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Digital Radio Array for Ultra-High-Energy Cosmic Particles

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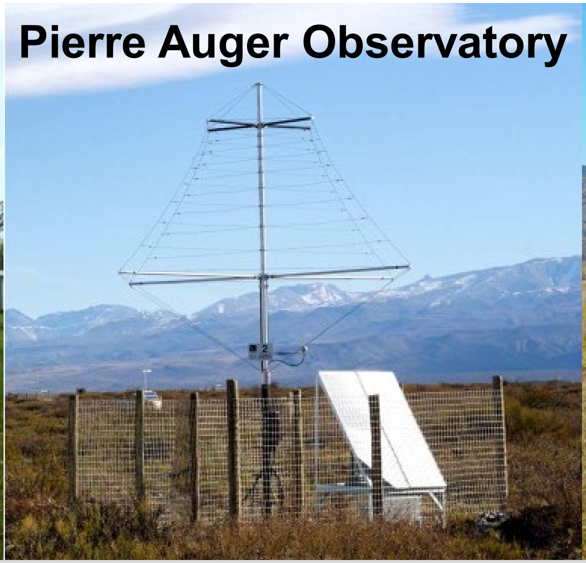

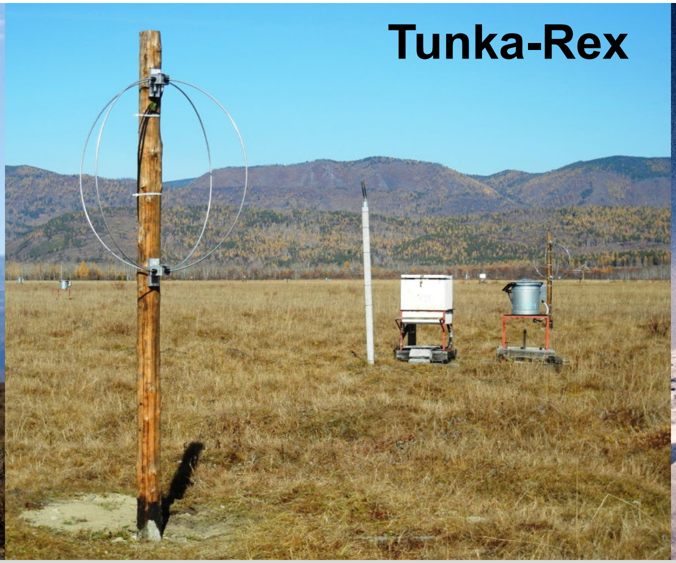

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KIT – The Research University in the Helmholtz Association

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Content

- Radio emission by cosmic-ray air showers
- Energy and X_{max} measurement by radio
- Selected radio experiments for cosmic-ray air showers (with personal bias)
  - LOPES, Tunka-Rex, AERA, SKA, IceCube

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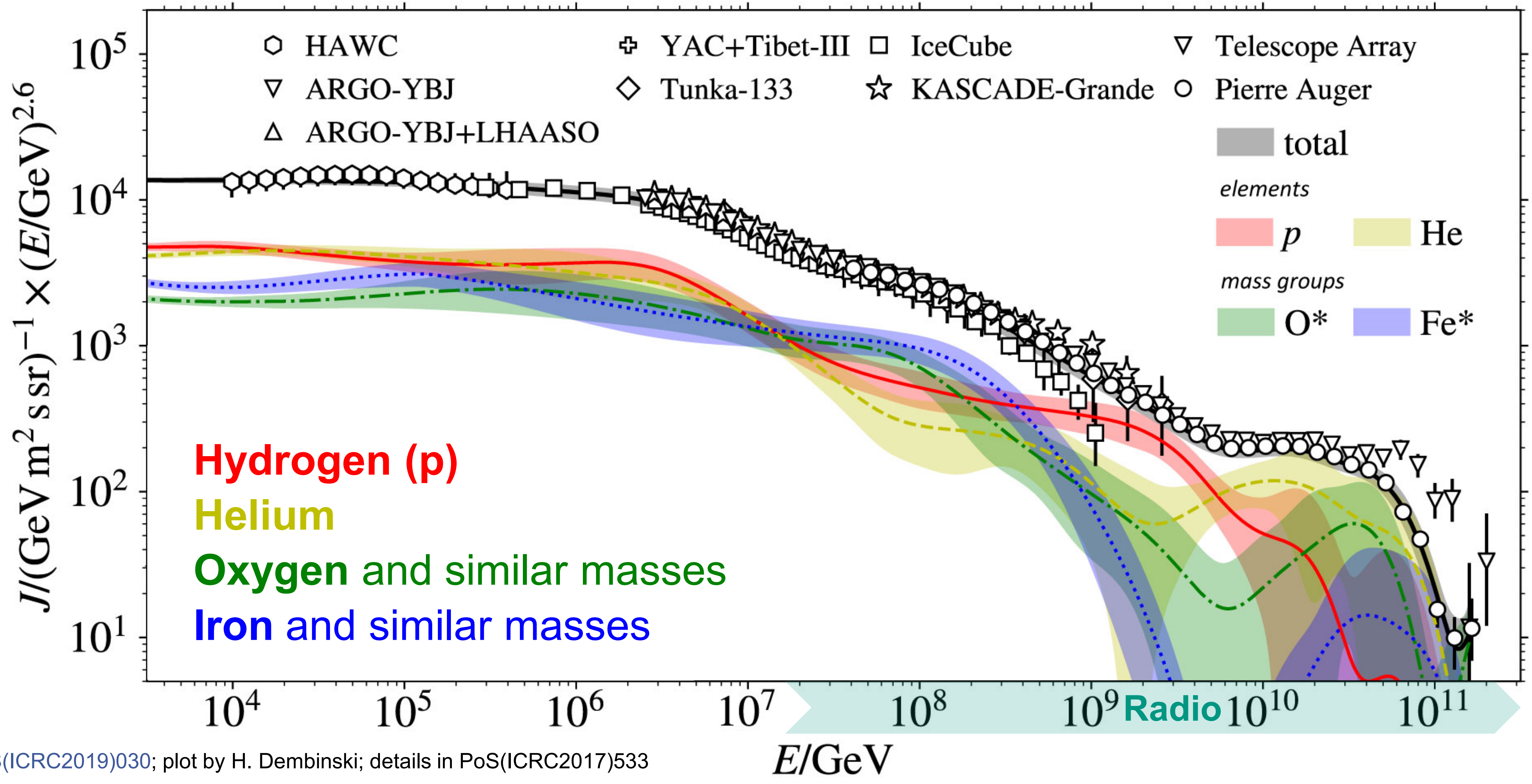
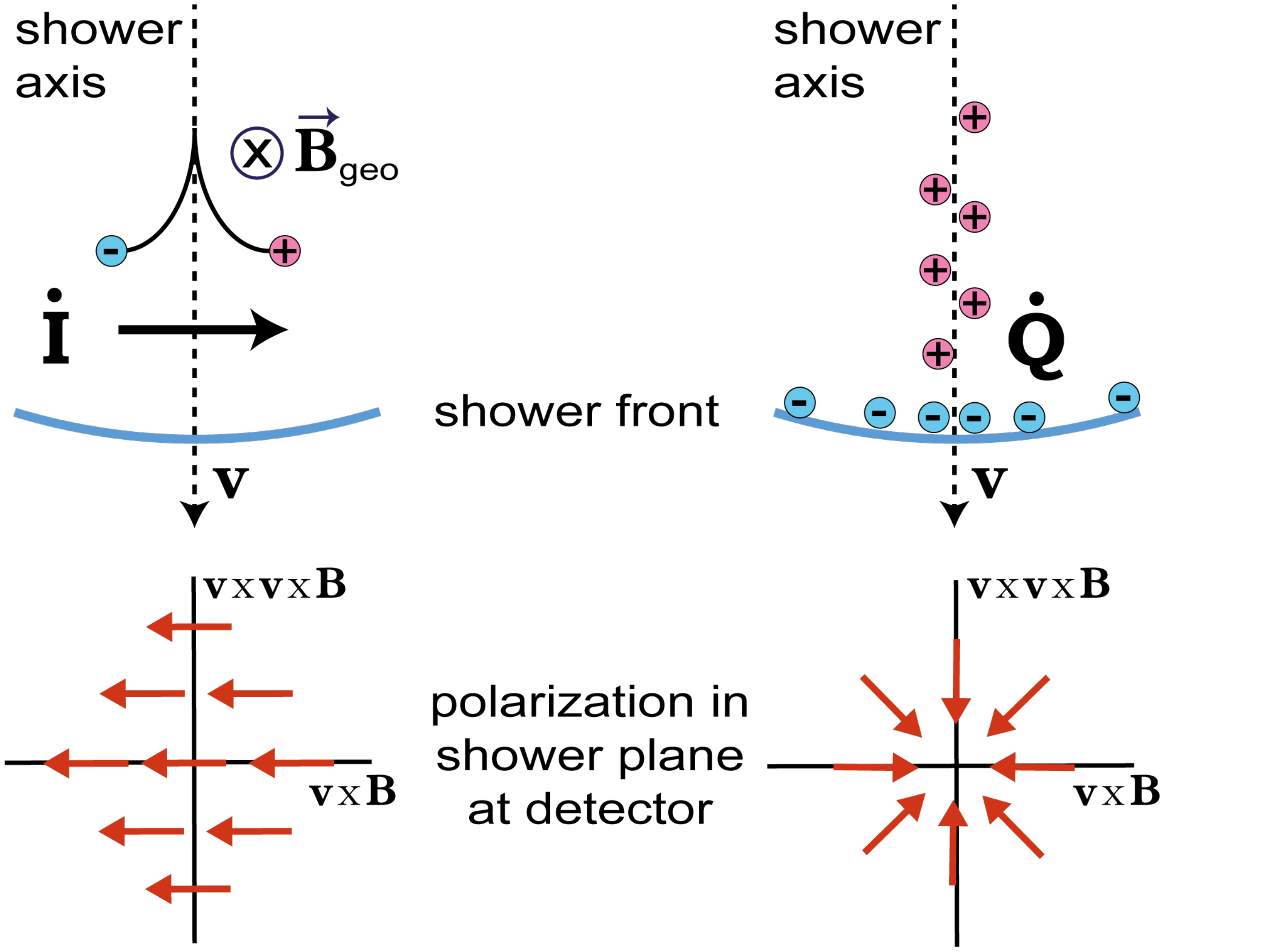
Energy Spectrum and Mass Composition



