Overview on Radio Detection of Air Showers

with focus on LOPES, Tunka-Rex, and AERA

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Outline

- Properties of the radio signal
  - amplitude: footprint and scale
  - polarization
  - wavefront
- Reconstruction of air-shower parameters
  - direction
  - energy
  - X_{max}
- Scientific applications
  - highest potential for inclined showers and in combination with particle detectors

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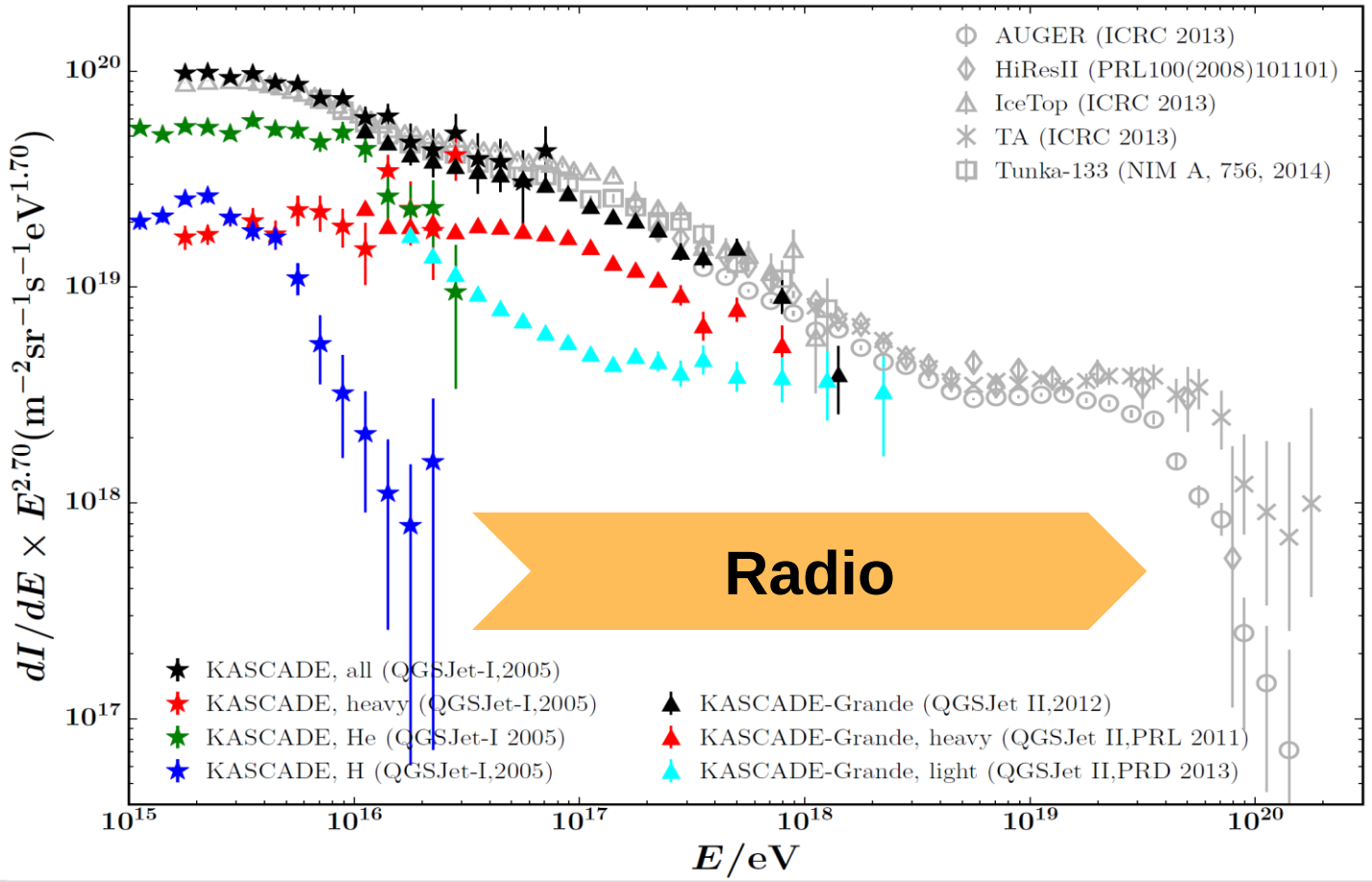
Advantages of radio technique

- Accurate measurement of direction, electro-mag. energy + X_{max} around the clock
- Energy range of highest-energy galactic CR + extragalactic CR



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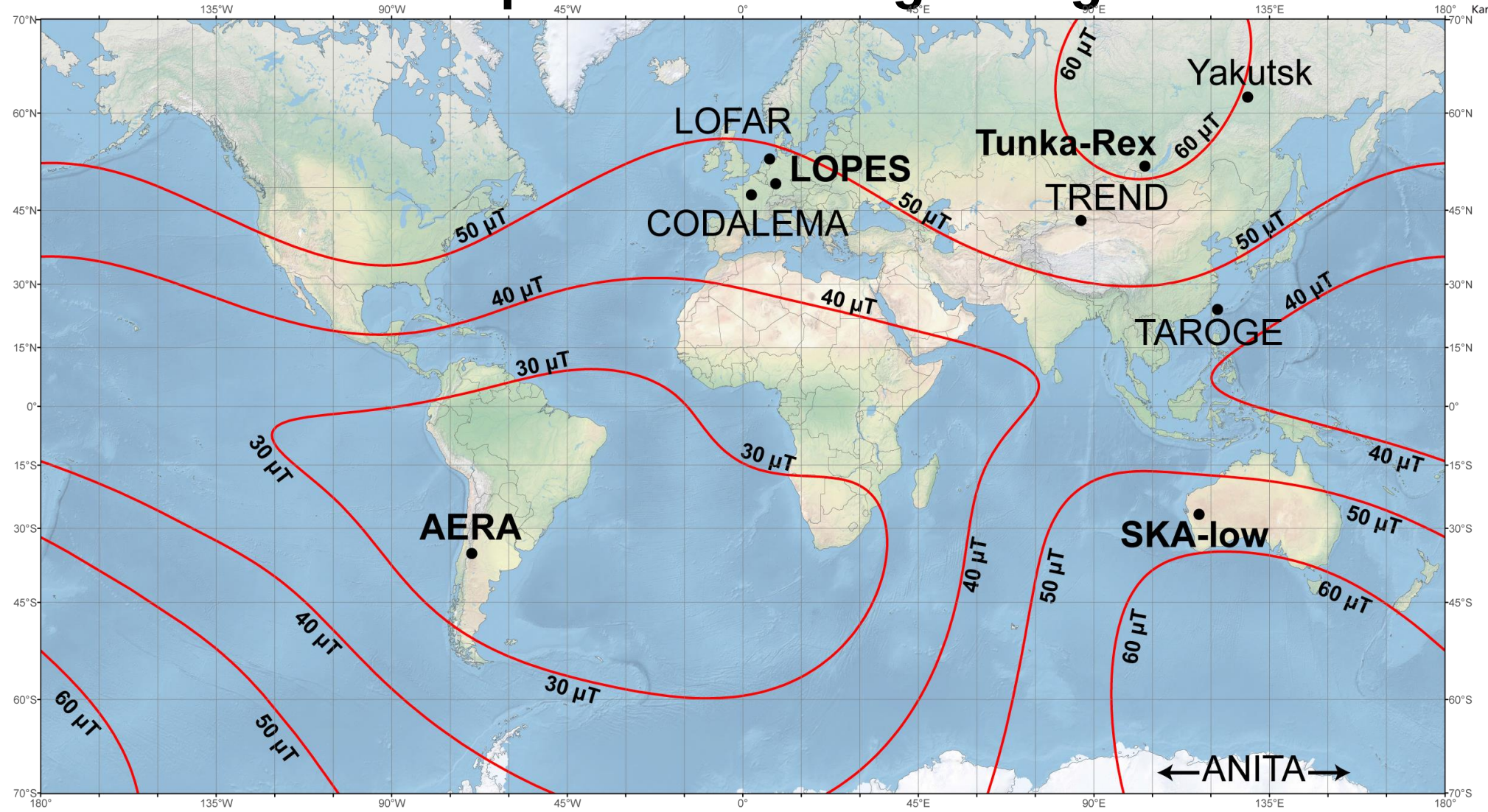
Location of selected experiments and geomagnetic field



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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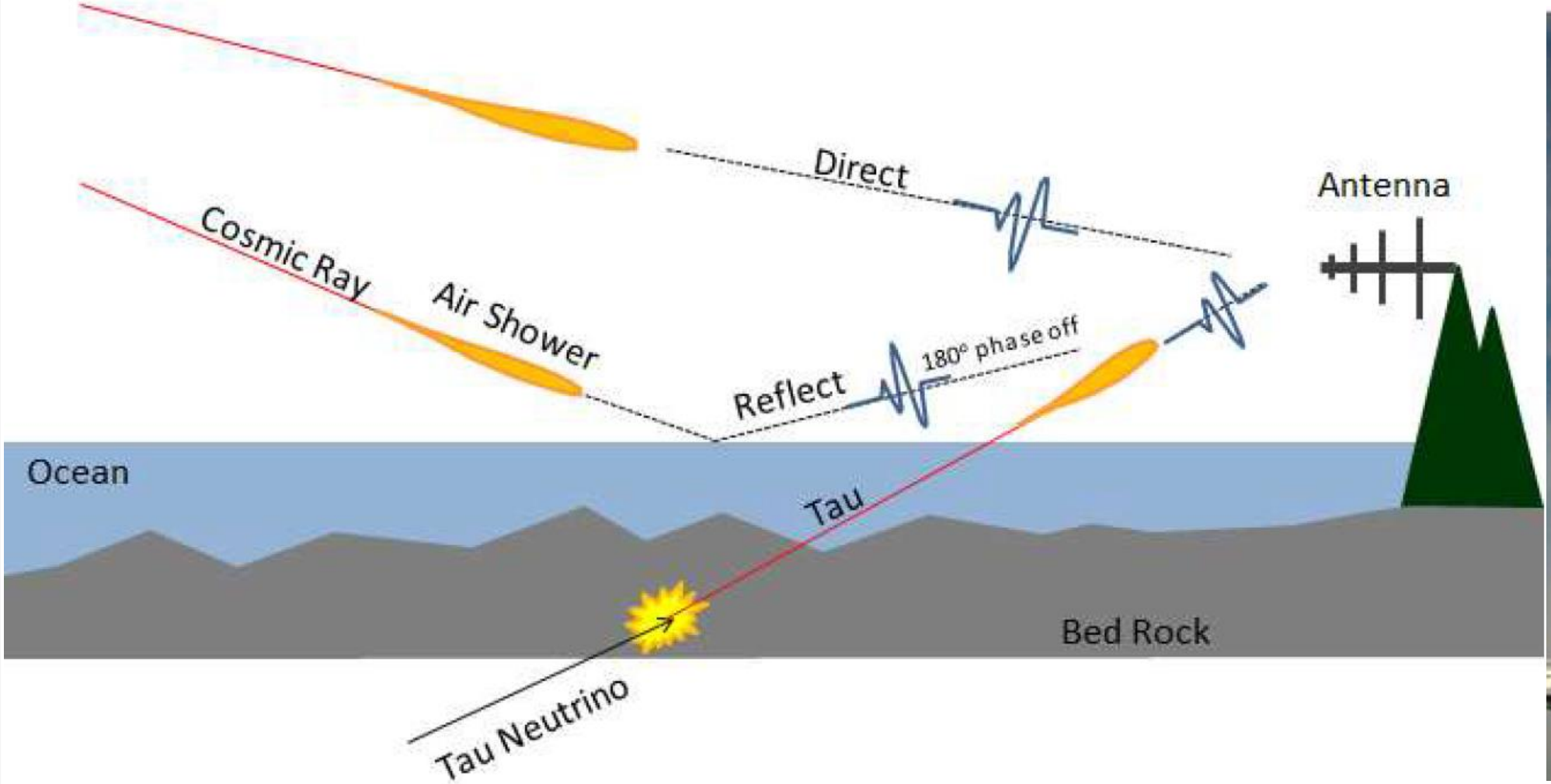
TAROGE - Taiwan Astroparticle Radiowave Observatory for Geo-synchrotron Emissions



