Results and Perspectives of the Auger Engineering Radio Array (AERA)

Christian Glaser
for the Pierre Auger Collaboration

PIERRE AUGER OBSERVATORY

AERA Auger Engineering Radio Array

DFG

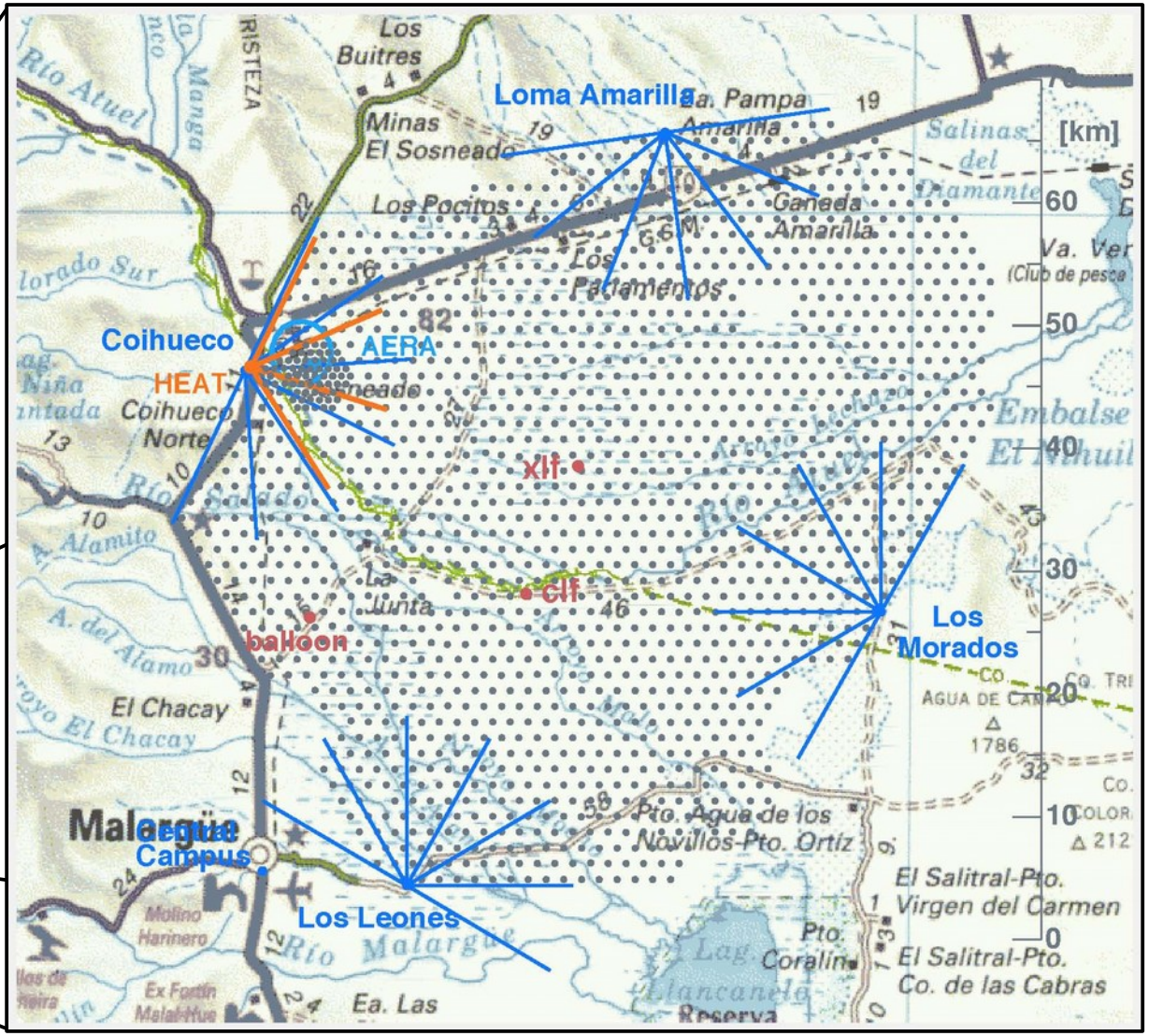
HELMHOLTZ ASSOCIATION
Alliance for Astroparticle Physics

SPONSORED BY THE
Federal Ministry of Education and Research

RWTH AACHEN UNIVERSITY

Pierre Auger Observatory

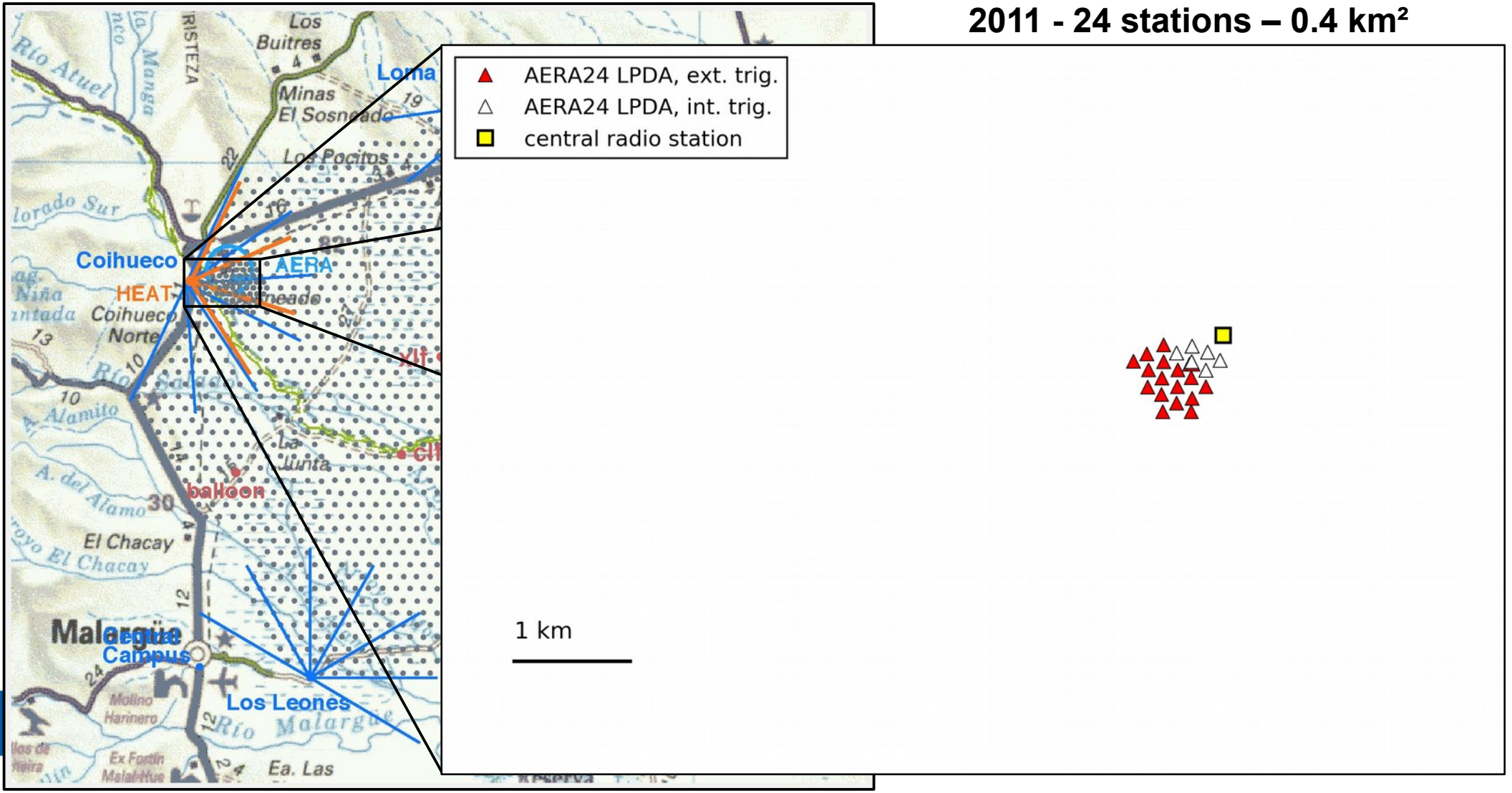
- Mendoza, Argentina
- World's largest cosmic-ray detector (~3000 km²)
- 1660 surface detectors (SD)
- 27 fluorescence telescopes (FD)



Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

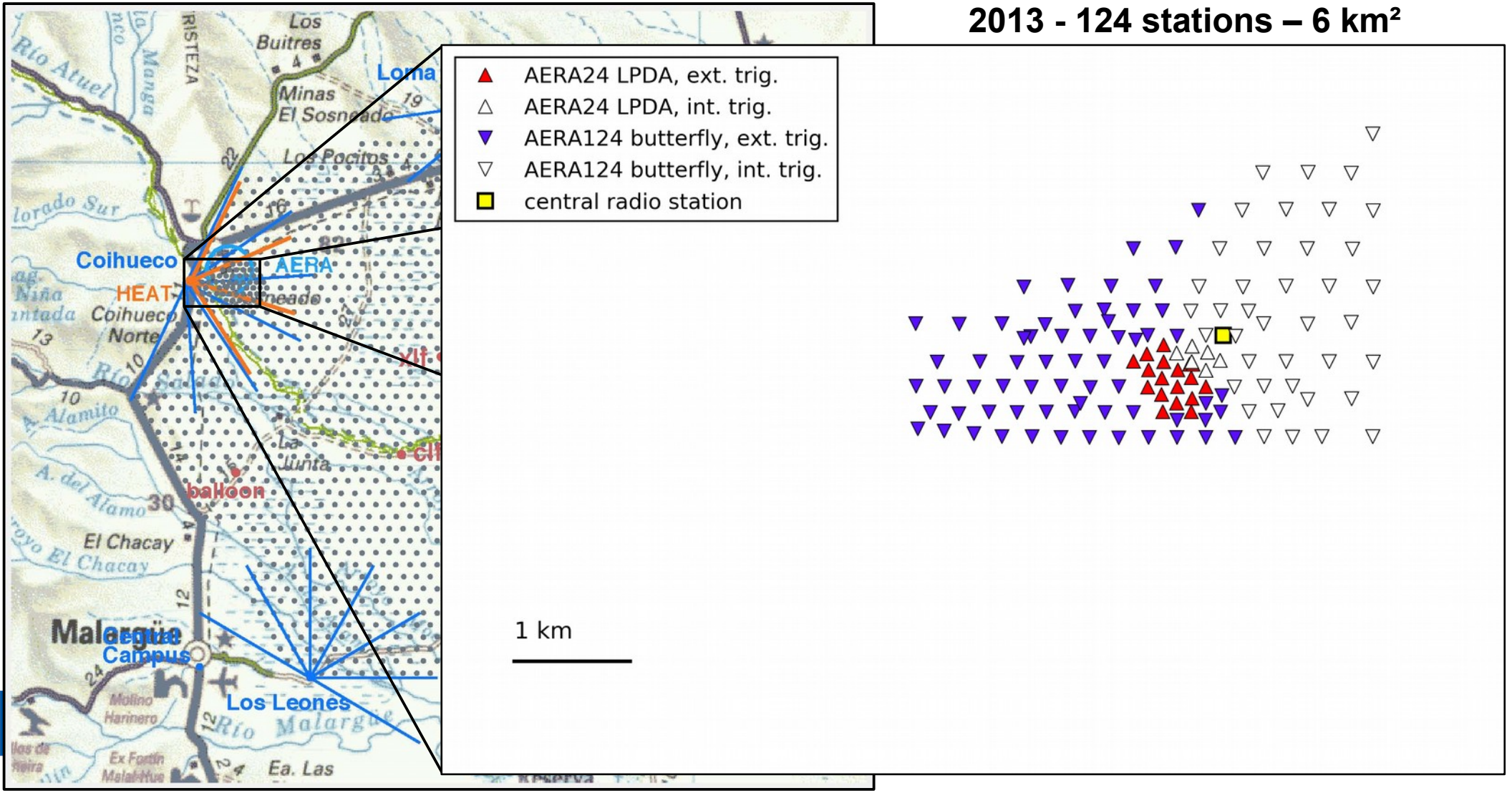
Auger Engineering Radio Array (AERA)

