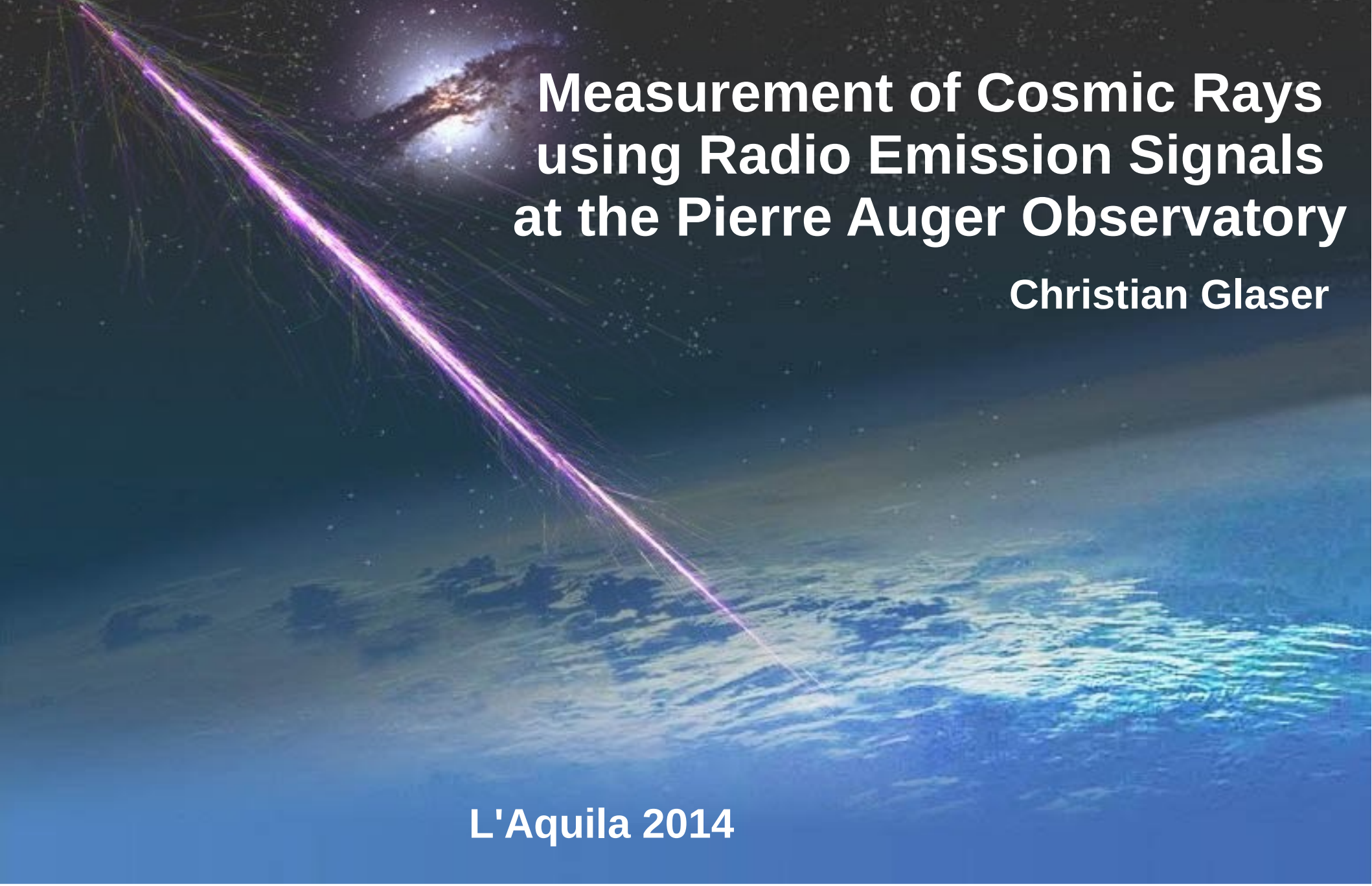

Measurement of Cosmic Rays using Radio Emission Signals at the Pierre Auger Observatory

Christian Glaser

L'Aquila 2014

DFG Deutsche Forschungsgemeinschaft

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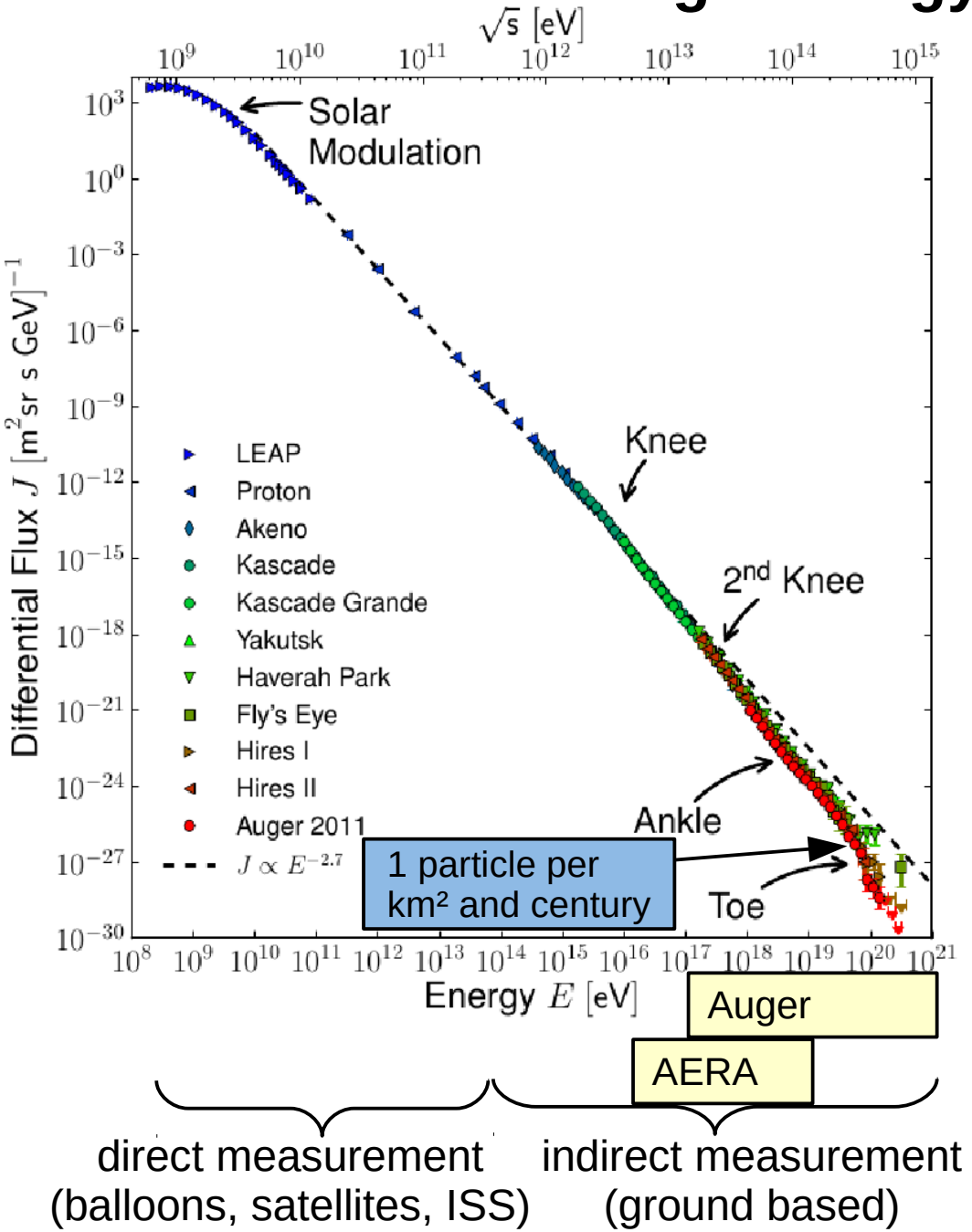
Ultra High Energy Cosmic Rays

