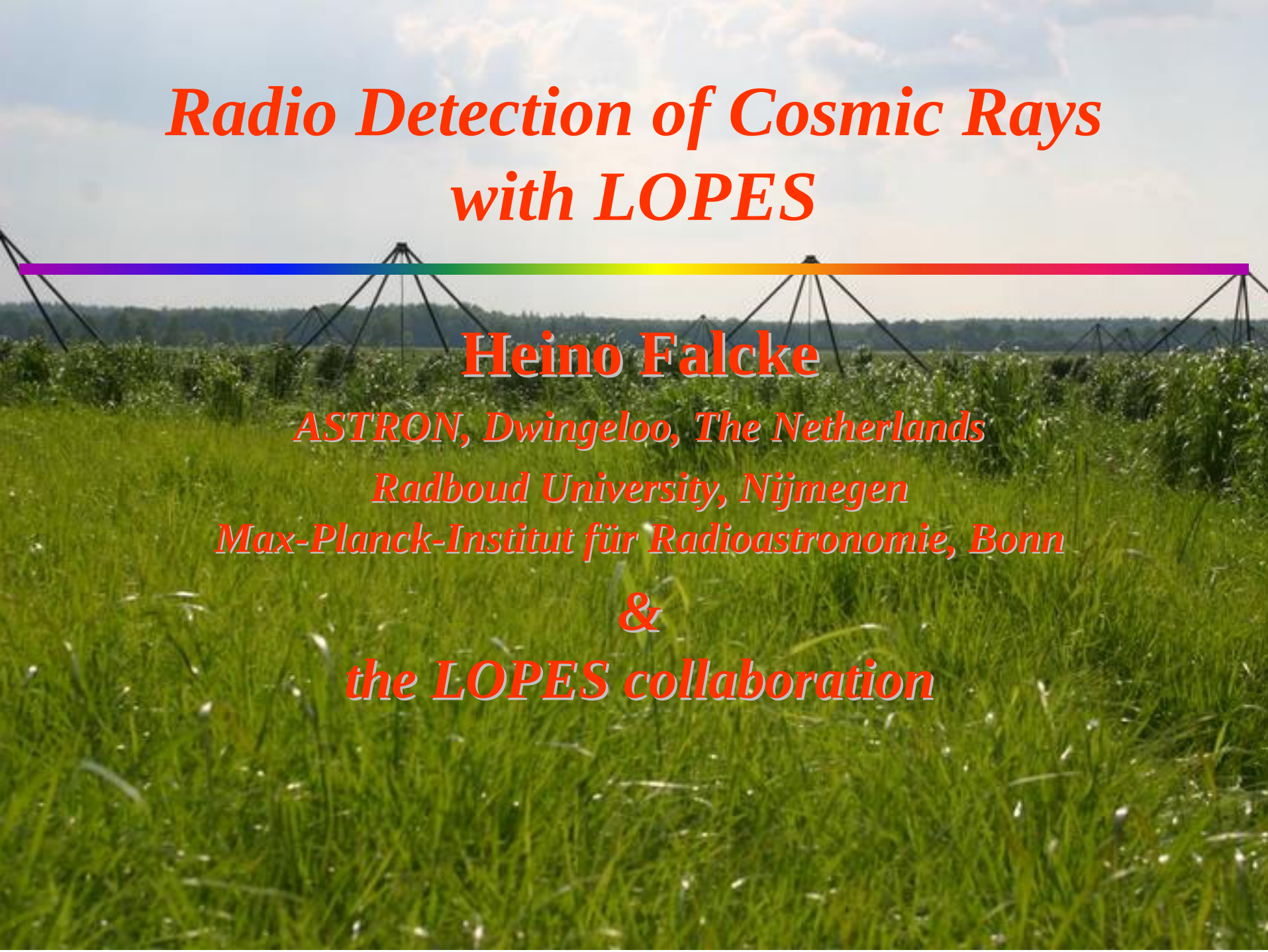


Radio Detection of Cosmic Rays with LOPES

Heino Falcke

ASTRON, Dwingeloo, The Netherlands

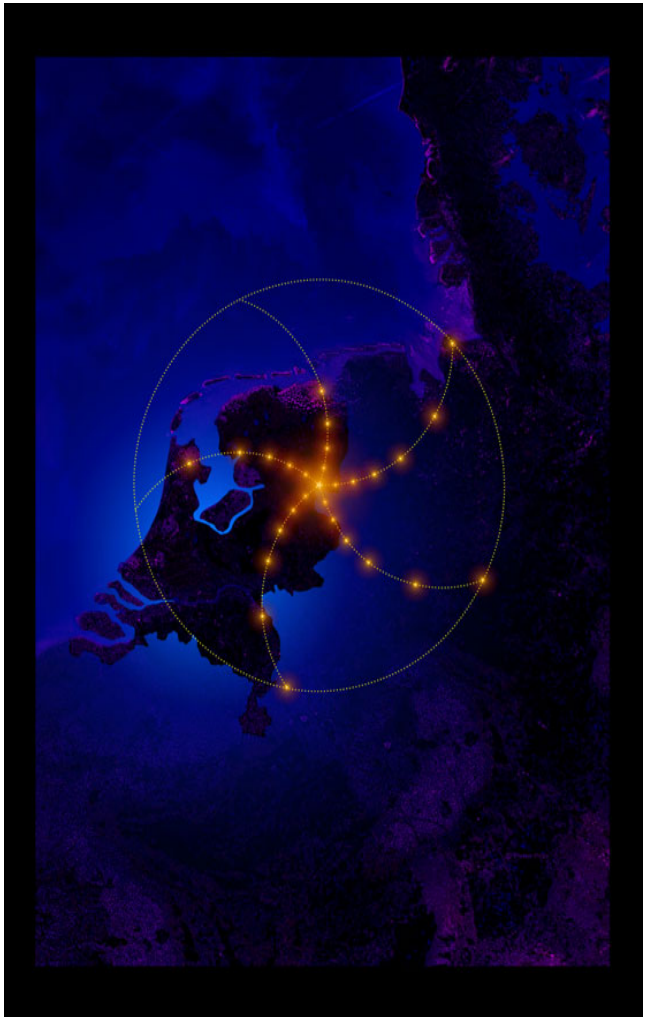
Radboud University, Nijmegen

Max-Planck-Institut für Radioastronomie, Bonn

&

the LOPES collaboration

Initial motivation: LOFAR

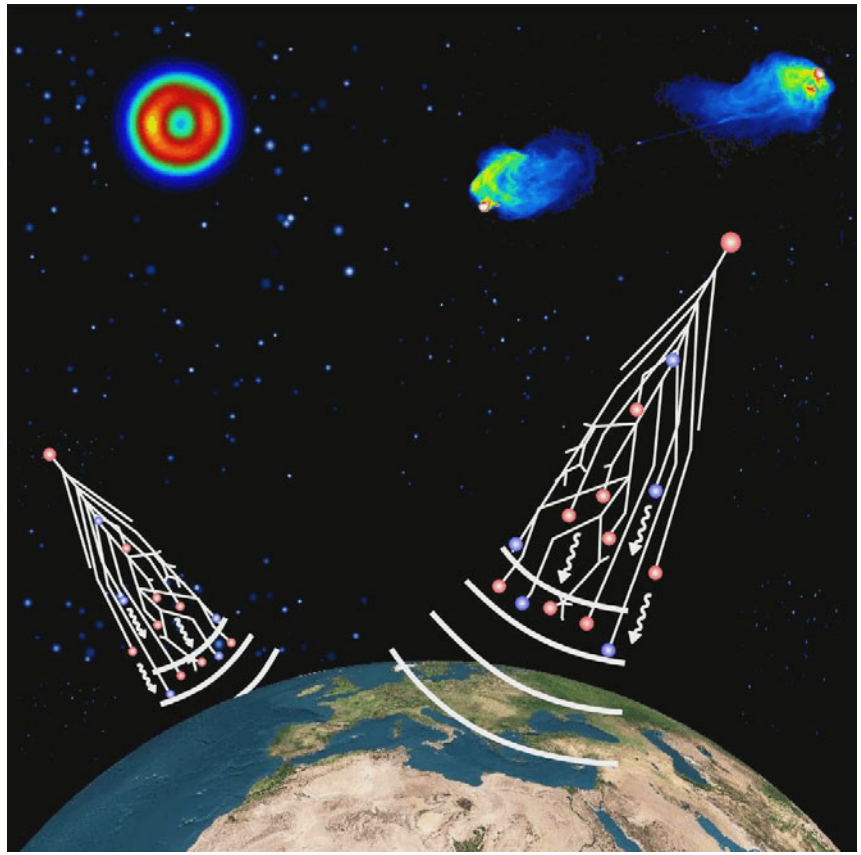


- ~10,000 low frequency radio antennas connected by high-speed internet grouped in ~100 stations
- IBM Blue Gene/L (27 Tflop) supercomputer forms and stears “digital beams”
- Antenna-based buffering
- Size:
  - Concentrated on central few square kilometers
  - remote stations out to several hundred kilometers
- Radio applications: Cosmology, bursting universe, Cosmic Rays & Neutrinos