PoS(ICRC2019)030; plot by H. Dembinski; details in PoS(ICRC2017)533

Radio: Emission Mechanisms



geomagnetic effect ~ 90%   Askaryan effect ~ 10%

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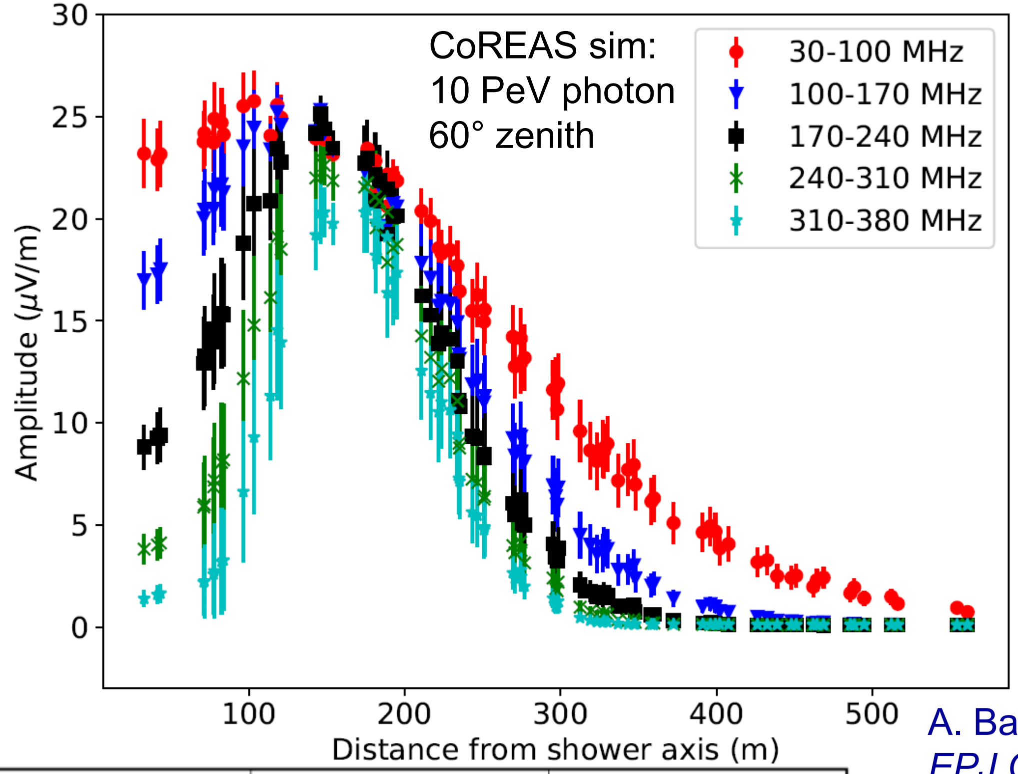
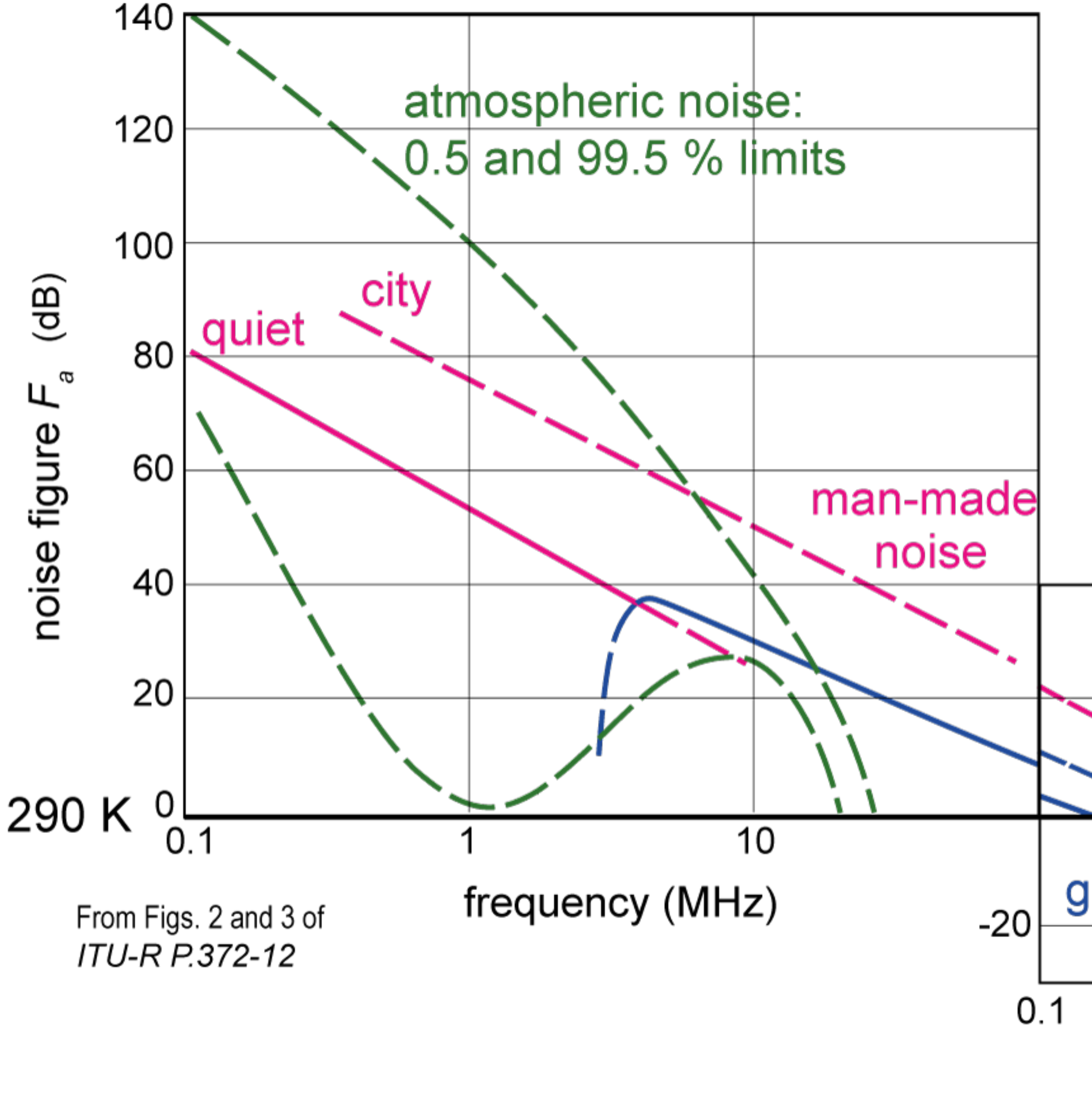
Radio Background and Signal

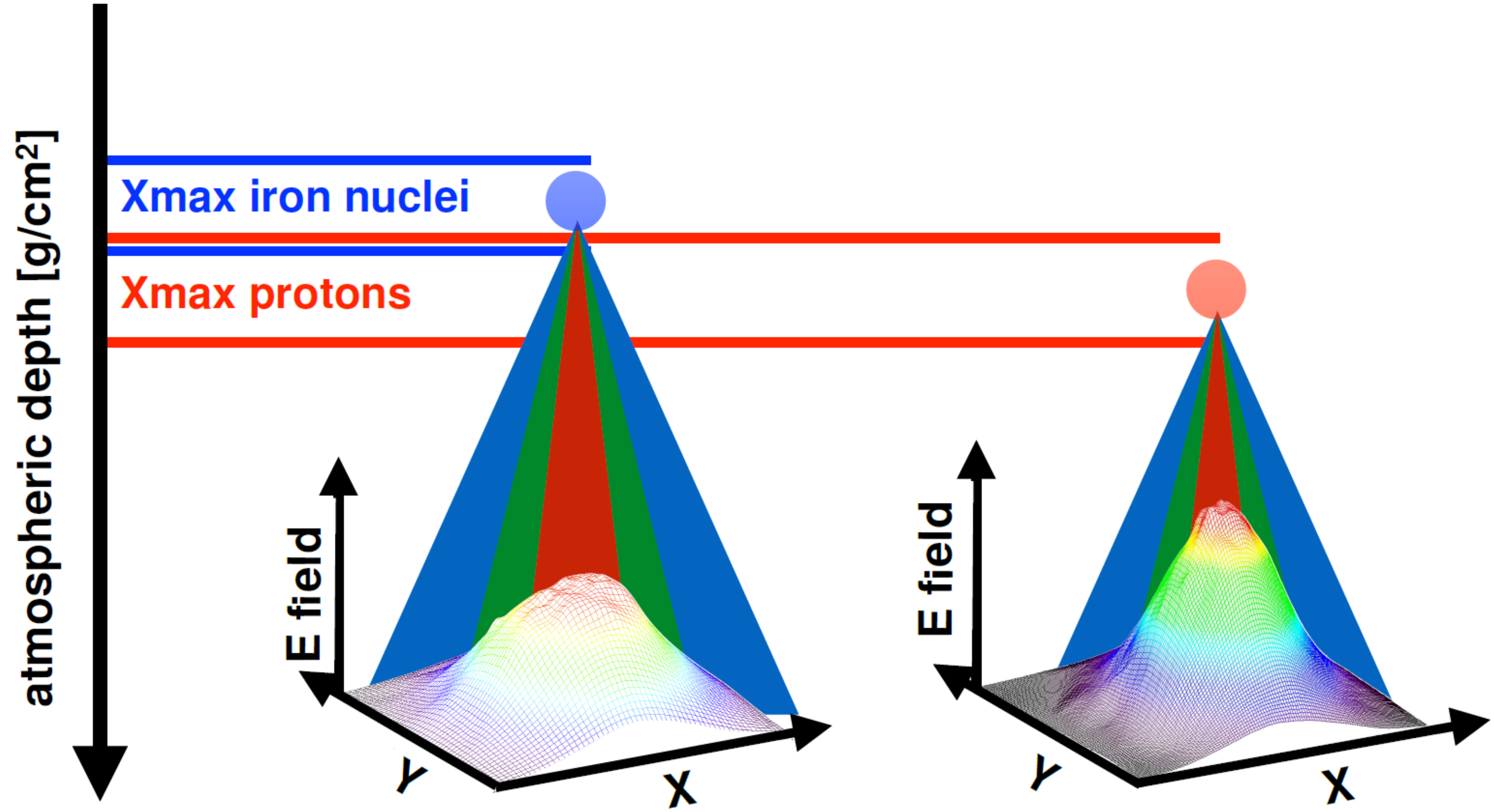


A. Balagopal V., et al. *EPJ C 78 (2018) 11*



From Figs. 2 and 3 of *ITU-R P.372-12*

Radio emission beamed in forward cone



Auger Coll.

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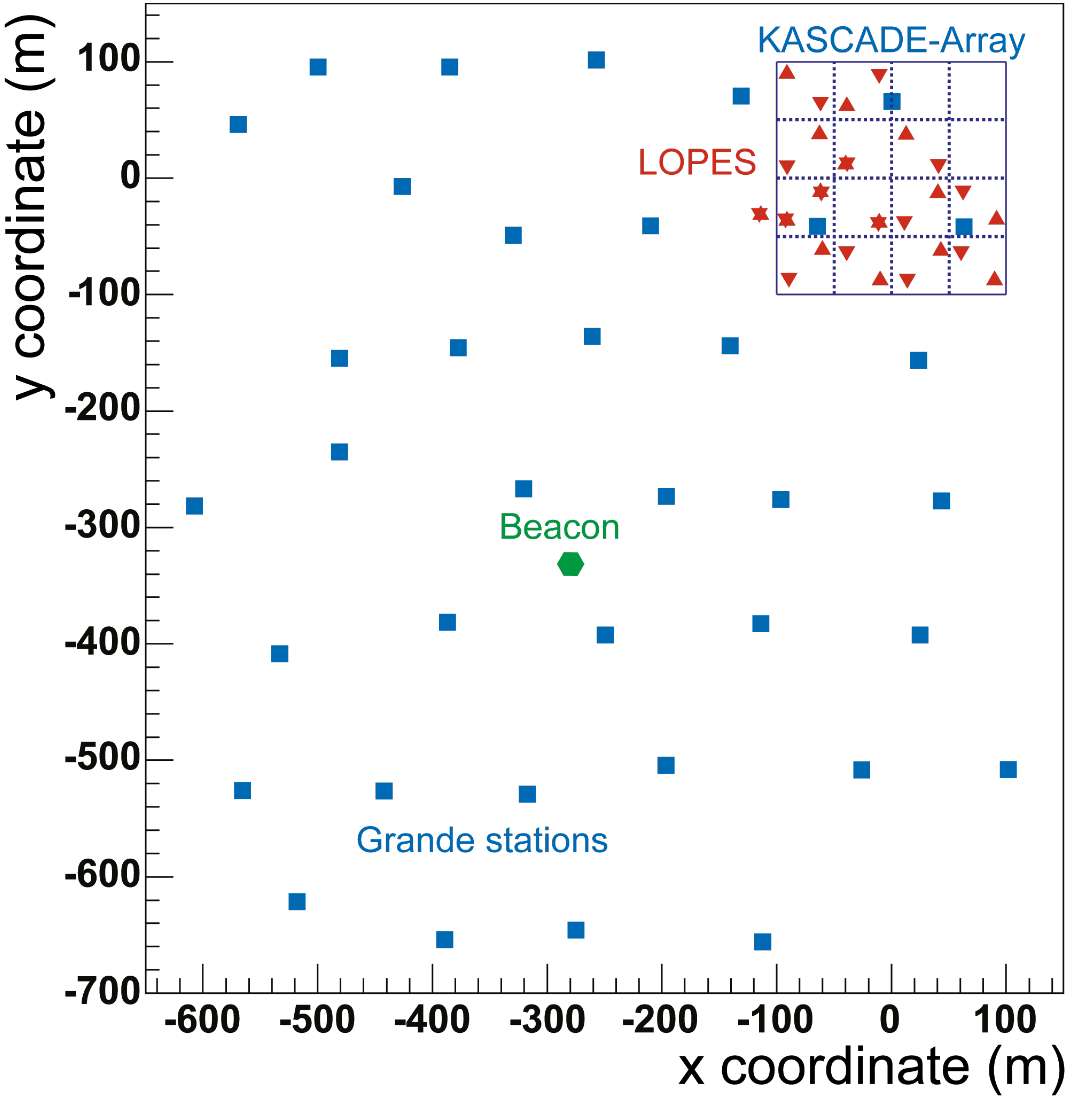
LOPES – Digital radio detection of air-showers



- Operation: 2003 – 2013
  - 30 antennas, 40 – 80 MHz
  - Trigger by KASCADE particle detectors

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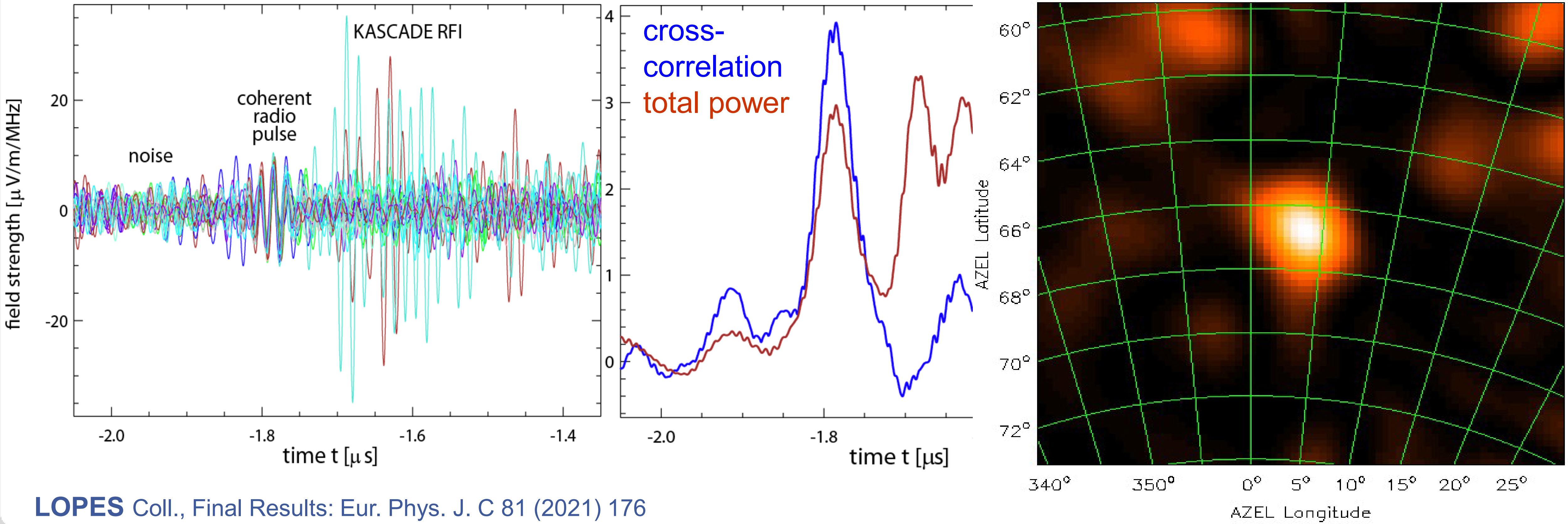
Interferometric beamforming at LOPES