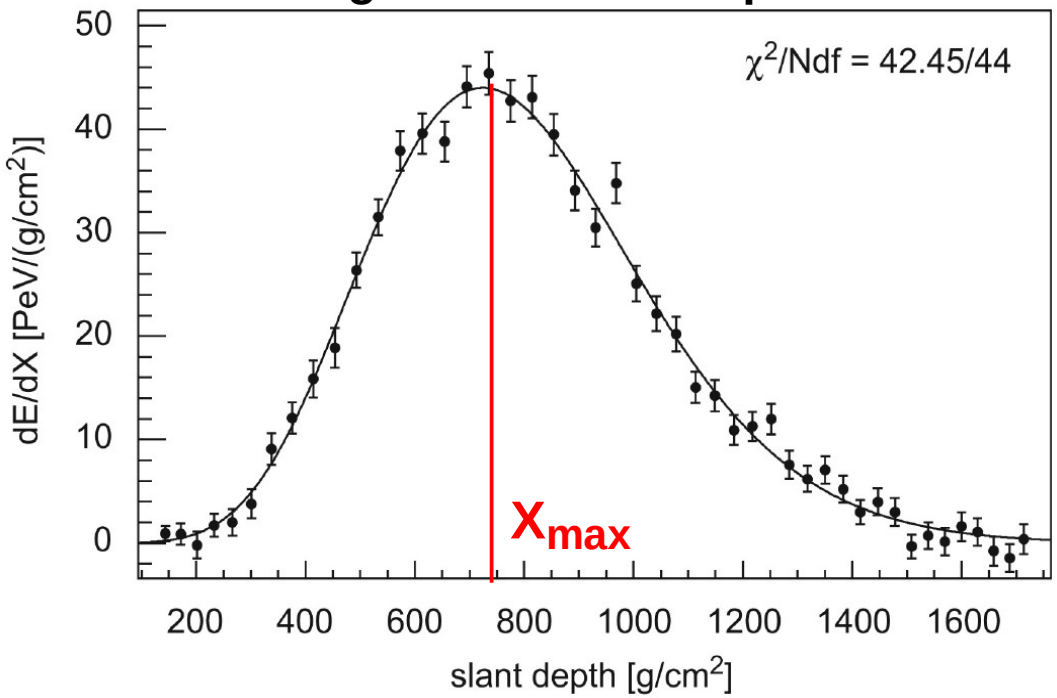


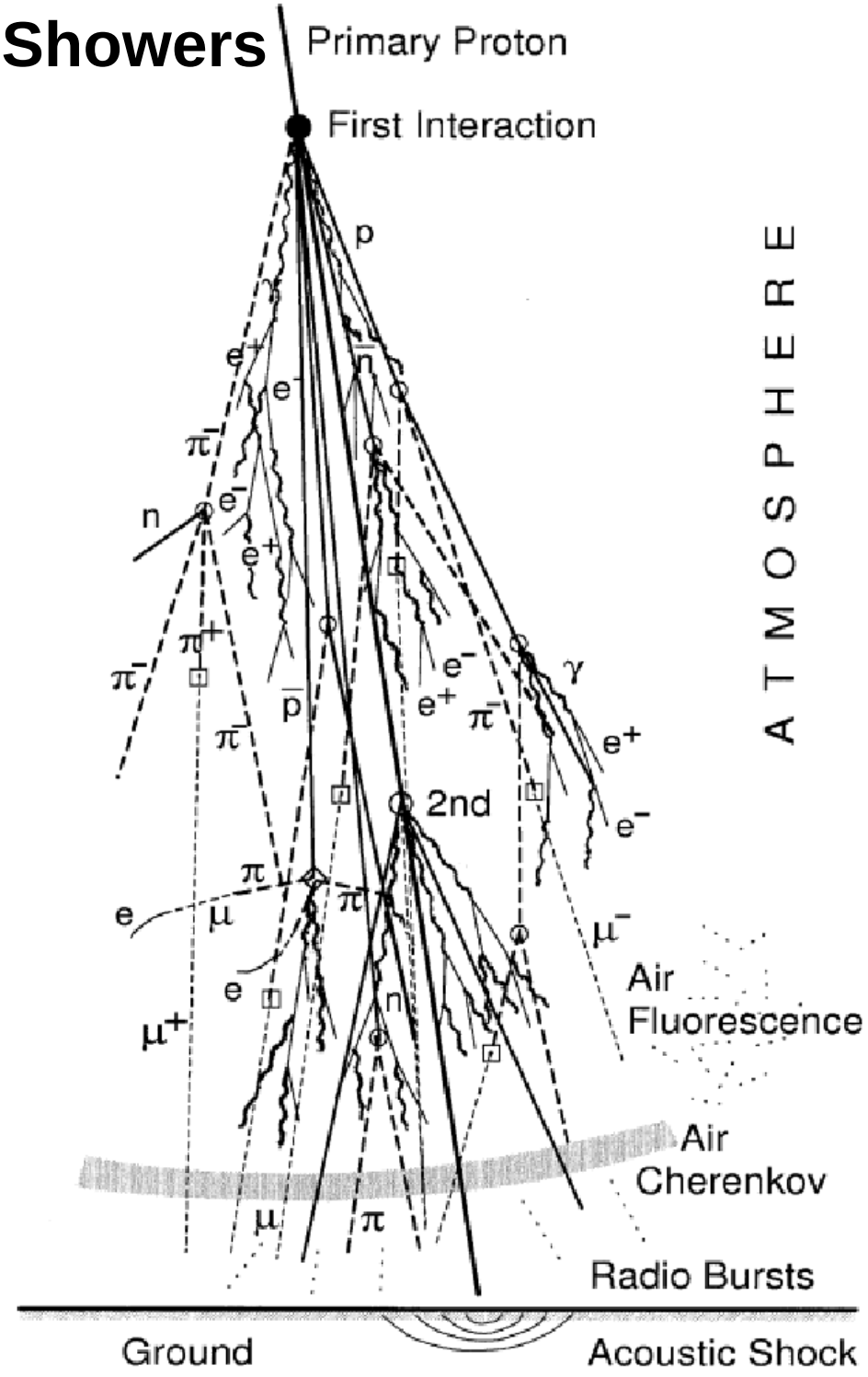
- most of the energy spectrum can be described by a simple power law
- open questions:
  - where do they come from?
  - how are they accelerated?
  - is cut-off at highest energies due to GZK effect?
- key observable: particle type
  - radio detection: potential to combine good mass resolution with high duty cycle

Extensive Air Showers

- huge particle cascade (hadronic and electromagnetic)
- observation methods:
  - → particle distribution on ground
  - → fluorescence light
    - 300 nm - 430 nm, isotropic
  - → radio emission

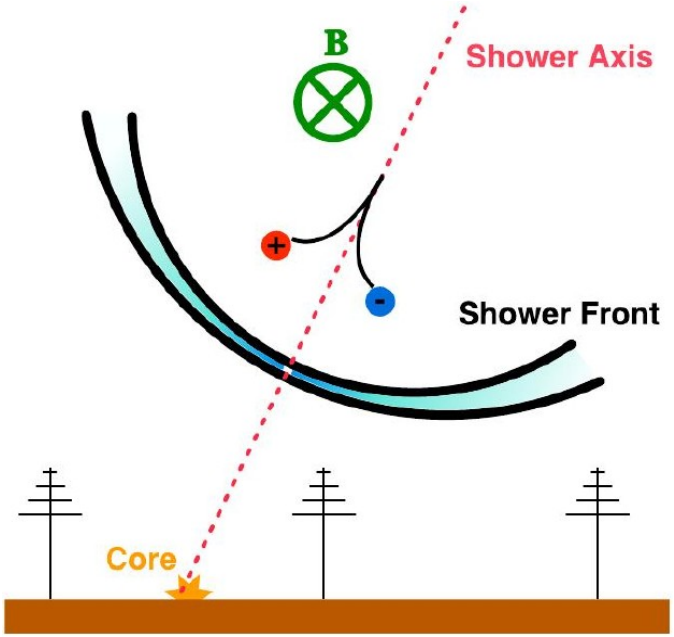
longitudinal shower profile

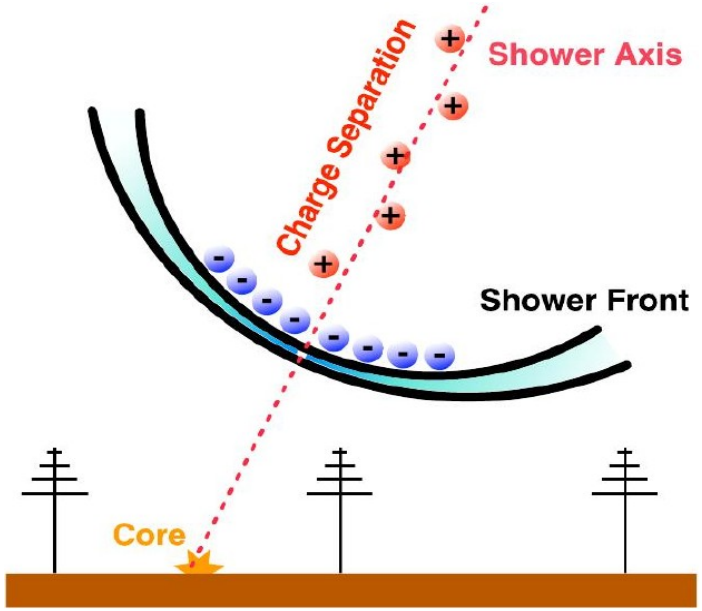




Radio Emission from Extensive Air Showers

- **1st order: geomagnetic radiation**
  - electrons/positrons deflected in Earth magnetic field **B**
  - polarized into direction of Lorentz force
  - scales with angle α between shower axis and **B**

