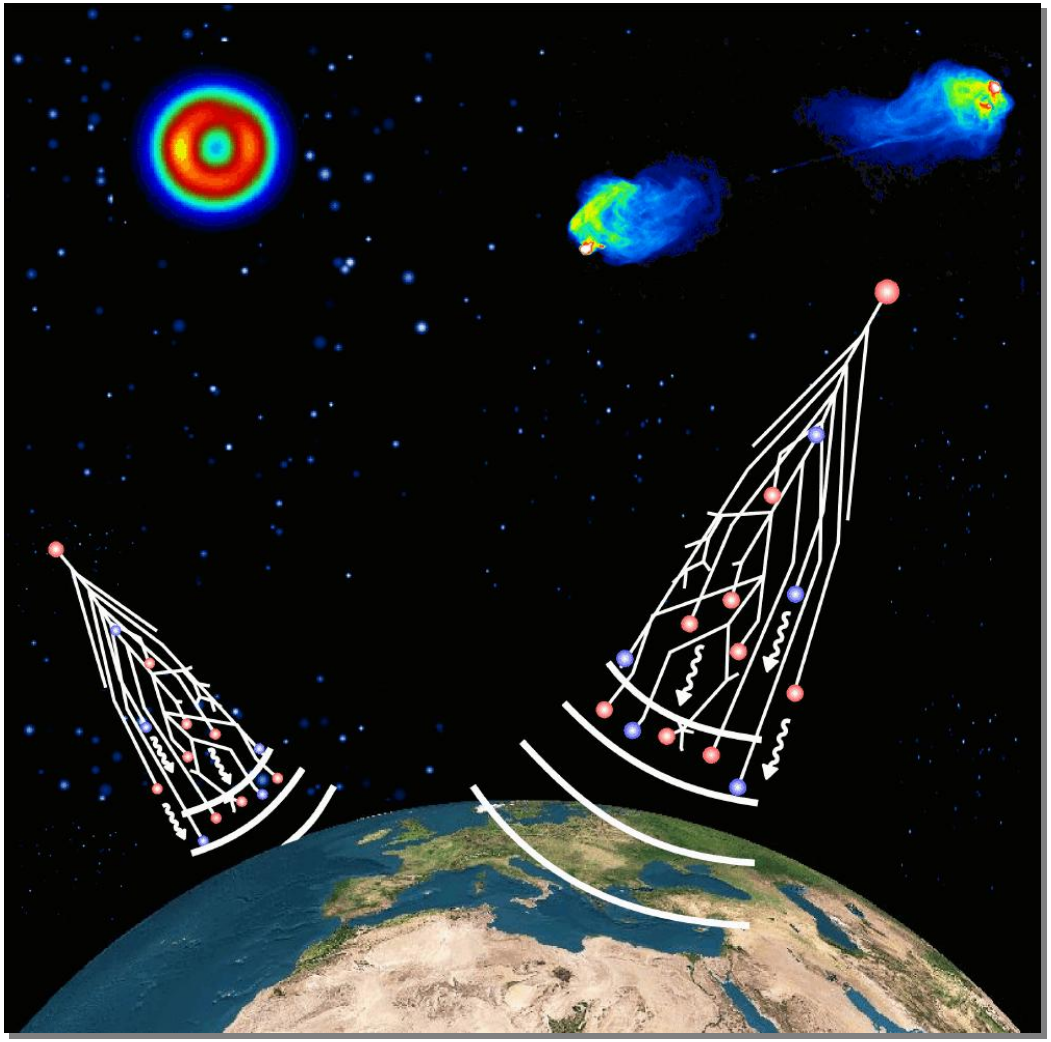
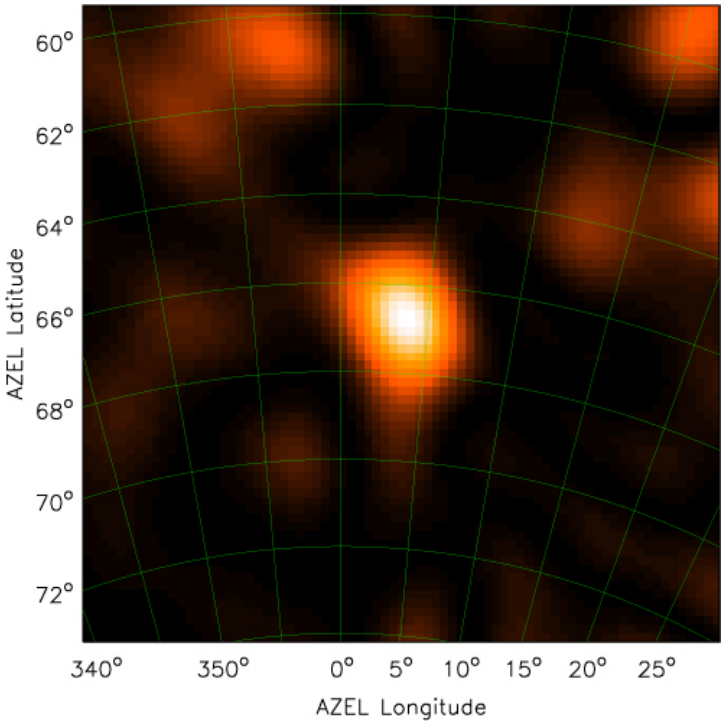
Contents

- the early days of CR radio detection
- **the revival of CR radio detection**
  - experiments
  - theory
  - **results**
- the future of CR radio detection



“Proof of Principle” with LOPES10



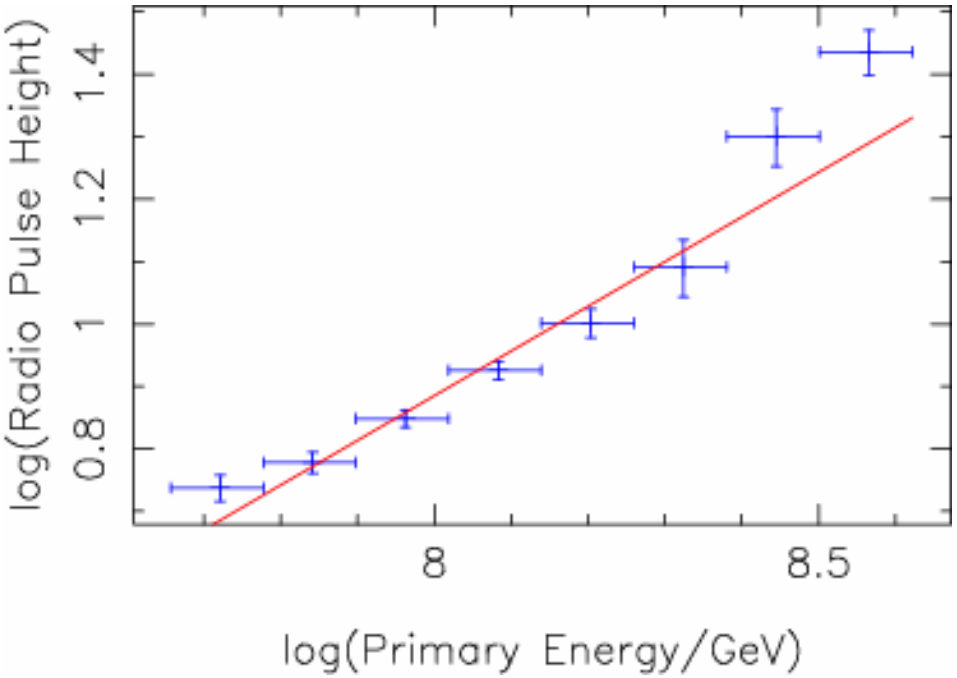
Radio map of an air shower detected with LOPES10.

Falcke et al. (LOPES coll.), Nature 2005

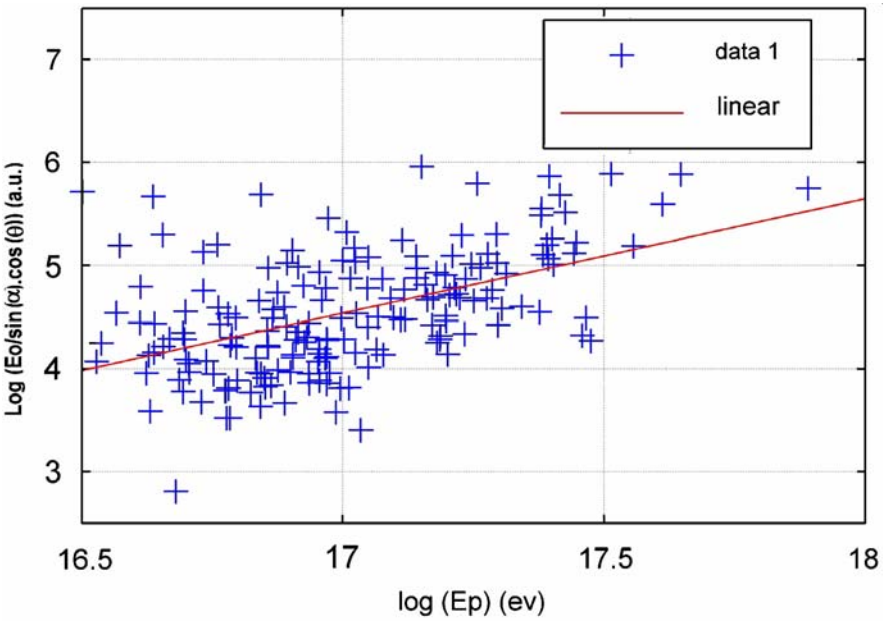
- for a few nanoseconds, air showers are the brightest radio source in the sky
  - still, only a few eV of the original >10^{16} eV received
- first time detection of radio emission from air showers with a completely digital setup
  - full sky observation of transient signals
  - high angular resolution
  - digital filtering of man-made radio-frequency interference

Scaling with Energy - Coherence

LOPES



CODALEMA



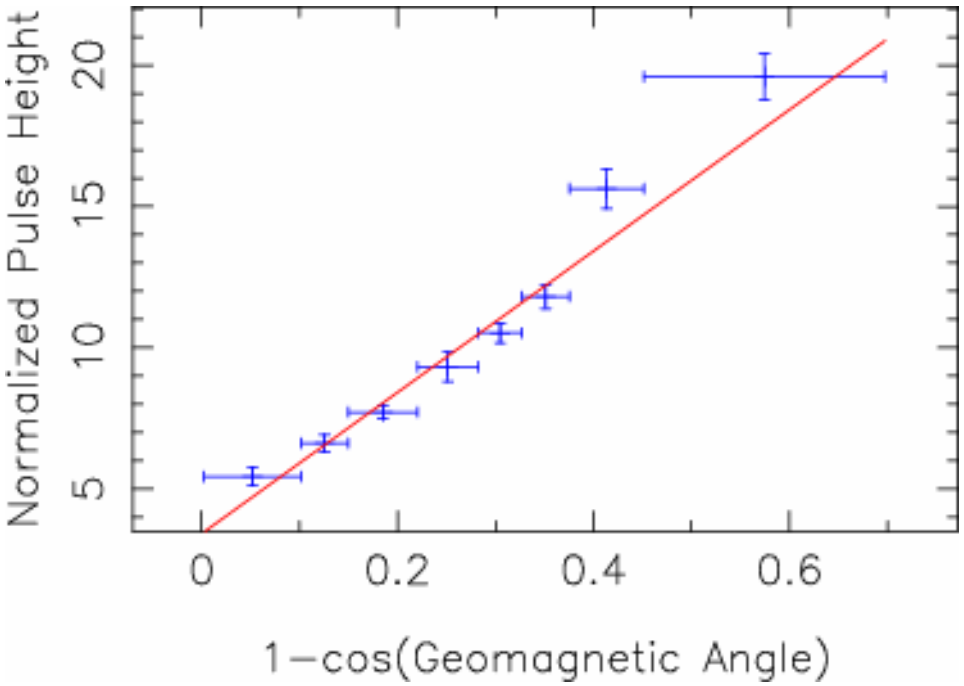
- **approximately linear scaling of radio pulse height with CR energy**
- **confirms theoretical prediction of coherent emission**

Haungs et al. (LOPES coll.), ARENA 2008

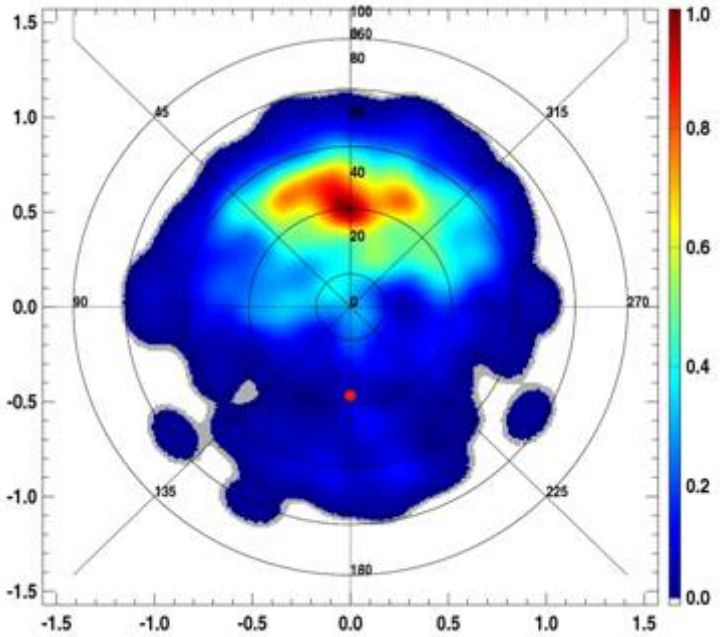
P. Lautridou et al. (CODALEMA coll.), ARENA 2008

