Karlsruhe Institute of Technology

Radio detection of air showers

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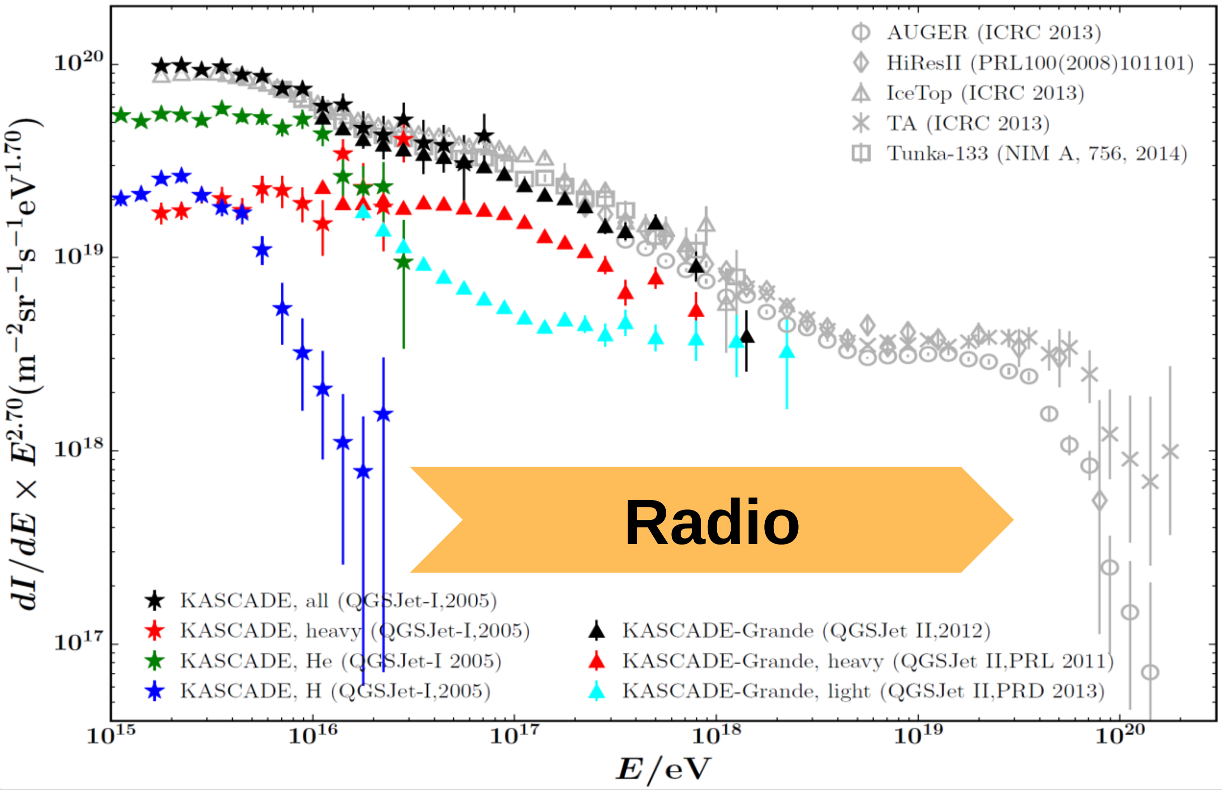
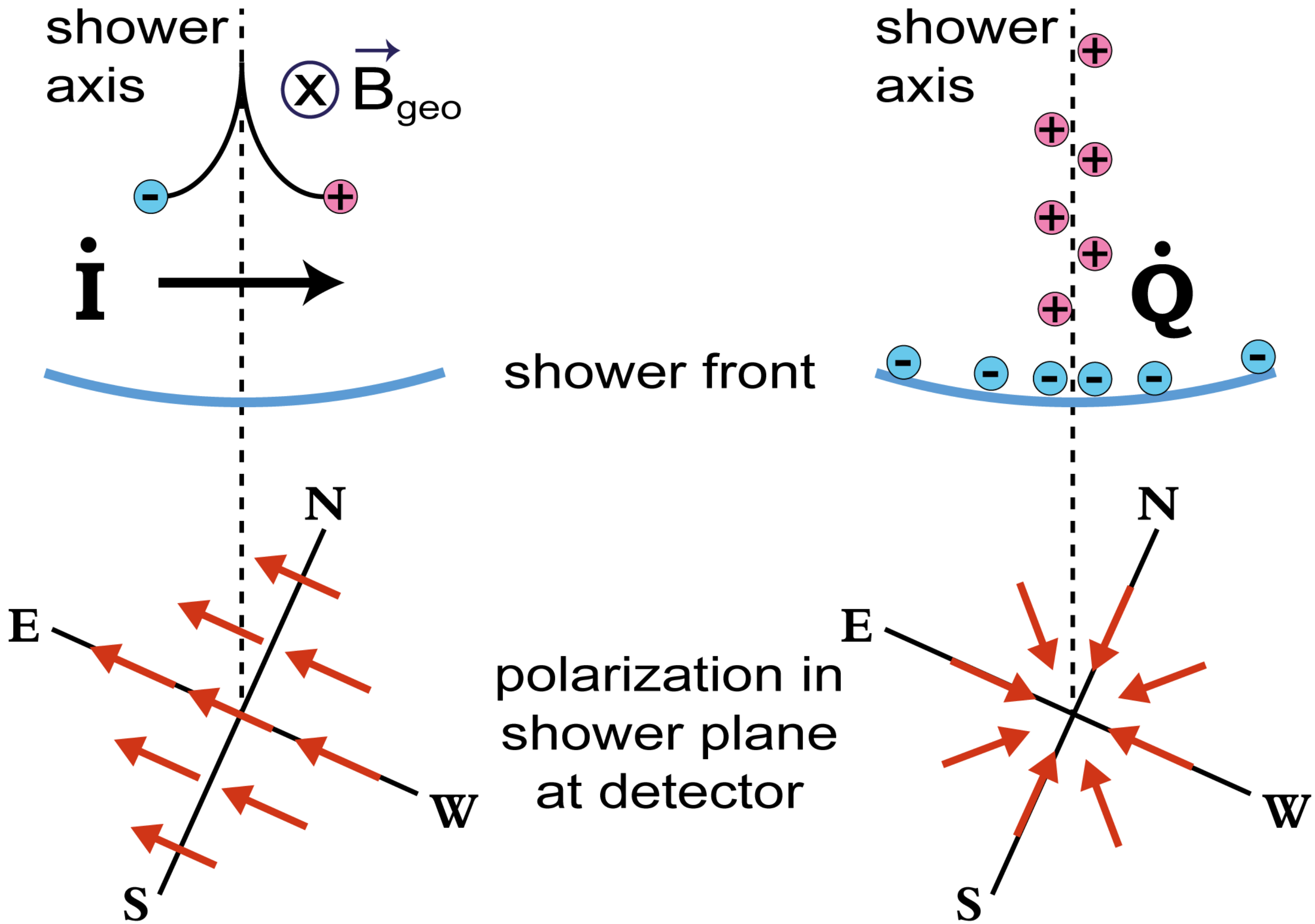
Advantages of radio technique

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



Emission mechanisms



geomagnetic effect ~ 90%

Askaryan effect ~ 10%

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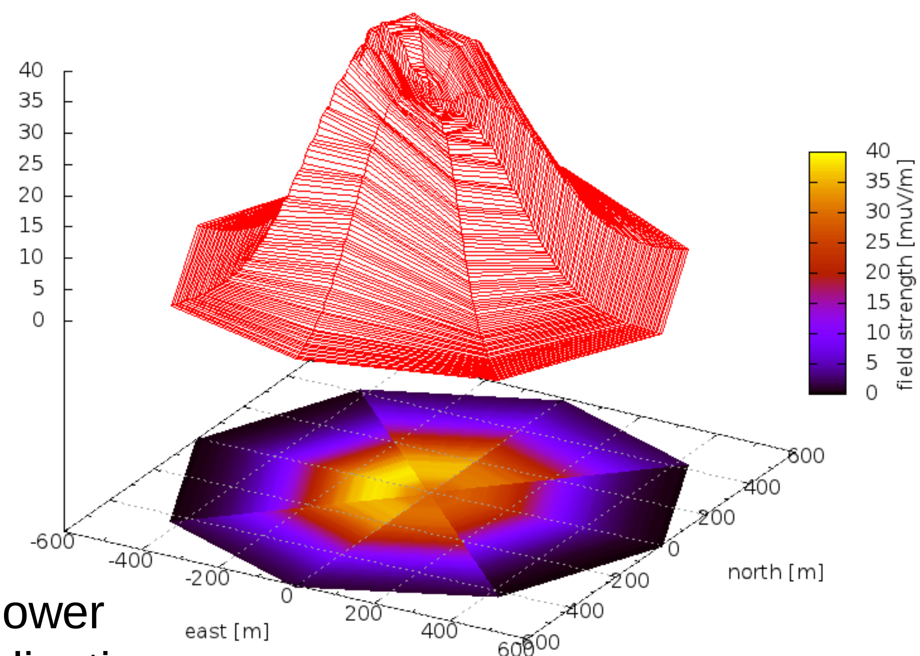
Simulated footprints of radio signal

- Slightly asymetric emission due to interplay of mechanism
- Forward beamed: large footprint only for inclined showers

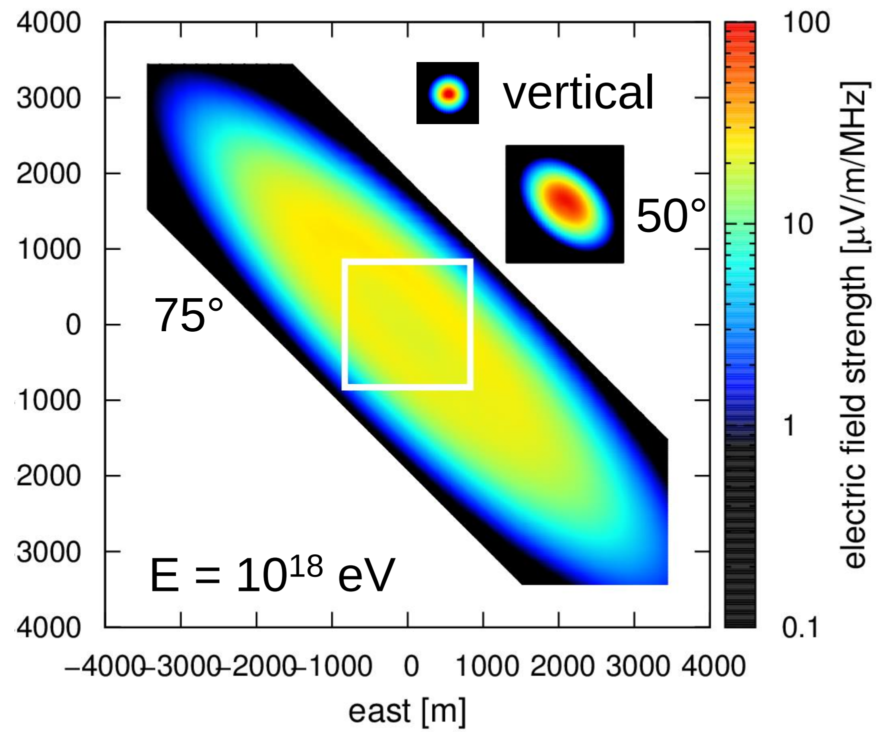
CoREAS simulations (by T. Huege)



shower inclination:
$\theta = 45°$

T. Huege et al., ARENA2012

43 – 74 MHz



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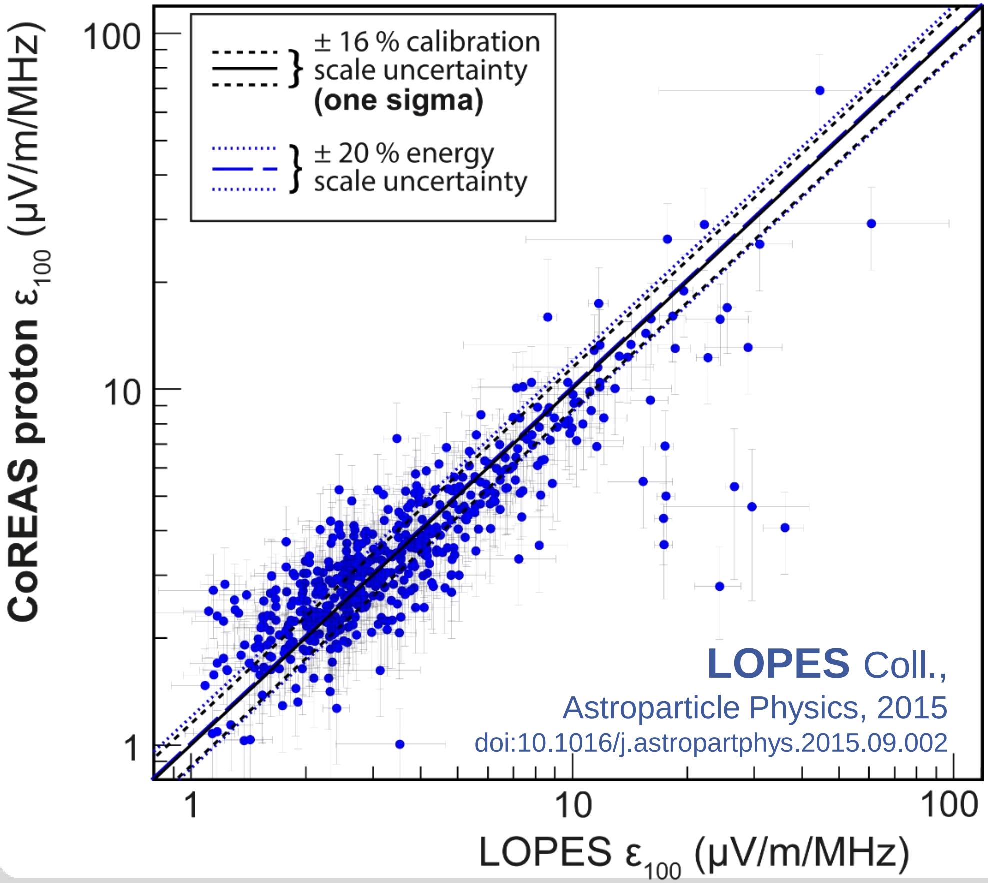
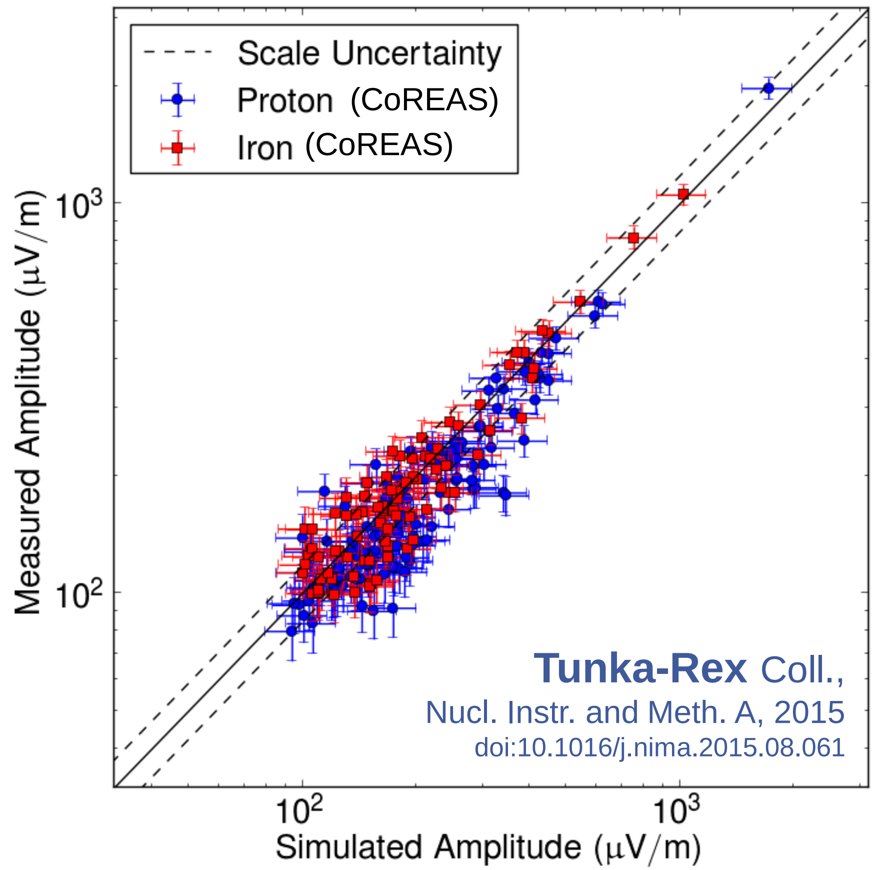
Do simulations describe reality?