- **2002:** Dutch/German funding for prototyping and investigating cosmic ray aspect (~1M€) - LOPES
- **2003:** Initial funding (52M€) from Dutch cabinet
- **2005:** Additional Dutch funding 22 M€ from provinces
- **2005:** German LOFAR White paper outlining German LOFAR participation presented

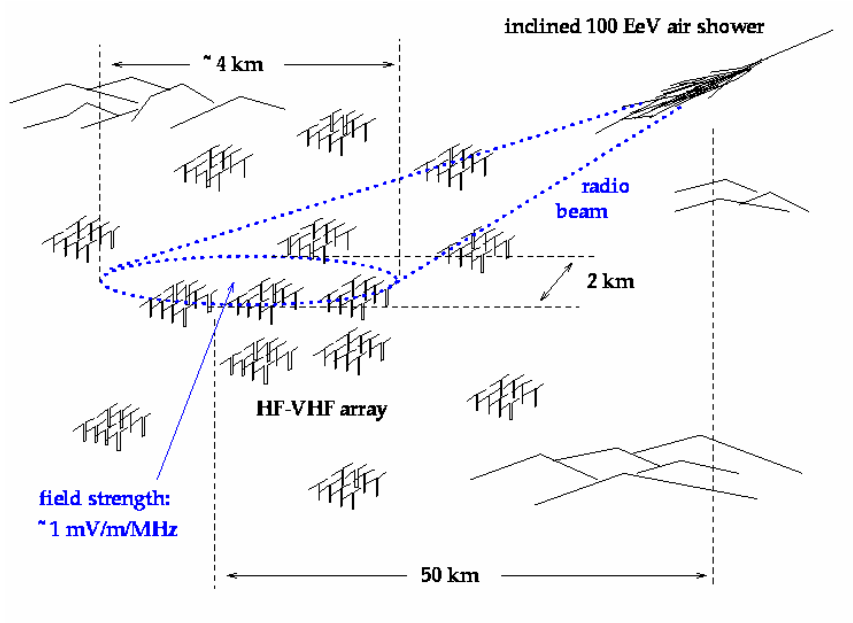
Radio Detection of CRs with LOFAR and AUGER …?

- Cosmic Ray Air Showers produce radio pulses as electrons rush through the geomagnetic field via “geosynchrotron” (Falcke & Gorham 2003).
- LOFAR will detect these pulses (“for free”) and become a interesting CR array in the energy range around 10^{18} eV.
- Interesting experiment also for possible extension of AUGER.



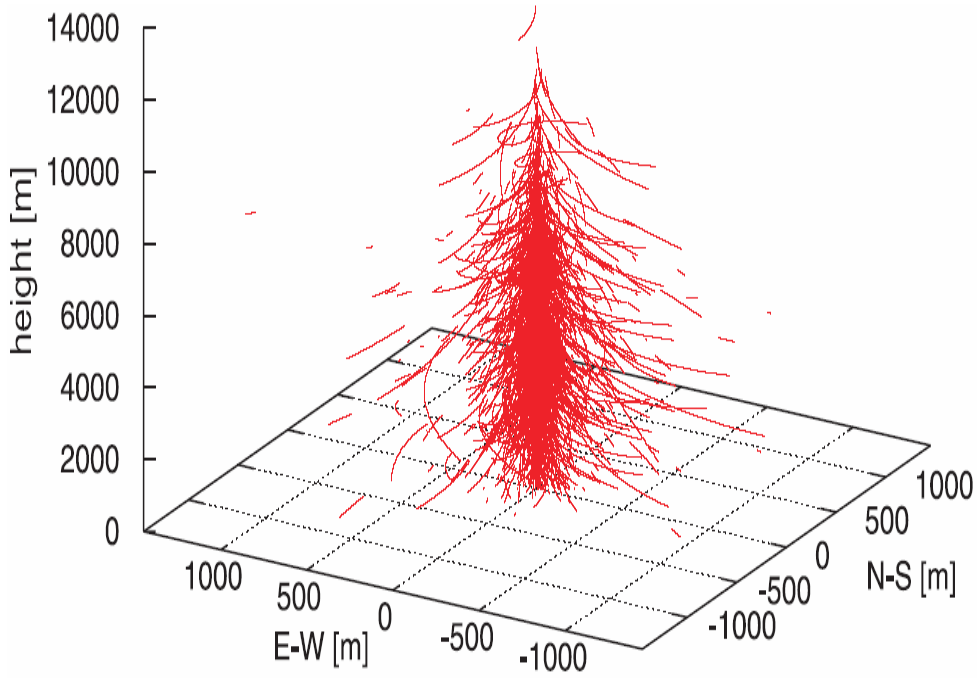
Advantages of Radio Emission from Air Showers