Geomagnetic field dependence

LOPES



CODALEMA



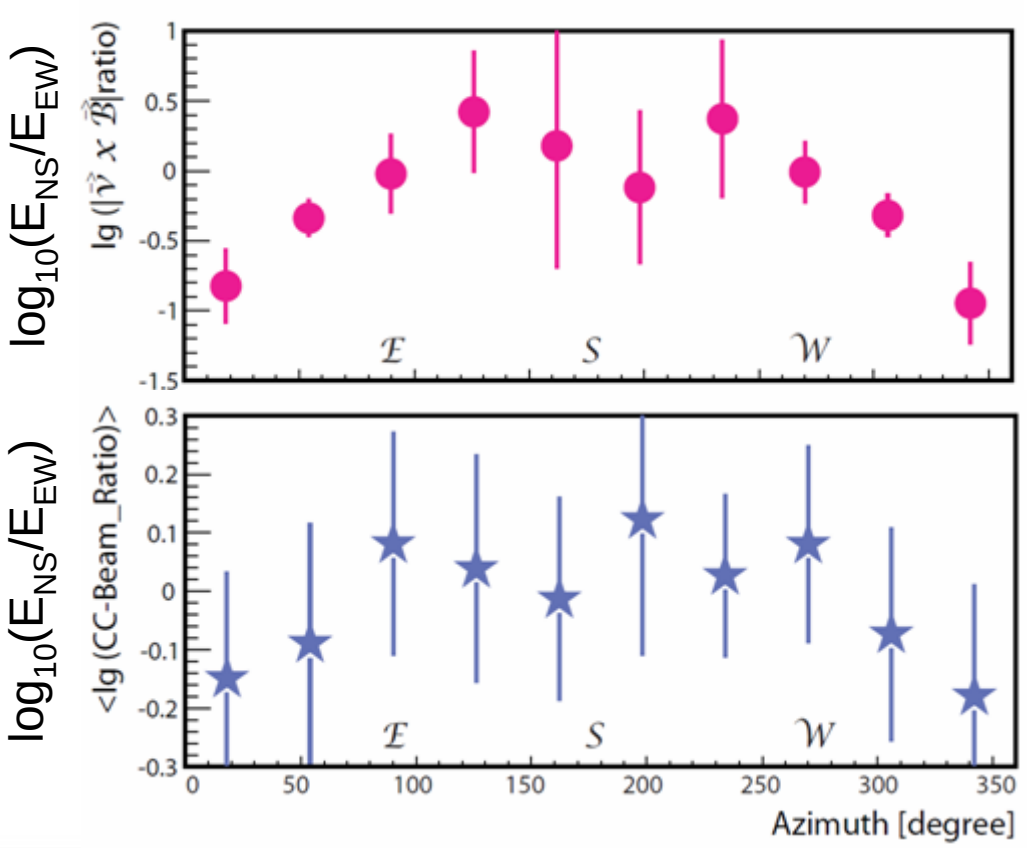
- **clear dependence of pulse height (near threshold: detection efficiency) on shower axis angle to geomagnetic field (α)**
- **LOPES uses 1-cos(α), CODALEMA uses sin(α) description [$\vec{v} \times \vec{B}$]**

Haungs et al. (LOPES coll.), ARENA 2008

Ardouin et al. (CODALEMA coll.), Astrop. Phys. 2009

LOPES polarization characteristics

- **geomagnetic emission models predict the polarization to depend on the azimuth angle of the air shower**
- **dual-polarized measurements in LOPES (10 EW, 10 NS, 5 with both polarisations) confirm this prediction**



simplified model

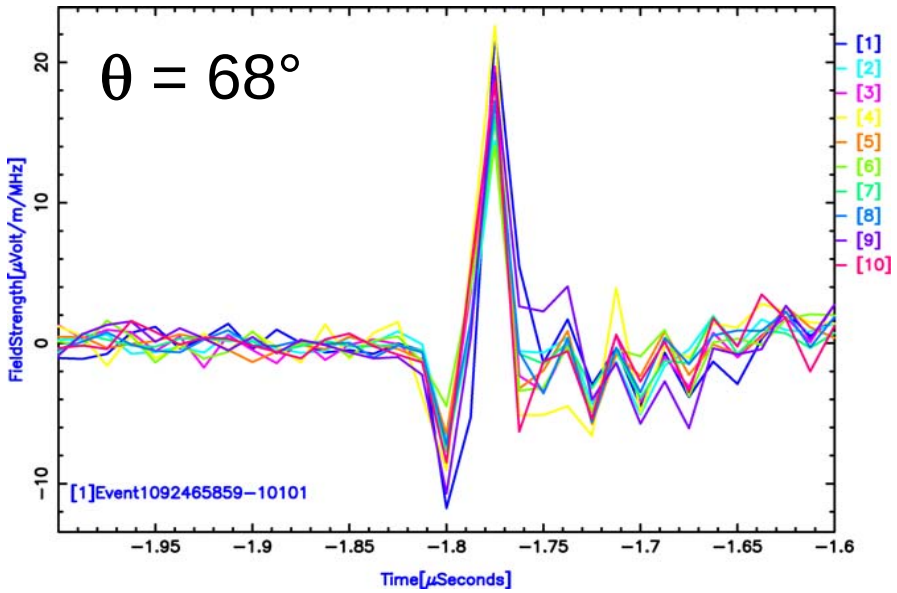
$$\vec{v} \times \vec{B}$$

LOPES data

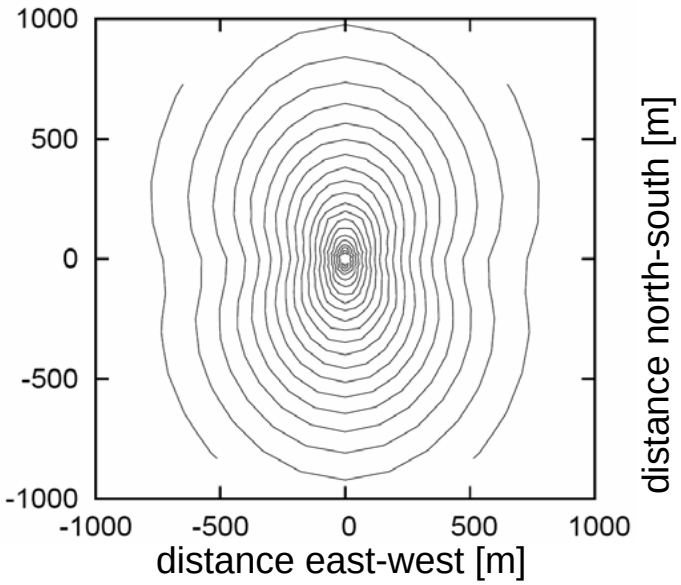
Isar et al. (LOPES coll.), ICRC 2009

LOPES inclined showers

- **strongy inclined showers (here up to 80°) are indeed well detectable with the radio technique**
  - **low attenuation of the radio signal**
  - **broader radio footprint (predicted by simulations)**
  - **advantage in case of LOPES: lower PMT noise (electromagnetic component has died out)**



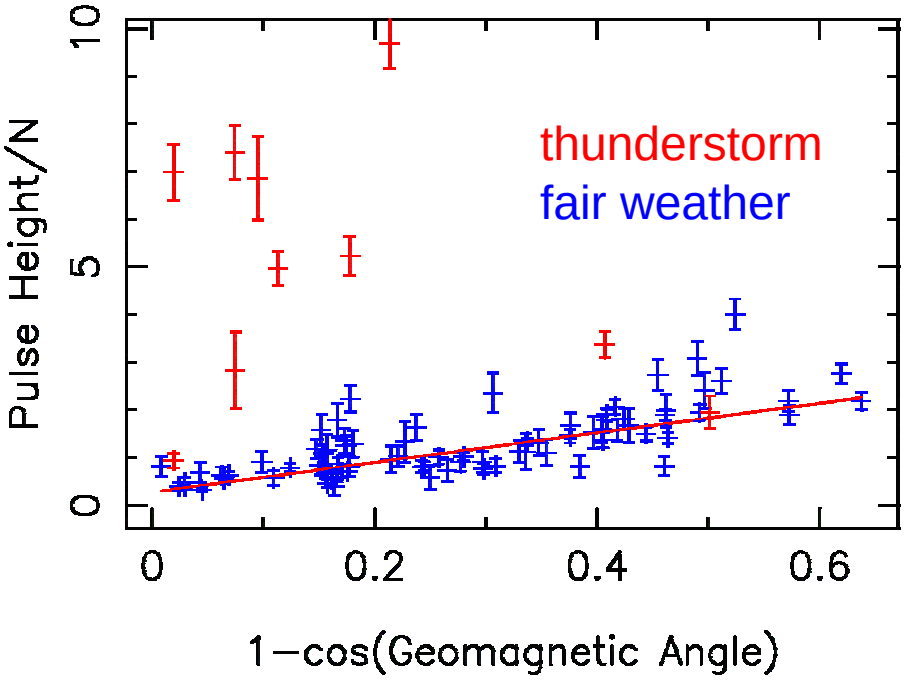
Petrovic et al. (LOPES coll.), Astron. Astrophys. 2007



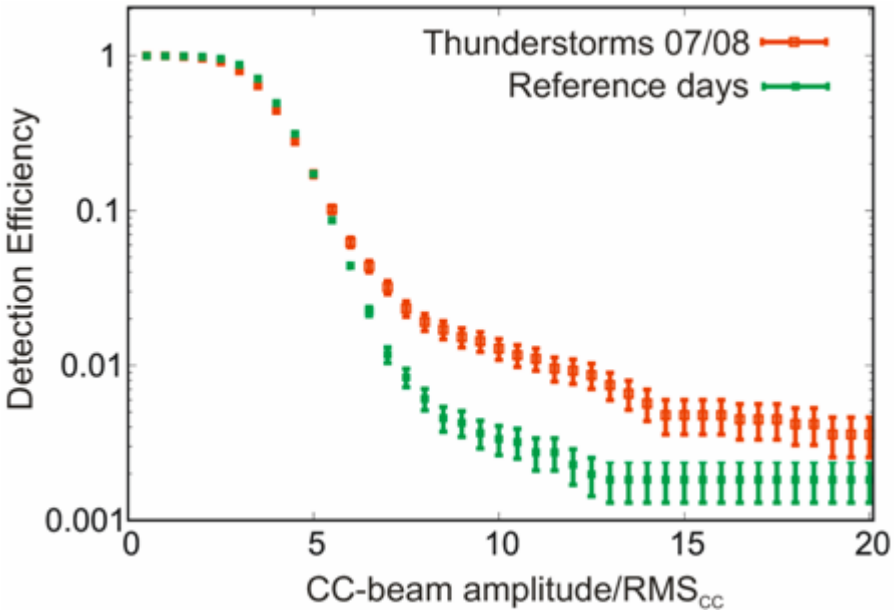
Huege & Falcke, Astrop. Phys. 2005

LOPES thunderstorm events

- events during thunderstorm conditions show unusually strong pulses
  - additional emission due to strong atmospheric electric fields (> kV/m)
- an E-field meter in LOPES monitors thunderstorms
  - study possible connections between cosmic rays and lightning
- fair weather atmospheric fields (~10 – 100 V/m) have negligible influence
  - confirmed also by REAS2-simulations



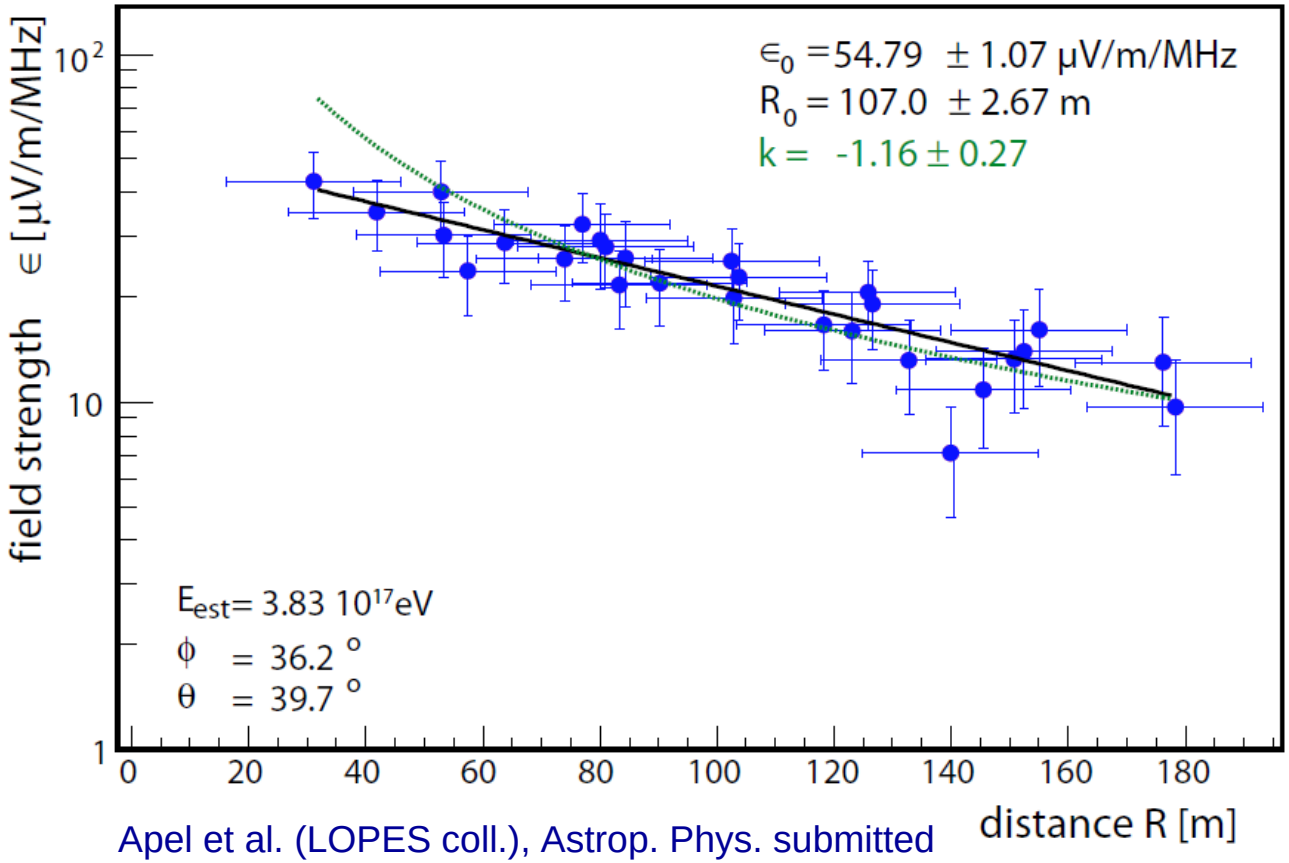
Buitink et al. (LOPES Coll.), Astron. Astroph. 2007



Ender, Diploma Thesis 2009

LOPES lateral radio distributions

- measure signal in individual dipoles (strongest events)
- fit exponential decay (expected from theory and older results)
- fitting power-law also possible, but worse near core

