Radio detection of air showers

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Content

- Properties of radio detection
  - 100% duty cycle
  - energy threshold around 10^{17} eV
- Measurements
  - state-of-the-art antenna arrays
  - direction, energy, shower maximum
- Science applications for radio
  - absolute energy
  - mass composition
  - inclined showers

Emission mechanisms

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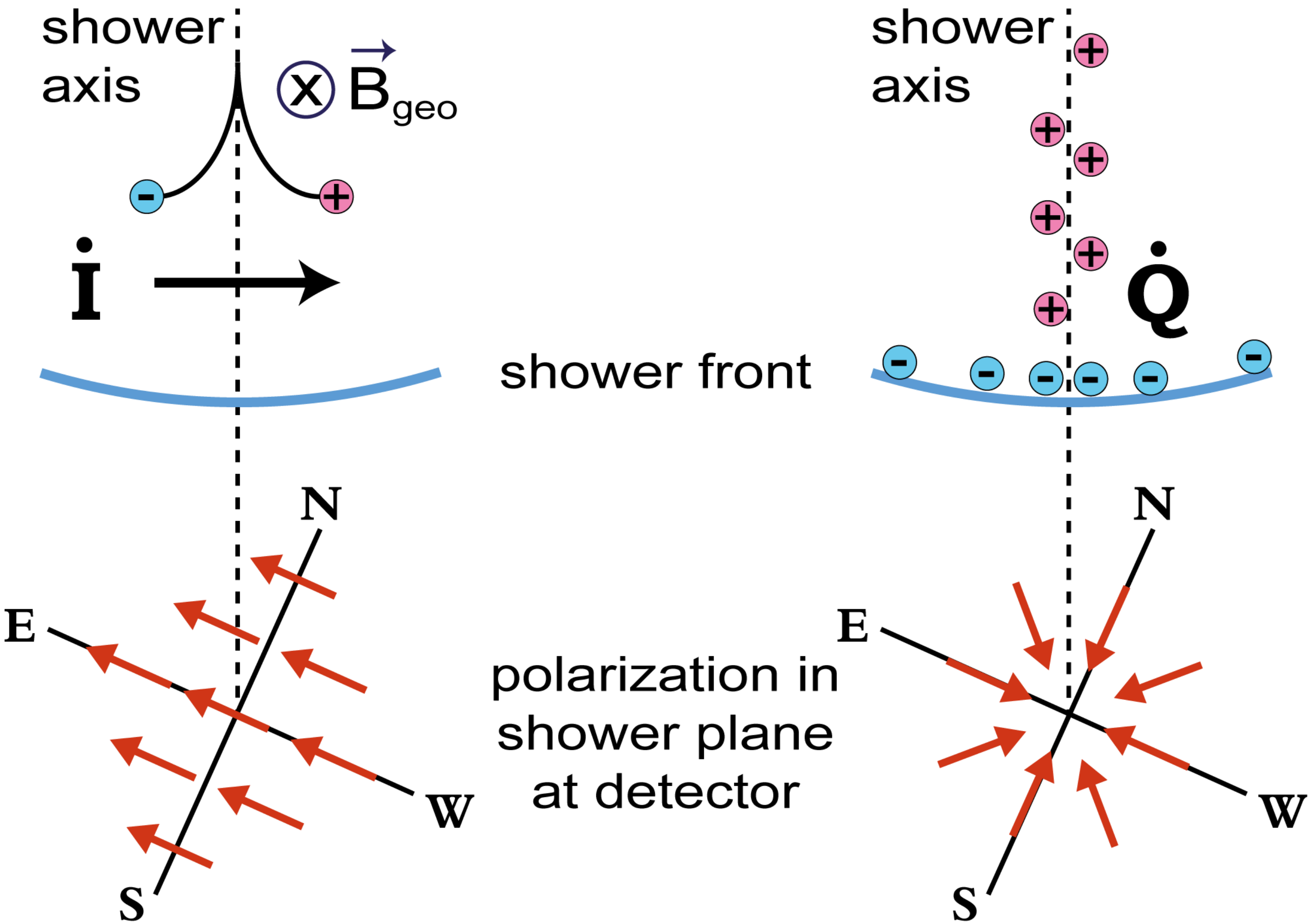

geomagnetic effect ~ 90%

Askaryan effect ~ 10%

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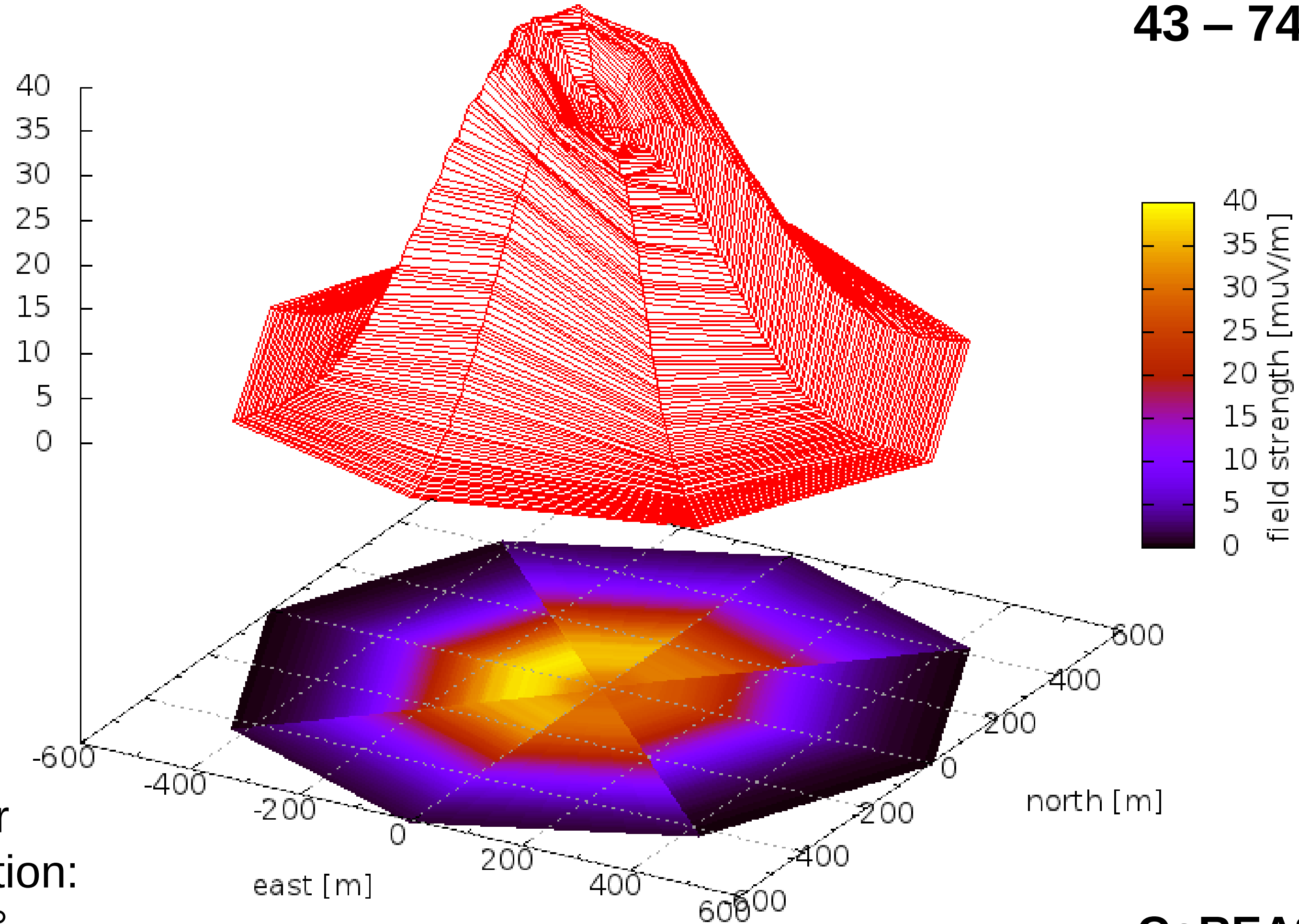
Asymmetric lateral distribution

43 – 74 MHz



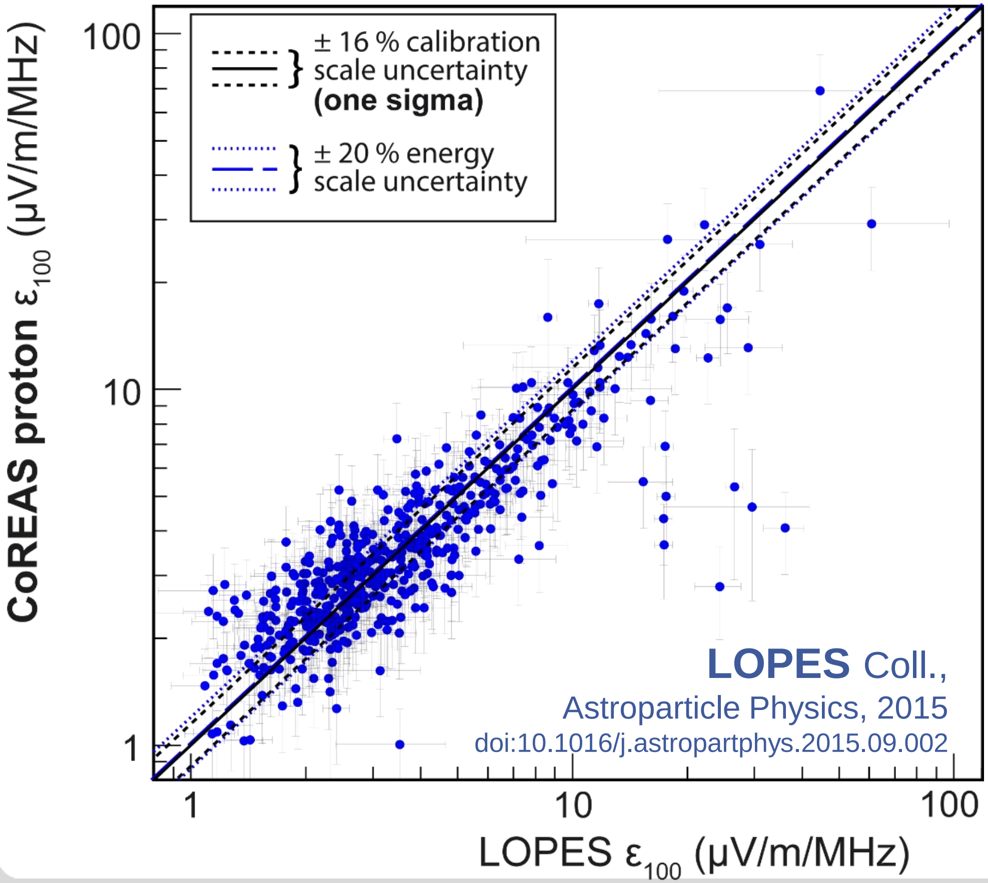
shower inclination: θ = 45°

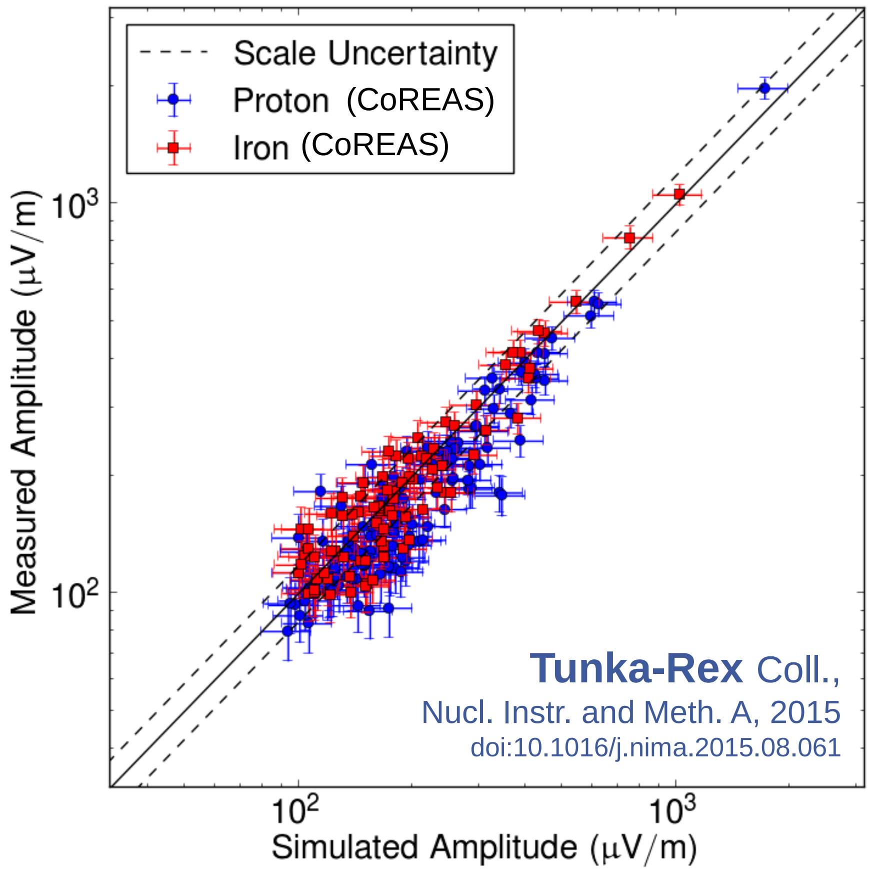
T. Huege et al., ARENA2012

CoREAS simulation for LOPES experiment

Do simulations describe reality?

- Different codes agree on main features
- Measured amplitudes reproduced within ~20% uncertainty





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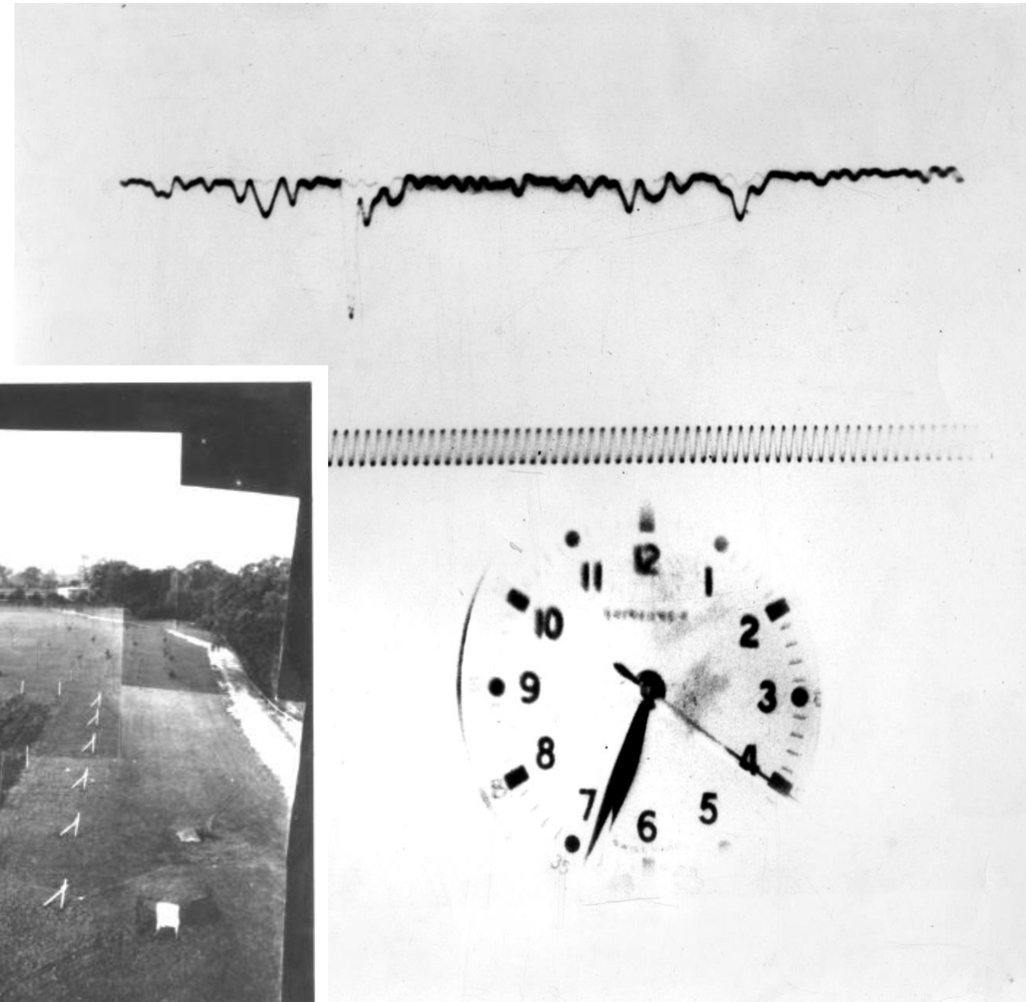
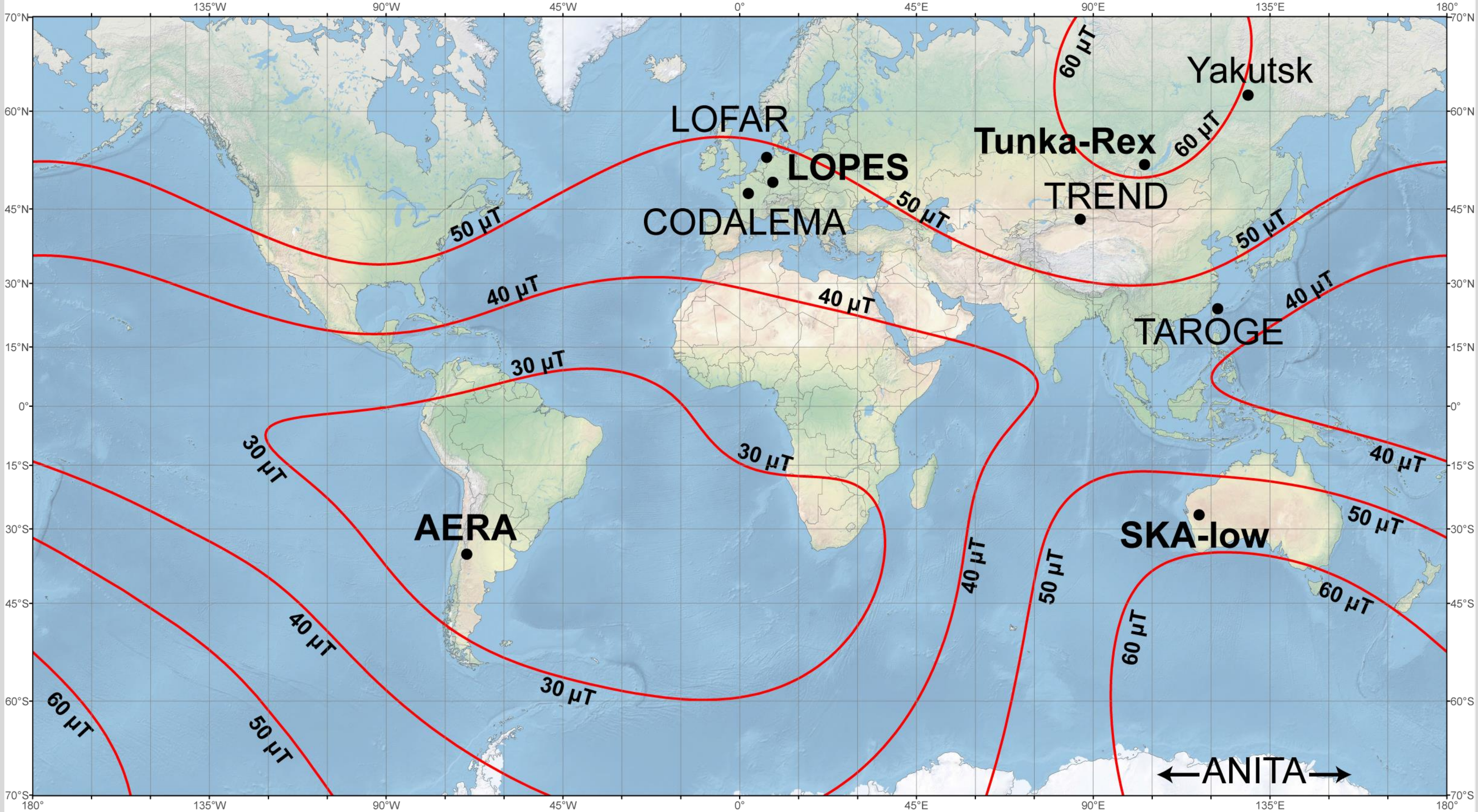
Experiments: First Detection

