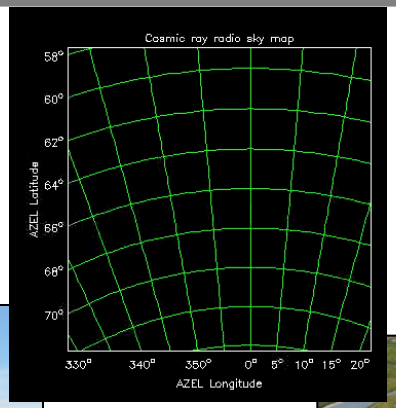
Karlsruhe Institute of Technology

Radio detection of cosmic rays and the SKA

Tim Huege (Karlsruhe Institute of Technology)



Highest energy cosmic rays

- studied for 100 years
- origin not yet understood
- need high quality data
  - energy
  - **mass!**
- need large experiments
  - highest energy particles very rare

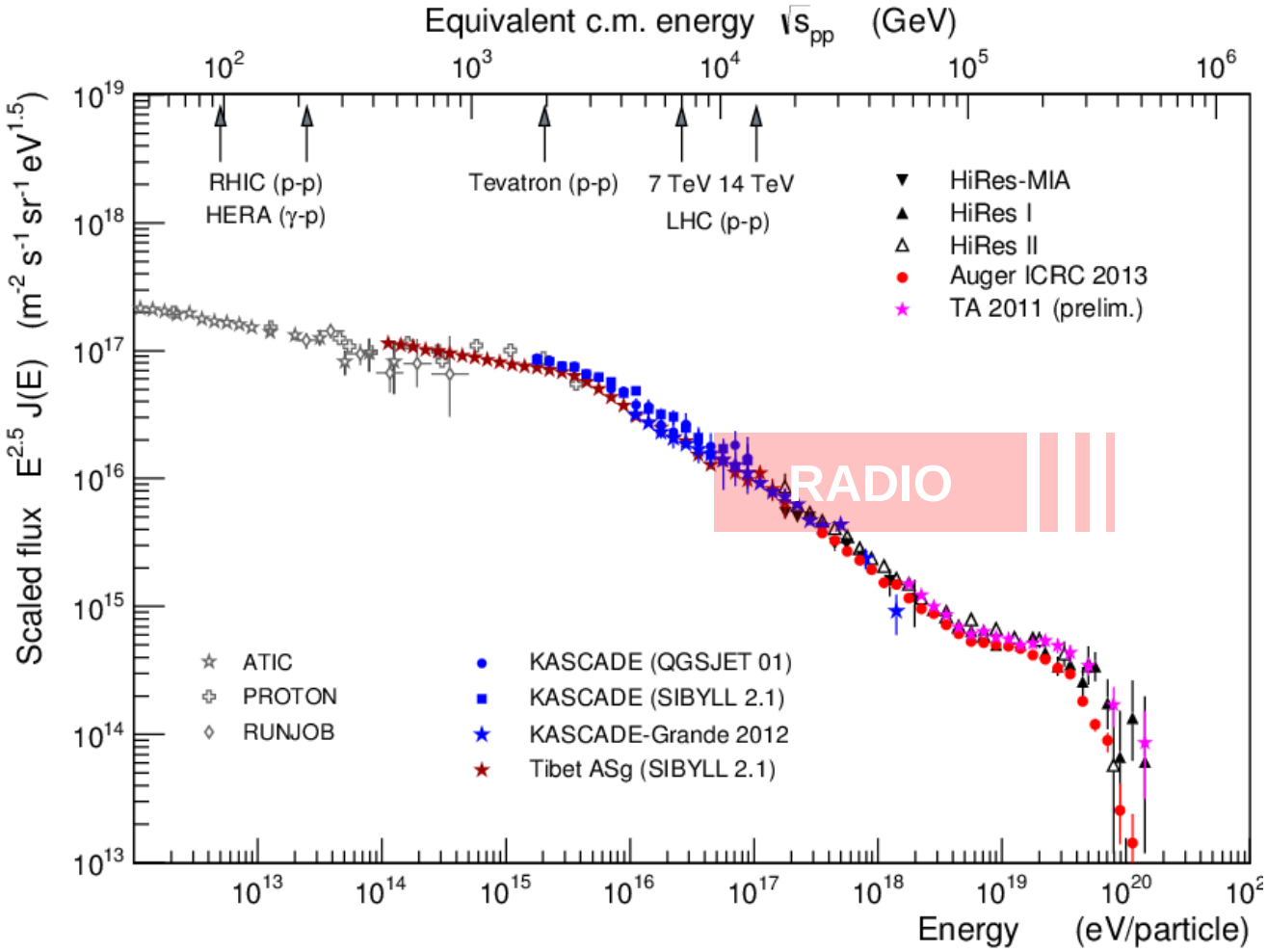
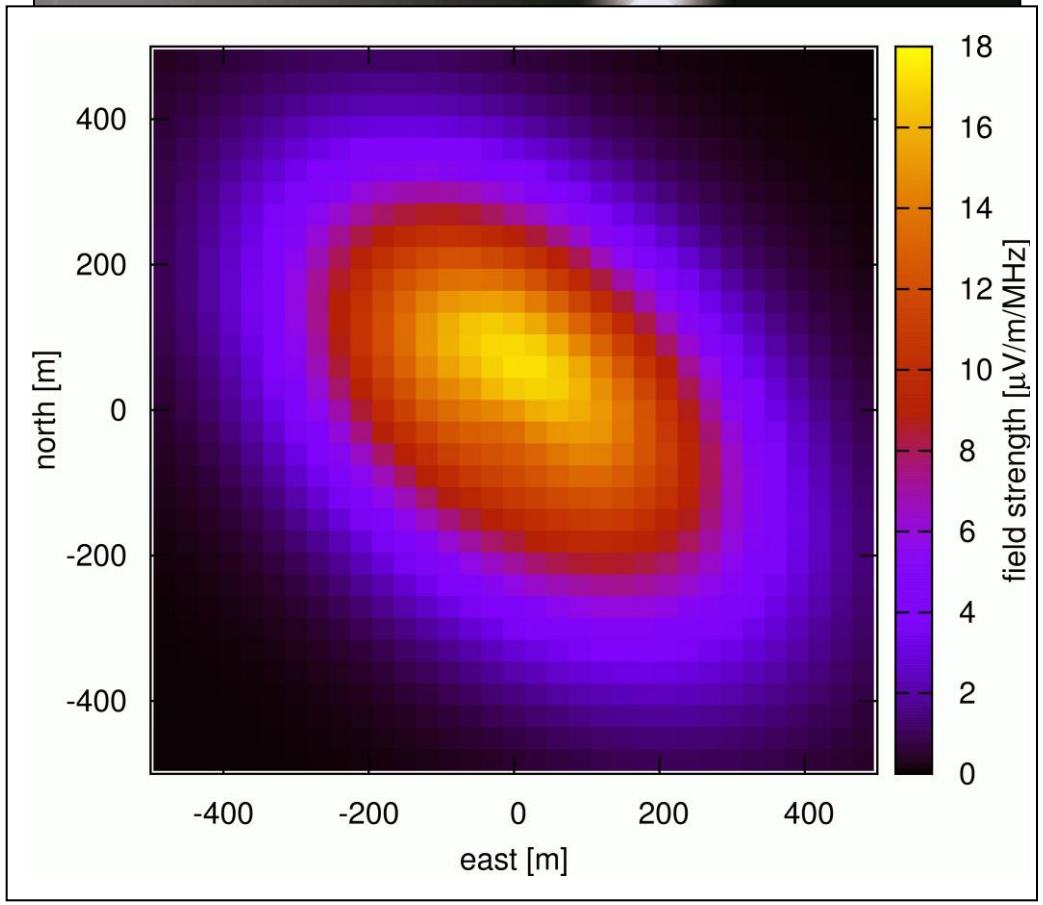


diagram by R. Engel

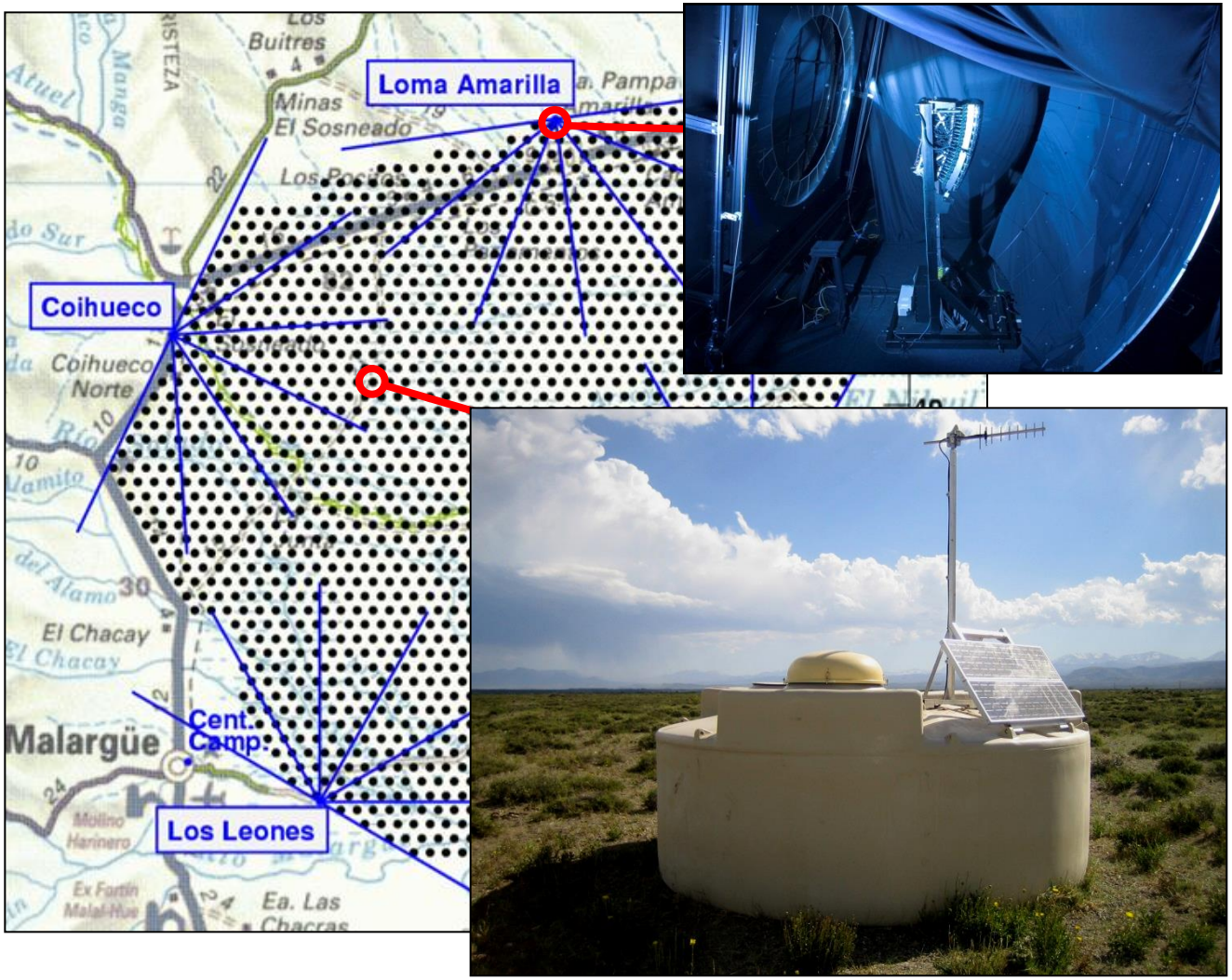
Extensive air showers and their detection