- Cheap detectors, easy to deploy
- High duty cycle (24 hours/day minus thunderstorms)
- Low attenuation (can see also distant and inclined showers)
- Bolometric measurement (integral over shower evolution)
- Also interesting for neutrinos
- Potential problems:
  - Radio freq. interference (RFI)
  - size of footprint
  - correlation with other parameters unclear
  - only practical above ~10^{17} eV.



Monte Carlo Simulations

- time-domain MC
- no far-field approximations
- Maxwell Equations
- full polarisation inf.
- thoroughly tested
- No Cherenkov yet!

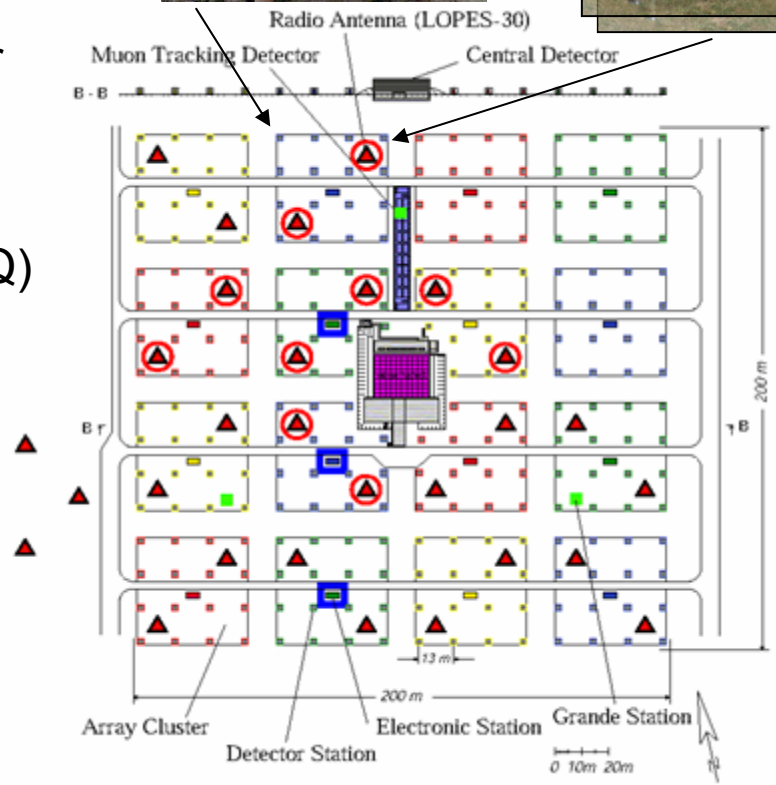


- takes into account:
  - longitudinal & lateral particle distributions
  - particle track length & energy distributions
  - air shower and magnetic field geometry
  - shower evolution as a whole

Huege & Falcke (2003-2005)

LOPES: Current Status

- 10 antenna prototype at KASCADE
  (all 10 antennas running)
- triggered by large event (KASCADE) trigger
  (10 out of 16 array clusters)
- offline correlation of KASCADE & LOPES
  (not integrated yet into the KASCADE DAQ)
- KASCADE can provide starting points for LOPES air shower reconstruction
  - core position of the air shower
  - direction of the air shower
  - size of the air shower
- Now: 30 antennas have been installed and take data
- Software and data archive on multi-TB raid system
- >1 Million events in database



Initial Funding:
bmb+f - Förderschwerpunkt
Astro-Teilchenphysik
Großgeräte der physikalischen Grundlagenforschung

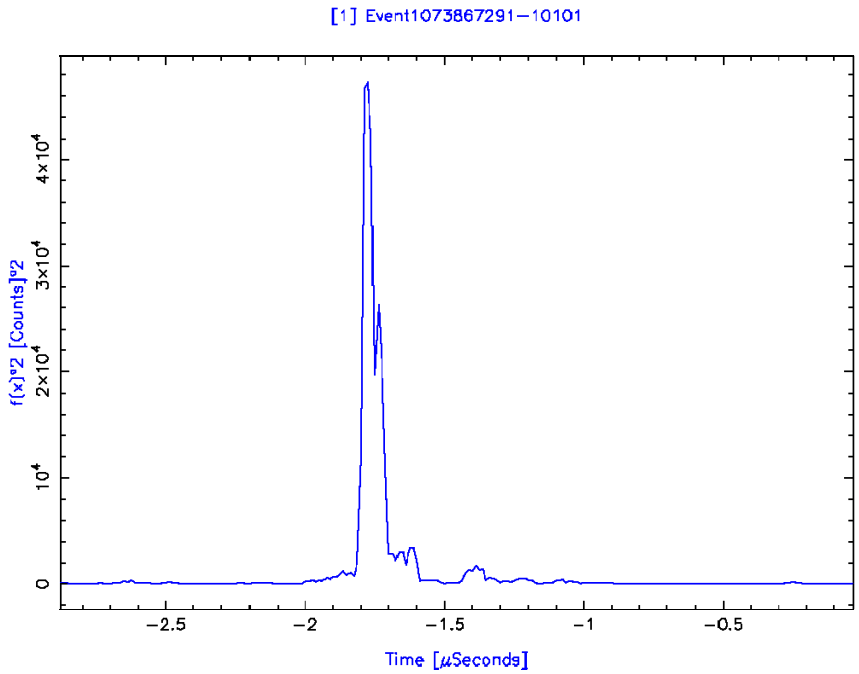
January 2004: First detection of CR radio pulse by LOPES

- Strong coherent radio pulse coincident with air shower
- All-sky radio-only mapping
  - Imaging (AZ-EL) with time resolution of 12.5 ns
  - Total duration is ~200 ns
  - No cleaning was performed, side lobes still visible
  - Location of burst agrees with KASCADE location to within 0.5°.

