Karlsruhe Institute of Technology

# Overview on Radio Detection of Air Showers

## with focus on LOPES, Tunka-Rex, and AERA


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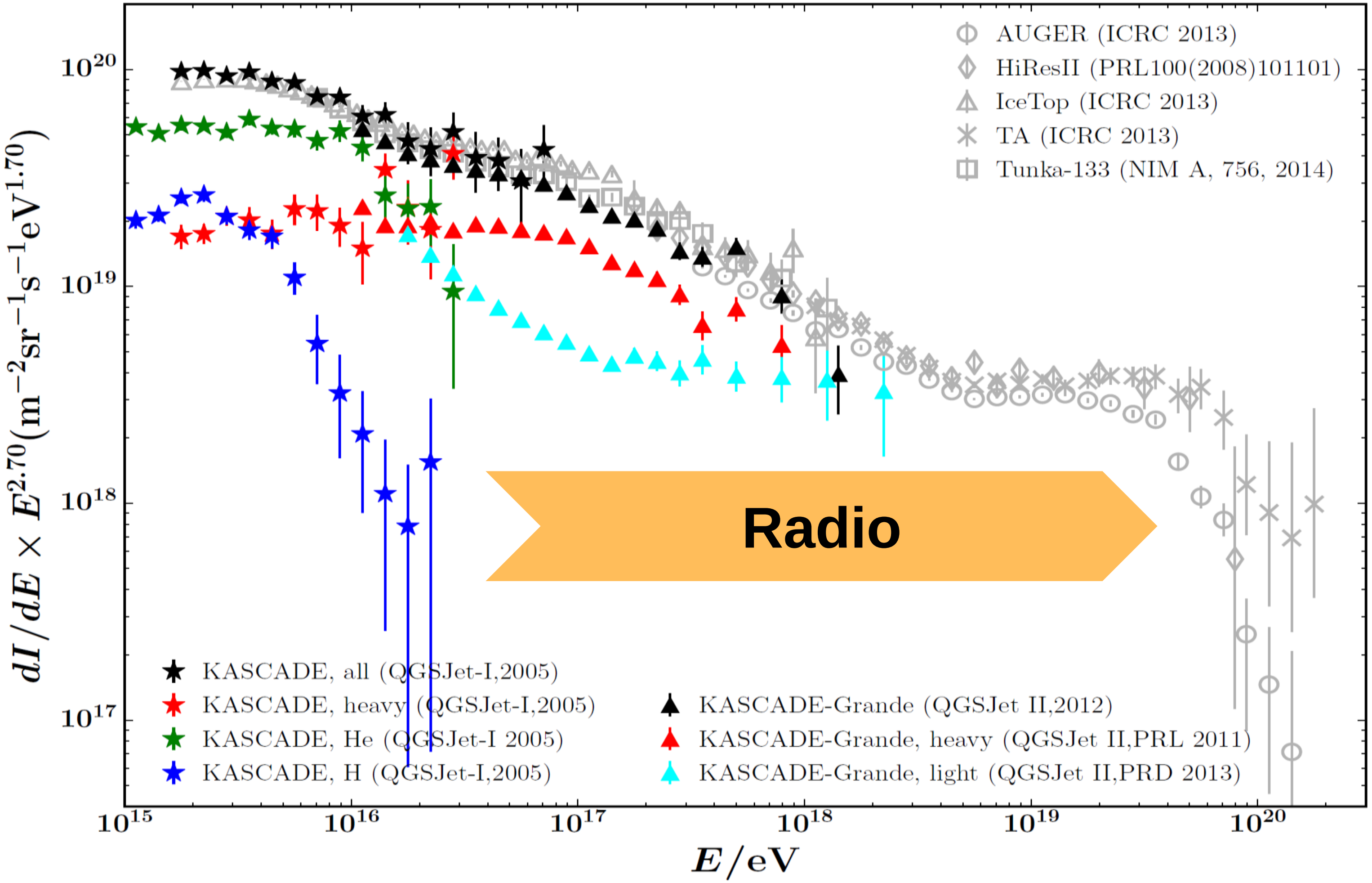
# Advantages of radio technique

- Accurate measurement of energy and $X_{max}$ around the clock



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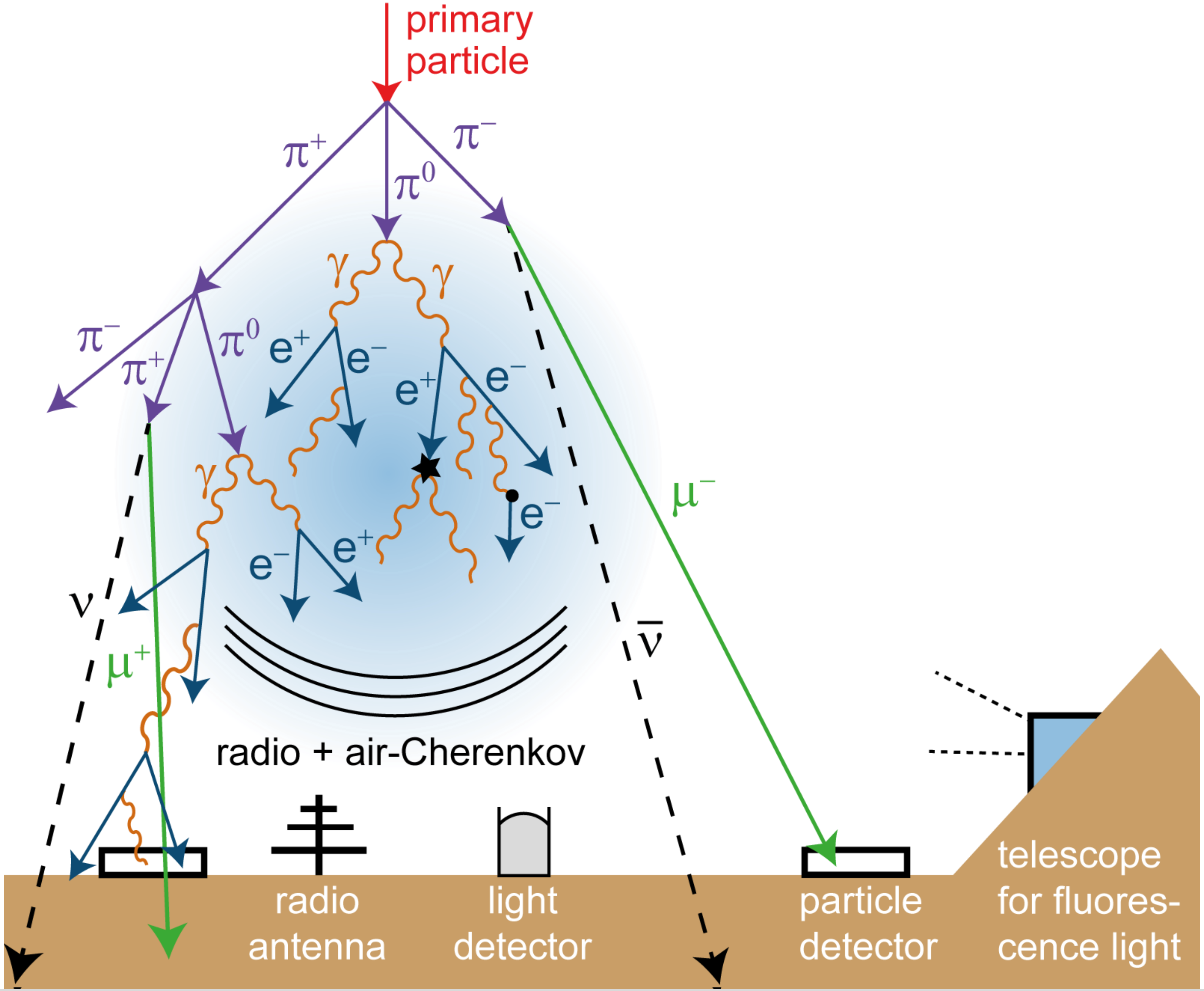
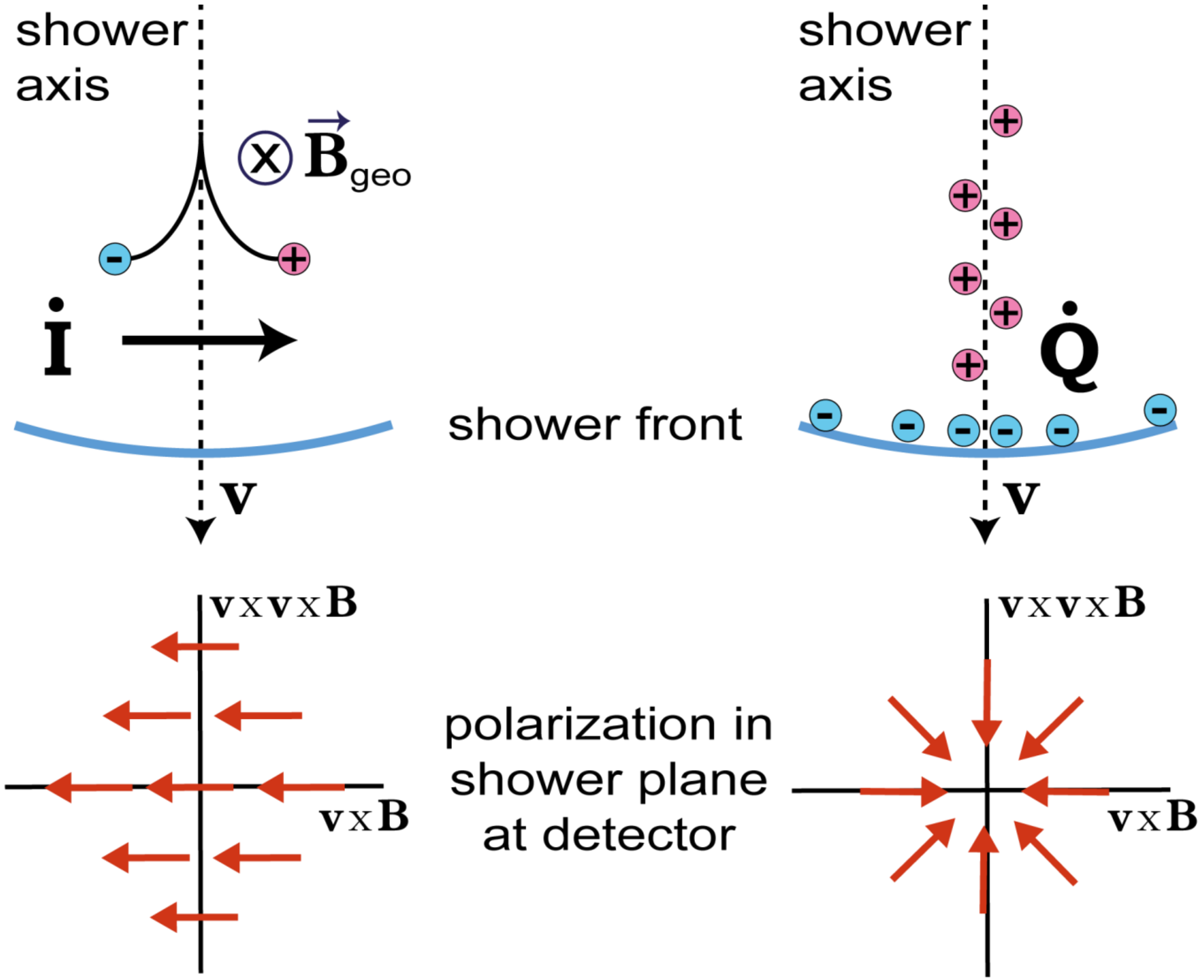



arXiv:
1607.08781

# Emission mechanisms




geomagnetic effect ~ 90%

Askaryan effect ~ 10%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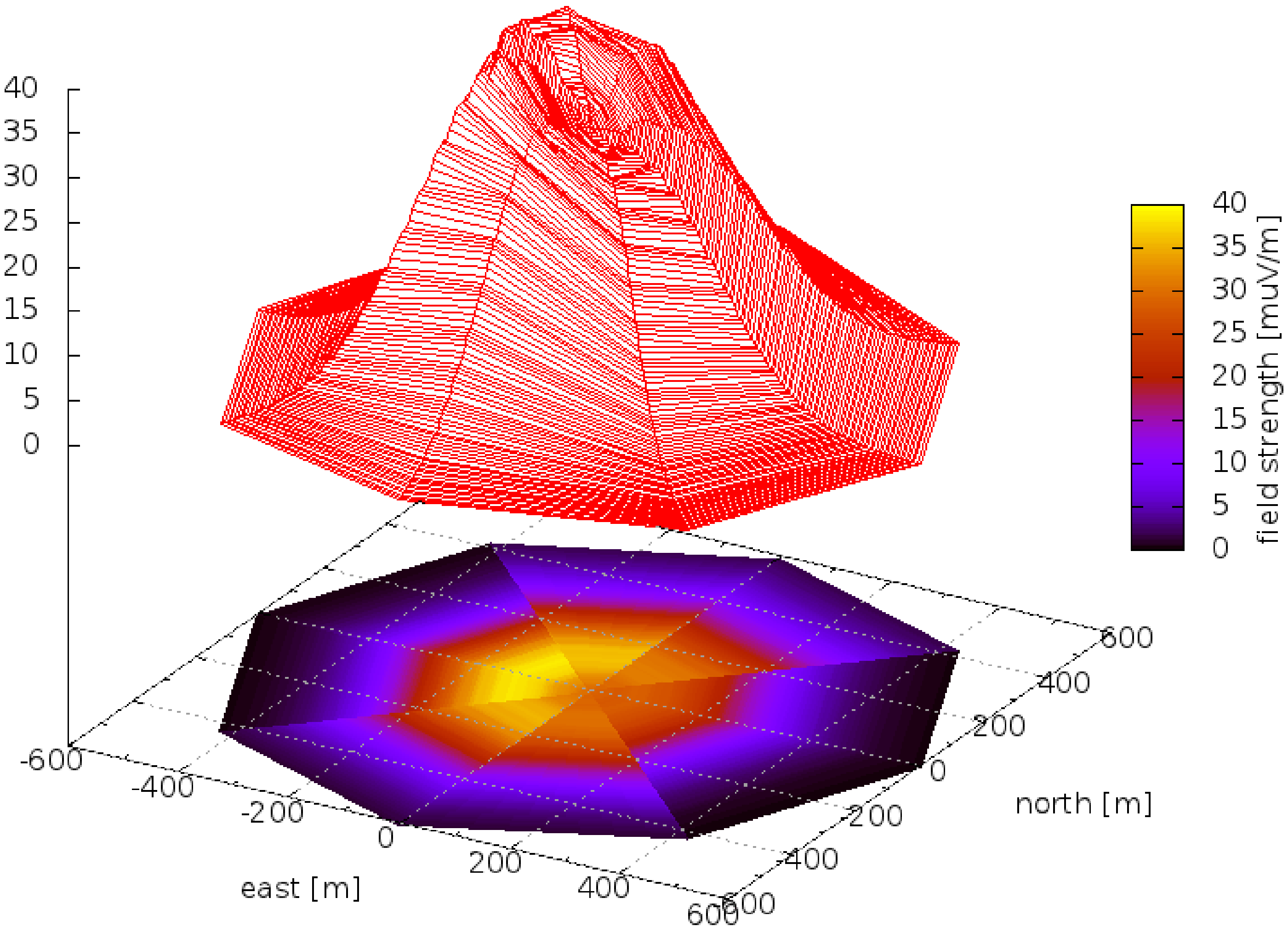
# Conical radio emission with asymmetric footprint



