Air-Shower Detection by Arrays of Radio Antennas

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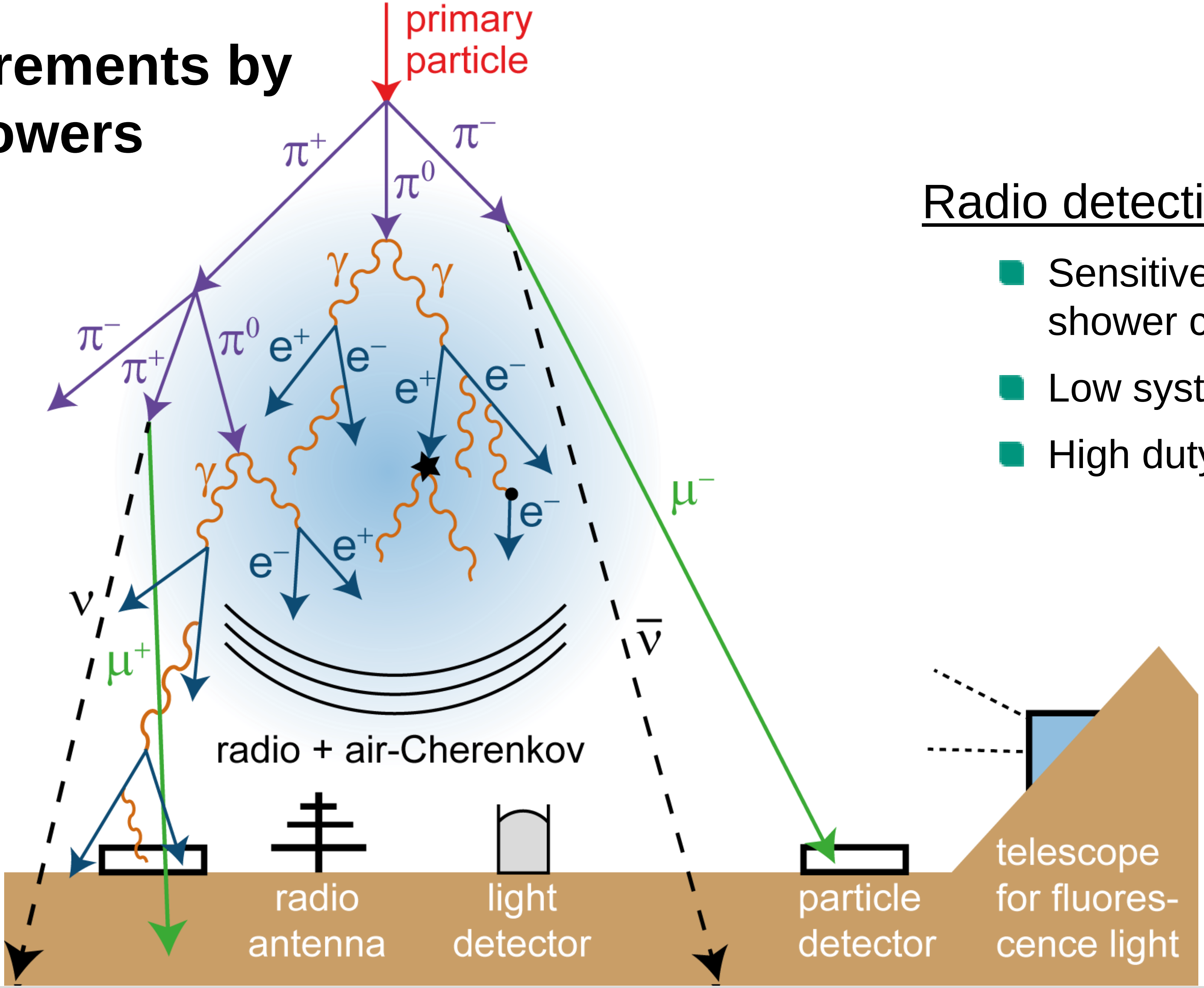
Content

- Radio emission by air showers (not covering dense media, such as ice)
  - Tests of simulation codes
- Results of selected experiments (focus on Tunka-Rex and Auger)
  - Energy and mass composition
- Future radio arrays for air-showers (plans and ideas)
  - Auger Radio Upgrade
  - GRAND
  - SKA
  - Radio array at the South Pole

Measurements by Air Showers

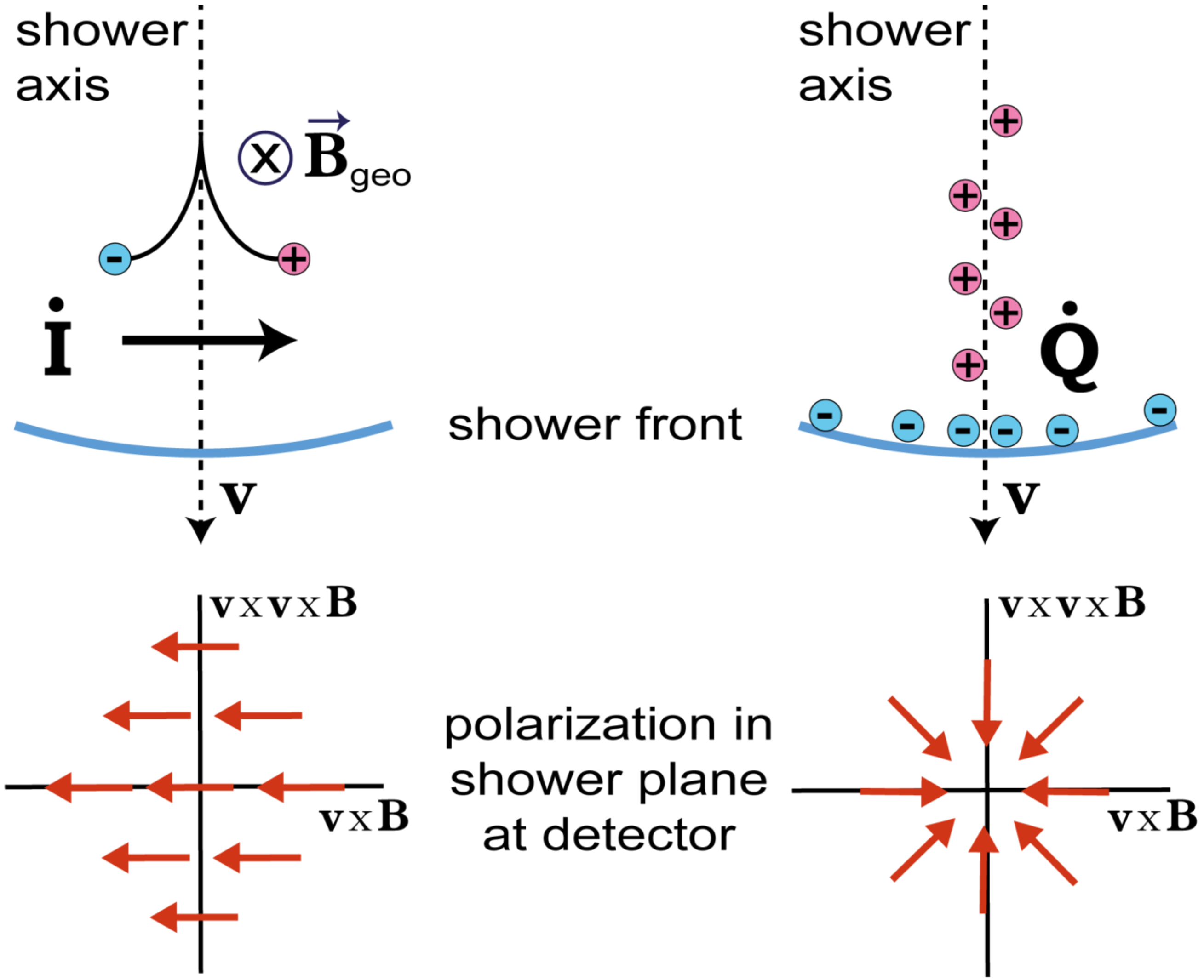


Radio detection of air showers:

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

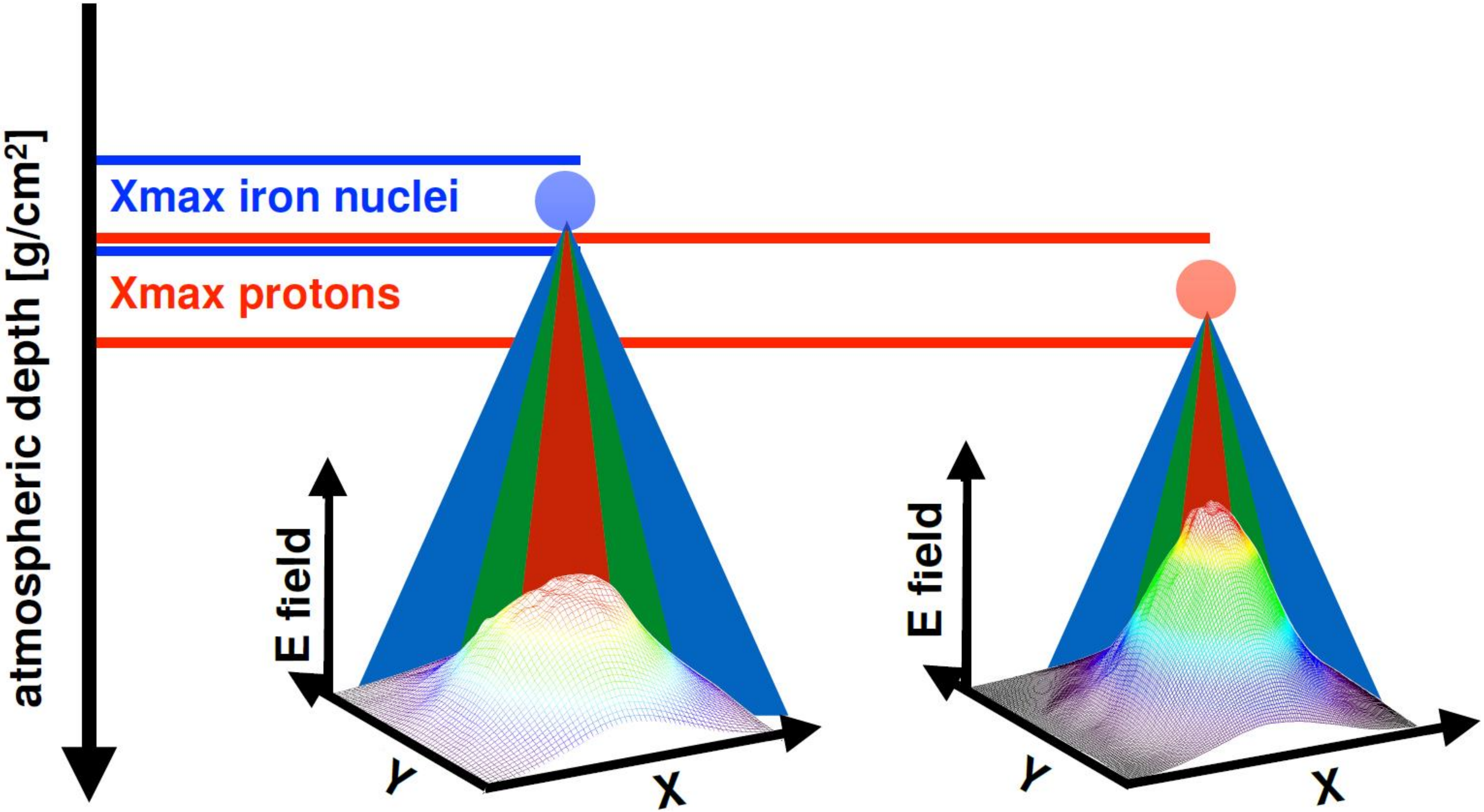
Prog. Part. Nucl. Phys. 93 (2017) 1-68
arXiv: 1607.08781

Radio: Emission Mechanisms



geomagnetic effect ~ 90% Askaryan effect ~ 10%

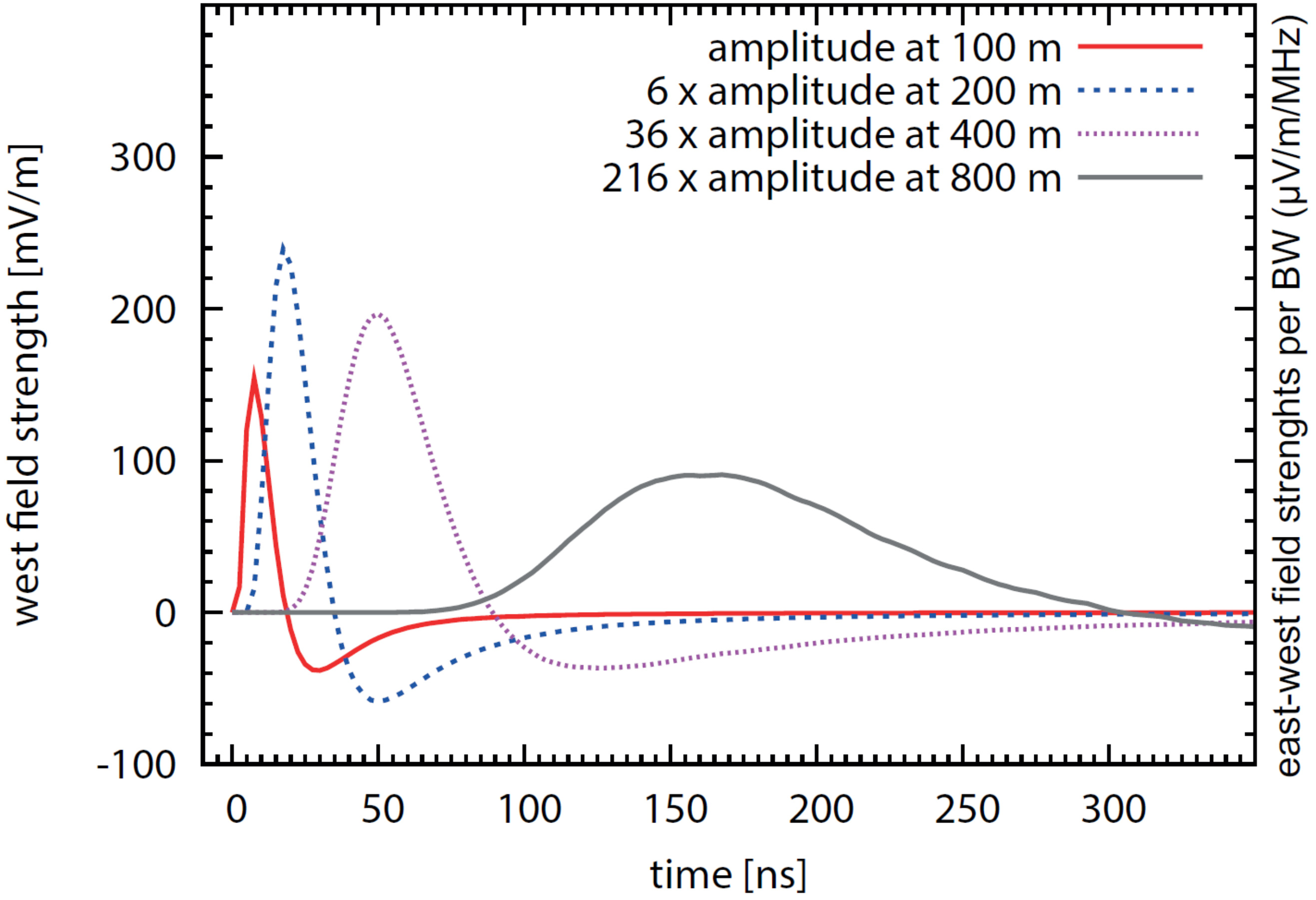
Radio emission beamed in forward cone



Auger Coll.

