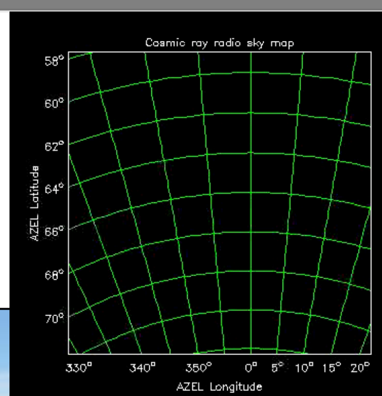
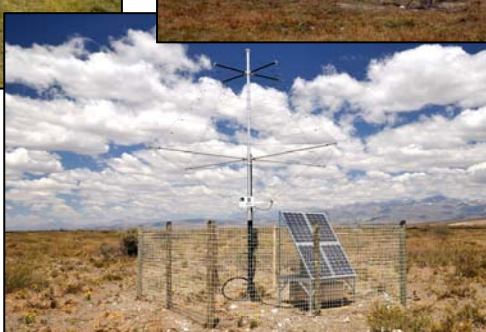
Radio detection of cosmic rays

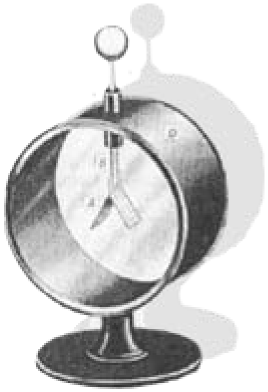
Tim Huege (Karlsruhe Institute of Technology), Helmholtz Young Investigators Group VH-NG-413





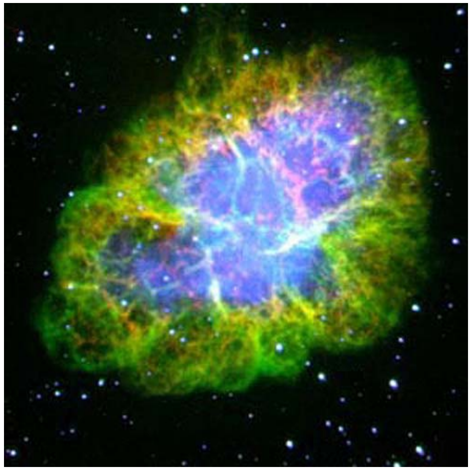
Cosmic rays

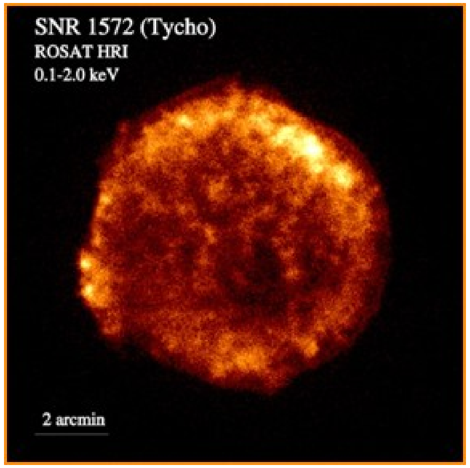
The discovery of cosmic rays

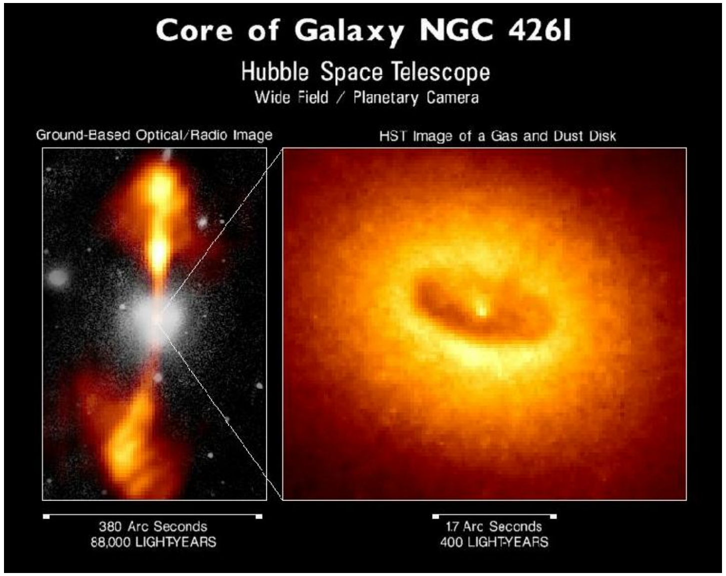


- 1912: balloon experiments by Victor Hess
- rate of “ionising radiation” first decreases with height, then rises again
  - radioactive decays in the earth’s crust
  - additional component from space
- Nobel prize in 1936

The sources of cosmic rays



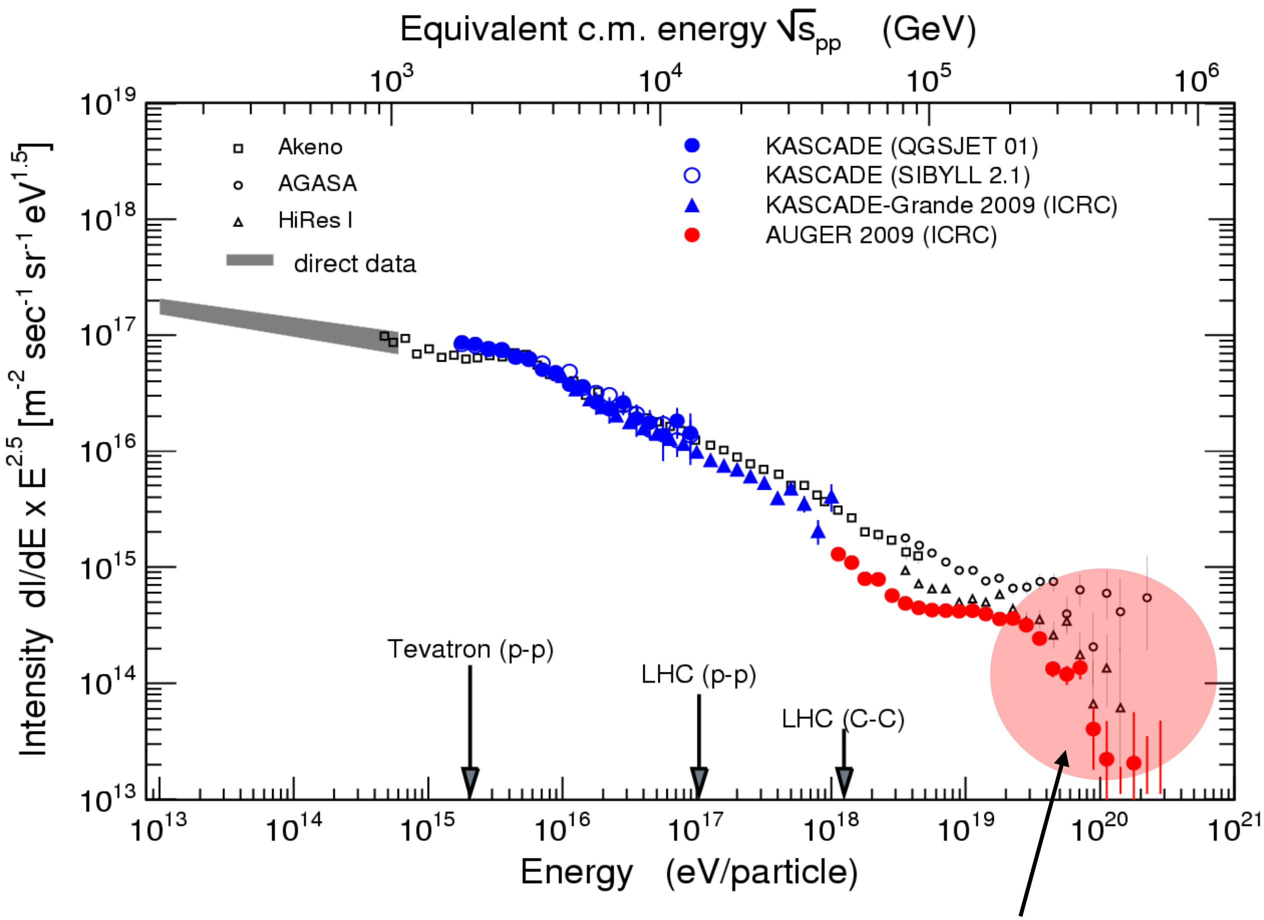




- sources not clearly identified even today
  - isotropisation by magnetic fields
- Galactic component
  - supernova remnants!
  - pulsars?
  - …?
- extragalactic component
  - AGN?
  - radio galaxies?
  - gamma ray bursts?
  - …?