- cosmic ray interacts with nucleus in atmosphere
- cascade of secondary particles evolves
  - particle detectors register particles at ground
  - optical telescopes measure energy deposit via N_2 fluorescence
  - radio detectors measure short (<100 ns) coherent radio pulses from time-varying currents

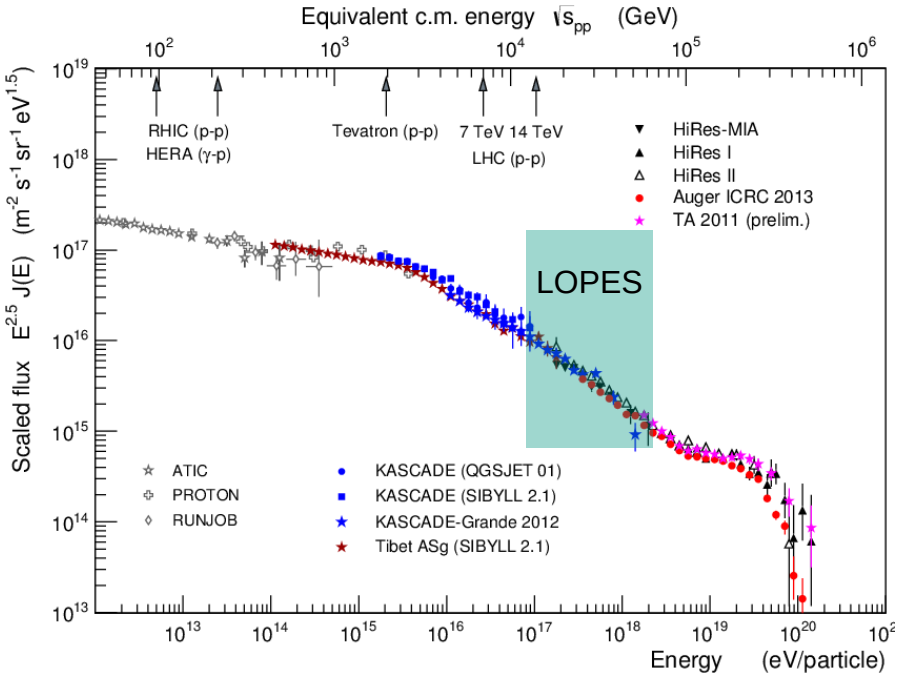


The Pierre Auger Observatory

- situated in Argentina
- covers 3000 km^2
- 1600 particle detectors
  - “statistics”
- 24 optical fluorescence telescopes
  - “quality” (mass!)
- radio detectors deliver complementary information

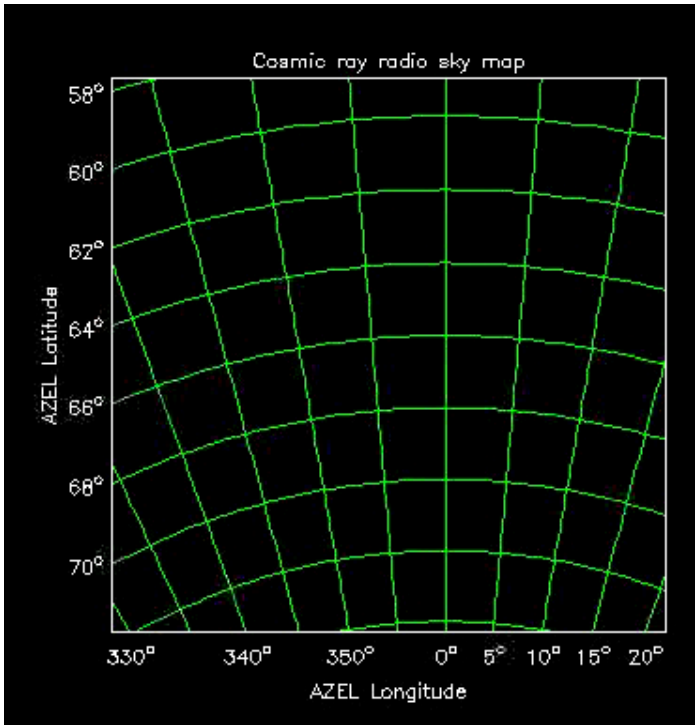


CR radio pioneer – the LOPES experiment



- digital radio interferometer, frequency band 40-80 MHz
- 30 antennas on a 200 x 200 m area, 0.04 km^2
- based on LOFAR prototype hardware
- integrated with KASCADE-Grande experiment
- has pioneered the technique

