

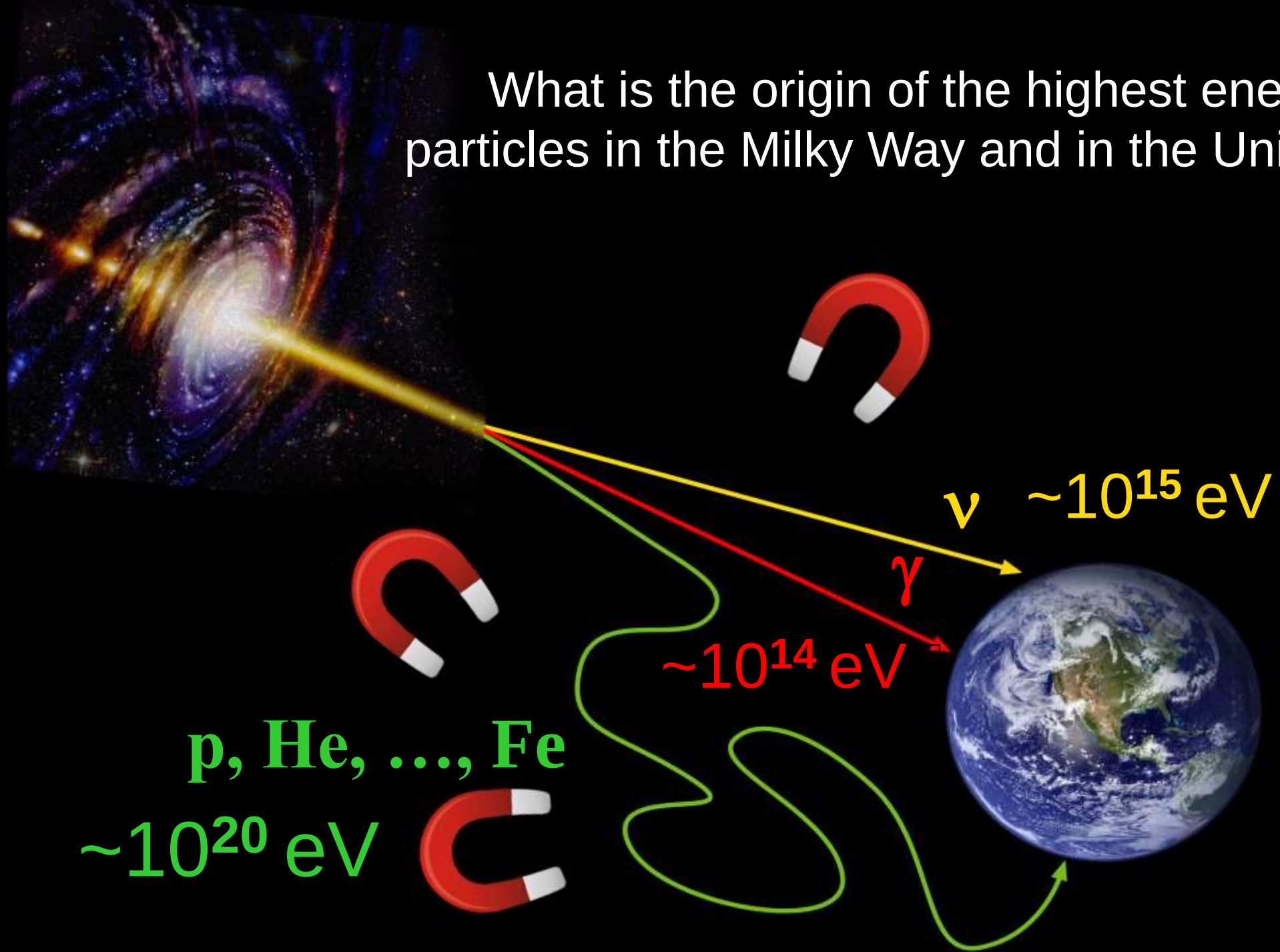
Radio Detection of High-Energy Cosmic Rays and Neutrinos

Frank G. Schröder

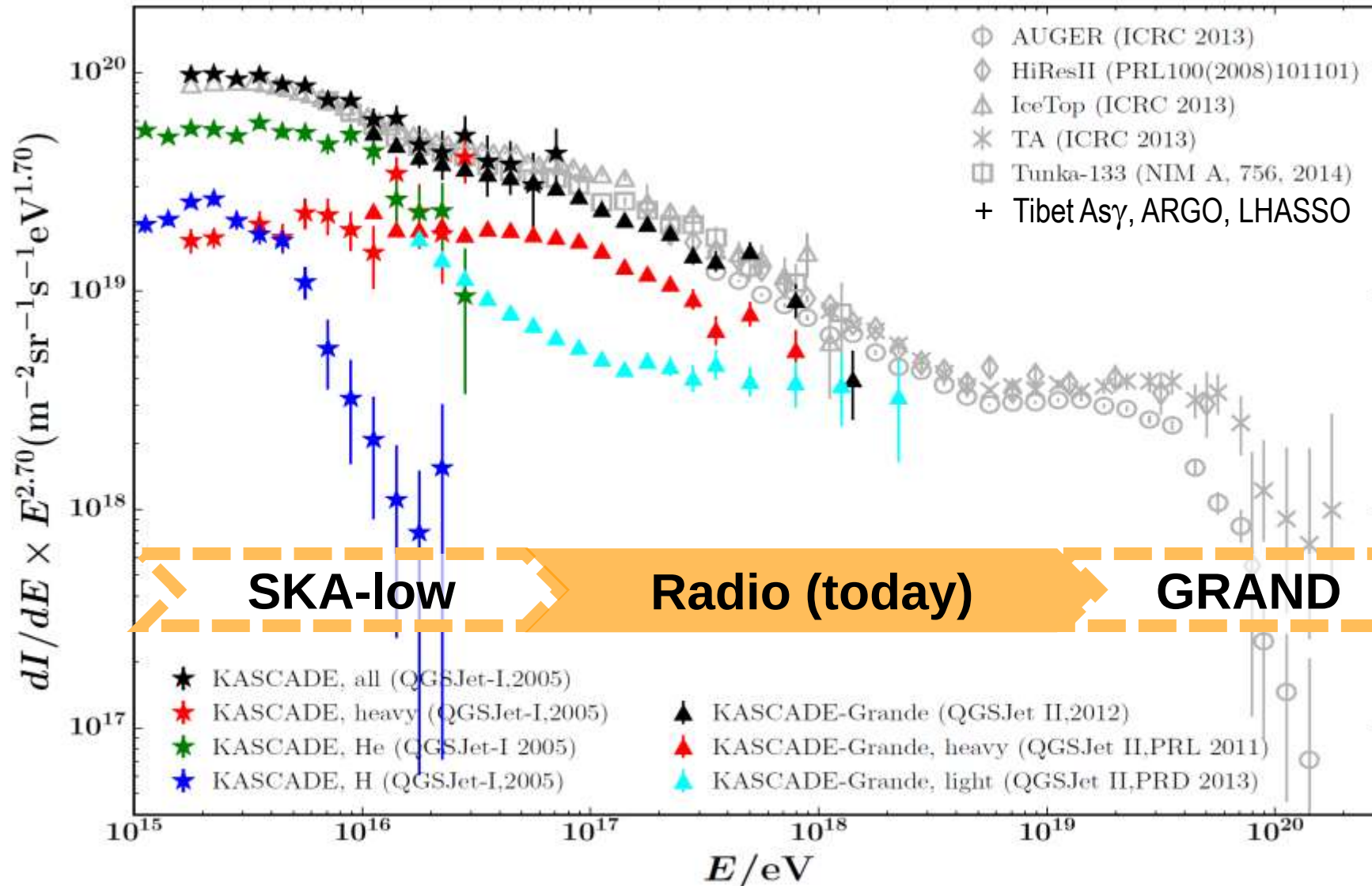
Karlsruhe Institute of Technology (KIT), Institut für Kernphysik, Karlsruhe, Germany



What is the origin of the highest energy particles in the Milky Way and in the Universe?



KASCADE-Grande: New component at 10^{17} eV



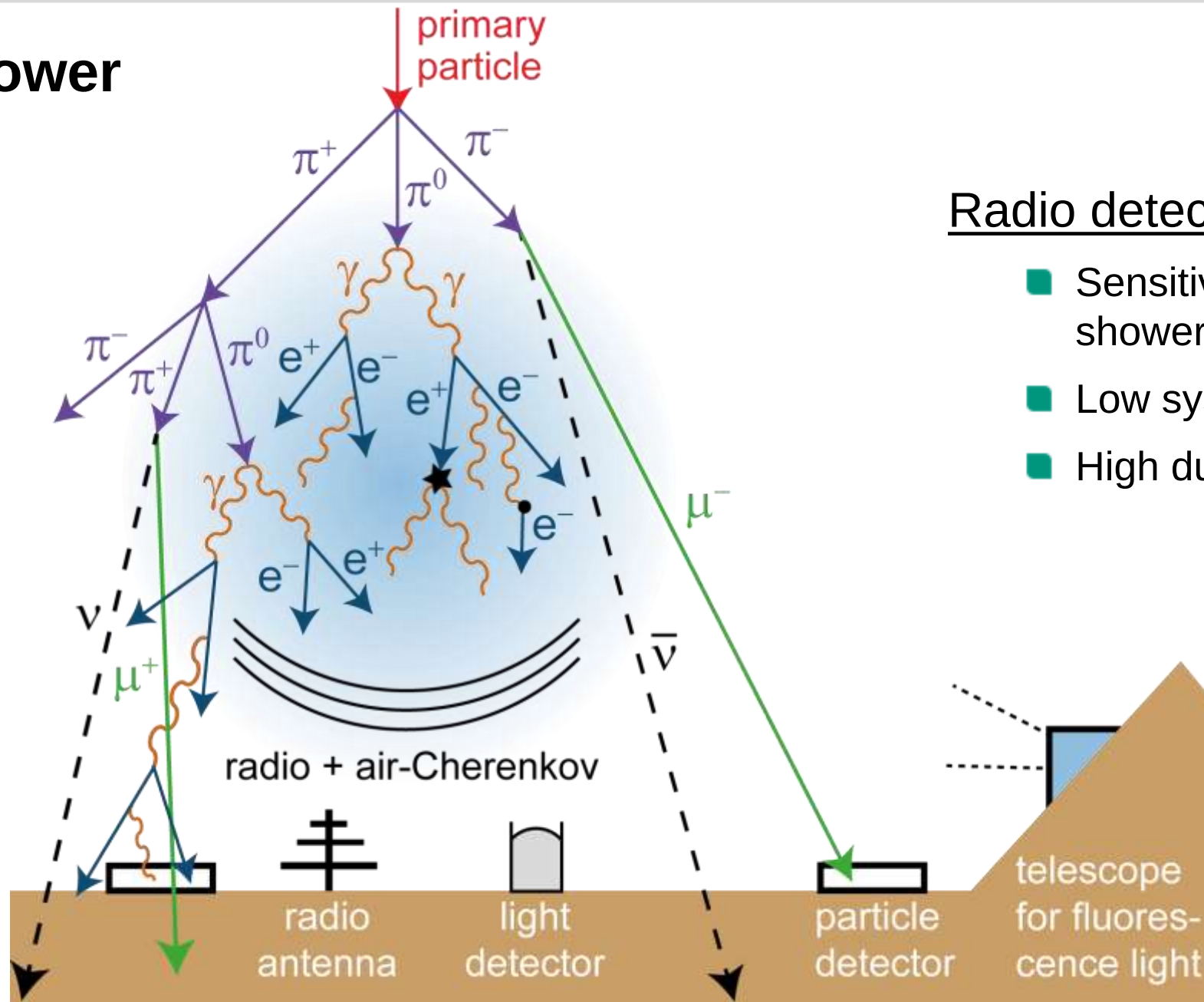
■ Light and heavy knees consistent with scaling by Z

■ Most energetic Galactic CR around 10^{17} eV?

■ Light ankle due to extragalactic CR inflow at 10^{17} eV?

■ Need more precise measurements...

