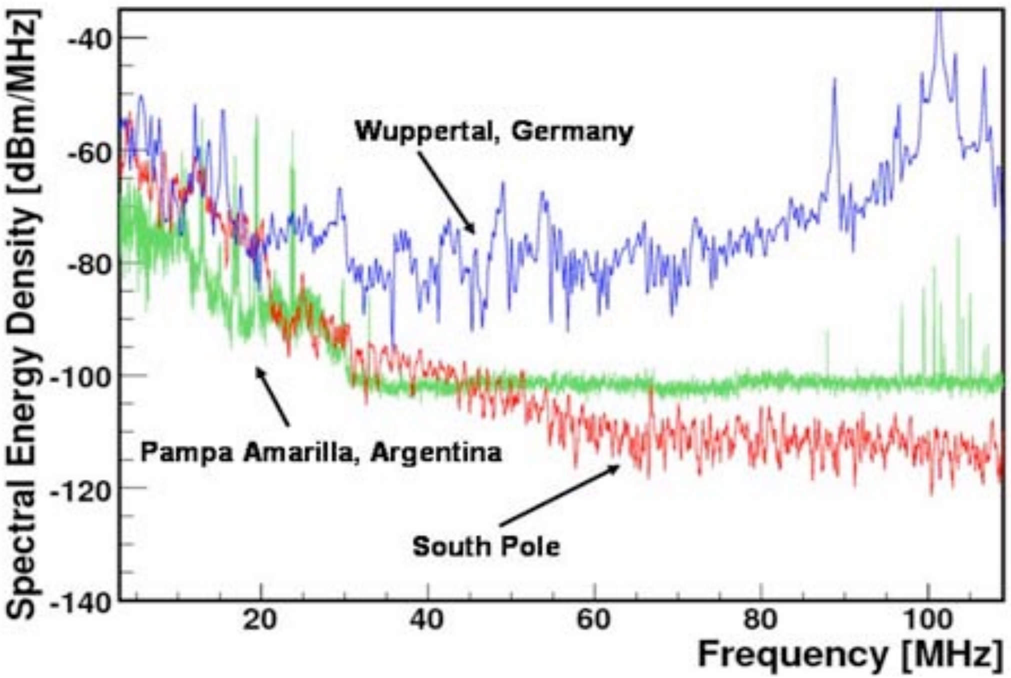
# Ice Cube: Radio Background Measurements at South Pole