Interferometric reconstruction with LOPES

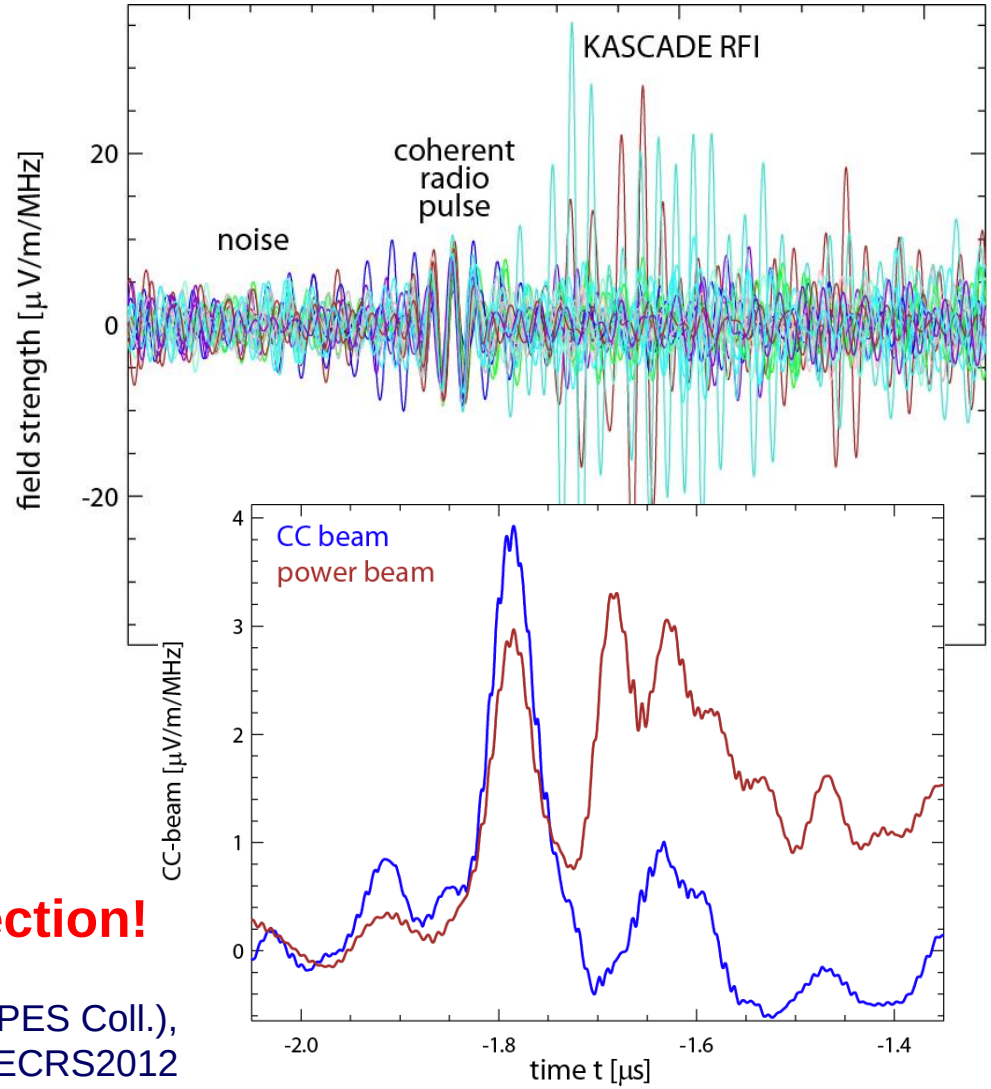


Sky map of a cosmic ray radio flash

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

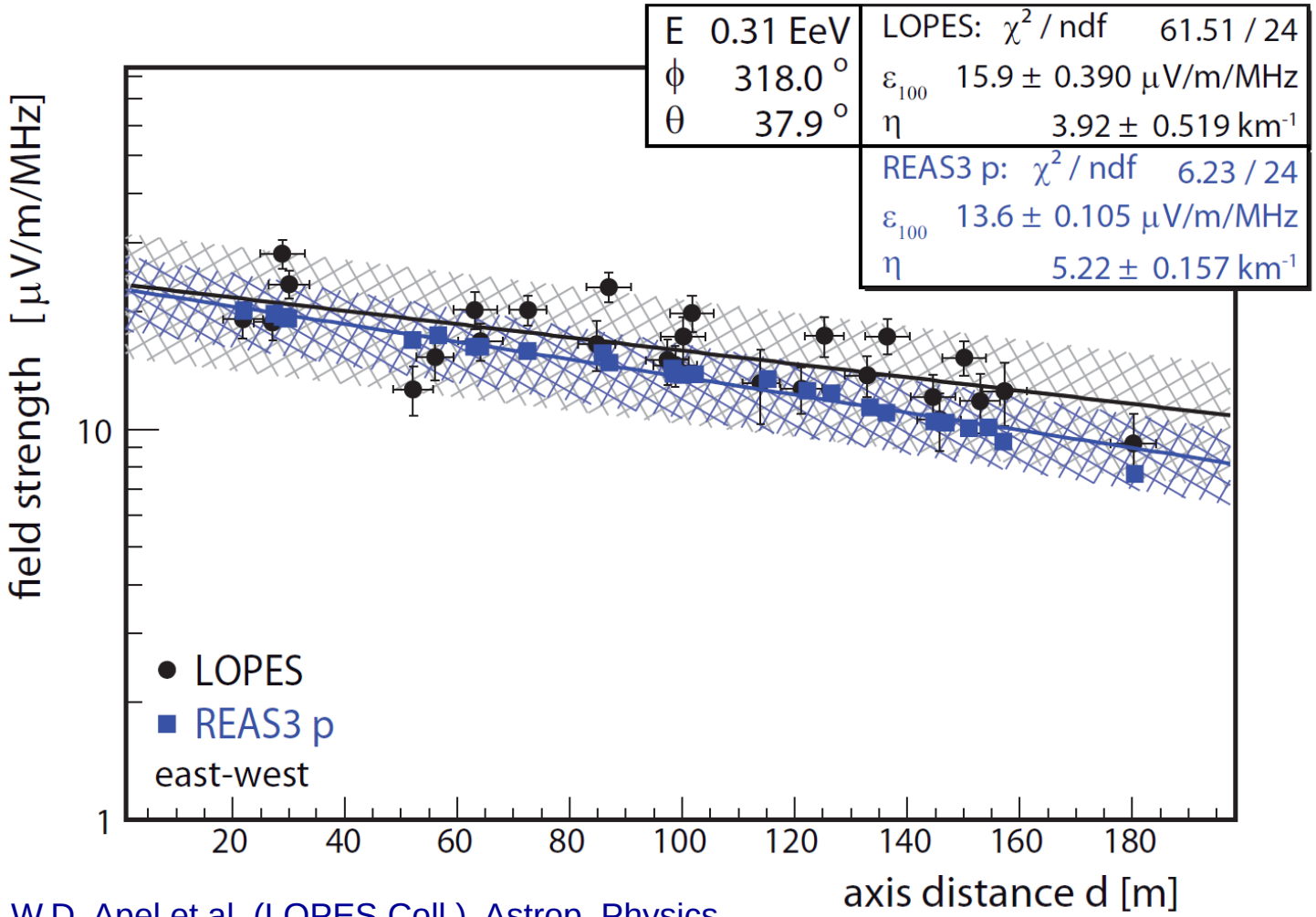
~50 ns!

unknown direction!



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

Individual event measured with LOPES

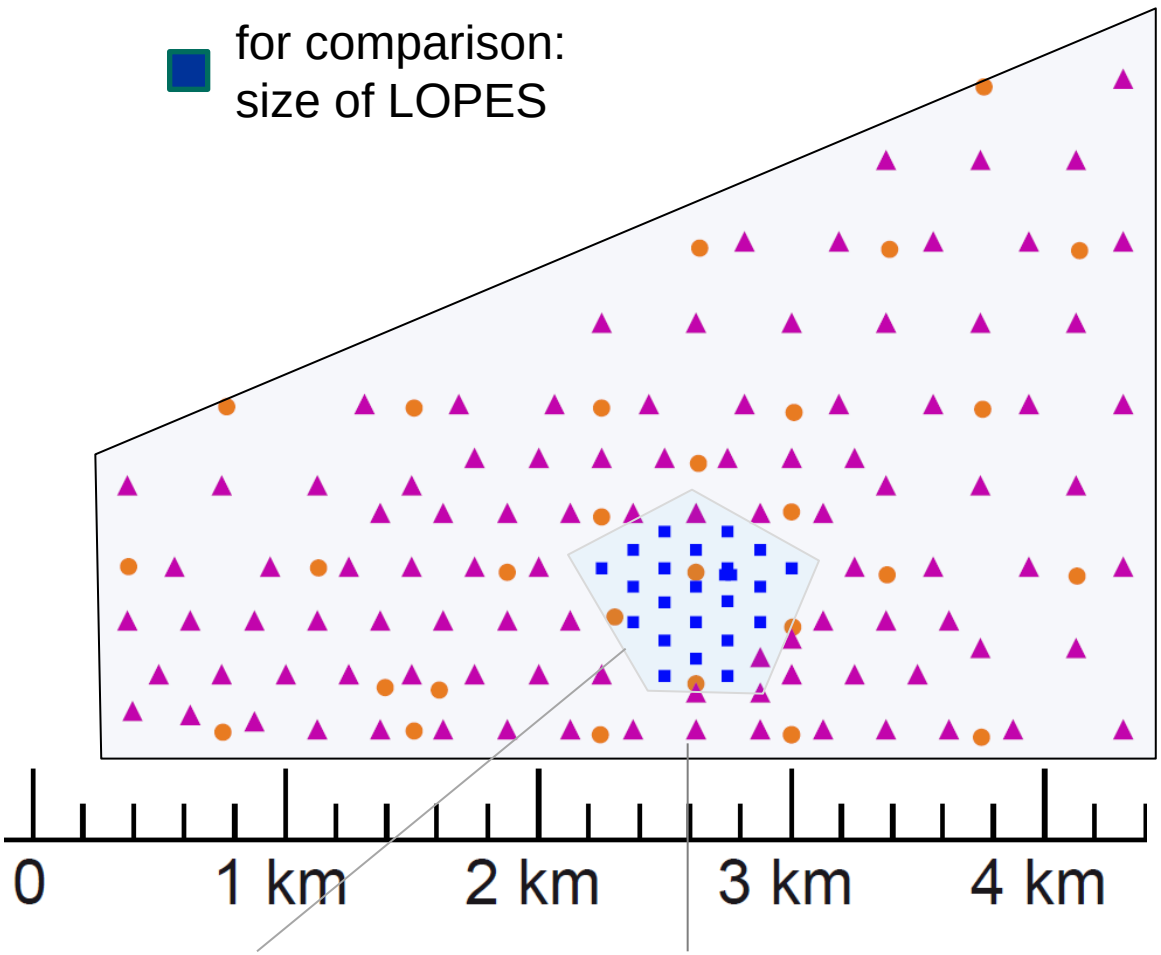


W.D. Apel et al. (LOPES Coll.), Astrop. Physics

- small lever arm
- noisy environ-ment
- but we have learned a lot from LOPES!

