Ultra-high energy cosmic rays (UHECRs) and the muon problem – an introduction

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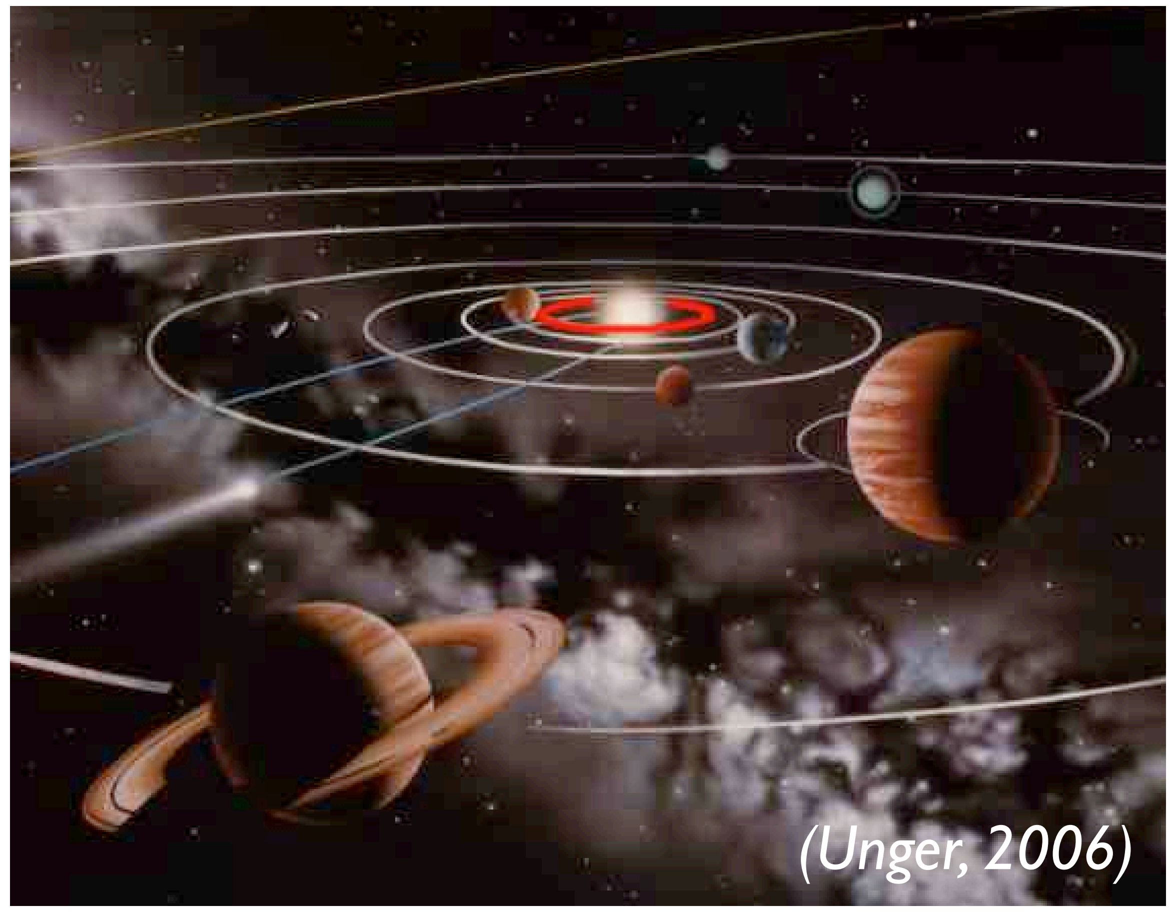
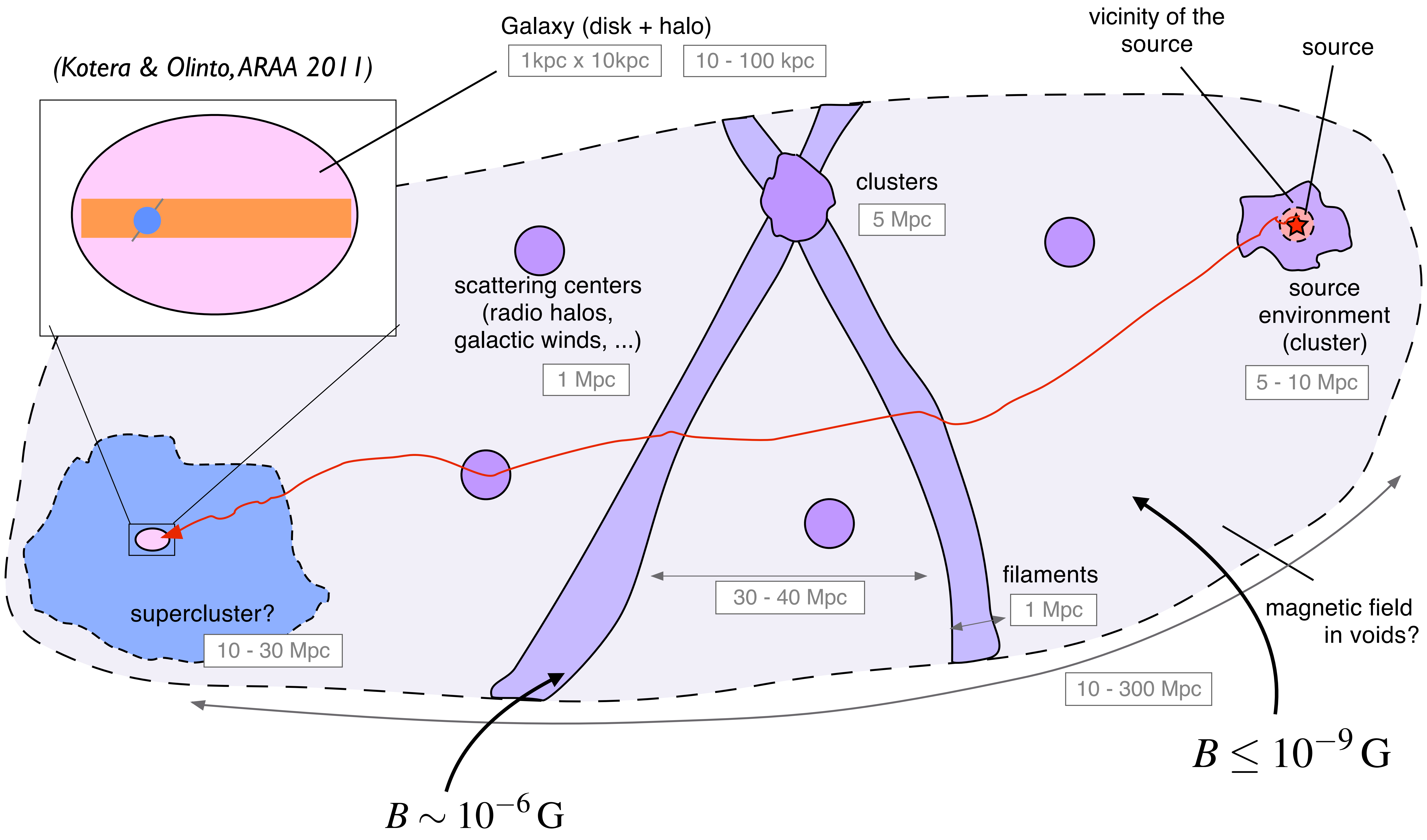
(picture curtesy S. Saffi)