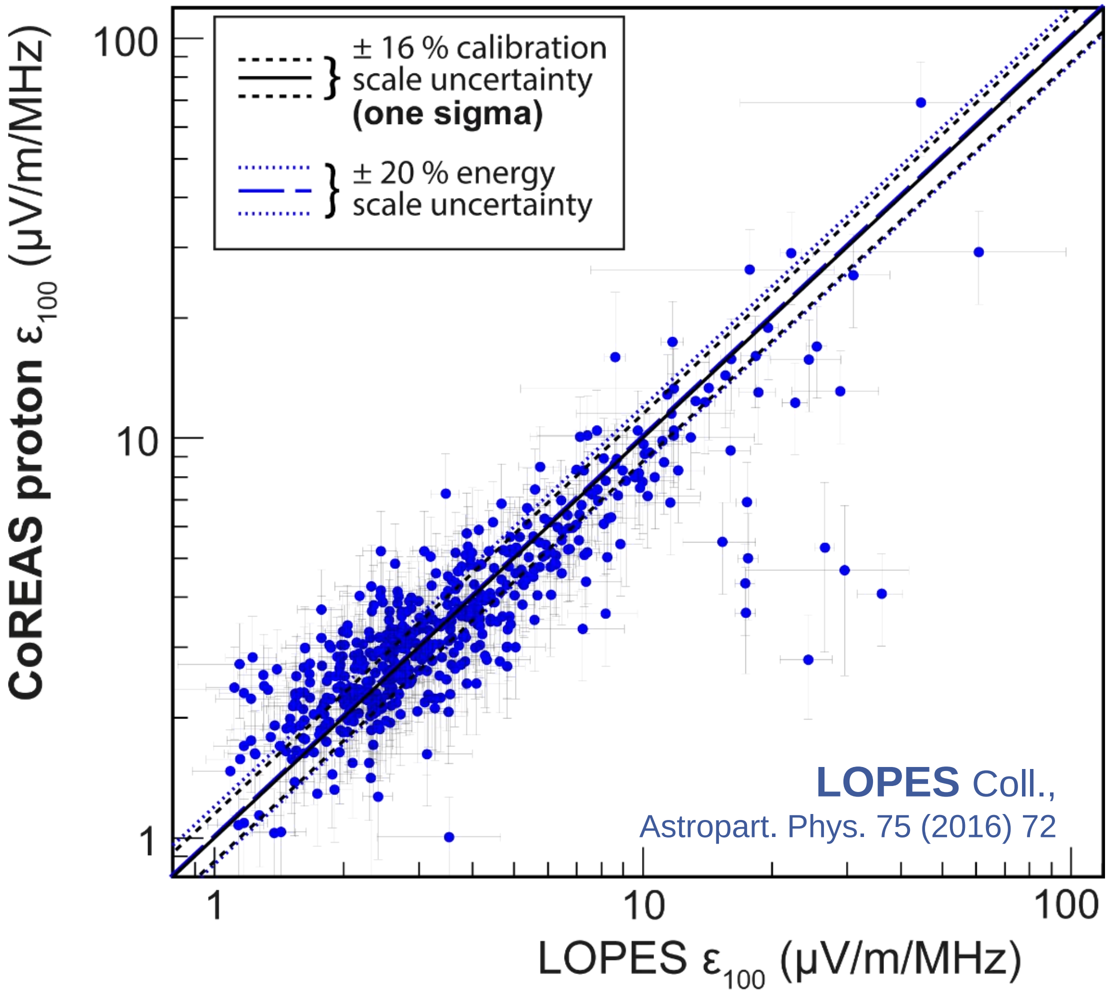

shower inclination:
$\theta = 45°$

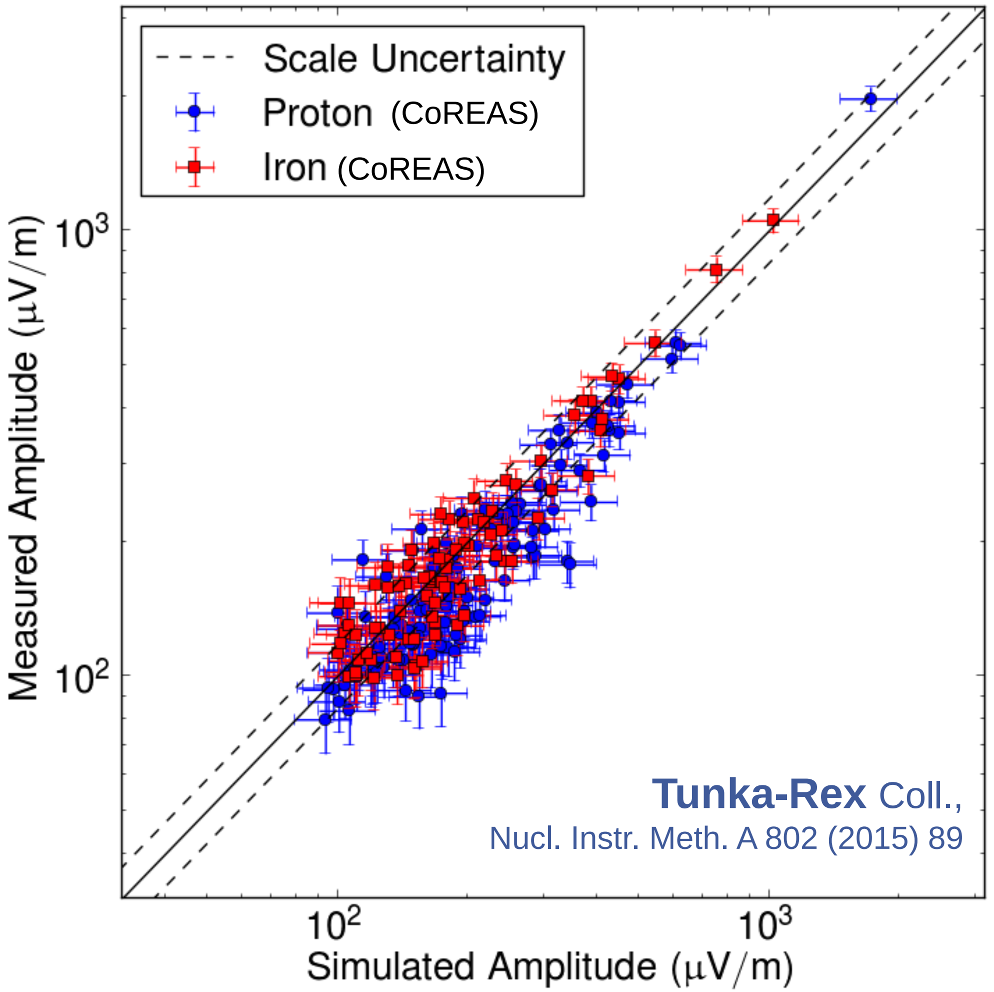
**CoREAS simulations**
By T. Huege et al., ARENA2012

**43 – 74 MHz**

# Do simulations describe reality?

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



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# 1st Answer: How well do we understand the radio emission?

- To a level of 10-20%
  - better than for muon content of air-showers
  - similarly good as fluorescence detection, but various systematics are not yet extensively studied

- Open questions for becoming even better
  - What is the impact of atmospheric humidity?
  - Is the proportionality with geomagnetic field exact?
  - How exactly behaves the emission for near-horizontal showers?


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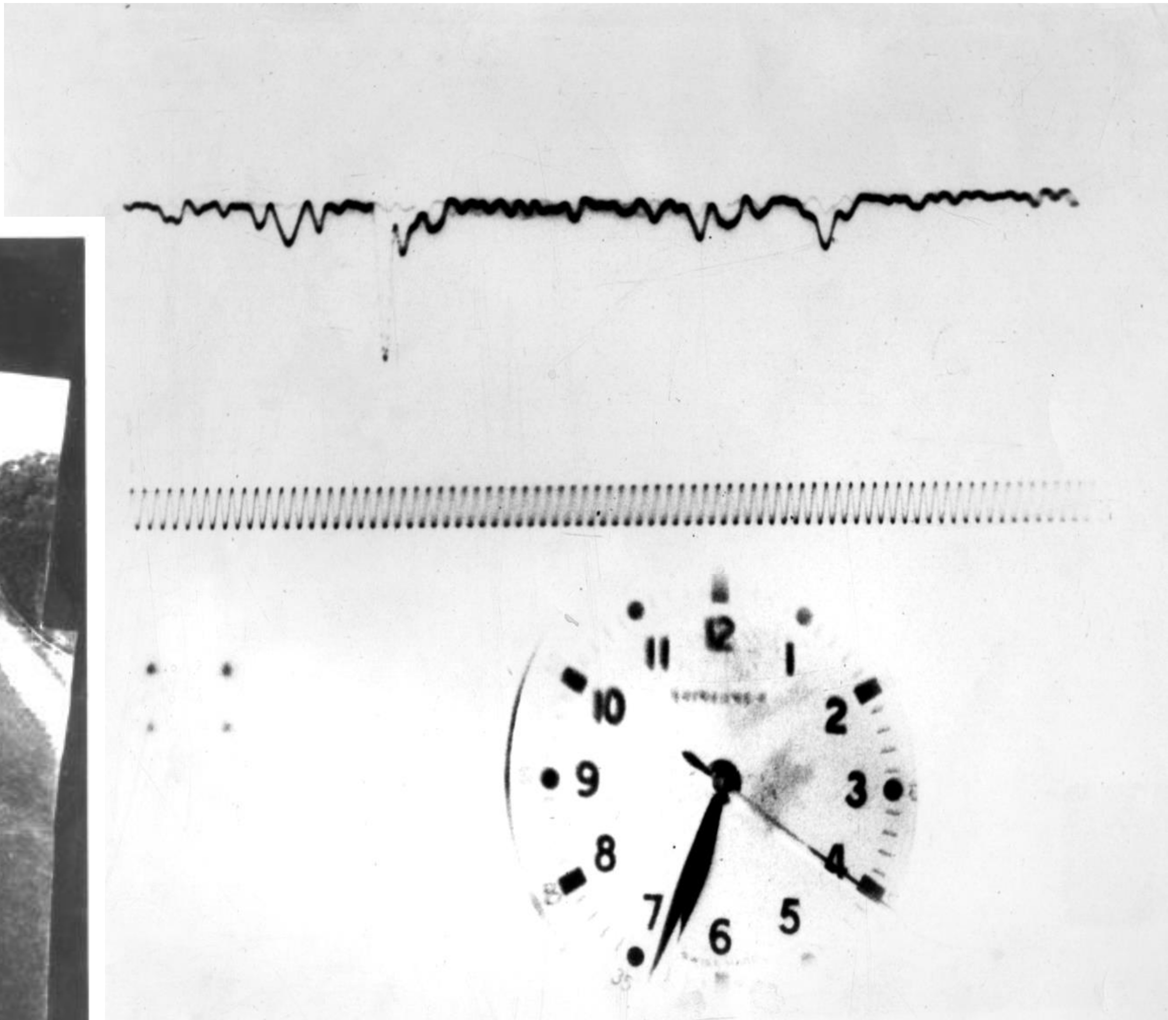
# Experiments: First Detection

- Qualitative features discovered 50 years ago, but measurements lacking accuracy




Jelley et al Nature 1965,
R. A. Porter MSc Thesis 1967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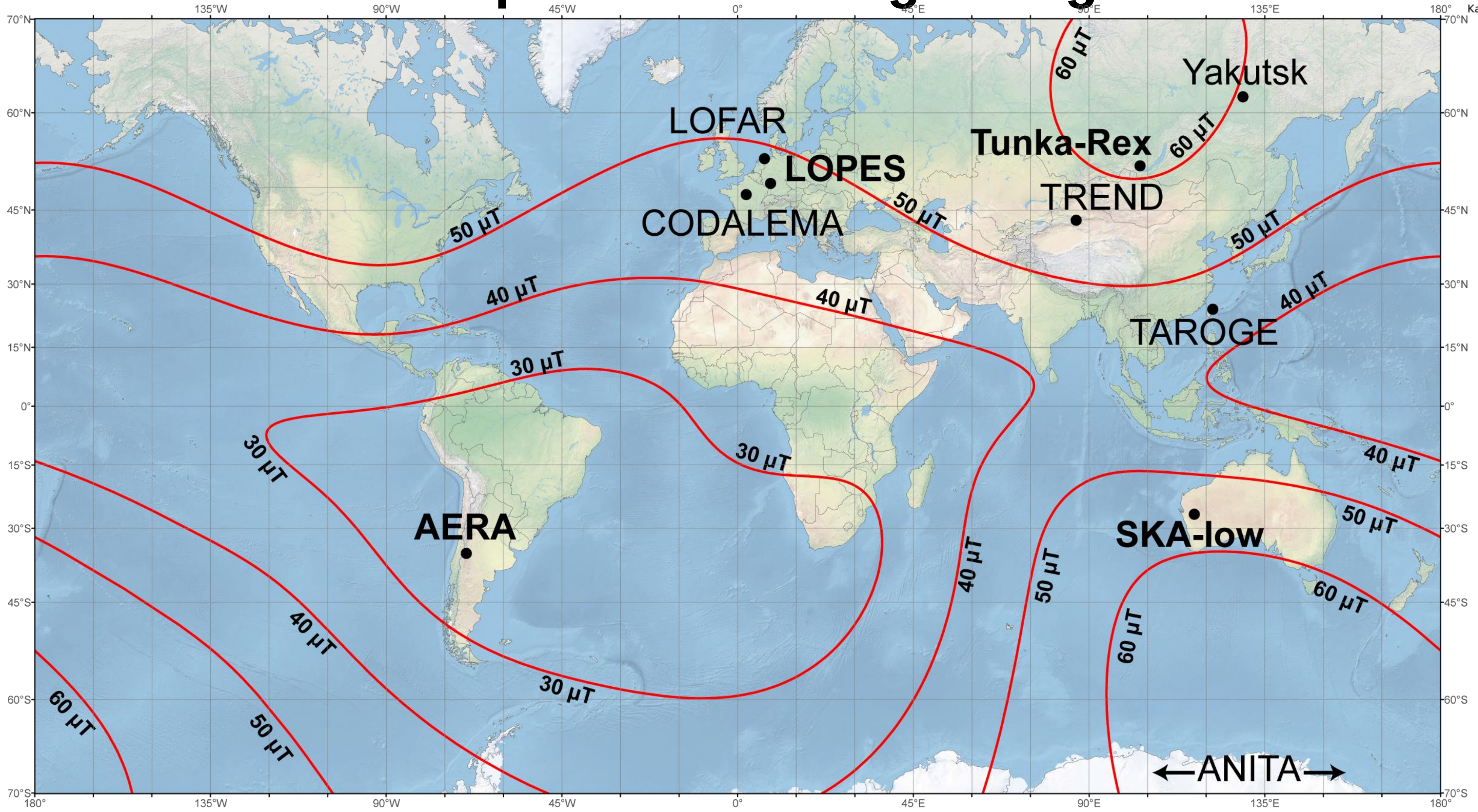
# Location of selected experiments and geomagnetic field