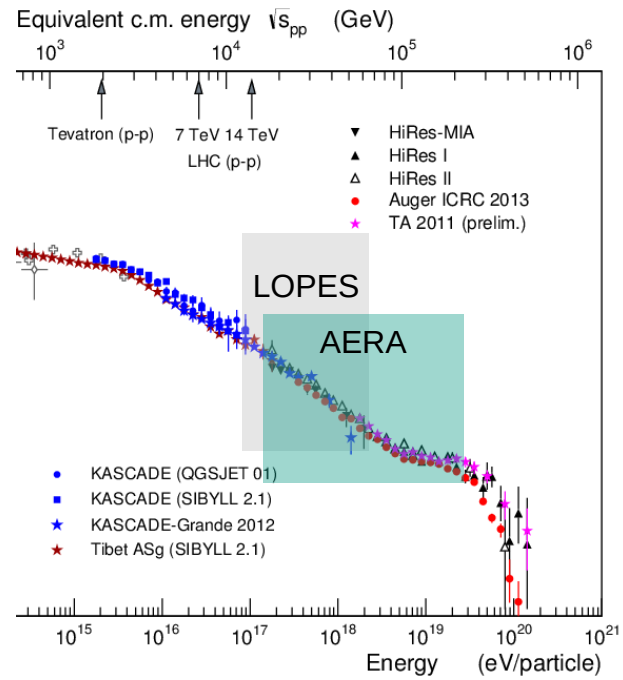
On the way to high energies – AERA

- for comparison: size of LOPES



24 stations since early 2011

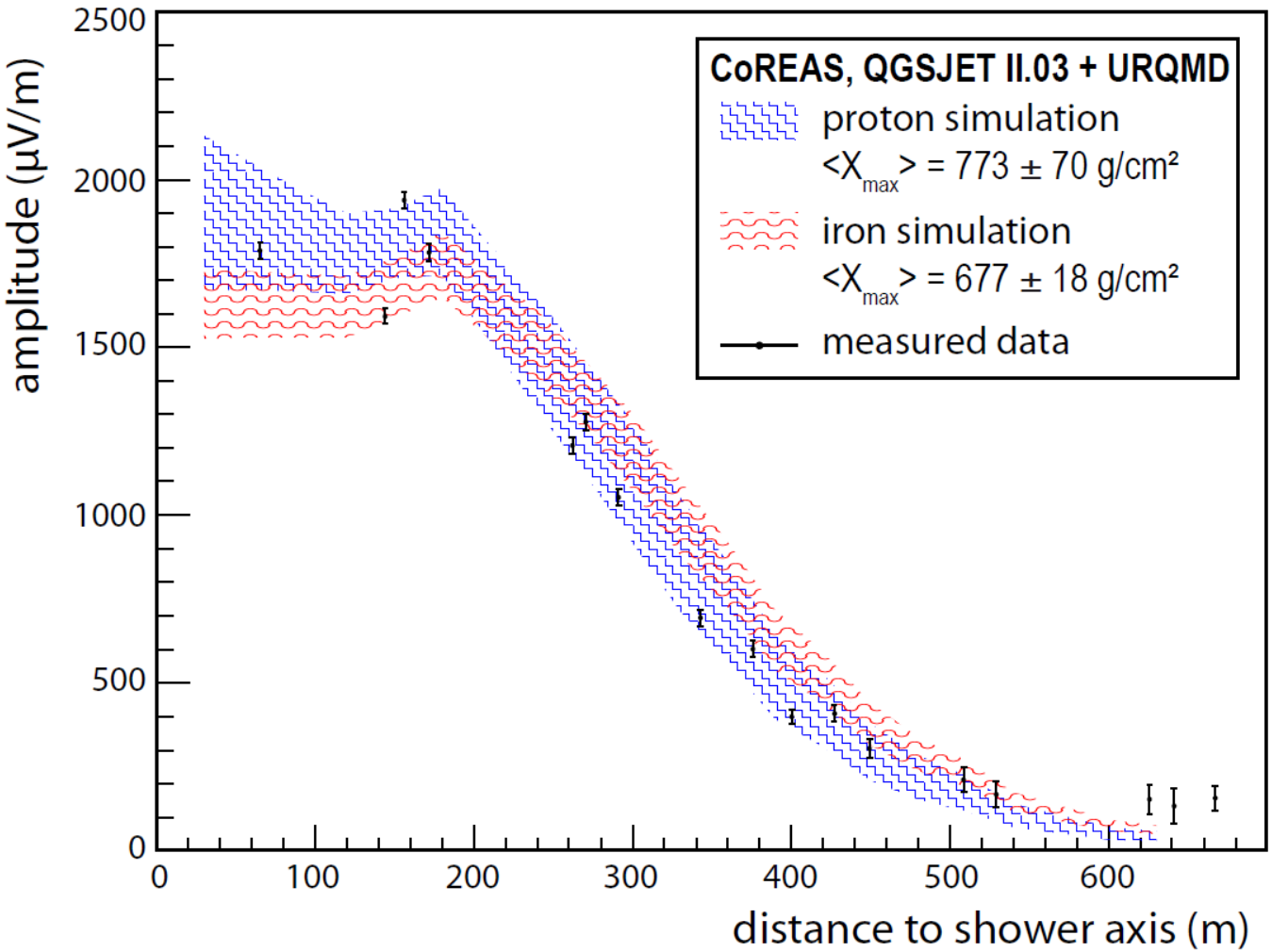
124 stations since May 2013



- scale to higher energies
  - fully autonomous detector stations
  - antenna spacing 150-375 metres
  - currently 6 km^2 area


9

Individual event measured with AERA



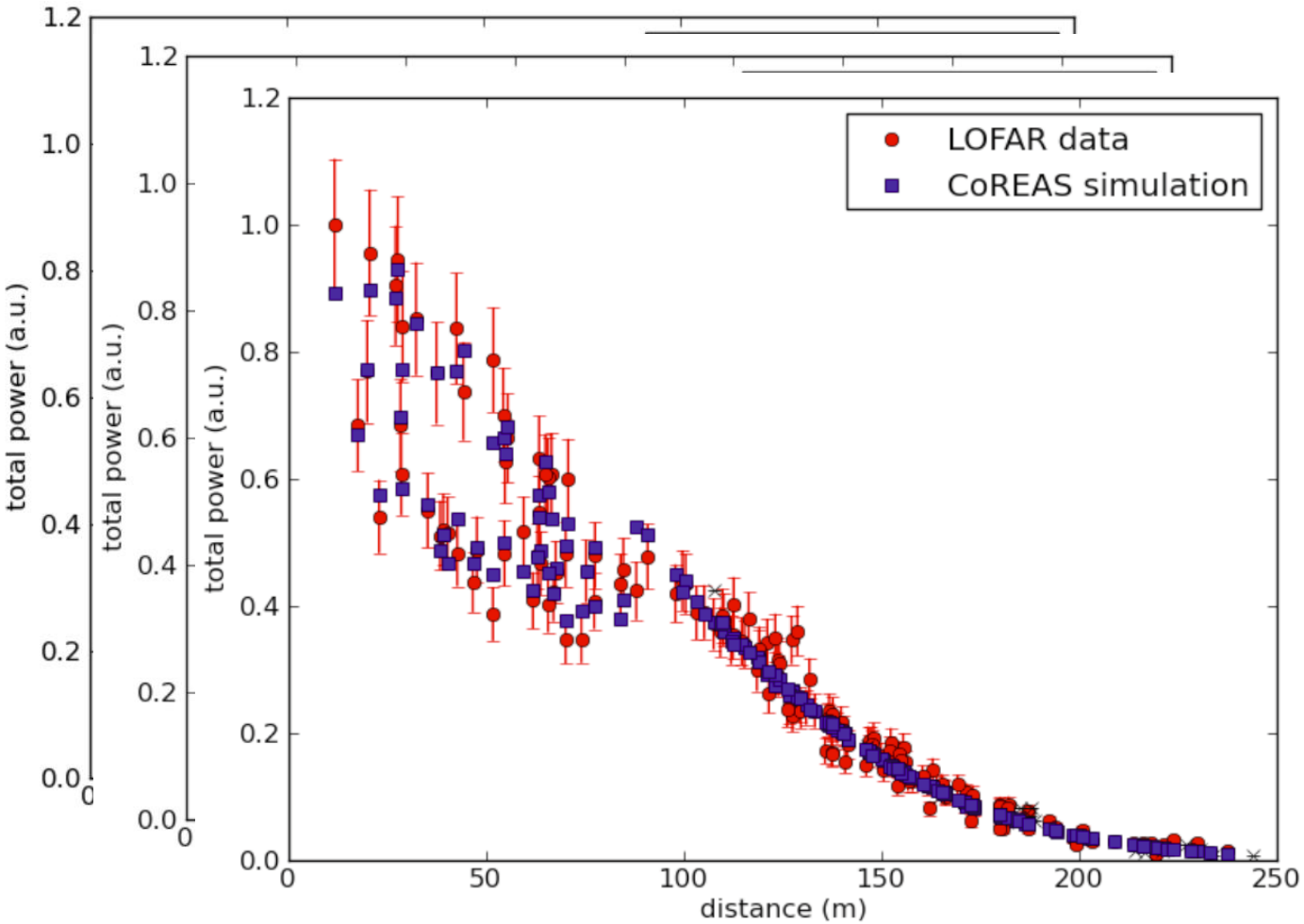
- this is as good as it gets with AERA due to sparse antenna spacing

Pierre Auger Collaboration, ICRC2013, id #899

Detailed studies – LOFAR dense core

- O(800) antennas in 400 m diameter circle, ~0.1 km^2
  - *either* 30 – 80 MHz *or* 120 – 240 MHz
- small particle detector array (trigger & event information)
- allows us extremely detailed studies of individual cosmic rays