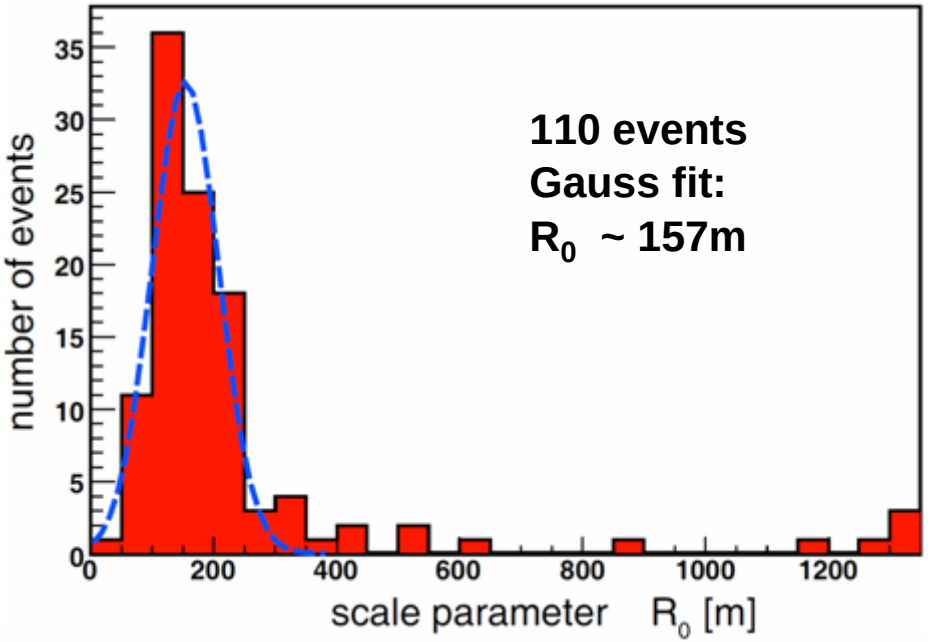


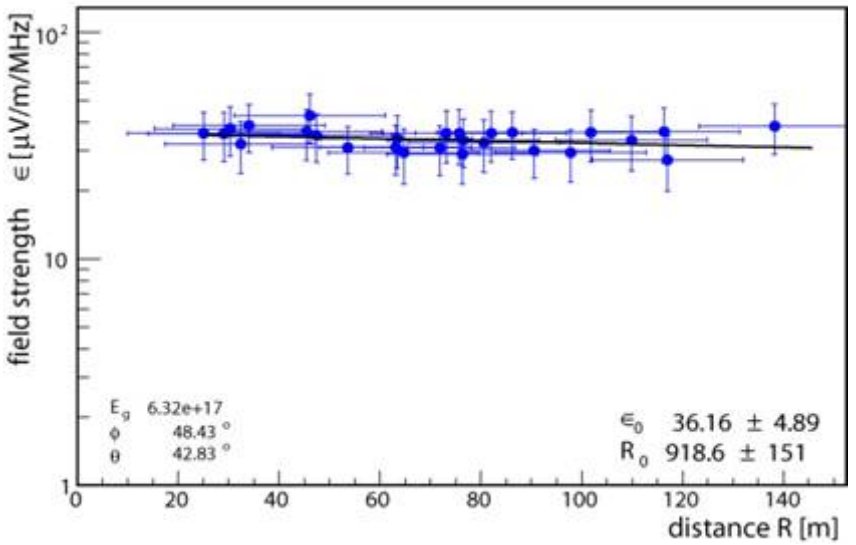
Apel et al. (LOPES coll.), Astrop. Phys. submitted

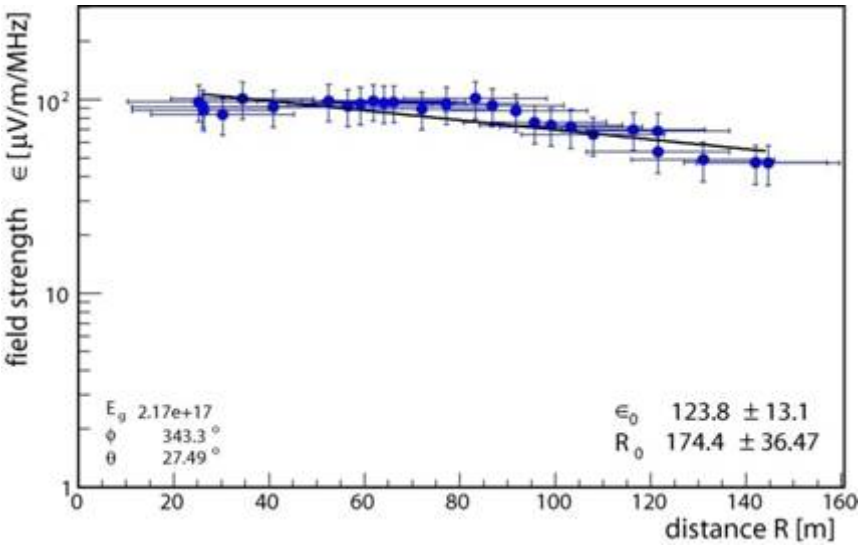
Peculiar LOPES lateral distributions

- about 20% of the events are flat or show a flattening towards the core
- not predicted by any theory

Apel et al. (LOPES coll.), Astrop. Phys. submitted



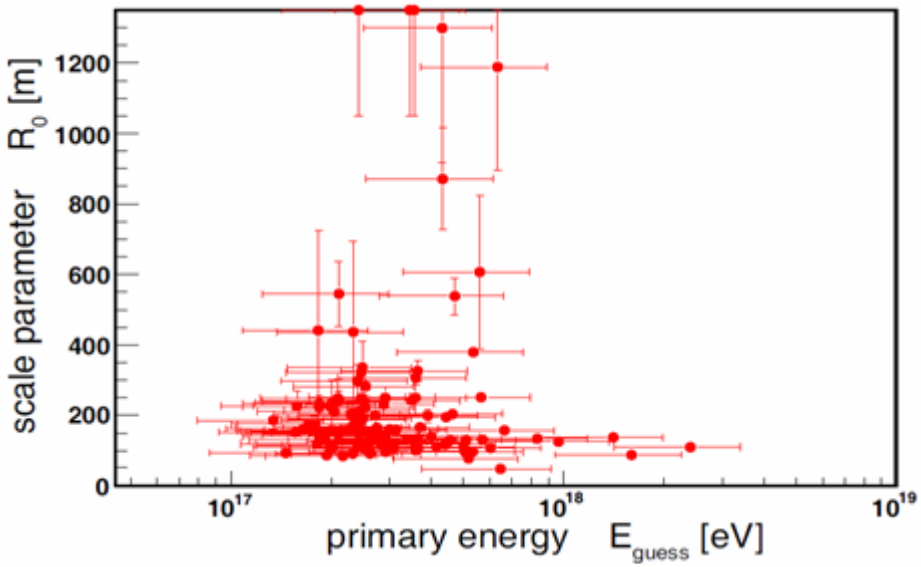


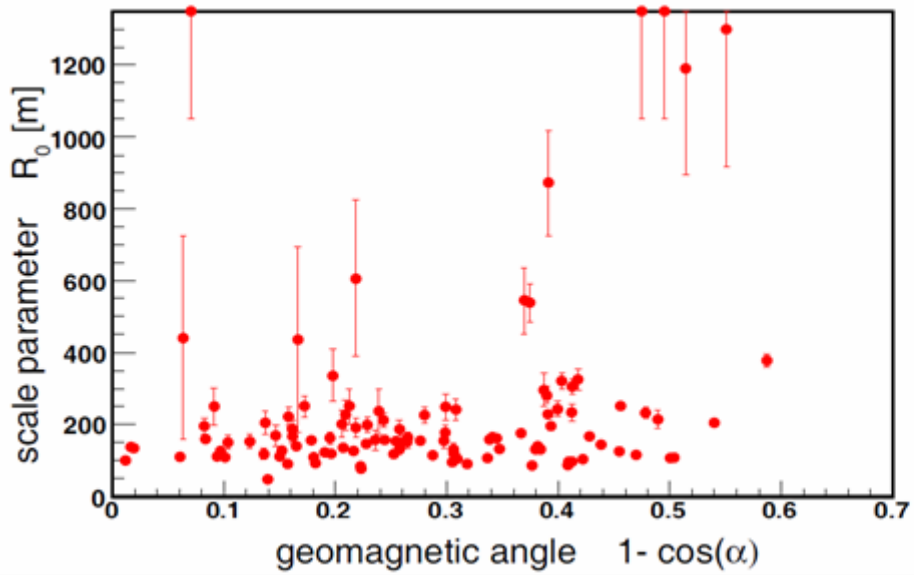


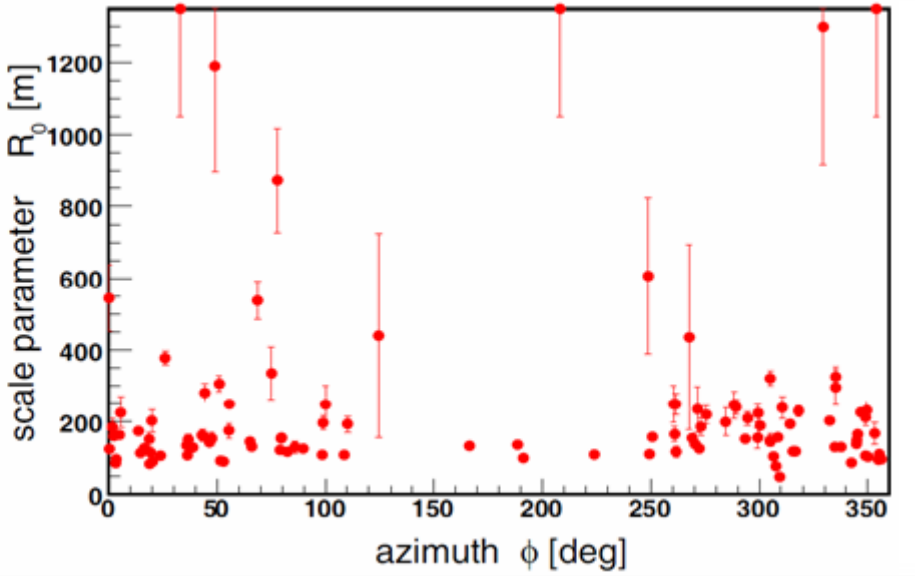
Scale parameter R_0 correlations

- no apparent correlation with
  - primary particle energy
  - angle to magnetic field
  - shower azimuth angle

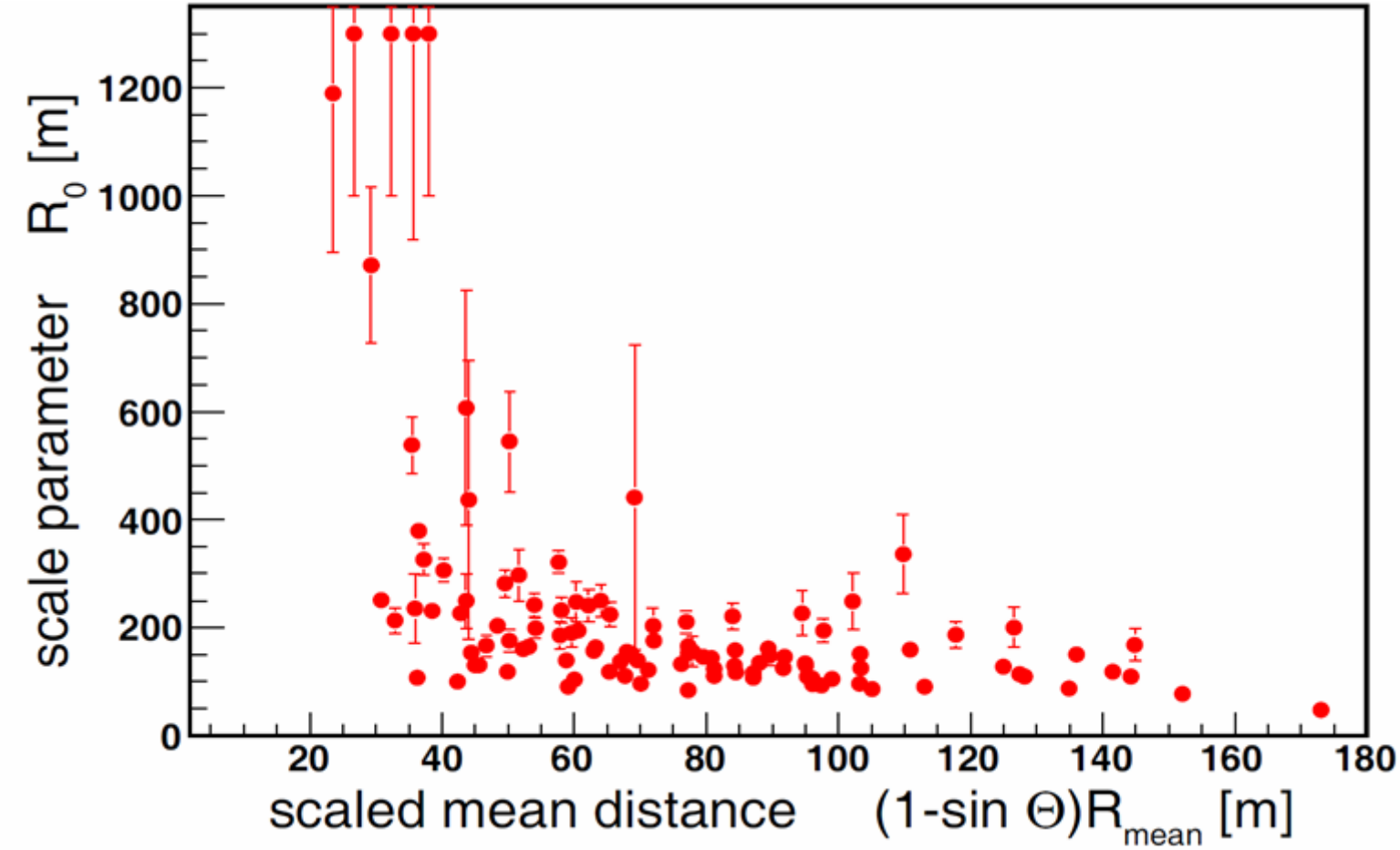
Apel et al. (LOPES coll.), Astrop. Phys. submitted