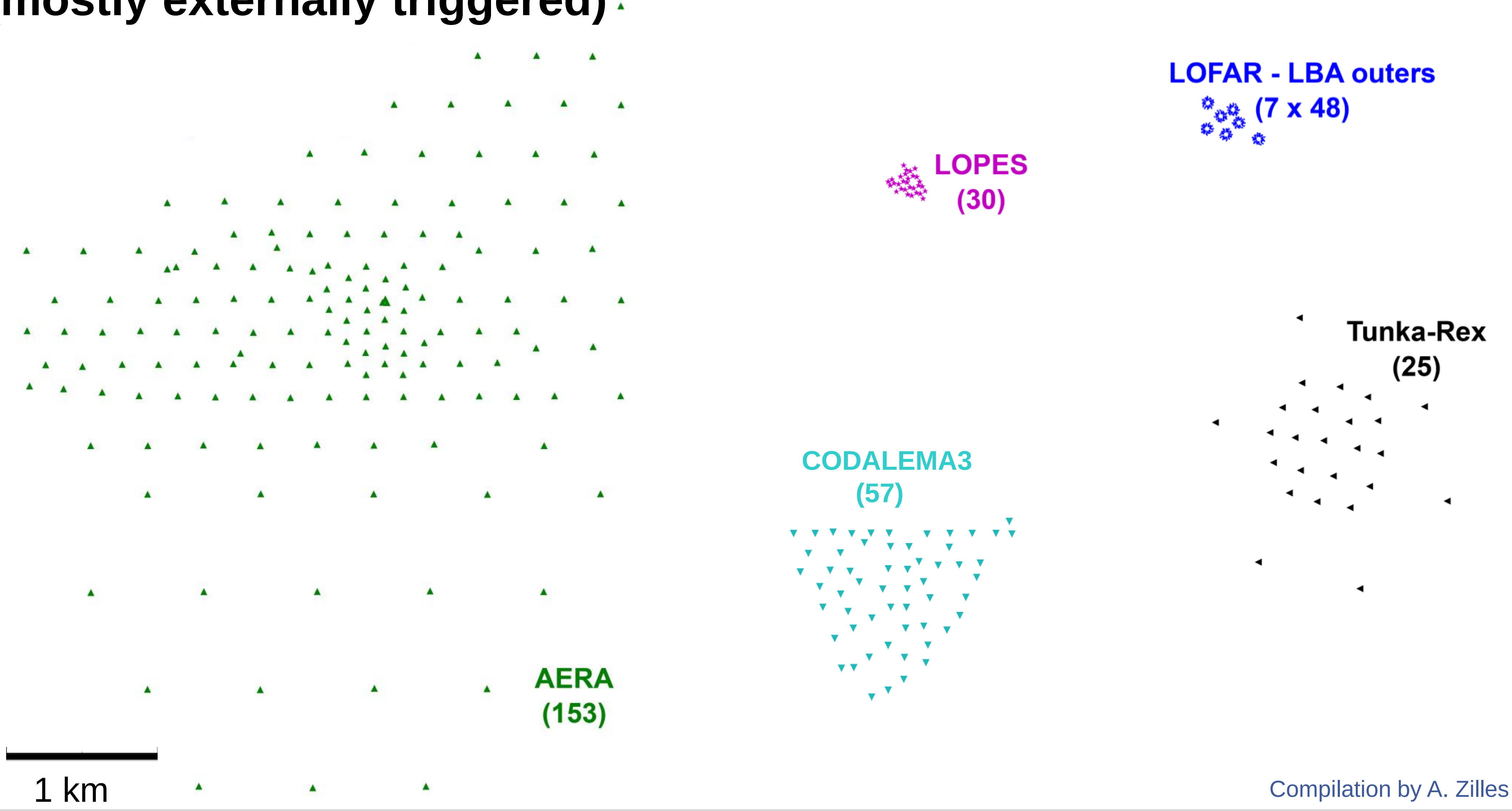

Underlying map (Mercator projection):
**Main Geomagnetic Field Total Intensity** with contour intervals of 1000 nT according to US/UK World Magnetic Model - Epoch 2015.0

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 Karlsruhe Institute of Technology (KIT), Germany

# Designs of modern radio arrays
## (mostly externally triggered)




Compilation by A. Zilles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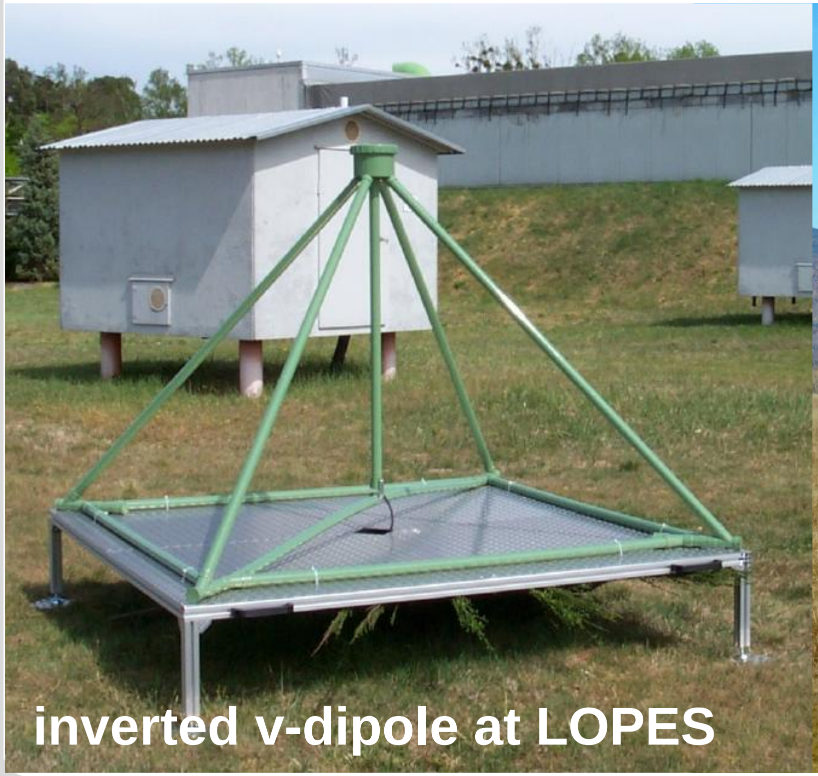
# Detectors: antennas

- 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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# Reconstruction of shower parameters

- Direction
  - example: LOPES
- Energy
  - example: AERA and others
- Shower maximum
  - example: Tunka-Rex (for LOFAR see next talk)


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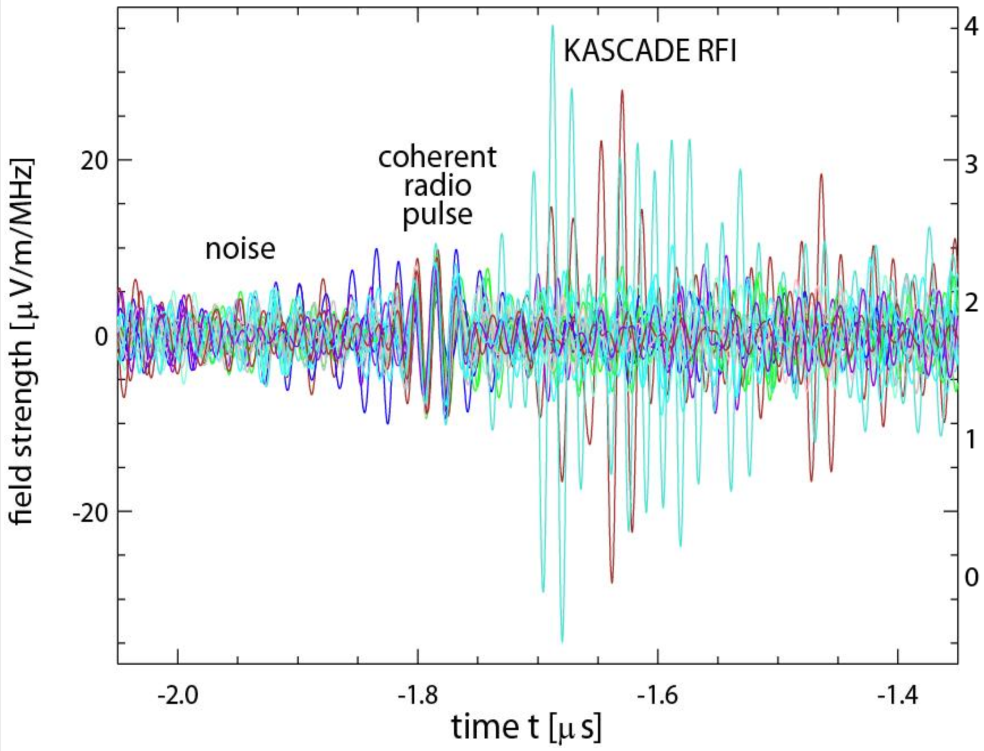
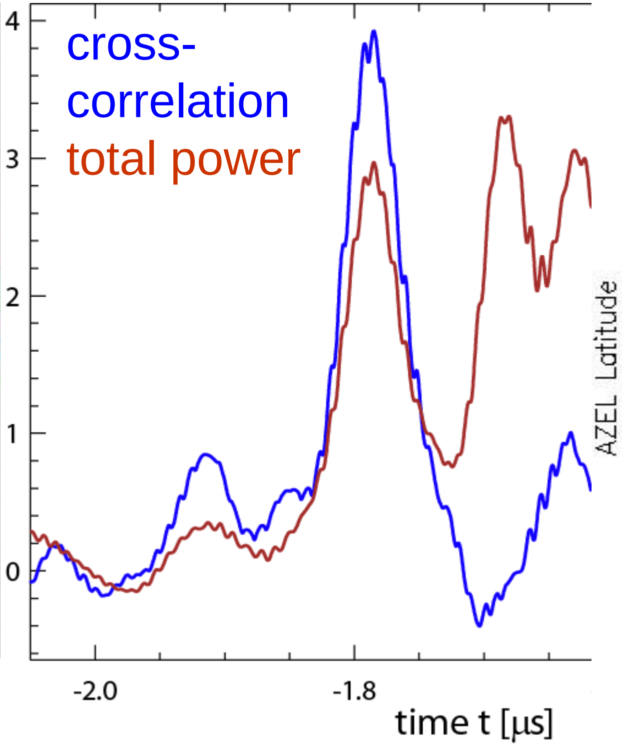
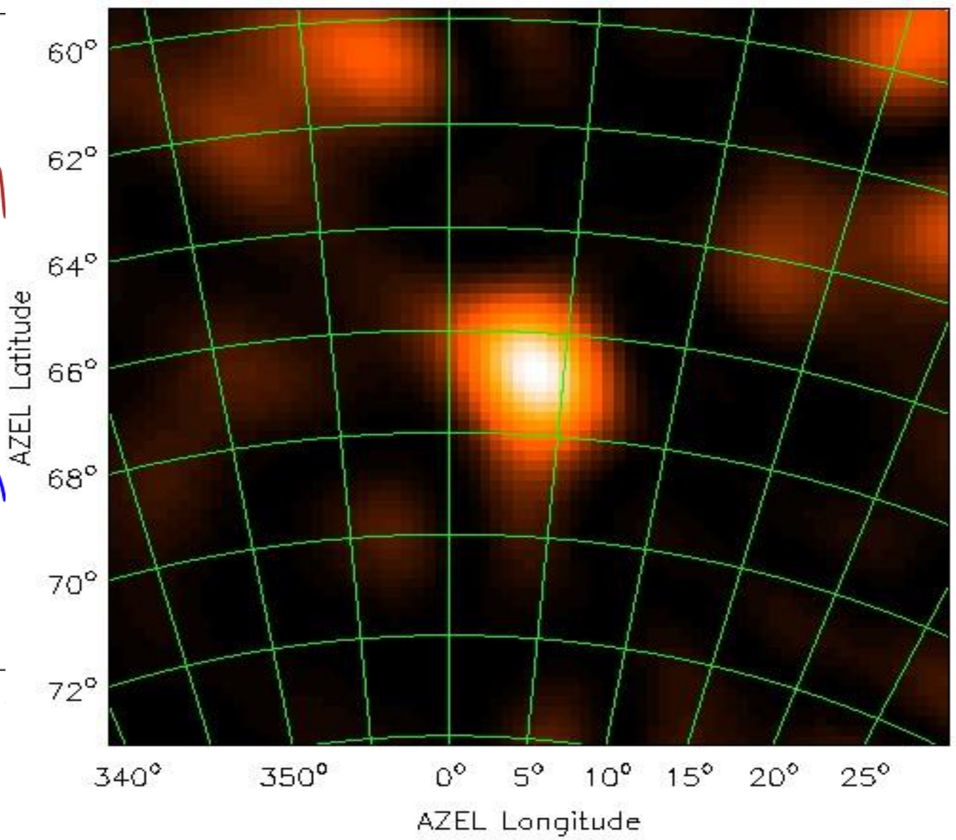
# Interferometric beamforming at LOPES