- World's largest cosmic-ray radio detector
- Autonomous detector stations
- Deployed in different stages (2011: 0.4 km², 2013: 6 km², 2015: 17 km²)



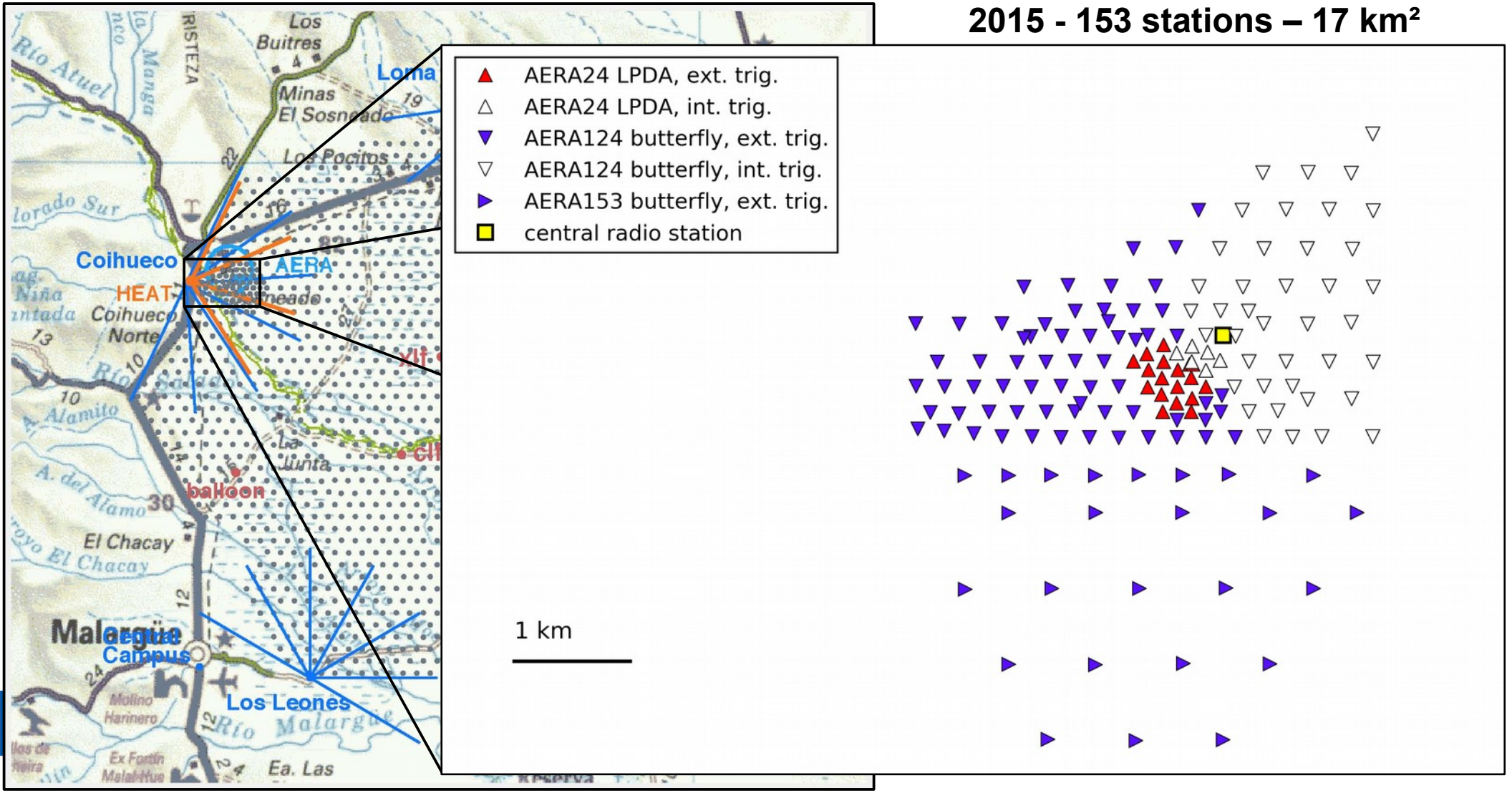
Auger Engineering Radio Array (AERA)

- World's largest cosmic-ray radio detector
- Autonomous detector stations
- Deployed in different stages (2011: 0.4 km², 2013: 6 km², 2015: 17 km²)



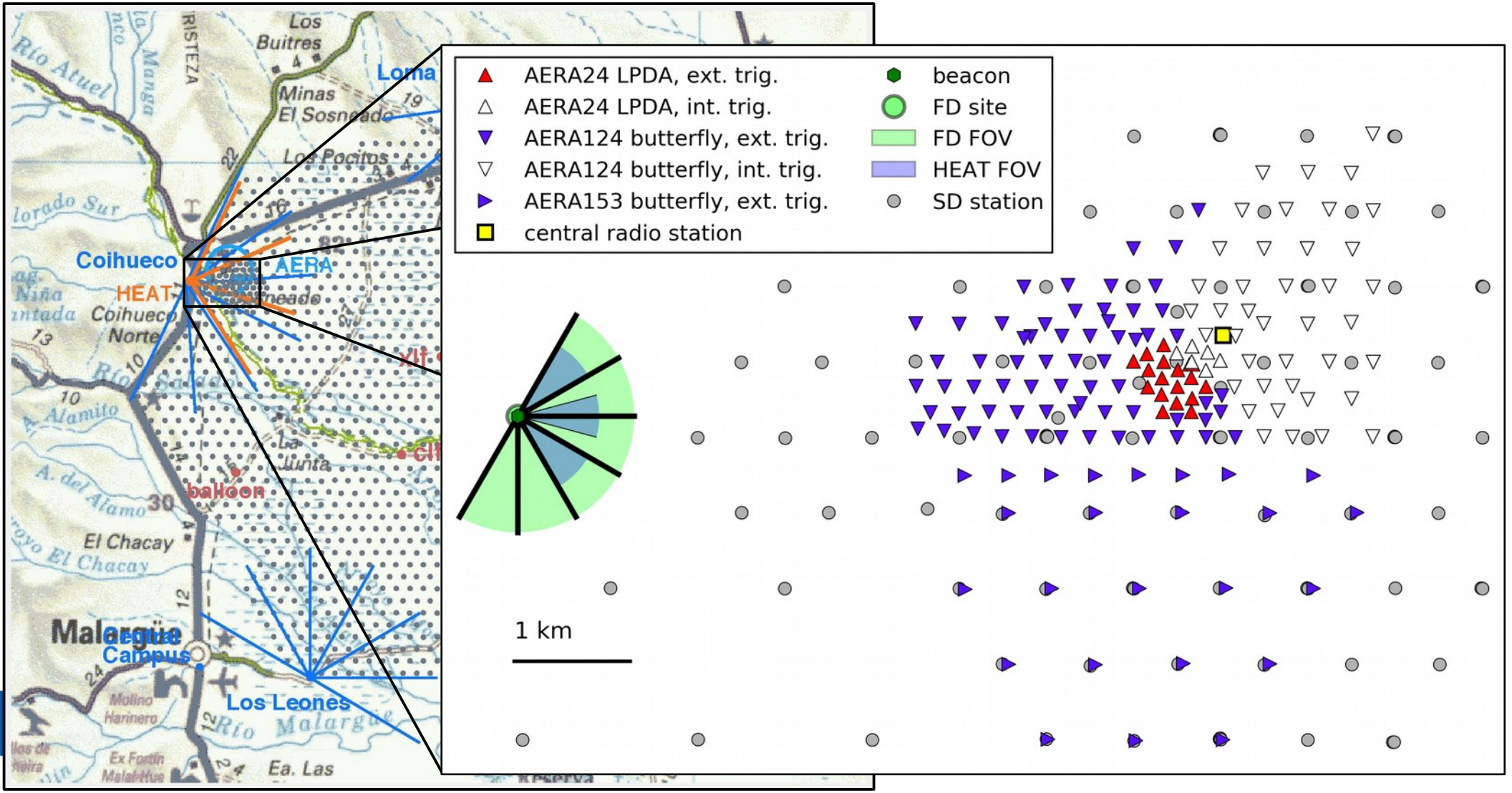
Auger Engineering Radio Array (AERA)

- World's largest cosmic-ray radio detector
- Autonomous detector stations
- Deployed in different stages (2011: 0.4 km², 2013: 6 km², 2015: 17 km²)