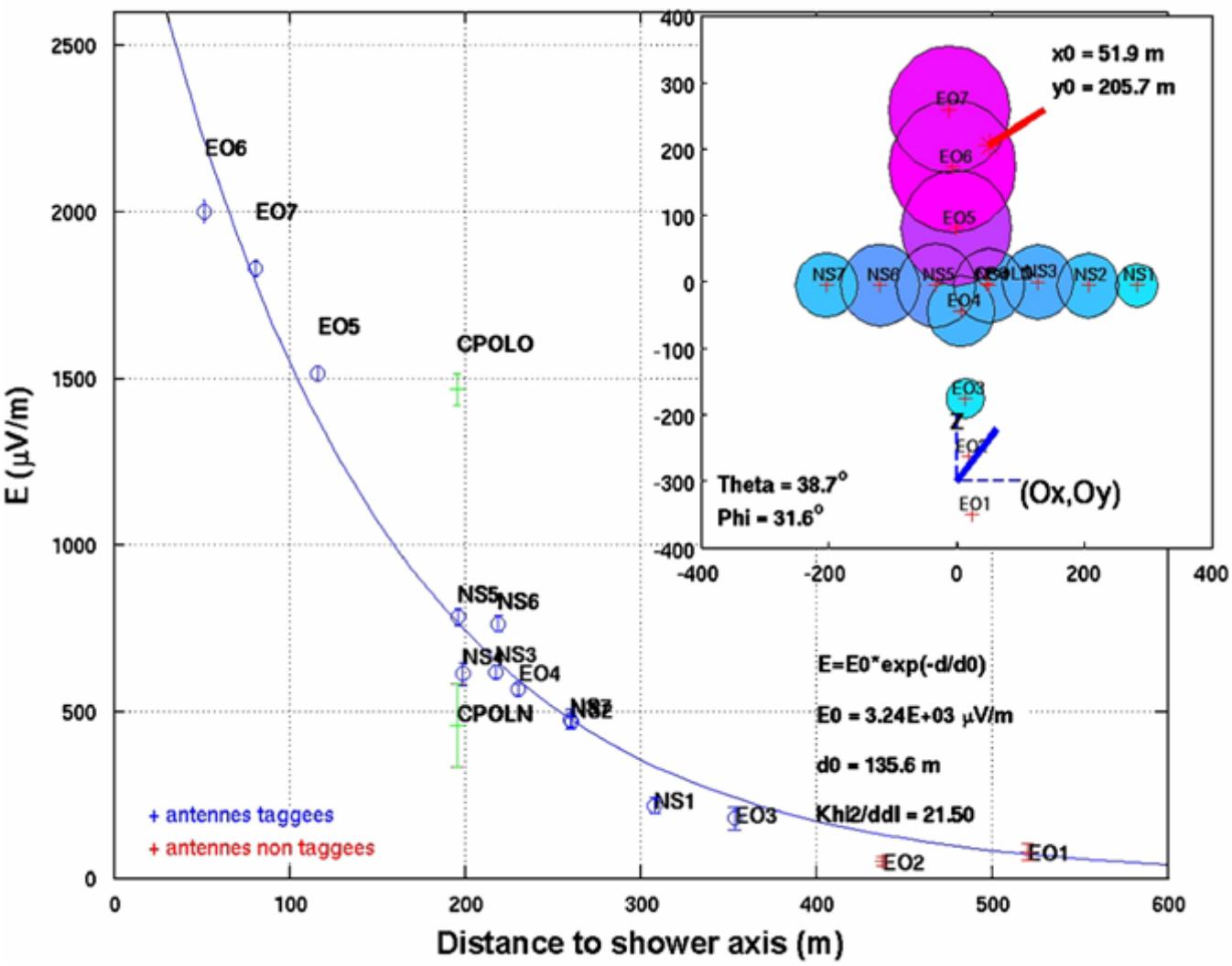
Flat events close to the core



- **flat events appear predominantly at small mean lateral distances and large zenith angles**

Apel et al. (LOPES coll.), Astrop. Phys. submitted

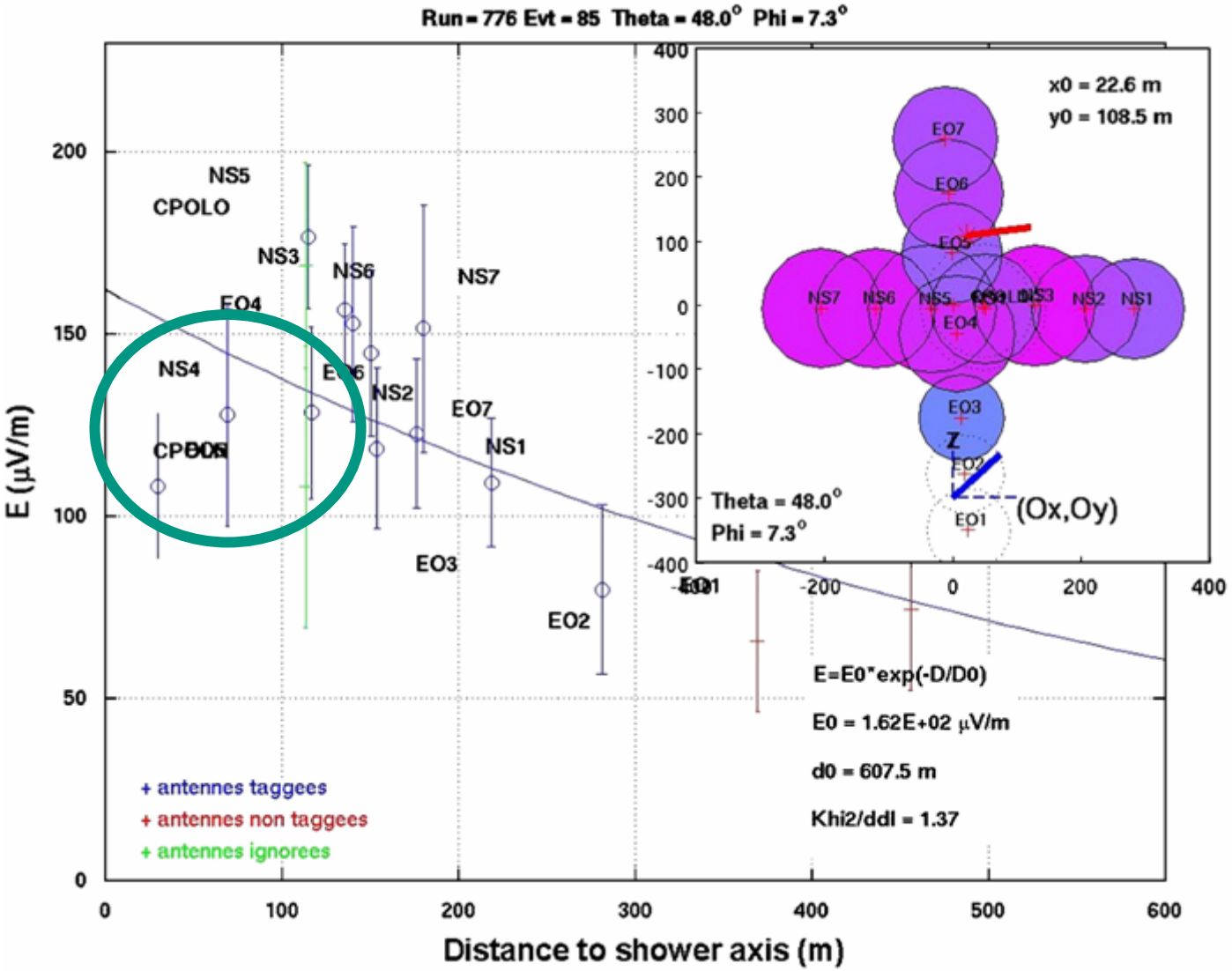
CODALEMA lateral radio distributions



- also find exponen-tial decay
- comparable scale parameters
- find some flat or flattening profiles, too

P. Lautridou et al. (CODALEMA coll.), ARENA 2008

CODALEMA lateral radio distributions

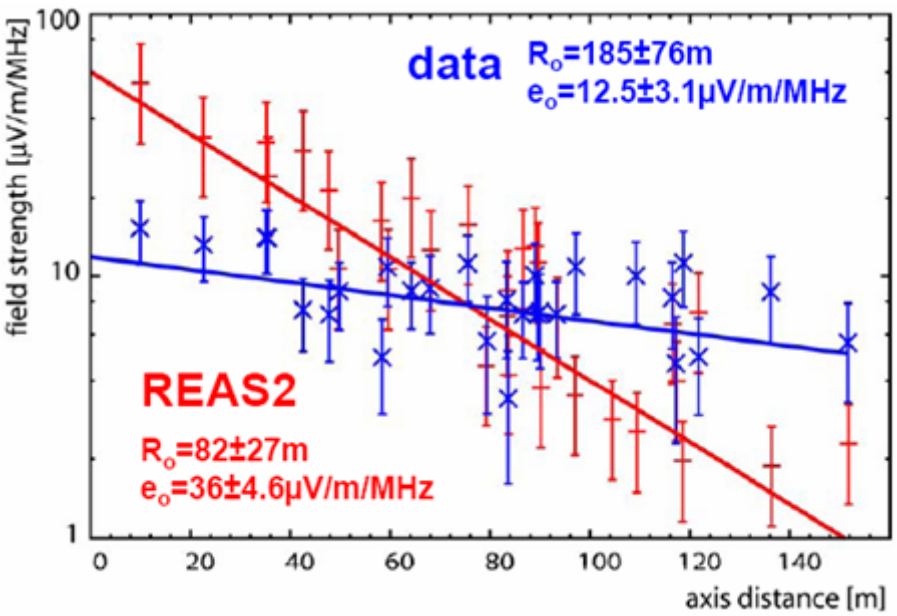


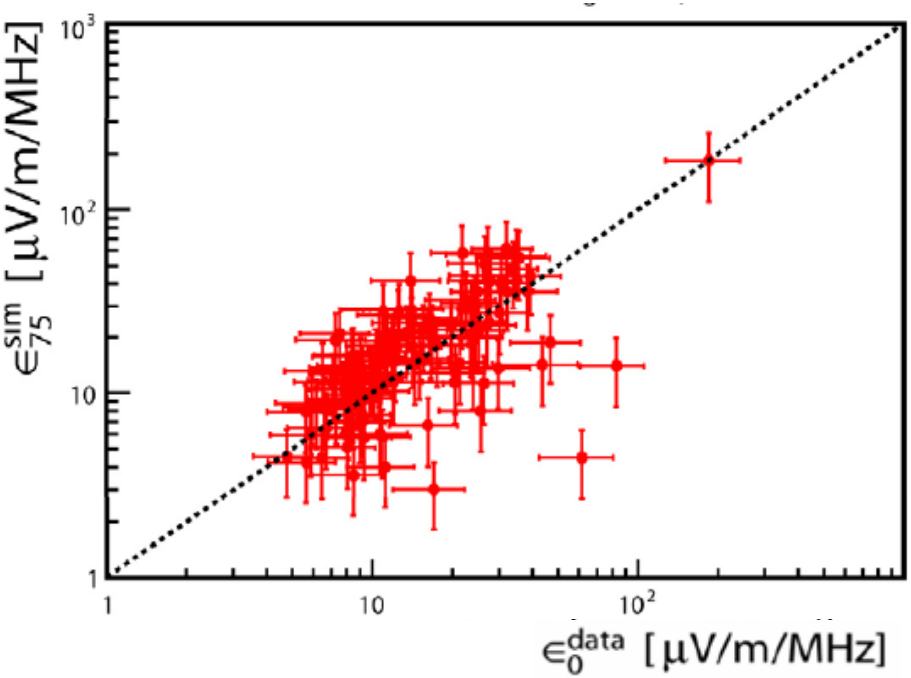
- also find exponen-tial decay
- comparable scale parameters
- find some flat or flattening profiles, too

P. Lautridou et al. (CODALEMA coll.), ARENA 2008

LOPES30 comparison with simulations

- LOPES30 fully calibrated (absolute field strengths)
- simulations per event with shower parameters from KASCADE
- lateral slopes in simulations steeper than in data
- overall amplitude fits very well (always) at 75 m





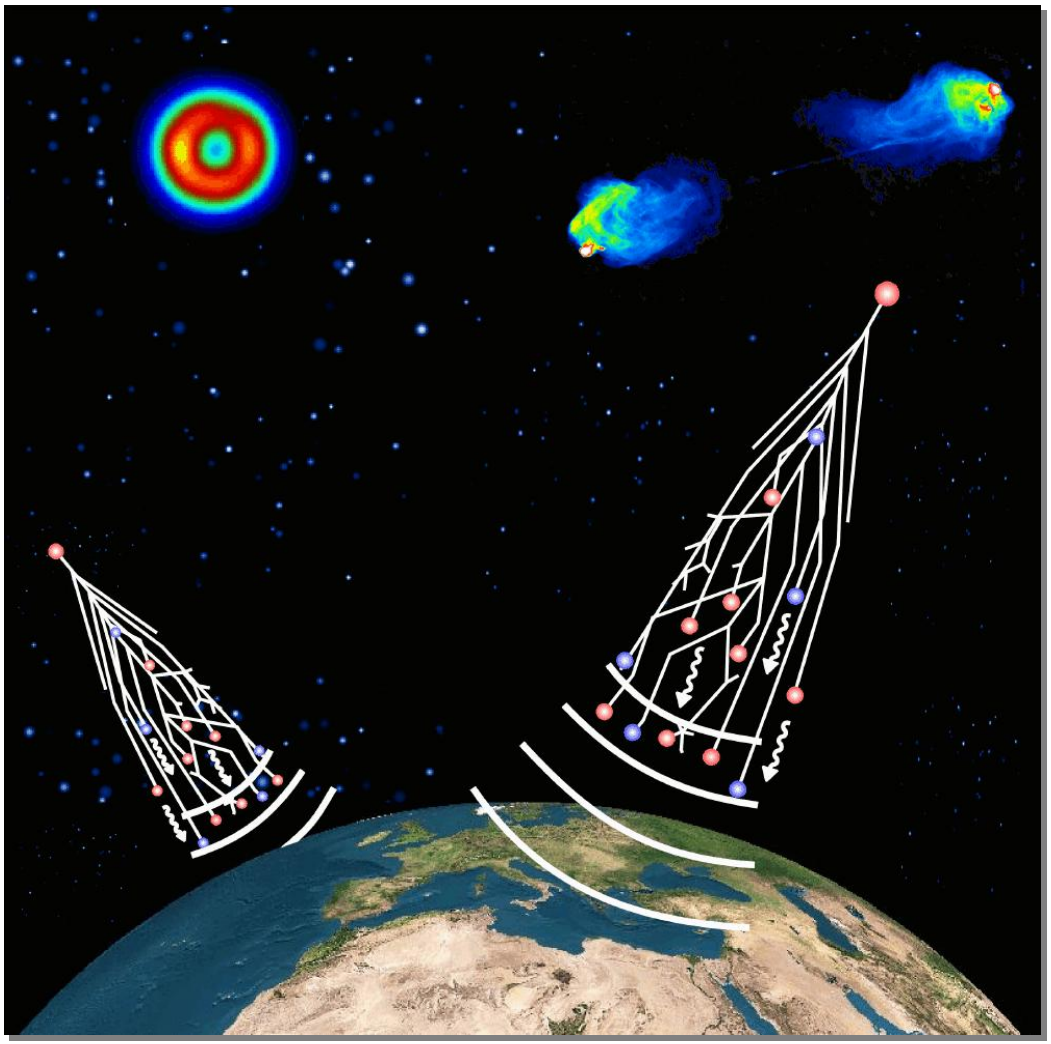
Haungs et al. (LOPES coll), ARENA 2008

General status

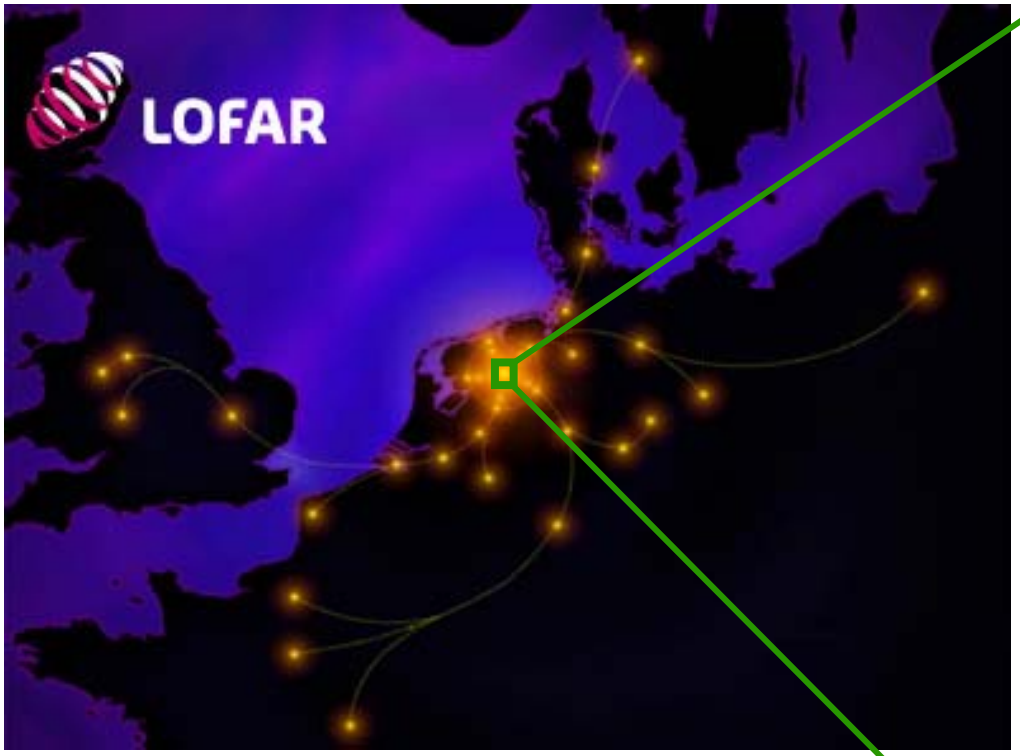
- LOPES and CODALEMA have studied radio emission up to ~10^{18} eV
  - scaling with CR energy – coherent emission
  - correlation with geomagnetic field direction – geomagnetic emission
  - polarisation characteristics – geomagnetic emission
  - exponential lateral distribution – flattening in some cases
  - absolute field strength of the emission
  - direction resolution of radio measurements
  - frequency spectra of the radio pulses
  - curvature of the electromagnetic radio front
  - dependence of radio emission on atmospheric electric fields
- some aspects have to be studied in more detail
  - flattening of lateral distributions
  - geomagnetic field dependence (amplitudes and polarisation)
  - energy reconstruction systematics
  - Xmax reconstruction capability
- radio emission above 10^{18} eV has yet to be studied
  - can we extrapolate from lower energies as predicted by theory?