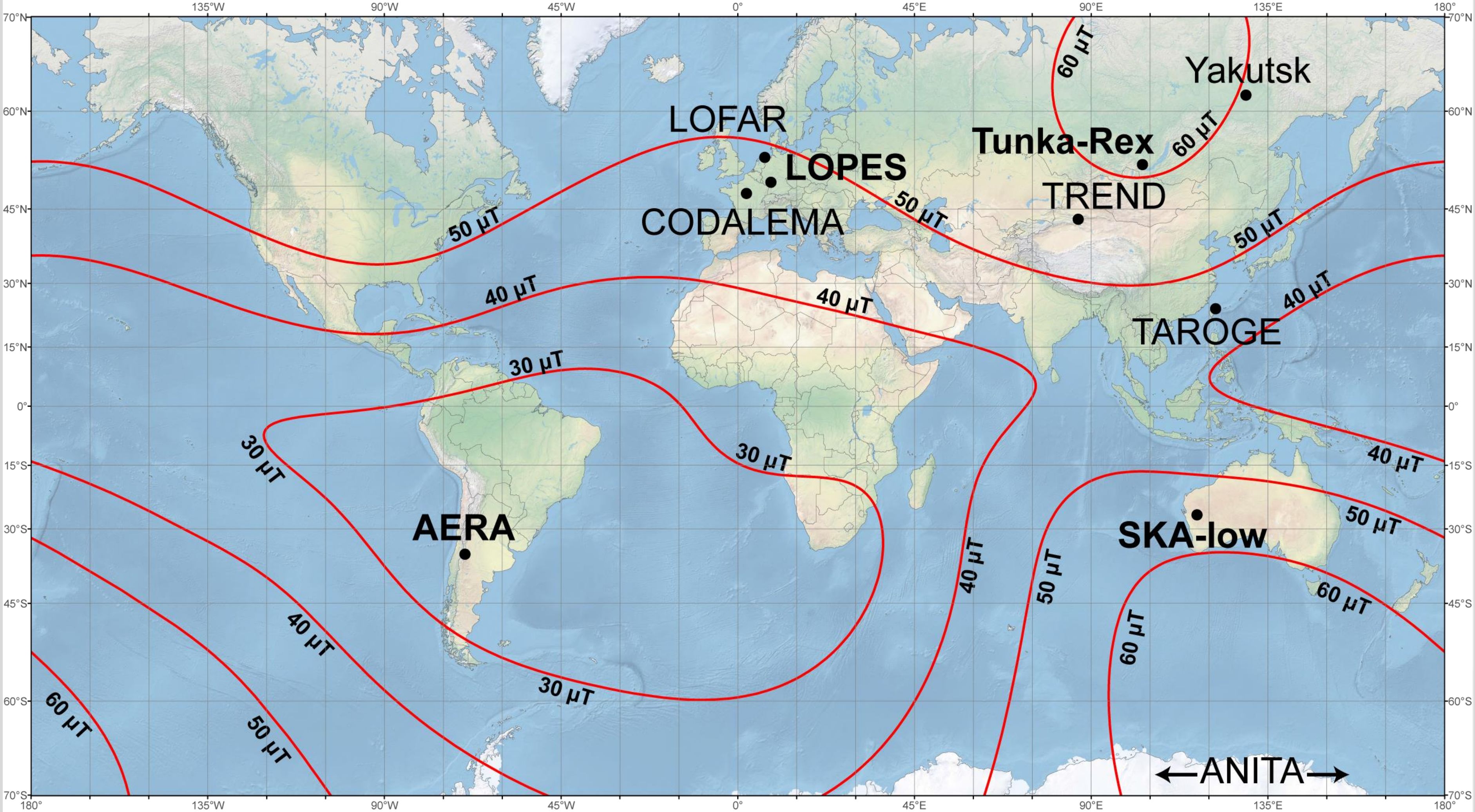
- Different codes agree on main features
- Measured amplitudes reproduced within ~20% uncertainty





Location of selected, modern experiments and geomagnetic field

Karlsruhe Institute of Technology



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

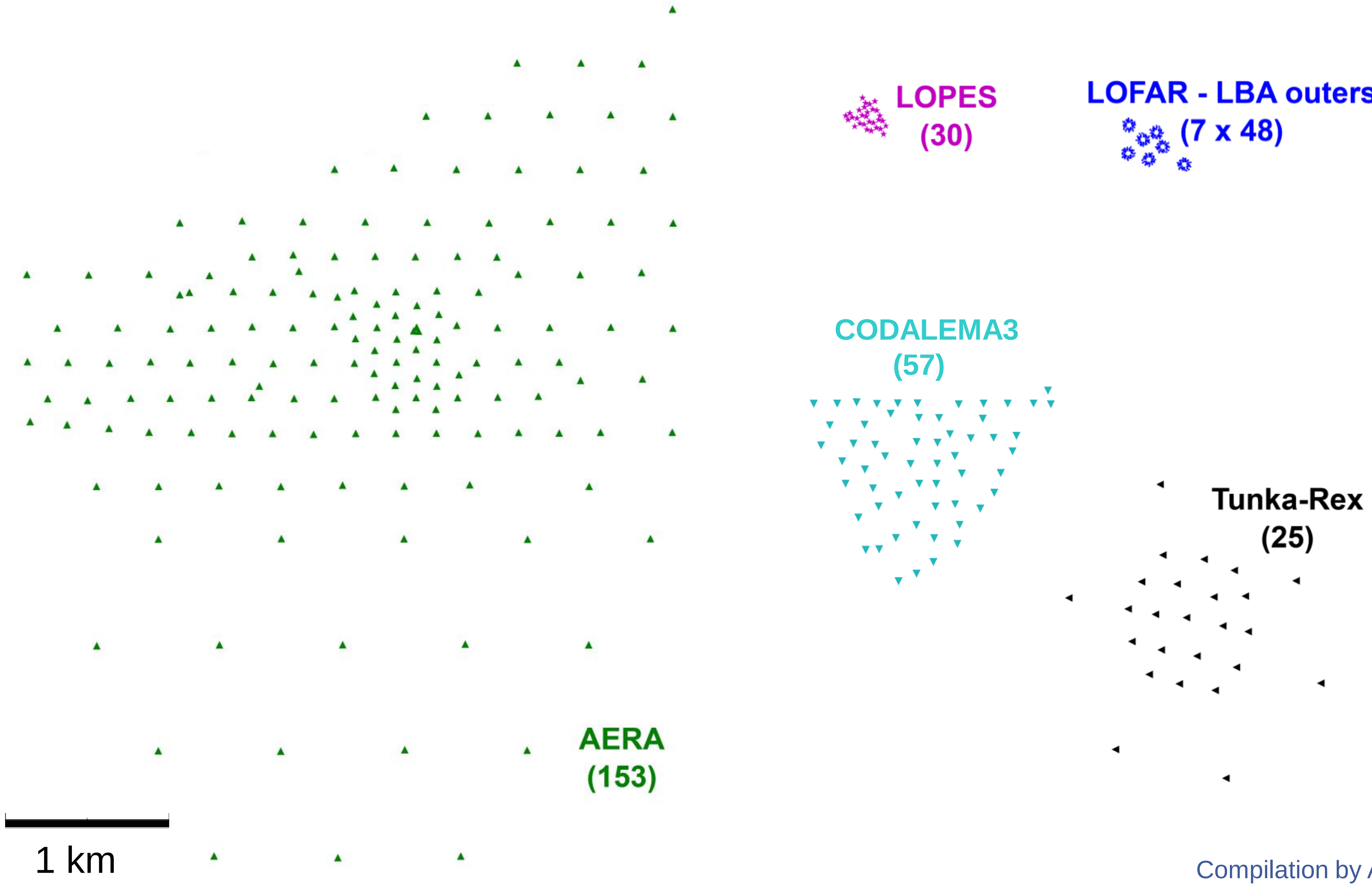
developed by NOAA/NGDC & CIRES
http://ngdc.noaa.gov/geomag/WMM

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

Karlsruhe Institute of Technology



Compilation by A. Zilles

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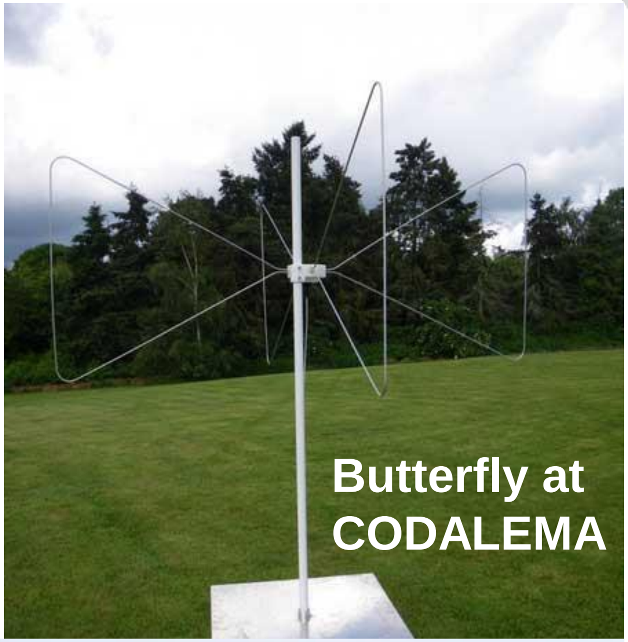
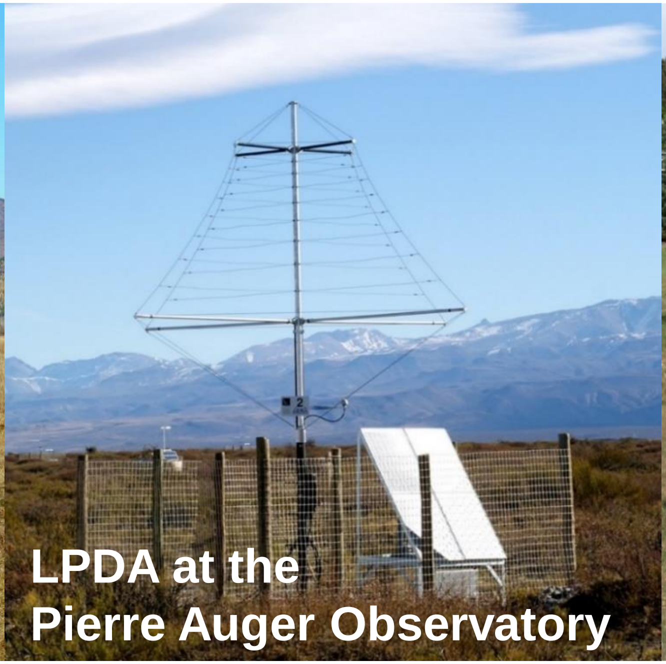
Detectors: antennas

- Typical properties
  - frequency band: 30-80 MHz
  - hybrid detection with particle detectors: external trigger or cross-check
  - digital DAQ and offline analysis





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Reconstruction of shower parameters

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

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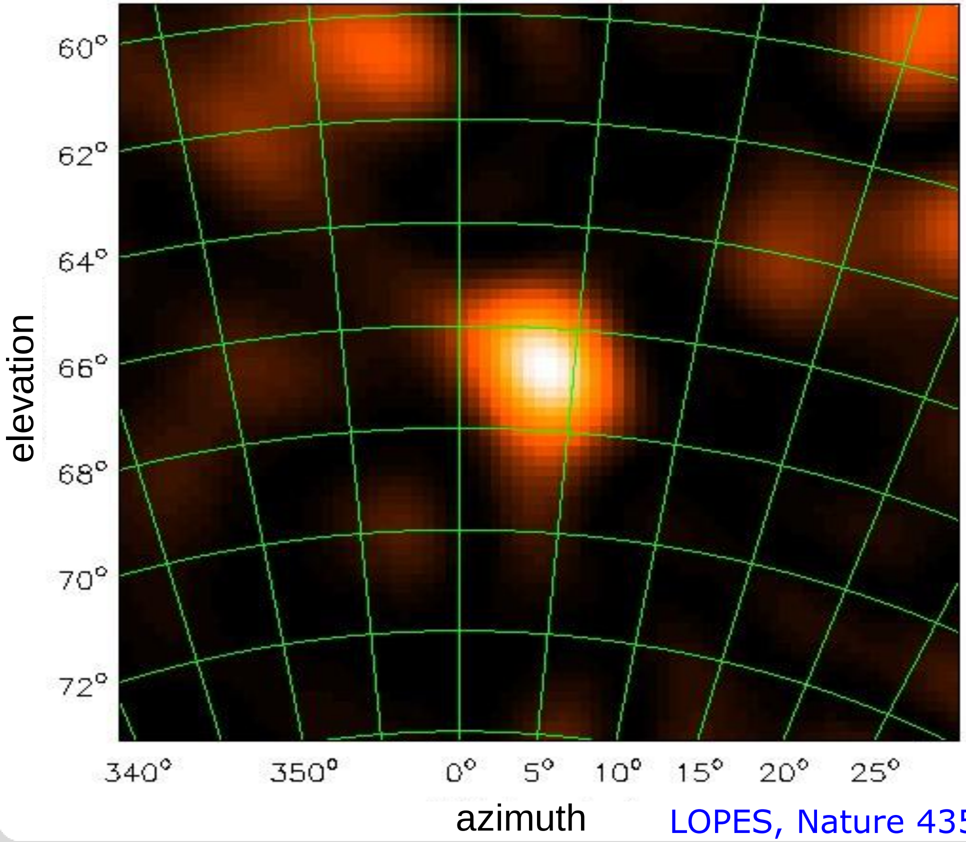
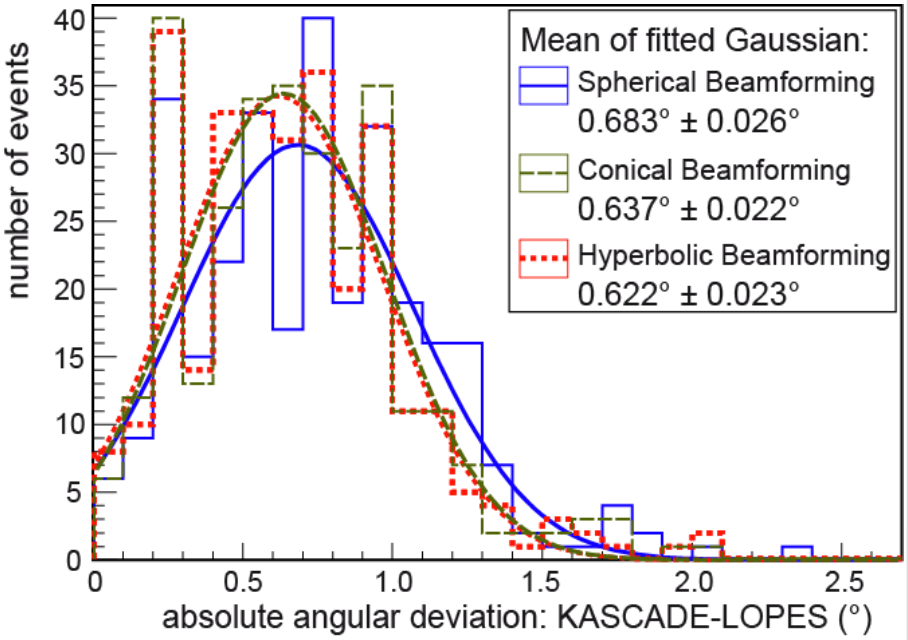
Arrival direction

- 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

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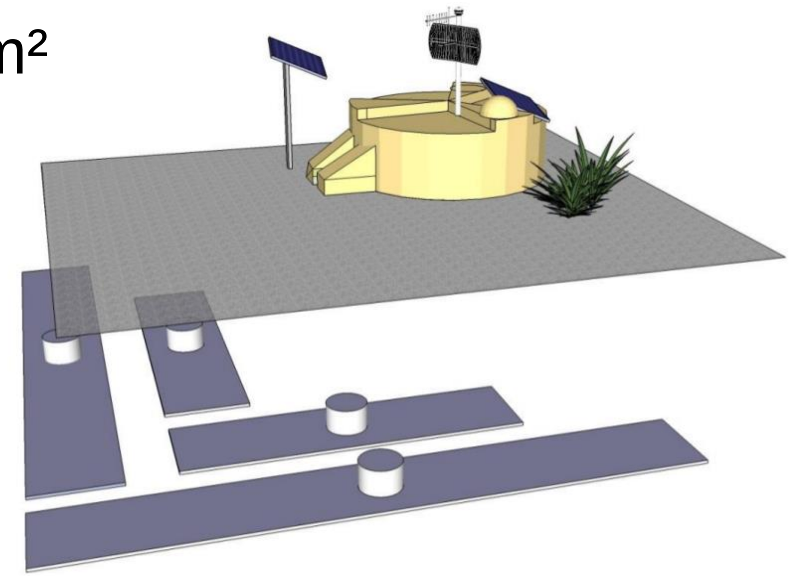
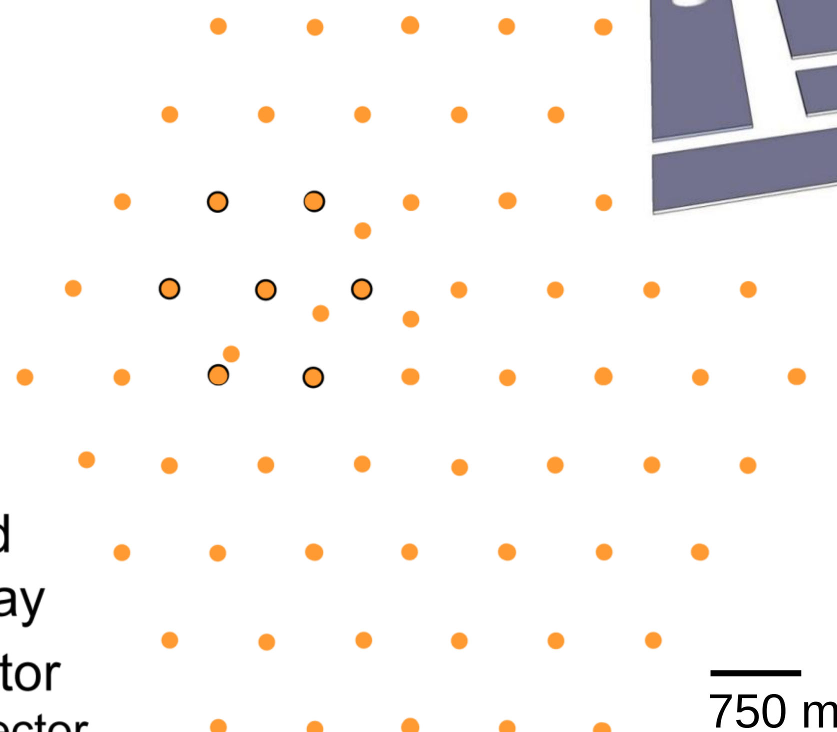
Auger Engineering Radio Array

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





Auger **M**uon and **I**nfill **G**round **A**rray

- **S**urface **D**etector
- with **M**uon **D**etector

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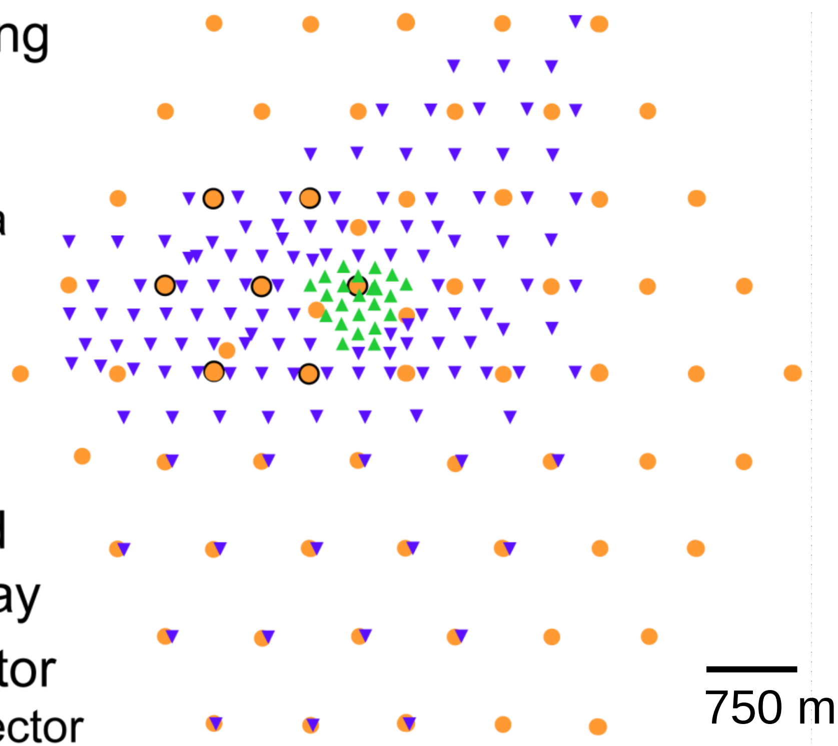
Auger Engineering Radio Array