Air shower

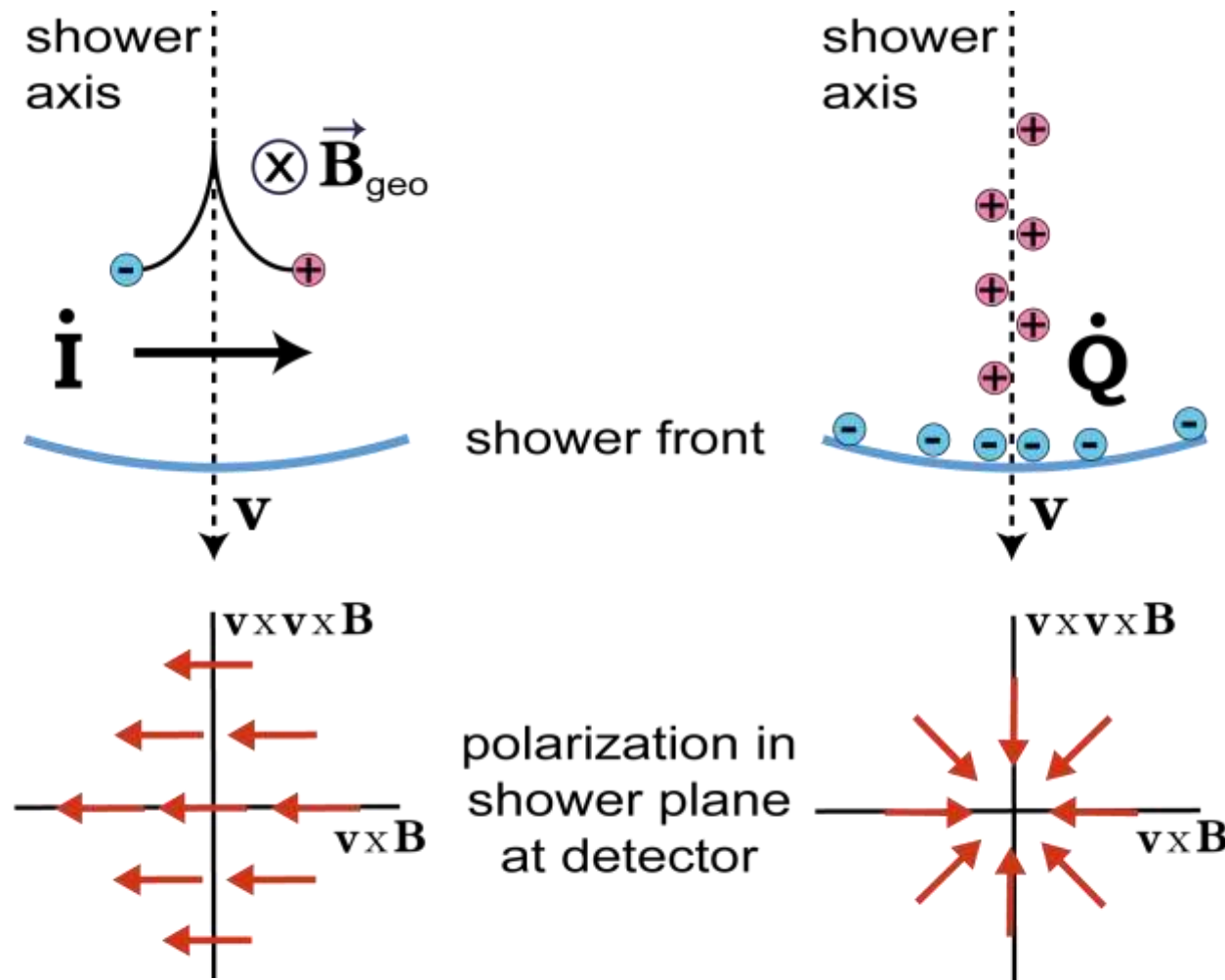


Radio detection of air showers:

- Sensitive to electromagnetic shower component
- Low systematic uncertainties
- High duty cycle

Prog. Part. Nucl. Phys.
93 (2017) 1-68
arXiv: 1607.08781

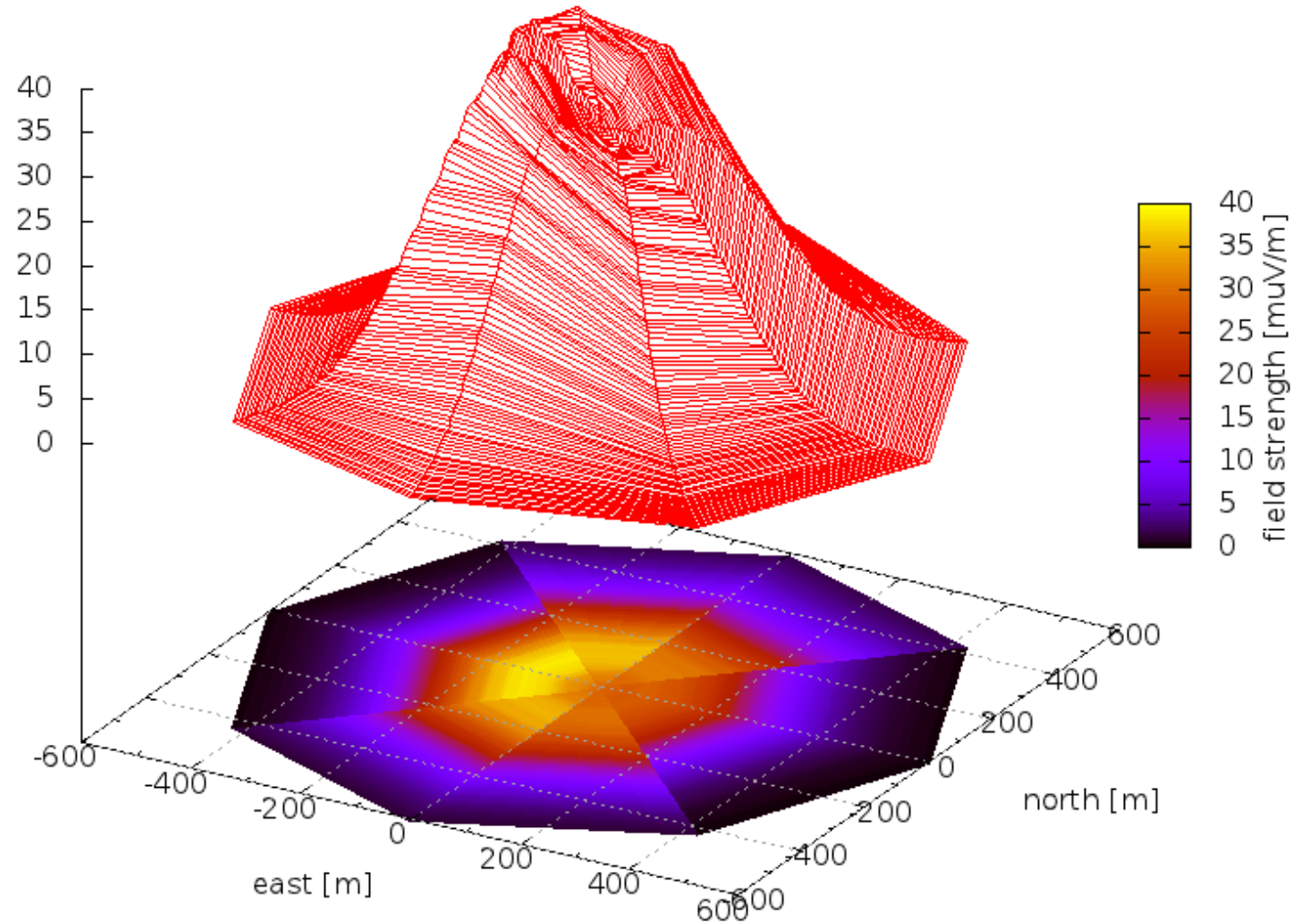
Emission mechanisms



Geomagnetic effect:
dominant in air

Askaryan effect:
dominant in ice, 10 – 20 % in air

Forward beamed, asymmetric radio emission



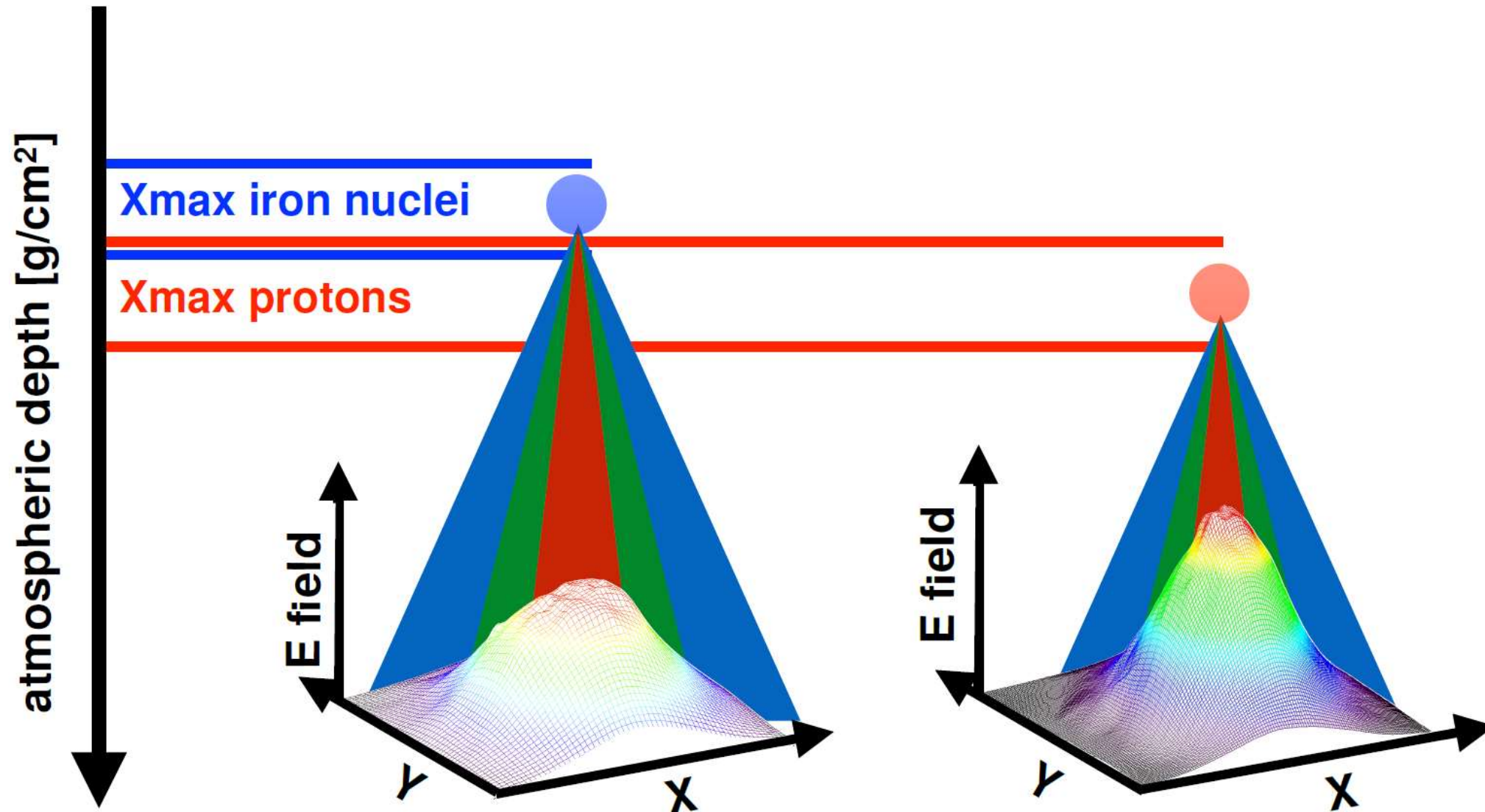
shower
inclination:
 $\theta = 45^\circ$