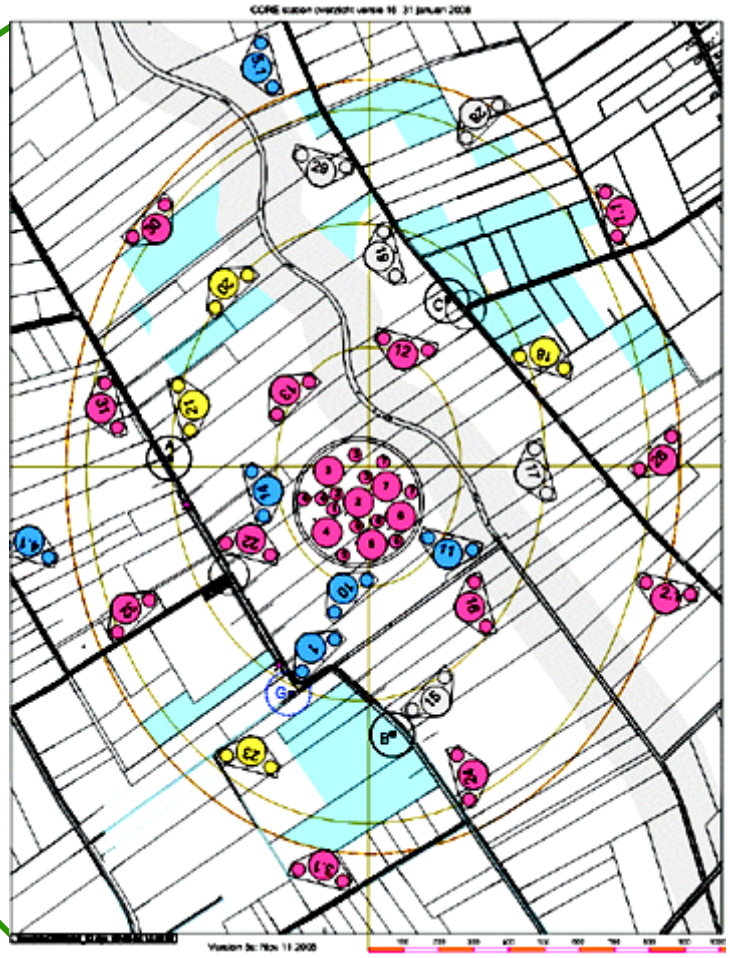
Contents

- the early days of CR radio detection
- the revival of CR radio detection
  - experiments
  - theory
  - results
- **the future of CR radio detection**



LOFAR will measure CRs

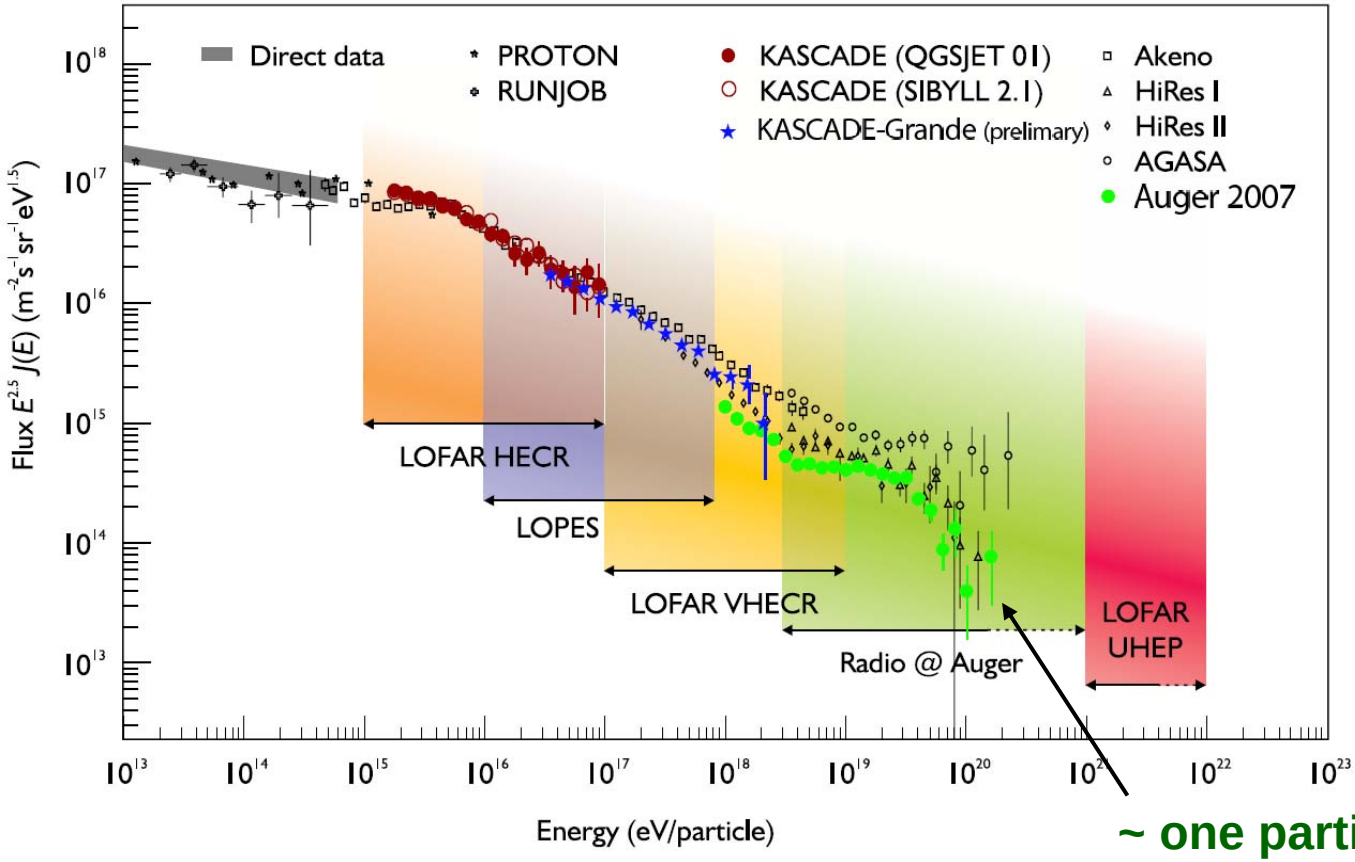




- LOFAR stations (96 antennas each) will be used for cosmic ray radio detection
- overall collecting area will be only ~80 km^2, but very densely instrumented
  - very detailed measurements of individual air showers, with good calibration

Horneffer et al., ICRC 2009

LOFAR CR programme

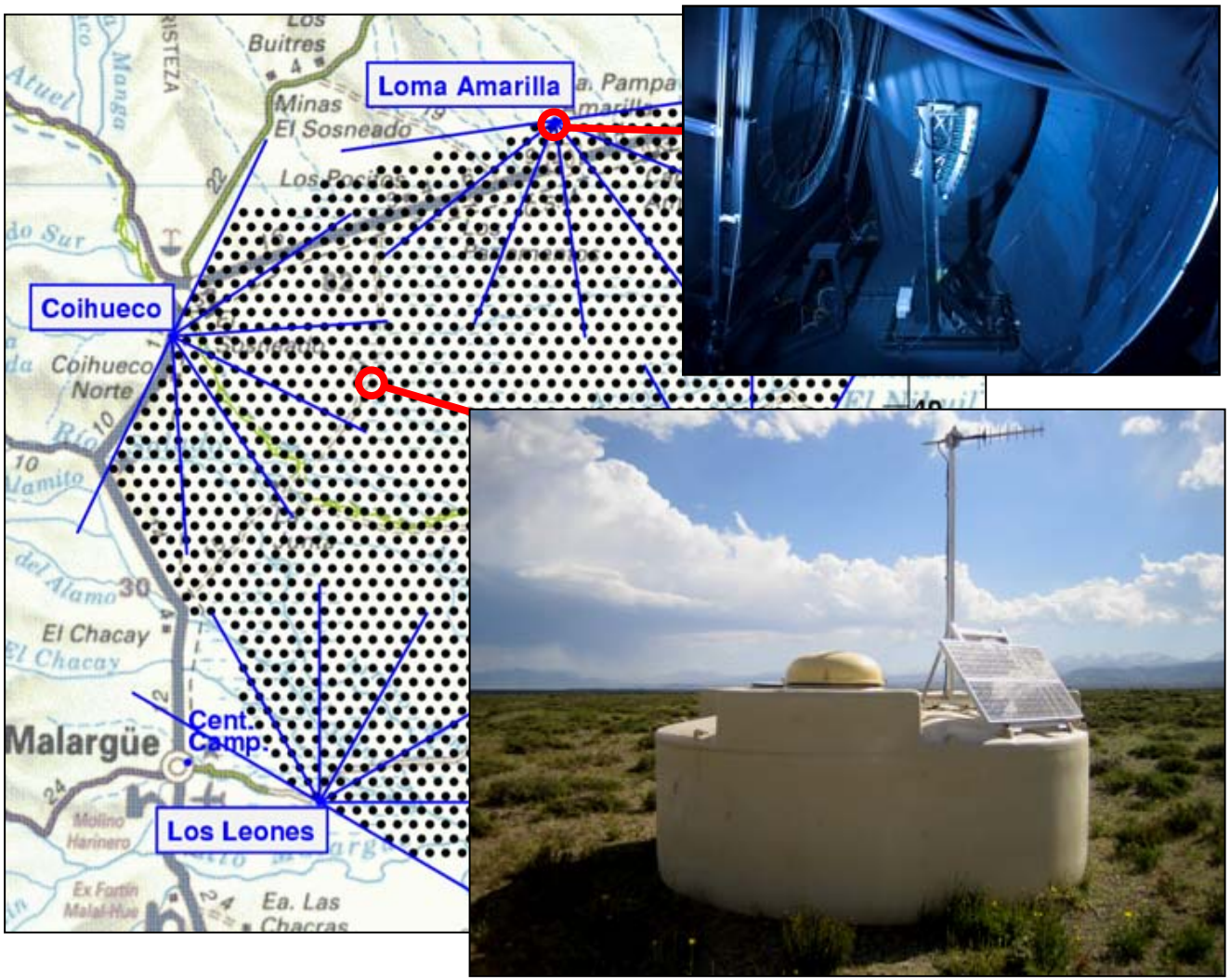


~ one particle per km^2 and century

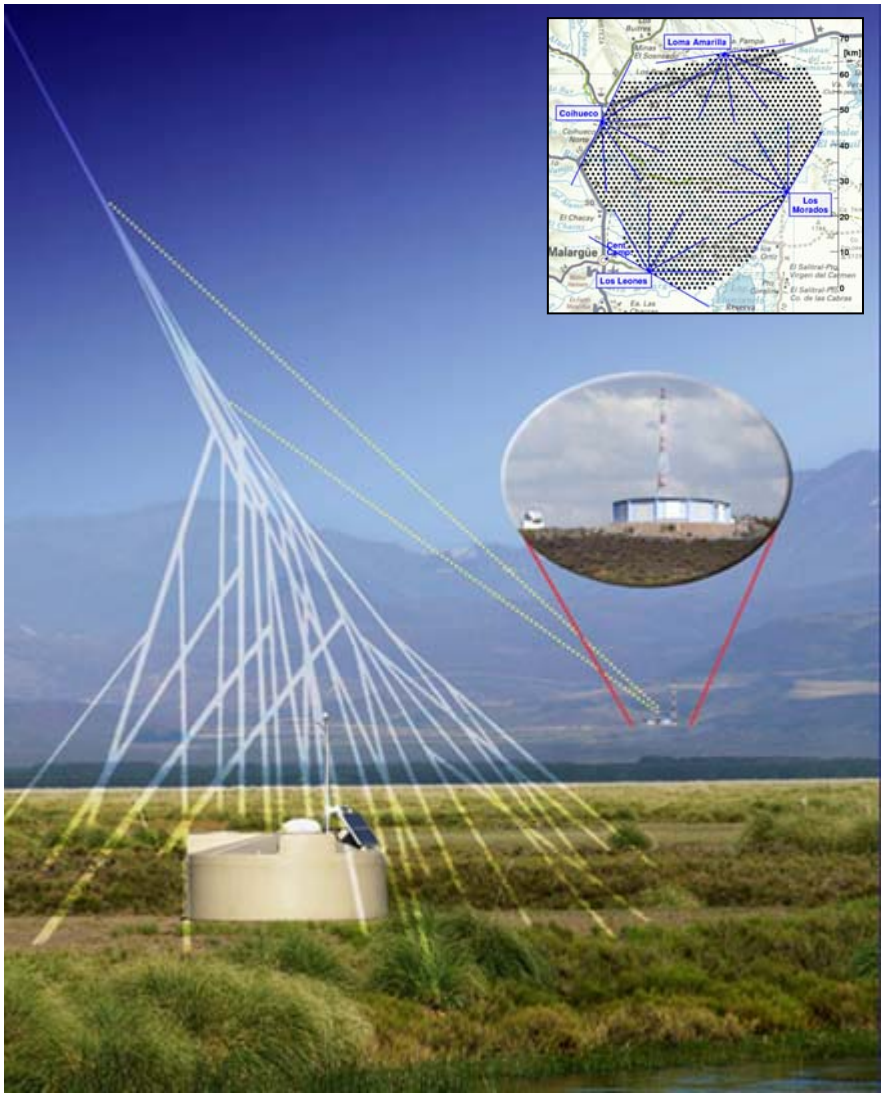
- VHECR: similar operation mode as in LOPES
- HECR: search for pulses in beam-formed station data (small FOV)
- UHEP: look for radio pulses from interactions in the lunar regolith