The cosmic ray energy spectrum

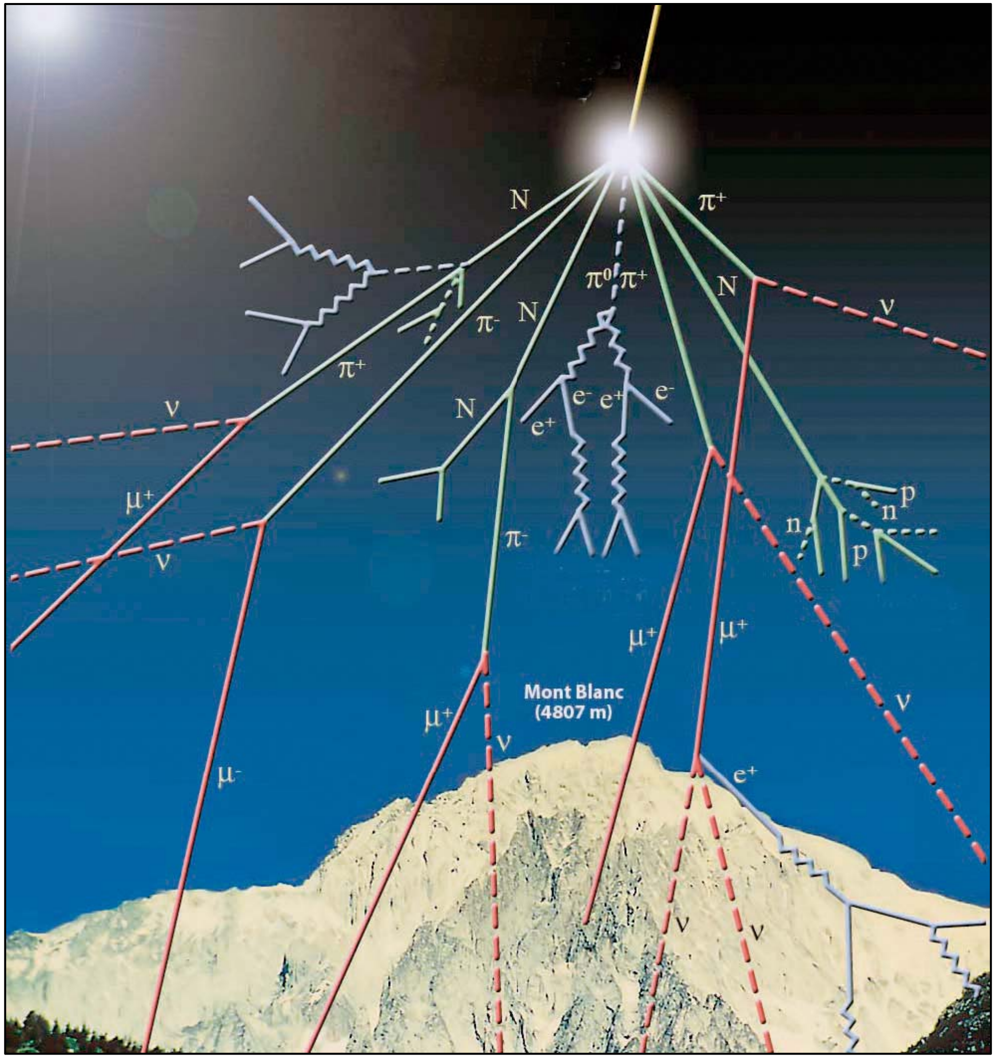
- power-law spectrum over many decades in energy
- some structures visible
- direct detection up to ~10^{14} eV
- indirect detection at higher energies



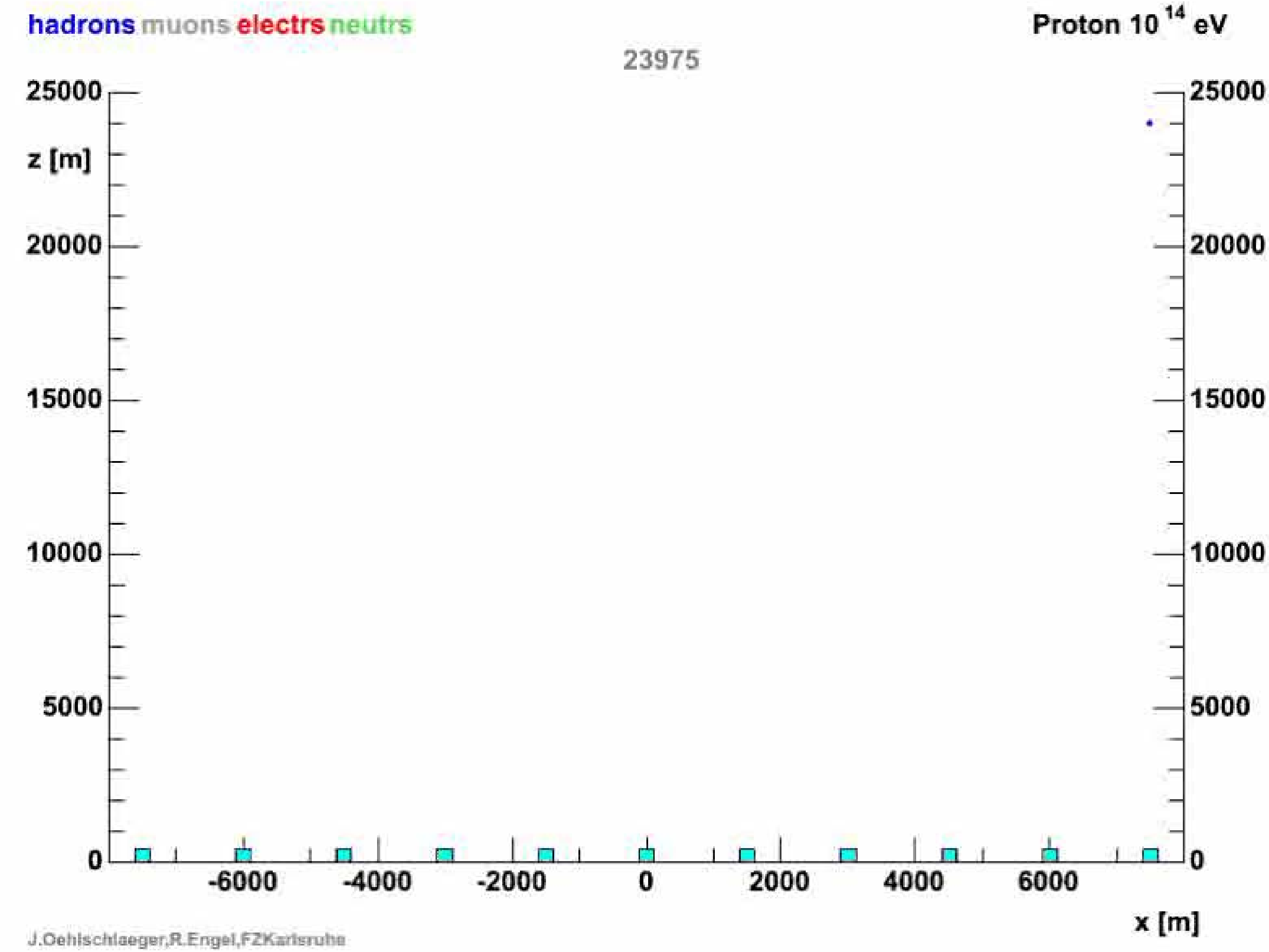
~ one particle per km² and century

Extensive air showers

- cosmic ray interacts with nucleus in the atmosphere
- cascade of secondary particles evolves
  - grows up to billions of particles before it declines again
- hadronic interactions at extremely high energies
  - Monte Carlo simulations with considerable model uncertainties



Extensive air shower simulations: CORSIKA

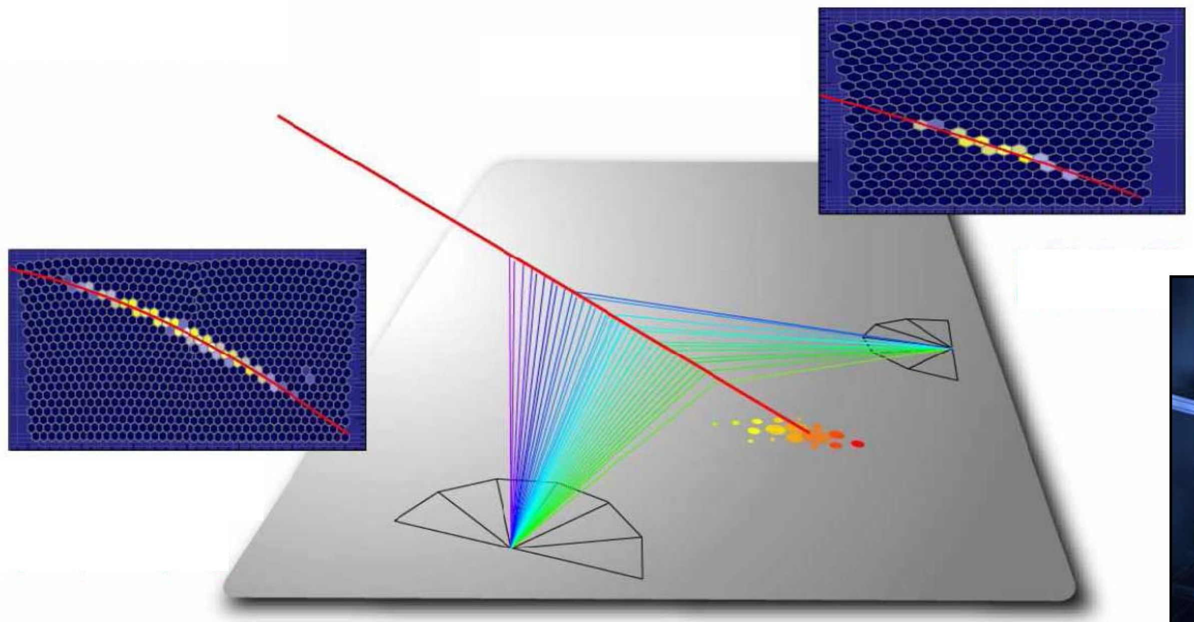


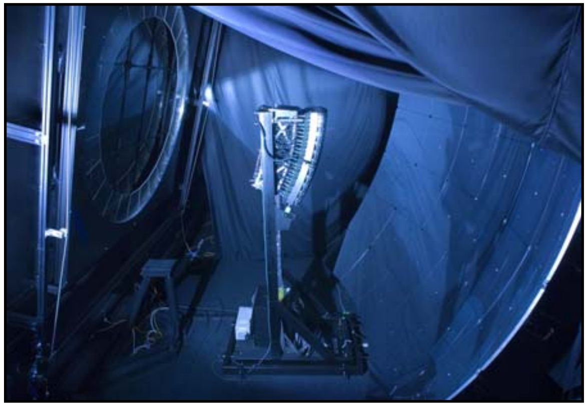
Particle detectors (e.g. KASCADE)

- particle detectors set up in ground-based arrays
- measure the secondary particles arriving at the ground
  - rather indirect information on the air shower

Fluorescence detectors (e.g. in Auger)