- Qualitative features discovered 50 years ago

Jelley et al Nature 1965
R. A. Porter MSc Thesis 1967,



Location of selected, modern experiments and geomagnetic field



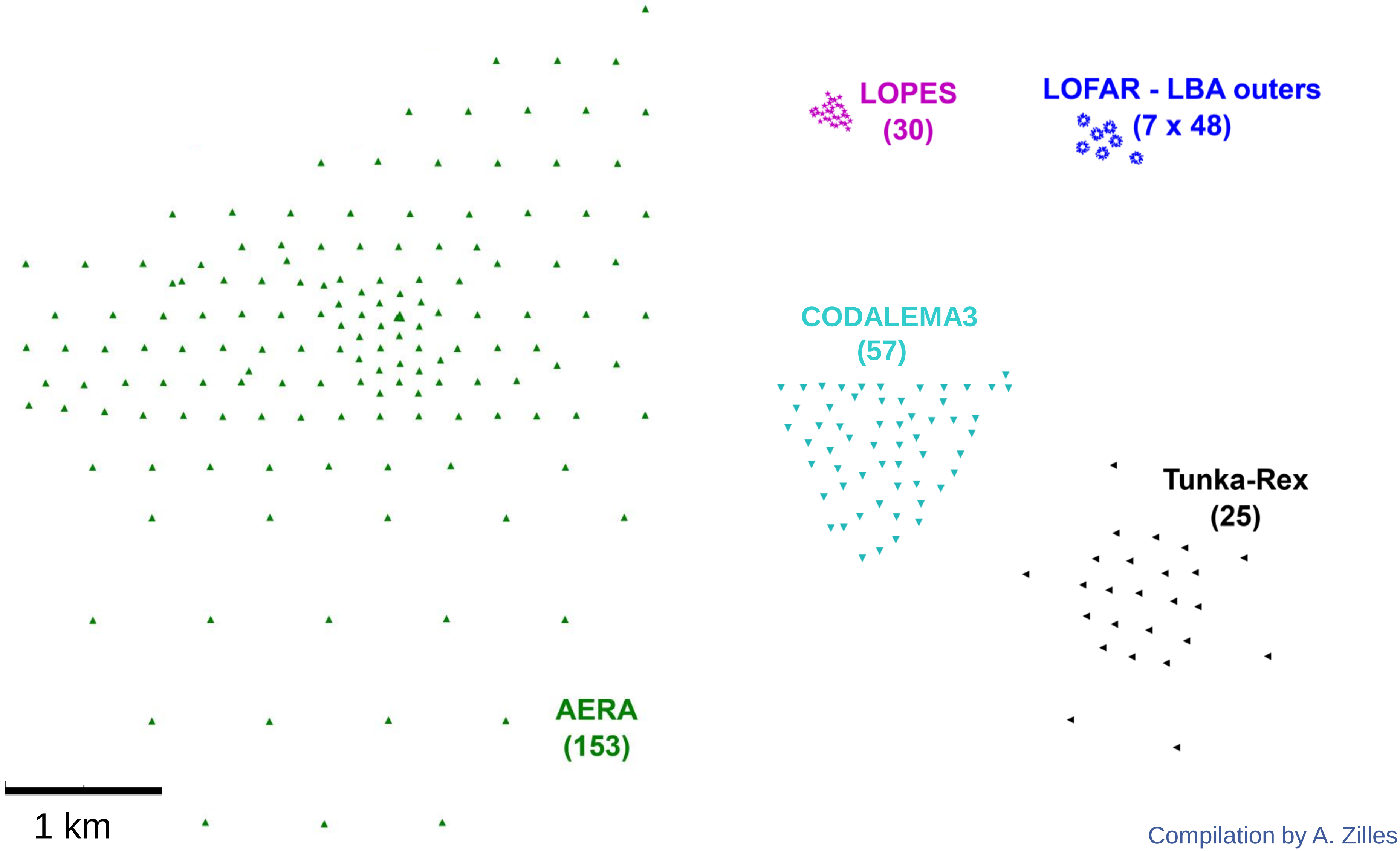
Underlying map (Mercator projection):
Main Geomagnetic Field Total Intensity with contour intervals of 1000 nT
according to US/UK World Magnetic Model - Epoch 2015.0

developed by NOAA/NGDC & CIRES
http://ngdc.noaa.gov/geomag/WMM

Map reviewed by NGA and BGS
Published December 2014

Overlayed: **Location of radio experiments for cosmic-ray air showers**
added on underlying map by Frank G. Schröder
Karlsruhe Institute of Technology (KIT), Germany

Designs of modern radio arrays



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Detectors: antennas

- Many working solutions with only slight differences in
  - threshold
  - frequency band
  - accuracy (systematic uncertainties)

Butterfly at CODALEMA

SALLA at Tunka-Rex

LPDA at the Pierre Auger Observatory

inverted v-dipole at LOPES

General concepts

- Typical frequency band: 30-80 MHz
  - optimal signal-to-noise ratio
  - large band slightly better, but requires more expensive electronics
- External trigger by other air-shower detectors
  - self-trigger possible, but challenging due to radio background
  - hybrid approach increases total accuracy
- Digital antenna stations
  - autonomous, remote stations possible (Auger, CODALEMA)
  - later offline analysis with dedicated software

Reconstruction of shower parameters

- Direction
  - example: LOPES
- Energy
  - example: AERA
- Shower maximum
  - examples: LOFAR, Tunka-Rex

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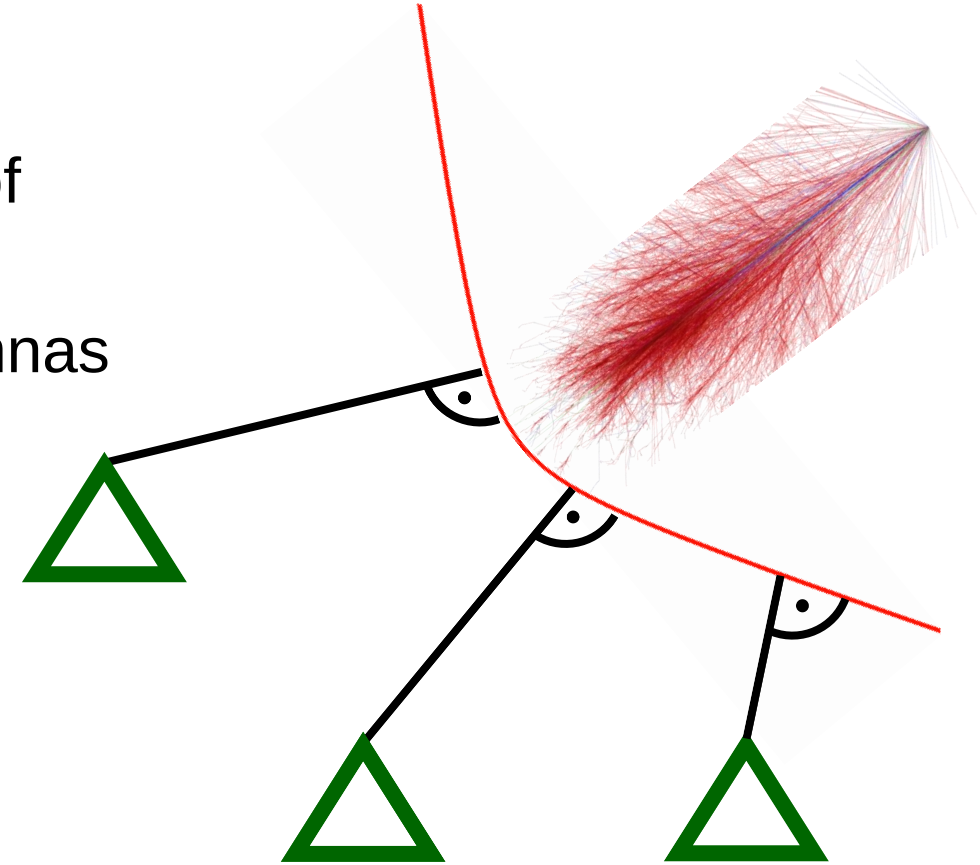
Interferometric beamforming at LOPES

- Digitally shift all traces according to arrival time of hyperbolic wavefront
- Cross-correlation of antennas



LOPES Coll.,

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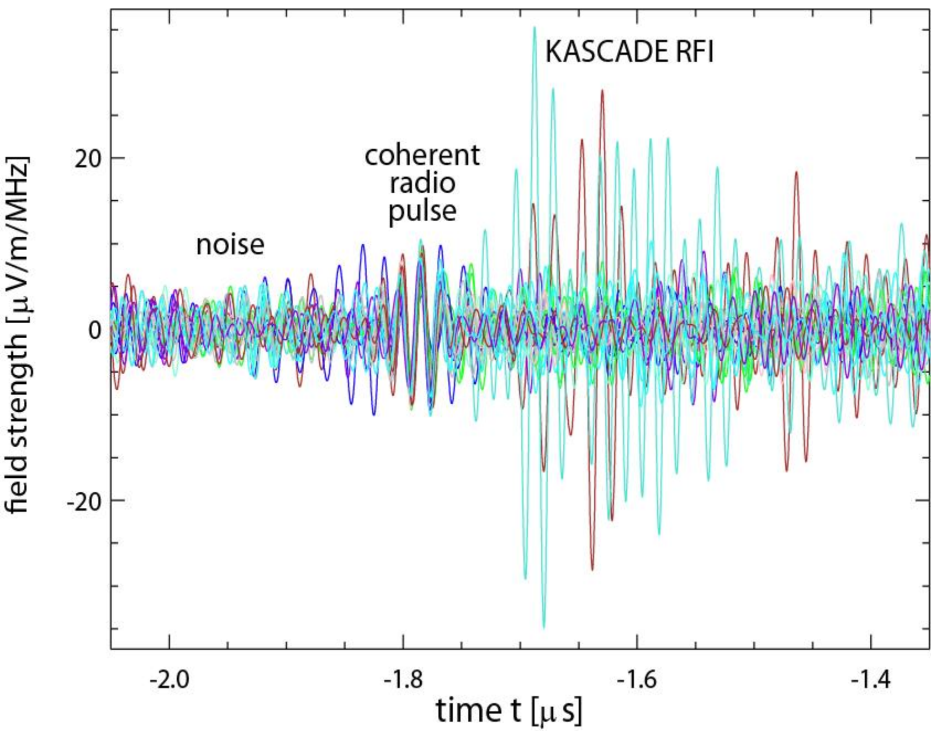
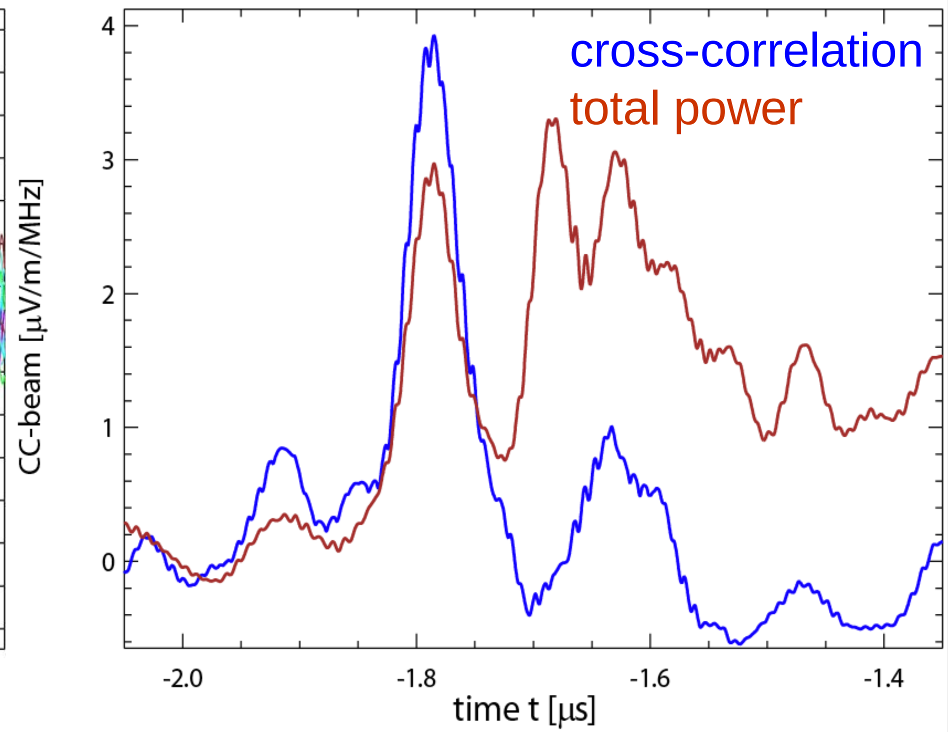
Cross-correlation beamforming

- Digital Interferometry: only air shower pulse correlated in all antennas, when looking in the arrival direction





LOPES Coll., Astroparticle Physics 50-52 (2013) 76

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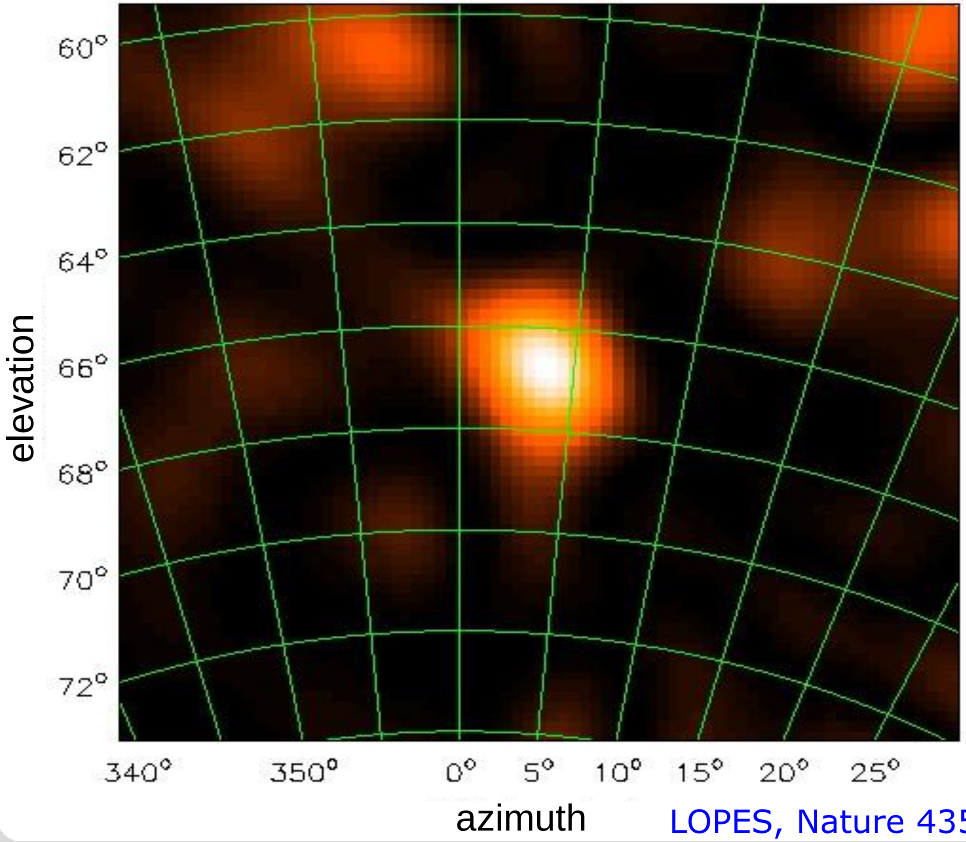
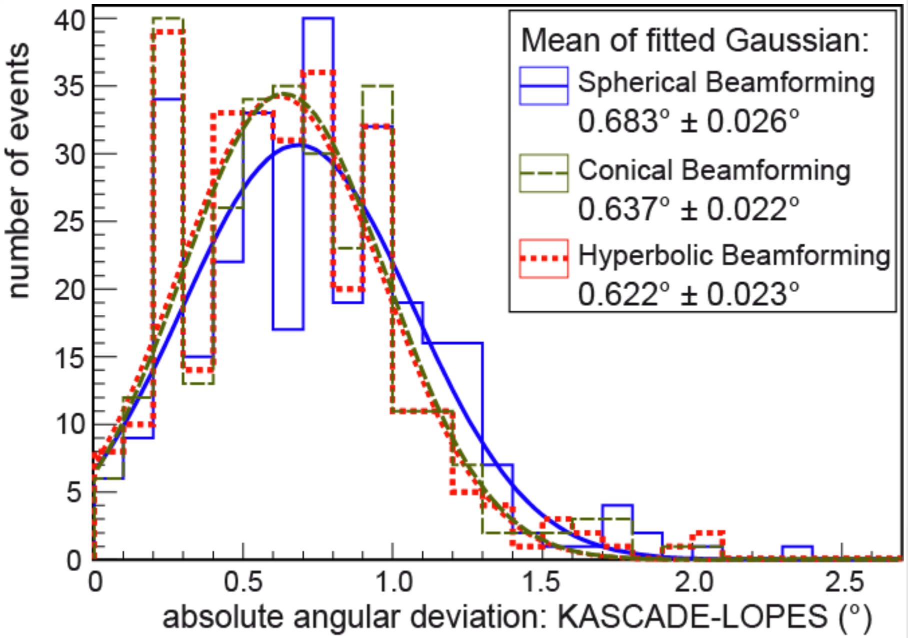
Arrival direction

- Air shower radio pulse = flash for a few 10 ns
- Interferometric imaging:
  → direction precision < 0.7°



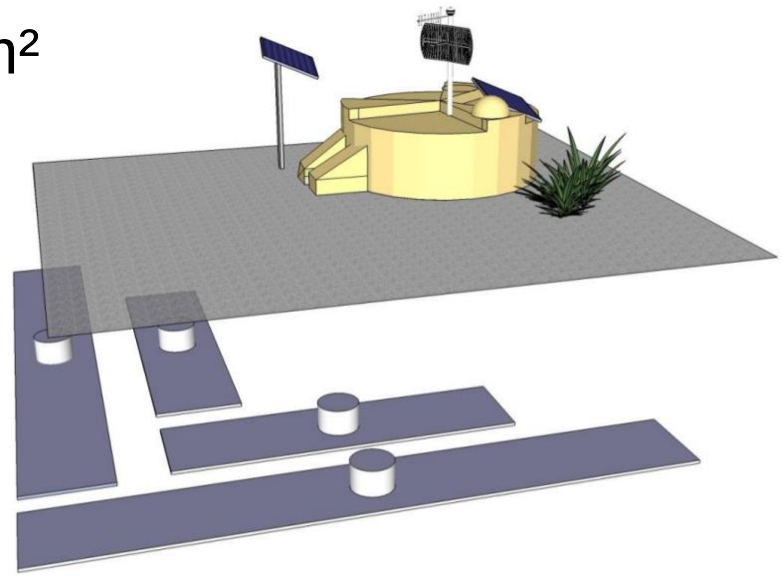
LOPES, Nature 435 (2005) 313

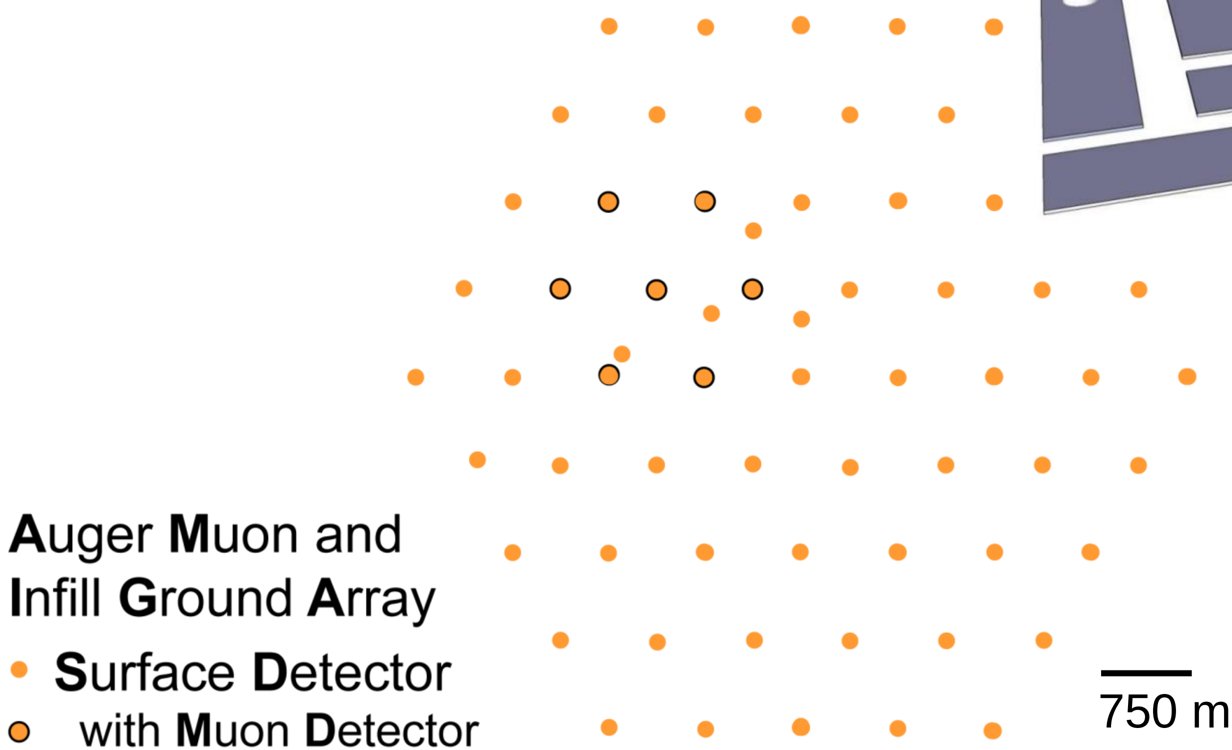


LOPES, JCAP 09 (2014) 025

Auger Engineering Radio Array

- 153 autonomous stations on 17 km²
  - world-largest radio array
  - part of the enhancement area of the Pierre Auger Observatory