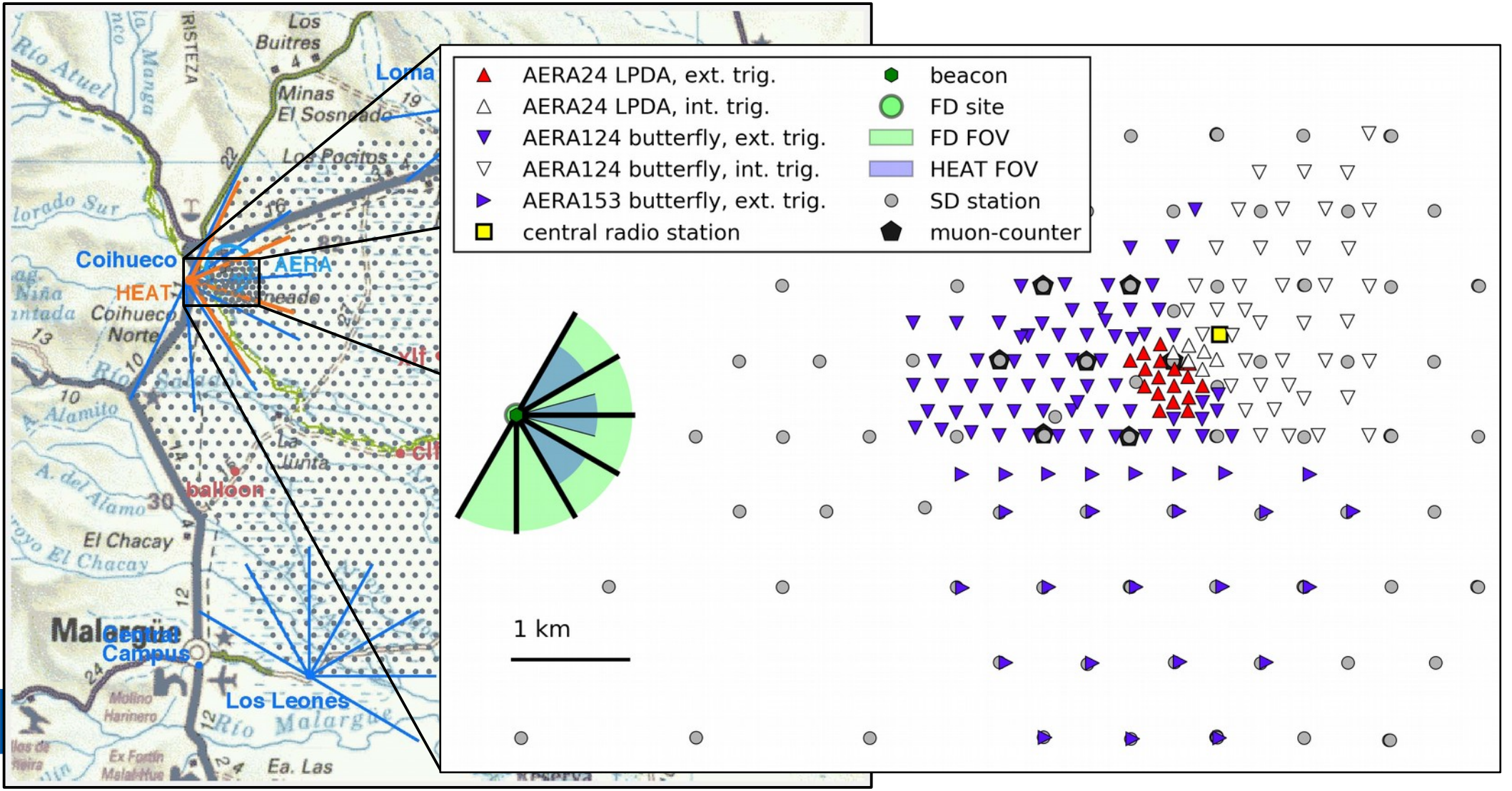
Auger Engineering Radio Array (AERA)

- World's largest cosmic-ray radio detector
- Autonomous detector stations
- Deployed in different stages (2011: 0.4 km², 2013: 6 km², 2015: 17 km²)
- Situated next to 3 complementary detectors



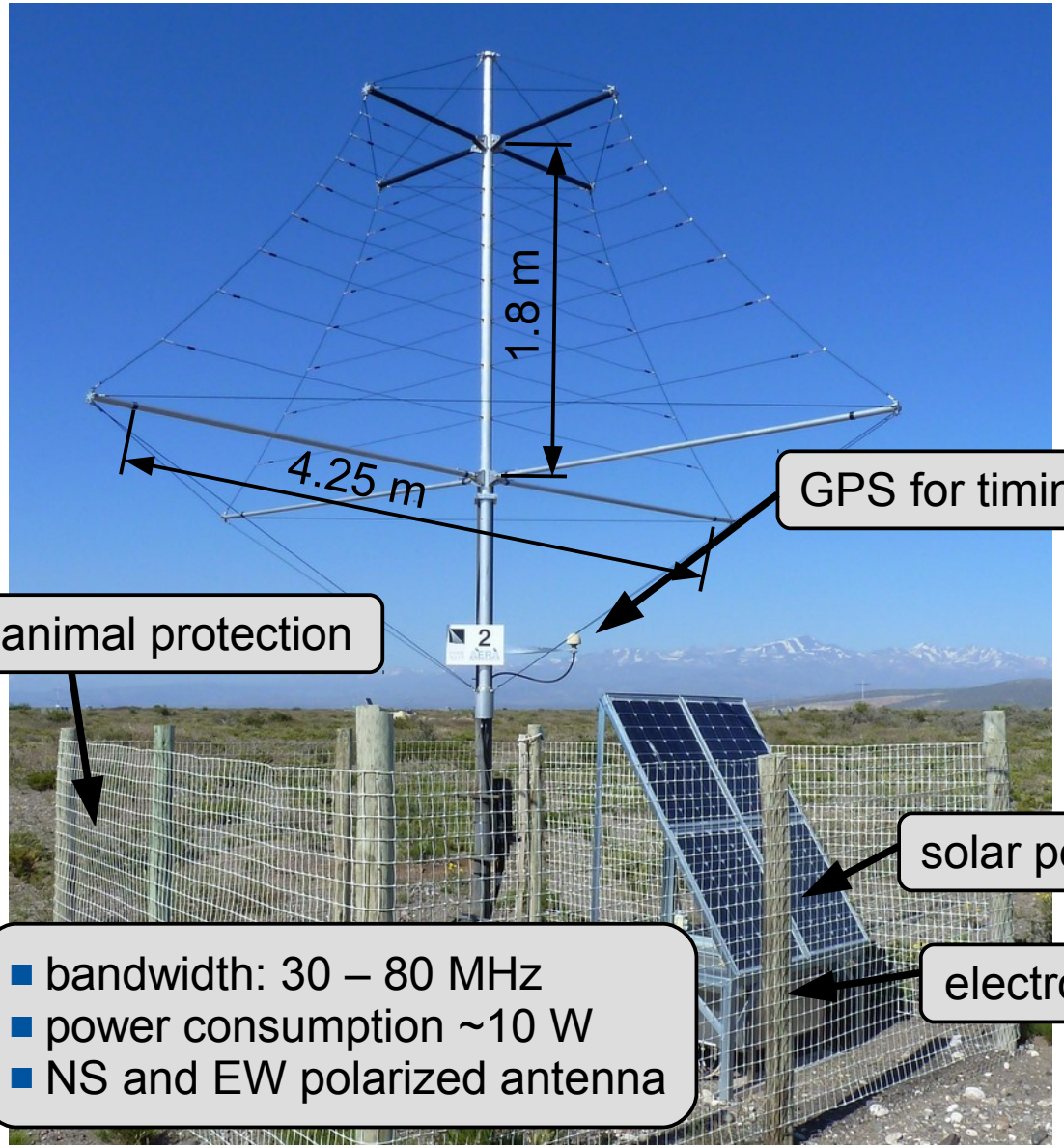
Auger Engineering Radio Array (AERA)

- World's largest cosmic-ray radio detector
- Autonomous detector stations
- Deployed in different stages (2011: 0.4 km², 2013: 6 km², 2015: 17 km²)
- Situated next to 3 complementary detectors



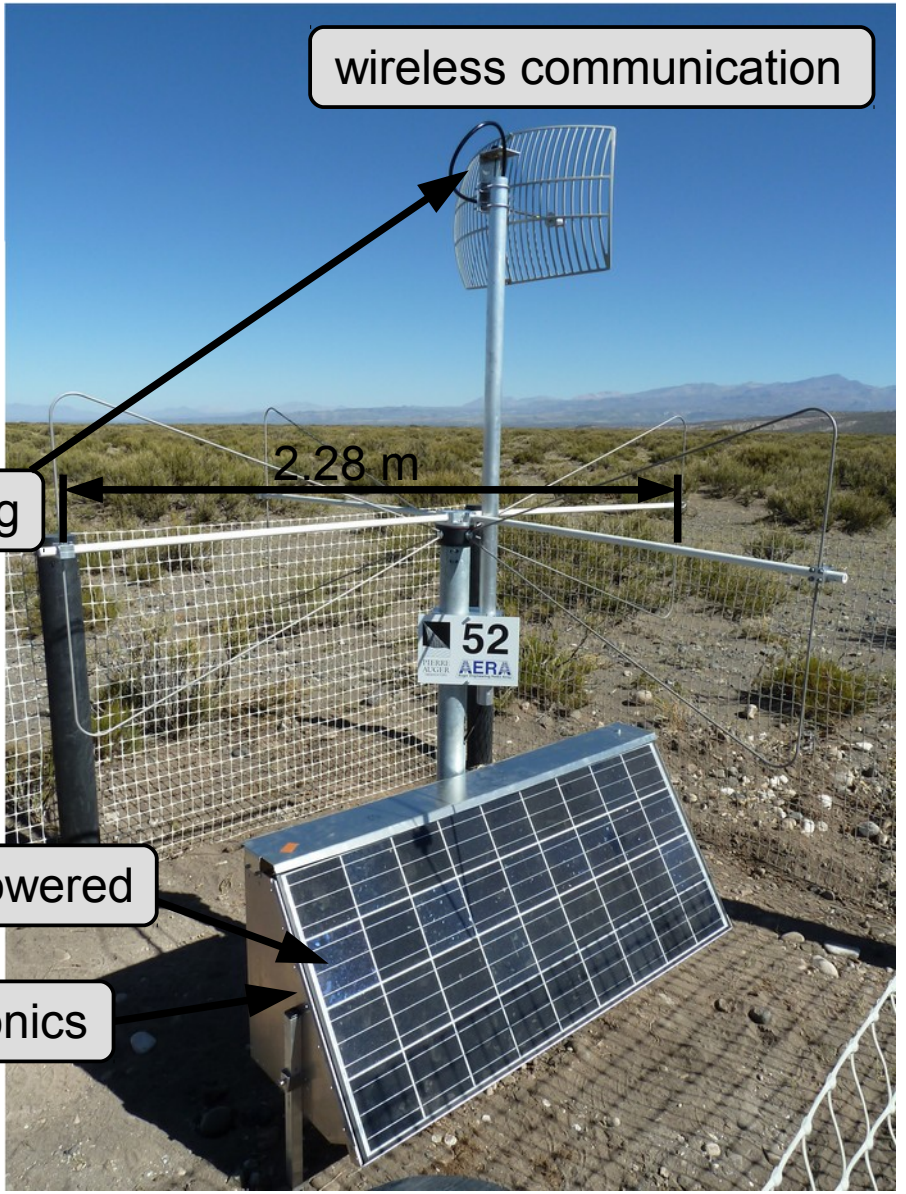
Autonomous Detector Stations

Log-Periodic Dipole Antenna (LPDA)