- First station built in 2014

TAROGE Coll., PoS (ICRC2015) 663

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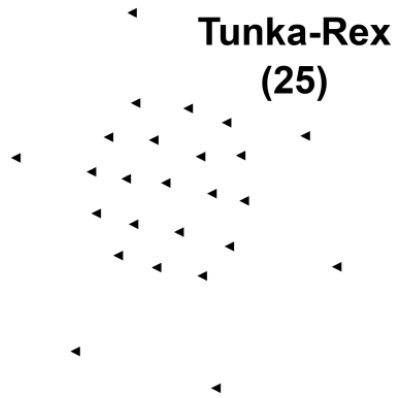
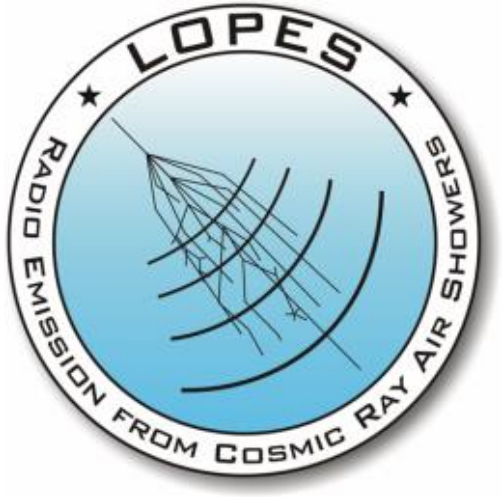
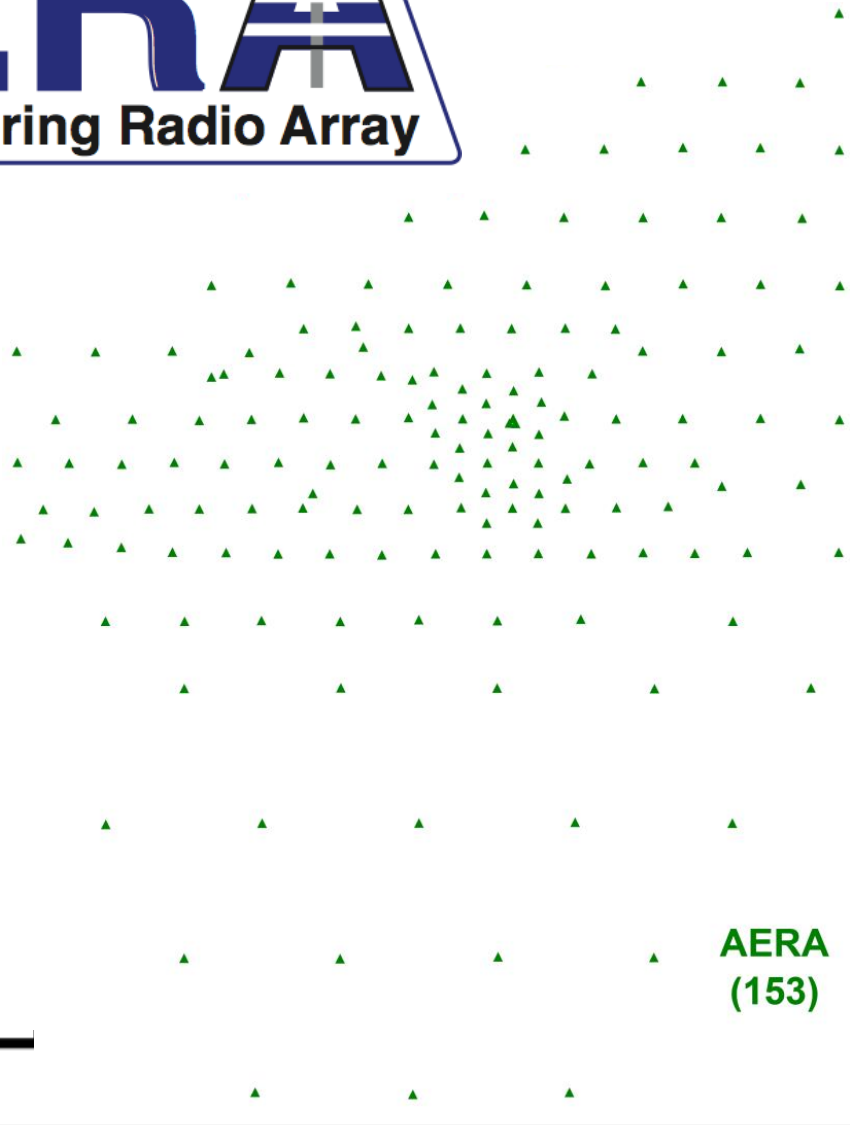
Arrays in Focus of this talk







Detectors: antennas

- Many working solutions with only slight differences in
  - threshold (typical 10^{17} eV) and frequency band (typical 30-80 MHz)
  - accuracy (systematic uncertainties, e.g., due to ground conditions)


inverted v-dipole at LOPES


SALLA at Tunka-Rex


LPDA at Auger


Butterfly at CODALEMA

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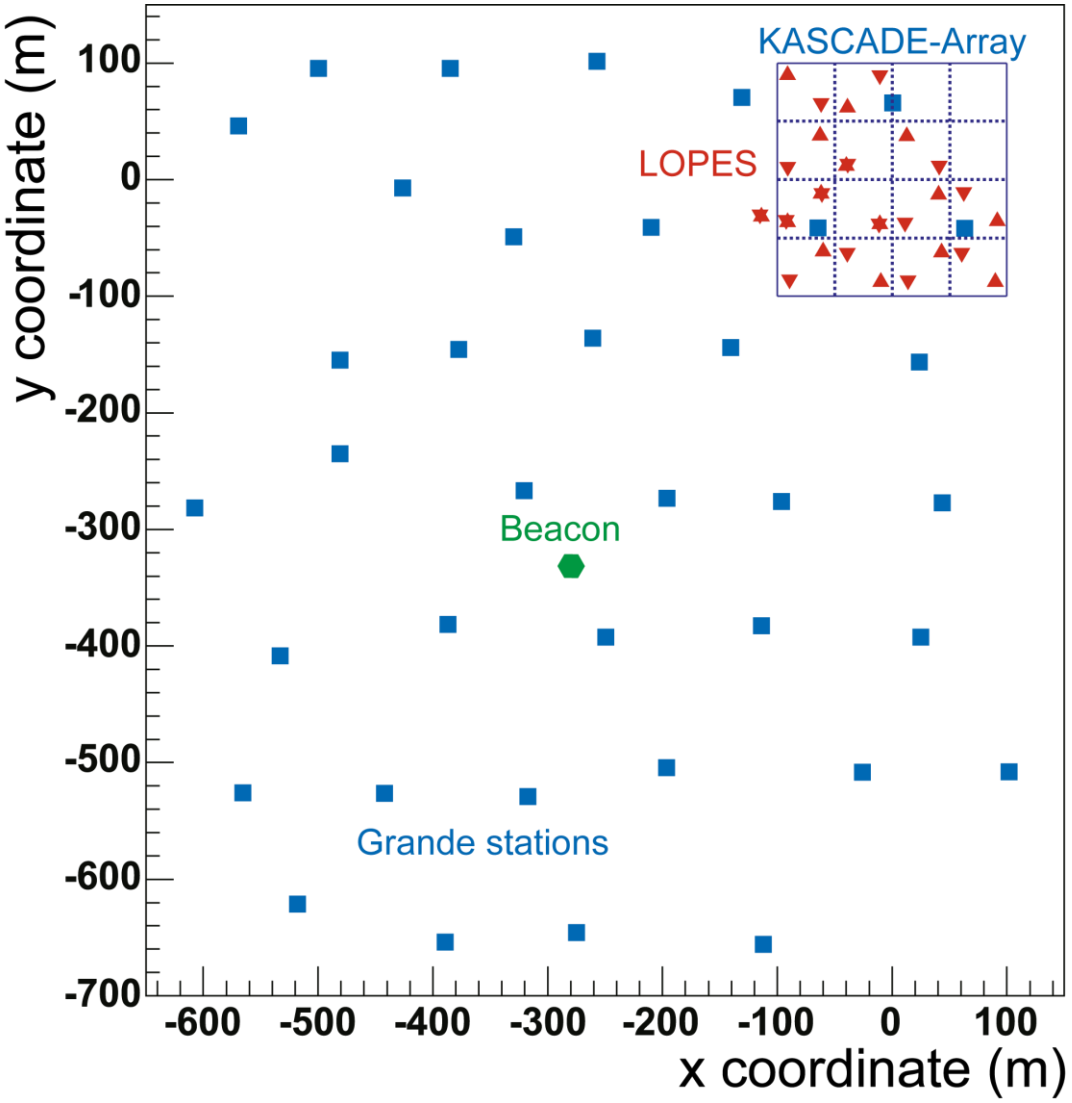
LOPES setup (map of 2009)



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

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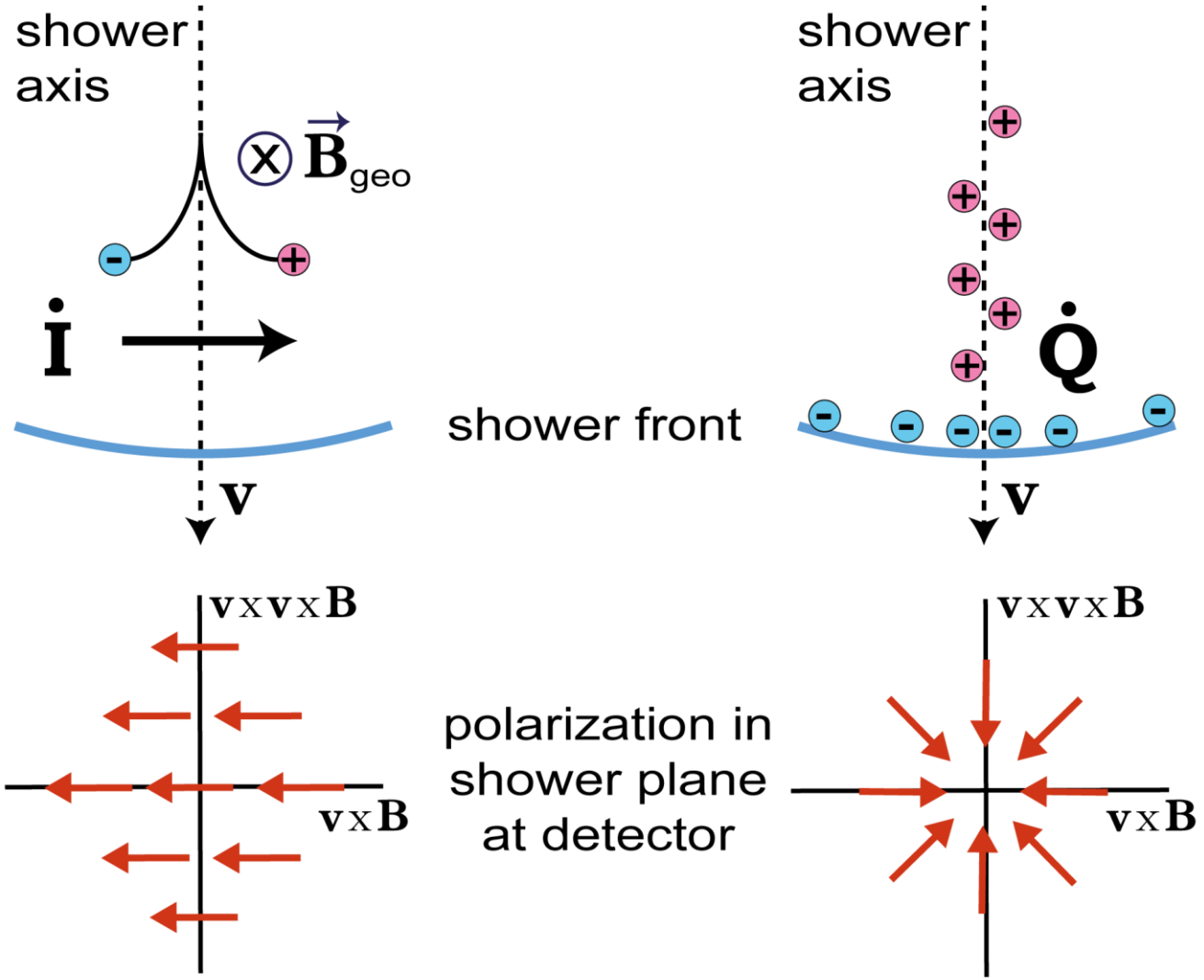
Emission mechanisms