CoREAS simulations

By T. Huege et al., ARENA2012

43 – 74 MHz

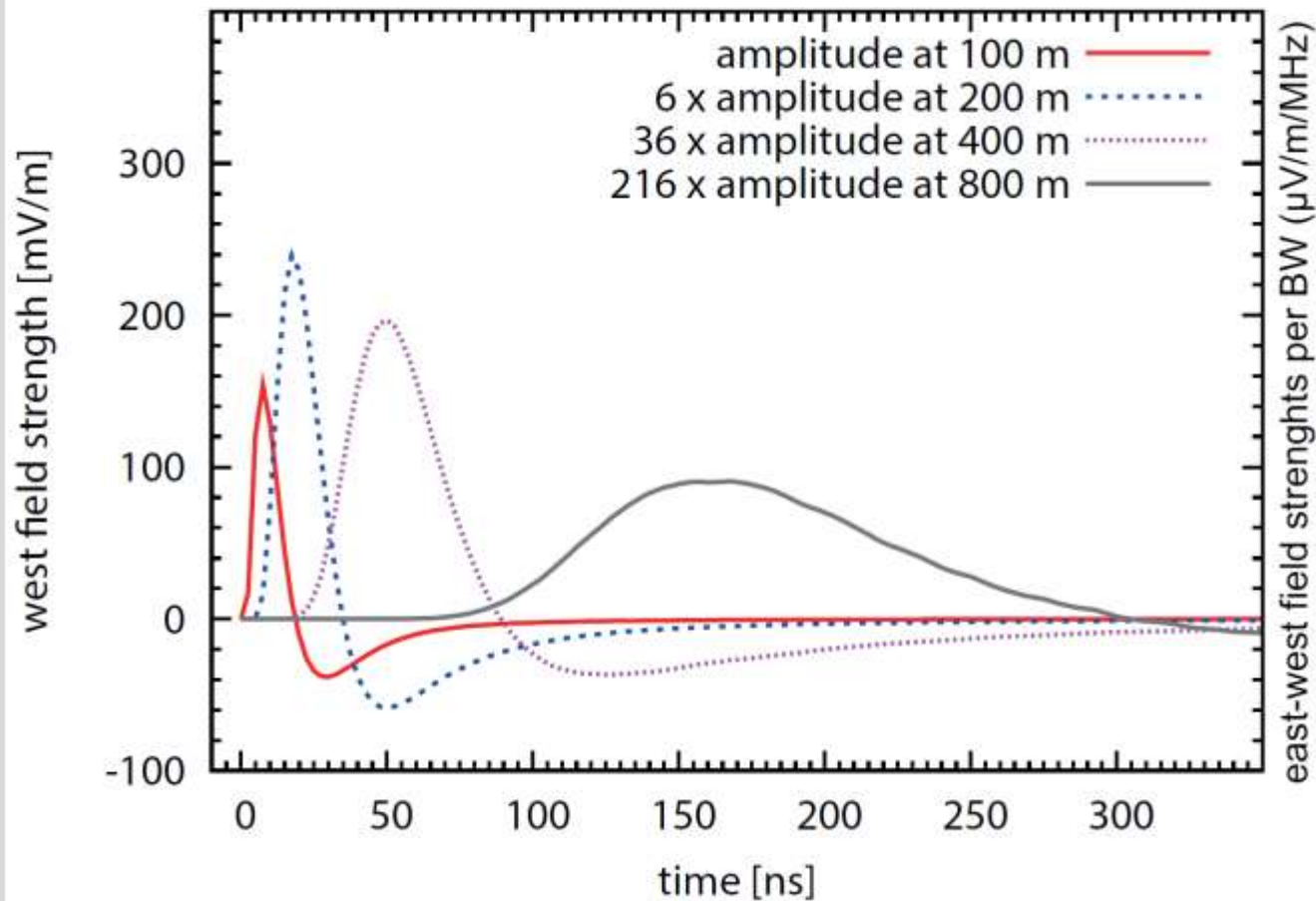
Radio emission beamed in forward cone



Auger Coll.
ICRC 2017

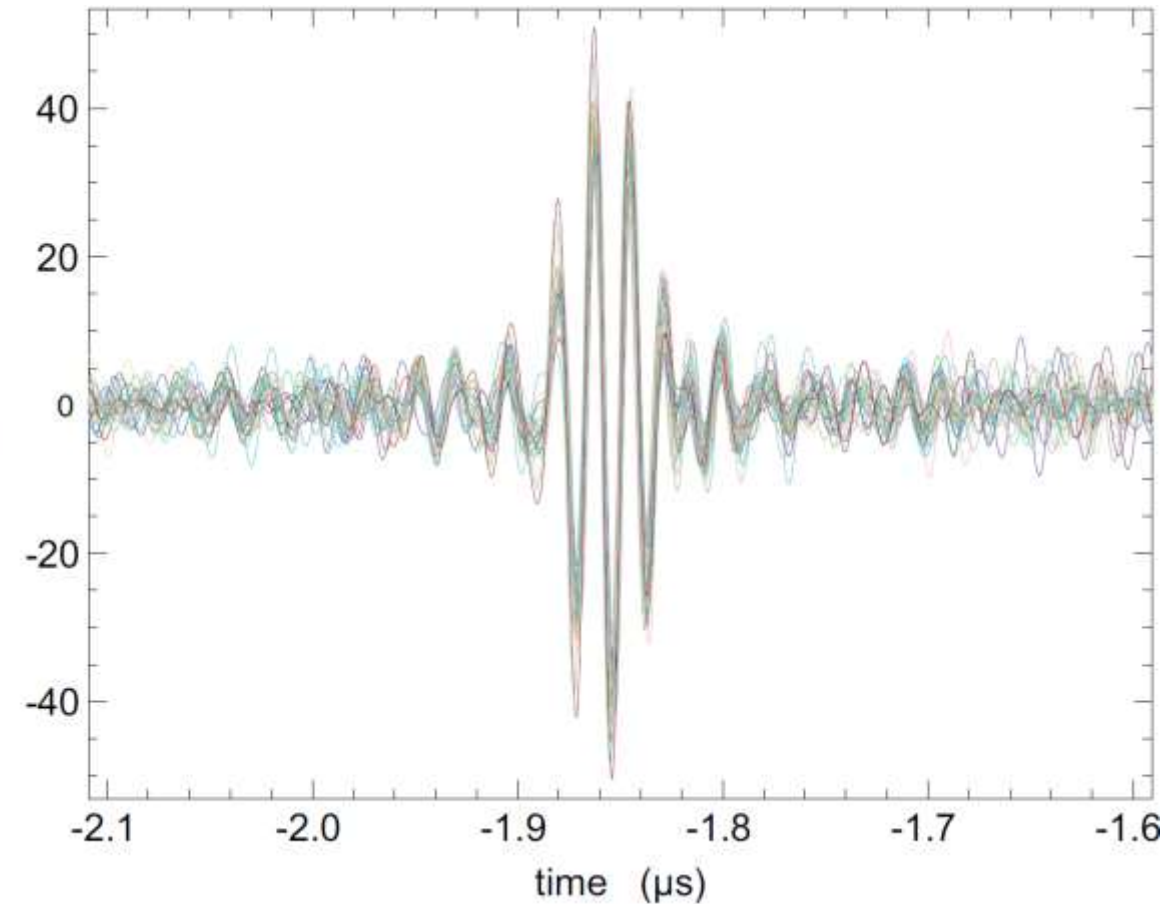
Radio pulse

CoREAS simulation, full bandwidth



T. Huege

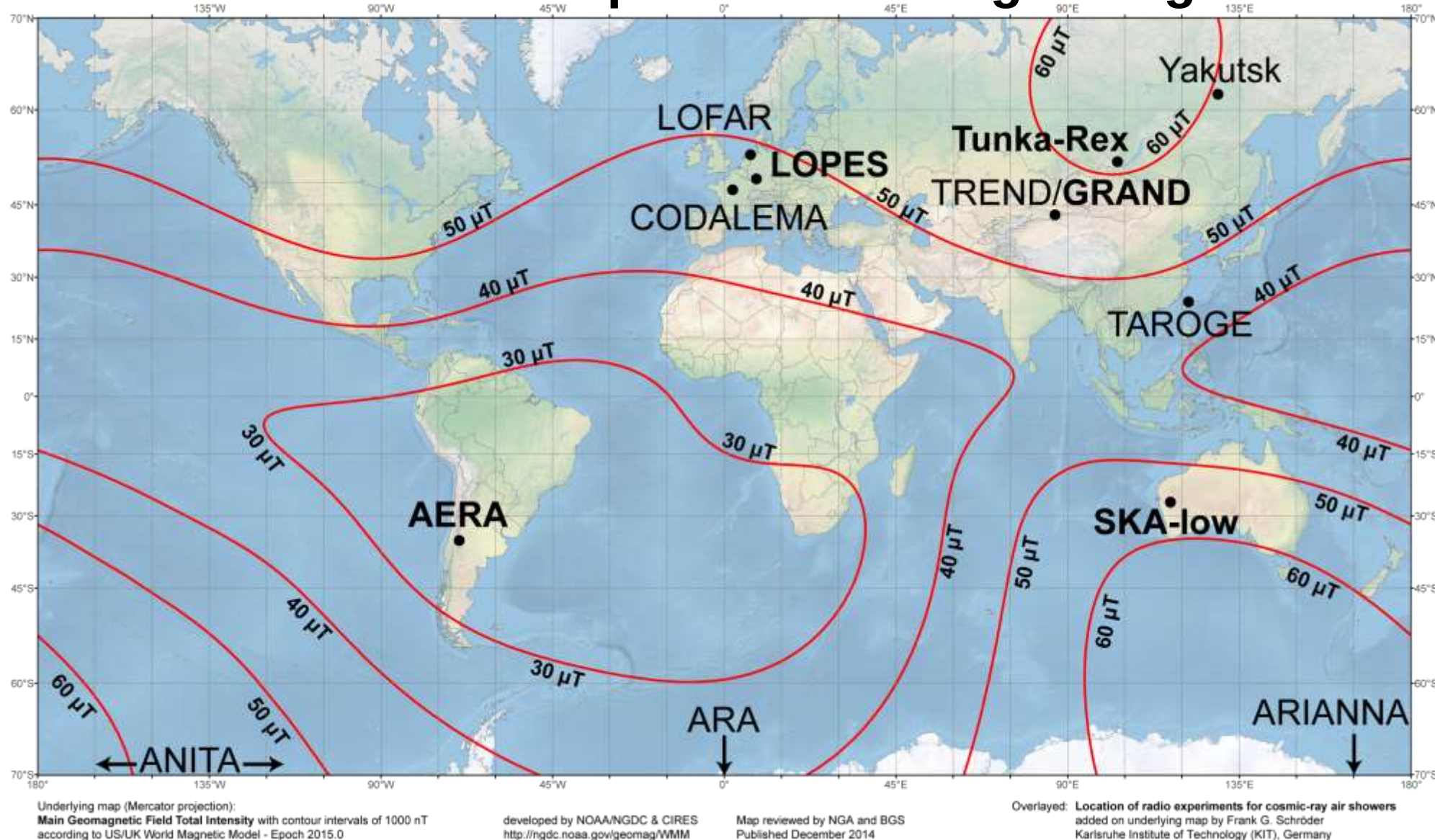
LOPES measurement, 43-74 MHz



Schröder et al., NIM A 615 (2010) 277

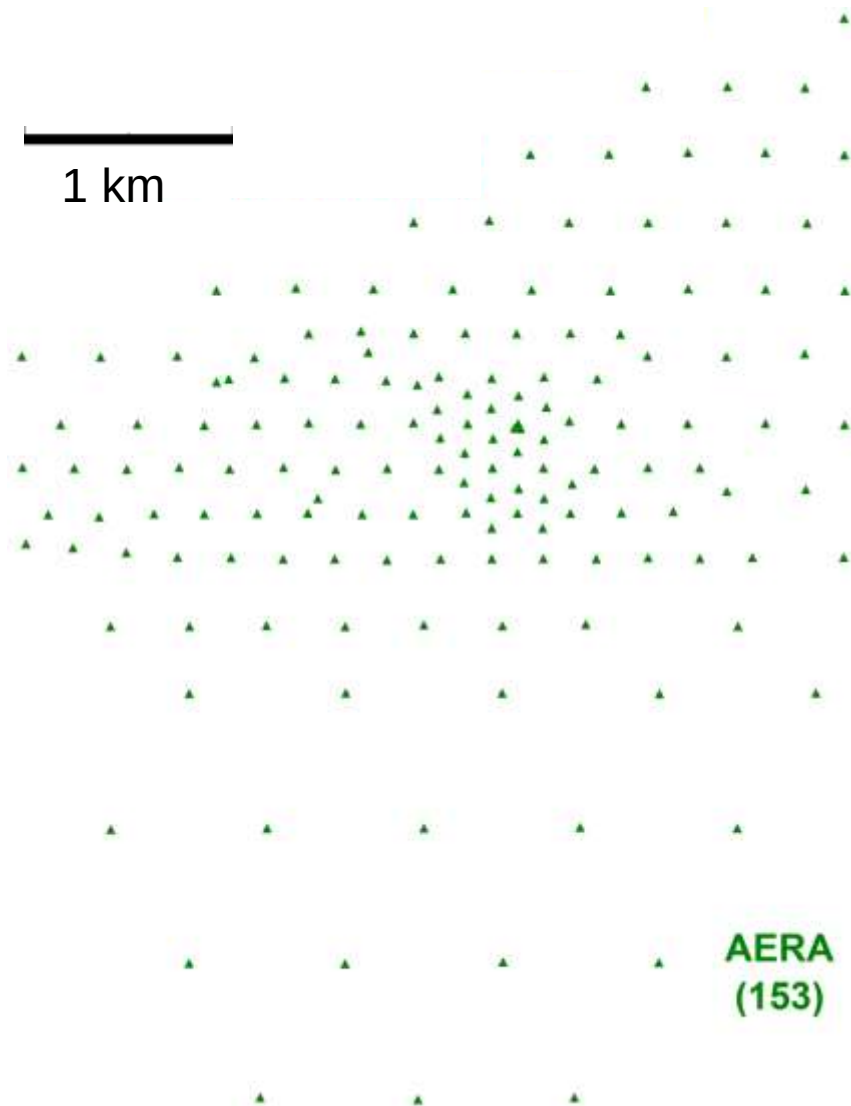
Radio Experiments

Location of selected experiments and geomagnetic field



Prog. Part. Nucl. Phys.
93 (2017) 1-68
[arXiv: 1607.08781](https://arxiv.org/abs/1607.08781)

Designs of modern radio arrays for air showers



LOFAR - LBA outers

(7 x 48)

LOPES
(30)

CODALEMA3
(57)

Tunka-Rex
(63)

