Karlsruhe Institute of Technology

Radio detection of air showers

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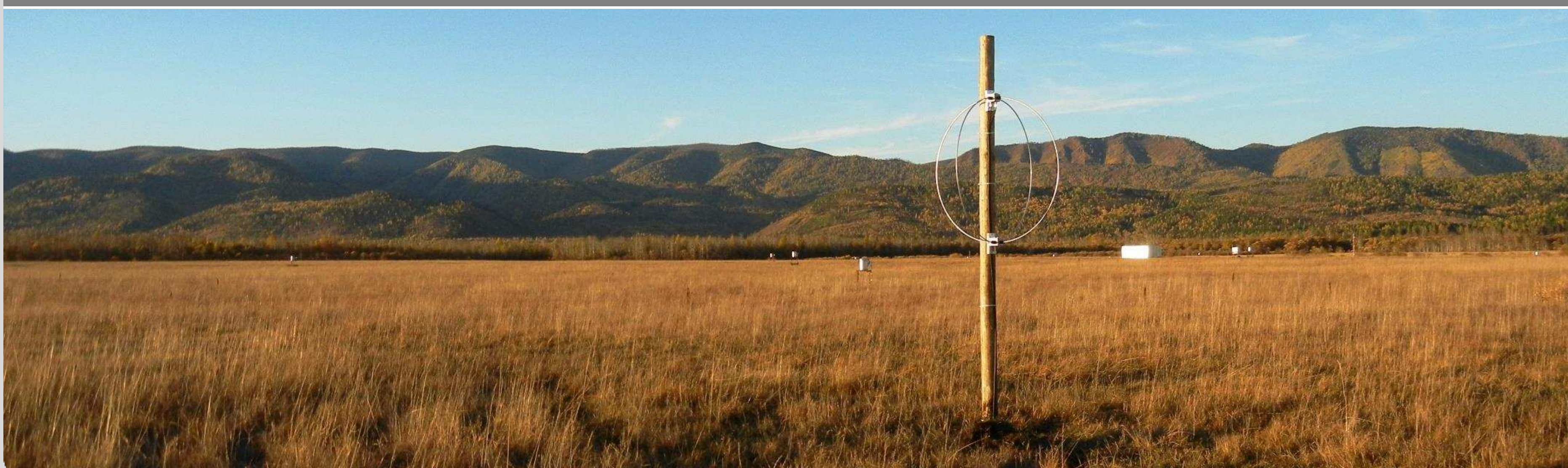
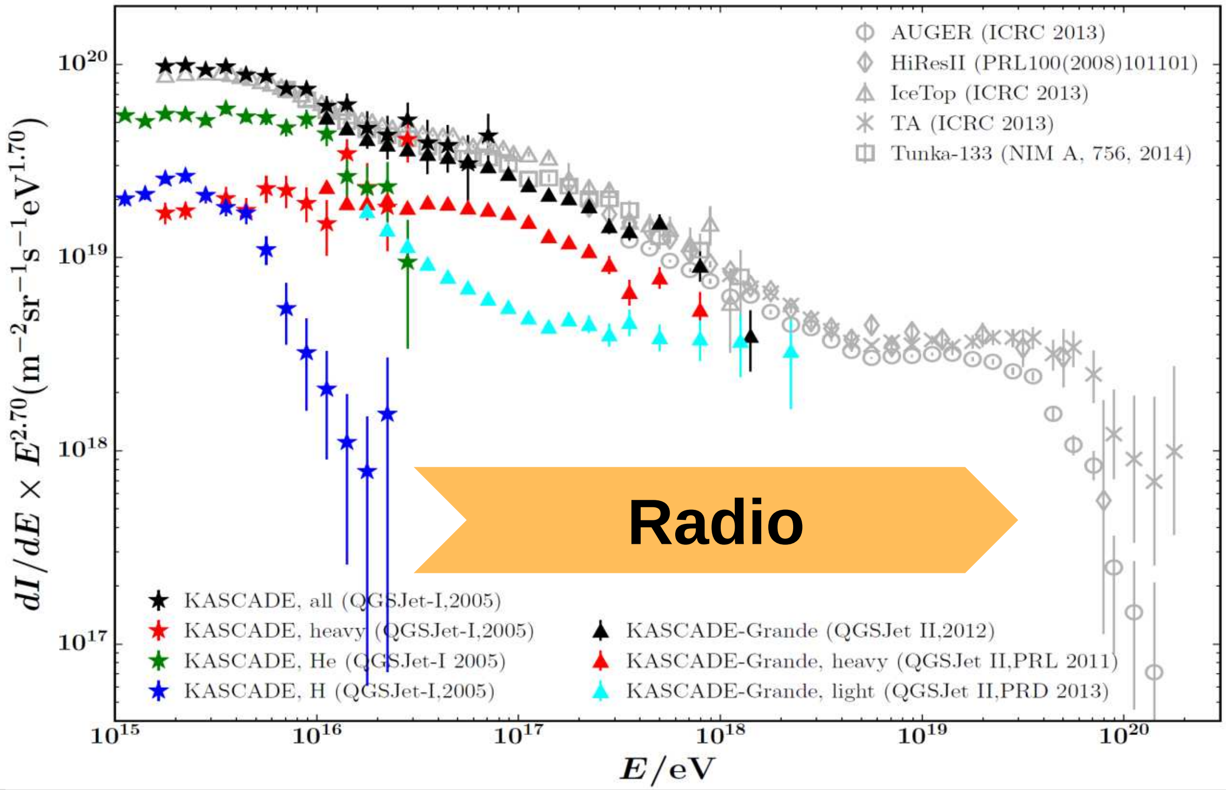


Advantages of radio technique

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



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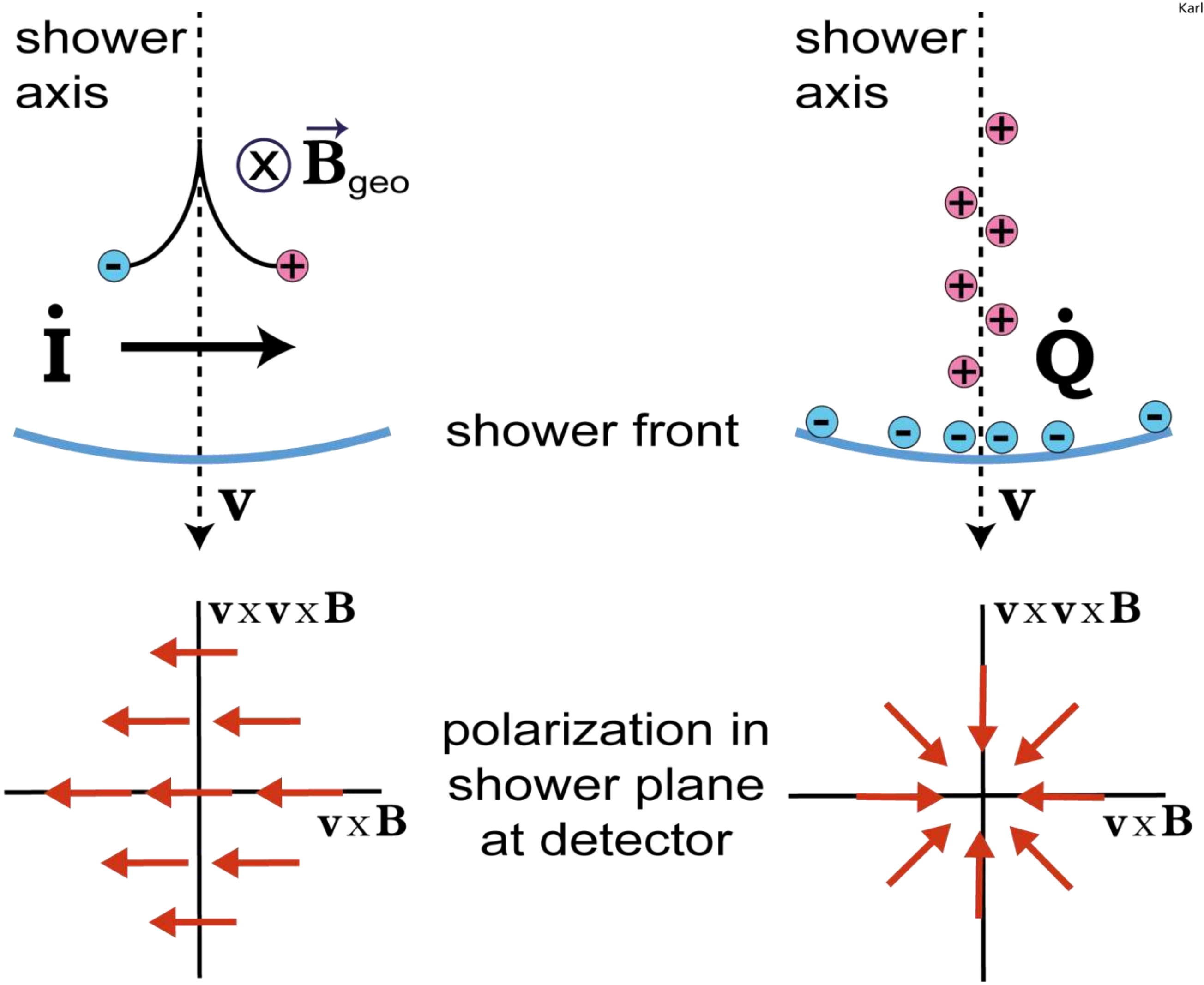
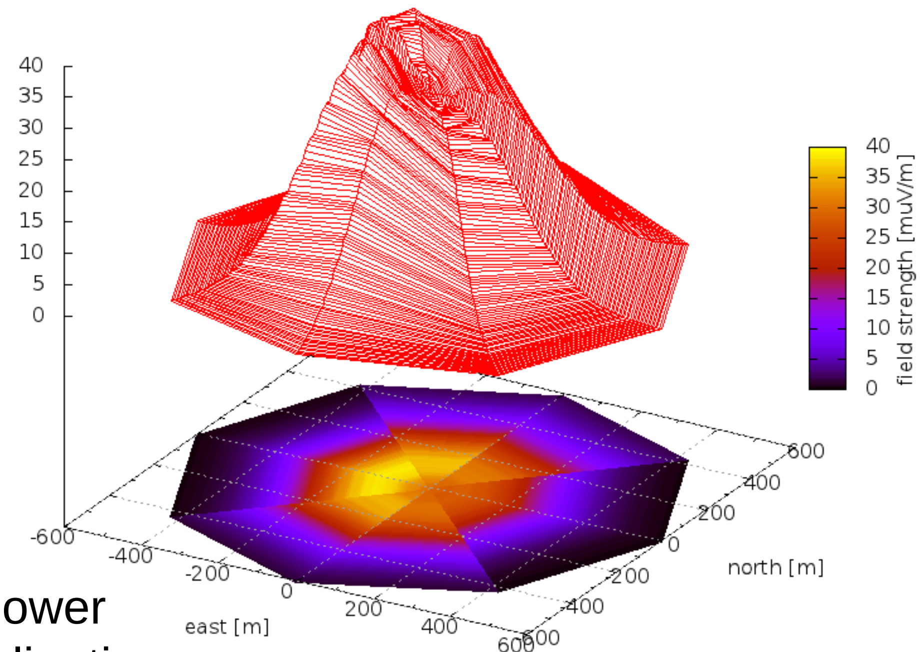
Emission mechanisms