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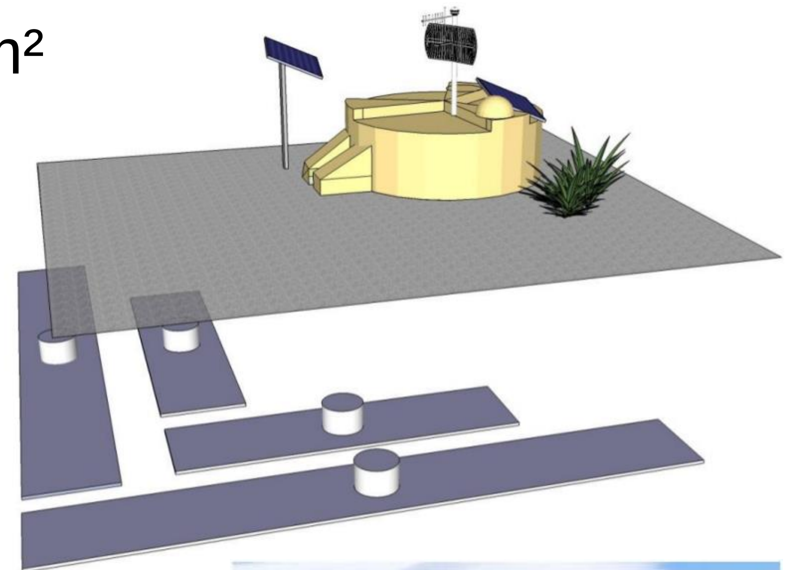
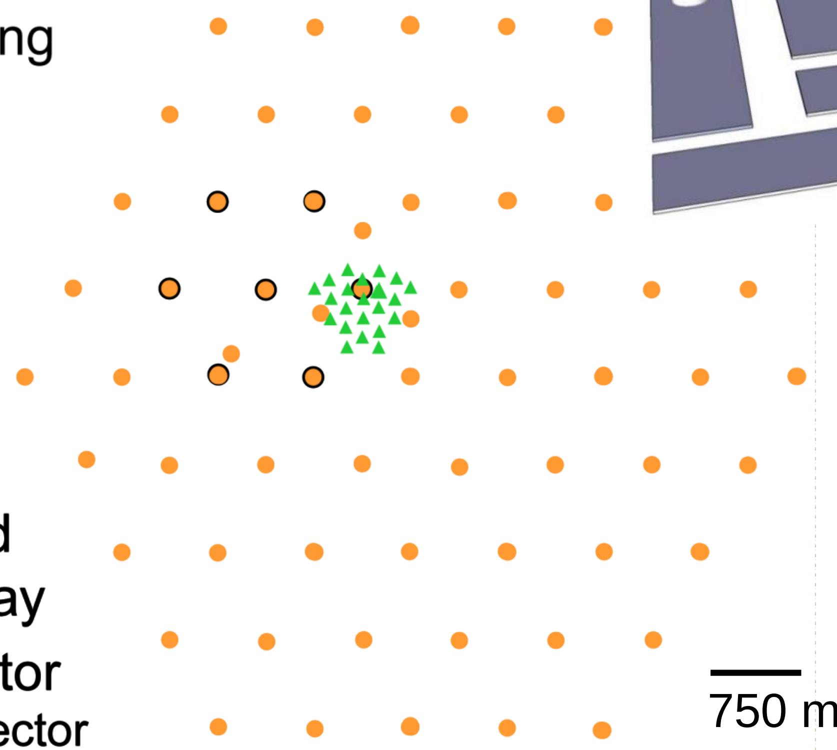
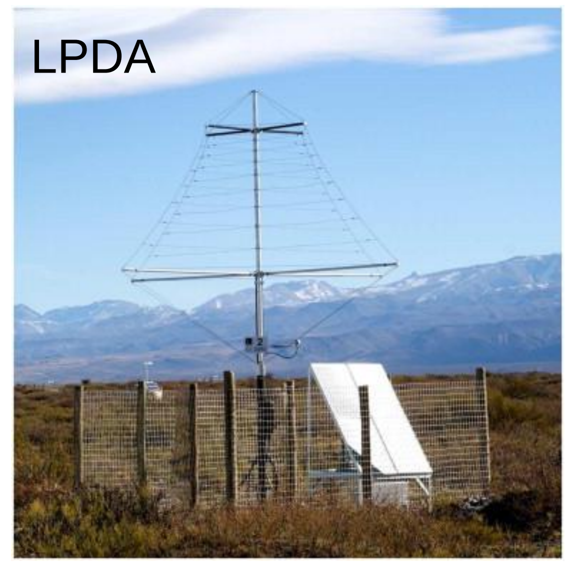


Auger **E**ngineering **R**adio **A**rray
▲ LPDA antenna



Auger **M**uon and **I**nfill **G**round **A**rray
- **S**urface **D**etector
- with **M**uon **D**etector



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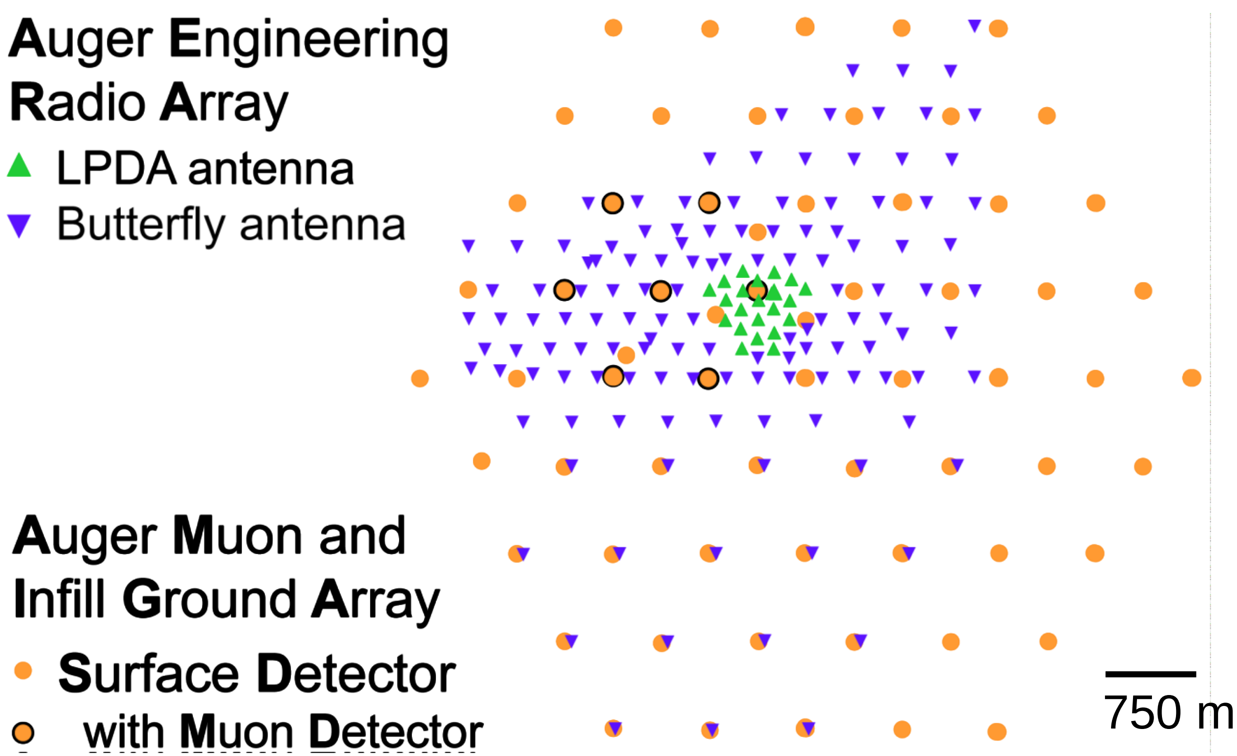

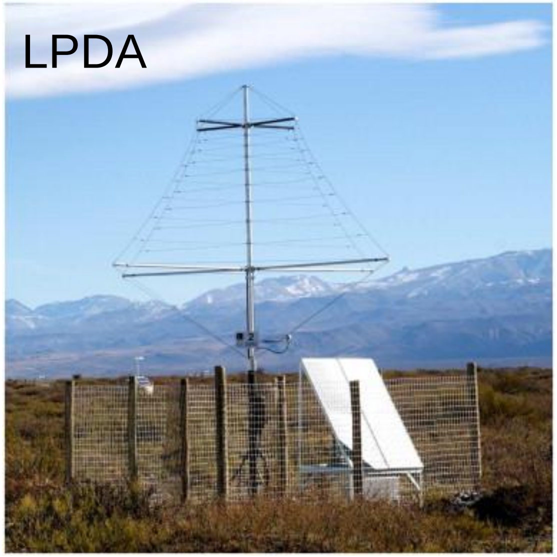

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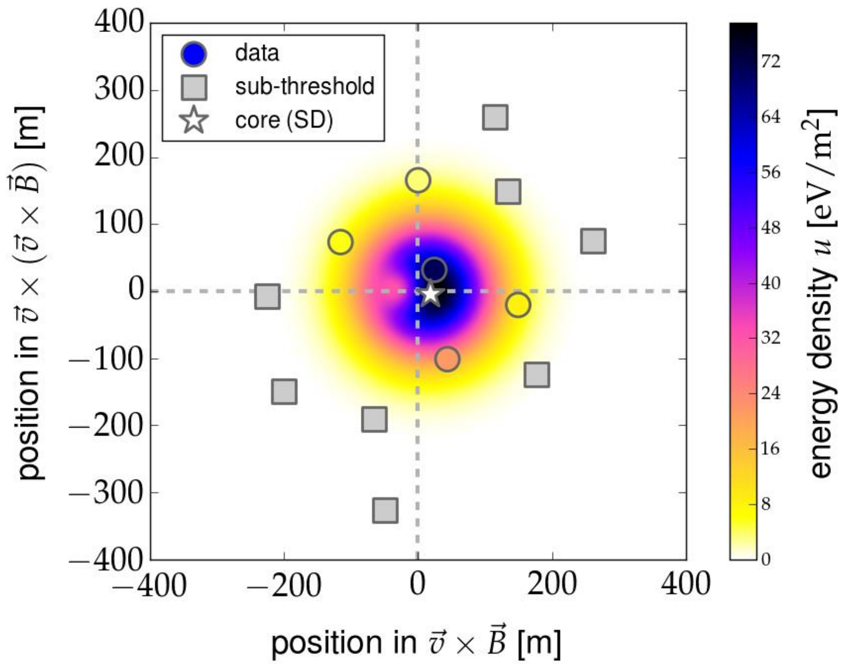
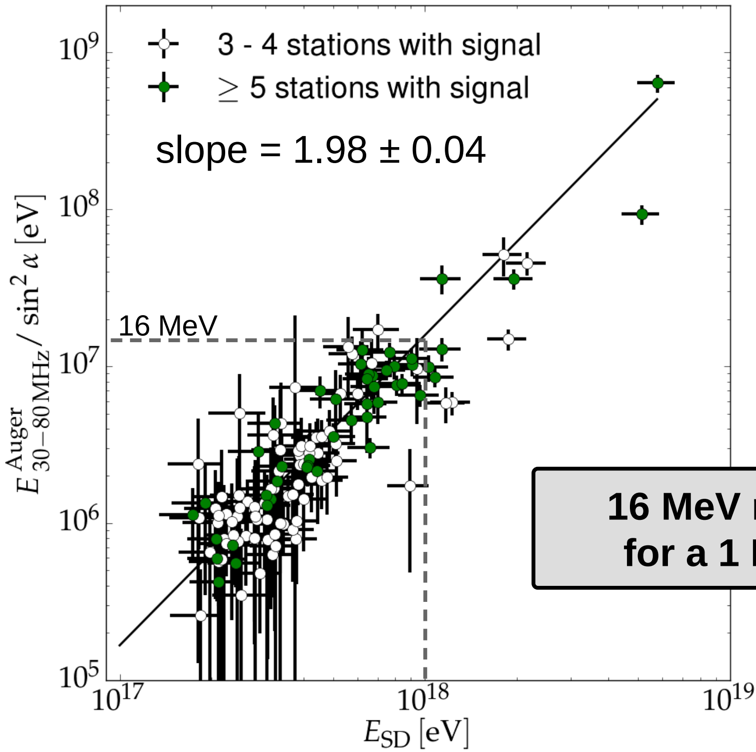
Energy reconstruction

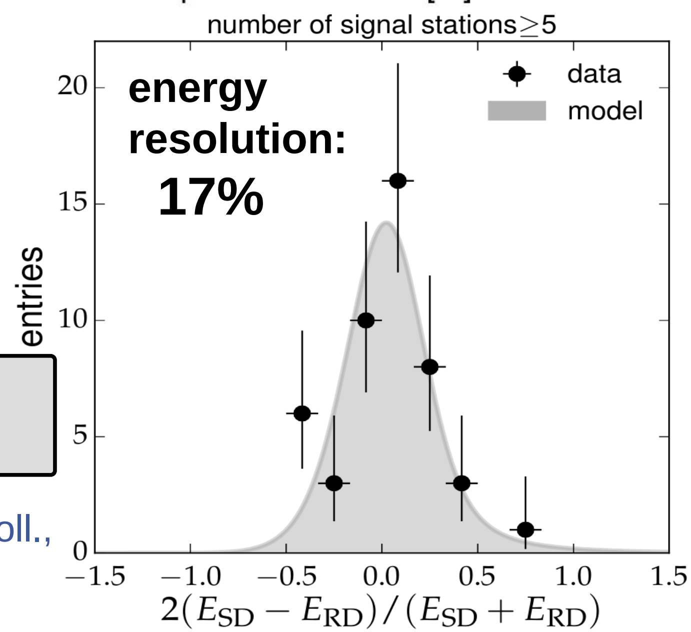
- Coherent radio emission

→ Radio energy squared
~ number of electrons
~ shower energy





16 MeV radiation energy for a 1 EeV cosmic ray



Pierre Auger Coll., ICRC 2015, arxiv: 1508.04267

More examples for energy reconstruction

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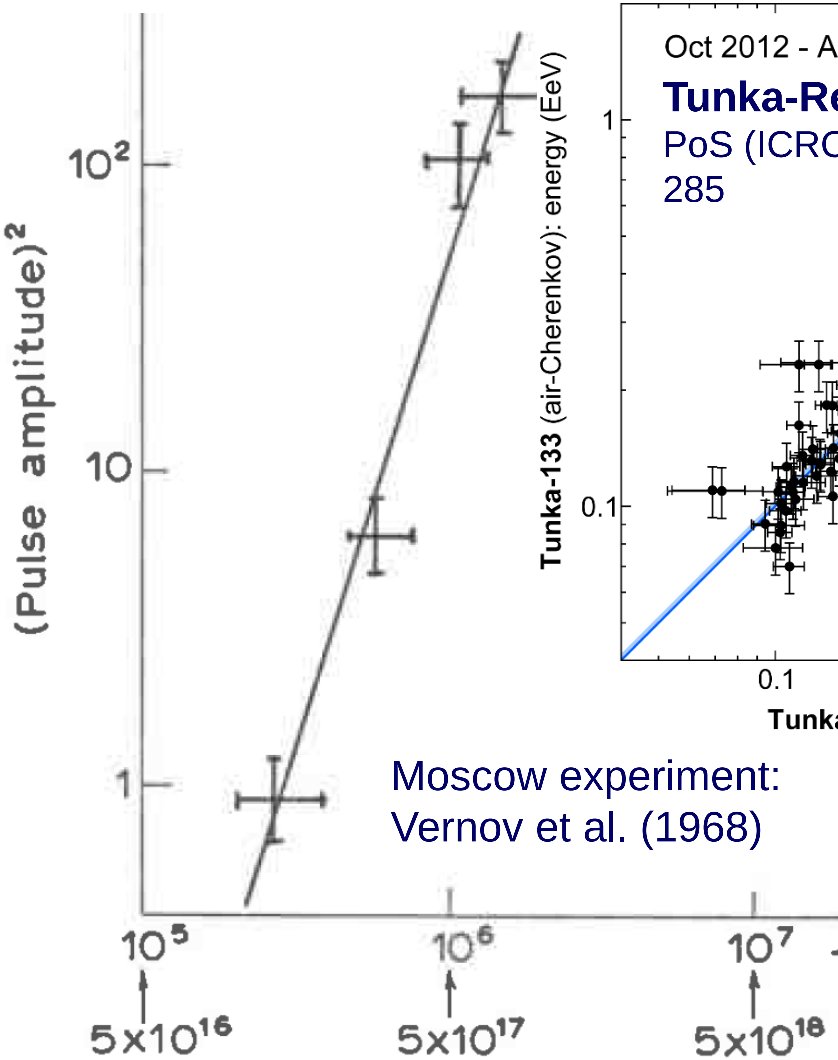
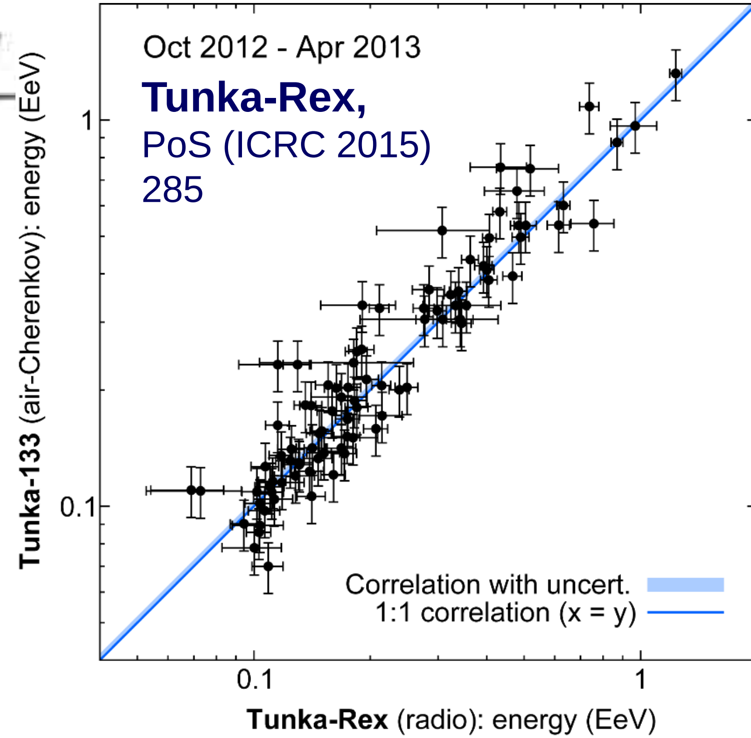
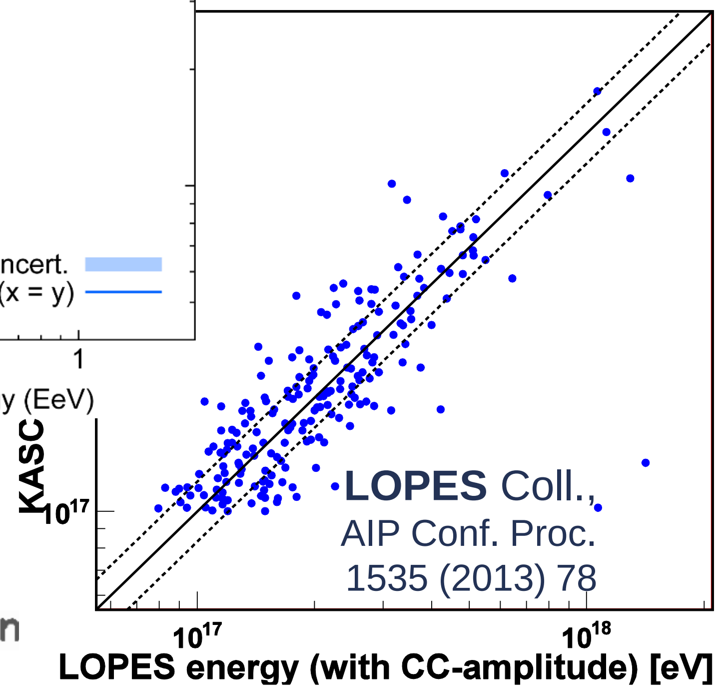


Moscow experiment:
Vernov et al. (1968)