- Cross-correlation of traces after time shift according to arrival direction
- Direction precision < 0.5° (by comparing LOPES to KASCADE)



LOPES Coll., Final Results: Eur. Phys. J. C 81 (2021) 176

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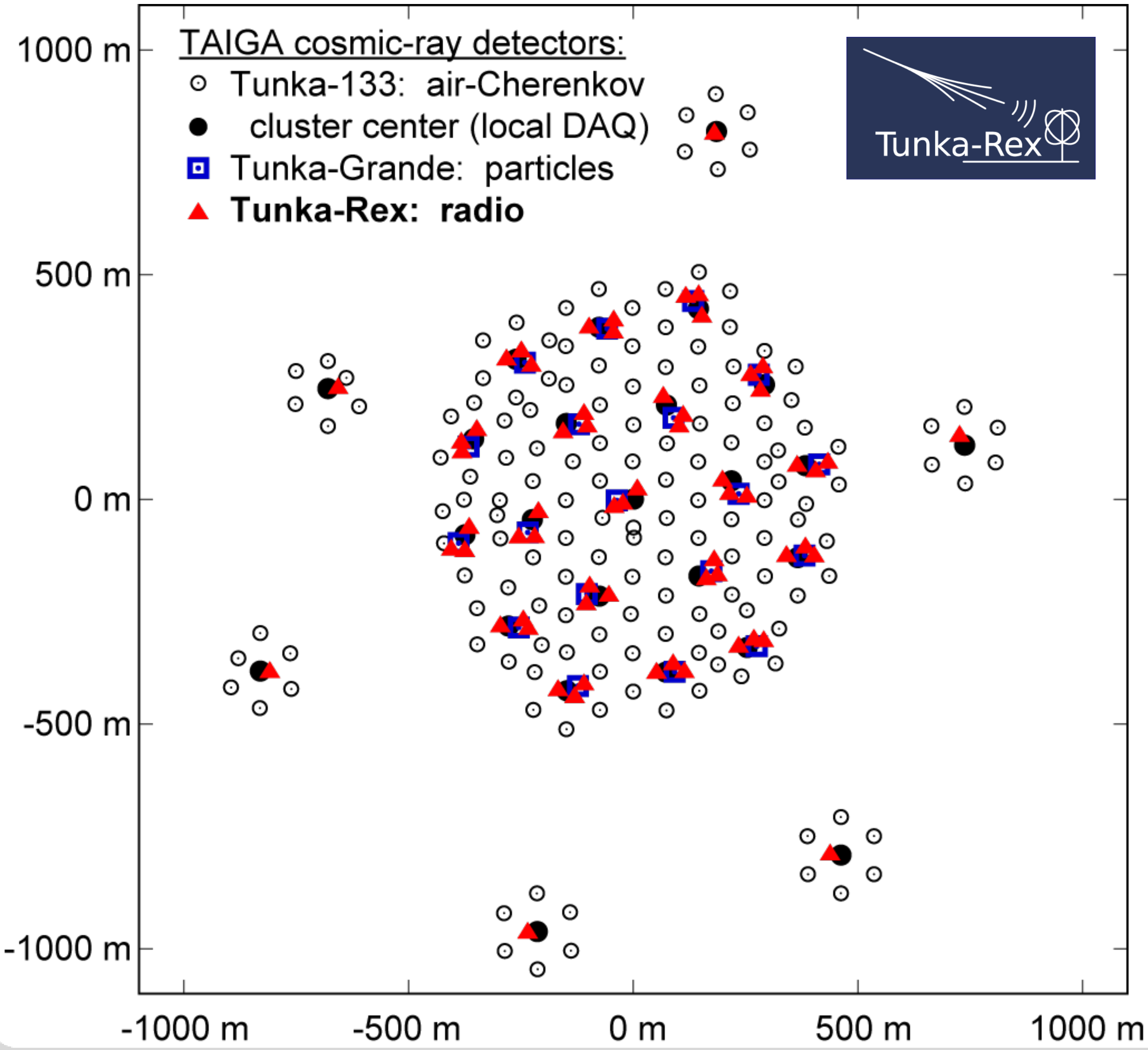
Tunka Radio Extension (Tunka-Rex) in Siberia, 2012 – 2018



- 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)

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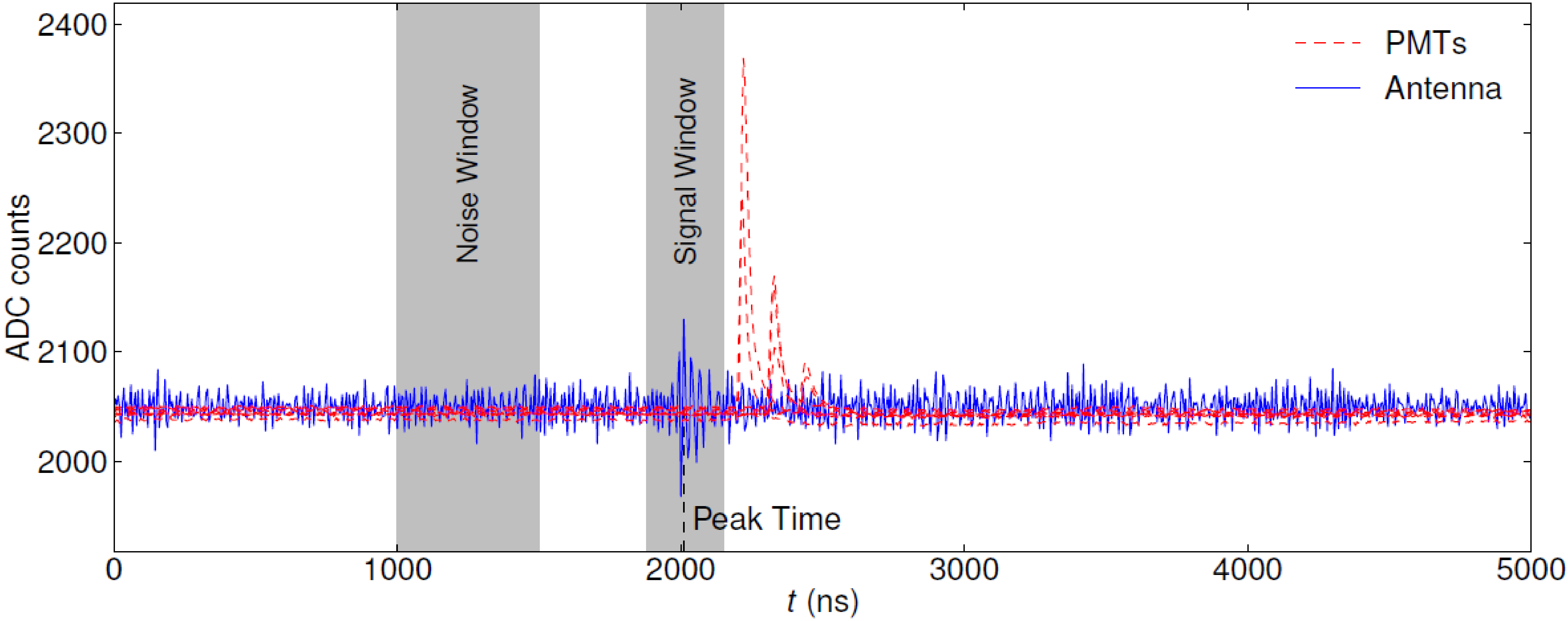
Example of Tunka-Rex event

- triggered by Tunka-133 air-Cherenkov array



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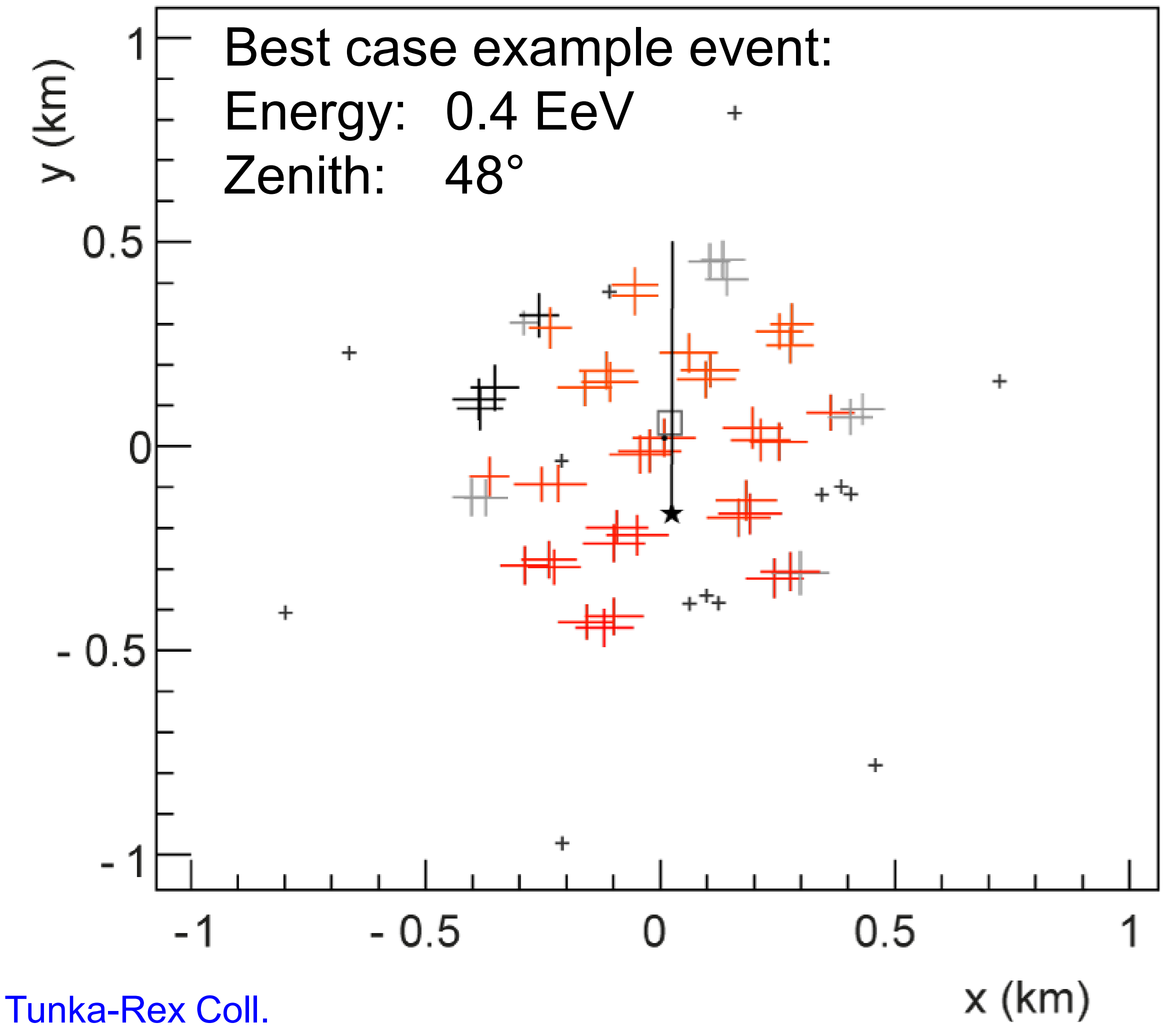
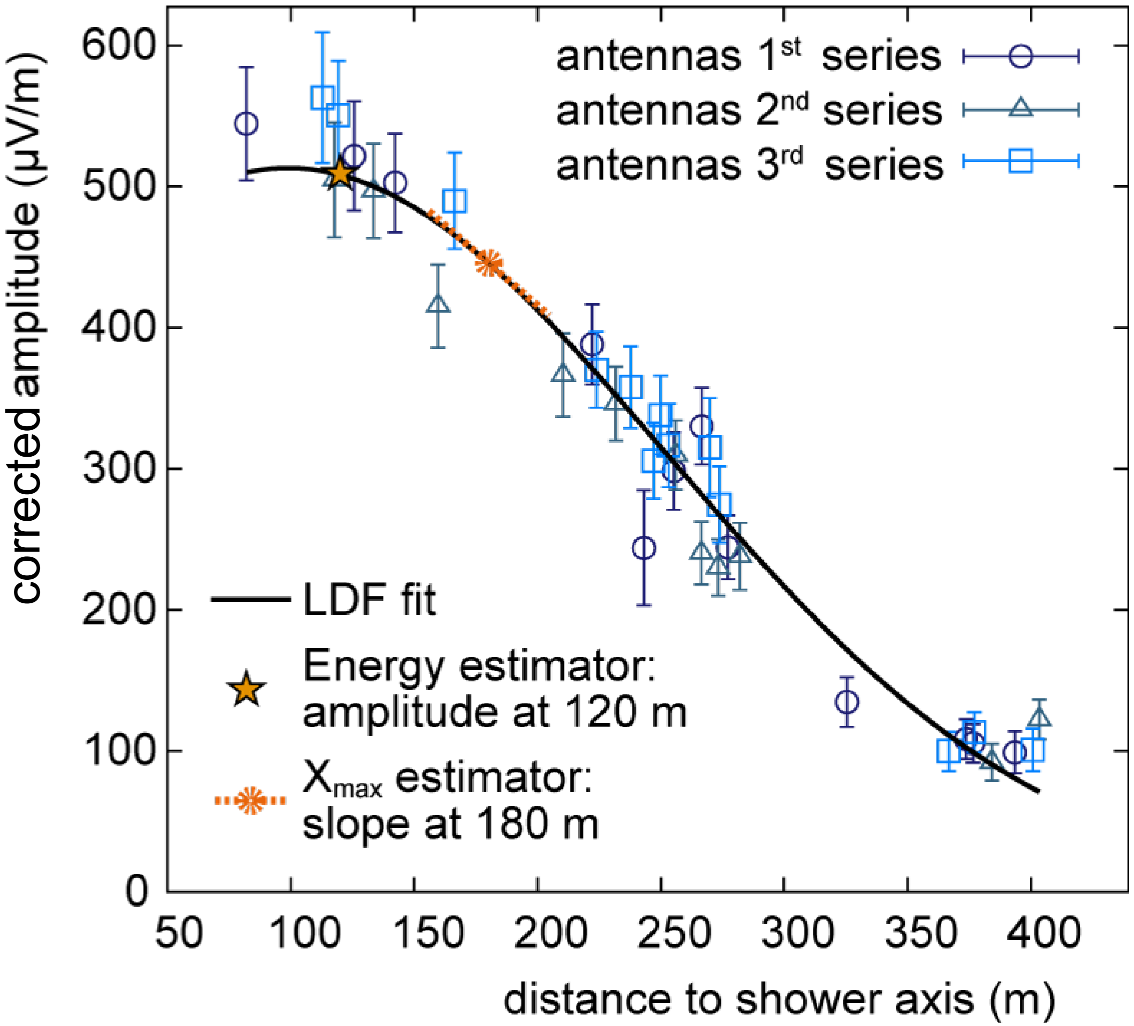
Simple standard method for reconstruction

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





Tunka-Rex Coll.

