Contribution
D21.00002

Ultra-high-energy Cosmic Rays: Recent Results and Future Plans

Frank G. Schroeder

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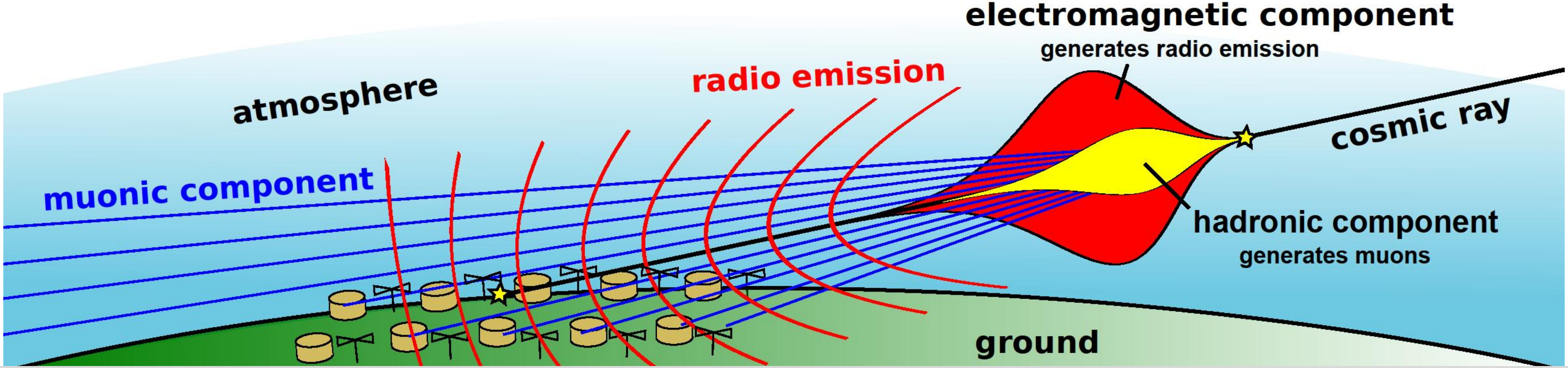
Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE, USA,
and Karlsruhe Institute of Technology (KIT), Institute for Nuclear Physics , Karlsruhe, Germany



Content

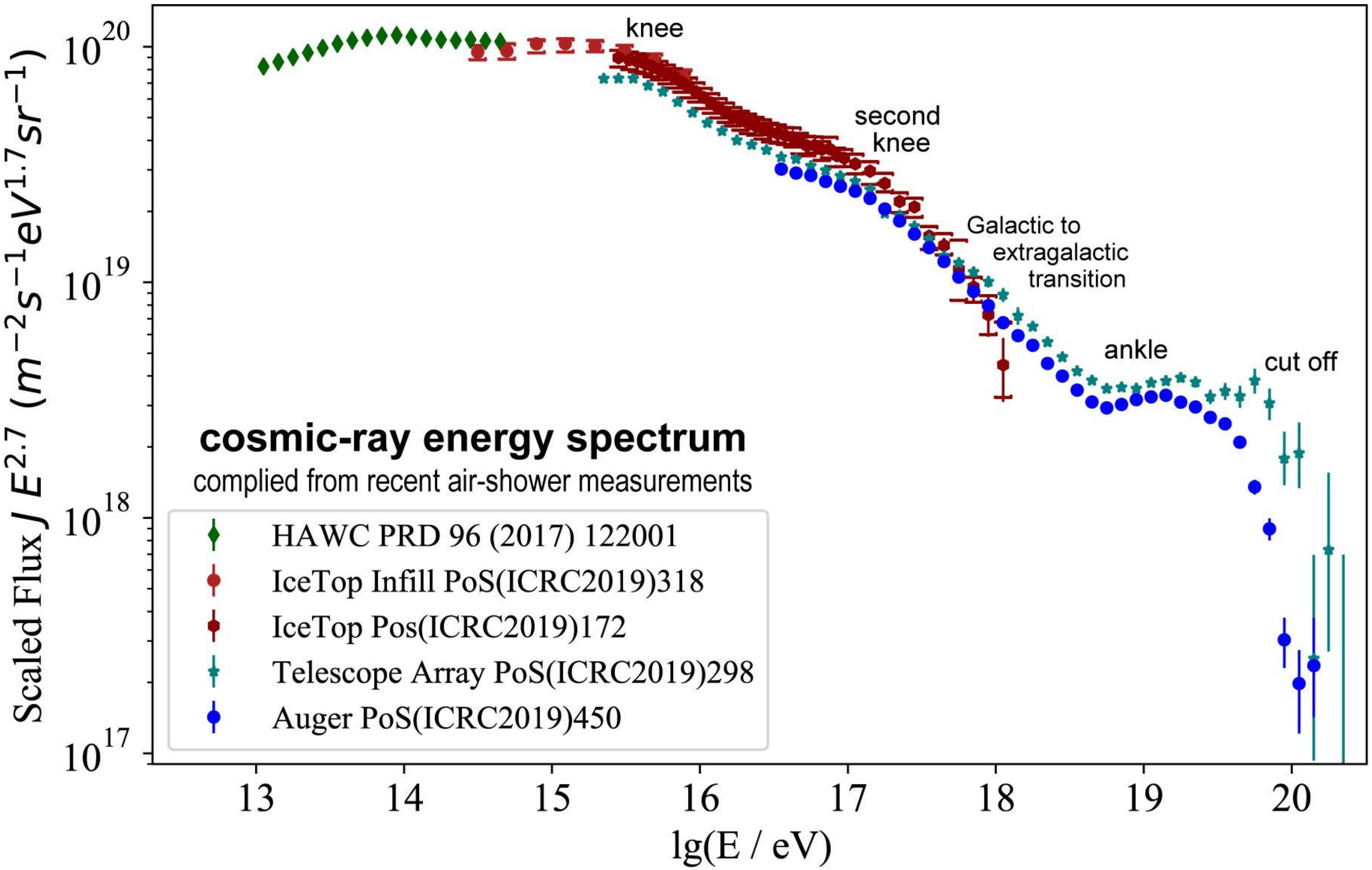
- Recent results in ultra-high-energy Cosmic Rays
  - Multimessenger picture
  - Cosmic-Ray Energy Spectrum and Mass Composition
  - Anisotropy
  - Testing Hadronic Interaction Models

- Ongoing upgrades and future *ground-based* experiments
  - Radio technique for air showers
  - AugerPrime – the Upgrade of the Pierre Auger Observatory
  - Telescope Array TA x 4 and low-energy extensions
  - GRAND
  - IceCube-Gen2 and its Surface Array

Remark: this talk will focus on ground-based cosmic-ray detectors because dedicated talks follow on balloon-borne and space missions.

fgs@udel.edu
frank.schroeder@kit.edu

All-particle Energy Spectrum by Air-Shower Arrays



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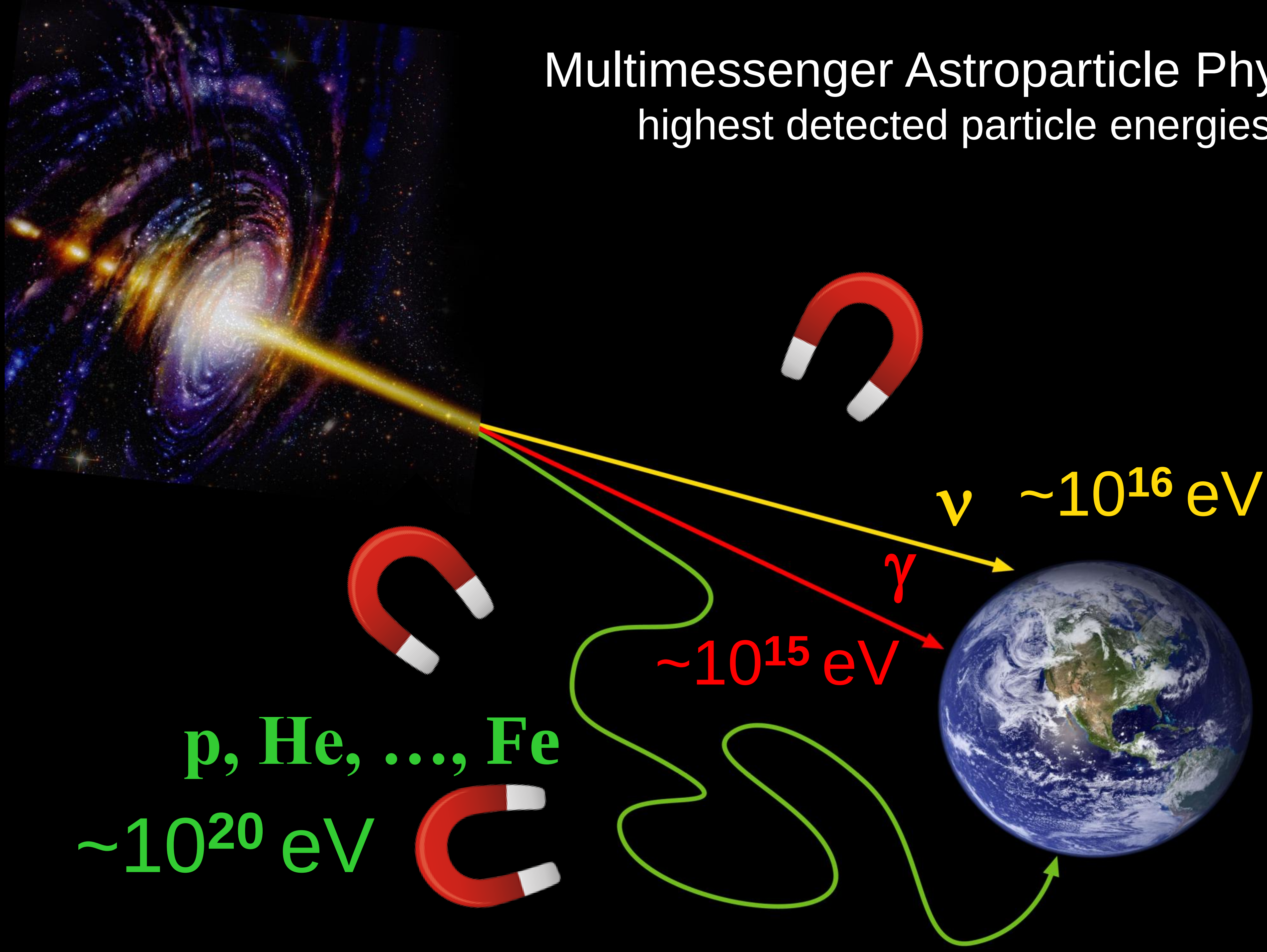
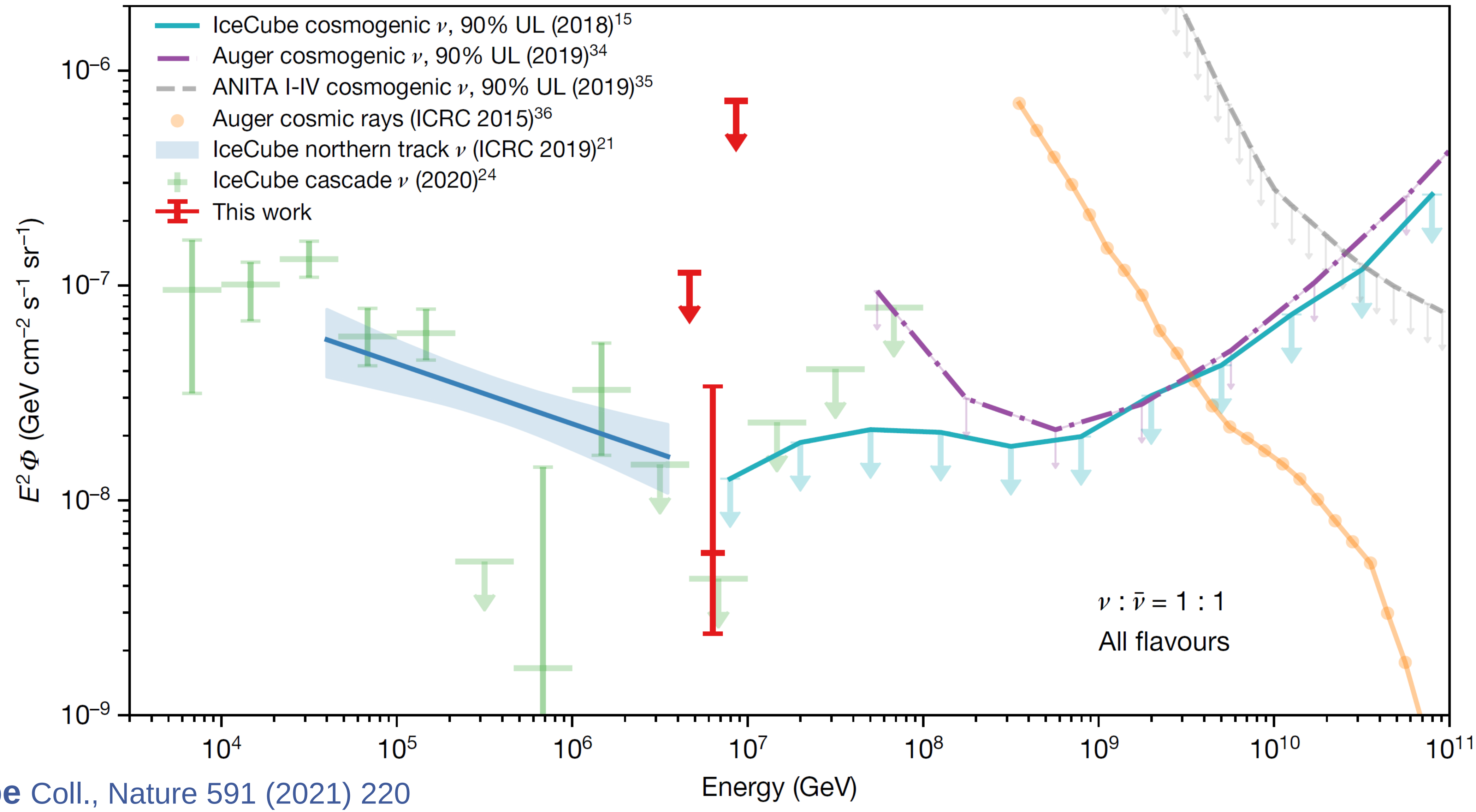
Multimessenger Astroparticle Physics
highest detected particle energies



Almost 10 PeV neutrino (at Glashow resonance of 6.3 PeV)



IceCube Coll., Nature 591 (2021) 220

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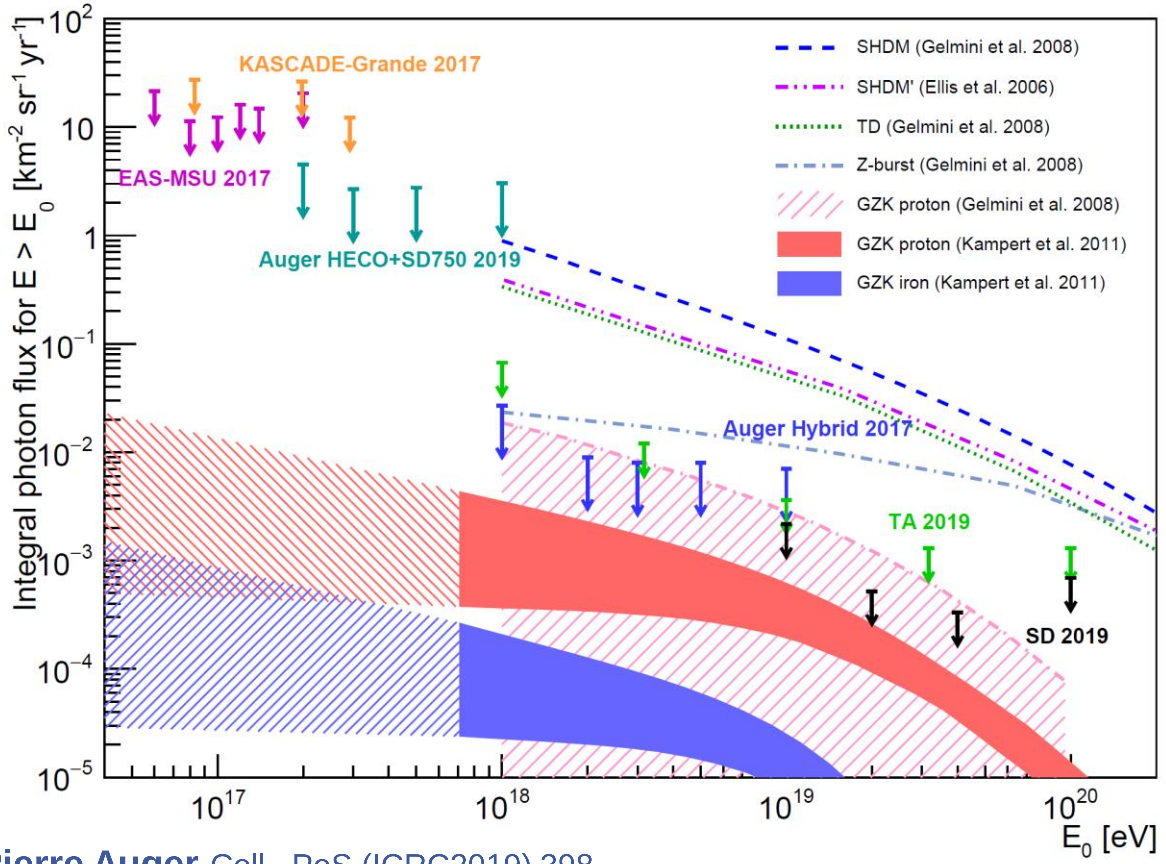
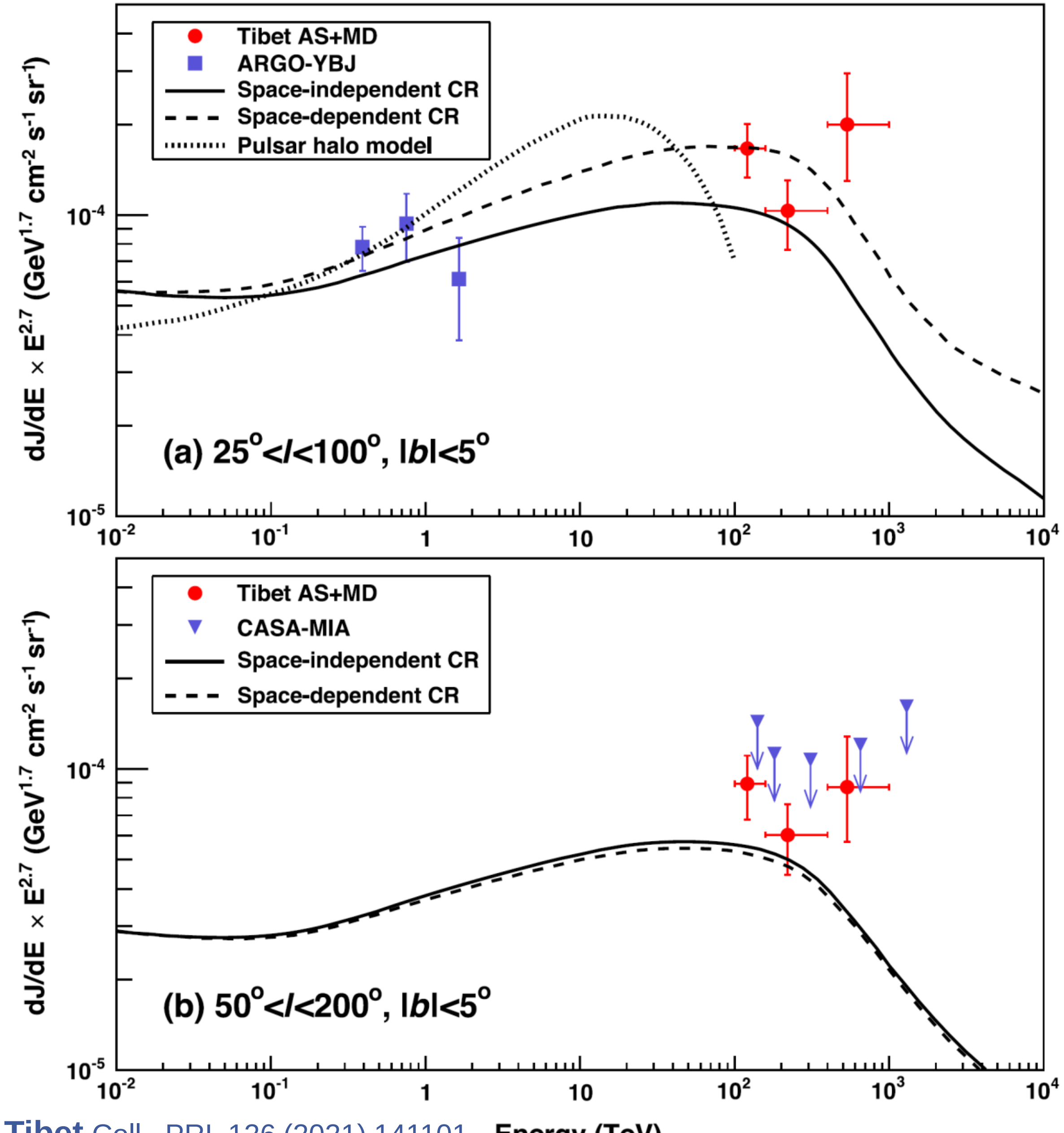
Almost PeV gamma rays

- Diffuse ~ PeV photons measured by Tibet AS gamma experiment
- Only limits at higher energies



Pierre Auger Coll., PoS (ICRC2019) 398



Tibet Coll., PRL 126 (2021) 141101

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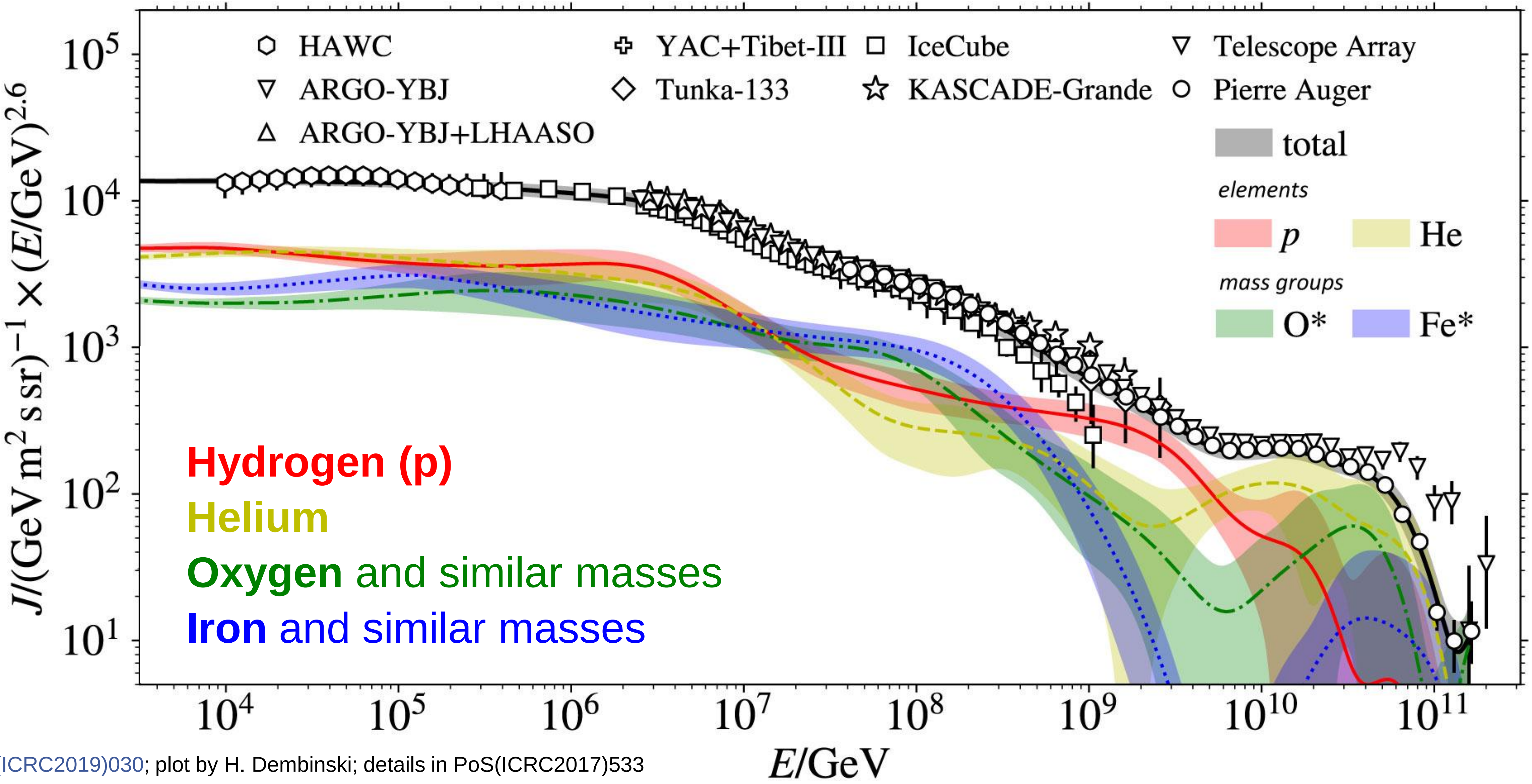
frank.schroeder@kit.edu