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

Auger **E**ngineering **R**adio **A**rray

▲ LPDA antenna

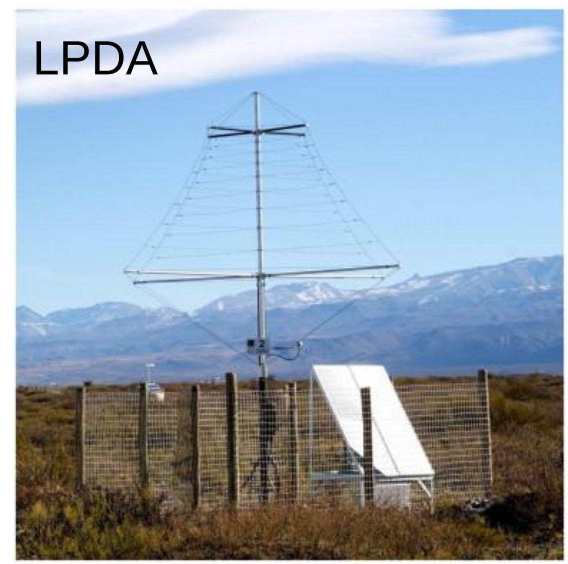
▼ Butterfly antenna



Auger **M**uon and **I**nfill **G**round **A**rray

● **S**urface **D**etector

○ with **M**uon **D**etector



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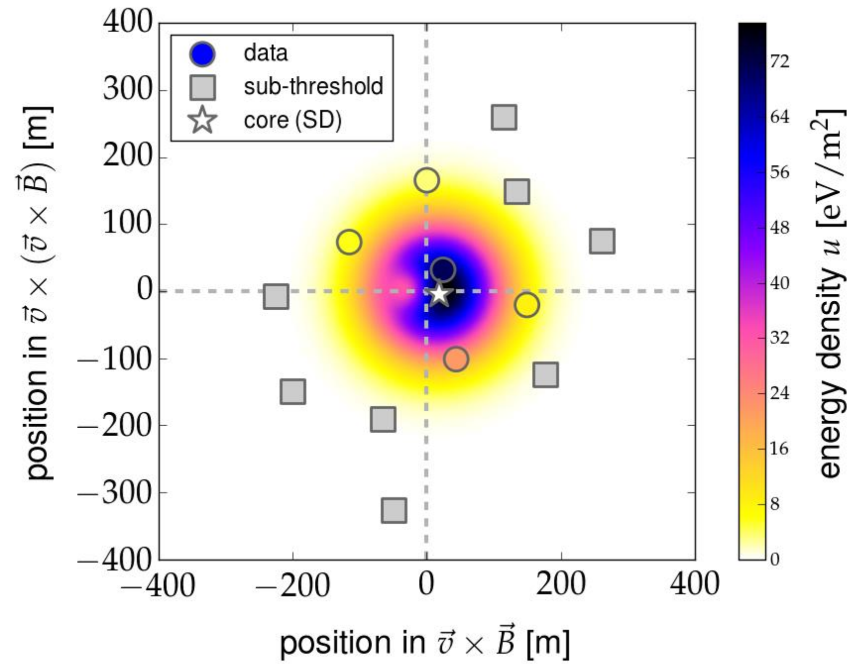
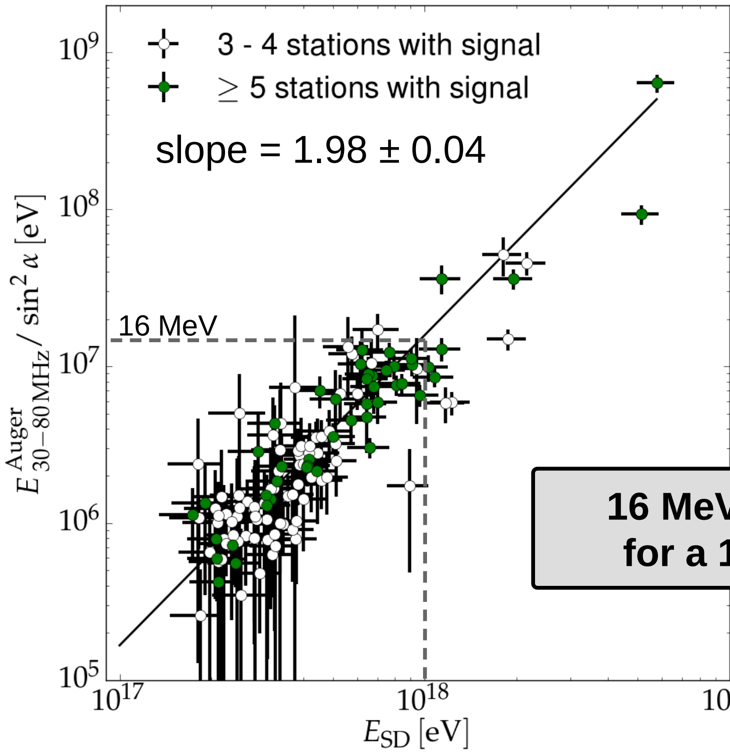
Energy reconstruction

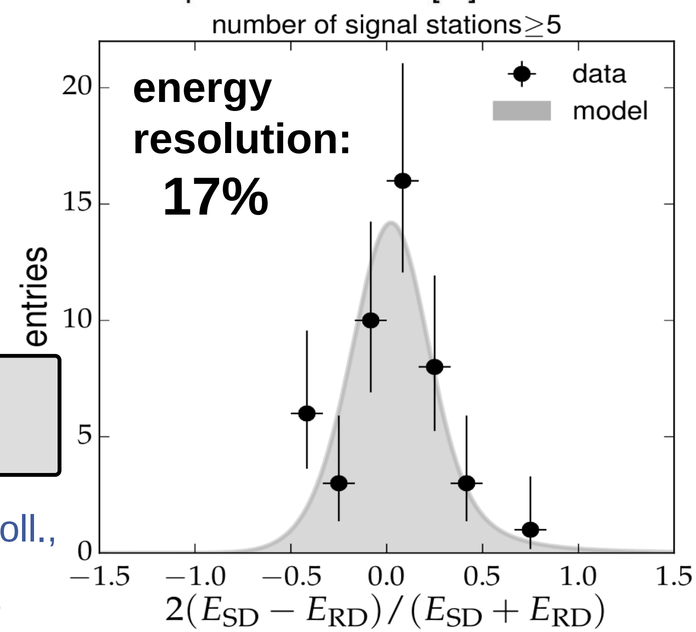
- Coherent radio emission

→ Radio energy squared
~ number of electrons
~ shower energy squared





16 MeV radiation energy for a 1 EeV cosmic ray



Pierre Auger Coll., ICRC 2015, arxiv: 1508.04267

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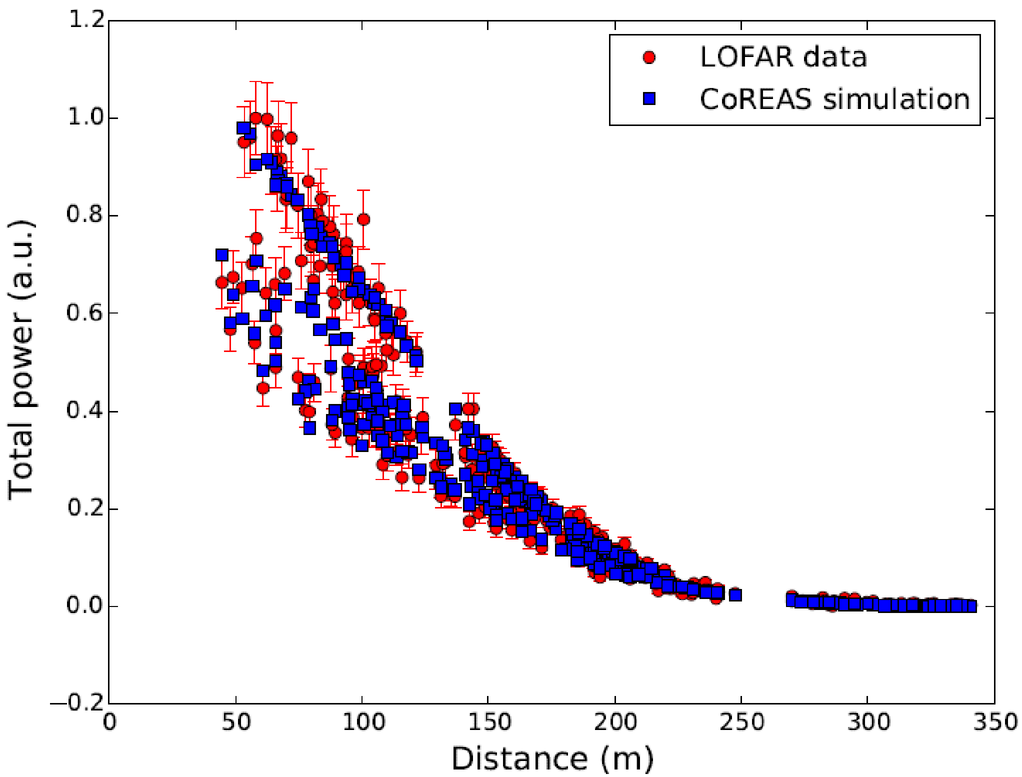
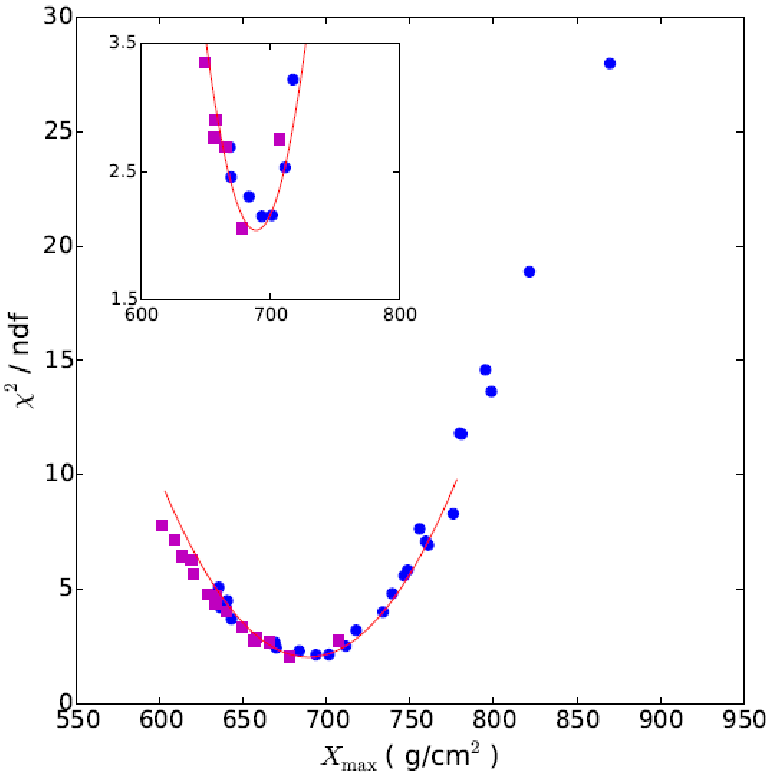
X_{max}: high precision exploiting simulations

- 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

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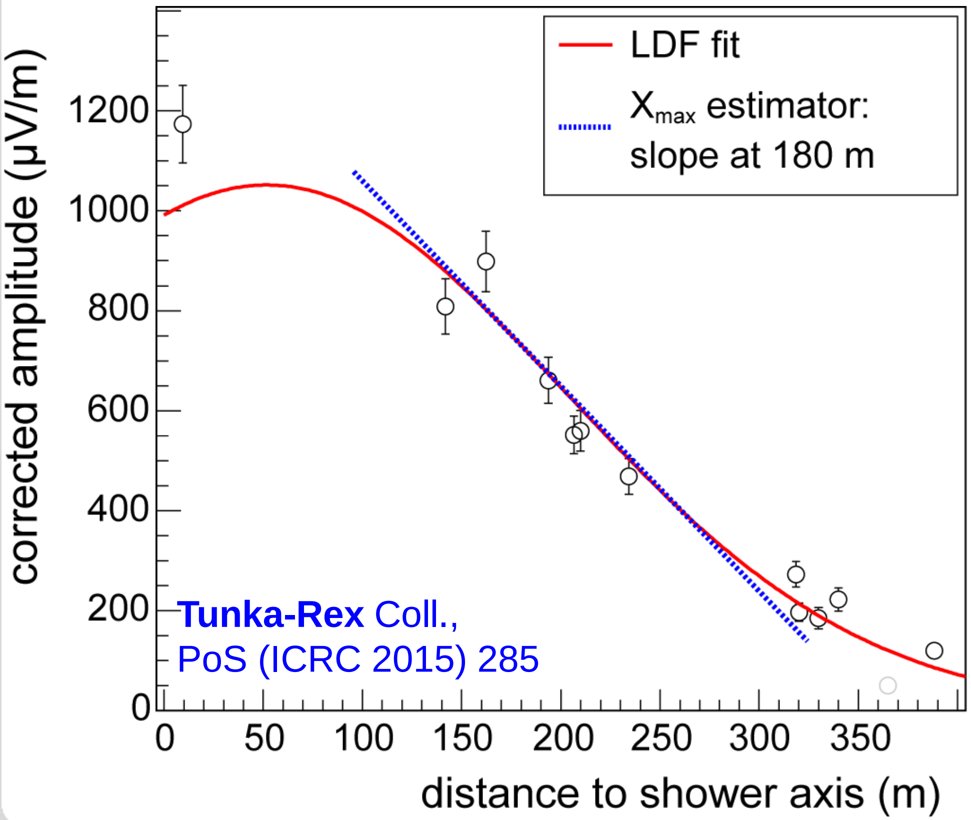
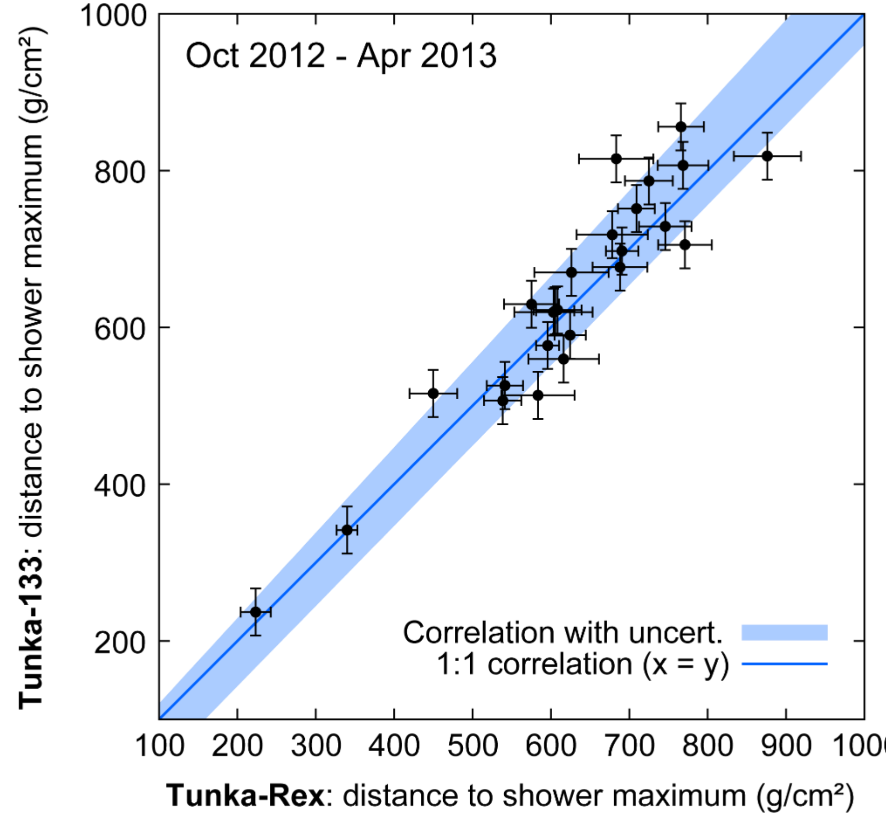
Shower maximum: proof by Tunka-Rex