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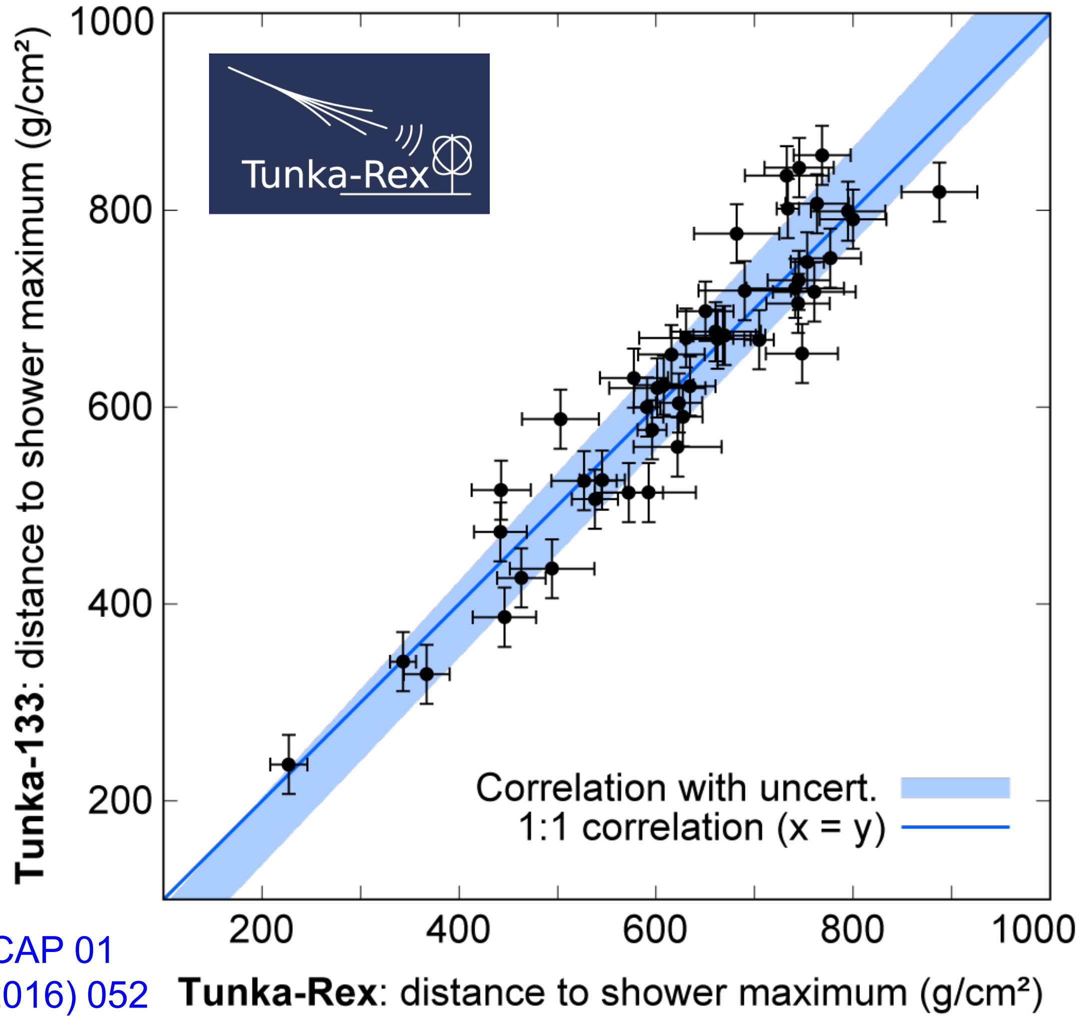
Tunka Radio Extension (Tunka-Rex) in Siberia, 2012 – 2018

- Direct proof of radio X_{max} sensitivity by comparison to Cherenkov-light detectors



JCAP 01 (2016) 052

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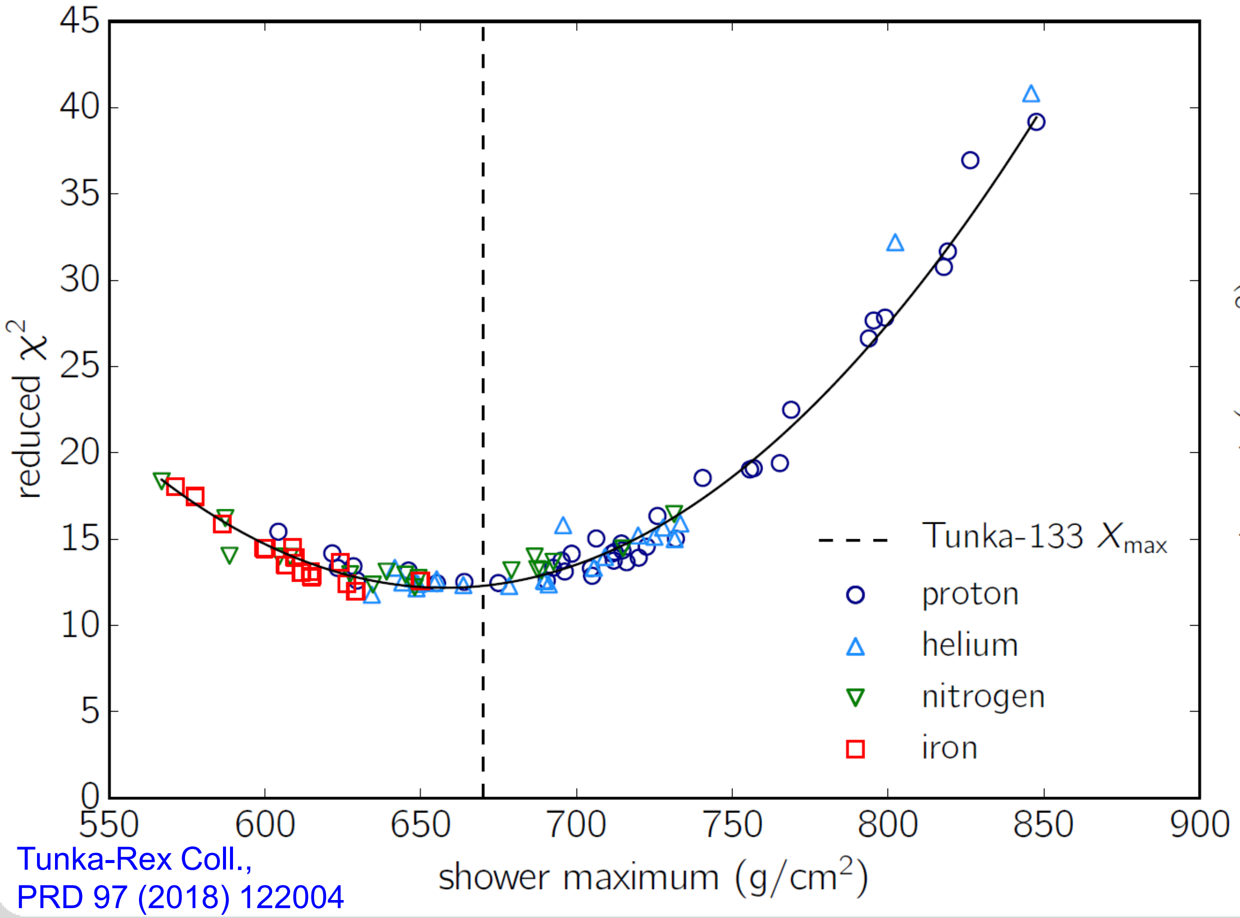
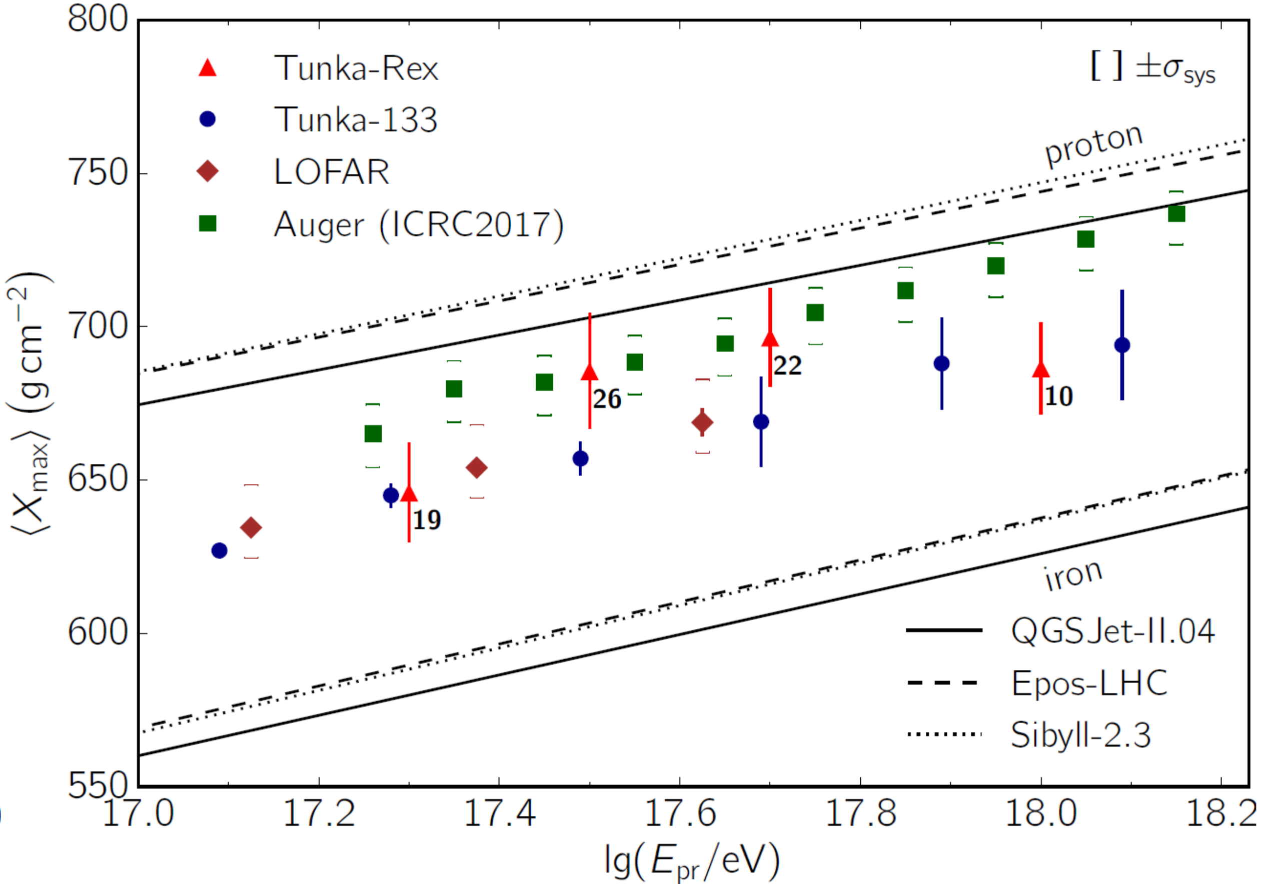
X_{max} reconstruction by Tunka-Rex (by LOFAR inspired method)