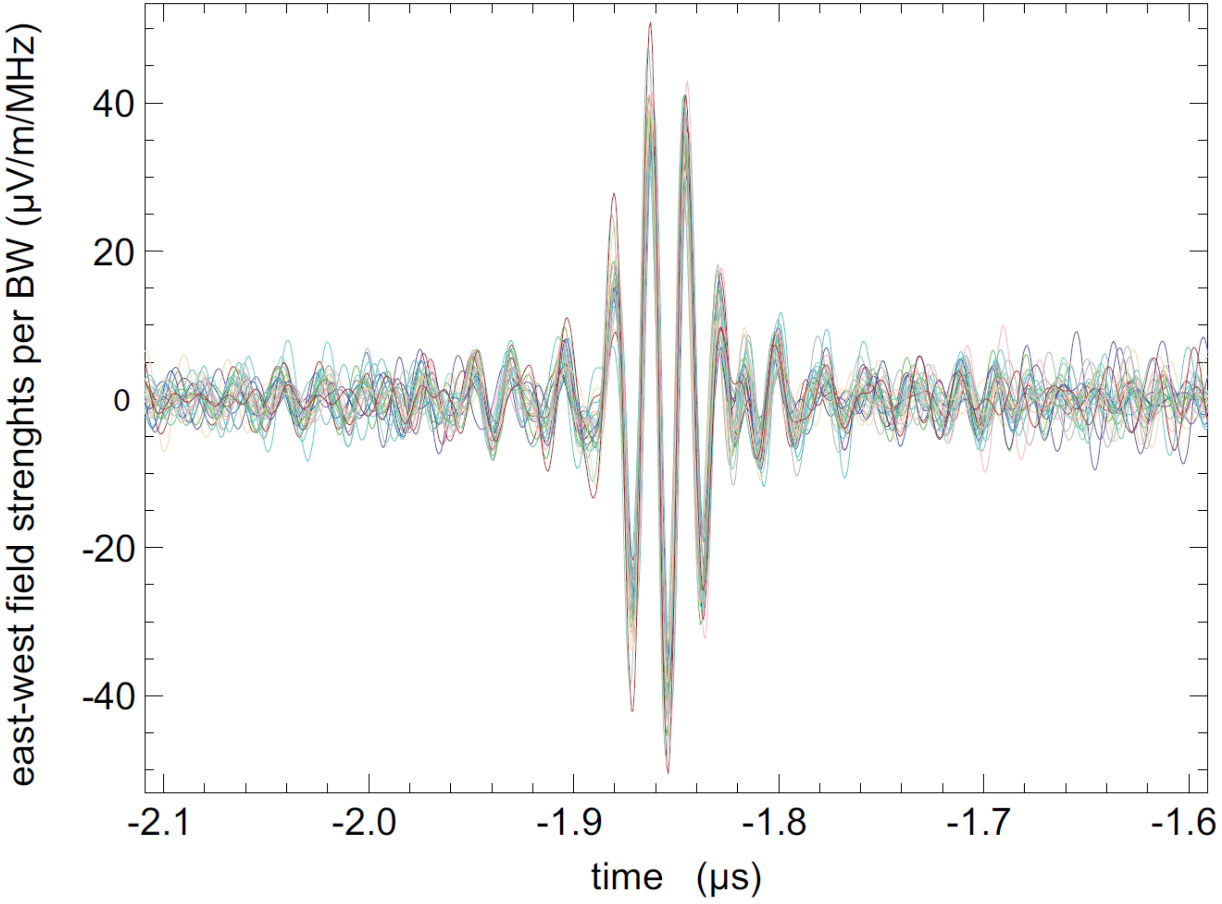
Radio pulse: detection of transients in time-domain

CoREAS simulation, full bandwidth



T. Huege

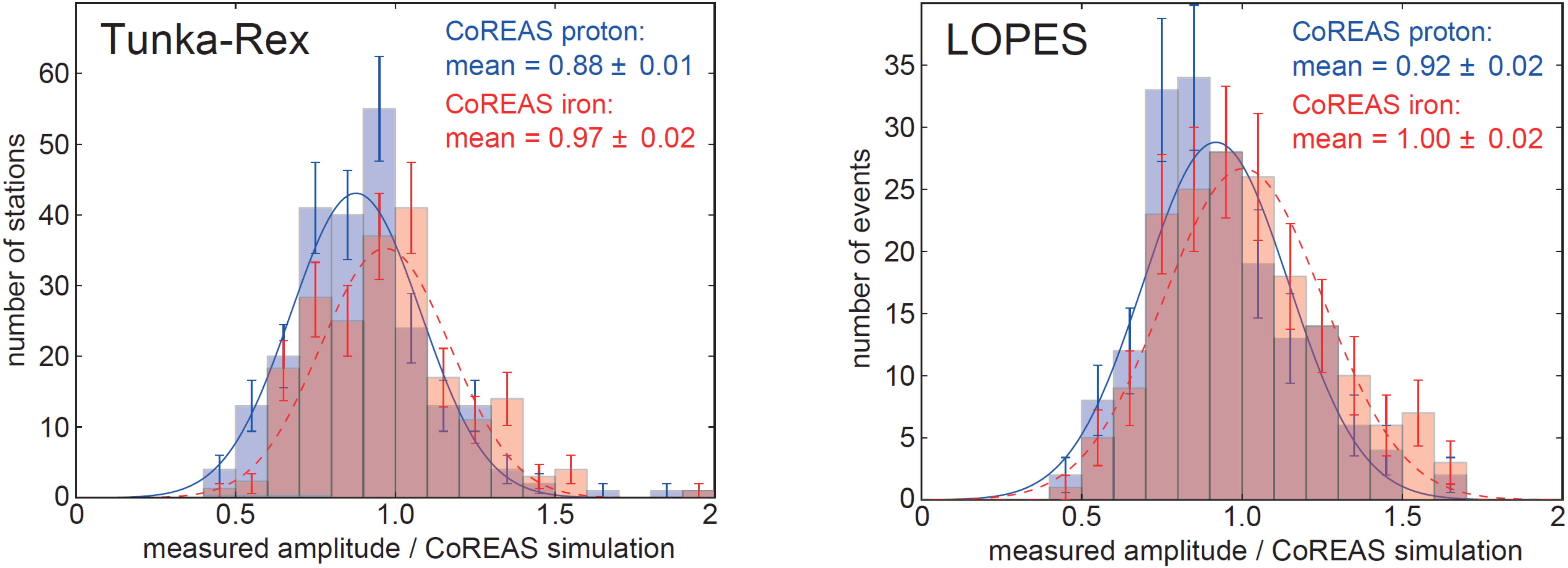
LOPES measurement, 43-74 MHz



Schröder et al., NIM A 615 (2010) 277

Testing simulations of radio emission by air-showers

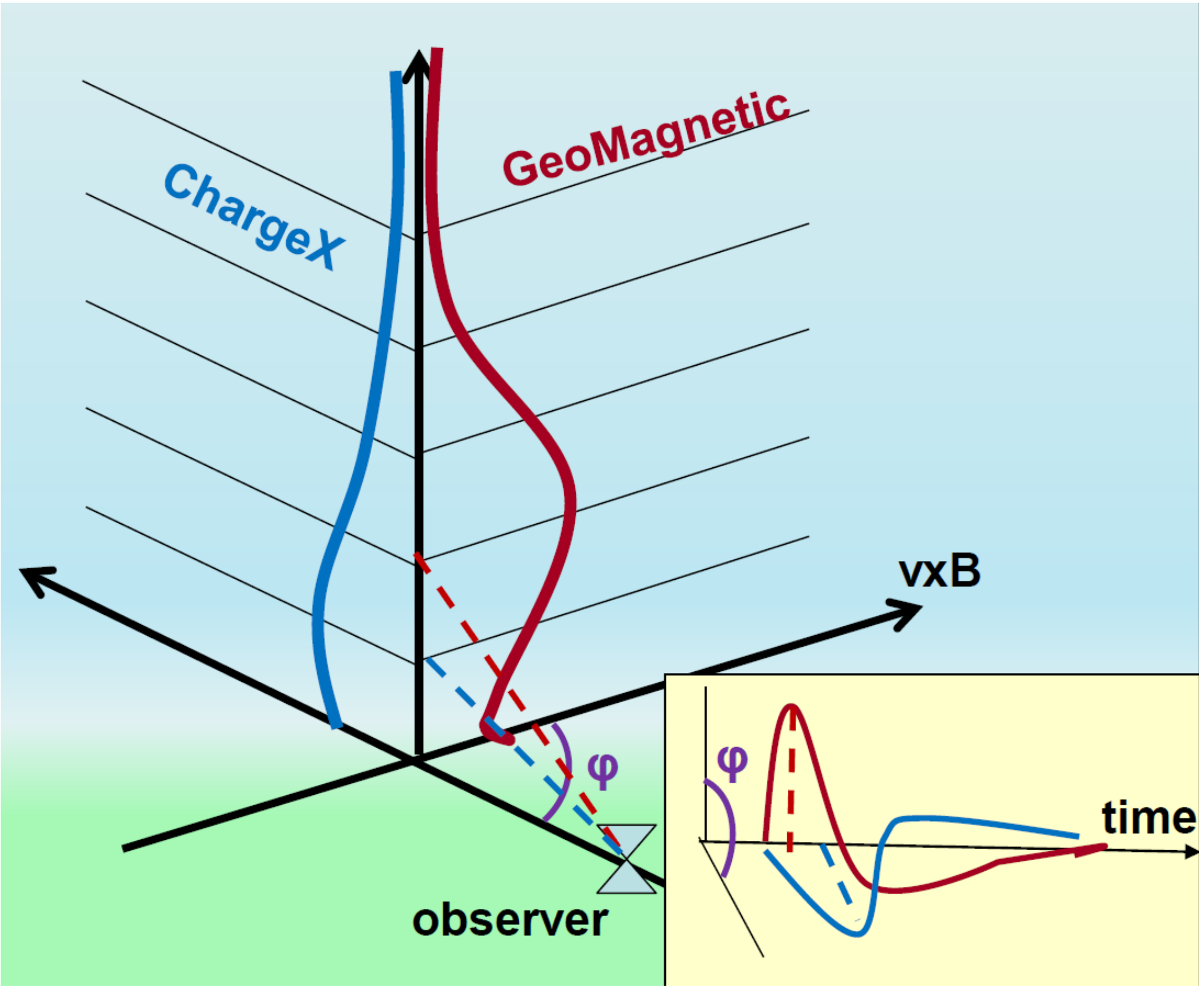
- Perfect agreement within experimental uncertainties of absolute scale (15-20%)
- Differences between various simulations codes < 10% → not testable today



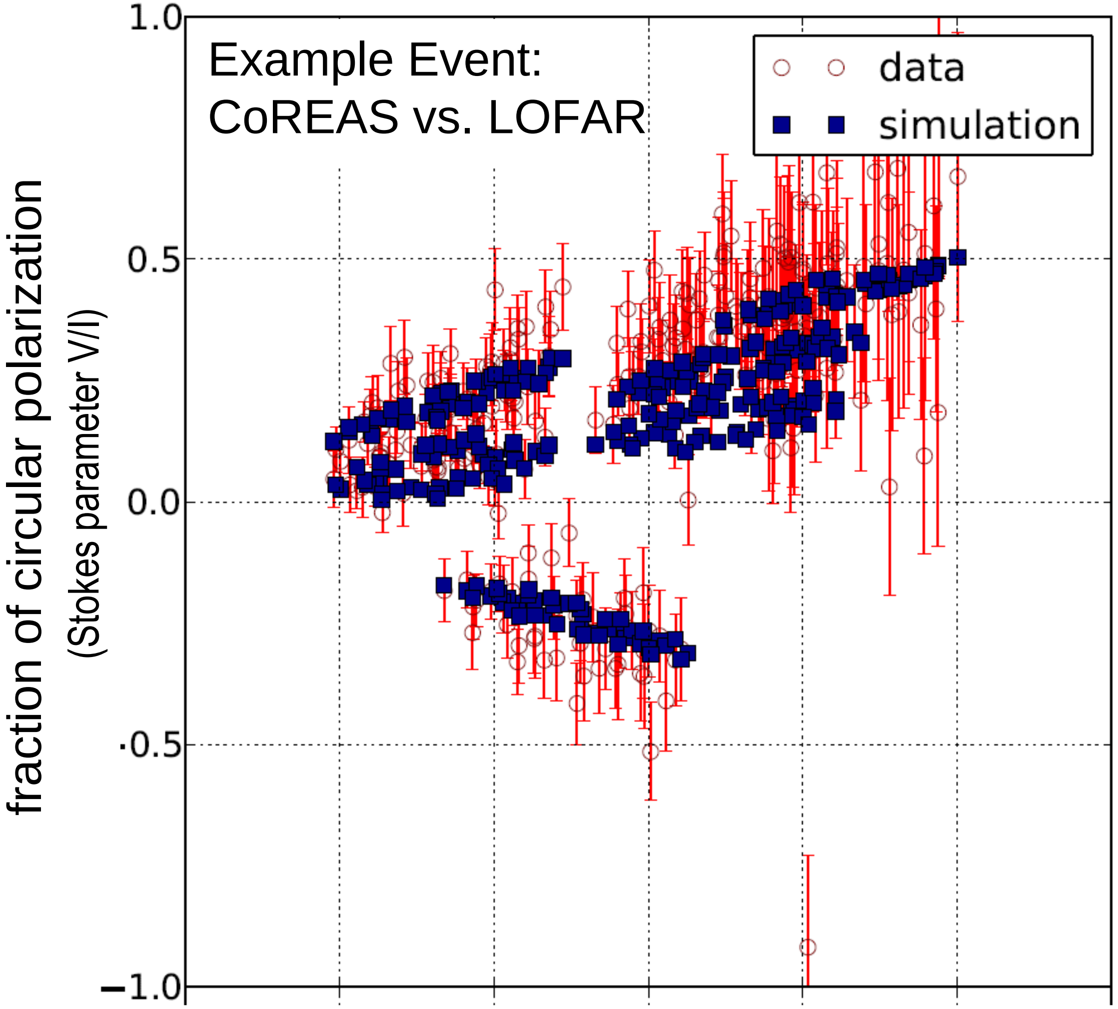
PLB 763 (2016) 179

LOFAR confirms slightly elliptical polarization

Precise LOFAR measurements reveal different emission regions for both processes.

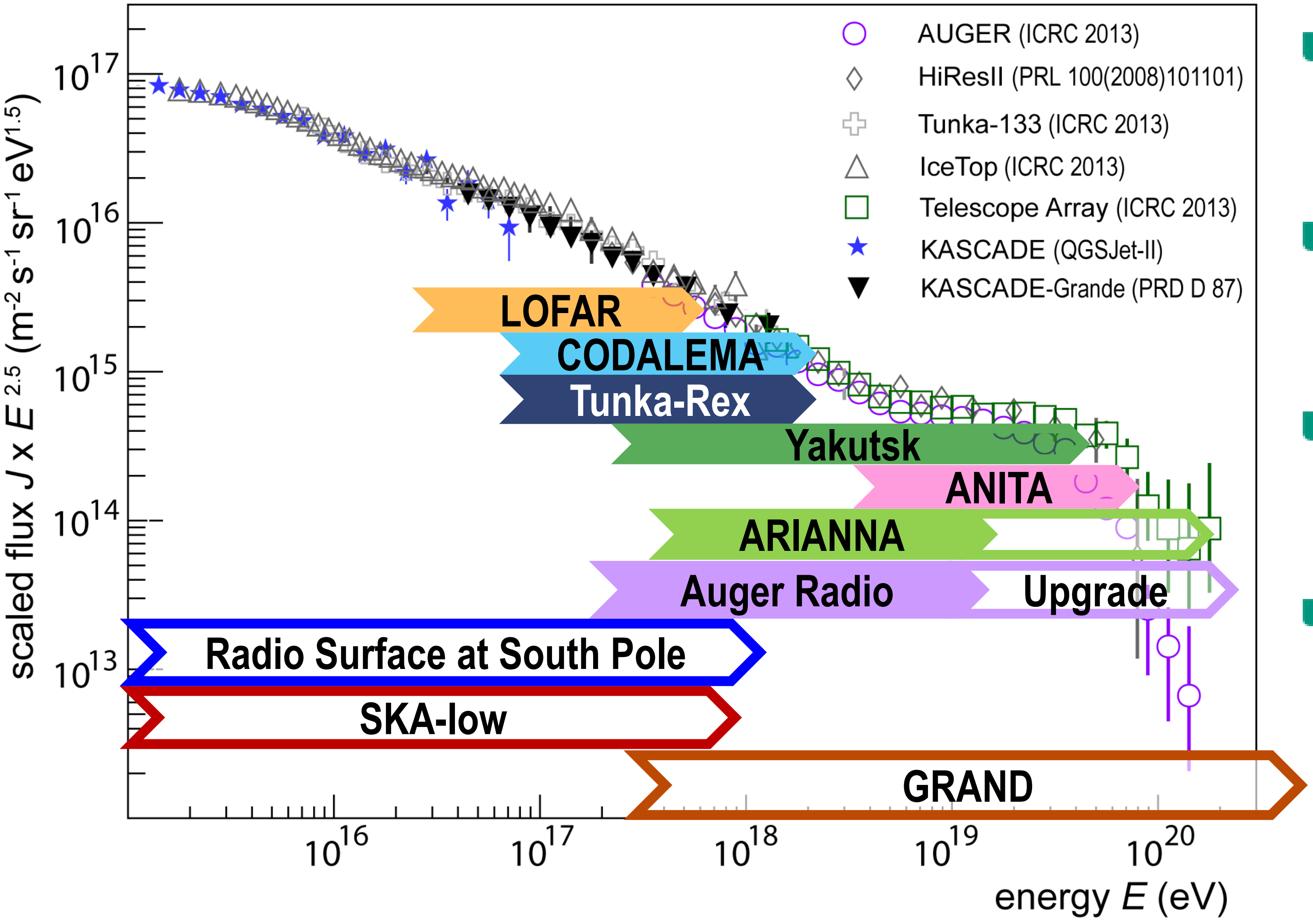


O. Scholten, et al. (LOFAR), PoS (ICRC2017) 324



LOFAR, PRD 94 (2016) 103010

Energy Range of Air-Shower Detection by Radio



- Approximate energy range of current and future arrays
- Currently in range of Galactic-Extragalactic transition
- Ideas for future arrays for lower and higher energies
- Caveats:
  - selection of air-shower experiments (neutrino experiments not shown)
  - exact threshold depends on analysis, cuts, etc.