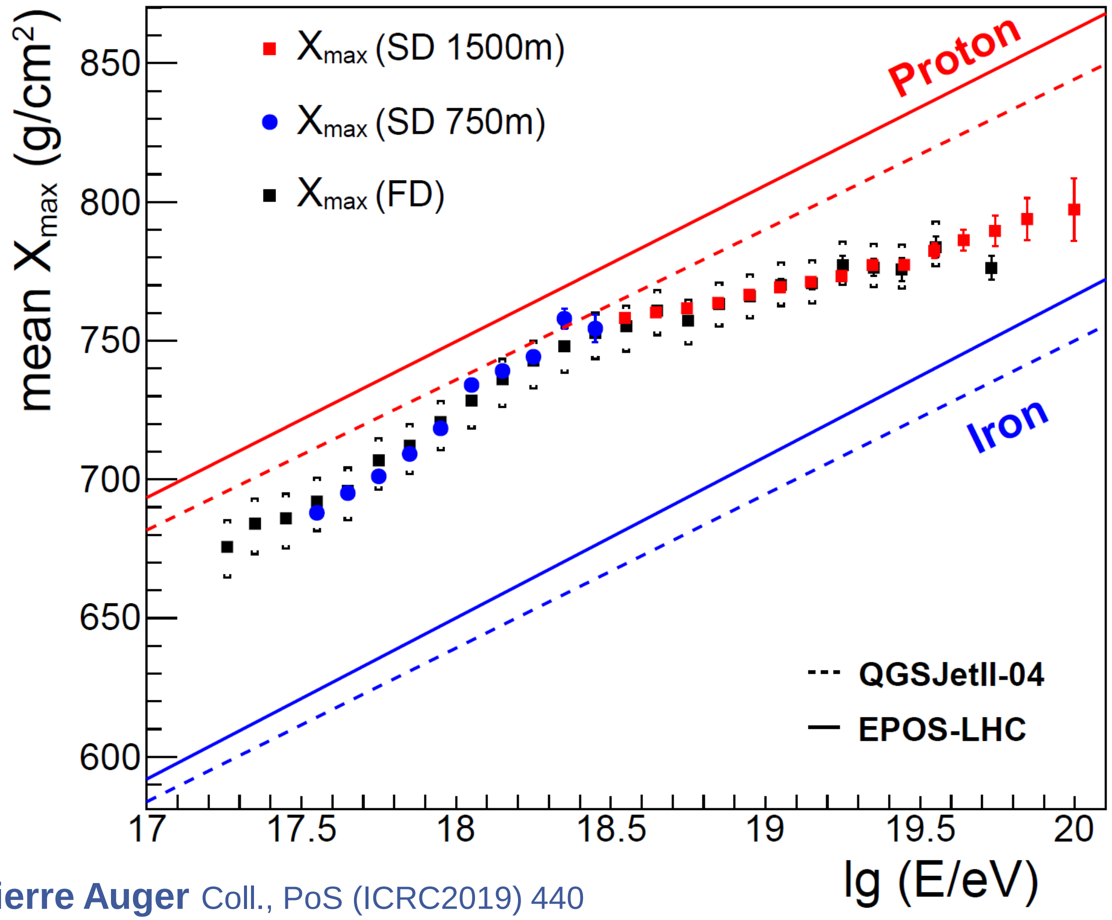
Cosmic-Ray Energy Spectrum and Mass Composition



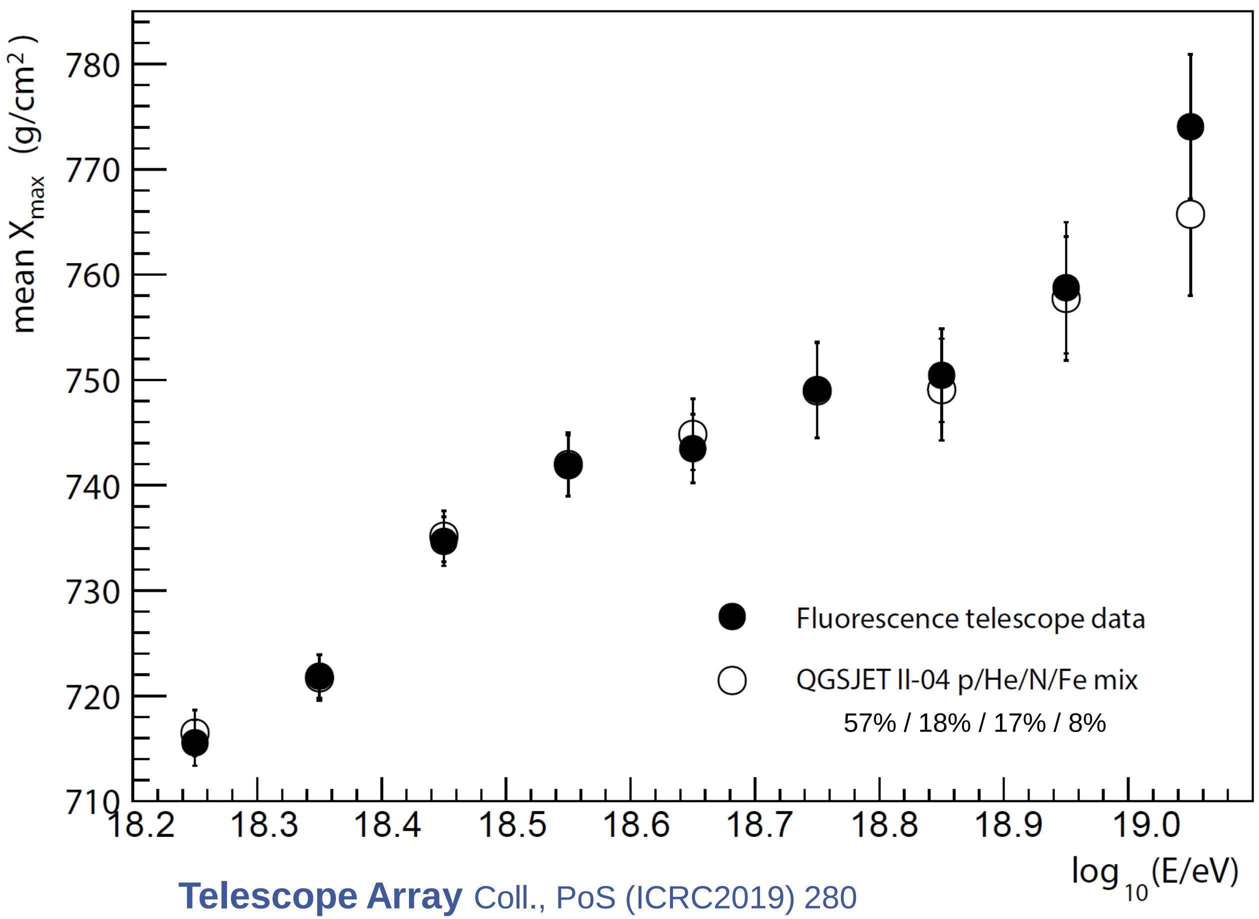
PoS(ICRC2019)030; plot by H. Dembinski; details in PoS(ICRC2017)533

Depth of Shower Maximum, X_{max}

- Dominantly light composition (p + He) around ankle, trend towards heavier composition
- Auger and Telescope Array consistent within uncertainties (TA also consistent with constant composition)



Pierre Auger Coll., PoS (ICRC2019) 440



Telescope Array Coll., PoS (ICRC2019) 280

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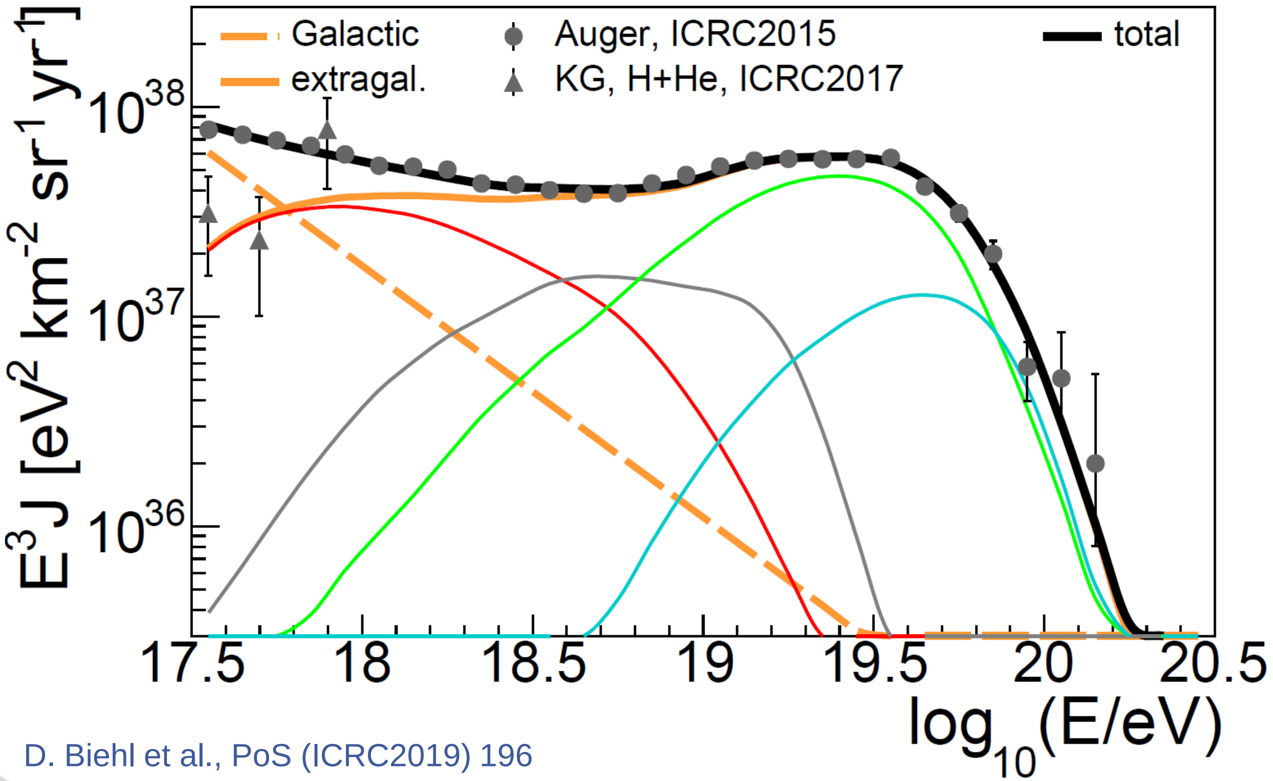
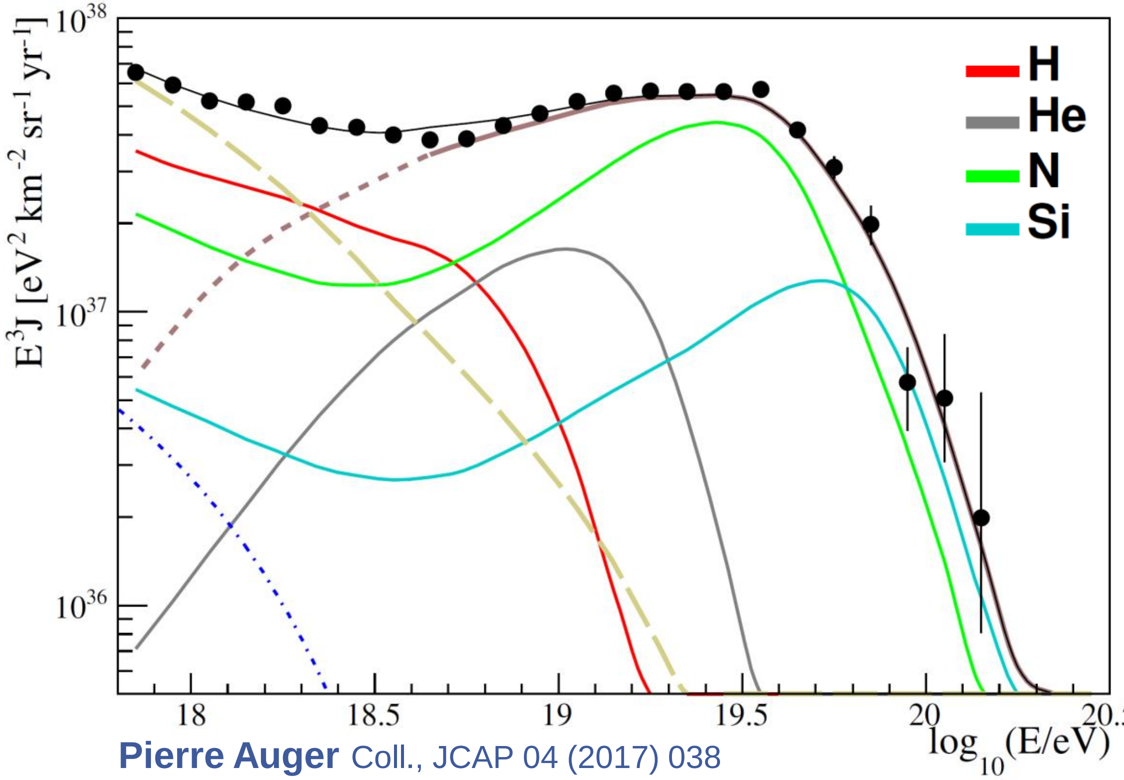
frank.schroeder@kit.edu

Interpretations of UHECR flux and open questions

- Cut-off due to maximum acceleration energy and/or due to propagation?
  - Need to determine proton fraction at highest energies
- Ankle likely a mixture of propagation effects and transition between components
  - Is this the transition from Galactic to extragalactic CR, or different extragalactic components?



D. Biehl et al., PoS (ICRC2019) 196

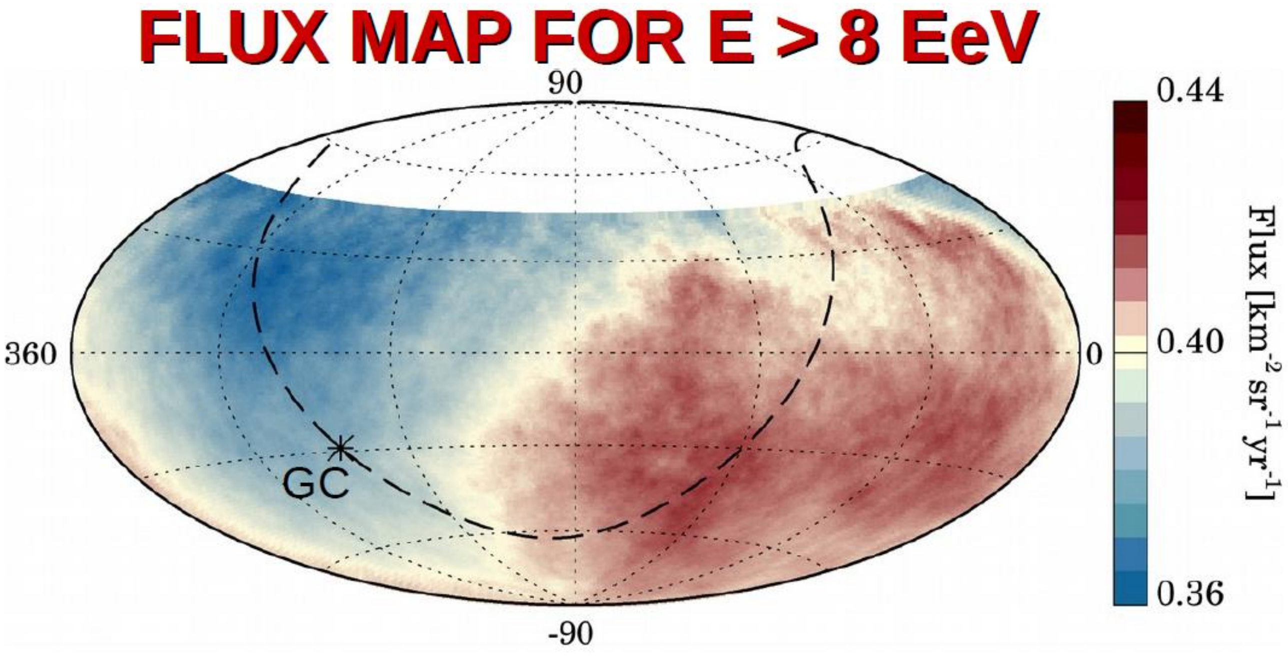


Pierre Auger Coll., JCAP 04 (2017) 038

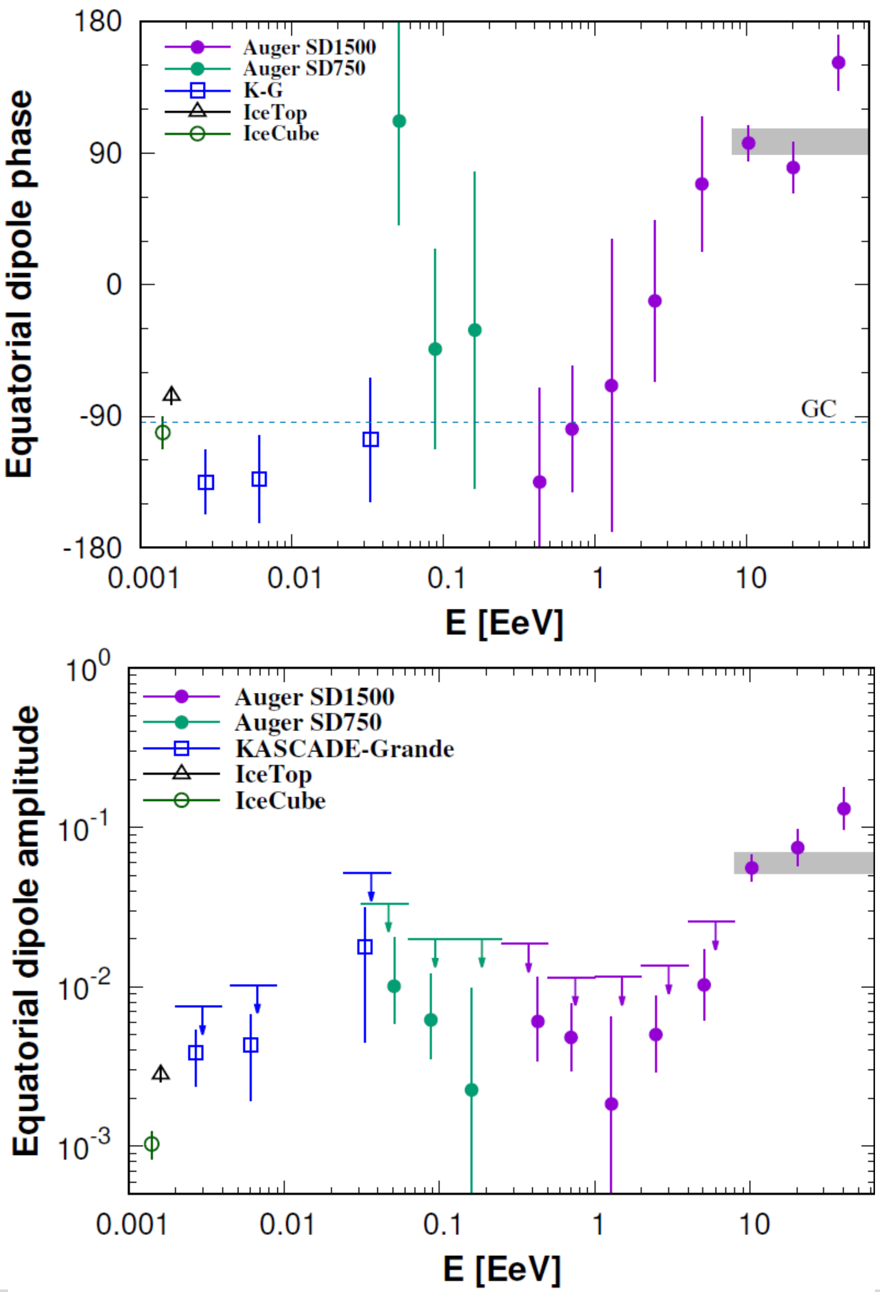
fgs@udel.edu
frank.schroeder@kit.edu

Auger Dipole – UHECR Anisotropy

- Dipole strengths increases with energy
- Direction consistent with extragalactic origin
- Transition of dipole phase around 1 EeV: hint for Galactic-to-extragalactic transition



equatorial coordinates, smoothed on 45° radius windows



Pierre Auger Coll., ICRC 2019 / APJ 891 (2020) 142

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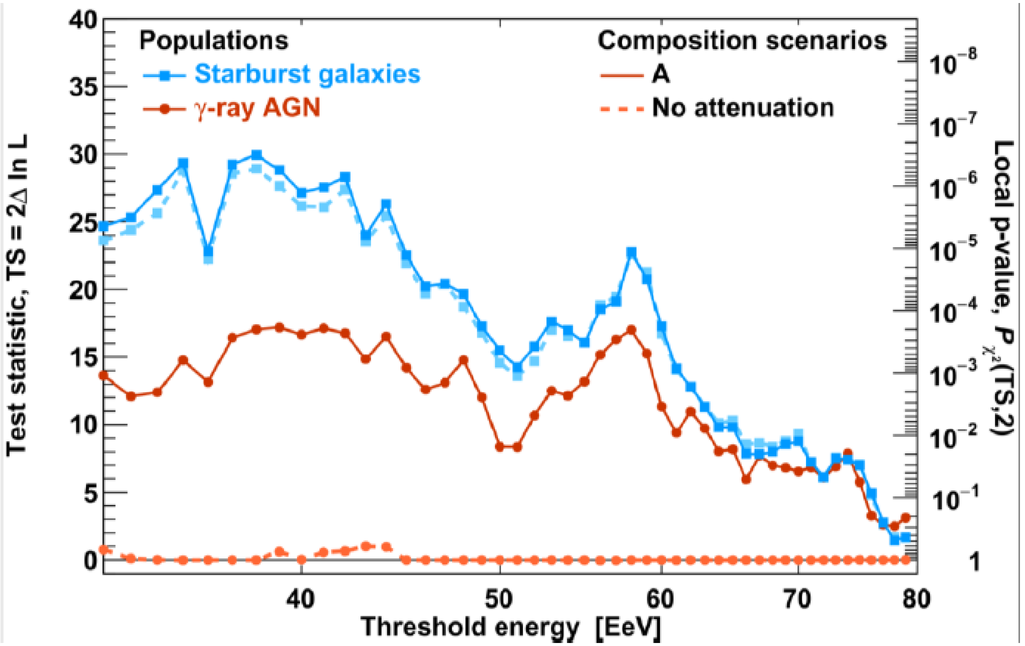
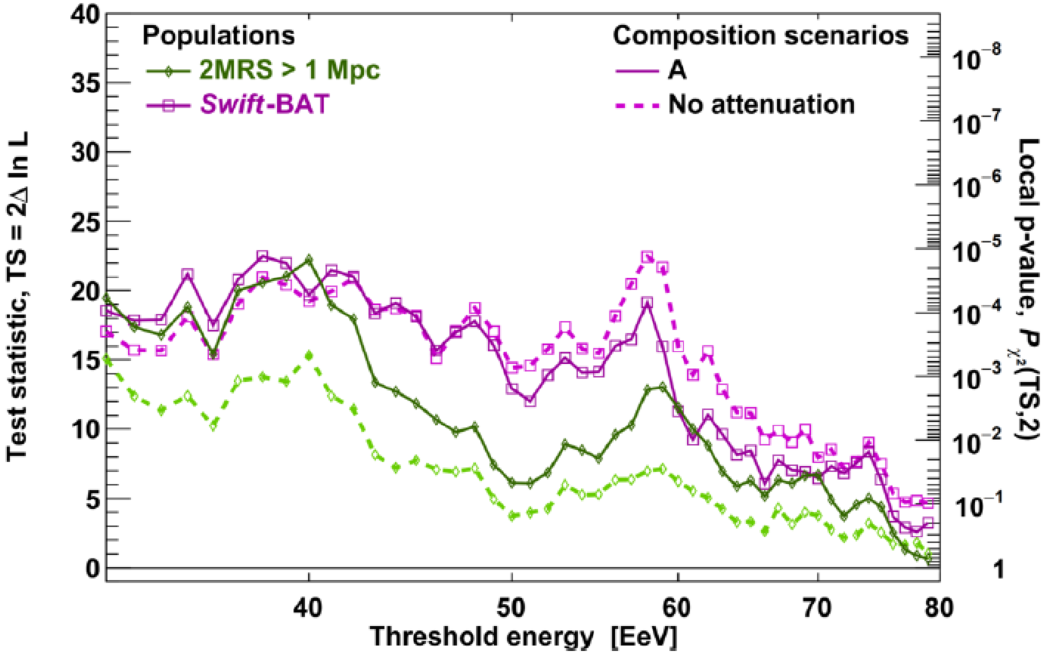
Auger: Correlations with Source Candidates





Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	15^{+5}_{-4}°	11^{+5}_{-4}%	29.5	4.5 σ
γ-AGNs	39 EeV	14^{+6}_{-4}°	6^{+4}_{-3}%	17.8	3.1 σ
Swift-Bat	38 EeV	15^{+6}_{-4}°	8^{+4}_{-3}%	22.2	3.7 σ
2MRS	40 EeV	15^{+7}_{-4}°	19^{+10}_{-7}%	22.0	3.7 σ