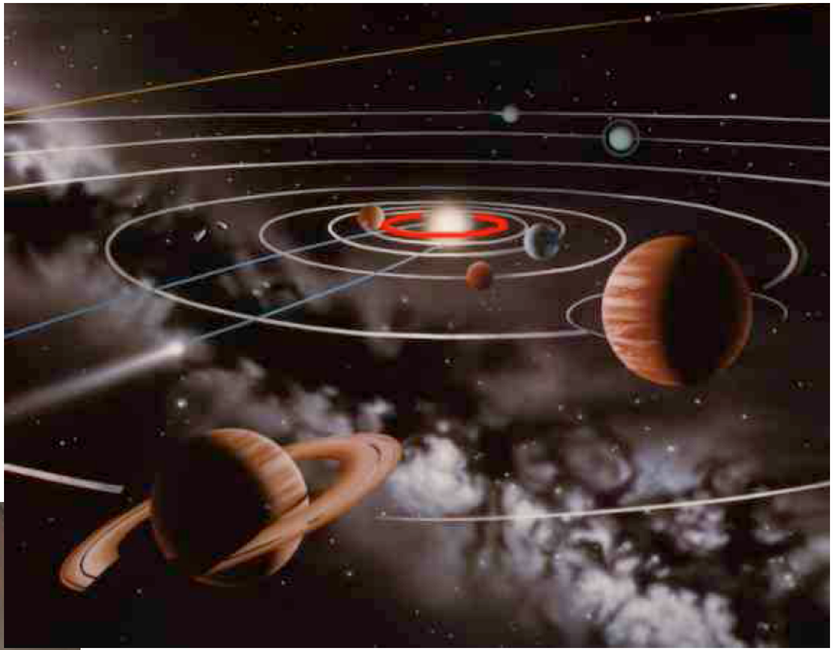
- air shower particles excite atmospheric nitrogen
- nitrogen molecules fluoeresce in ultraviolet light
- observable during dark, clear, moonless nights
- yield very direct information on air shower evolution
- works best at very high cosmic ray energies





Ultra-high energy cosmic rays

- probe fundamental physics in extreme environments at extreme energies
- are only weakly deflected in intergalactic magnetic fields
  - usable for “particle astronomy”

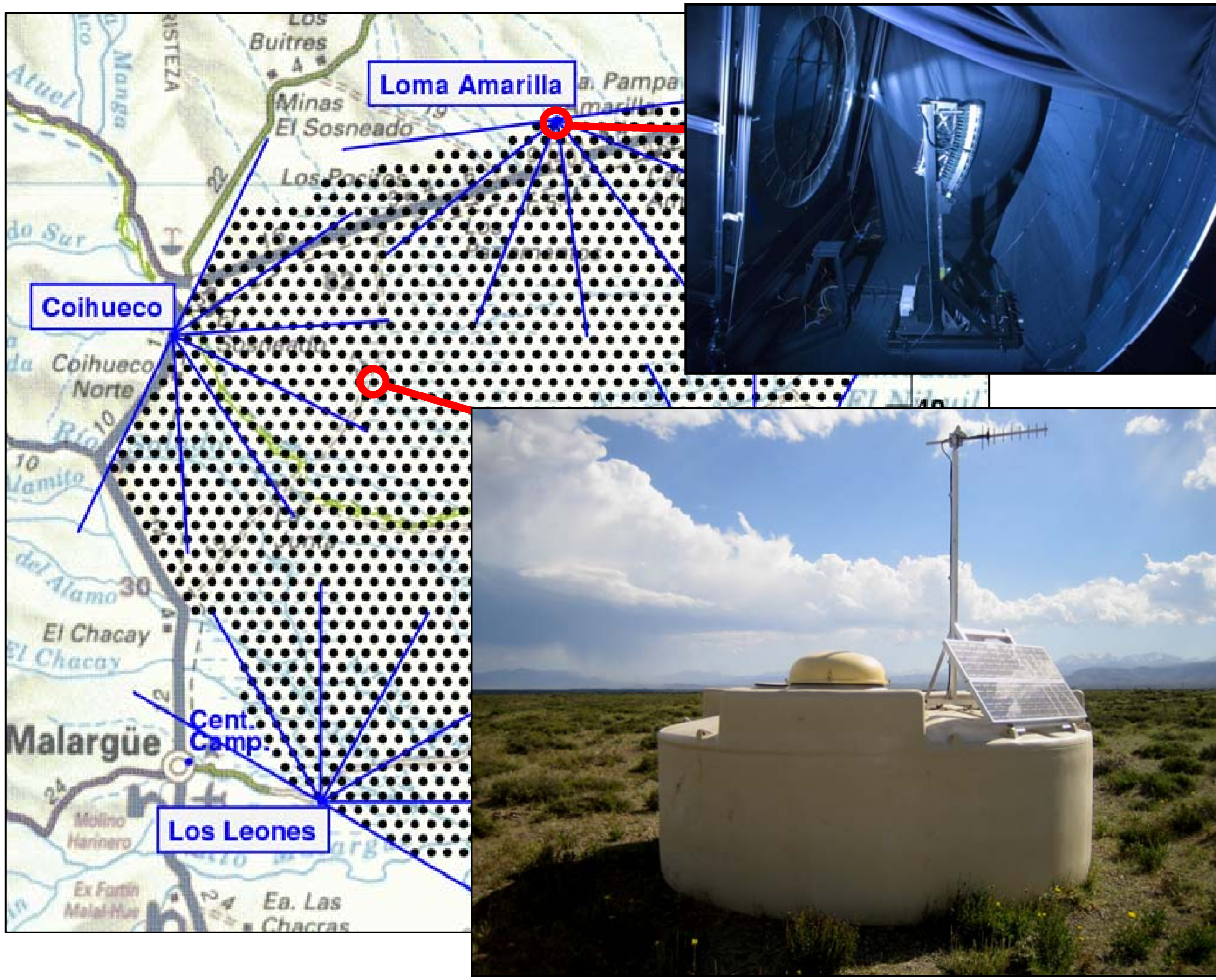


Acceleration of UHECRs would need LHC with size of Mercury orbit!

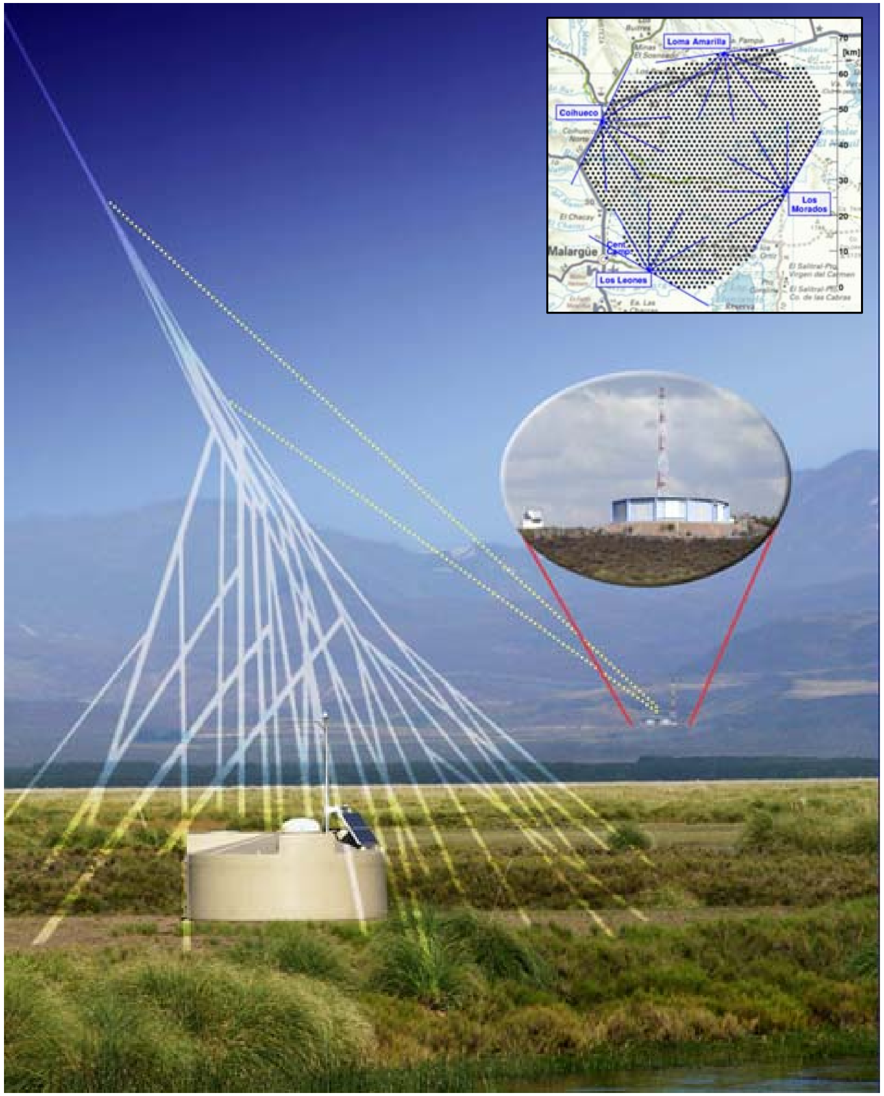
Large Hadron Collider (LHC), 27 km circumf., superconducting magnets

The Pierre Auger Observatory

- highest energies need huge arrays
- huge site in Argentina
  - 3000 km^2
  - 1600 particle detectors
  - 24 optical telescopes



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 ~10%

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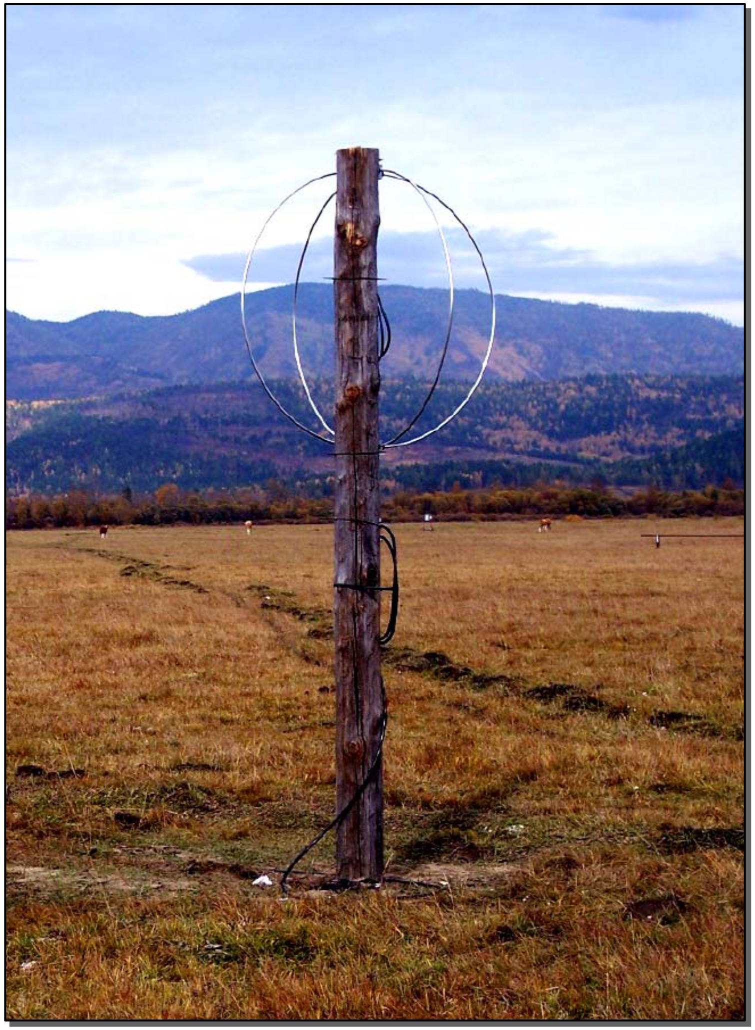
Radio detection