Physics of UHECRs in a nut shell

LHC: 27 km circumference



Need accelerator of size of Mercury orbit to reach 10^{20} eV with LHC technology

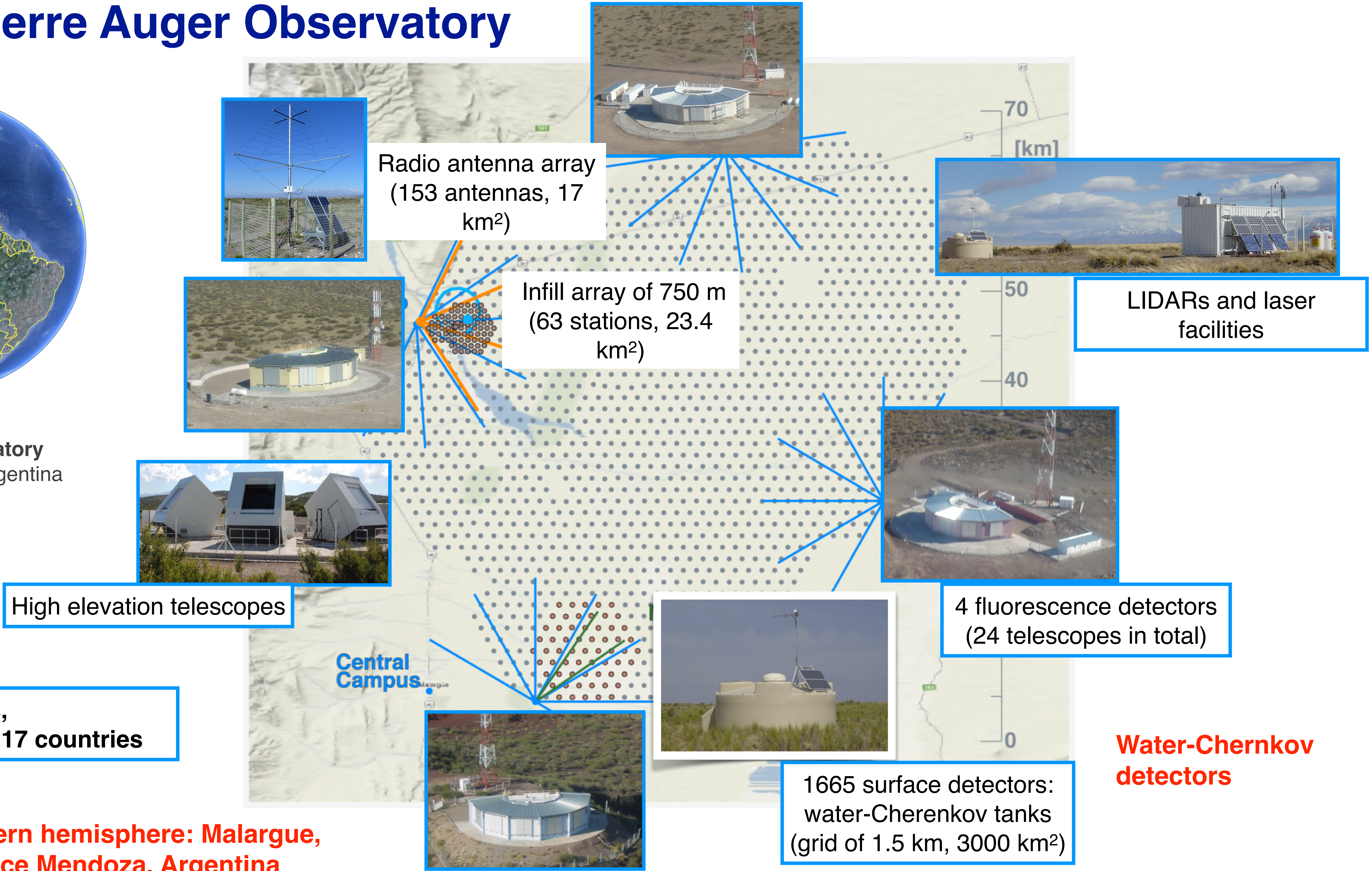


Deflection in Galactic and extragalactic mag. fields

Energy loss due to interaction with background radiations (GZK effect)