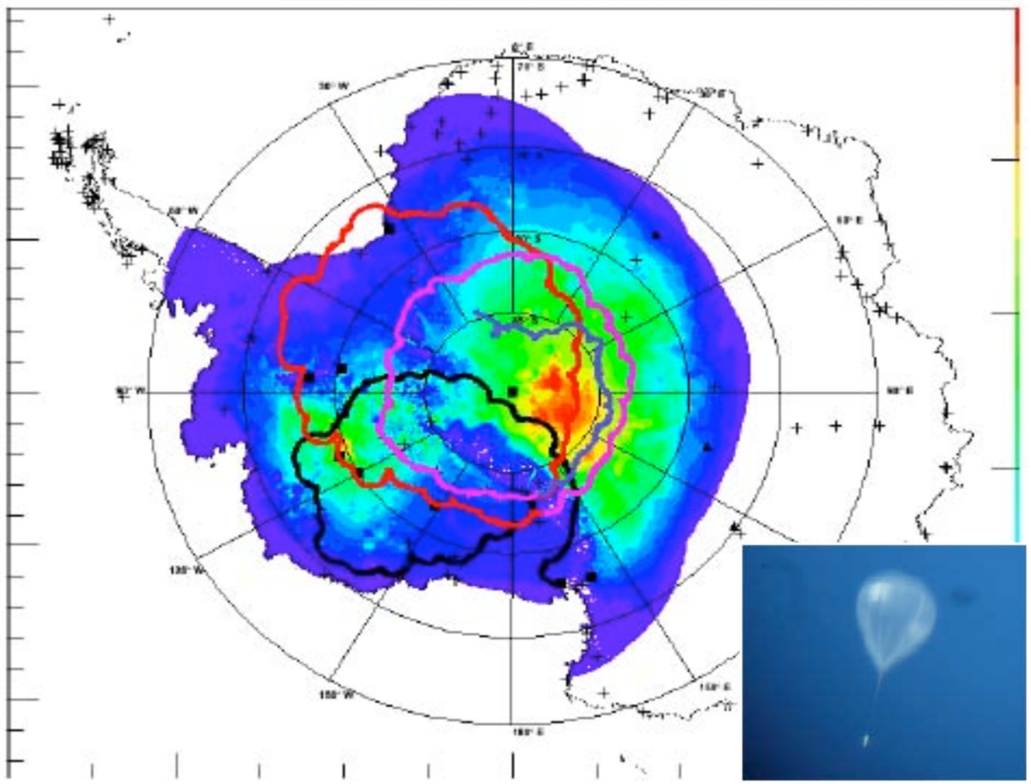

Auffenberg & Karg (2007, ICRC)

- Goal: Expansion of IceTop surface array to detect inclined showers
- 3m monopole antenna
 (horizontal and vertical)



# „Terestrial“ Radio Neutrino Experiment ANITA

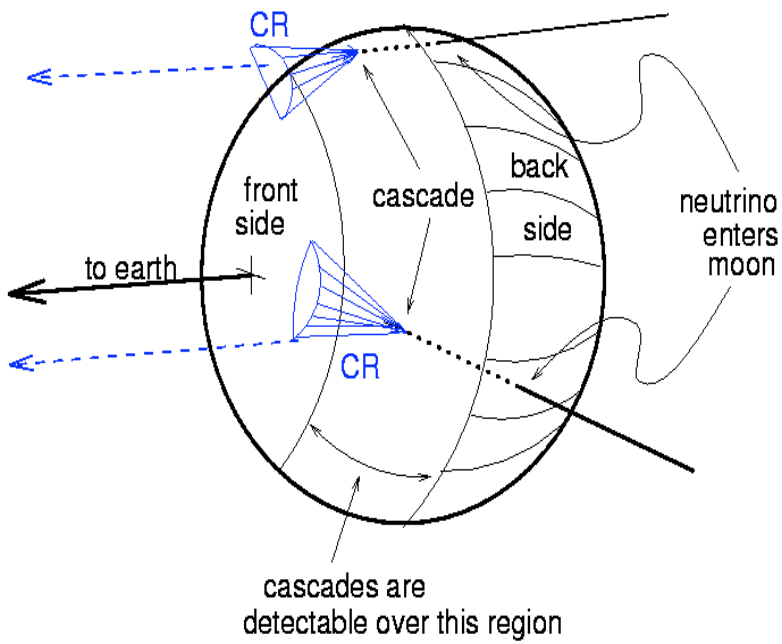
32 quad-ridged horns observe Cerenkov radiation

# Ultra-High Energy (Super-GZK) Neutrino Detections

- **Ultra-high energy particles (esp. ν's) hitting the moon and produce showers and radio Cherenkov emission (Zas, Gorham, …).**
- **largest and cleanest particle detector for direct detection at the highest energies.**
- **In the Cherenkov cone the maximum of the emission is in the GHz range**
- **Current Experiments:**
  - **ANITA**
  - **GLUE**
  - **FORTE**
  - **RICE**
  - **LOFAR**