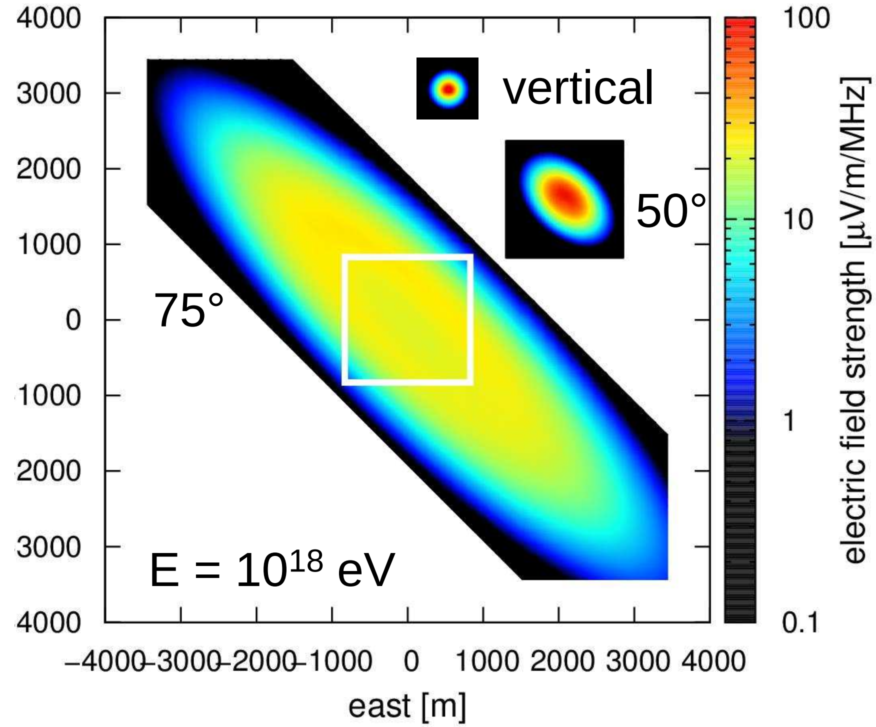


geomagnetic effect ~ 90%   Askaryan effect ~ 10%

Asymmetric footprint of radio signal

- Cone with 1-2° diameter: large footprint for inclined showers





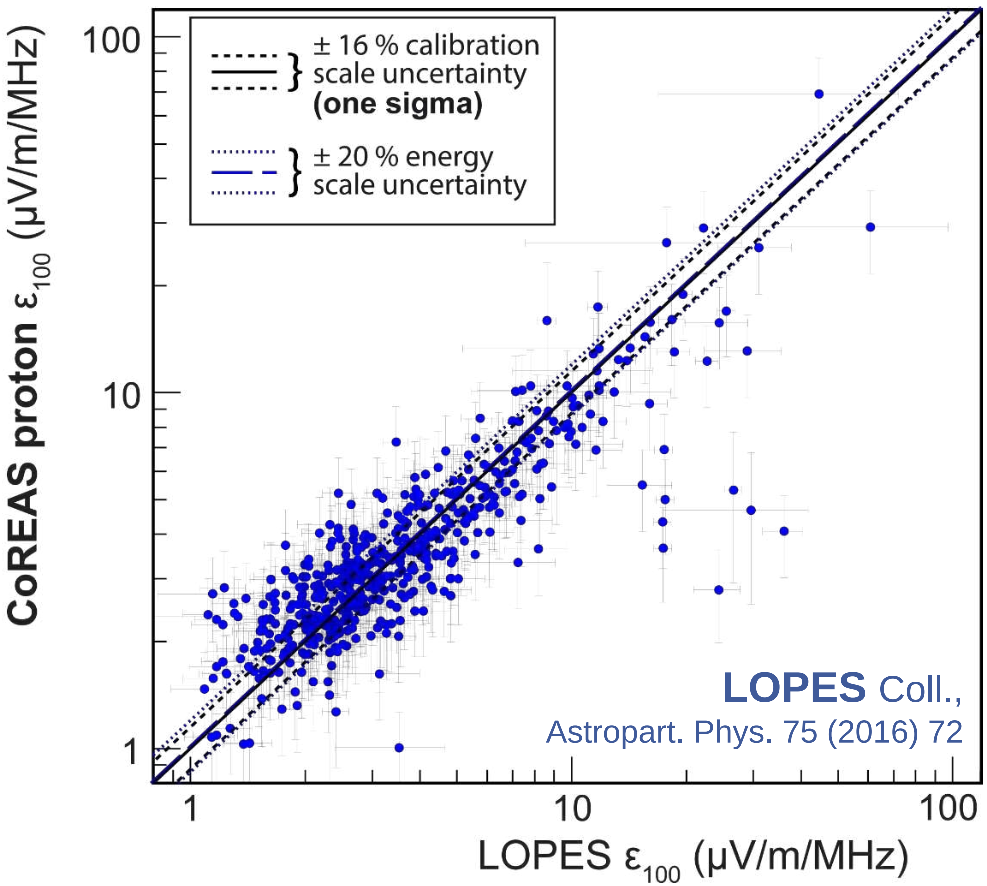
shower inclination:
$\theta = 45°$

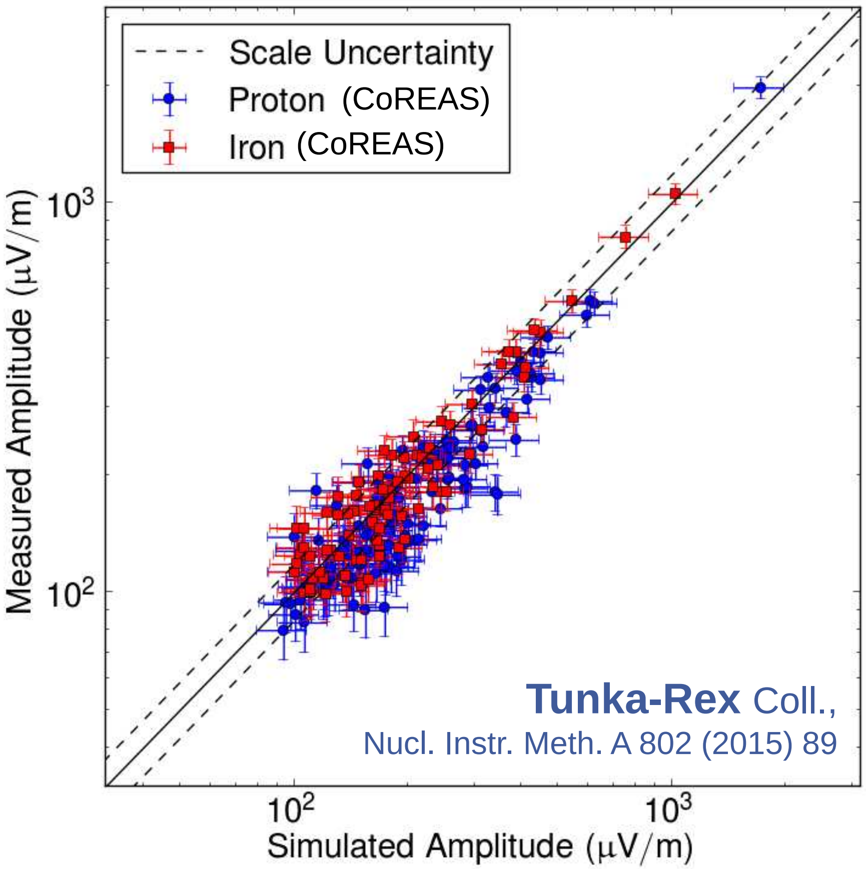
43 – 74 MHz

CoREAS simulations
byT. Huege et al., ARENA2012

Do simulations describe reality?