geomagnetic effect ~ 90%

Askaryan effect ~ 10%

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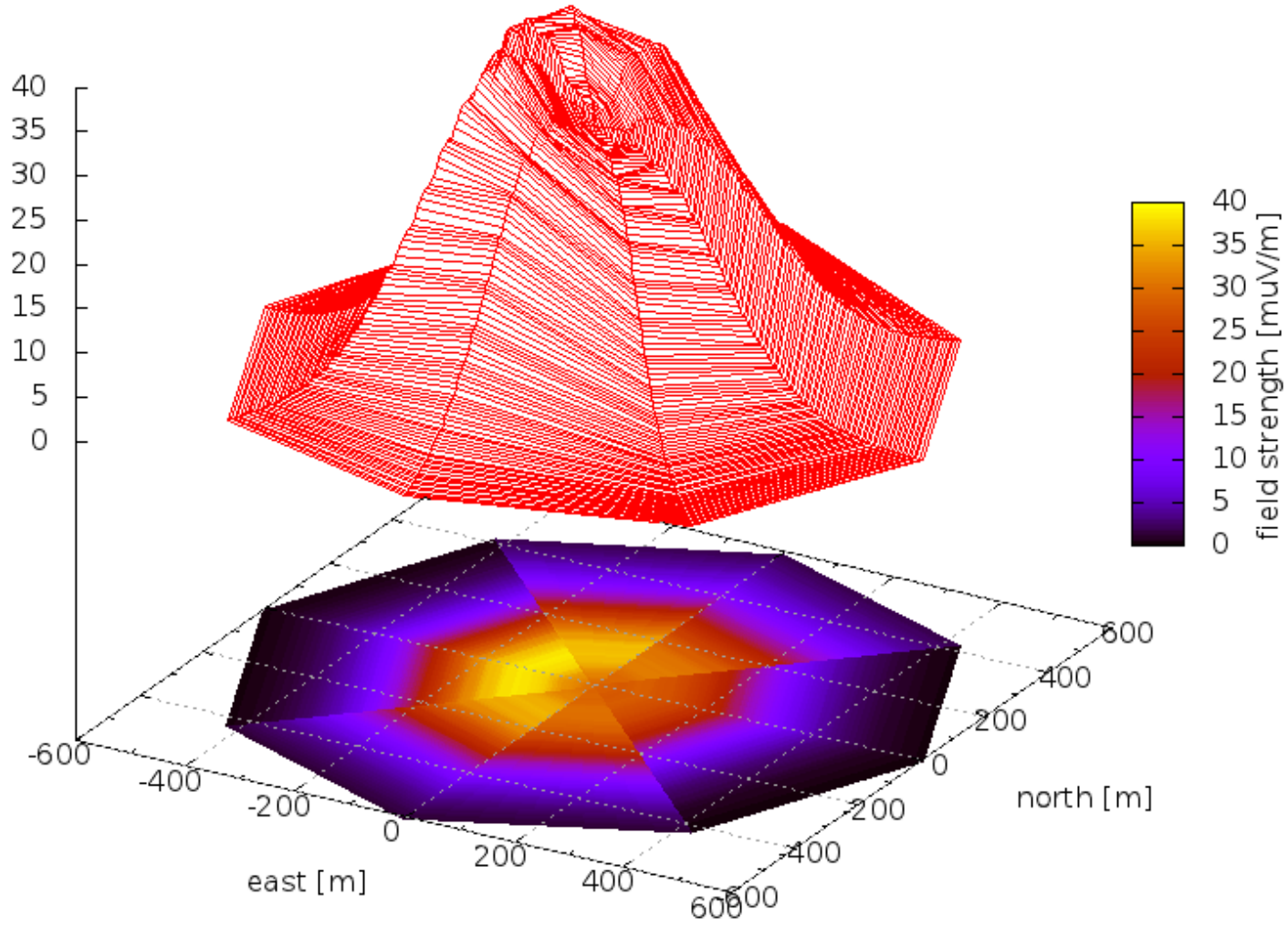
Conical radio emission with asymmetric footprint



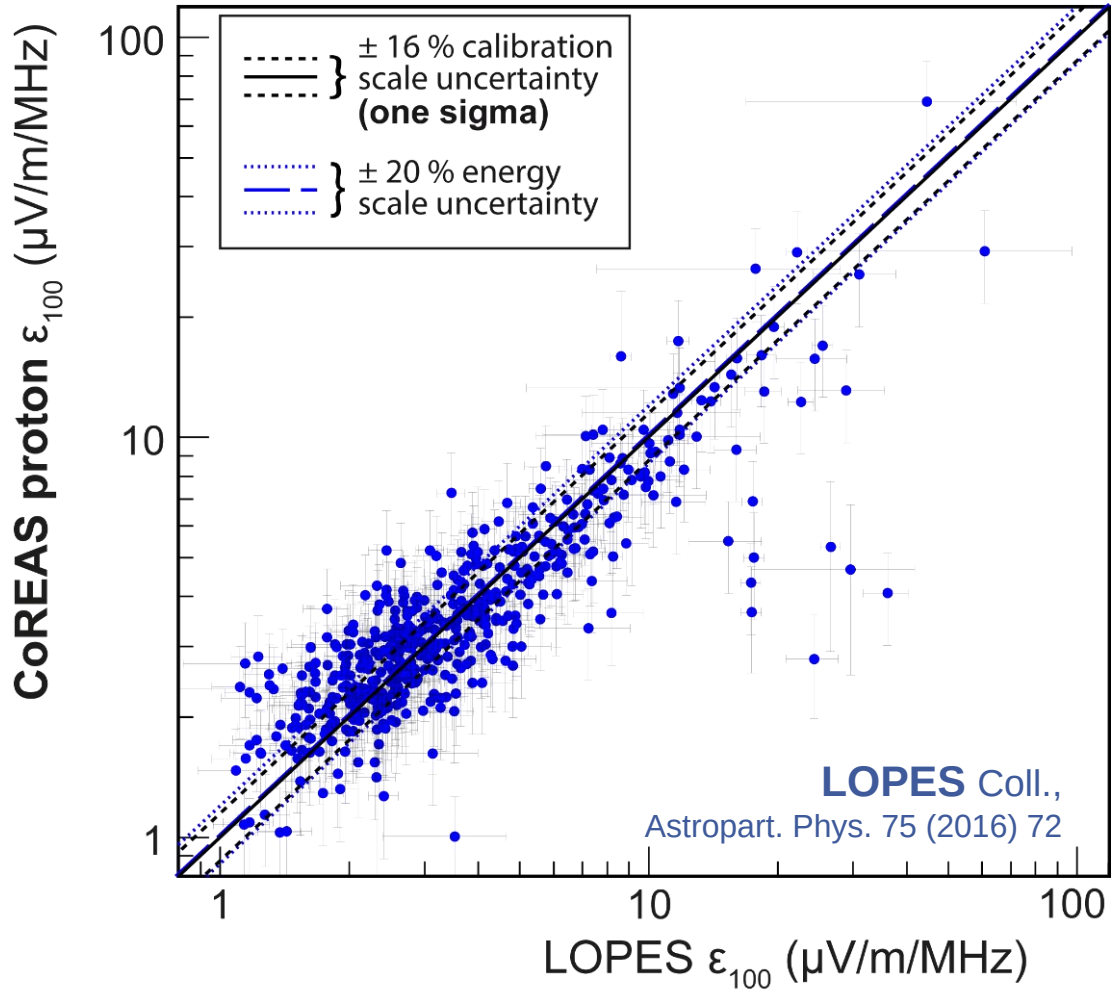
shower inclination:
$\theta = 45°$

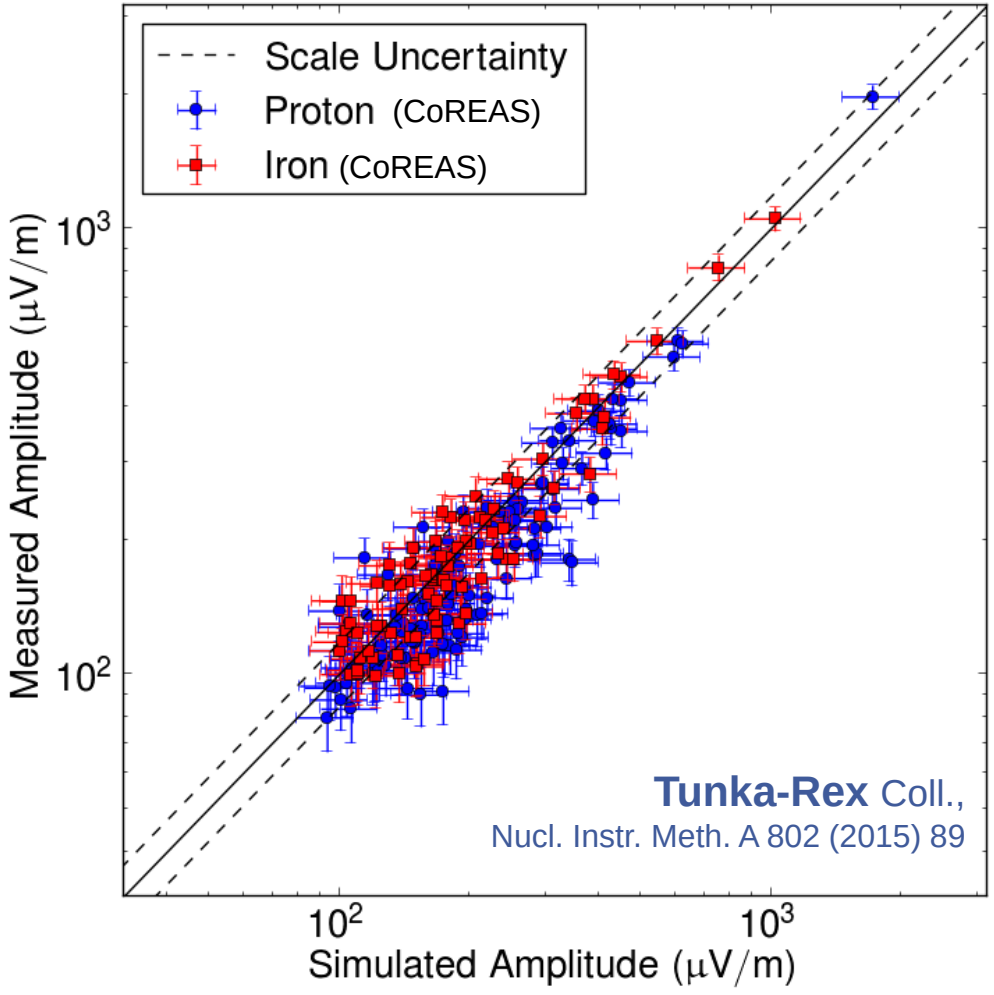
CoREAS simulations
By T. Huege et al., ARENA2012

43 – 74 MHz

Do simulations describe reality?