Compilation by A. Zilles

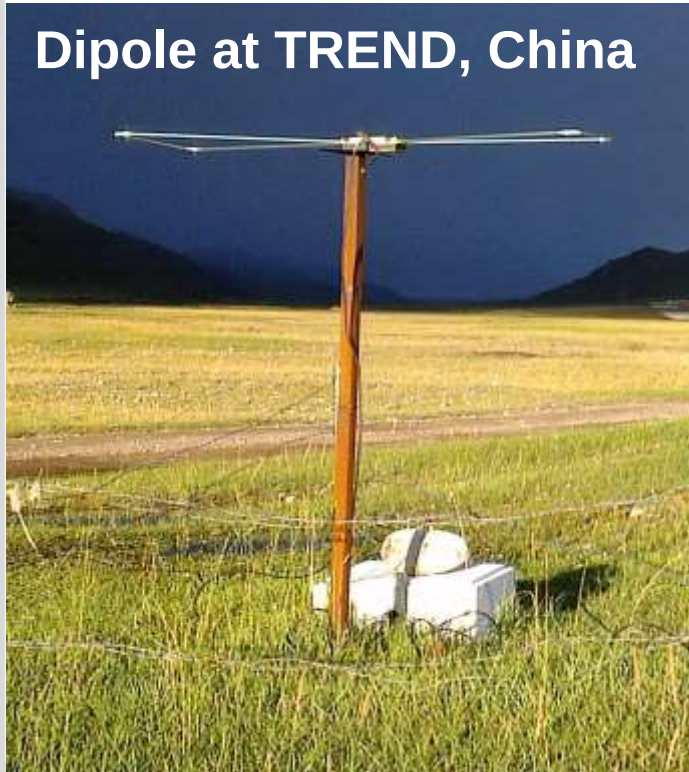
See also talks on:

- TREND
- ARIANNA
- GRAND

Detectors: antennas

- Many working solutions with only slight differences in
 - typical frequency band 30-80 MHz (higher band will lower detection threshold)
 - accuracy (systematic uncertainties, e.g., due to ground conditions)

Dipole at TREND, China



**SALLA at
Tunka-Rex**



LPDA at Auger

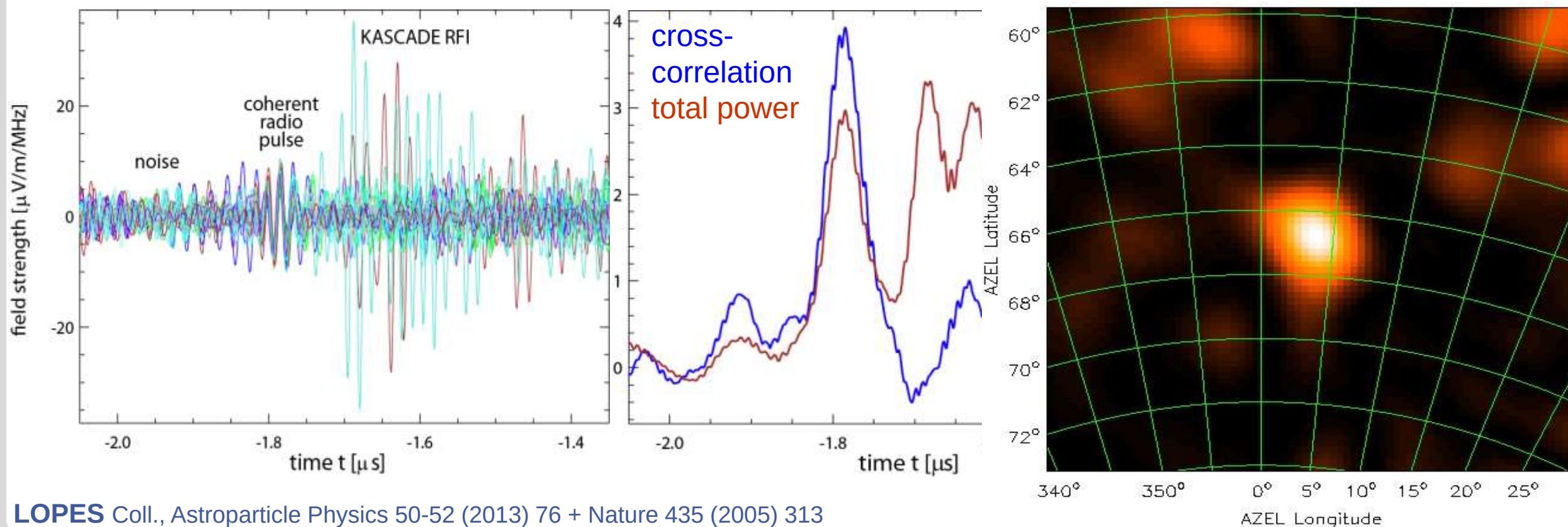


**Butterfly at
CODALEMA**



Sophisticated techniques for detection close to noise

- Accurate time calibration (1 ns) enables digital radio interferometry
- Direction precision better than 0.5° (by comparing LOPES to KASCADE)

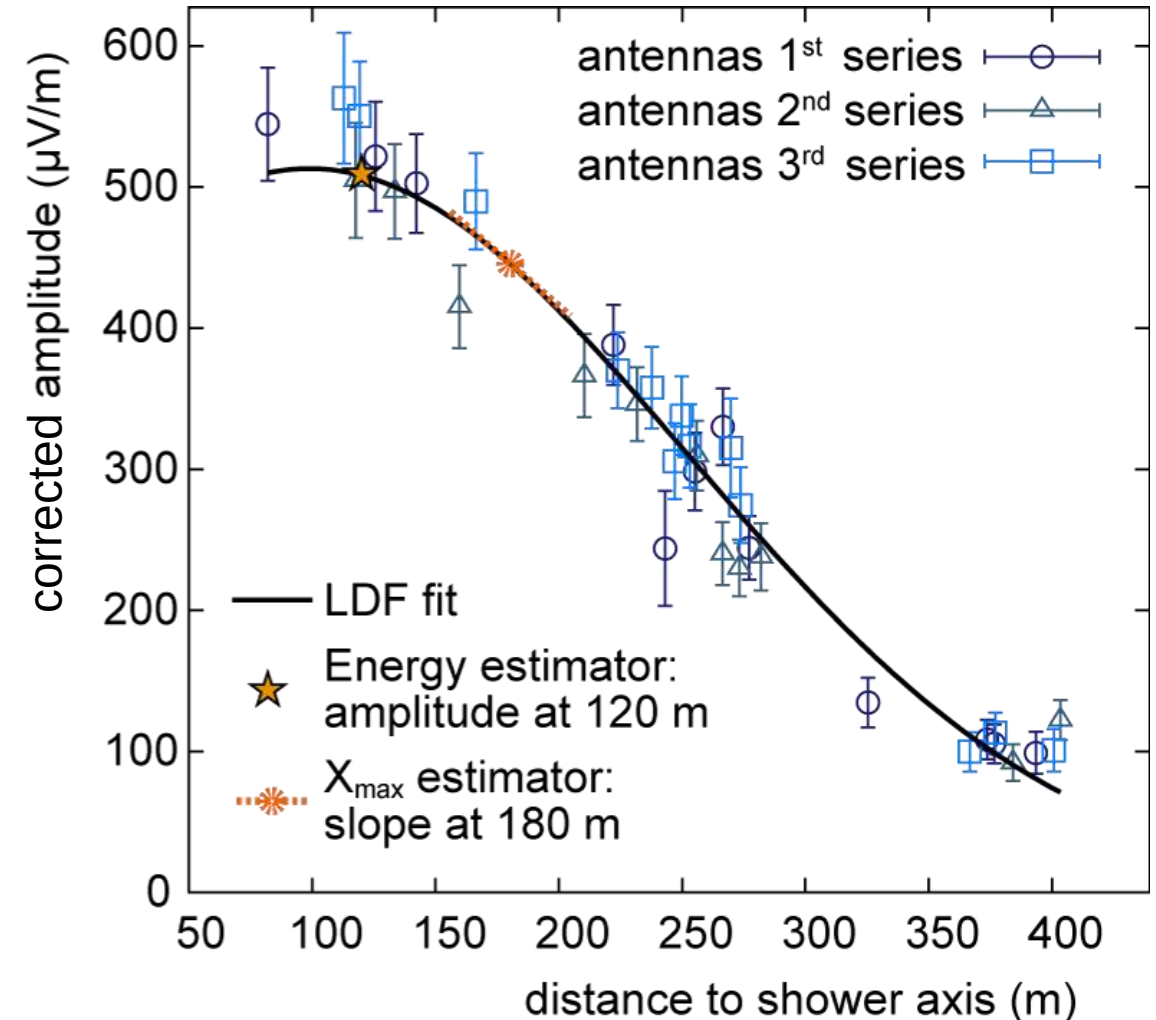
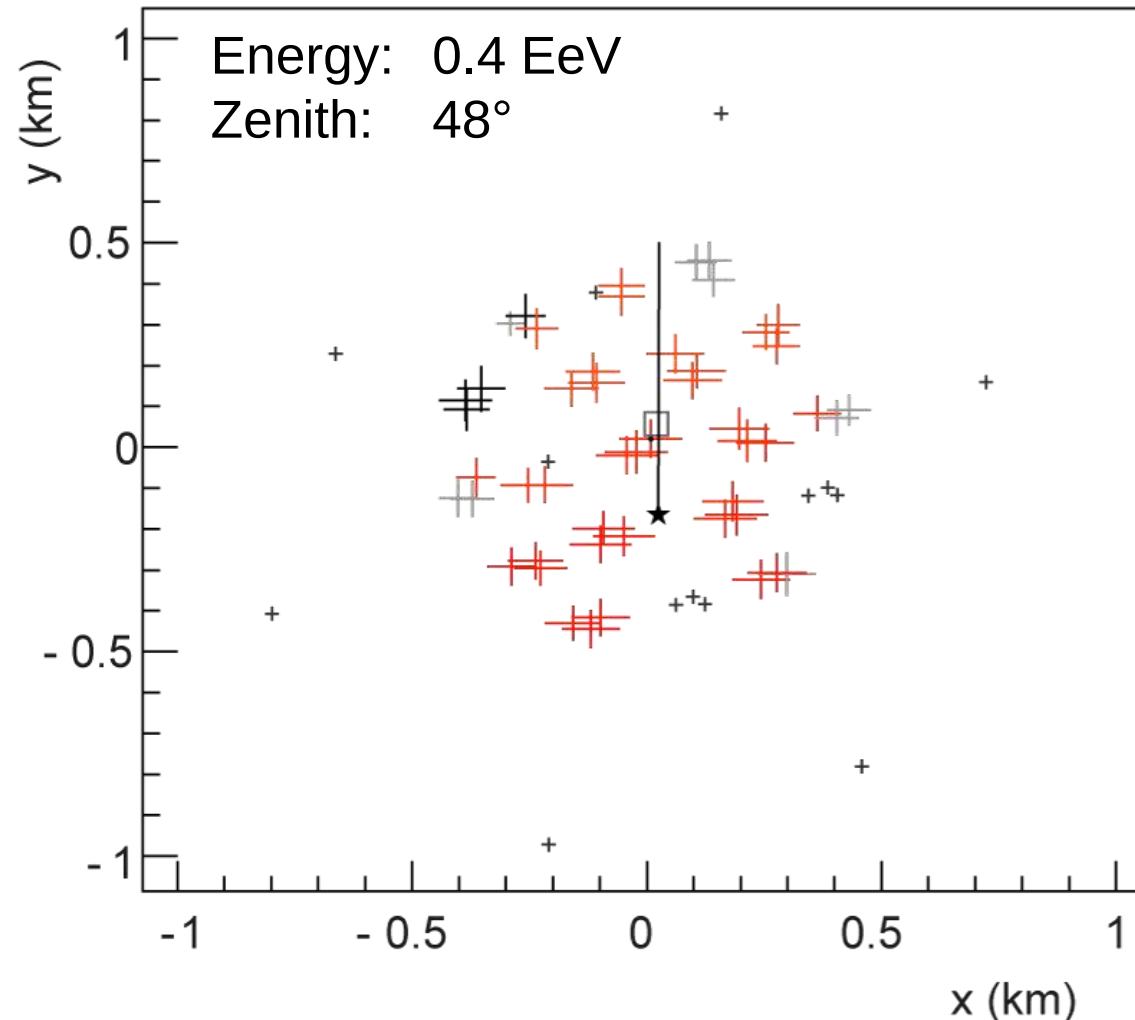