The Pierre Auger Observatory

Pierre Auger Observatory
Province Mendoza, Argentina



500 members,
98 institutes, 17 countries

Water-Chernkov detectors

Southern hemisphere: Malargue, Province Mendoza, Argentina

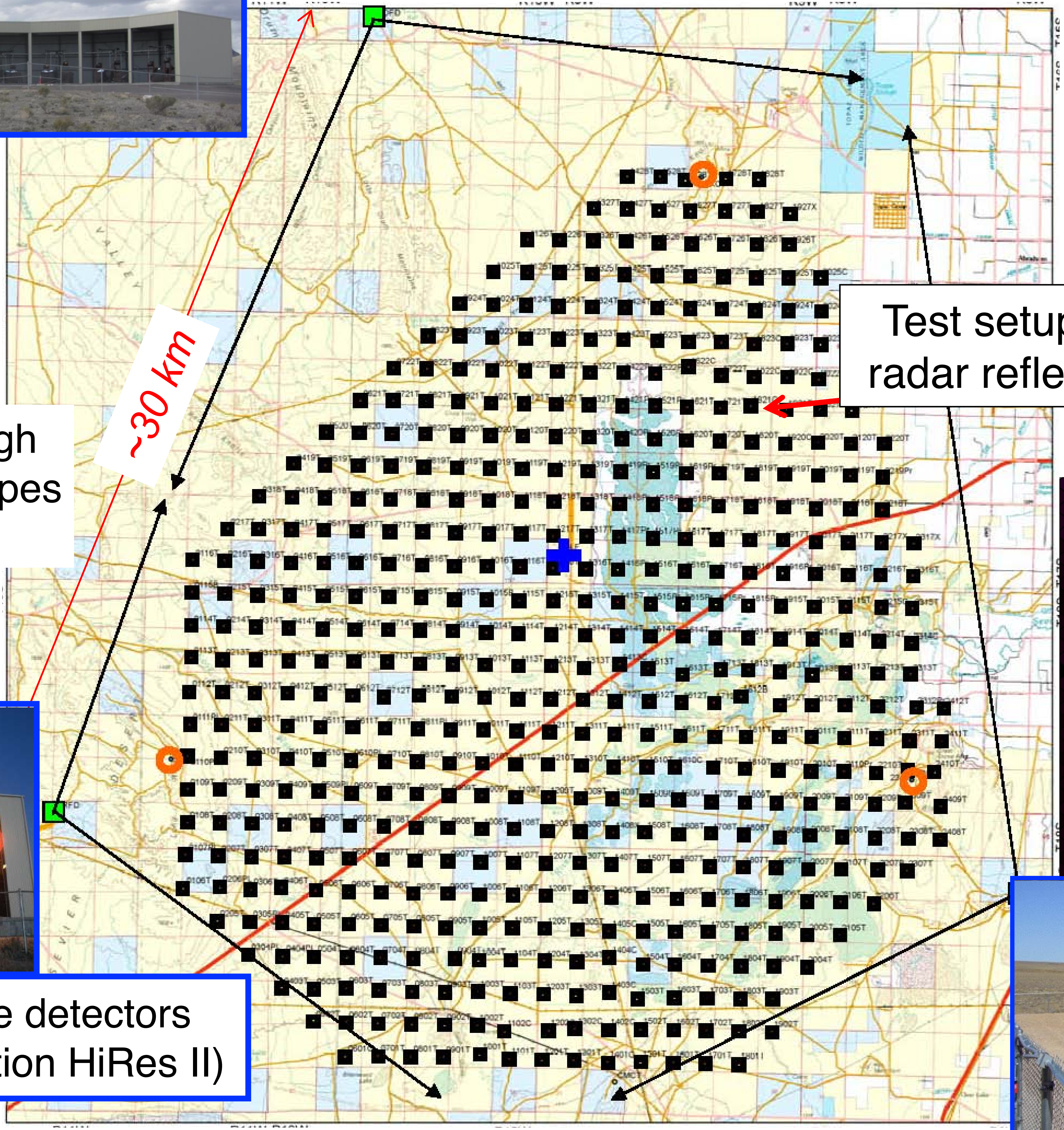
Telescope Array (TA)

Middle Drum: based on HiRes II

TALE (TA low energy extension)

LIDAR
Laser facility

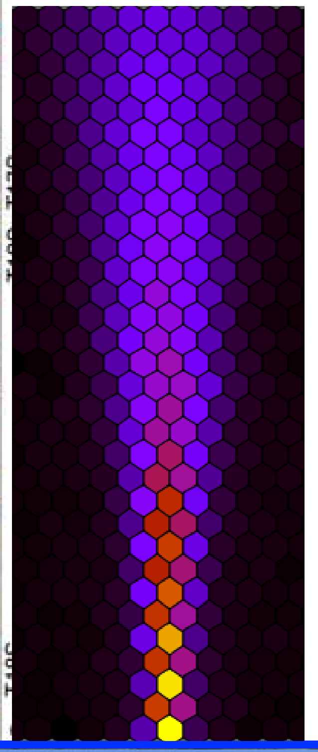
Infill array and high
elevation telescopes