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



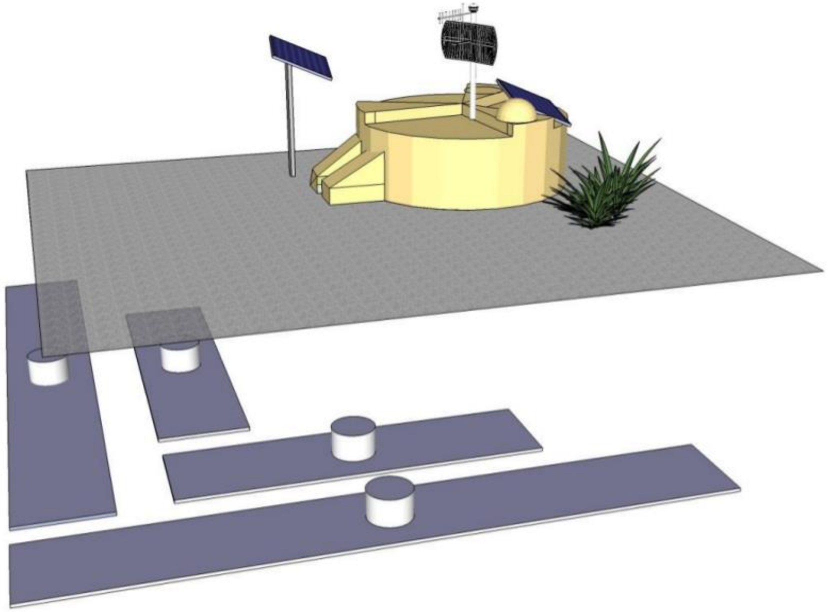




**LOPES** Coll., Astroparticle Physics 50-52 (2013) 76 + Nature 435 (2005) 313

# Auger Engineering Radio Array

- 153 autonomous stations on 17 km²



**A**uger **E**ngineering
**R**adio **A**rray

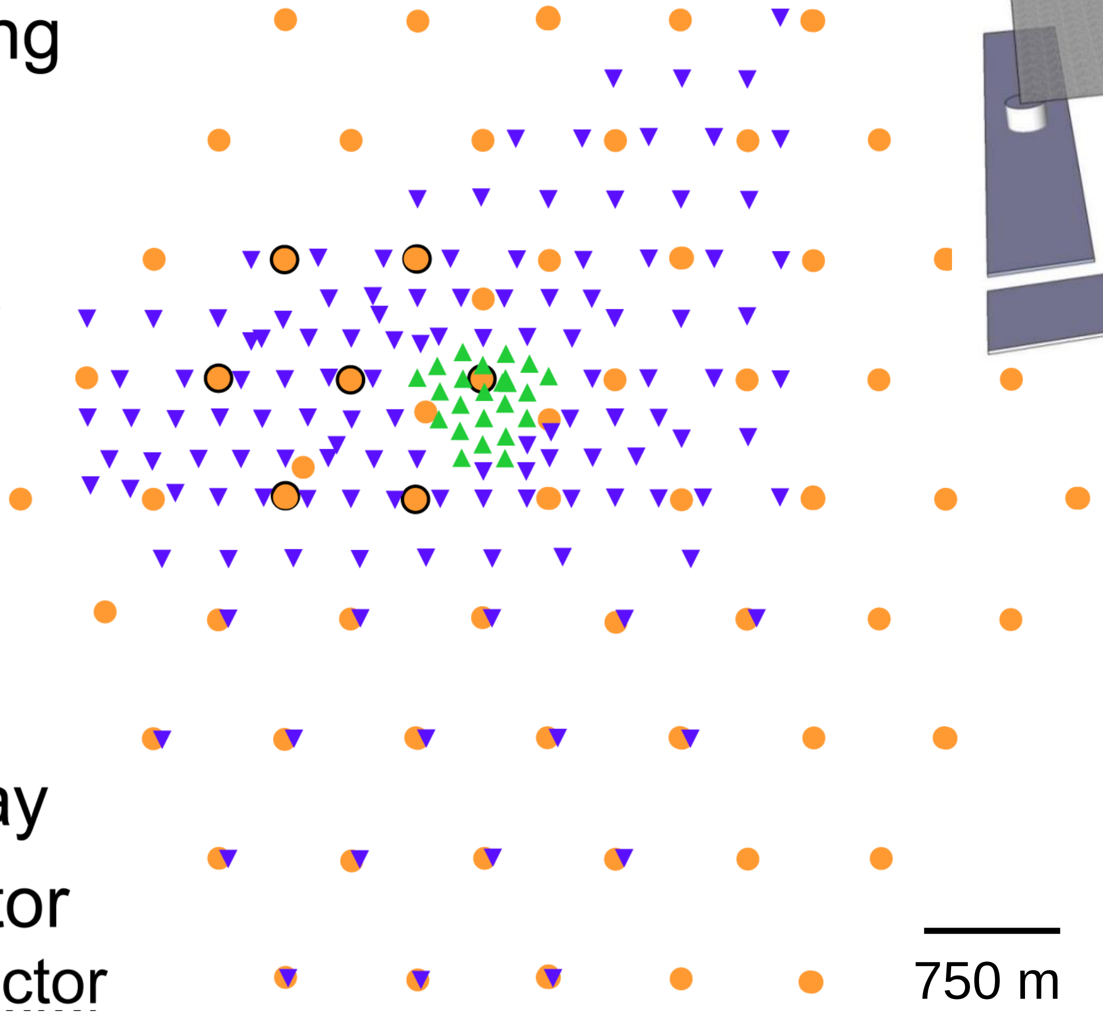
▲ LPDA antenna

▼ Butterfly antenna

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

• **S**urface **D**etector

o with **M**uon **D**etector




PIERRE AUGER OBSERVATORY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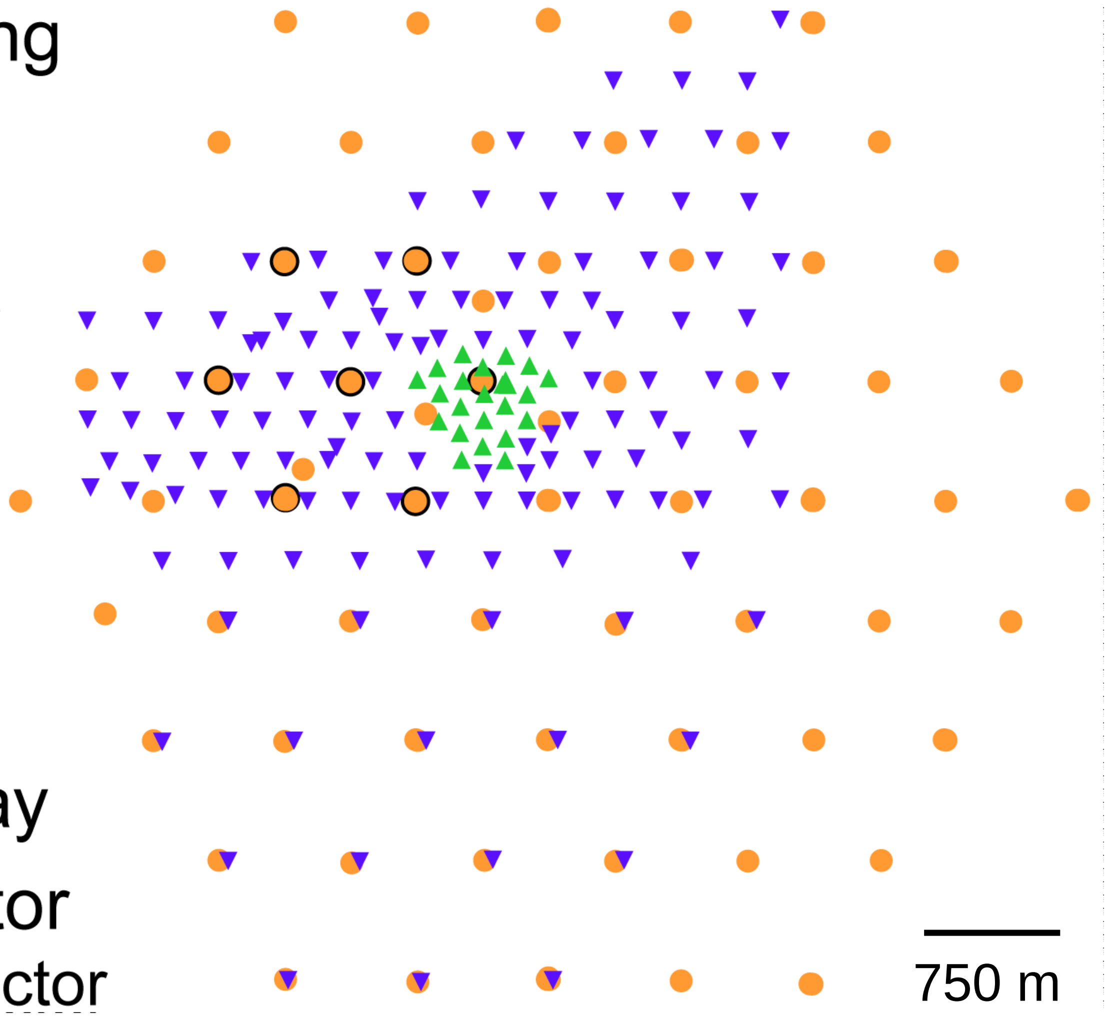
# Auger Engineering Radio Array

Auger Engineering Radio Array

- 153 autonomous stations on 17 km²

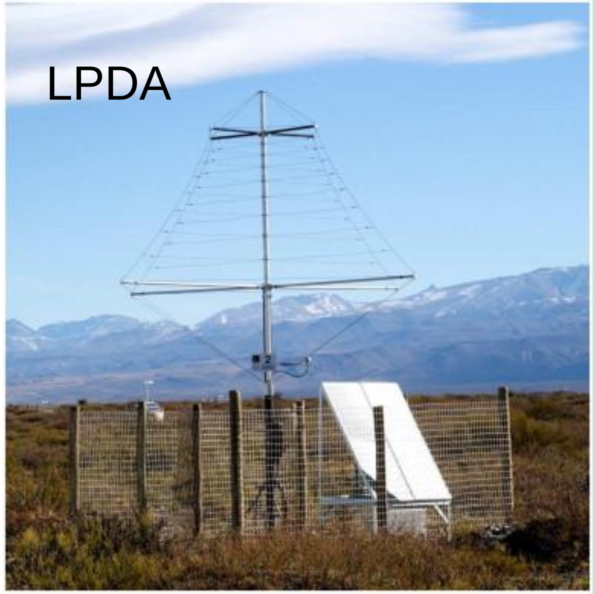
**A**uger **E**ngineering
**R**adio **A**rray

▲ LPDA antenna
▼ Butterfly antenna




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

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



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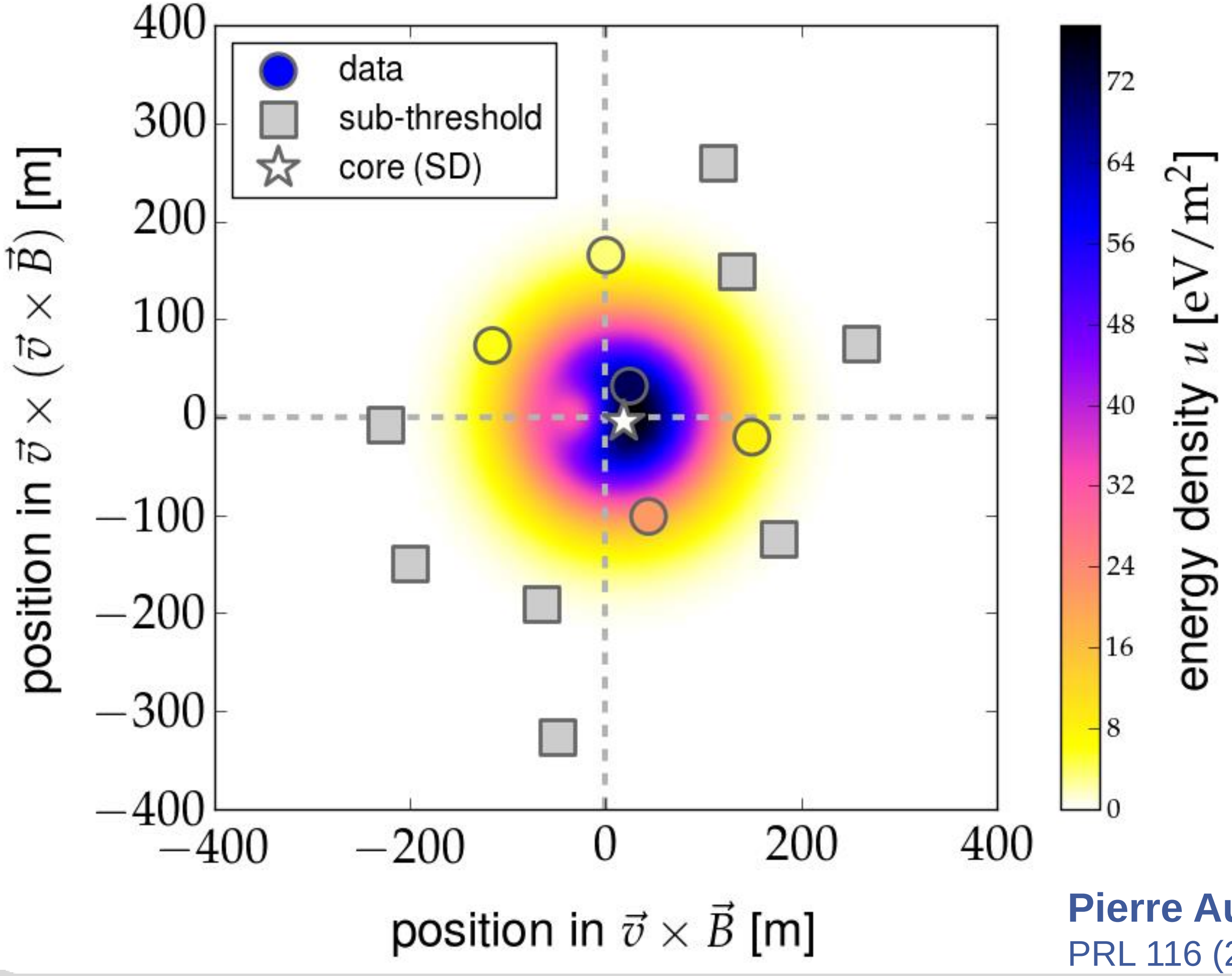
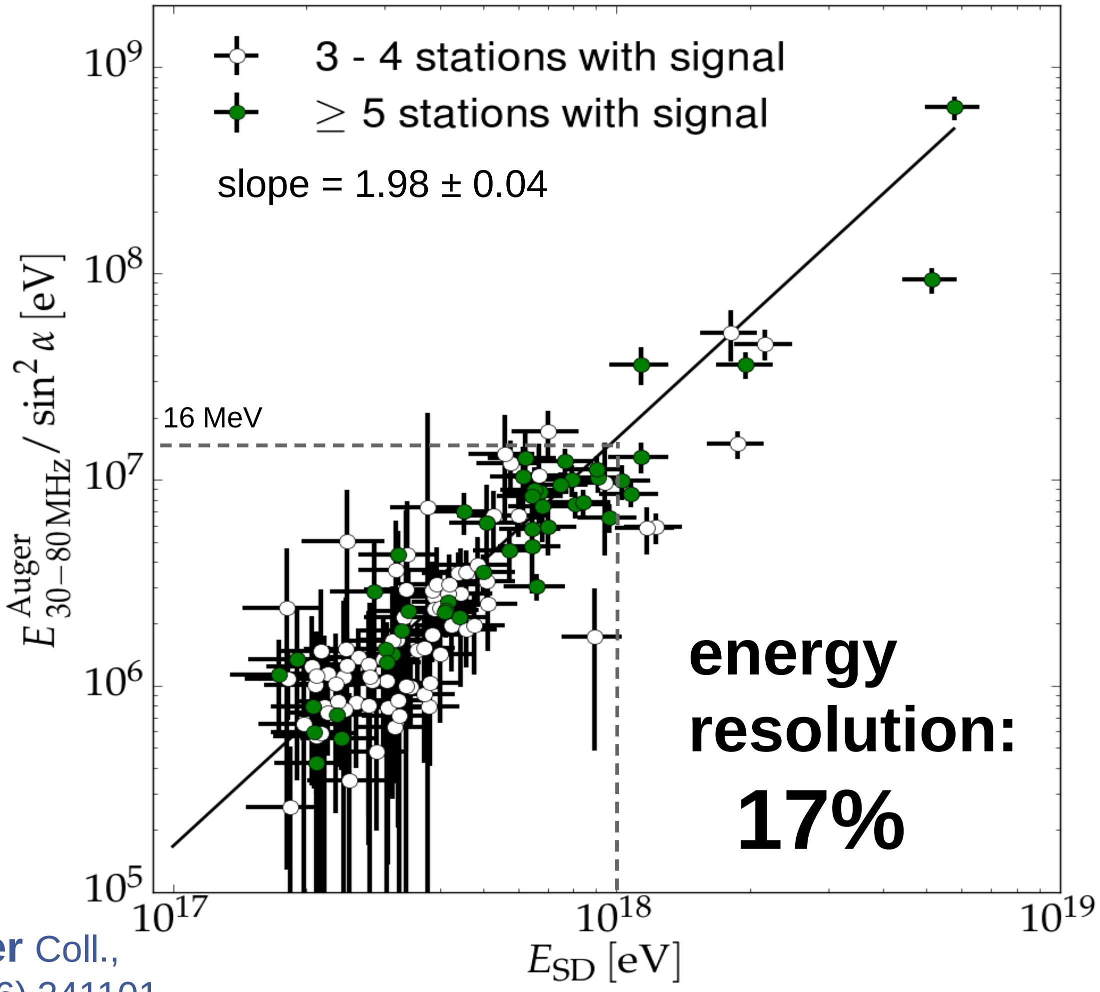
# Energy reconstruction by AERA