LOPES Coll., Astroparticle Physics 50-52 (2013) 76 + Nature 435 (2005) 313

Energy and $X_{\max}$ reconstruction with Tunka-Rex

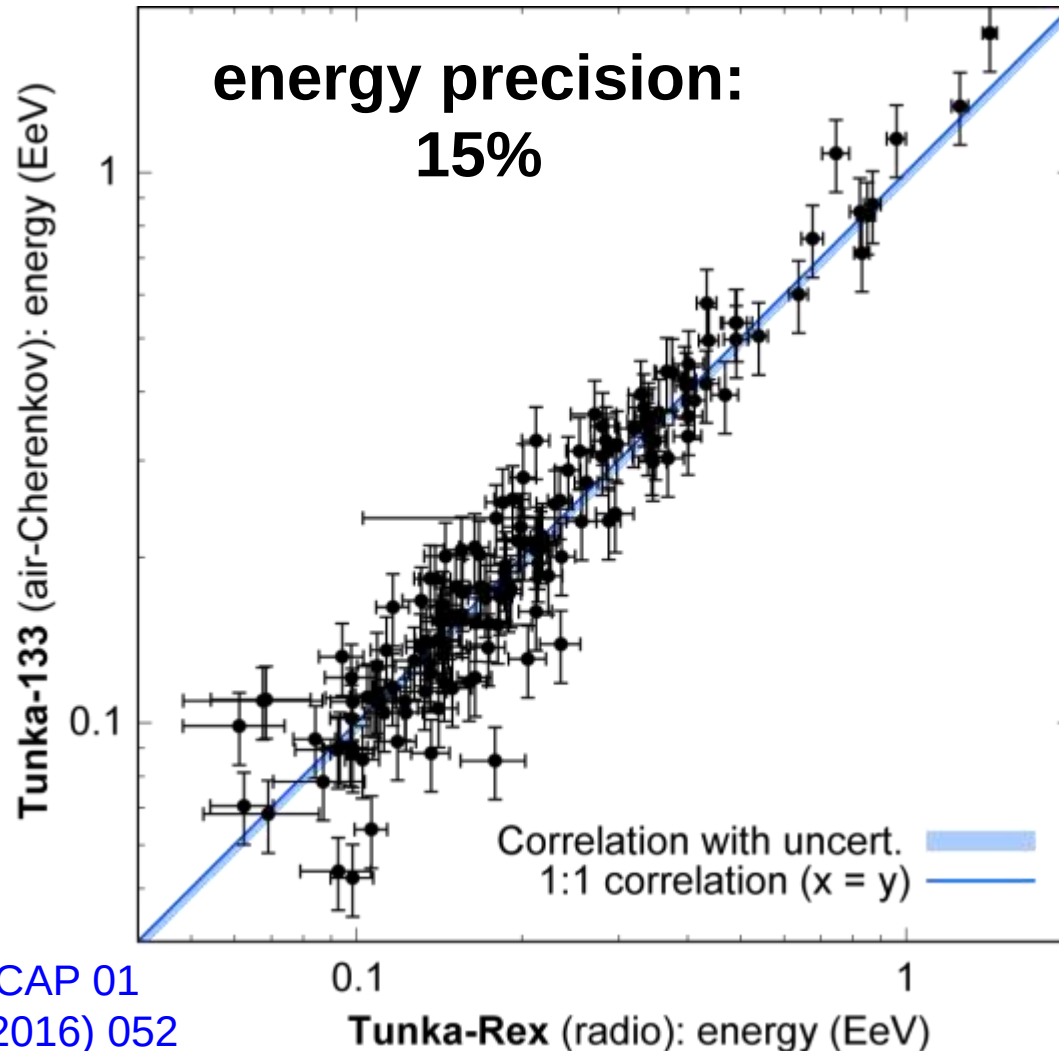


■ Reconstruction of energy and $X_{\max}$ tuned against CoREAS

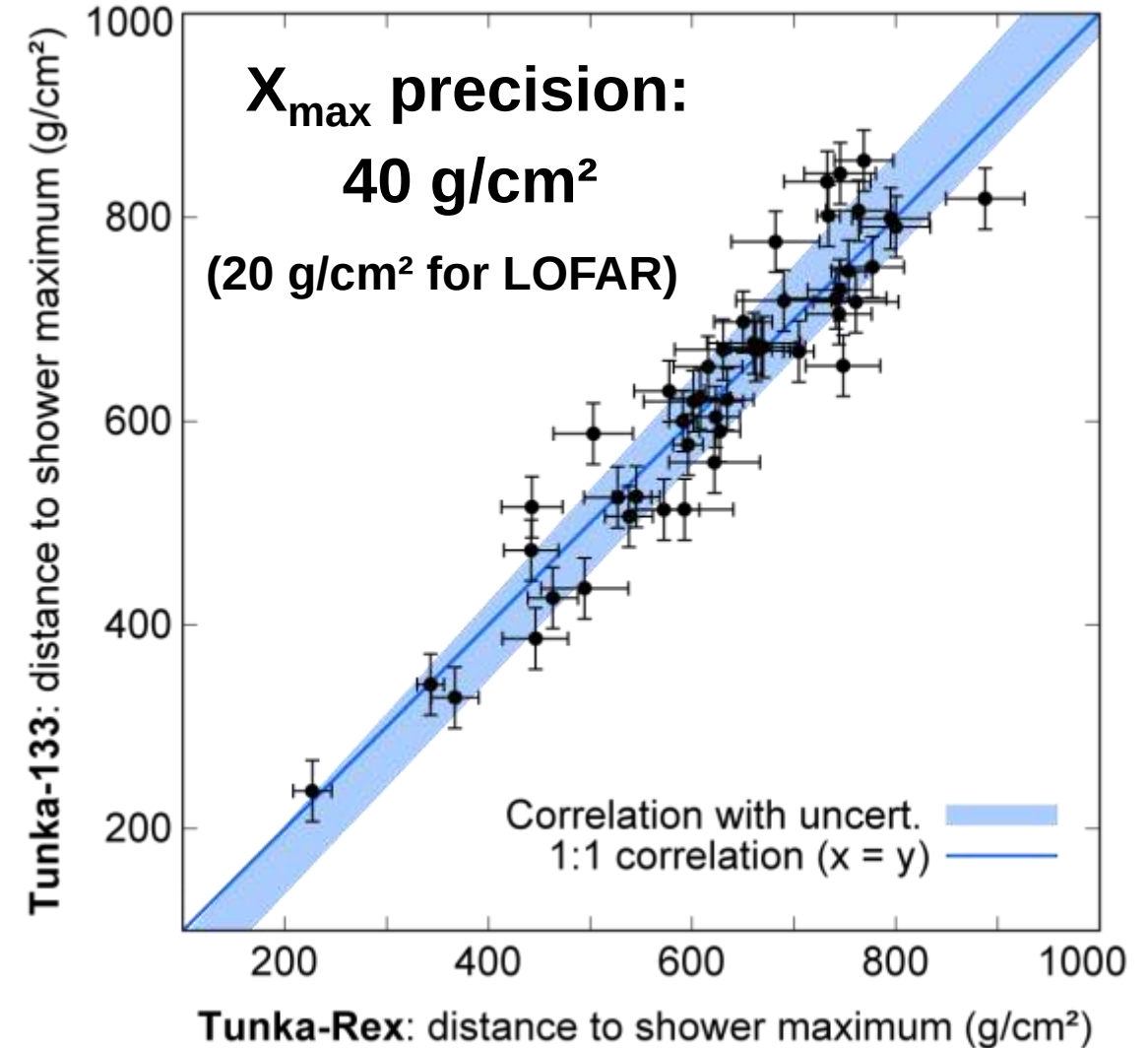


Correlation of Radio and Cherenkov-light measurements

- Direct experimental proof; confirmed also by AERA at Auger



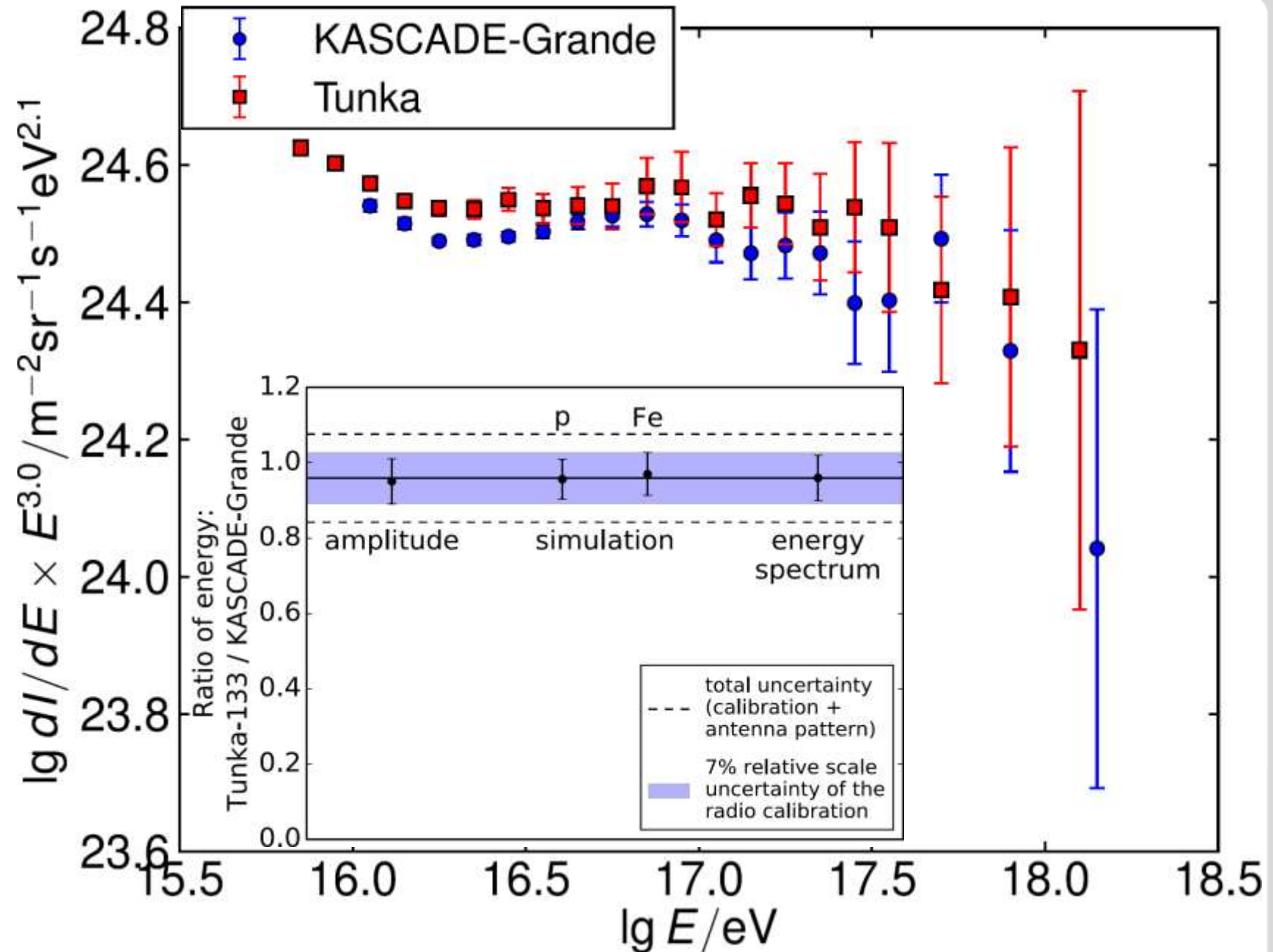
JCAP 01
(2016) 052



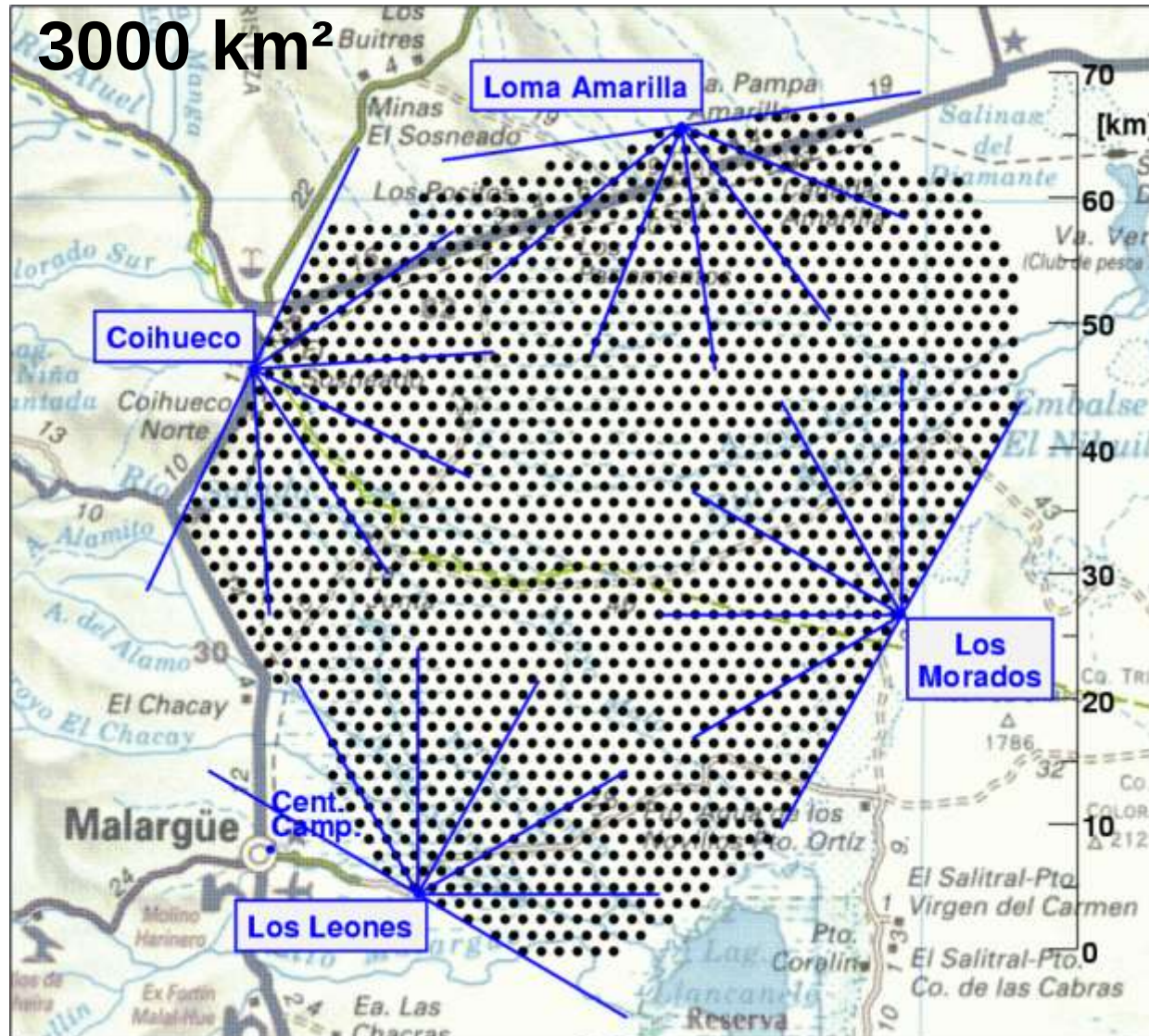
Comparing energy scales of KASCADE-Grande and Tunka-133 via their radio arrays