- 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.,
PRD 97 (2018) 122004

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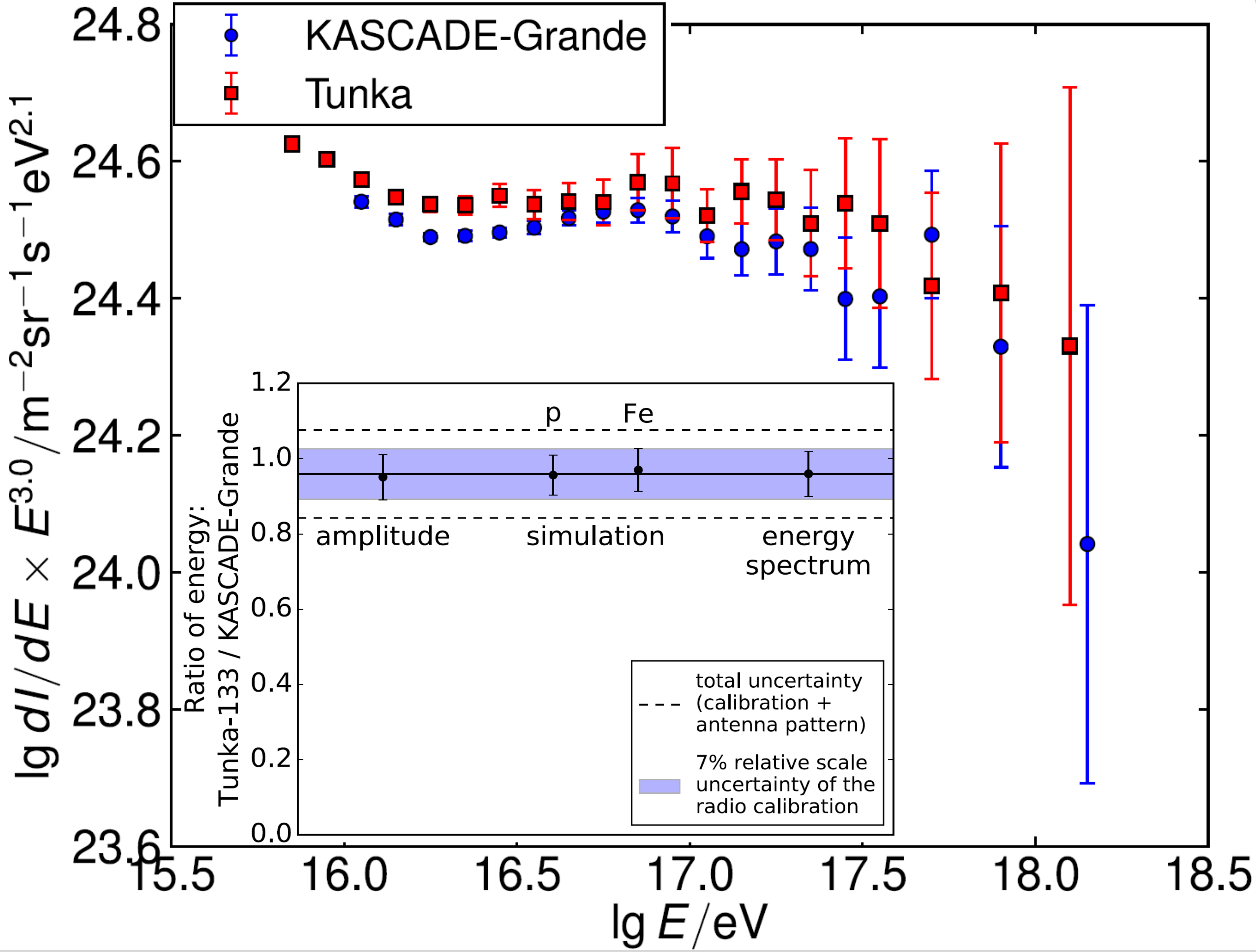
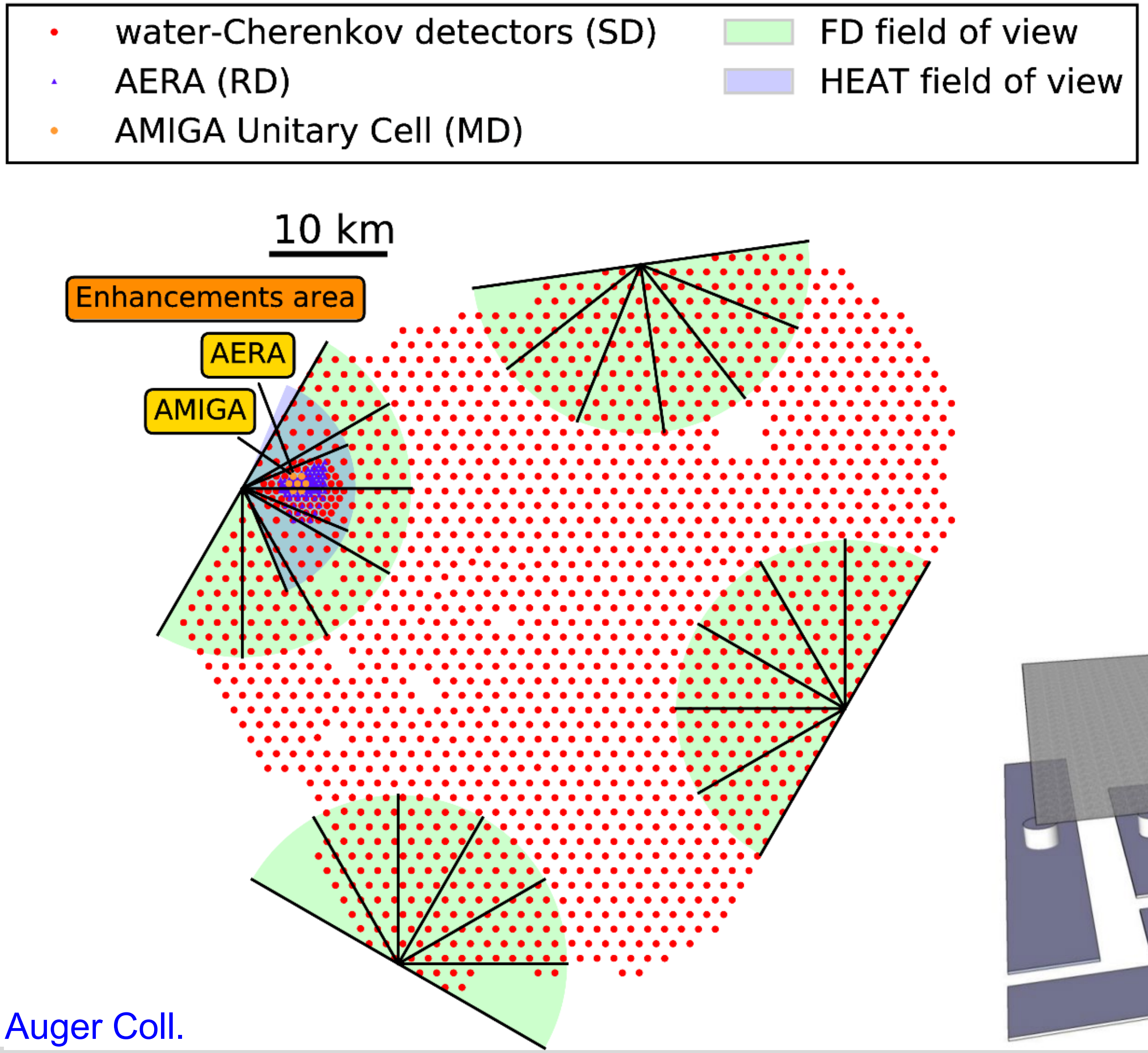
Comparing energy scales of KASCADE and Tunka-133 via their radio arrays

- 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

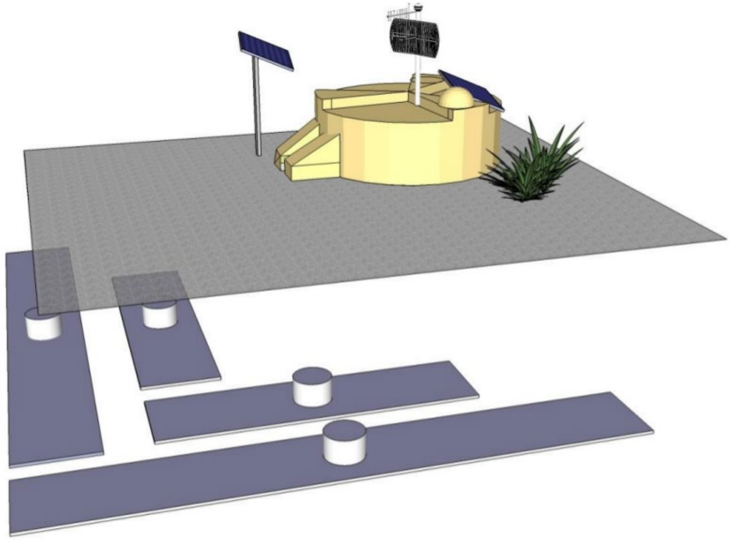


Auger Engineering Radio Array (AERA) at the Pierre Auger Observatory



Auger Coll.

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



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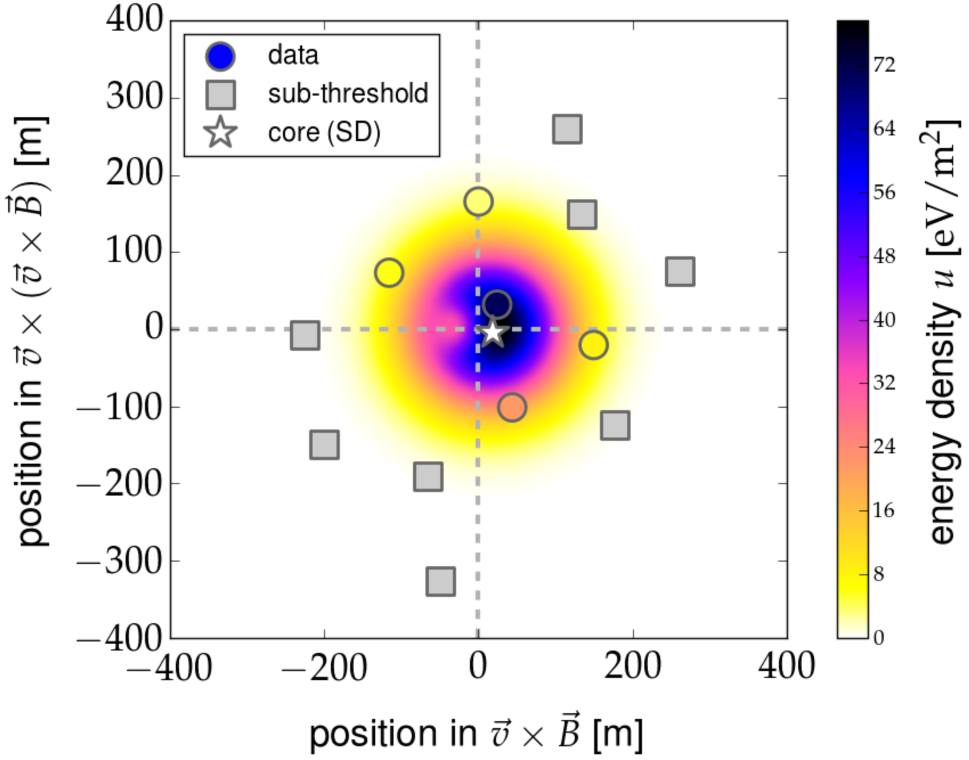
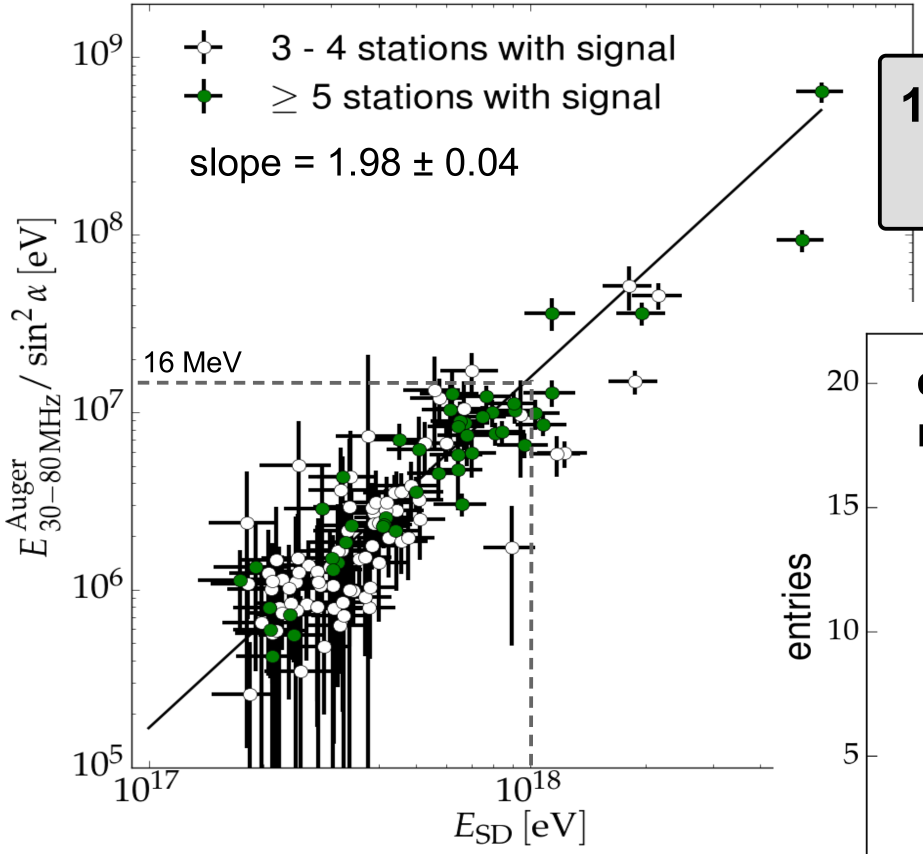
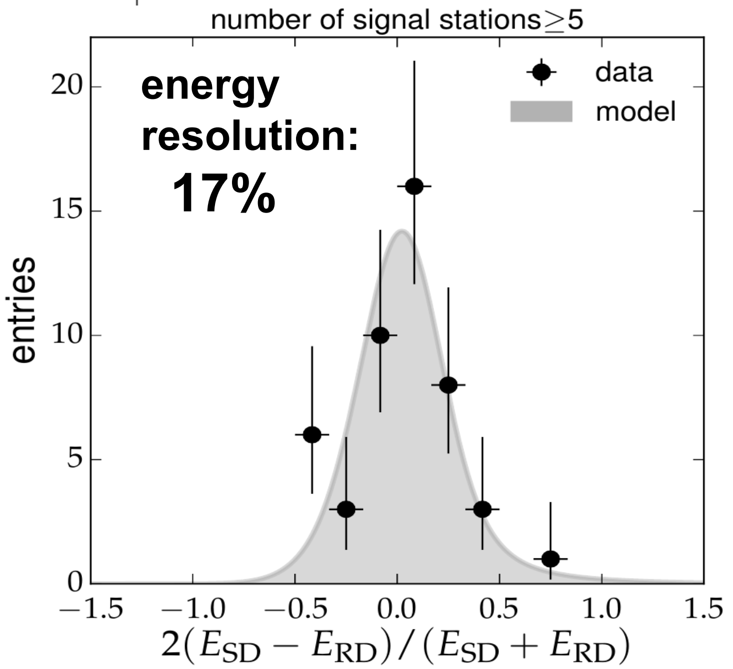
Coherent Emission: Radio amplitude proportional to shower energy