⇒ First detection of Cosmic Ray radio pulse in “modern times”, with highest temporal and spatial resolution ever achieved.

⇒ Shows direct association of radio with shower core

Confirmed by CODALEMA at Nancay …



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

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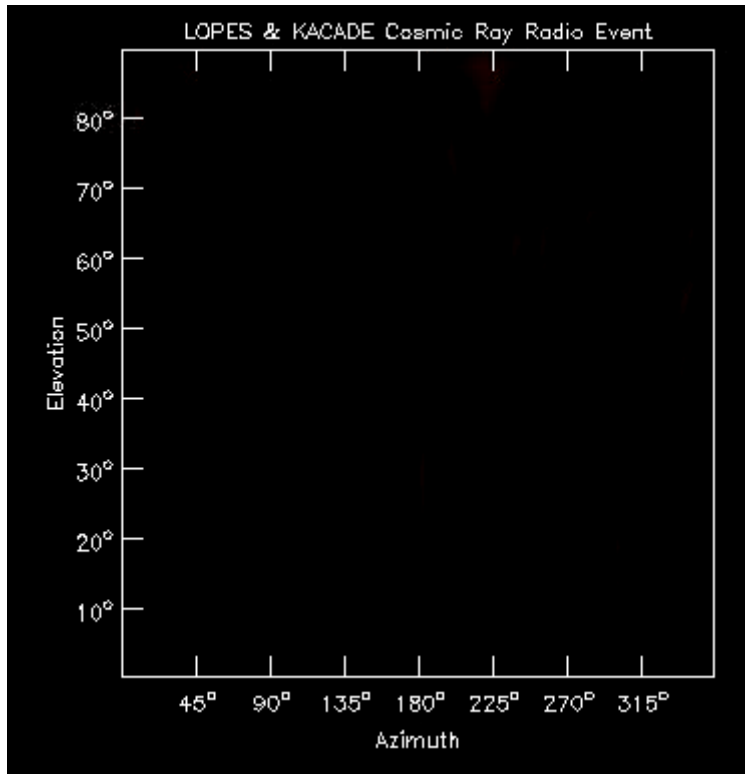
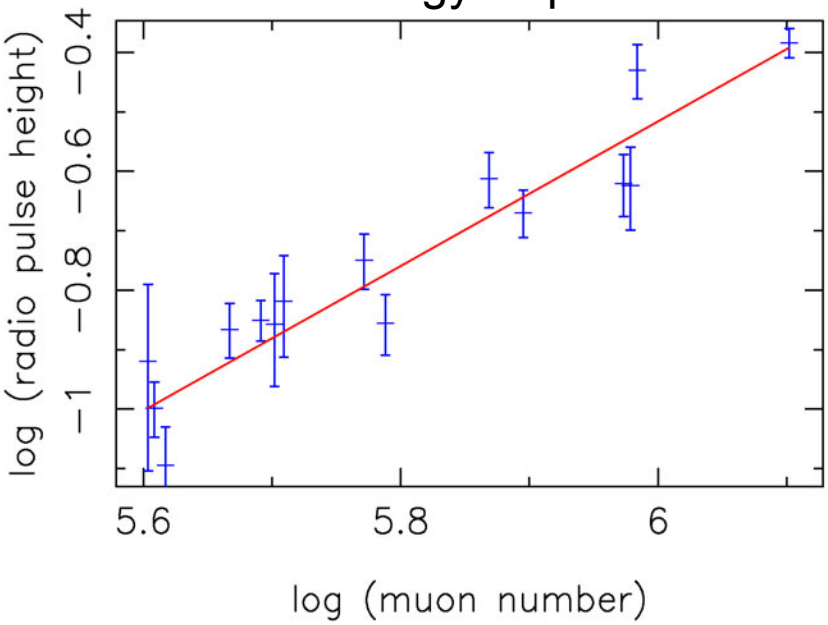


Falcke et al. (LOPES collaboration) 2005, Nature, 435, 313

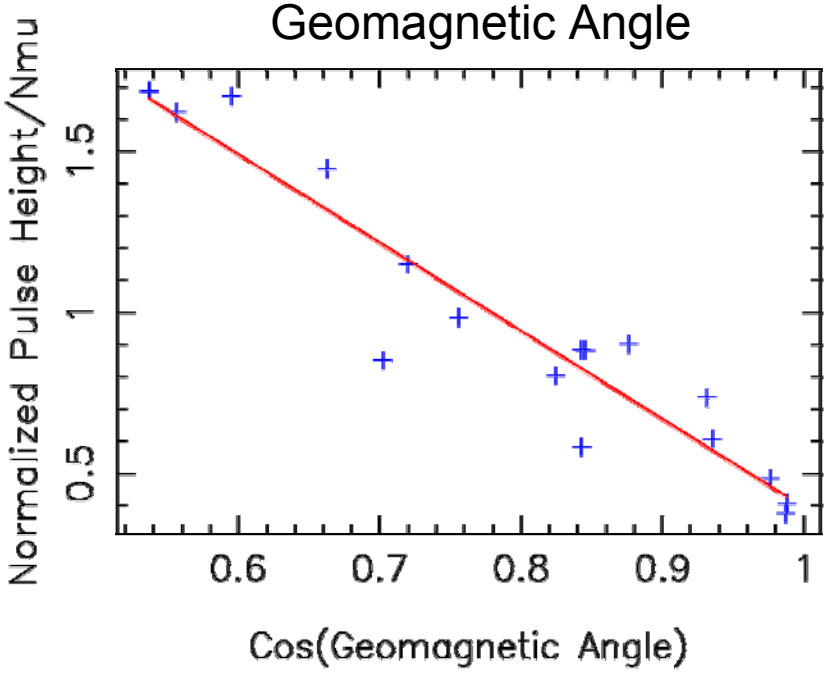
First Basic Results

All events with muon number >4×10^5 (to have sure detections) and R<70 m (to avoid fiddling with radius effects) → 17 events