The promises of radio detection

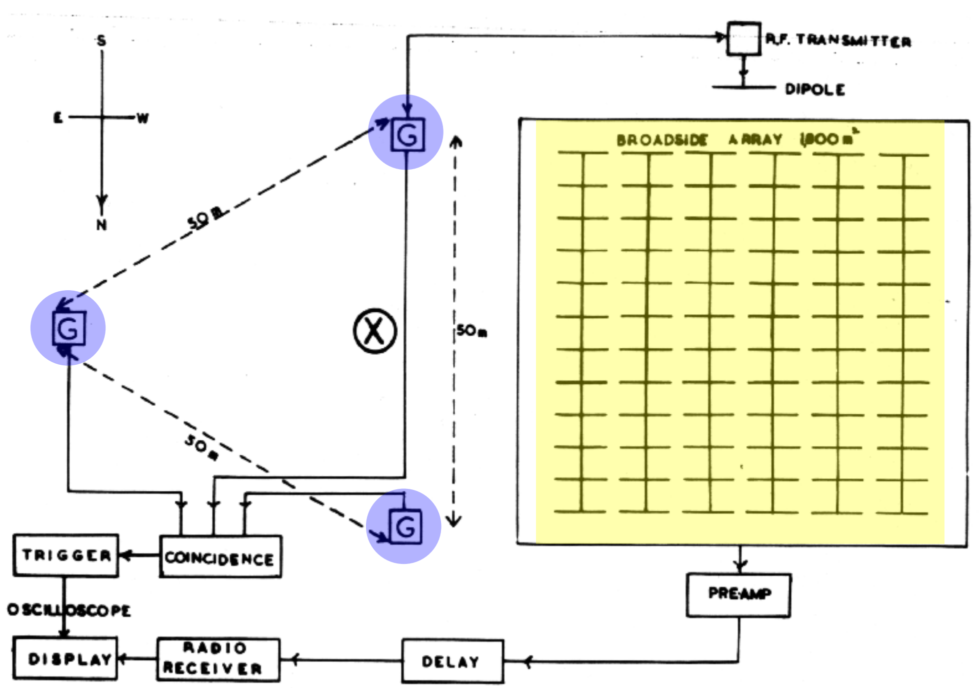
- information complementary to surface particle detectors
  - pure electromagnetic component
- calorimetric energy measurement
- near 100% duty cycle (cf. 10% of optical fluorescence detectors)
- particle mass sensitivity
- high angular resolution (< 0.5°)
- simple (potentially cheap) detectors

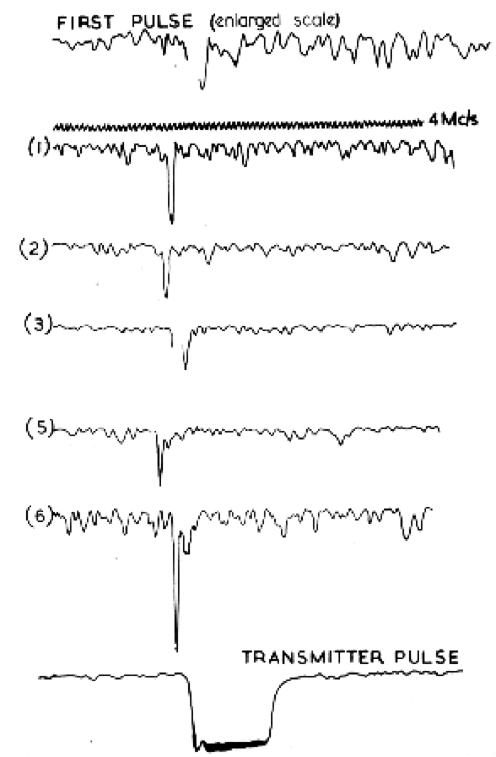
- *how well does it all work in practice and on large scales?*



The Jodrell Bank experiment (1965)

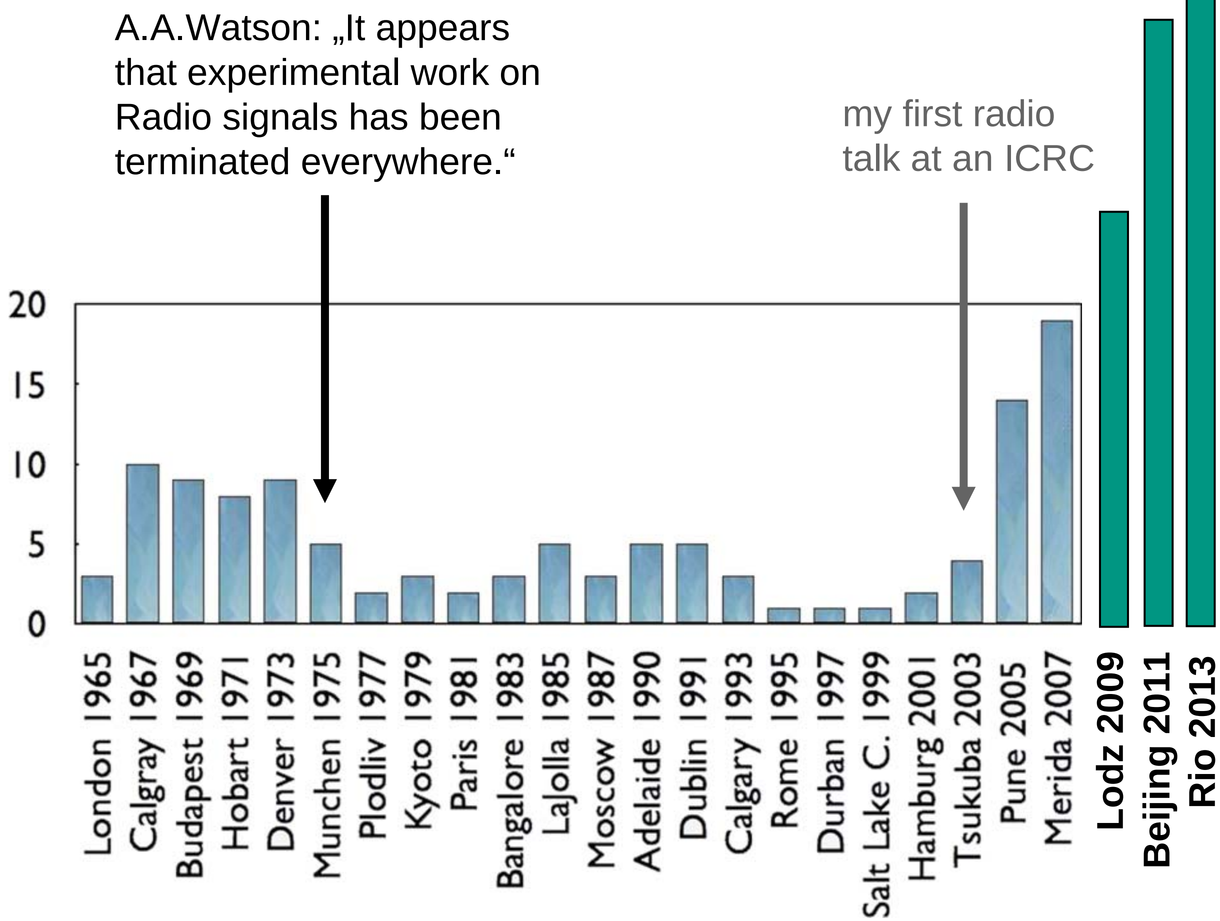
- array of dipoles with 10° FWHM beam width
- operation at 44 MHz with 2.75 MHz bandwidth
  - BBC TV channel, turned off from midnight to 9 a.m.
- Geiger counter coincidence triggers photograph of oscilloscope traces





Decline and revival of radio detection

- number of ICRC contributions related to radio detection of neutrinos or cosmic rays



T.C. Weekes, RADHEP2000

R.J. Nichol et al. (ANITA Coll.), NIM A 2011

The LOPES experiment

- digital radio interferometer measuring in the 40-80 MHz frequency window
- integrated with KASCADE-Grande experiment
  - provides the trigger for LOPES
  - provides the air shower geometry (core, direction)
  - provides high-quality per-event air shower parameters (N_e, N_μ, …) for study of radio emission systematics
- effective energy range ~$10^{16.7}$ eV to ~10^{18} eV