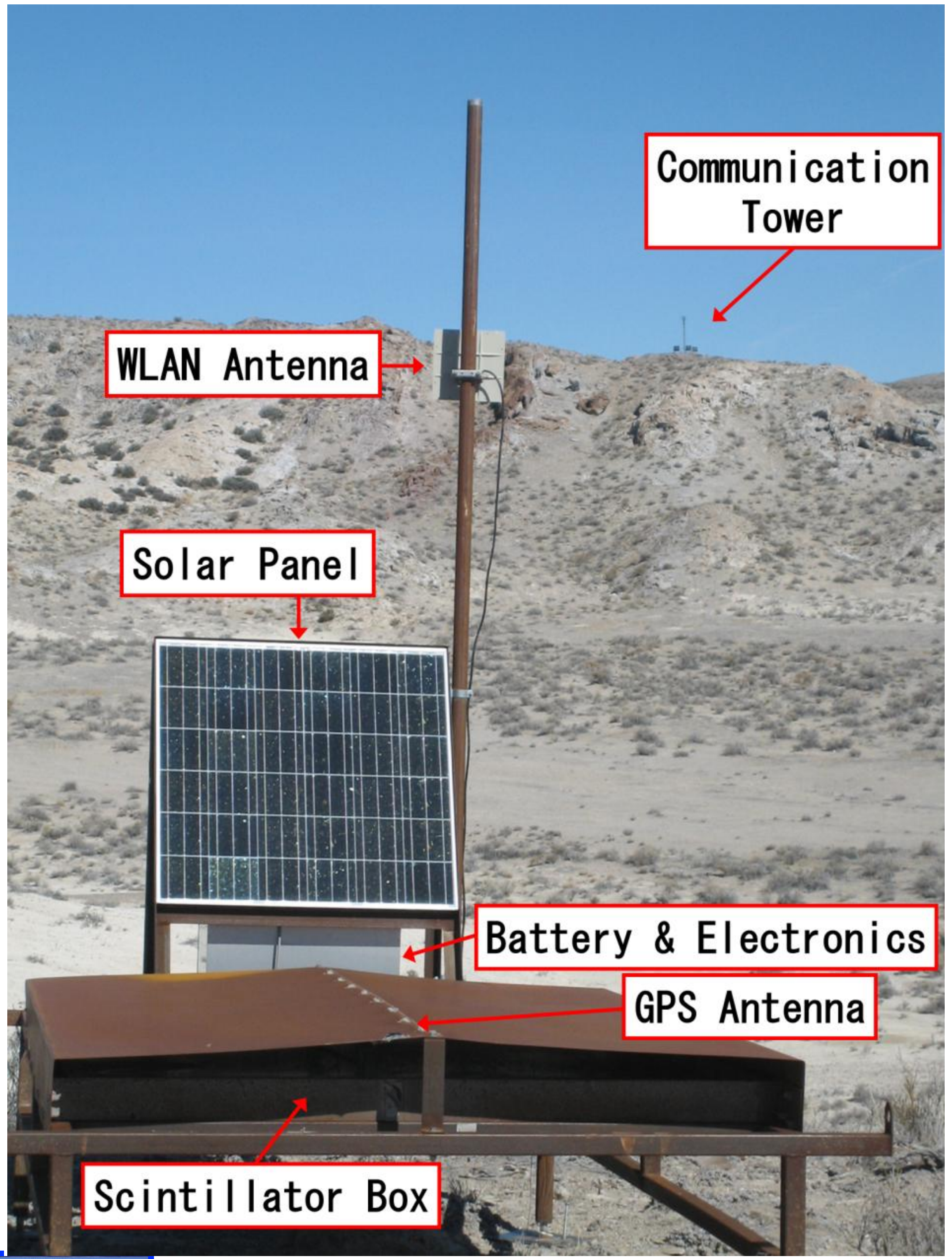
Test setup for
radar reflection

3 fluorescence detectors
(2 new, one station HiRes II)