- 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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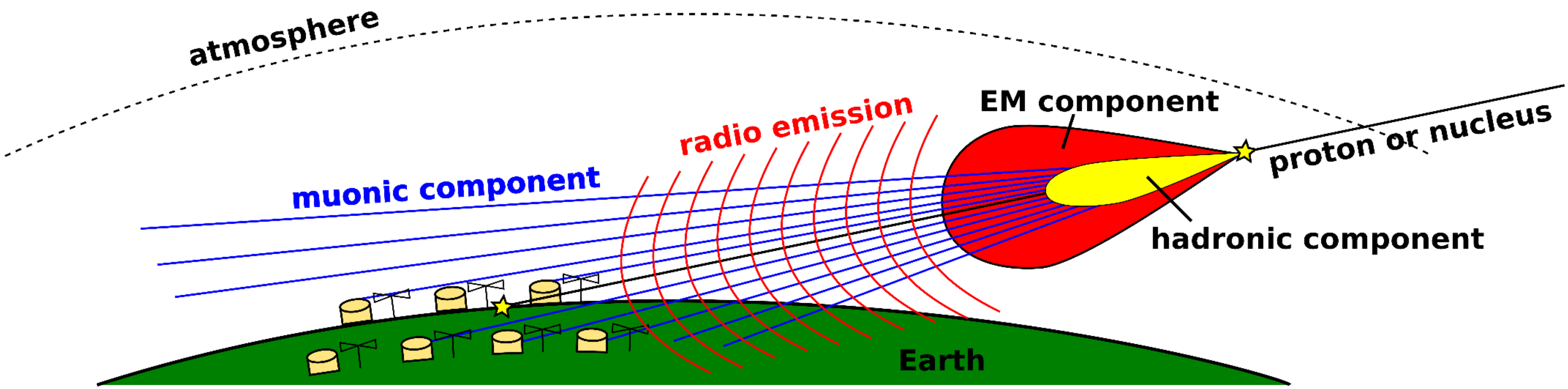
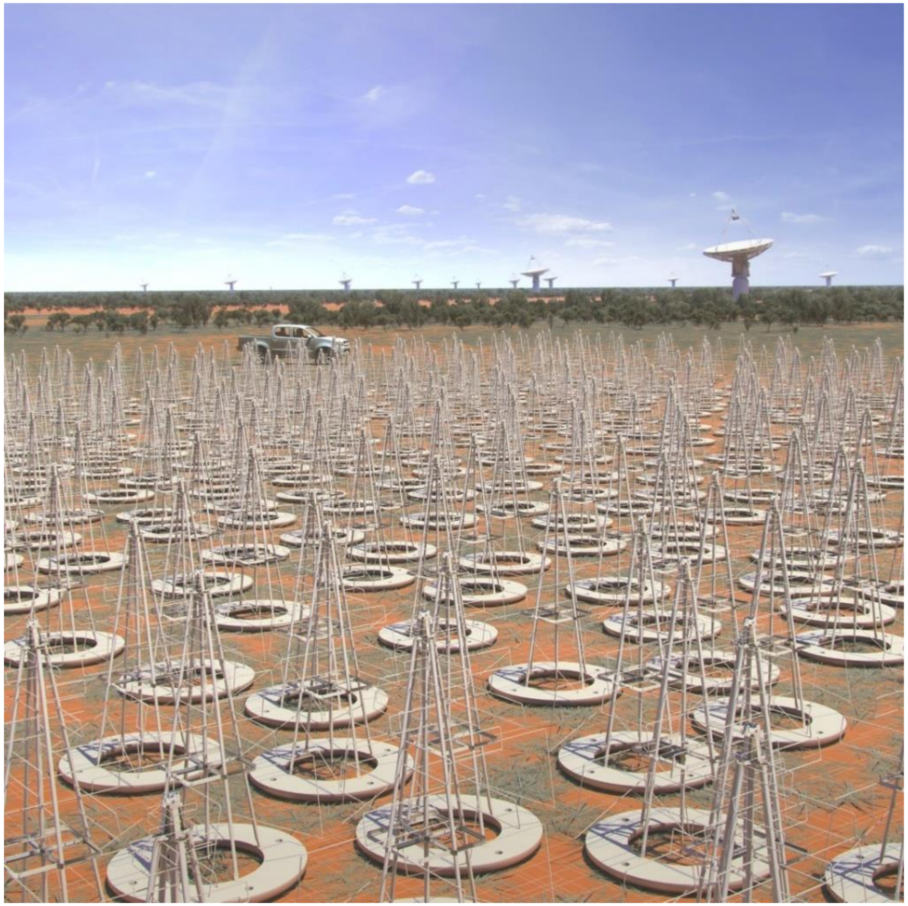
Outlook 1: inclined showers

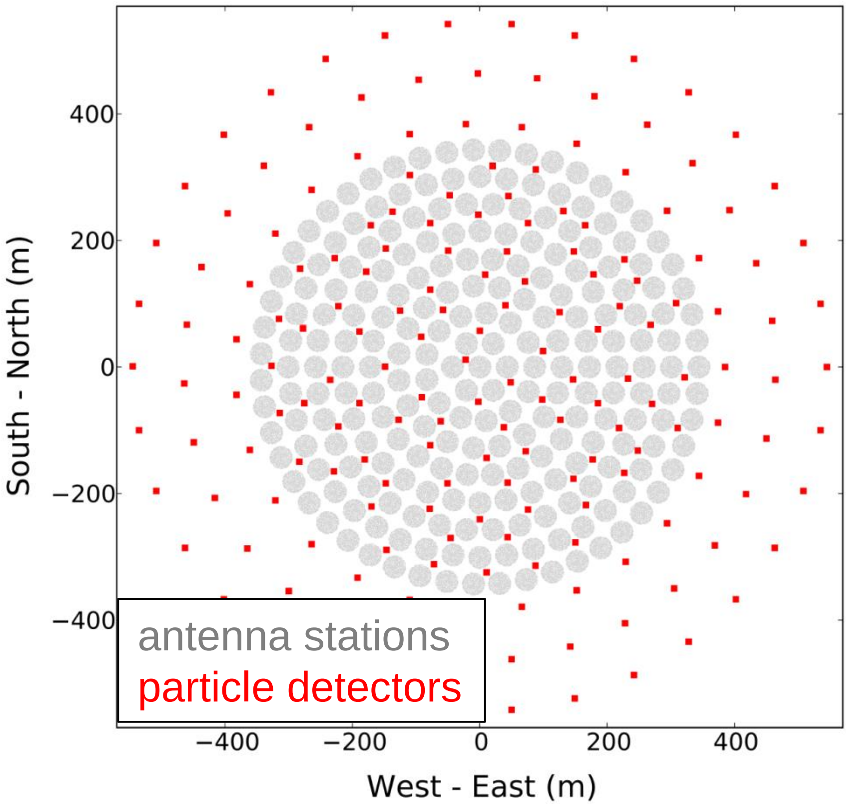


- Electrons and photons attenuate in atmosphere
- Only muons and radio emission survives (no absorption)
  - Complementary information on shower → primary particle type

Outlook 2: SKA

- 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 has highest potential combined with particles
  - cross-calibration of absolute energy scale
  - mass composition around the clock (X_{max} + e/μ)

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Backup

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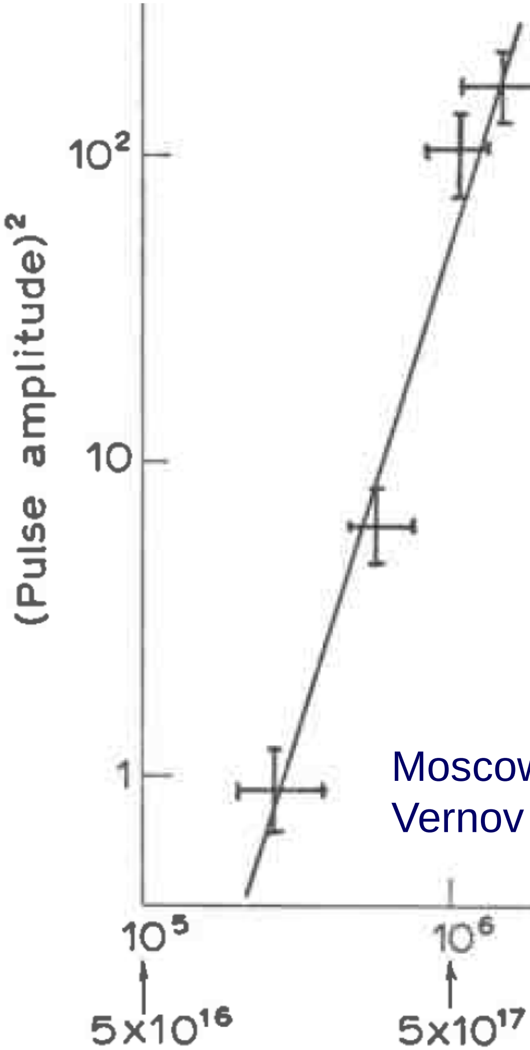
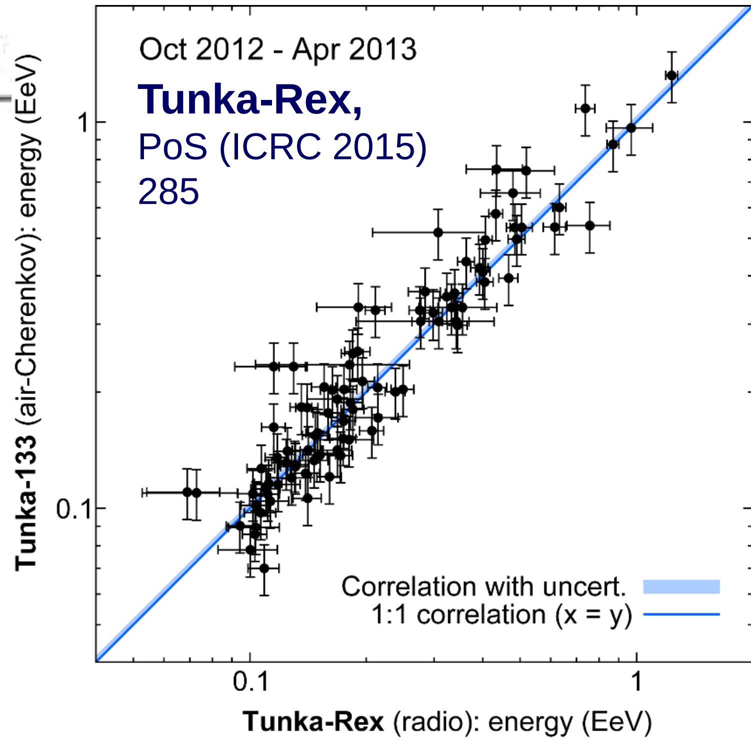
More examples for energy reconstruction

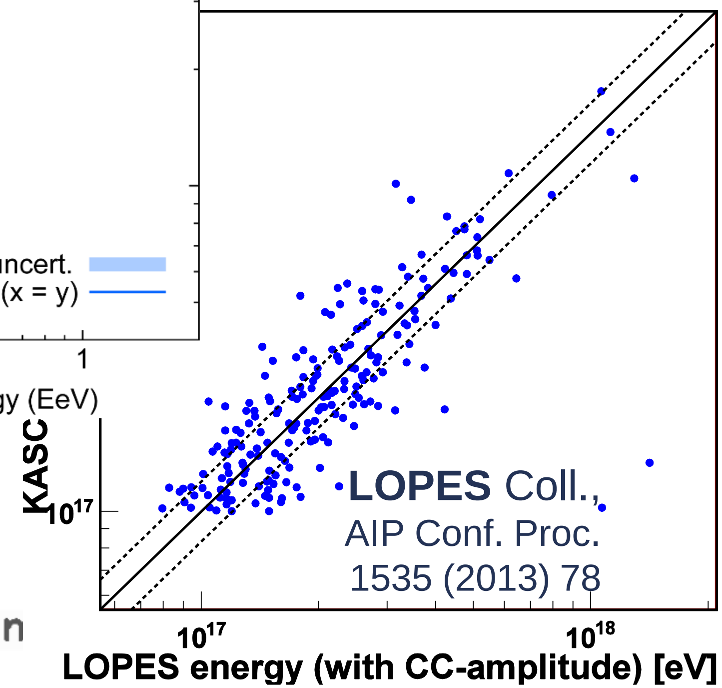


Moscow experiment:
Vernov et al. (1968)



Tunka-Rex,
PoS (ICRC 2015)
285

Also seen by:
CODALMEA,
LOFAR, …

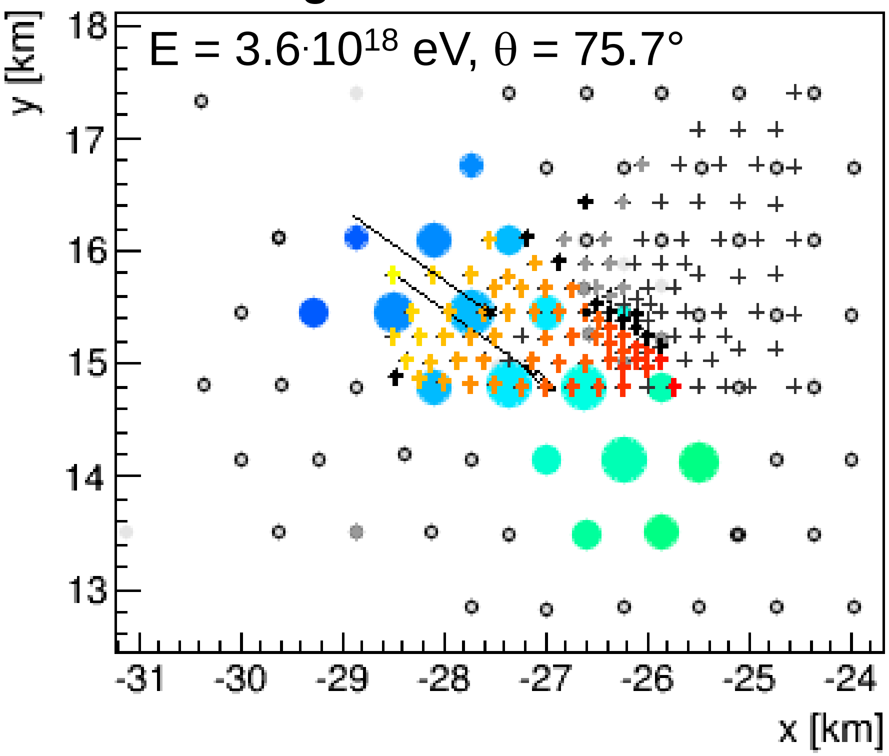


LOPES Coll.,
AIP Conf. Proc.
1535 (2013) 78

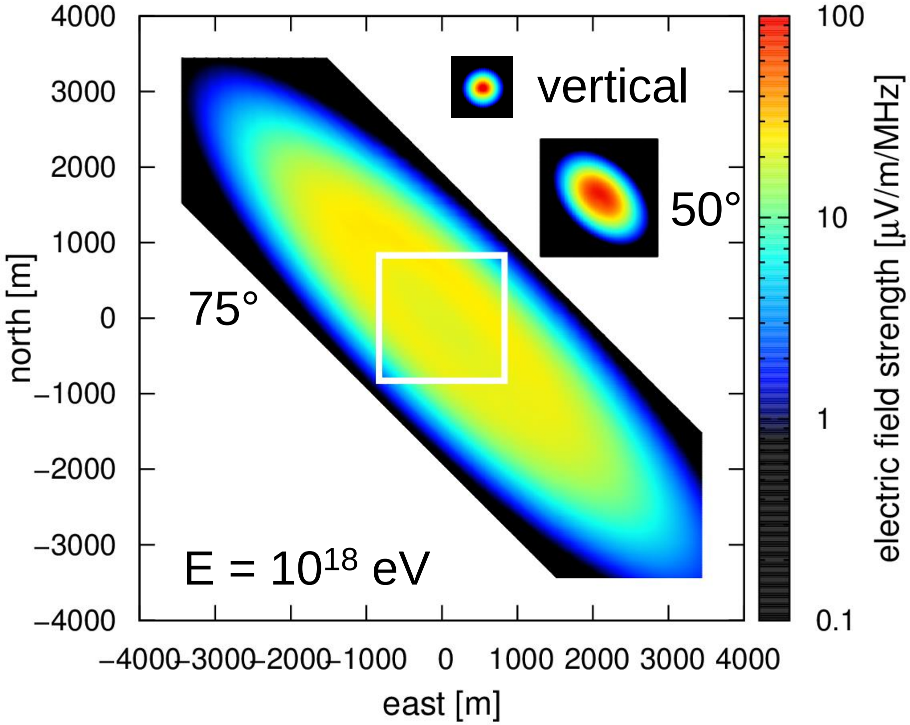
Huge footprint for inclined showers

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

Auger measurement



CoREAS simulation



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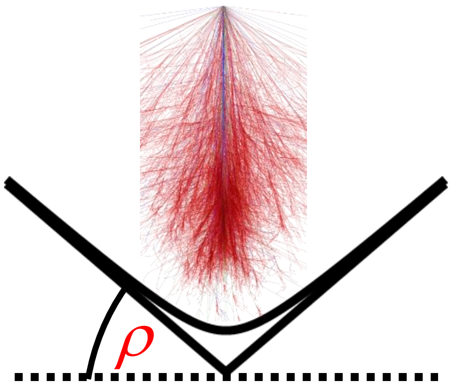
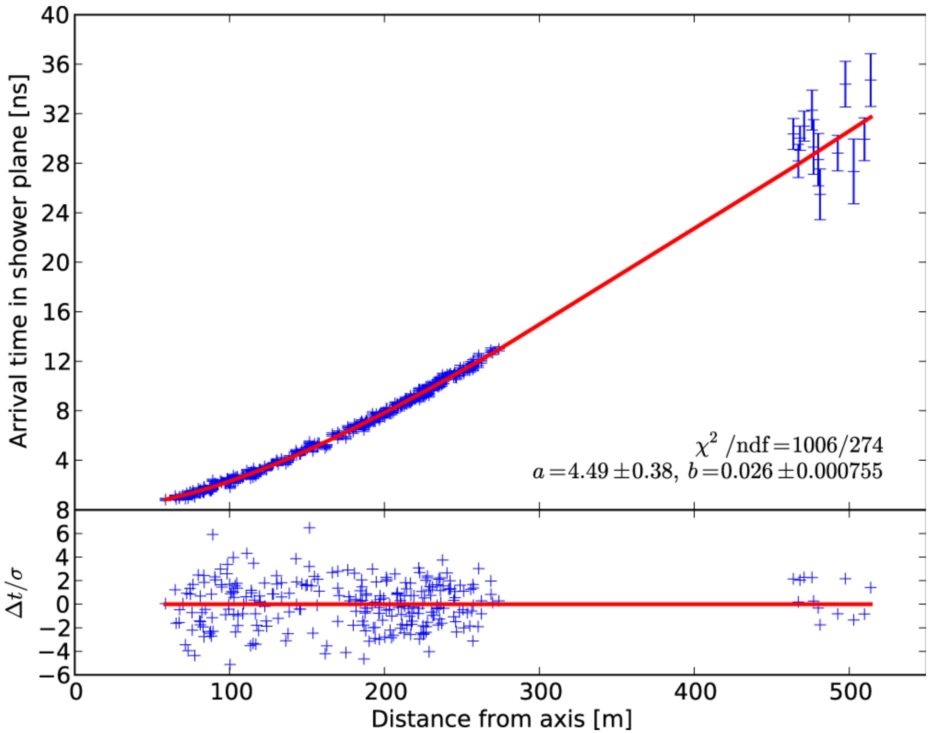
1) Shower maximum via wavefront