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



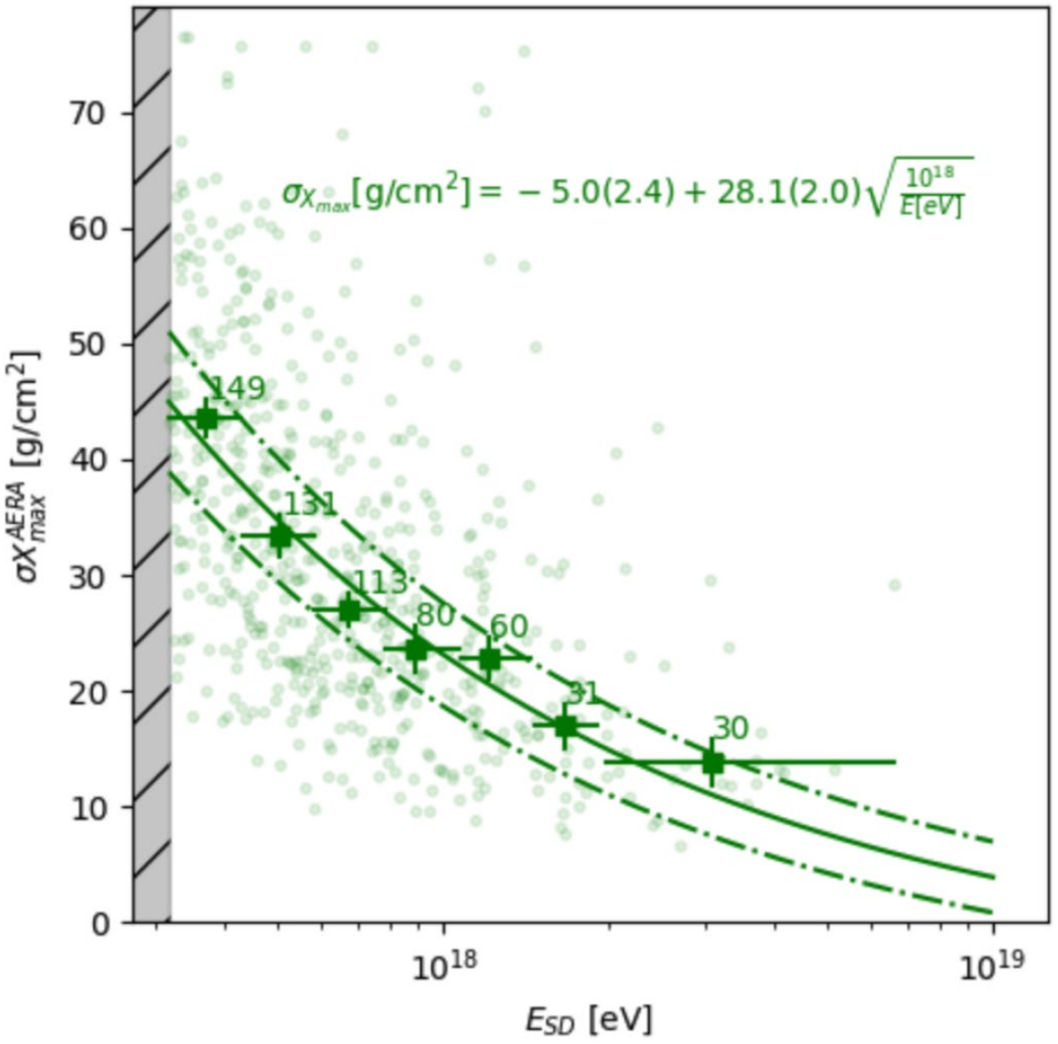


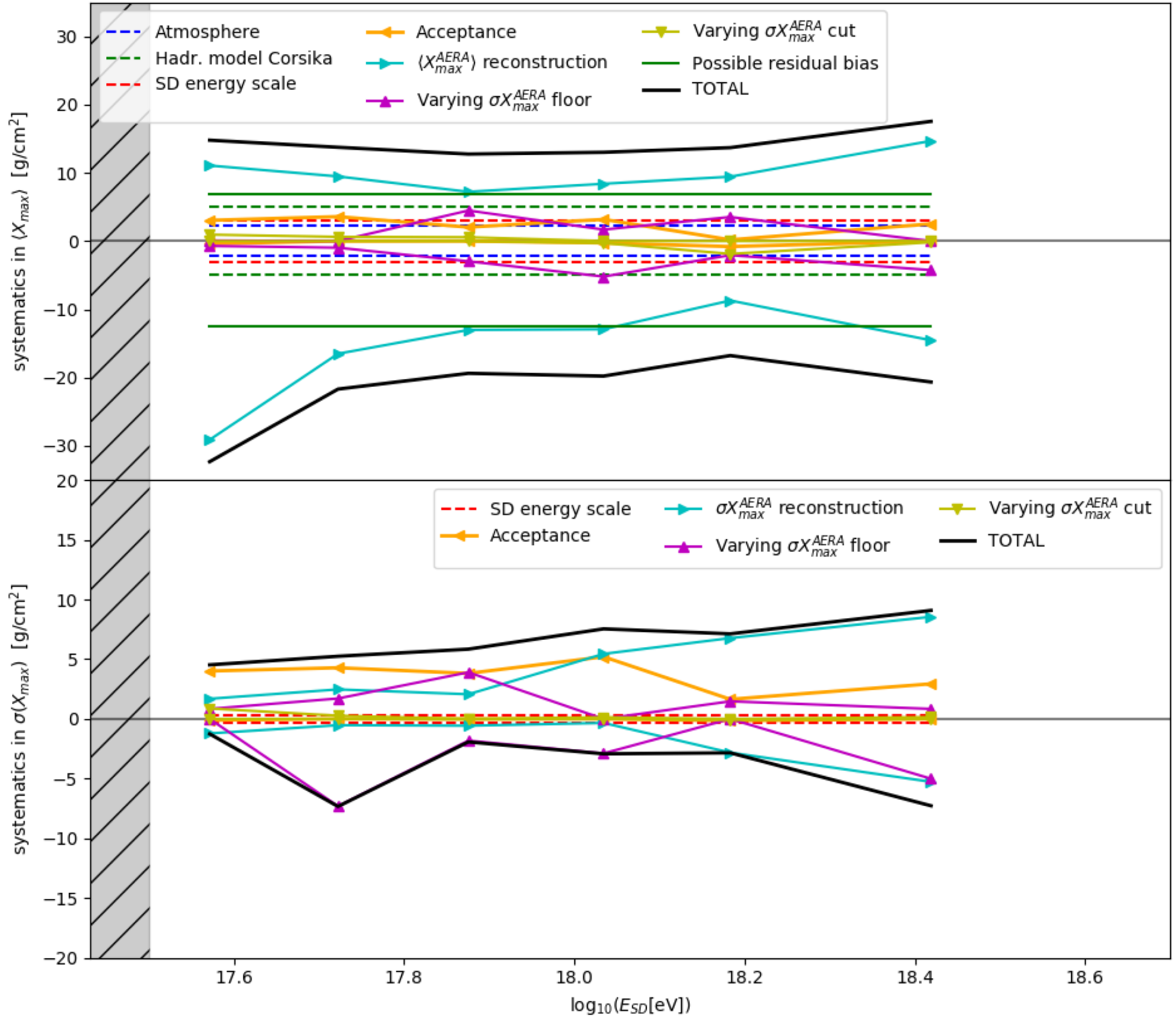
16 MeV radiation energy for a 1 EeV cosmic ray



Pierre Auger Coll.,
PRL 116 (2016) 241101

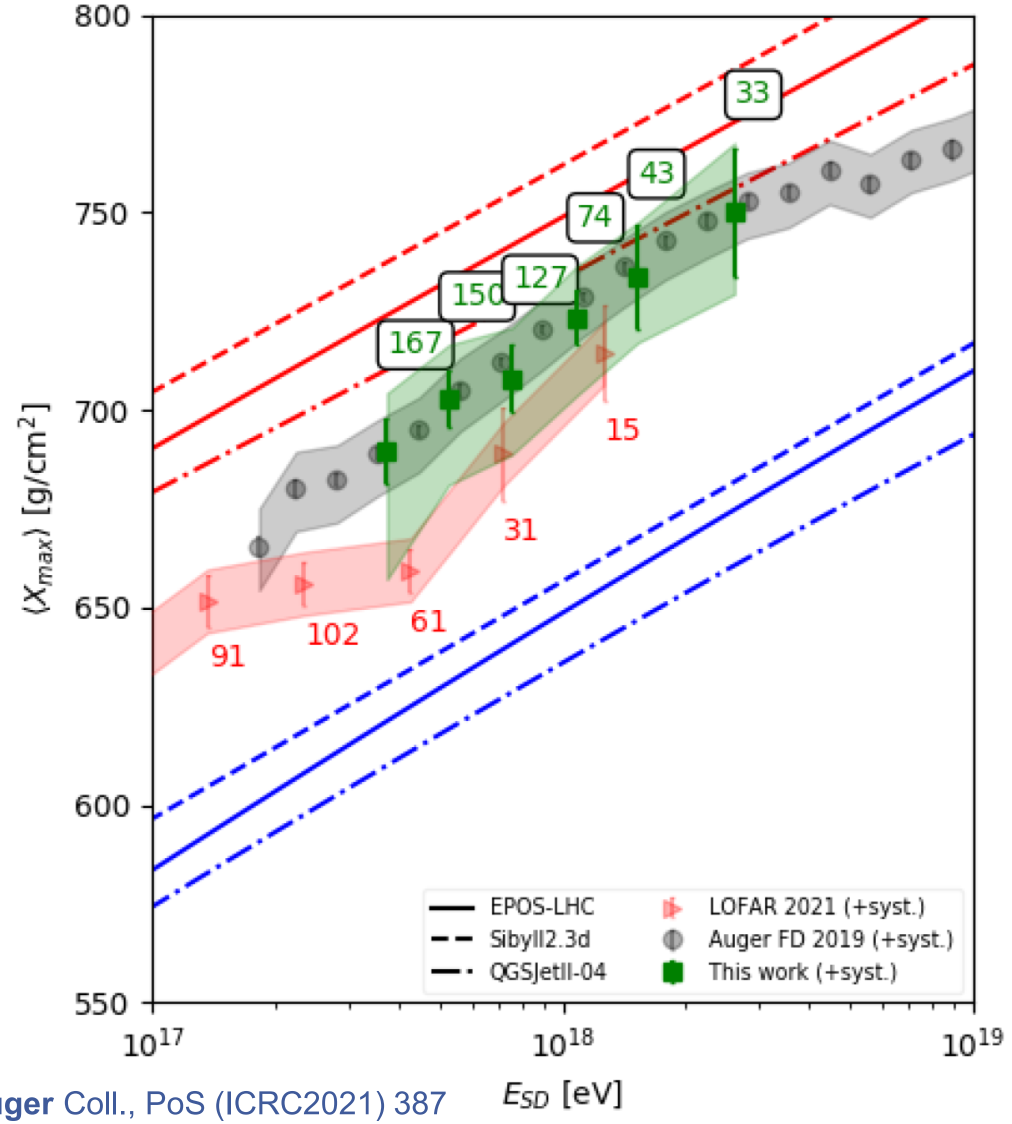
Radio X_{max} uncertainties studied in detail for AERA