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

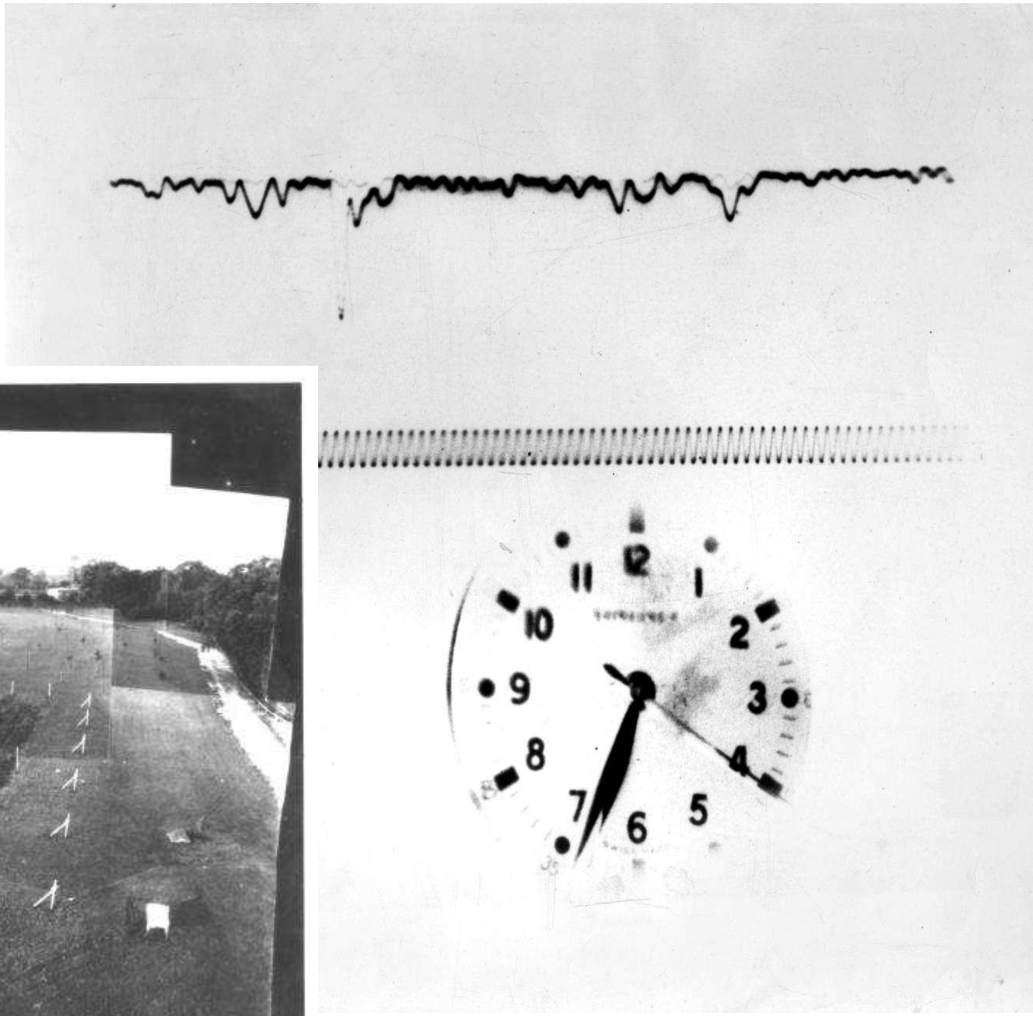




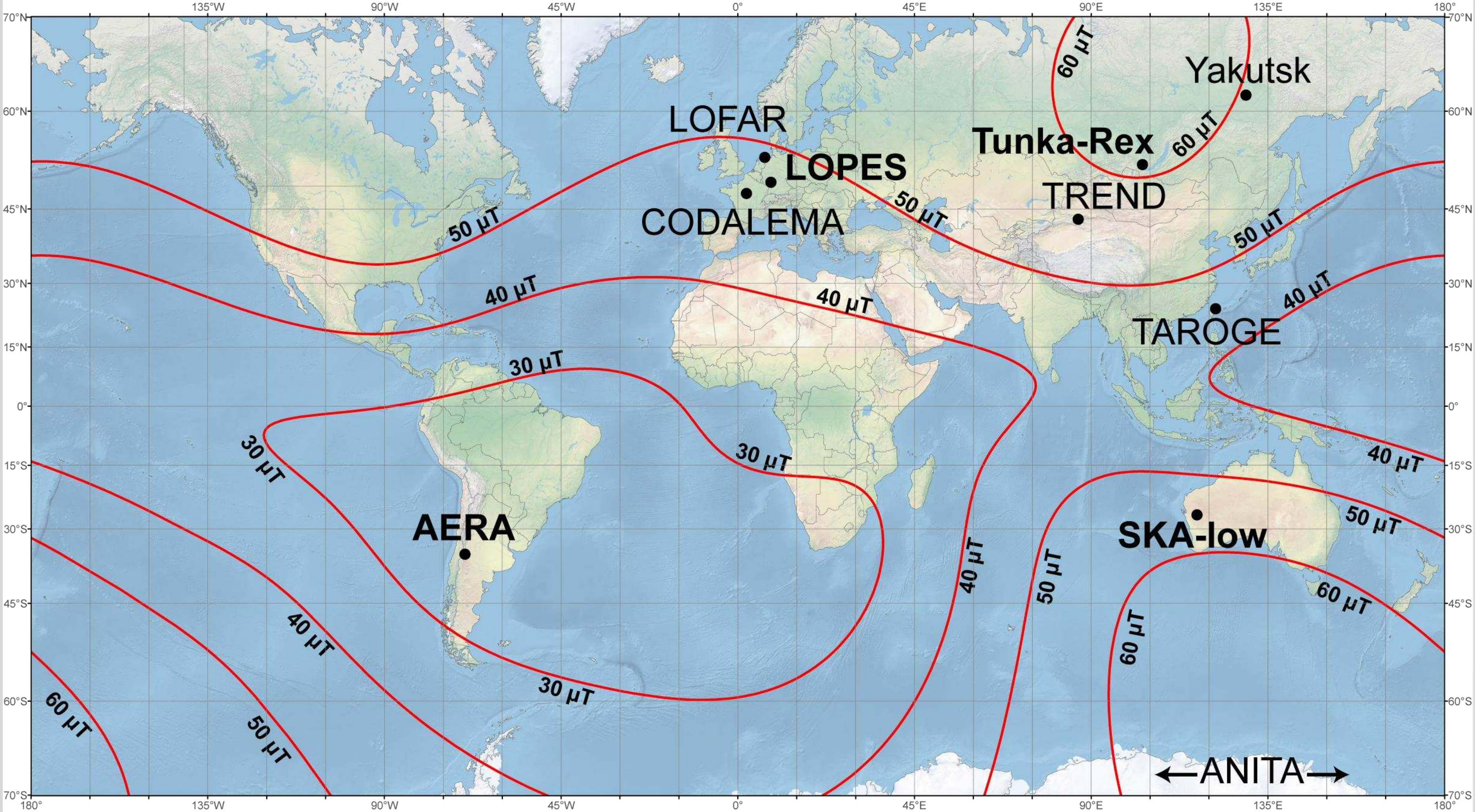
Experiments: First Detection

- 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
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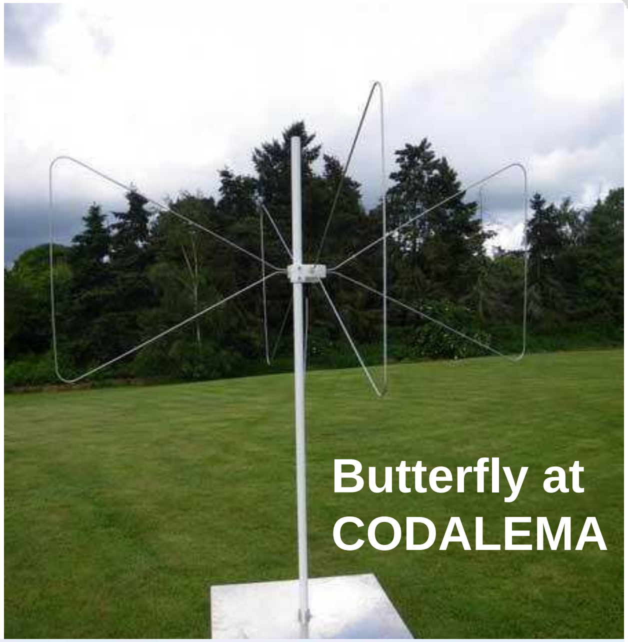
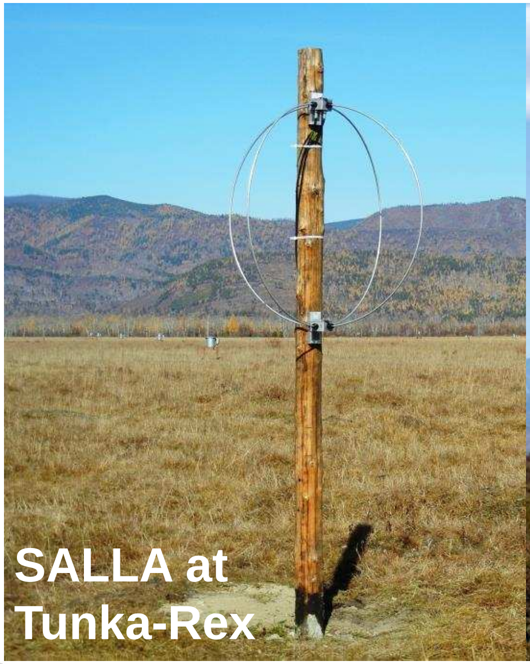
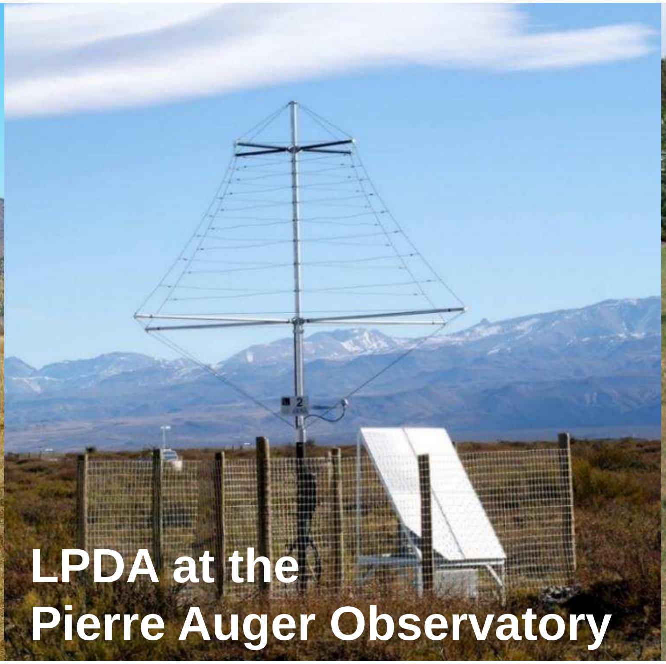
Detectors: antennas

- Many working solutions with only slight differences in
  - threshold (typical 10^{17} eV)
  - frequency band (typical 30-80 MHz)
  - accuracy (systematic uncertainties)







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Reconstruction of shower parameters

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

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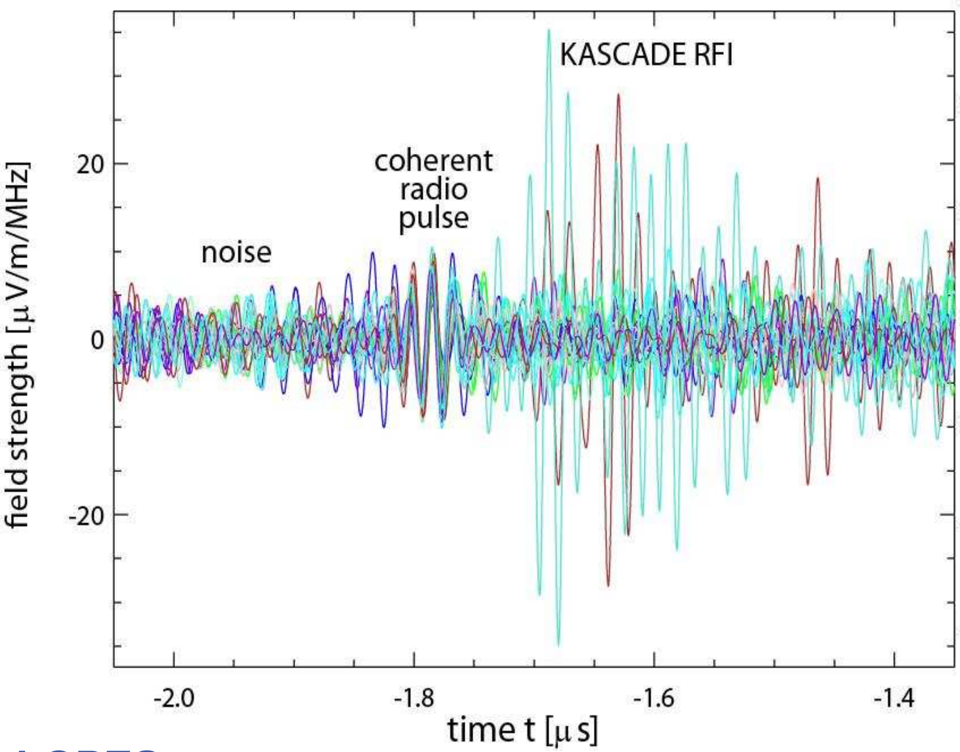
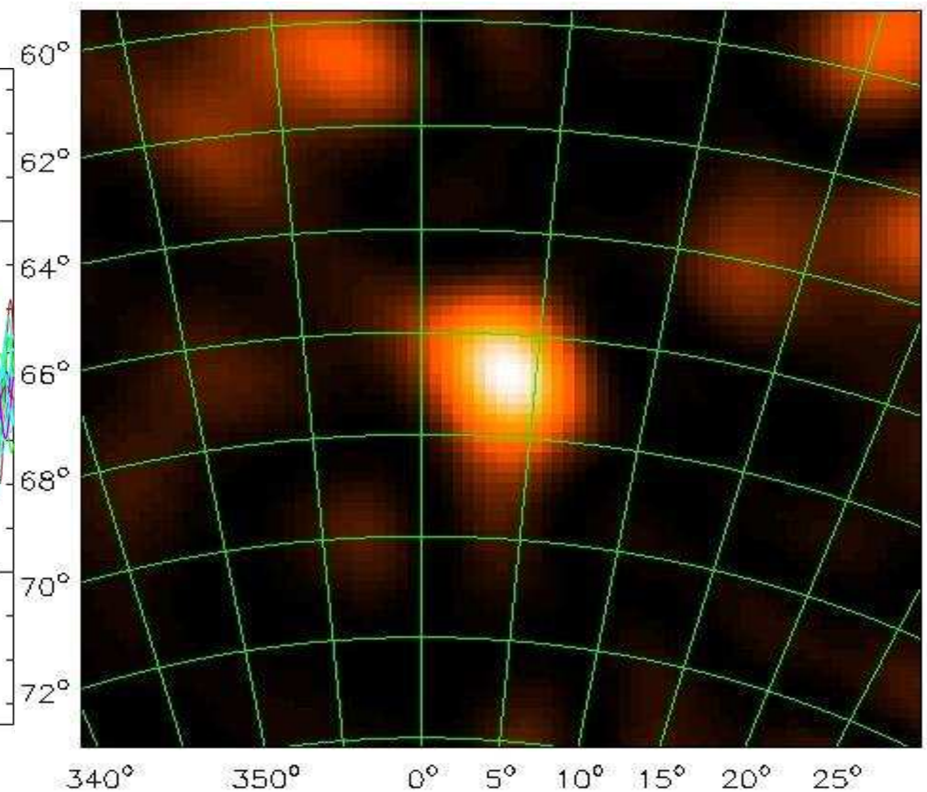
Interferometric beamforming at LOPES