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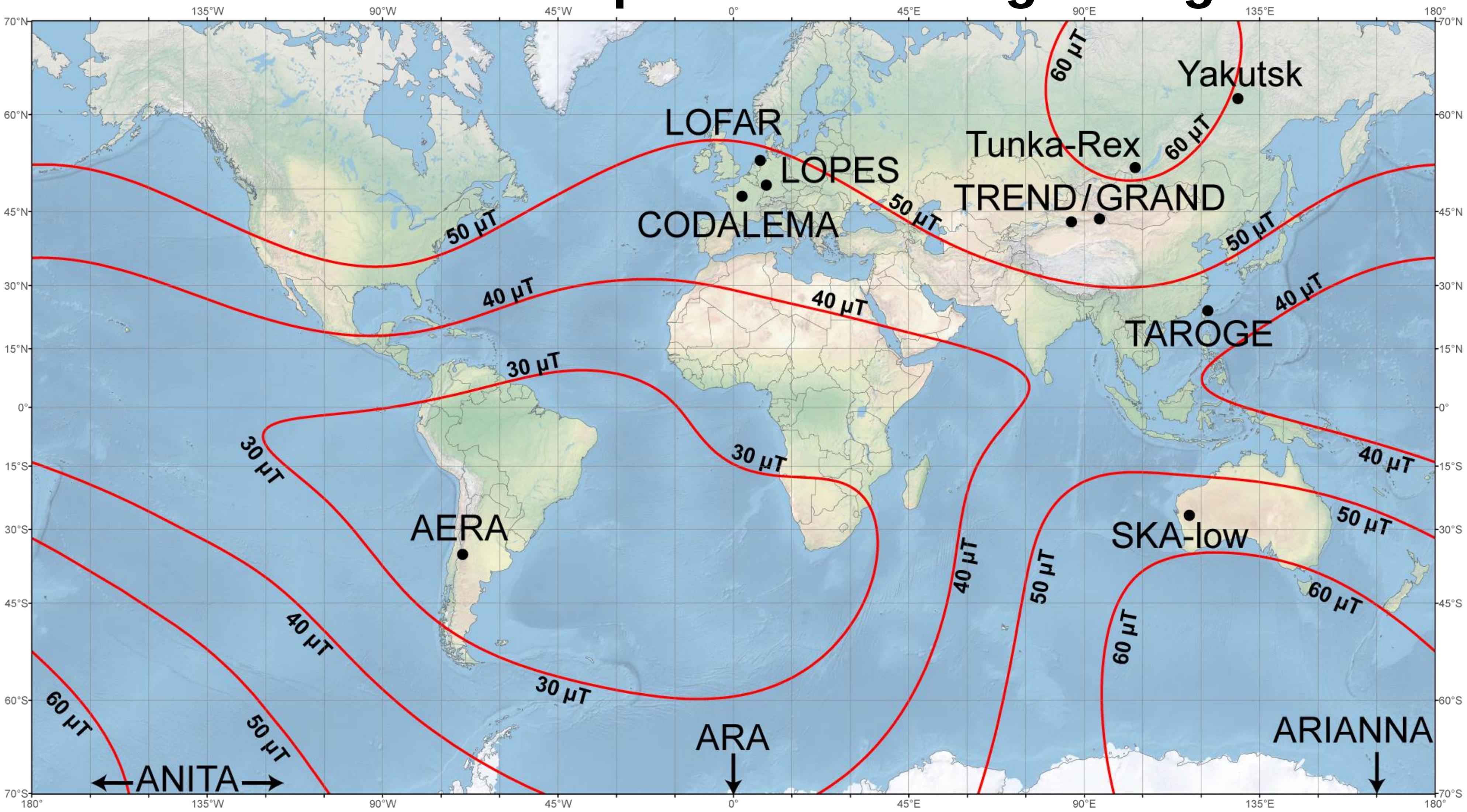
Location of selected experiments and geomagnetic field



Underlying map (Mercator projection):
Main Geomagnetic Field Total Intensity with contour intervals of 10 µT
according to US/UK World Magnetic Model - Epoch 2015.0

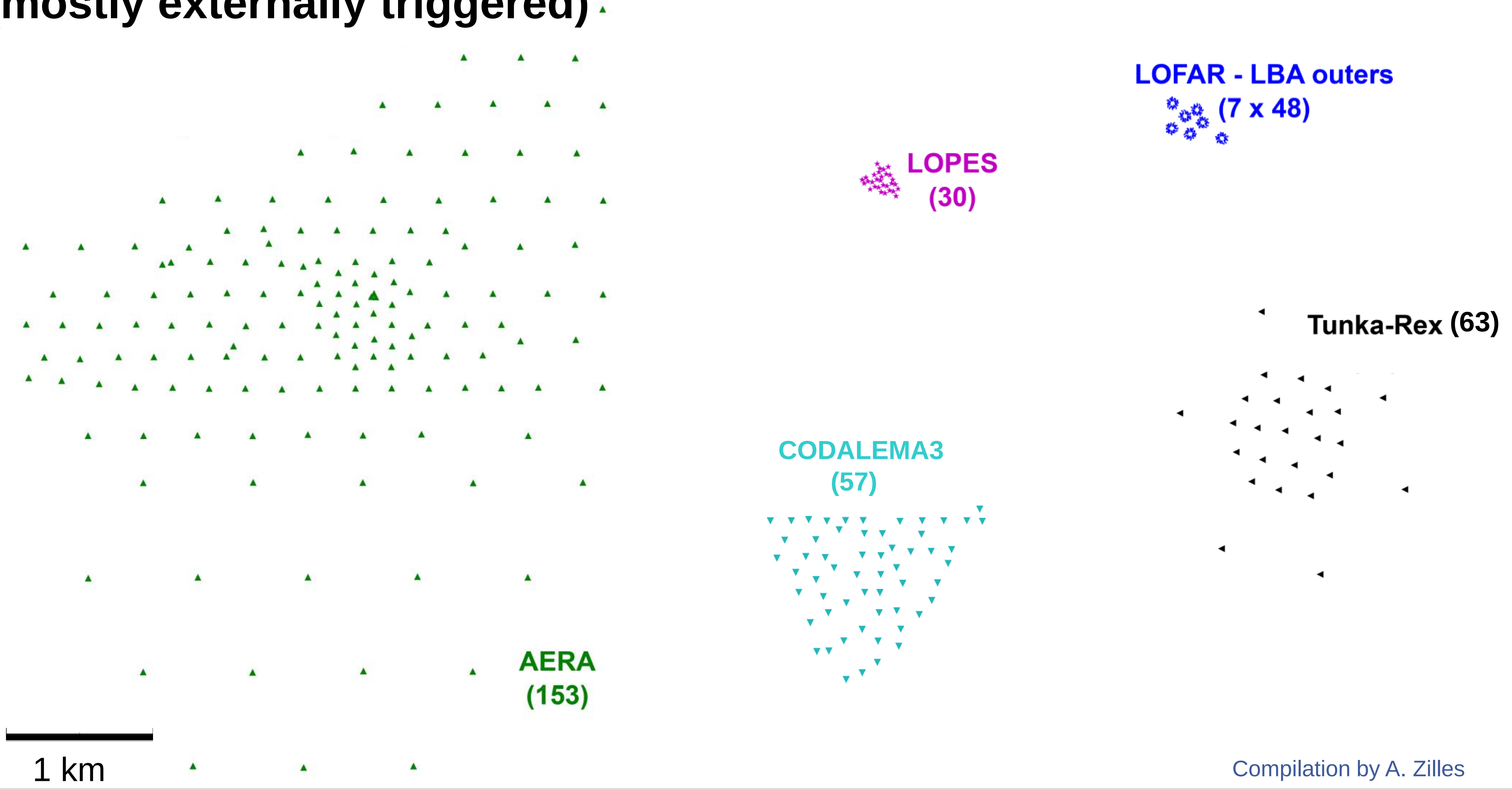
developed by NOAA/NGDC & CIRES
http://ngdc.noaa.gov/geomag/WMM

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

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

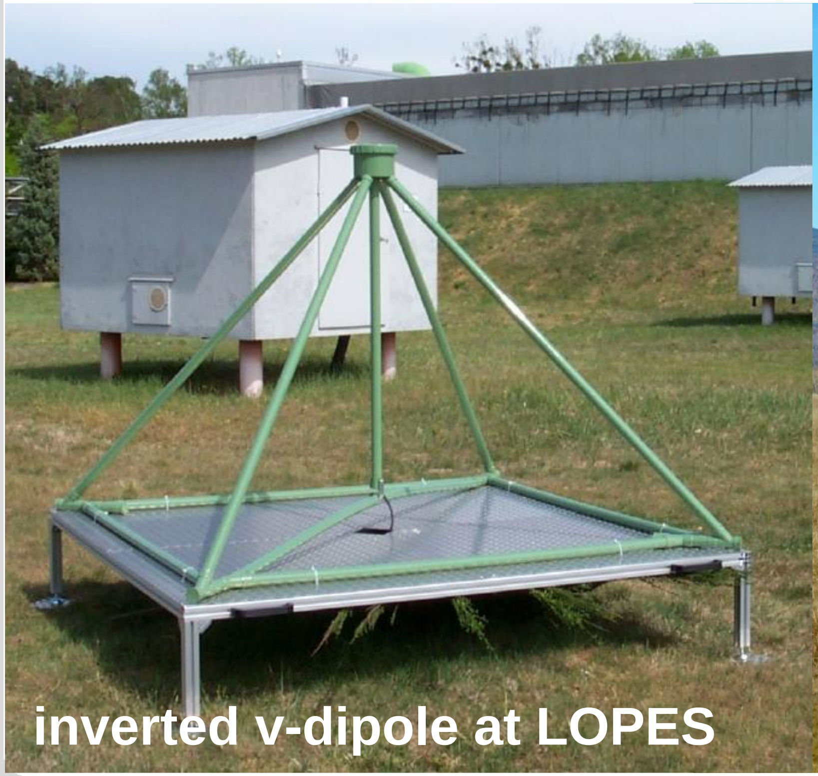
Designs of modern radio arrays
(mostly externally triggered)



Compilation by A. Zilles

Detectors: antennas

- Many working solutions at different experiments
  - LOPES, CODALEMA, Yakutsk, LOFAR, AERA, Tunka-Rex, …
- Typical band today: 30-80 MHz (other bands under investigation)



Details on two selected experiments (personal bias)

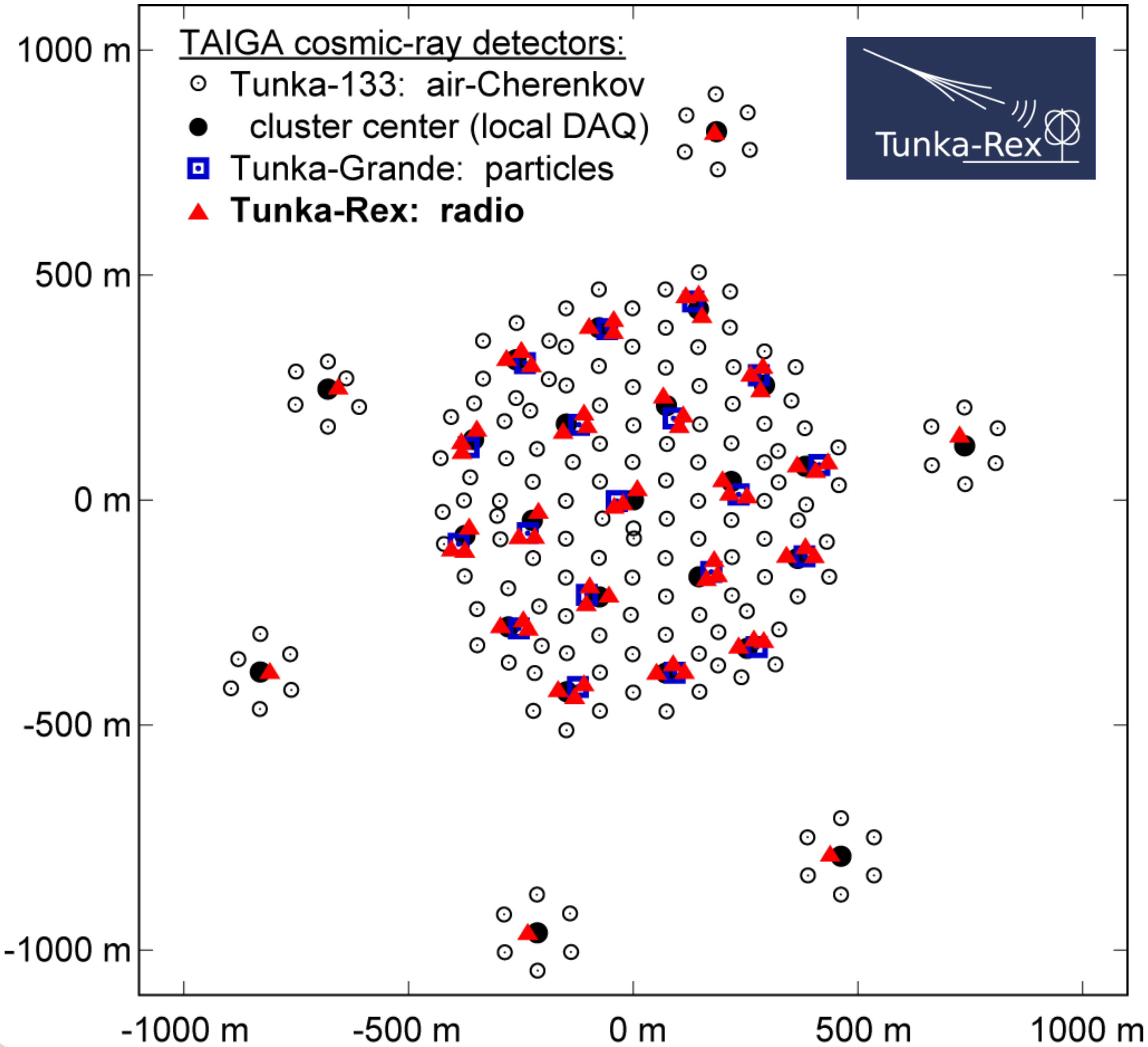
Tunka Radio Extension (Tunka-Rex)

63 antennas on 3 km² in Siberia

Auger Engineering Radio Array (AERA)

153 antennas on 17 km² in Argentina

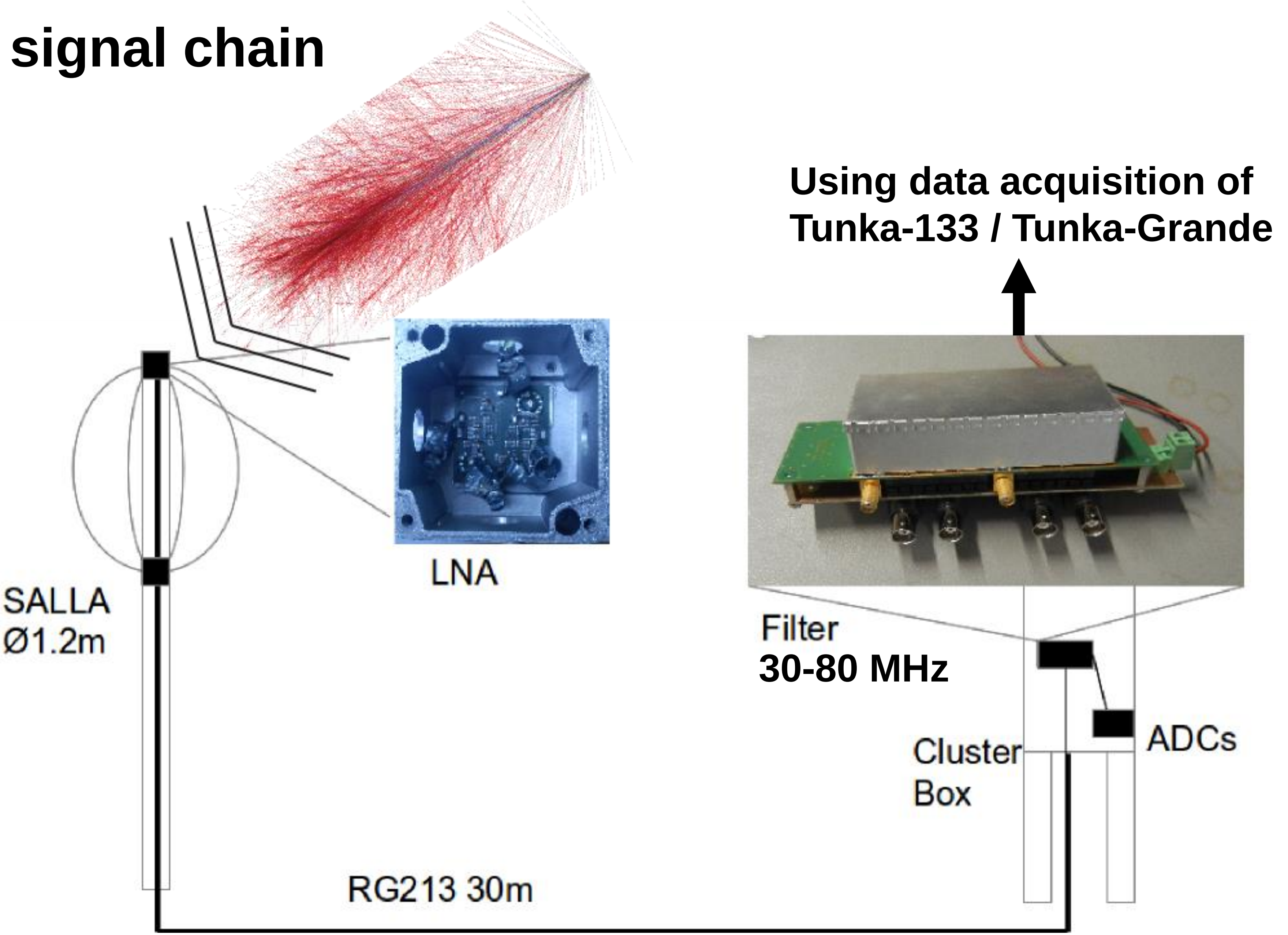
Tunka Radio Extension (Tunka-Rex)



- at TAIGA facility in Siberia for Gamma Astronomy and Cosmic Rays
- 63 antennas on 3 km²
  - 3 antenna stations per cluster
  - cluster spacing of 200 m
- Frequency range: 30 – 80 MHz
- Trigger by
  - air-Cherenkov detectors (Tunka-133)
  - particle detectors (Tunka-Grande)

