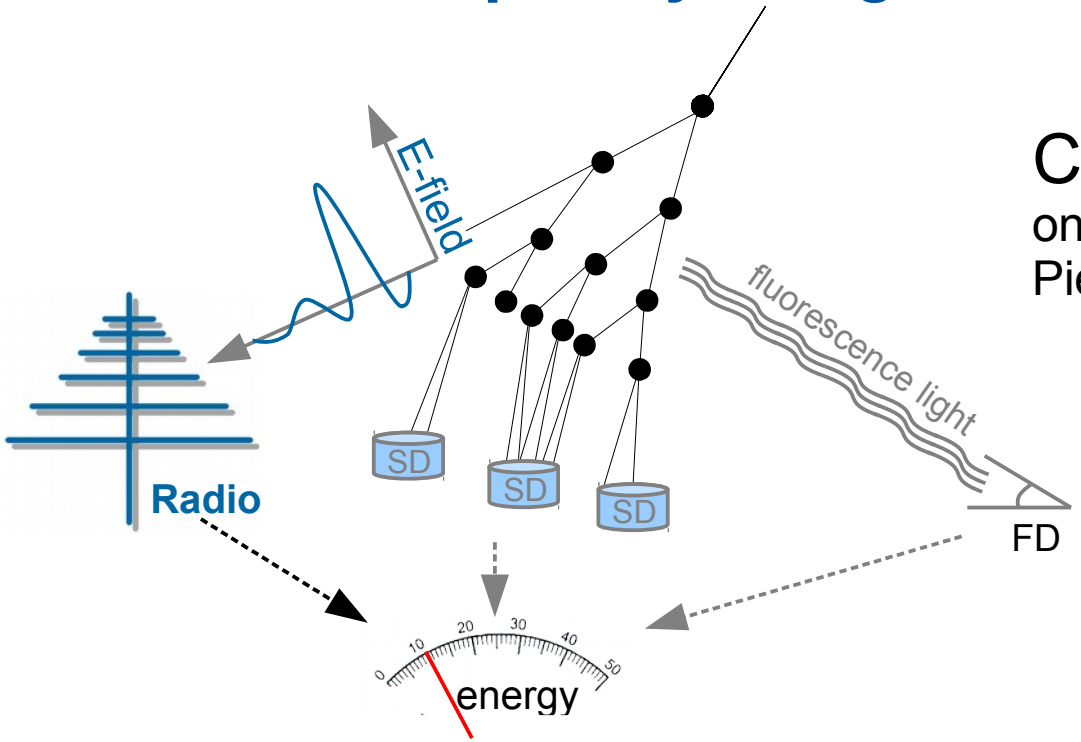
The Energy Content of Extensive Air Showers in the Radio Frequency Range of 30-80 MHz



Christian Glaser
on behalf of the
Pierre Auger Collaboration

PIERRE AUGER OBSERVATORY

AERA Auger Engineering Radio Array

DFG

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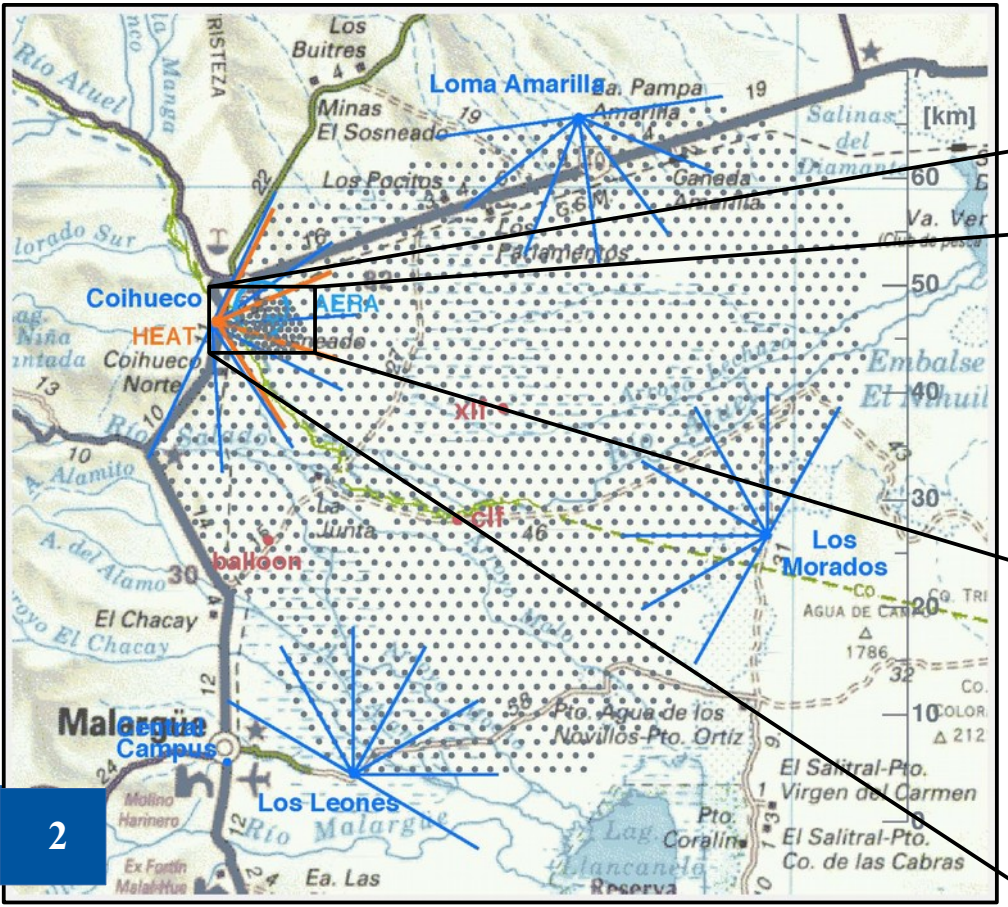
RWTH AACHEN UNIVERSITY