Muon/Energy Dependence



Geomagnetic Angle



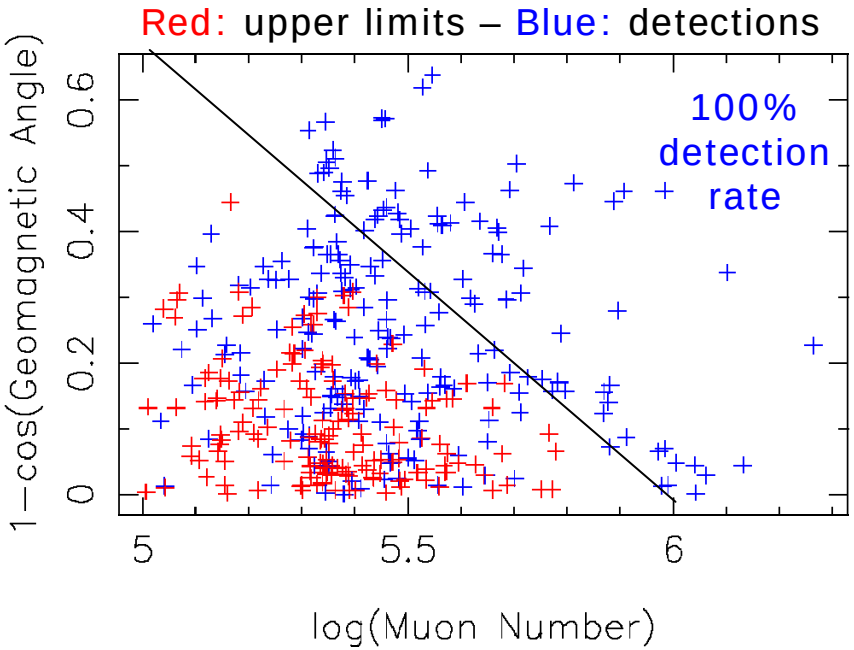
⇒Dependence on angle to Earth magnetic field

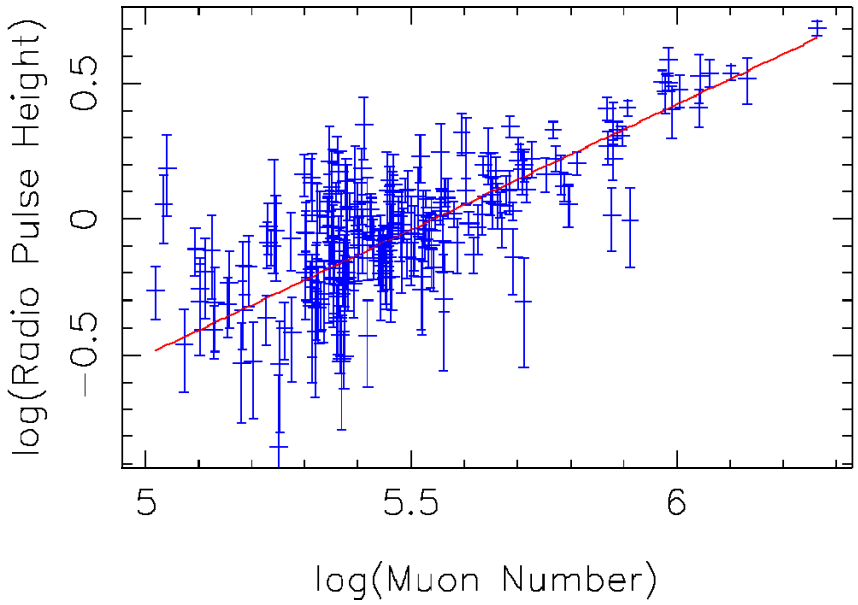
⇒E-field scales linearly with primary particle energy

⇒Power (E-field2) scales quadratically

Extended (low SNR) sample

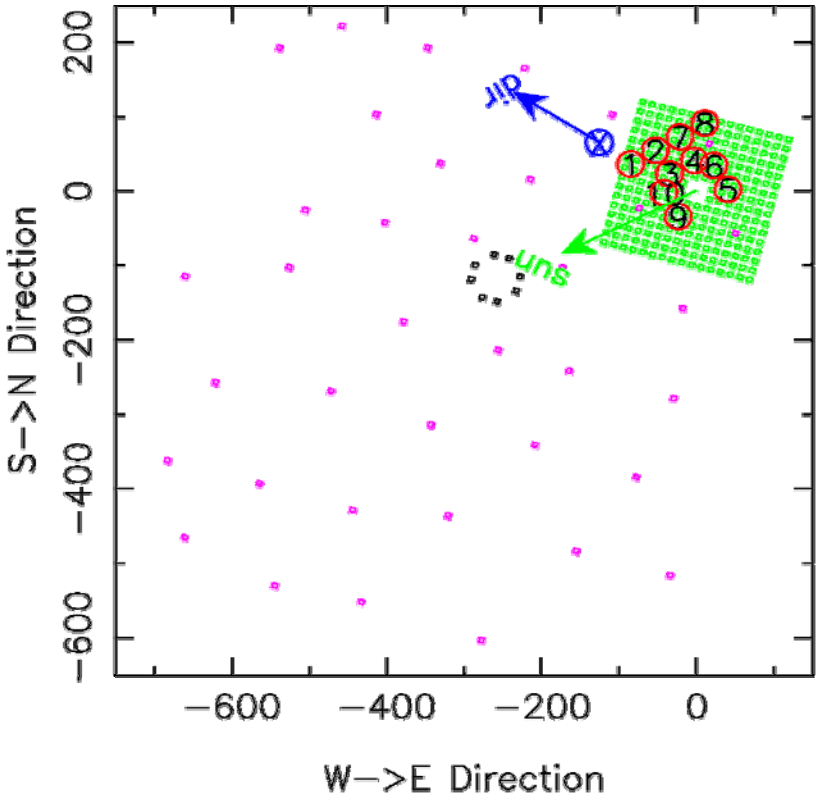
- detected air shower pulse in 213 out of 375 events
- fraction of detected events increases with muon number and geomagnetic angle
- Geomagnetic angle and energy dependence persist