Tunka-Rex signal chain

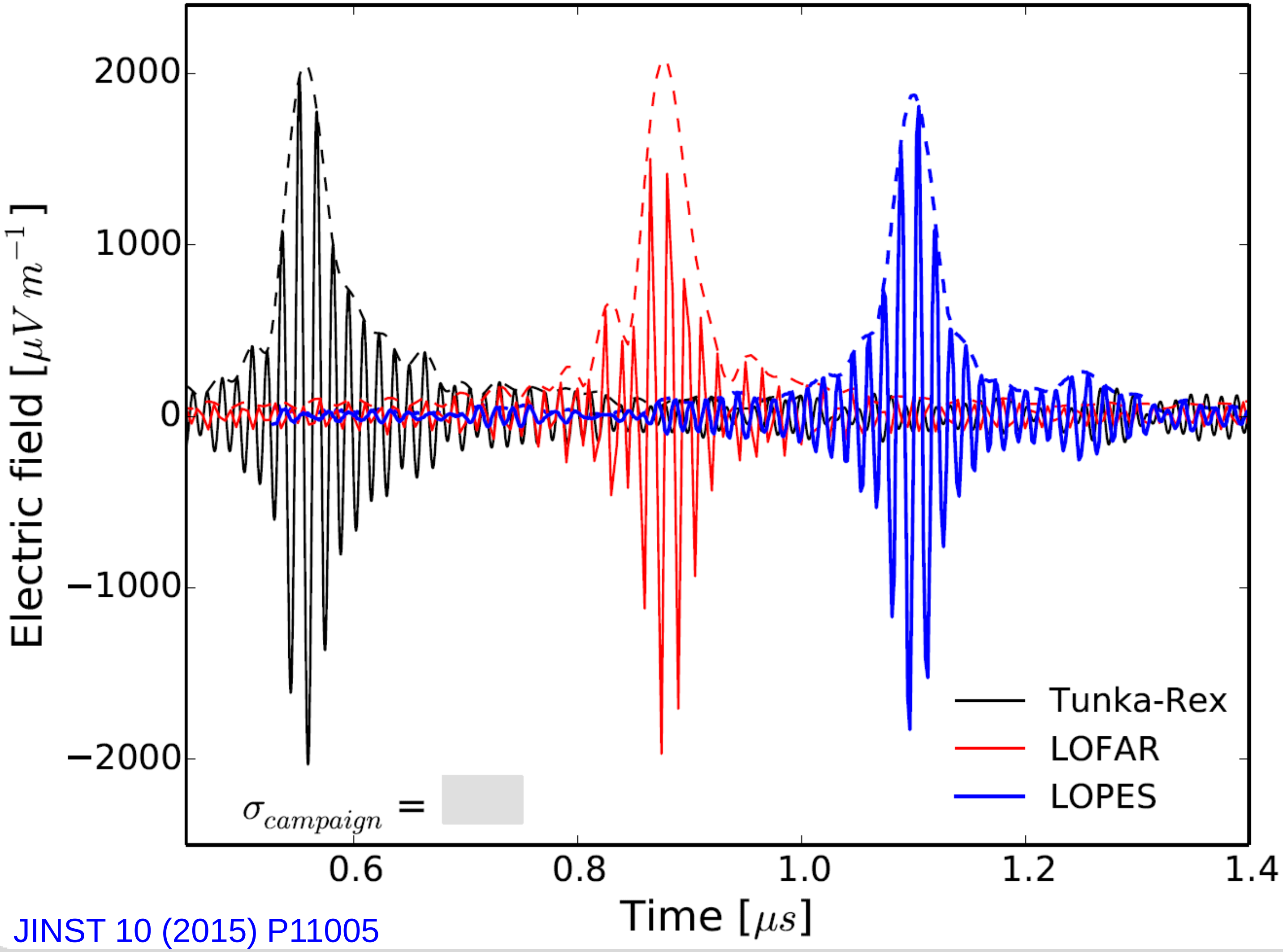
Using data acquisition of
Tunka-133 / Tunka-Grande

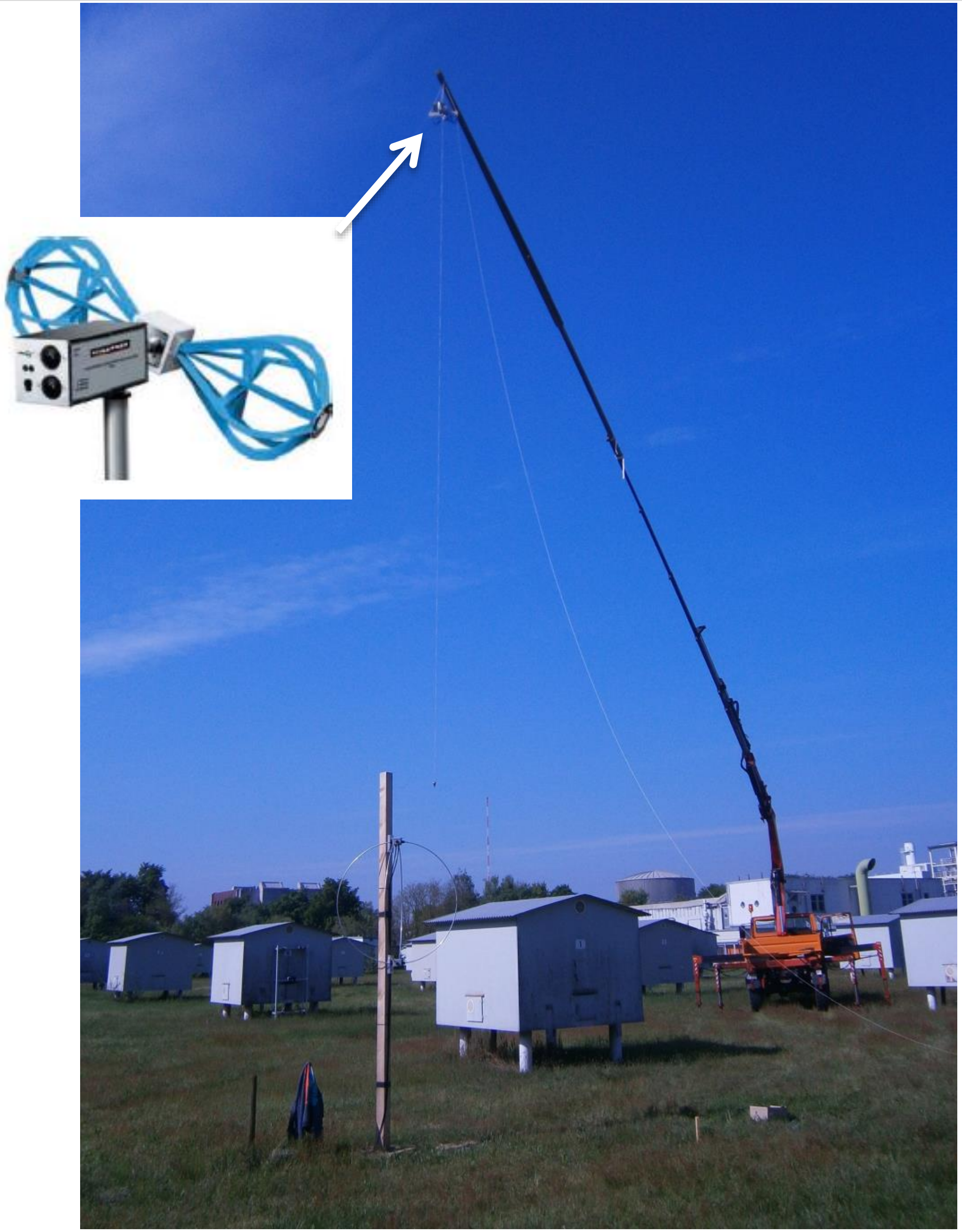


Tunka-Rex Coll.

Amplitude Calibration

- External reference gives absolute scale

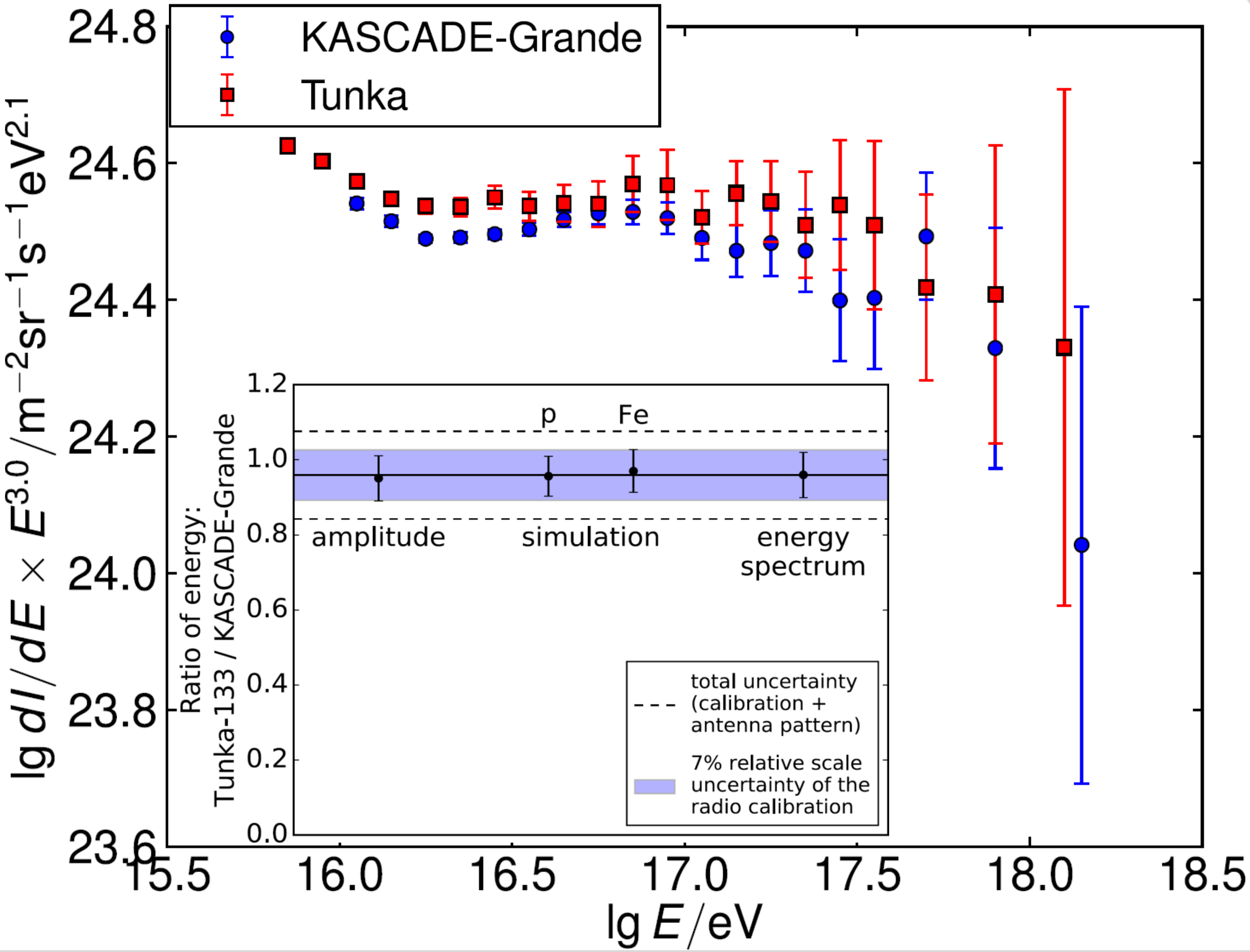




JINST 10 (2015) P11005

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

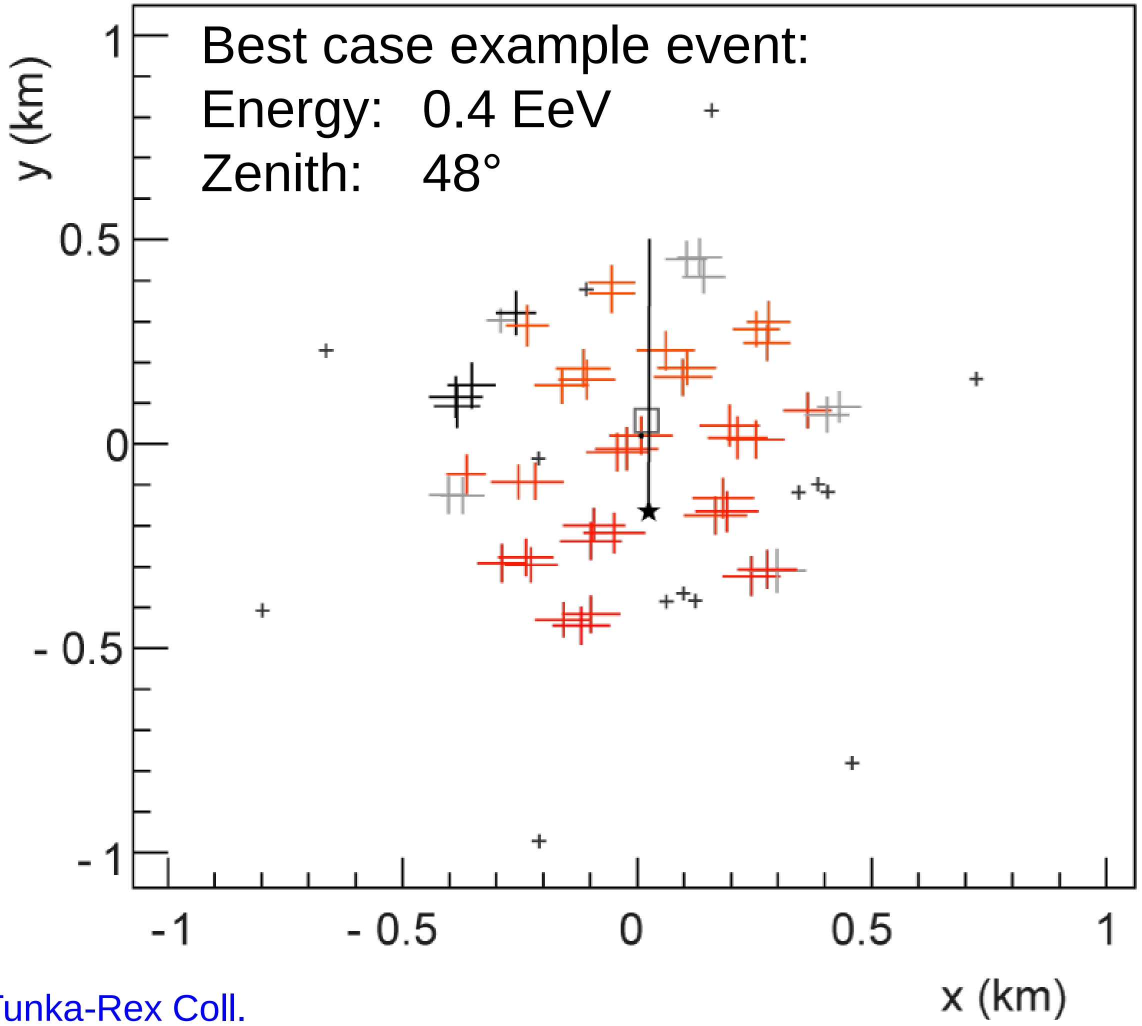
- Relative comparison, absolute accuracy of both arrays is 20 %
- The energy scales of both experiments agree within 10%

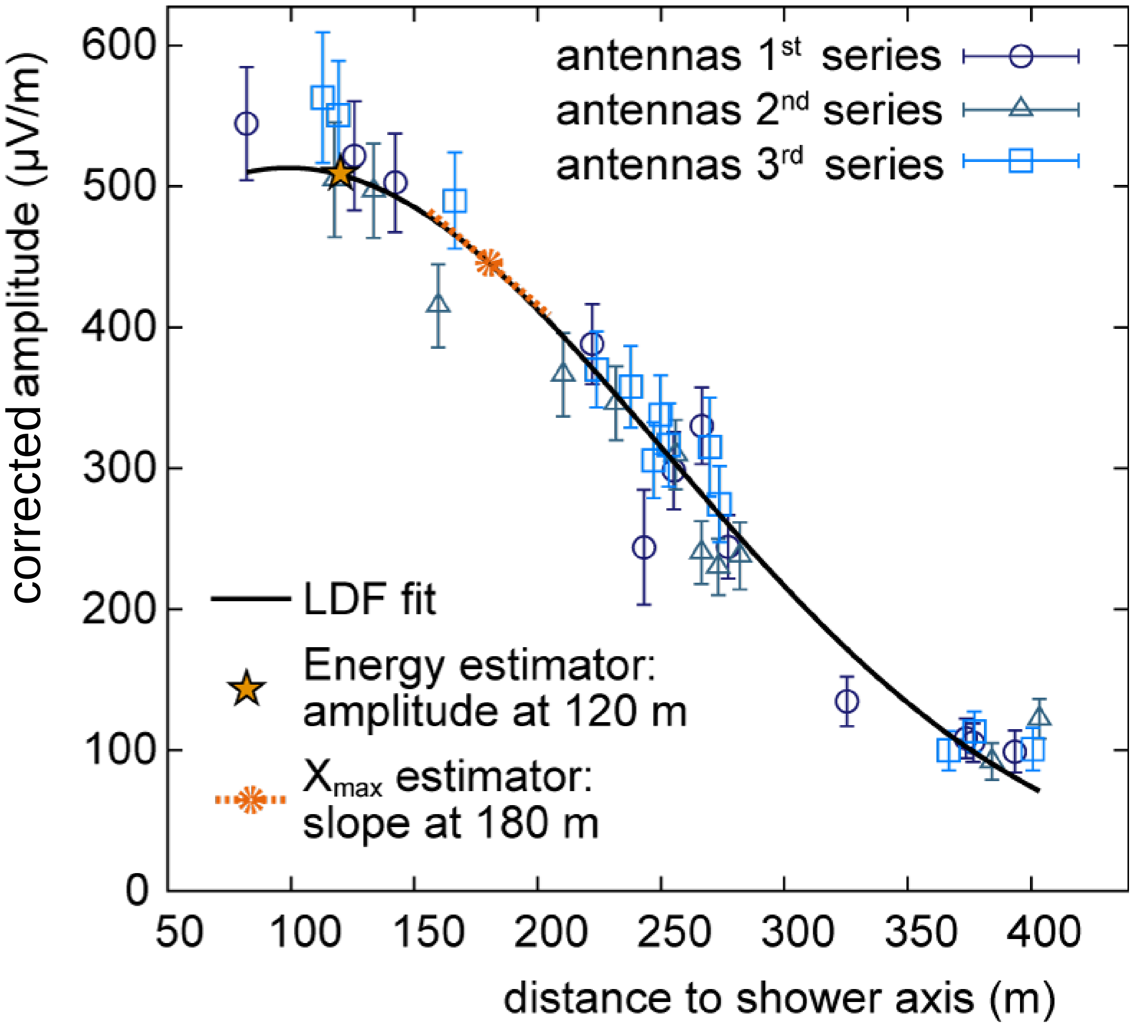


Tunka-Rex + **LOPES** Colls.,
PLB 763 (2016) 179

Simple standard method for reconstruction

- energy by amplitude (after asymmetry correction); distance to X_{max} by slope of LDF





Tunka-Rex Coll.