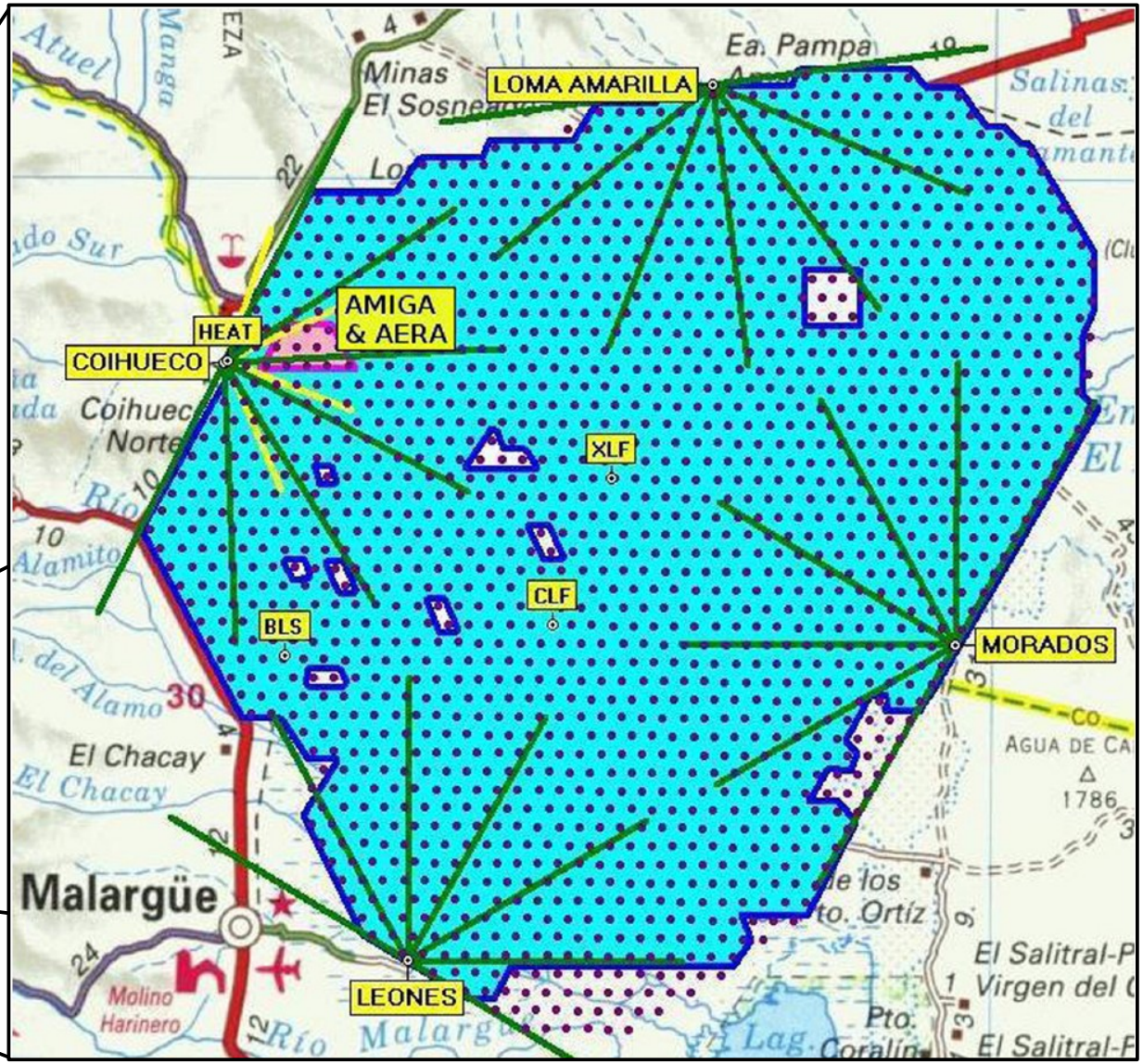




- **2nd order: charge excess / Askaryan effect**
  - time varying net charge excess
  - electrons from air nucleus are knocked out
  - positrons annihilate in shower front
  - radially polarised towards shower axis

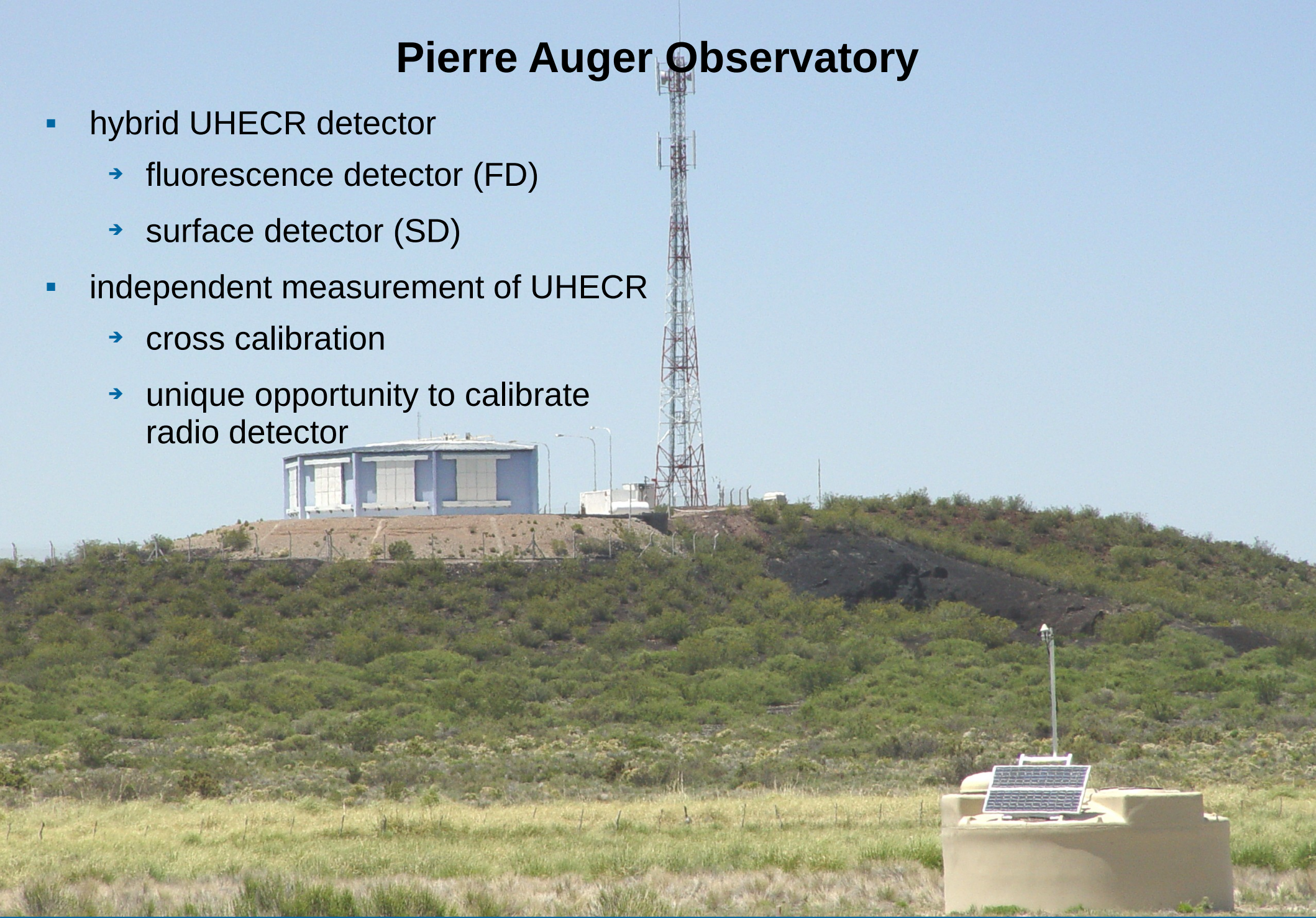
Pierre Auger Observatory

- Mendoza, Argentina
- world's largest cosmic ray detector (~3000 km²)
- 27 fluorescence telescopes
- 1600 water Cherencov detectors
- low energy extension



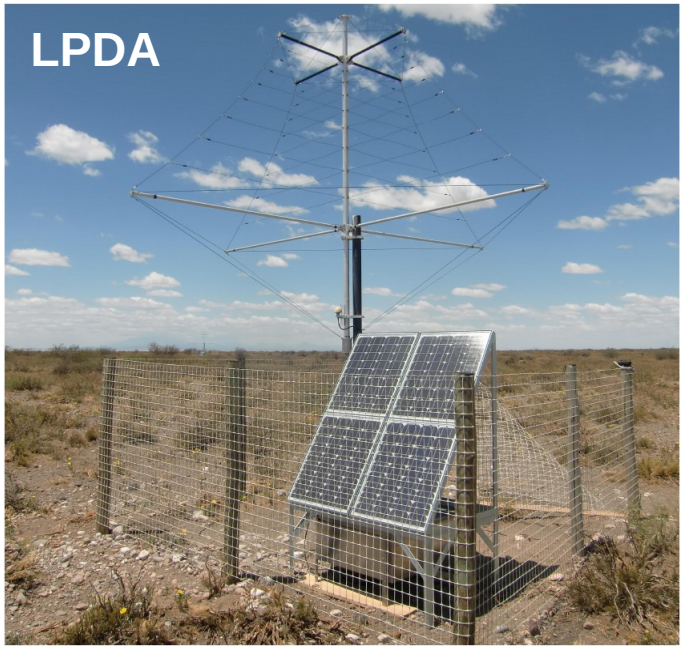
Pierre Auger Observatory

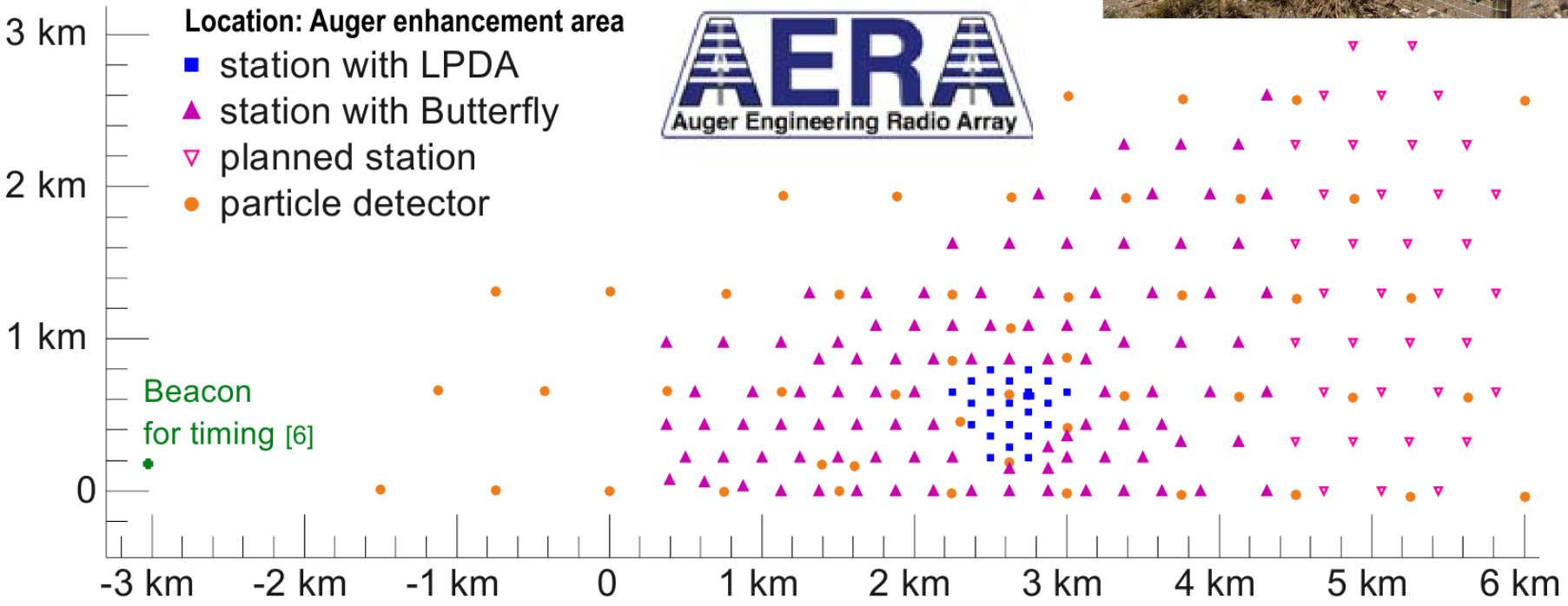
- hybrid UHECR detector
  - fluorescence detector (FD)
  - surface detector (SD)
- independent measurement of UHECR
  - cross calibration
  - unique opportunity to calibrate radio detector