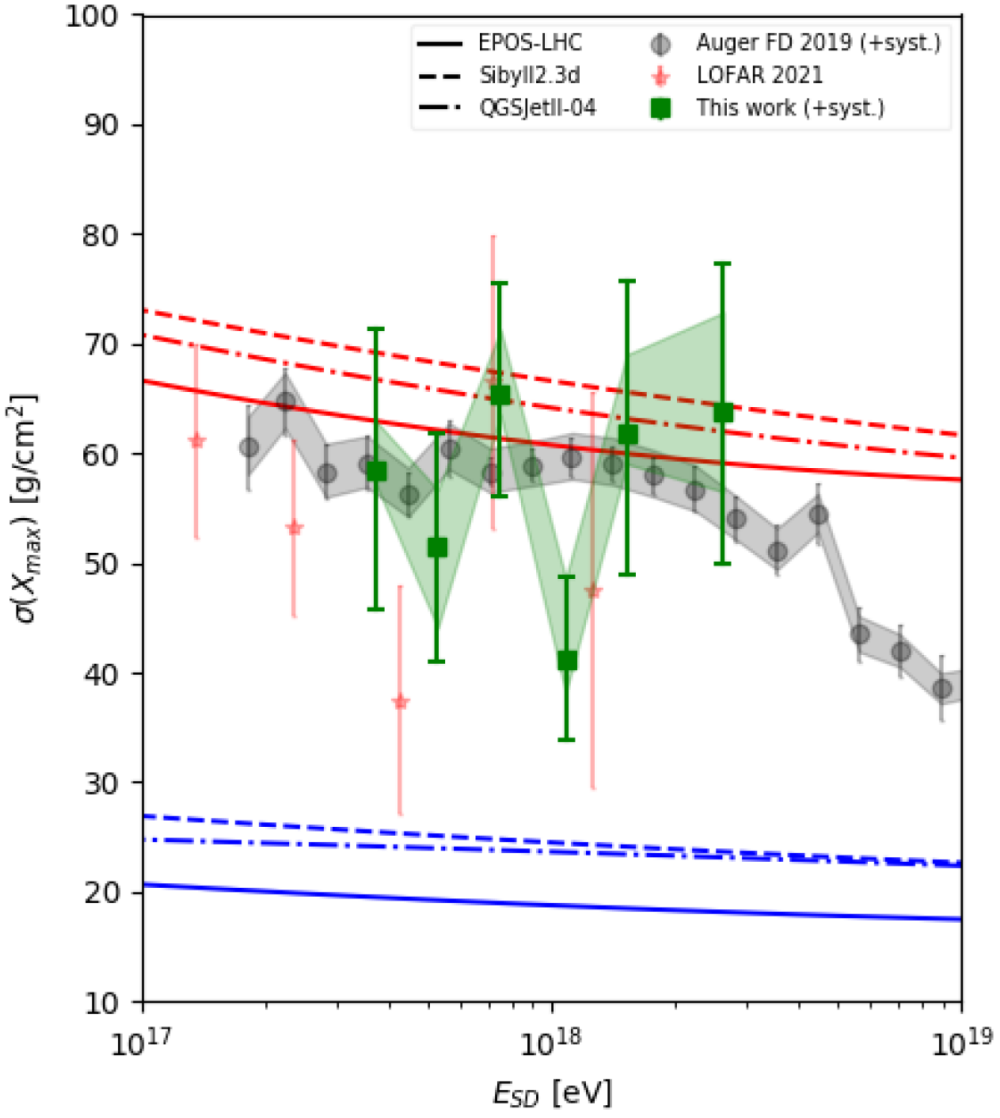




Pierre Auger Coll., PoS (ICRC2021) 387

Radio X_{max} in agreement with Fluorescence X_{max} at Auger





Pierre Auger Coll., PoS (ICRC2021) 387

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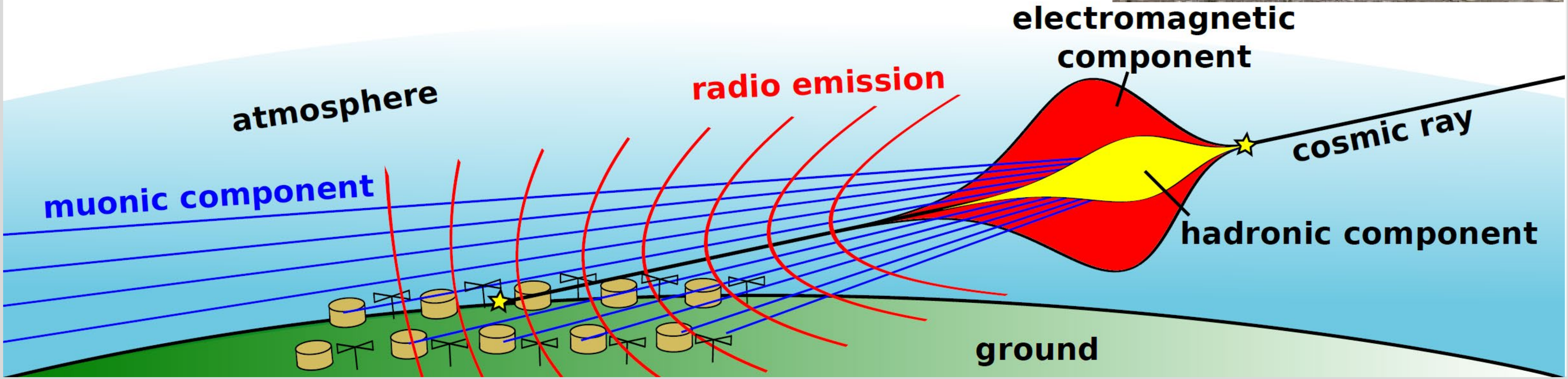
AugerPrime:
Upgrade of the Pierre Auger Observatory

- Improved quality of surface detector:
  - scintillators + radio antennas
  - underground muon detectors
  - better electronics
- Enables per-event mass discrimination



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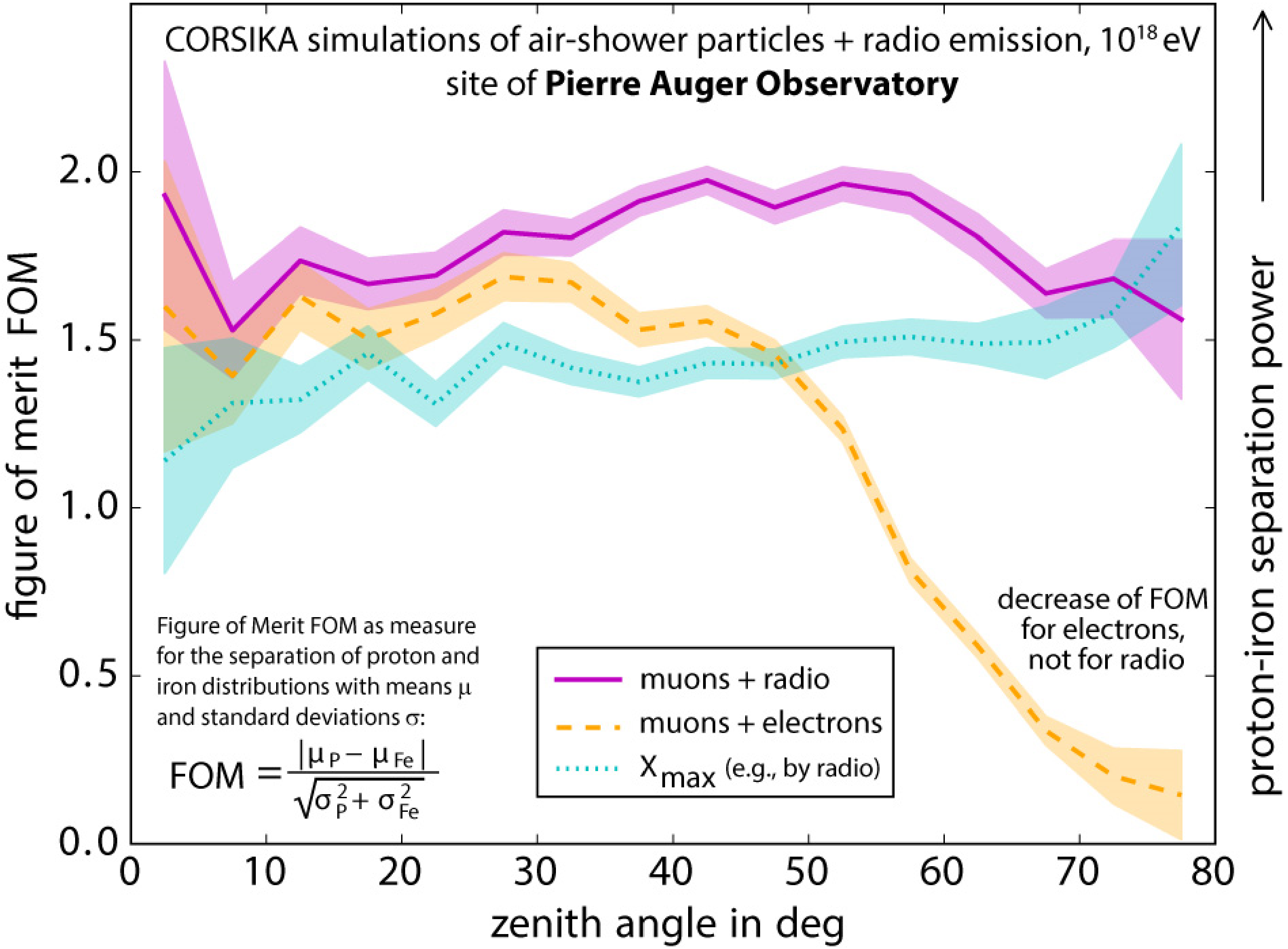
Key for many science goals: Mass Separation power

- Radio enhances mass sensitivity for all zenith angles, in particular for inclined showers
- Plots show potential of the methods (no detector properties considered)
  - while km-spaced arrays are sufficient for inclined showers, antenna spacings of o(100m) are required for vertical showers.



Pierre Auger Coll., EPJ WoC 216 (2019) 02002
more details in E. Holt et al., EPJ C 79 (2019) 371

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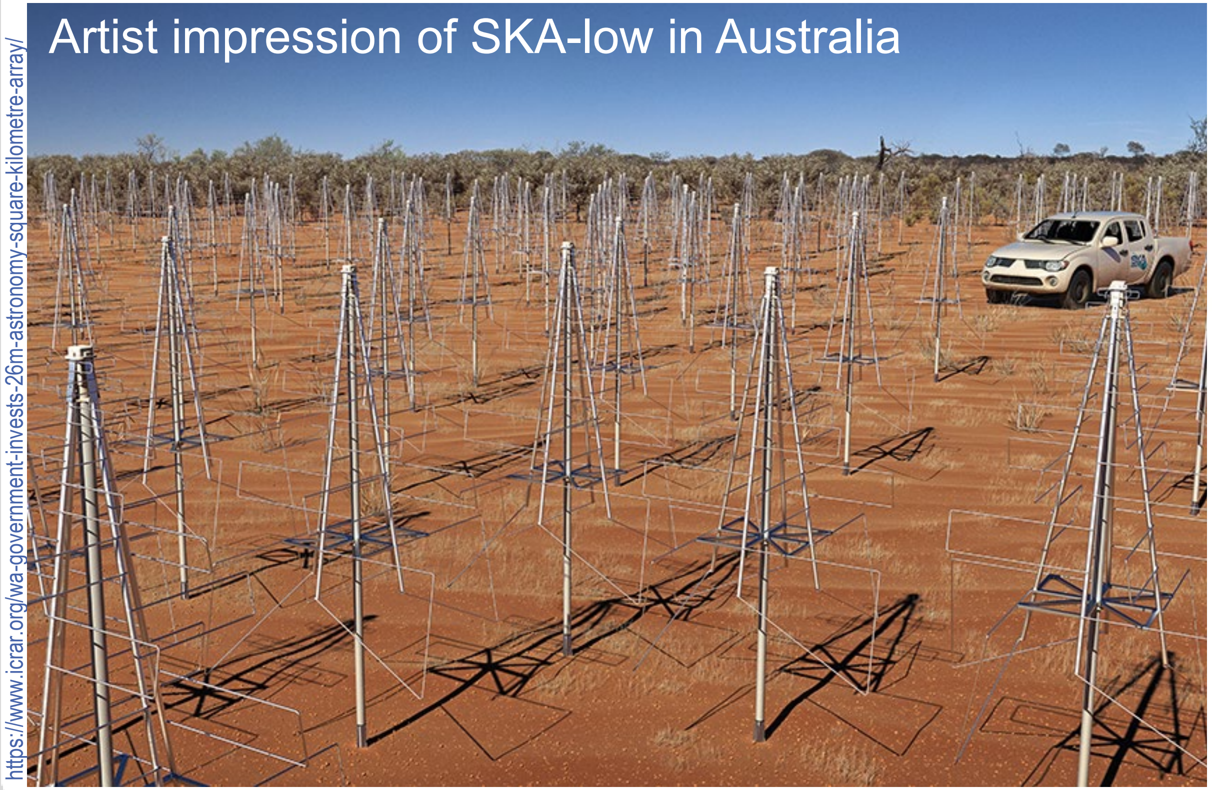
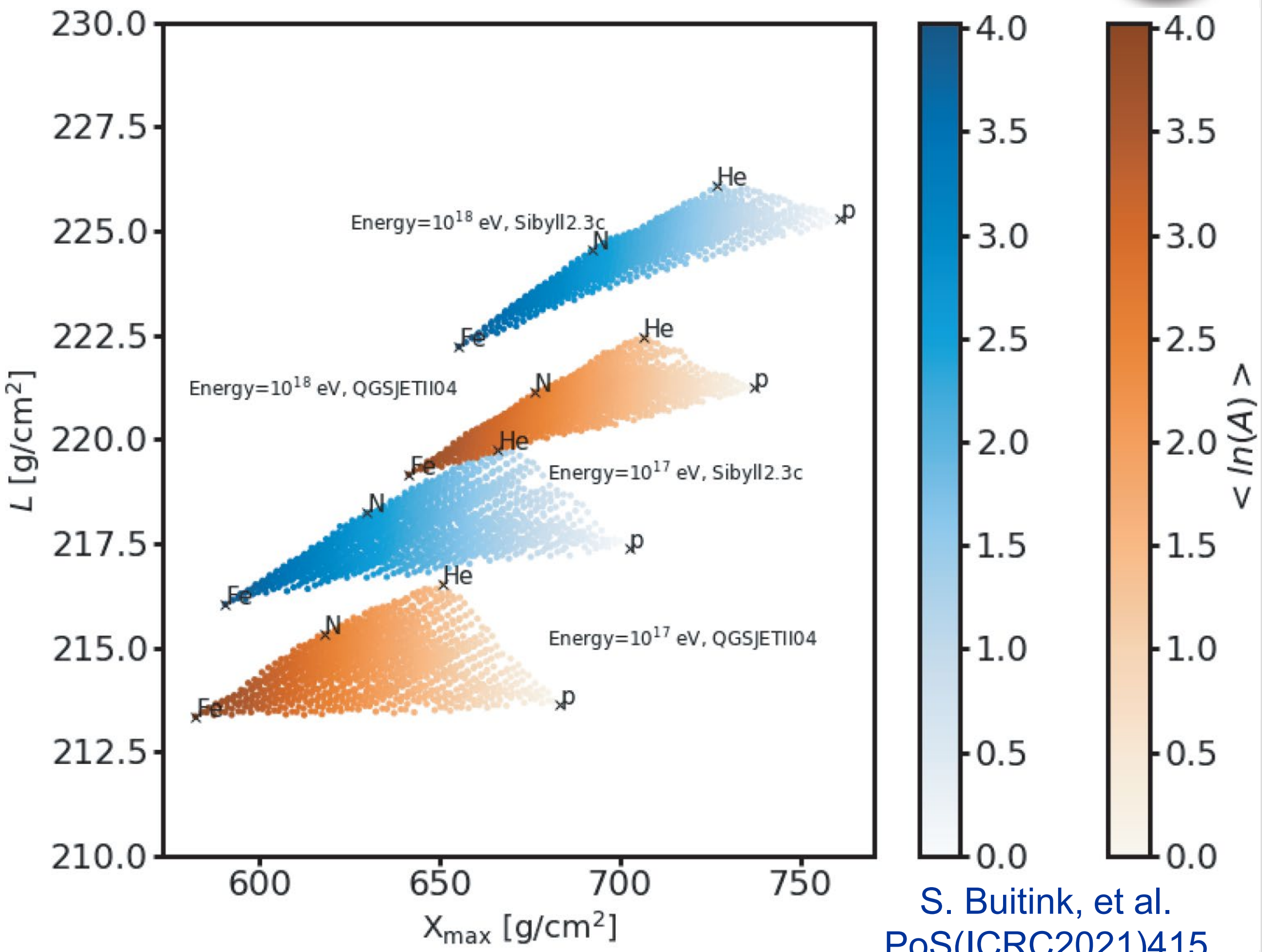
Square Kilometer Array: SKA-low in Australia