- Shift traces in time according to arrival direction
- Cross-correlation of antennas → image of radio pulse
- Direction precision < 0.7°





LOPES Coll., Astroparticle Physics 50-52 (2013) 76 + Nature 435 (2005) 313

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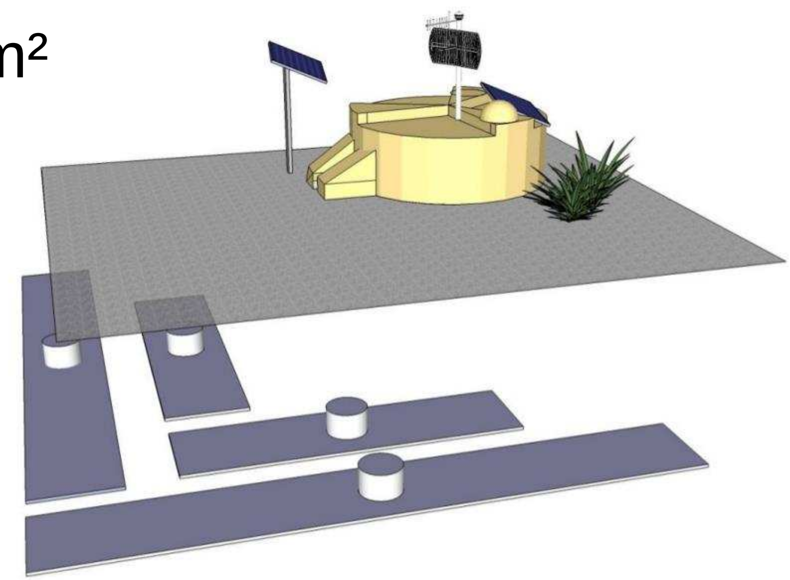
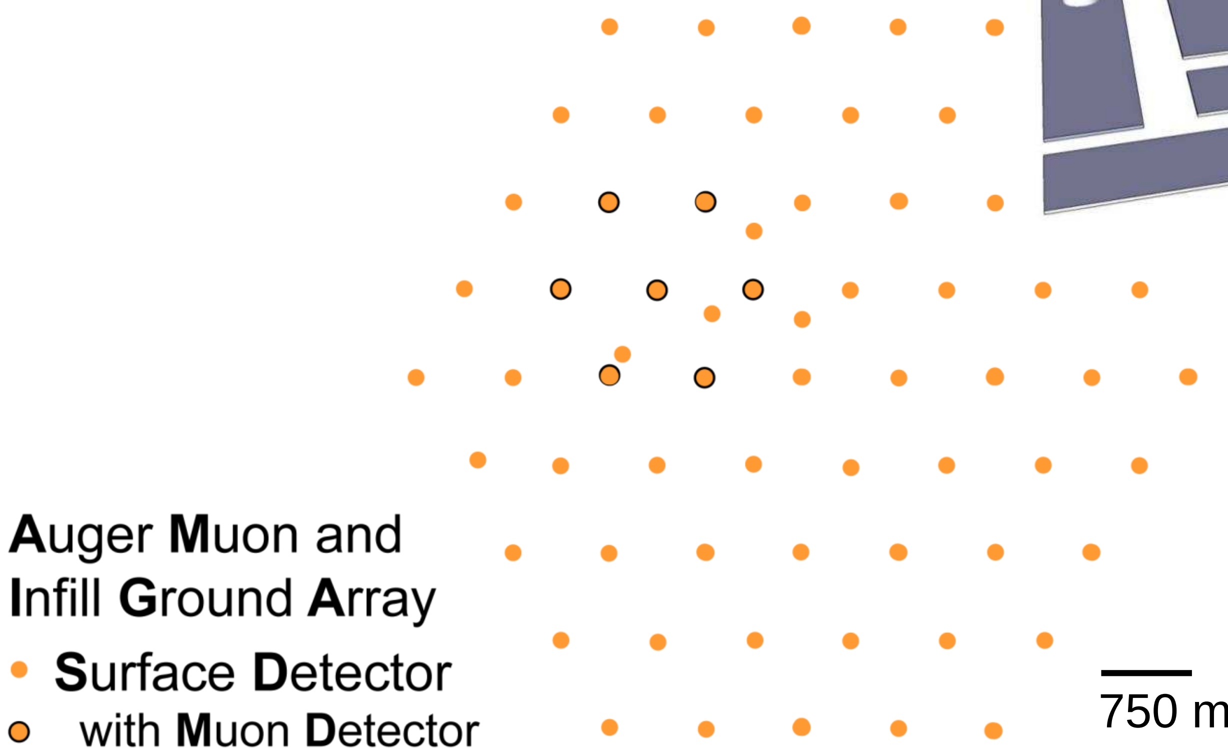
Auger Engineering Radio Array

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





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- 153 autonomous stations on 17 km²
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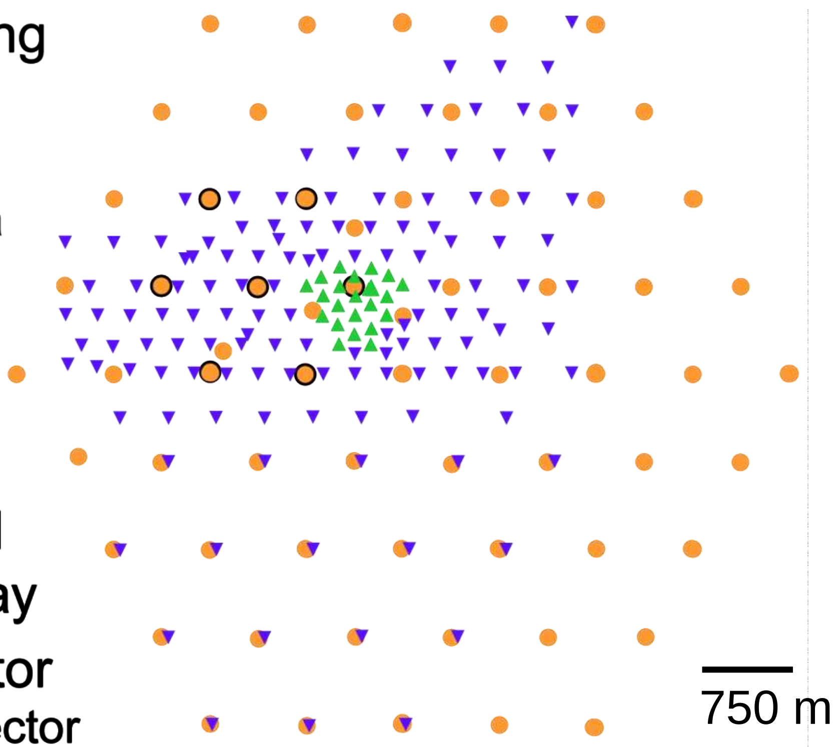
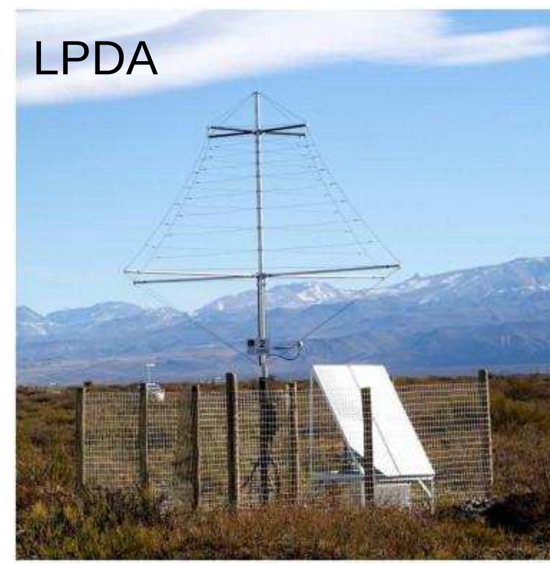
Auger **E**ngineering **R**adio **A**rray
▲ LPDA antenna
▼ Butterfly antenna

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





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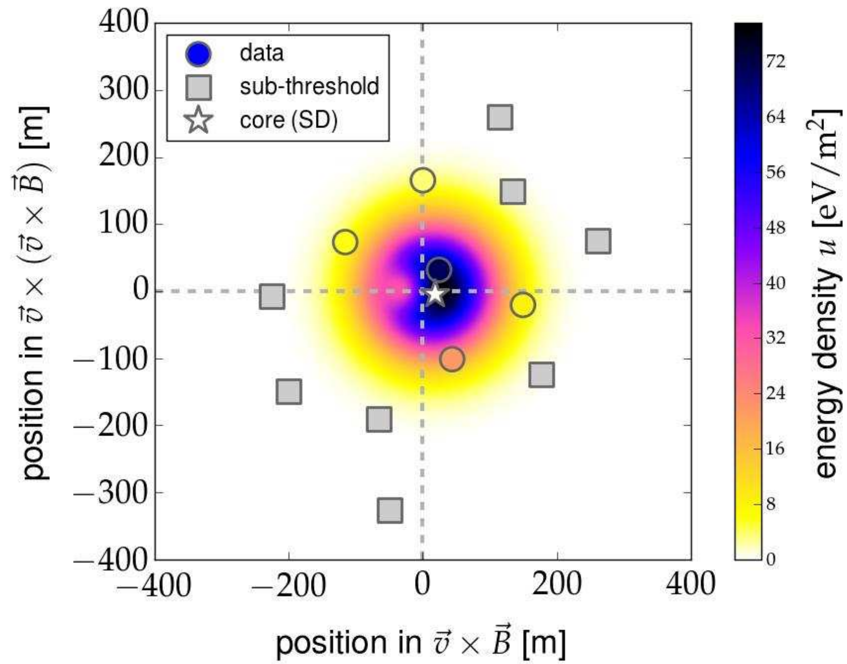
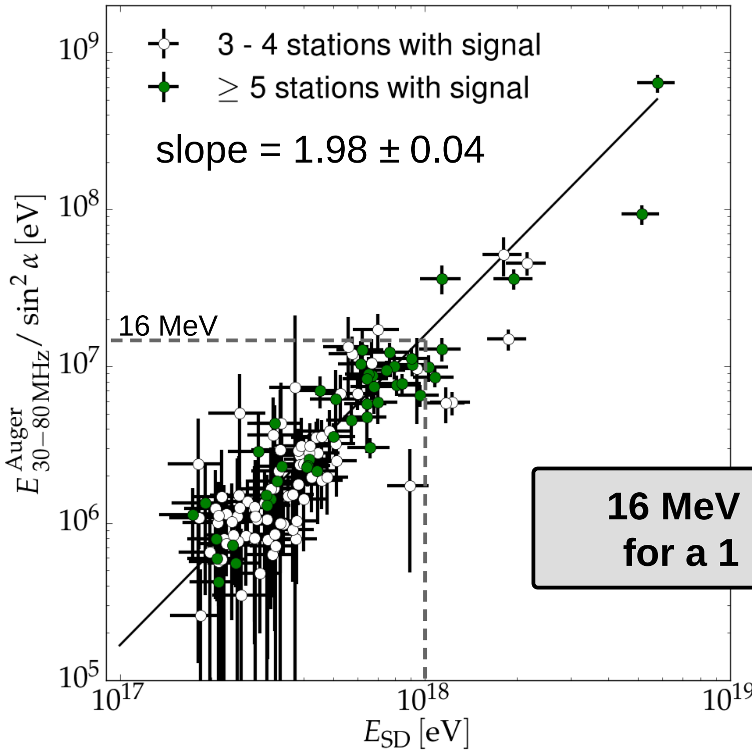
Energy reconstruction