- bandwidth: 30 – 80 MHz
- power consumption ~10 W
- NS and EW polarized antenna

Butterfly Antenna

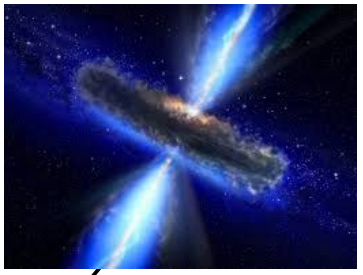


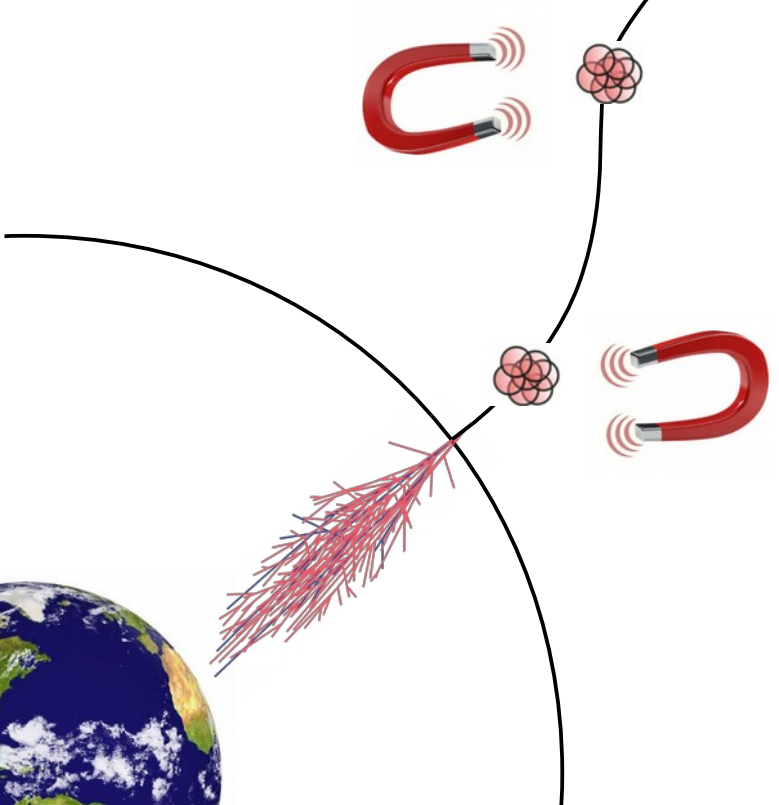
Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

Scientific Potential

- **Explore optimal setup** to measure UHECRs
  - LPDA and butterfly antennas
  - Different detector spacing 144 m, 250 m, 375 m, 750 m
  - Trigger schemes (self-trigger, external trigger, internal particle trigger)

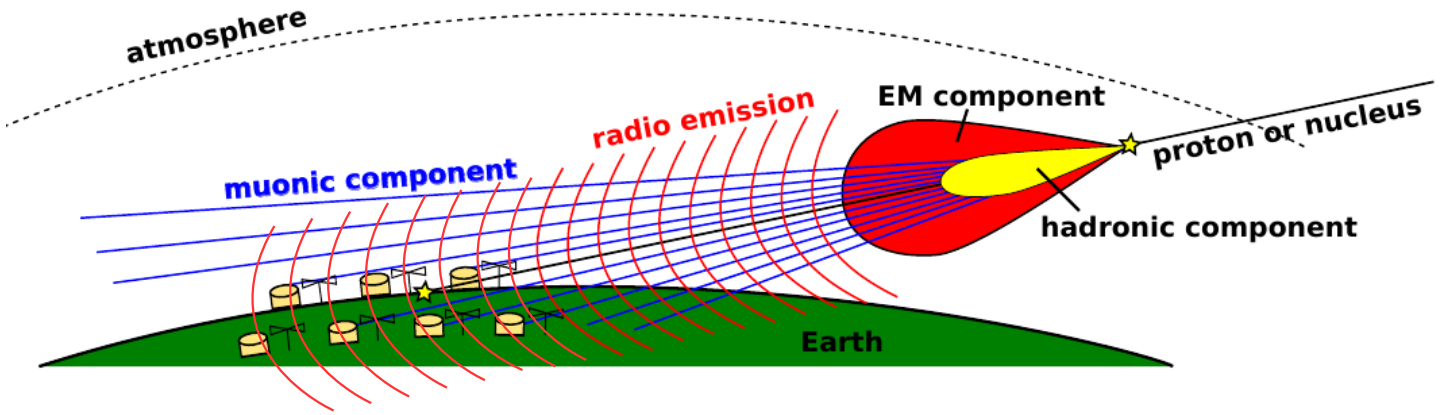
- **Energy** measurement
  - Comparison with SD
- X_{max} measurement → talk Florian Gate
  - Direct comparison with FD
- **Composition** measurement
  - EM shower component (radio)
  - Muonic shower component
    - Buried muons detectors
    - Horizontal air showers





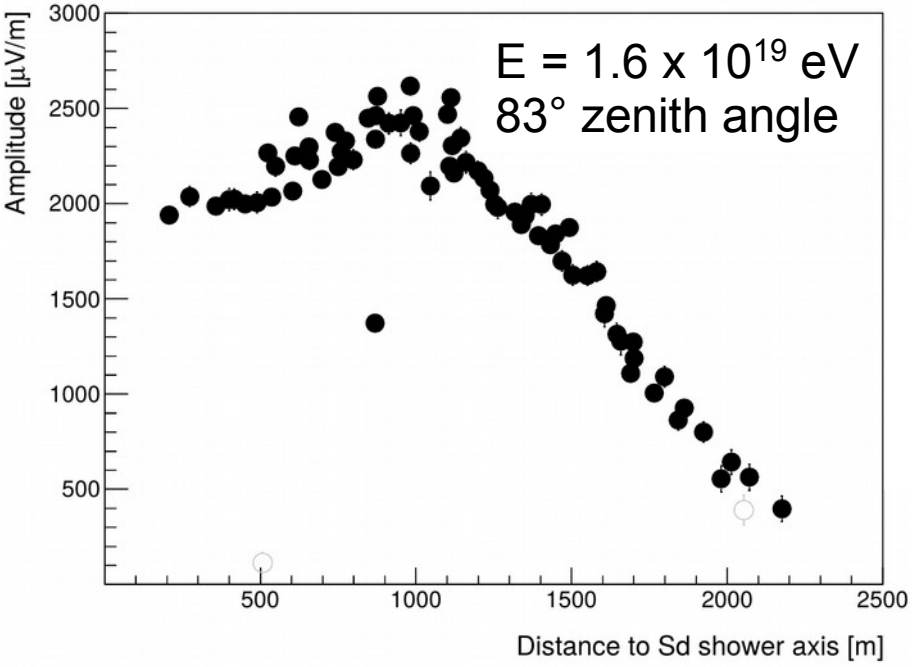
Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

Horizontal Air Showers - 3D Prototype Stations



- Separate measurement of EM and muonic shower component
  - ➔ cosmic-ray mass
- Huge radio footprint
- Prototype antennas with 3 polarizations