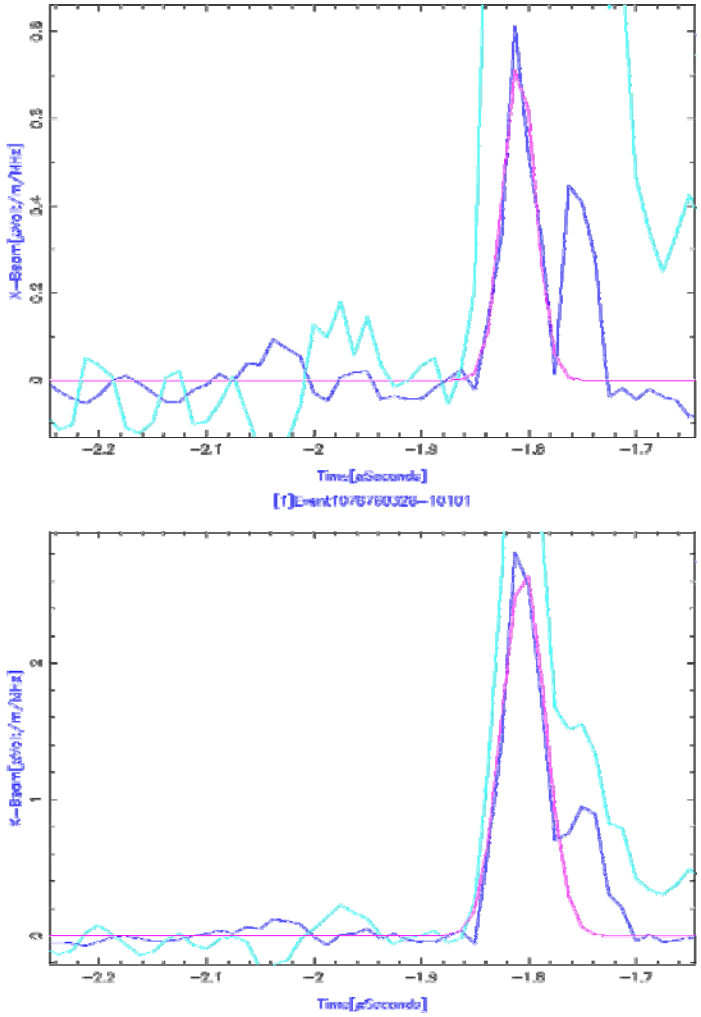


Andreas Horneffer, PhD thesis

KASCADE Grande events

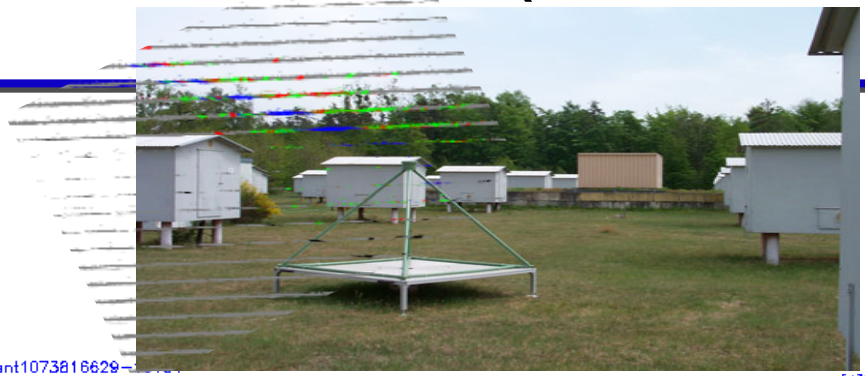


Badea, Haungs, et al. (LOPES), in prep.



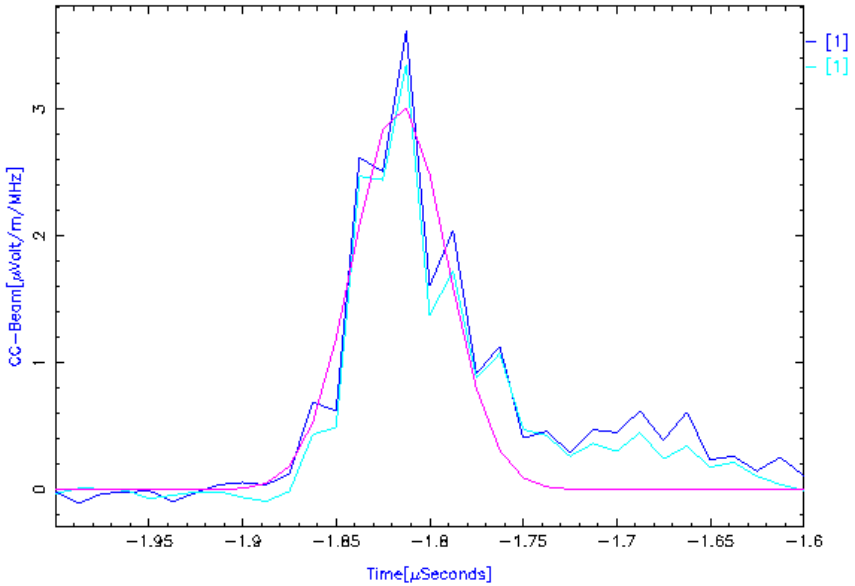
improve KASCADE shower parameters by maximizing radio signal

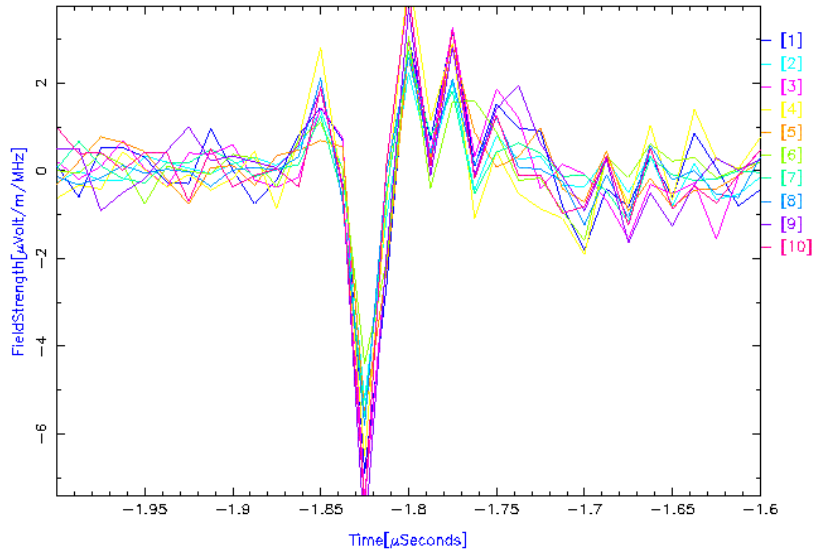
Inclined Showers (i=50-90°)