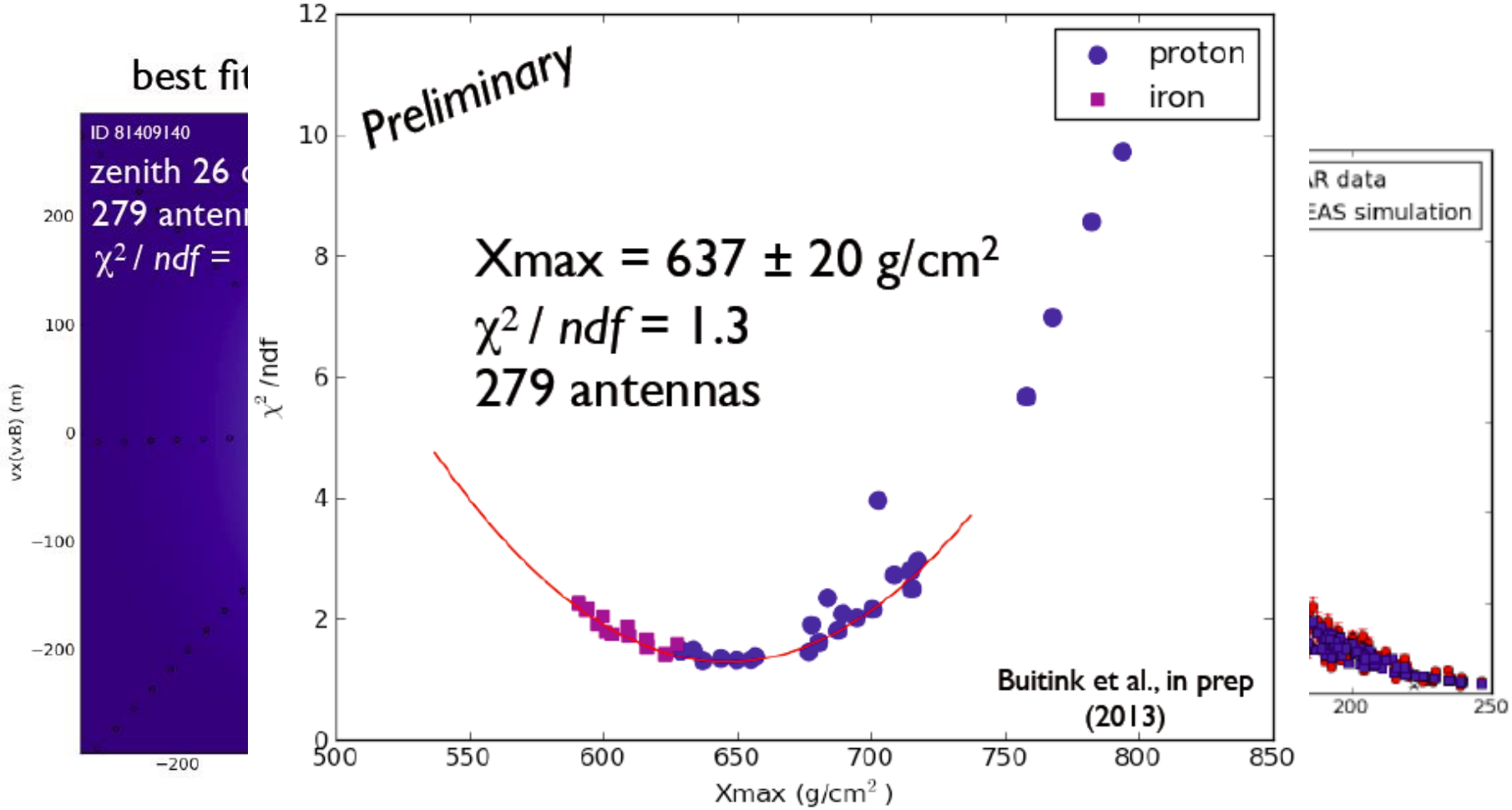
Individual events measured with LOFAR



- extreme level of detail
- but area of only ~0.1 km^2 limits reach in energy

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

Global fit of particle and radio LDF with LOFAR

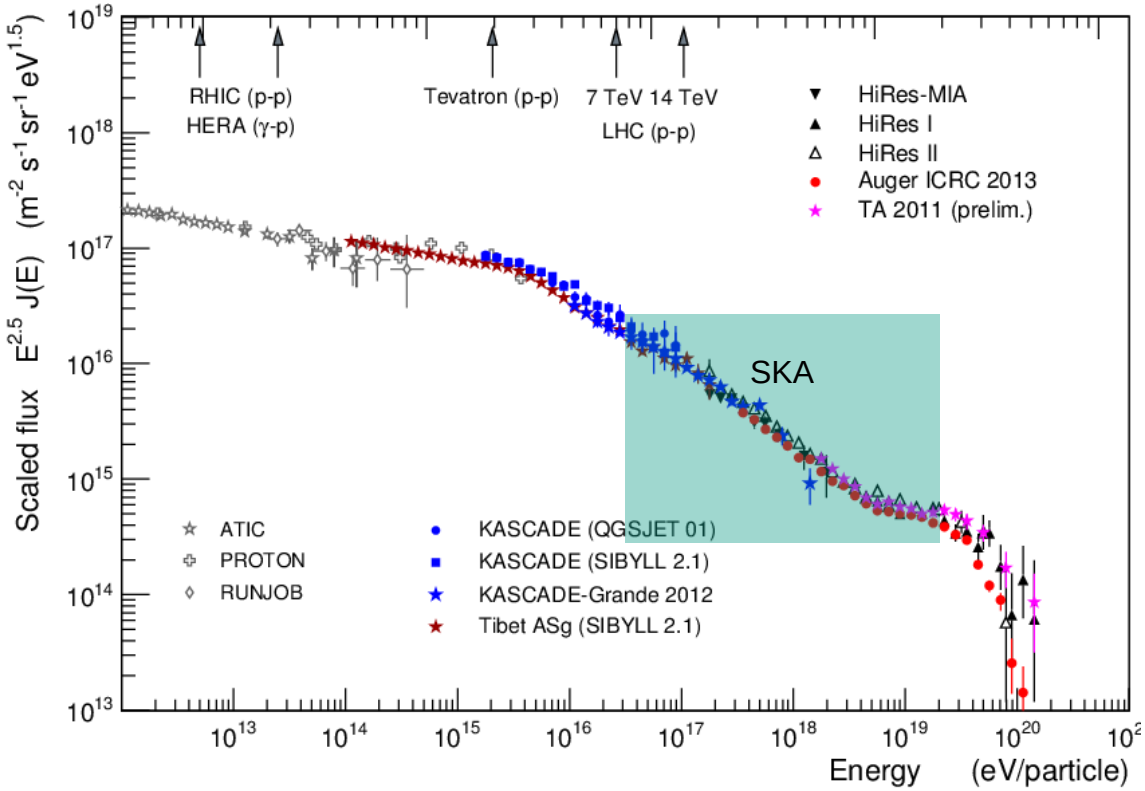


- very competitive cosmic ray mass determination via depth of shower max

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

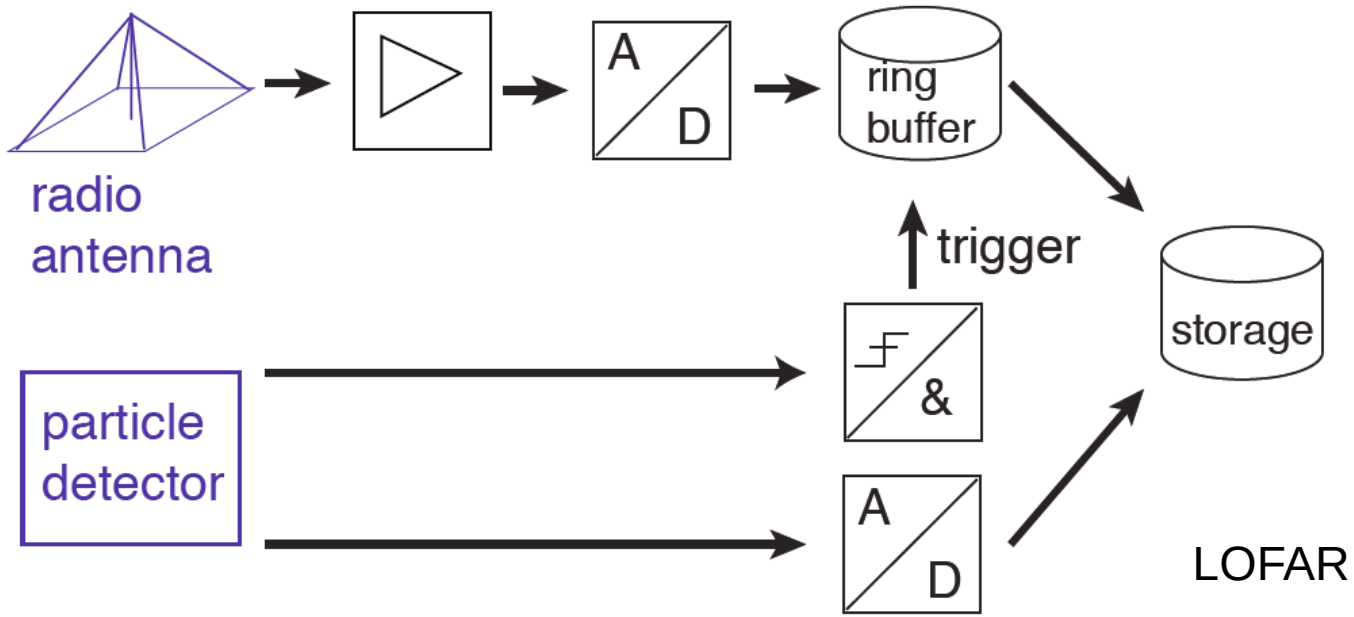
The SKA could play a very significant role here

- observing frequencies 50 – 350 MHz (now typically 30-80 MHz)
- bandwidth of 250 – 300 MHz (now typically 50 MHz)
- dense core of ~7 km^2
- **„detail of LOFAR on the scale of AERA“**
  - detailed mass-composition studies in range 10^{17} eV to >10^{19} eV



Technical requirements

- read out ~50 μs original **raw data** of **individual antennas** upon trigger
- can run in piggy-back mode to normal observations
- has successfully been implemented in LOFAR

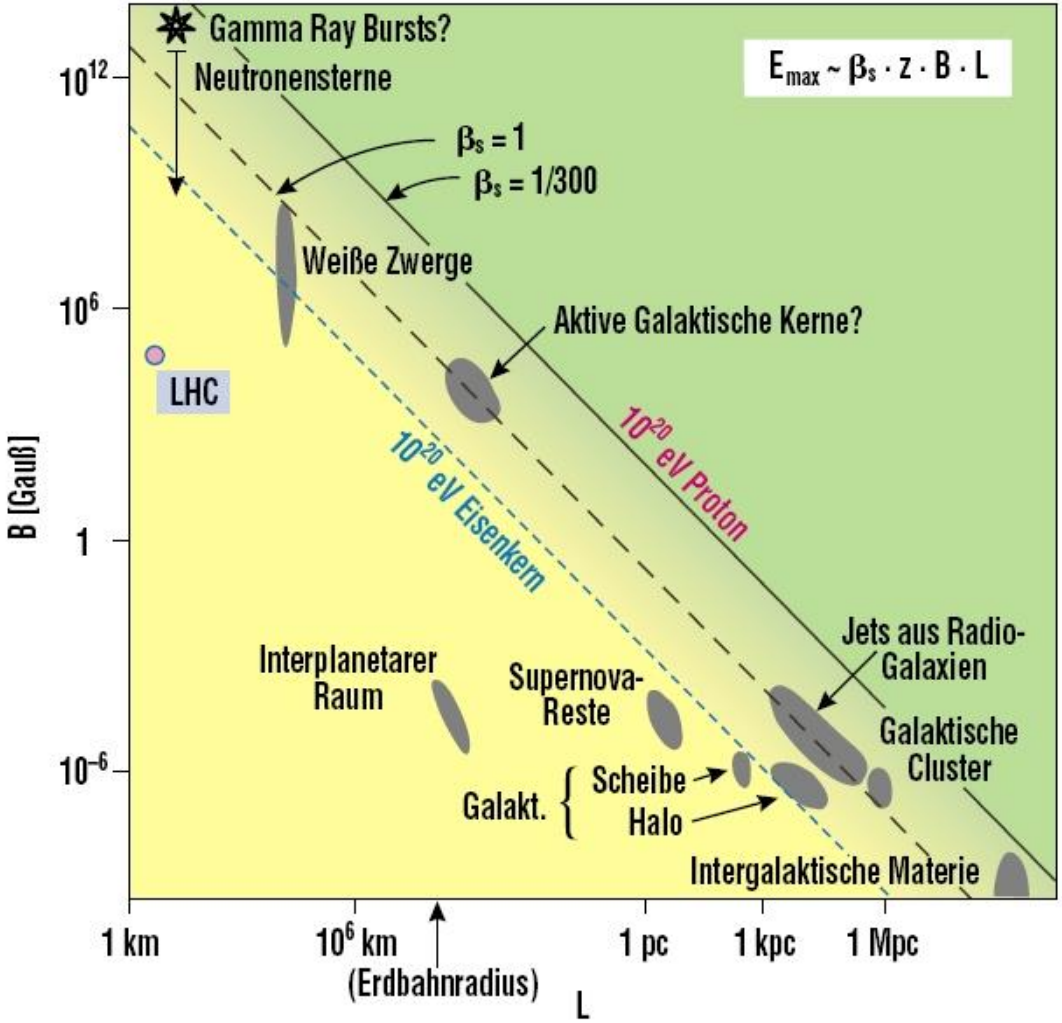


Conclusions

- high-energy cosmic rays are a major research interest with large active collaborations (Auger has >500 authors)
- radio detection of cosmic rays has matured in the past few years and can deliver very competitive results
- the SKA could do cosmic ray research in the region of transition from galactic to extra-galactic cosmic rays
- this would require buffering (~few hundred ms) and readout of antenna raw data upon trigger by a small particle detector array
  - how much effort would that be? cf. transient studies …