- CoREAS (+ other codes) reproduce measured amplitudes within ~20% uncertainty





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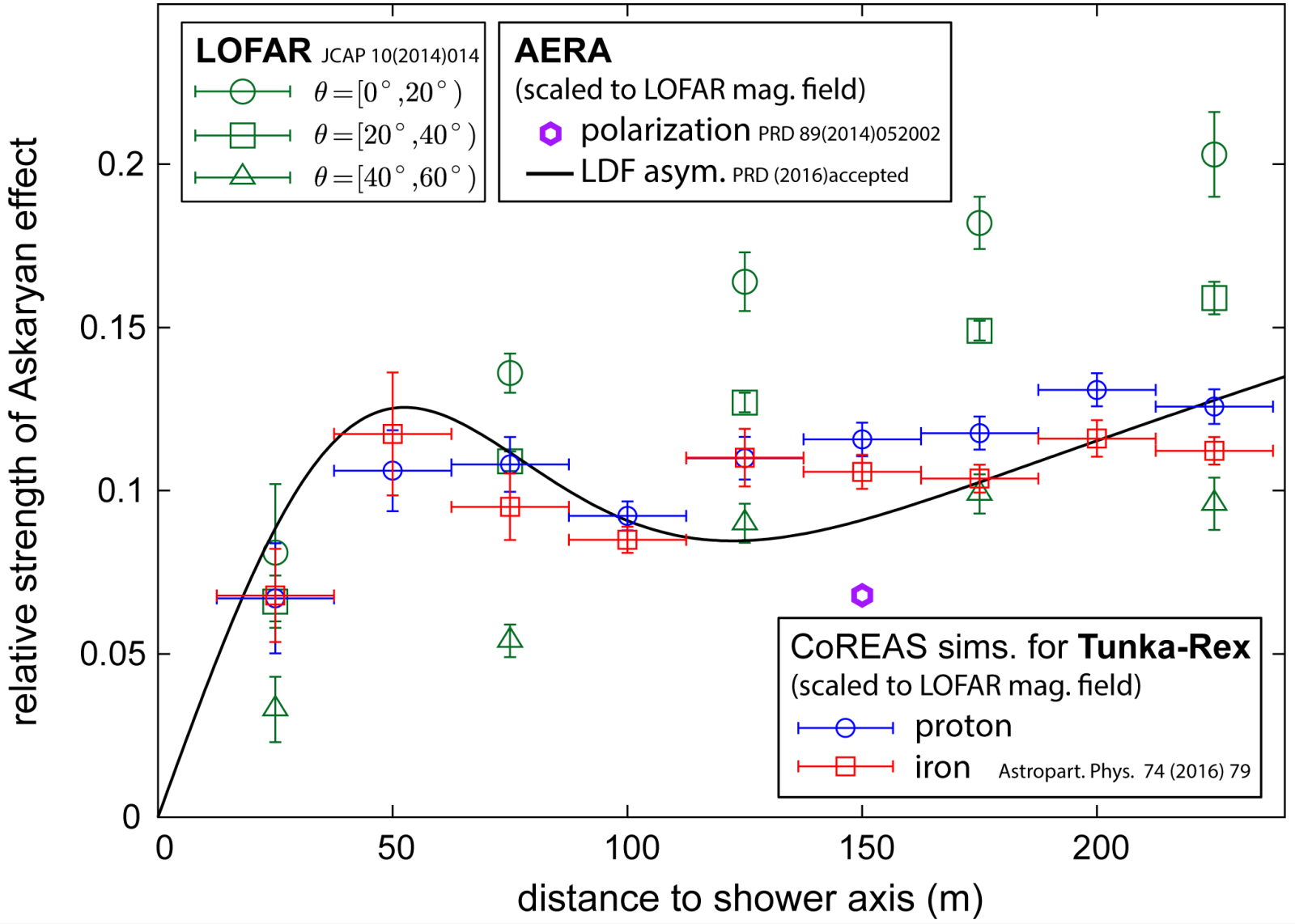
Relative strength of Askaryan effect



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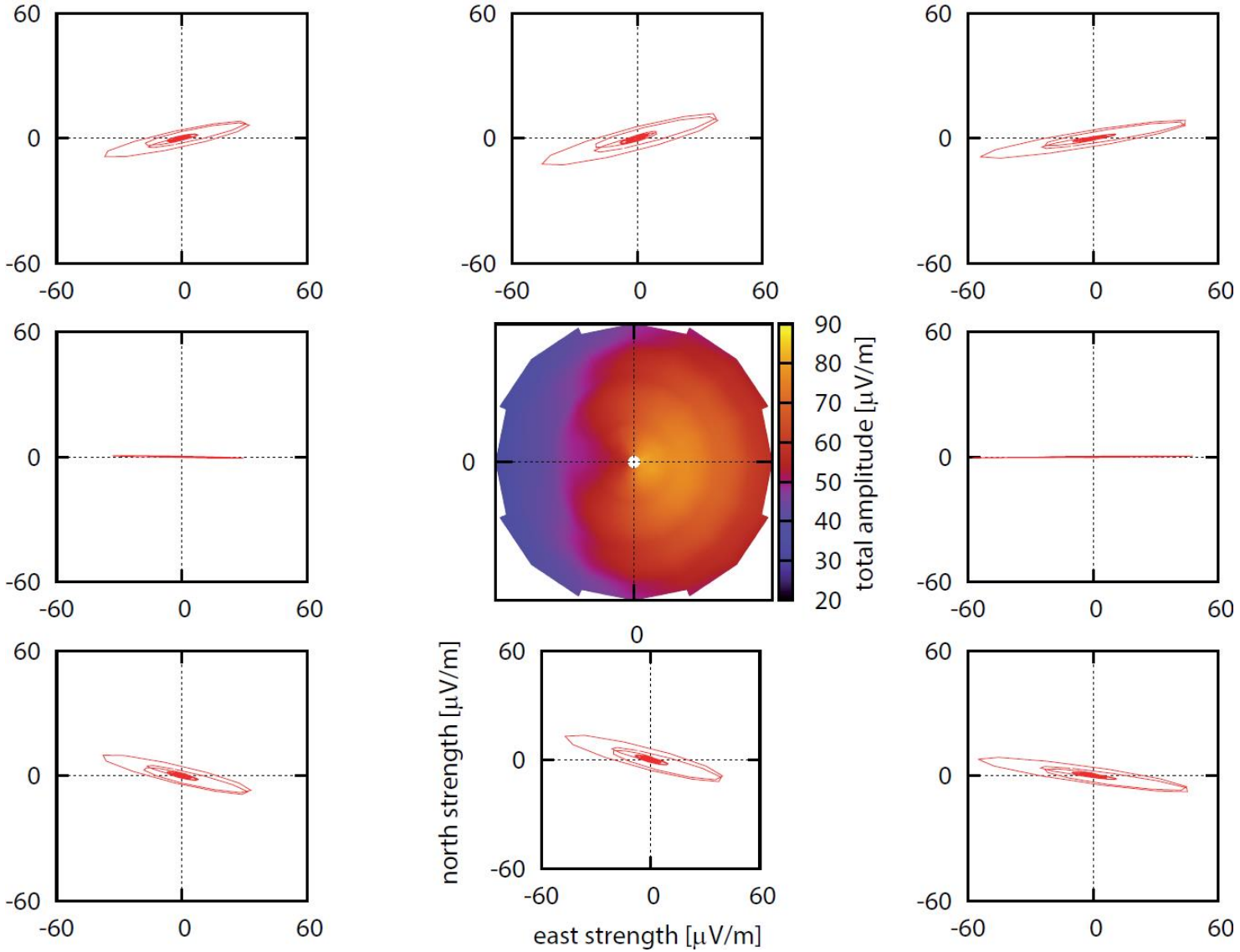
Slightly elliptical polarization



Geomagnetic and Askaryan emissions not in phase?

Requires experimental confirmation!

T. Huege, ARENA2012

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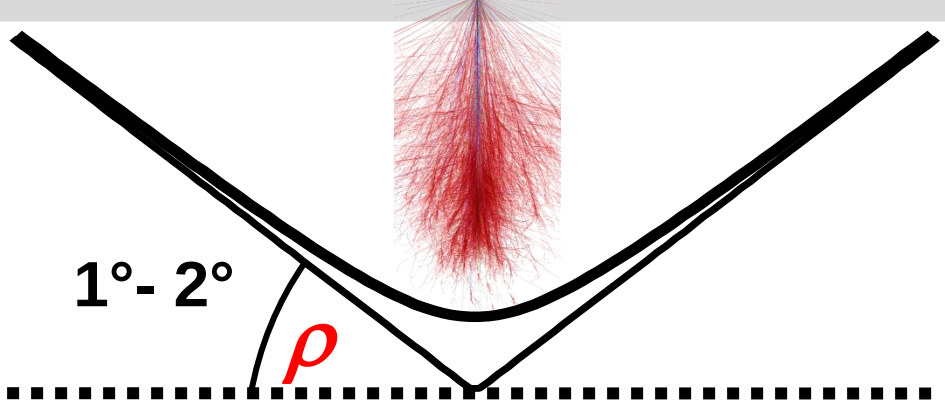
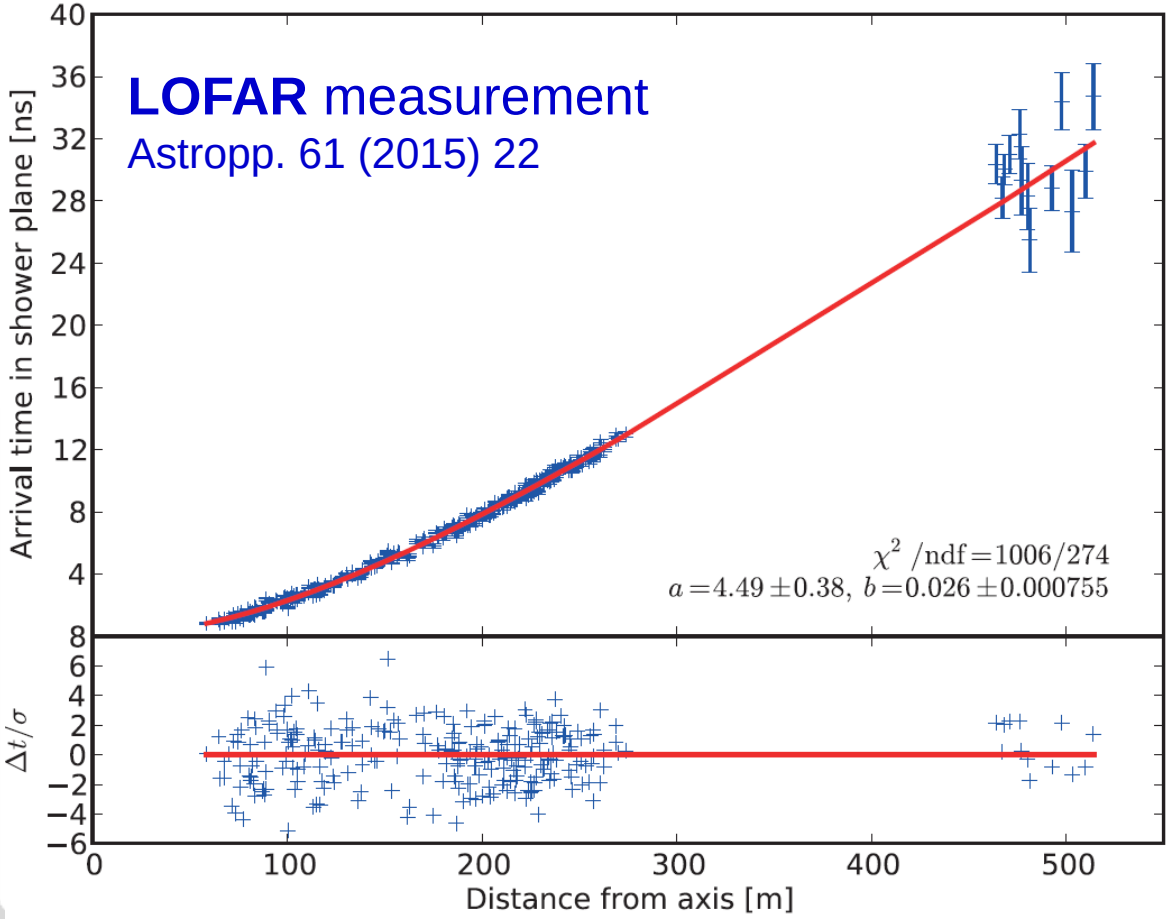
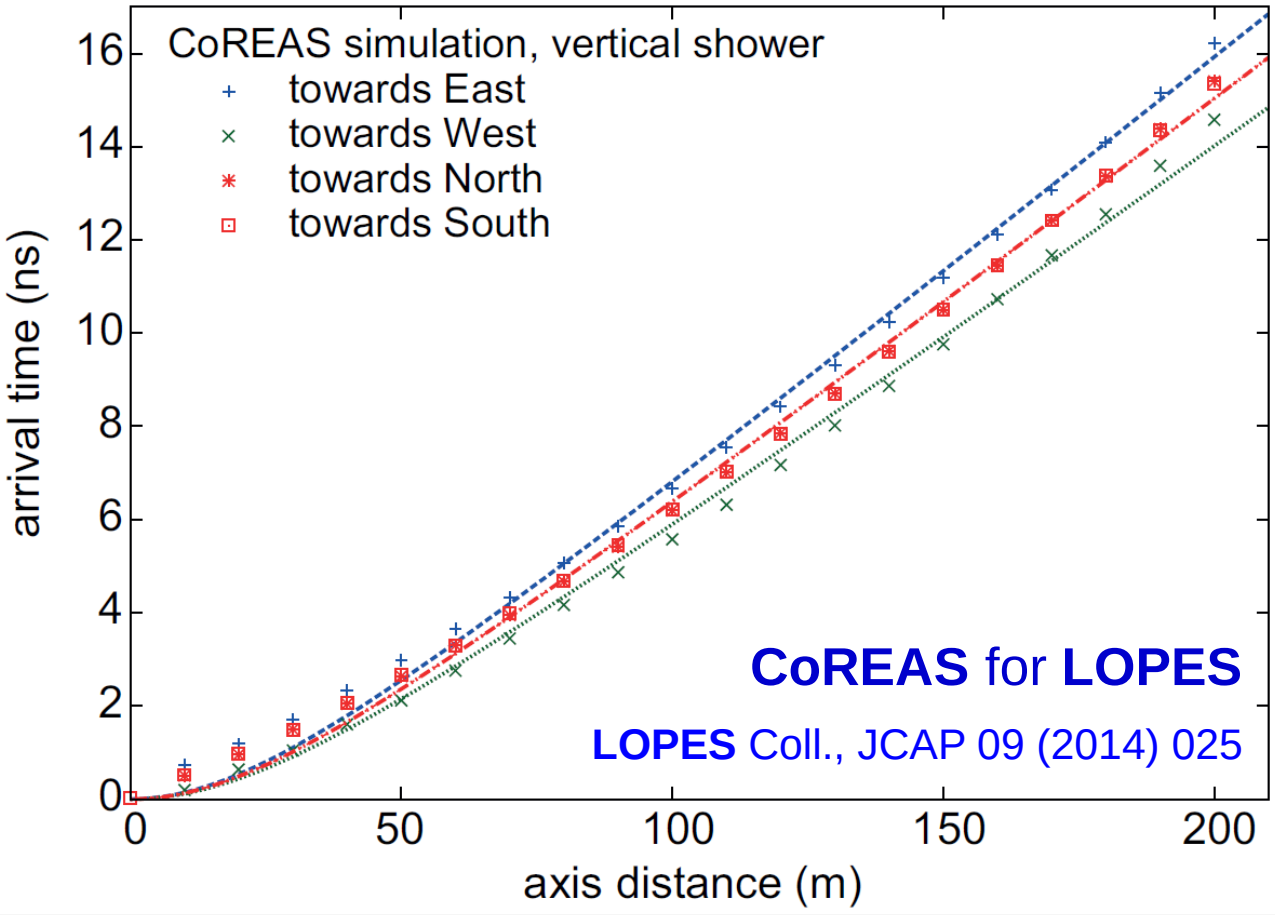
Hyperbolic radio wavefront