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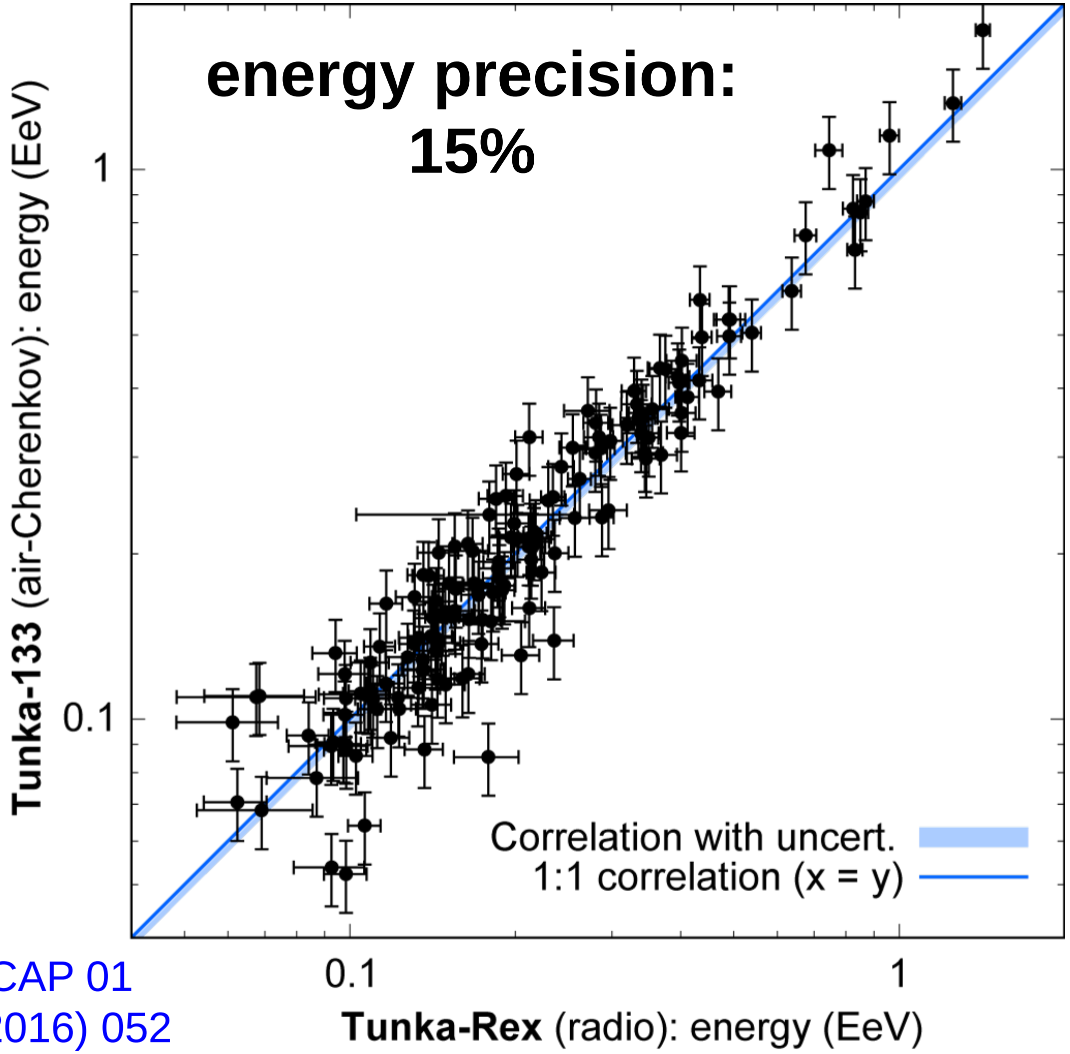
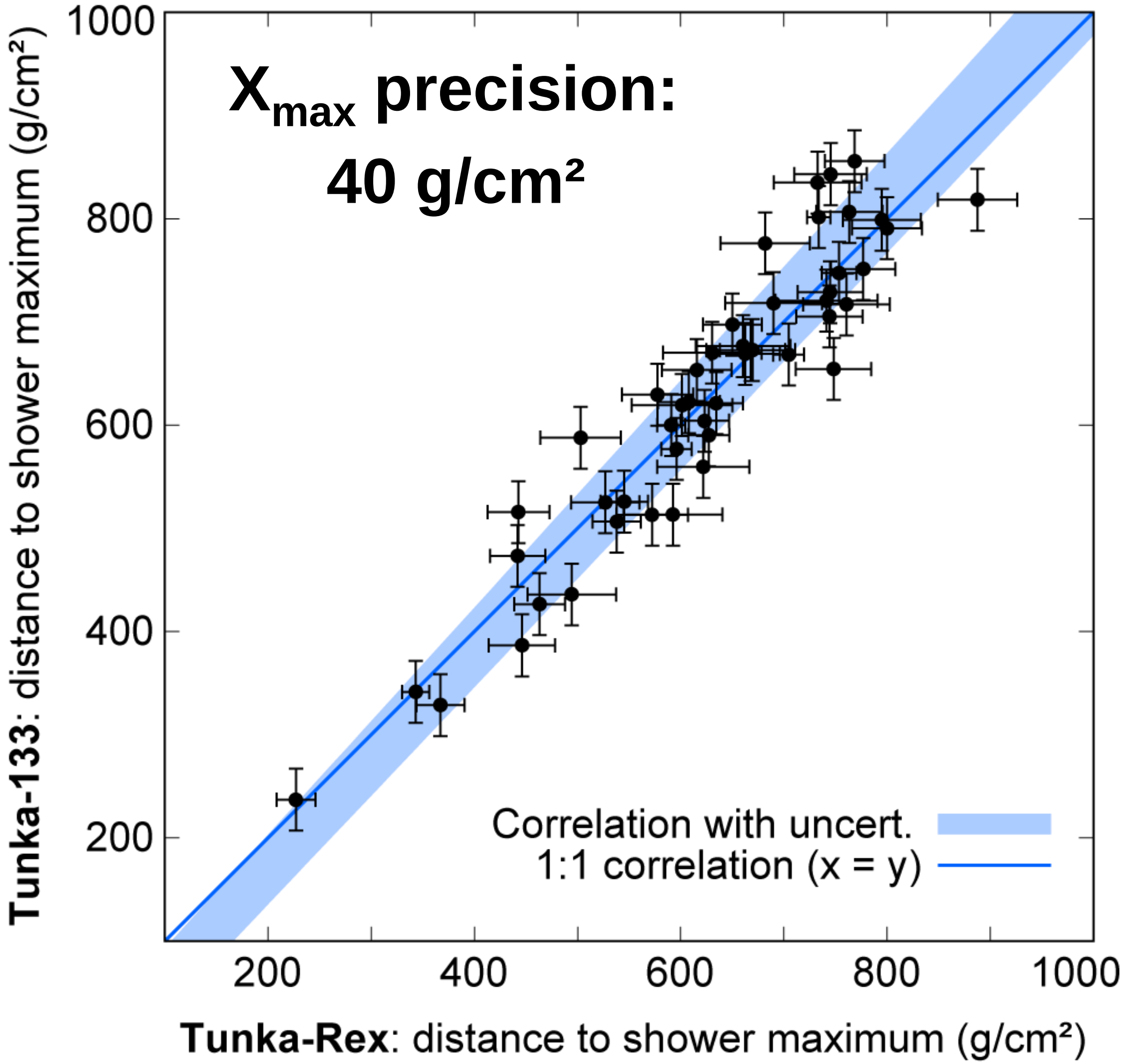
Correlation of Radio and Cherenkov-light measurements

- Experimental proof that radio is sensitive to distance to shower maximum

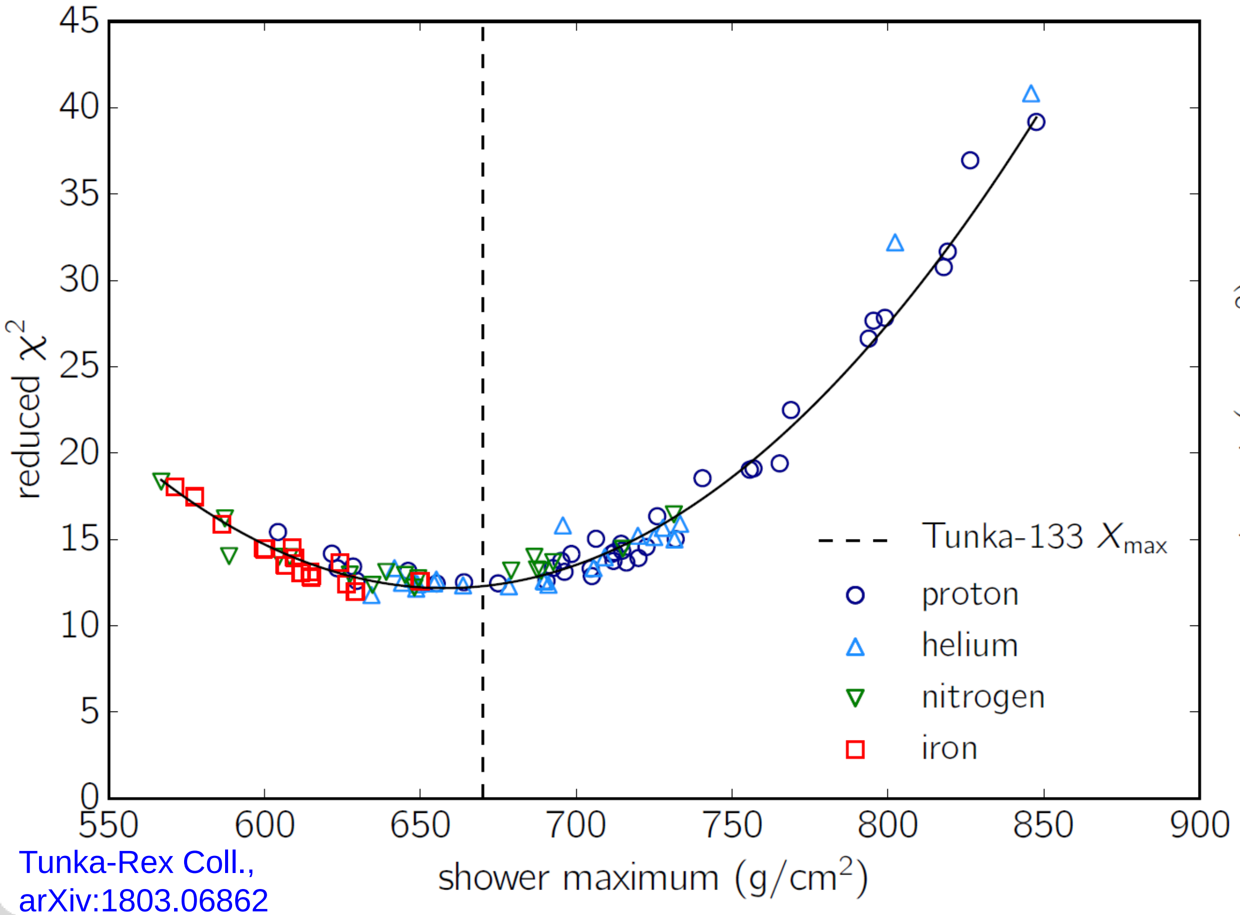


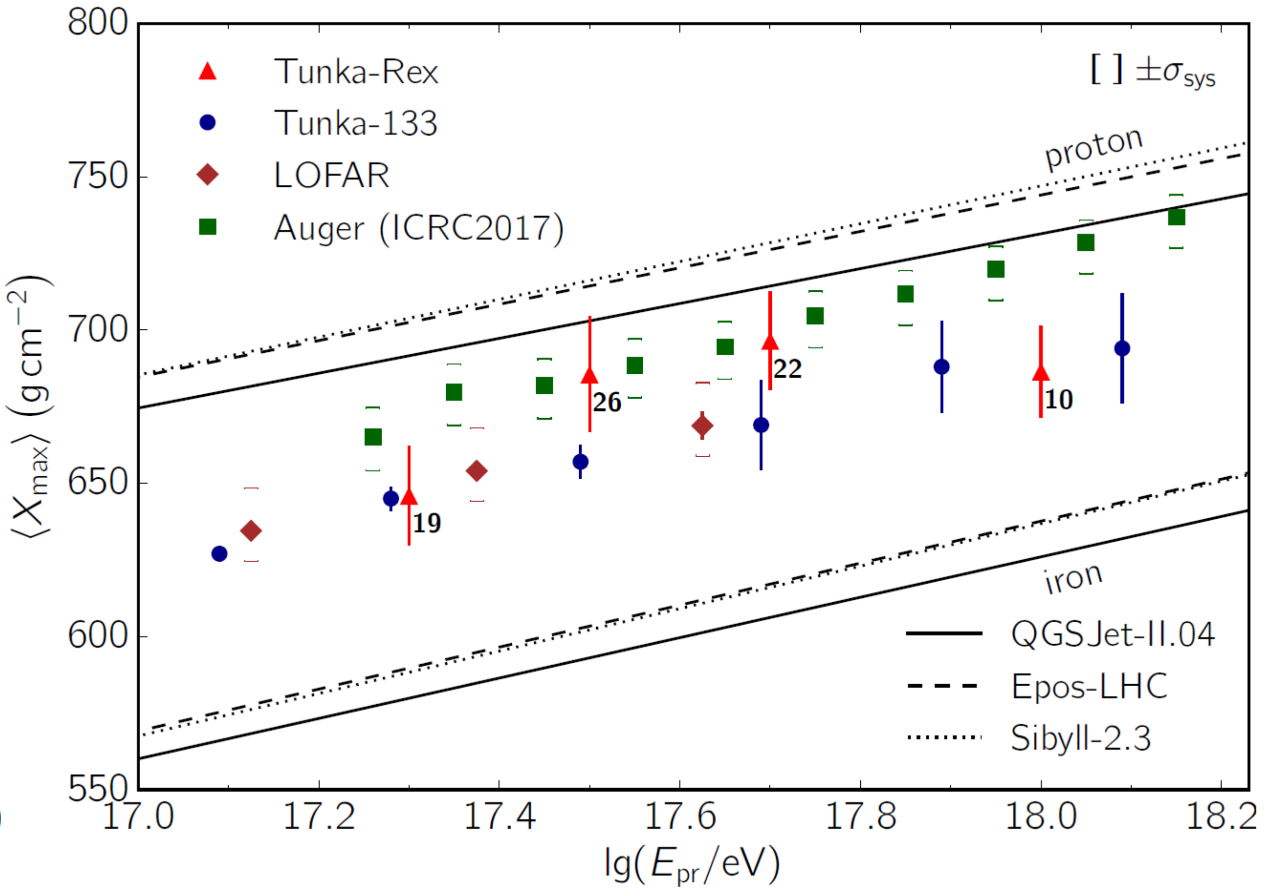


JCAP 01 (2016) 052

X_{max} reconstruction by Tunka-Rex

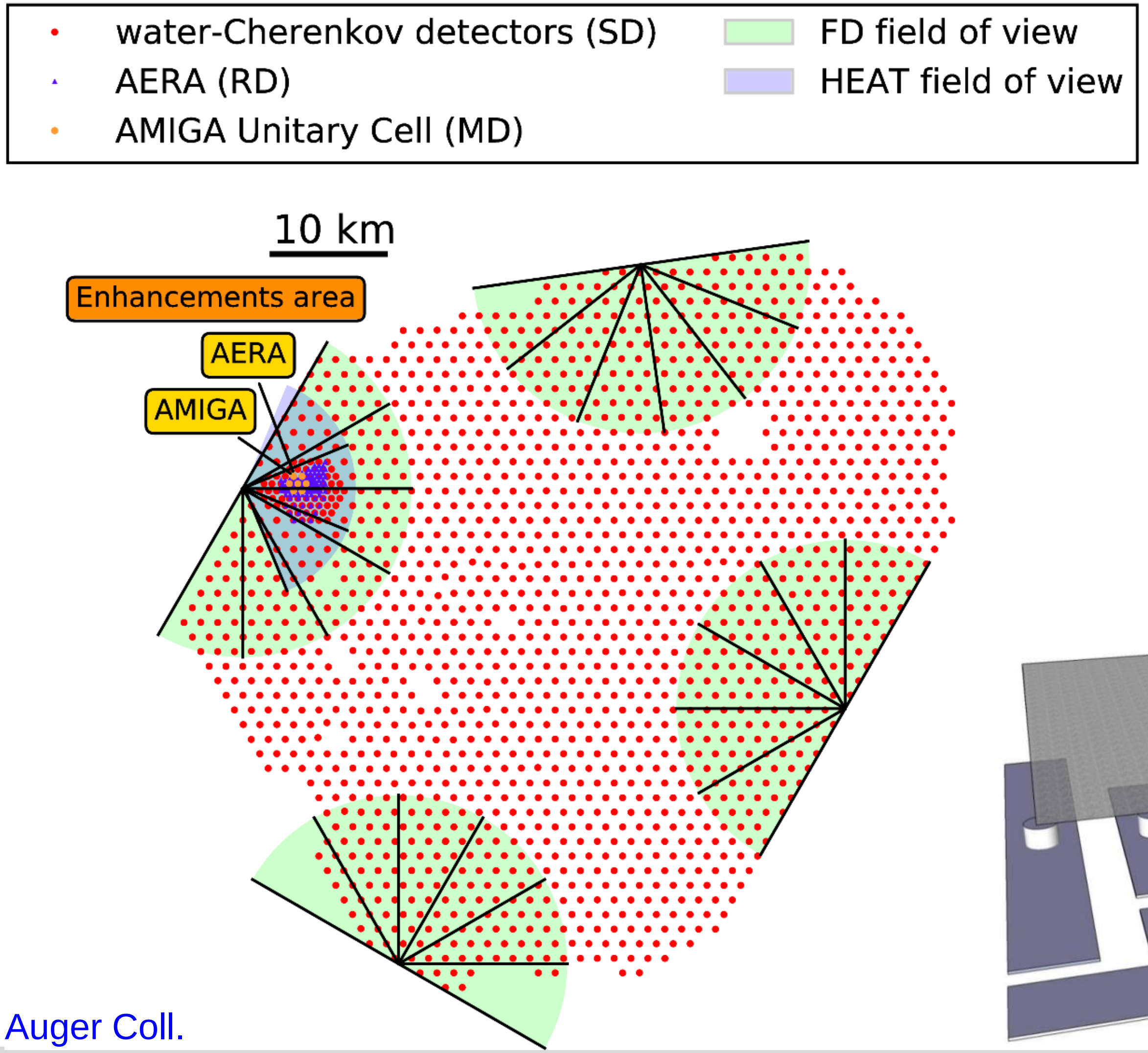
- Many CoREAS simulations per event → select X_{max} of best fitting simulation
- Precision ~ 30 g/cm² by using pulse shape (< 20 g/cm² for dense LOFAR using maximum amplitude)