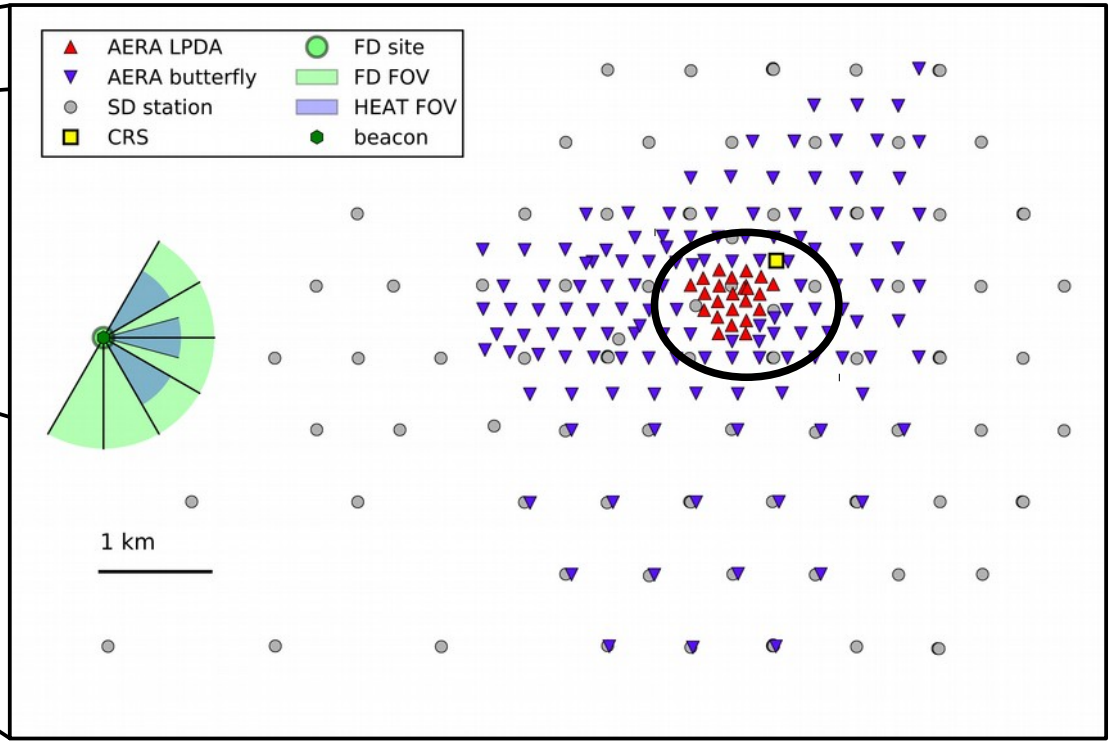
ICRC The Astroparticle Physics Conference
34th International Cosmic Ray Conference
July 30 - August 6, 2015
The Hague, The Netherlands

Engineering Radio Array of the Pierre Auger Observatory

- World's largest radio detector
- Deployed in different stages (2011: 0.6 km², 2013: 6 km², 2015: 17 km²)

more information
→ J. Schulz, Poster 615



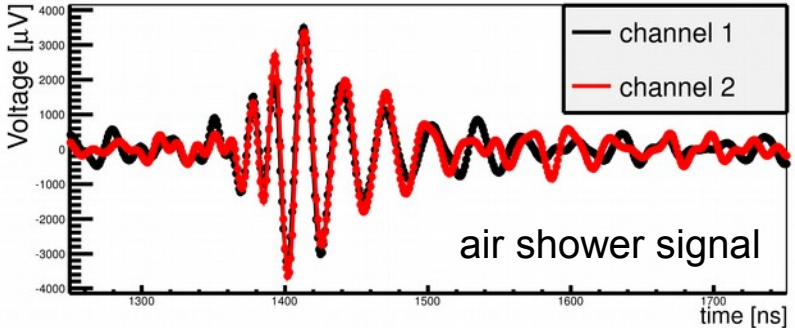


Auger Engineering Radio Array (AERA)

- AERA phase 1 detector well understood
  → 24 antennas (out of 153 deployed)
  → 144 m spacing
  → ~2 years of runtime
- Antenna characteristics (LPDA) measured and simulated *Abreu et al., Jinst 7, 10011 (2012)*
- Individual measurement of whole signal chain
  → **Systematic uncertainty 14%**

Data set

- Coincidences with surface detector (750 m array)
- Zenith angle < 55°
- Quality cuts
  - Polarization of radio signal (removes noise pulses)
  - No thunderstorm conditions
- 126 events with E > 10^{17} eV



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From Voltage to Cosmic Ray Energy

Voltage [V]

↓ antenna + detector response

Electric field [V/m]

↓ time integral of Poynting vector

Radiation energy density [eV/m²]

↓ fit 2D-LDF + spatial integral

Radiation energy of air shower [eV]