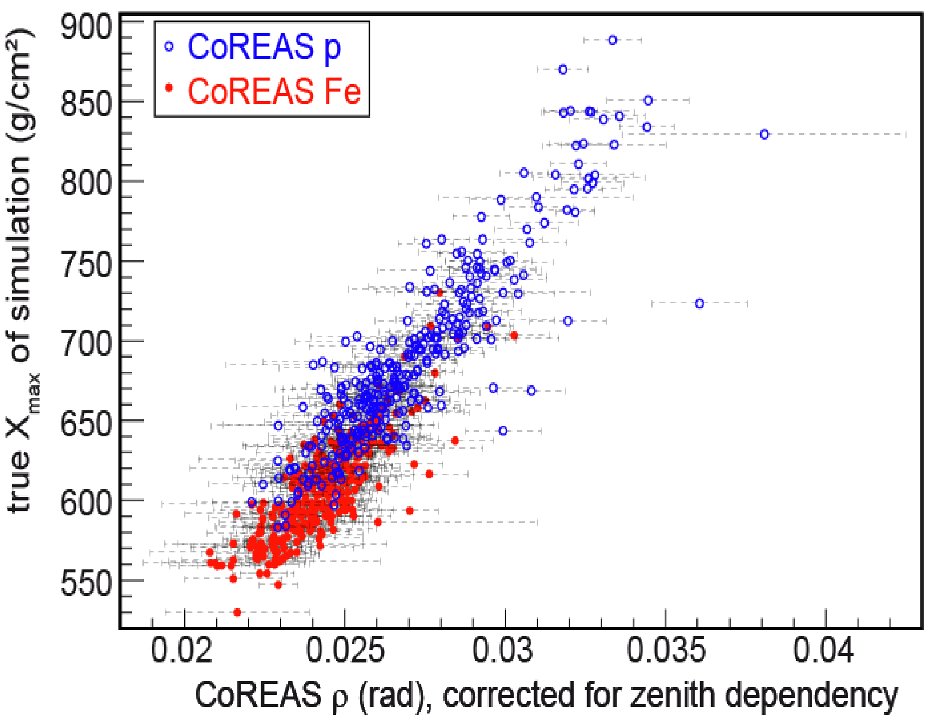
- Radio wavefront has hyperbolic shape
- Cone angle → shower maximum



ca. 1° - 2°



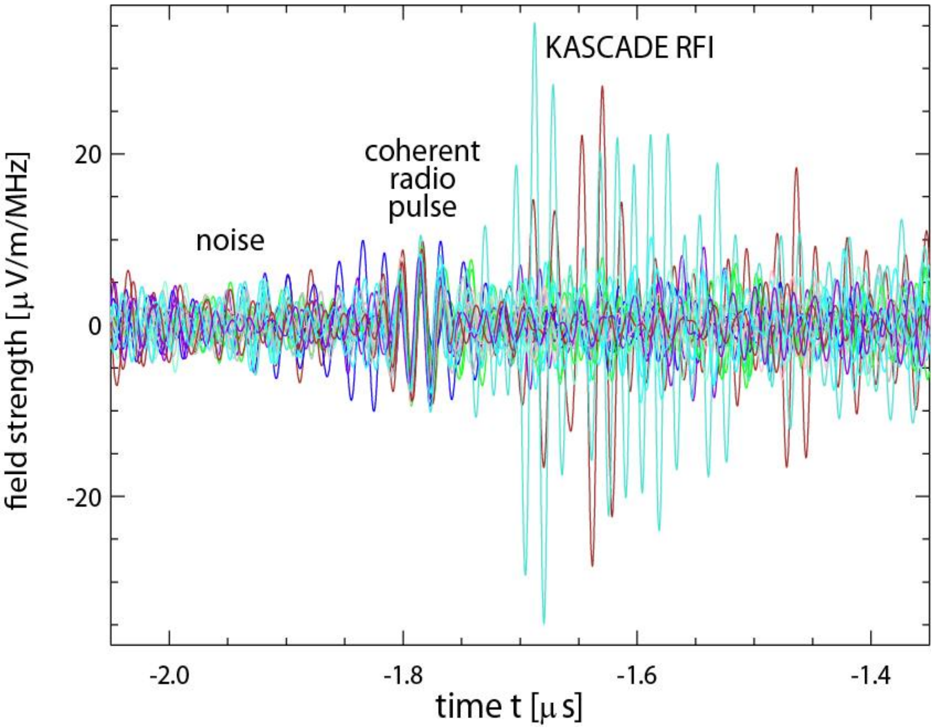
LOFAR Coll, Astropp. 61 (2015) 22

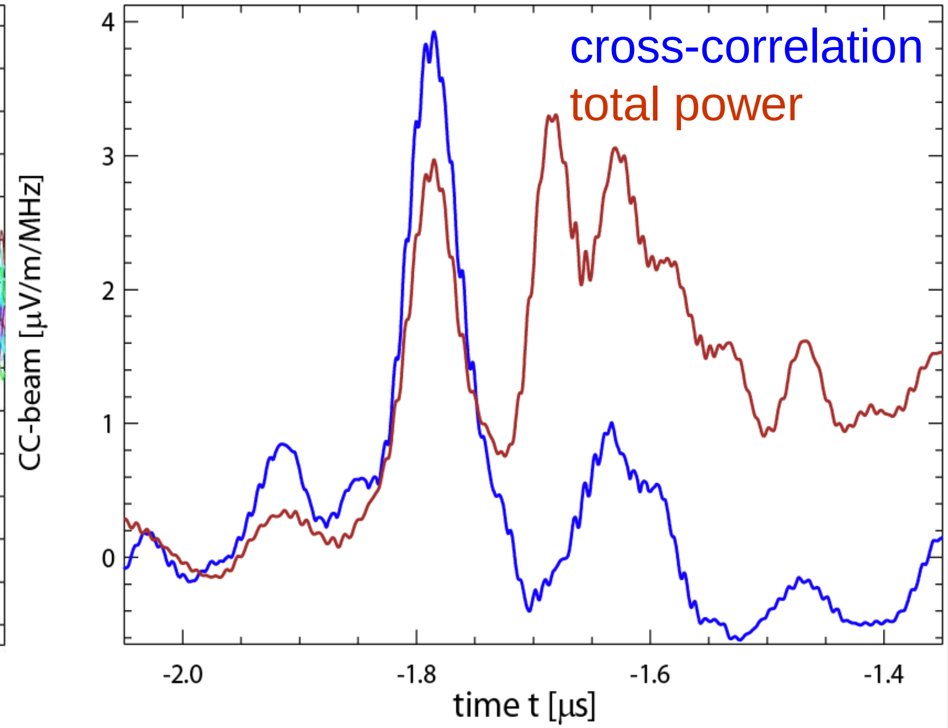


LOPES Coll., JCAP 09 (2014) 025

Cross-correlation beamforming

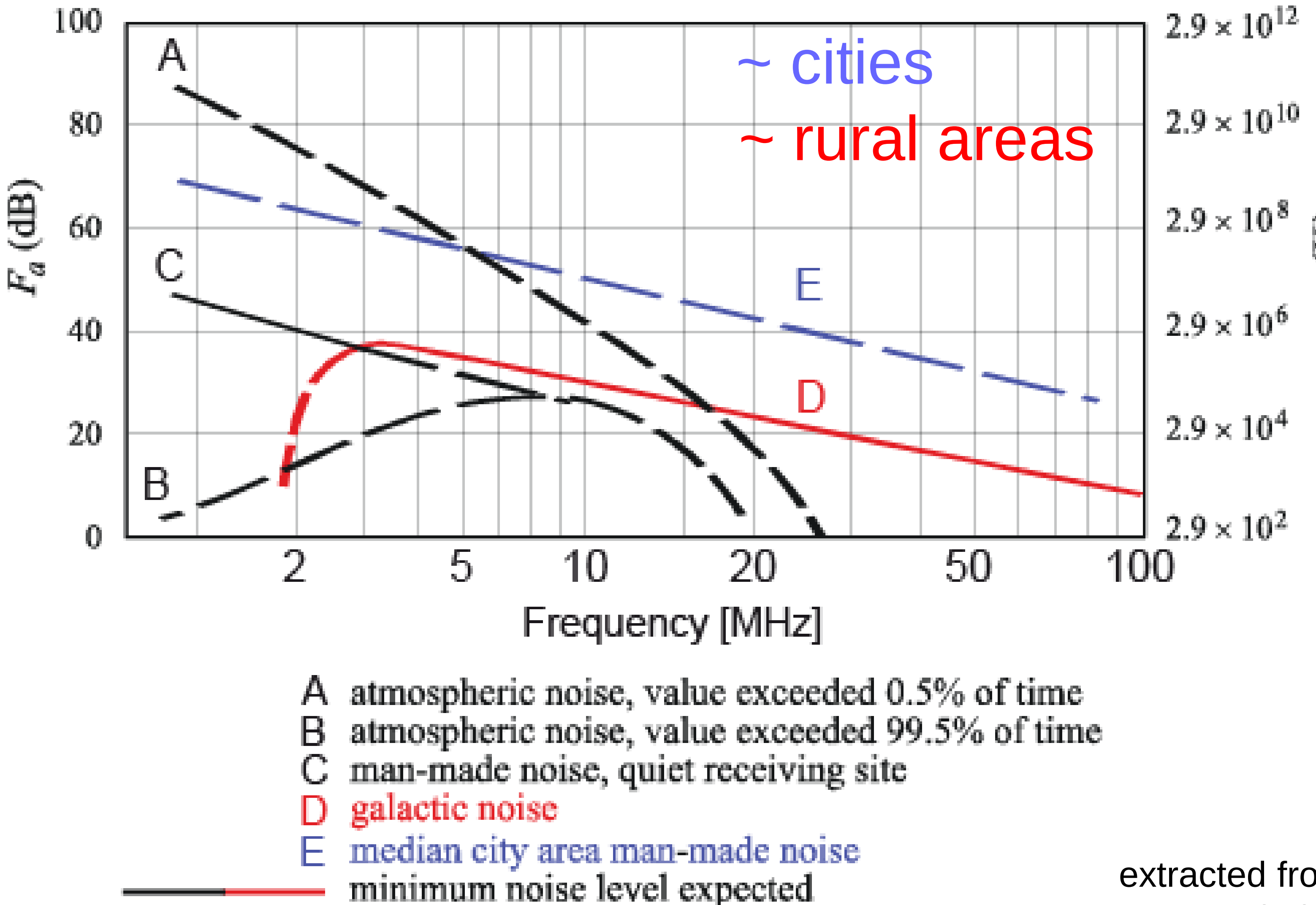
- Digital Interferometry: only air shower pulse correlated in all antennas, when looking in the arrival direction





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

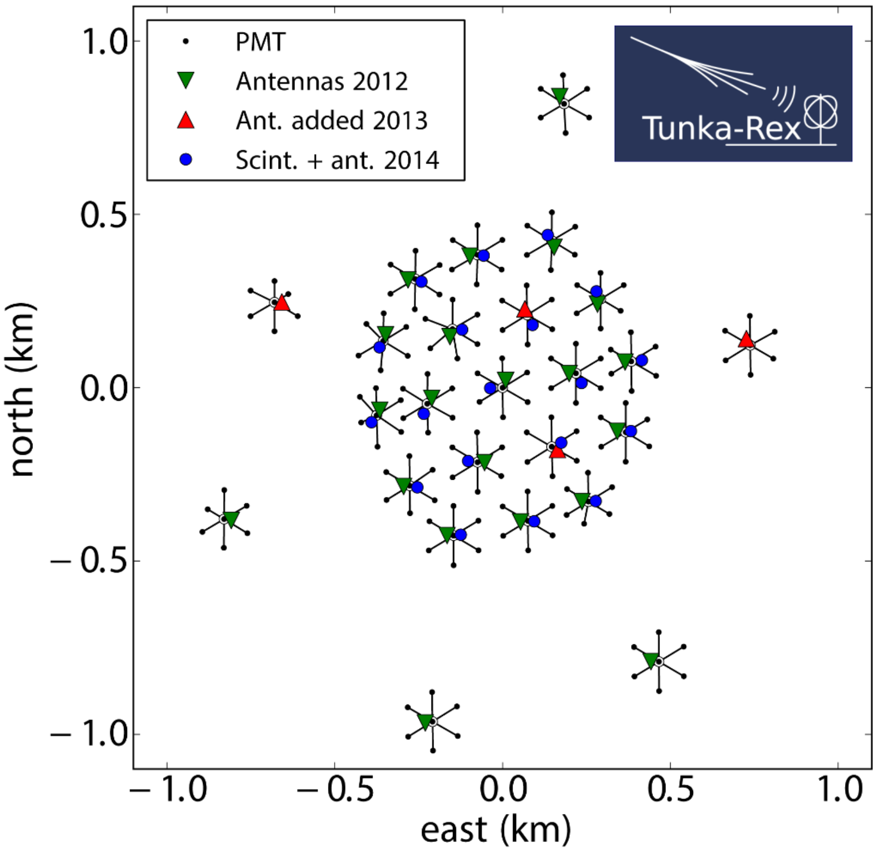
General noise situation

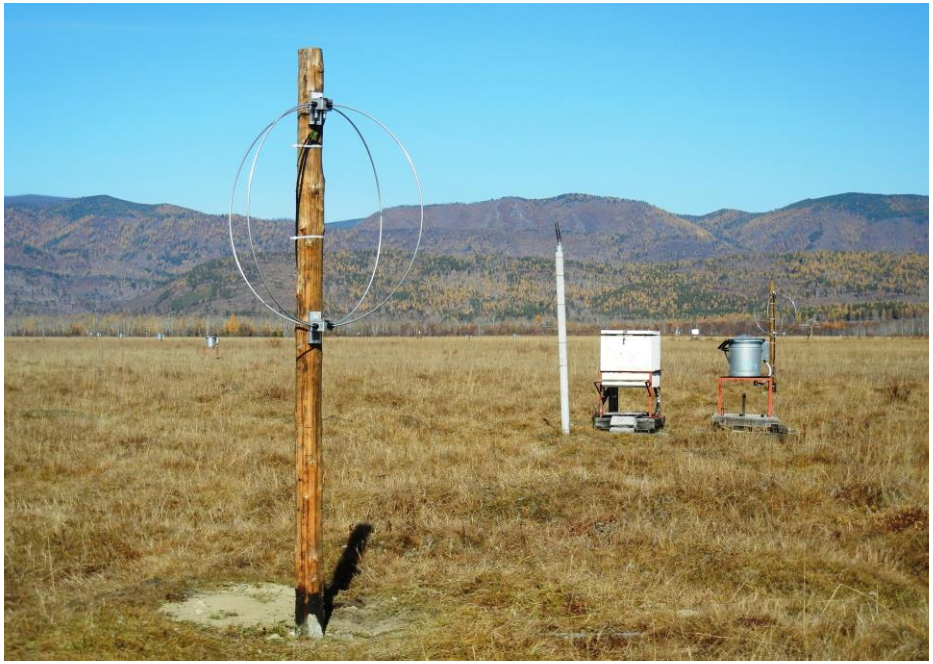


extracted from
ITU-R P.372.10

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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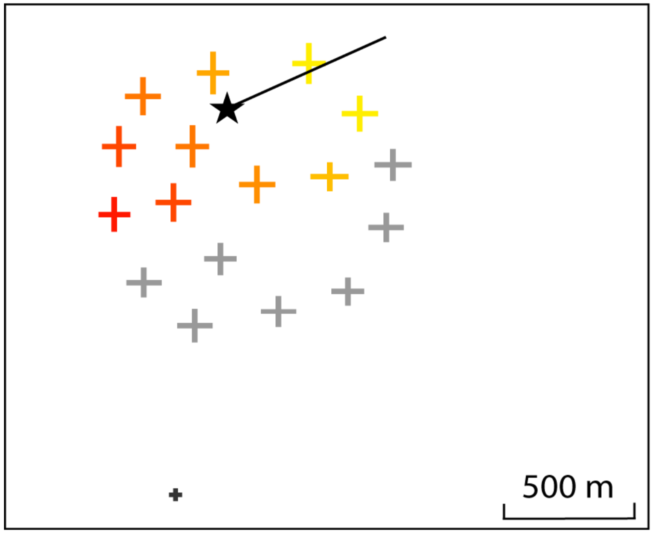
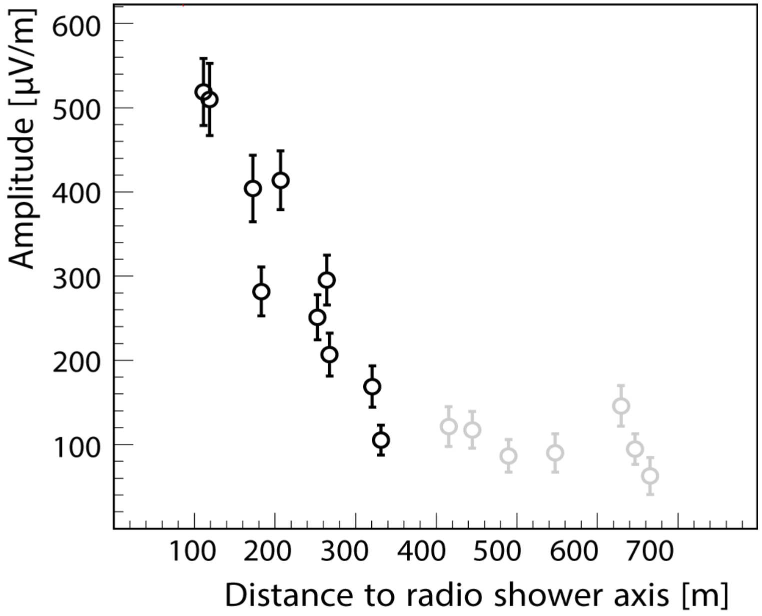
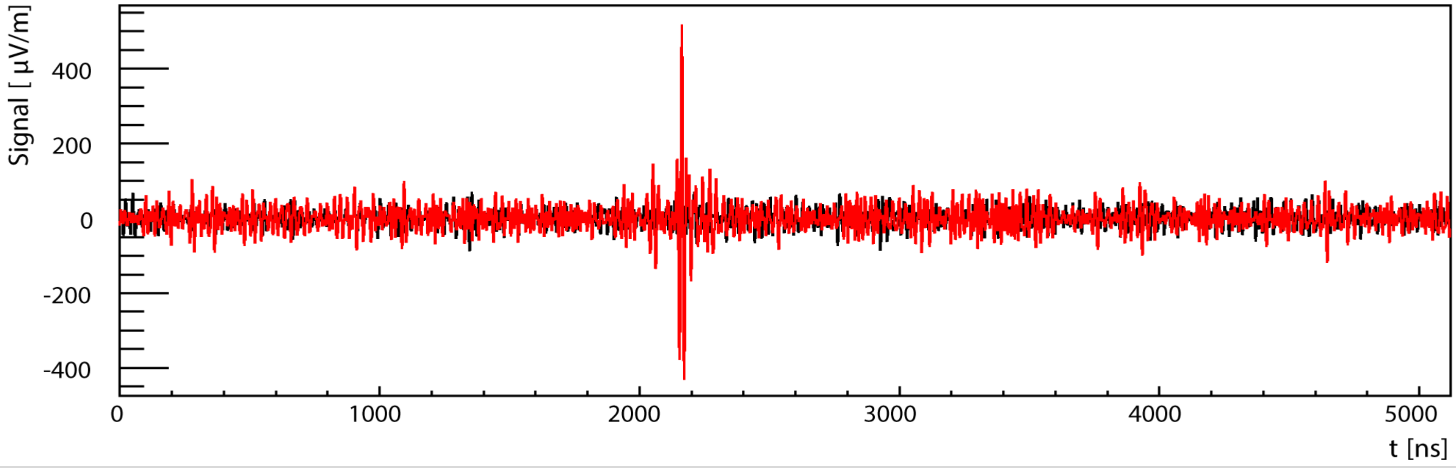
Tunka-Rex example event