Tunka-Rex,
PoS (ICRC 2015)
285

Also seen by:
CODALMEA,
LOFAR, …



LOPES Coll.,
AIP Conf. Proc.
1535 (2013) 78

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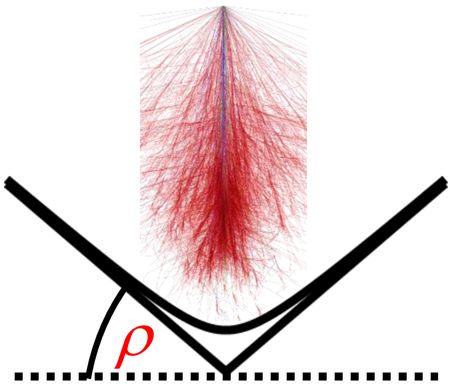
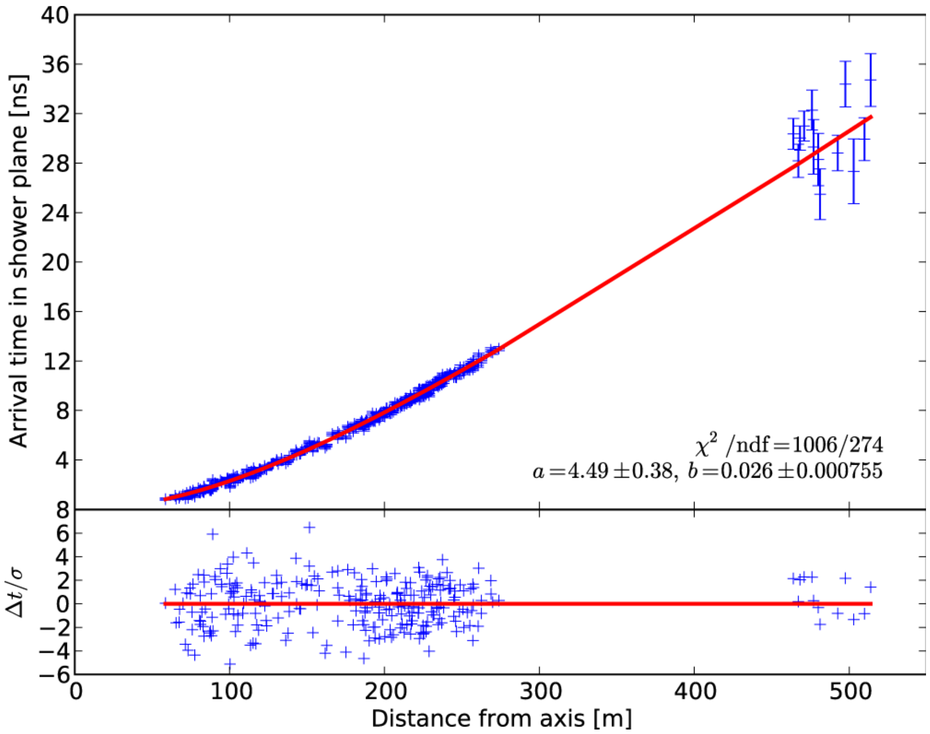
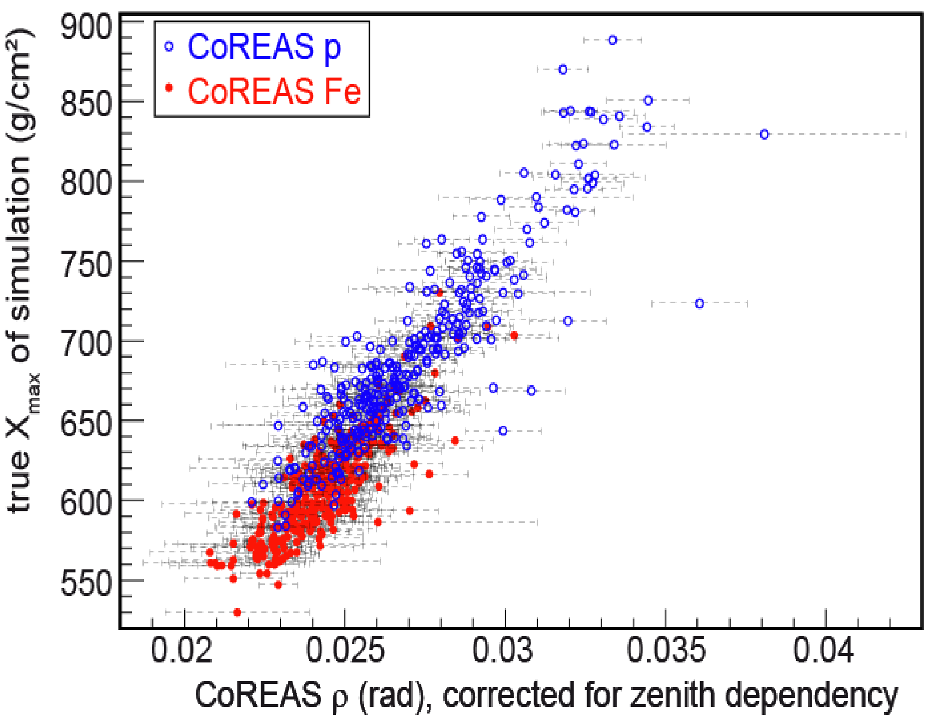
1) Shower maximum via wavefront

- Radio wavefront has hyperbolic shape
- Cone angle → shower maximum





LOFAR Coll, Astropp. 61 (2015) 22



LOPES Coll., JCAP 09 (2014) 025

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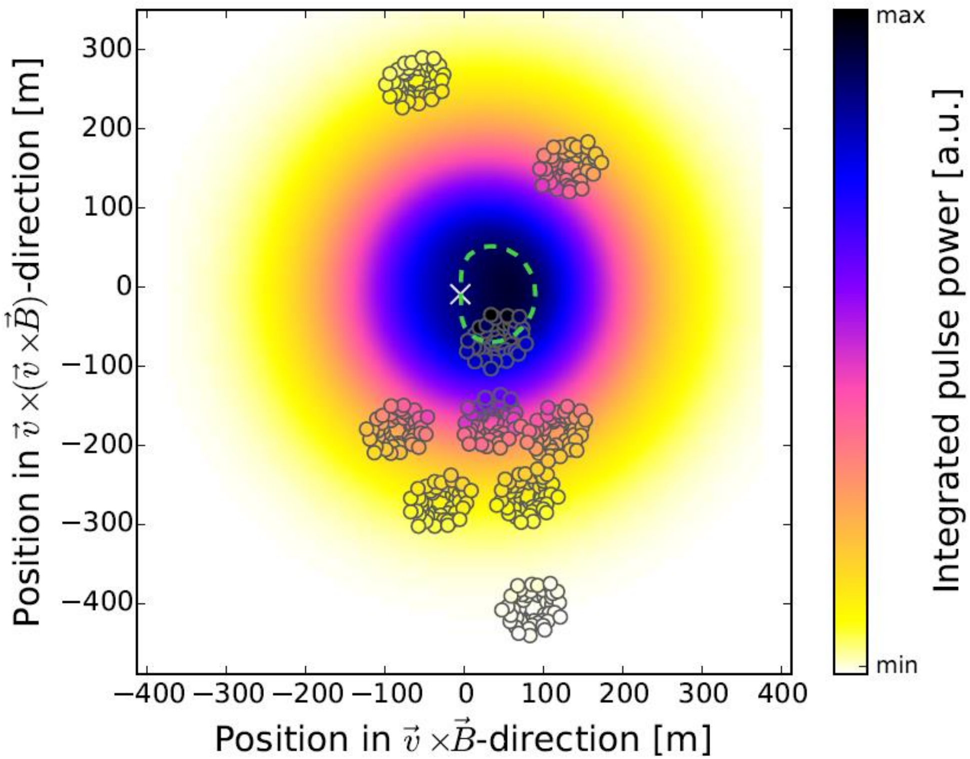
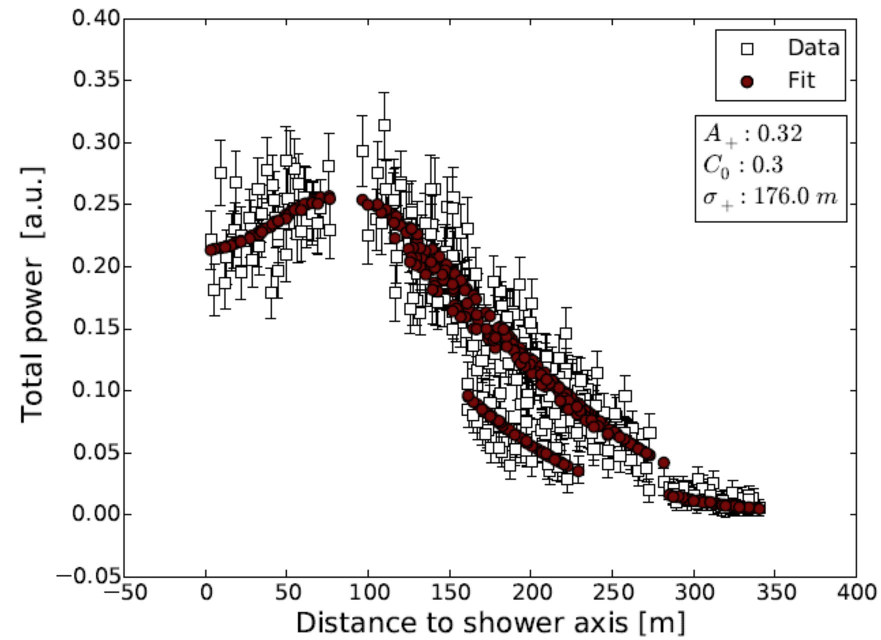
2) Shower maximum via lateral distribution

- Fitting 2-dim asymmetric LDF:

  slope and width parameters sensitive to shower maximum





LOFAR Coll, JCAP05(2015)018

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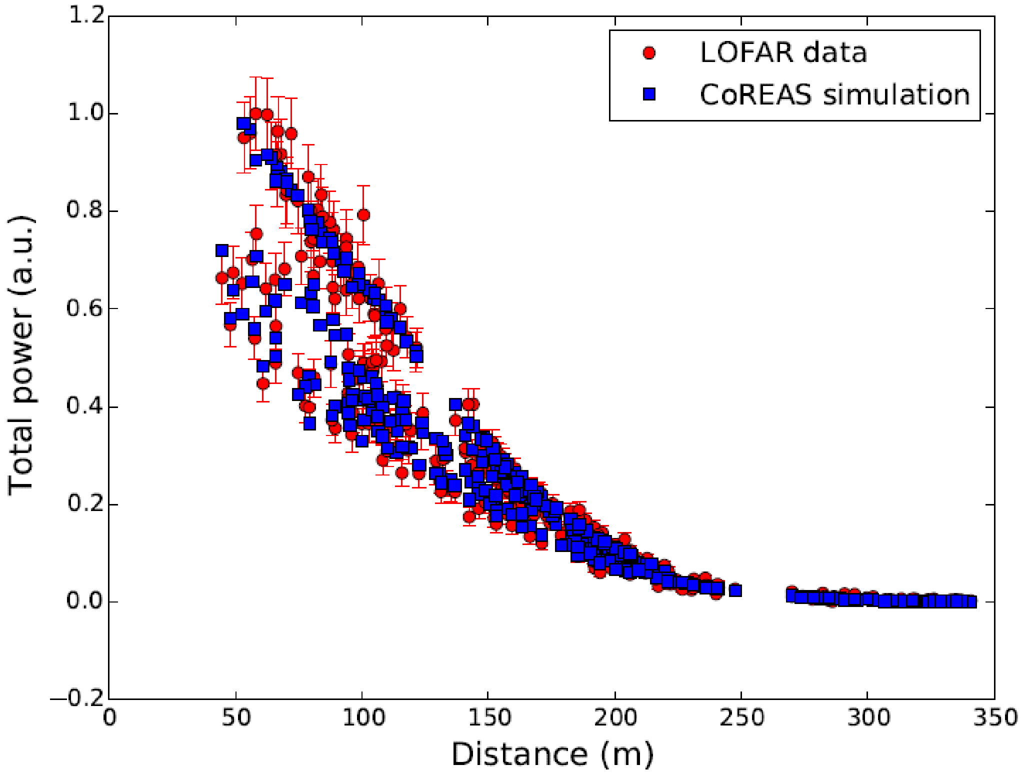
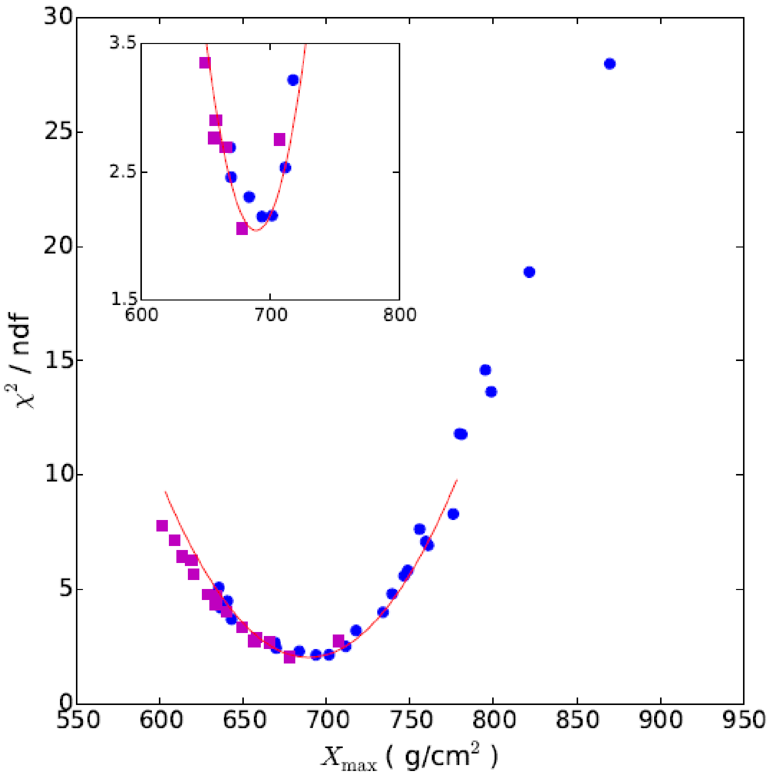
High precision by intensive simulations

- Pick the one of many simulations describing data best
  - very high precision < 20 g/cm²
  - provided no unknown systematics: competitive with fluorescense

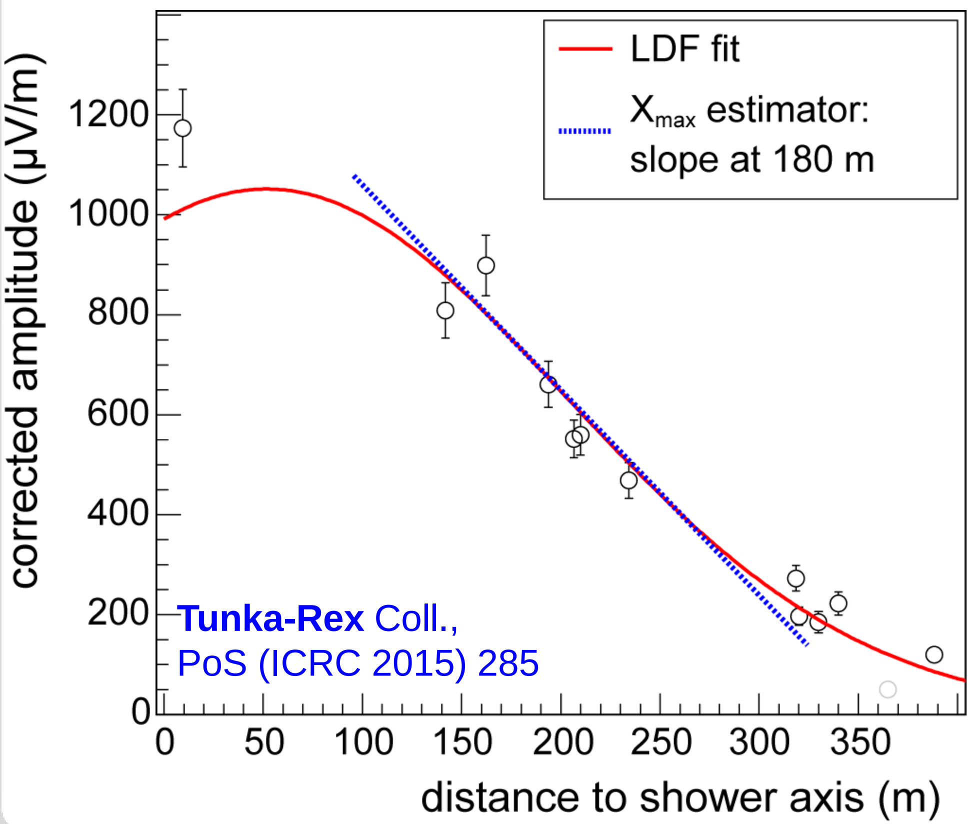


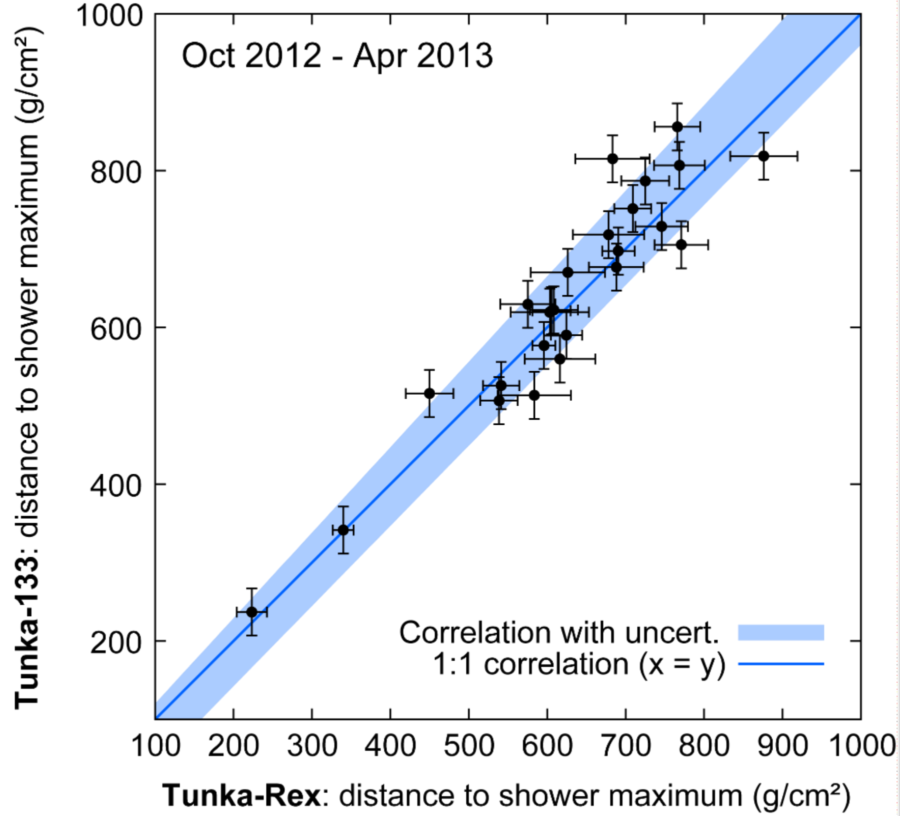


LOFAR Coll, PRD 90 (2014) 082003

Shower maximum: proof by Tunka-Rex

- Sparse (200 m distance) and economic radio array
- Correlation of radio and air-Cherenkov measurements
  - Tunka-Rex accuracy with ~ 5-10 antennas: 40 g/cm²





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Future applications for radio

- Calorimetric, independent energy measurement
  - cross-calibration of absolute scale
- Shower maximum with almost 100 % duty cycle
  - radio = useful extension for any particle detector array
- Additional mass sensitivity in hybrid measurements
  - electron / muon approach → radio + particle detectors
  - radio is ideal for inclined showers
- Ultra-high precision measurements

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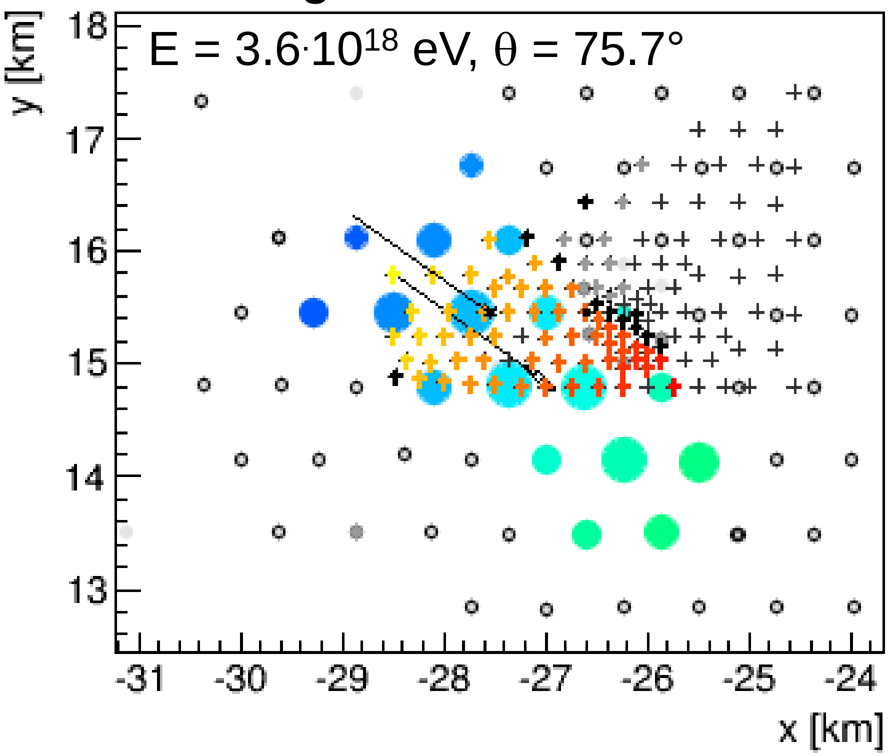
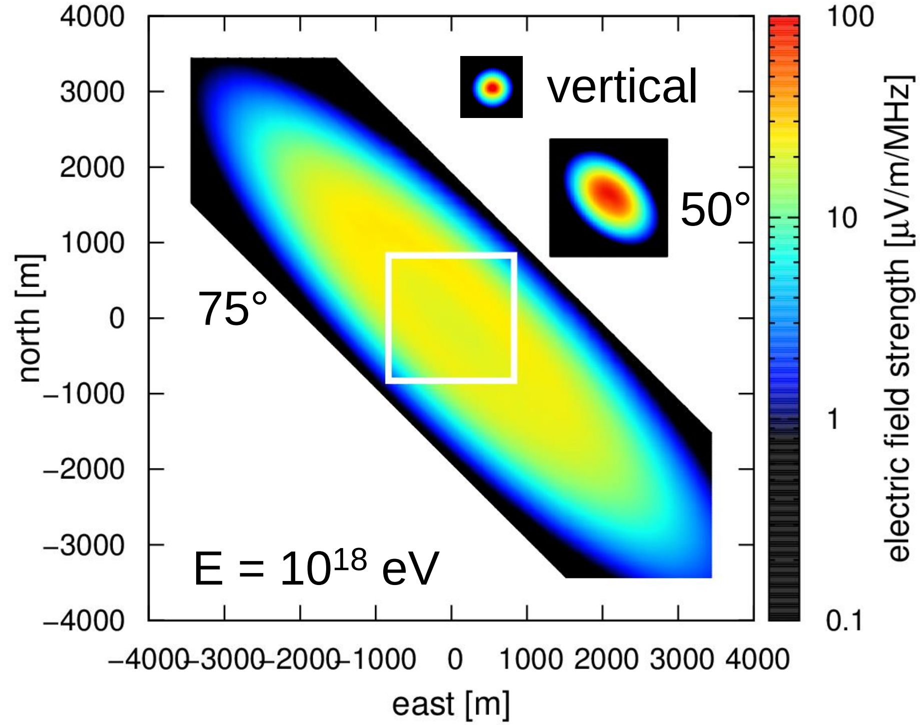
Huge footprint for inclined showers