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

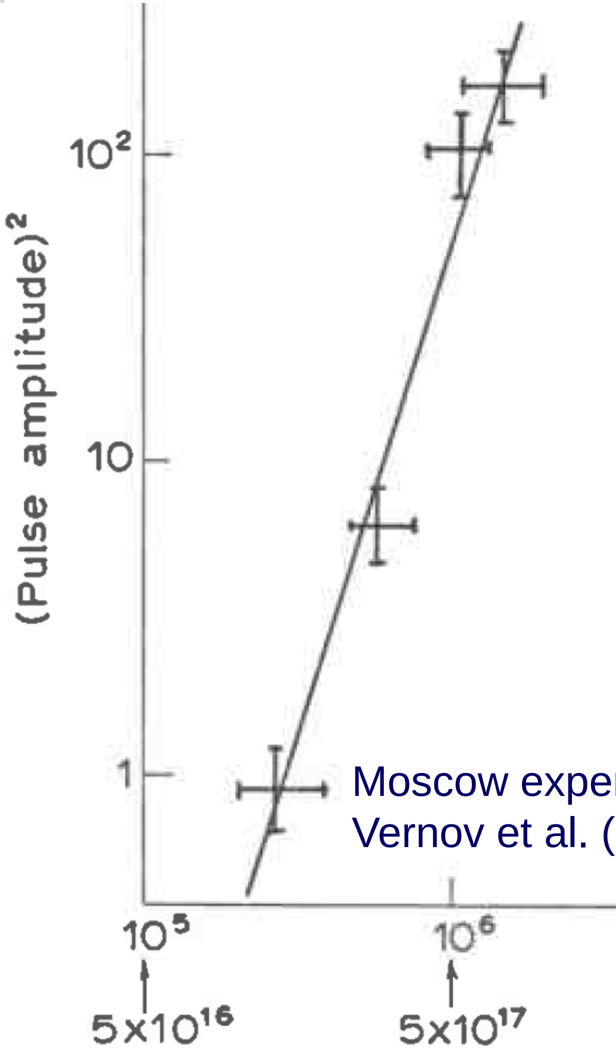


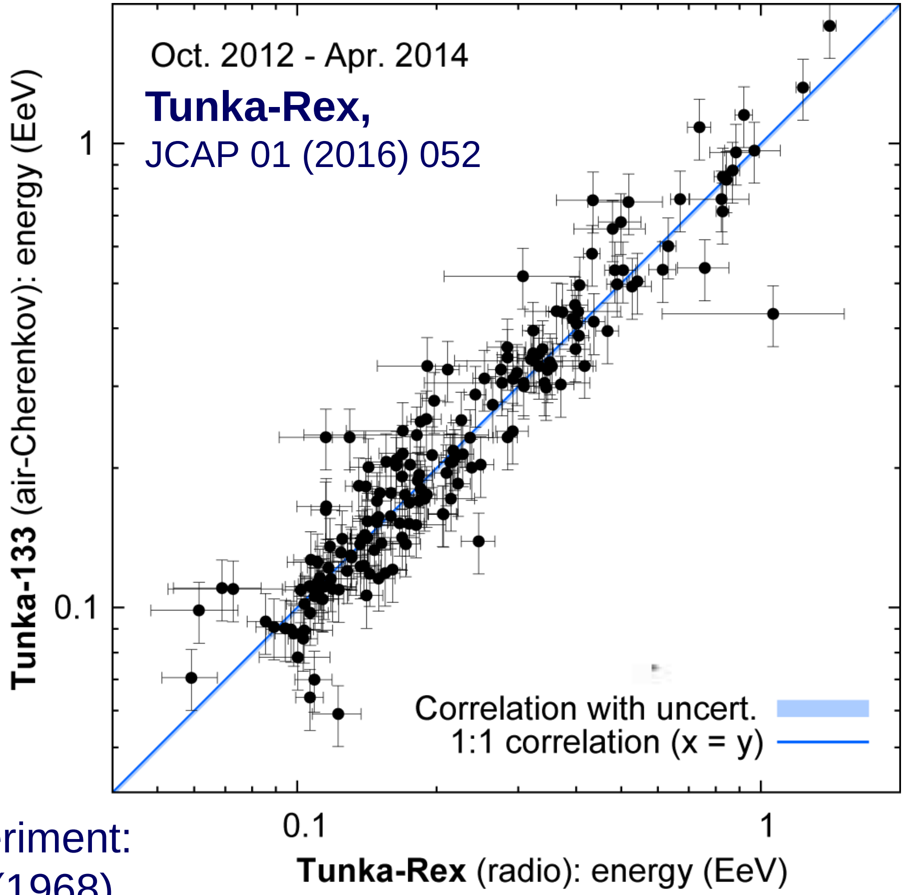

**energy resolution:**
**17%**

**Pierre Auger** Coll.,
PRL 116 (2016) 241101

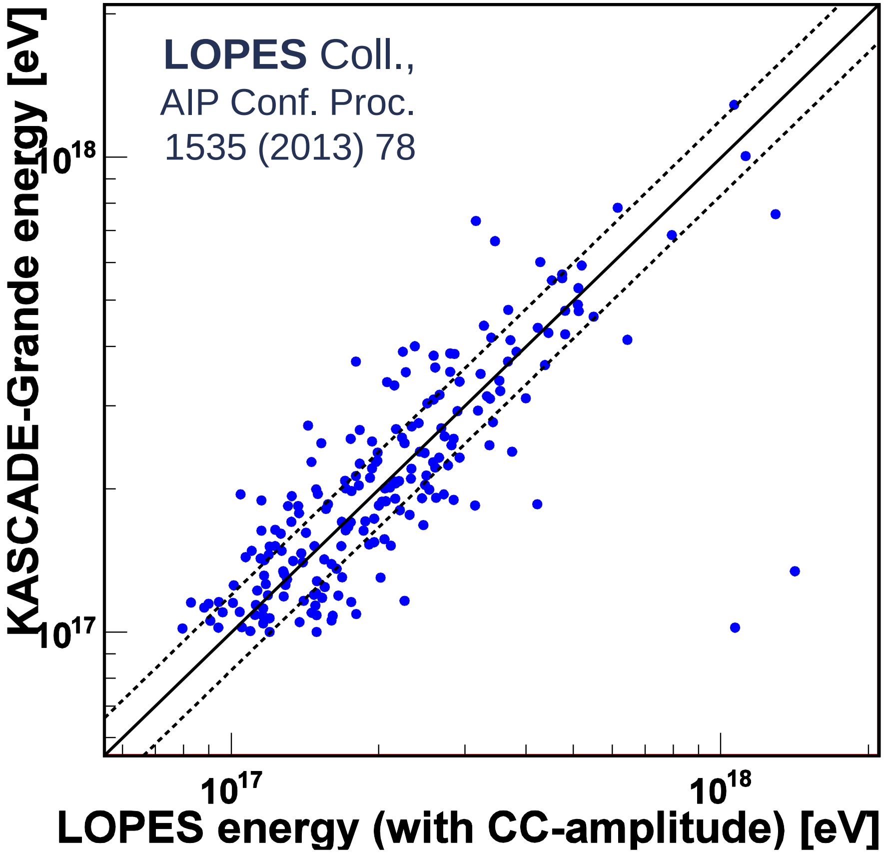
# Similar energy precision by other experiments




Moscow experiment:
Vernov et al. (1968)




**+ several other experiments**





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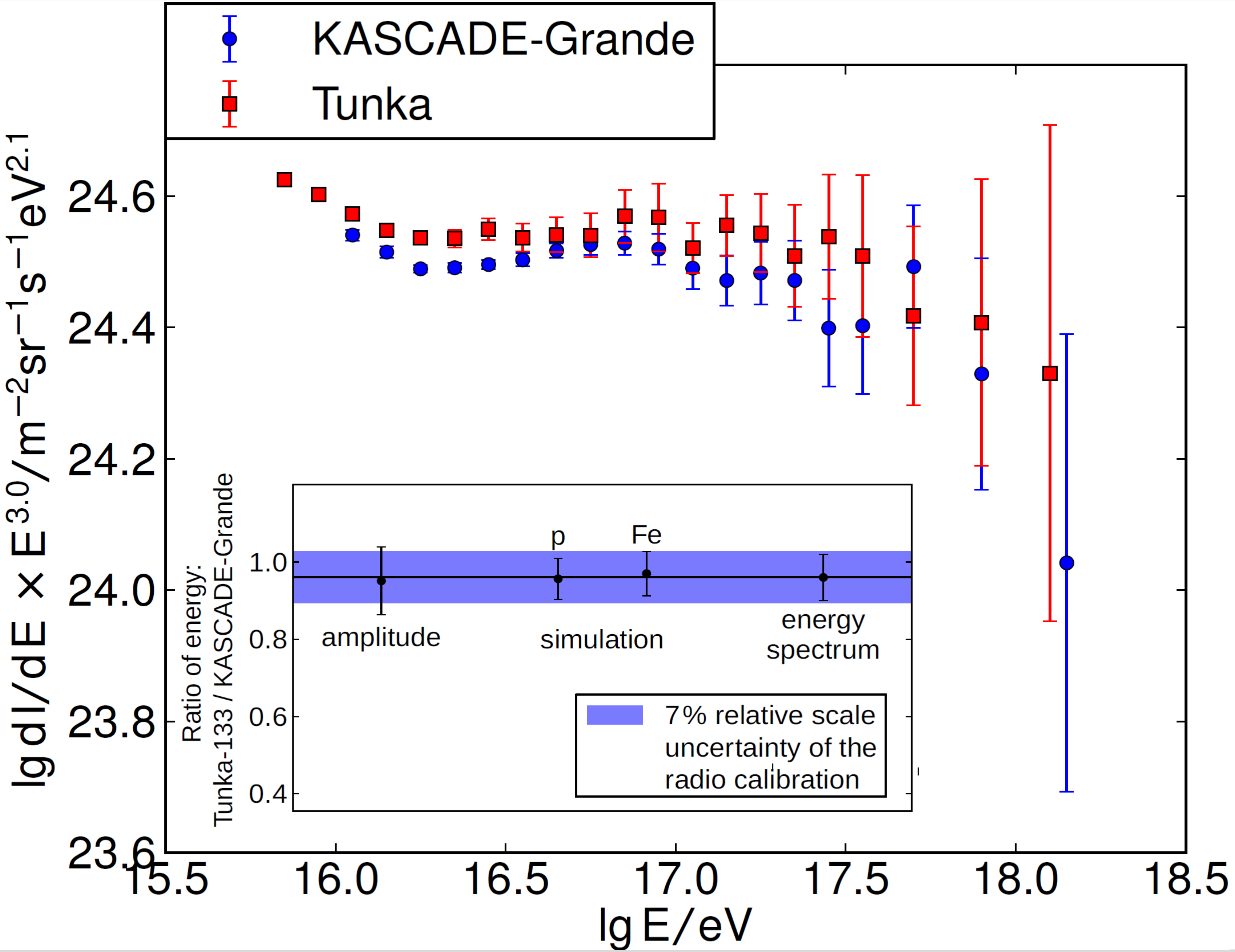
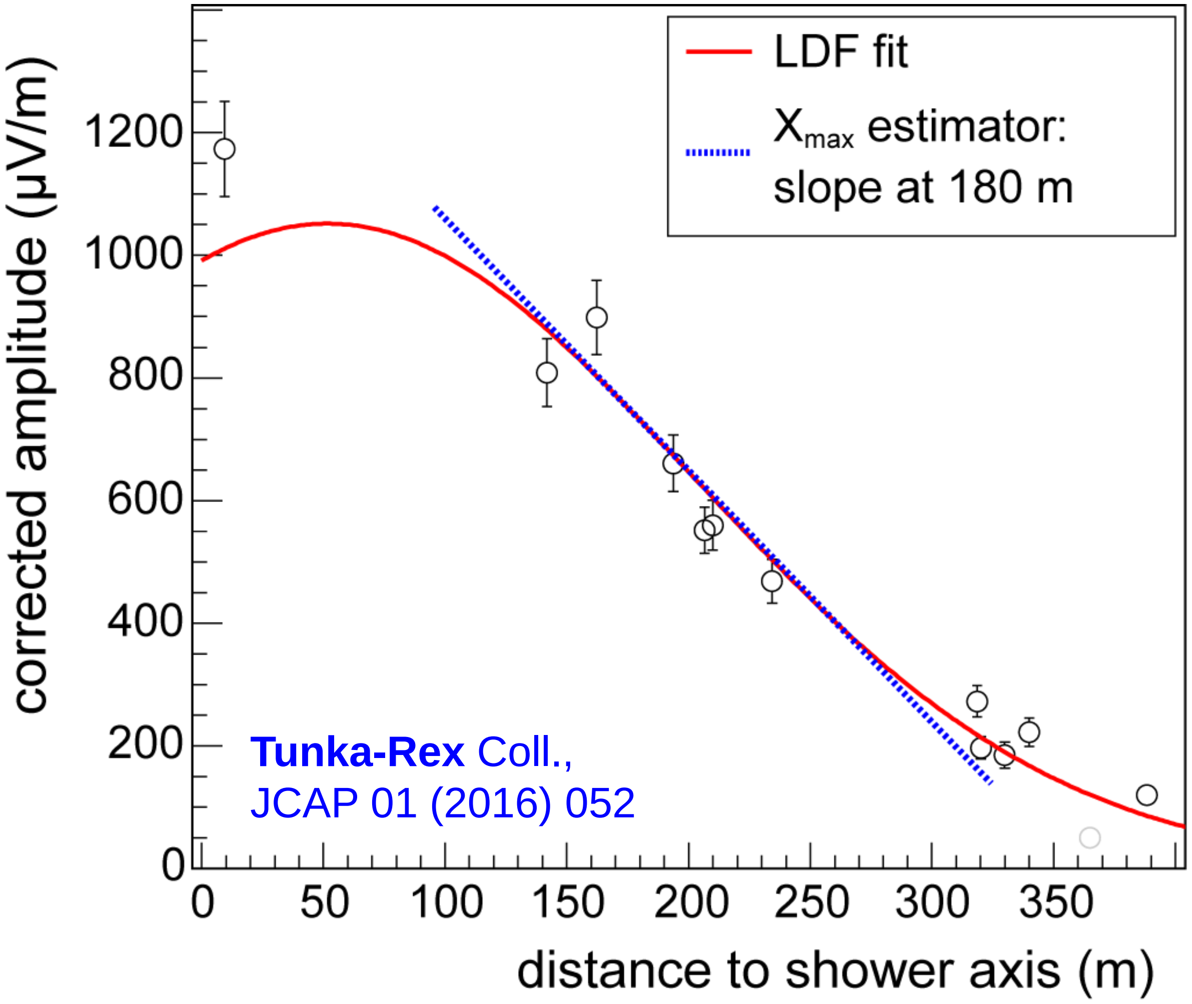
# Comparing energy scales via radio