↓ geometry correction

$1/\sin^2(\alpha)$ with $\alpha = \measuredangle(\mathbf{v},\mathbf{B})$

Cosmic ray energy estimator

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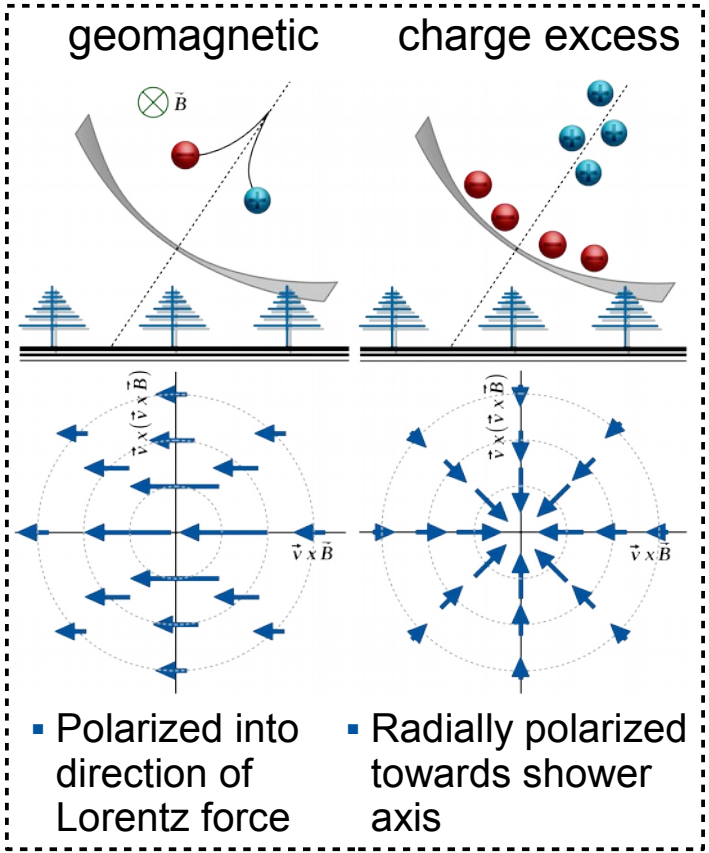
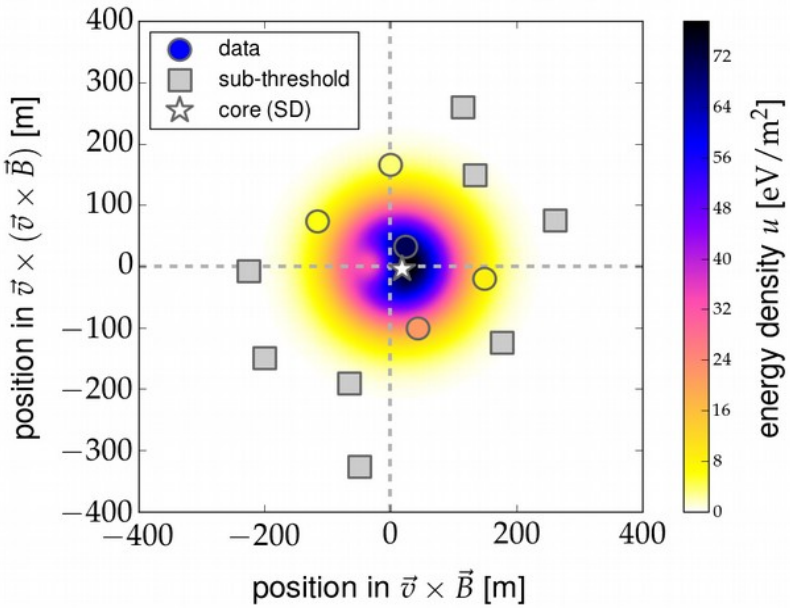
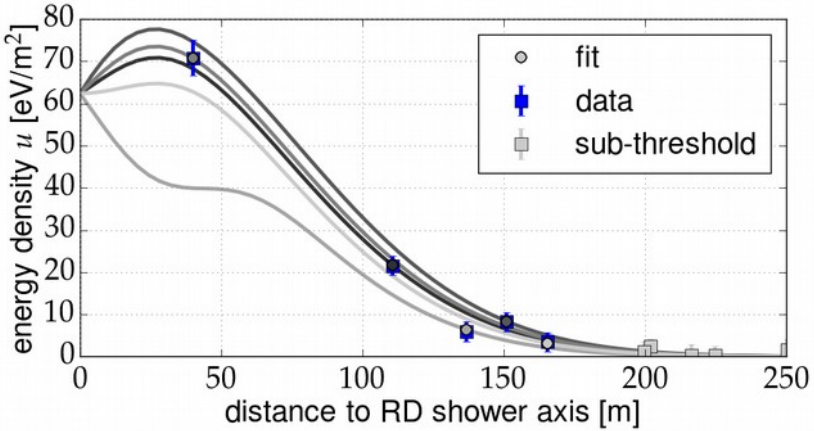
Radiation Energy of Air Showers



- Polarized into direction of Lorentz force
- Radially polarized towards shower axis





- Interference between emission mechanisms
  - 2D lateral distribution function *Nelles et al., Astropart. Phys. 60, 13 (2015)*
- ≥ 5 signal stations or 3-4 signal stations and SD core