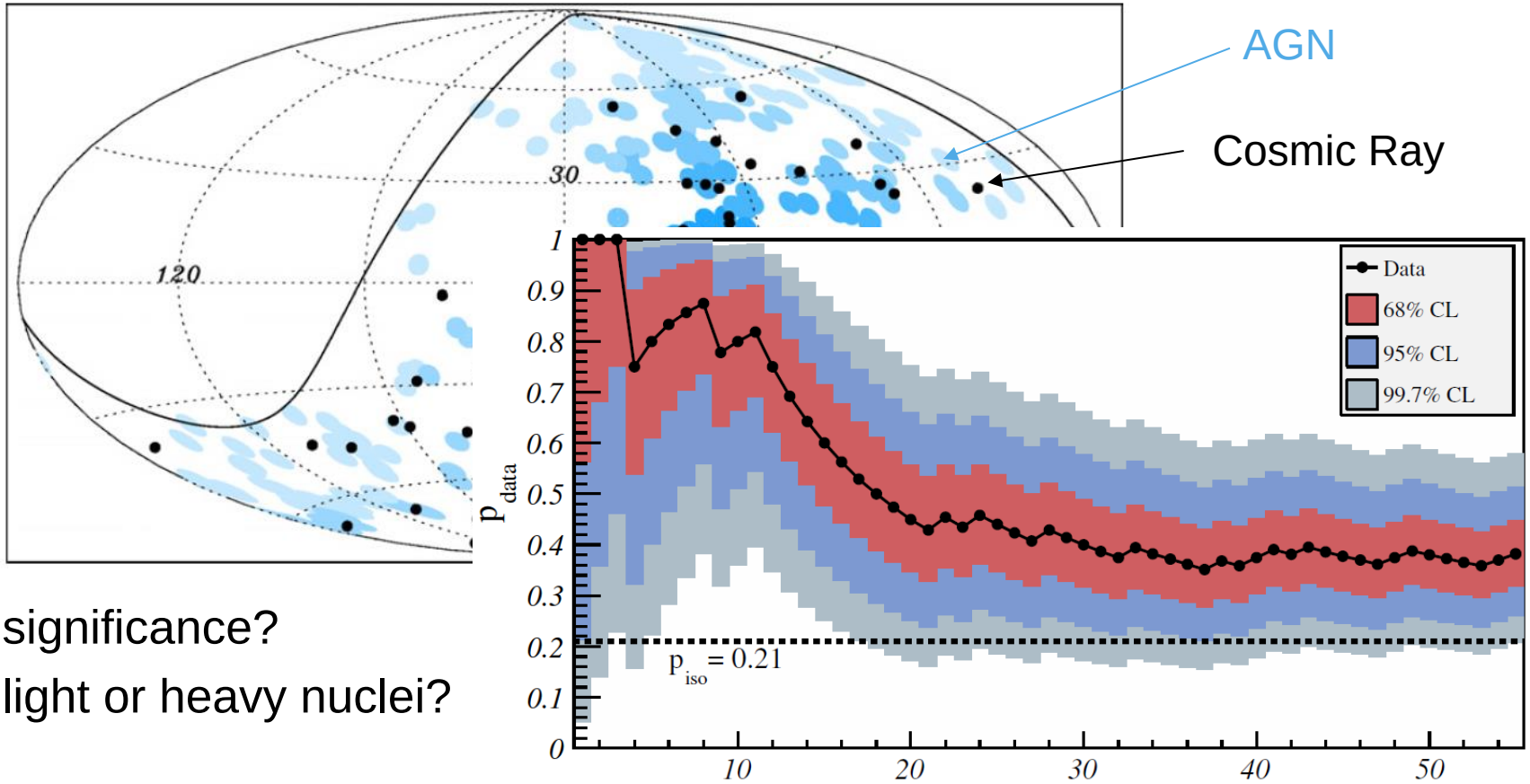
Backup Slides

Hillas Diagram



Indications for sources

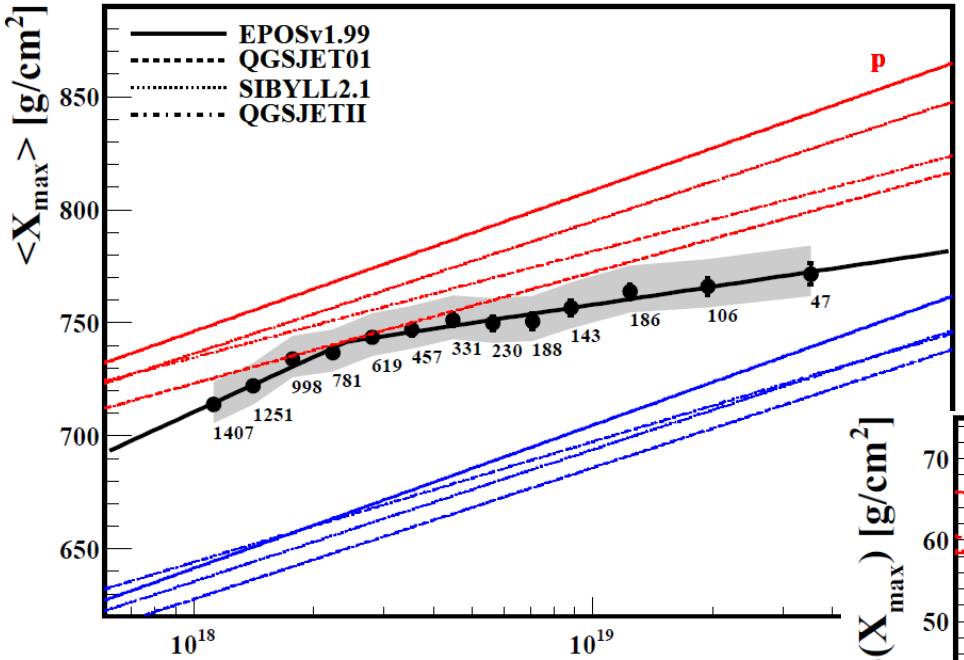
- indications for correlation with active galactic nuclei



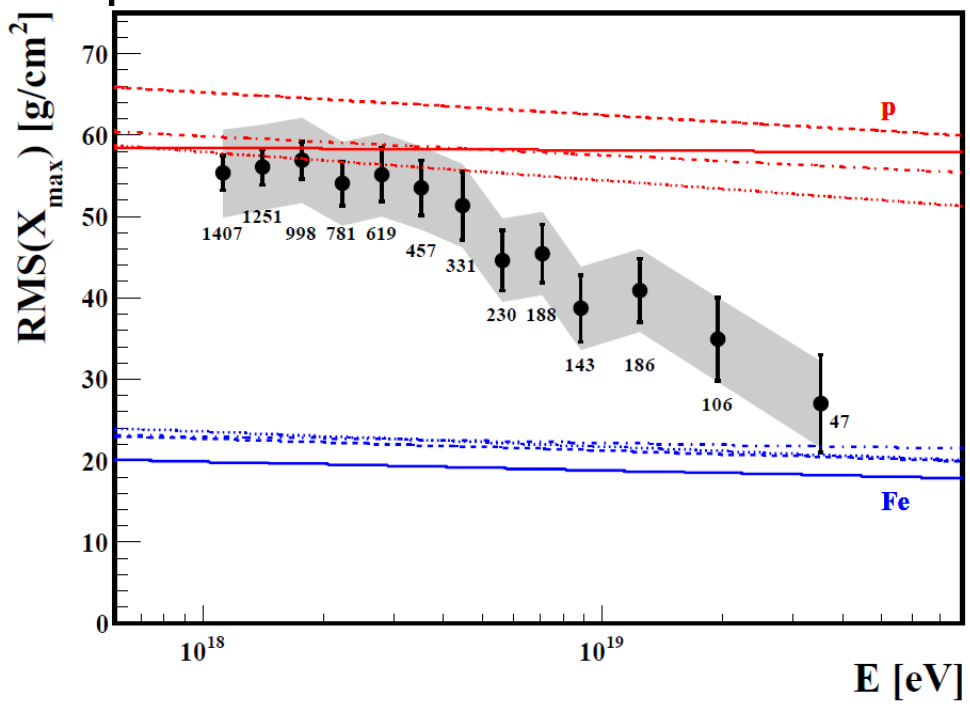
- significance?
- light or heavy nuclei?

J. Abraham et al. (Auger Collaboration), Science 318 (2007) 938-943
P. Abreu et al. (Auger Collaboration), Astrop. Physics 34 (2010) 314-326

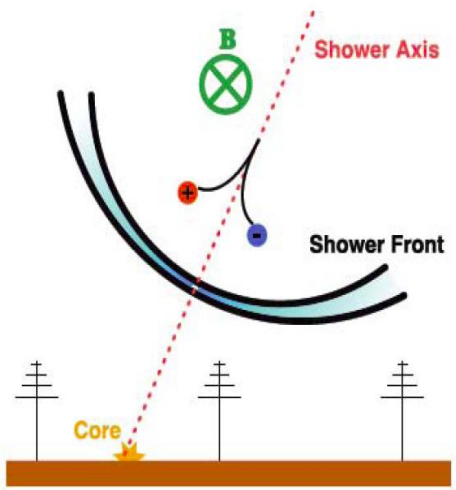
Mass composition of UHECR



- composition seems to become heavier again at highest energies

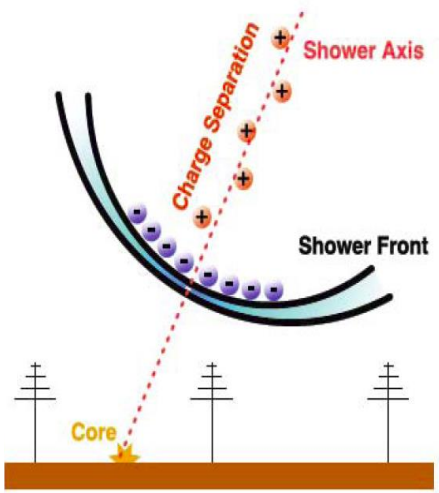


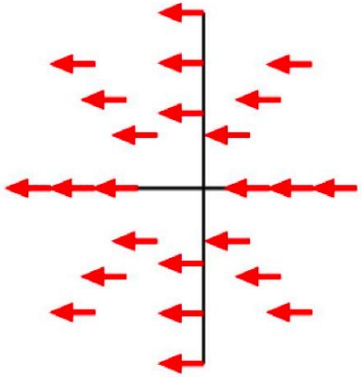
Radio emission physics



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

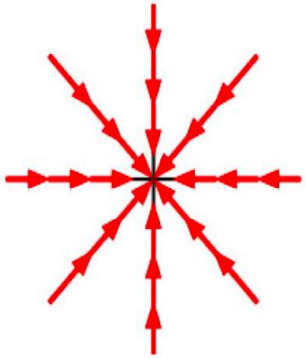
Kahn & Lerche (1967)