- Sparse antenna spacing feasible for inclined showers
  - Radio becomes applicable to largest scales for reasonable costs

Auger measurement



CoREAS simulation



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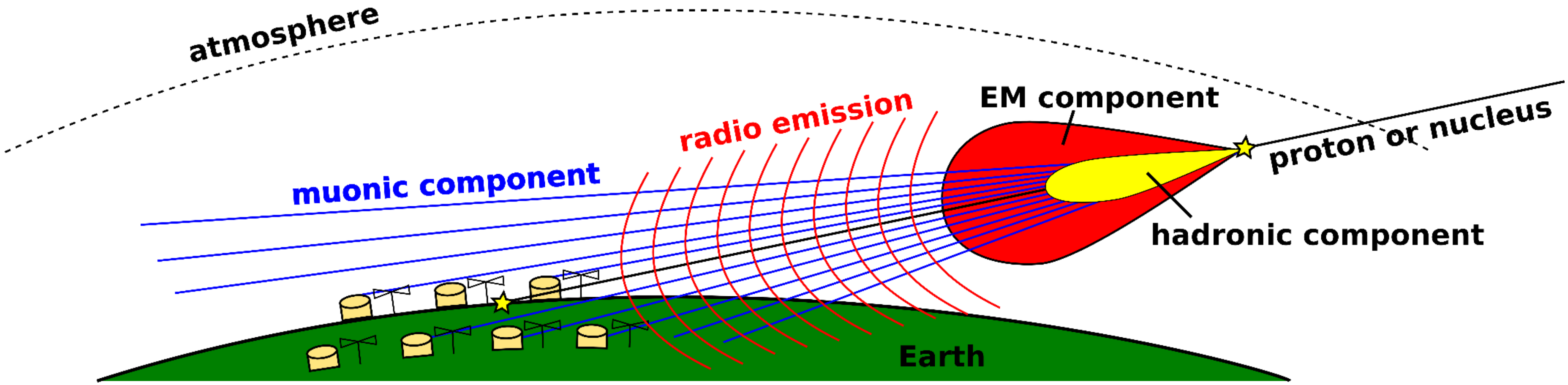
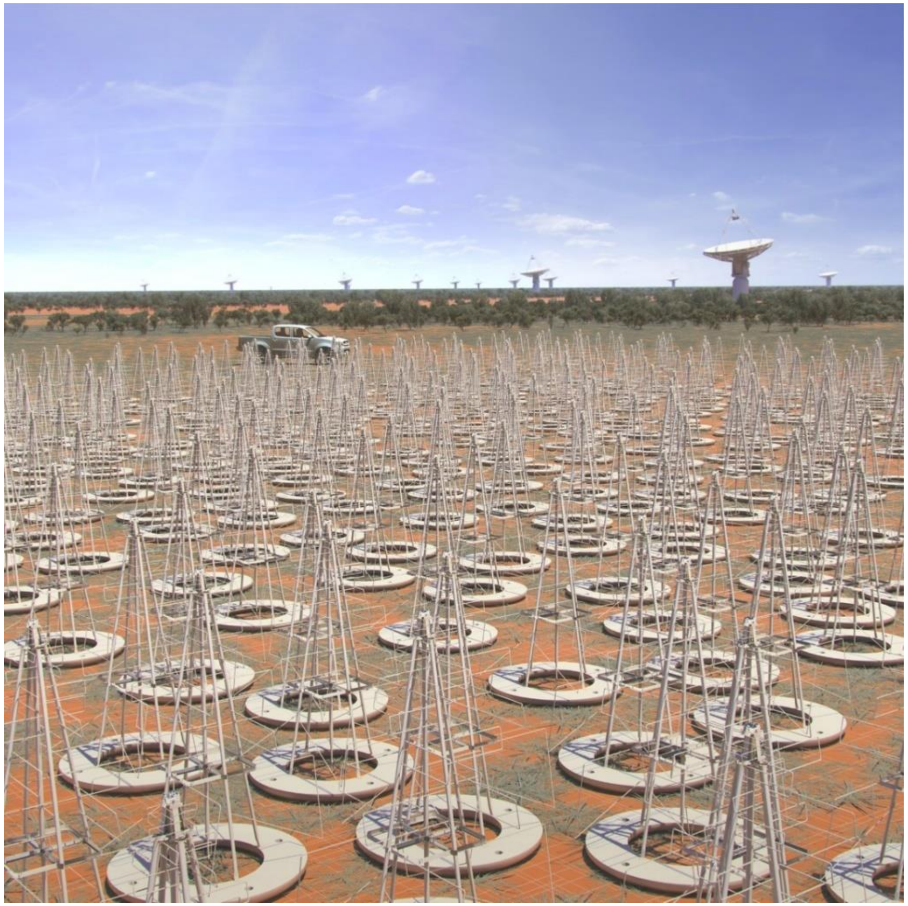
Radio ideal for inclined showers

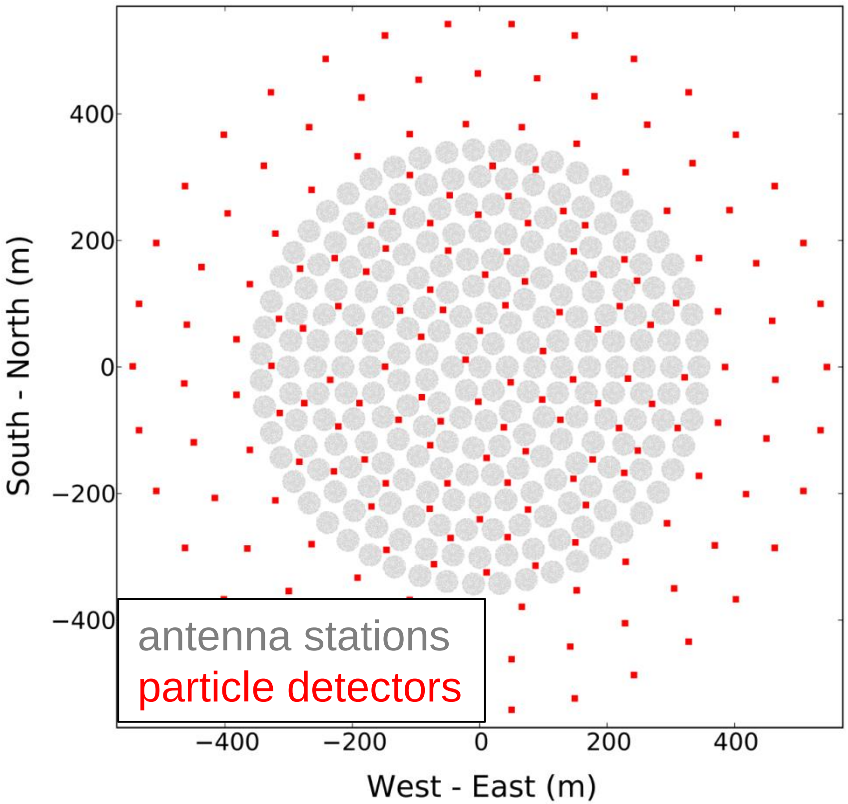


- Electrons and photons attenuate in atmosphere
- Only muons and radio emission survives (no absorption)
  - Complementary information on shower → primary particle type

SKA: ultra high precision

- Phase 1: ~ 60,000 antennas on ½ km²
- Scintillator array planned for E > 10^{16} eV





T. Huege et al., ICRC 2015, Den Haag

Conclusion

- Significant progress in last years
  - digital techniques enabled revival of radio detection
  - radio emission understood to at least 10-20 % accuracy

- Competitive accuracy for air shower parameters
  - direction < 0.7°
  - energy < 20% (precision + scale)
  - X_{max} < 40 g/cm² (better with high antenna density)

- Radio is close to providing cosmic-ray science
  - highest potential in combination with particle measurements

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Backup

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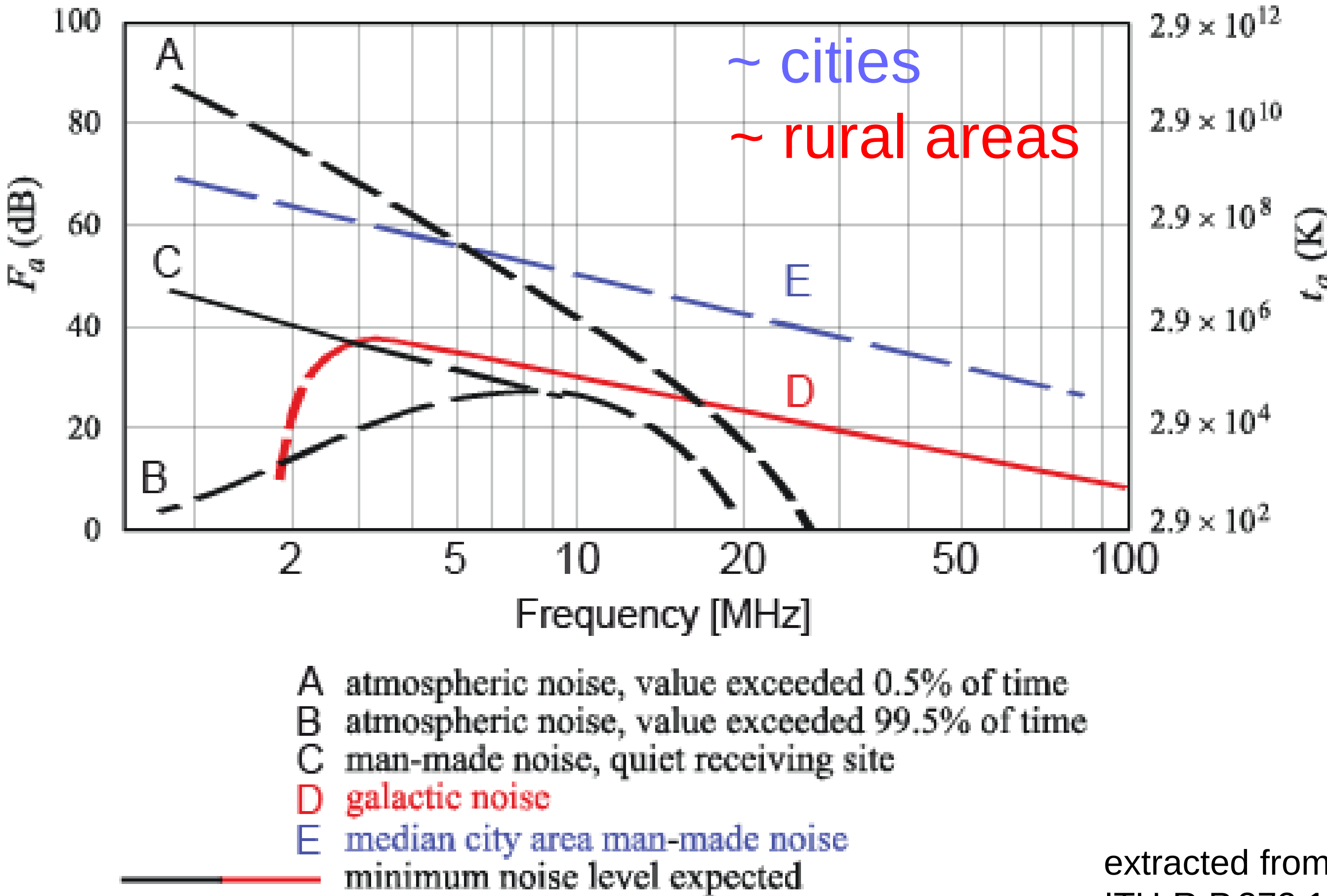
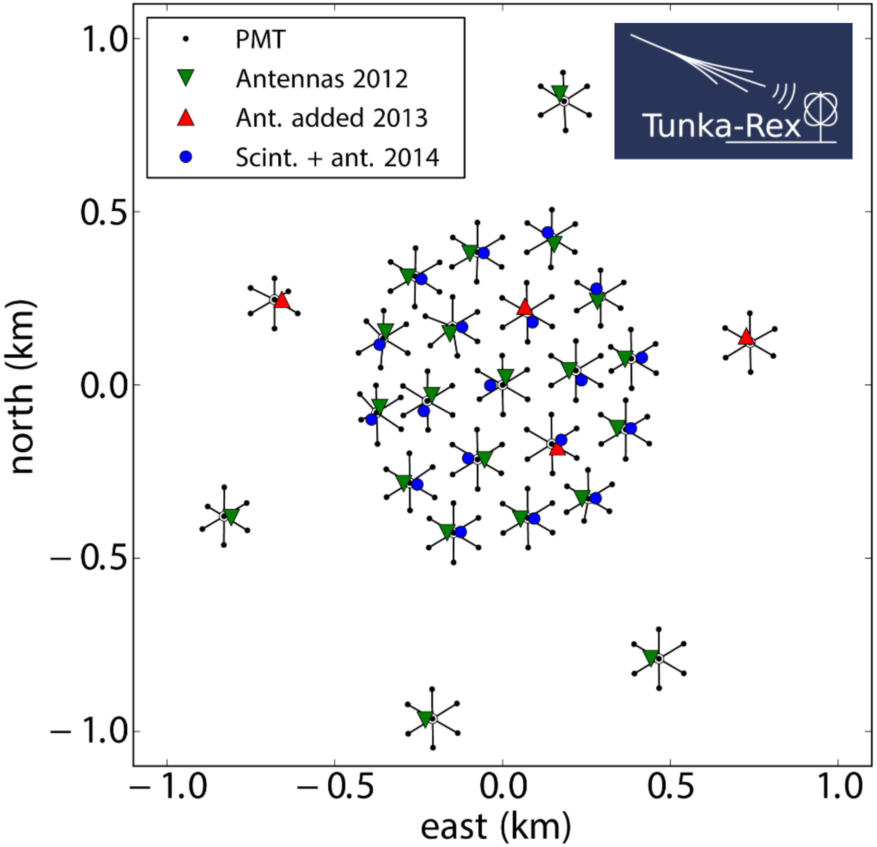
General noise situation

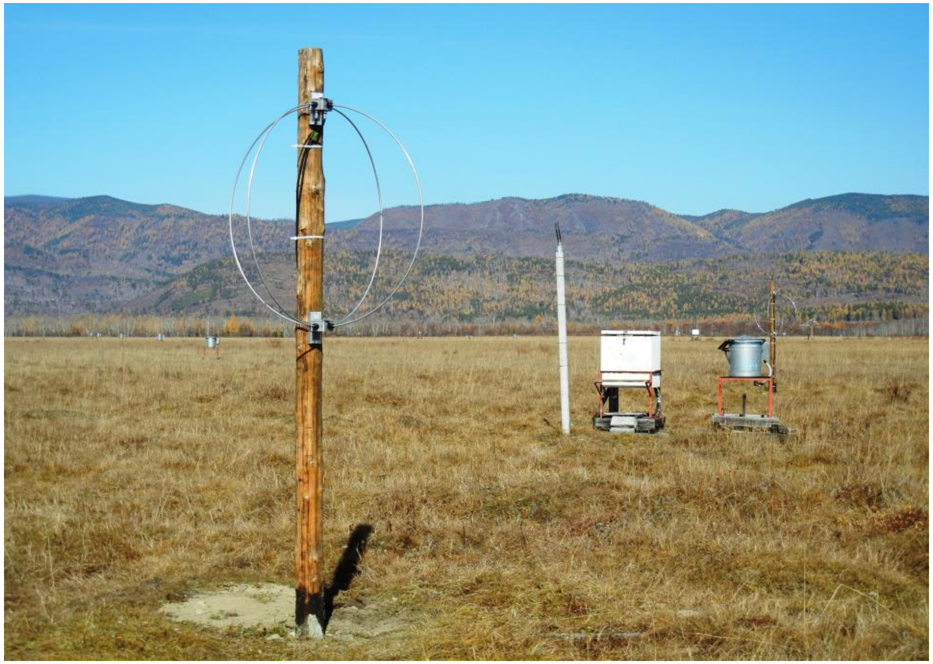


extracted from
ITU-R P.372.10

Tunka-Rex in Siberia close to Lake Baikal

- SALLA antennas, 30 - 80 MHz
- Cross-calibration with co-located air-Cherenkov detector
  - Precision and absolute scale of energy and shower maximum





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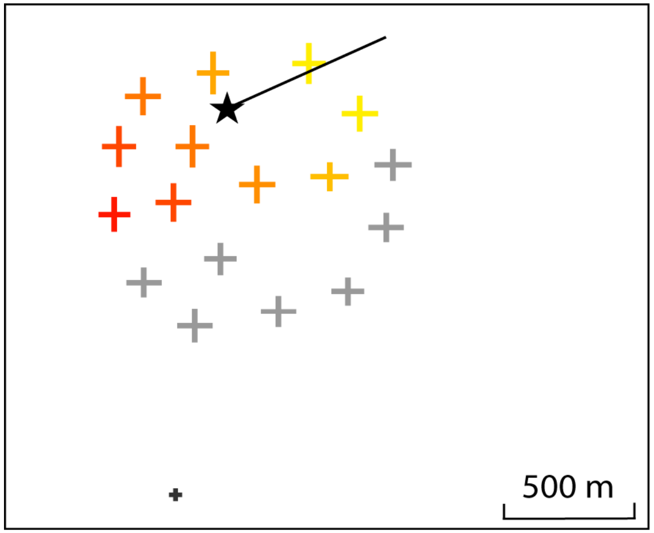
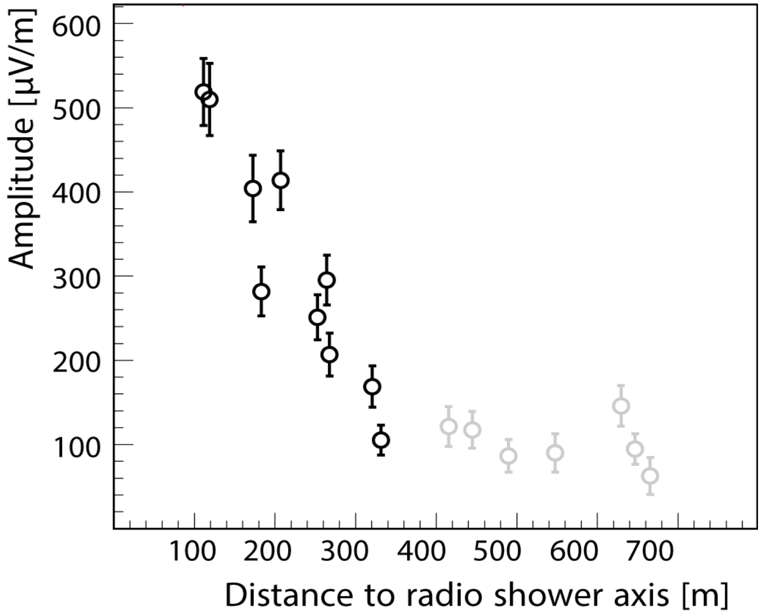
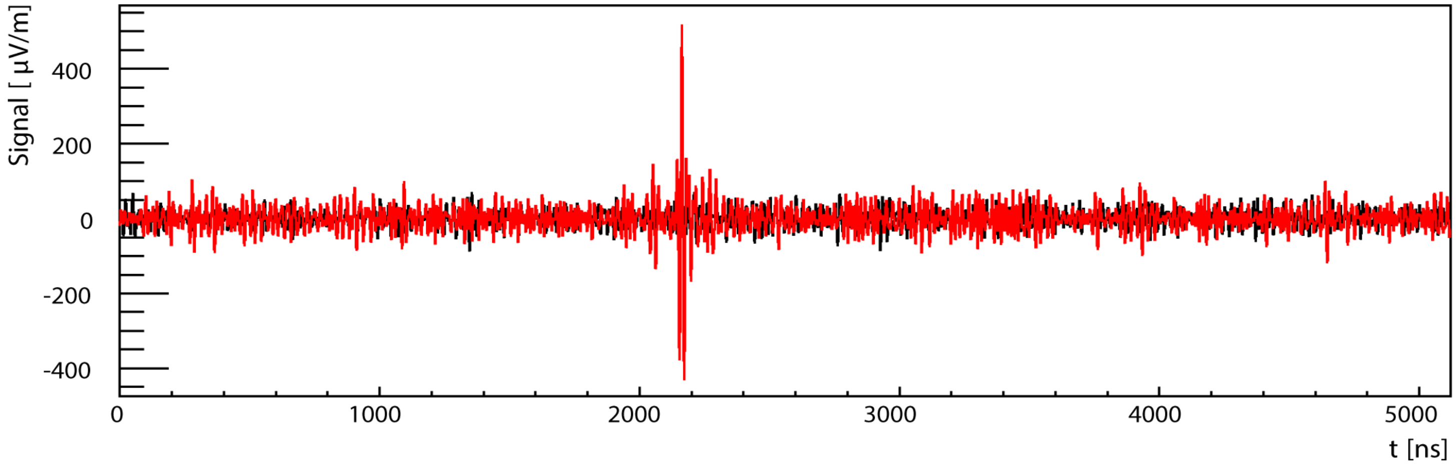
Tunka-Rex example event