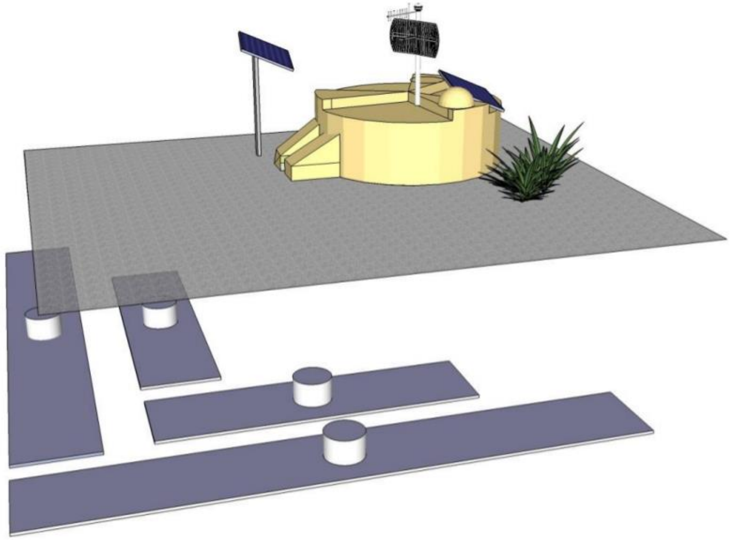
Tunka-Rex Coll., arXiv:1803.06862

Auger Engineering Radio Array (AERA) at the Pierre Auger Observatory



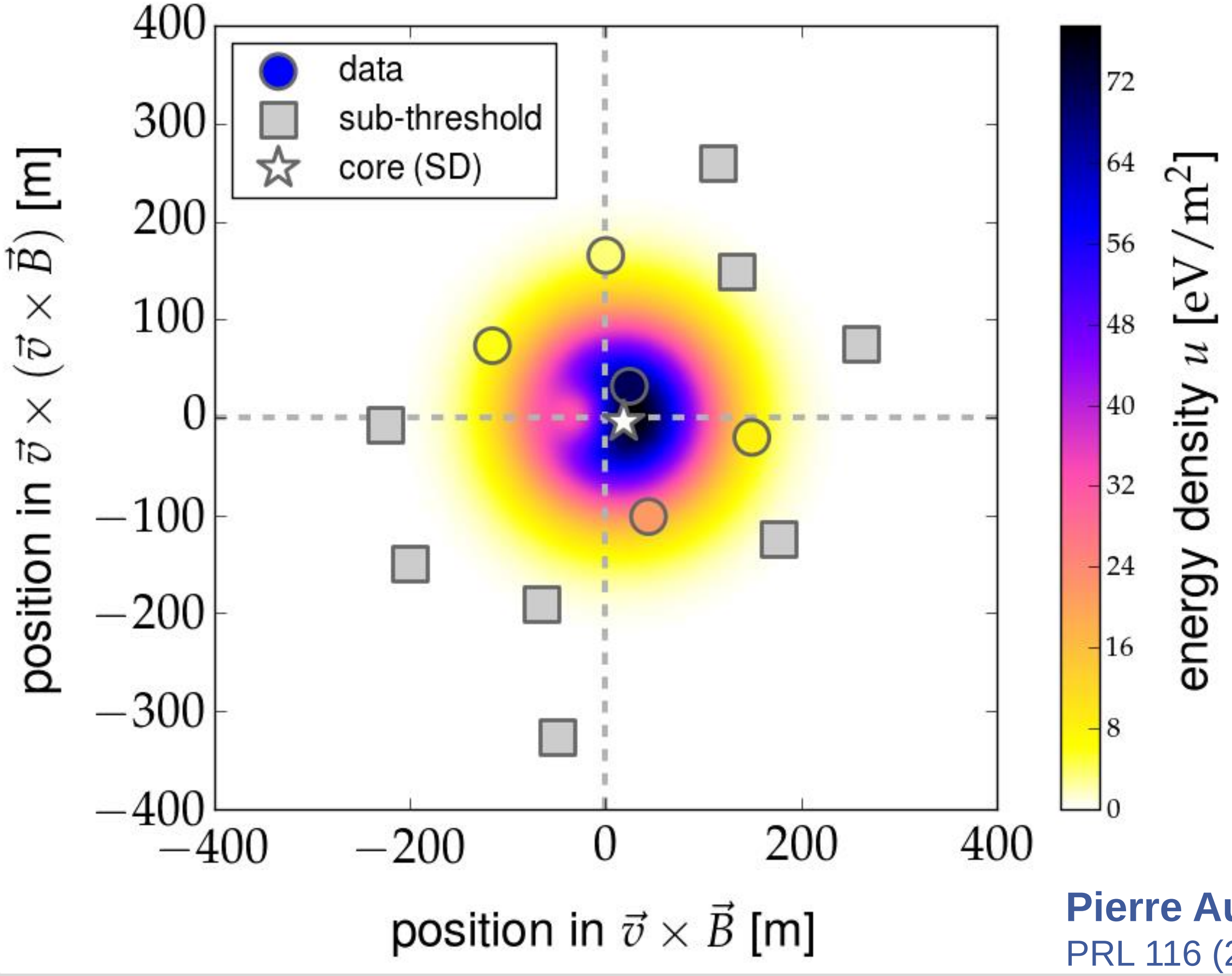
Auger Coll.

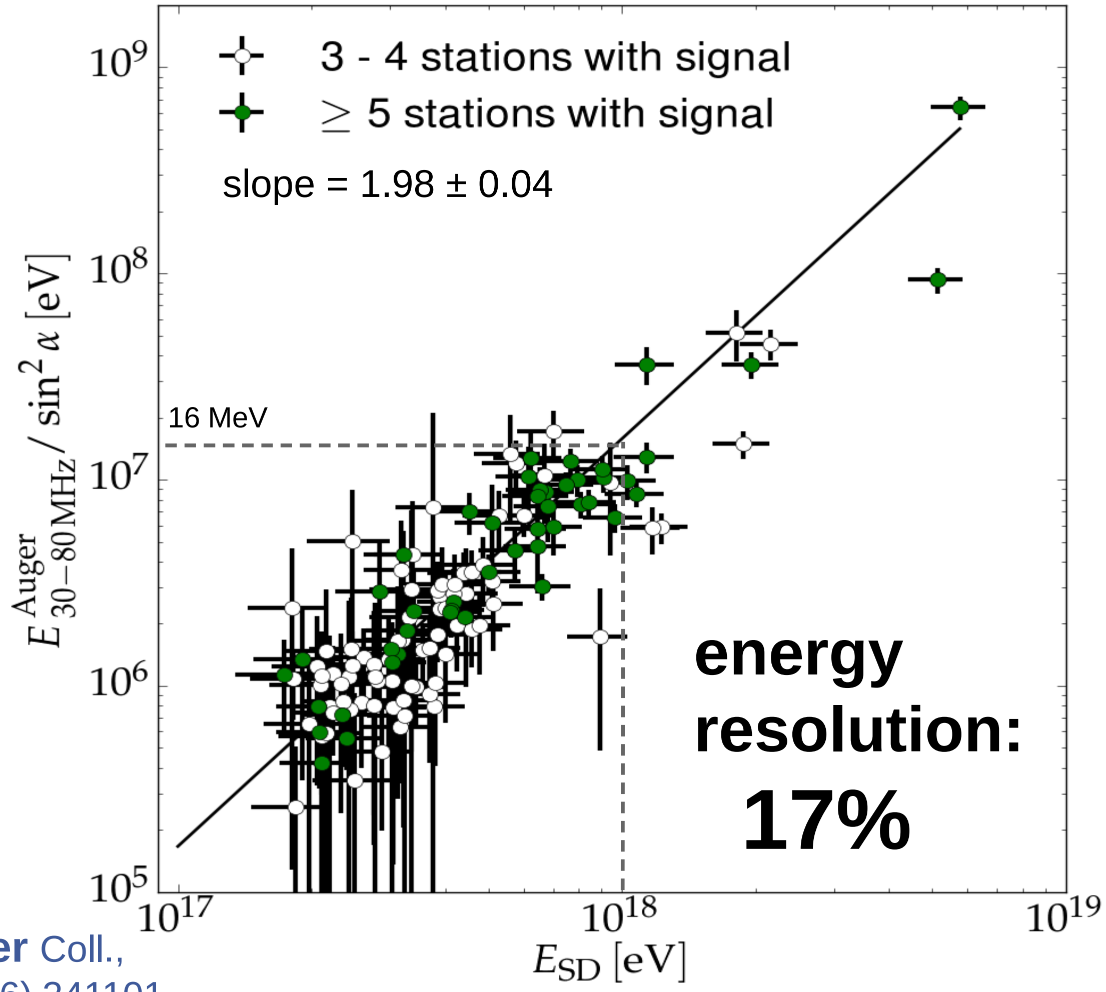
- 153 autonomous radio stations on 17 km²
  - different antennas, electronics, triggers,…
- Coincident measurements with surface, underground and fluorescence detectors



Energy reconstruction by AERA

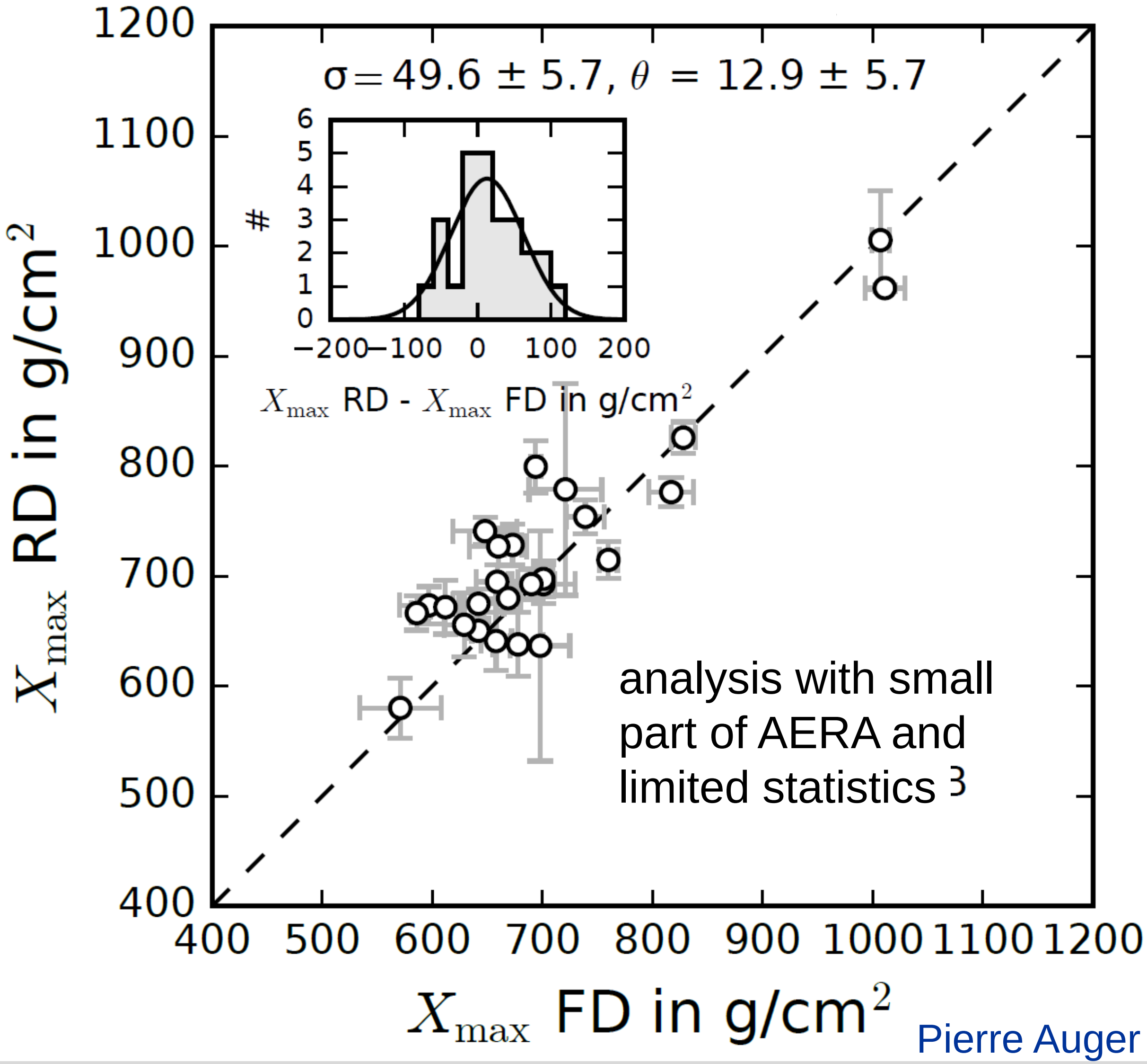
- Total energy in radio signal scales quadratically with electro-magnetic shower energy





Pierre Auger Coll.,
PRL 116 (2016) 241101

Radio-Fluorescence correlation of shower maximum

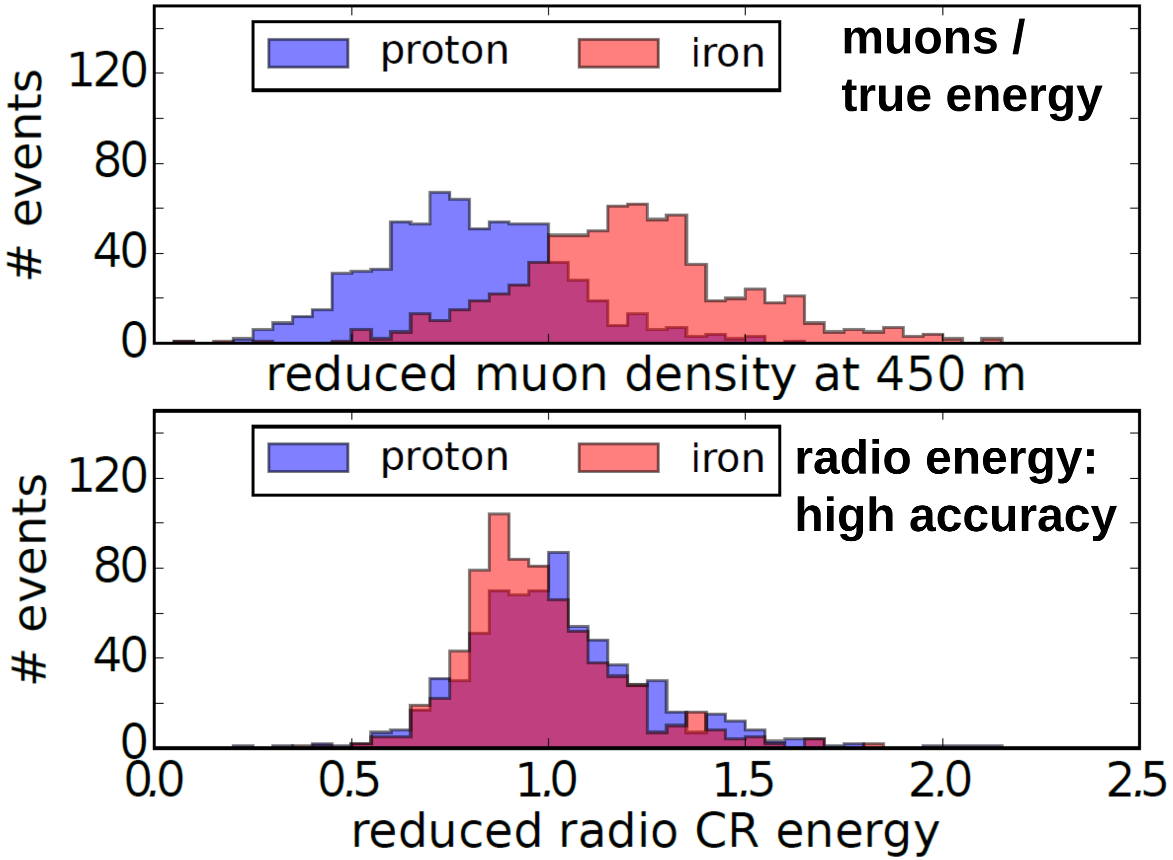


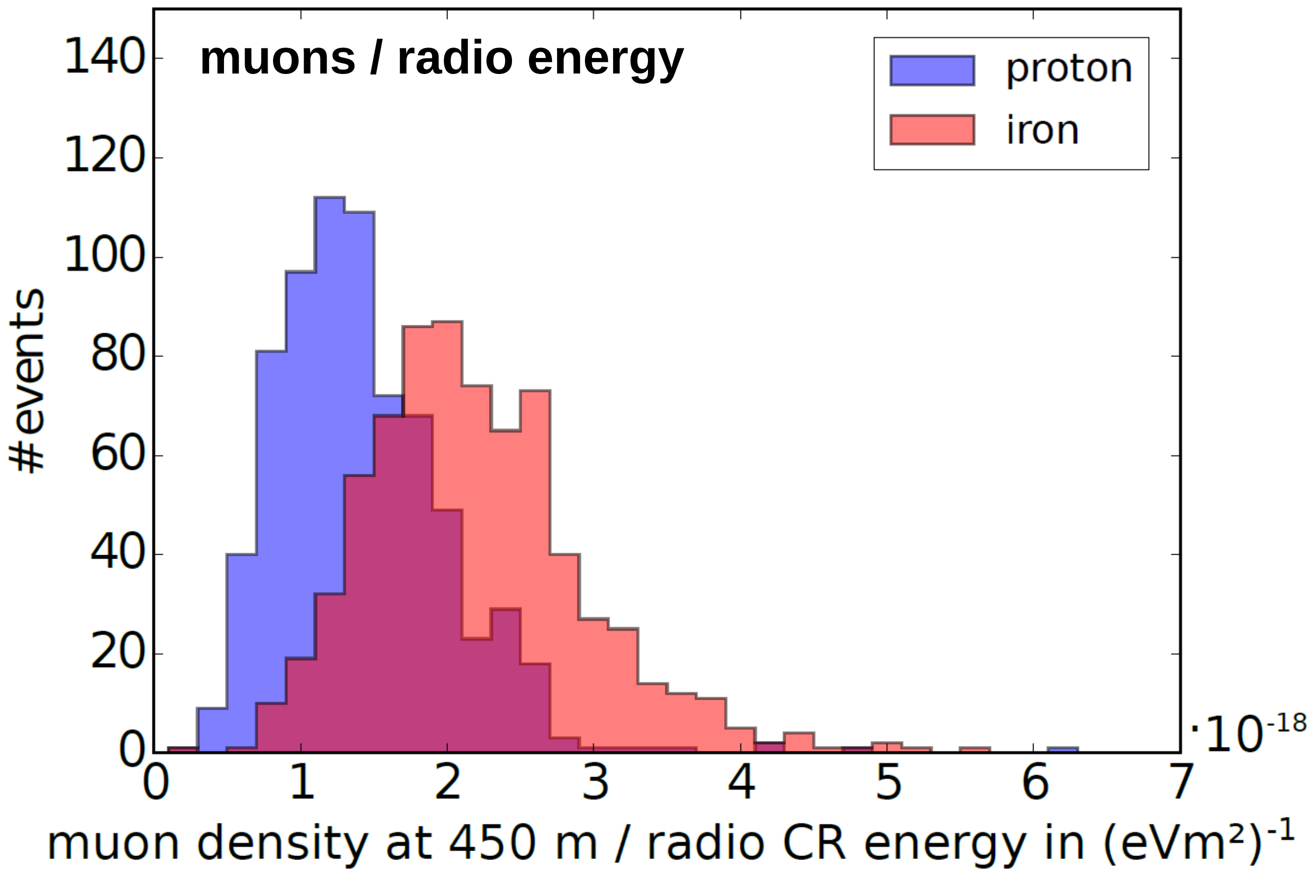
Pierre Auger Coll., ICRC 2017

- AERA results on energy and X_{max} consistent with other radio arrays
- First analysis shows correlation between fluorescence and radio
- Accuracy likely to improve by better methods and quality of data set