- Hyperbolic shape seen by LOPES and LOFAR
- Slight east-west asymmetry not yet confirmed







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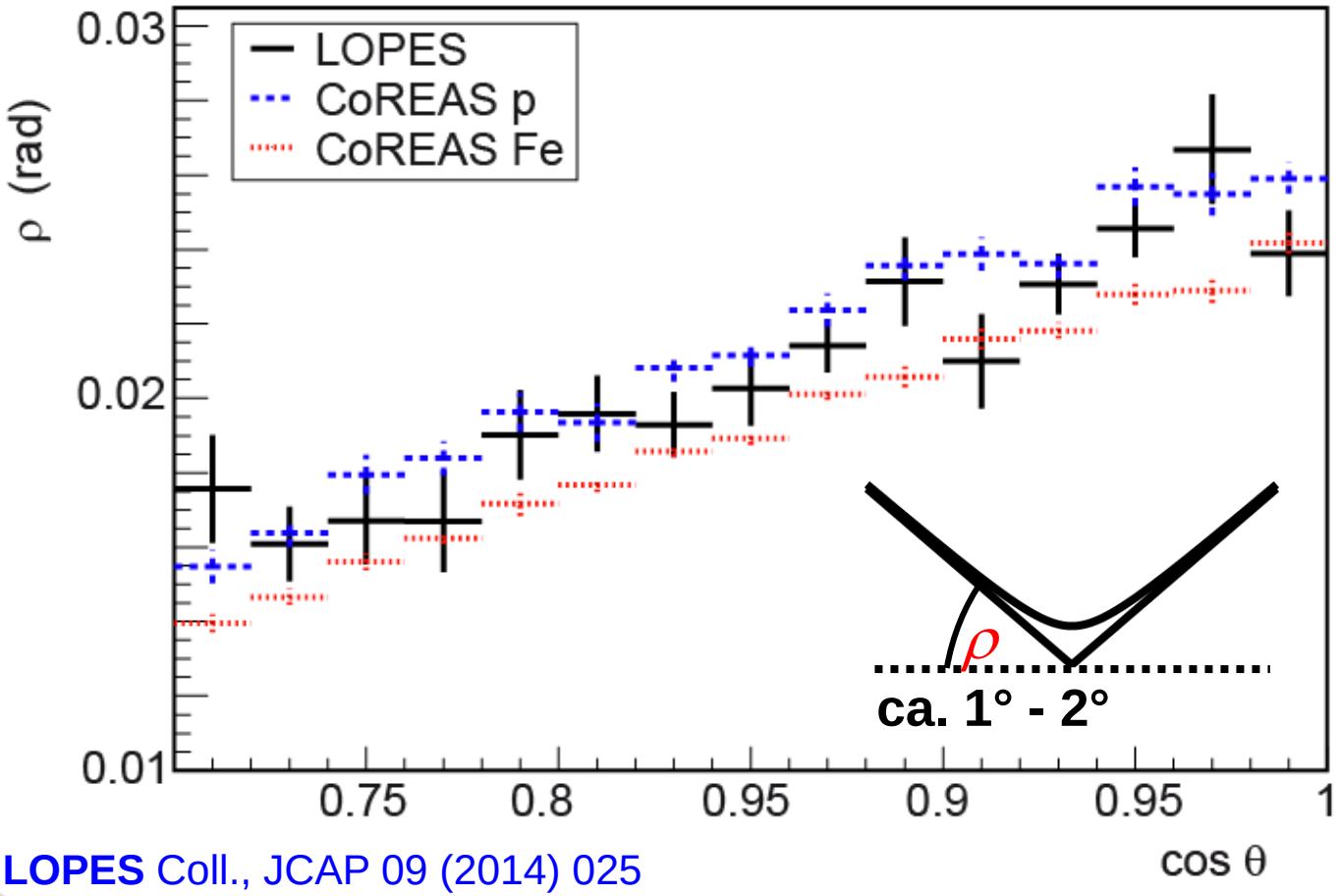
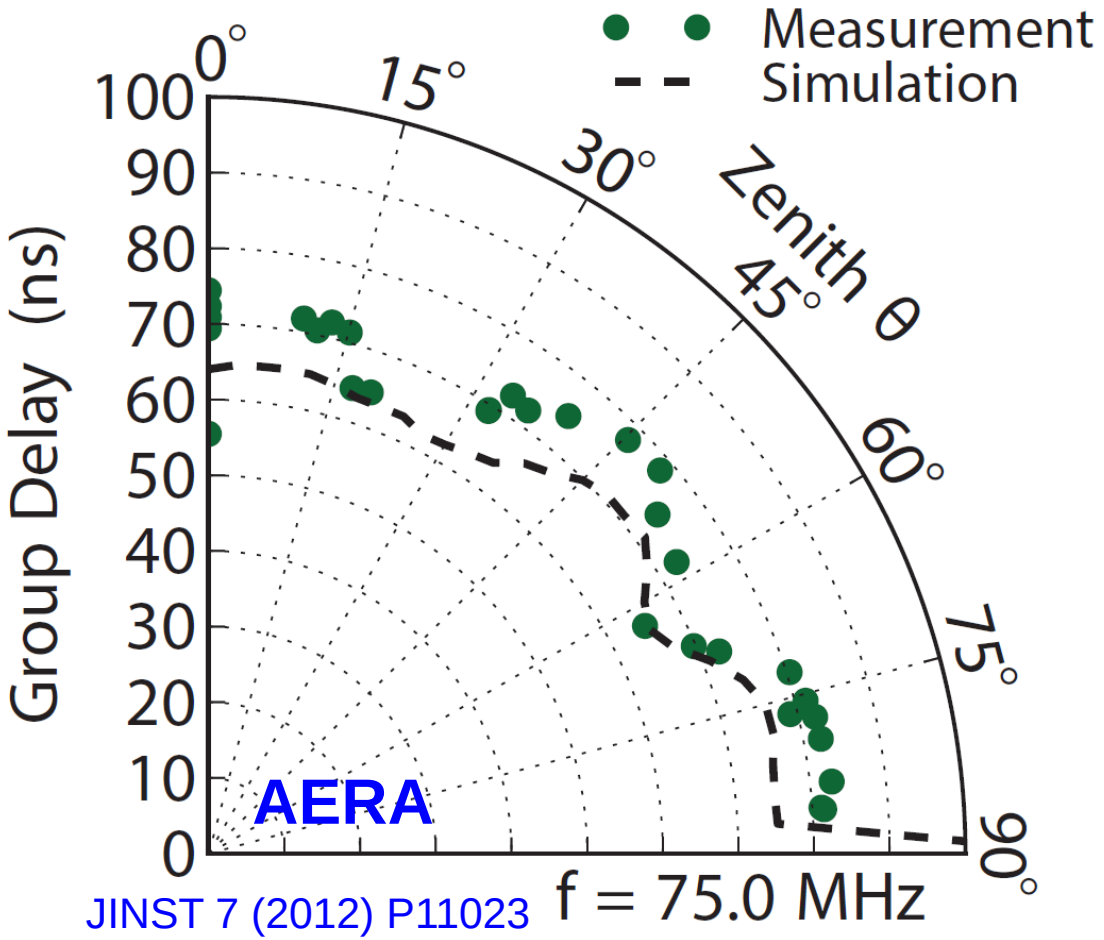
Cone angle depends on distance to shower maximum

- Measured dependence on zenith angle



LOPES Coll., JCAP 09 (2014) 025

- Antenna models accurate enough?