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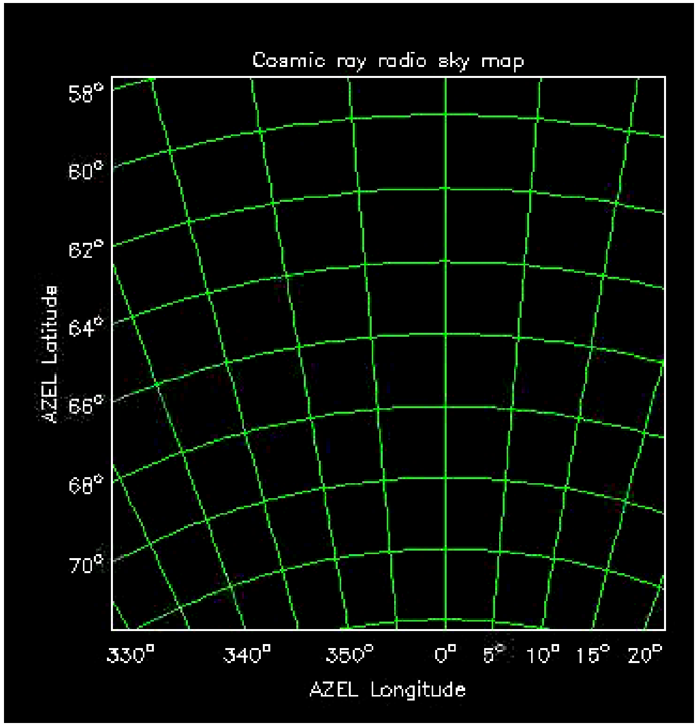
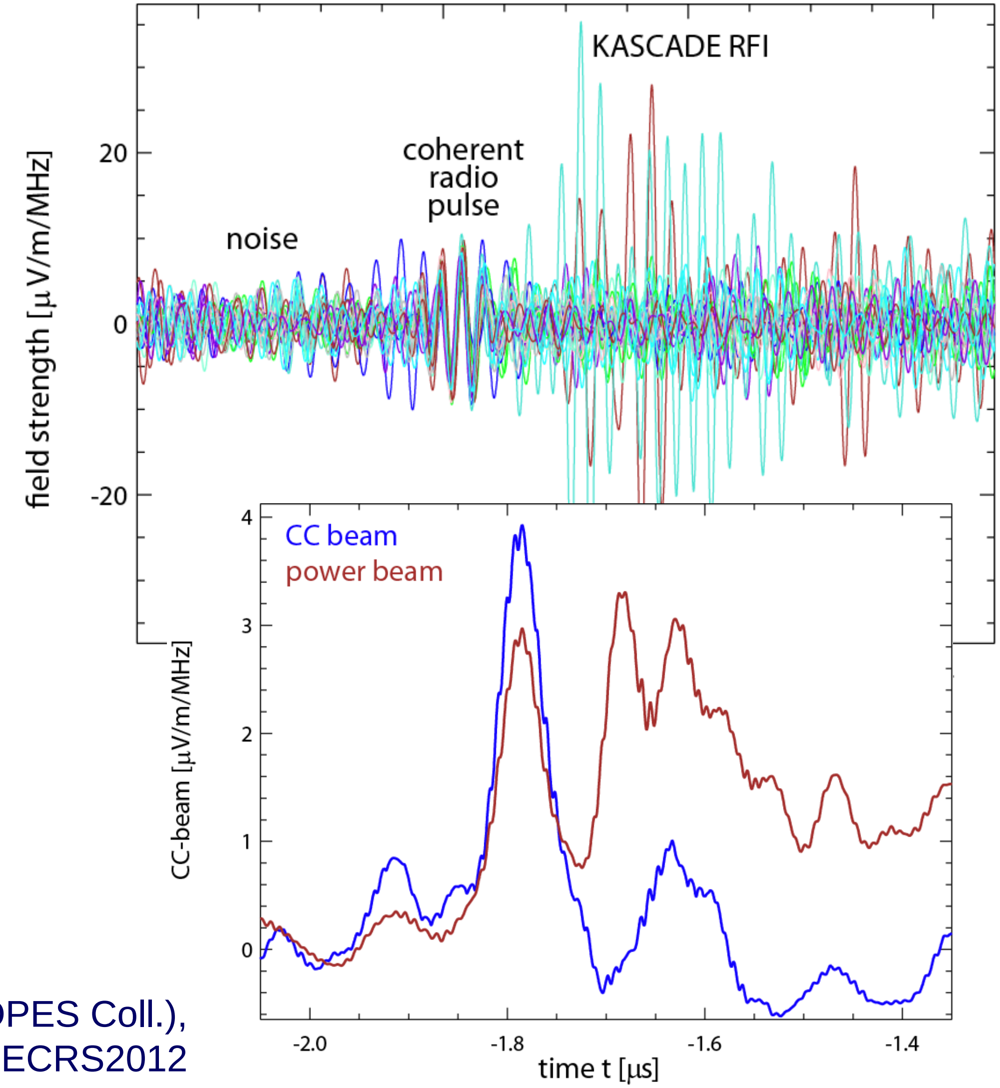
Modern digital radio interferometry (LOPES)



Sky map of a cosmic ray radio flash

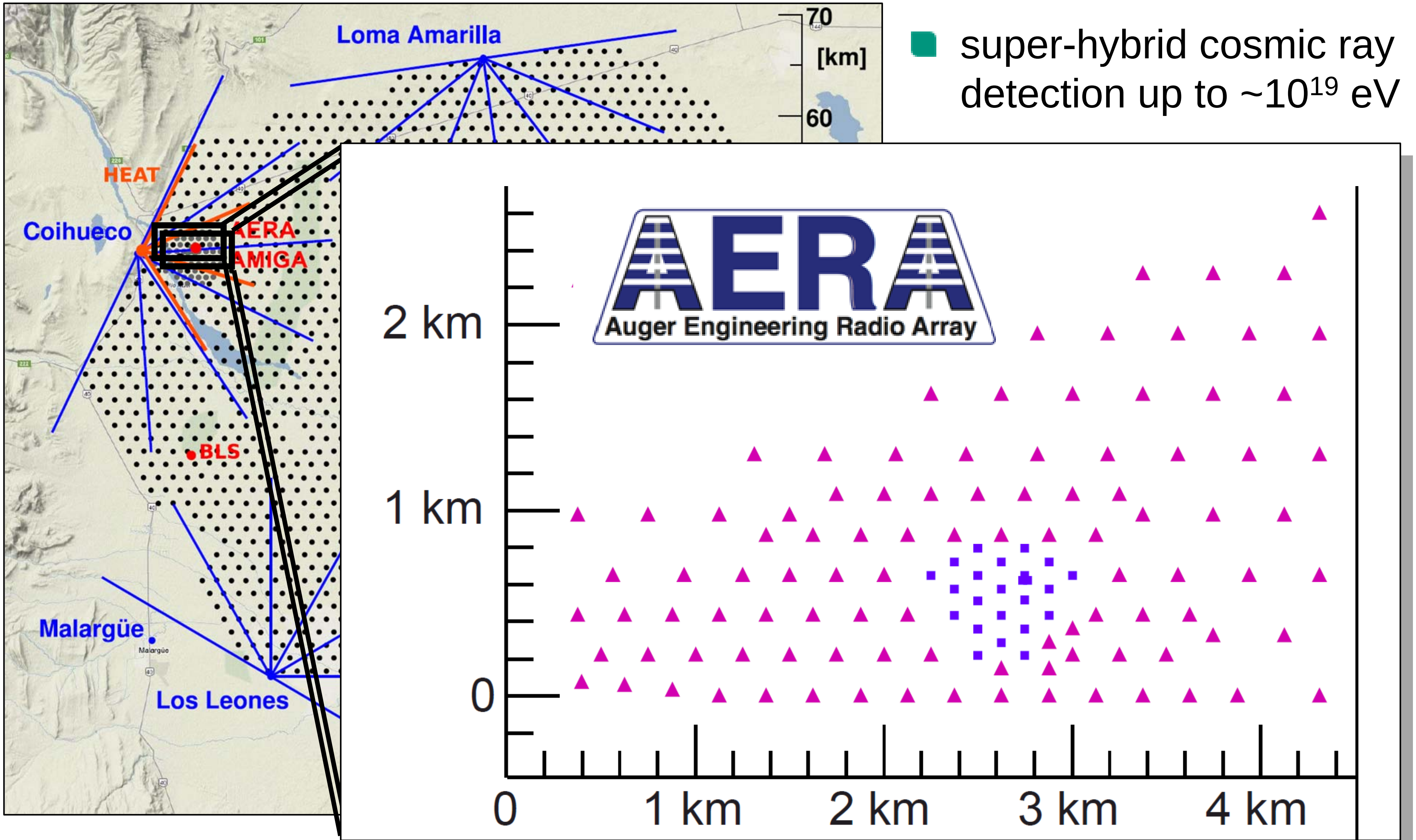
H. Falcke et al. (LOPES Coll.), Nature 2005



F.G. Schröder et al. (LOPES Coll.), ECRS2012

AERA in the Pierre Auger Observatory

- super-hybrid cosmic ray detection up to ~10^{19} eV



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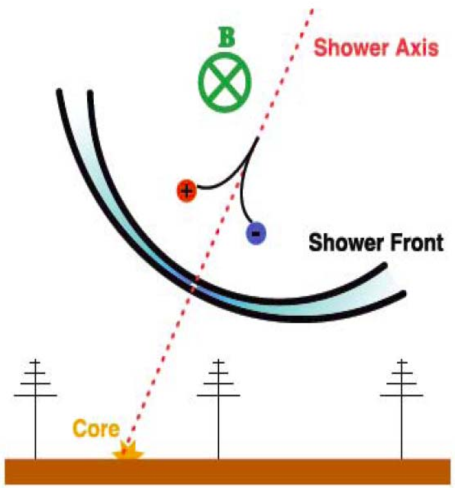
AERA stations in the pampa

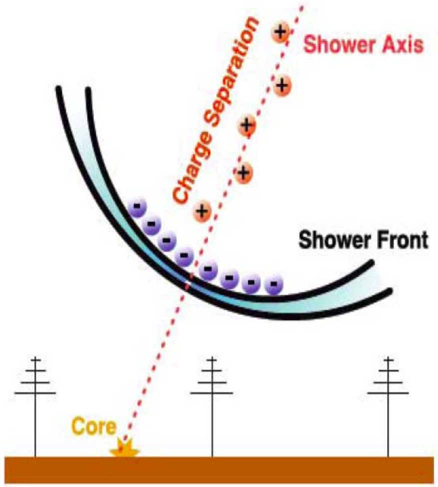
Radio emission physics

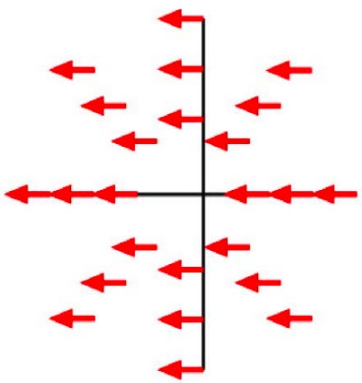
Radio emission physics as predicted by theory