Mass separation by radio + muon detection

- CORSIKA + CoREAS simulations for AERA + buried muon detectors
- Complementary to shower maximum → maximize accuracy for composition



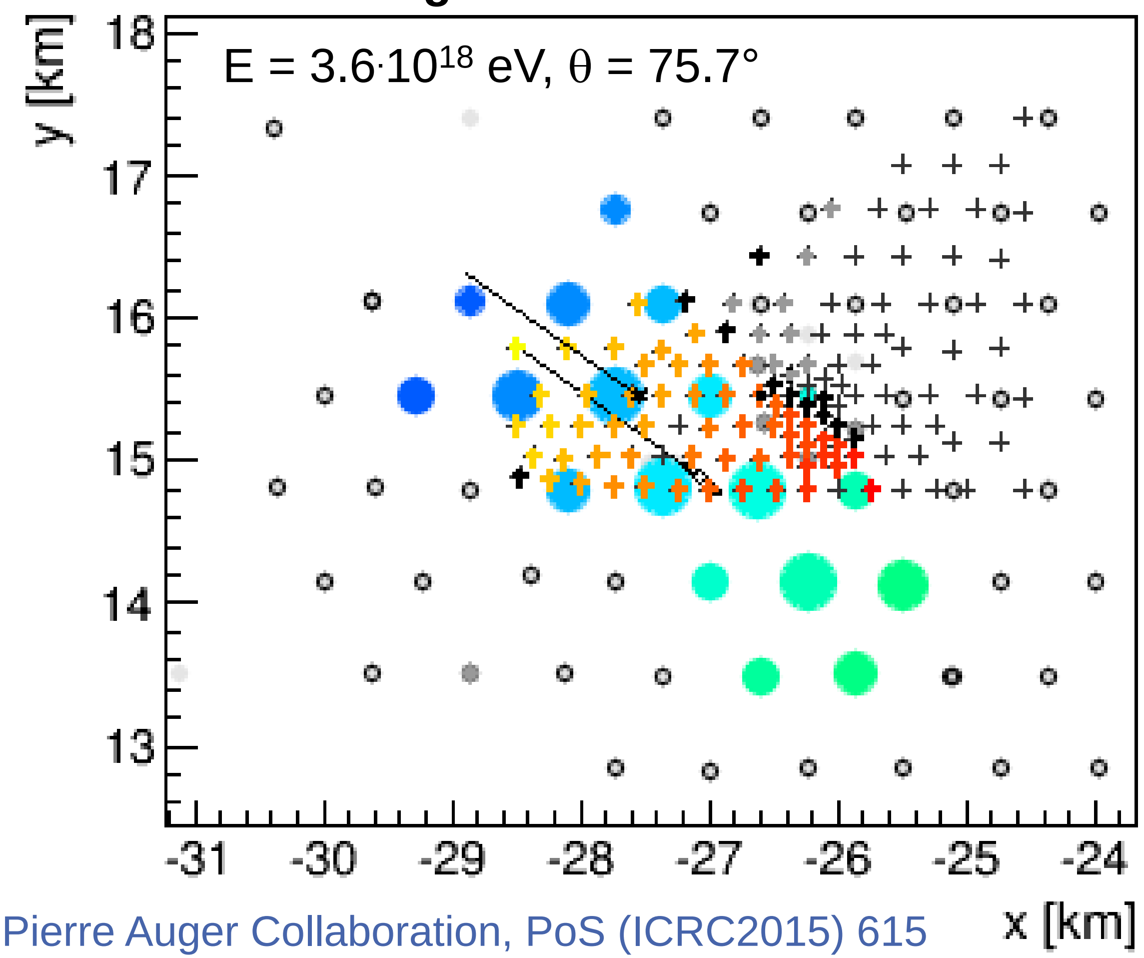


E. Holt (Auger Coll.) [best poster prize], PoS (ICRC2017) 492

Huge footprint for inclined showers

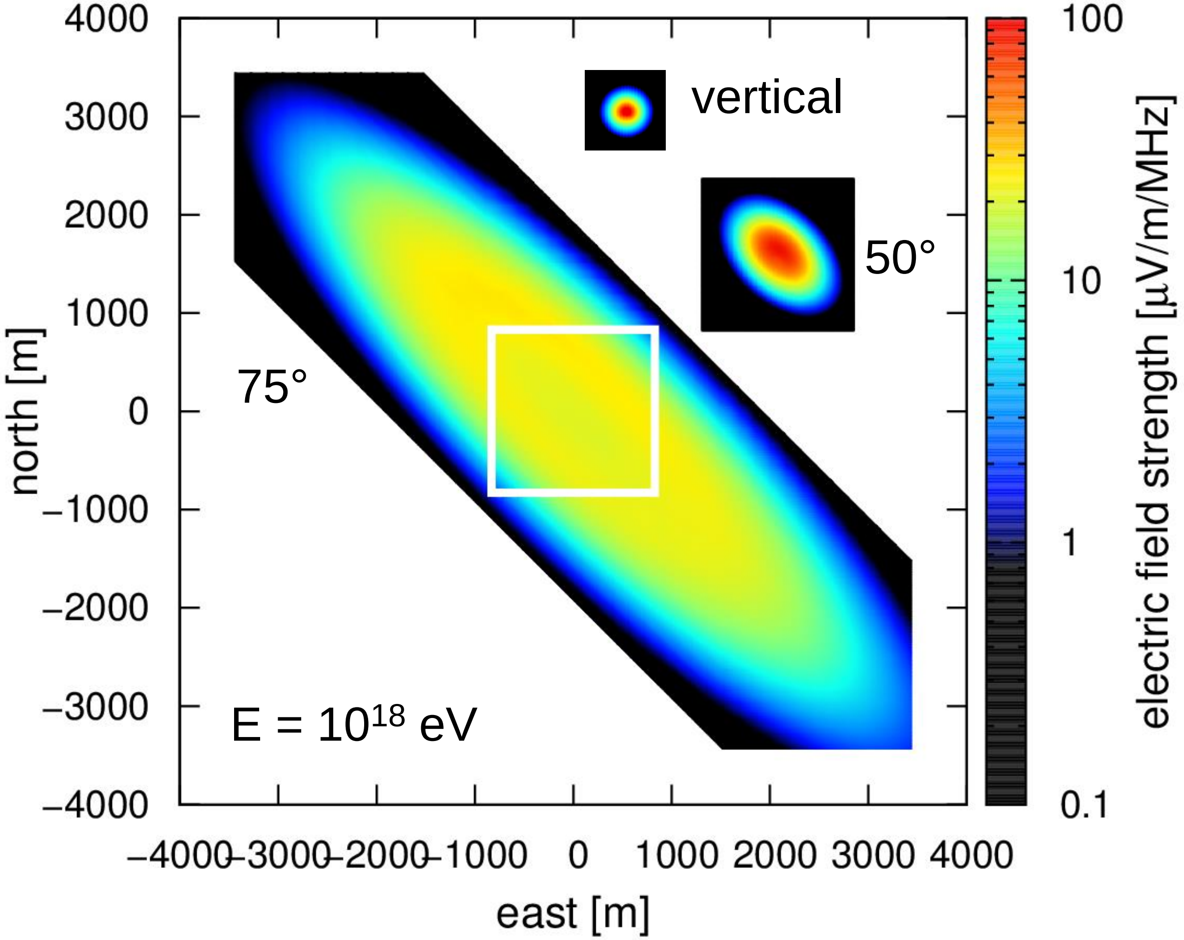
- Enables sparse antenna arrays for highest energies at reasonable costs

Auger measurement



Pierre Auger Collaboration, PoS (ICRC2015) 615

CoREAS simulation



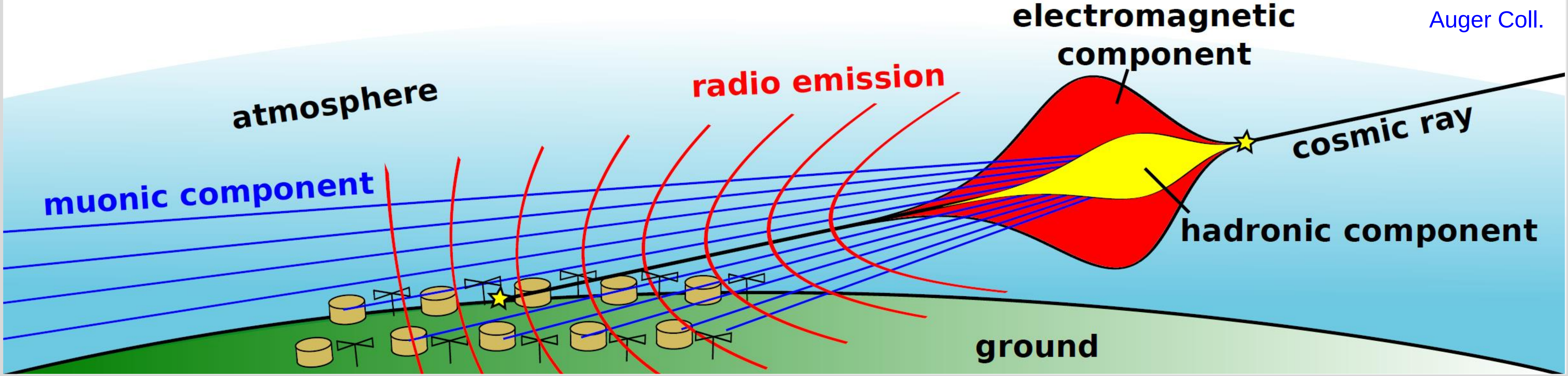
Content

- Radio emission by air showers (not covering dense media, such as ice)
  - Tests of simulations / models
- Results of selected experiments (focus on Tunka-Rex and Auger)
  - Energy and mass composition
- **Future radio arrays for air-showers (plans and ideas)**
  - **Auger Radio Upgrade**
  - **GRAND**
  - **SKA**
  - **Radio array at the South Pole**

Idea for future radio upgrade

- Potentially add one antenna to each upgraded surface detector
  - Enhanced mass-sensitivity for inclined showers
  - Mass-sensitive anisotropy studies with increased sky coverage
  - Search for neutrinos + photons

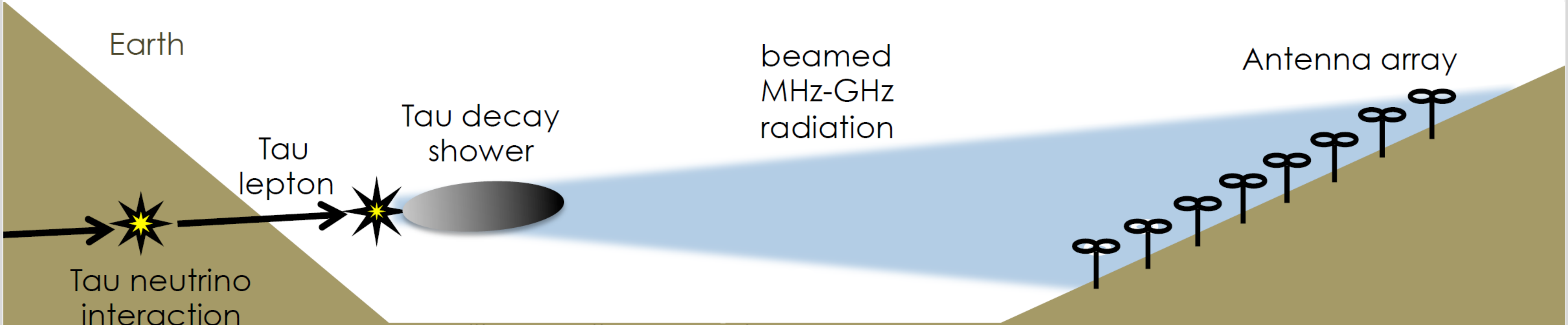
Auger Coll.



Giant Radio Array for Neutrino Detection (GRAND)

- Huge array in China for cosmic rays and neutrinos above 10^{17} eV

GRAND	Start	Antennas	Size	Main Goal
Phase 1	2018	35	2 km²	technical prototype
Phase 2	2020	300	ca. 200 km²	galactic cosmic rays
Phase 3	2025	10.000	10.000 km²	extragalactic CR + neutrinos
Phase 4	2030's	200.000	200.000 km²	cosmogenic neutrinos



credit: O. Martineau-Huynh

Search for GZK (cosmogenic) neutrinos

- GZK for protons $E_p \geq 4 \cdot 10^{19}\,\mathrm{eV}$

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow n/p + \pi^{+/-}$$

$$\pi^{+/-} \rightarrow \mu^{+/-} + \nu_{\mu}/\bar{\nu}_{\mu}$$

$$\mu^{+/-} \rightarrow e^{+/-} + \nu_e/\bar{\nu}_e + \bar{\nu}_{\mu}\,/\nu_{\mu}$$