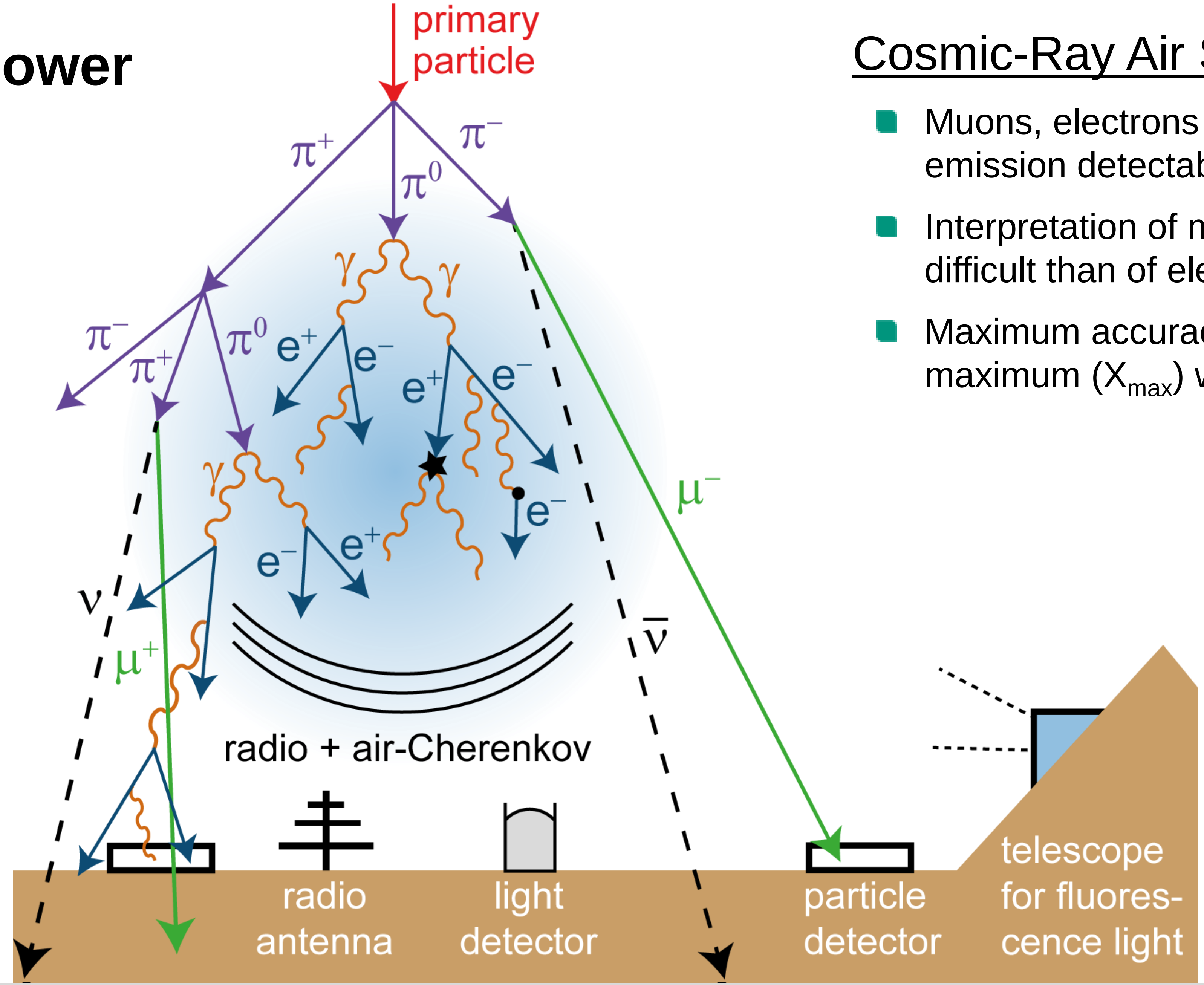
Highest TS = 29.5 found for starburst galaxies with E_{th}=38 EeV

All the most significant excesses happen at similar E_{th} and angular scale

Note: 15° smearead Fisher-Von Misses distribution ~1.59×15°=24±8° top-hat

Pierre Auger Coll., PoS (ICRC2019) 206

Air shower



Cosmic-Ray Air Showers

- Muons, electrons and electromagnetic emission detectable at ground
- Interpretation of muon component more difficult than of electromagnetic one
- Maximum accuracy by combining shower maximum (X_{max}) with electron-muon ratio

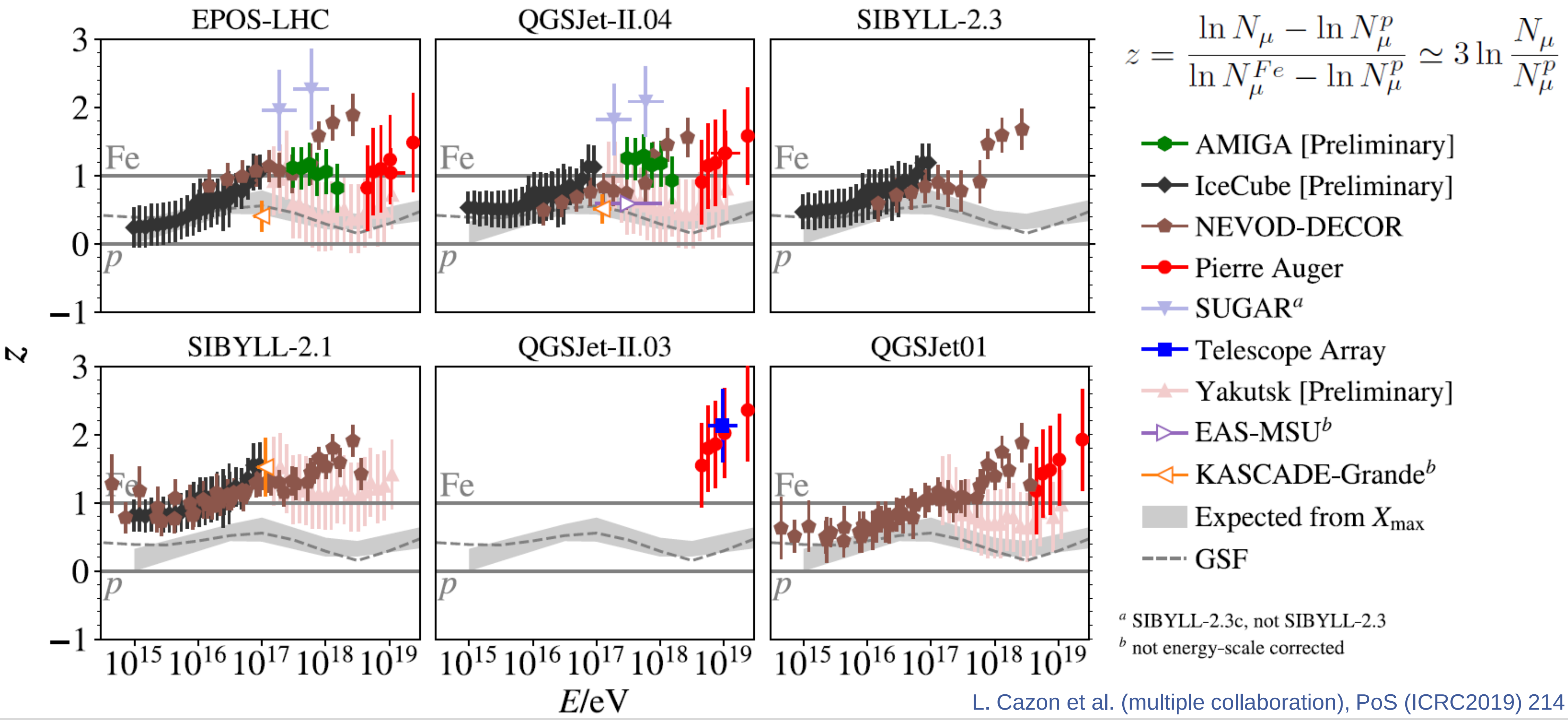
Radio detection of cosmic-ray air showers and high-energy Neutrinos“

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

fgs@udel.edu
frank.schroeder@kit.edu

Problems in Hadronic Interaction Models

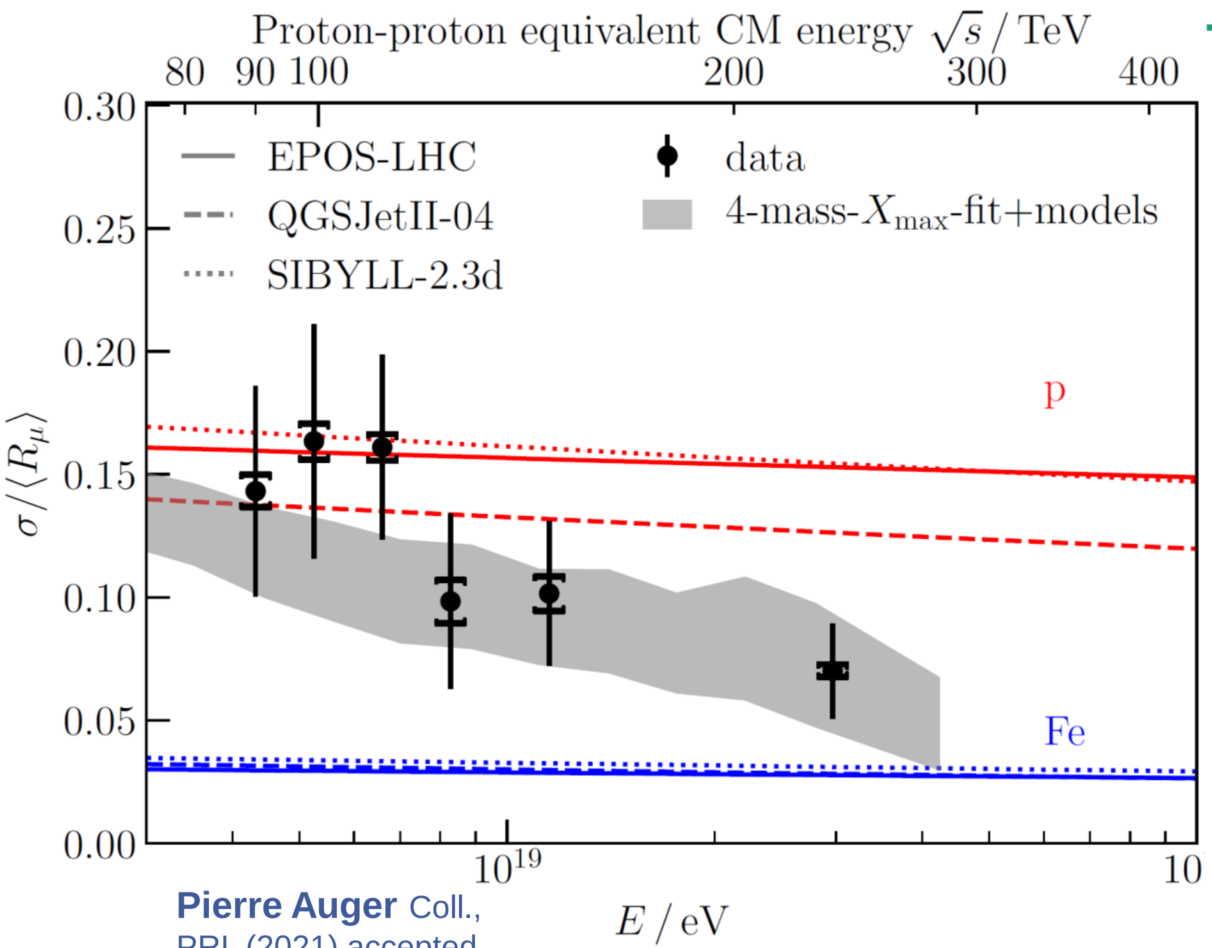
- Accelerator Data not well described + Muon deficit in high-energy air showers

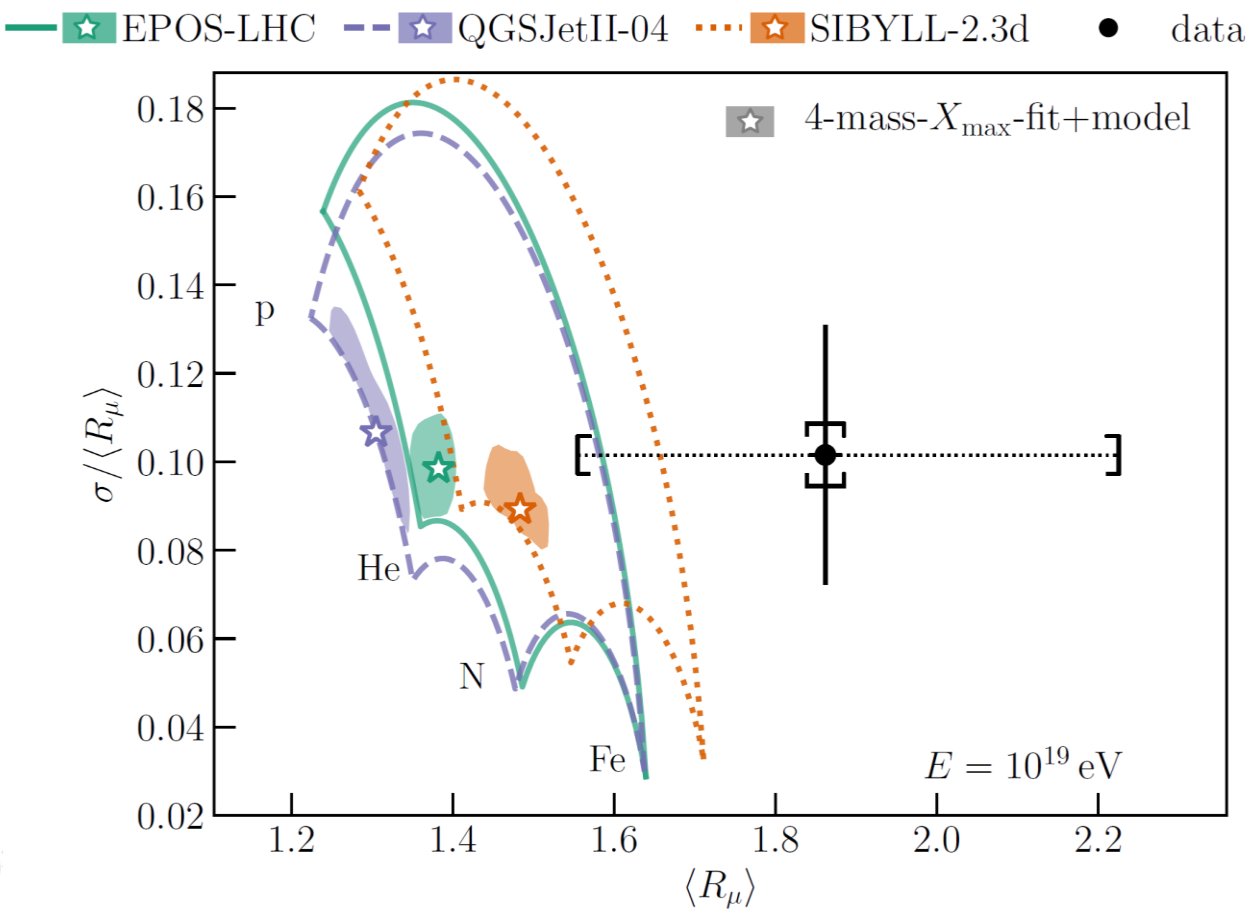


L. Cazon et al. (multiple collaboration), PoS (ICRC2019) 214

Fluctuation of muon number measured by Auger

- Hadronic interaction models can describe variations in muon number, but not absolute number



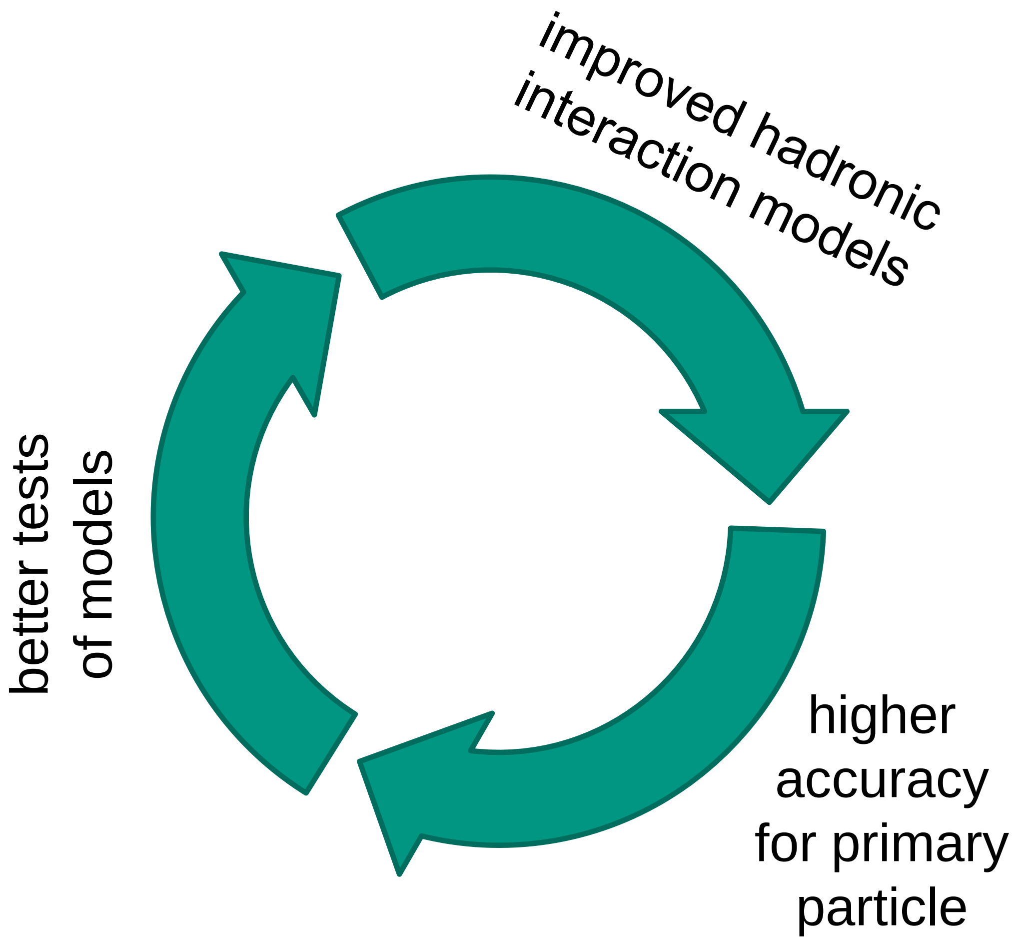


Pierre Auger Coll.,
PRL (2021) accepted

How to increase accuracy for CRs?

- Accuracy of **mass** of primary particle depends on interpretation of air-showers observables measured by detectors
  - unknown systematic uncertainty for interpretation of muons (all models out of range)
  - small systematic uncertainty for interpretation of X_{max} (approx. H to He difference)
- Improvements of hadronic interaction models critical for field of CR
  - input from by air-shower experiments
  - accelerator measurements (e.g, p-O at LHC …)

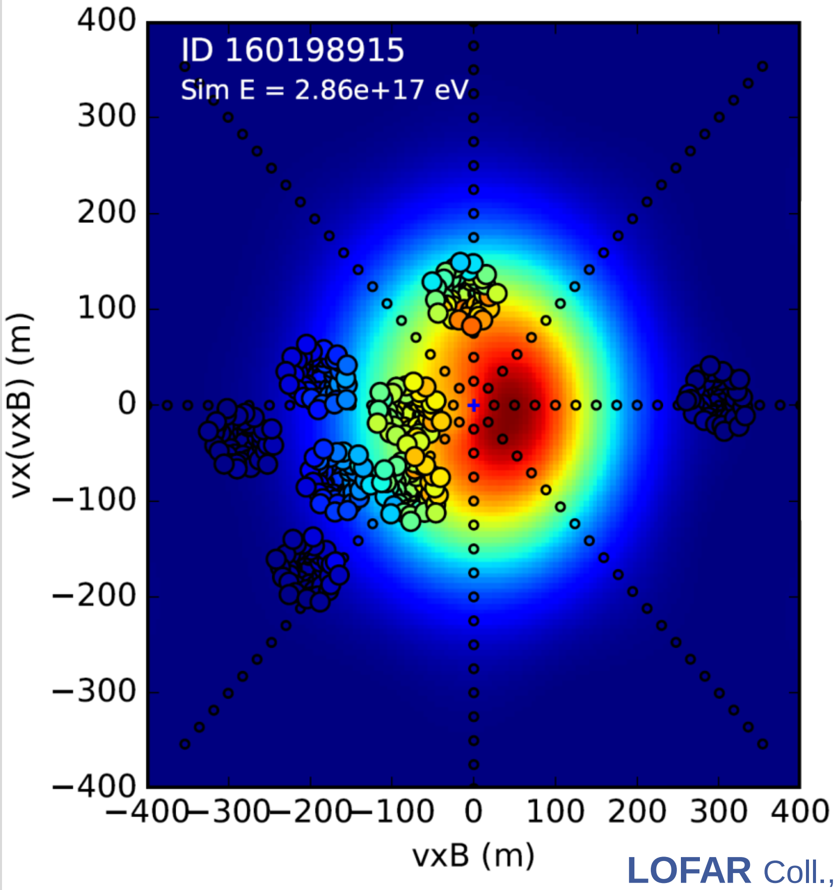
virtuous circle of cosmic-ray physics



fgs@udel.edu
frank.schroeder@kit.edu

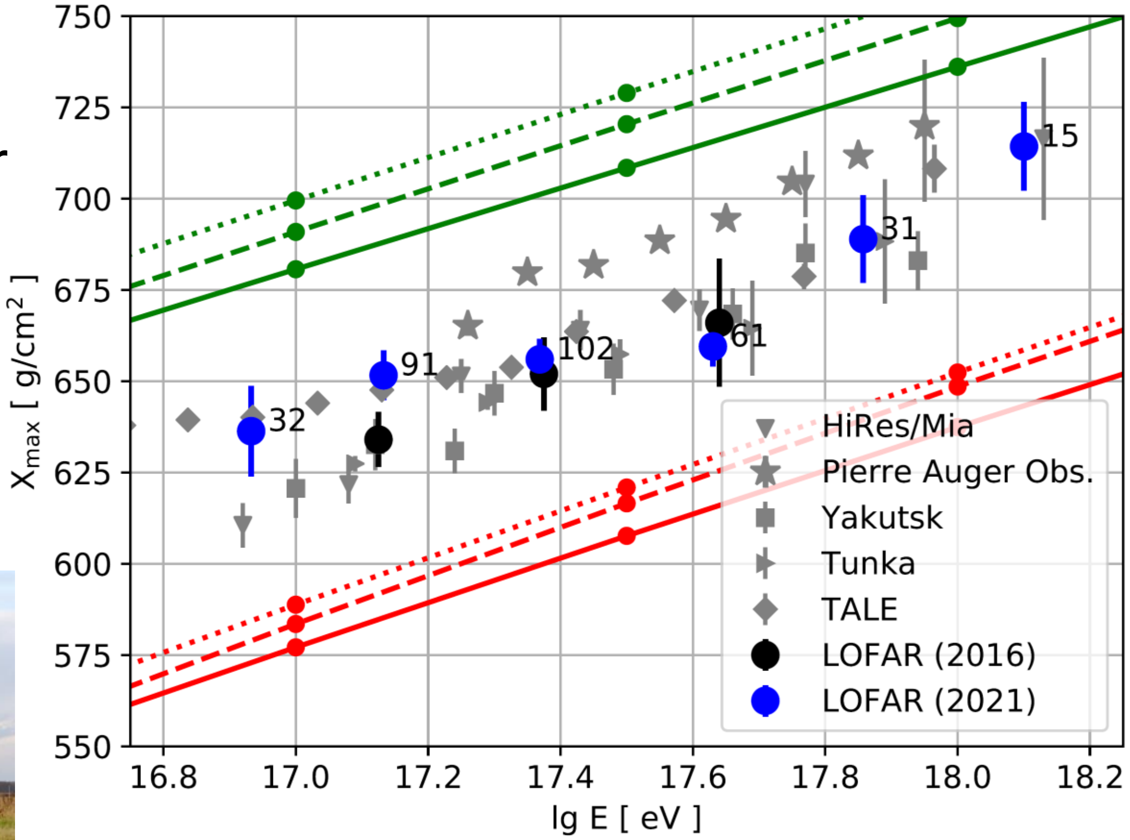
Radio Detection

- Radio emitted by em.-component of shower
- Accurate energy and X_{max} measurement



LOFAR antenna

LOFAR Coll., arXiv:2103.12549



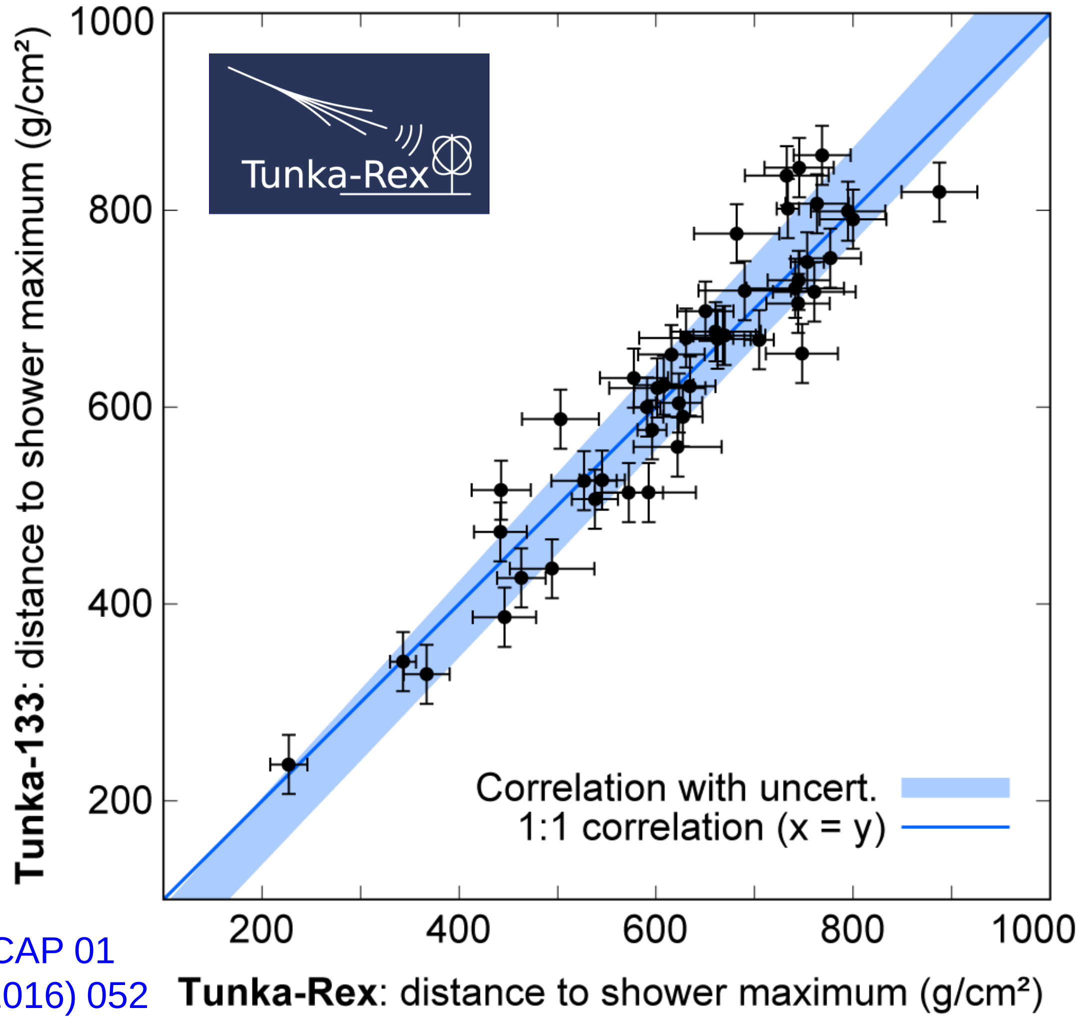
Example:
Most recent X_{max} measurement by LOFAR based on fitting CoREAS simulations to antenna signals