Auger Engineering Radio Array (AERA)

- world's largest radio detector:
  - 124 radio stations covering 6 km²
  - Stage 1: data taking since April 2011
  - Stage 2: deployed April - May 2013
- log periodic dipole (LPDA) and Butterfly antennas
- frequency range: 30 - 80 MHz
- external and self-trigger





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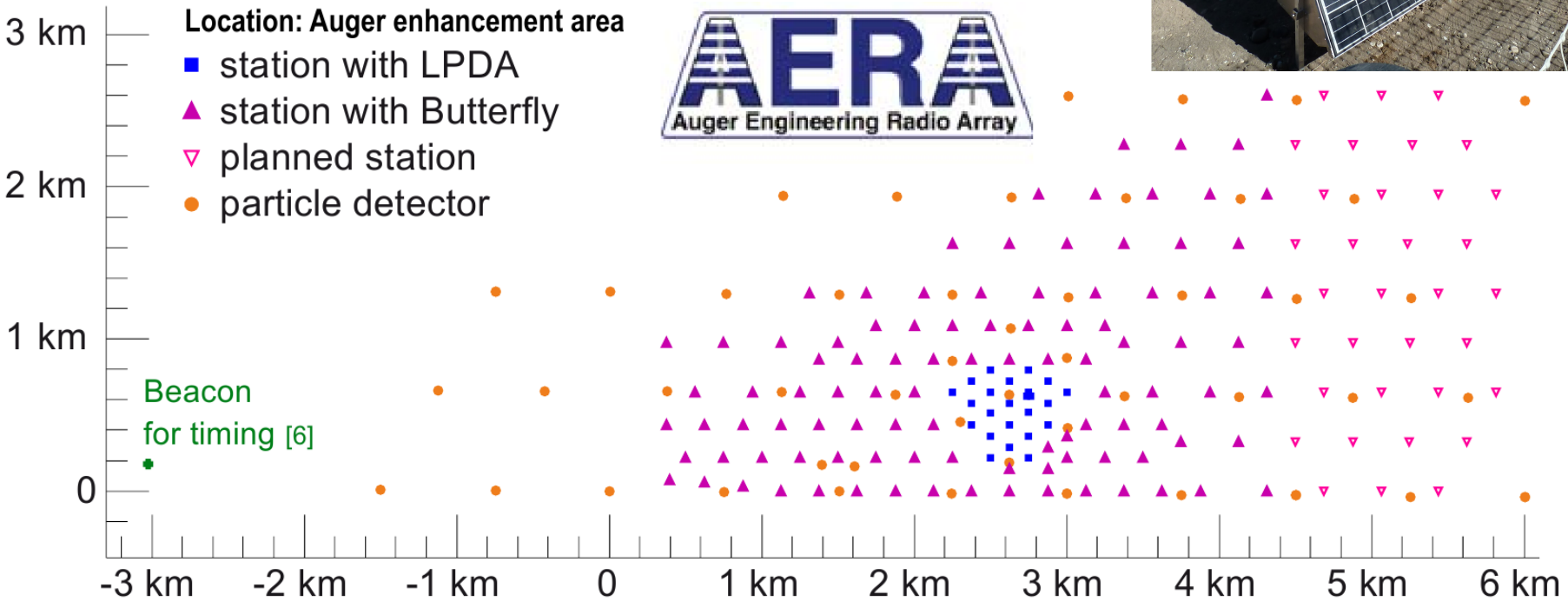
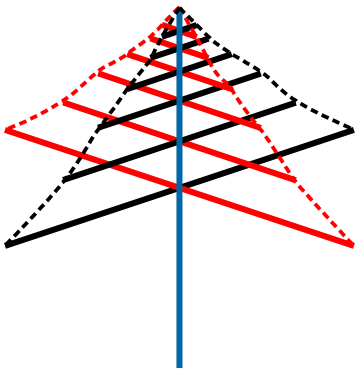
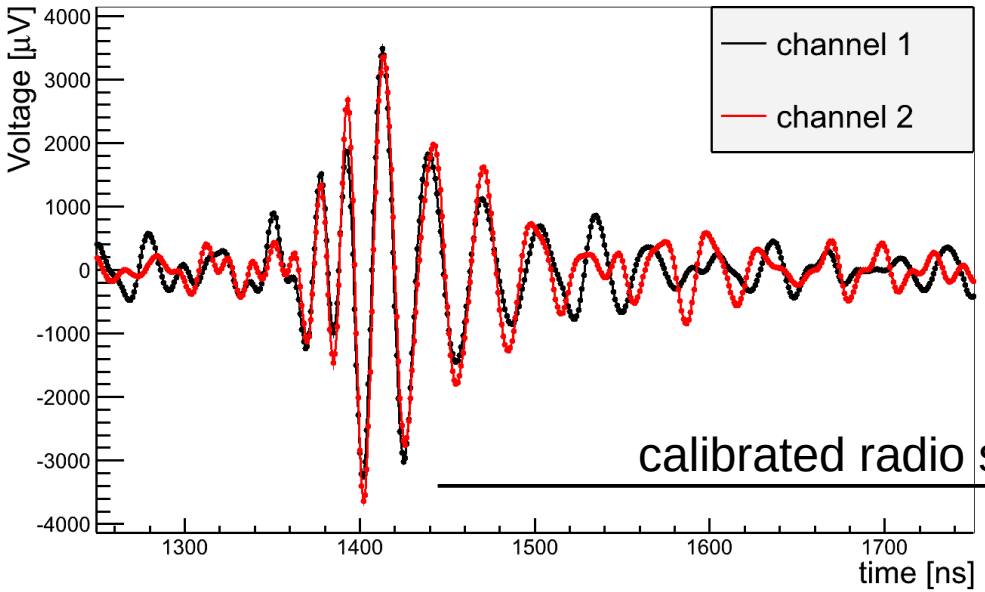


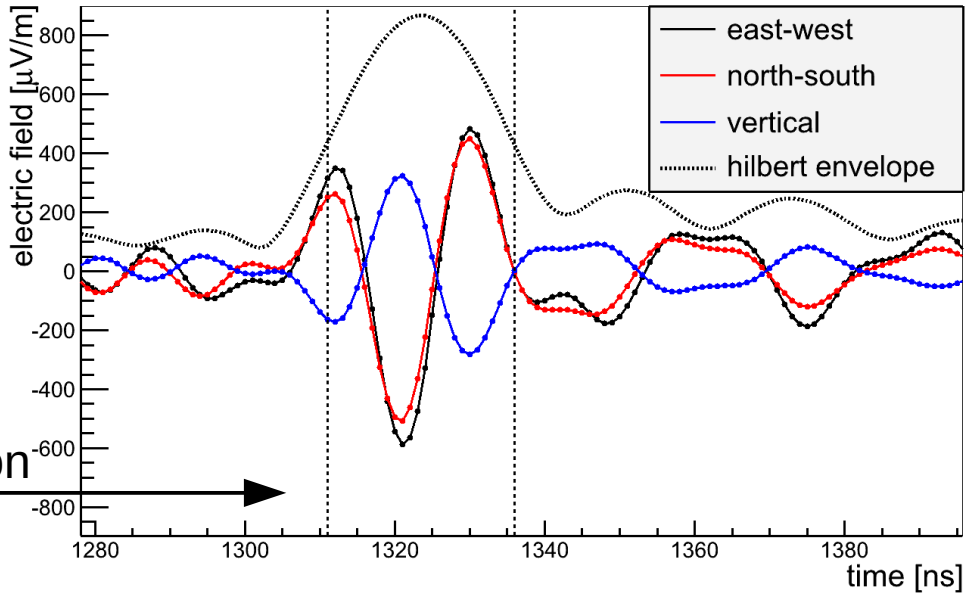
Reconstruction of Electric Field

- voltage measured in two polarisations (east-west, north-south)
- arrival direction can be reconstructed via timing differences in multiple antenna stations
- with arrival direction and known antenna characteristics the three-dimensional electric field is reconstructed
  - ➔ signal dispersion due to antenna and electronics is corrected for