Northern hemisphere: Delta, Utah, USA

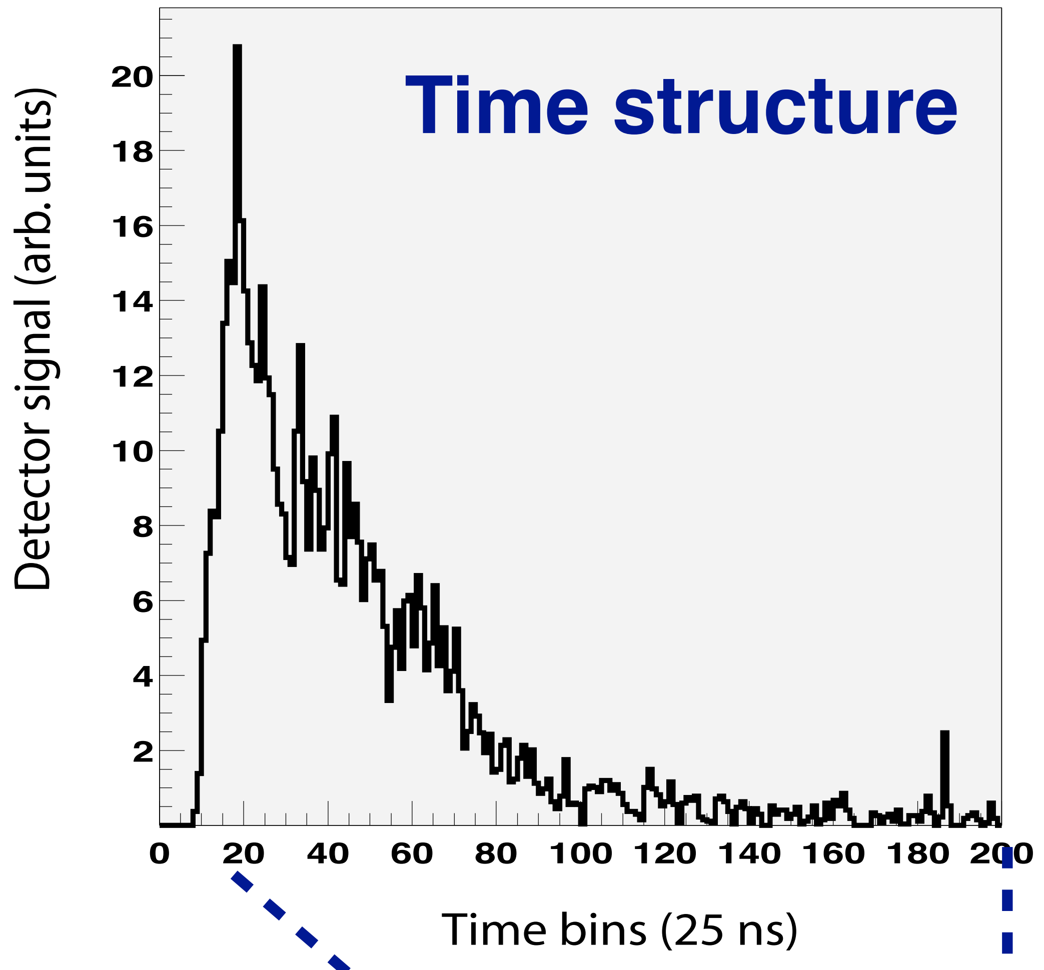


Electron light
source (ELS):
~40 MeV

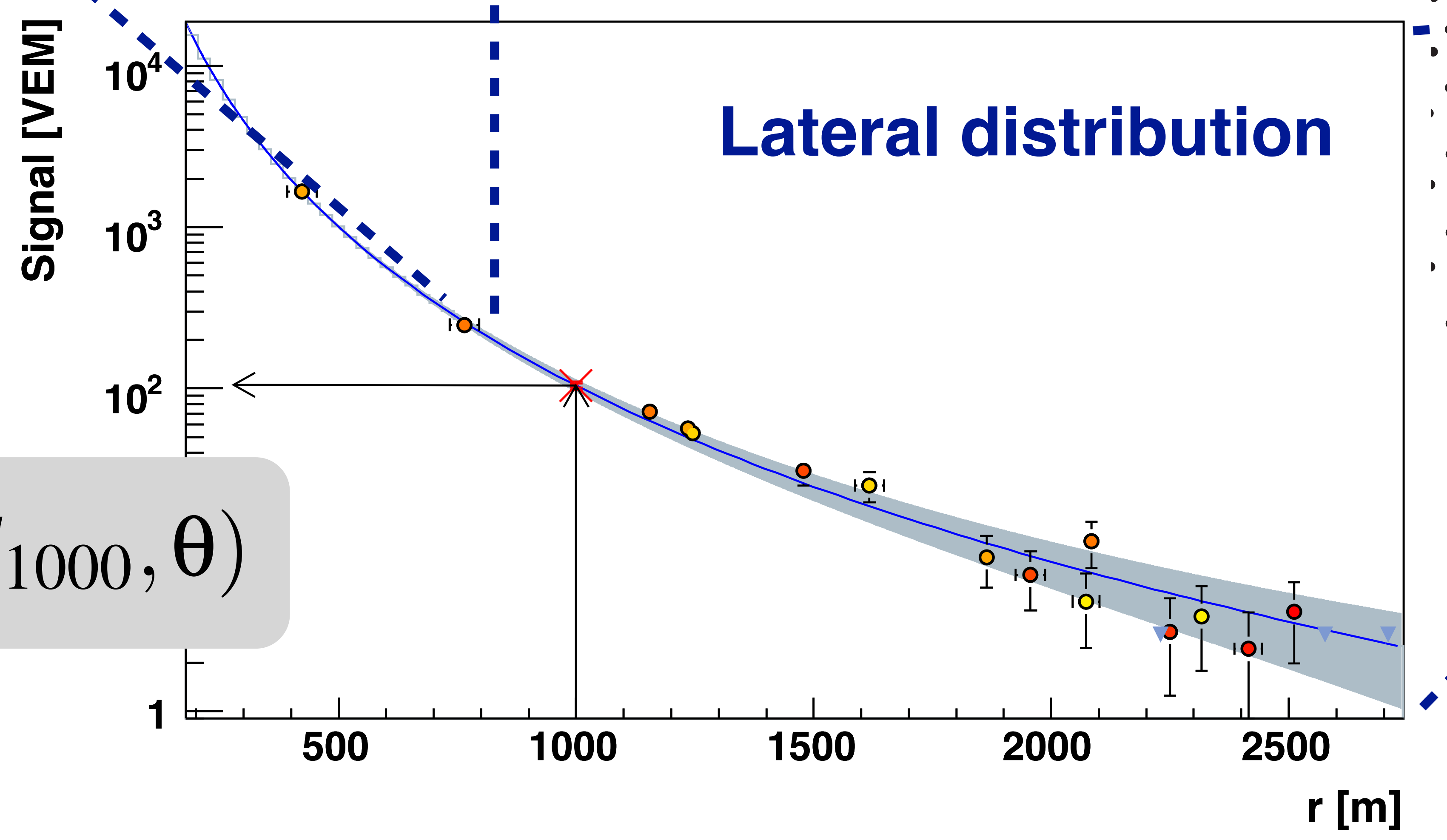


507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 680 km^2)