- primary effect: geomagnetic field induces *time-varying* transverse currents

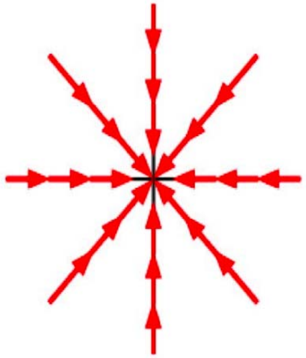
Kahn & Lerche (1967)





Askaryan (1962,1965)

- secondary effect: *time-varying* net charge excess (Askaryan effect)

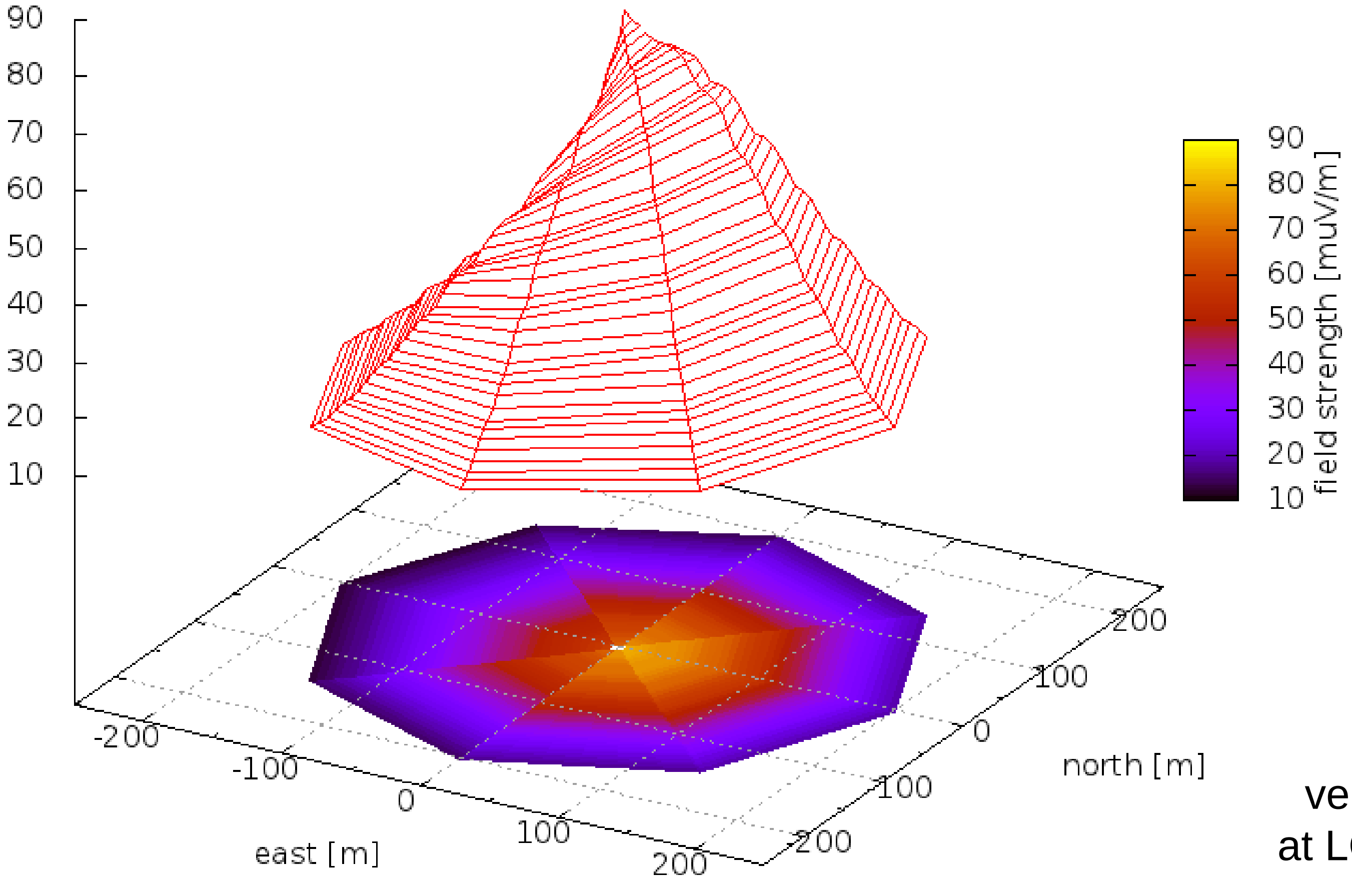


„v x ***B"***

Diagrams by H. Schoorlemmer & K.D. de Vries

„radial"

Complexity of radio LDF

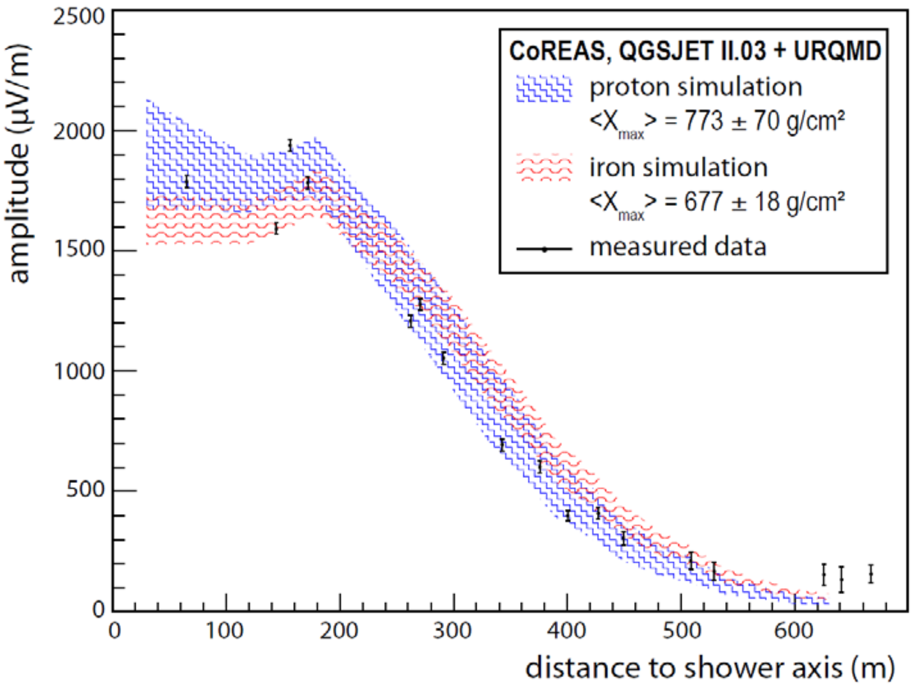


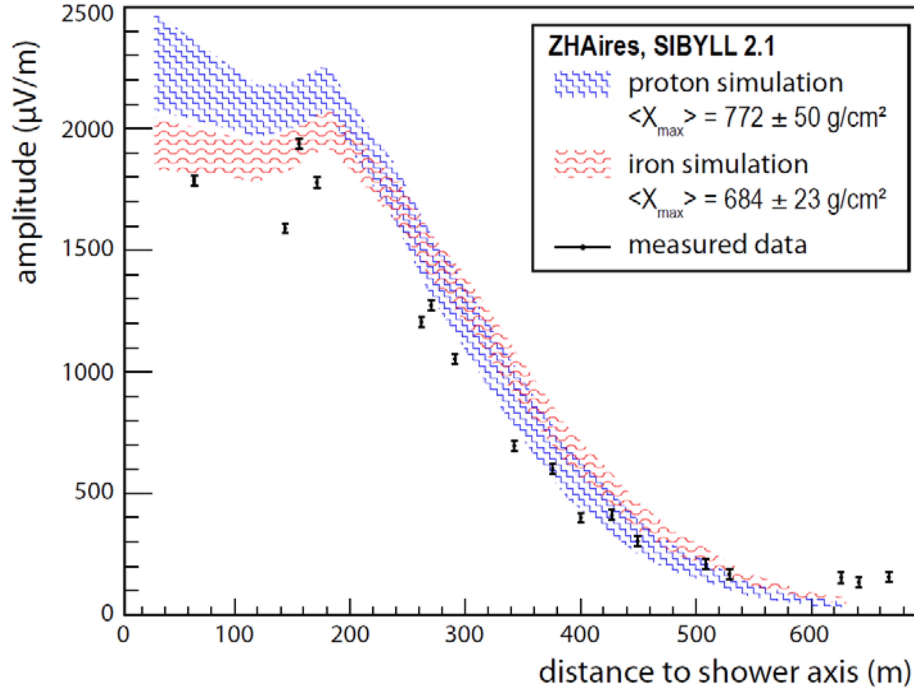
vertical iron shower
at LOPES frequencies
simulated with CoREAS