Askaryan (1962,1965)

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

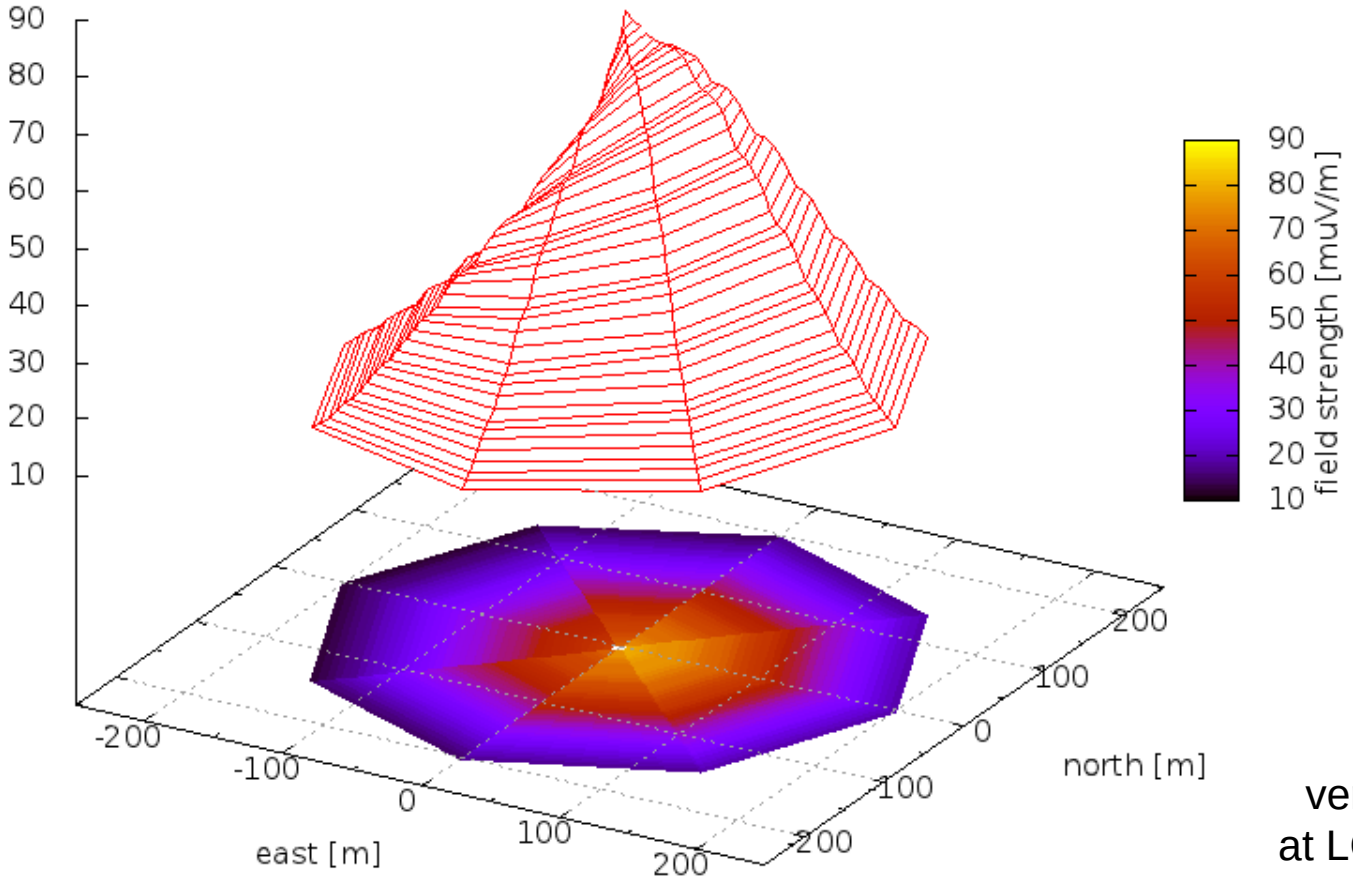


„*v* x *B*“

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

„*radial*“

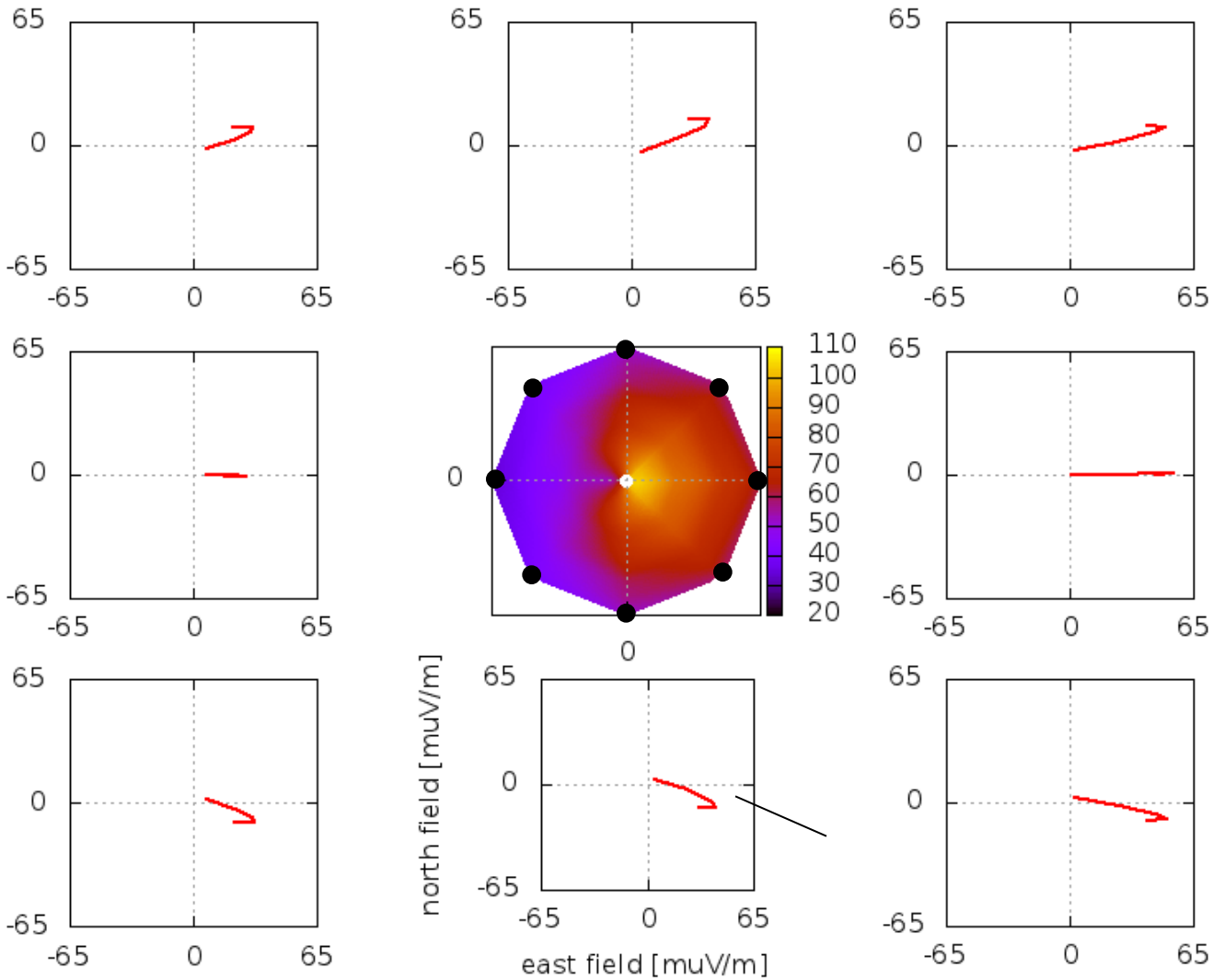
Complexity of radio lateral distribution



vertical iron shower
at LOPES frequencies
simulated with CoREAS

TH et al., ARENA2012

Complexity of signal polarization



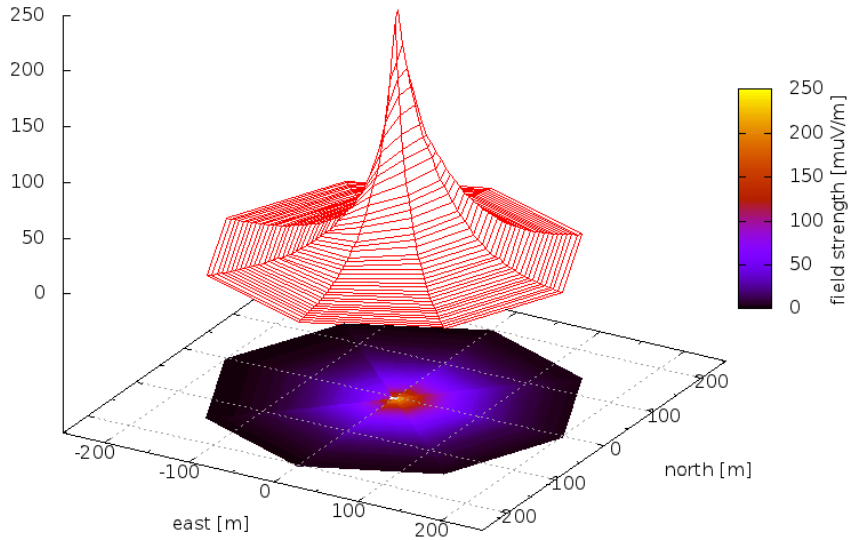
- complex time evolution of electric field vector
- superposition of geomagnetic and charge excess emission