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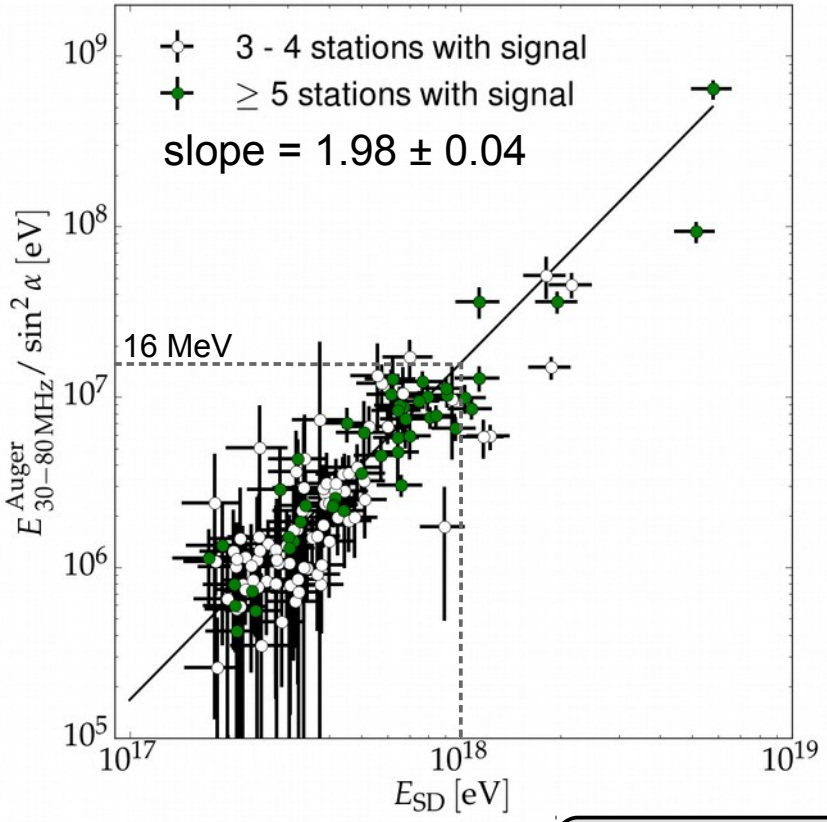
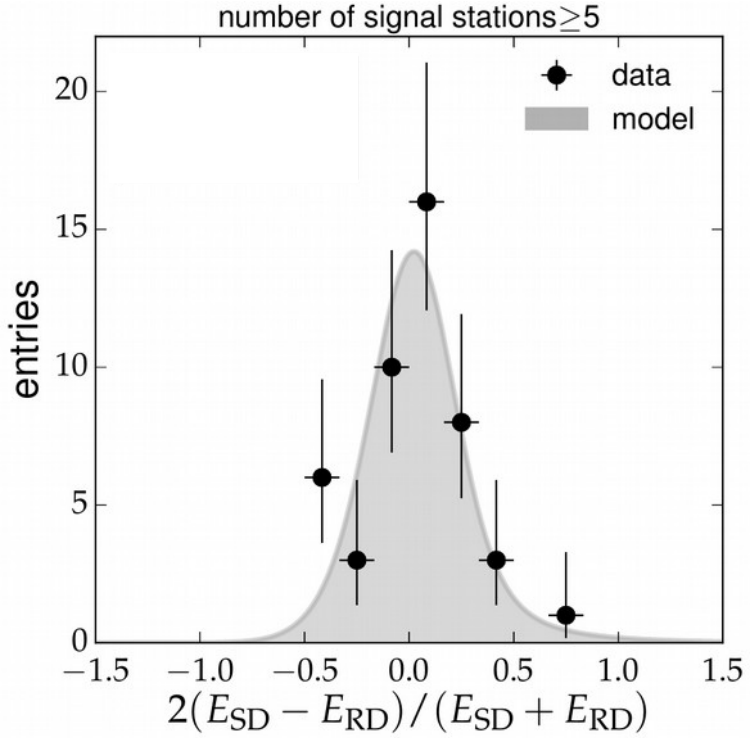
Energy Calibration

- Likelihood fit of calibration function taking into account detection efficiencies



energy resolution 17%



16 MeV radiation energy for a 1 EeV cosmic ray

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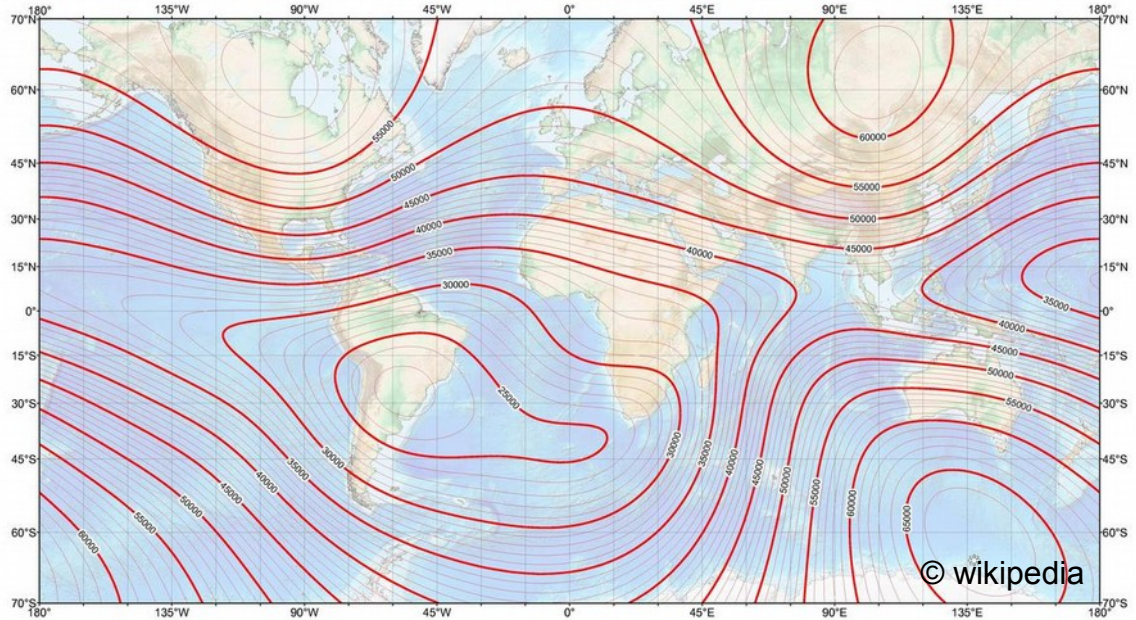
Radiation Energy of Air Showers