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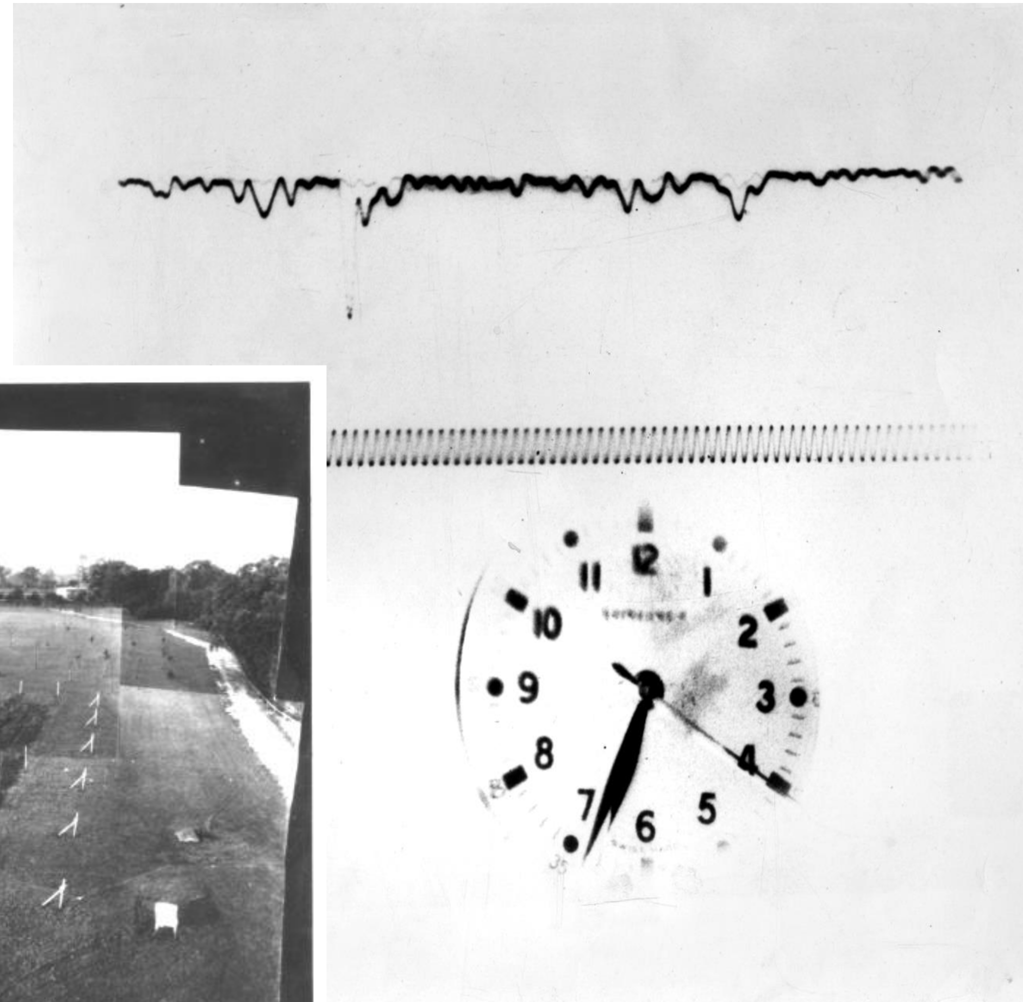
Experiments: First Detection

- Qualitative features discovered 50 years ago

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



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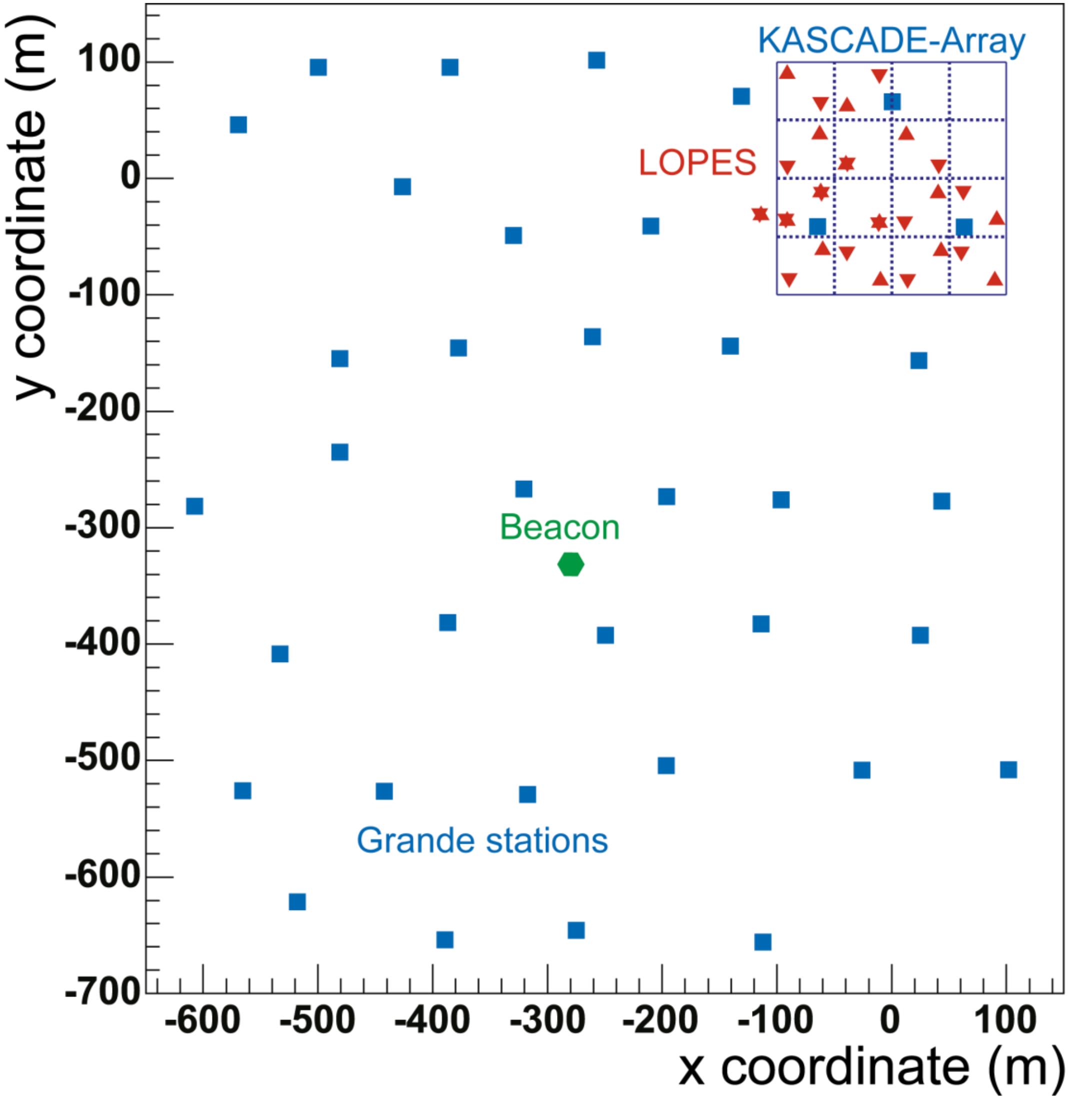
LOPES (also since 2003, was at KIT)



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

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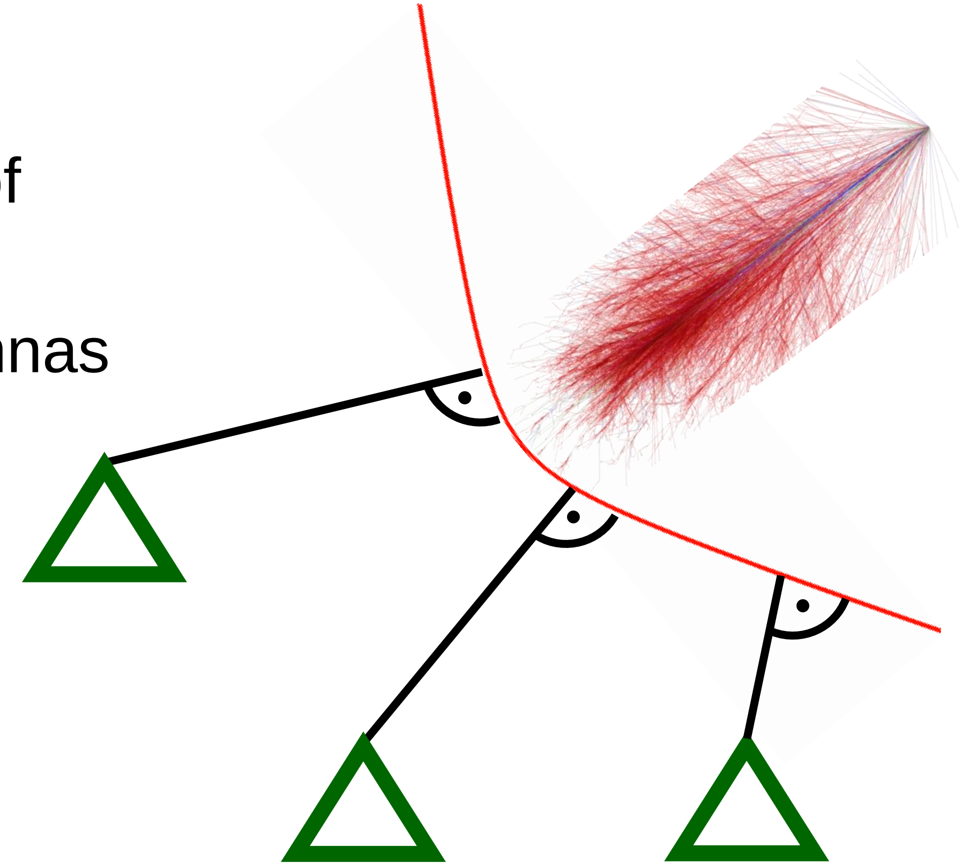
Interferometric beamforming at LOPES

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



LOPES Coll.,

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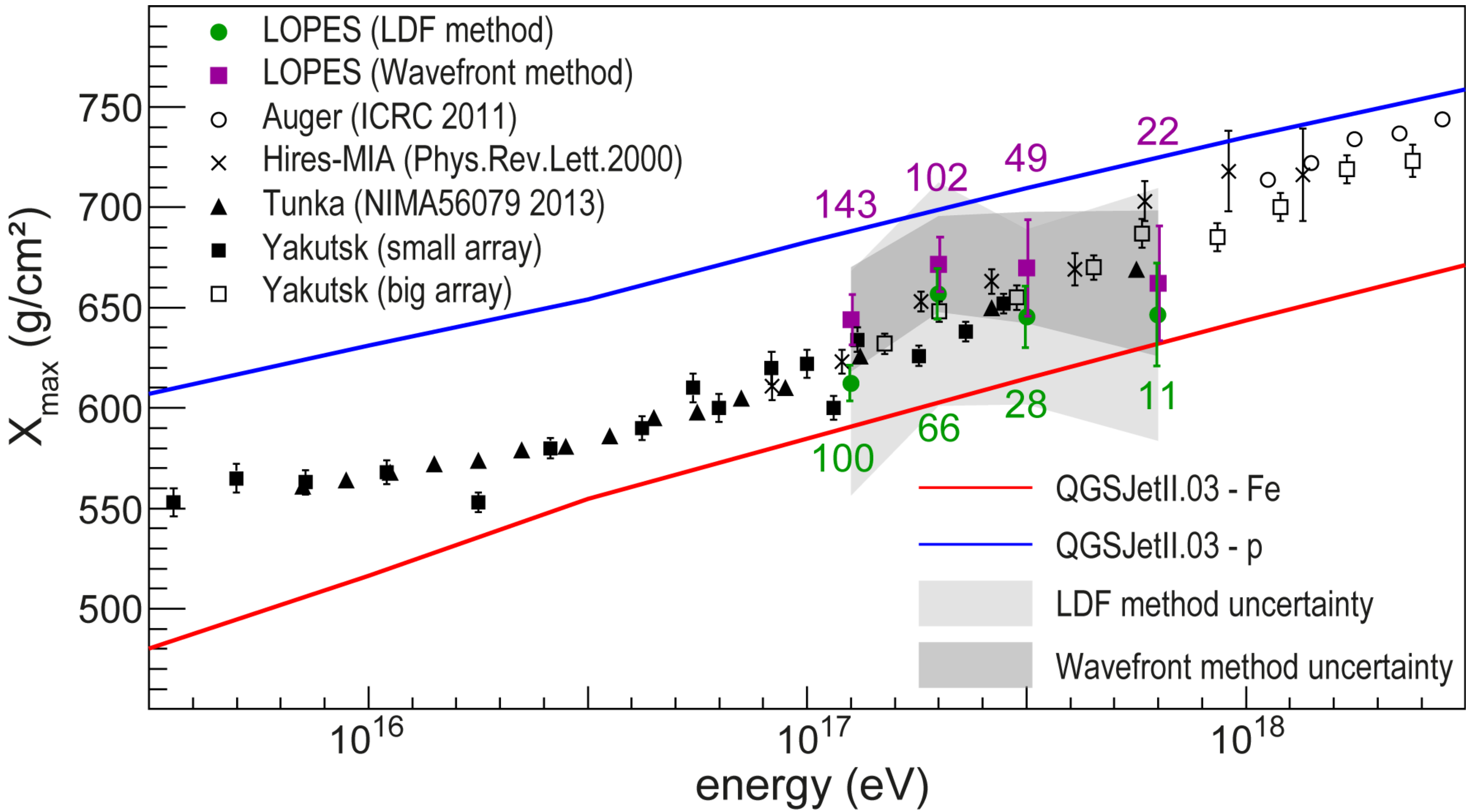
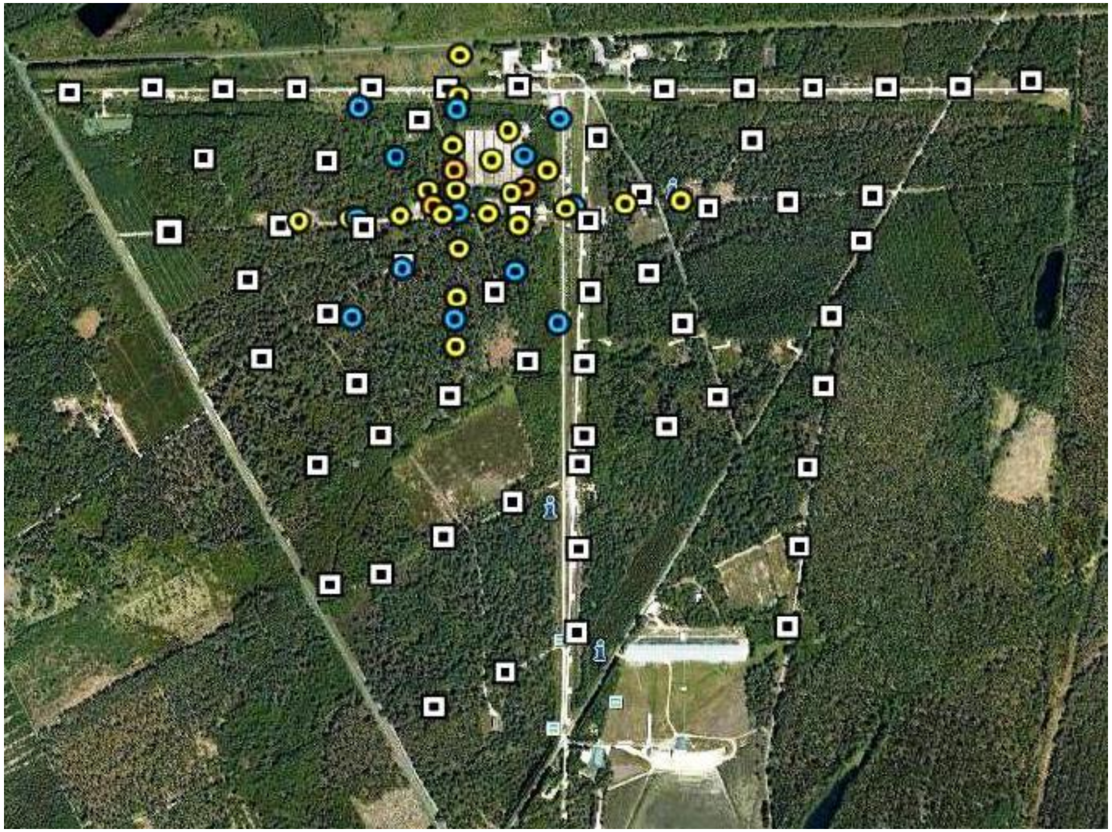
Radio shower maximum consistent