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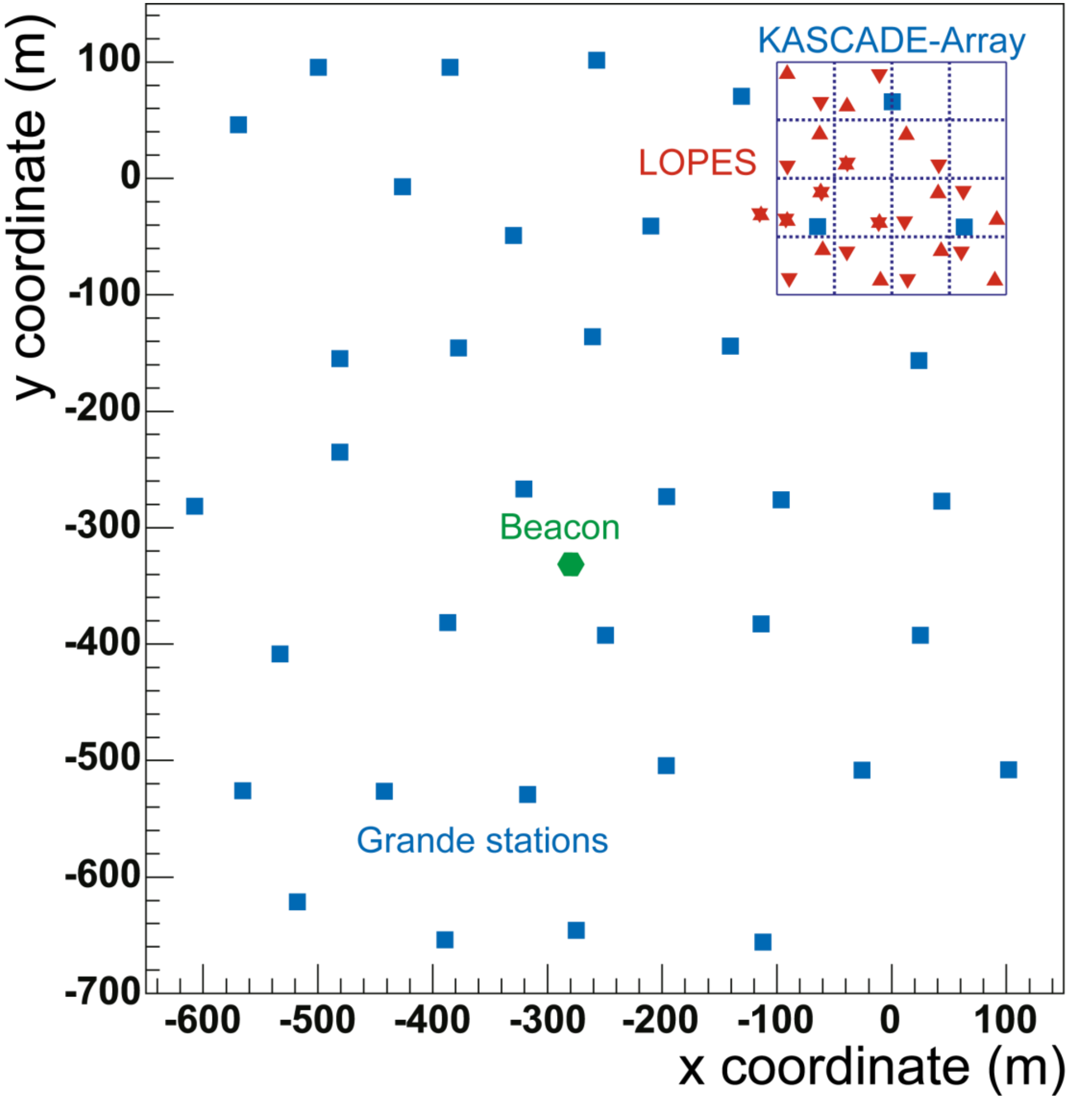
LOPES (also since 2003, was at KIT)



- 30 dipole antennas
  - 40 – 80 MHz
  - **east-west** / north-south
- Trigger by KASCADE

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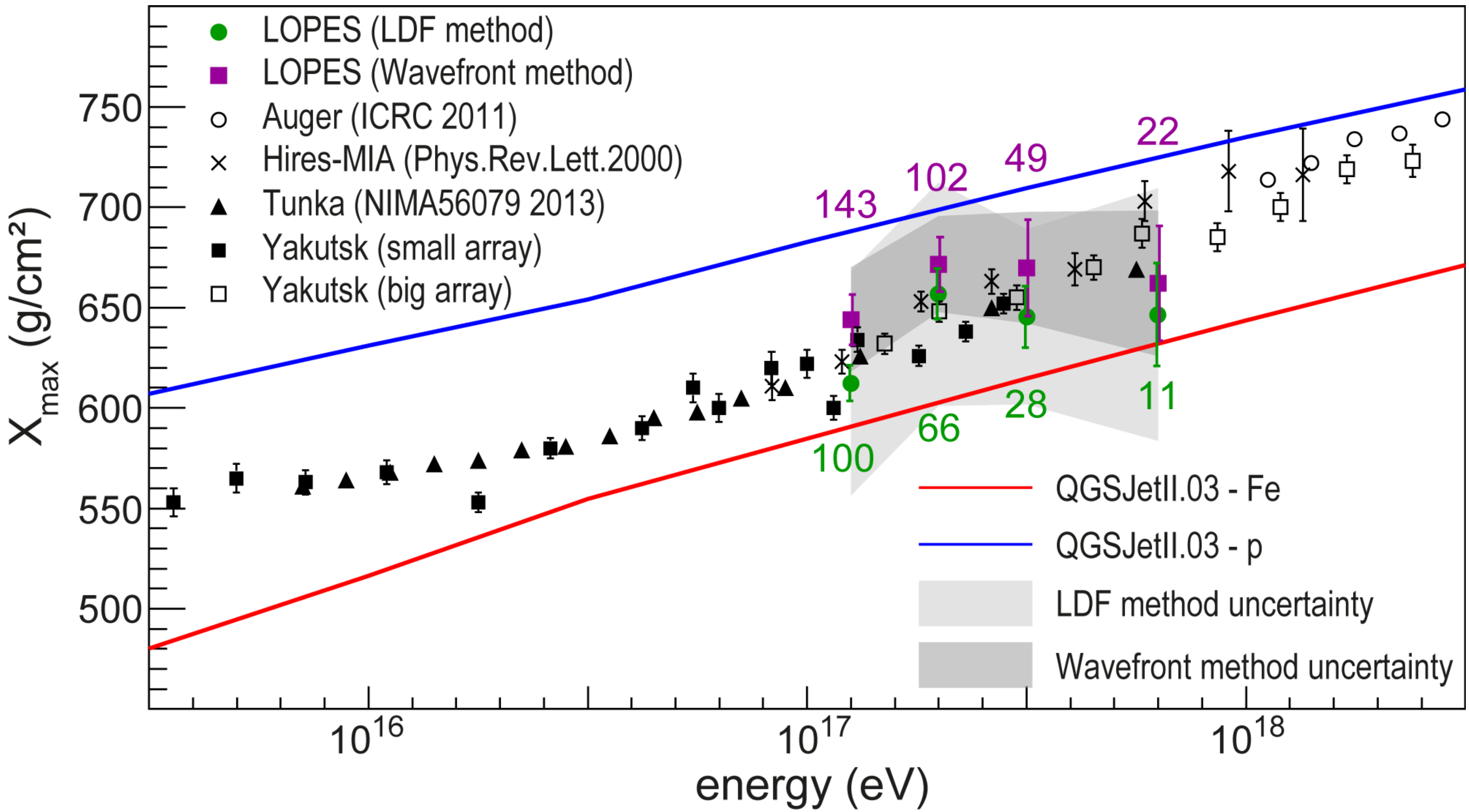
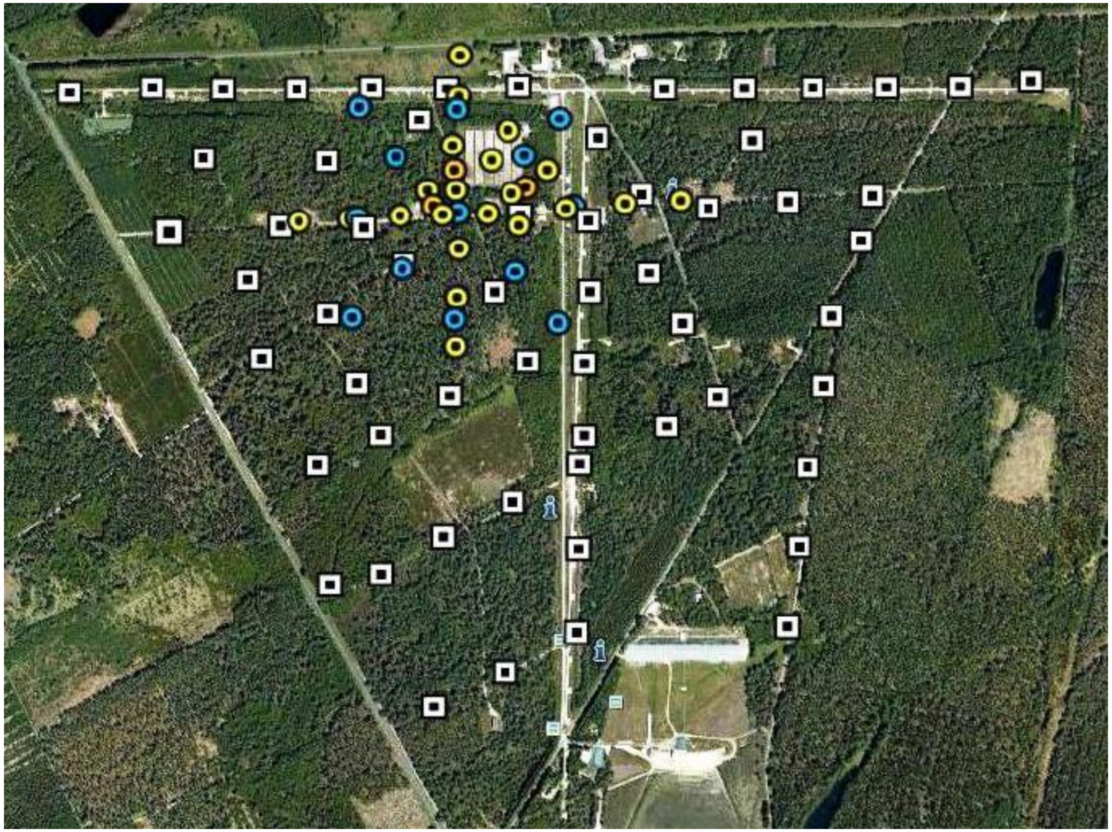
Radio shower maximum consistent



LOPES Coll., ECRS 2014

CODALEMA

- Several configurations since 2003, close to Nancy, France
  - now: self-triggering stations (30-80 MHz) + particle detectors



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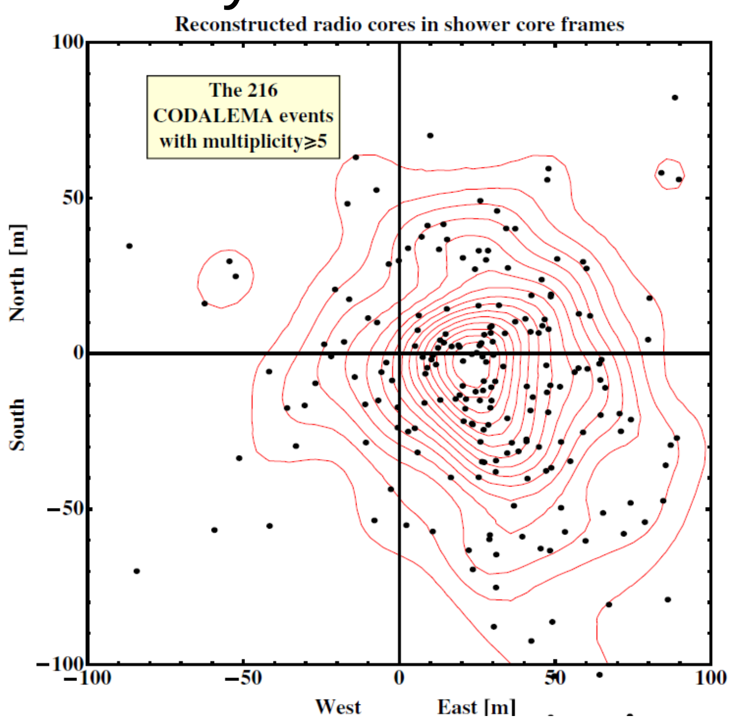
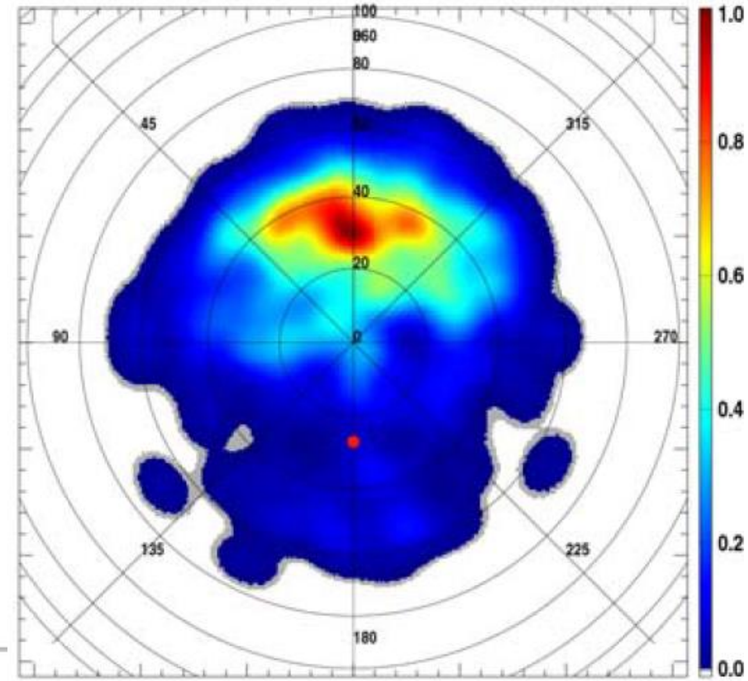
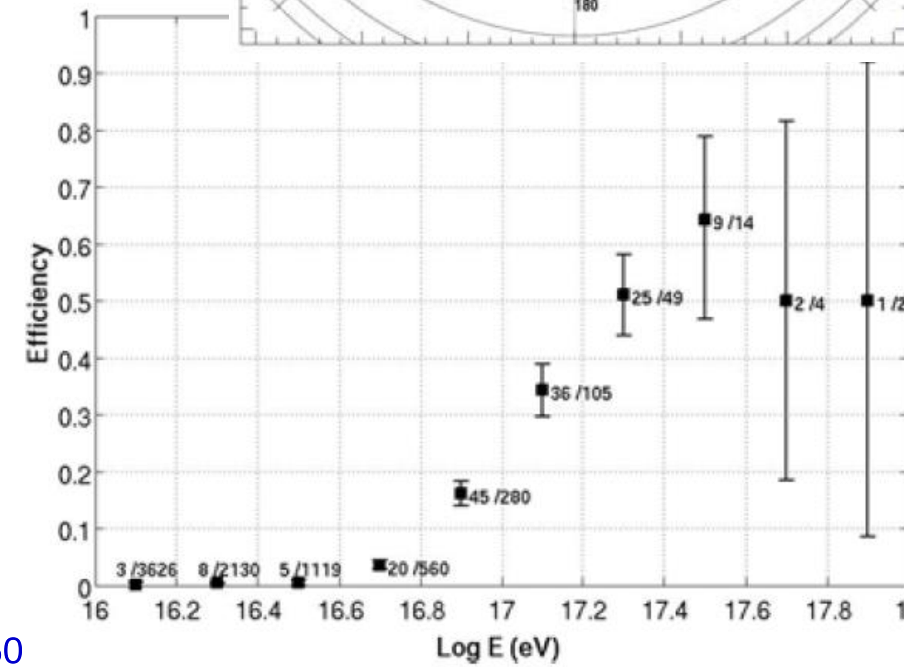
Evidence for emission mechanisms

- Geomagnetic angle determines efficiency
- Core shift due to Askaryan effect







CODALEMA, Astropp. 31 (2009) 192 and 69 (2015) 50

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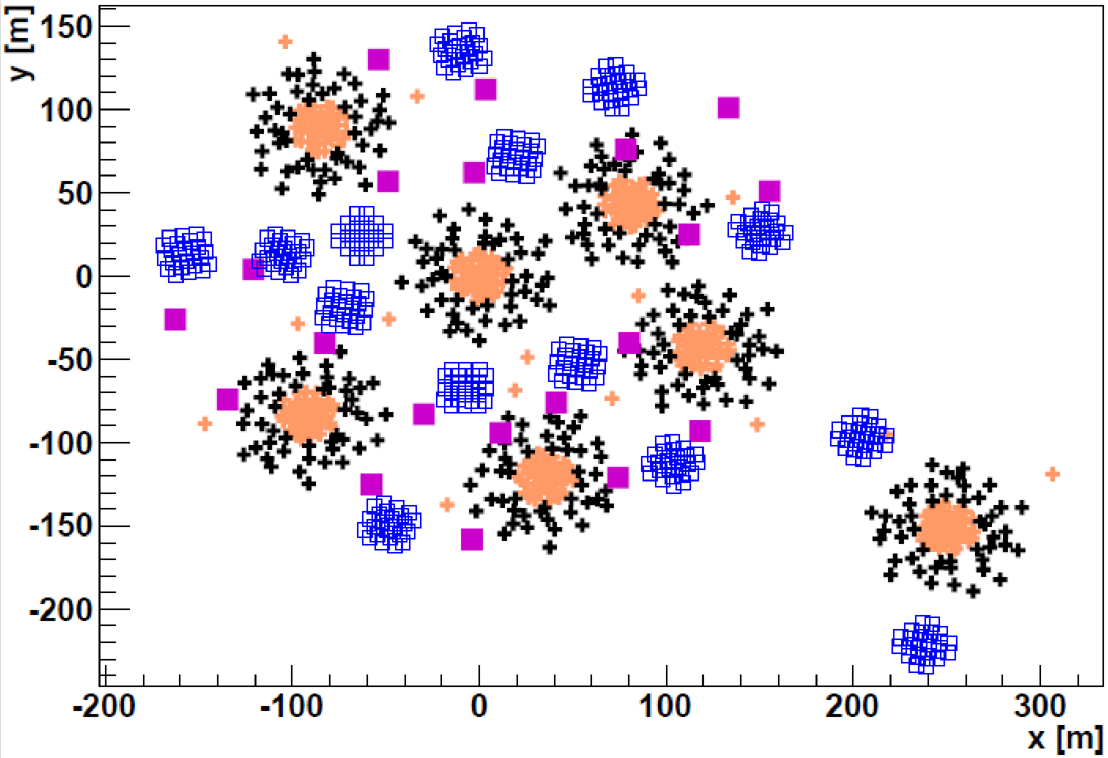
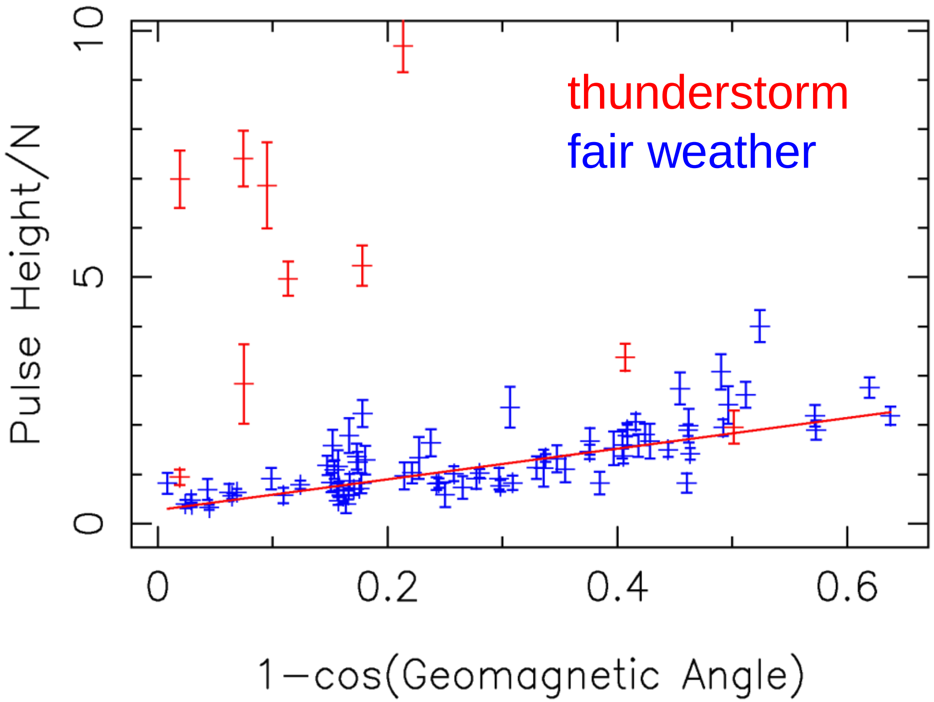
LOFAR superterp, the Netherlands