- Generalization: normalizing to local geomagnetic field
  - $$E_{30-80\,\mathrm{MHz}} = 16\,\mathrm{MeV}\left(\sin\alpha\,\frac{E}{10^{18}\,\mathrm{eV}}\,\frac{B_{\mathrm{Earth}}}{0.24\,\mathrm{G}}\right)^2$$

    28% syst. uncertainty 16% systematic uncertainty
  - Can be used anywhere on Earth
  - Cross calibration of cosmic ray observatories

magnetic field intensity



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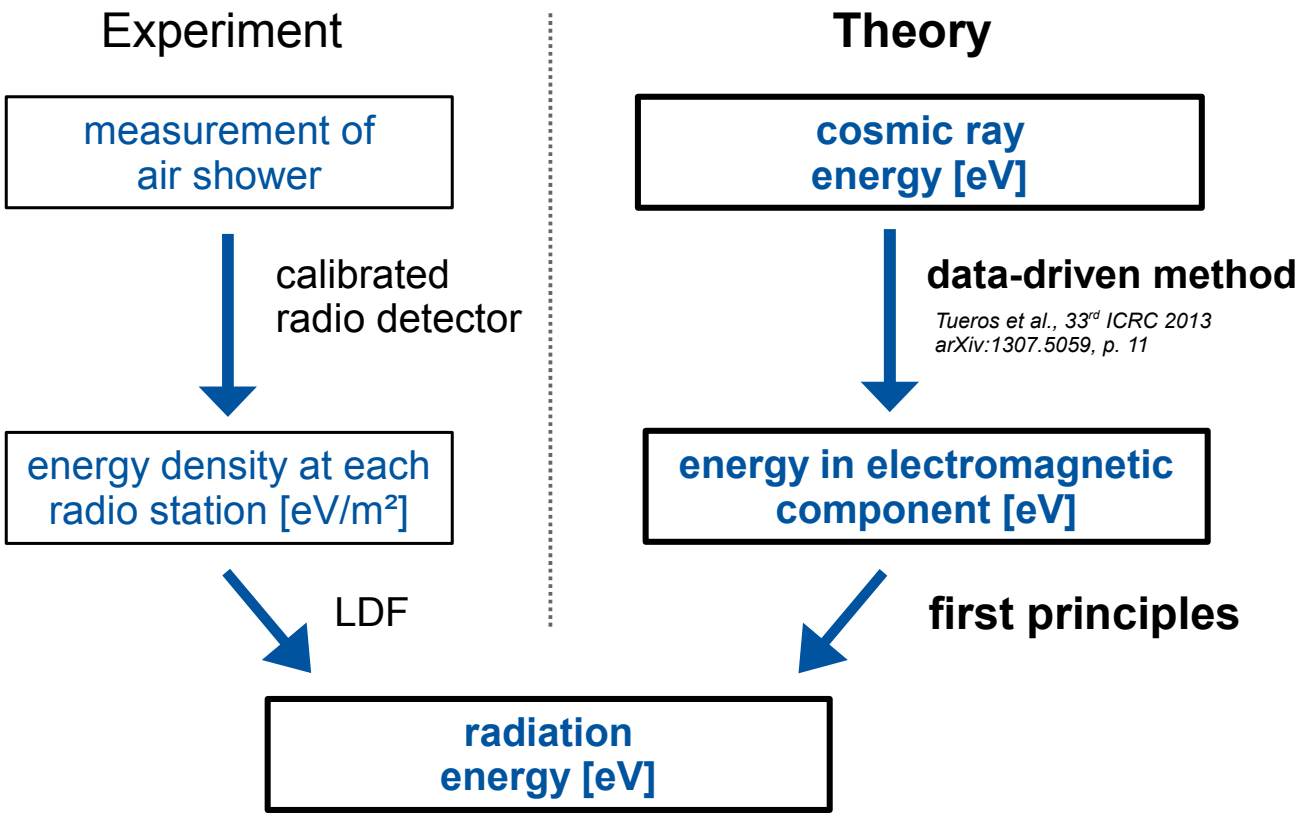
Potential of Independent Determination of Energy Scale



- Radio emission purely described by classical electrodynamics (no free parameters)
- Atmosphere transparent to radio emission