Hybrid detection of UHECRs

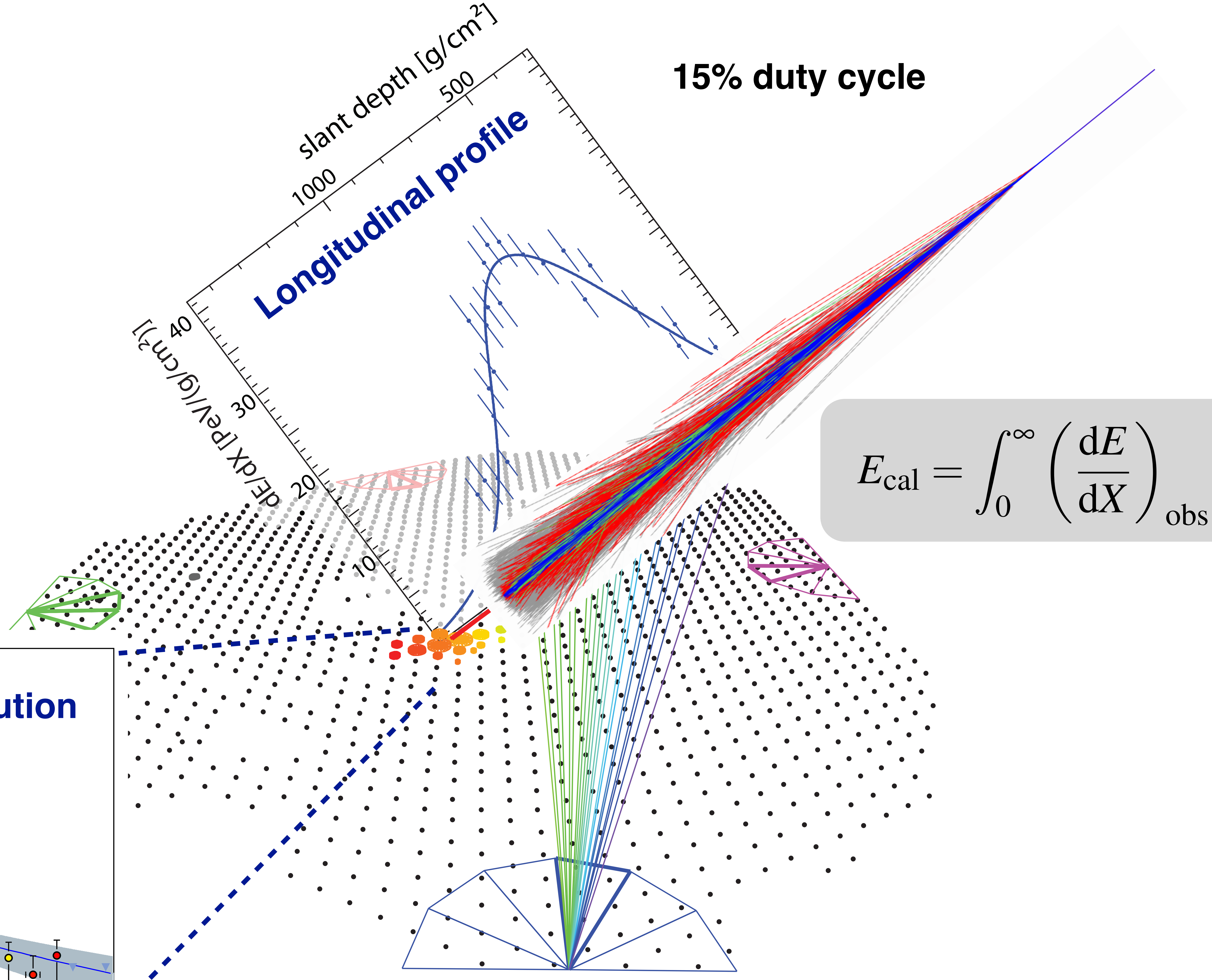


100% duty cycle