JINST 7 (2012) P11023

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Reconstruction of shower parameters

- Direction
  - example: LOPES
- Energy
  - examples: AERA, LOPES, Tunka-Rex
- Shower maximum
  - examples: Tunka-Rex (for LOFAR + AERA see other talks)

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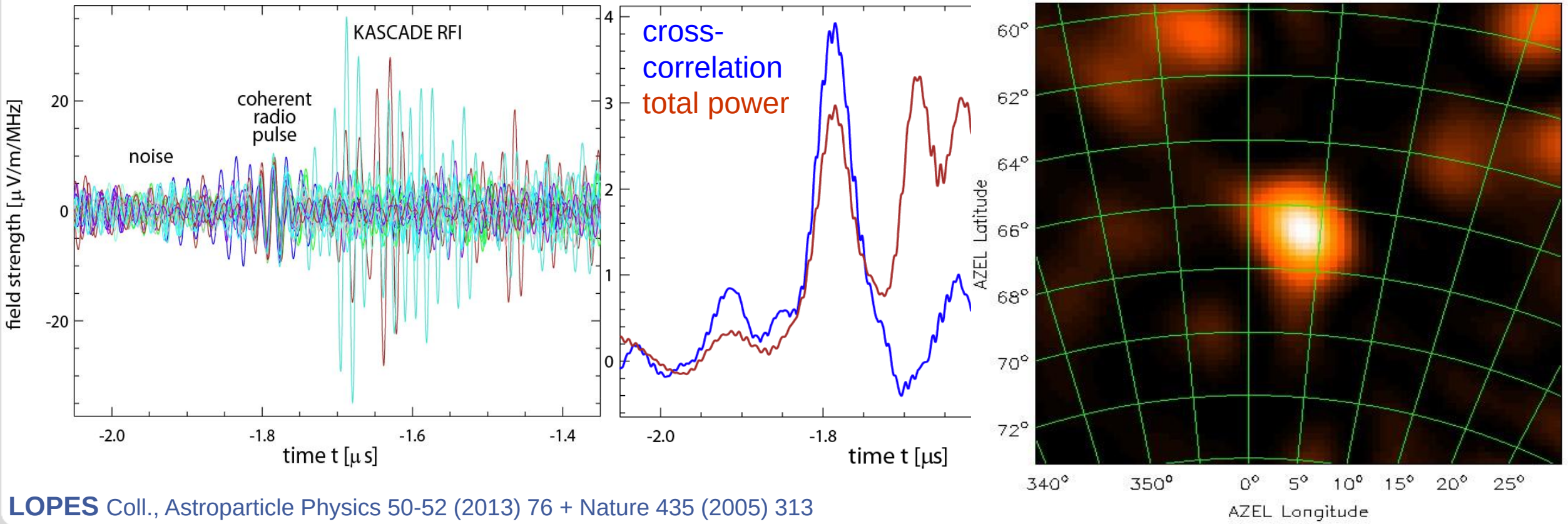
Interferometric beamforming at LOPES

- Cross-correlation of traces after time shift according to arrival direction
- Direction precision < 0.7° (by comparing LOPES to KASCADE)



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

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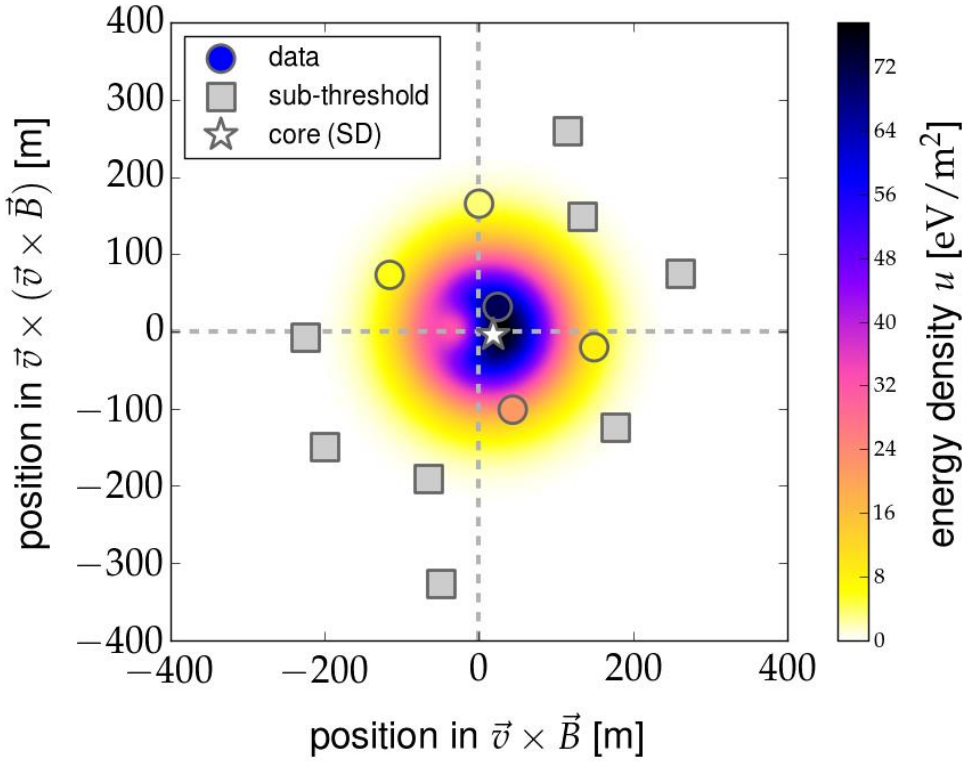
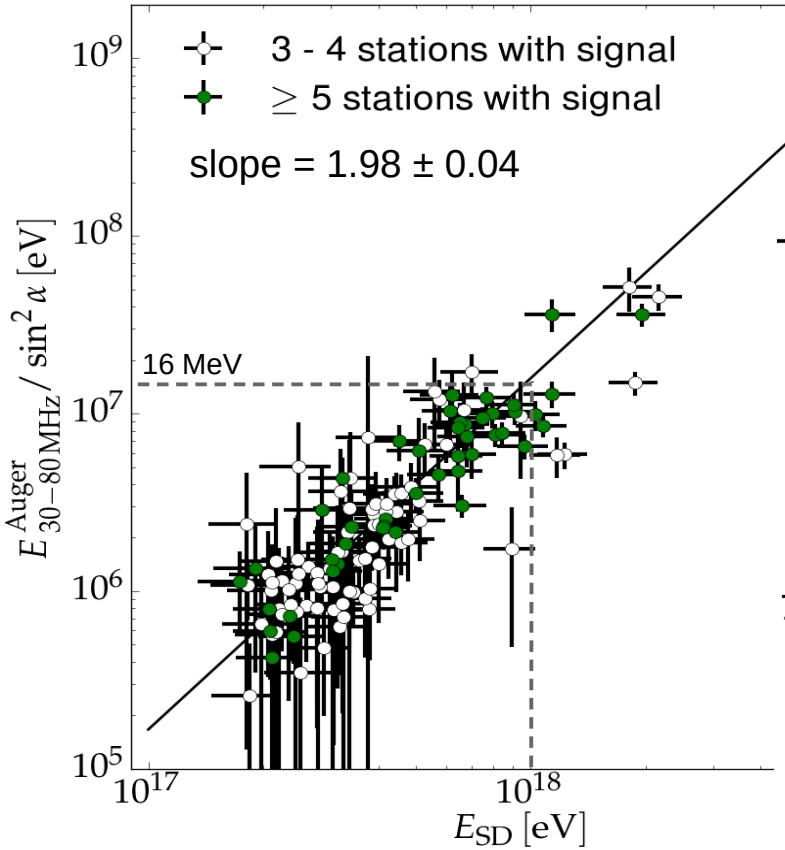
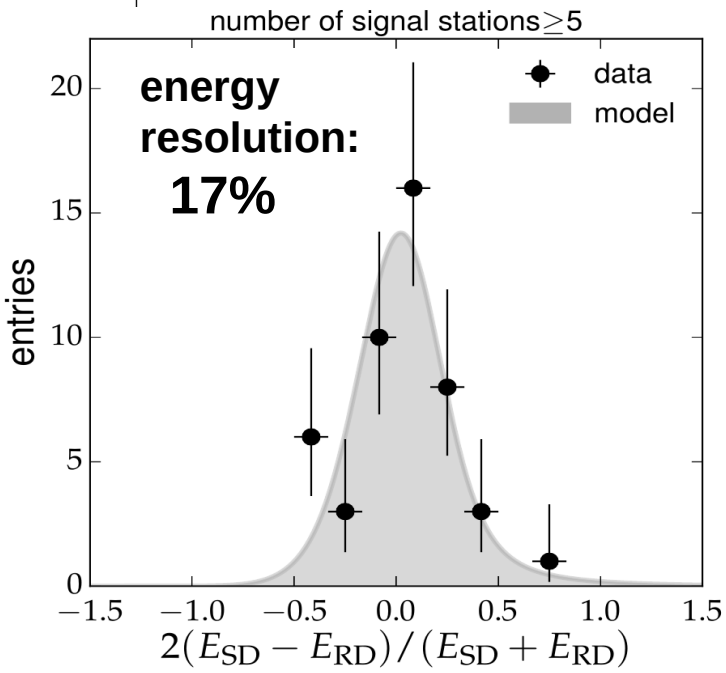
Energy reconstruction by AERA

- Total energy in radio signal scales quadratically with electro-mag. shower energy





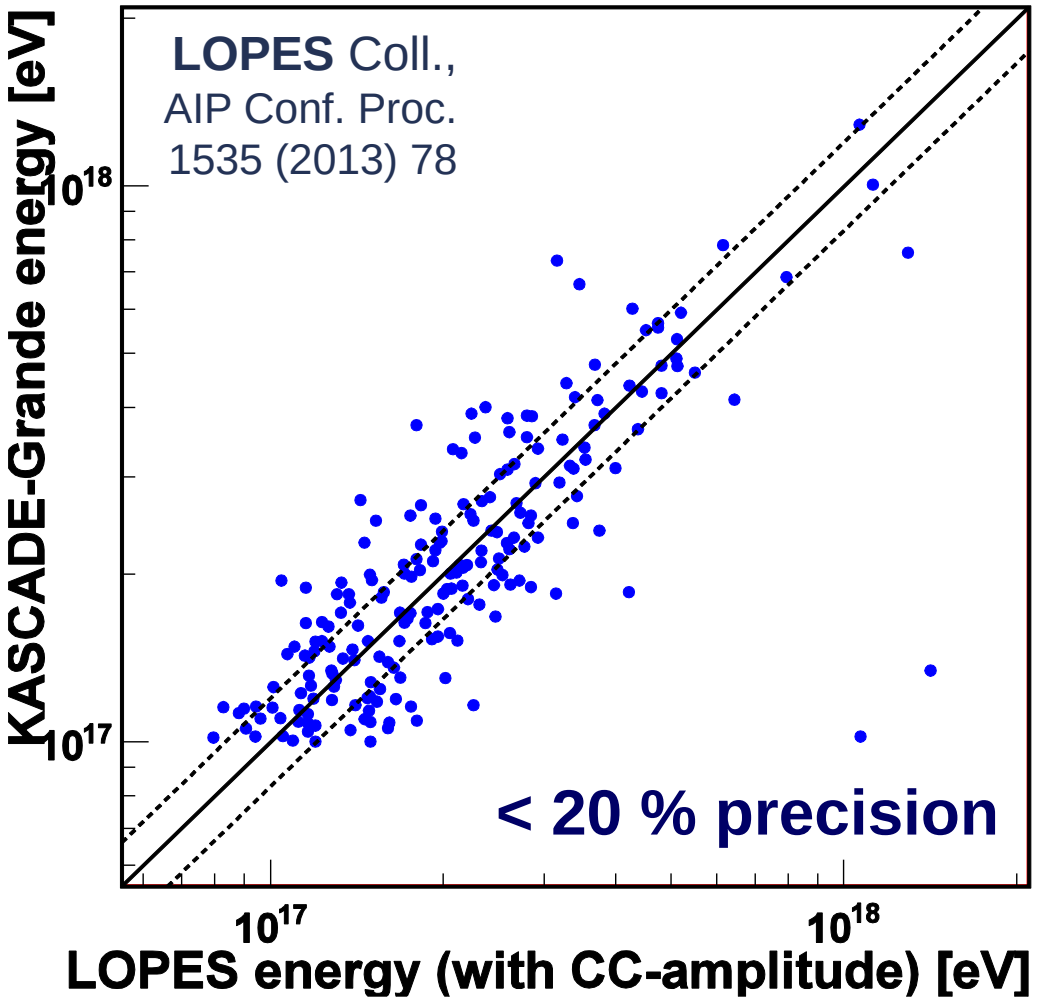
16 MeV radiation energy for a 1 EeV cosmic ray