The Pierre Auger Observatory

- highest energies need huge arrays
- Southern site
  - Argentina
  - 3000 km^2
  - 1600 particle detectors
  - 24 optical telescopes
- Northern site
  - planned
  - USA
  - >20000 km^2



Hybrid detection in Auger



- hybrid detection
  - particle detectors
  - fluorescence telescopes
- many advantages
  - cross-calibration
  - general redundance
  - minimisation of model dependence (energy scale)
- duty cycle of combined measurements only ~13%

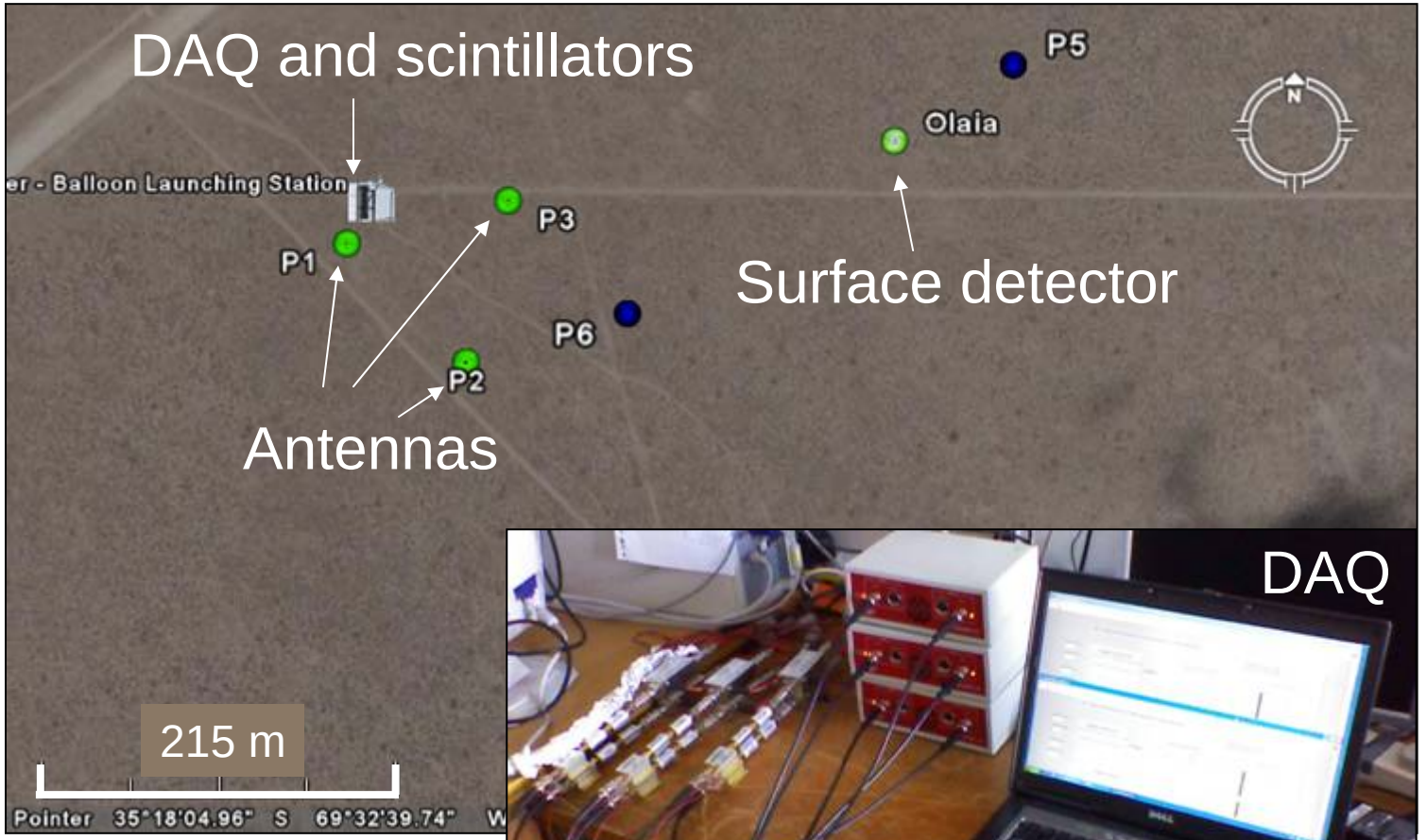
Large scale radio detection in Auger

- so far only small experiments (<0.5 km^2)
- radio detection is most interesting for ultra-high energy cosmic rays
- develop large-scale application

- R&D in the Pierre Auger Observatory
  - allows hybrid analysis together with particle and fluorescence detectors
  - in Argentinian pampa has very good radio noise conditions

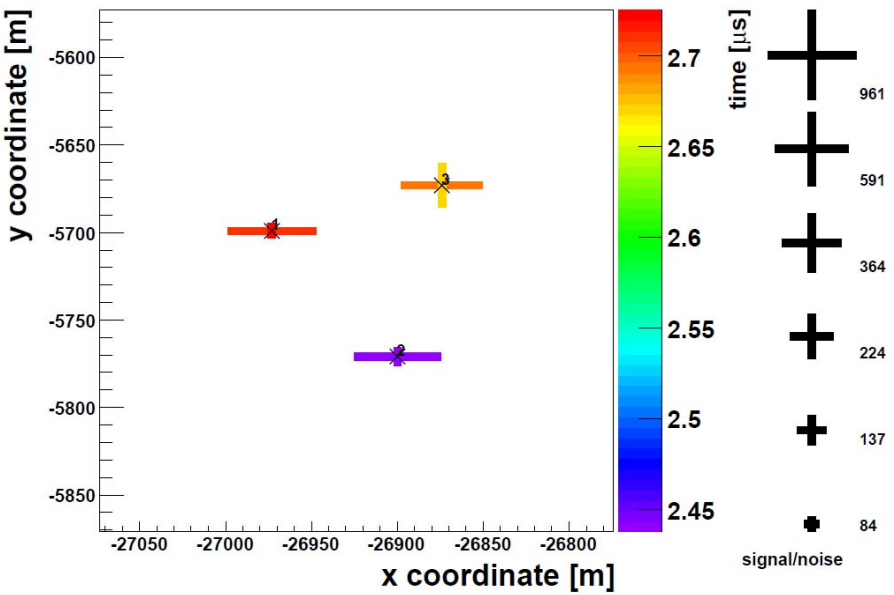
- many technological challenges
  - decentralized array organisation
  - autonomous, self-powered detector stations
  - wireless communication between stations
  - self-triggering on radio signals
  - robustness (cows, strong winds, …)
- R&D so far with a number of small test cells operating in various configurations

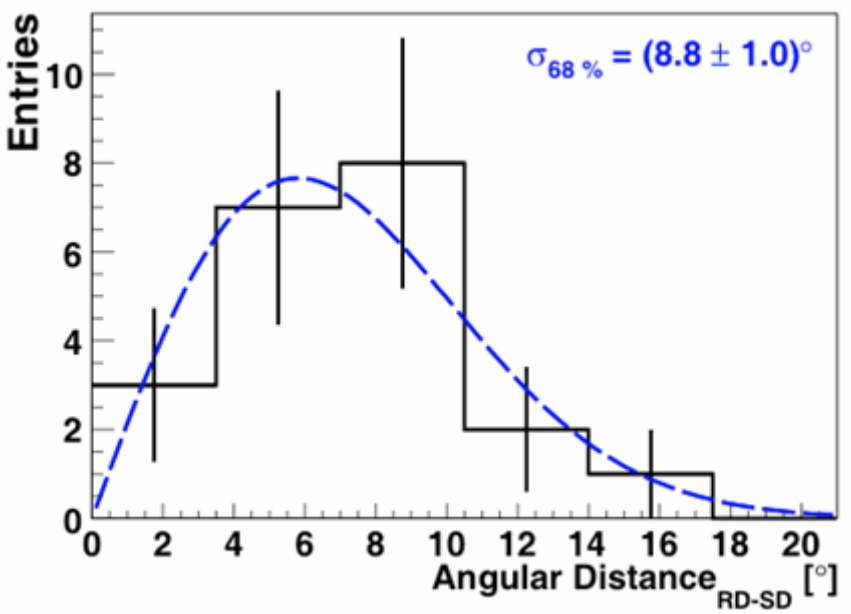
Externally triggered measurements at BLS



- **Two scintillators provide external trigger. “Offline” search for coincidences with Auger SD.**

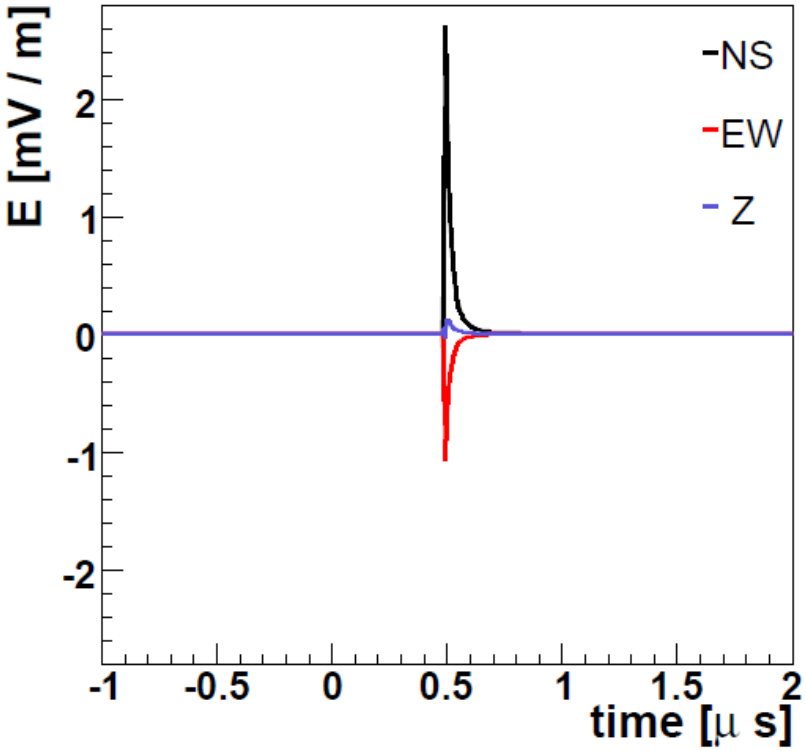
Results of measurements near BLS

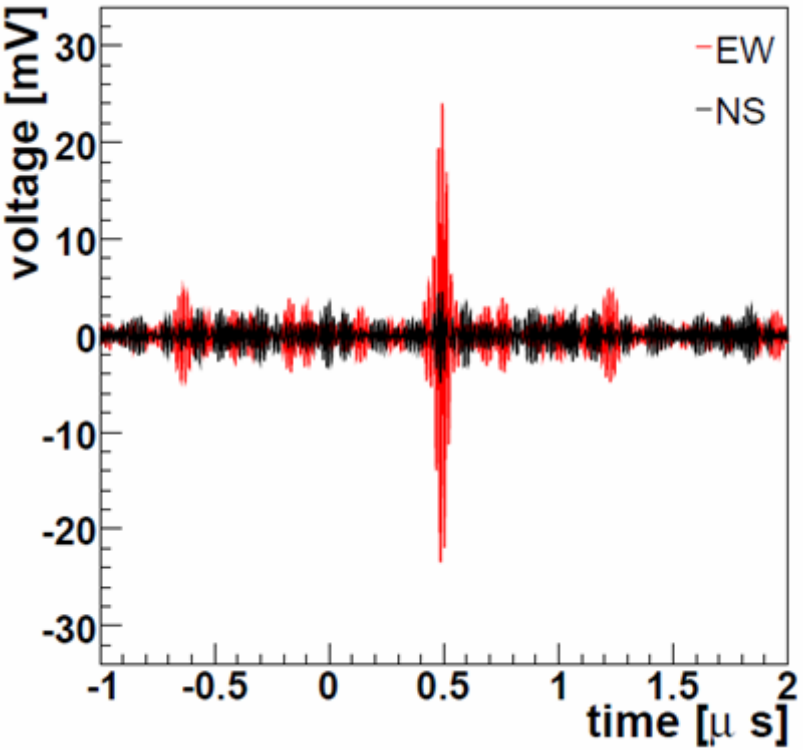




- >25 coincident events between Auger SD and all 3 radio antennas
- signal usually seen in both antenna polarisations
- directions reconstructed with SD and radio are compatible
- angular resolution limited by GPS-only timing

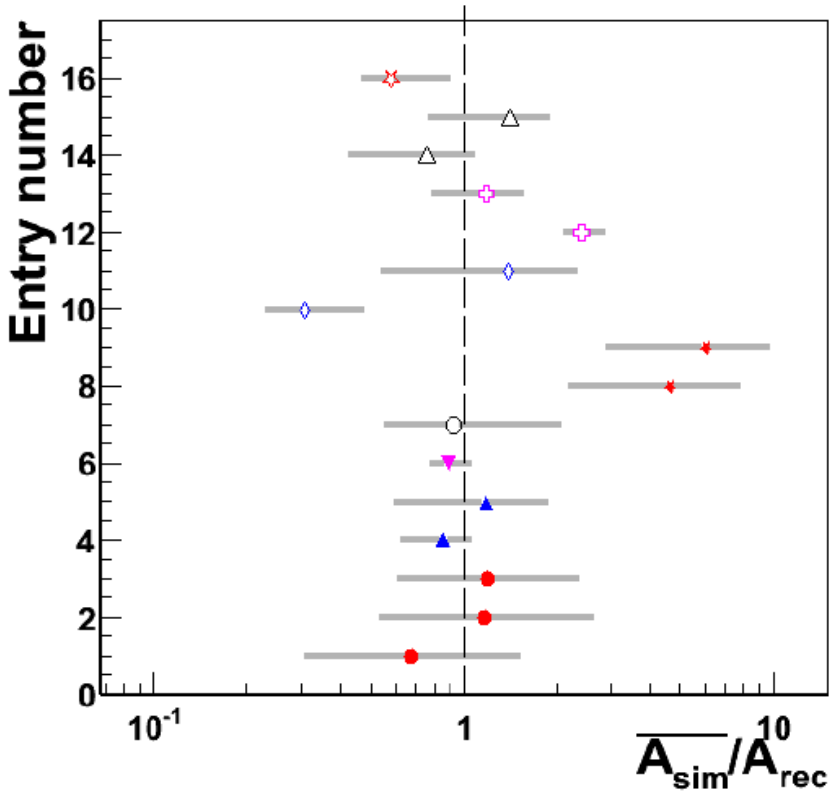
Further results from BLS measurements





- full event and detector simulation chain (CORSIKA, REAS2, RDAS)
- fair agreement within (relatively large) uncertainties