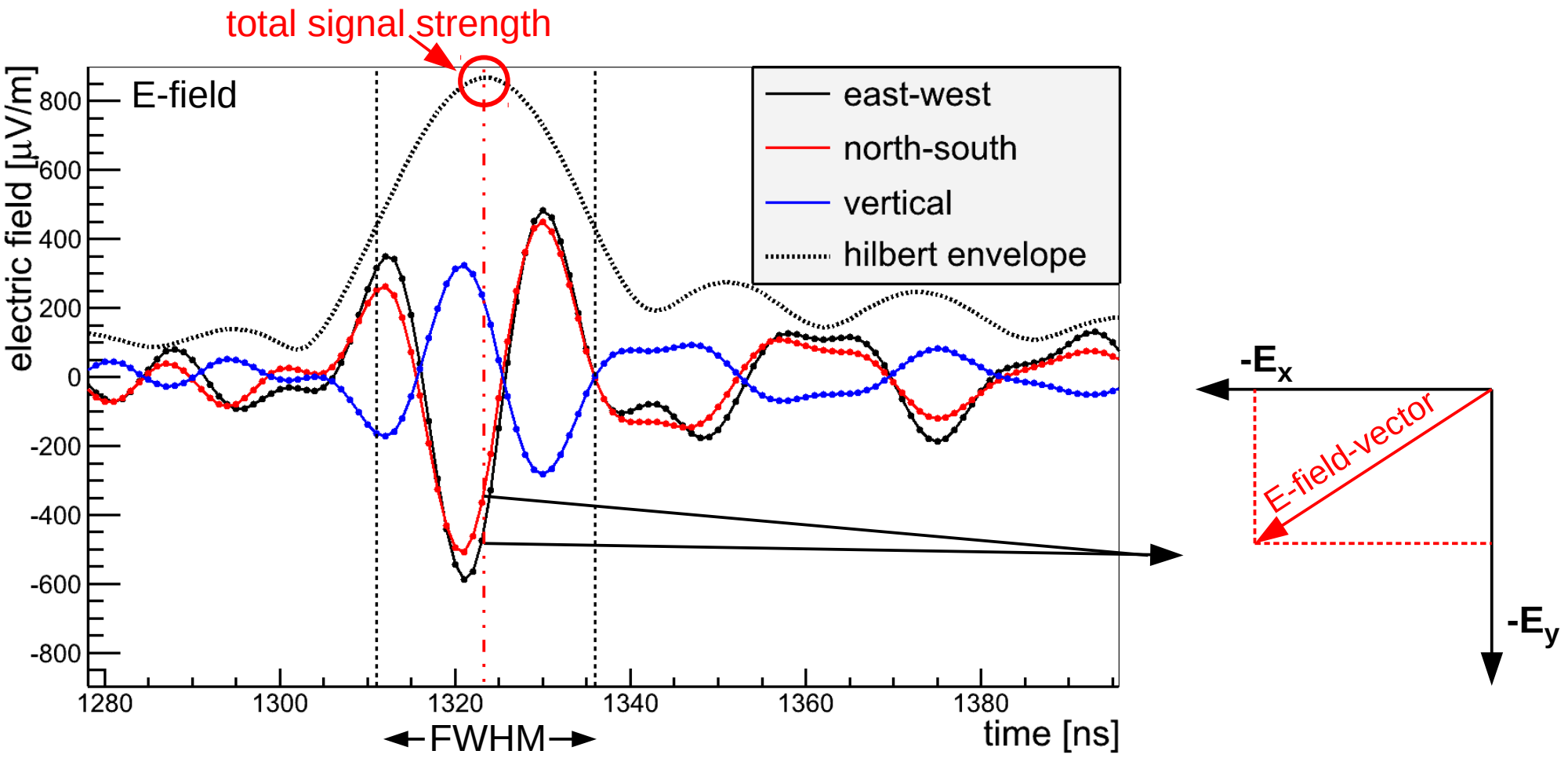


calibrated radio station



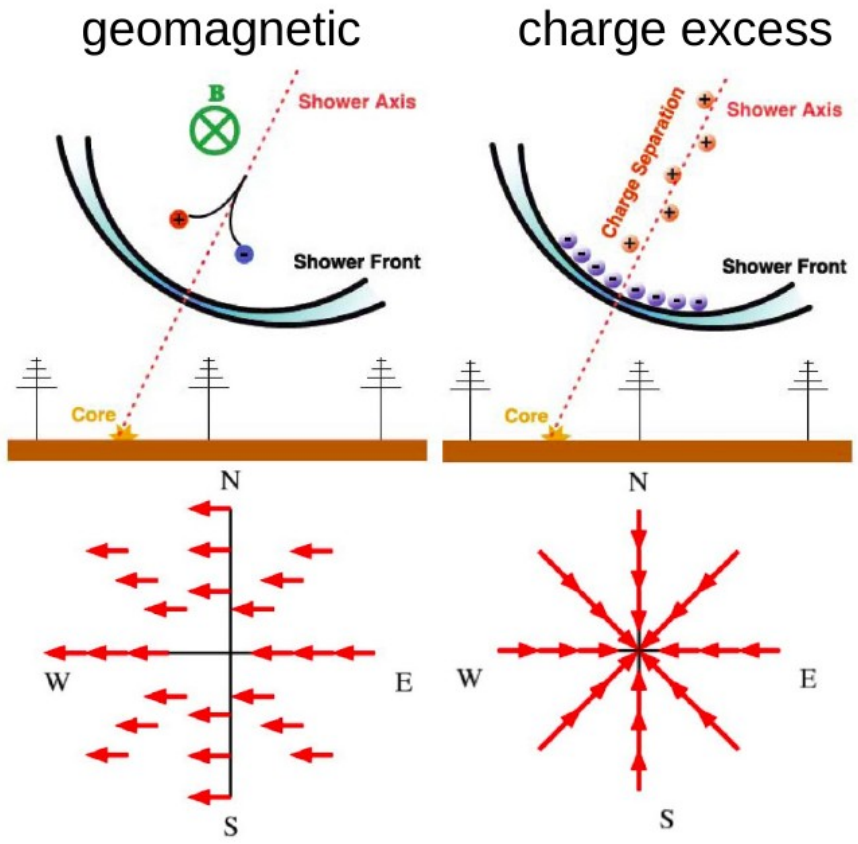
Signal Strength and Polarisation

- total signal strength determined from Hilbert envelope
- direction of 3-dim. electric field is determined in FWHM
- $|\vec{E}| = \text{max. of hilbert envelope}$



Measurement of Radio Emission Processes

- radio emission processes have different polarization signature
  - measurement of polarization is ideal tool to disentangle emission processes
- assume presence of geo-magnetic and radial component
- relative strength of radial wrt. geomagnetic component:
  - $a = \dfrac{|E_\mathrm{r}|}{|E_\mathrm{g}|/\sin\alpha}$



$$\vec{E}_{expected} = \sin\alpha \cdot \vec{e}_L + a \cdot \vec{e}_{CE}$$

Measurement of Radio Emission Processes

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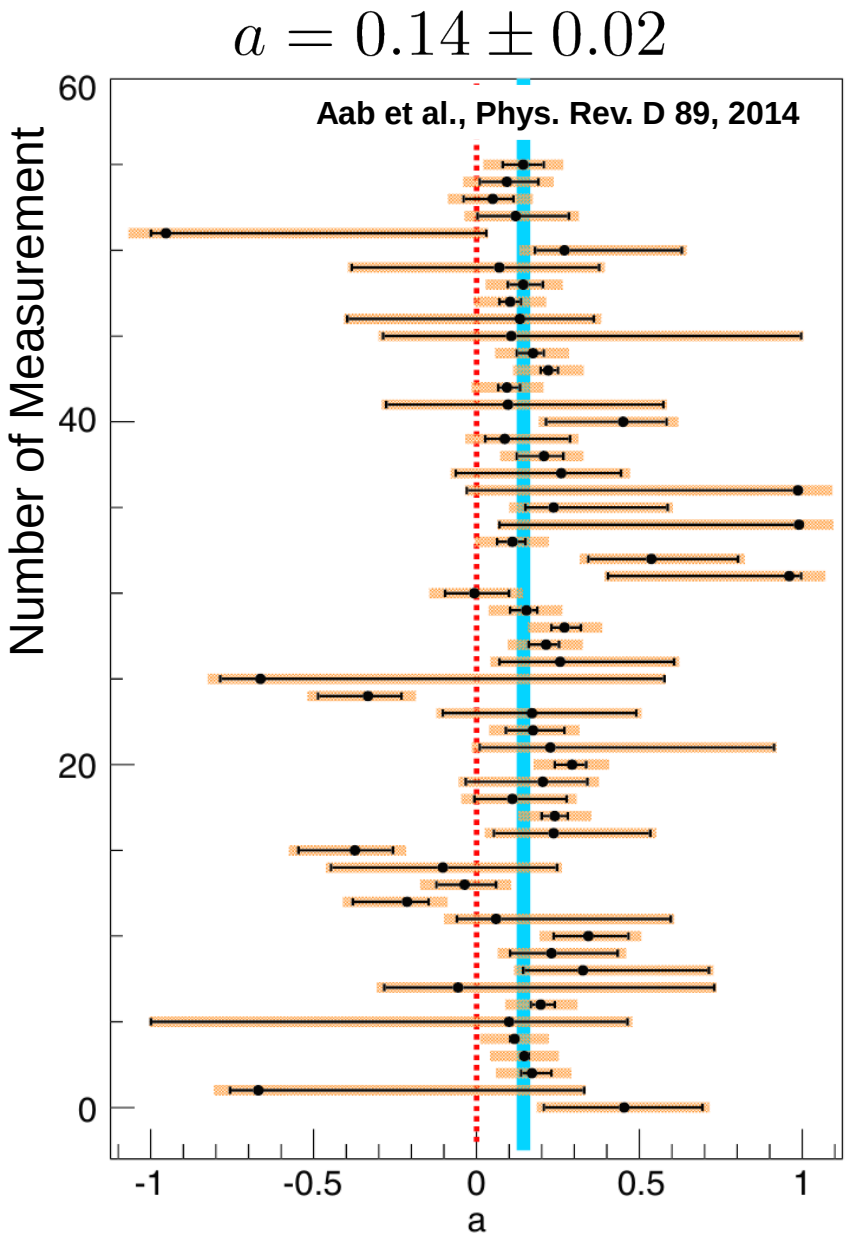