- Calibration by same external reference
- Energy scales of both experiments agree within 10%

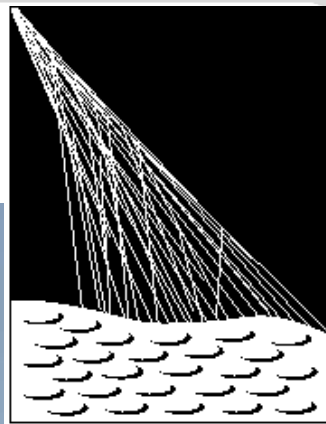
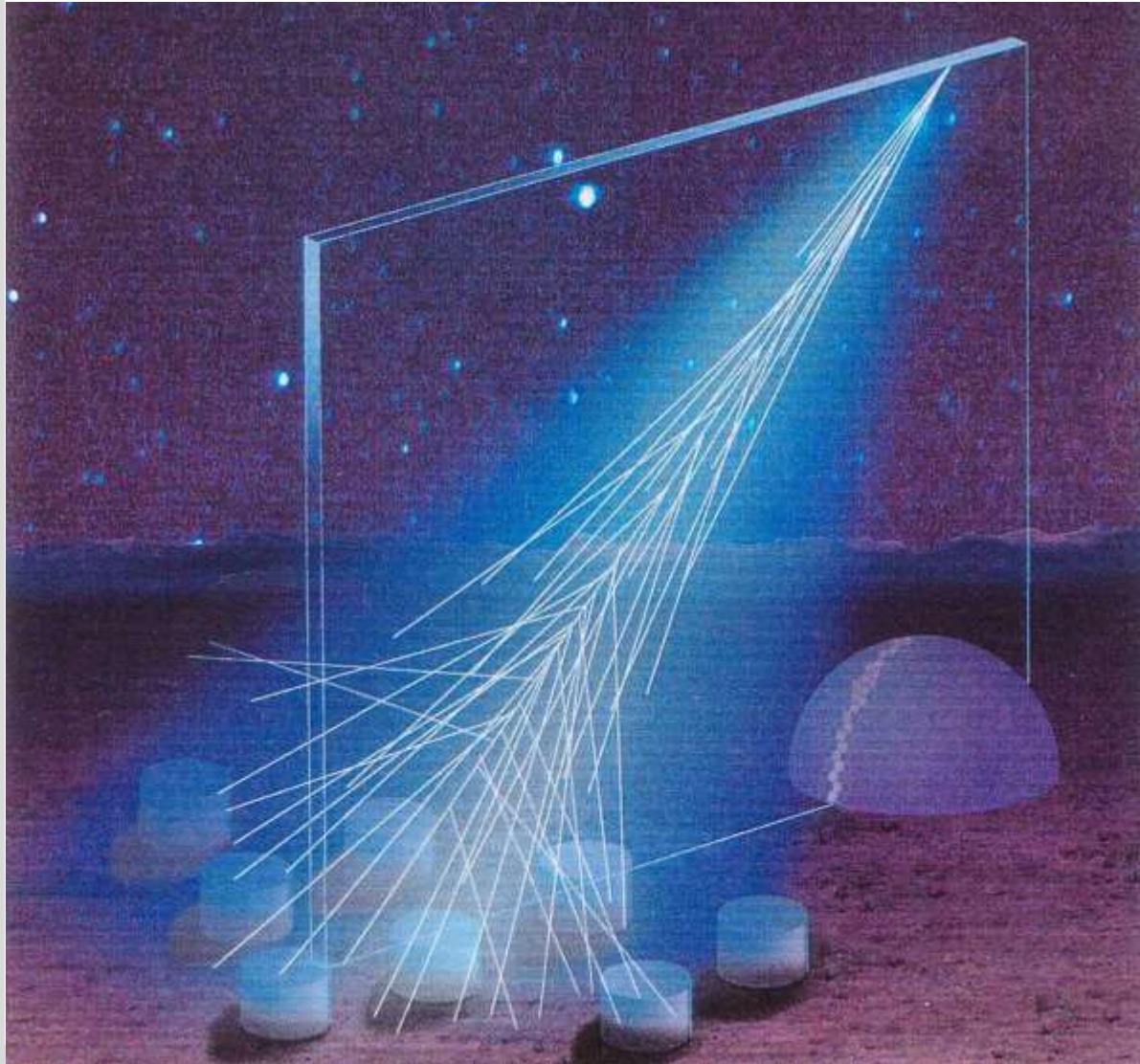
Tunka-Rex + LOPES Colls.,
PLB 763 (2016) 179



Pierre Auger Observatory in Argentina



Hybrid detection for highest accuracy



**PIERRE
AUGER**
OBSERVATORY

Auger Engineering Radio Array (AERA)

- 153 autonomous stations on 17 km²

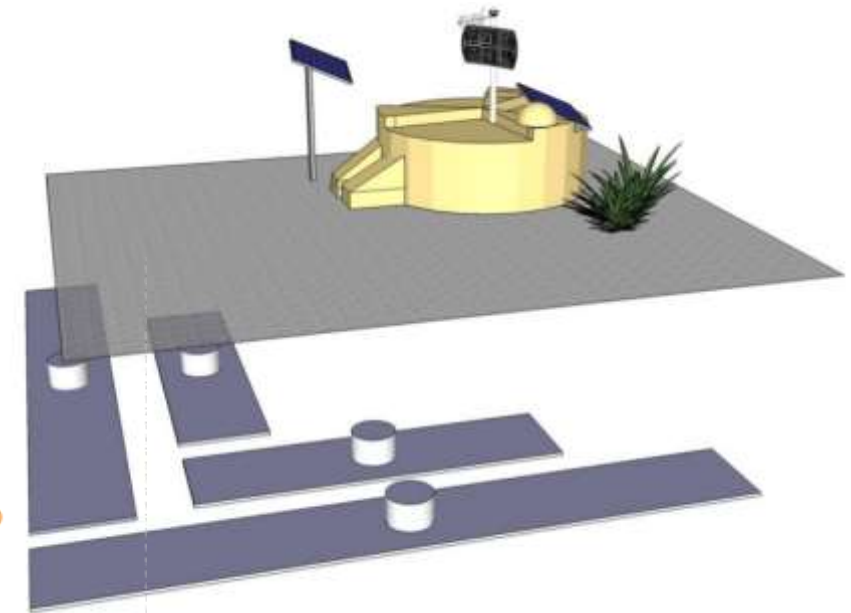
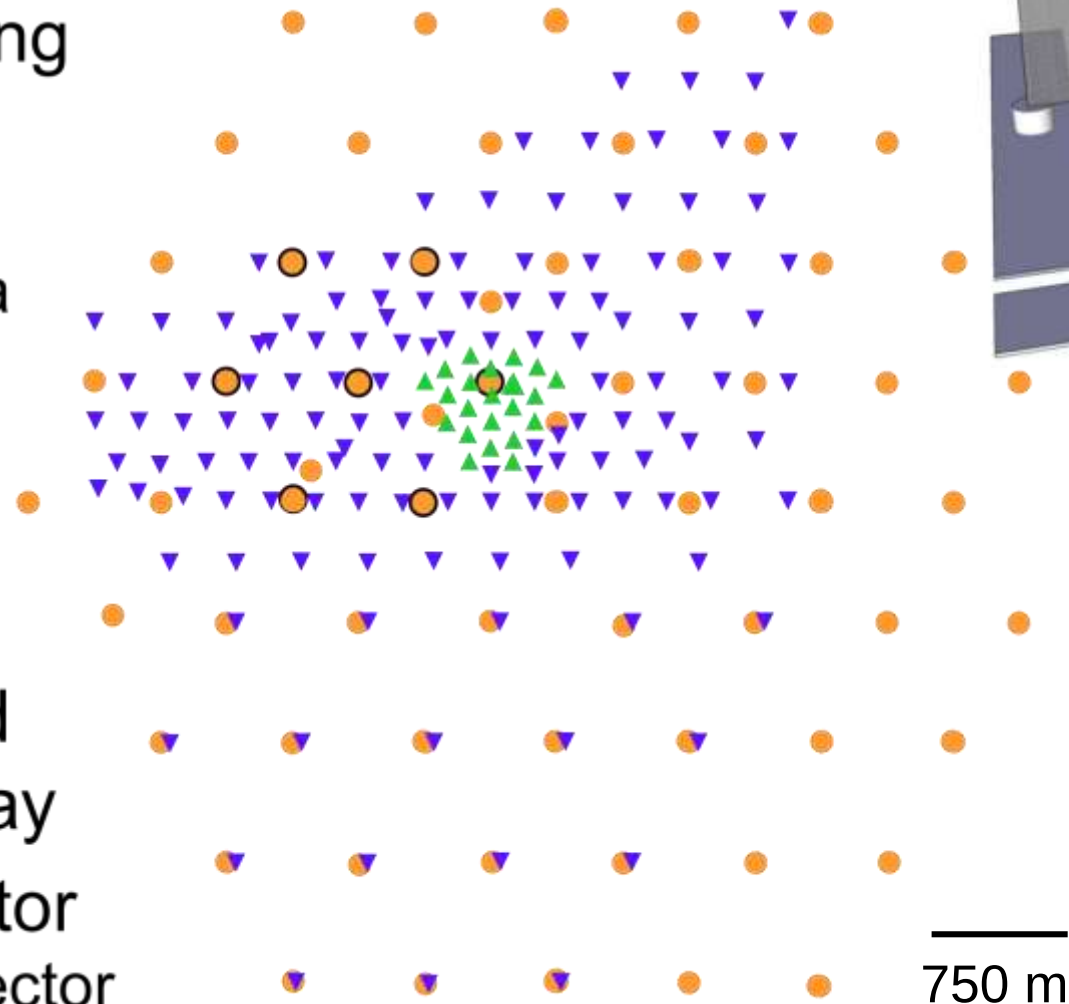
Auger Engineering Radio Array