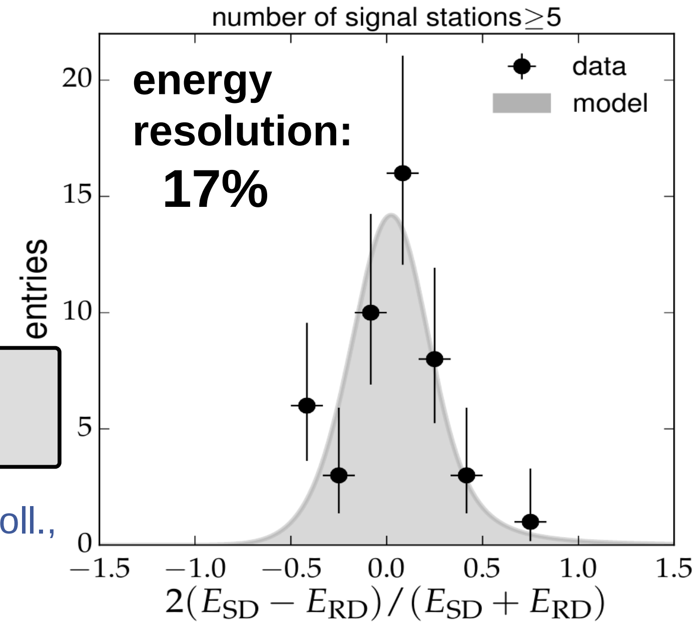
- Coherent radio emission

→ Radio energy squared
~ number of electrons
~ shower energy





16 MeV radiation energy for a 1 EeV cosmic ray



Pierre Auger Coll., accepted by PRD

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More examples for energy reconstruction

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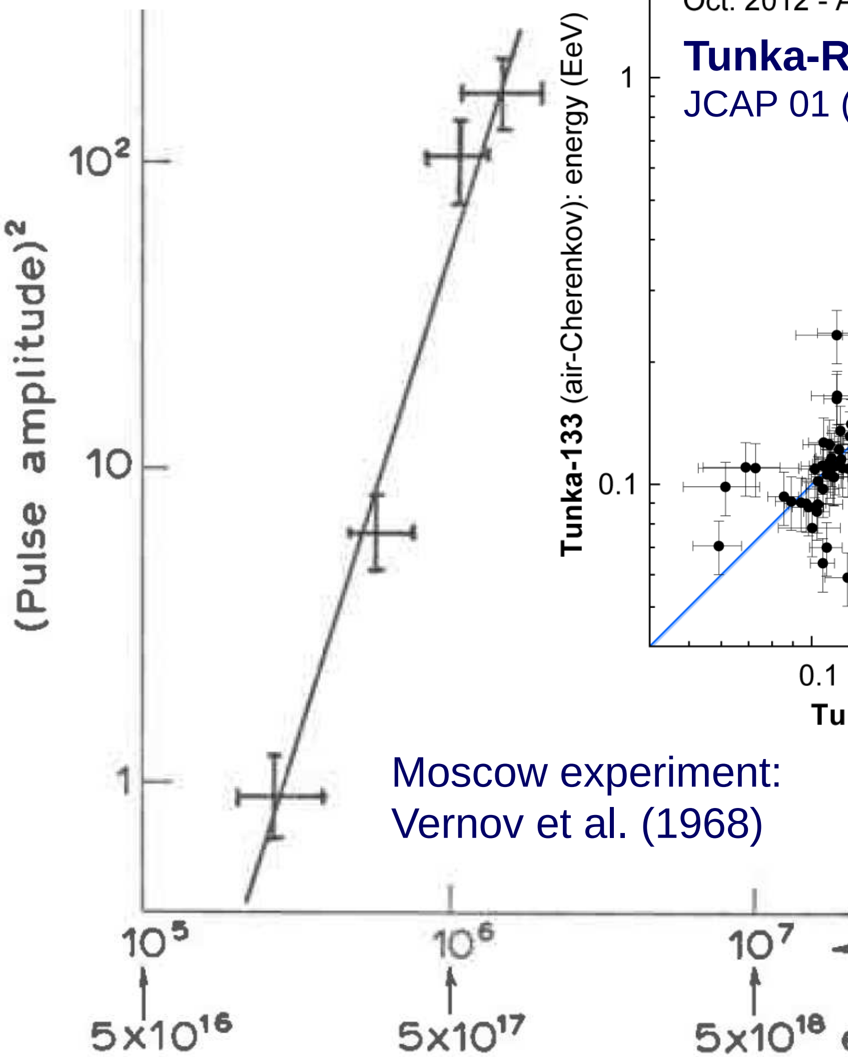
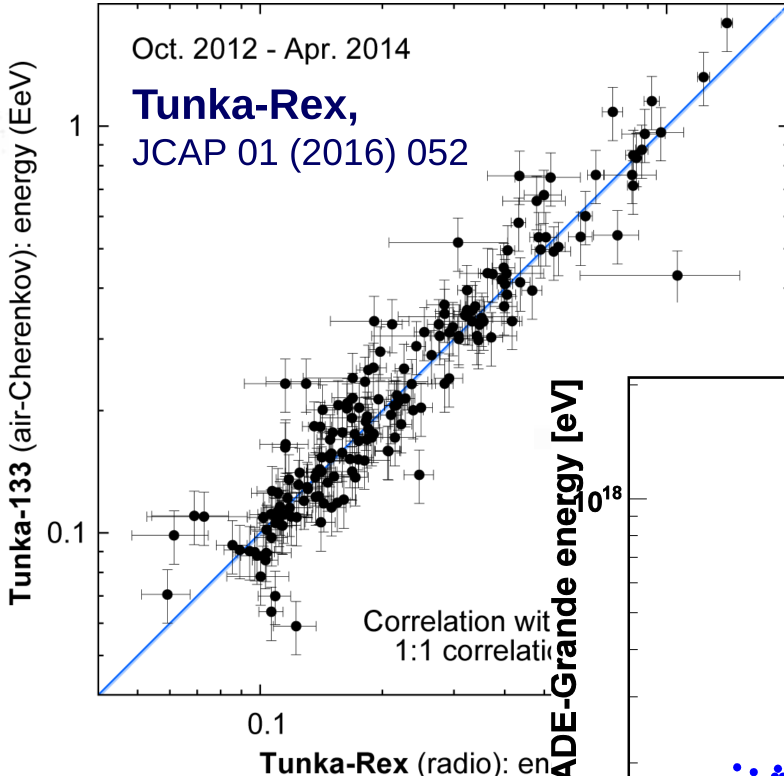
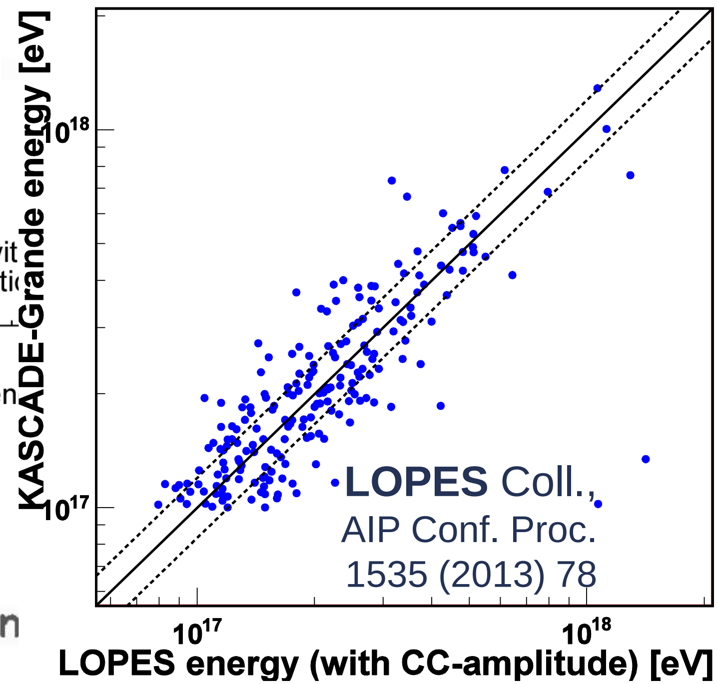


Moscow experiment:
Vernov et al. (1968)



Tunka-Rex,
JCAP 01 (2016) 052

Also seen by:
CODALMEA,
LOFAR, …



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

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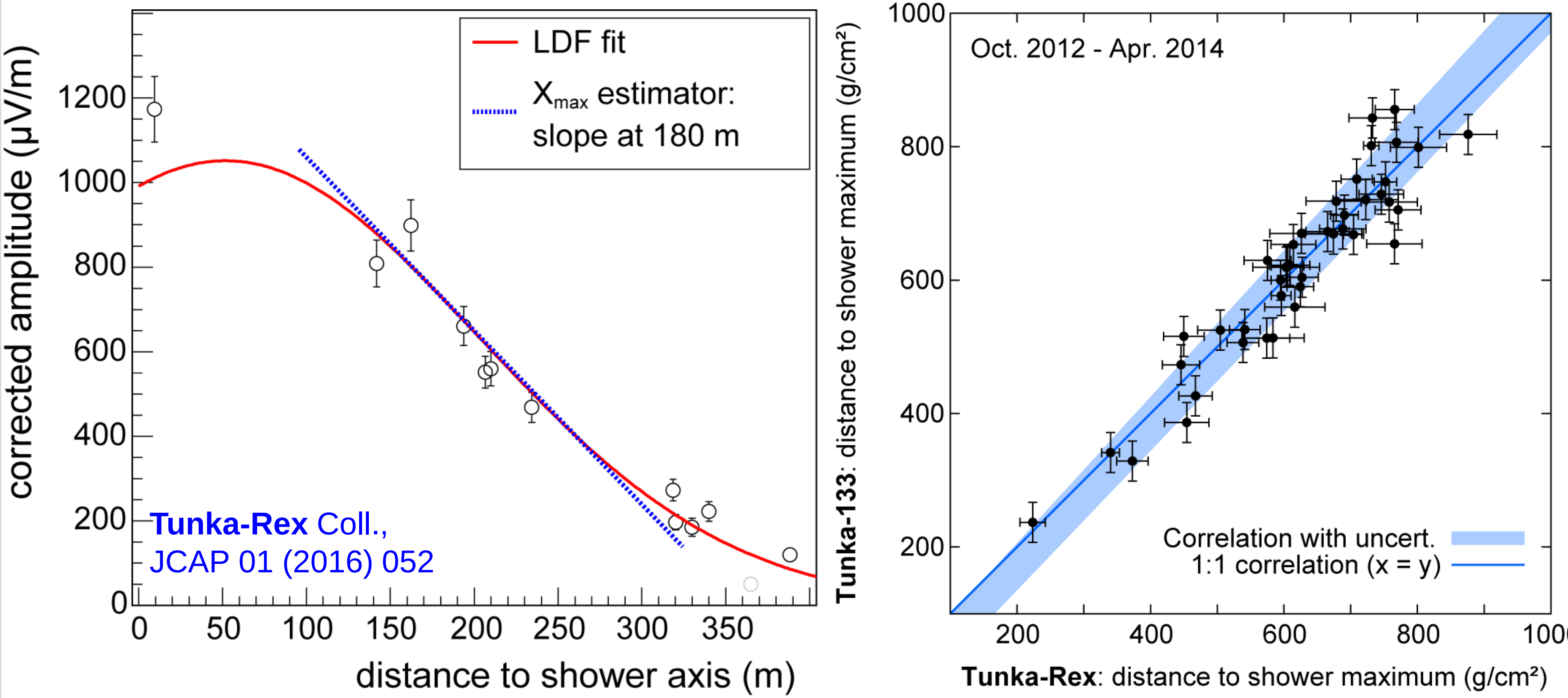
Shower maximum: proof by Tunka-Rex