Radio X_{max} also by Auger and Tunka-Rex

fgs@udel.edu
frank.schroeder@kit.edu

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

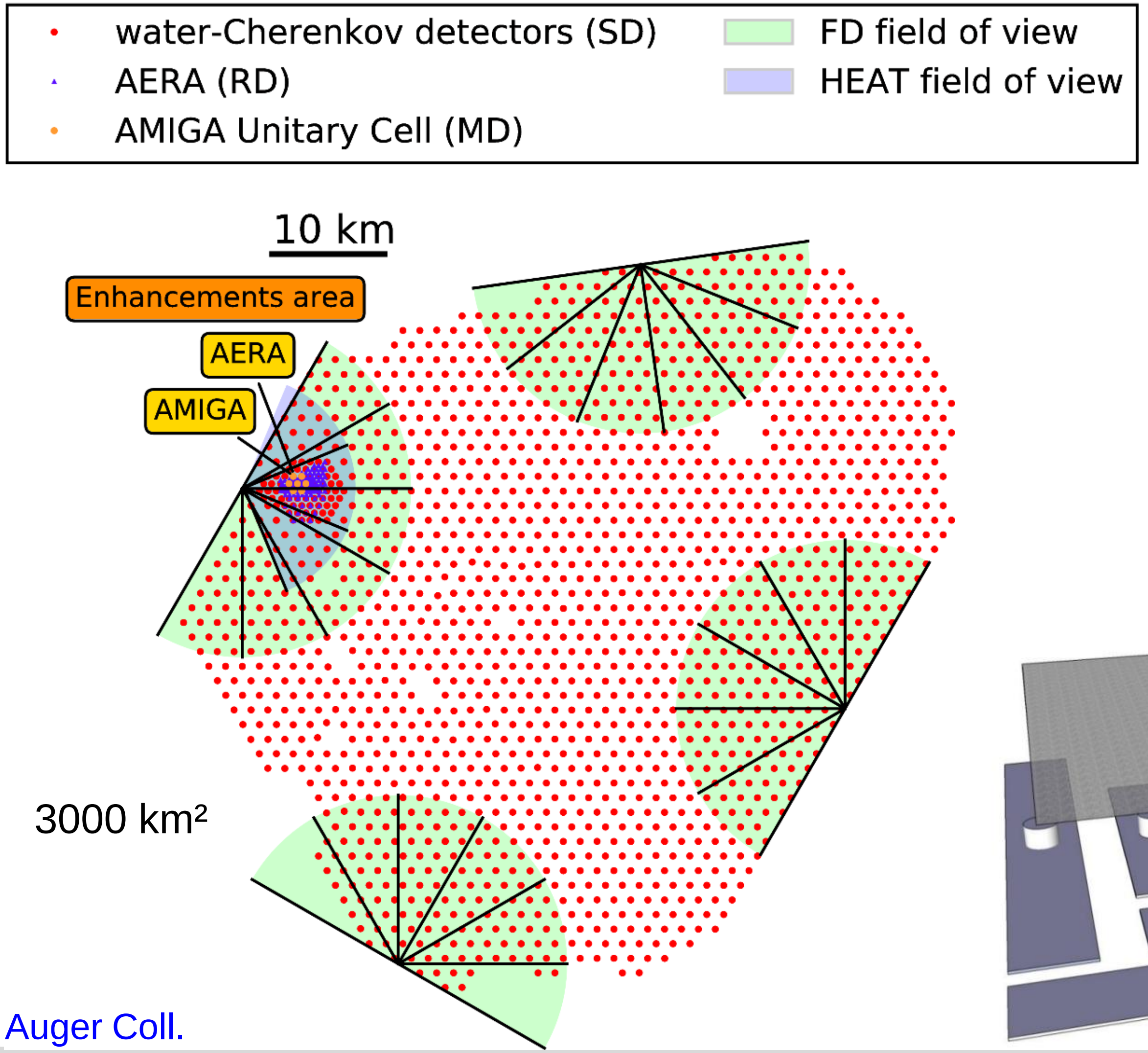
- Direct proof of radio X_{max} sensitivity by comparison to Cherenkov-light detectors



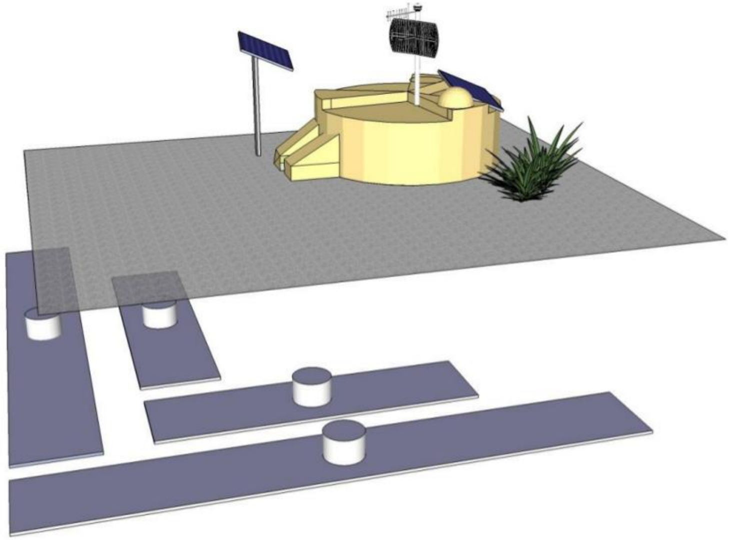
JCAP 01 (2016) 052

fgs@udel.edu
frank.schroeder@kit.edu

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



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



Auger Coll.

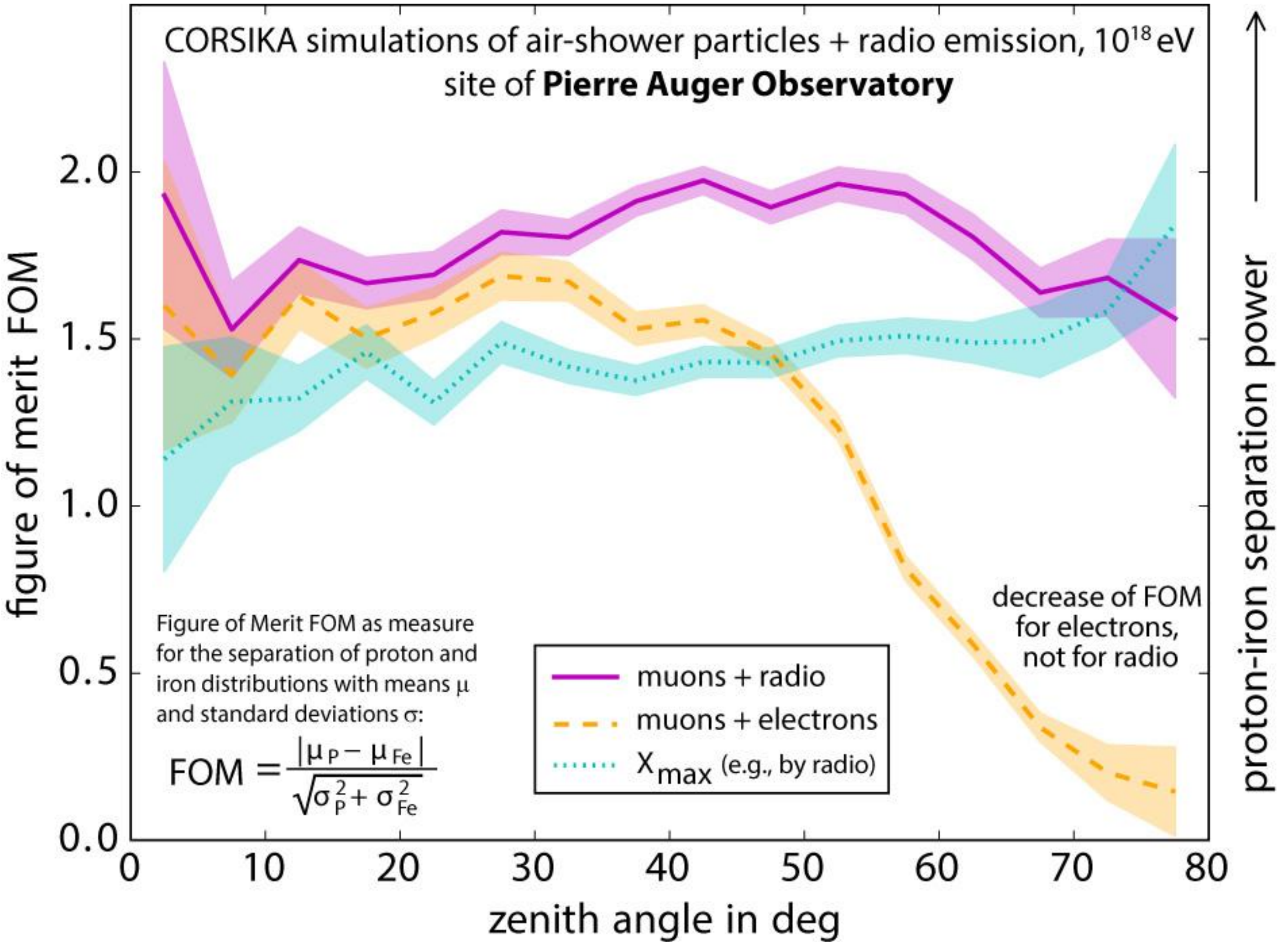
fgs@udel.edu
frank.schroeder@kit.edu

Key for many science goals: Mass Separation power

- Radio can enhance mass sensitivity for all zenith angles, in particular for inclined showers
- Radio + Muons have similar mass separation power as X_{max}

→ **maximum accuracy for air-shower measurements by combining radio + muons!**

- Plots show potential of the methods (no detector properties considered; vertical showers require a dense antenna spacing)

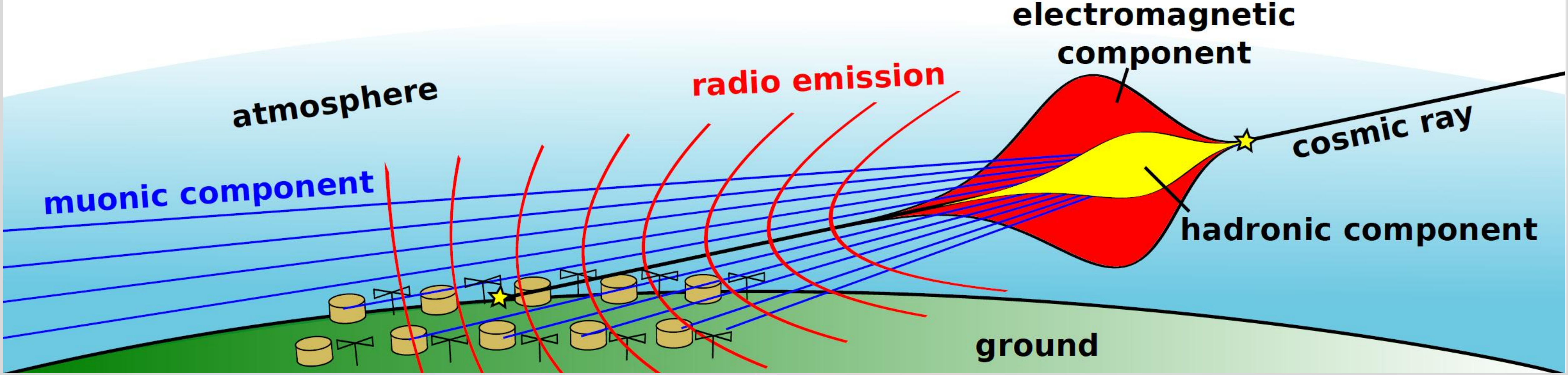


Pierre Auger Coll., EPJ WoC 216 (2019) 02002
more details in E. Holt et al., EPJ C 79 (2019) 371

fgs@udel.edu
frank.schroeder@kit.edu

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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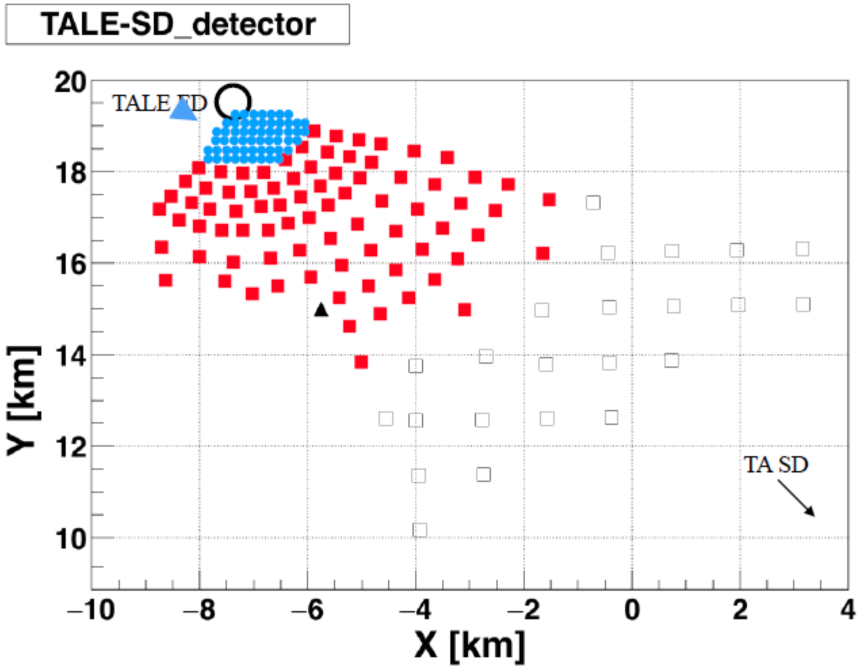
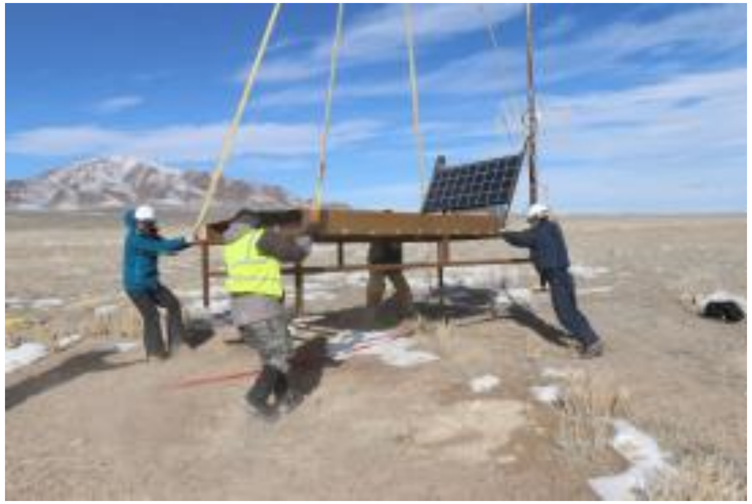
frank.schroeder@kit.edu

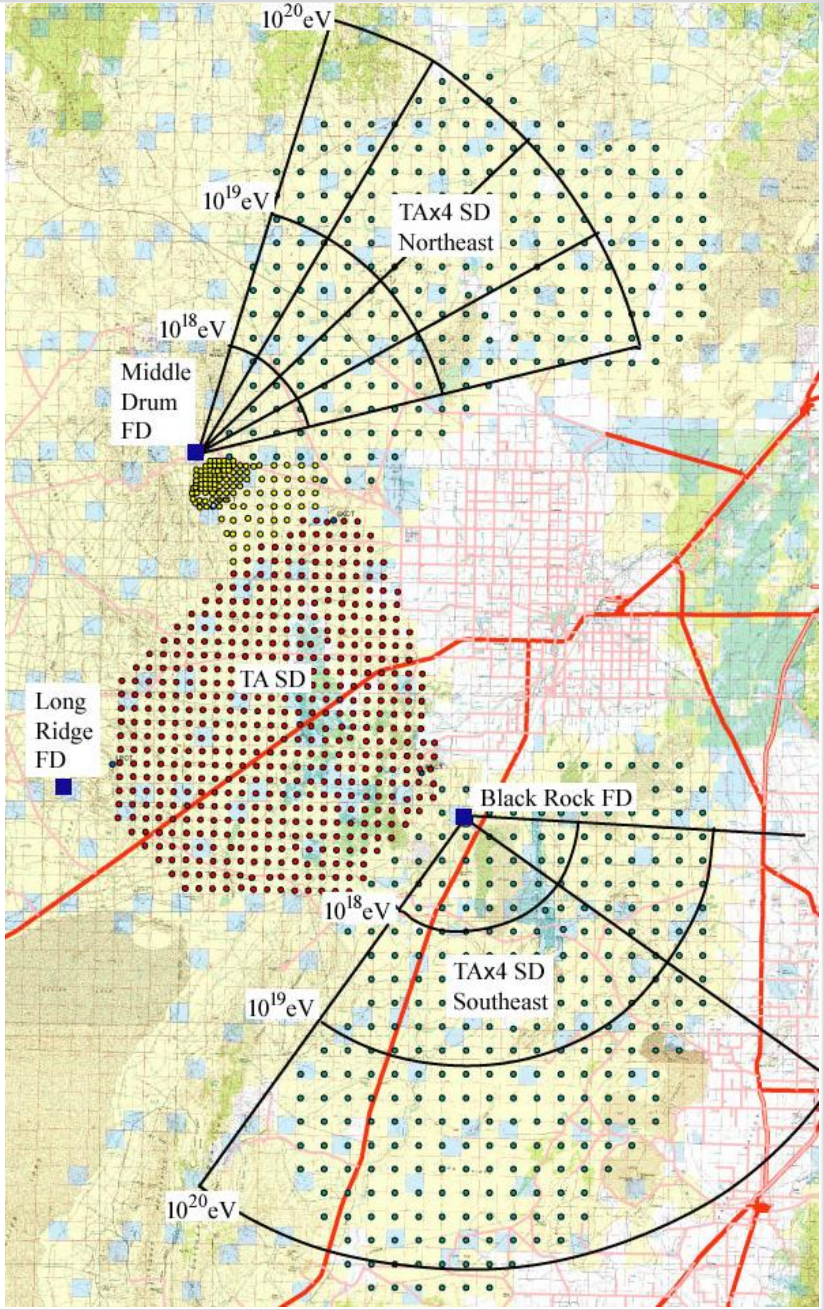
Telescope Array: Upgrades

- Highest energies ($E > 10^{19.8}$ eV)
  - TAx4 → 3000 km² scintillator array
  - new fluorescence telescopes
- Lower energies ($E > 10^{15.5}$ eV):
  - TALE SD array complementing NICHE and FD





Telescope Array Coll.,
PoS (ICRC2019) 013 + 375



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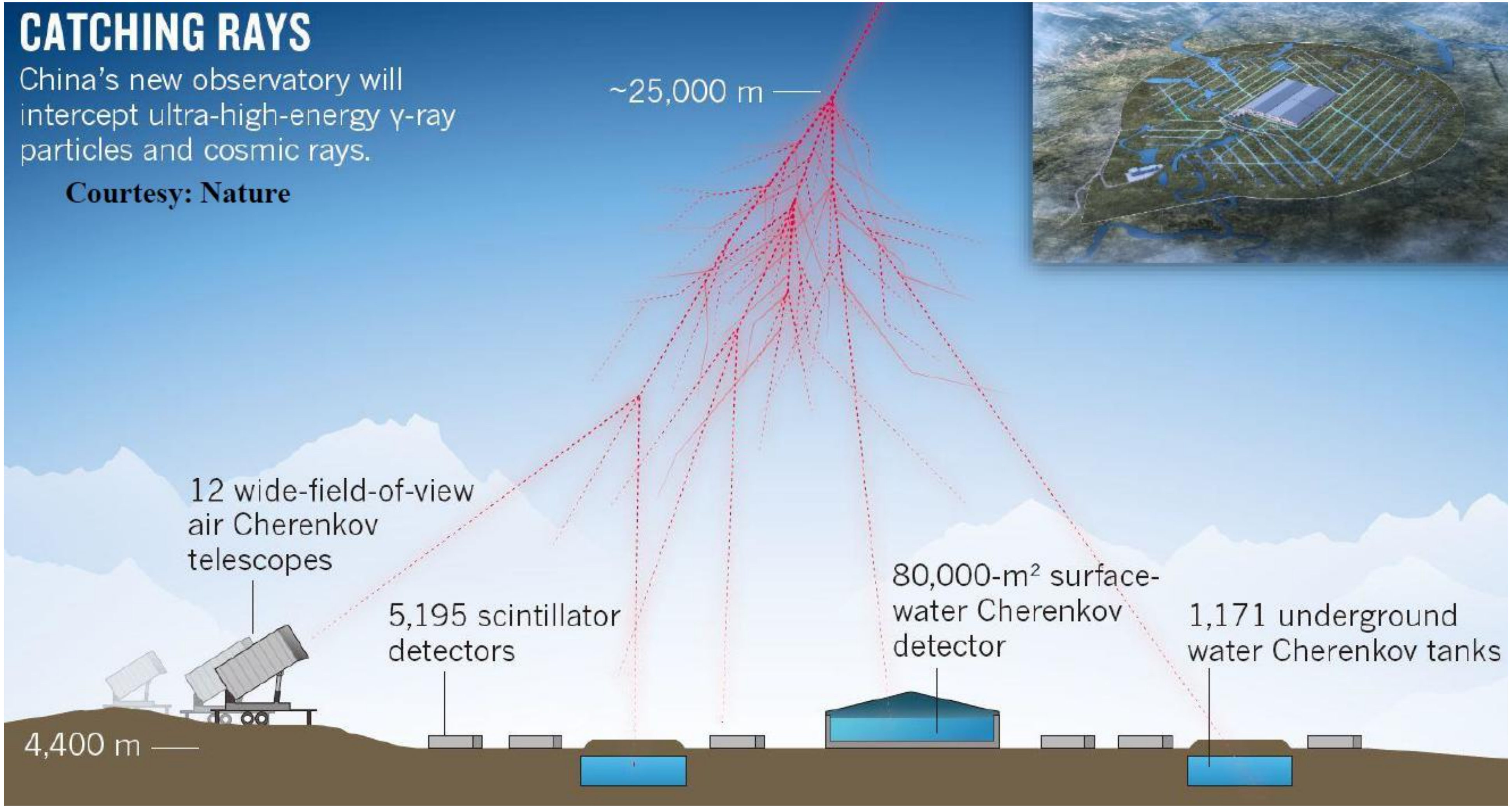
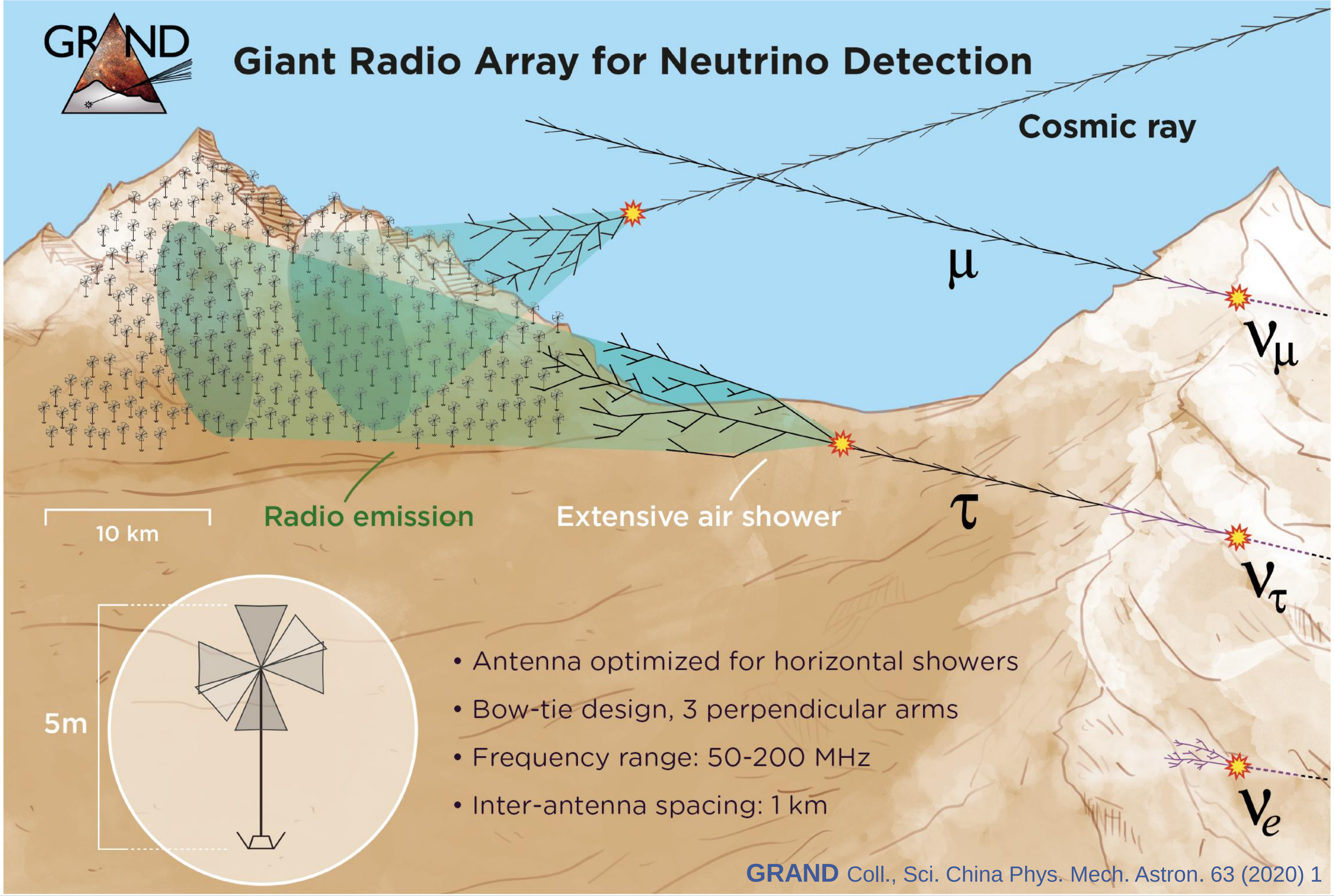
LHAASO – a 1 km^2 multi-hybrid detector in China