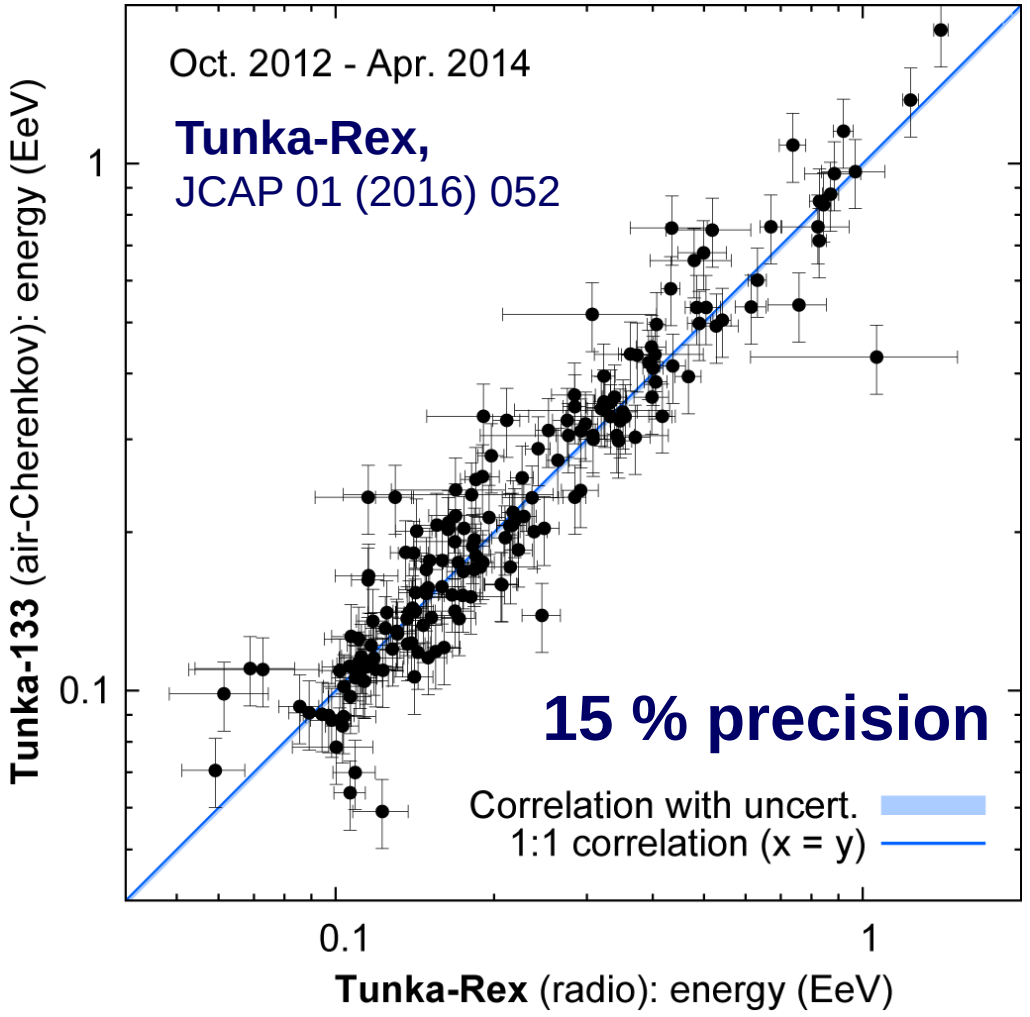


Pierre Auger Coll.,
accepted by PRL and PRD

Similar energy precision by LOPES + Tunka-Rex

- Amplitude at detector-specific reference distance ~ 100 m





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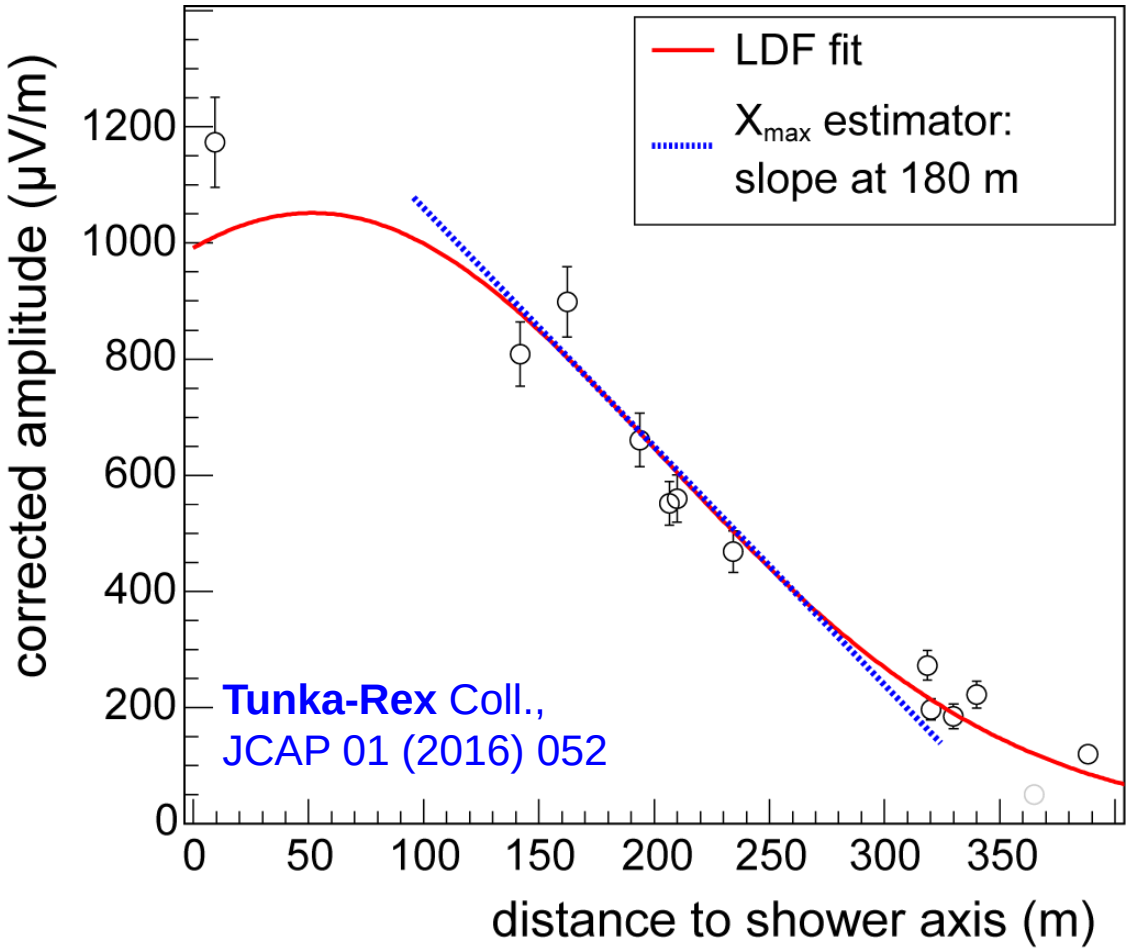
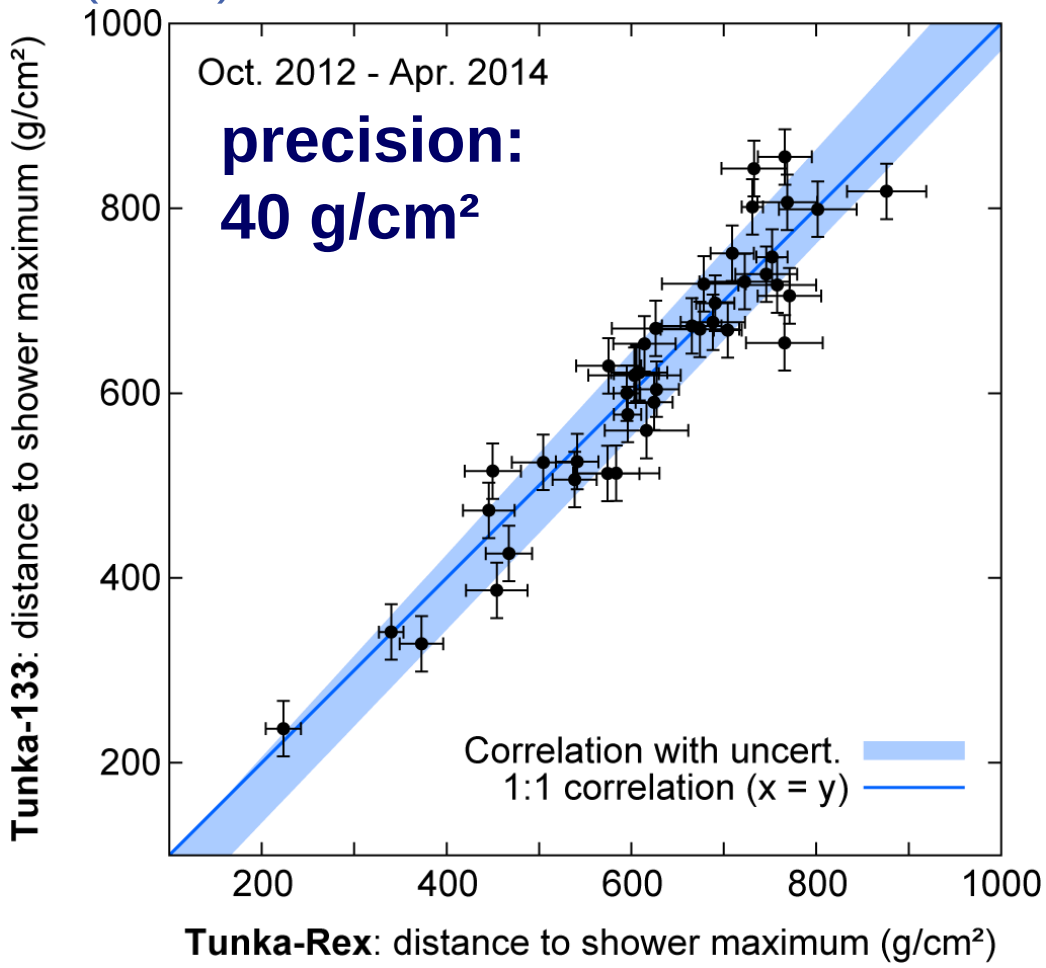
Shower maximum: proof by Tunka-Rex

- Slope of lateral distribution depends on distance to X_{max}
  - First experimental proof by LOPES Coll., PRD 85 (2012) 071101