- Several 100 antennas on several 100 m²
  - Low band: 10-90 MHz
  - High band: 110-190 MHz

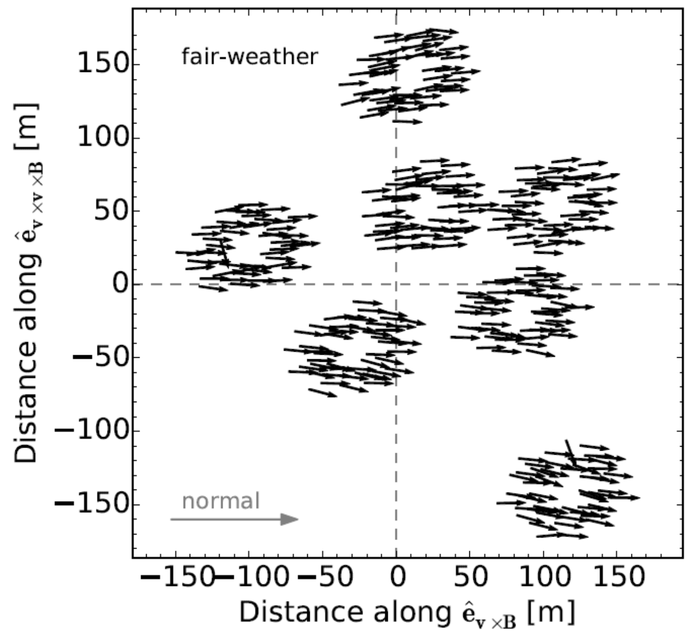


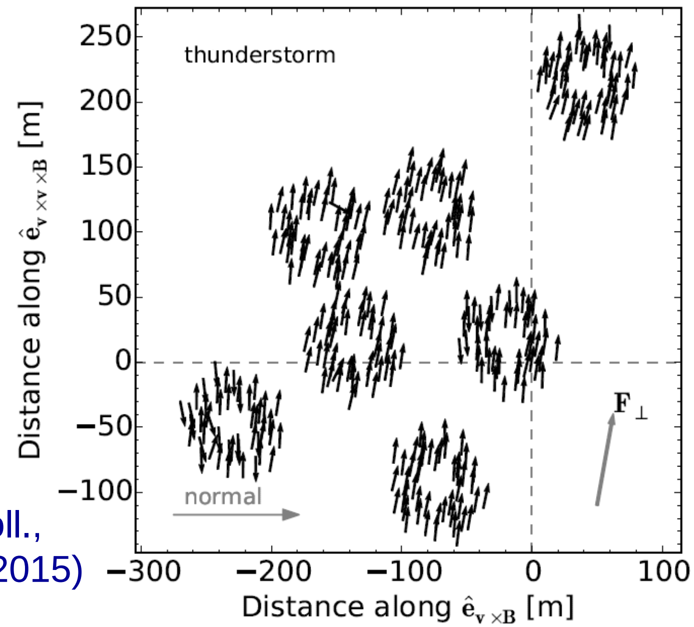
Thunderstorms

- High atmospheric E-fields influence radio emission
  - air-showers could probe atmospheric E-fields



LOPES Coll., A&A 467 (2007) 385

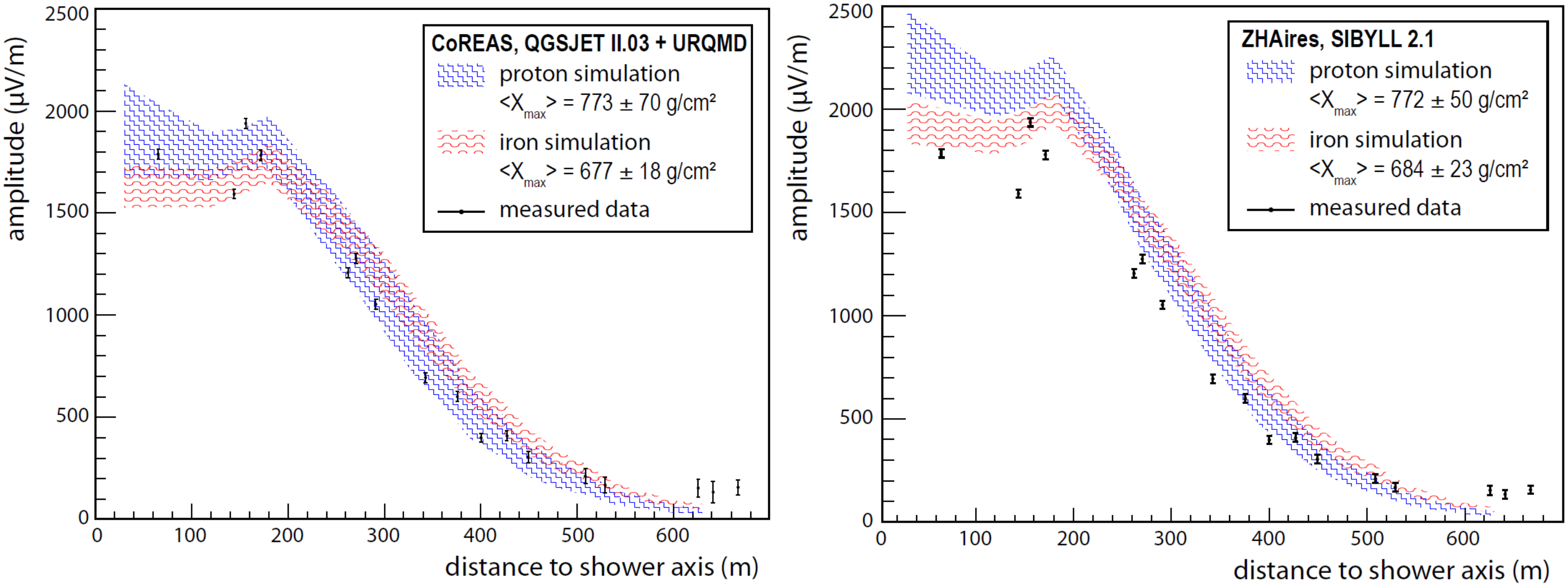




LOFAR Coll., PRL 114 (2015) 165001

Comparing simulations with AERA event

Karlsruhe Institute of Technology



- Example event with calibrated AERA measurements
- CoREAS and ZHAires simulations reproduce shape
  - differences compatible with calibration scale uncertainty?

Pierre Auger Collaboration, ICRC2013, id #899

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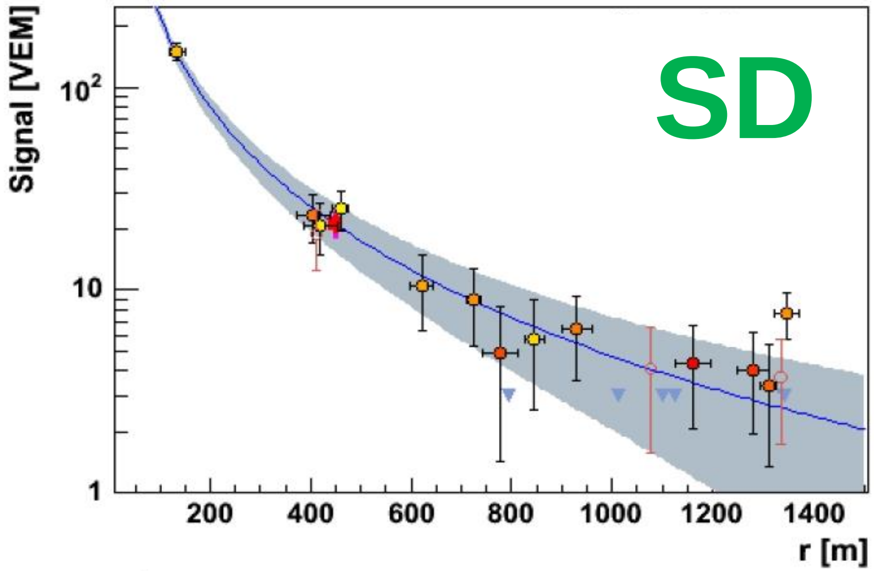
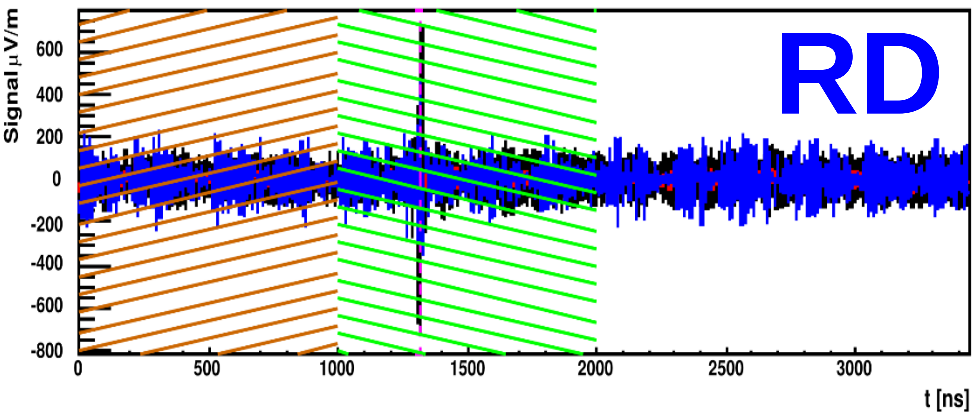
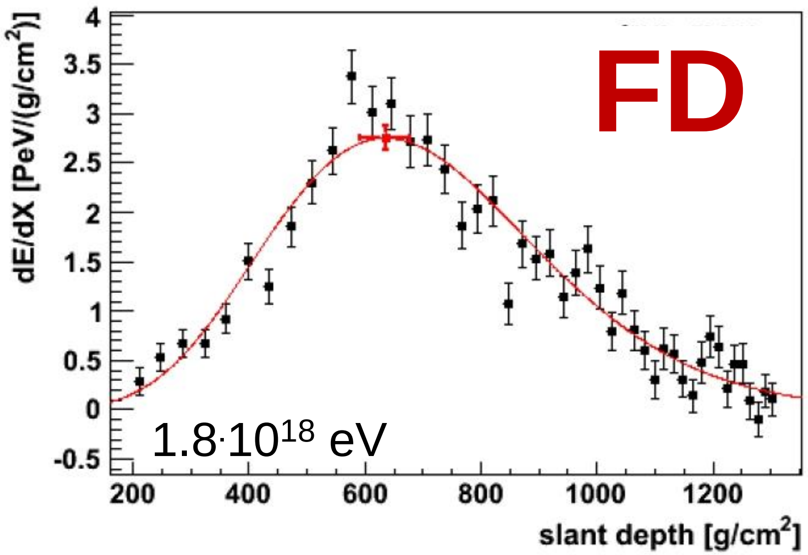
Example event

- Radio measurement
  - hybrid measurements with particles and fluorescence
  - trigger / combined analysis
- Vectorial measurement
  - 2 polarizations
  - both 30-80 MHz







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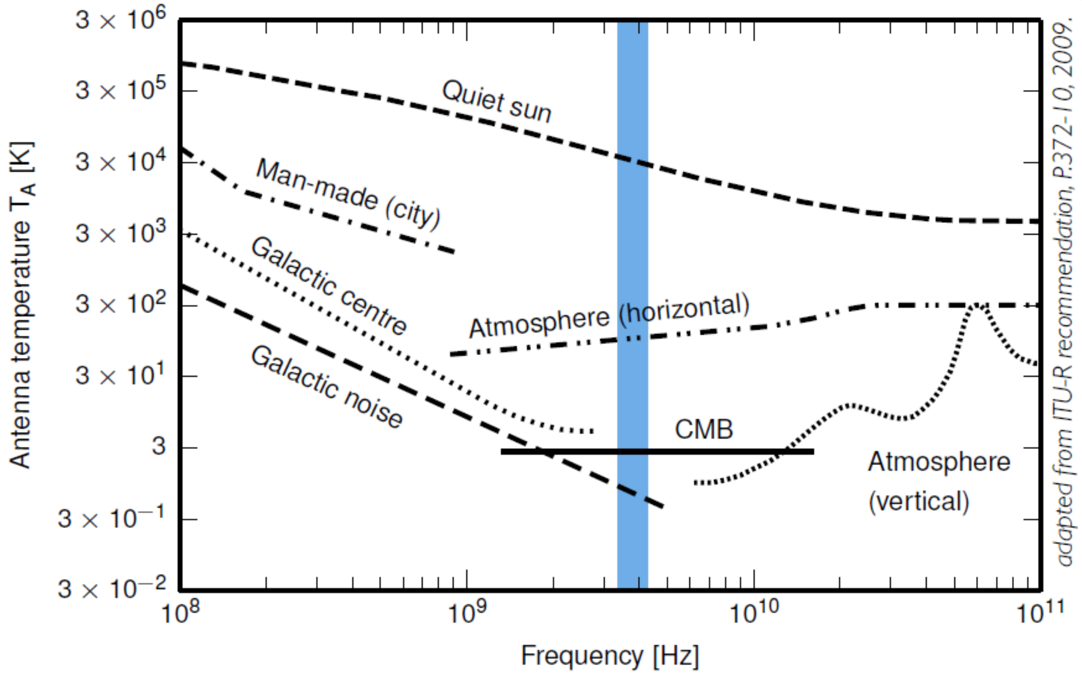
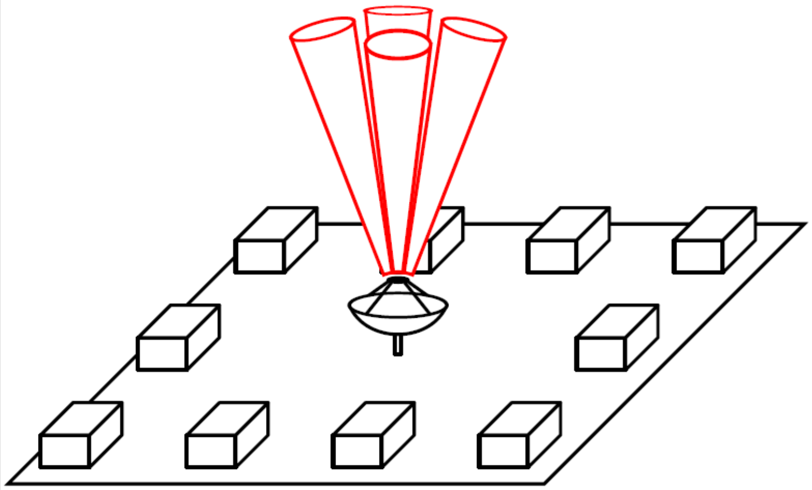
CROME at KIT

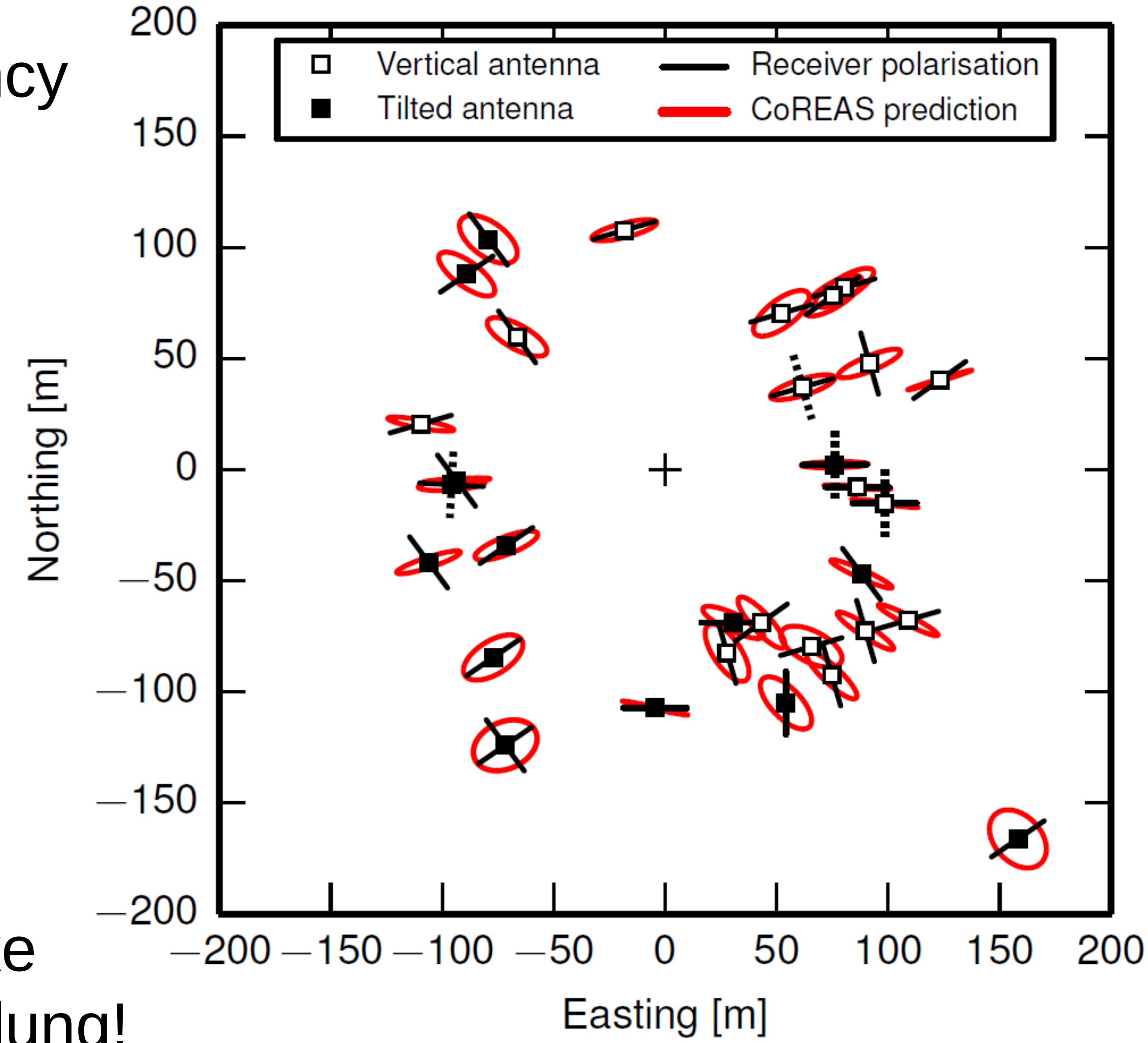
- Commercial GHz electronics
- Detection in C band
  - 3.4 -4.2 GHz
- Low noise: T ~ 80 K





Cherenkov ring seen with CROME

- High detection efficiency on Cherenkov ring at GHz frequencies
- Compatible with CoREAS prediction of geomagnetic and Askaryan emission
- Polarization is not compatible with un-polarized emission, like molecular bremsstrahlung!