[1]Event1073816629–

[1]Event1084814631–10101



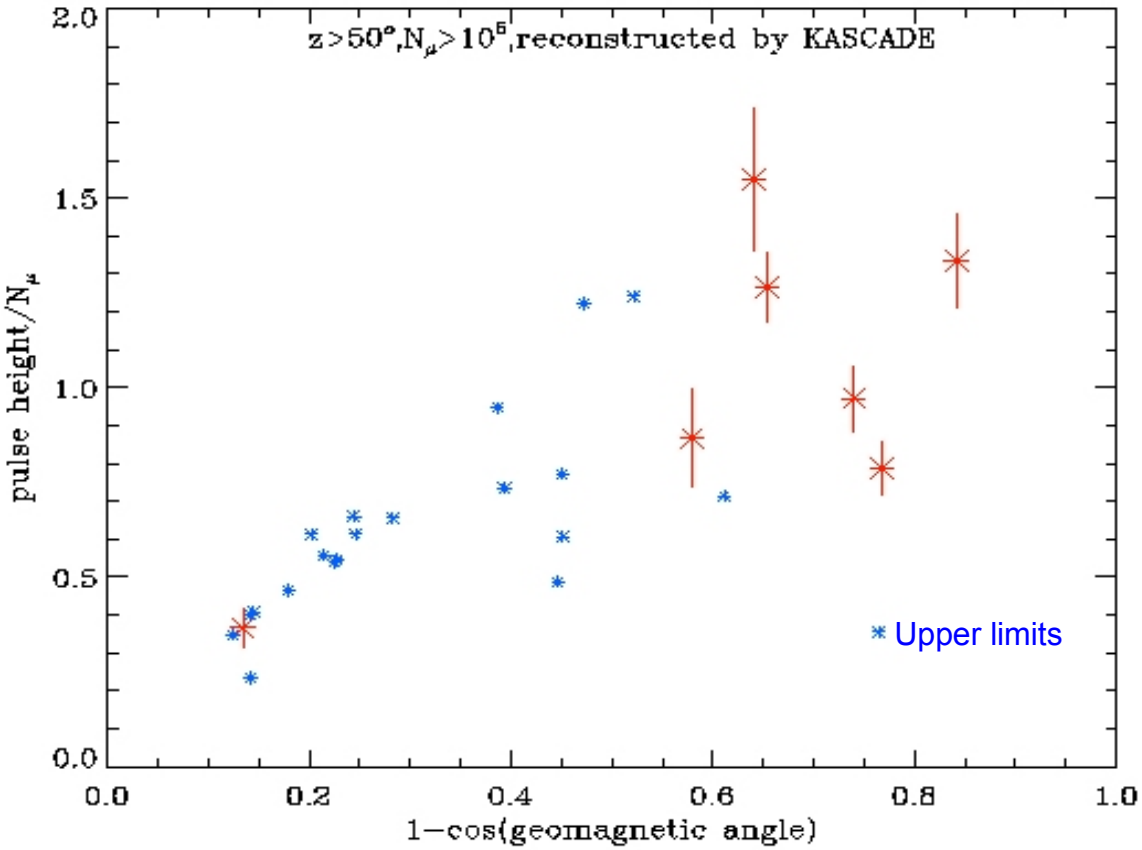


i ~ 75°

Coherent airshower signal over 250 ns …

J. Petrovic et al., in prep.

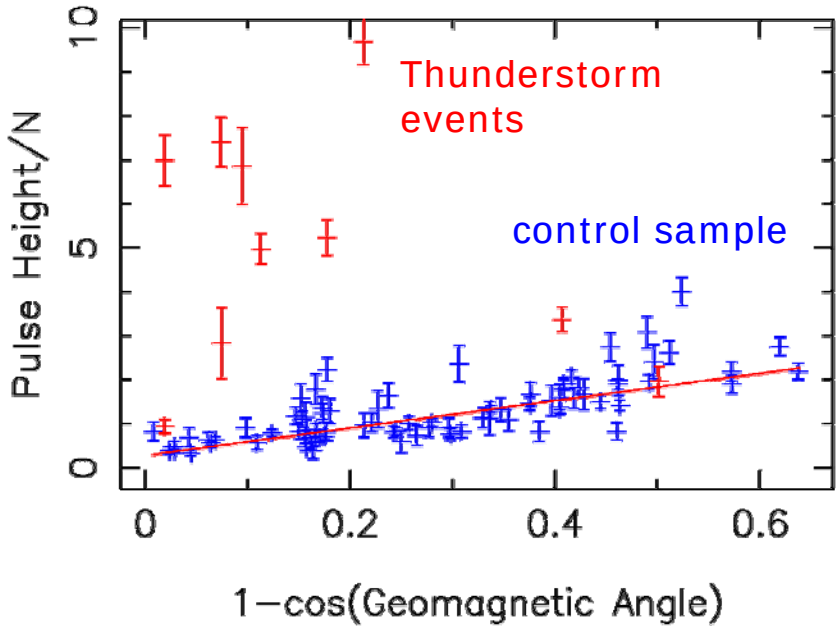
Inclined showers: Radio vs. geomagnetic angle correlation



Petrovic et al. LOPES collab., 2005, in prep.

Thunderstorm Events

- Does the Electric field of the atmosphere influence CR radio signal?
- For E>100 V/cm E-field force dominates B-field:
  - Fair weather: E=1 V/cm
  - Thunderstorms: E=1 kV/cm
- 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.) 2005, in prep.

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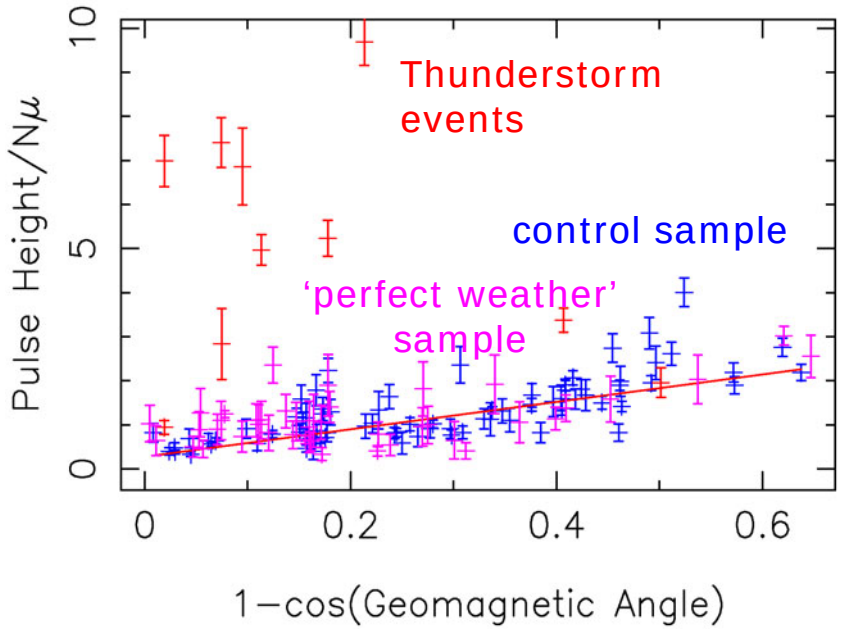
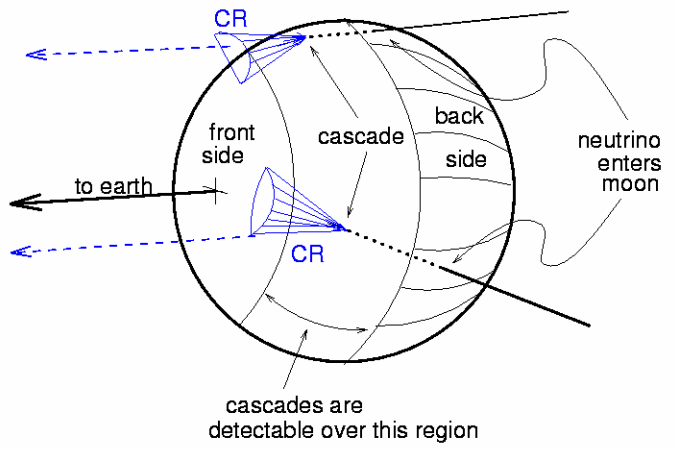