radio from CR's and neutrinos hitting the moon

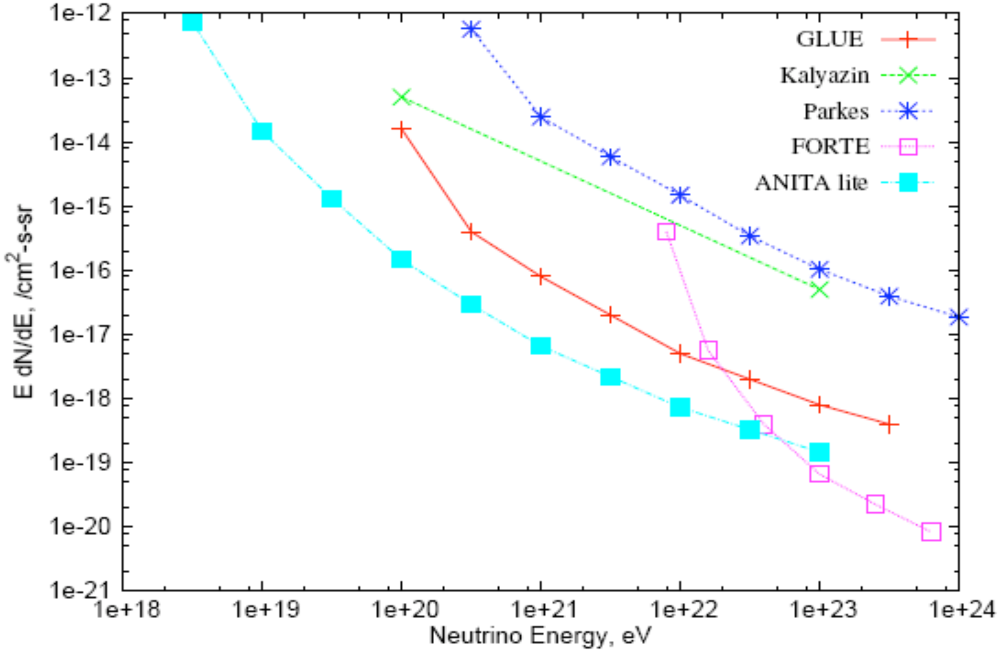



from Gorham et al. (2000)

target mass = $\text{surface}_{moon}/2 \cdot 2\text{m} \cdot \text{rho}_{moon} \approx 100$ Tt

# Radio Moon Experiments

James et al. (2007)



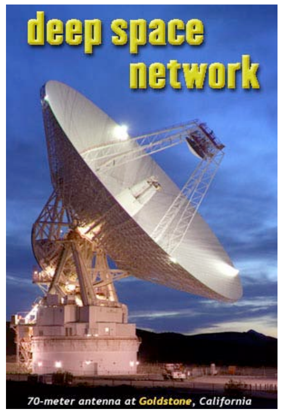


Hankins, Ekers, O'Sullivan (1996)


Scholten et al. (2007, ICRC)

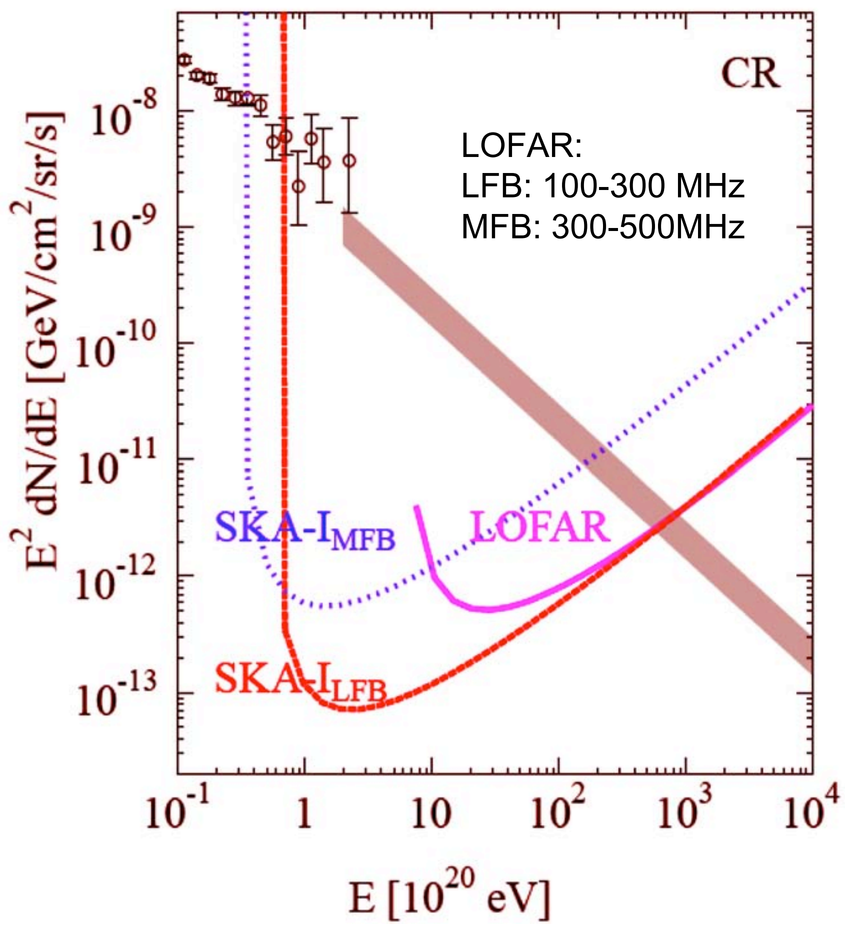

Beresnyak A. R. et al. (2005)