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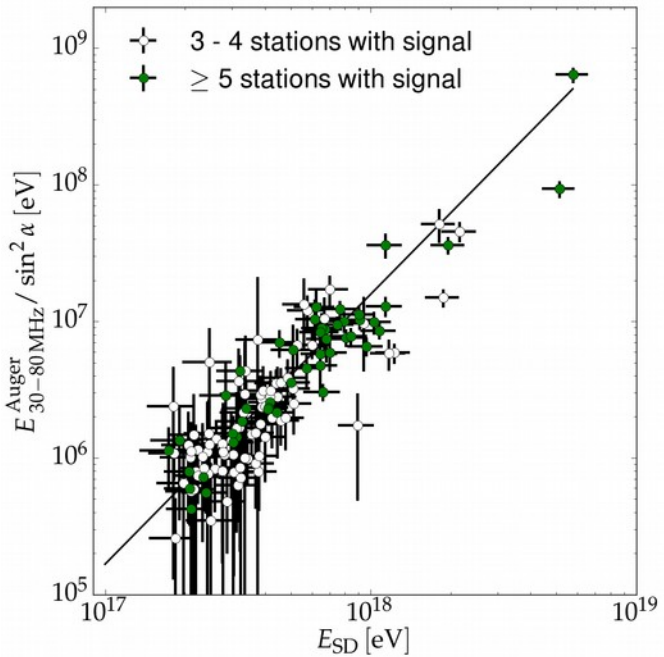
Summary

- Pierre Auger Observatory: well calibrated environment for development of future detector technologies
- Auger Engineering Radio Array
  - Thoroughly calibrated through the entire signal chain
  - Reconstruction of energy density at detector station
- Radiation energy of air showers measured
  - 16 MeV for E_{CR} = 1 EeV
- Cosmic ray energy resolution 17%
- Universal prediction of radiation energy
- Potential of determination of energy scale by first principles



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Backup

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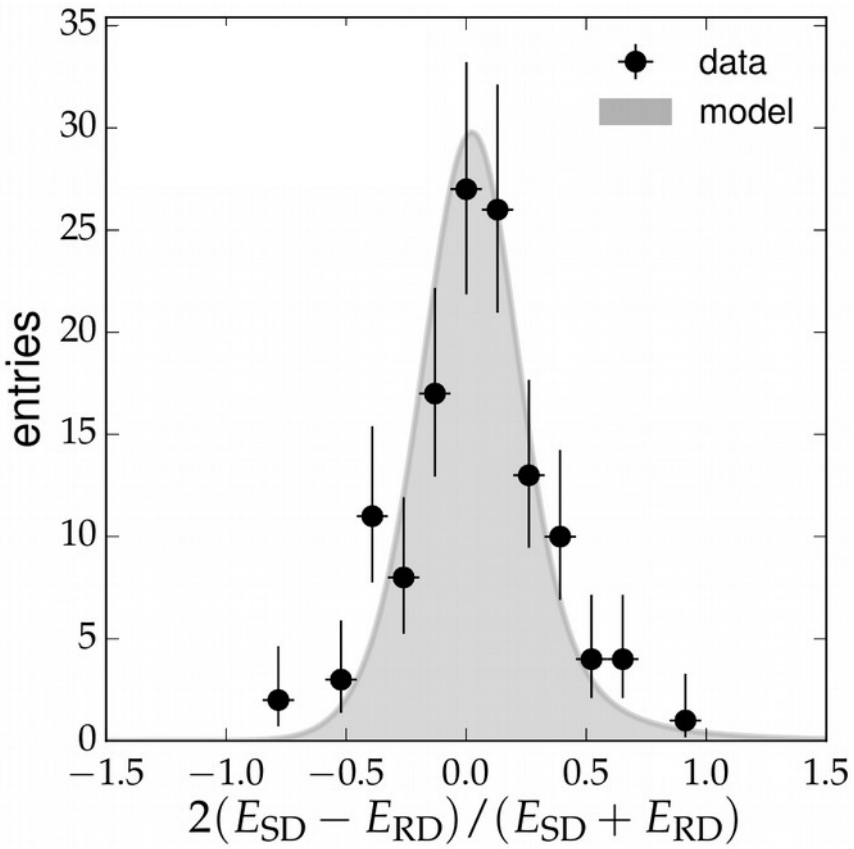
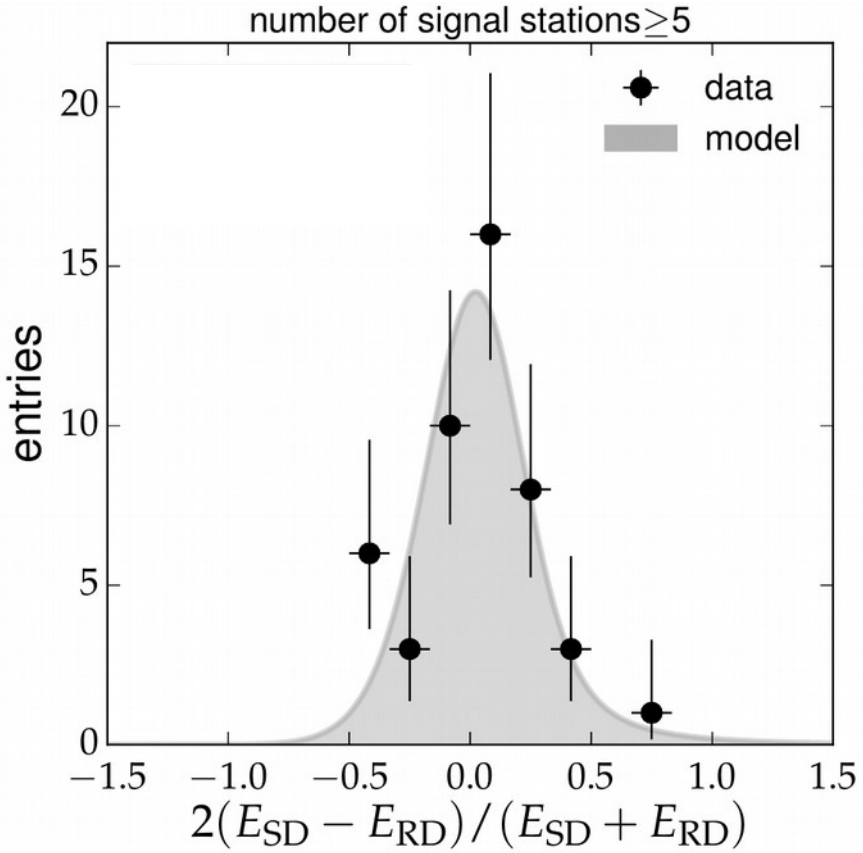
Energy Resolution