- 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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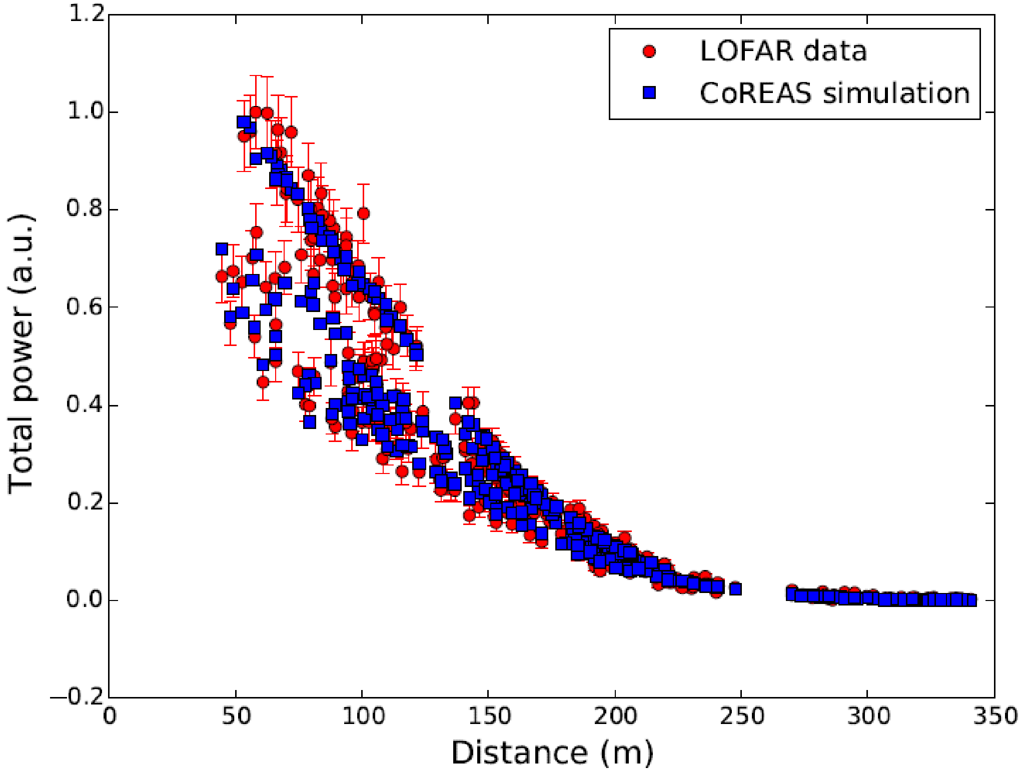
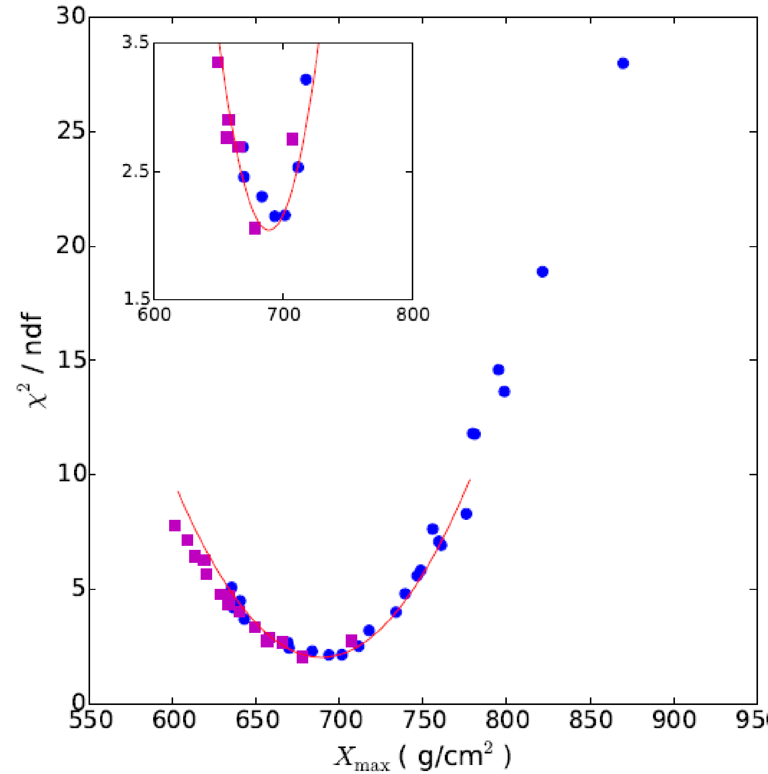
LOFAR: High precision using simulations

- 100s of antennas measuring details of the radio footprint
  - Pick the one of many simulations describing data best
  - X_{max} precision better than 20 g/cm² (like fluorescence)





LOFAR Coll, PRD 90 (2014) 082003,and **LOFAR** Coll. Nature 531 (2016) 70

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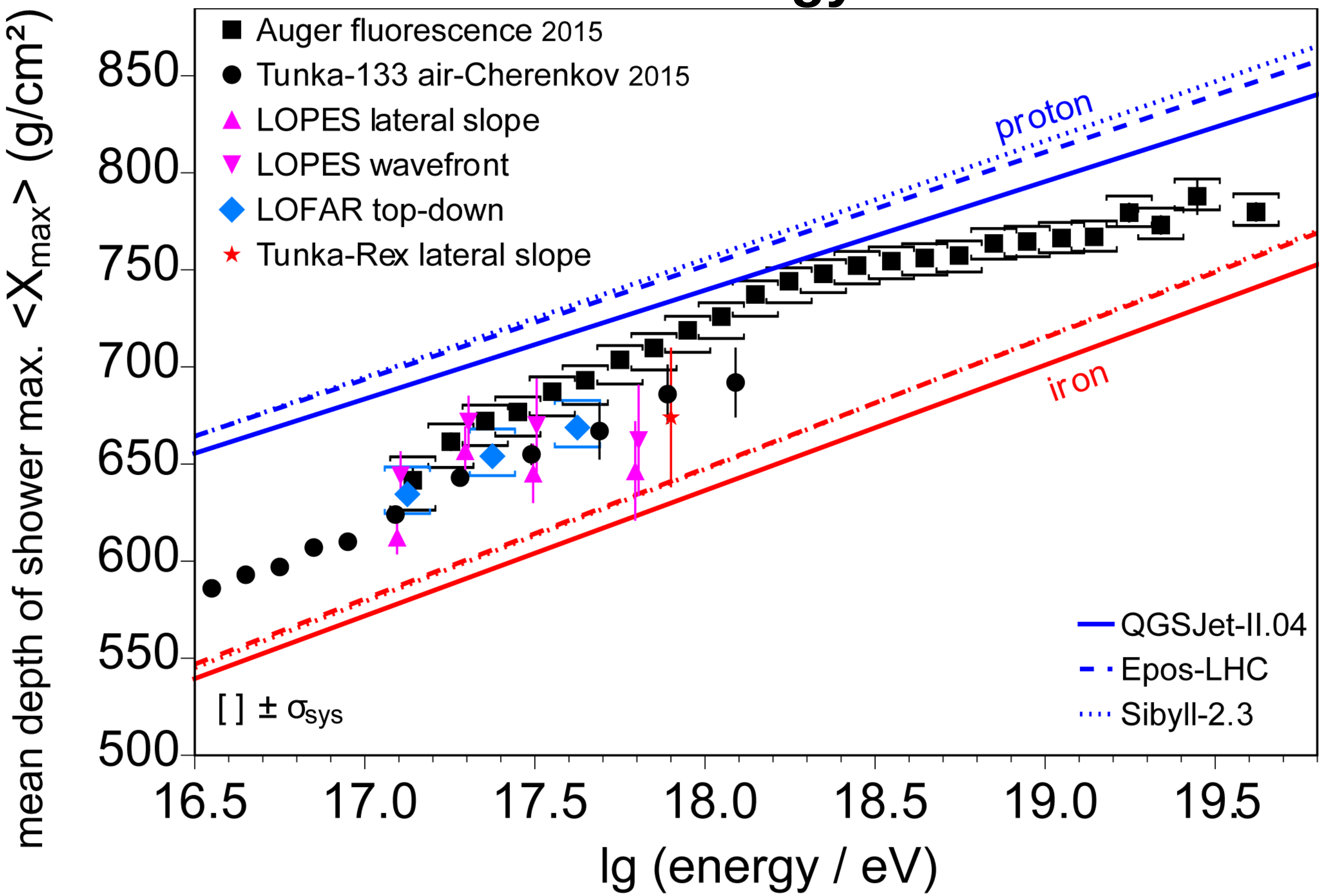
Shower maximum over energy



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Some future applications for radio

- Calorimetric, absolute energy measurement
  - cross-calibration of cosmic-ray energy 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
  - huge footprint and no absorption

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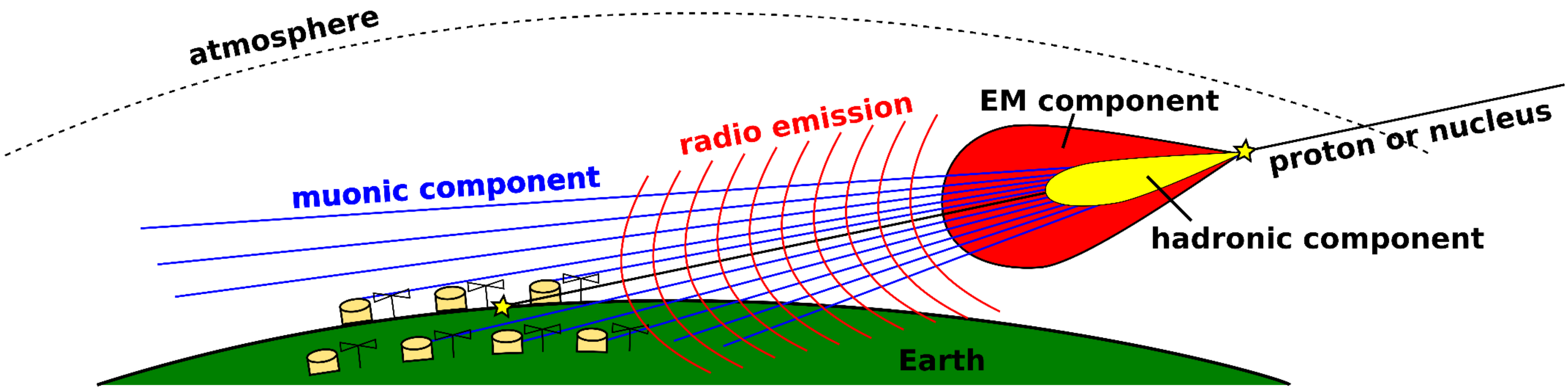
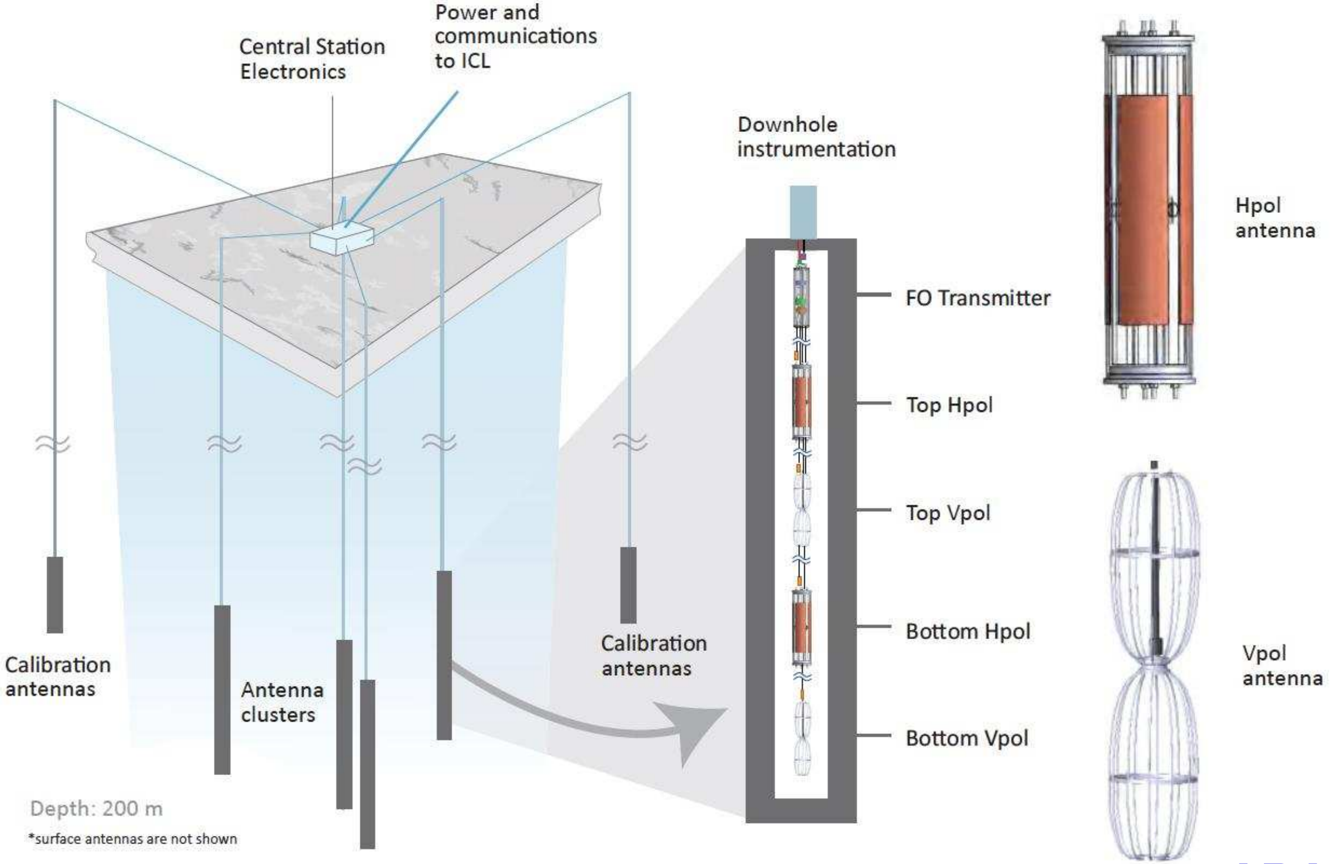
Radio ideal for inclined showers