→ talk Olga Kambeitz

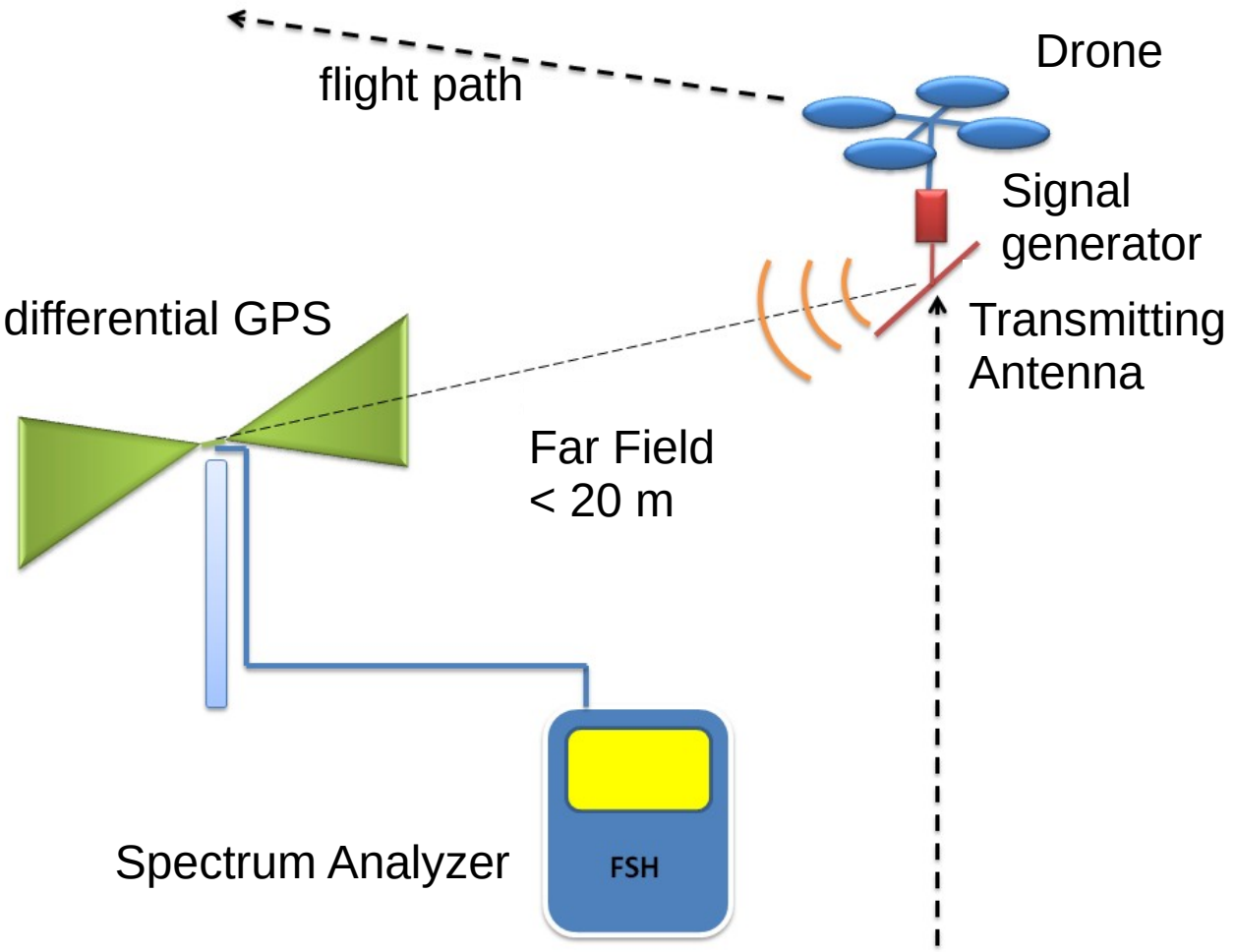


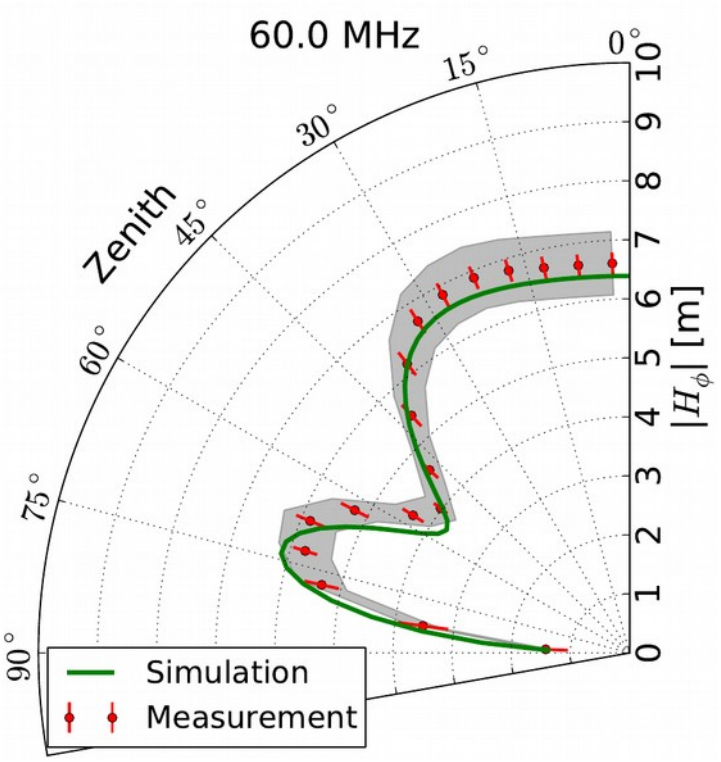
Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

In-Situ Calibration of Antenna Response

$$\mathcal{V}(f) = \vec{\mathcal{H}}(f,\theta,\phi) \cdot \vec{\mathcal{E}}(f)$$

Vector Effective Length





Amplitude calibration
→ talk Florian Briechle
Time calibration
→ talk Tim Huege

Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

Measurement of Radiation Energy

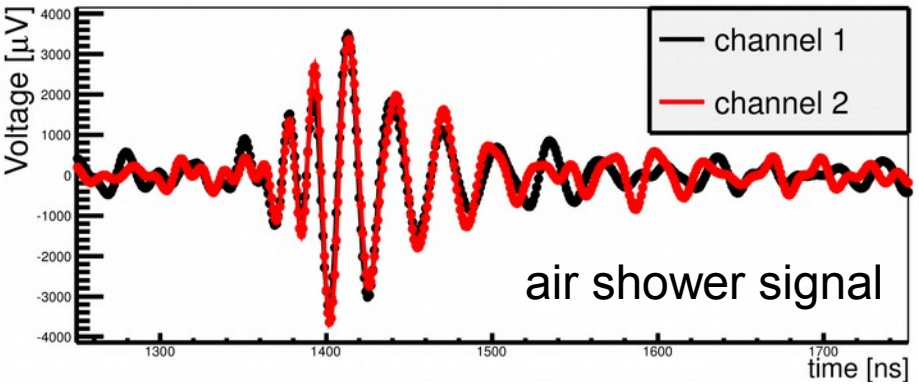
Aab et al., PRL in Press
Aab et al., PRD in Press
arXiv:1605.02564, 1508.04267

- AERA phase 1 detector
  → 24 antennas (out of 153 deployed), 144 m spacing
  → first ~2 years of runtime used
- Antenna characteristics (LPDA) measured and simulated *Abreu et al., Jinst 7, 10011 (2012)*
- Measurement of the whole signal chain for each station

  → **Systematic uncertainty 14%**

Data set

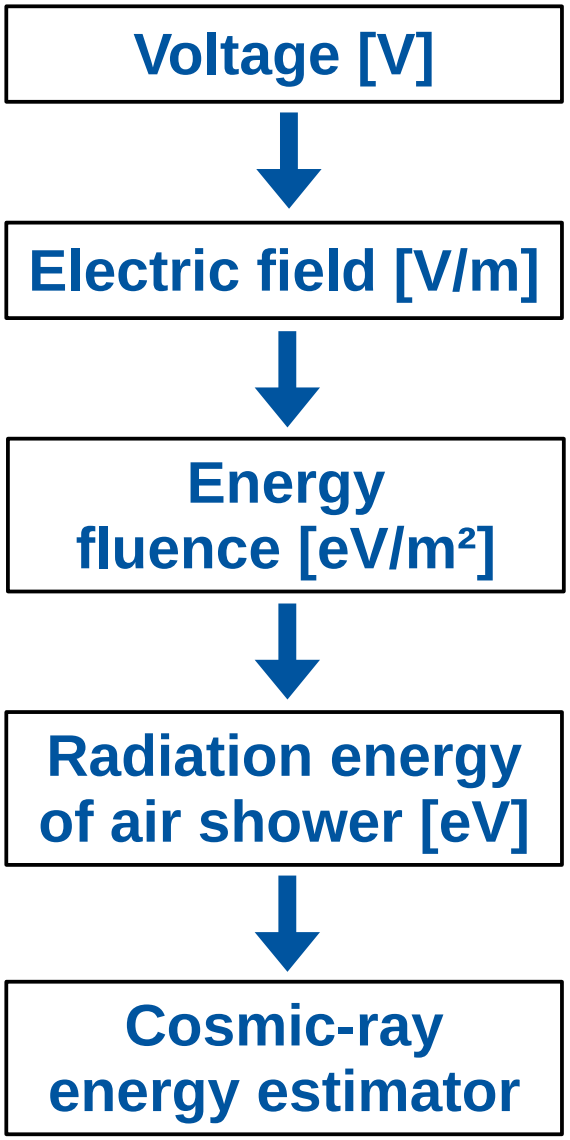
- Coincidences with surface detector (750 m array)
- Zenith angle < 55°
- Quality cuts
  - ➔ Polarization of radio signal (removes noise pulses)
  - ➔ No thunderstorm conditions
- 126 events with E > 10^{17} eV



Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

From Voltage to Cosmic-Ray Energy

Aab et al., PRL in Press
Aab et al., PRD in Press



unfold antenna + detector response

time integral of Poynting vector

fit 2D-LDF + spatial integral

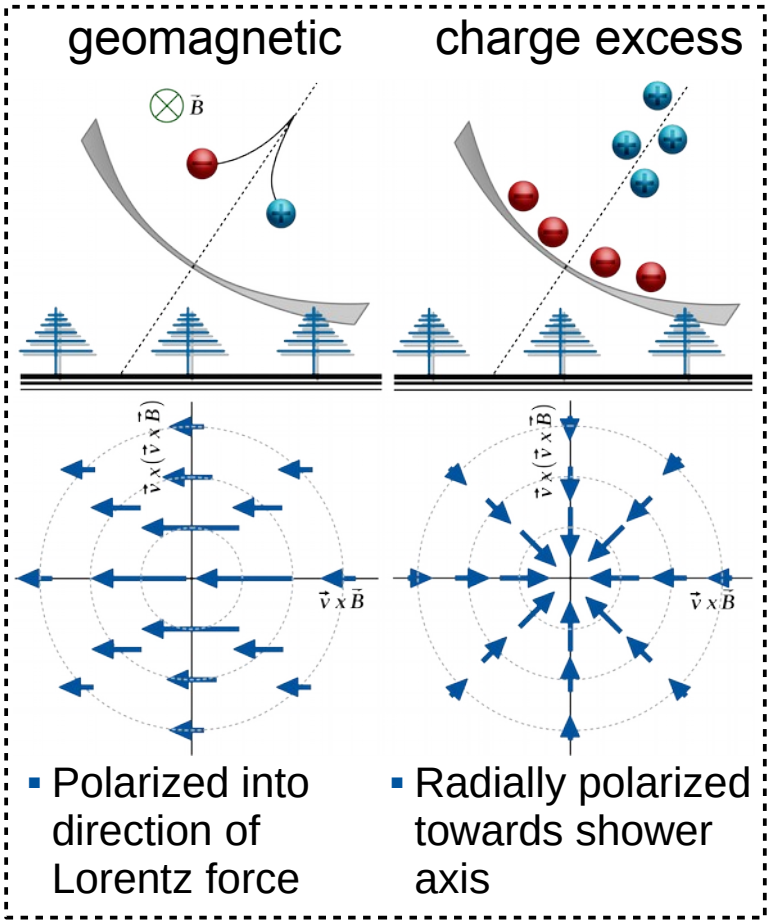
geometry correction

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

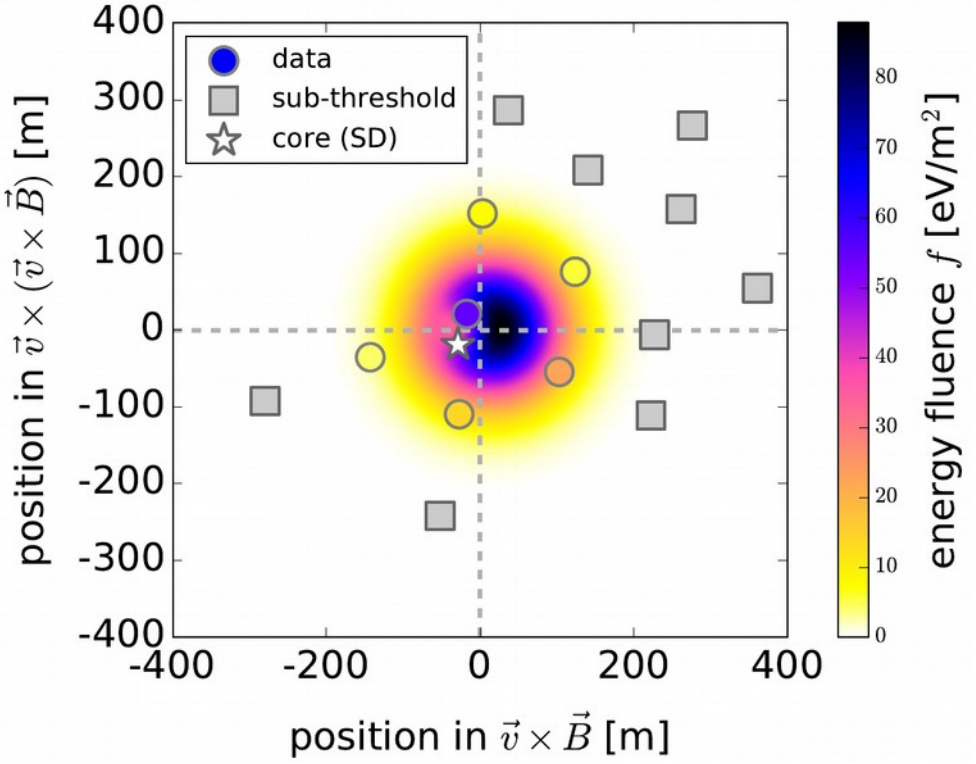
Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