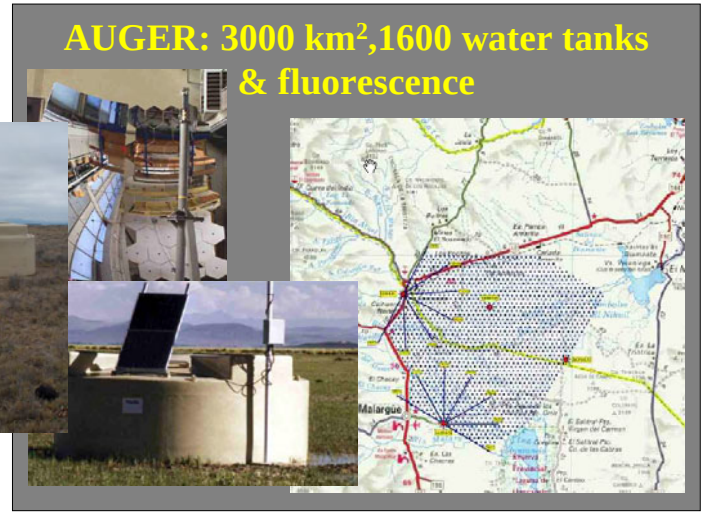
Buitink et al. (LOPES coll.) 2005, in prep.

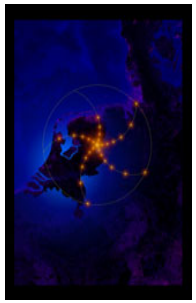
The Future

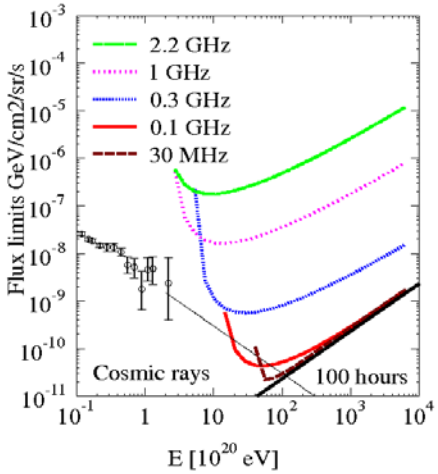
Radio observation of the moon



Radio at AUGER

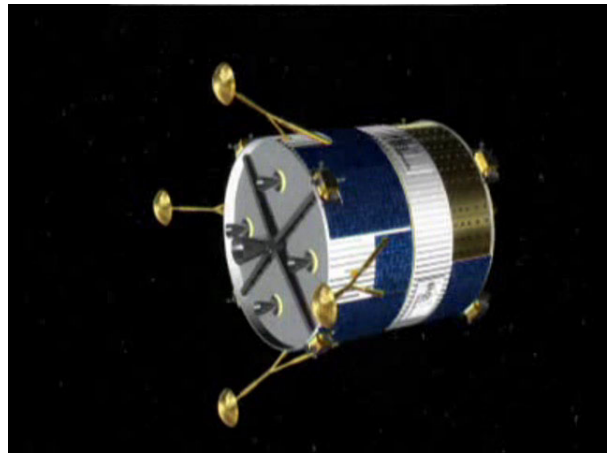






Scholten et al. (NuMoon collab.), Astropart. Phys. subm.

Radio observations on the moon



EADS/ASTRON study

Summary & Conclusions

- LOPES works; the geosynchrotron effect has finally been confirmed; new technique available
- Radio is a faithful tracer of air showers
- Radio gives very good energy information and arrival directions.
- AUGER: increase hybrid events by factor 10
- Inclined showers: Excellent prospects for composition studies and neutrino hunting
- Next steps: Argentina, Moon

LOPES Collaboration

ASTRON, Dwingeloo, The Netherlands

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

Department of Astrophysics, Nijmegen The Netherlands

S. Buitink, S. Lafebre, J. Petrovic, J. Kuijpers, A. Nigl

National Institute of Physics and Nuclear Engineering Bucharest, Romania

A. Bercuci, B. Mitrica, O. Sima, I.M. Brancus, M. Petcu, G. Toma

Universität Wuppertal, Germany

R. Glasstetter, K.H. Kampert

Institut für Kernphysik, Forschungszentrum Karlsruhe Germany

W.D. Apel, K. Bekk, H. Bozdog, P. Doll, A. Haungs, T. Huege, H.J. Mayer, M. Müller, R. Obenland, S. Ostapchenko, S. Plewnia, H. Schieler, J. van Buren, J. Wochele, A.F. Badea, J. Blümer, K. Daumiller, R. Engel, D. Heck, H.J. Mathes, J. Milke, S. Nehls, J. Oehlschläger, T. Pierog, H. Rebel, H. Ulrich, A. Weindl

Universität Siegen, Germany

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

Max-Planck-Institut für Radio-astronomie, Bonn, Germany

P.L. Biermann, J.A. Zensus, A. Horneffer

Radioastronomisches Institut der Universität Bonn, Germany

U. Klein

Istituto di Fisica dello Spazio Interplanetario, Torino, Italy

P.L. Ghia, G.C. Trinchero, C. Morello

Institut für Prozessdatenverarbeitung und Elektronik, FZK Germany

H. Gemmeke, O. Krömer

Soltan Institute for Nuclear Studies, Lodz, Poland

A. Risse, J. Zabierowski

Dipartimento di Fisica Generale dell'Universita, Torino, Italy

M. Bertaina, F. di Pierro, S. Valchierotti, A. Chiavassa, G. Navarra

Institut für Experimentelle Kernphysik Universität Karlsruhe Germany

A. Hakenjos, M. Roth, J.R. Hörandel, M. Stümpert