CoREAS simulations, TH et al., see id 548

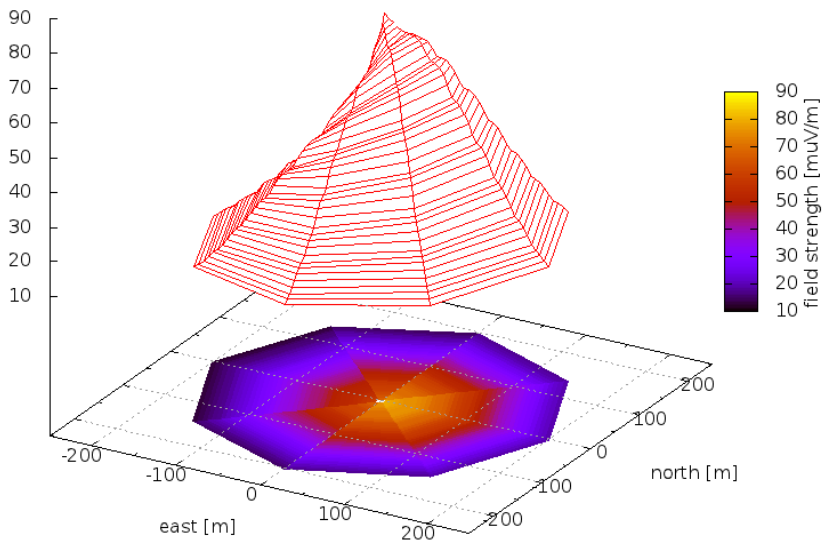
Lateral distribution as probe for composition

- simulations for proton and iron primaries show systematic differences

TH et al., ARENA2012



vertical proton shower
at LOPES frequencies
simulated with CoREAS

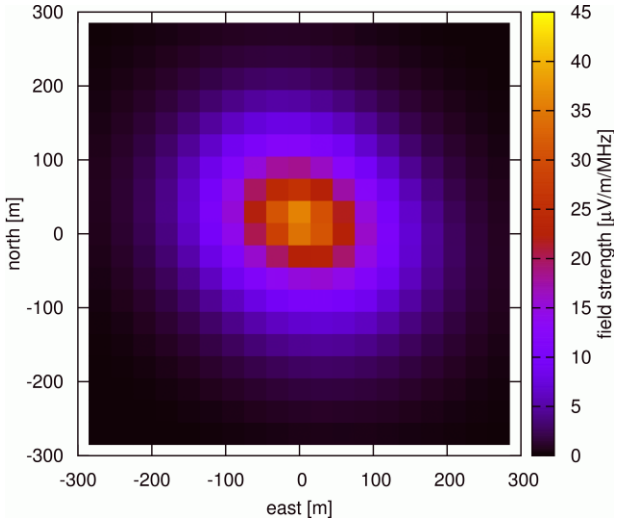


vertical iron shower
at LOPES frequencies
simulated with CoREAS

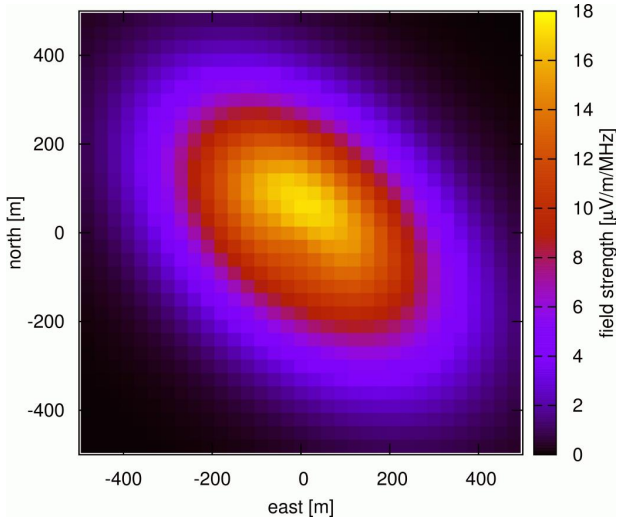
Large area needs large antenna spacings

- radio detection works well, but illuminated area is usually limited
  - investigate inclined showers
  - investigate lower frequencies
  - investigate hybrid analysis with single radio antenna
    - Xmax from pulse shape, spectral index?
    - Xmax from wavefront timing?

30° zenith angle



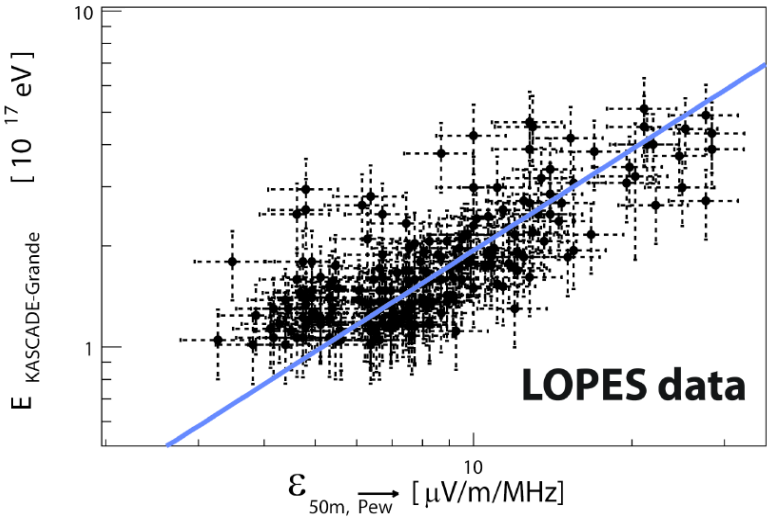
50° zenith angle



75° zenith angle

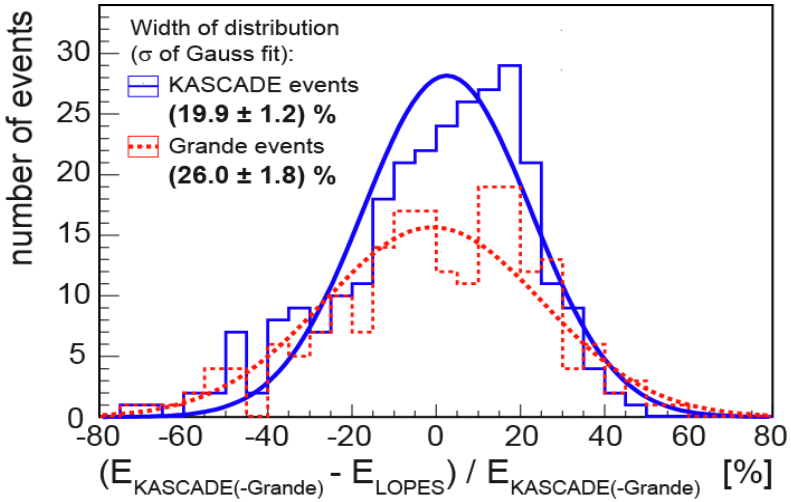
TH et al., this conference, id #548

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

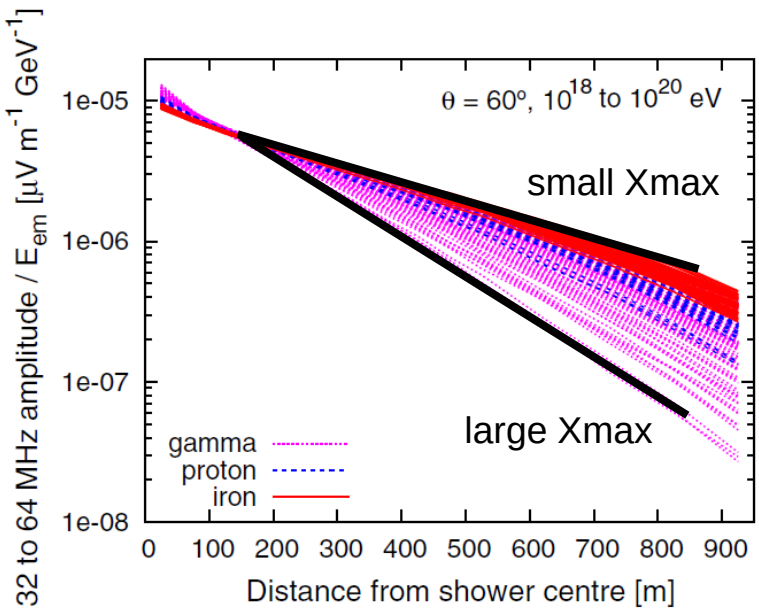


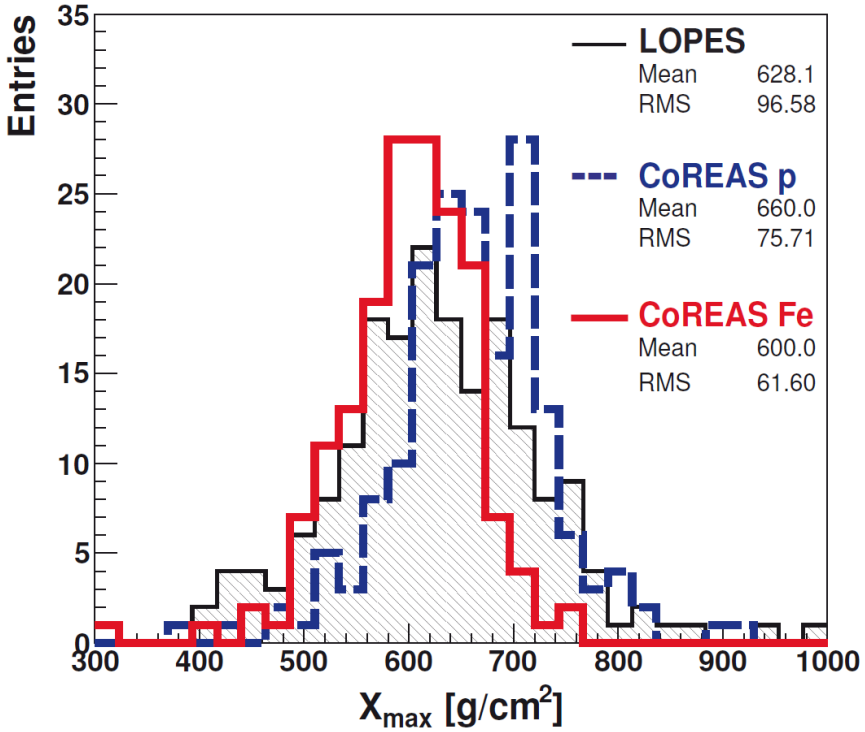
- also works with interferometric analysis, yielding again ~20% uncertainty

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

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