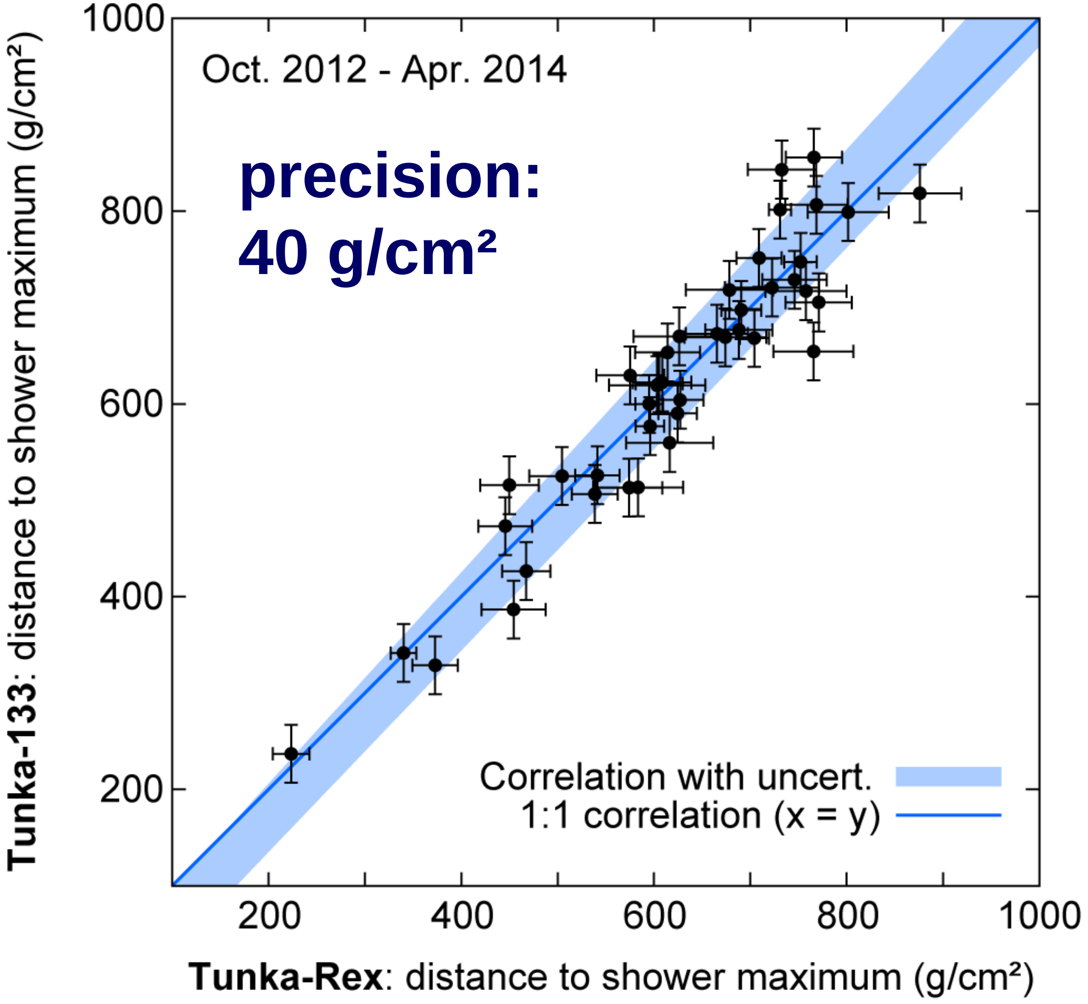



**Tunka-Rex** + **LOPES** Colls., submitted to PLB

# Shower maximum: proof by Tunka-Rex

- One of several methods: slope of lateral distribution





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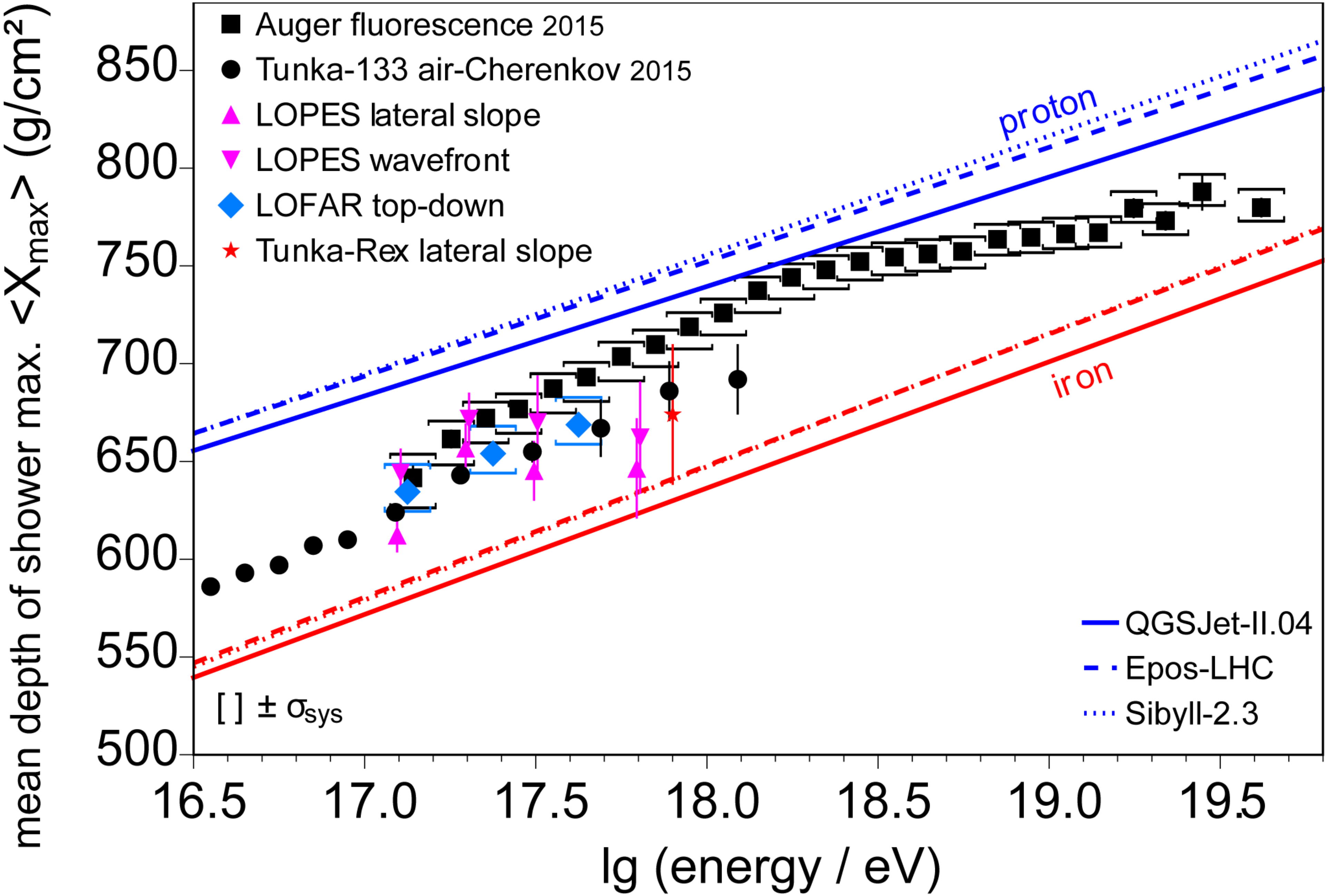
Auger fluorescence 2015
Tunka-133 air-Cherenkov 2015
LOPES lateral slope
LOPES wavefront
LOFAR top-down
Tunka-Rex lateral slope
proton
iron
QGSJet-II.04
Epos-LHC
Sibyll-2.3
[ ] ± σsys
mean depth of shower max. <Xmax> (g/cm²)
lg (energy / eV)
850
800
750
700
650
600
550
500
16.5
17.0
17.5
18.0
18.5
19.0
19.5

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# 2nd Answer: What is the accuracy for shower observables?

- Accuracy competitive to fluorescence technique
  - direction < 0.7°
  - energy < 20% (precision + scale)
  - $X_{max}$ < 20 g/cm² (with high antenna density)

- Next steps currently under investigation
  - Can we reach an energy accuracy of 5-10%?
  - Can we achieve 20 g/cm² $X_{max}$ resolution with sparse arrays?
  - Can we exploit composition sensitivity beyond $X_{max}$?


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# 3rd Answer: What ideas and plans are there beyond $X_{max}$?

- Highest apertures for $10^{20}$ eV
  - huge arrays for inclined showers, satellites, the Moon
  - draw backs: poor energy resolution and composition sensitivity
  - science case, if composition at $10^{20}$ eV is not mixed, but either pure proton or pure iron
- Neutrino search above $10^{16}$ eV
  - radio arrays in and on ice – ARA, ARIANNA
- Ultimate precision around $10^{17}$ eV
  - the low-frequency core of the Square Kilometer Array (SKA)


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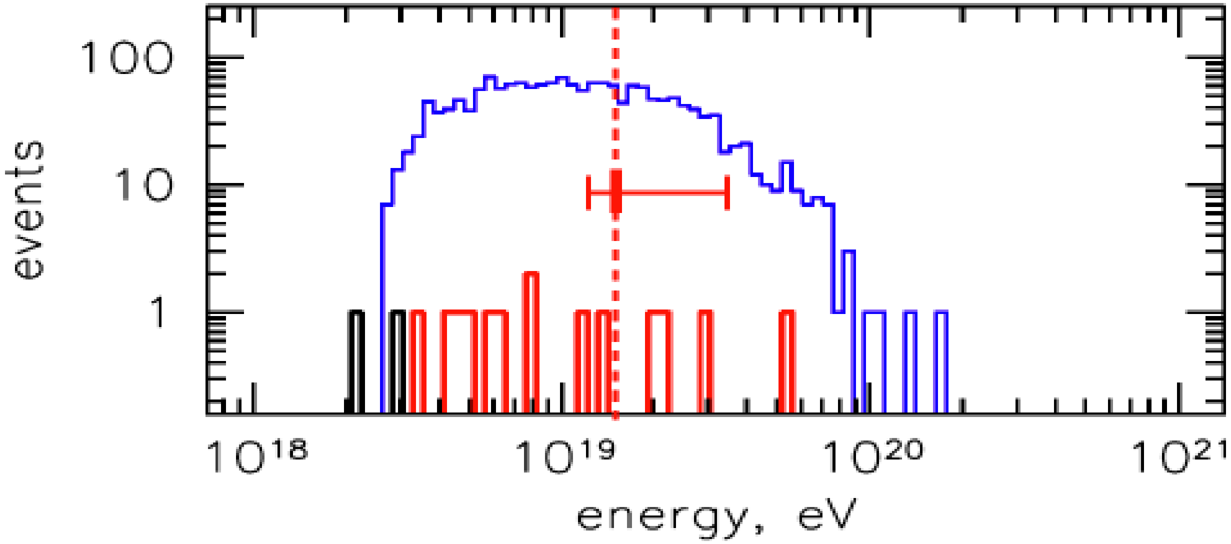
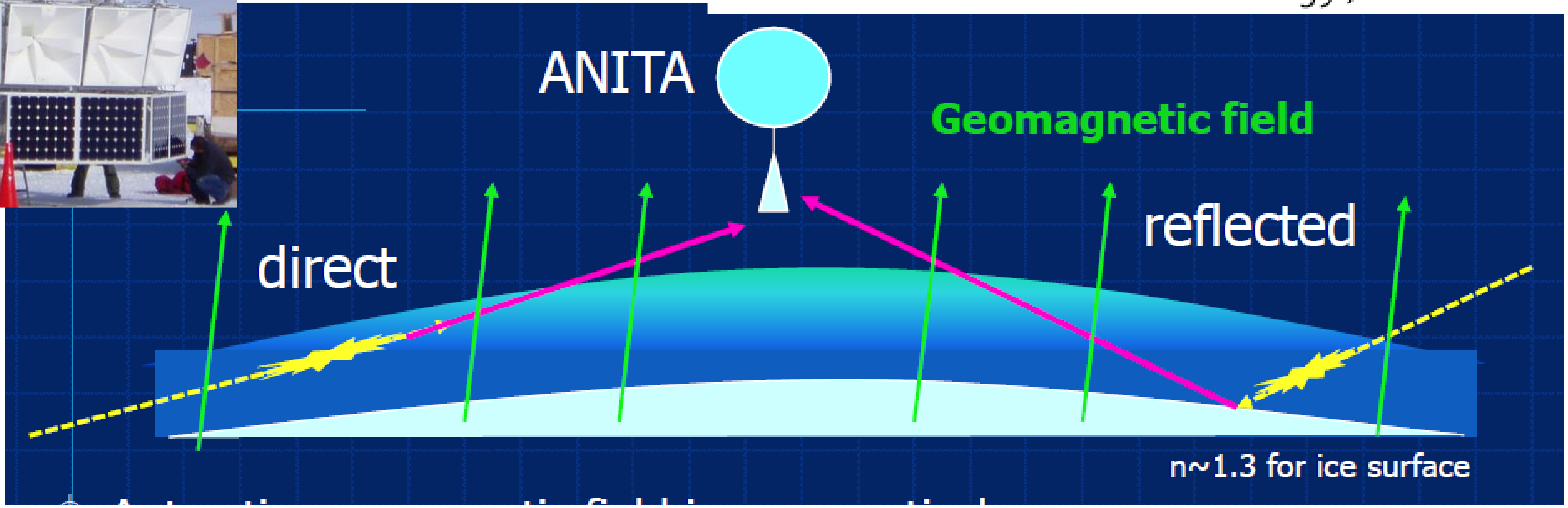
# Cosmic-Ray detection by ANITA




**P. Gorham, et al.**
**(ANITA Coll.)**





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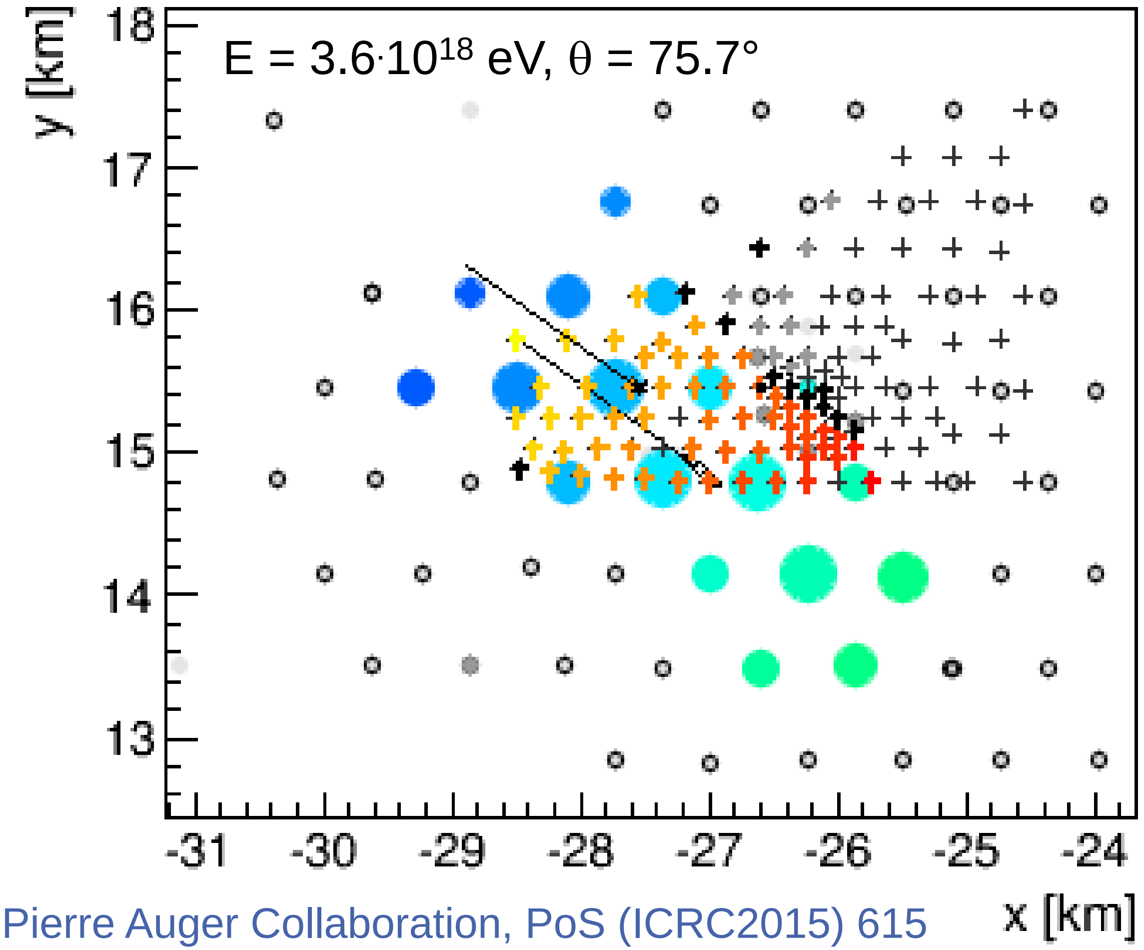
# Huge footprint for inclined showers

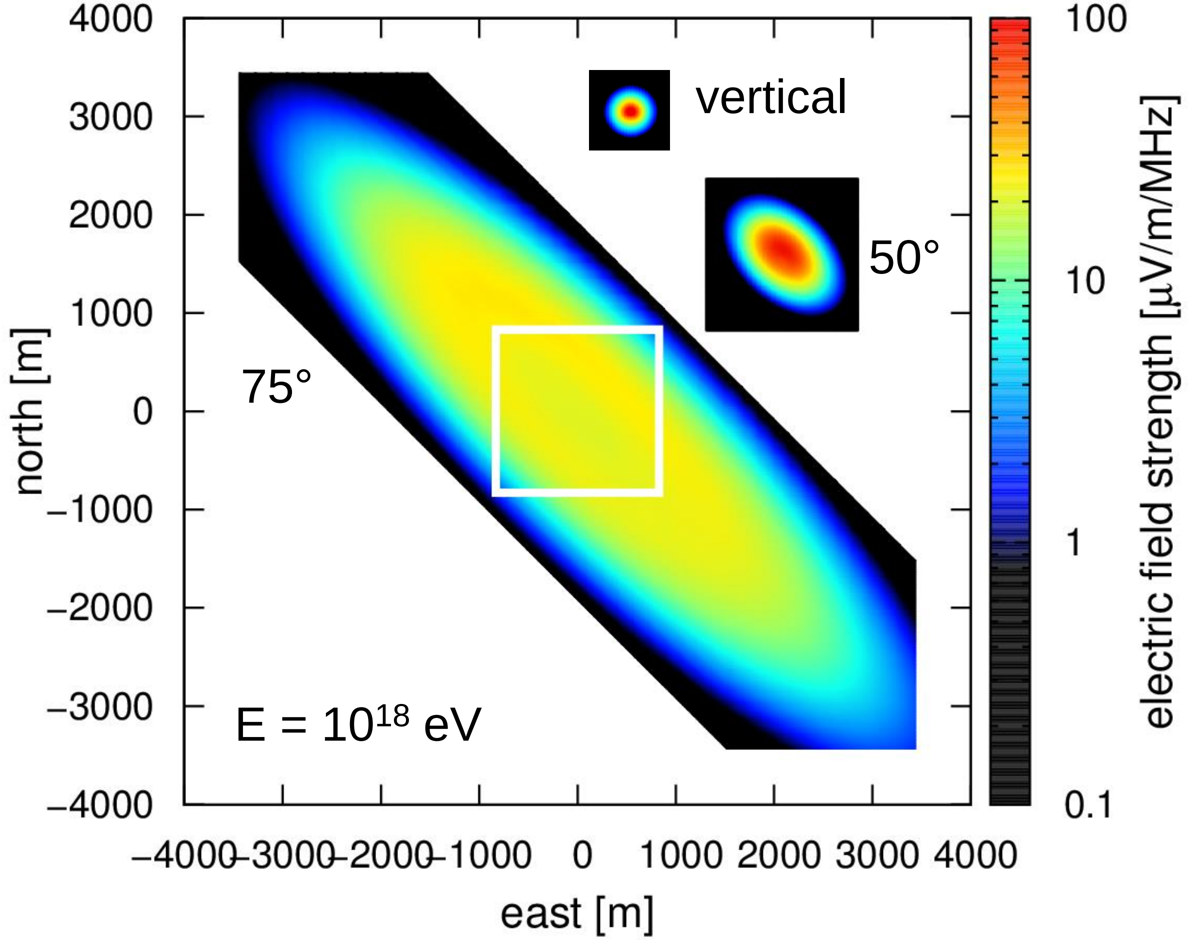
- Enables large-scale, sparse antenna arrays for reasonable costs