TH et al., ARENA2012

Comparison of simulations with AERA data

KIT
Karlsruhe Institute of Technology

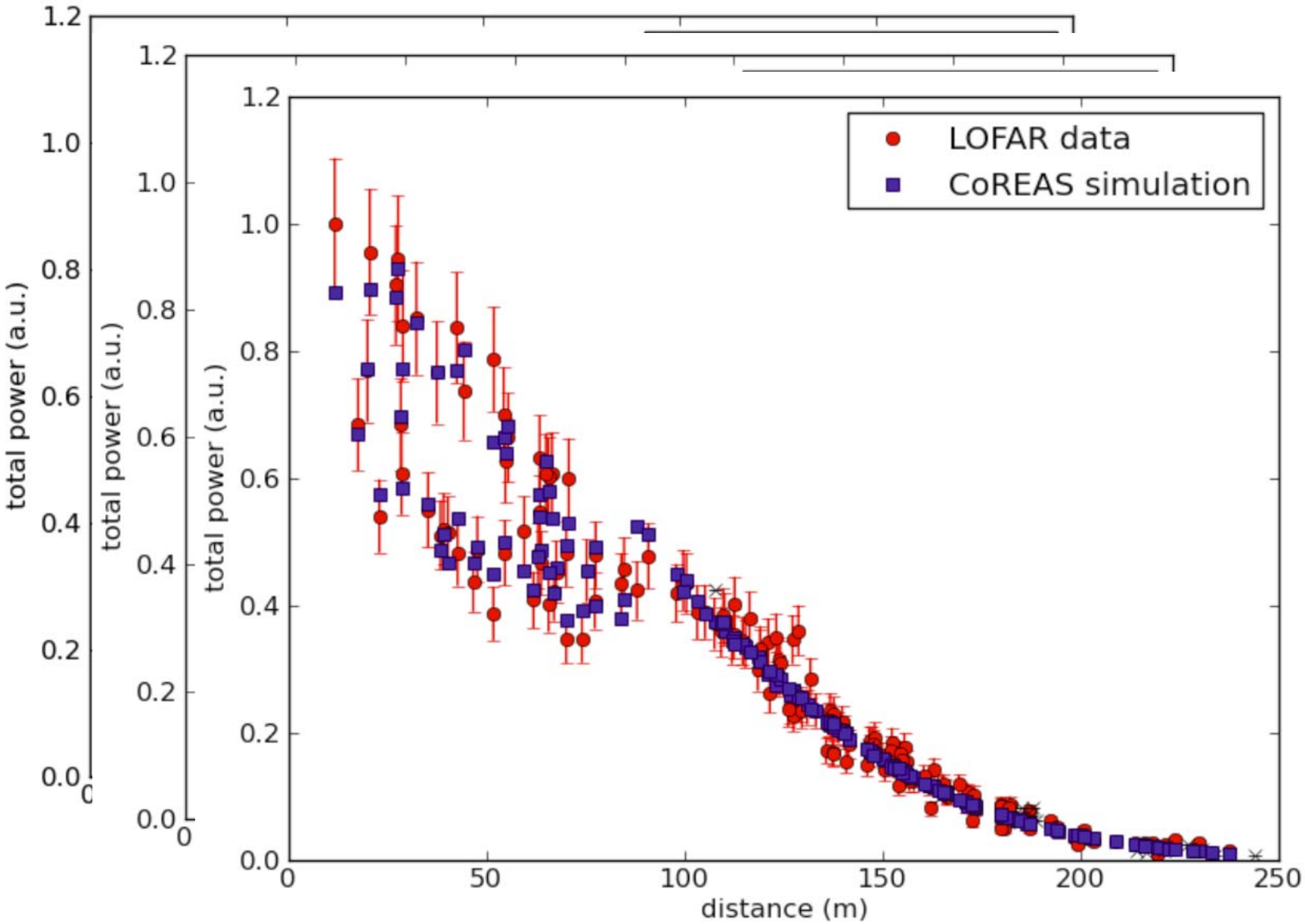




- AERA provides detailed, well-calibrated event data
- simulations can reproduce measurements
  - absolute amplitude
  - complex LDF

Pierre Auger Collaboration, ICRC2013, id #899

Comparison of simulations with LOFAR data



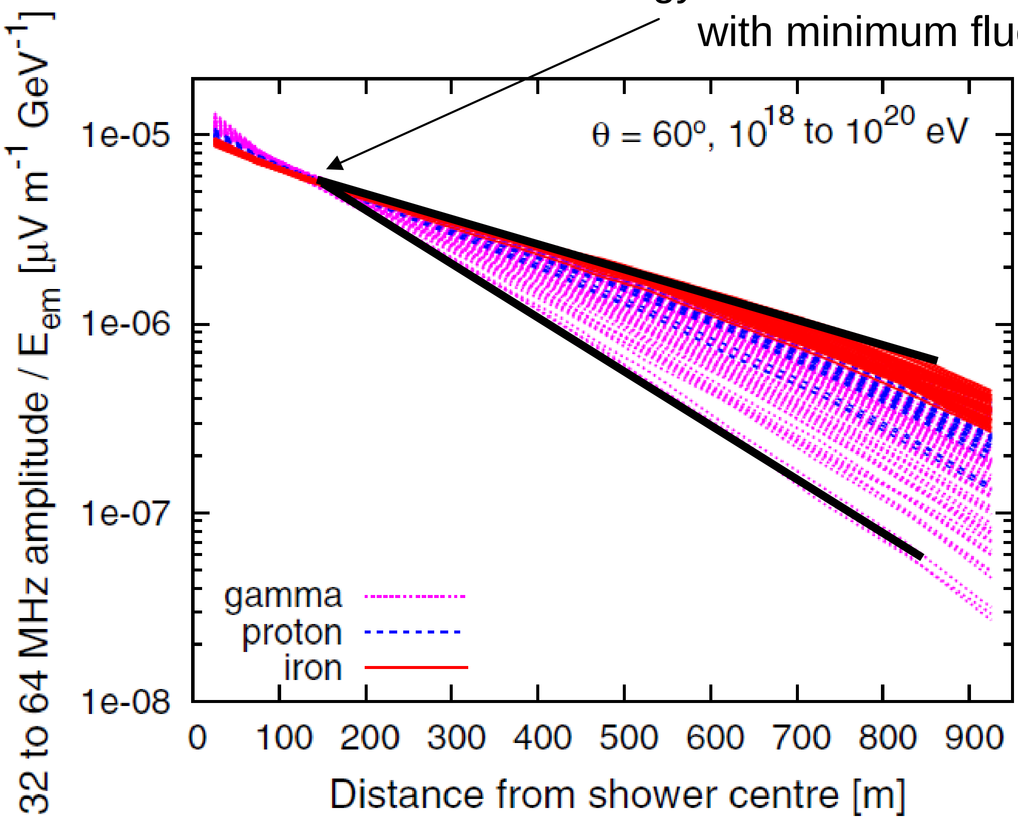
S. Buitink for the LOFAR Collaboration, ICRC2013, id #579

- measurement of individual shower with extreme level of detail
- data can be reproduced by simulations
- see geomagn., charge excess and Cherenkov effects
- but: no calibration of absolute amplitude scale yet

Energy determination

Expected energy sensitivity of radio detection

energy determination at distance with minimum fluctuations



Fe – flat

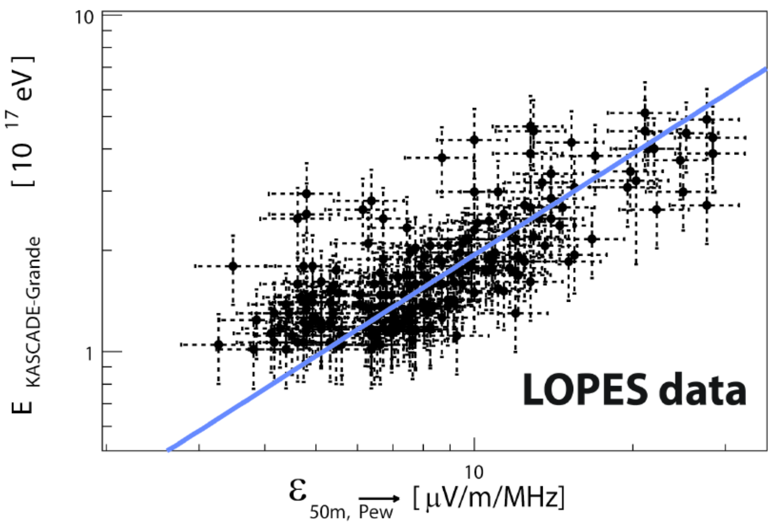
p – steeper, fluctuating

γ – steepest, fluctuating

TH, Ulrich, Engel (Astrop. Phys. 2008)

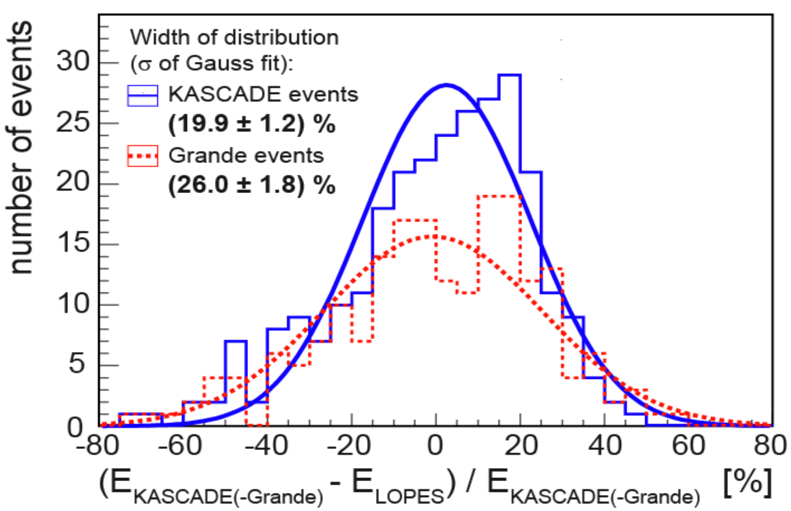
- linear scaling & characteristic distance for best energy estimate

LOPES has made quantitative analyses



- linear correlation with 20-25% combined LOPES-KASCADE-Grande energy resolution
  - radio probably better, limited by KASCADE-Grande energy uncertainty of ~20%
  - simulations: ~8% intrinsic

N. Palmieri et al. (LOPES Coll.), ICRC2013, id #439



- also works with interferometric analysis, yielding again ~20% uncertainty

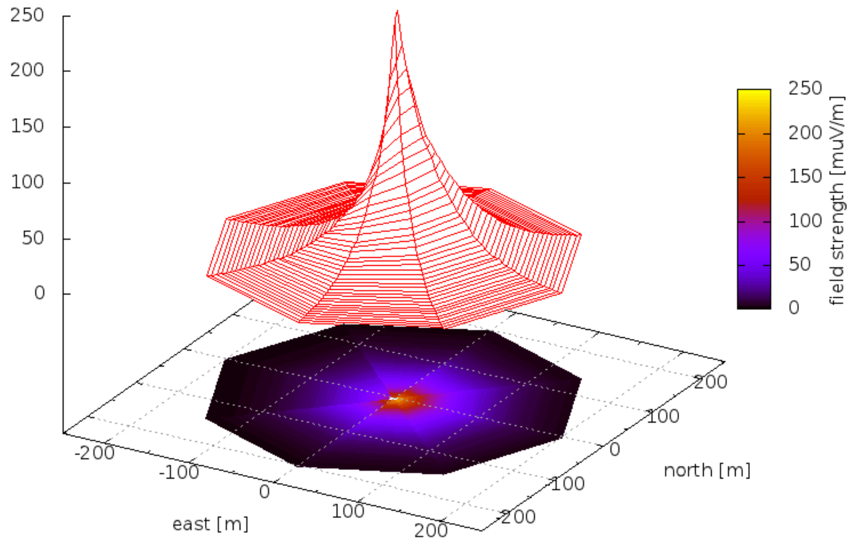
F.G. Schröder et al. (LOPES Coll.), ARENA2012