▲ LPDA antenna

▼ Butterfly antenna

Auger Muon and Infill Ground Array

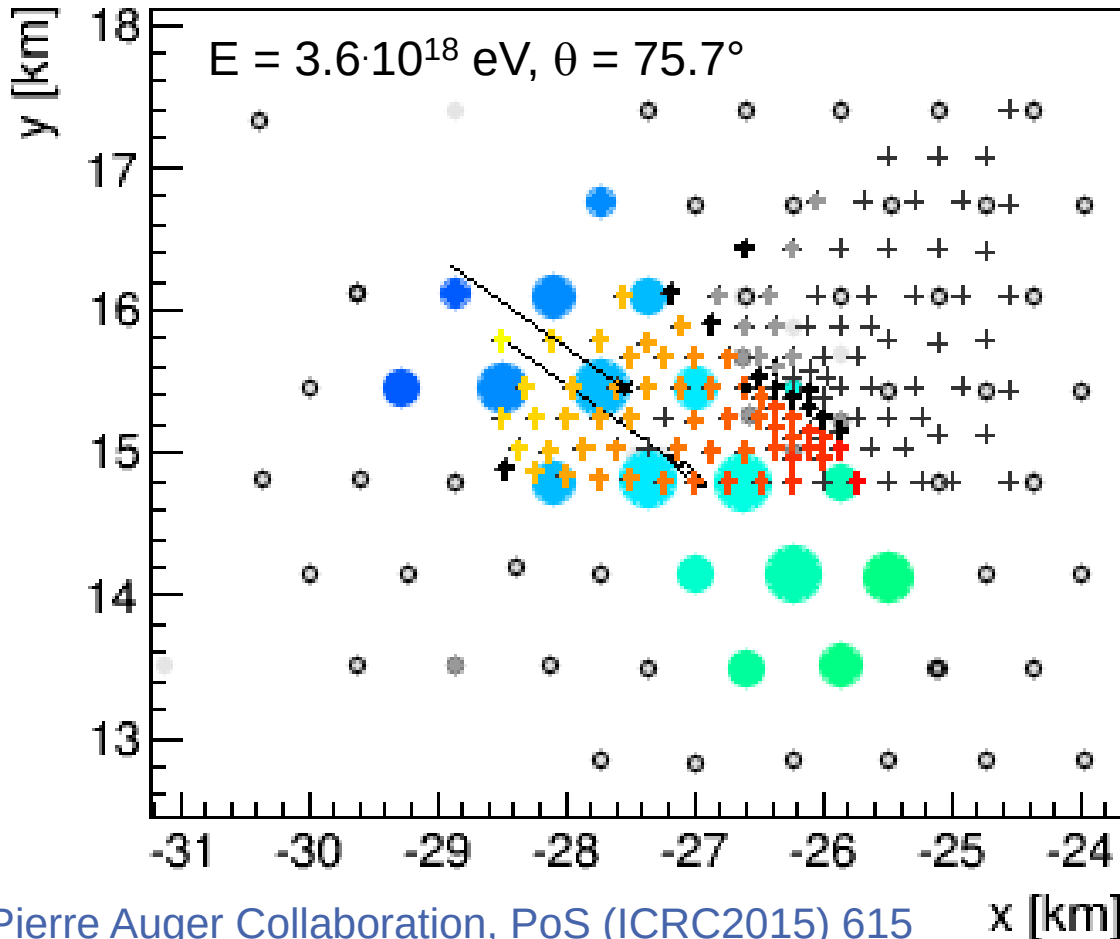
- Surface Detector
- with Muon Detector



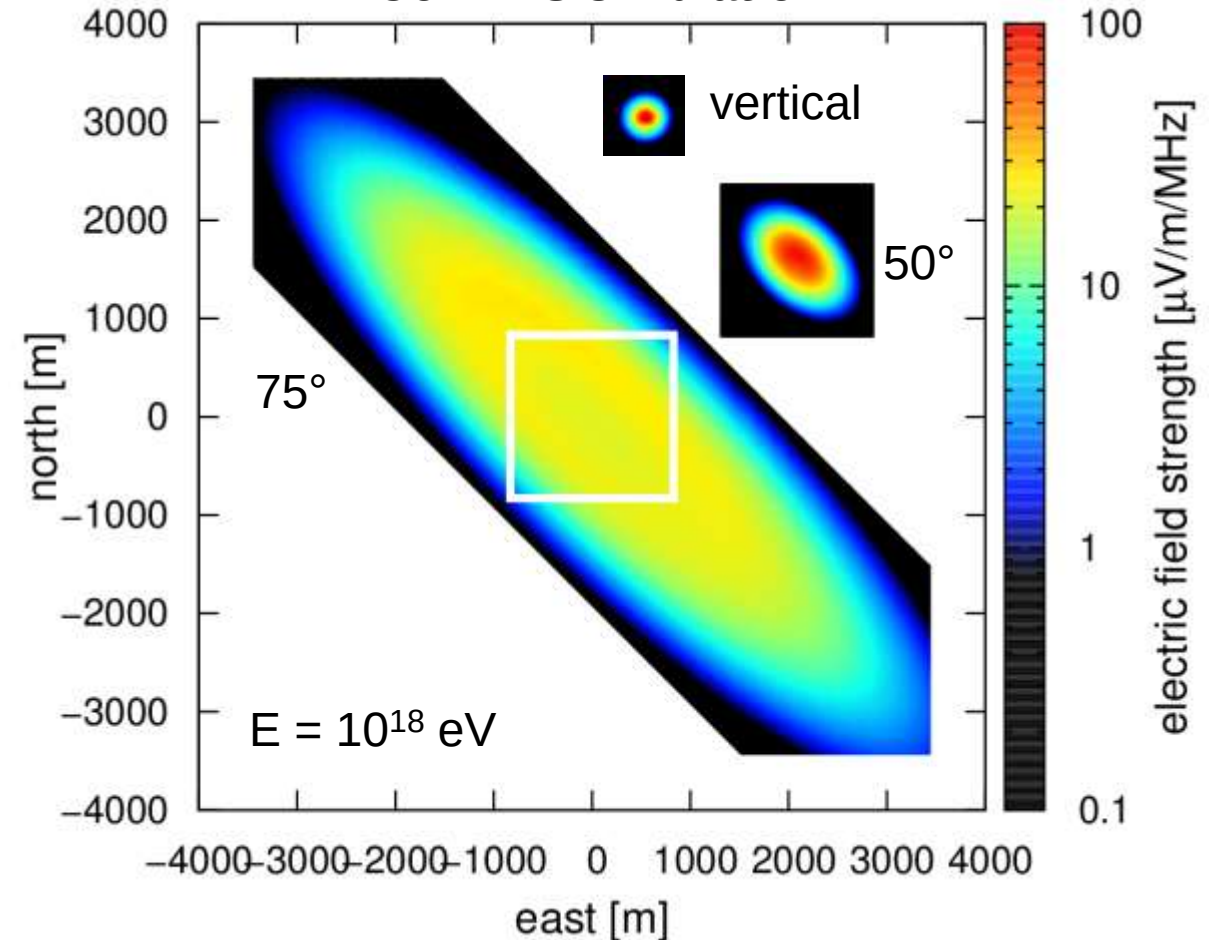
Huge footprint for inclined showers

- Enables sparse antenna arrays for highest energies at reasonable costs

Auger measurement



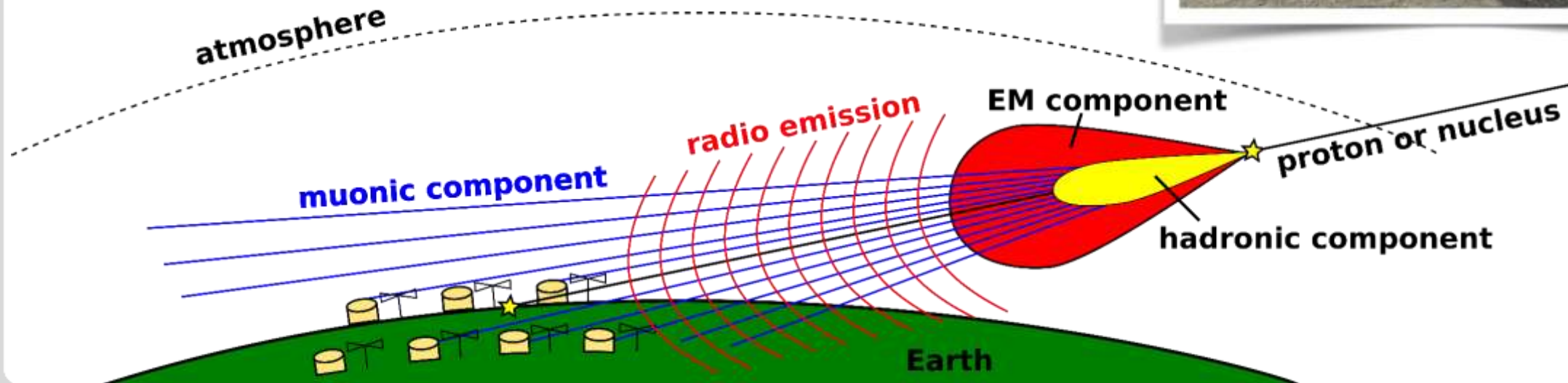
CoREAS simulation



Pierre Auger Collaboration, PoS (ICRC2015) 615

Sparse radio arrays for inclined showers

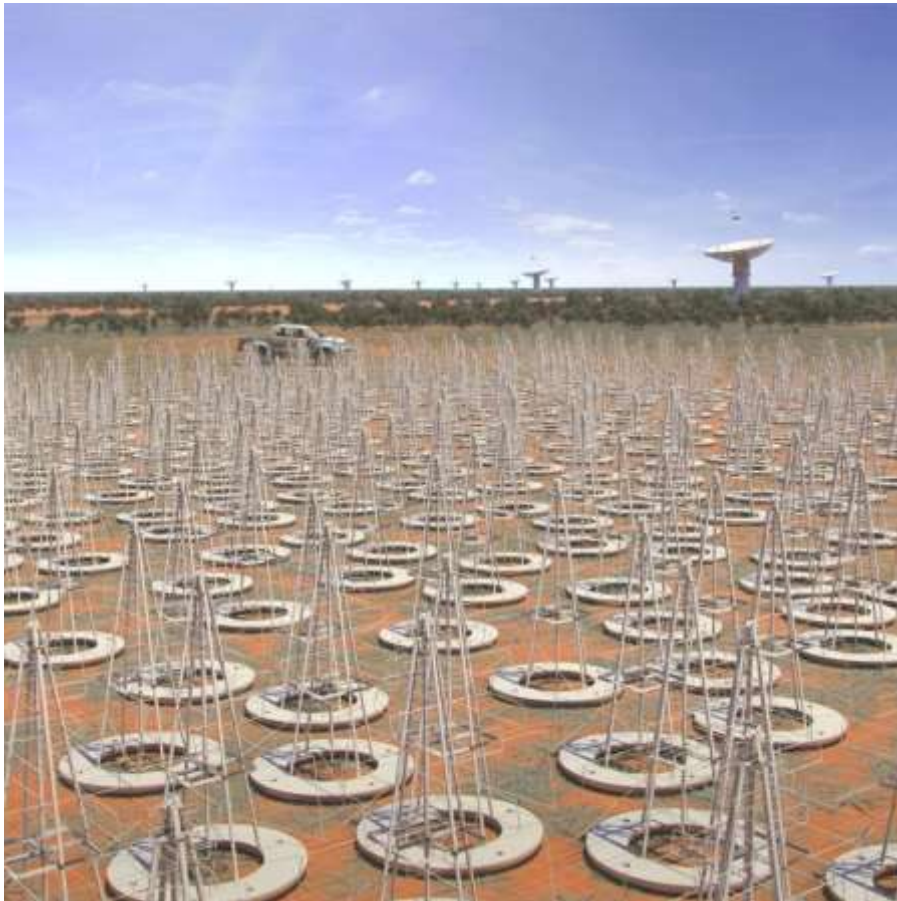
- Idea to upgrade each Auger detector by antenna
 - Study mass-sensitivity for inclined showers by radio $X_{\max}$ and by radio-muon-ratio
 - Pathfinder for GRAND cosmic-ray physics



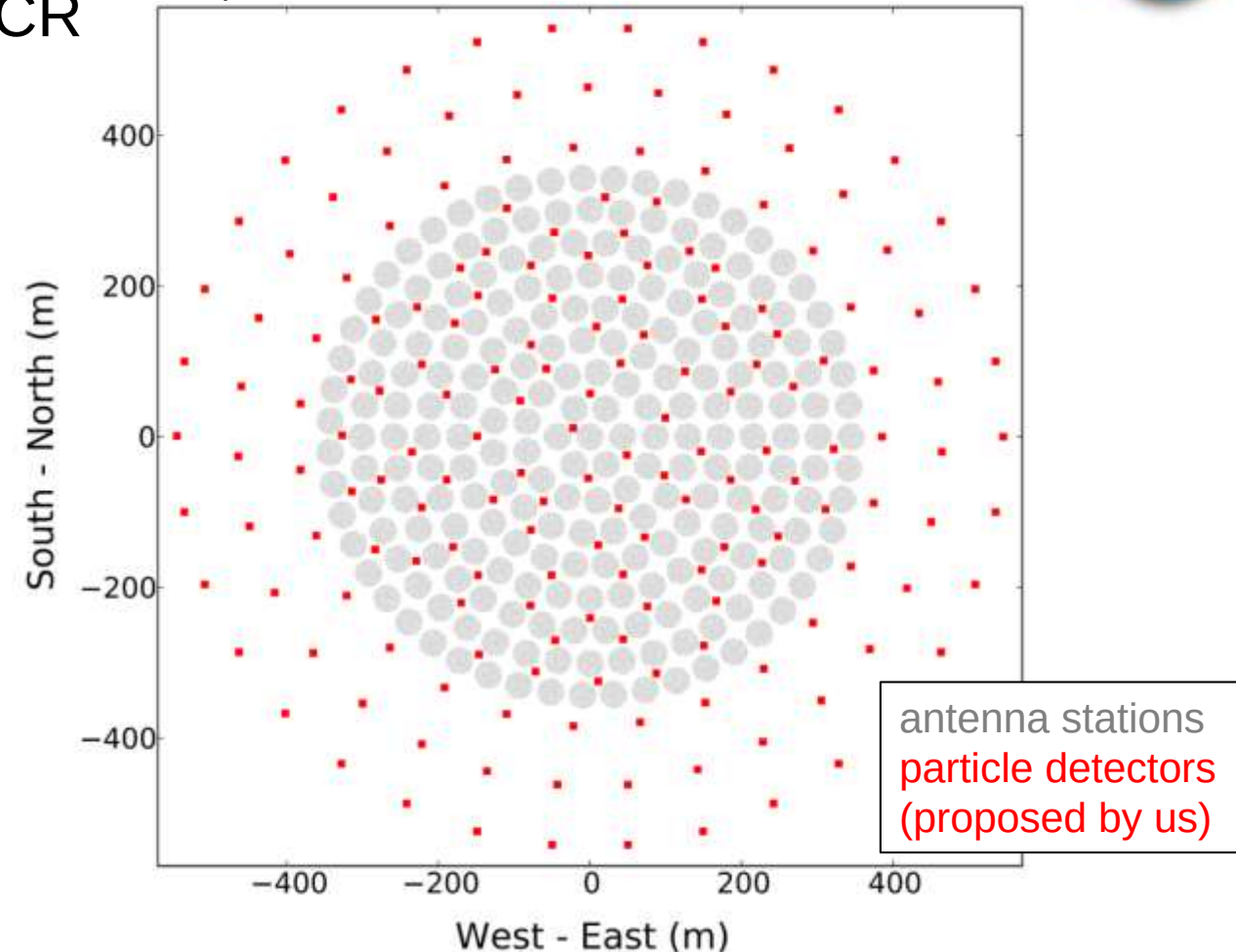
The Square Kilometer Array: ultra high precision