Further results from BLS measurements



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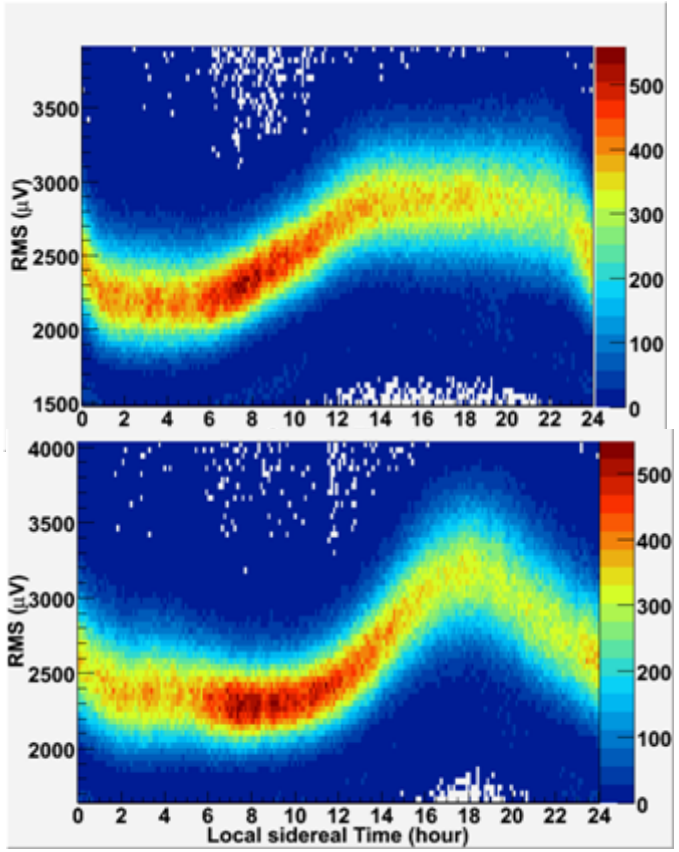
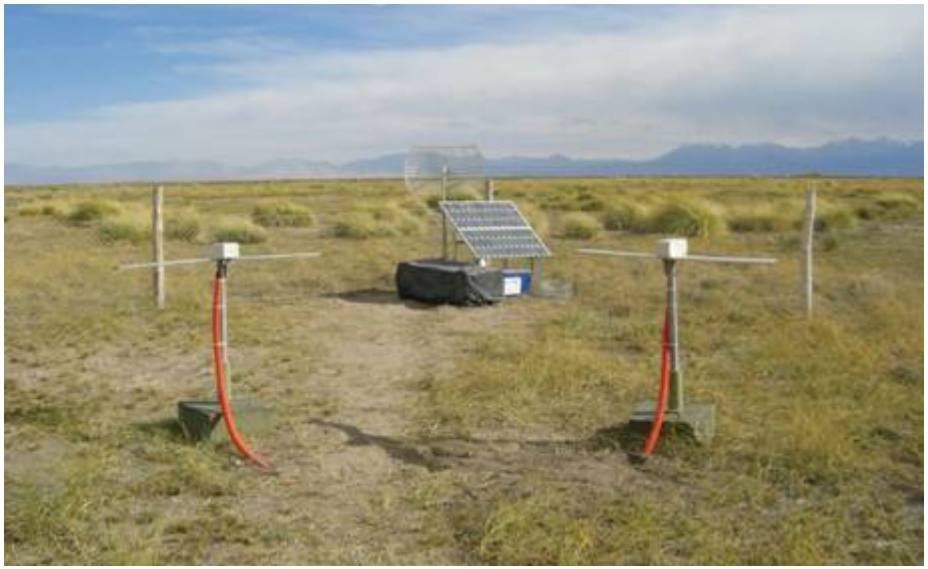
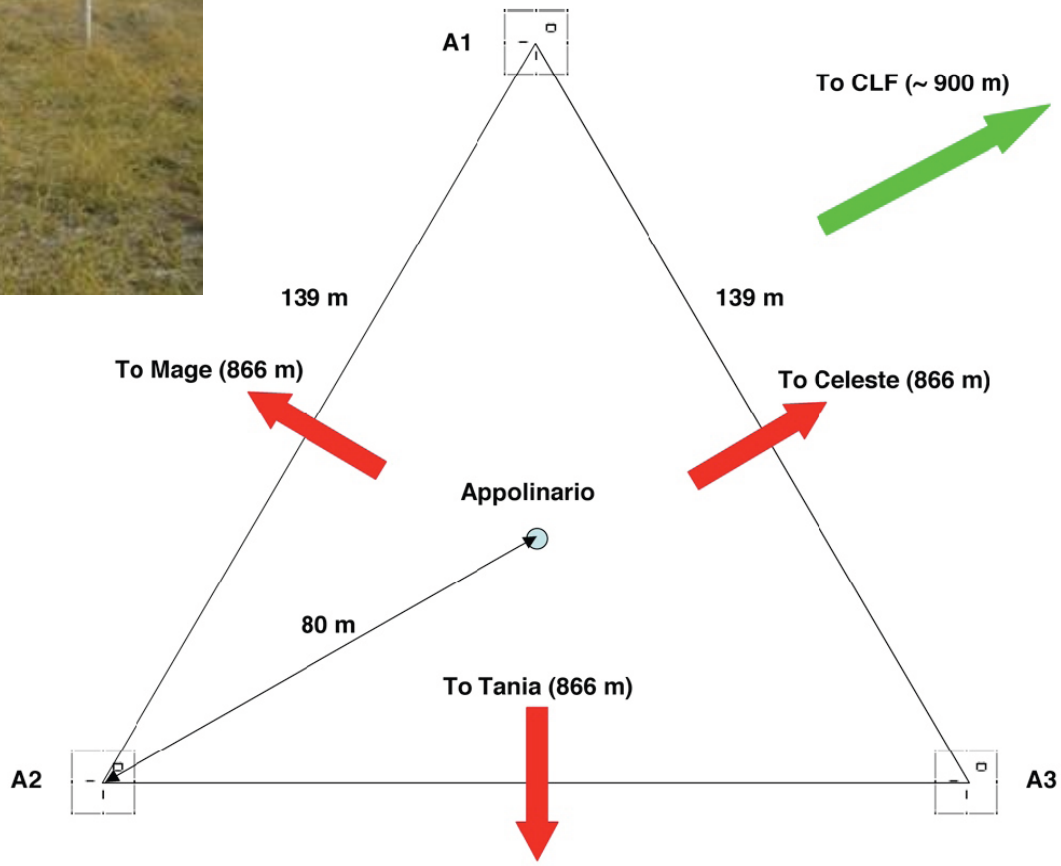


- radio noise in both polarisations shows passage of Galactic centre
- can be used for amplitude calibration and antenna diagnosis

Self-triggered measurements near CLF



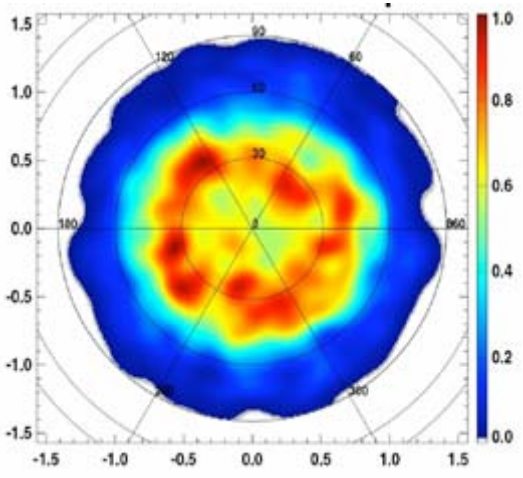
- 3 autonomous stations
  - solar-powered
  - dual-polarisation
  - wireless data link
  - self-triggered on radio signals (50-70 MHz)



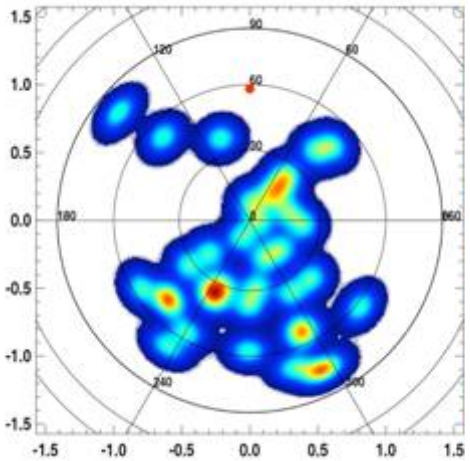
Results of measurements near CLF

- detectors have successfully self-triggered on radio pulses
- found 36 self-triggered radio events coincident with SD events
- 72% of the radio-triggered events come from south
  - threshold effect
  - confirmation of geomagnetic radio emission mechanism

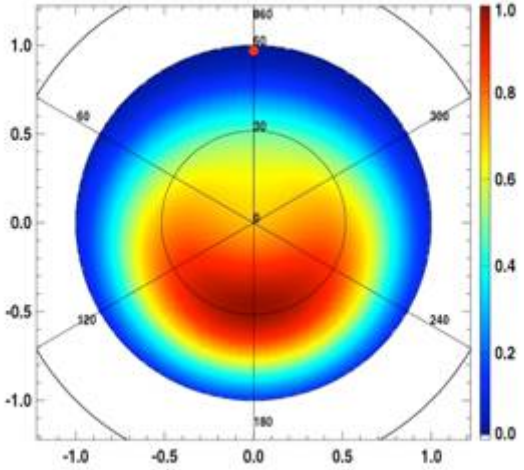
SD events



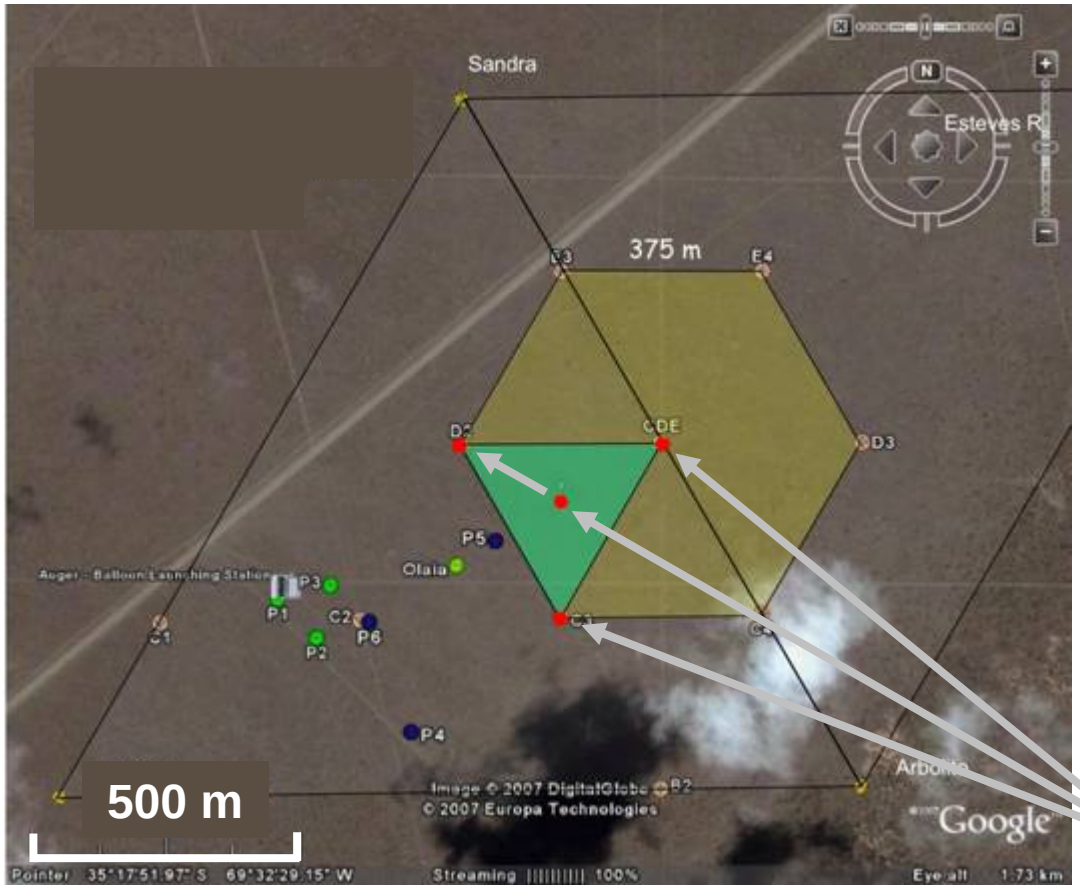
Radio events



$\vec{v} \times \vec{B}$ model



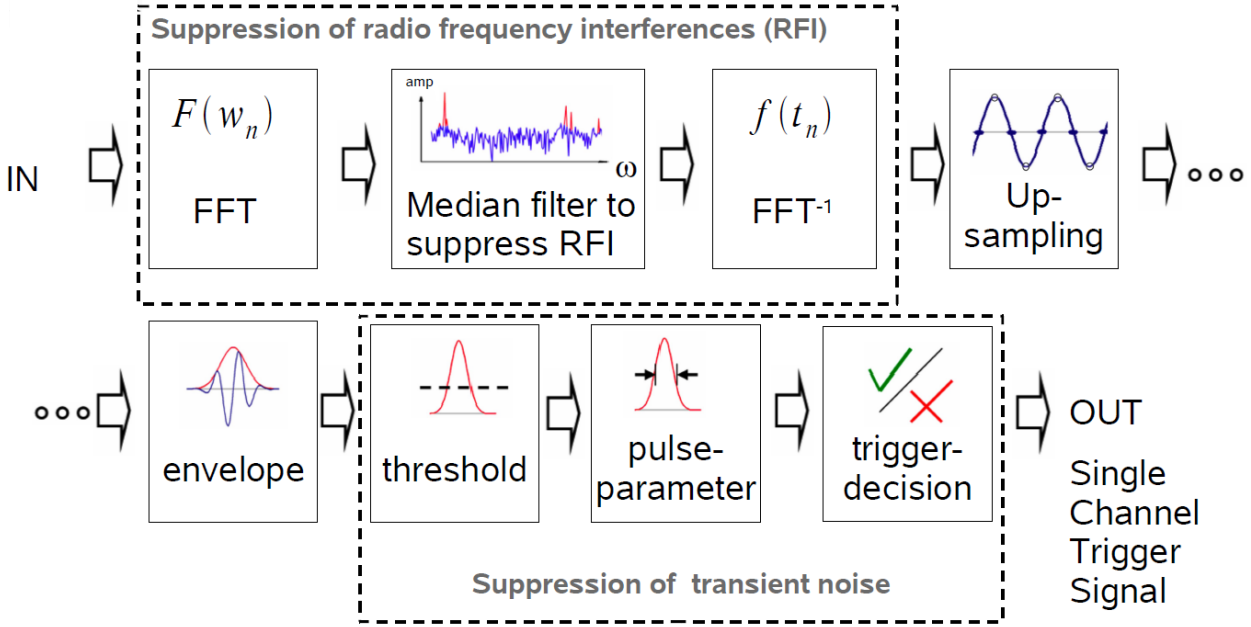
Self-triggered setup at BLS: MAXIMA



- autonomous stations
- LPDA antennas
- solar-powered
- wireless comms
- self-triggered