Reconstruction of Core Position using Polarization

charge excess strength ~ 14%

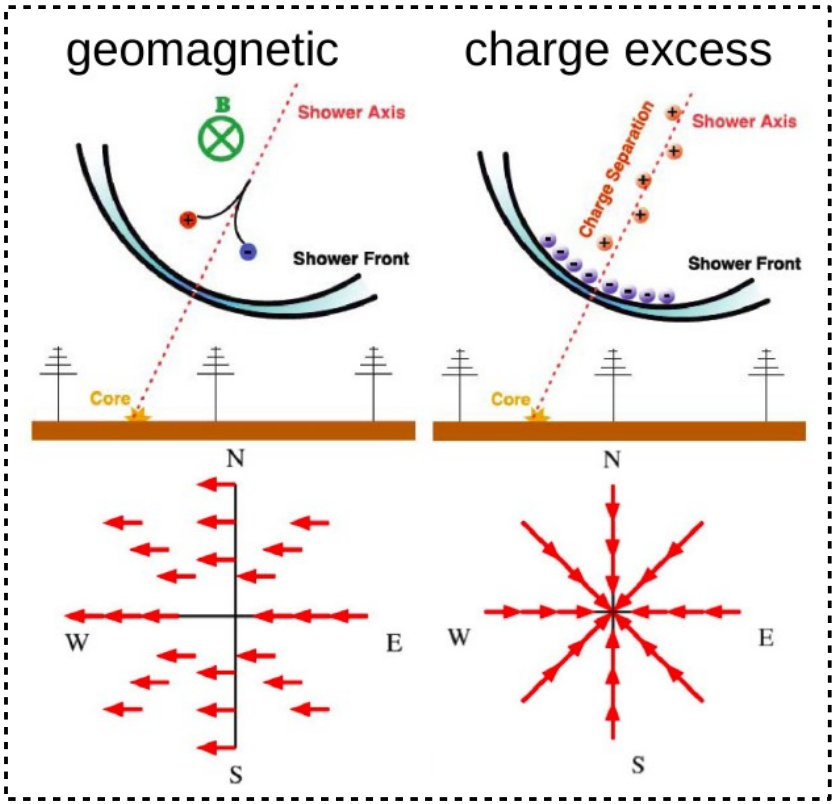
Lorentz vector

charge excess vector

$$\vec{E}_{expected} = \sin\alpha \cdot \vec{e}_L + a \cdot \vec{e}_{CE}(core, ...)$$

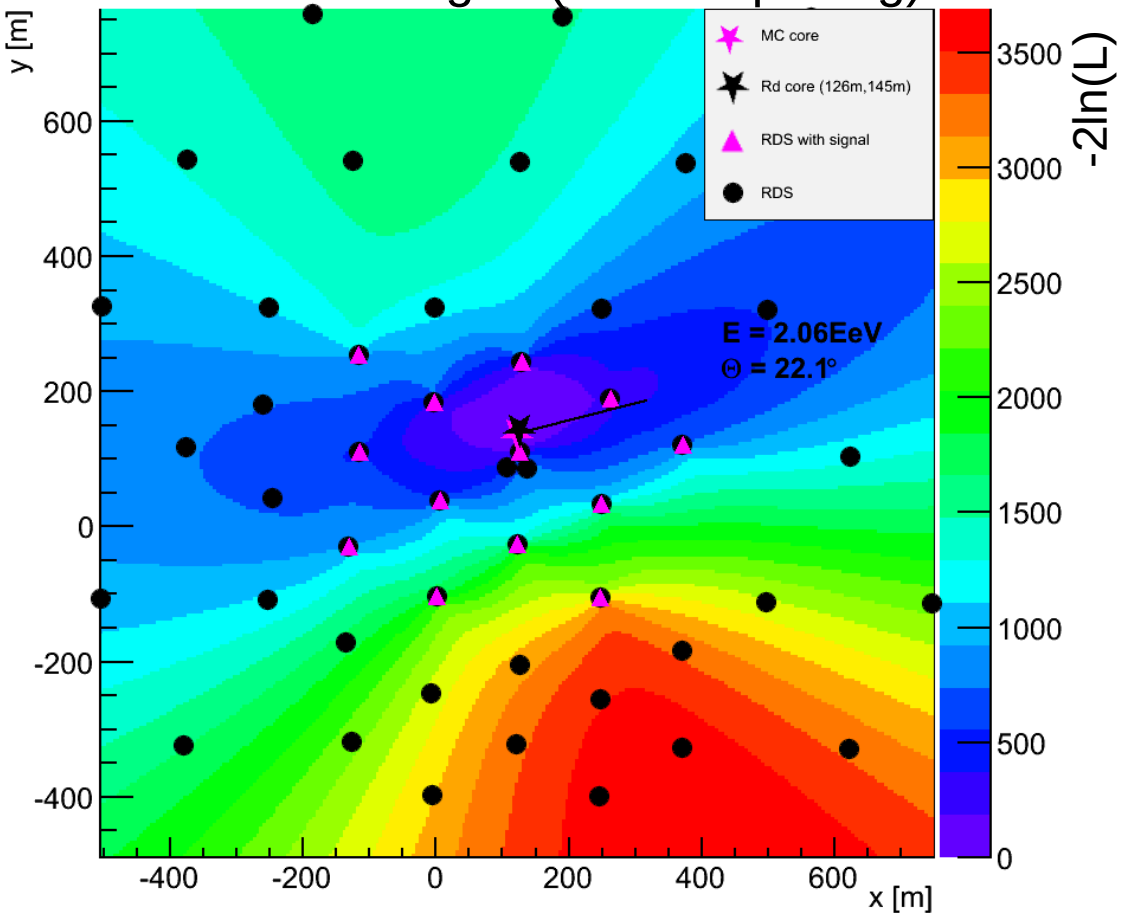
Estimator: $\beta = \angle(\vec{E}_{expected}, \vec{E}_{measured})$

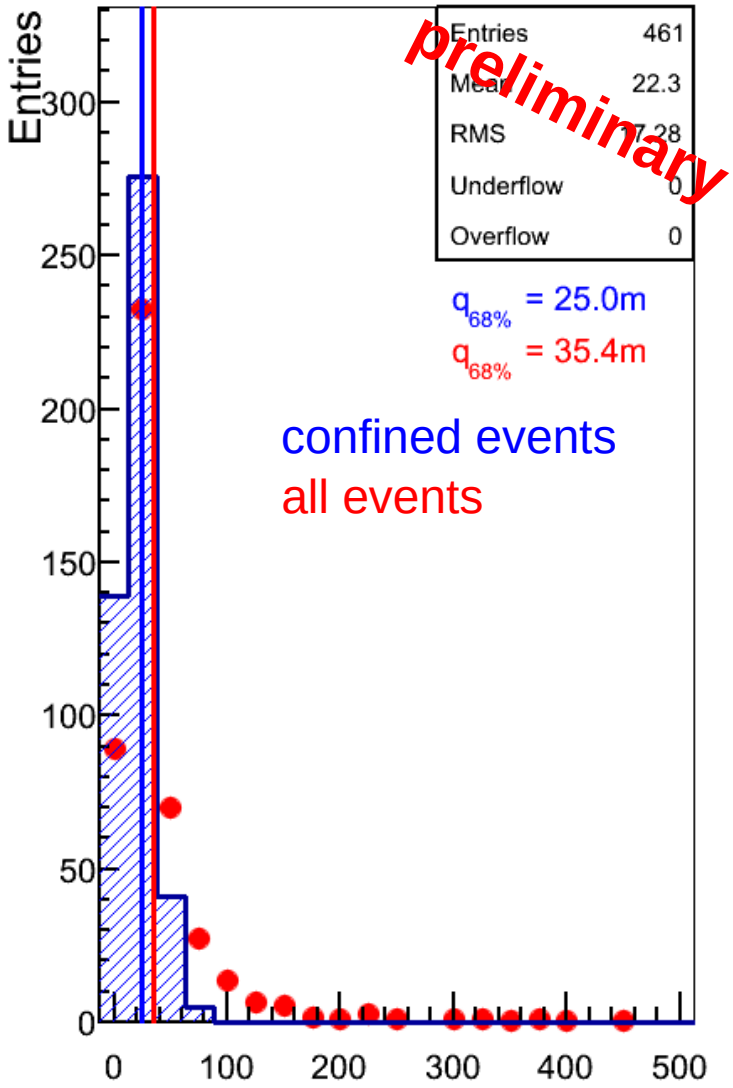
- polarization gives estimator for core position
- fit core position using polarization by maximising Likelihood $\mathcal{L} = \prod_i P(\beta_i)$



Reconstruction of Core Position using Polarization

- test method using air shower simulations (CoREAS)
- data set:
  - energy 0.1 – 5 EeV
  - azimuth uniform, zenith < 40°
  - AERA 24 grid (150 m spacing)