**Auger measurement**




Pierre Auger Collaboration, PoS (ICRC2015) 615

**CoREAS simulation**



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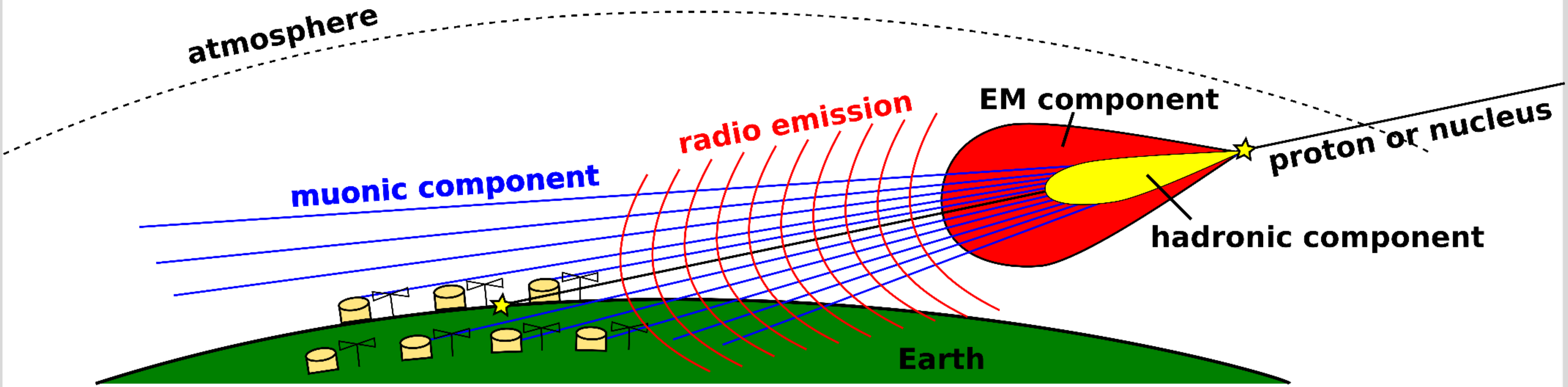
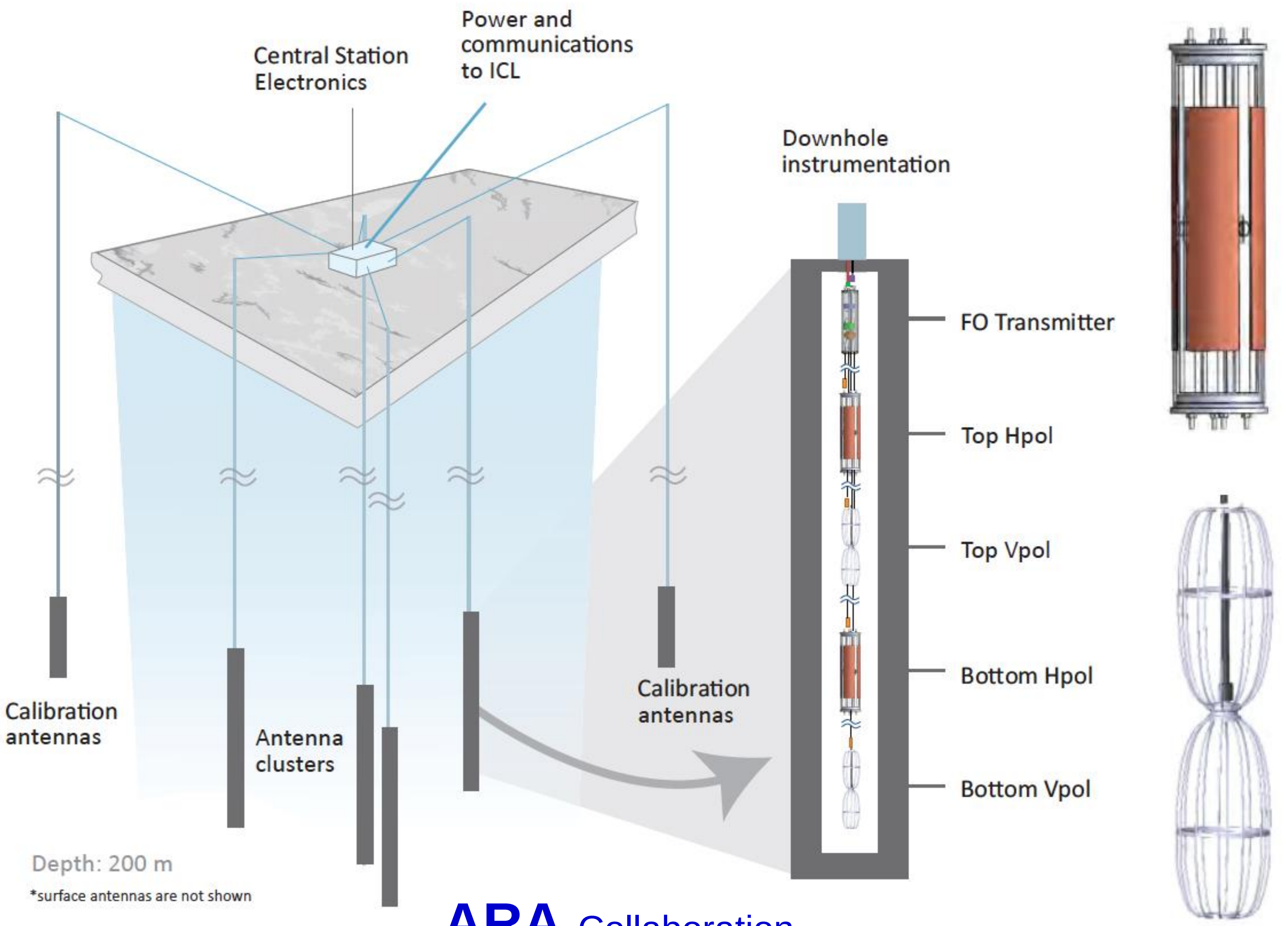
# Composition sensitivity for inclined showers

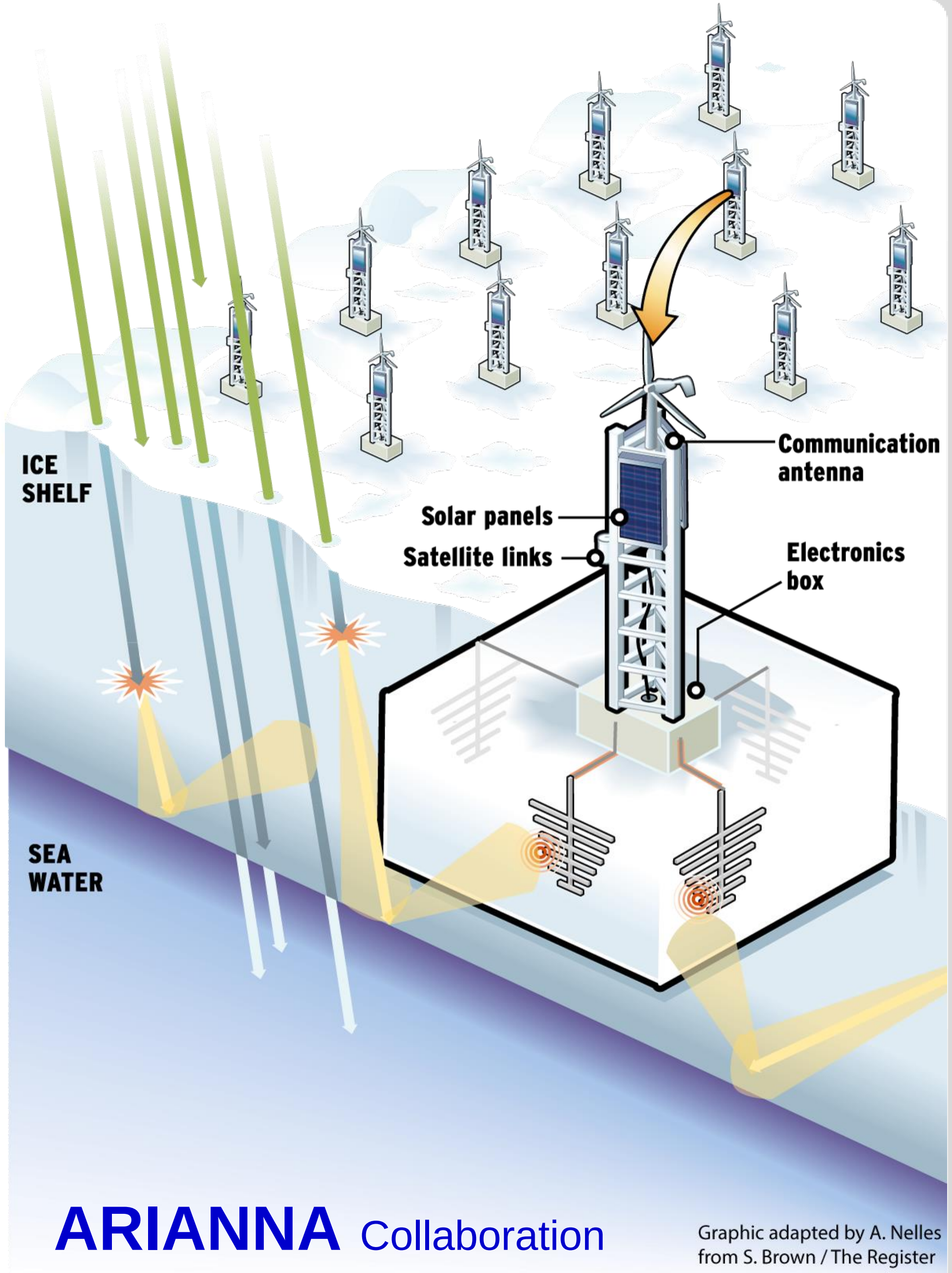



- Only radio emission + muons survive for inclined showers
  - Complementary information on shower → primary particle type

# Neutrino-induced showers in ice




**ARA** Collaboration




**ARIANNA** Collaboration

Graphic adapted by A. Nelles from S. Brown / The Register



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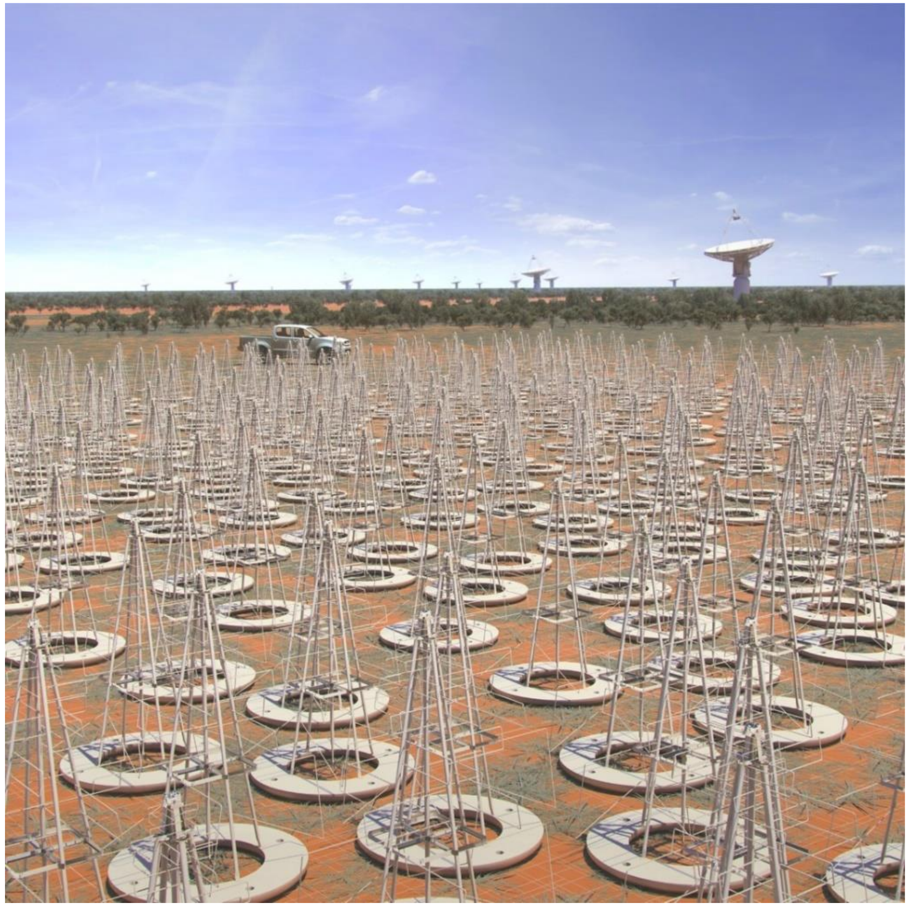
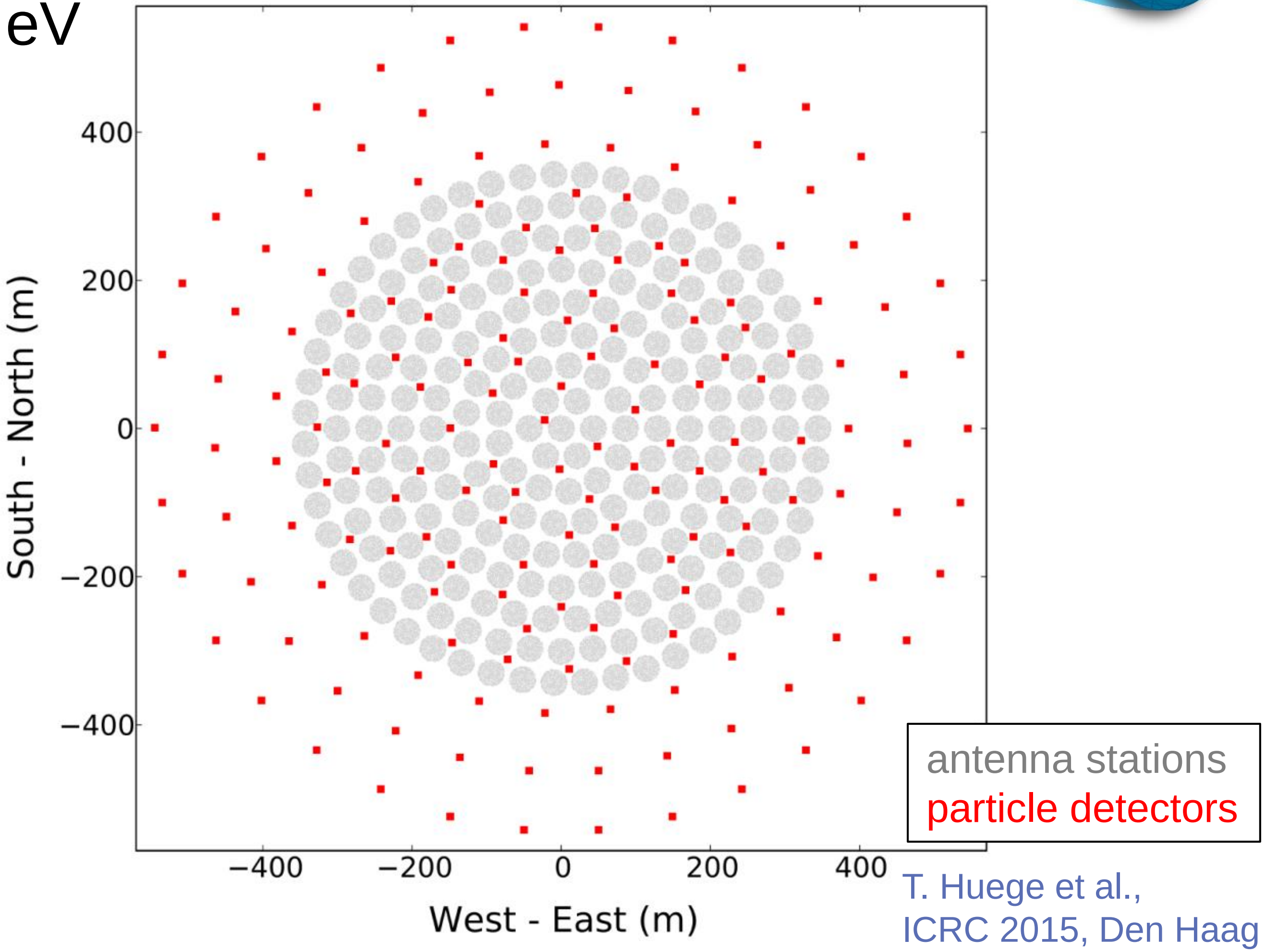
# The Square Kilometer Array: ultra high precision