ARENA 2014 and **PRL 113 (2014) 221101**

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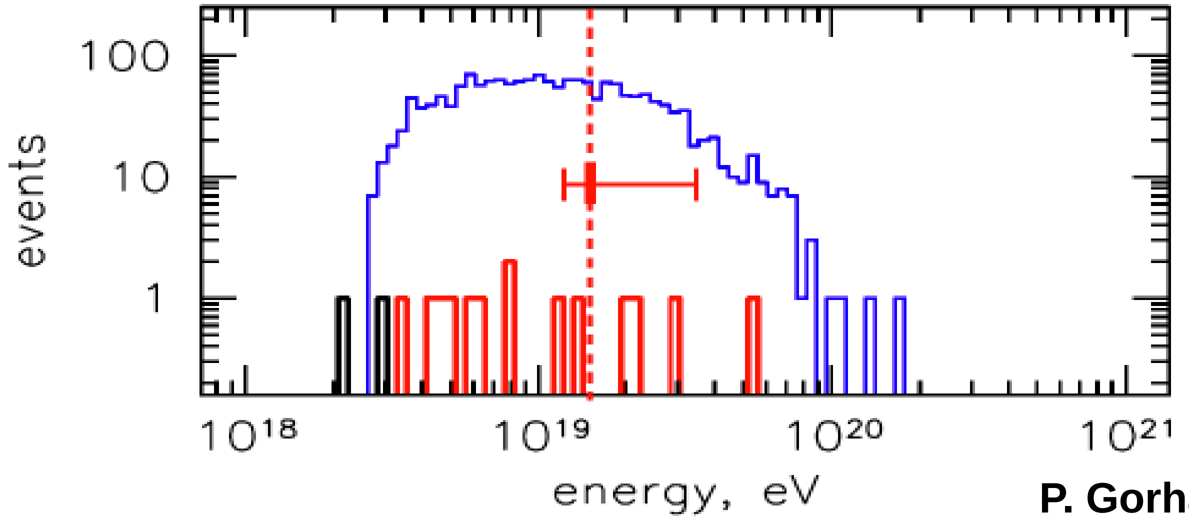
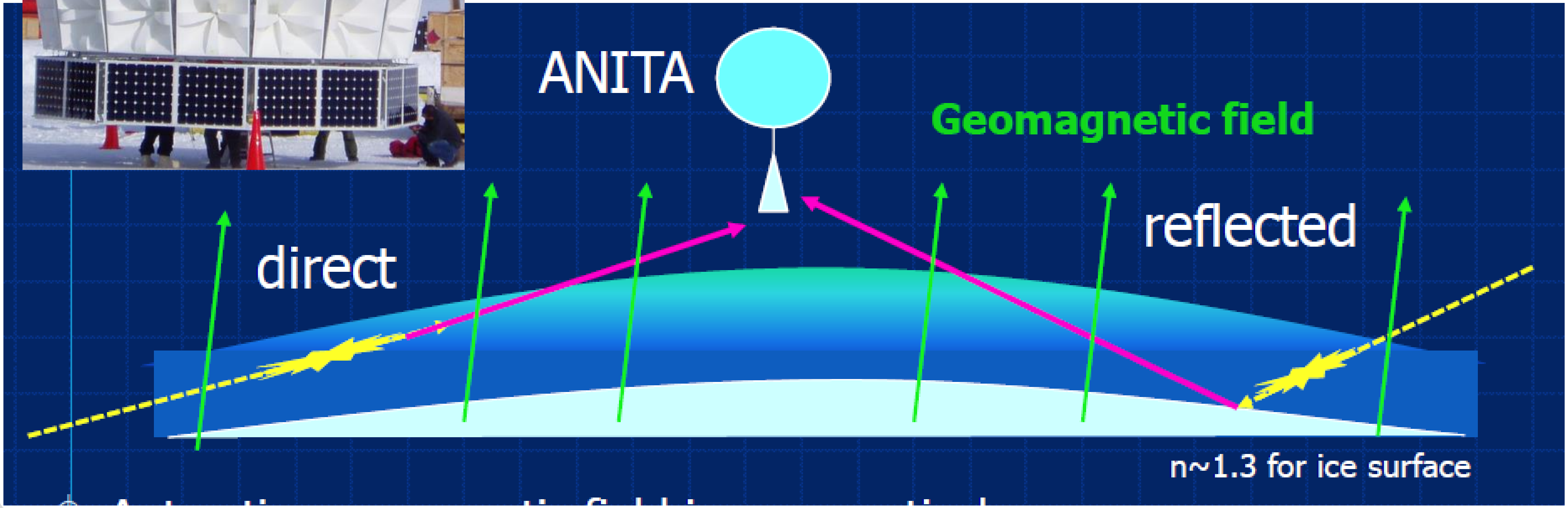
ANITA (detected ~ 14 CR events)



P. Gorham



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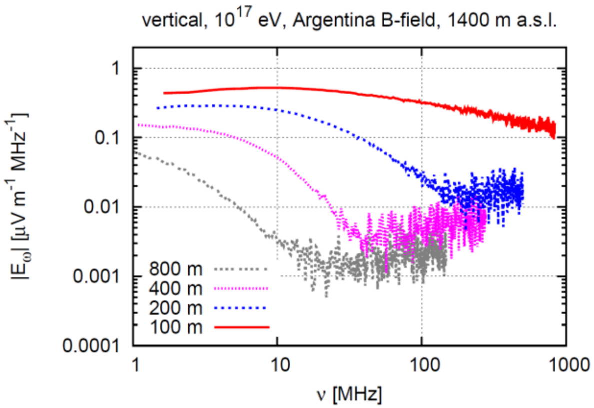
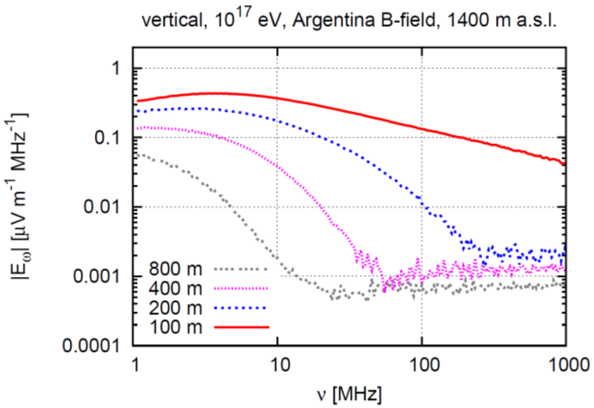
Simulated frequency spectra

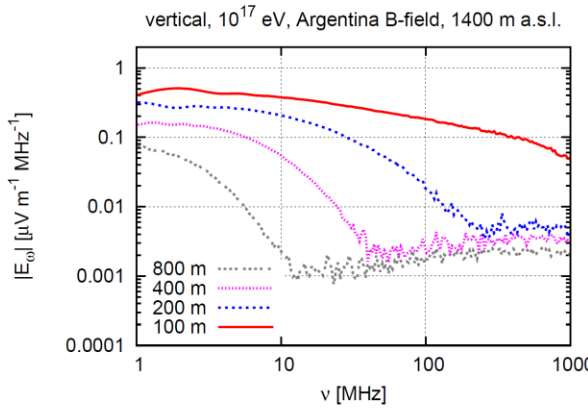
REAS3.1

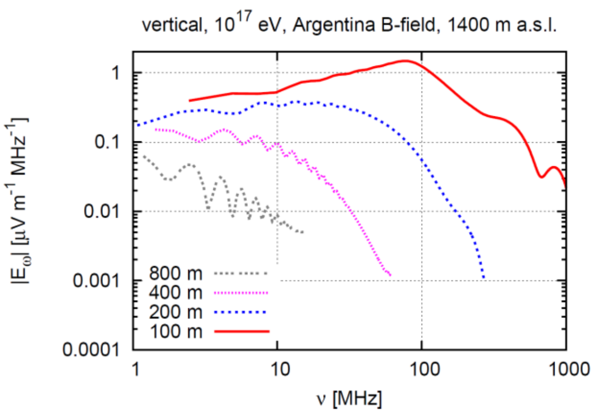


CoREAS

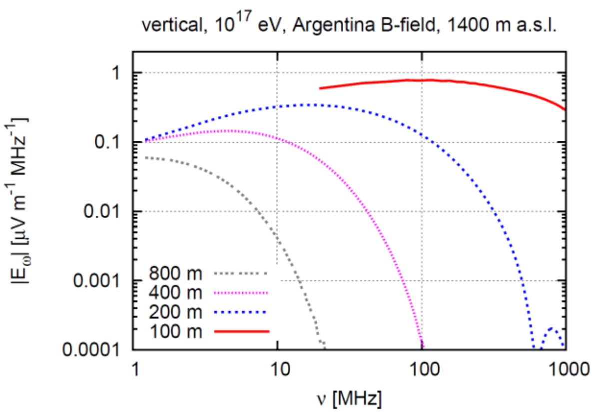


ZHAireS

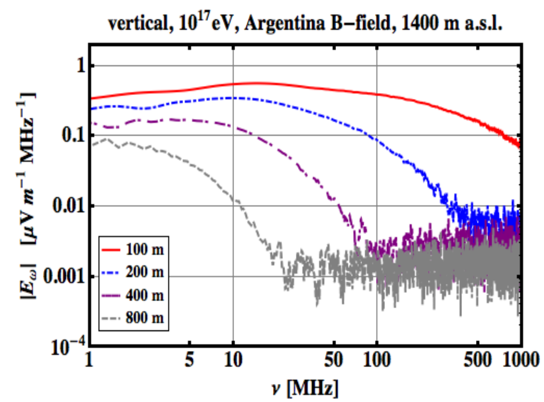




MGMR



EVA

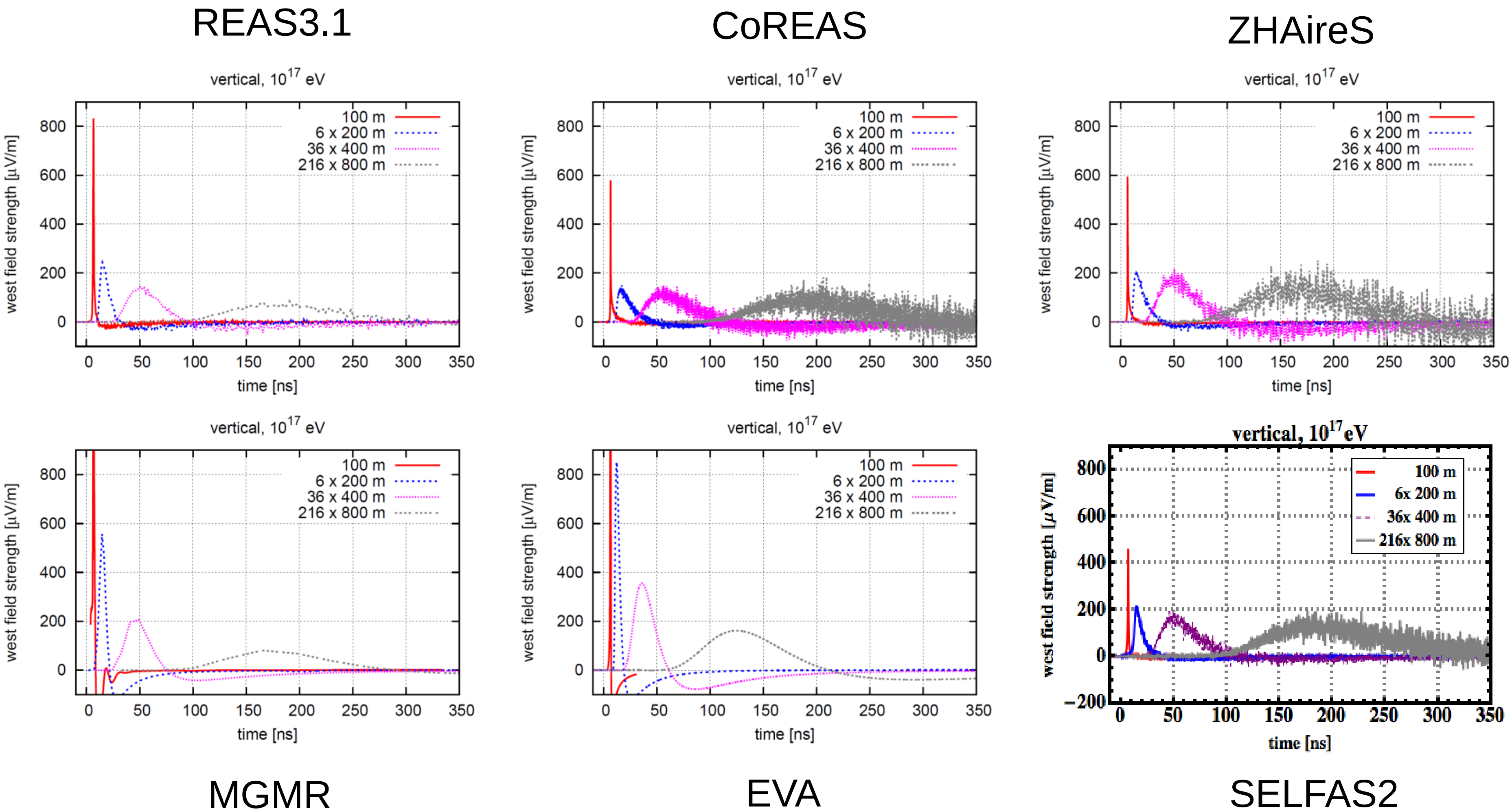


SELFAS2

vertical 10^{17} eV shower, total field, n=r

T. Huege et al., ARENA2012

Simulated pulses: time series



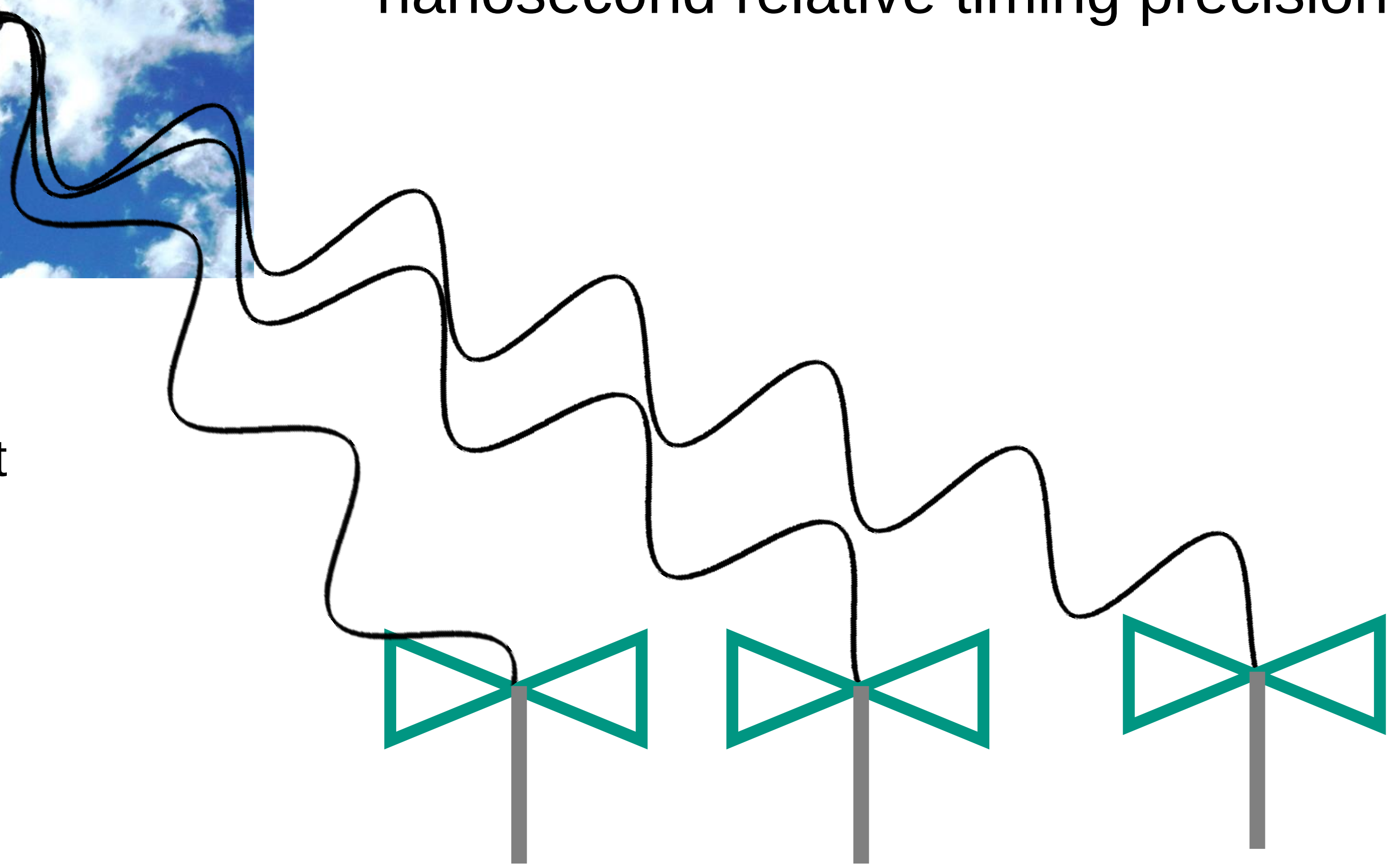
vertical 10^{17} eV shower, west field, n=1

T. Huege et al., ARENA2012

AERA Beacon

- Phasing of sine waves provides nanosecond relative timing precision

Beacon:
continuous wave emitter, 3 km west of AERA



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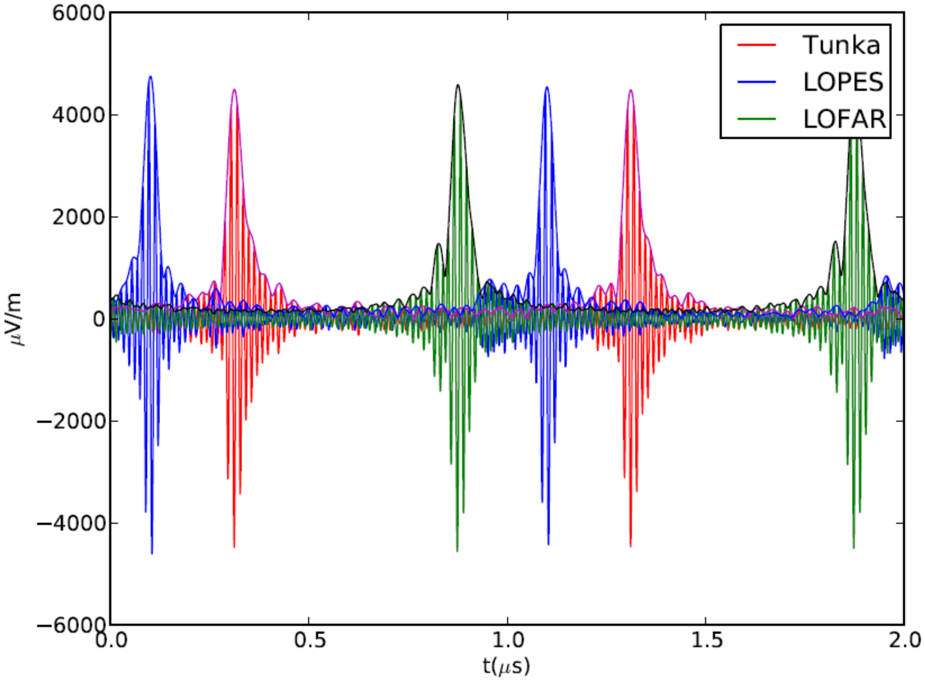
Amplitude calibration

- Commercial reference source also used by LOPES and LOFAR

→ Common amplitude scale



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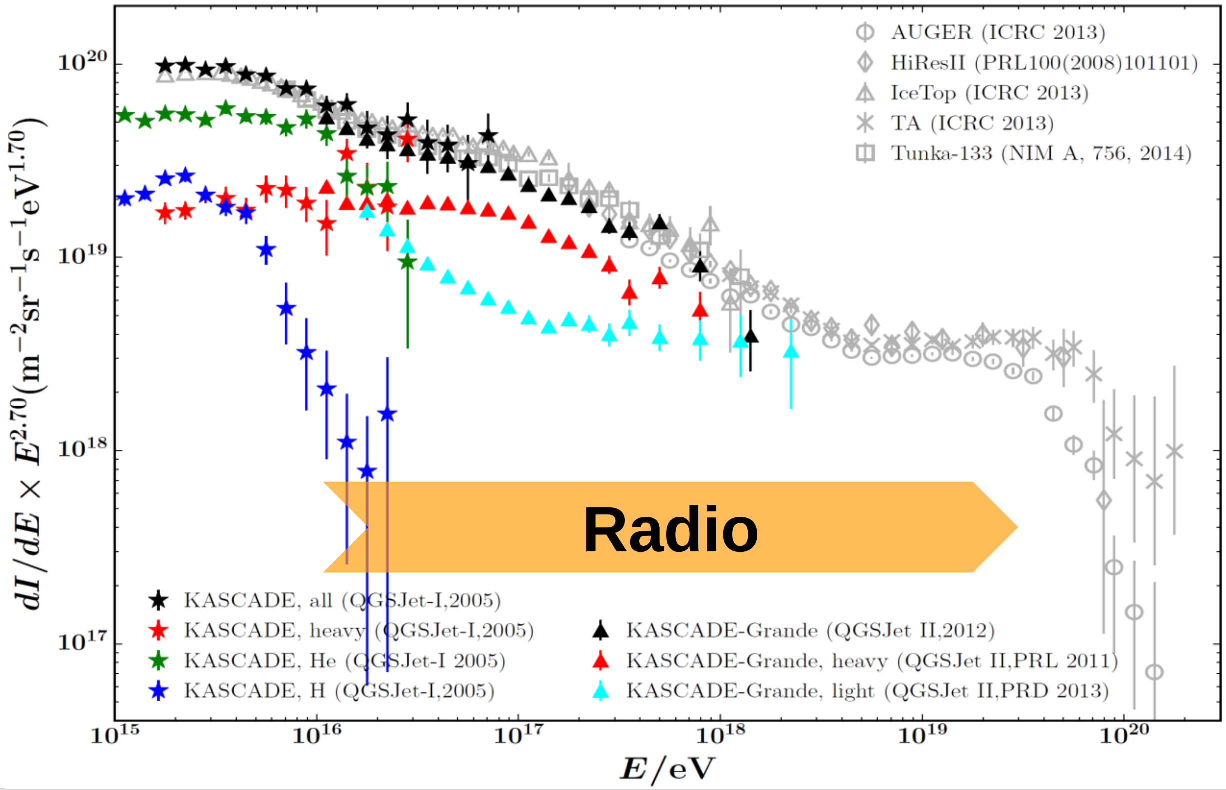
Advantages of radio technique

- Direction, energy and Xmax around the clock
- Accurate measurement of em. shower component
- Energy range of assumed galactic – extragalactic transition



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