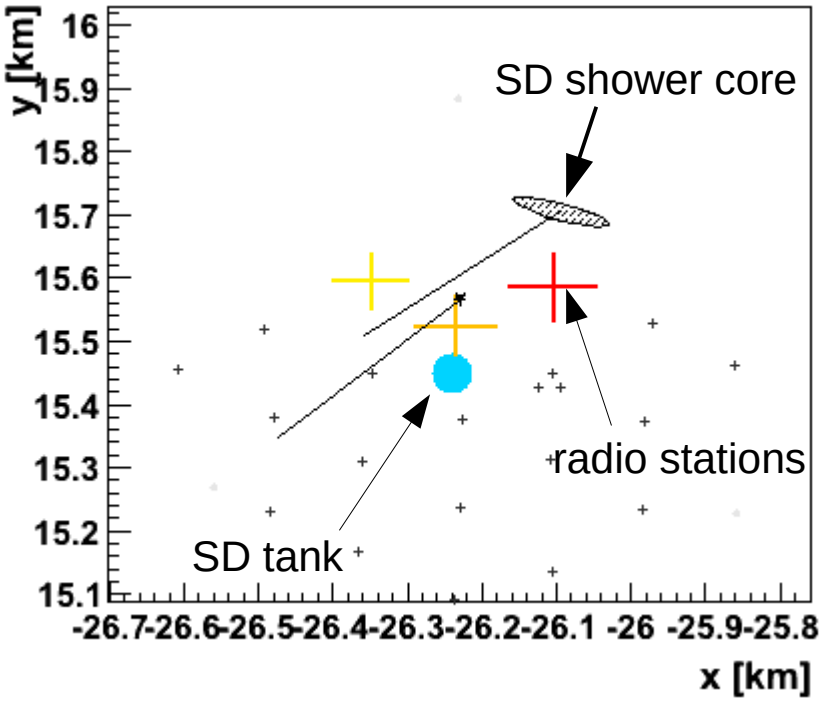


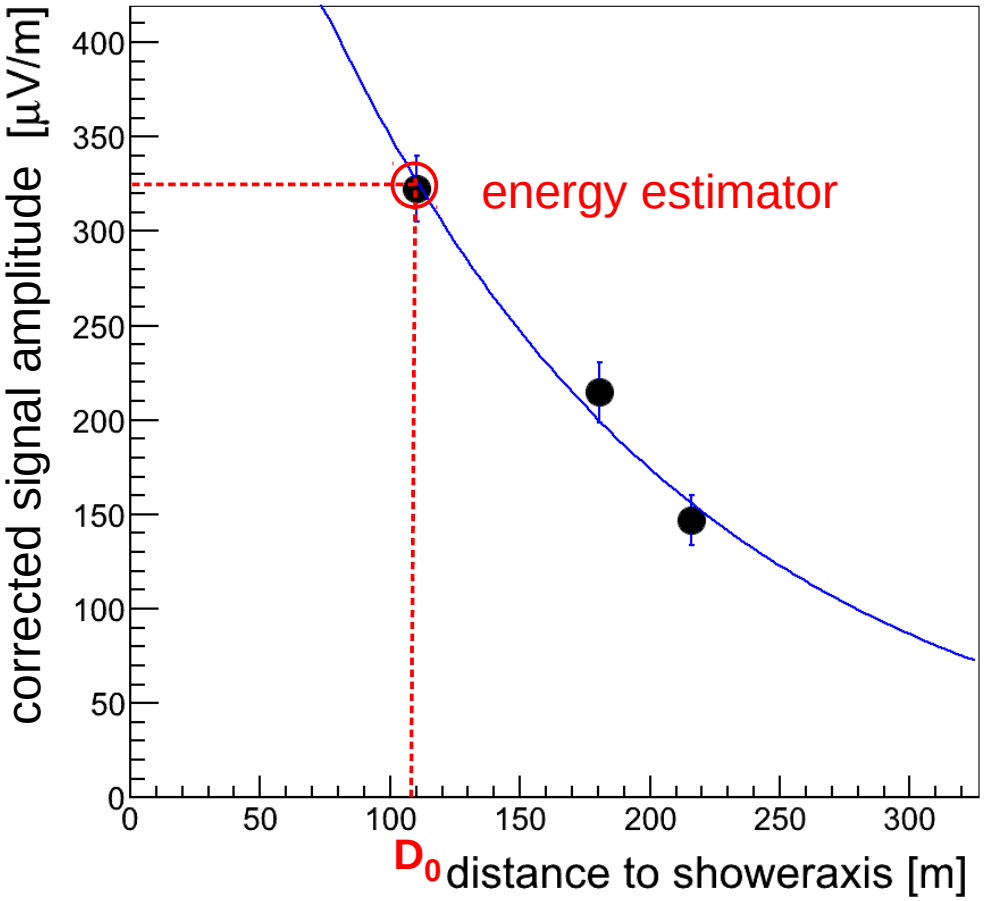


Energy Reconstruction

- correct signal amplitude for incoming direction:
  - $\left| \sin\alpha \cdot \vec{e}_L + a \cdot \vec{e}_{CE} \right|$
- radio signal measured at discrete positions
- use exponential function to interpolate between data points

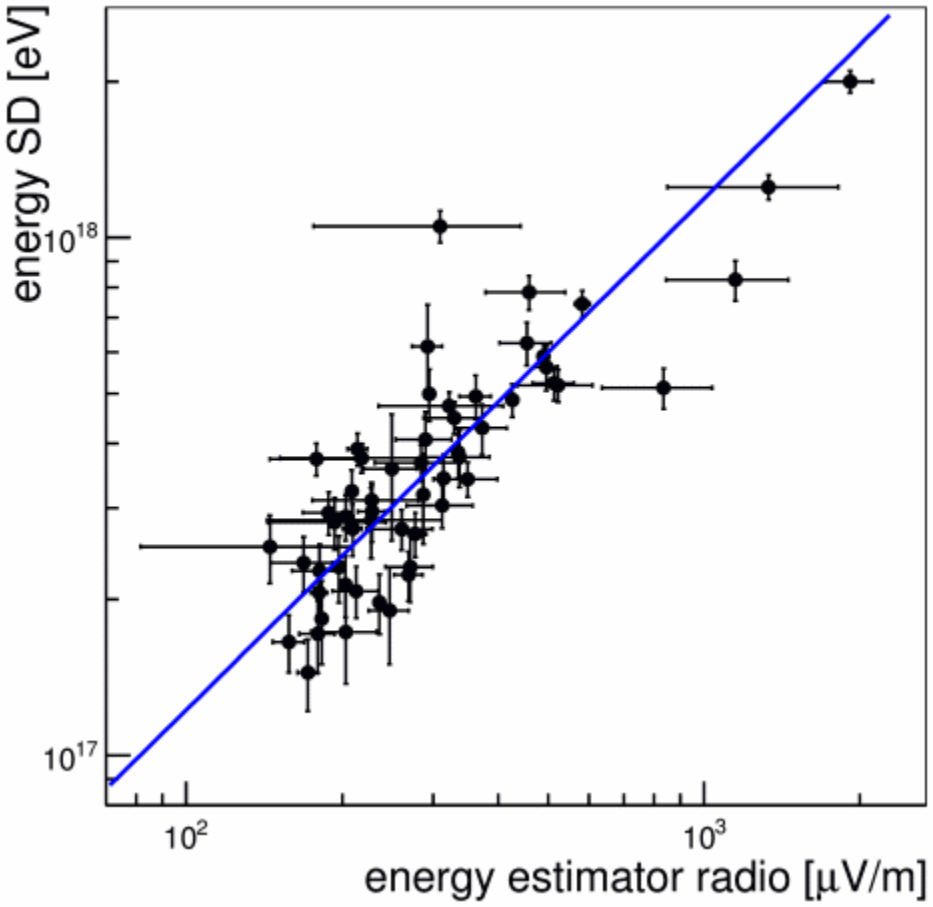
$$E_{scaled} = A \cdot exp(D/R_0)$$

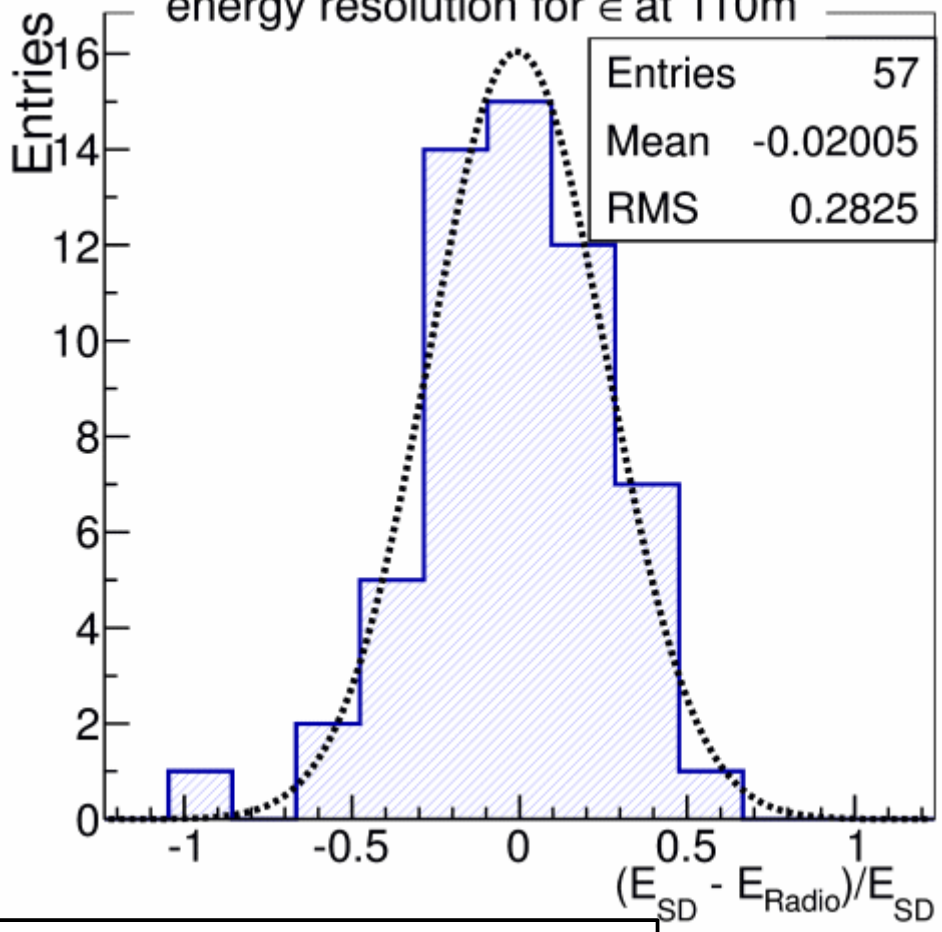




Energy Calibration

energy resolution 28%
(incl. surface detector resolution)