Primary goal are gamma-rays, but also excellent cosmic-ray detector



LHAASO Coll.,
PoS (ICRC2019) 693



GRAND Coll., Sci. China Phys. Mech. Astron. 63 (2020) 1

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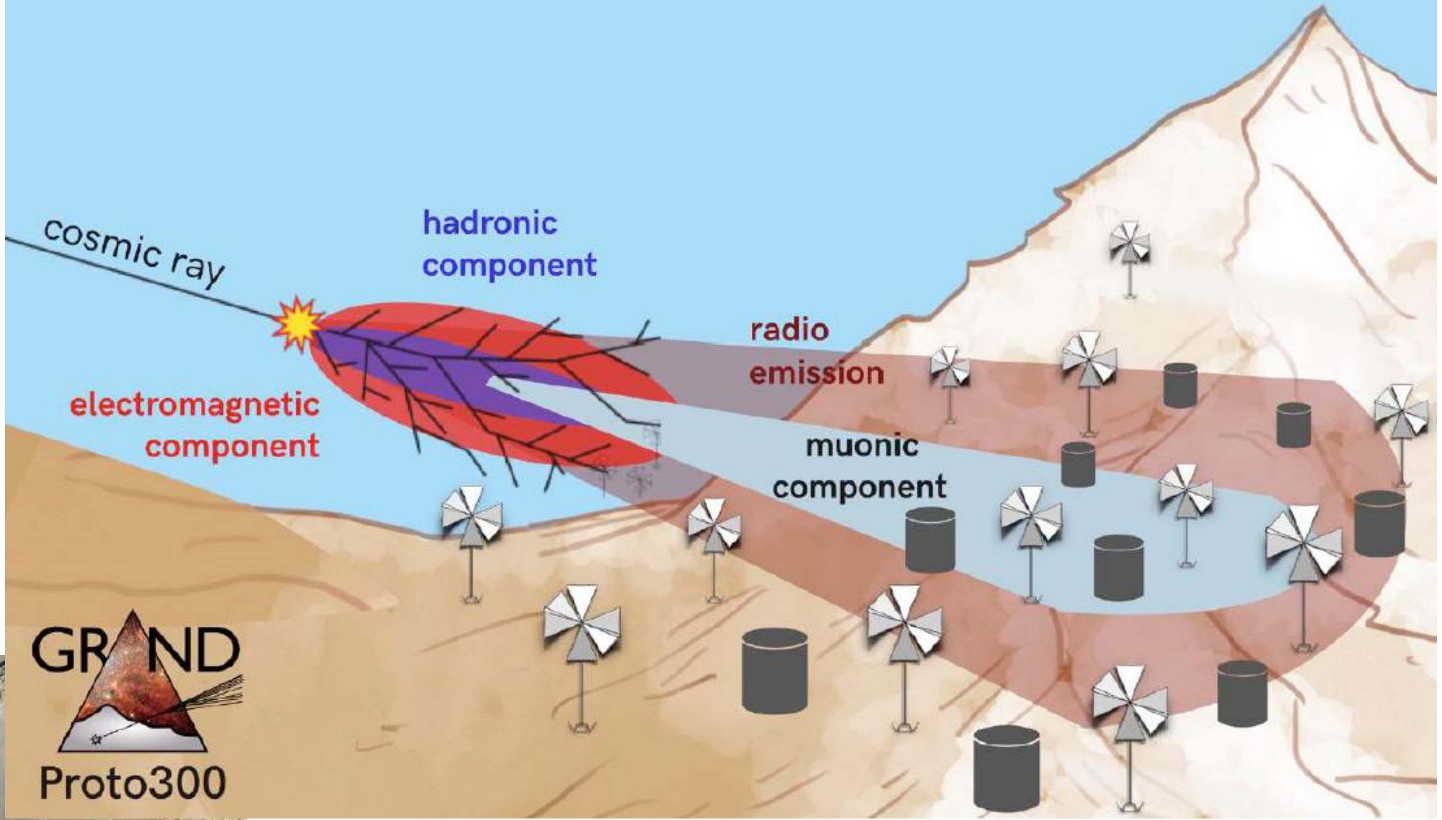
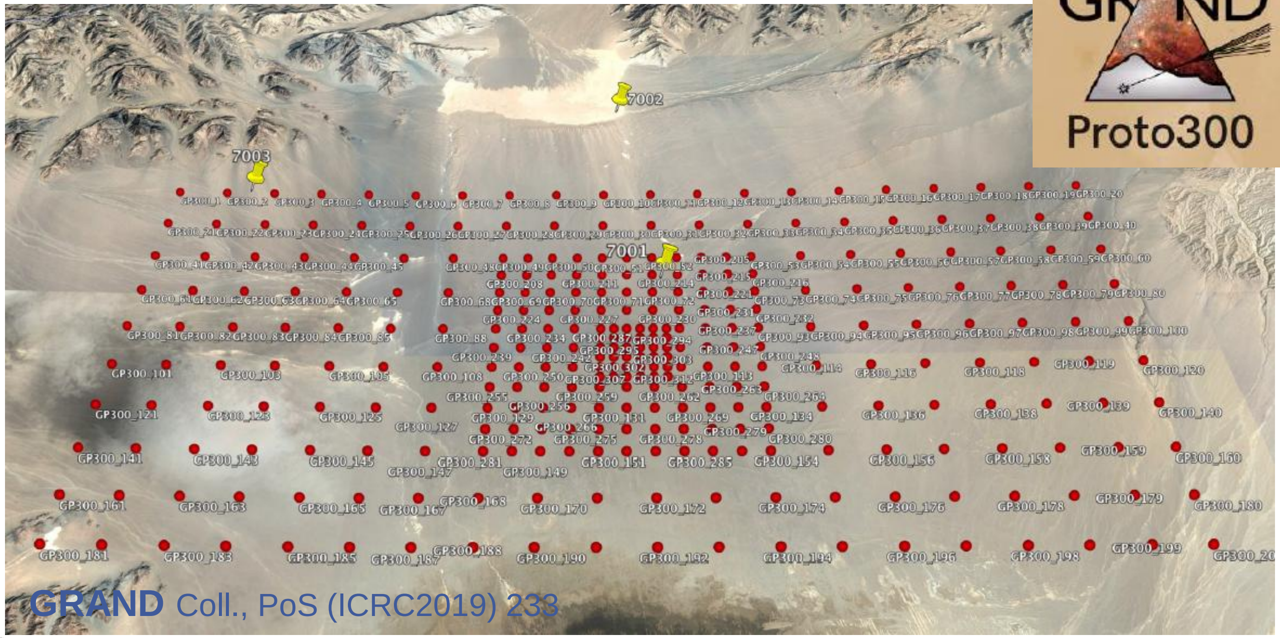
GRANDproto300

- Cosmic-Ray science in EeV range with inclined air showers
  - 300 antennas on 200 km²
  - Auger-like water-Cherenkov detectors for muons
  - future stages will be antennas only





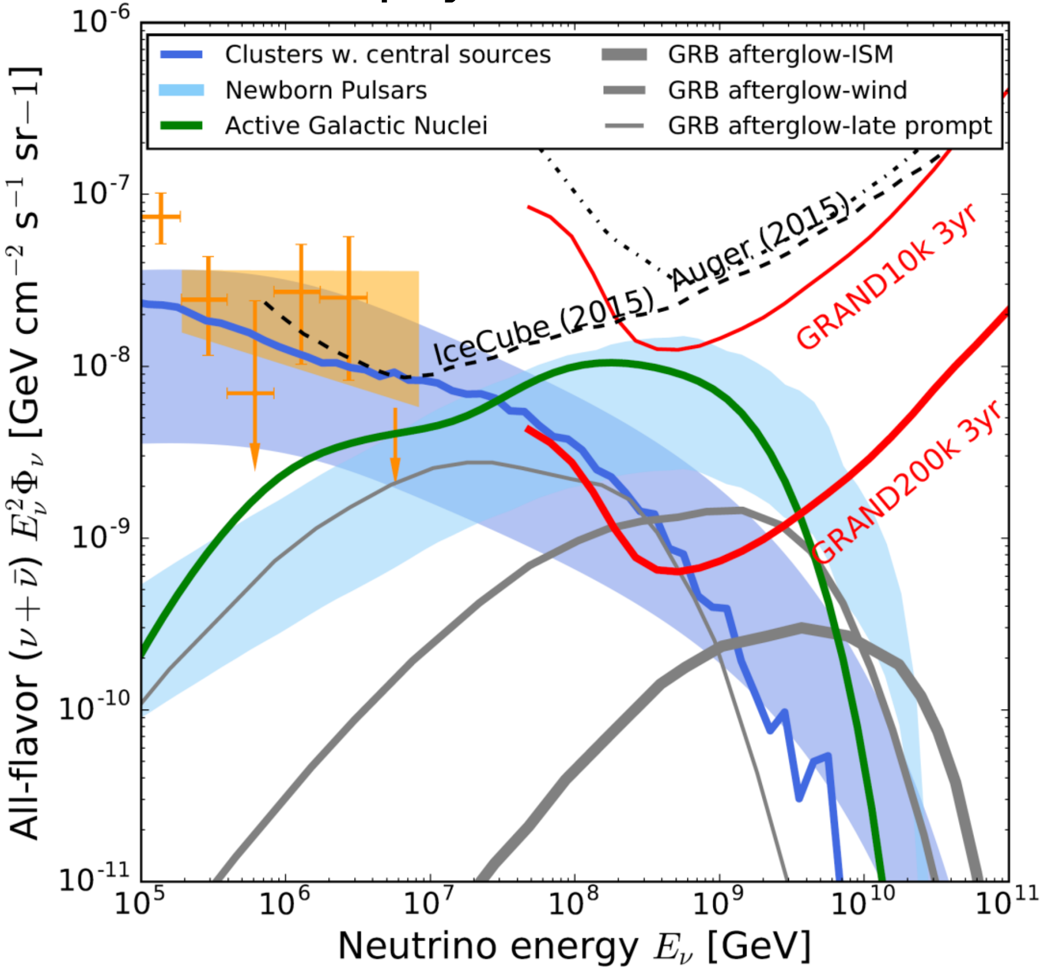
GRAND Coll., PoS (ICRC2019) 233

- Prototype for next stages of GRAND
  - GRAND 10k will have comparable exposure to Auger for cosmic rays
  - GRAND 200k (if build) may complement future space missions for UHECR

fgs@udel.edu
frank.schroeder@kit.edu

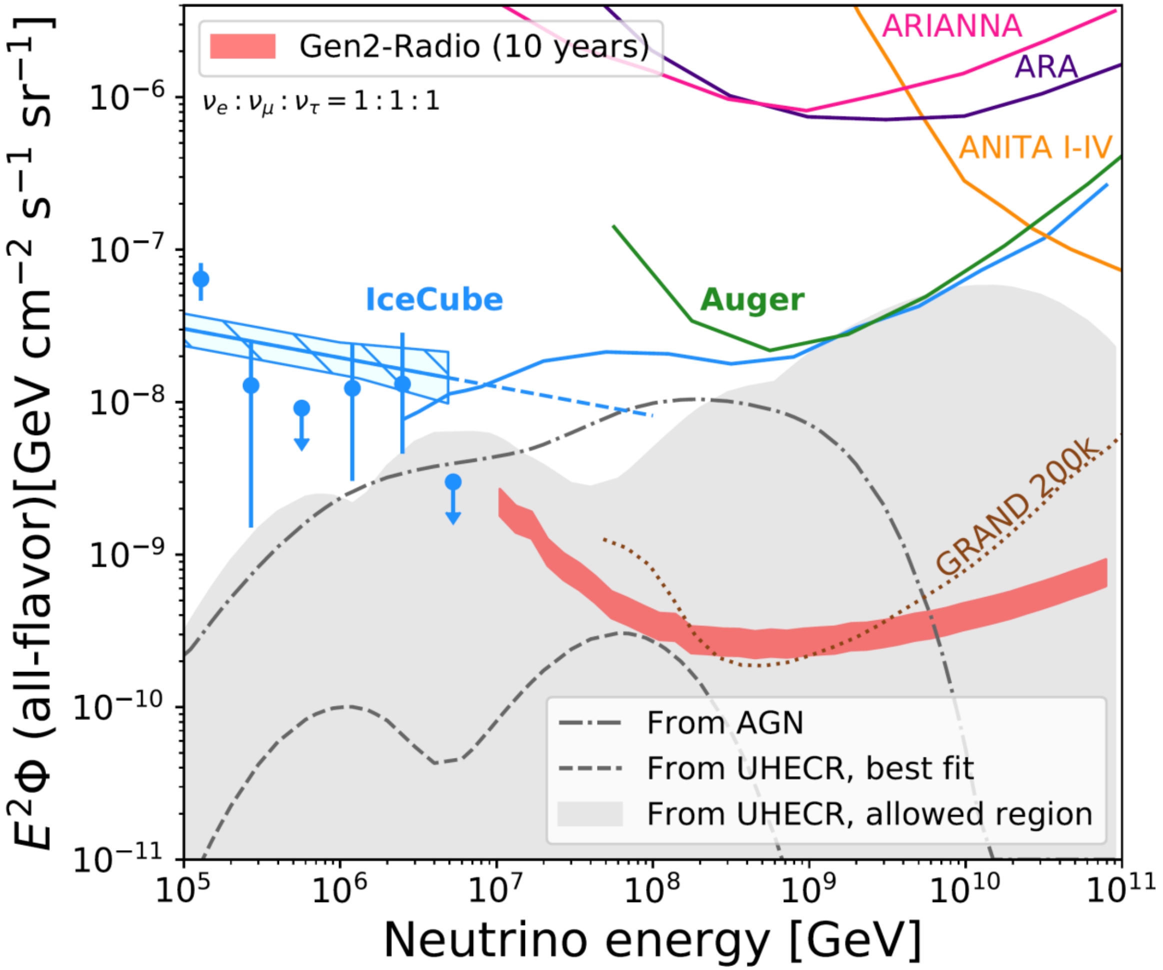
GRAND and IceCube-Gen2 sensitivities for EeV neutrinos

Astrophysical Neutrinos



GRAND Coll., Sci. China Phys. Mech. Astron. 63 (2020) 1

Cosmogenic Neutrinos



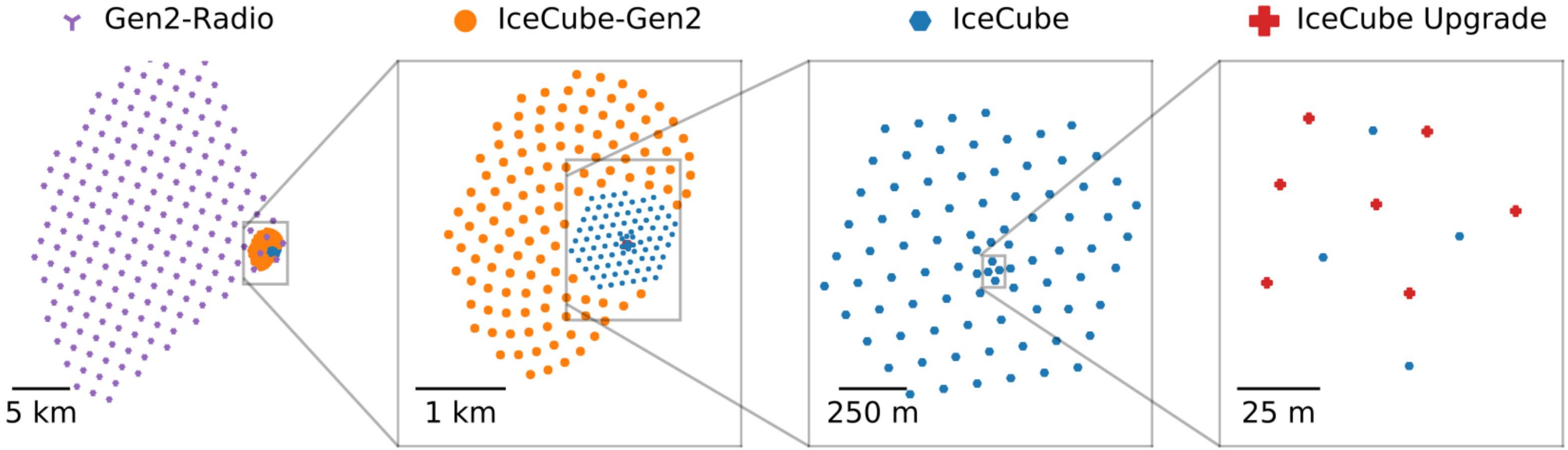
IceCube-Gen2 Whitepaper, arXiv:2008.04323

fgs@udel.edu
frank.schroeder@kit.edu

IceCube-Gen2

- an order of magnitude larger optical and surface arrays
- sparse *in-ice radio* array for detection of Askaryan emission from ultra-high-energy neutrions

arXiv:2008.04323

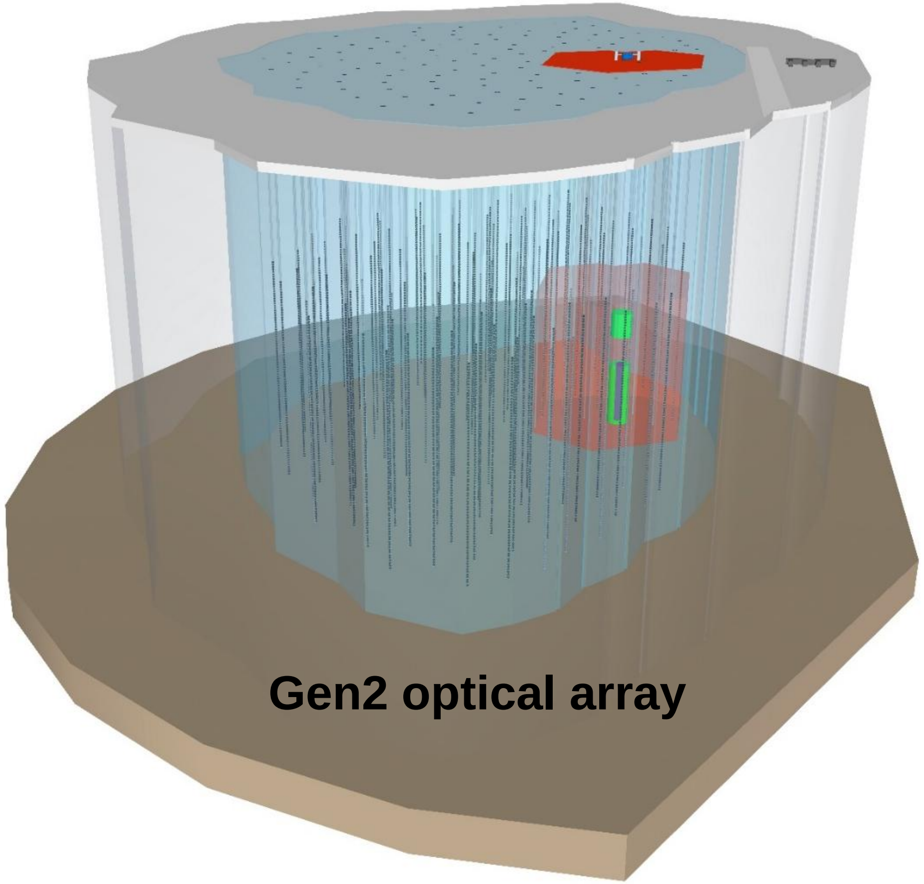


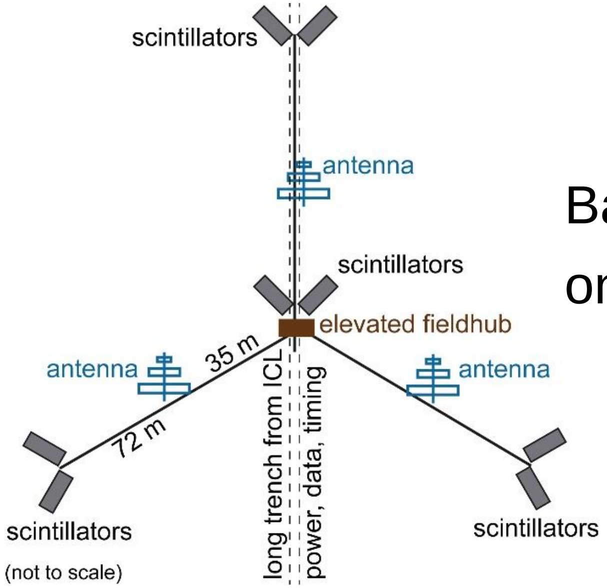
IceCube-Gen2 planed construction: 2024-2032 **completed in 2010** **under construction**

fgs@udel.edu
frank.schroeder@kit.edu

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 (122)