- Air-showers detection in parallel to astronomy (50-350 MHz)
- 60,000 antennas on ½ km²
- X_{max} better than 10 g/cm² + L parameter


Artist impression of SKA-low in Australia

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



S. Buitink, et al.
PoS(ICRC2021)415

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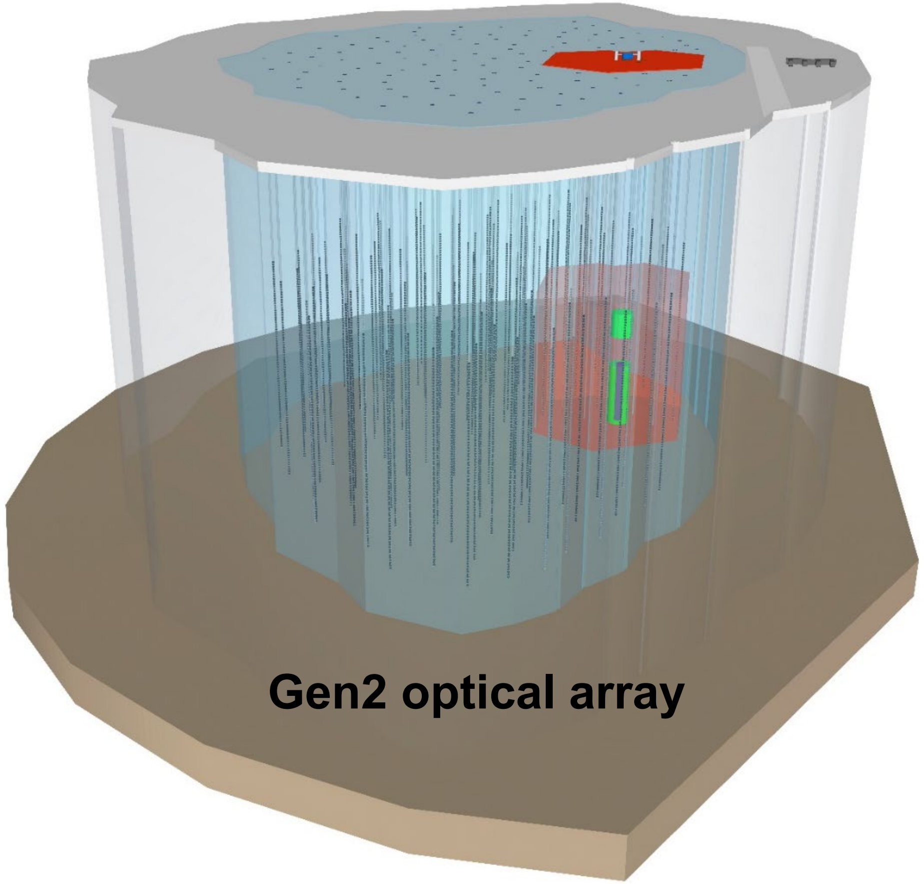
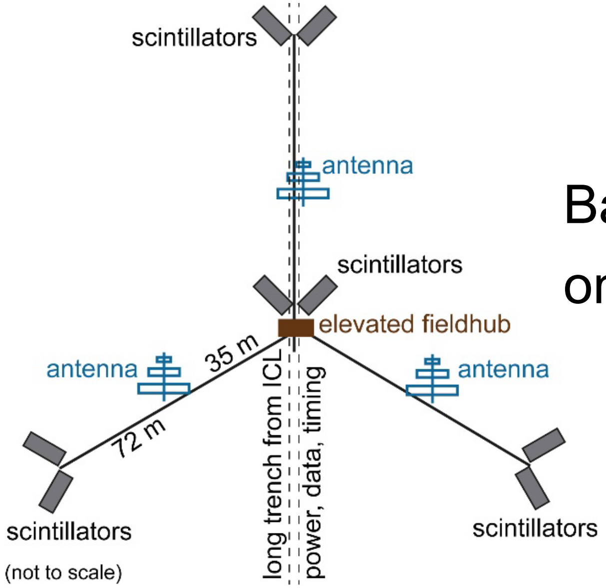
IceCube-Gen2 Surface Array

- Enhancement of IceTop surface array continued for IceCube-Gen2 surface array
- High accuracy for most energetic Galactic cosmic rays in the PeV to EeV region





Baseline design of Gen2 Surface Array: one station per optical string (120)

- 4 pairs of scintillators enabling low threshold for veto
- 3 radio antennas increasing accuracy at high energies

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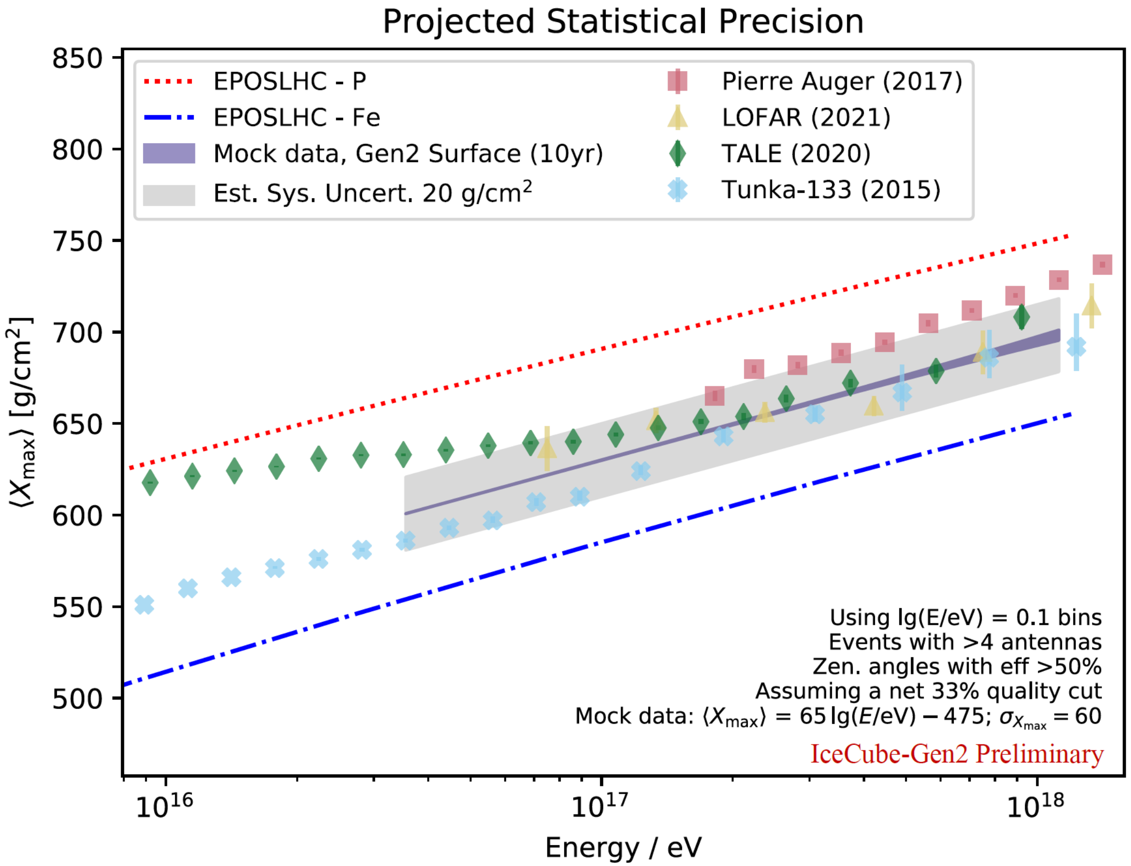
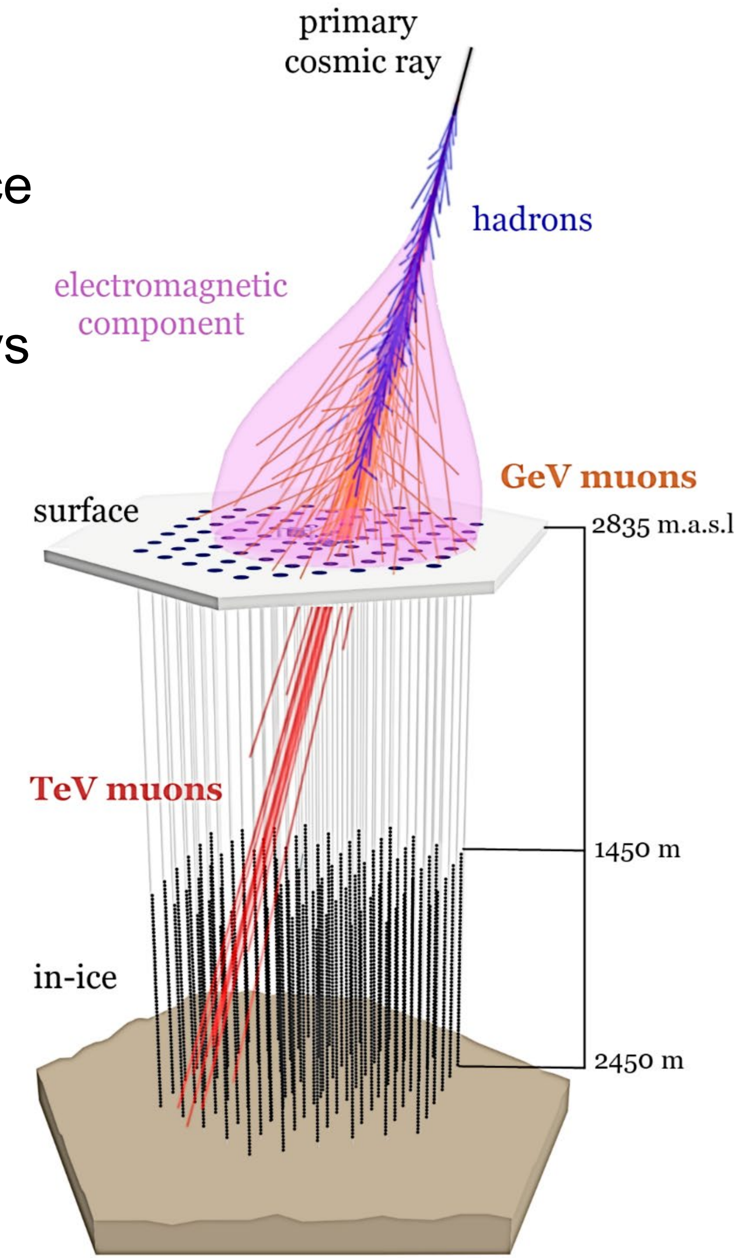
Unique Combination of Air-Shower Detectors

- Low-energy particles + radio signal on ground, TeV muons in the ice
- Enables unprecedented accuracy for mass of cosmic rays
- Physics relevant for atm. neutrino backgrounds, e.g., prompt decays





D. Soldin et al. (IceCube Coll.) PoS 369 (ICRC2021) 357

Conclusion

- Significant progress in radio technique for cosmic rays during last years
  - high accuracy at almost 100% duty cycle
  - competitive direction, energy, and X_{max} accuracy – including the absolute scales
  - ideal for inclined showers and in combination with muon detectors

- Several running and planned antenna arrays for all types of cosmic particles, e.g.:
  - Auger Radio Upgrade: mass-sensitivity for inclined showers of extragalactic cosmic rays
  - Giant Radio Array for Neutrino Detection (GRAND): huge aperture for ultra-high energies
  - Global Cosmic Ray Observatory (GCOS) may include radio antennas
  - IceCube(-Gen2): surface radio for Galactic cosmic rays + in-ice radio for EeV neutrinos

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