Radiation Energy of Air Showers

Aab et al., PRL in Press
Aab et al., PRD in Press

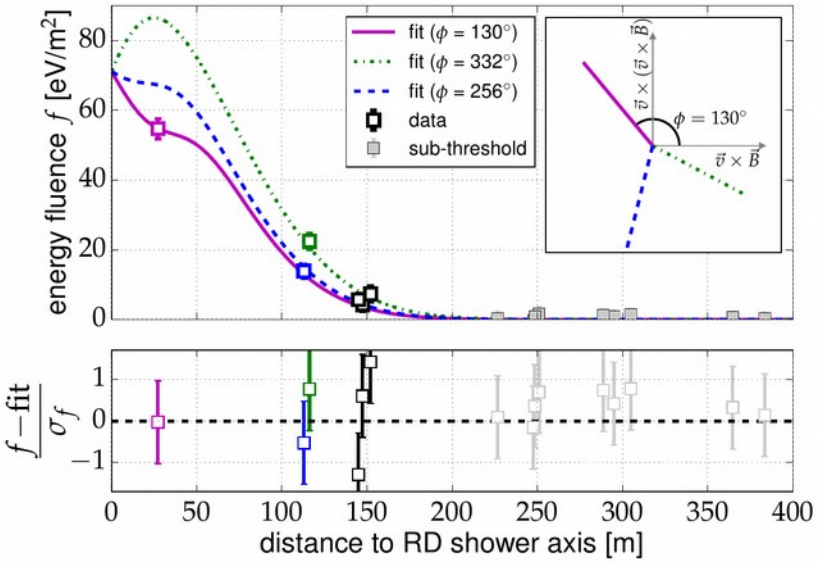


- Polarized into direction of Lorentz force
- Radially polarized towards shower axis



- Interference between emission mechanisms
  - 2D lateral distribution function

Nelles et al., Astropart. Phys. 60, 13 (2015)



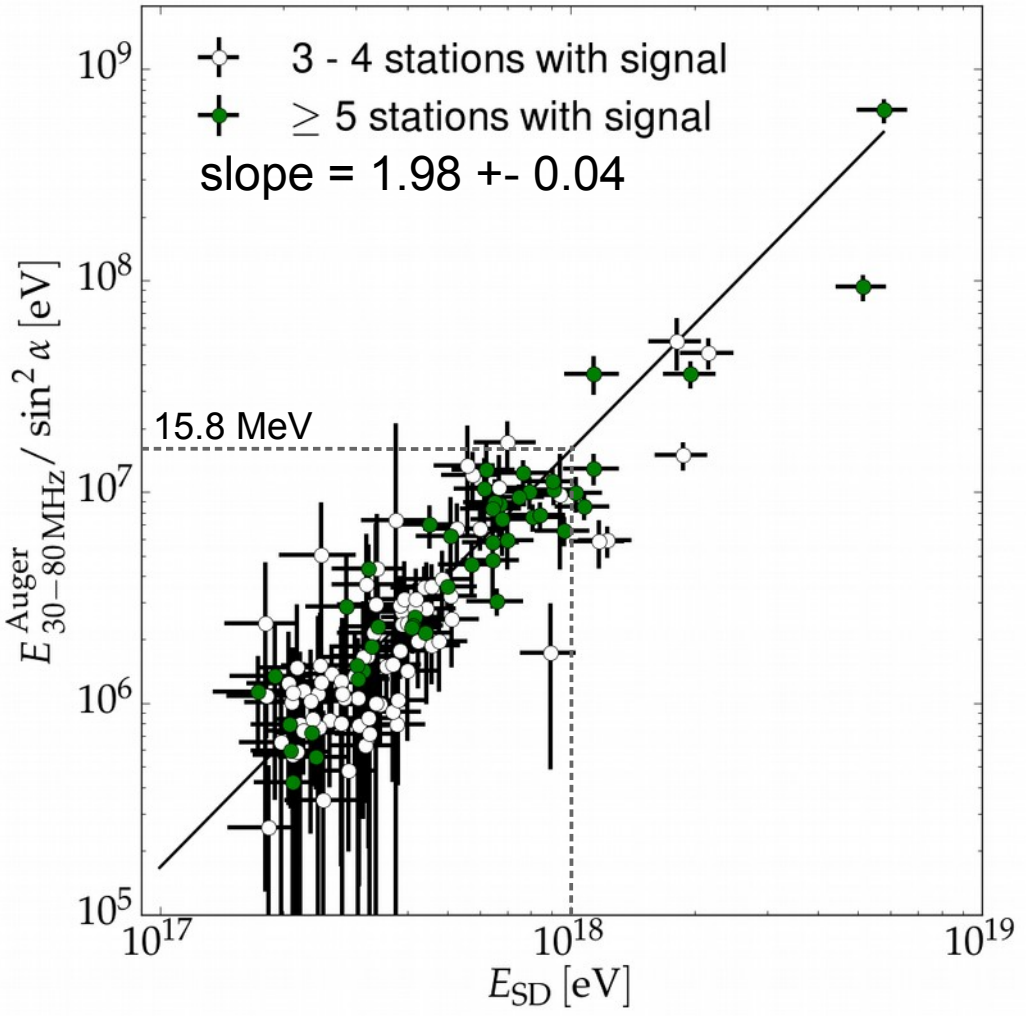
- ≥ 5 signal stations or
  3-4 signal stations and SD core

Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

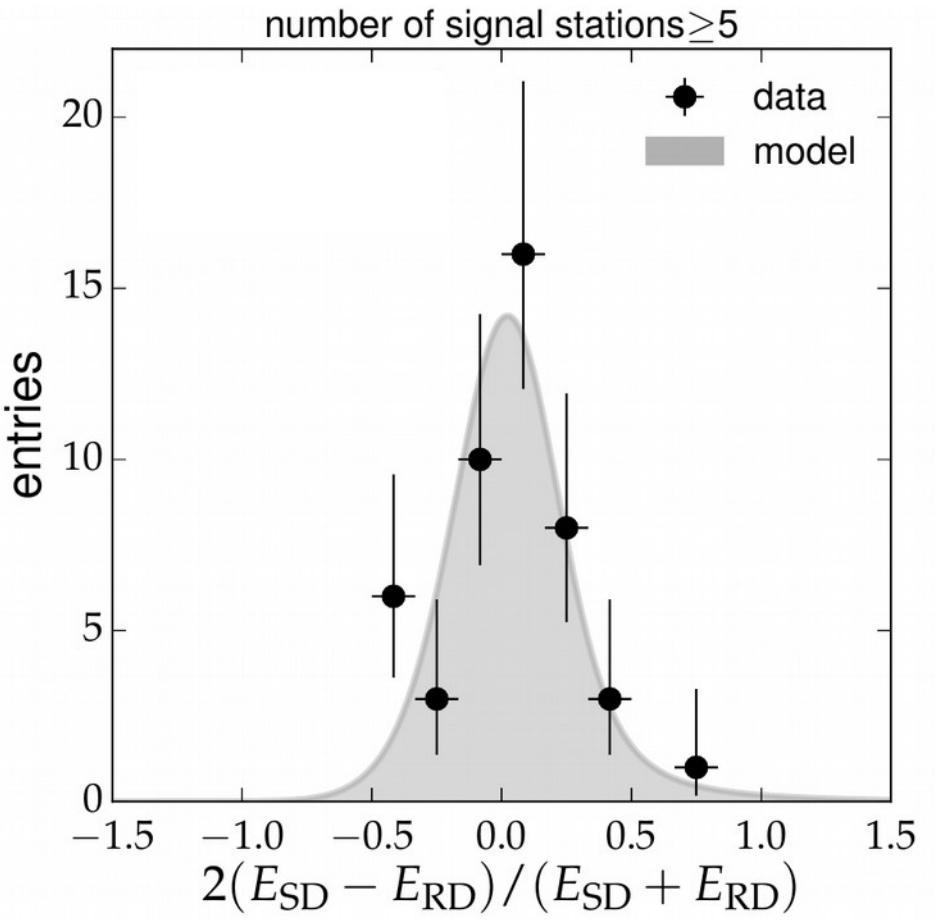
Energy Calibration

Aab et al., PRL in Press
Aab et al., PRD in Press

- Likelihood fit of calibration function taking into account detection efficiencies



energy resolution 17%



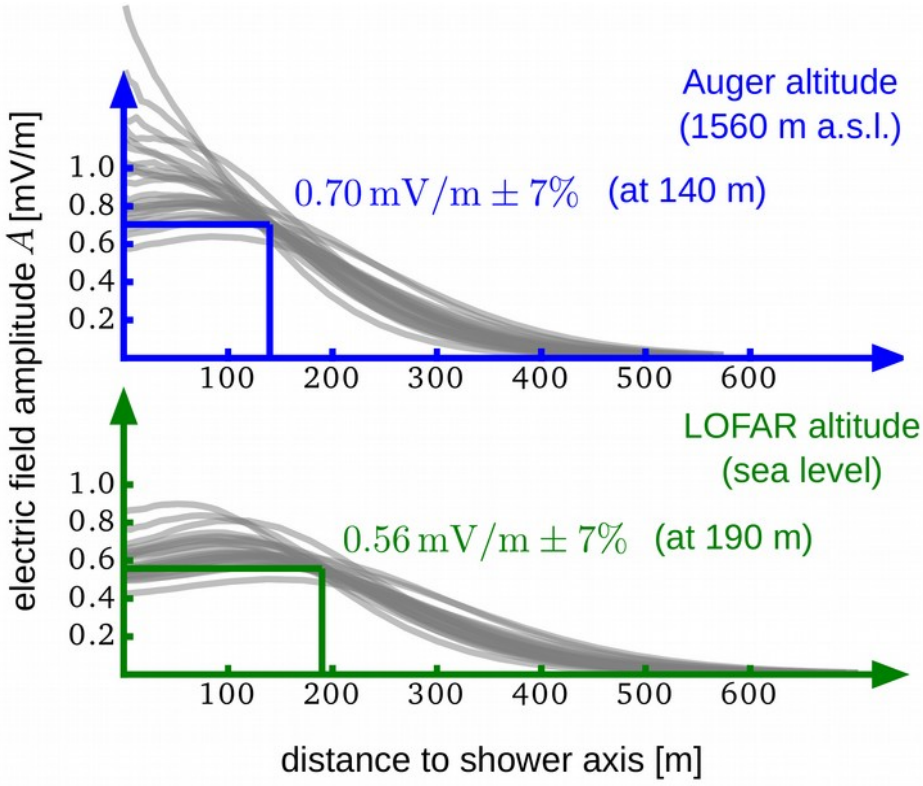
15.8 ± 0.7 (stat) ± 6.7 (syst) MeV
radiation energy for a 1 EeV cosmic ray

Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

Aab et al., PRL in Press
Aab et al., PRD in Press

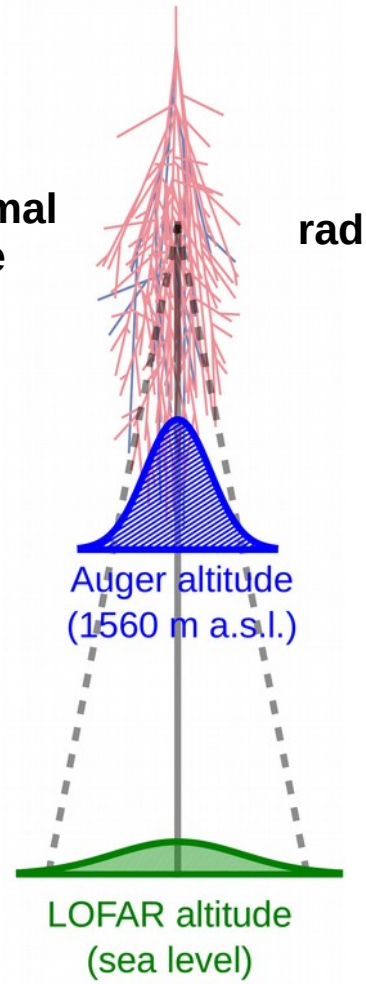
Radiation Energy of Air Showers

- Generalization: normalization to local geomagnetic field
  - $E_{30-80\mathrm{MHz}} = 15.8\ \mathrm{MeV} \left(\sin\alpha \frac{E}{10^{18}\ \mathrm{eV}} \frac{B_{\mathrm{Earth}}}{0.24\ \mathrm{G}} \right)^2$
  - Can be used anywhere on Earth
  - Cross calibration of cosmic-ray observatories
- Advantage compared to previous techniques



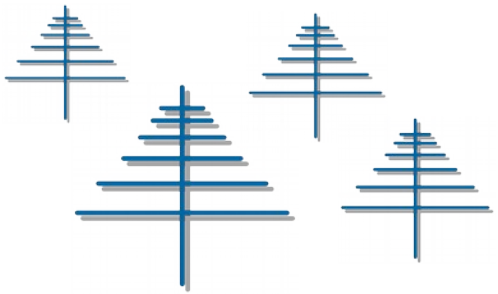
amplitude at optimal lateral distance

radiation energy



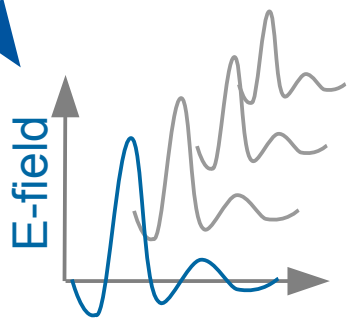
Independent Determination of Cosmic-Ray Energy Scale

Measurement



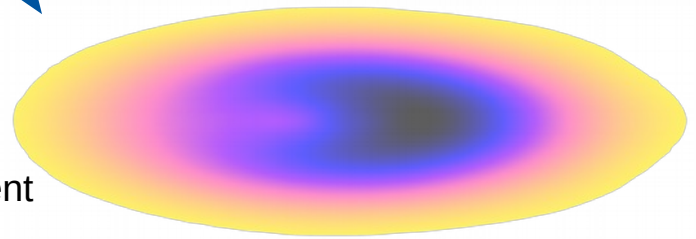
antenna and
detector response

Meassurement
15.8 ± 6.7 MeV



2-dim LDF model

coincident measurement
with other detectors

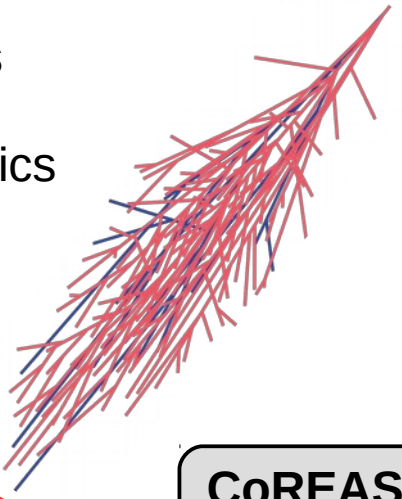


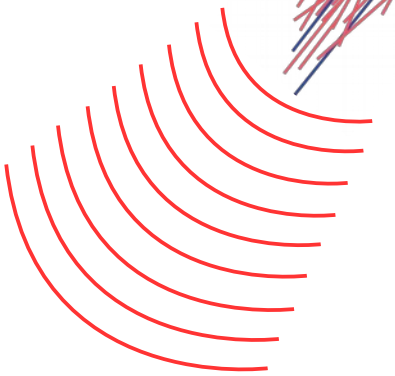
radiation energy
per unit area

Theoretical calculation

EM shower energy

first principles
classical
electrodynamics





atmosphere transparent
to radio waves

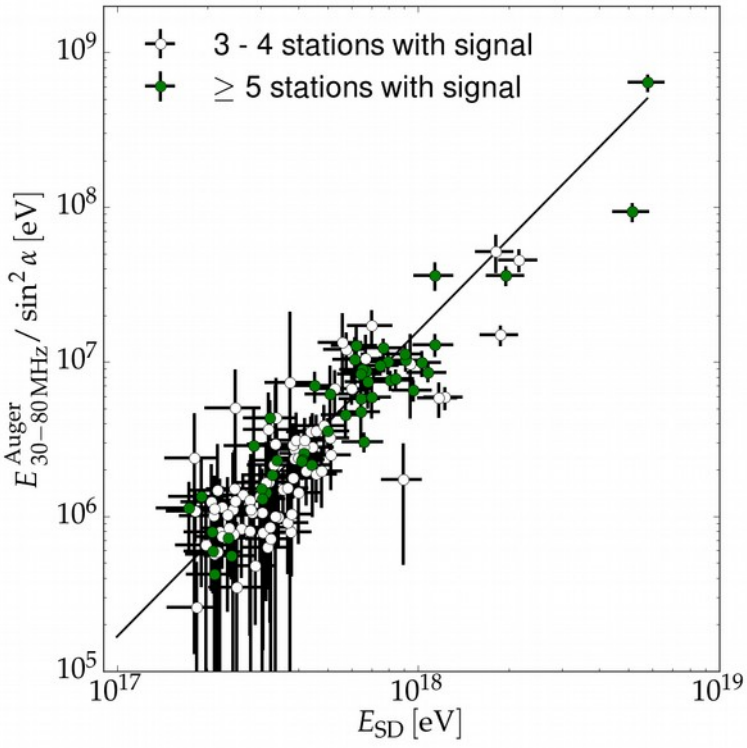
CoREAS: 11.9 MeV
ZHAireS: 11.3 MeV

Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

Summary

- Pierre Auger Observatory: well calibrated environment for development of future detector technologies
- Auger Engineering Radio Array
  - 153 autonomous radio detector stations (17 km²)
  - Thoroughly calibrated through the entire signal chain
  - Reconstruction of energy fluence at detector station
- Radiation energy of air showers measured
  - 15.8 MeV in 30–80 MHz for E_{CR} = 1 EeV
- Cosmic-ray energy resolution 17%
- Universal prediction of radiation energy
- Determination of energy scale by first principles
  - σ = 14% envisioned

Aab et al., PRL in Press arXiv:1605.02564
Aab et al., PRD in Press arXiv:1508.04267



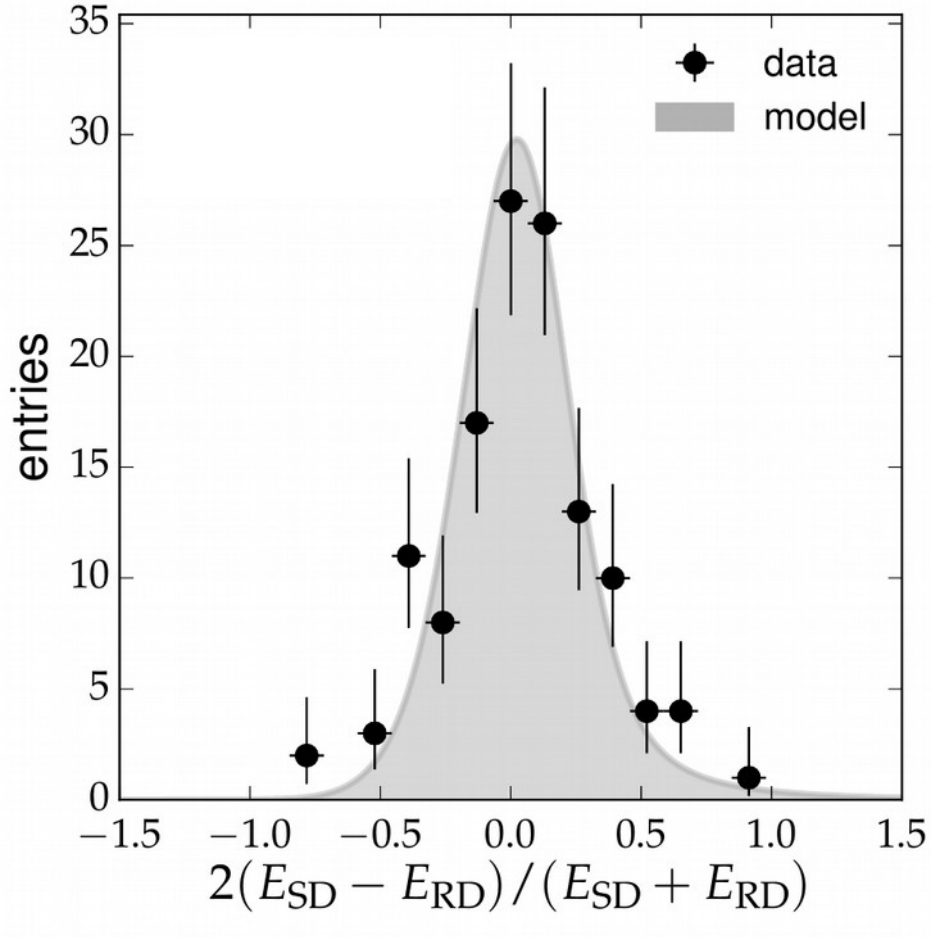
Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