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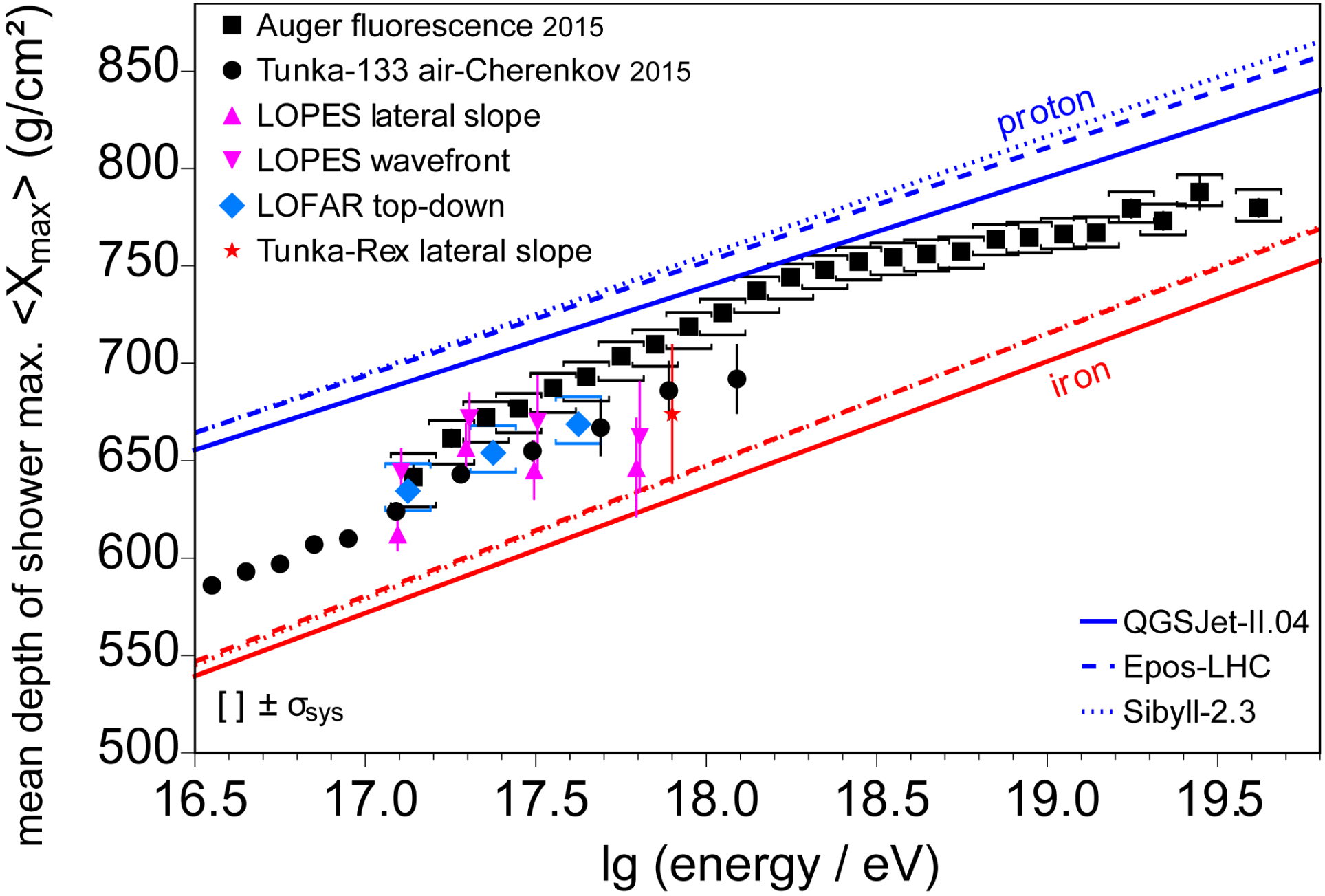

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Some future applications for radio

- 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
- Radio is ideal for inclined showers
  - huge footprint and no absorption
- Additional mass sensitivity in hybrid measurements
  - electron / muon approach → radio + particle detectors

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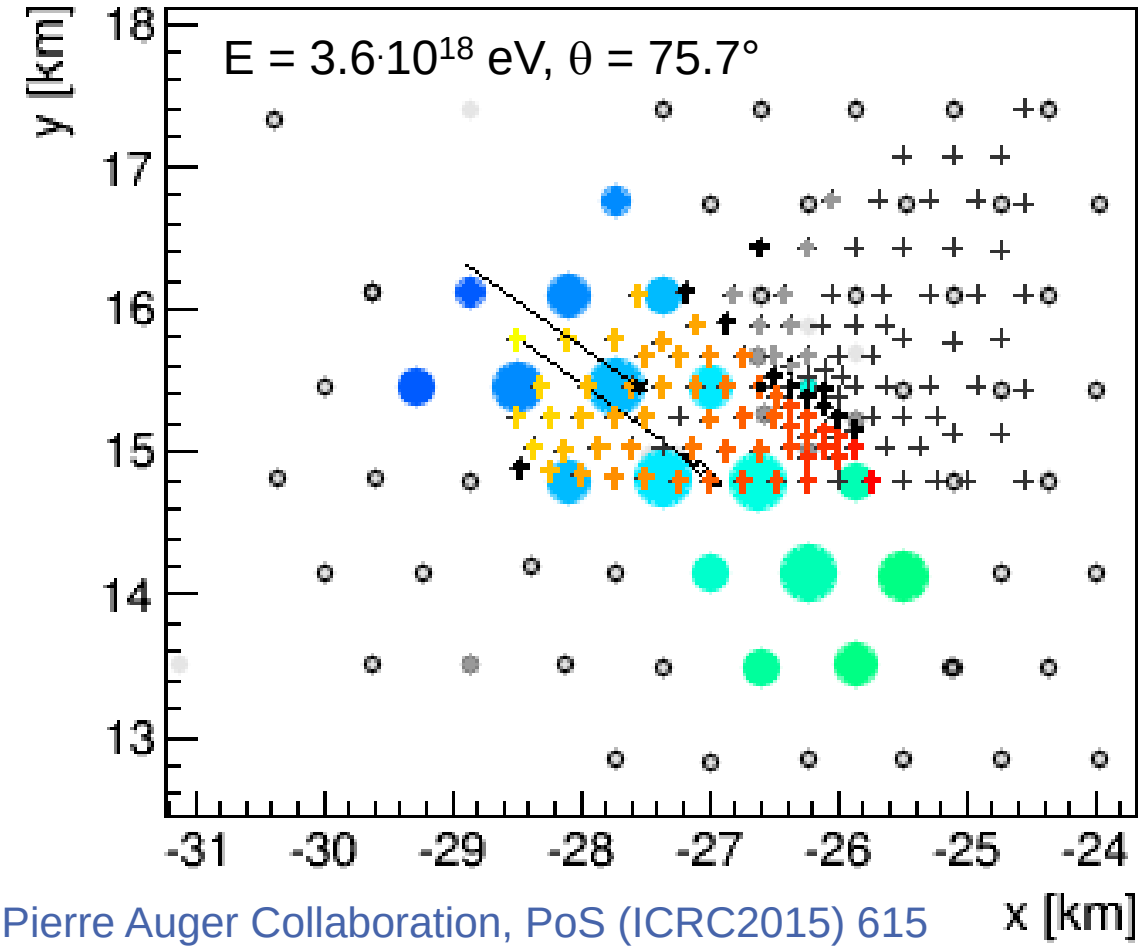
Huge footprint for inclined showers

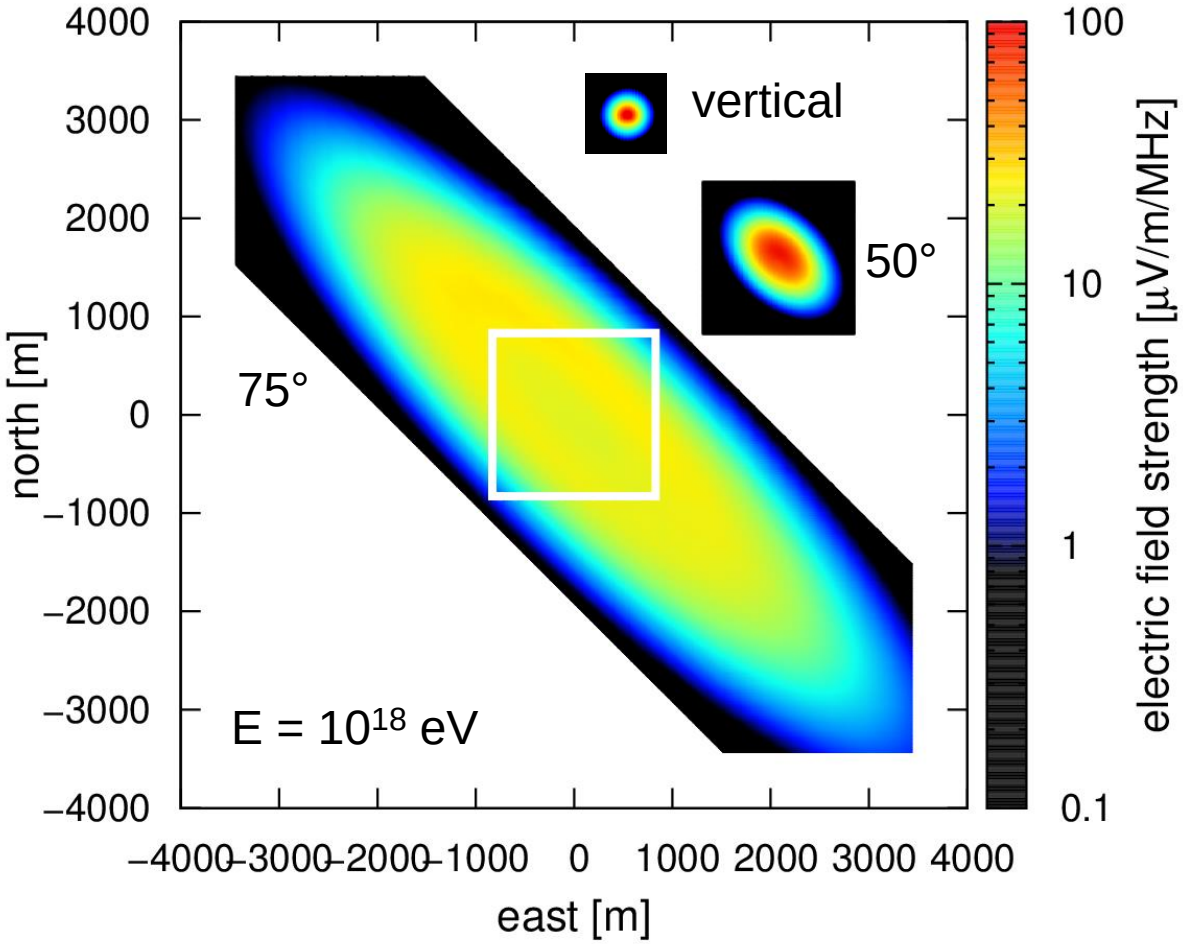
- Enables large-scale, sparse antenna arrays for reasonable costs

Auger measurement



Pierre Auger Collaboration, PoS (ICRC2015) 615

CoREAS simulation



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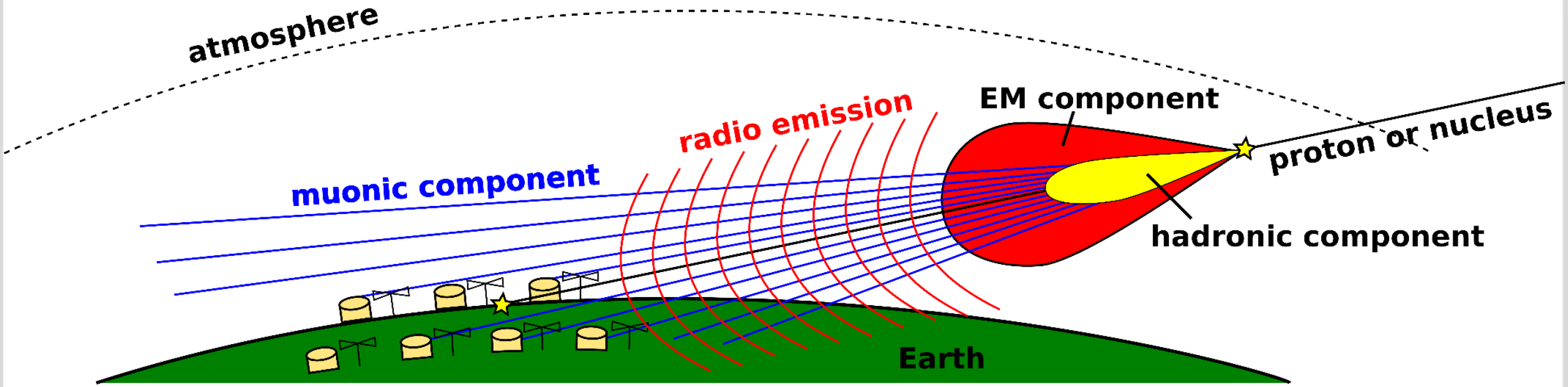
Composition sensitivity for inclined showers



- Only radio emission + muons survive for inclined showers
  - Complementary information on shower → primary particle type

Conclusion

- Properties of the radio signal
  - amplitude understood to a 10 - 20% level
  - other features barely tested: wavefront, polarization, pulse shape
  - **required:** more accurate calibration + more tests
- Reconstruction of air-shower parameters
  - direction < 0.7°, energy < 15 - 20%, X_{max} < 20 g/cm²
  - energy accuracy limited by calibration
  - X_{max} limited by methods?
- Scientific applications
  - plenty of applications, not just mass-composition
  - radio essential for the accuracy-age of cosmic-ray physics

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