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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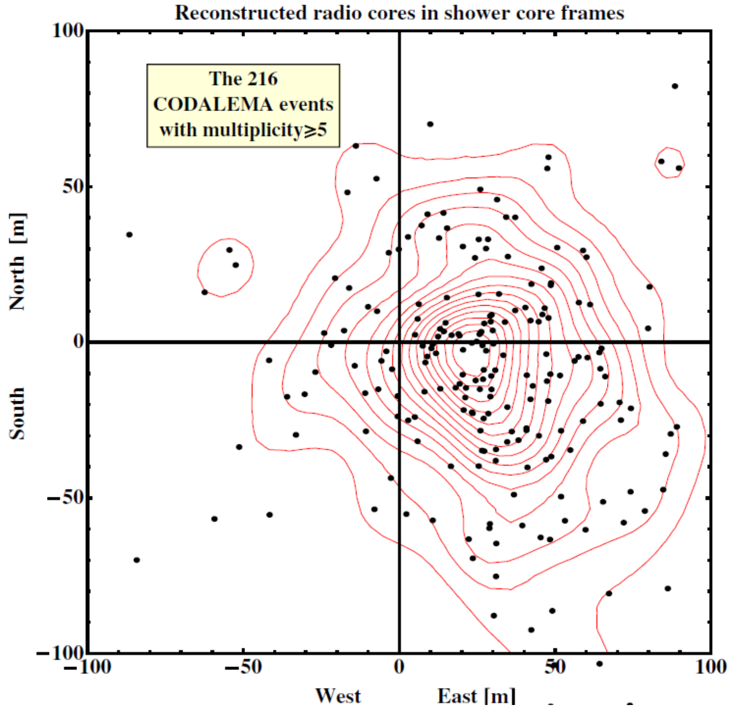
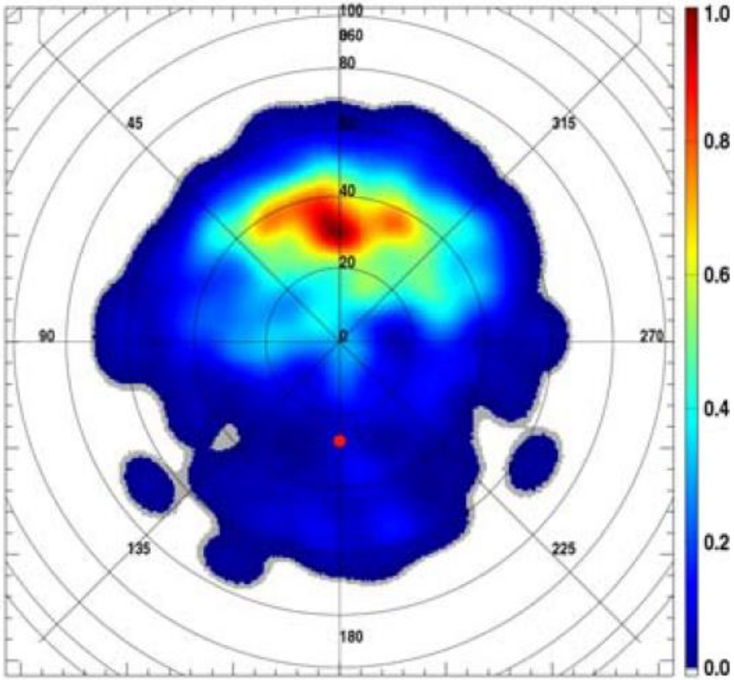
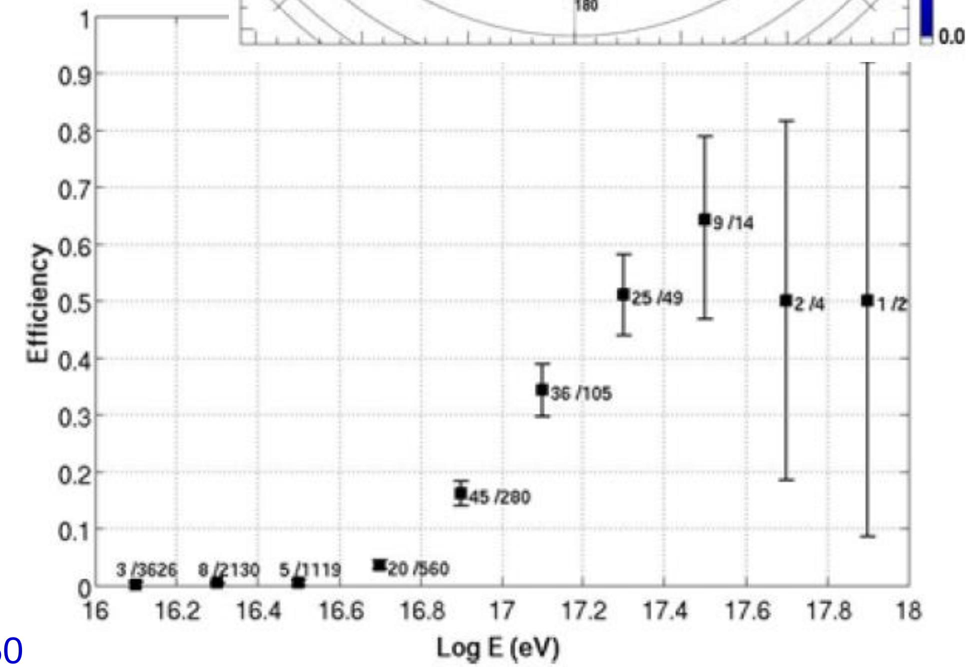
Evidence for emission mechanisms

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



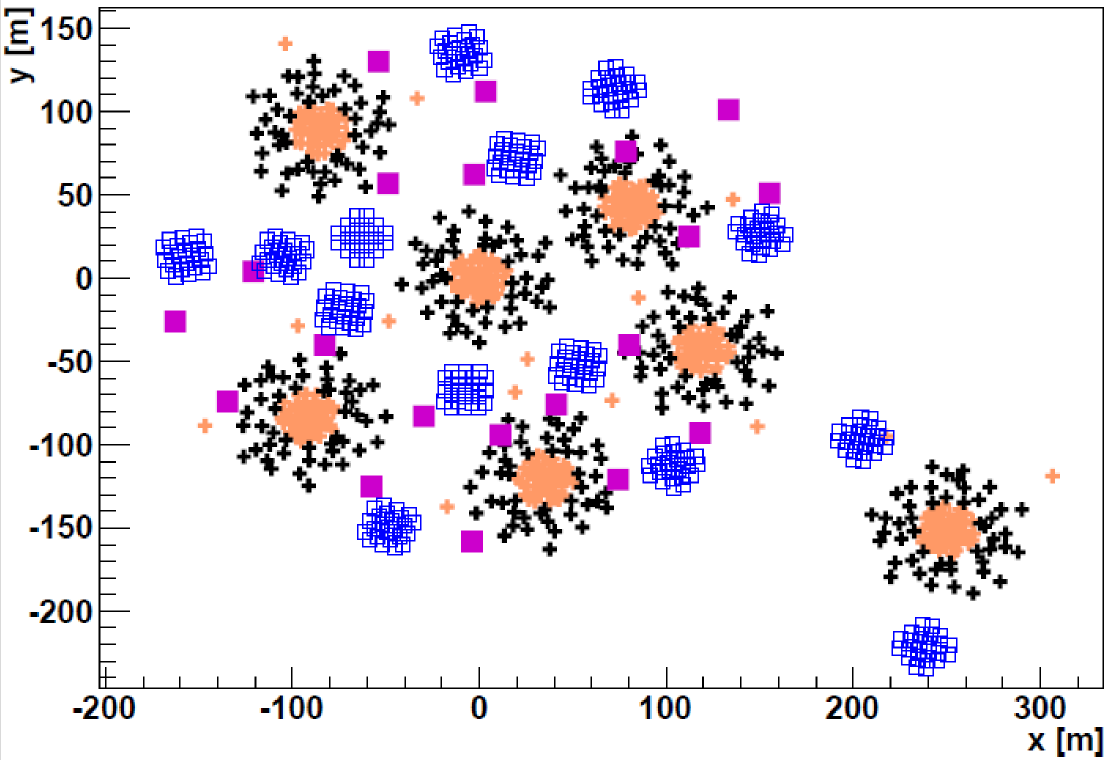




CODALEMA, Astropp. 31 (2009) 192 and 69 (2015) 50

LOFAR superterp, the Netherlands

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



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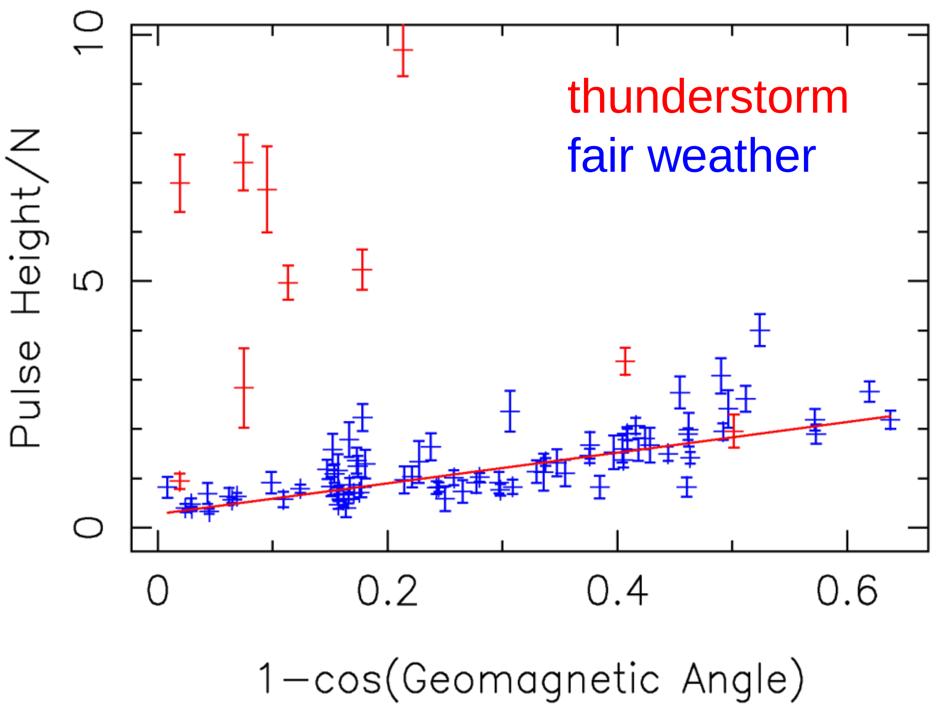
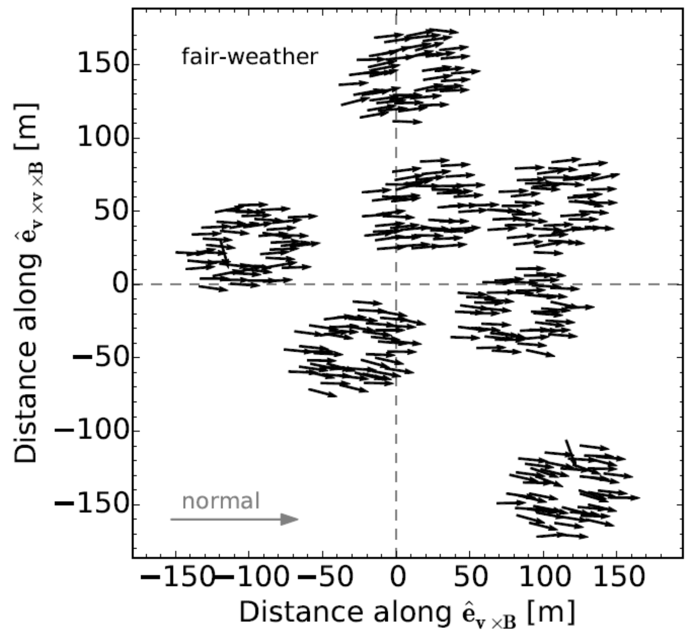
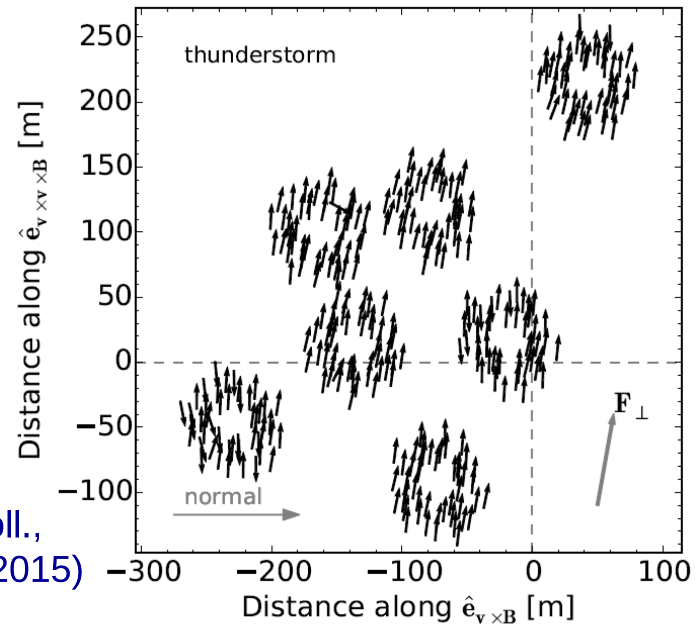
Thunderstorms

- 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

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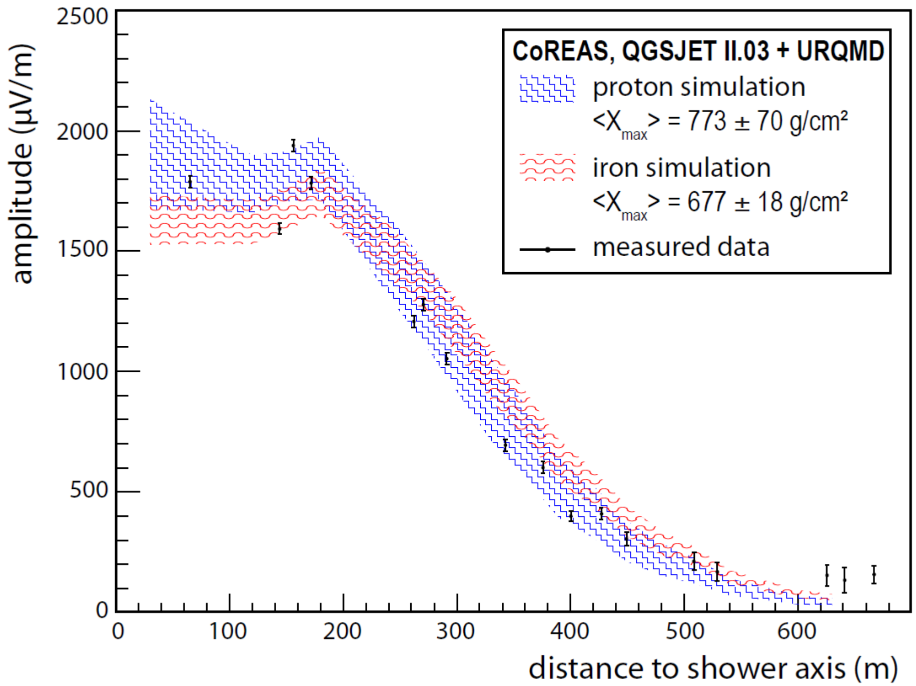
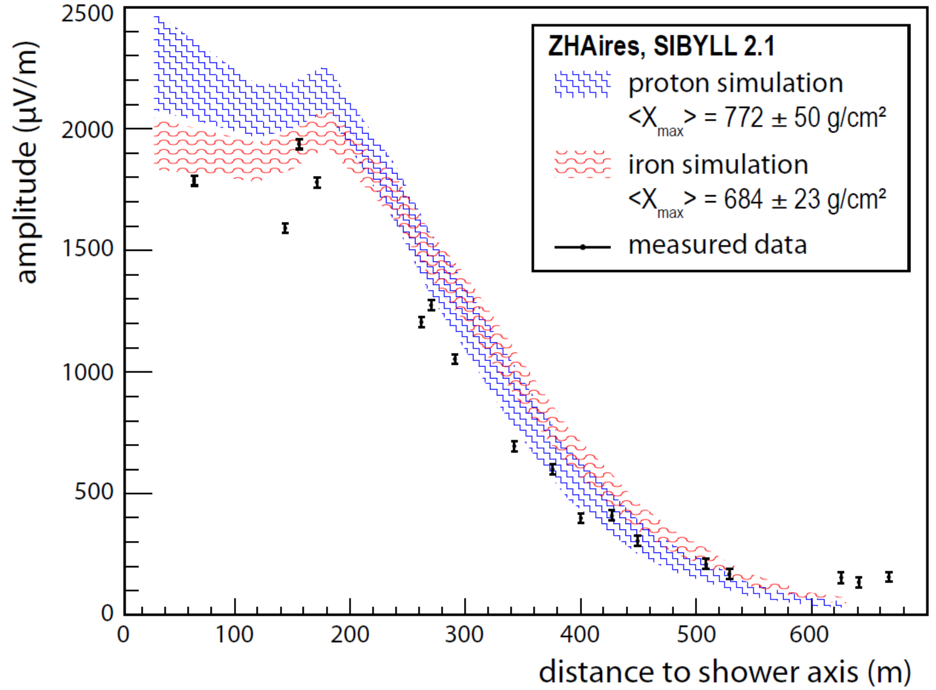
Comparing simulations with AERA event



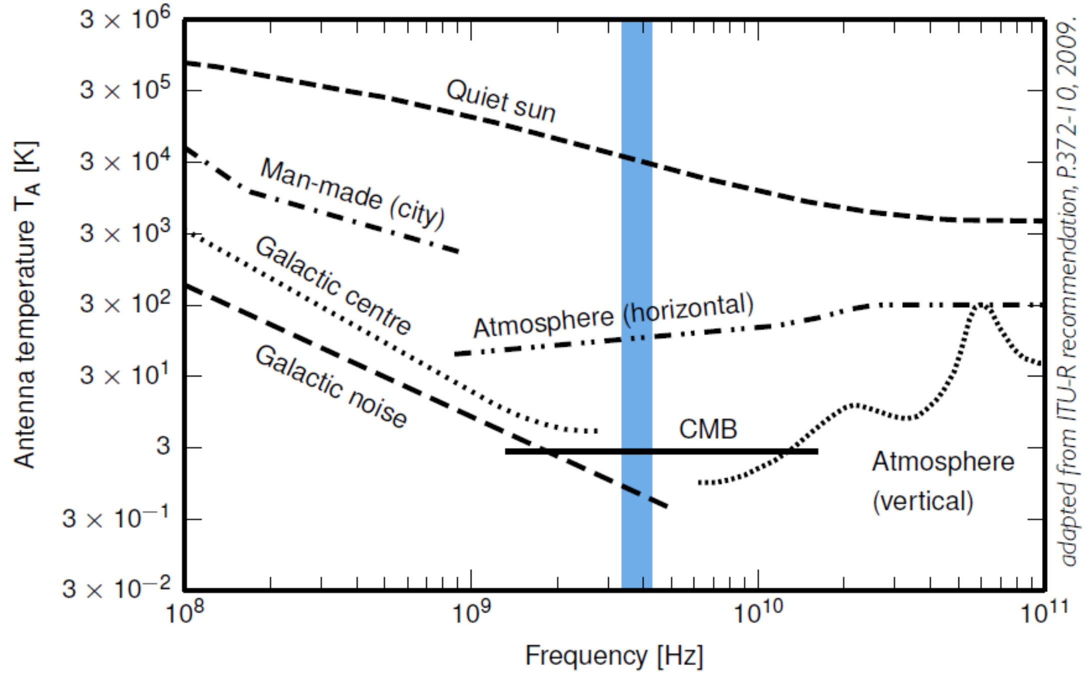


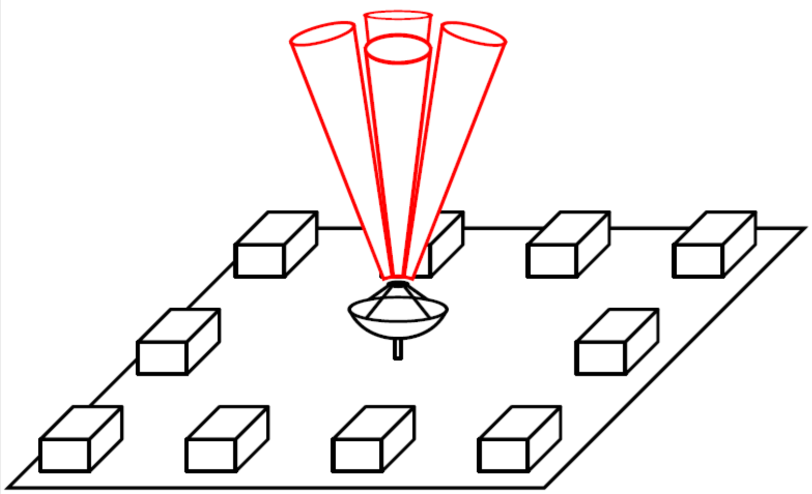
- Example event with calibrated AERA measurements
- CoREAS and ZHAires simulations reproduce shape
    - differences compatible with calibration scale uncertainty?