- Huge radio footprint of several km²
- Only radio emission + muons survive for inclined showers
  - Complementary information on shower → primary particle type
- Interesting also for satellites and balloons, e.g., ANITA

Related: Radio emission in dense media

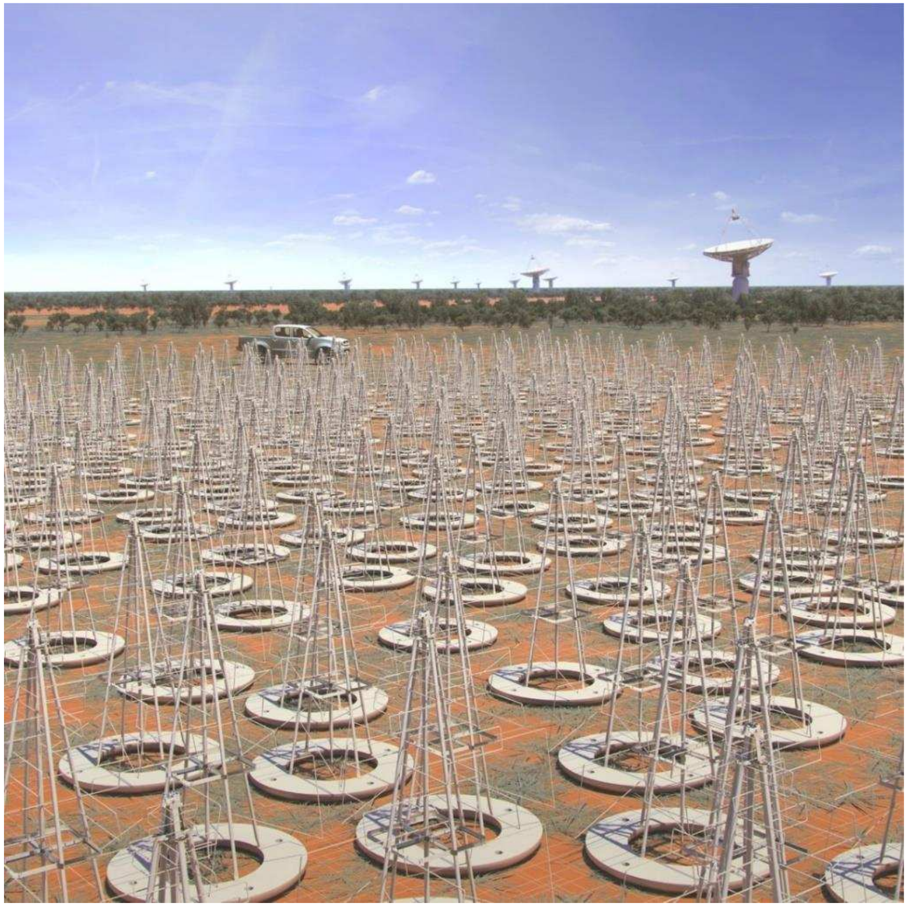
- Cosmic-rays and neutrinos in the lunar regolith
- Neutrino-induced showers in the Antarctic ice

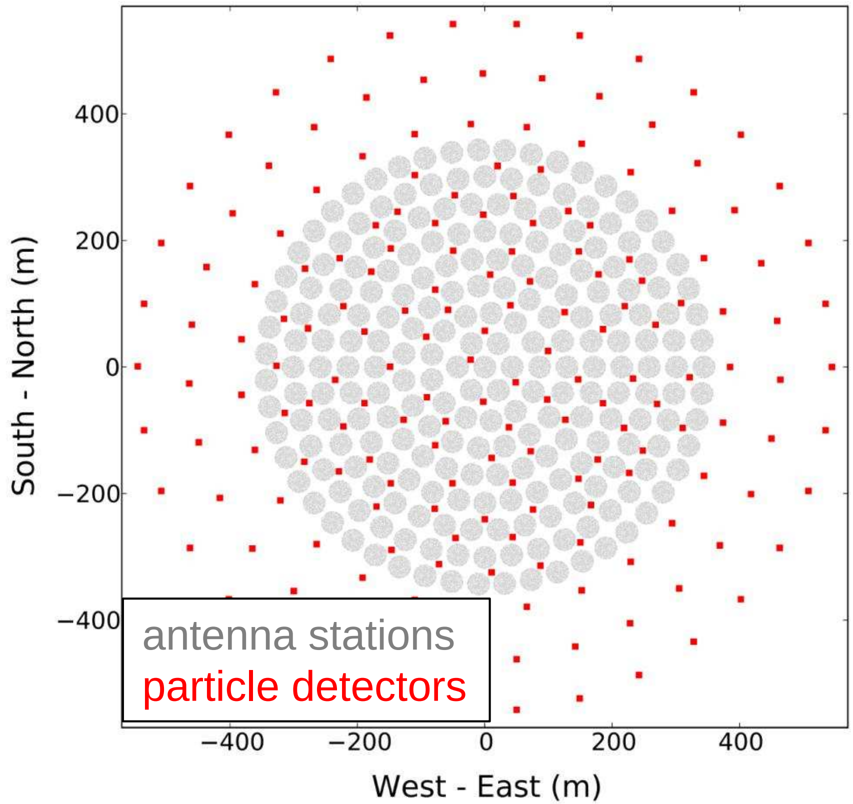


ARA Collaboration

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} < 20 g/cm² (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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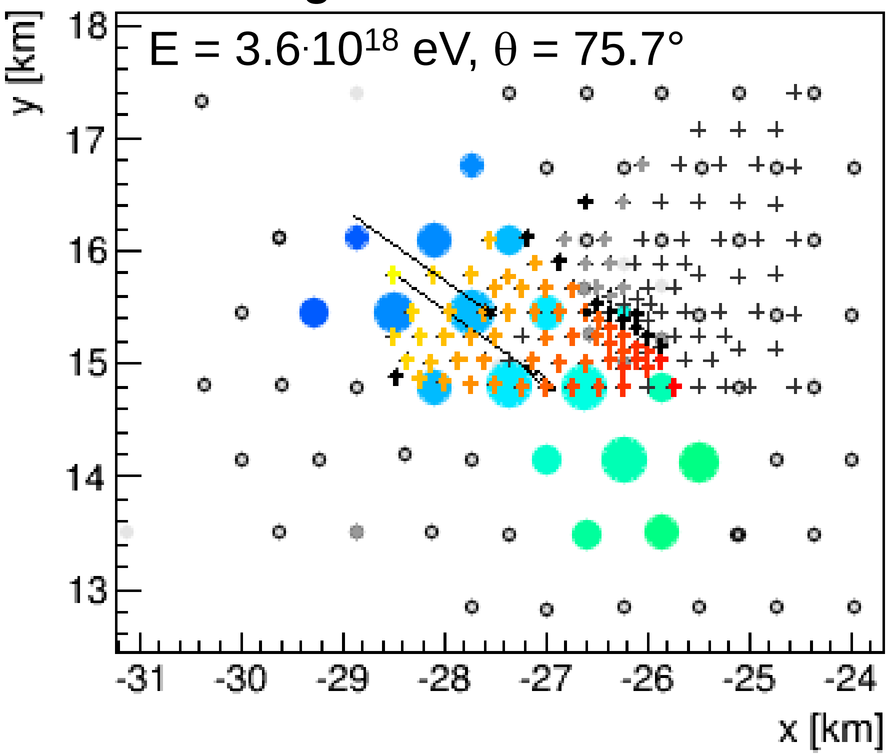
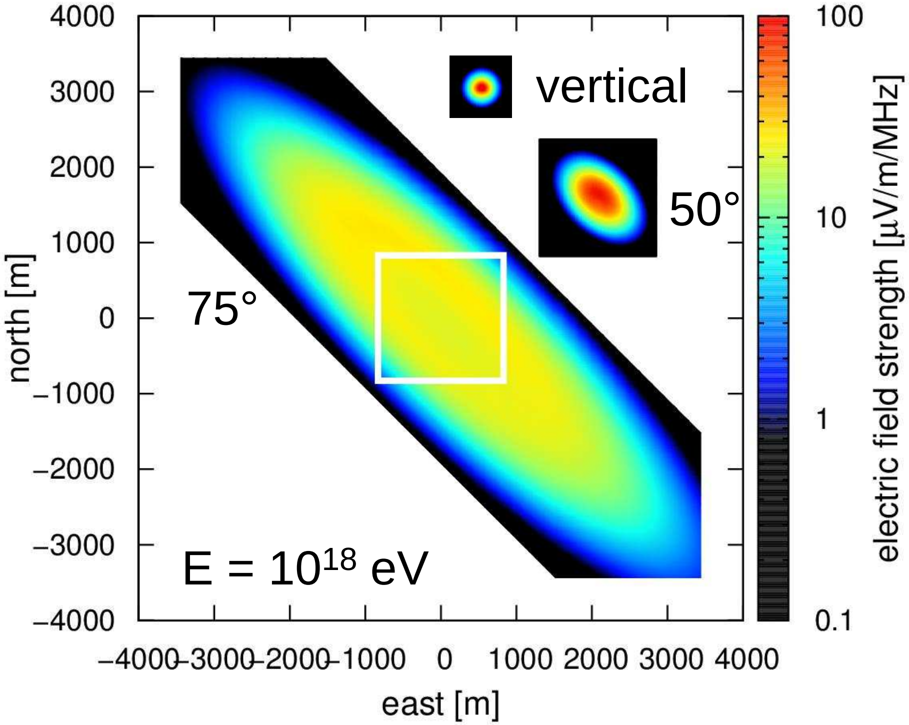
Huge footprint for inclined showers