energy resolution 22%



energy resolution 17%



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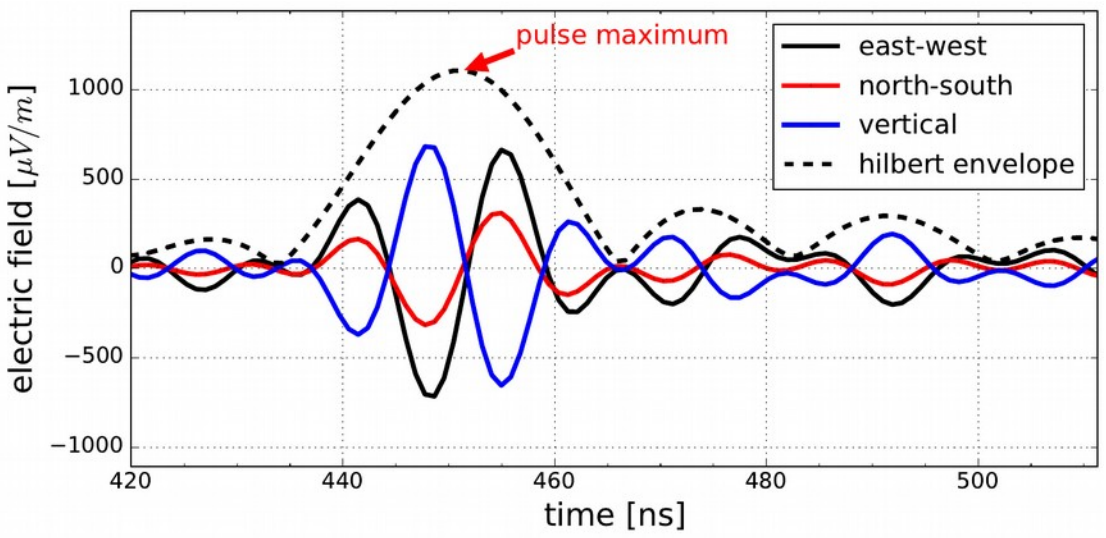
Calculating Energy Density



- Window around maximum of Hilbert envelope
- Energy density in eV/m²
  - Time integral of Poynting vector
  - Noise expectation subtracted
  - $u = \varepsilon_0 c \left(\Delta t \sum_{t_1}^{t_2} |\vec{E}(t_i)|^2 - \Delta t \frac{t_2 - t_1}{t_4 - t_3} \sum_{t_3}^{t_4} |\vec{E}(t_i)|^2 \right)$

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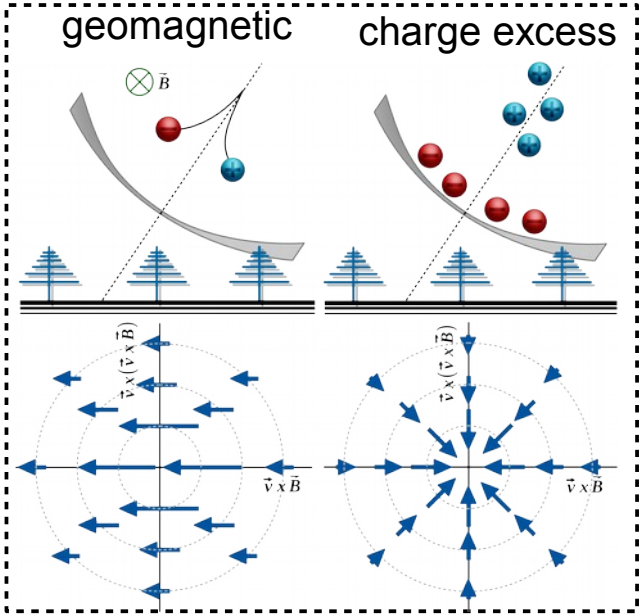
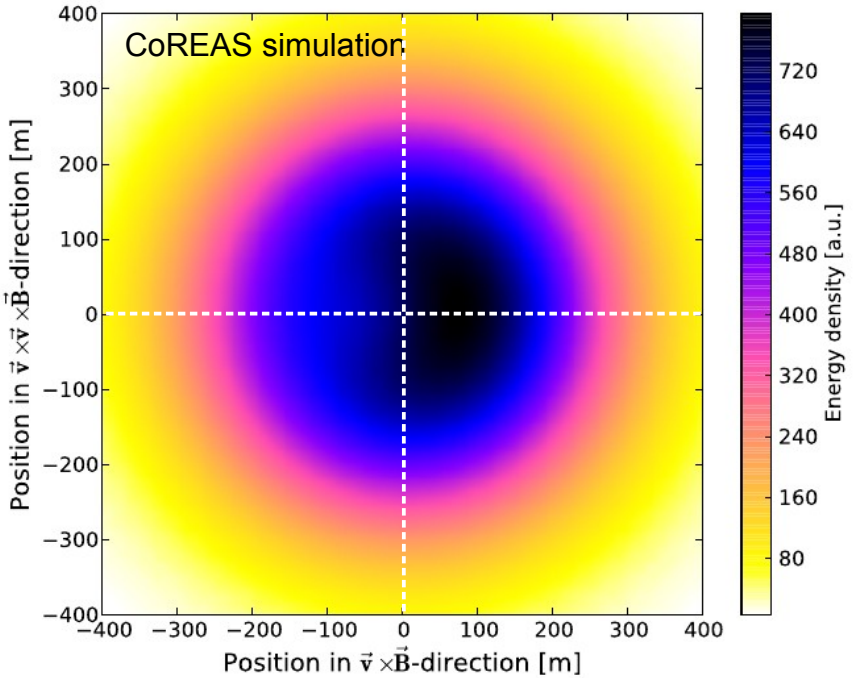
LDF – Interference between Emission Mechanisms