Pierre Auger Collaboration, ICRC2013, id #899

CROME at KIT

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





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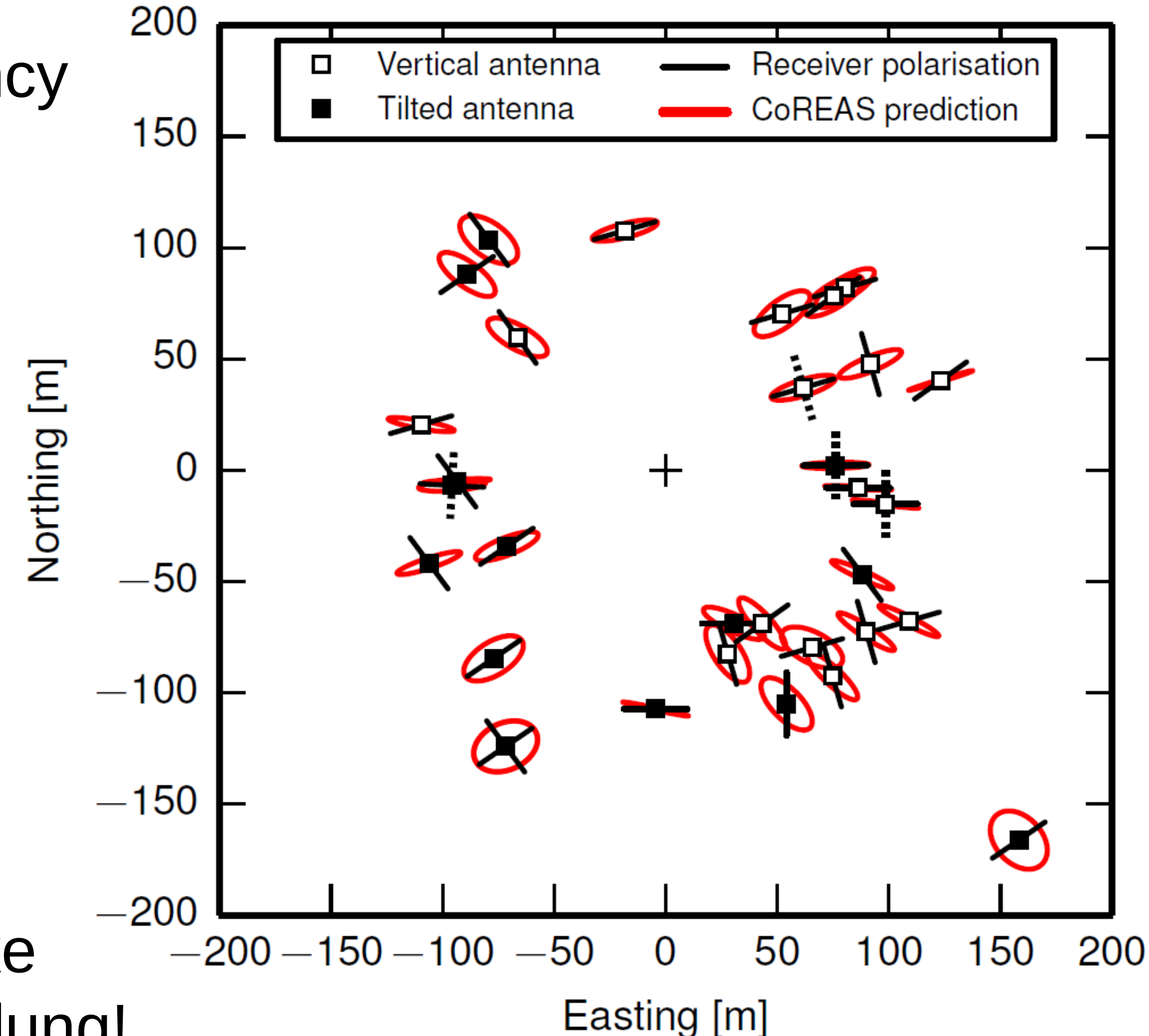
Cherenkov ring seen with CROME

- 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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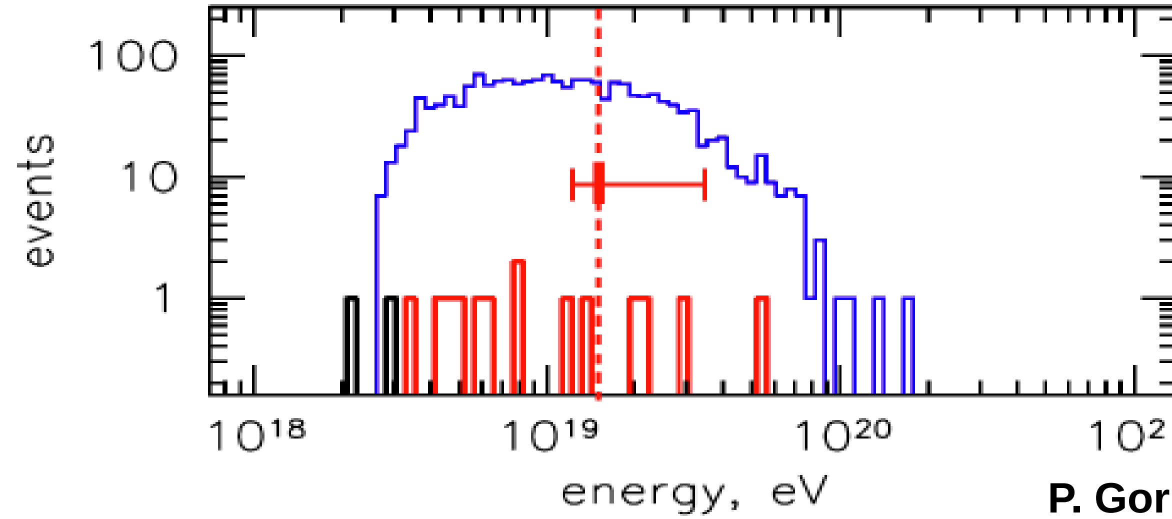
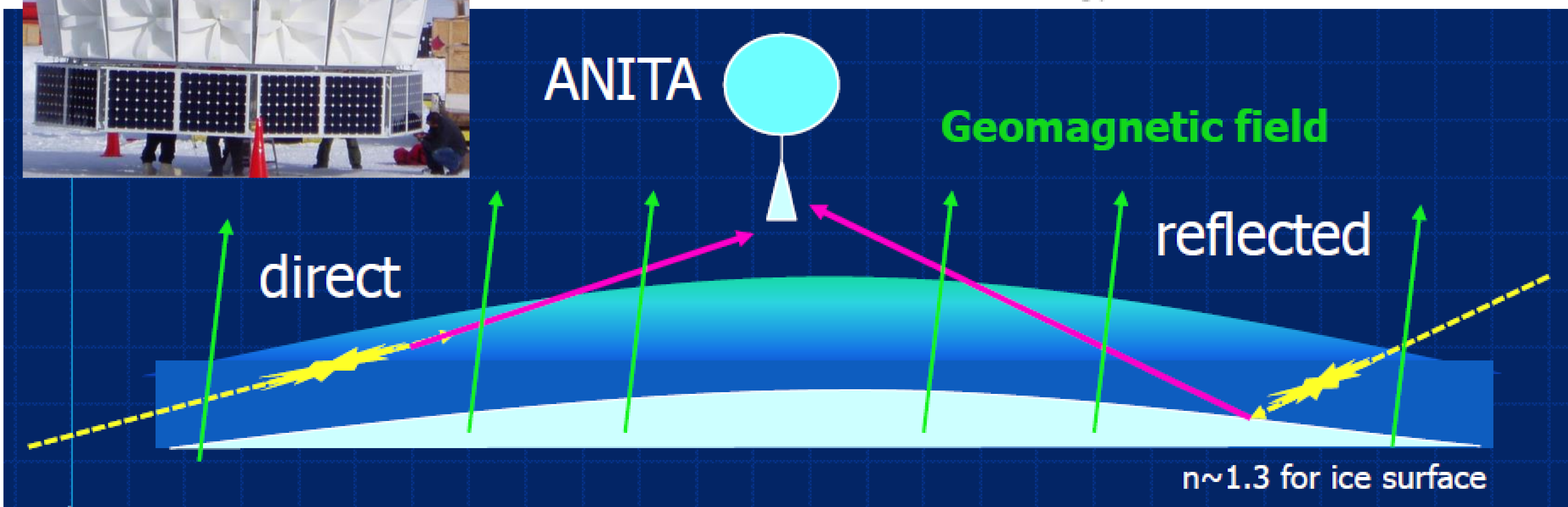
ANITA (detected ~ 14 CR events)



P. Gorham



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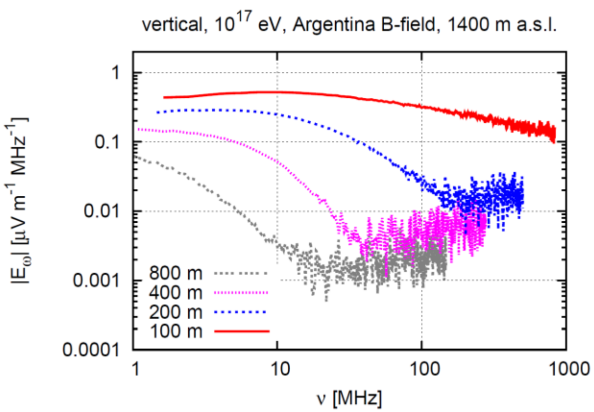
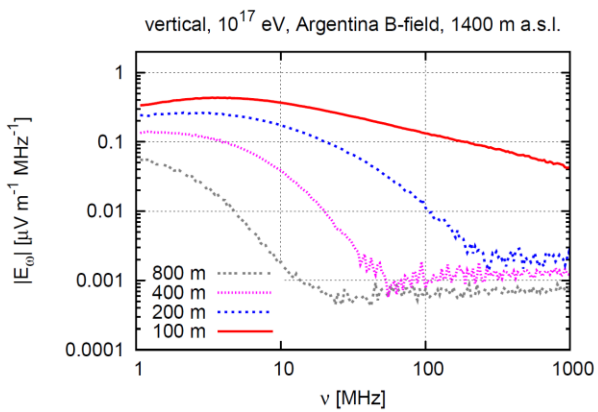
Simulated frequency spectra

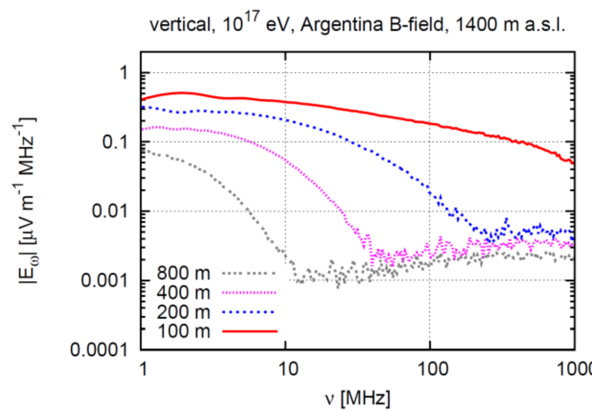
REAS3.1

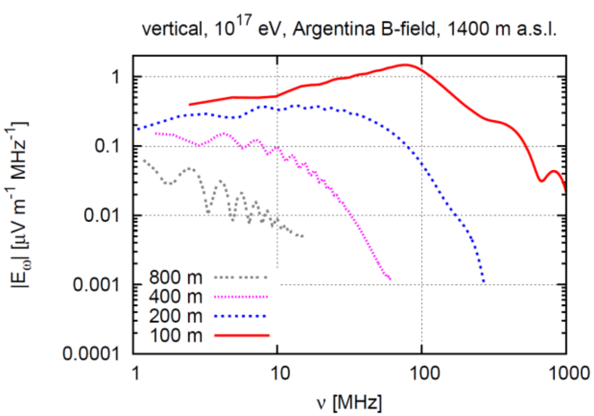


CoREAS

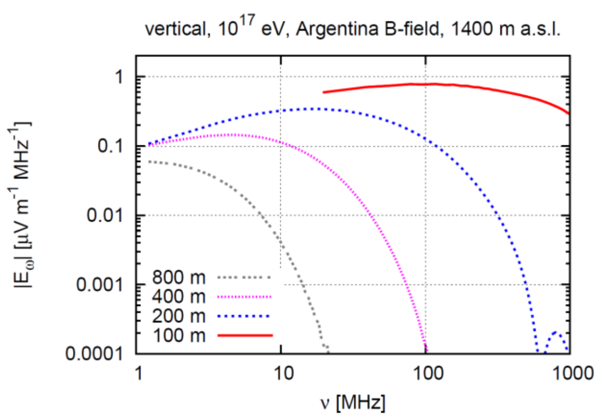


ZHAireS

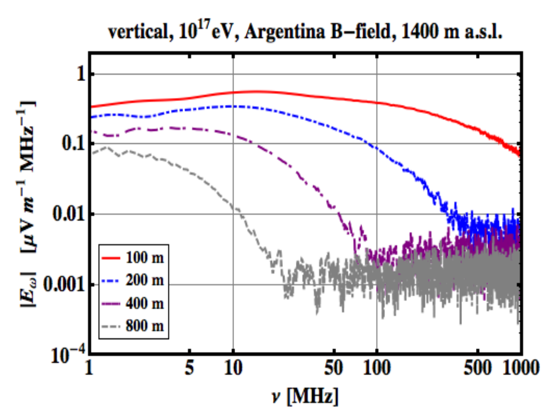




MGMR



EVA



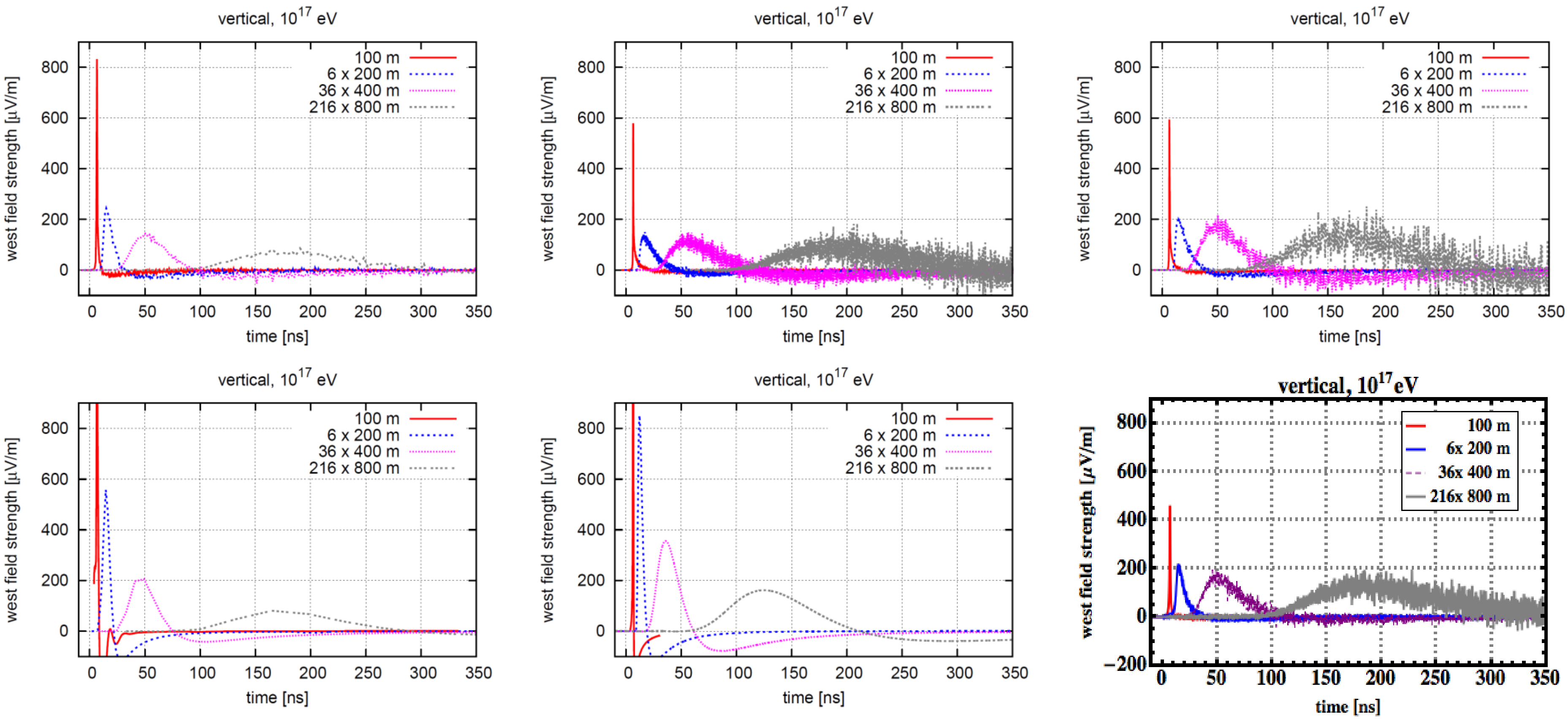
SELFAS2

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

T. Huege et al., ARENA2012

Simulated pulses: time series

REAS3.1 | CoREAS | ZHAireS



MGMR | EVA | SELFAS2

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

T. Huege et al., ARENA2012