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

Auger measurement



CoREAS simulation



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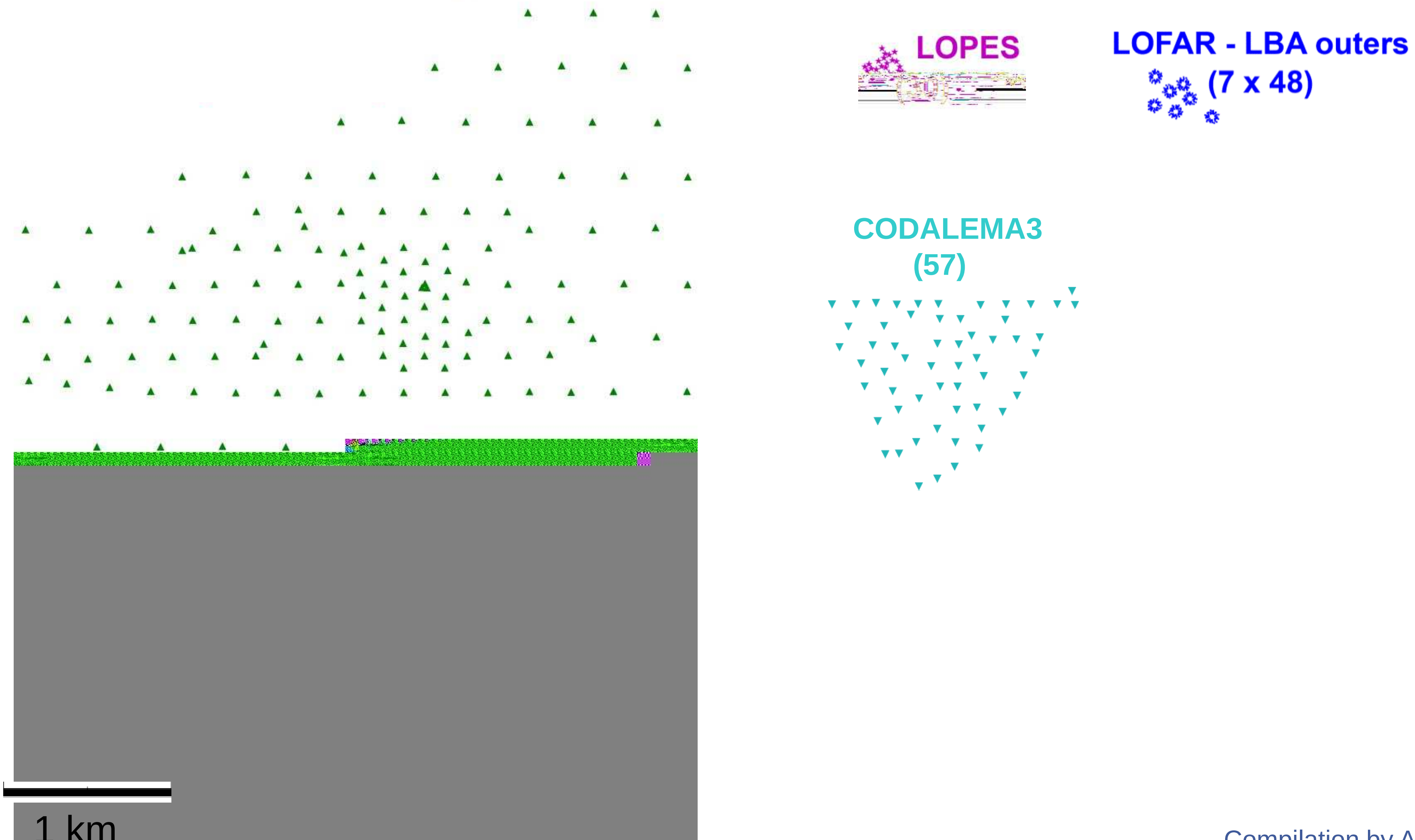
Designs of modern radio arrays
(mostly externally triggered)



Compilation by A. Zilles

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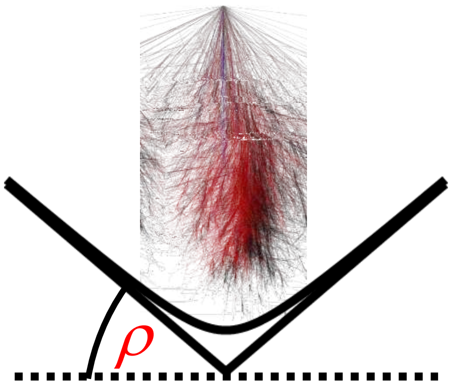
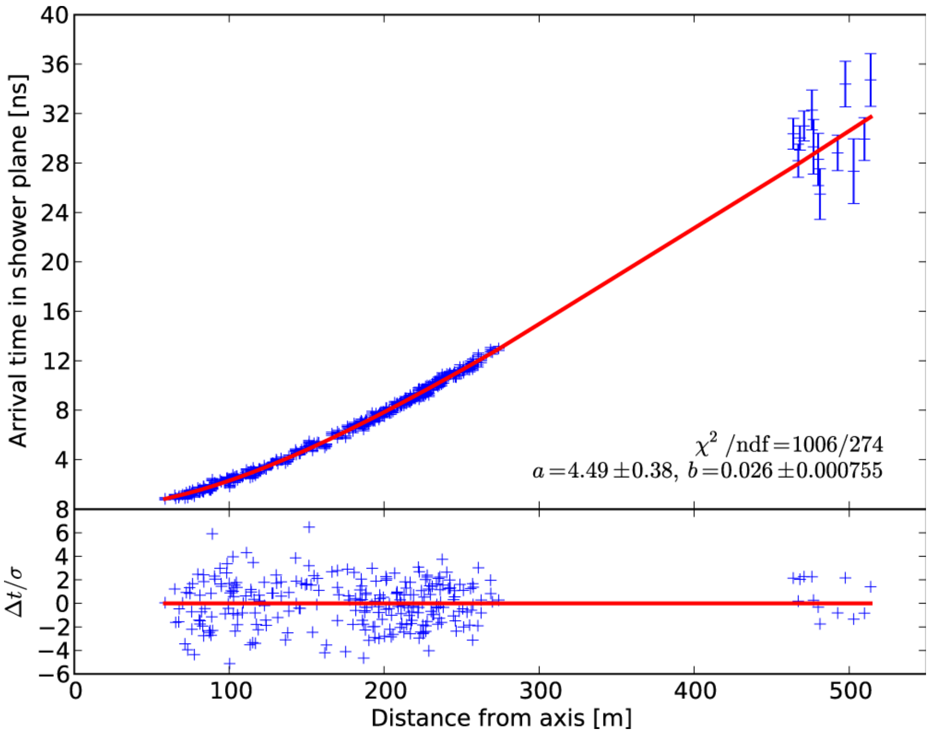
Shower maximum via wavefront

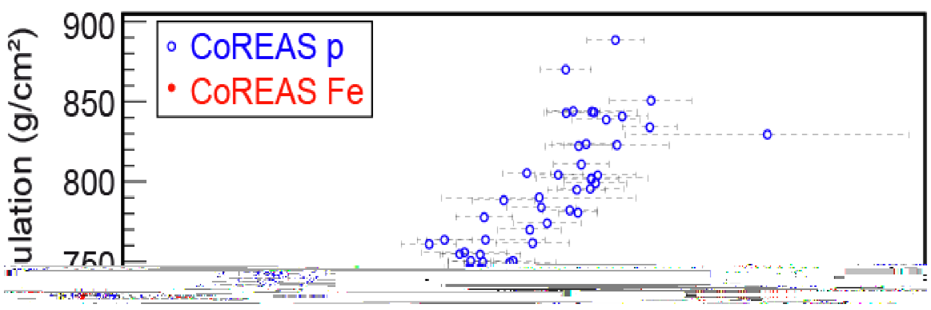
- Radio wavefront has hyperbolic shape
- Cone angle → shower maximum



ca. 1° - 2°



LOFAR Coll, Astropp. 61 (2015) 22



LOPES Coll., JCAP 09 (2014) 025

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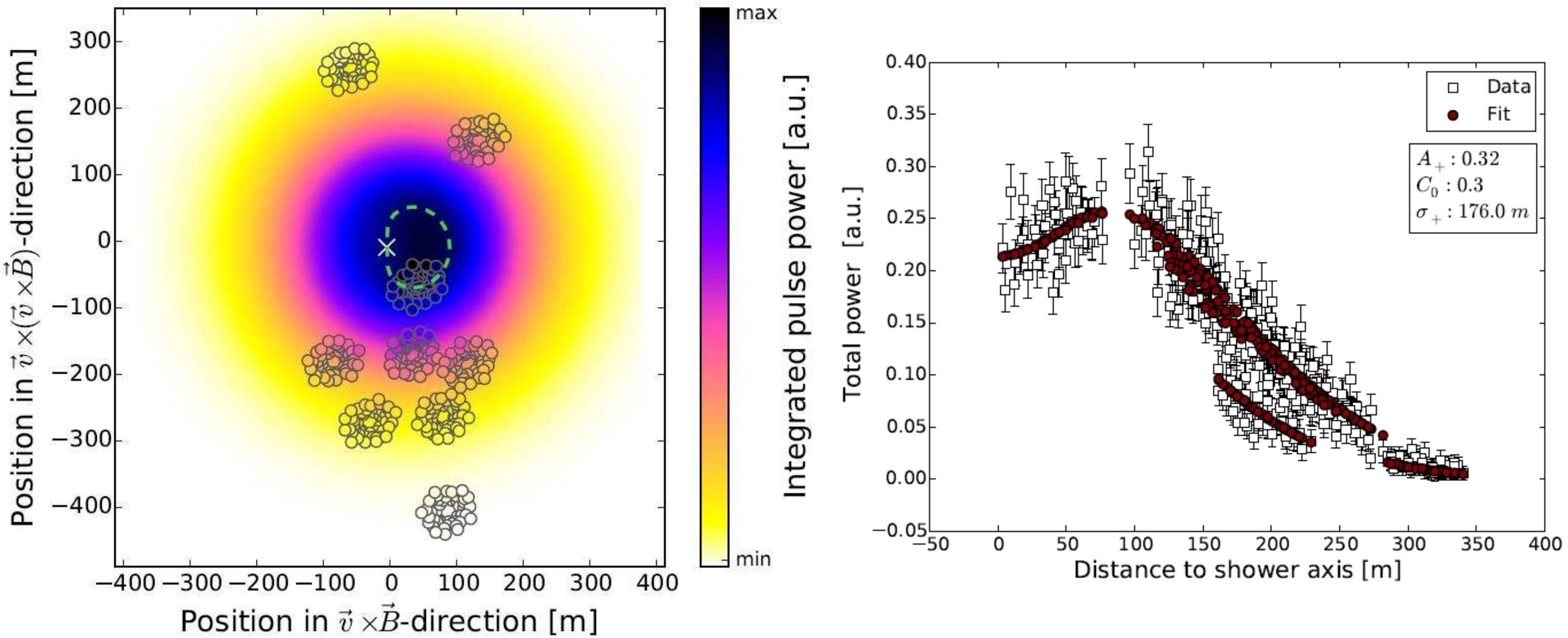
Maximum Accuracy by LOFAR

- Fitting 2-dim asymmetric LDF:
  slope and width parameters sensitive to shower maximum



LOFAR Coll, JCAP05(2015)018