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

fgs@udel.edu
frank.schroeder@kit.edu

Conclusion: Ultra-high-energy Cosmic Rays

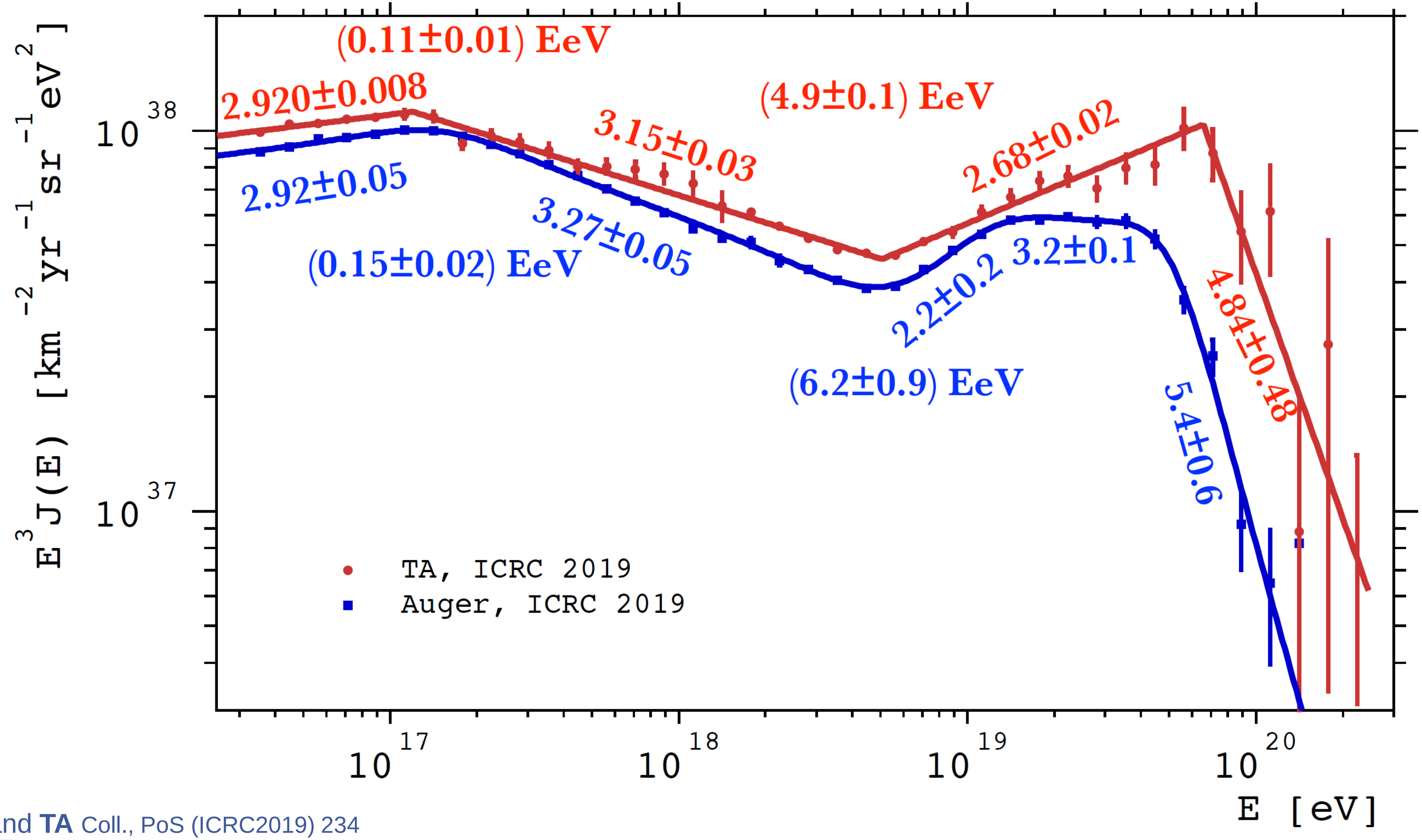
- Recent results
  - New features in cosmic-ray energy spectrum (many features known by now)
  - Mixed mass composition of cosmic rays varies over energy
  - Various experiments mostly consistent within systematic uncertainties
- Open questions
  - What is the origin and maximum energy of the most energetic *Galactic* cosmic rays?
  - What are the *extragalactic* sources at the highest energies?
  - What causes the mismatch between muon measurements and predictions by models?
- Future plans: *statistics and accuracy*
  - Upgrades of current ground arrays aim at per-event estimation of primary particle type
  - Proposals for new ground arrays: GRAND and the Global Cosmic Ray Observatory (GCOS)
  - Future space experiments important to increase exposure at highest energies

fgs@udel.edu
frank.schroeder@kit.edu

Additional Slides

fgs@udel.edu
frank.schroeder@kit.edu

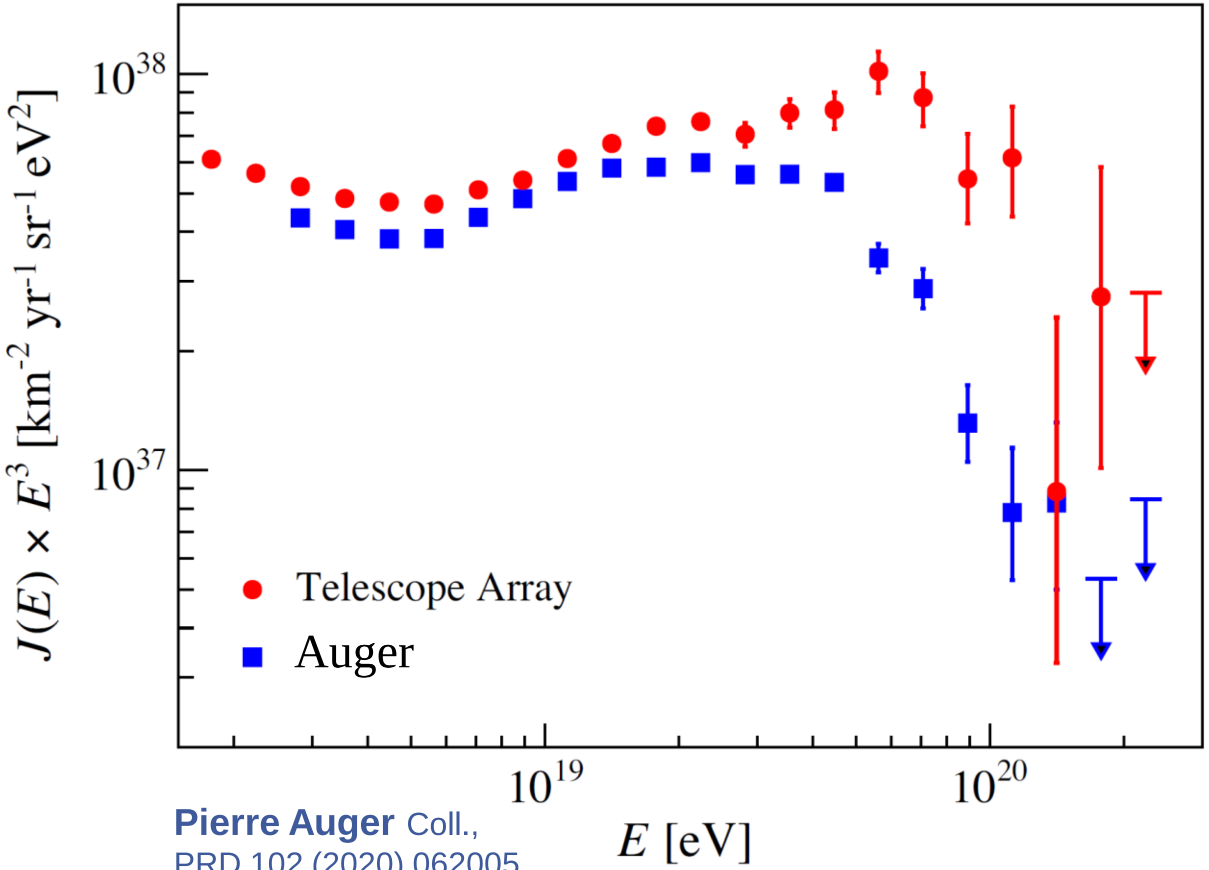
Comparison of TA and Auger Energy Spectra



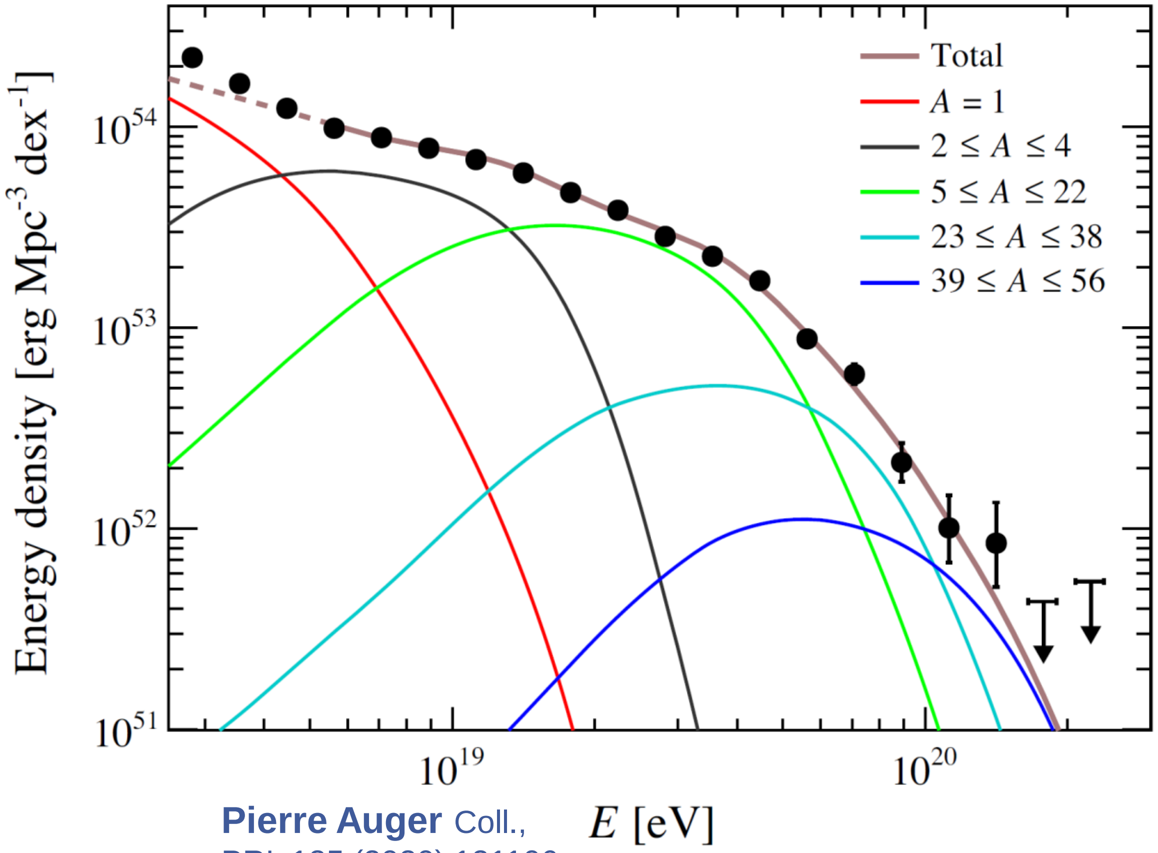
Pierre Auger and **TA** Coll., PoS (ICRC2019) 234

Interpretations of UHECR flux

- Only significant difference between Auger and TA is flux at highest energies
- Auger measurements more precise (also more accurate?) and often used for interpretations



Pierre Auger Coll.,
PRD 102 (2020) 062005

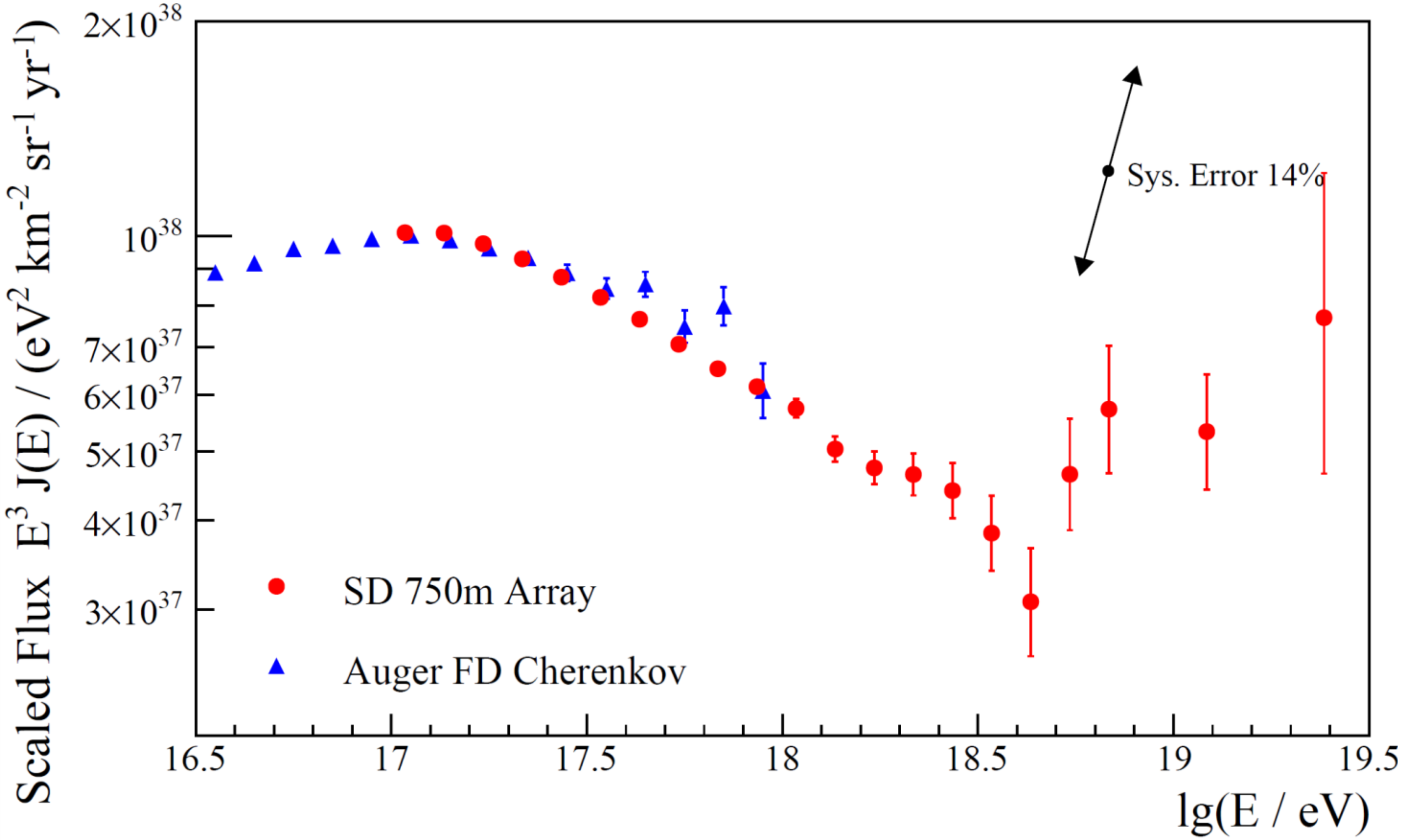


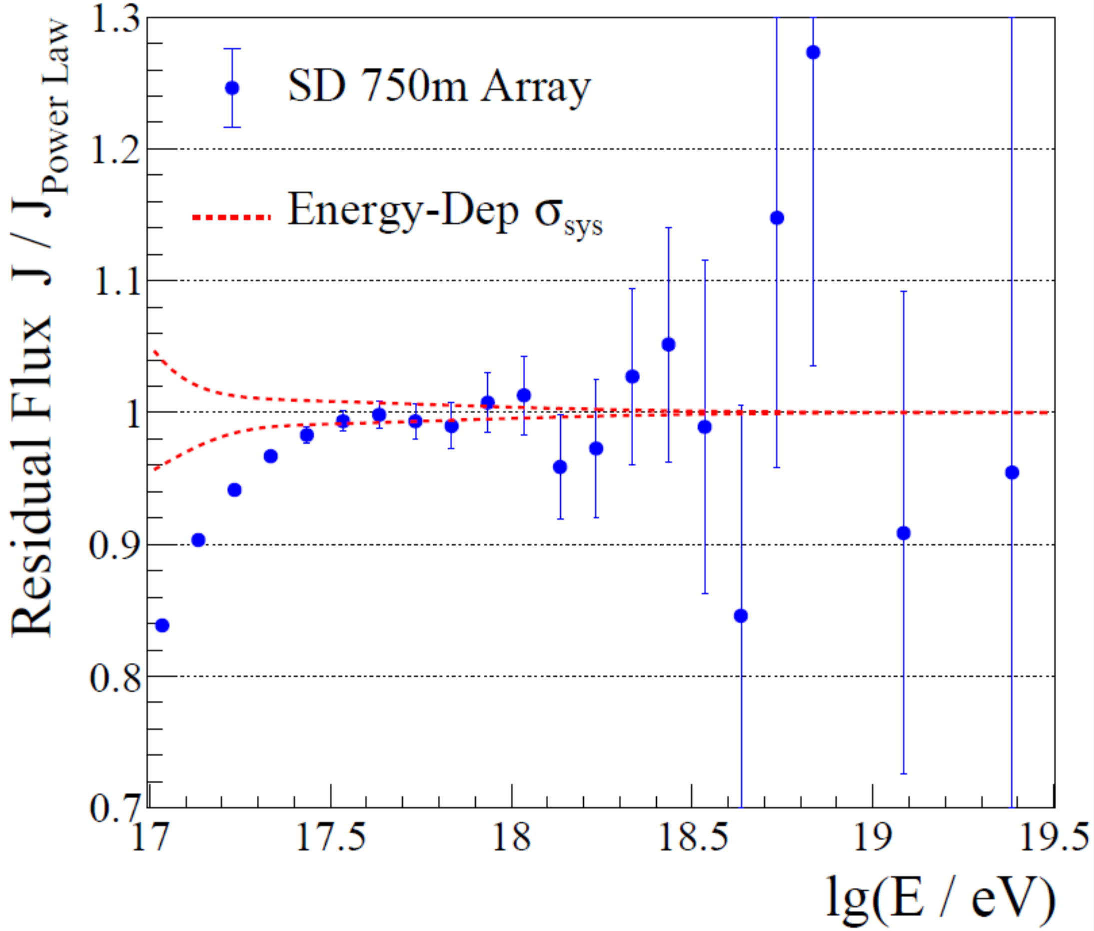
Pierre Auger Coll.,
PRL 125 (2020) 121106

fgs@udel.edu
frank.schroeder@kit.edu

Low-energy spectrum by Auger: Second Knee is a smooth feature

- Gradual change of spectral slope may explain apparently inconsistent measurements of second knee positions reported in the past.





Pierre Auger Coll., PoS (ICRC2019) 225

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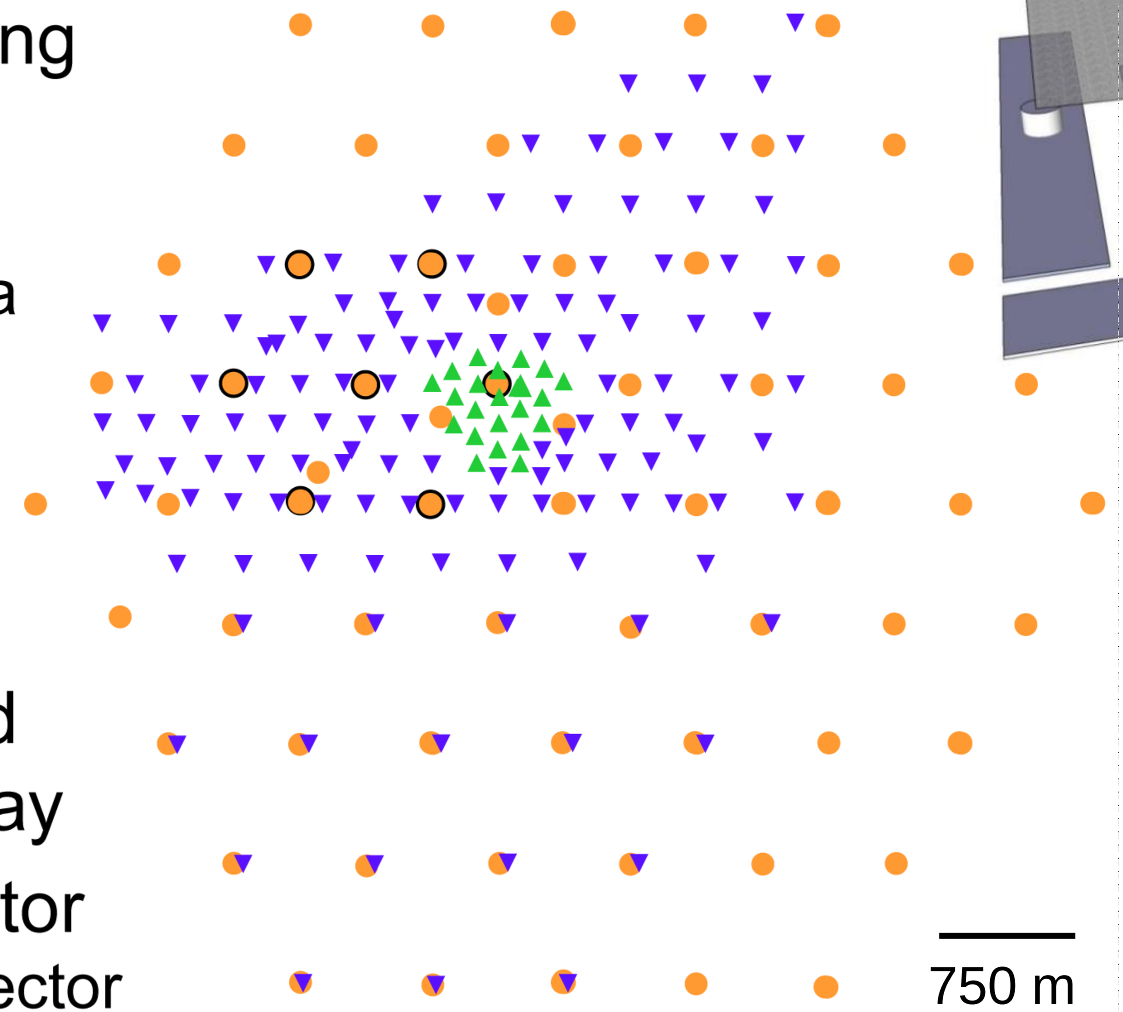
frank.schroeder@kit.edu