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






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



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# Conclusion

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- Significant progress in last years
  - radio is on the way to a standard technique
  - 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 ideal for particle-detector arrays at E >$10^{17}$ eV
  - enhancement of accuracy for energy + composition

more in arXiv: 1607.08781


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# Backup


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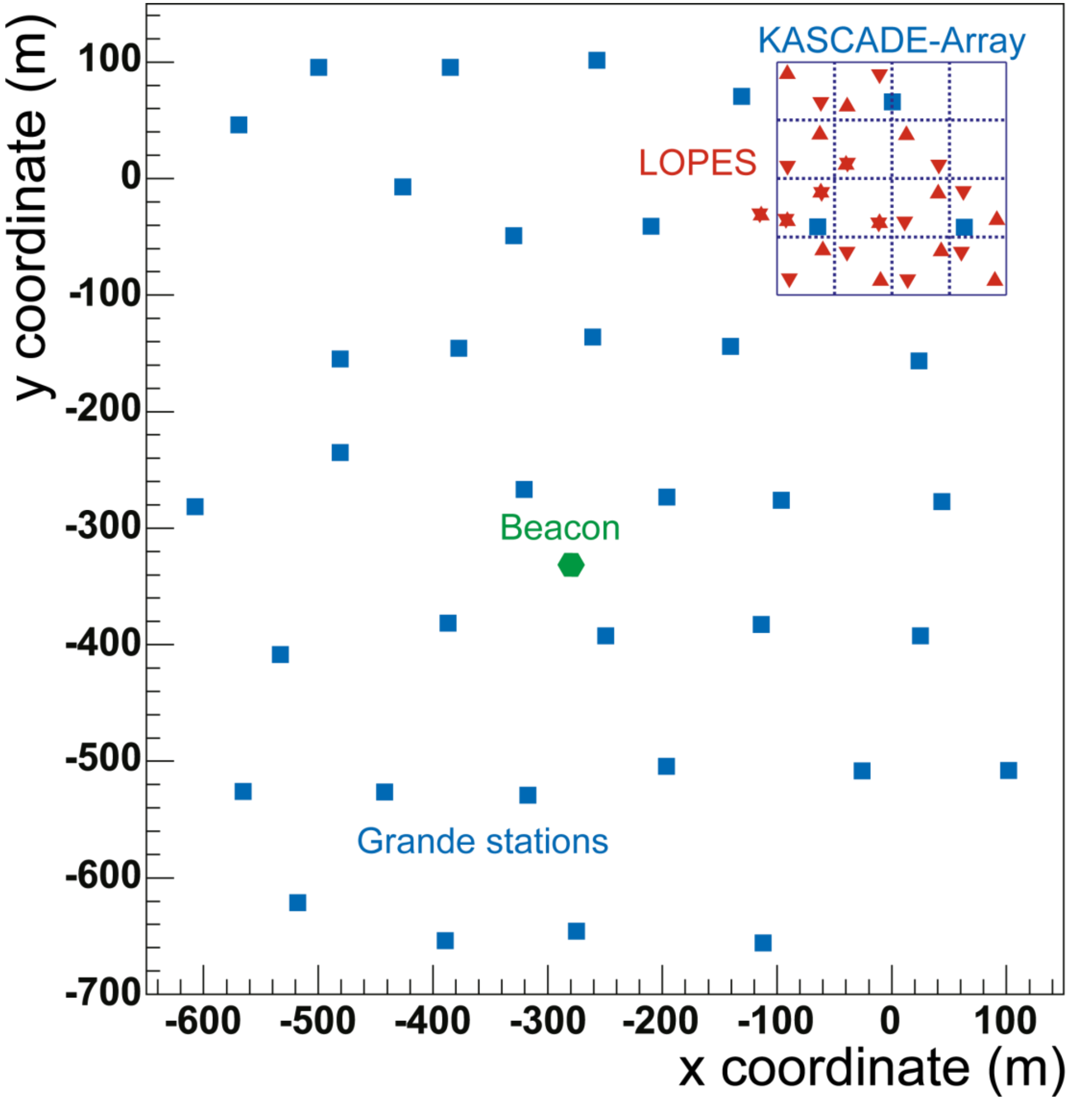
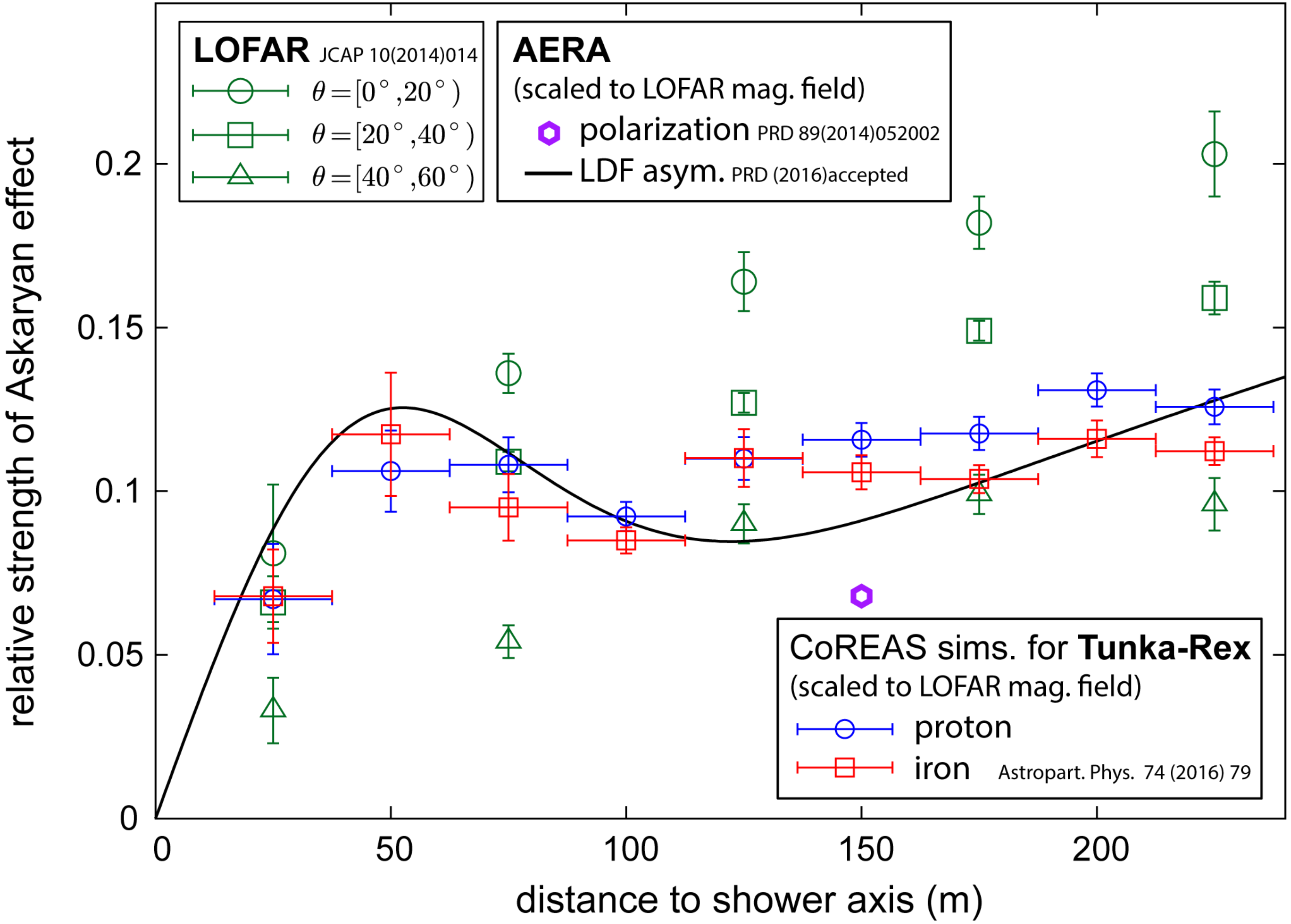
# LOPES setup (map of 2009)




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

# Relative strength of Askaryan effect



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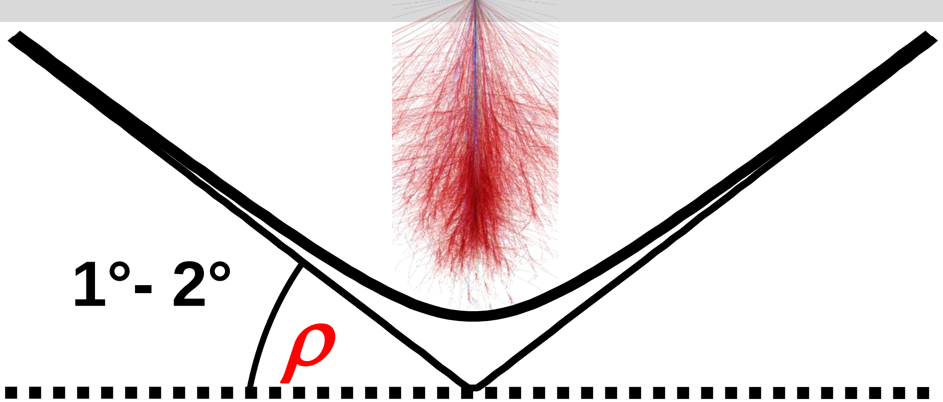
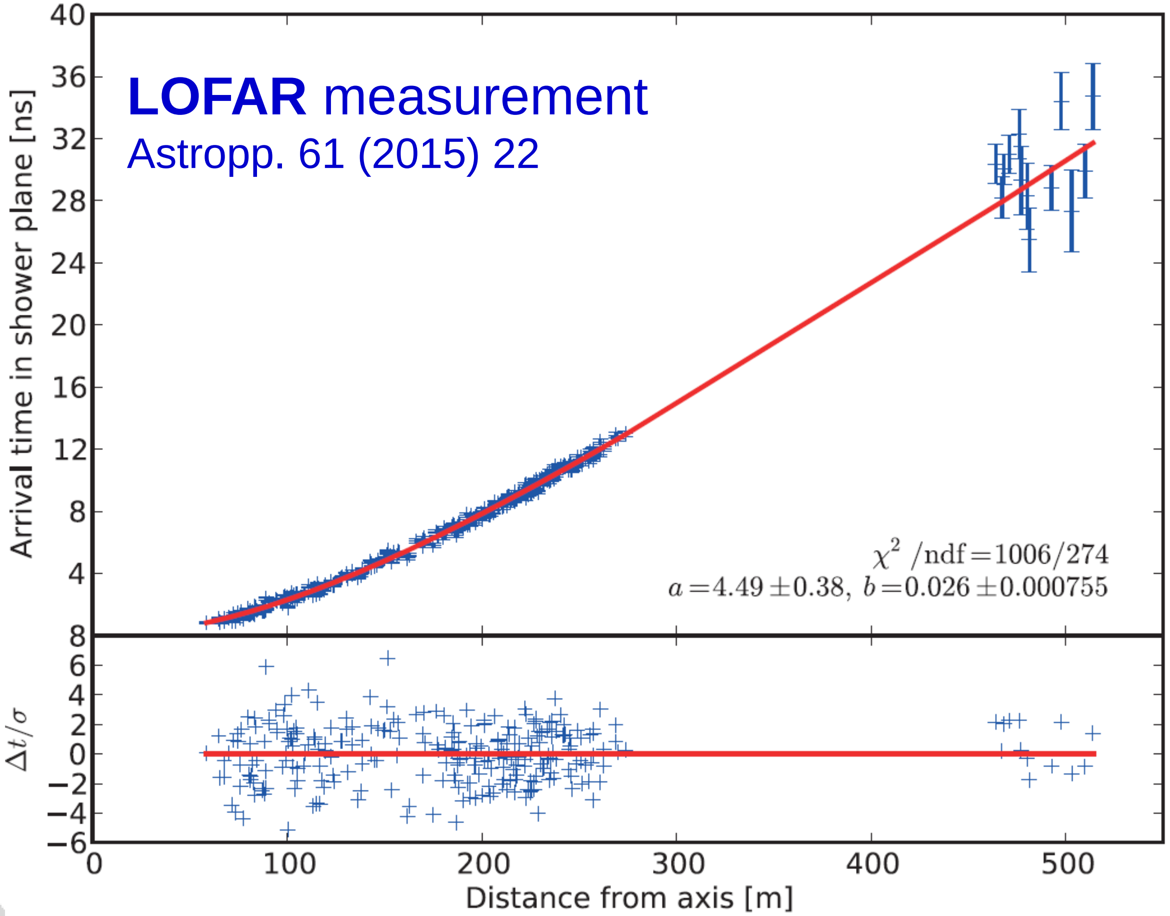
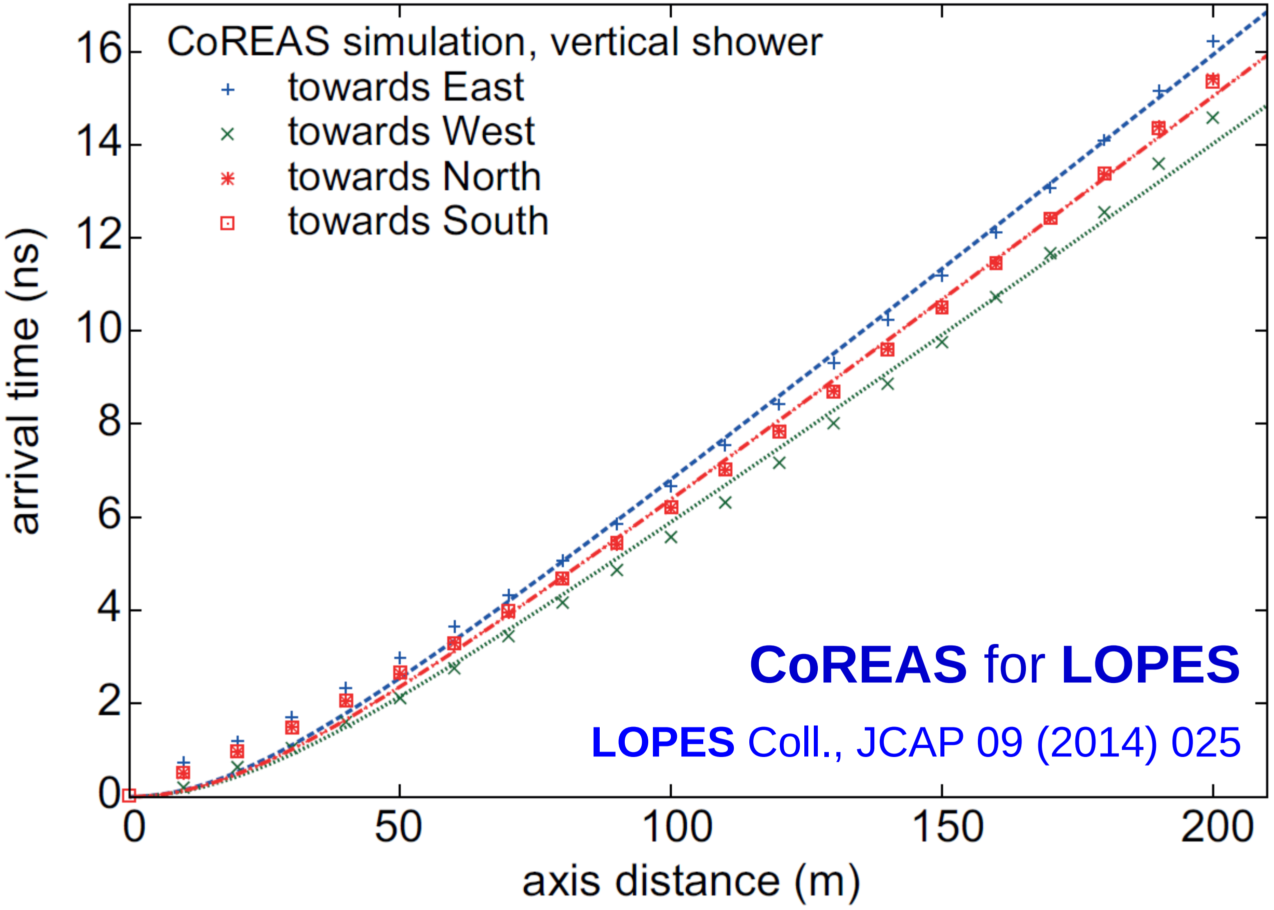
# Hyperbolic radio wavefront

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



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