- **1st order: geomagnetic radiation**
  - Electrons/positrons deflected in Earth magnetic field **B**
  - Polarized into direction of Lorentz force



- **2nd order: charge excess / Askaryan effect**
  - Time varying net charge excess
  - Radially polarized towards shower axis



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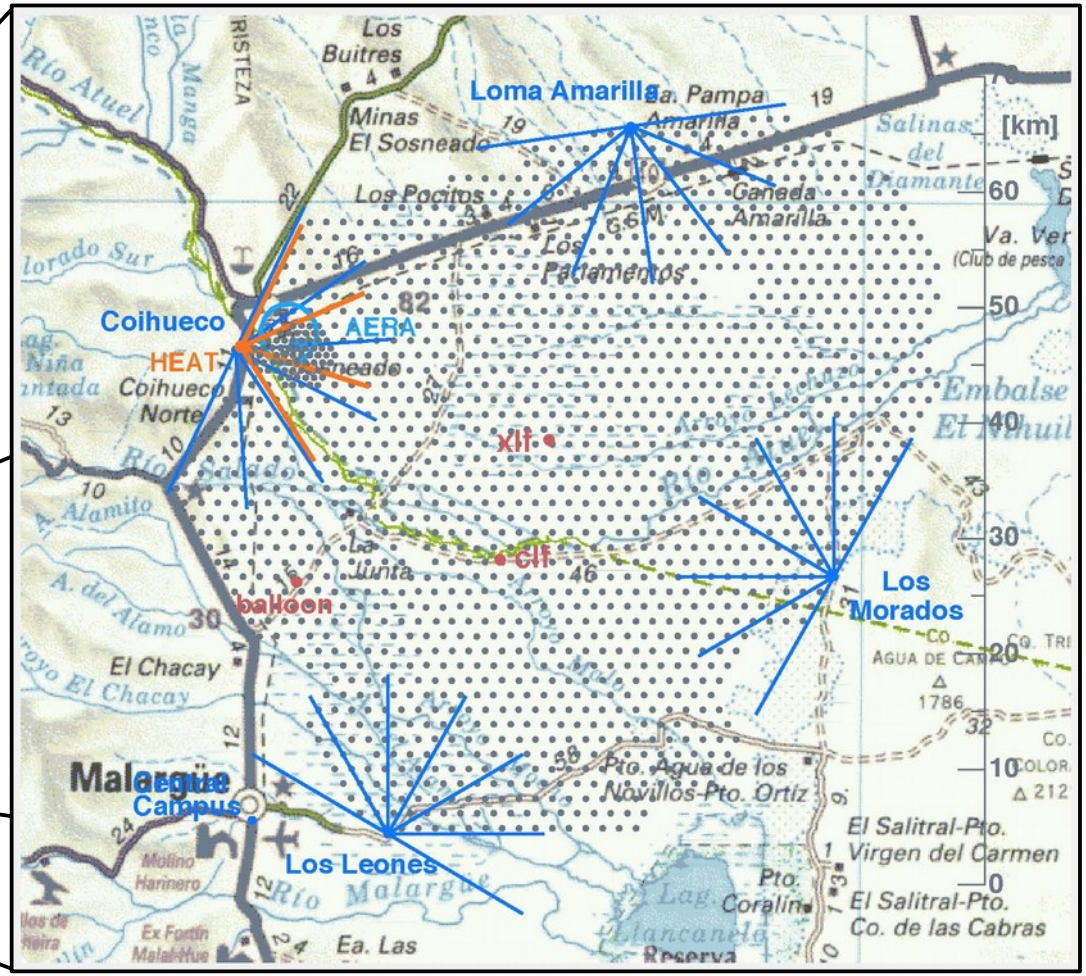
Pierre Auger Observatory

- Mendoza, Argentina
- World's largest cosmic ray detector (~3000 km²)
- 27 fluorescence telescopes
- 1660 surface detectors



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