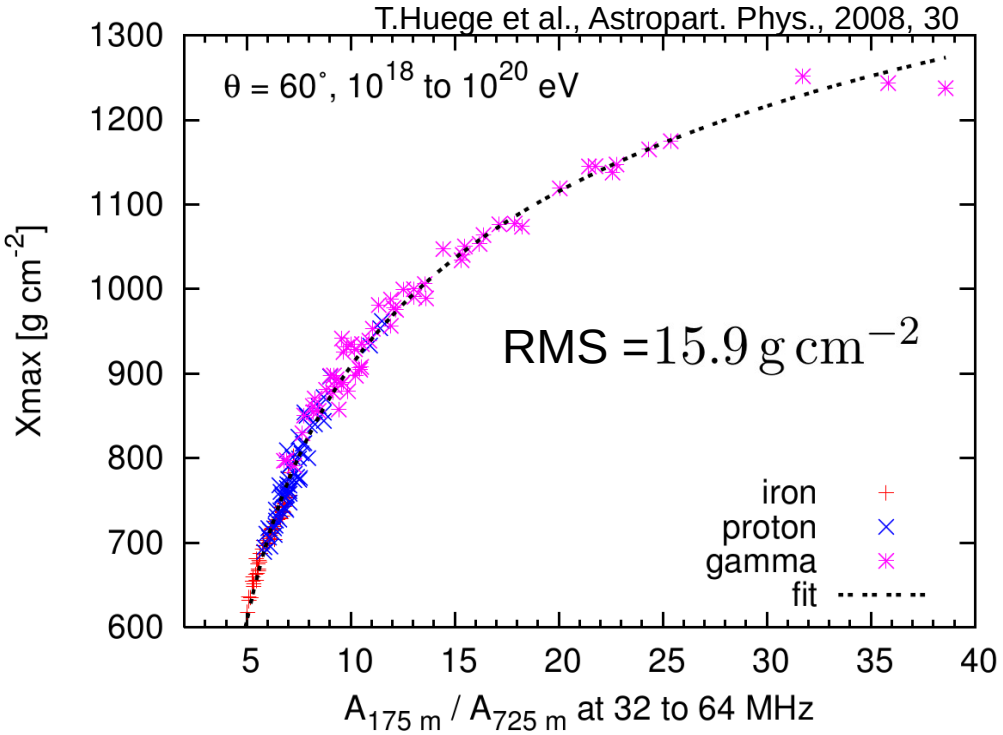


$$E = (1.35 \pm 0.31) \cdot 10^{15} \cdot \left(\frac{\varepsilon_{110m}}{\mu V/m}\right)^{0.98 \pm 0.04} eV$$

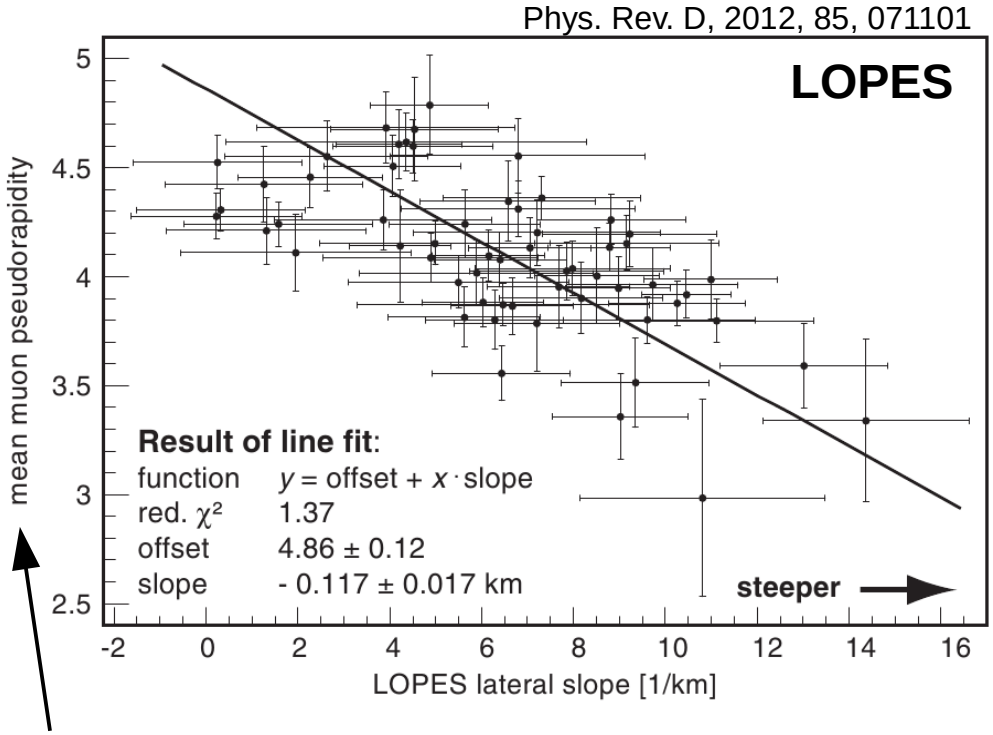
Sensitivity to Primary Cosmic Ray Mass

- theory predicts good sensitivity to Xmax (shower maximum, observable of mass)

theoretical prediction



experimental proof of principle

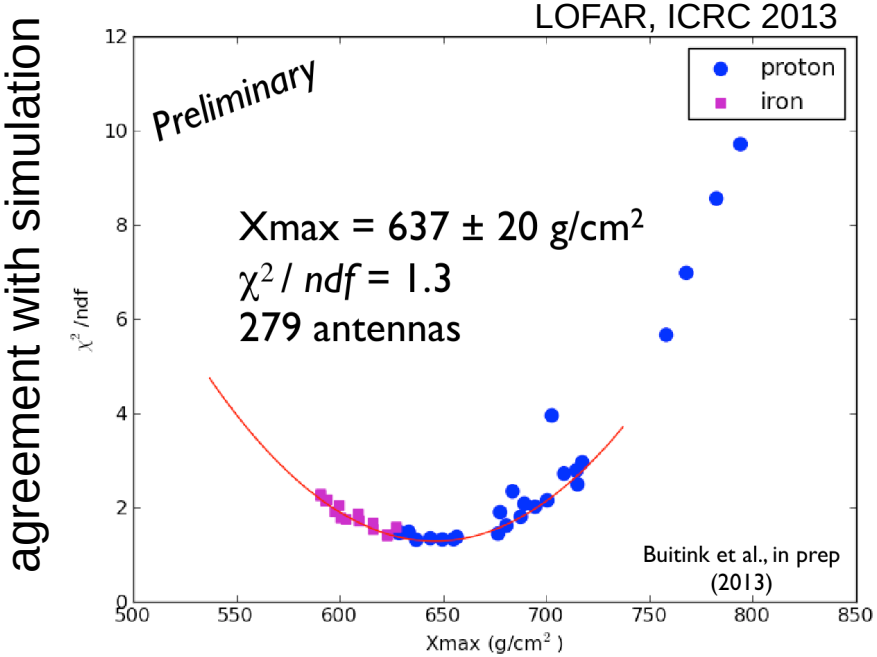


Xmax observable

Sensitivity to Primary Cosmic Ray Mass

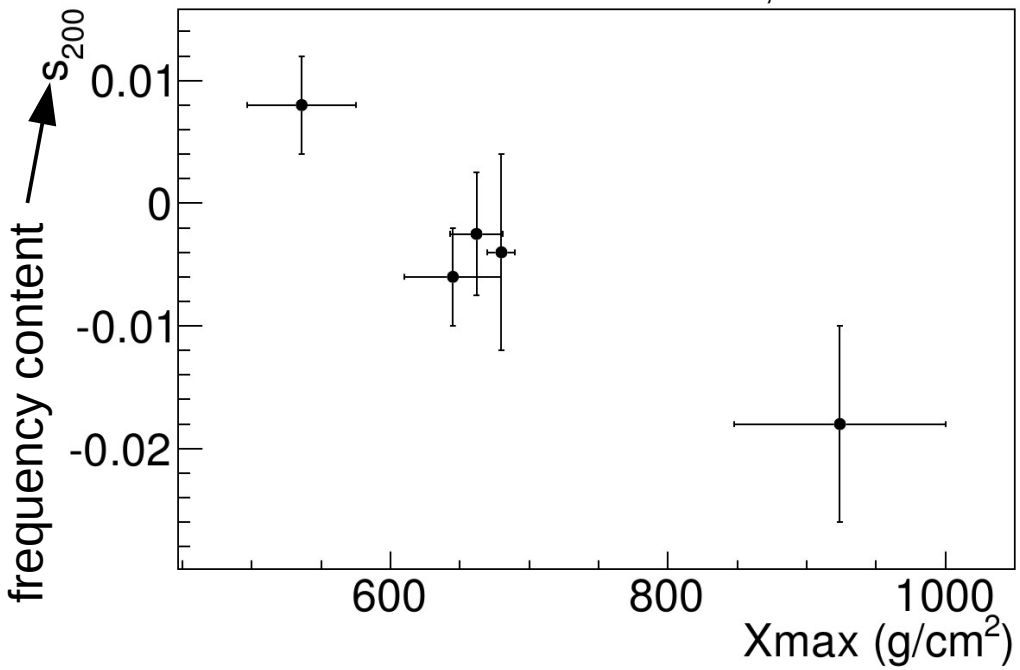
- different “radio” observables under investigation:
  - LDF slope
  - frequency content of radio pulse
  - form of wavefront of radio signal

LOFAR, ICRC 2013



from shower simulations

AERA, PhD. S.Grebe



measurement from fluorescence detector

Summary

- Pierre Auger Observatory
  - world's largest detector for cosmic rays
  - well calibrated environment for development of future detector technologies
- Auger Engineering Radio Array
  - feasibility for a large scale radio cosmic ray detector under investigation
  - reconstruction of 3-dim. electric field vector at each radio station
  - primary and secondary emission process determined:
    - 1st. geomagnetic emission
    - 2nd. charge excess emission
  - polarization of radio signal is estimator of the core position
  - energy of primary particles is reconstructed at 28% accuracy (incl. surface detector resolution)
  - primary cosmic ray mass sensitivity is under investigation