- collecting valuable experience for larger array under realistic conditions

FPGA self-trigger tests at BLS



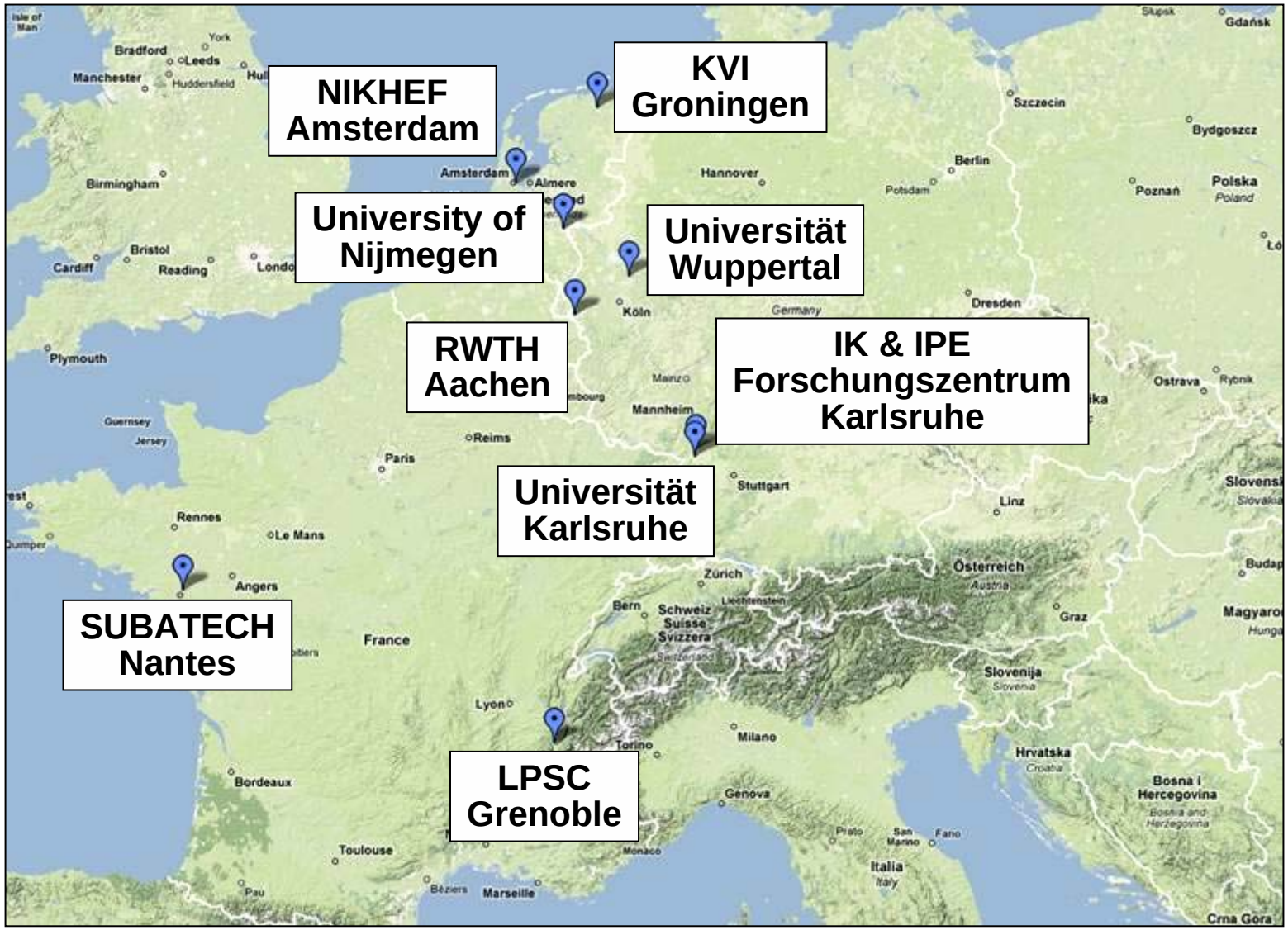
- tests of a new antenna design (SALLA)
- test of a sophisticated self-trigger implemented on an FPGA
  - real-time RFI suppression for 40-80 MHz band
  - real-time pulse characterisation (after upsampling, enveloping)
  - trigger decision depending on pulse parameters

The Auger Engineering Radio Array

- small-scale tests concluded successfully
- next step: ~20 km^2 radio array, ~150 antennas
  - prototype array for large-scale radio detection
- super-hybrid measurements
  - co-located with HEAT (high-elevation fluorescence telescopes)
  - co-located with AMIGA (SD infill and muon counters)
- science goals of AERA
  1. study and understand in detail radio emission above $10^{17.5}$ eV
  2. evaluate capabilities of large scale radio detection wrt.
     - cosmic ray energy
     - cosmic ray mass
     - cosmic ray arrival direction
  3. perform cosmic ray measurements in the region of transition from galactic to extragalactic sources
     - energy spectrum
     - mass composition

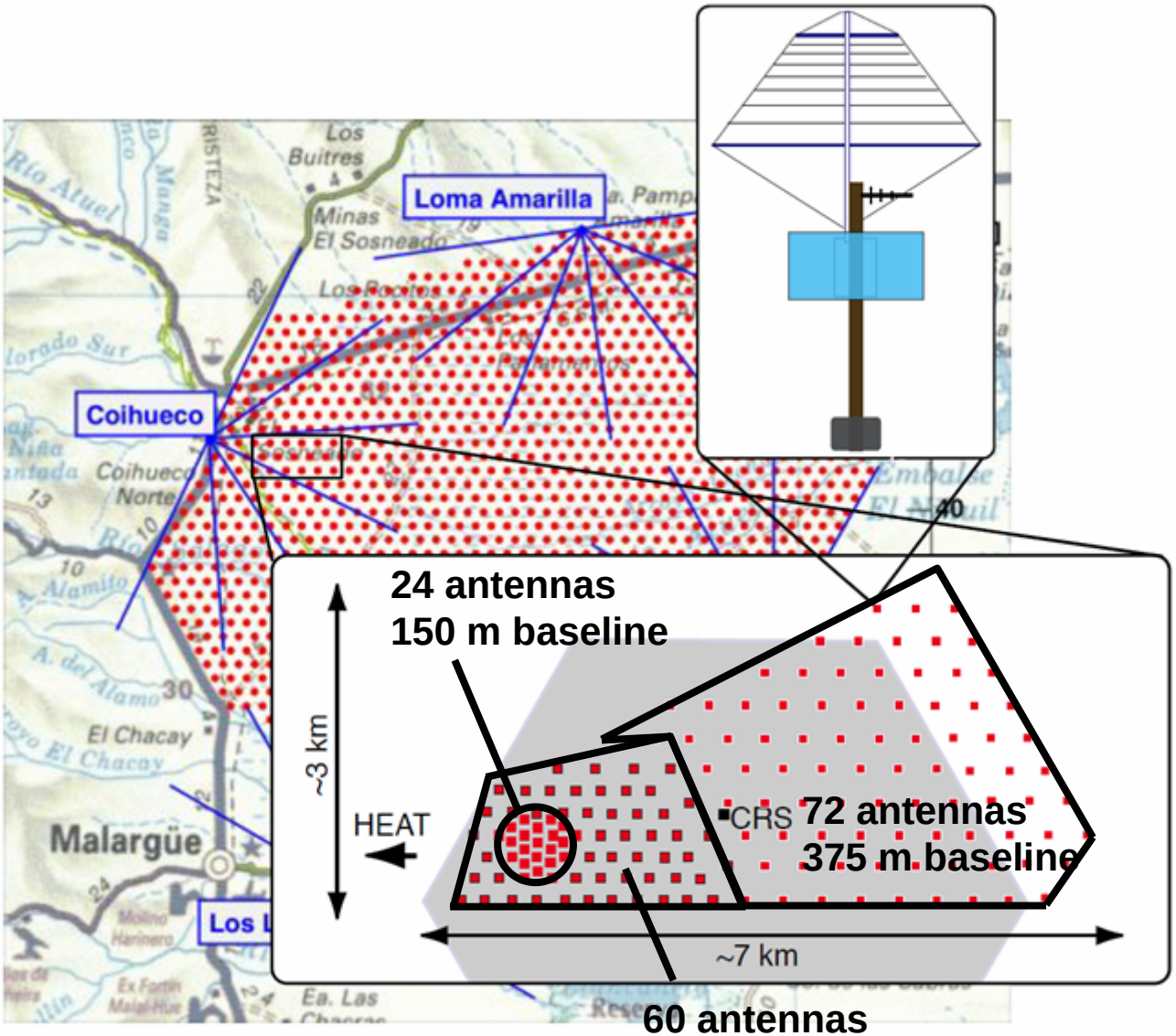
Institutions participating in AERA

Auger Engineering Radio Array



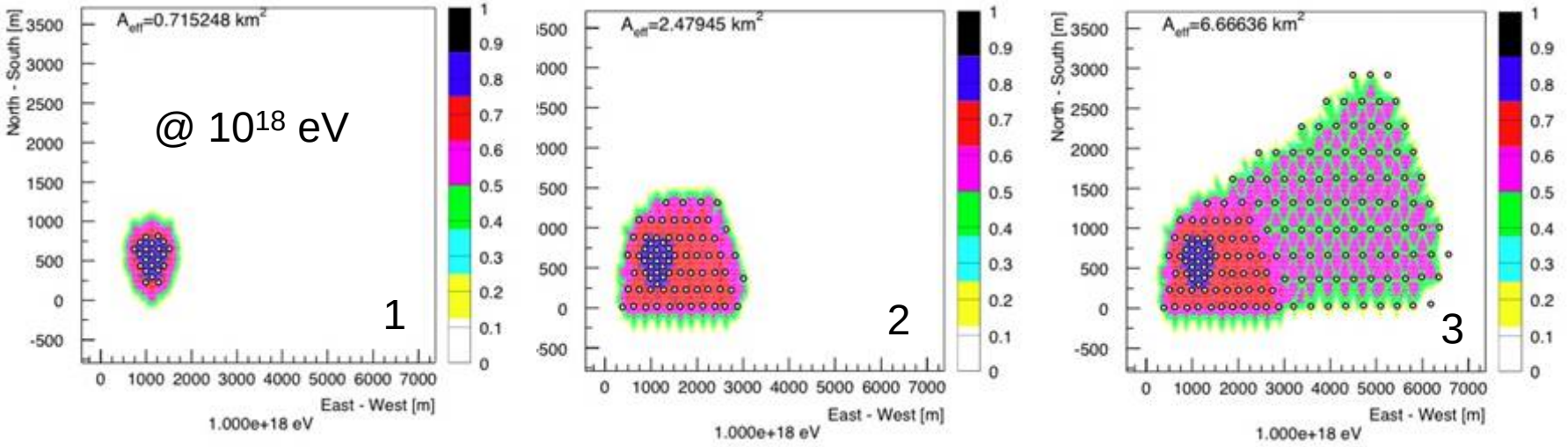
Planned configuration of AERA

Auger Engineering Radio Array

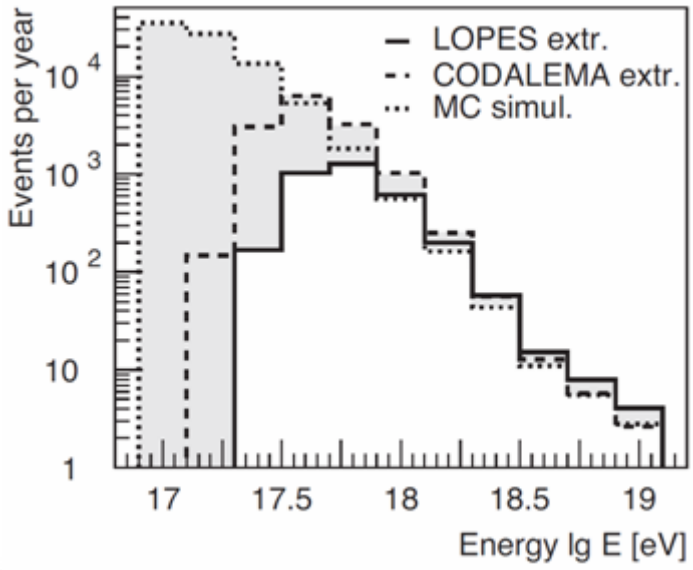


- autonomous stations
- solar-powered
- wireless links
- 30-80 MHz
- 4 channels
- 200 MS s^{-1}
- 12 bit ADCs
- ring buffer for ~3 seconds
- first stage: LPDA antennas

Projected array performance



- array will be set up in three stages
- 24 antenna stations in first phase
  - parallel R&D for later upgrades
- event rates have been projected based on different data
  - complete array will see ~1000 events per year at energies >10^{18} eV
  - small baseline region will reach 100% efficiency at energies of ~1-2 10^{18} eV
  - complete array will reach 100% efficiency at energies of ~ 4-5 10^{18} eV



Summary and conclusions

- radio detection of cosmic rays has experienced a true revival
- modern experiments have been very successful at $<10^{18}$ eV
  - LOPES in Karlsruhe
  - CODALEMA in Nançay
  - we have made huge progress in understanding the radio emission – but a number of open questions are still under investigation
- large-scale application of radio detection can increase “hybrid” statistics at ultra-high energies by a factor of 10
  - the Auger Engineering Radio Array (AERA) will be the pioneering experiment for large scale radio detection of cosmic rays

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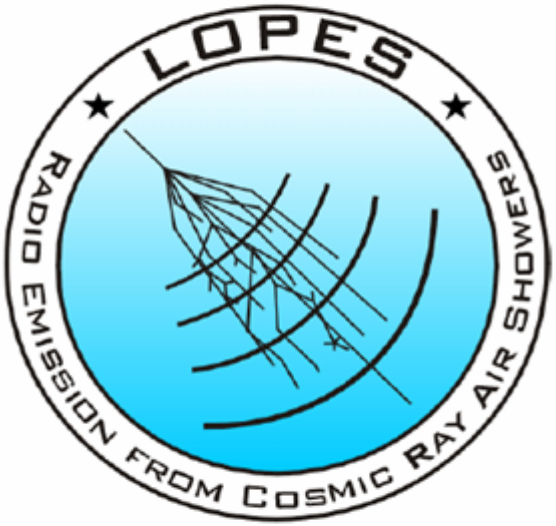

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