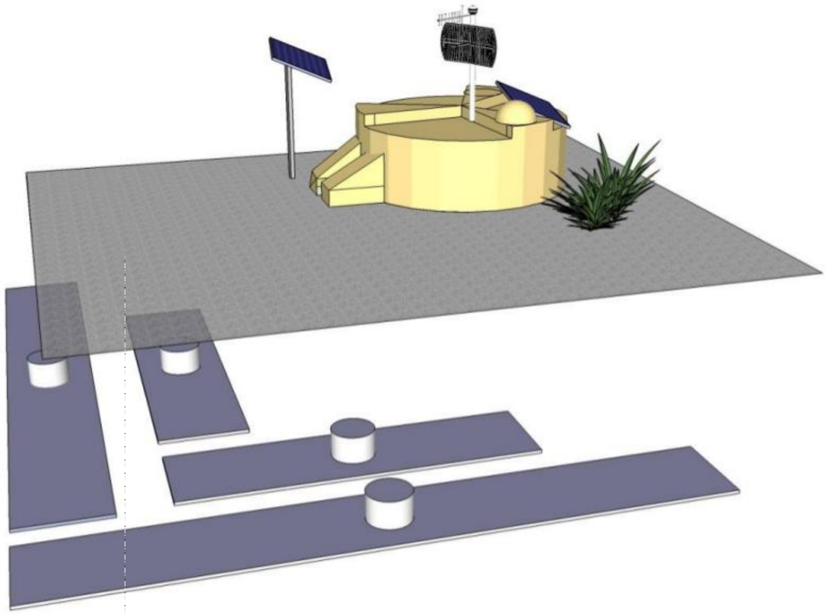
Large: Auger Engineering Radio Array

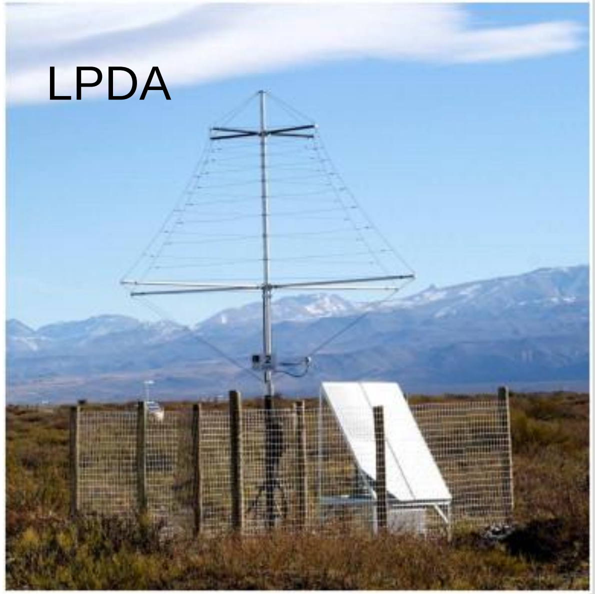
- 153 autonomous stations on 17 km²

Auger **E**ngineering
Radio **A**rray

▲ LPDA antenna
▼ Butterfly antenna





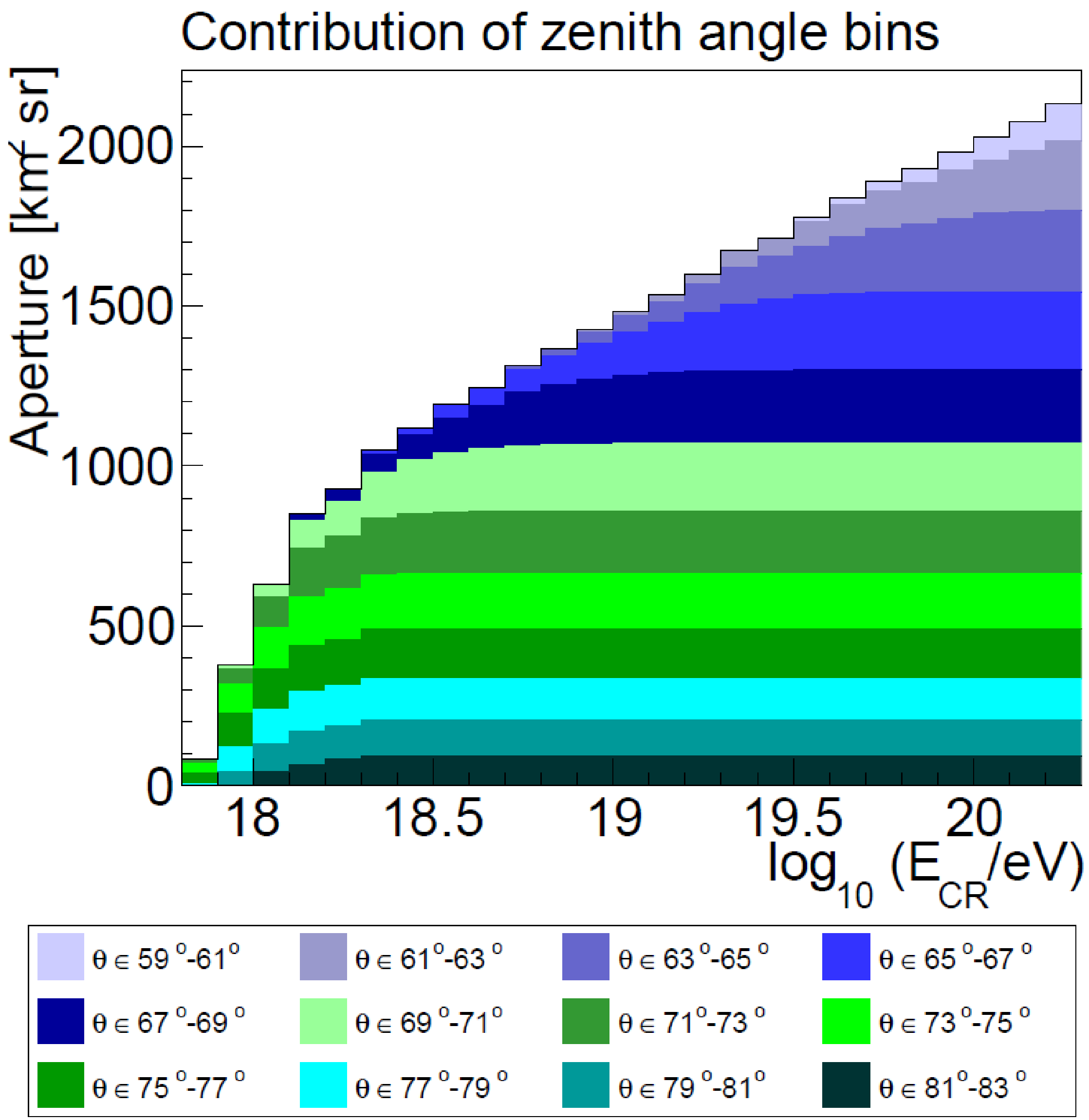


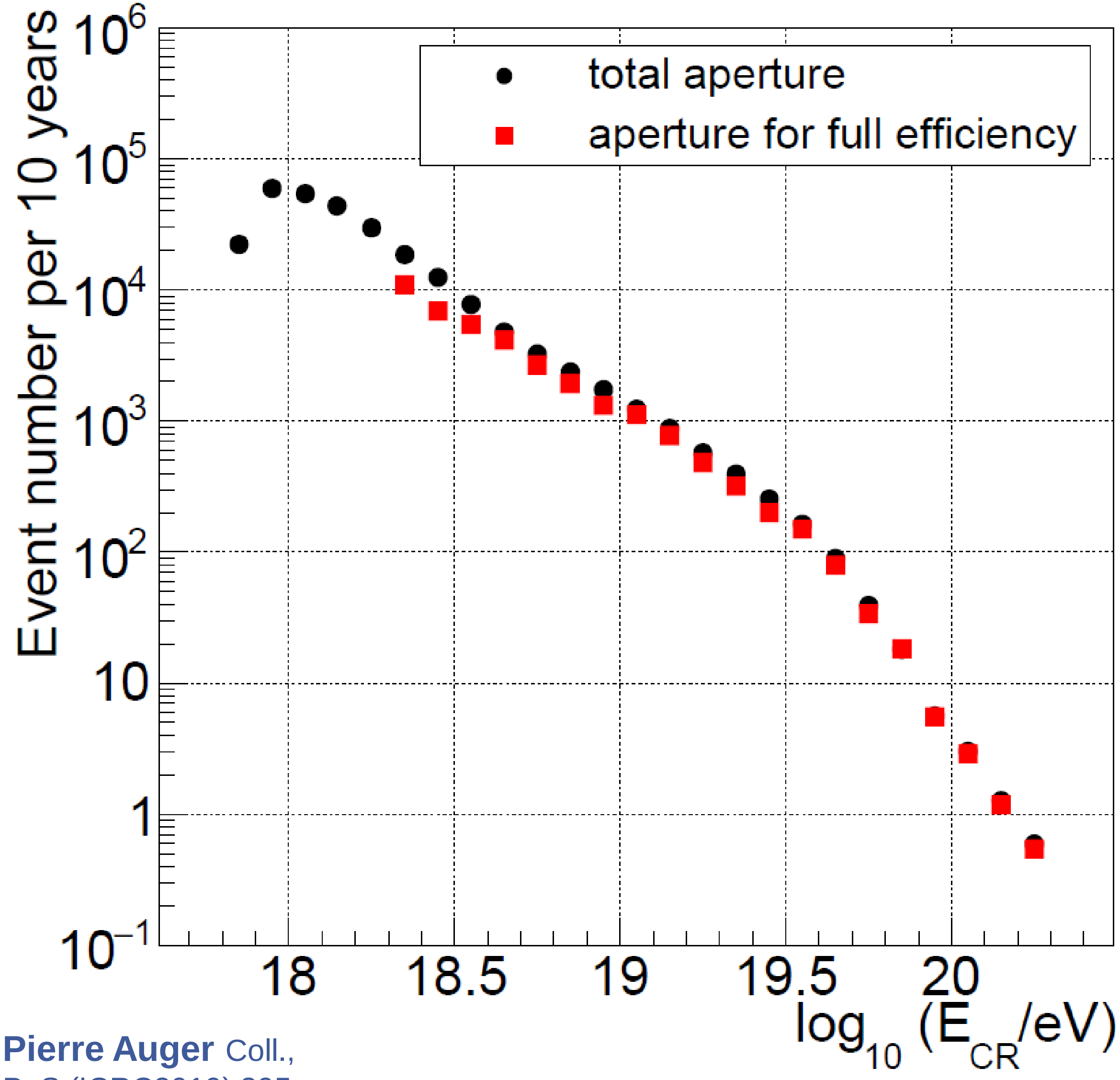
Auger **M**uon and
Infill **G**round **A**rray

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

fgs@udel.edu
frank.schroeder@kit.edu

Aperture of Auger Radio Upgrade





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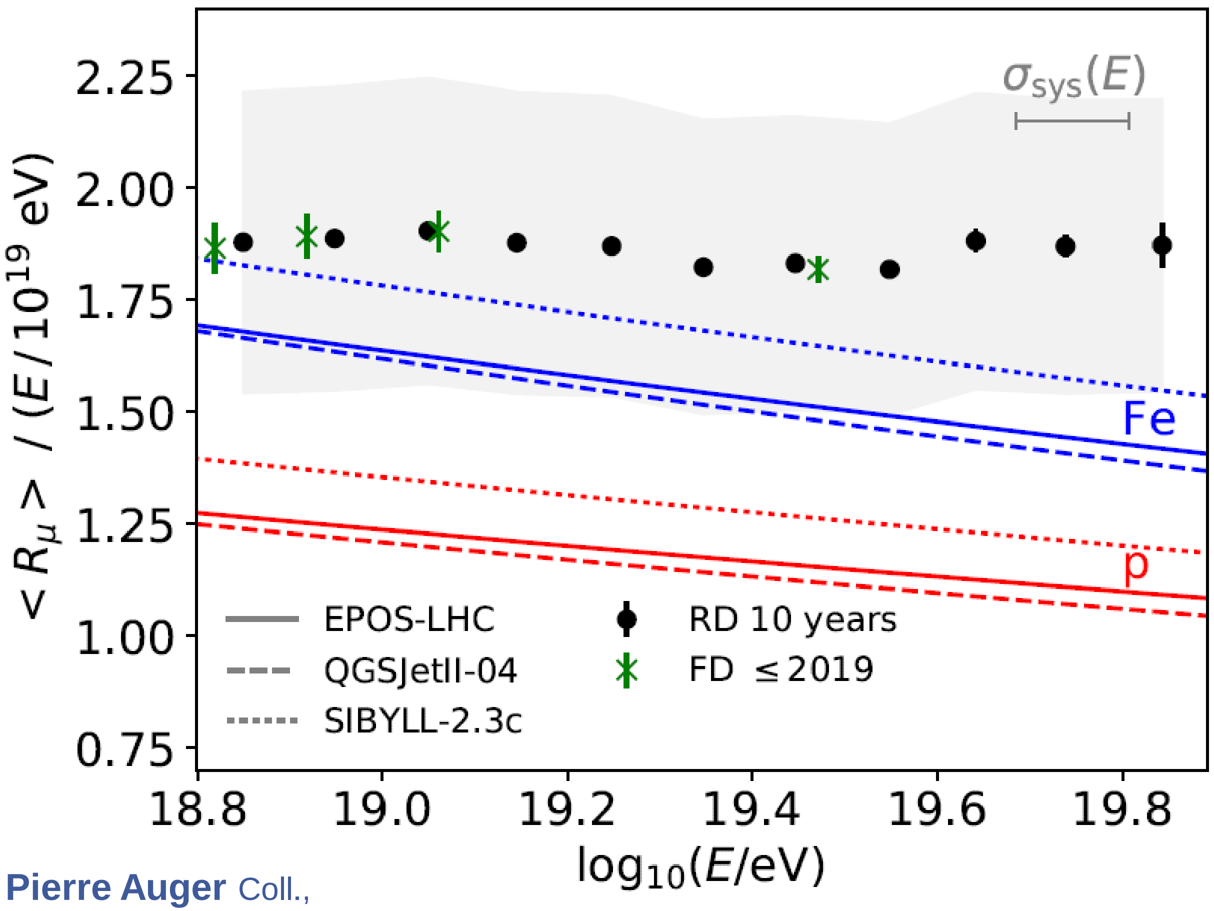
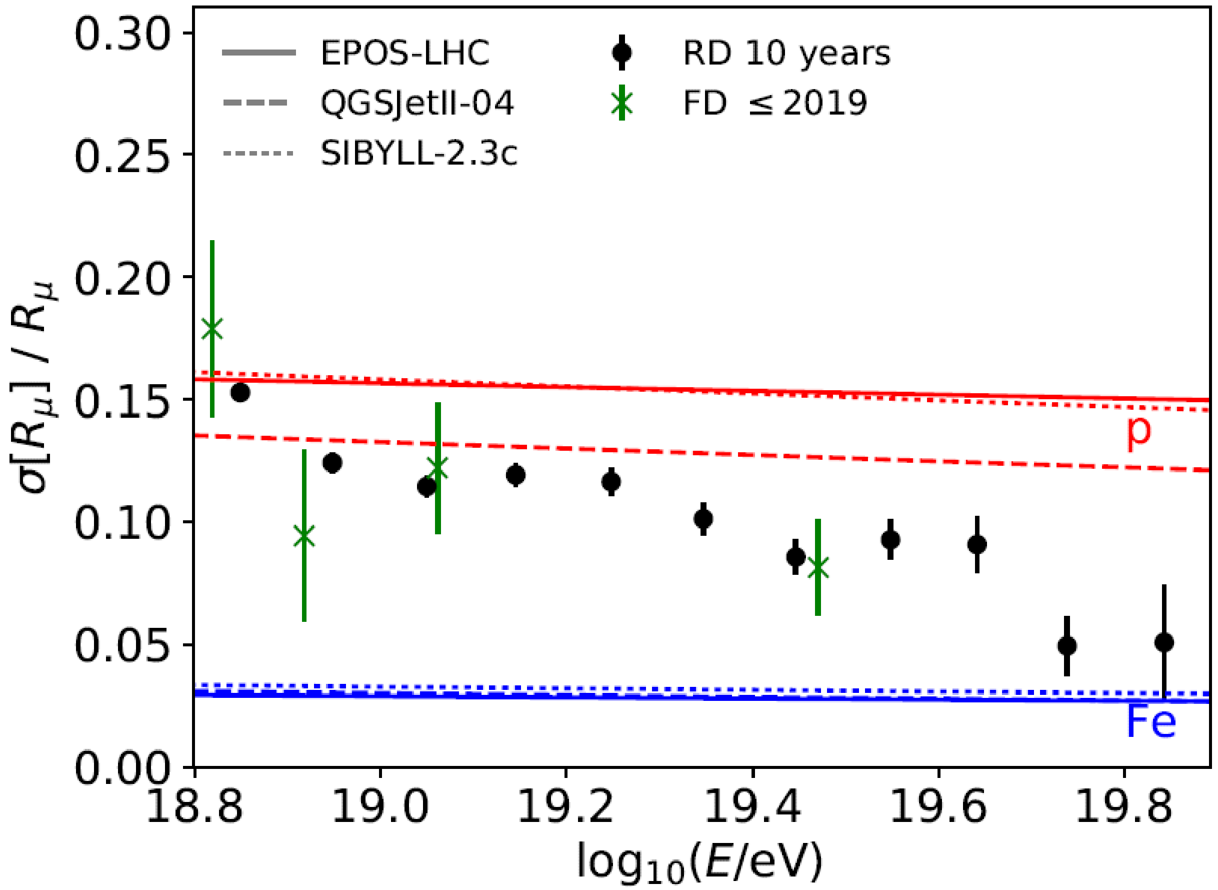
PoS (ICRC2019) 395

fgs@udel.edu
frank.schroeder@kit.edu

Predictions for combined muon and radio measurements

- Energy by radio antennas; muons by water-Cherenkov detectors





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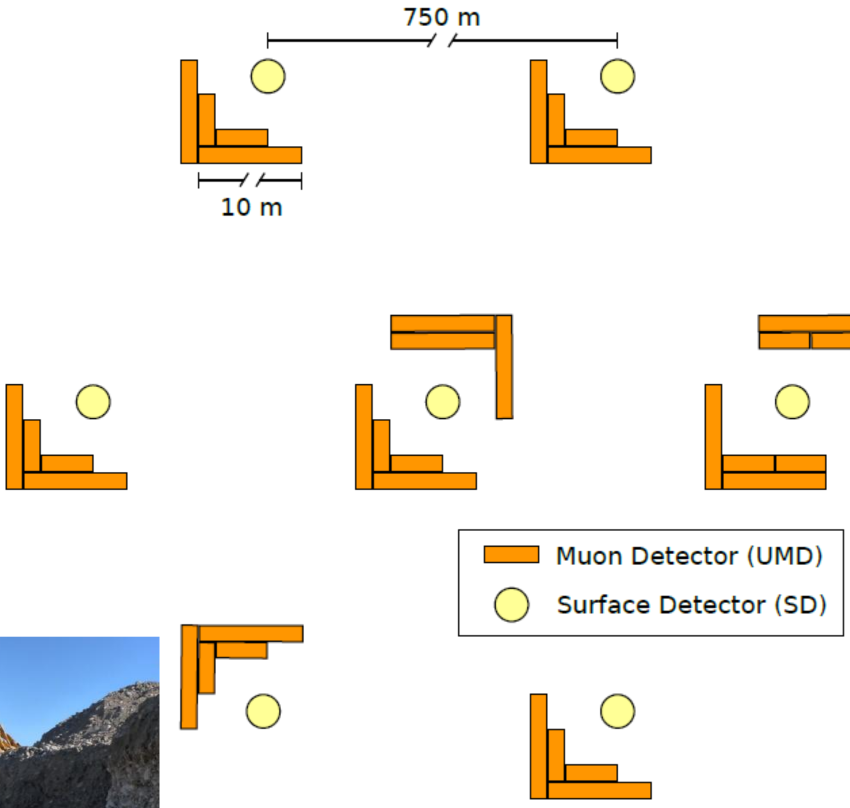
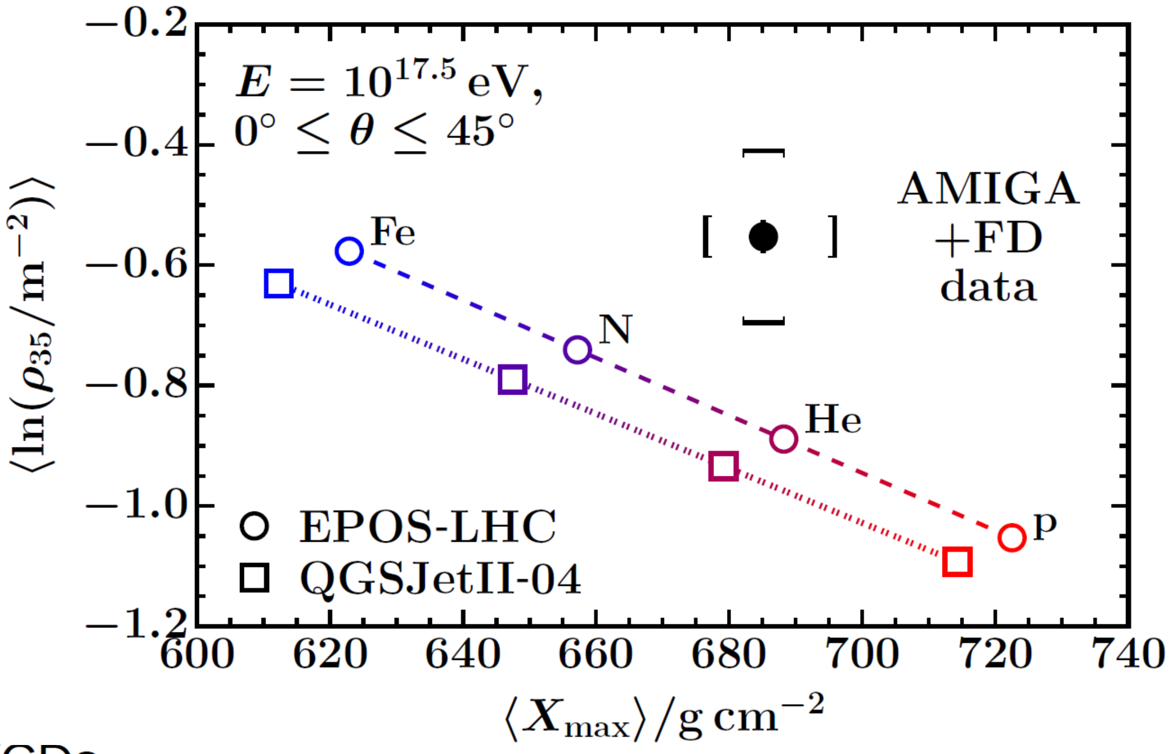
Muon Measurements of AMIGA Engineering Array



UMD-750m
23.5 km²
61x30m² Plastic Scintillators
buried 2.3m triggering from WCDs

Combination of pure muon and pure electro-magnetic measurement (by fluorescence) confirms muon deficit in simulations



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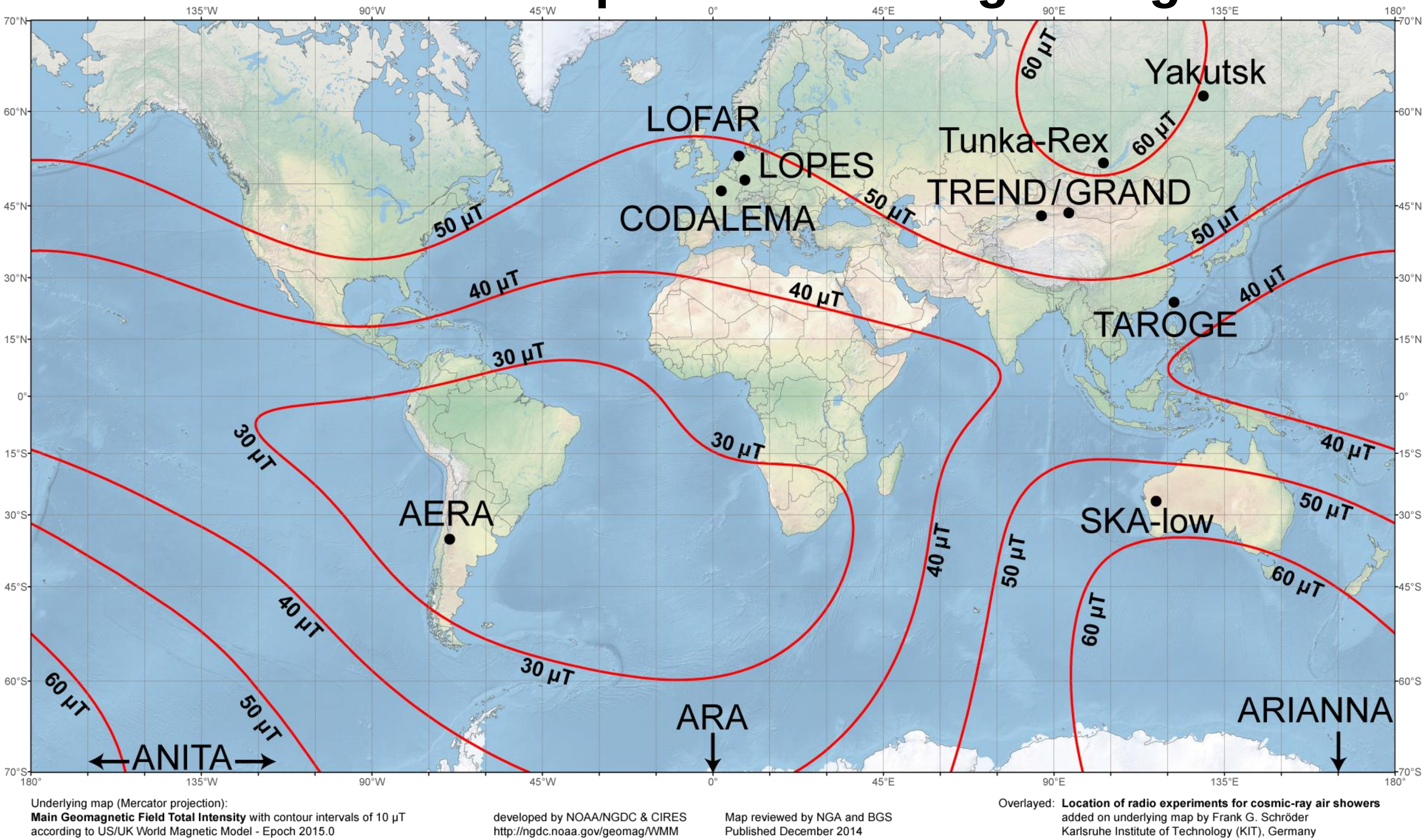
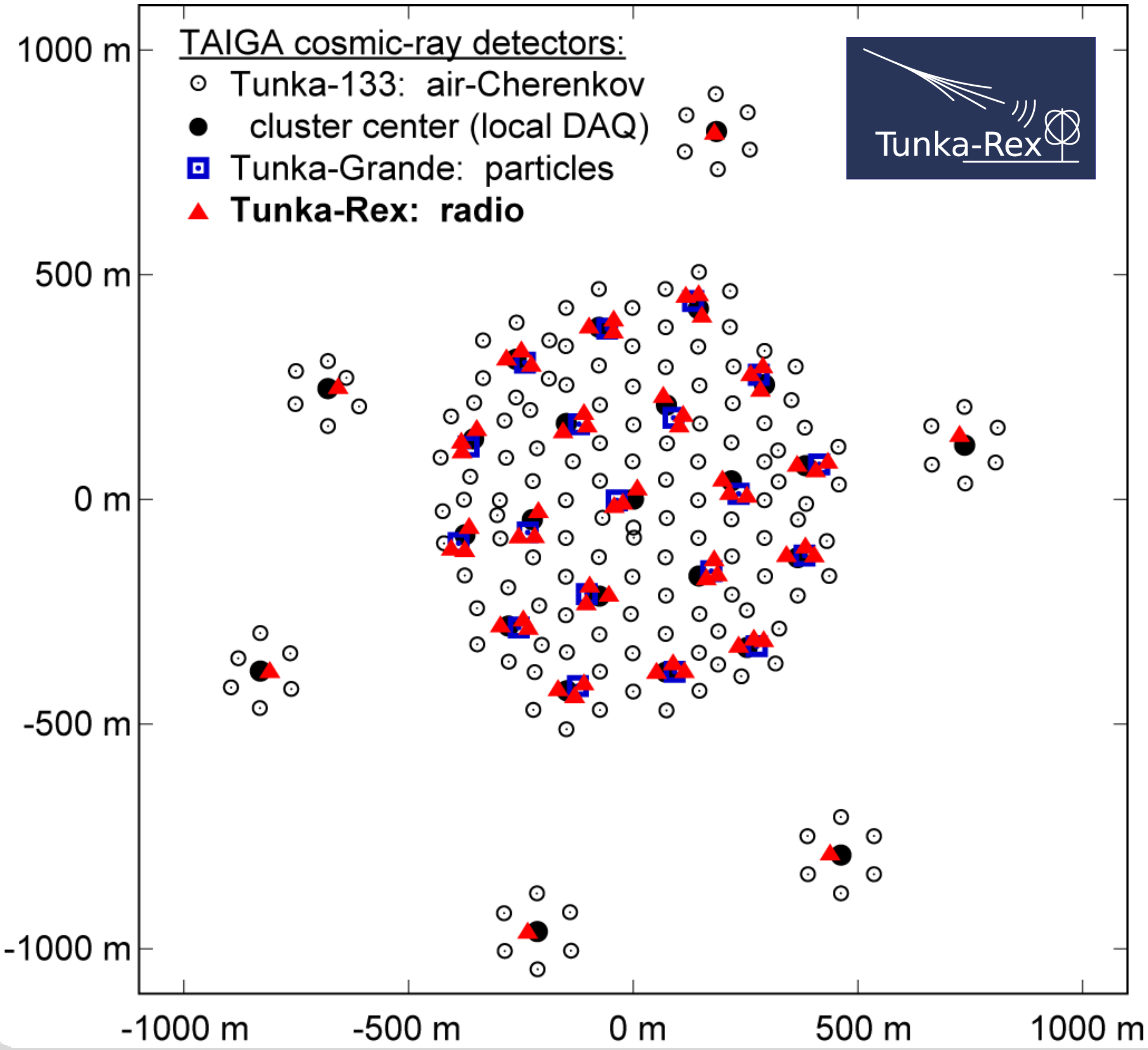
Location of selected experiments and geomagnetic field