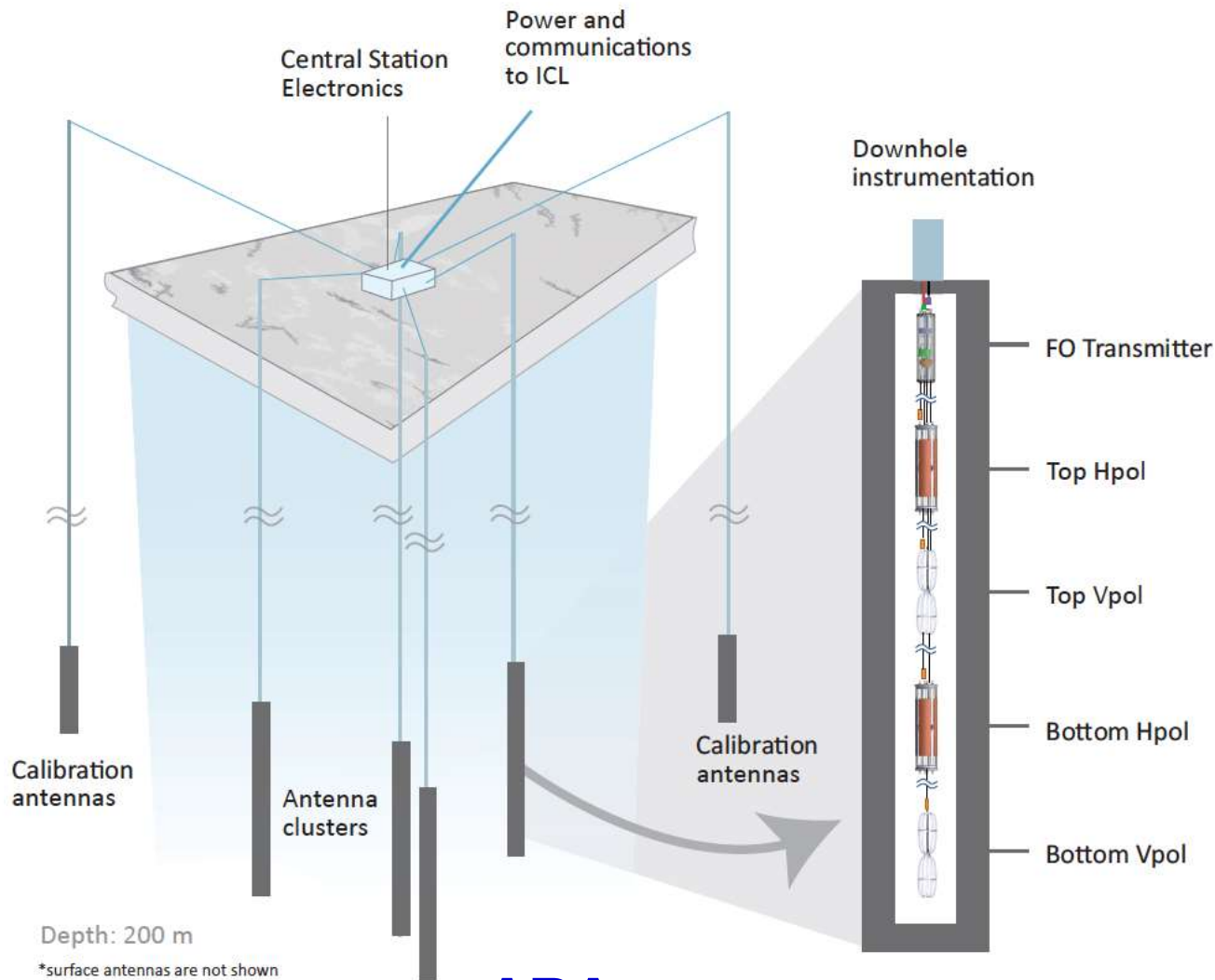
- Air showers: 10^{15} - 10^{18} eV cosmic rays
- Moon showers: $> 10^{20}$ eV neutrinos + CR



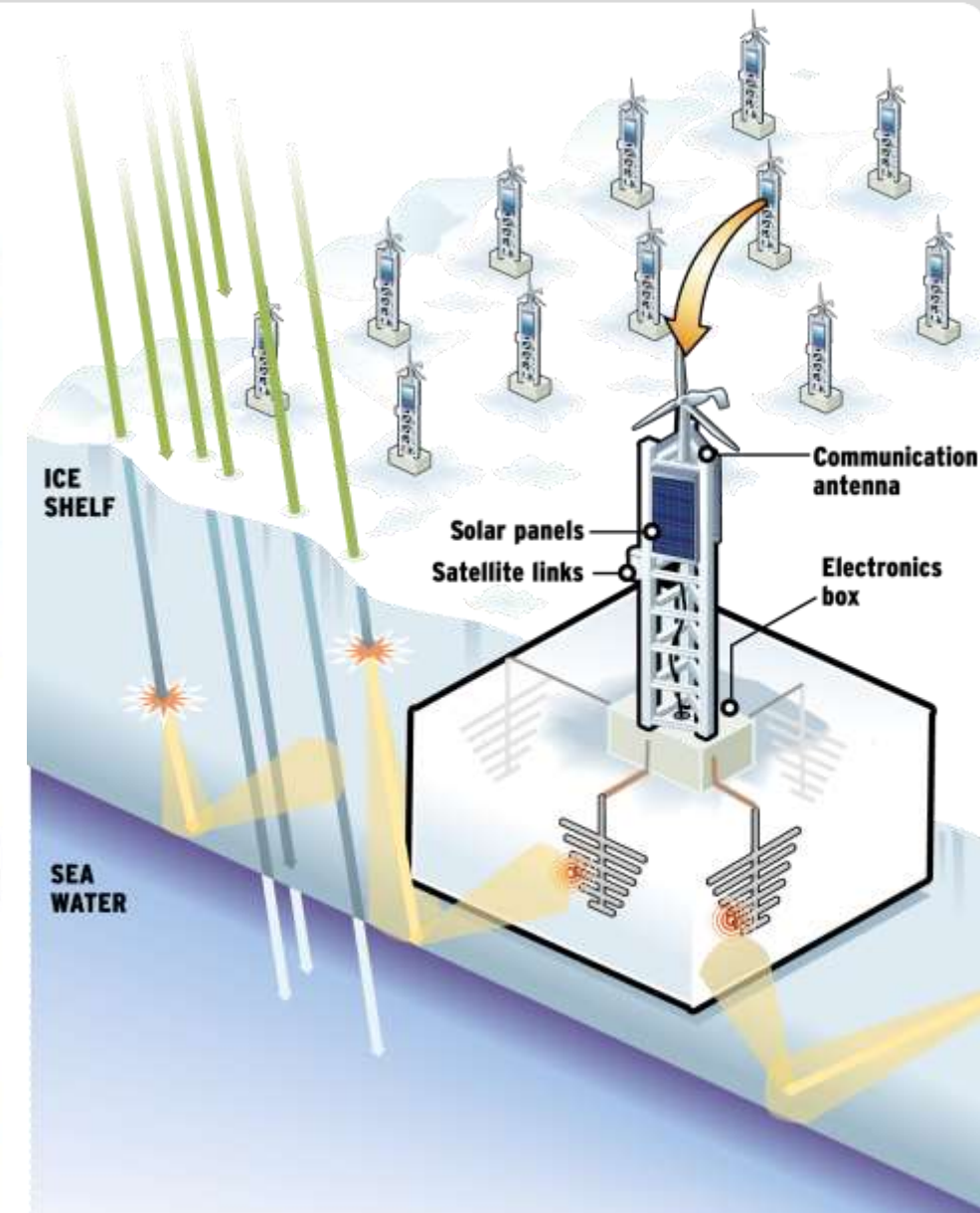
60,000 antennas on $\frac{1}{2}$ km²



Neutrino-induced showers in ice



ARA Collaboration



ARIANNA Collaboration

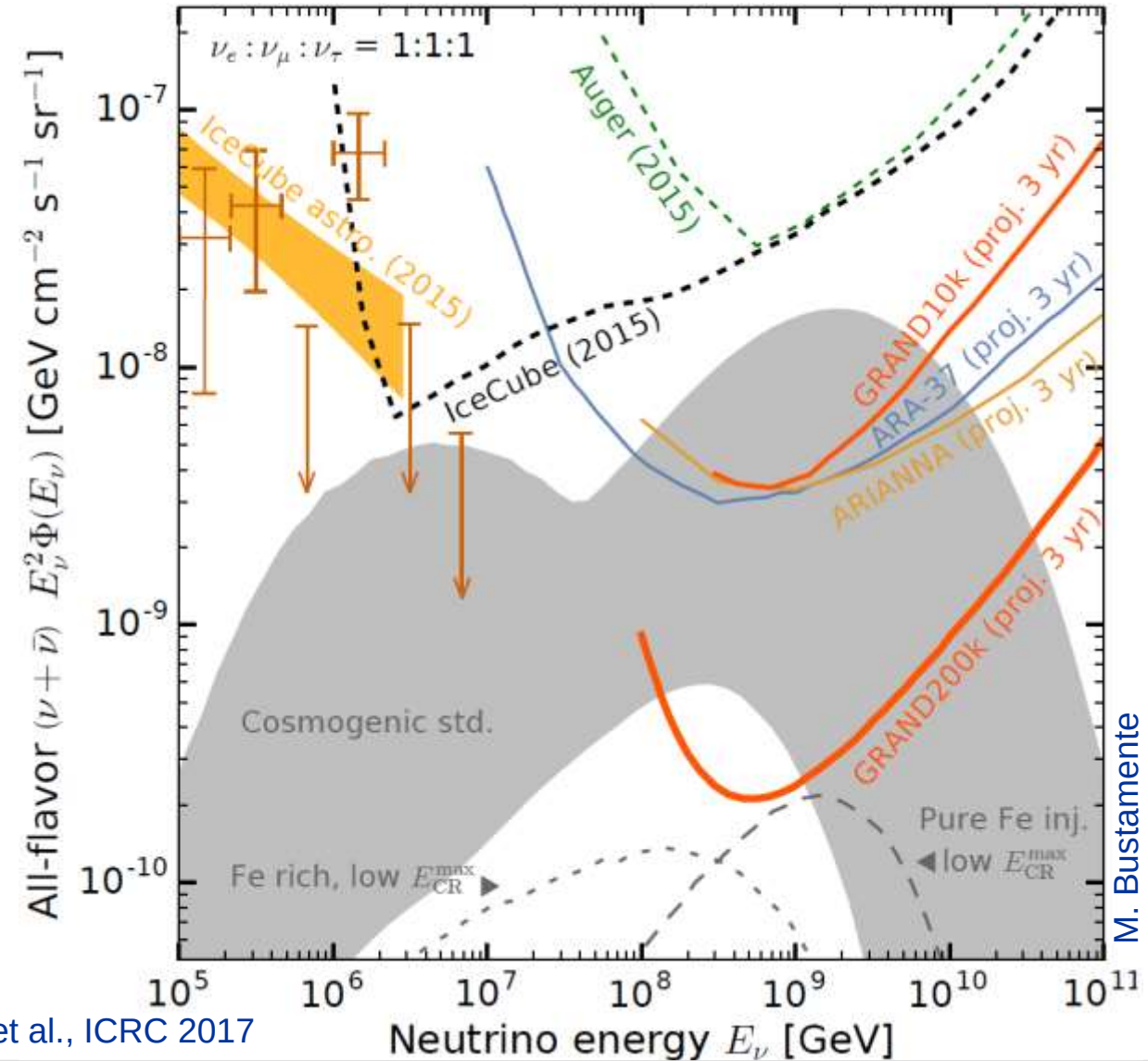
Graphic adapted by A. Nelles from S. Brown / The Register

GRAND: schedule and sensitivity

- Prototype at TREND site in Xinjiang
- Inclined showers for CR + neutrinos
- Final extension (2030s): 200,000 km²



Ke Fang, et al., ICRC 2017



Conclusion

- Significant progress in radio technique for cosmic rays during last years
 - high accuracy at almost 100% duty cycle
 - emission understood to at least 10 - 20 % accuracy
 - ideal for inclined showers and / or in combination with muon detectors
- Competitive accuracy for air shower parameters
 - direction $< 0.5^\circ$
 - energy $< 20\%$ (precision + scale)
 - $X_{\max}$ $< 20 \text{ g/cm}^2$ (with high antenna density)
- Radio becomes the standard technique of the future:
 - additional accuracy for cosmic rays
 - search for ultra-high-energy neutrinos

[more in:](#) F.G. Schröder,
Prog. Part. Nucl. Phys.
93 (2017) 1-68
[arXiv: 1607.08781](#)