backup

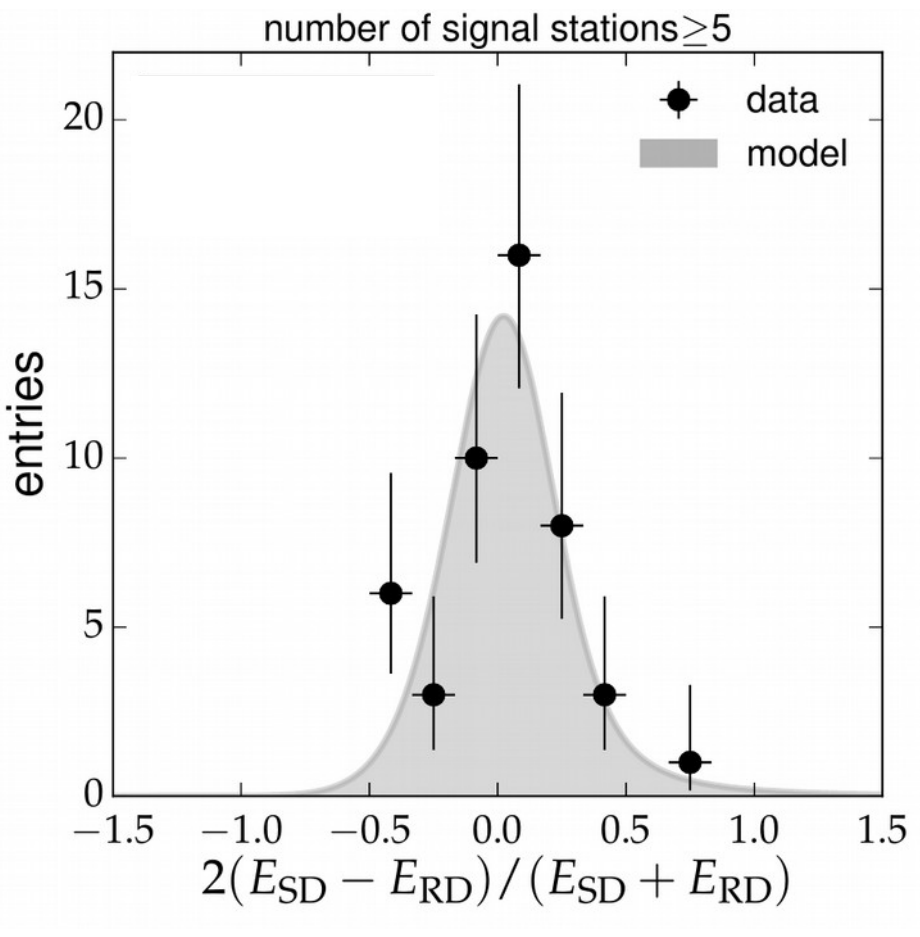
Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

Energy Resolution

energy resolution 22%

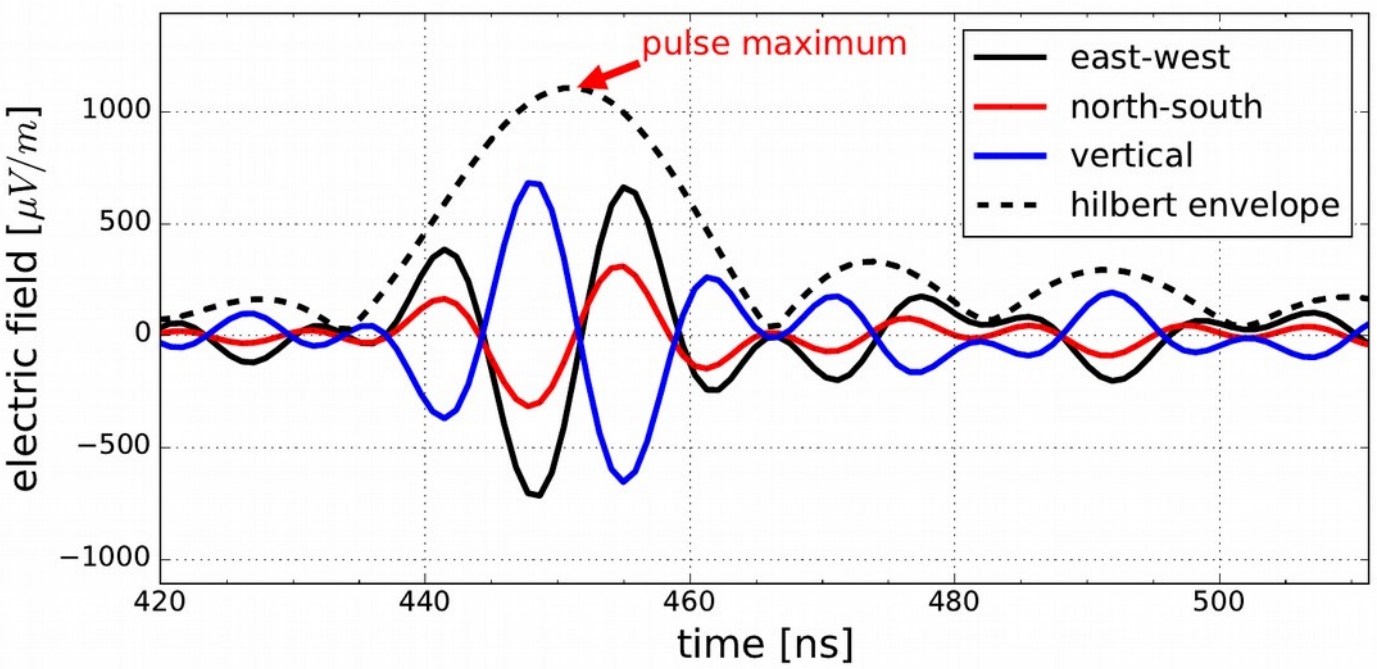


energy resolution 17%



Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

Calculating Energy Density

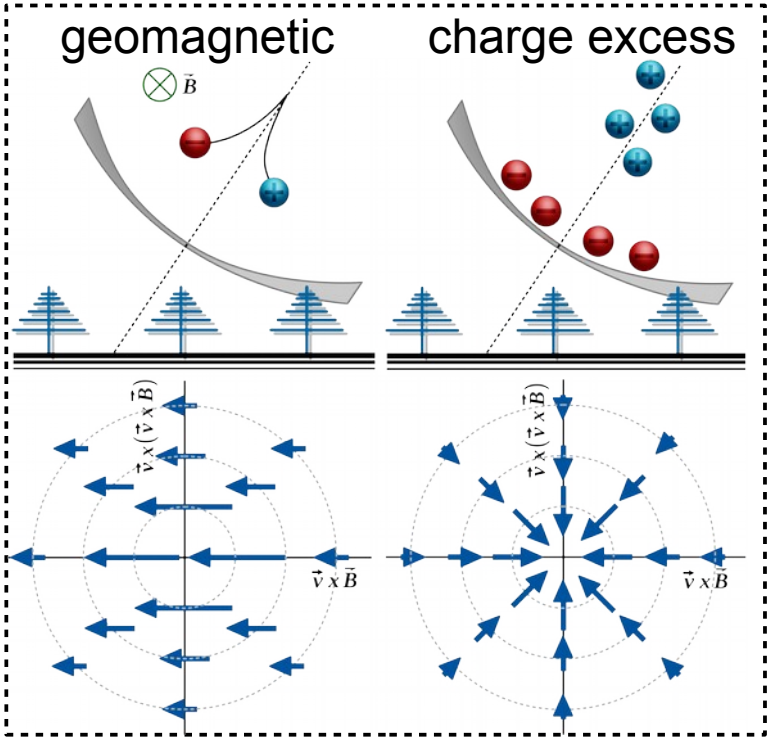


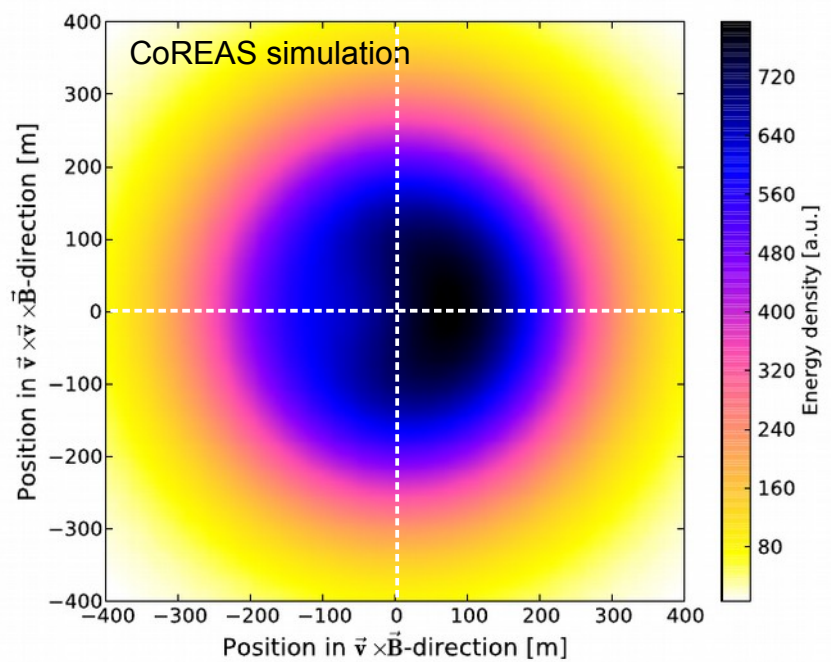
- Window around maximum of Hilbert envelope
- Energy density in eV/m²
  - ➔ Time integral of Poynting vector
  - ➔ Noise expectation subtracted
  - ➔ $$u = \varepsilon_0 c \left(\Delta t \sum_{t_1}^{t_2} |\vec{E}(t_i)|^2 - \Delta t \frac{t_2 - t_1}{t_4 - t_3} \sum_{t_3}^{t_4} |\vec{E}(t_i)|^2 \right)$$

Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de

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
- Interference
  - two-dimensional LDF needed





Christian Glaser | ARENA 2016
glaser@physik.rwth-aachen.de