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

Tunka Radio Extension (Tunka-Rex) in Siberia, since 2012



- 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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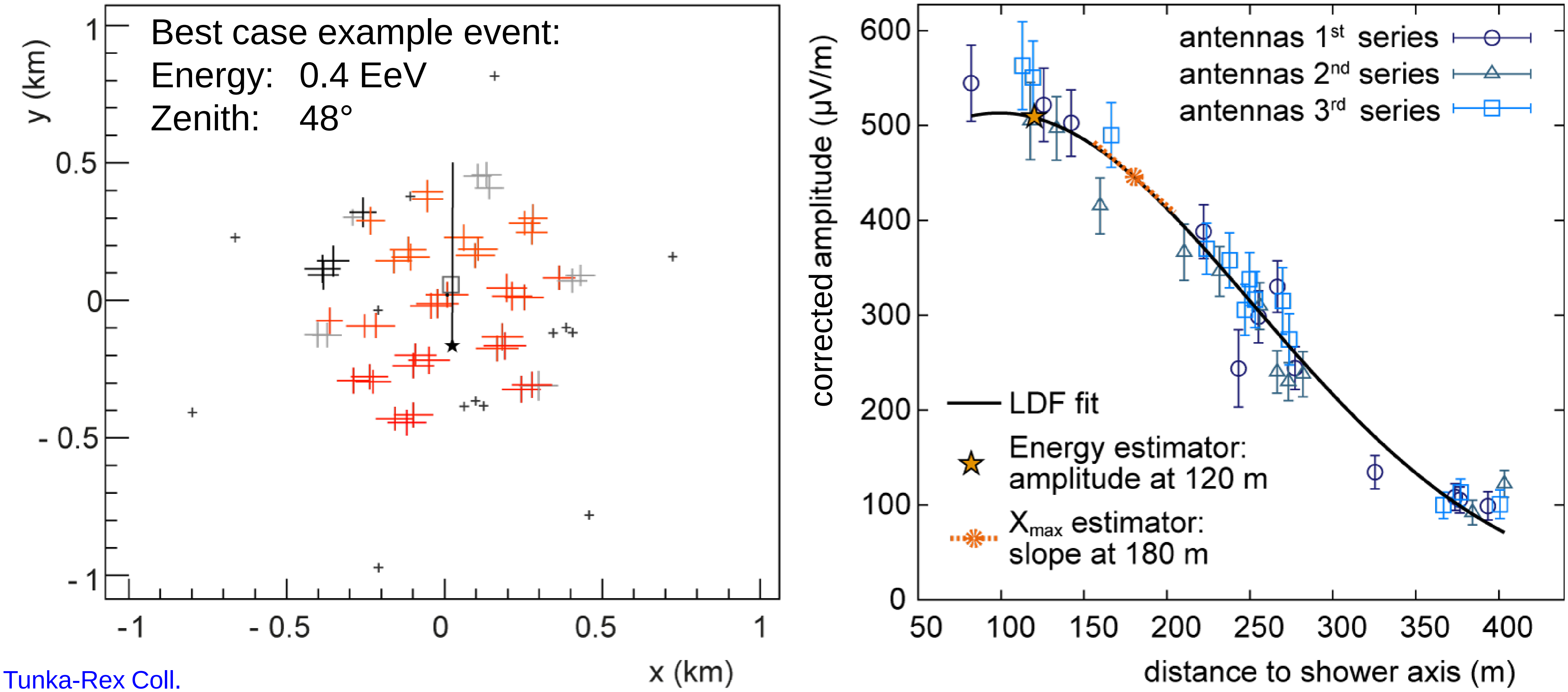
fgs@udel.edu
frank.schroeder@kit.edu

Simple standard method for reconstruction

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



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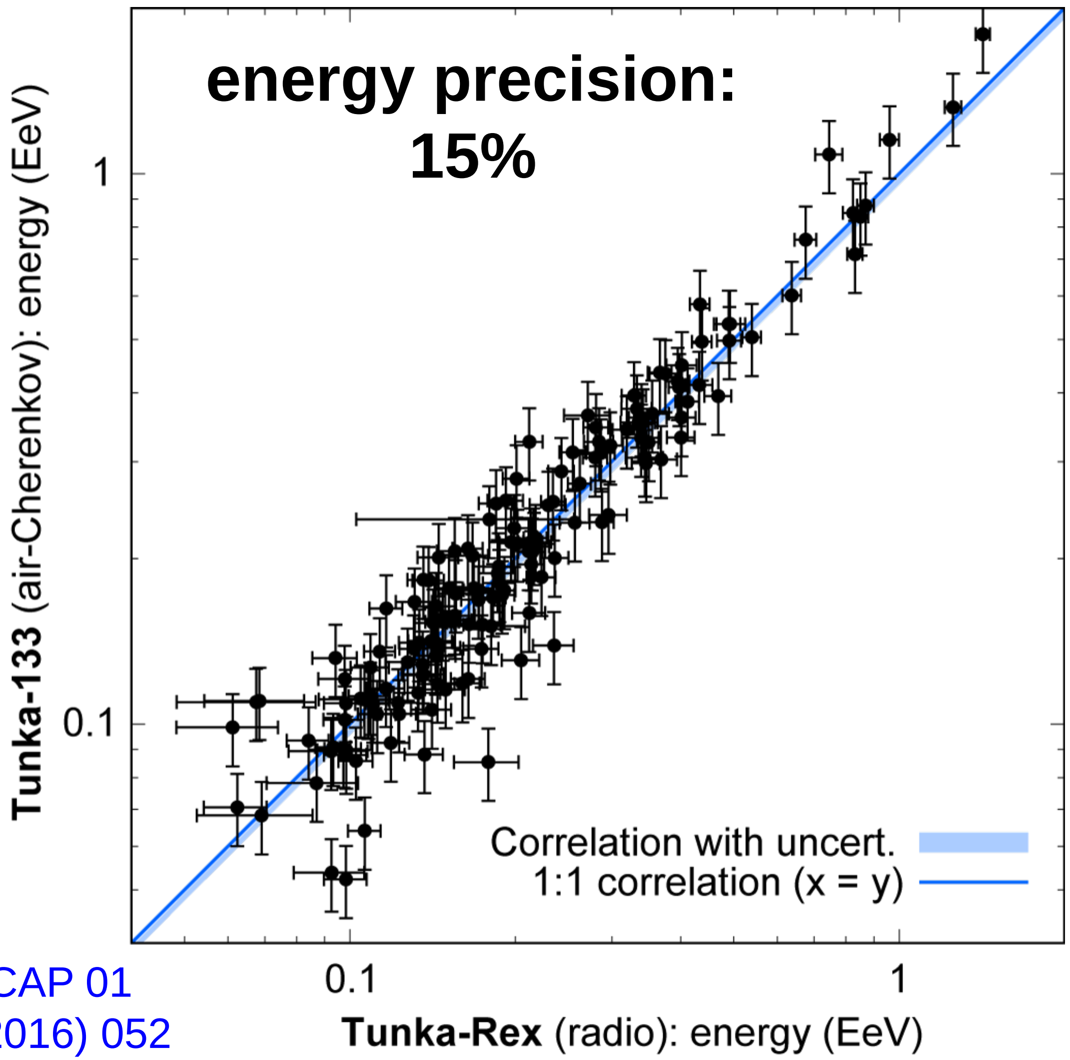
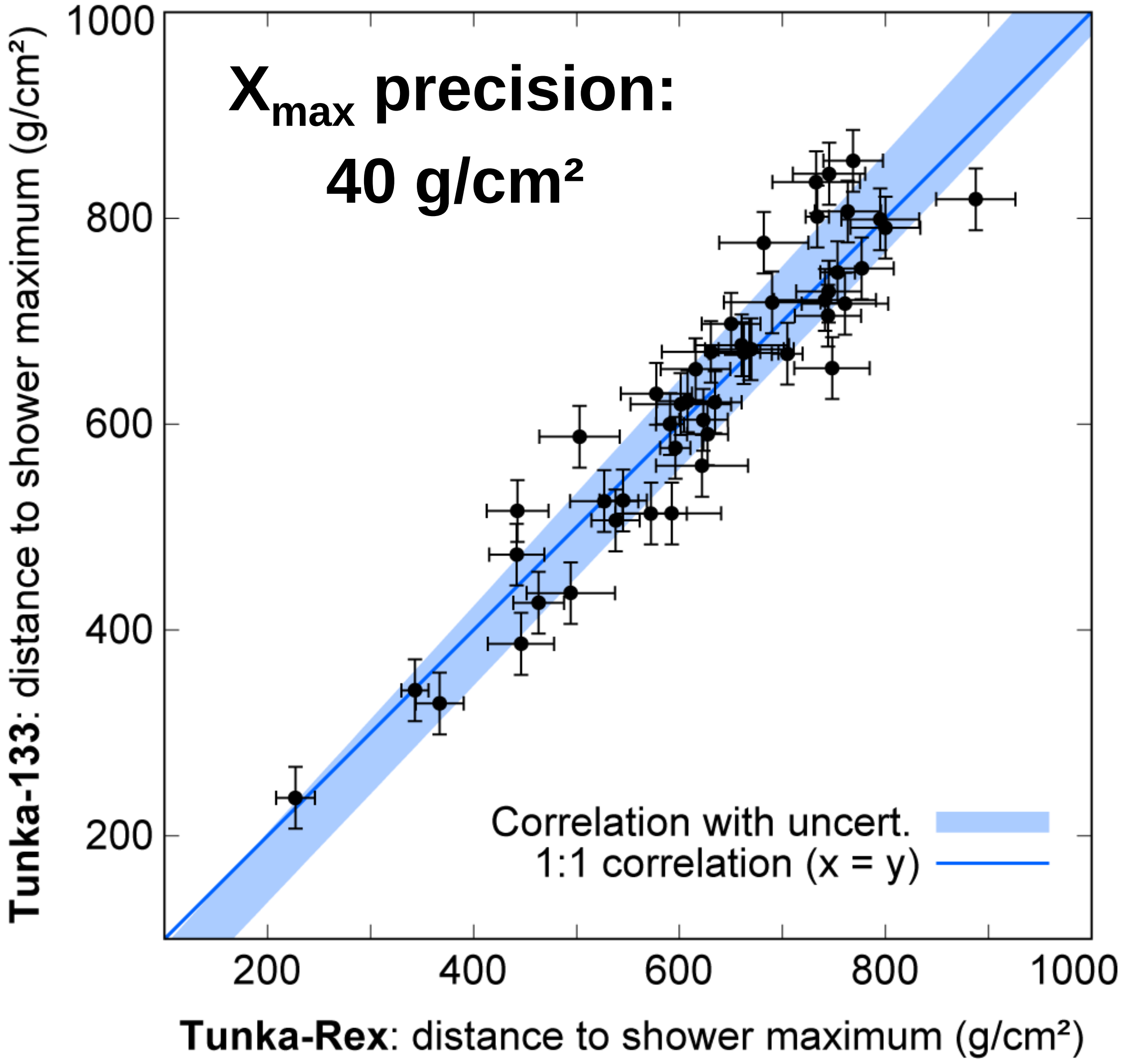
fgs@udel.edu
frank.schroeder@kit.edu

Correlation of Radio and Cherenkov-light measurements

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



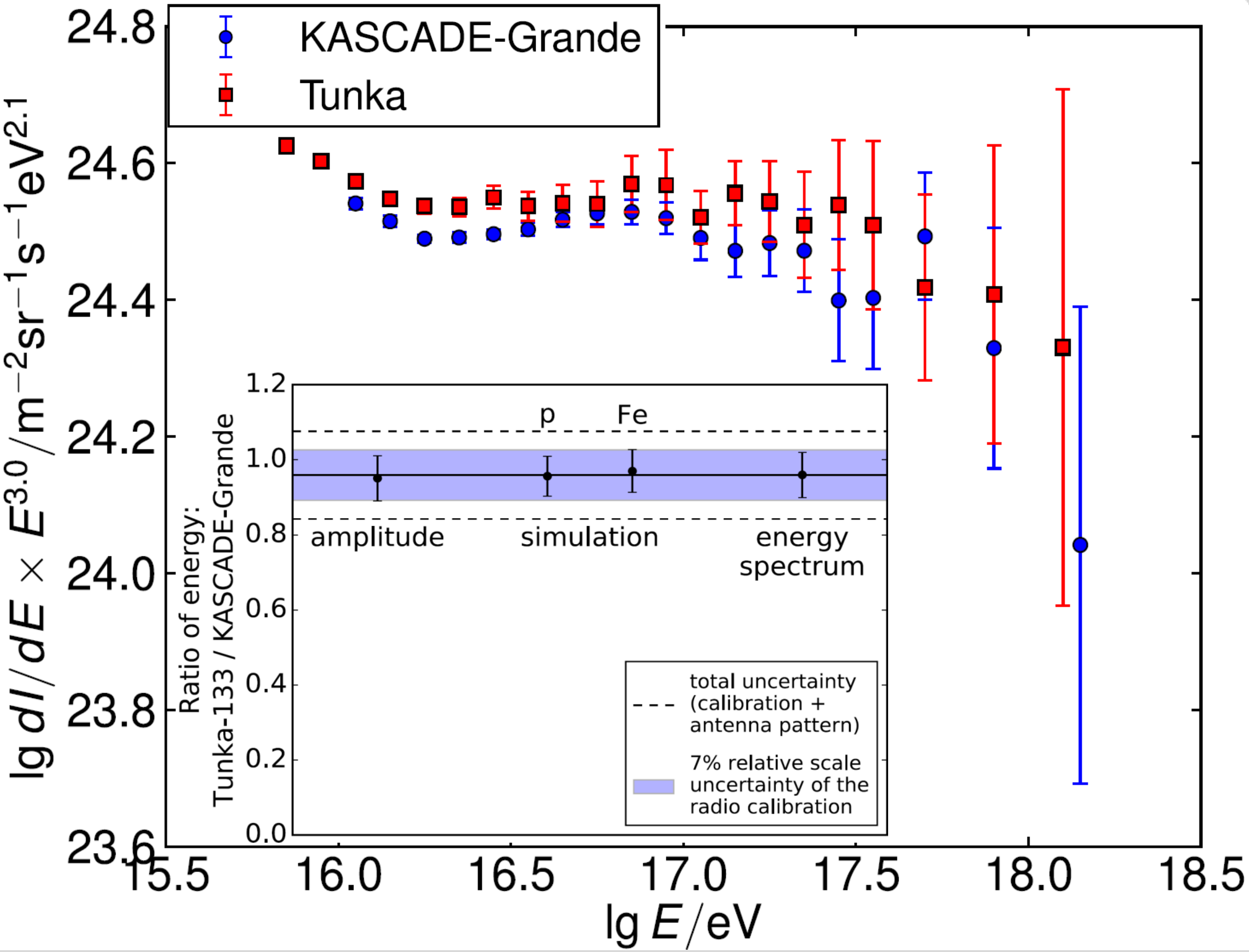


JCAP 01 (2016) 052

fgs@udel.edu
frank.schroeder@kit.edu

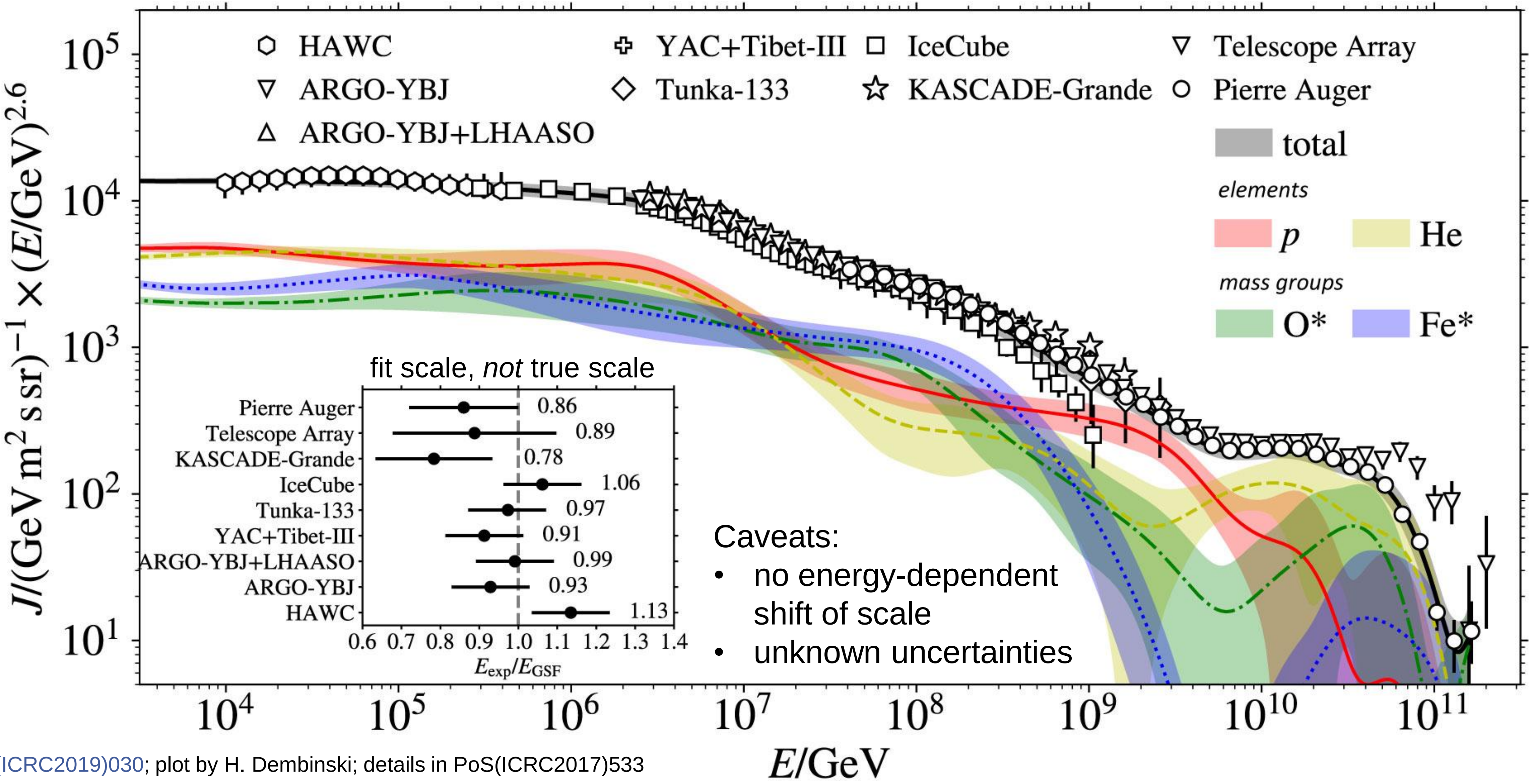
Comparing energy scales of KASCADE and Tunka-133 via their radio arrays

- 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

Cosmic-Ray Energy Spectrum and Mass Composition



Caveats:

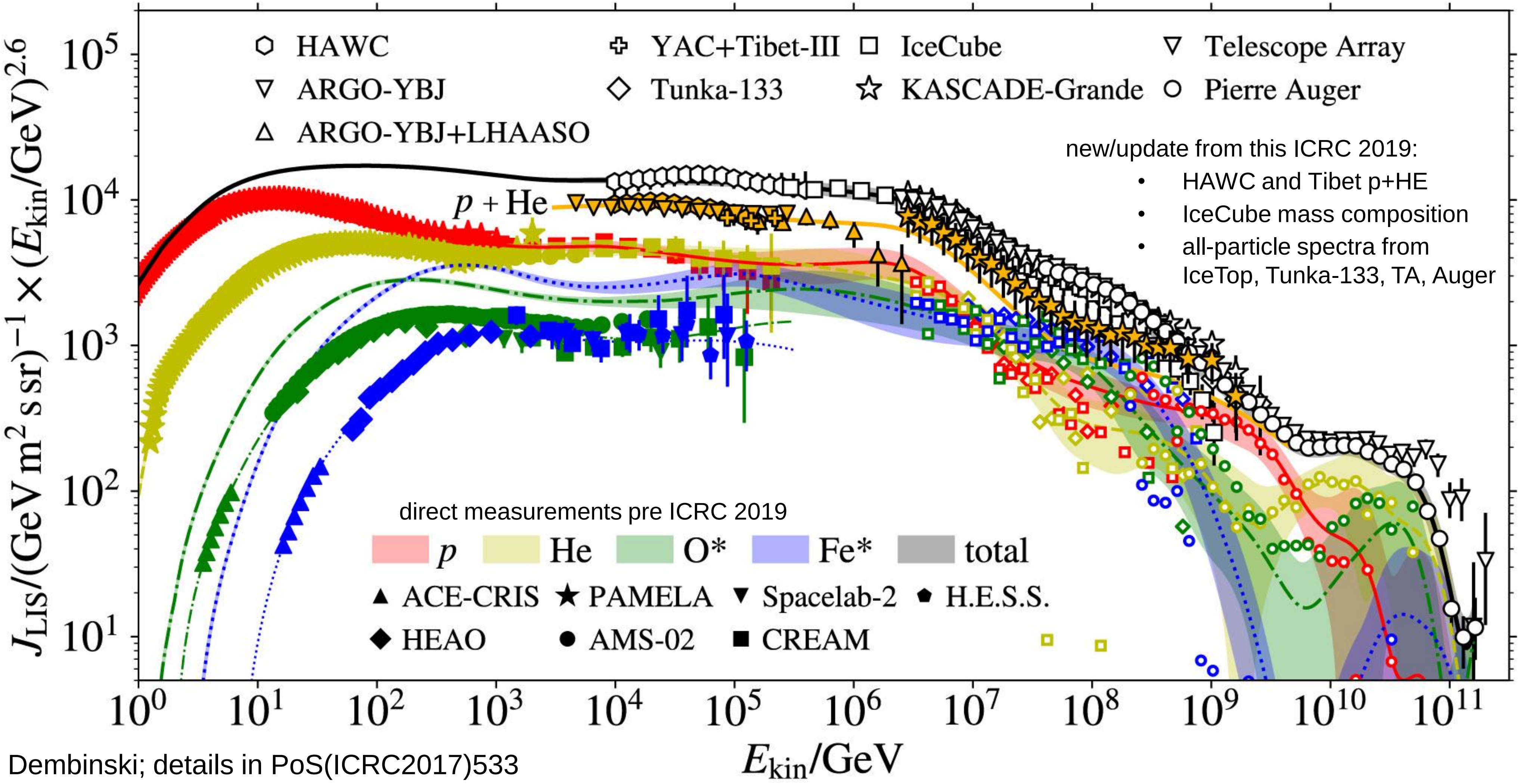
- no energy-dependent shift of scale
- unknown uncertainties

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

fgs@udel.edu
frank.schroeder@kit.edu

Global Spline Fit (Composition and Energy Spectrum)

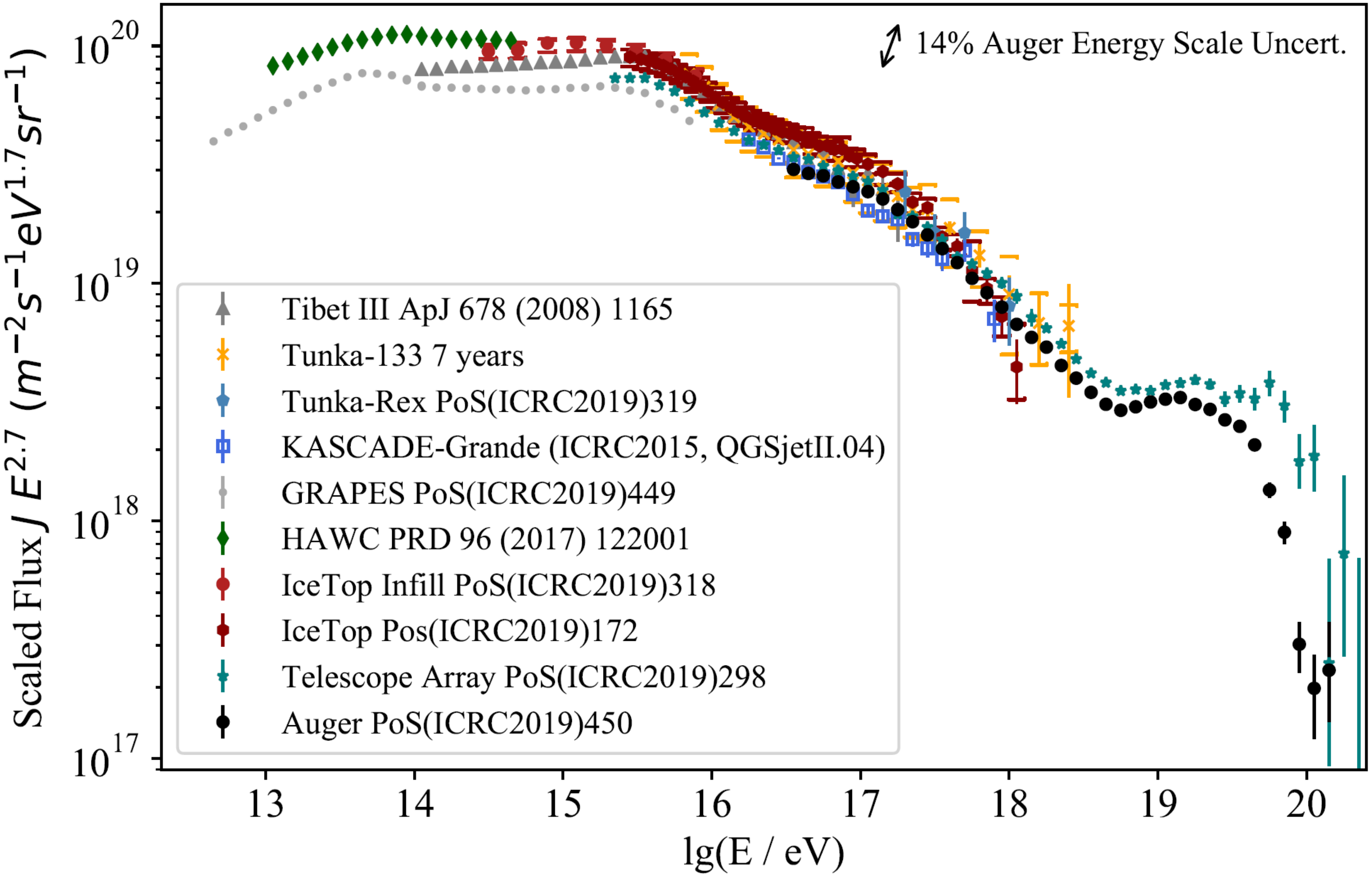
Fit of spectra *within experimental uncertainties*, allowing for constant shift in energy scales



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

fgs@udel.edu
frank.schroeder@kit.edu

All-particle Energy Spectrum by Air-Shower Arrays



Caveat:
different quality of
measurements