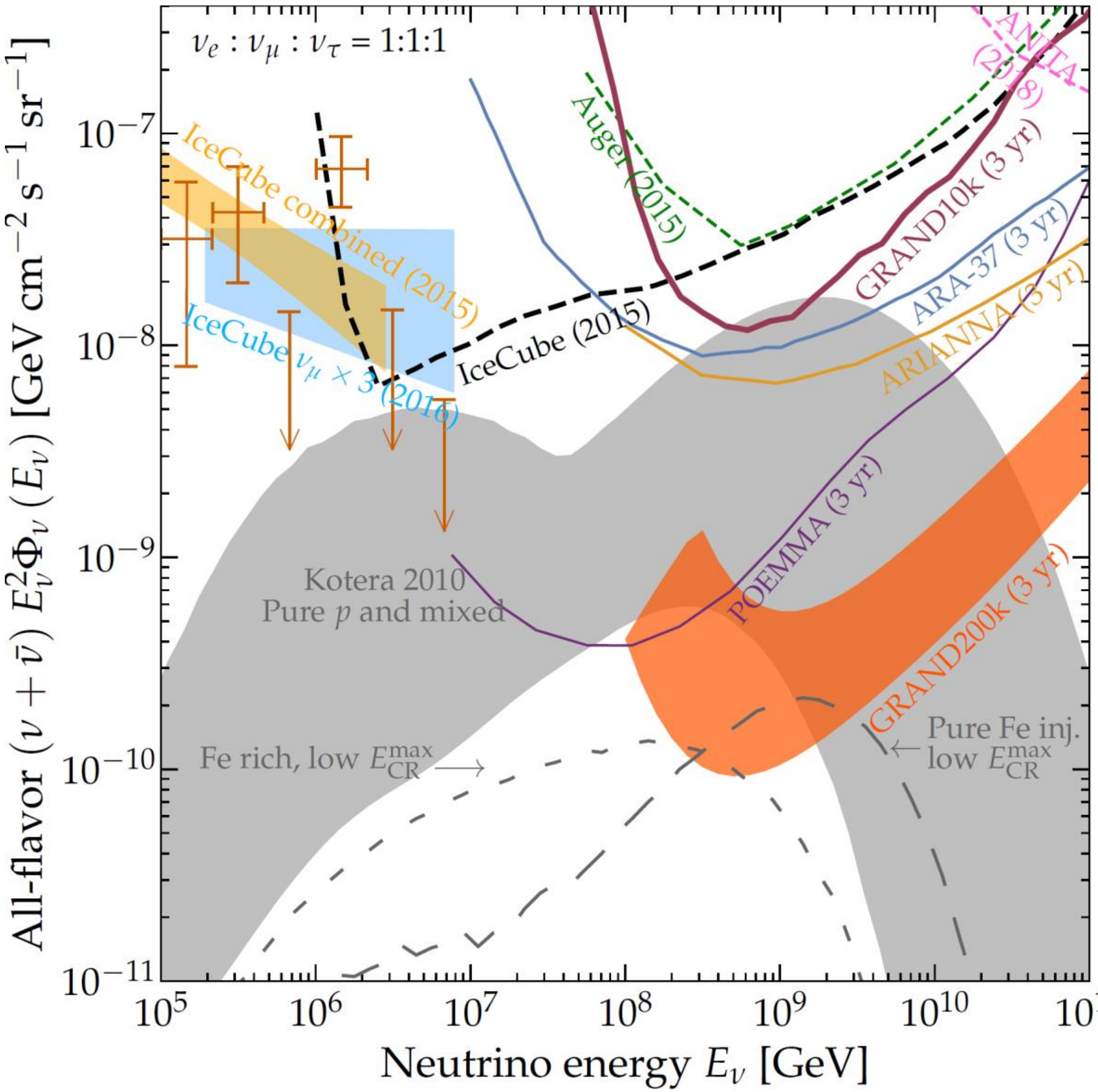
$$E_\nu \approx 0.05\,E_p$$

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

$$E_\nu \approx 0.001\,E_p$$

- For nuclei also interactions other photon backgrounds

A nucleons → $E_\nu \approx 0.05\,E_A/A$



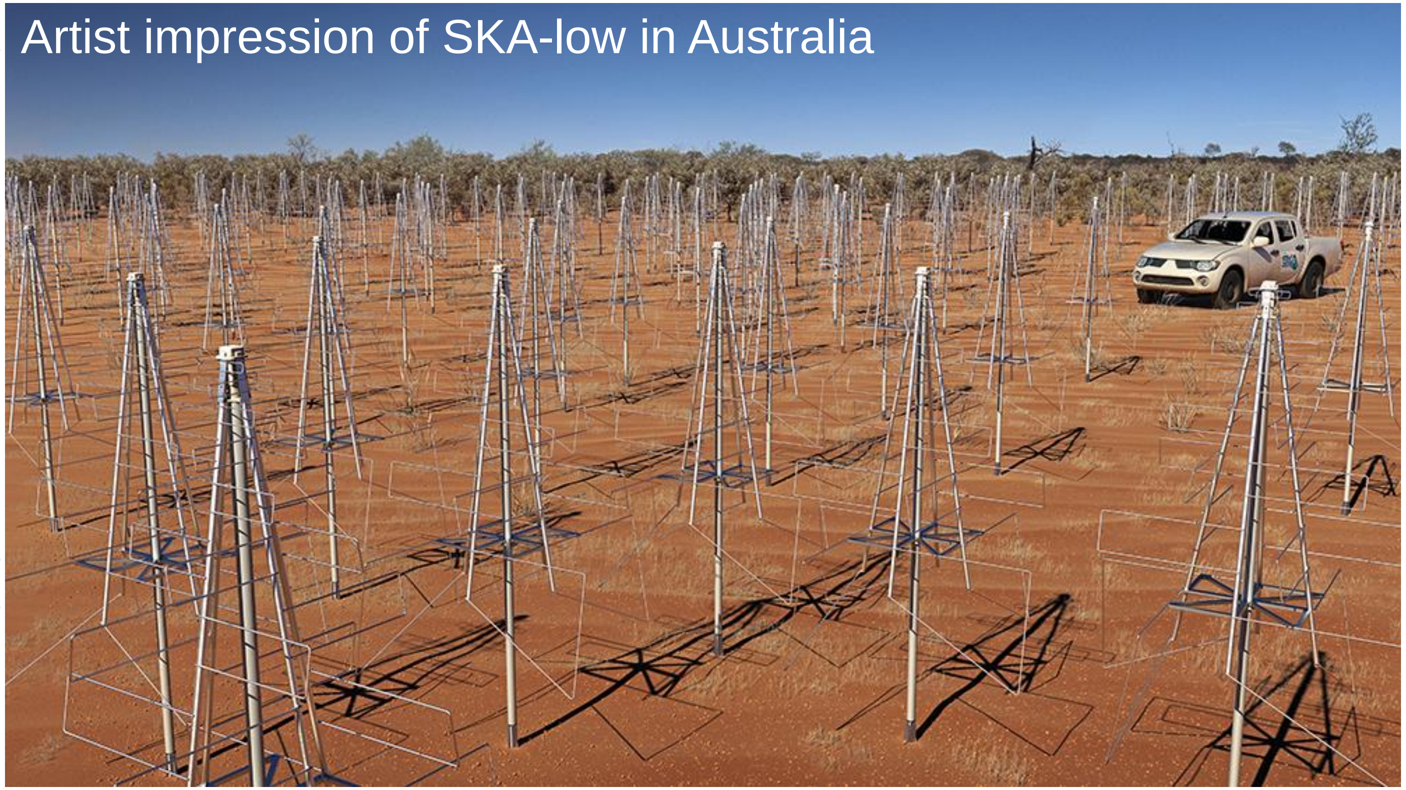
M. Bustamenta, et al., (GRAND Collaboration)

The Square Kilometer Array: ultra high precision

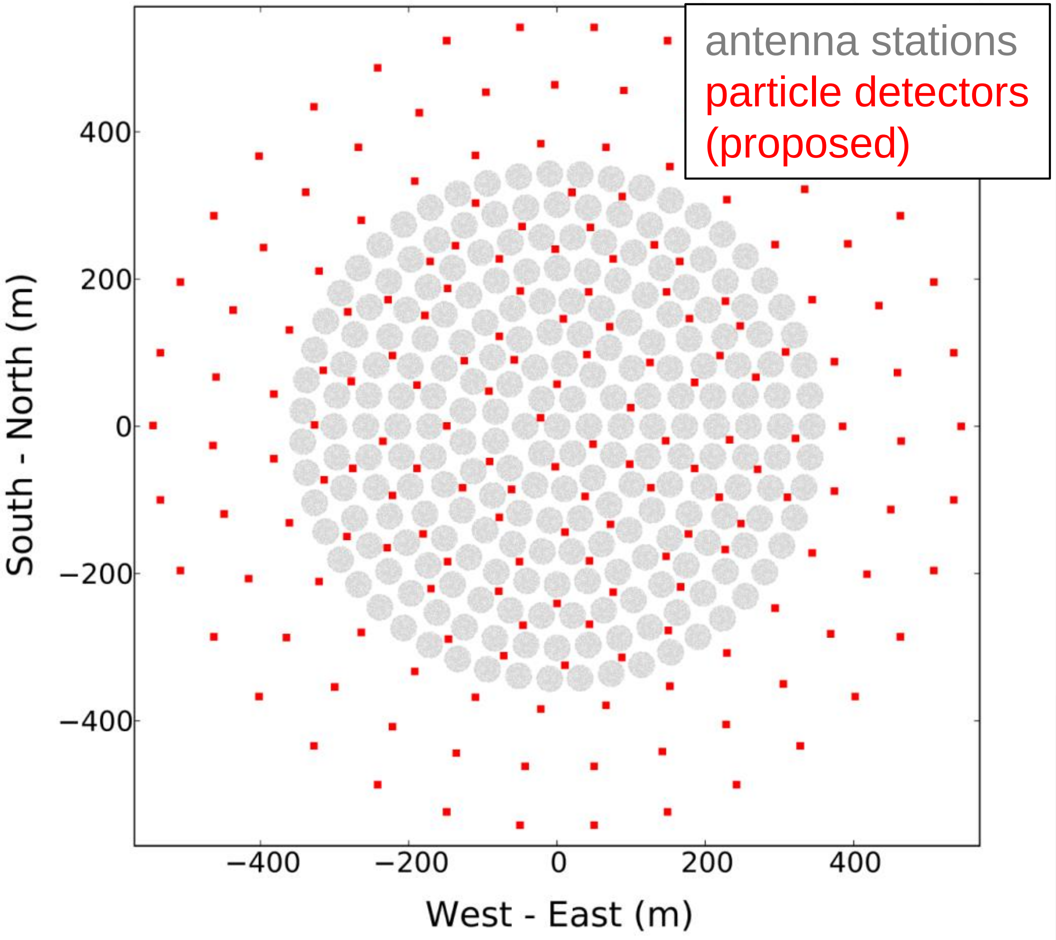
- Air-showers detection in parallel to astronomy (50-350 MHz)
- X_{max} resolution of < 10 g/cm²
- Might enable detailed shower physics with radio

60,000 antennas on ½ km²

Artist impression of SKA-low in Australia



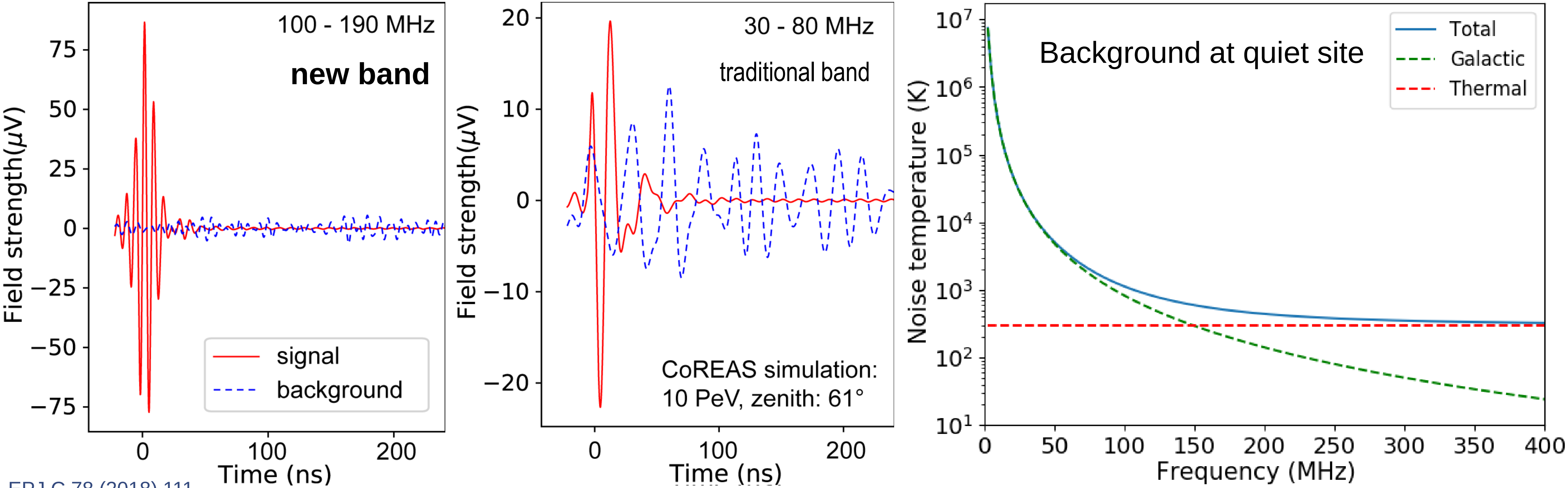
https://www.icrar.org/wa-government-invests-26m-astronomy-square-kilometre-array/



New Idea: Array with PeV threshold at South Pole

- Background at radio-quiet sites falls rapidly towards higher frequencies
- Radio threshold can be lowered to PeV by extending frequency band

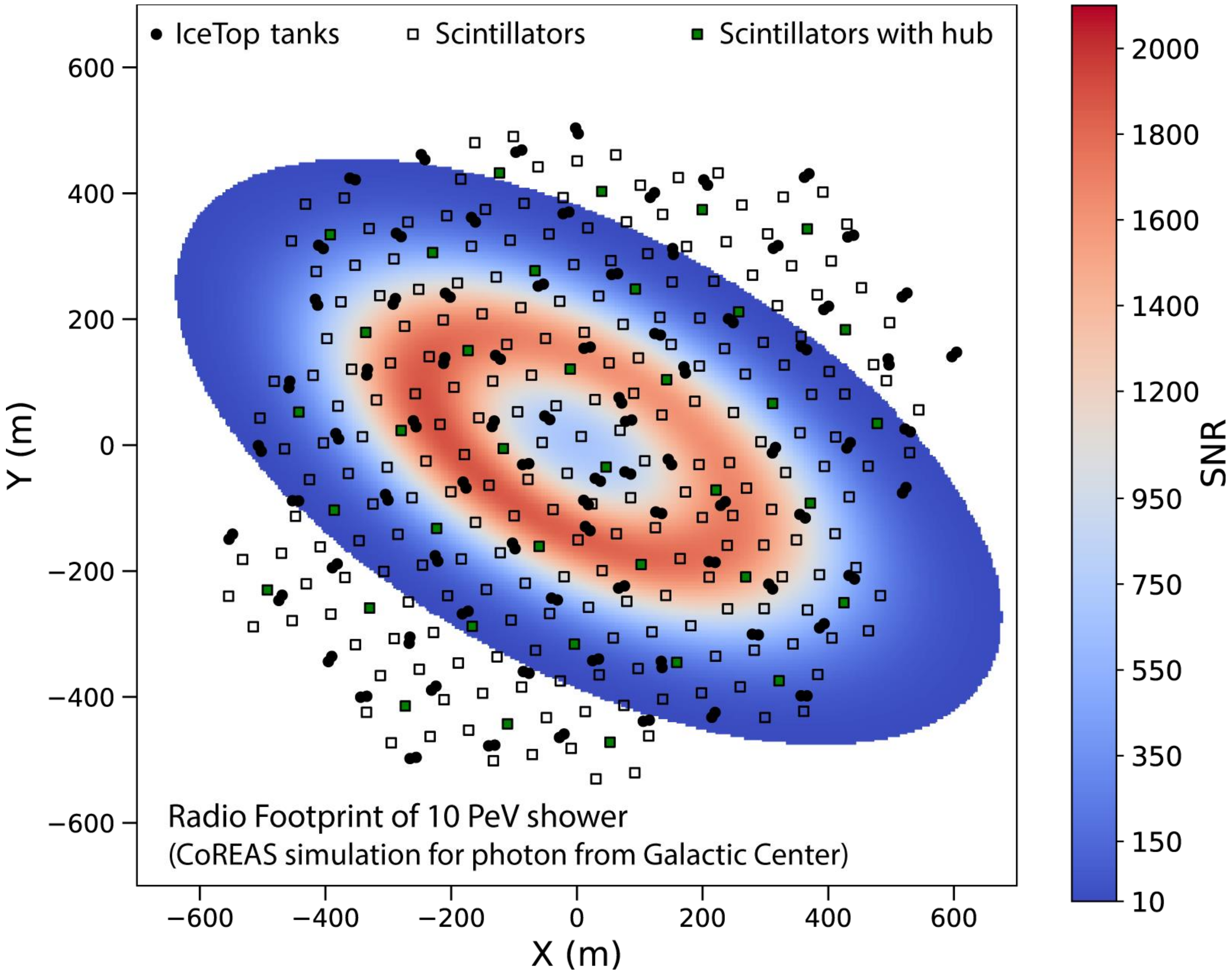
  → New science goal of PeV photon search in addition to air-shower and cosmic-ray physics

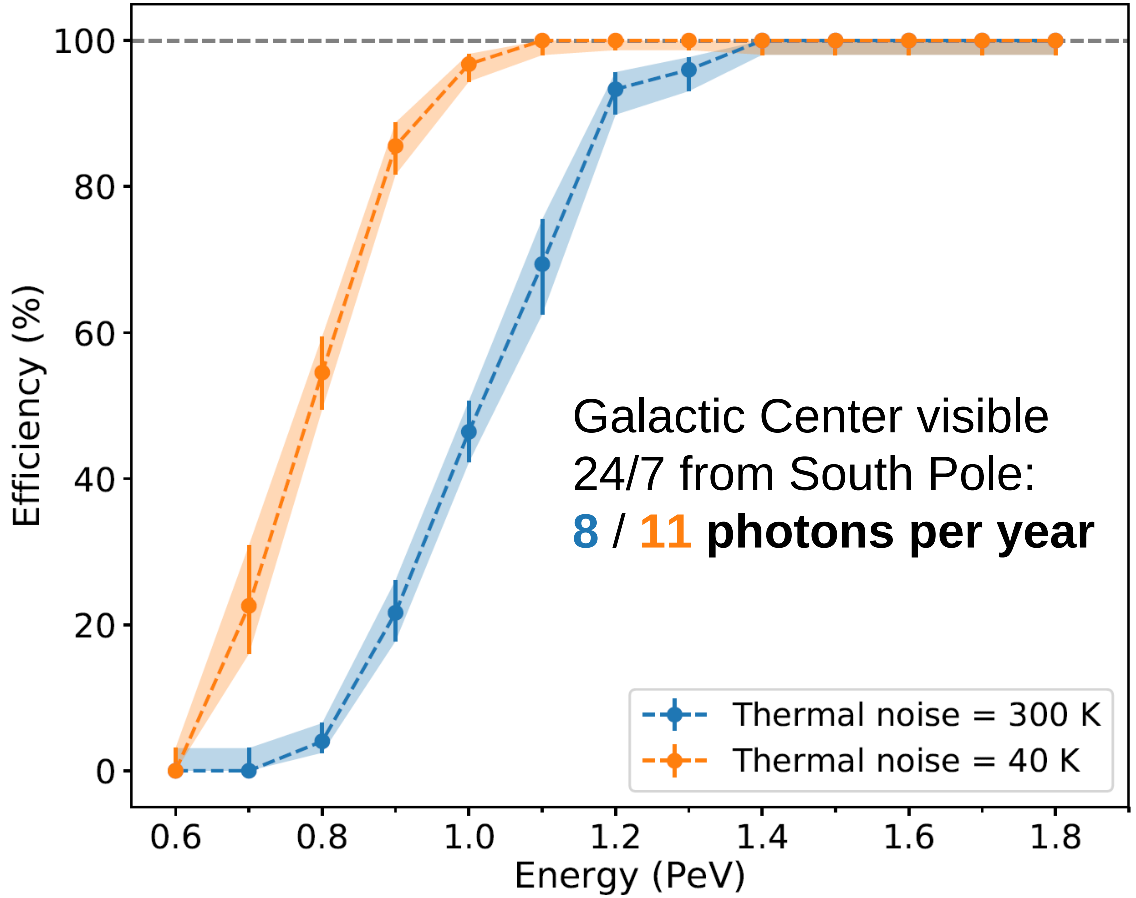


EPJ C 78 (2018) 111

Simulation study on proposed radio array at South Pole

- 1 km² with 125 m spacing between antennas





Galactic Center visible 24/7 from South Pole:
8 / 11 photons per year

Search for PeVatrons at the Galactic Center using a radio air-shower array at the South Pole
A. Balagopal V., A. Haungs, T. Huege, F.G. Schröder,
European Physics Journal C 78 (2018) 111

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; models consistent on that level
  - ideal for inclined showers and in combination with muon detectors

- Competitive accuracy for air shower parameters
  - direction < 0.5°
  - energy 15 - 20% (precision + scale)
  - X_{max} 20 - 30 g/cm² (depending on antenna density)

- Future projects will extend energy range to 10^{15} eV – 10^{21} eV
  - cosmic-ray mass-composition, energy, and anisotropy
  - photon and neutrino searches

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

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