Mass sensitivity

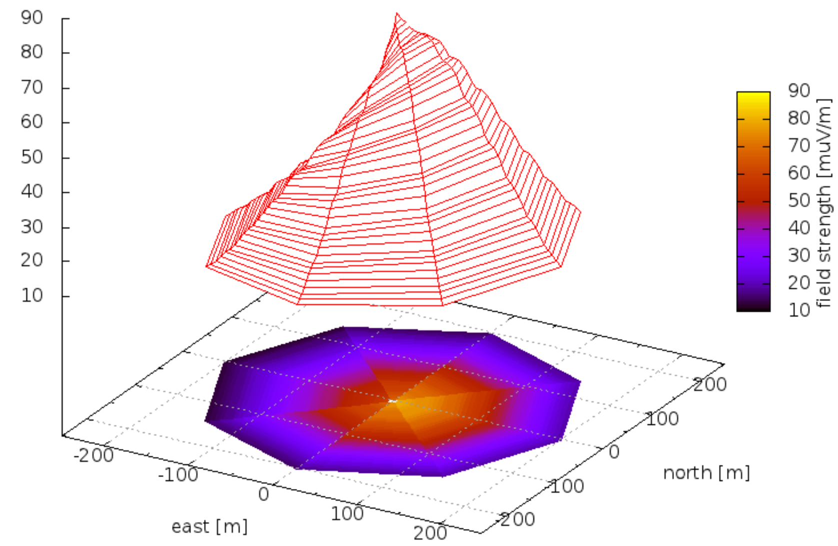
Lateral distribution as probe for composition

- simulations for proton and iron primaries show systematic differences

TH et al., ARENA2012



vertical proton shower
at LOPES frequencies
simulated with CoREAS



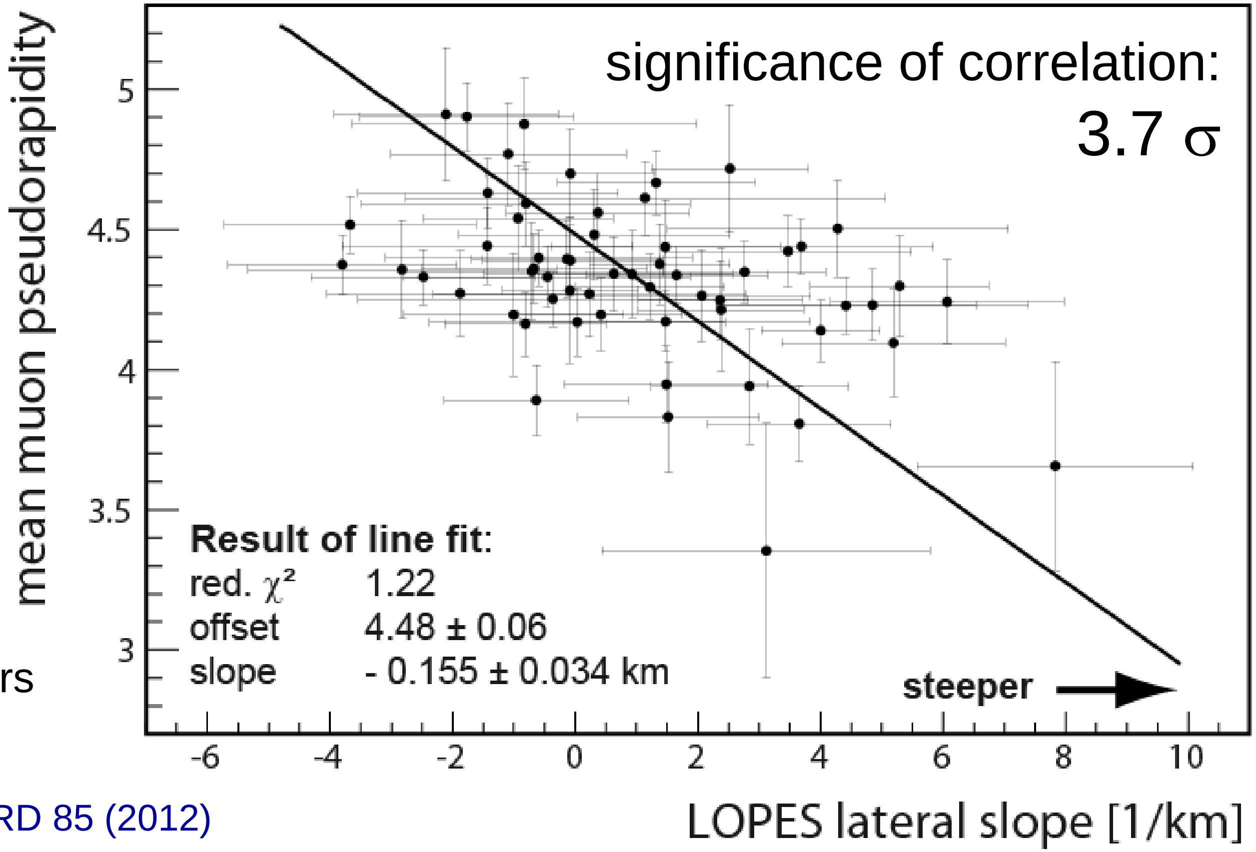
vertical iron shower
at LOPES frequencies
simulated with CoREAS

Experimental proof from LOPES

- radio is sensitive to longitudinal shower development
  (direct sensitivity to geometrical distance)
- Sensitivity to geometrical distance implies X_{max} sensitivity

old showers

young showers

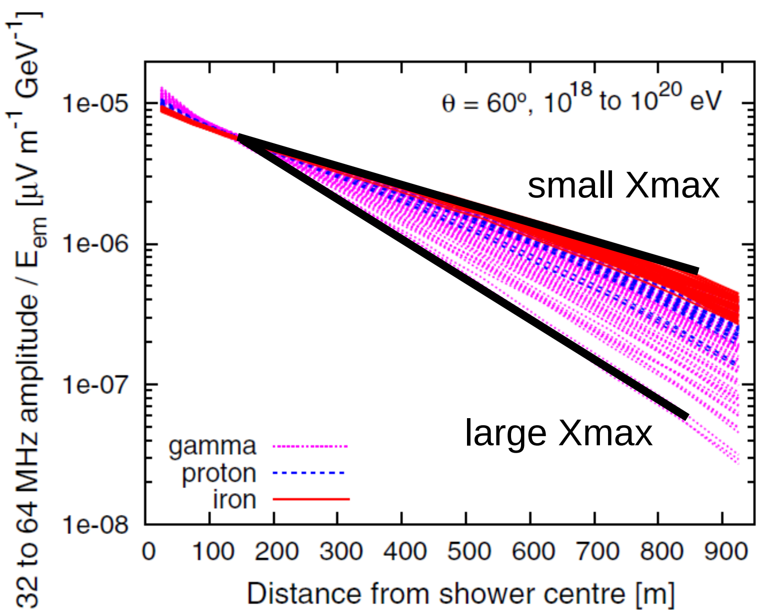


59 events:
after corr. for
axis distance
+ zenith angle

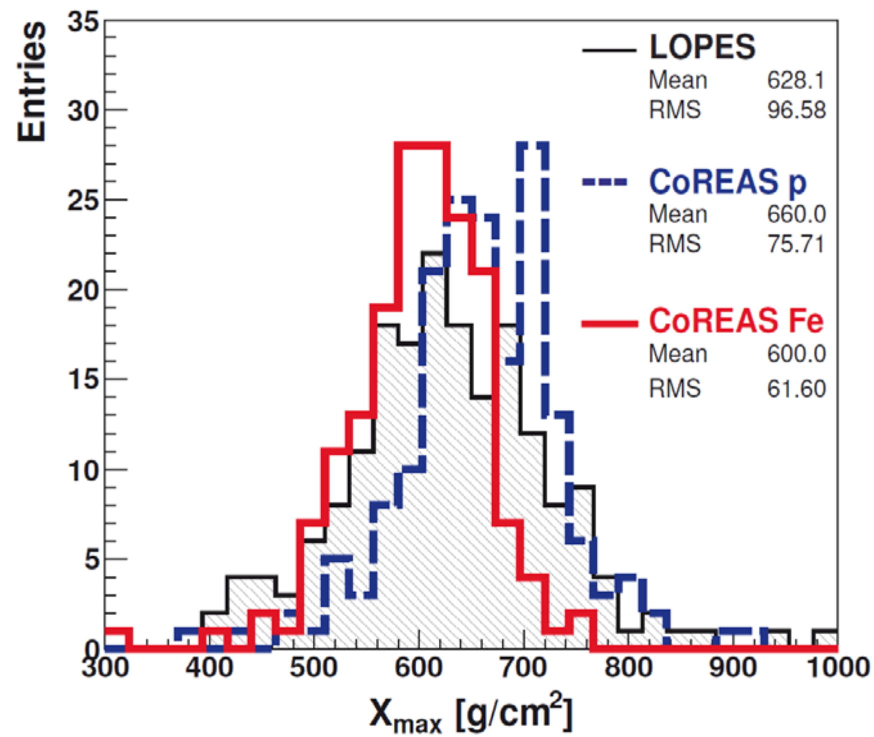
LOPES Coll. PRD 85 (2012)

Xmax reconstruction with LOPES

- with simulations, radio LDF slope can be related to Xmax
- using parameterisations derived with CoREAS simulations, Xmax is estimated for each individual LOPES event (method σ_{Xmax} ~ 50 g/cm^2)



TH, Ulrich, Engel (Astrop. Phys. 2008)



N. Palmieri et al. (LOPES Coll.), ICRC2013, id #439

Summary and conclusions

- radio detection of CRs has great potential
- radio detection of CRs has boomed and matured in the last decade
- we have clearly established
  - detailed understanding of complex emission physics
  - determination of air shower energy (<~20%, maybe 10%?)
  - radio signal sensitivity to air shower evolution
- we still need to demonstrate
  - how well Xmax determination can work in practice (~20 g/cm^2?)
  - how we can scale everything to truly large areas/high energies
- the second-generation experiments strive to do just that