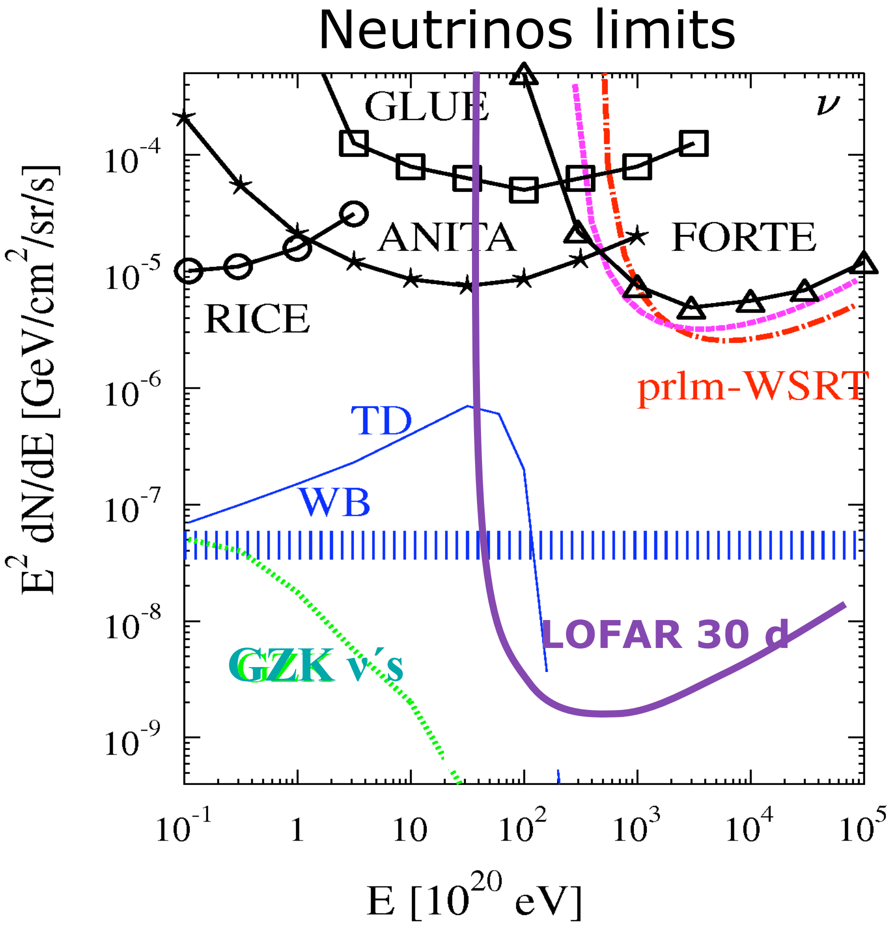

Gorham et al. (2004)



# Future Radio Observations of the Moon: LOFAR & SKA

1 year, 10% SKA, full LOFAR




LPM effect taken into account!

**νMoon Collaboration, Scholten 2006, SKA book**

# Conclusions

- *Geosynchrotron effect* allows direct detection of EAS with radio antennas.
- New method for cosmic ray studies with advantages:
  1. *Angular Resolution*: discovery of point sources with Radio: $\Delta\theta < 1°$
     - with more antennas a resolution of ≤ 0.1° seems feasible
  2. *Bolometric* Measurement of Energy
  3. *coherent* emission
  4. *Polarization* observed
  5. *Thunderstorms* can be discriminated
- LOFAR & SKA observations of the Moon:
  - low-frequencies preferred for highest energies
  - 3 orders of magnitude improvement over existing facilities
  - Superb possibility for super-GZK particles (>$10^{21}$ eV)
- Installation of an engineering array in Argentina 2008 planned

  ⇒ complementary information to Fluorescence and Surface detectors in Auger

  ⇒ Auger-South is the necessary test-field for the future of radio

  ⇒ But much has to be done before it may be applied to Auger-North

# Auger: Hybrid Detection of UHCRs

Future of Auger: **Super-Hybrid Detection of UHECRs**