$$E_{\text{rec}} = f(S_{1000}, \theta)$$

15% duty cycle

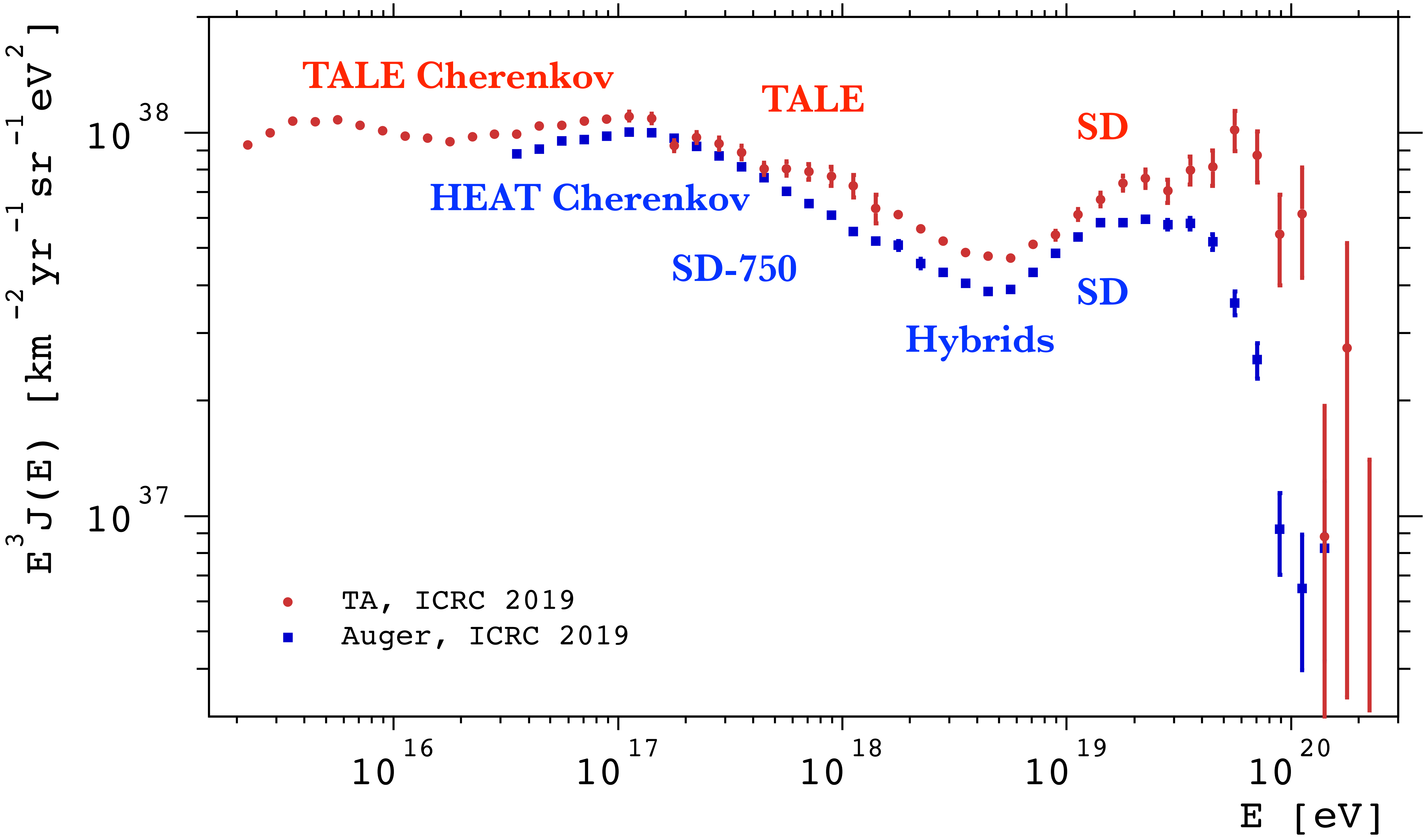


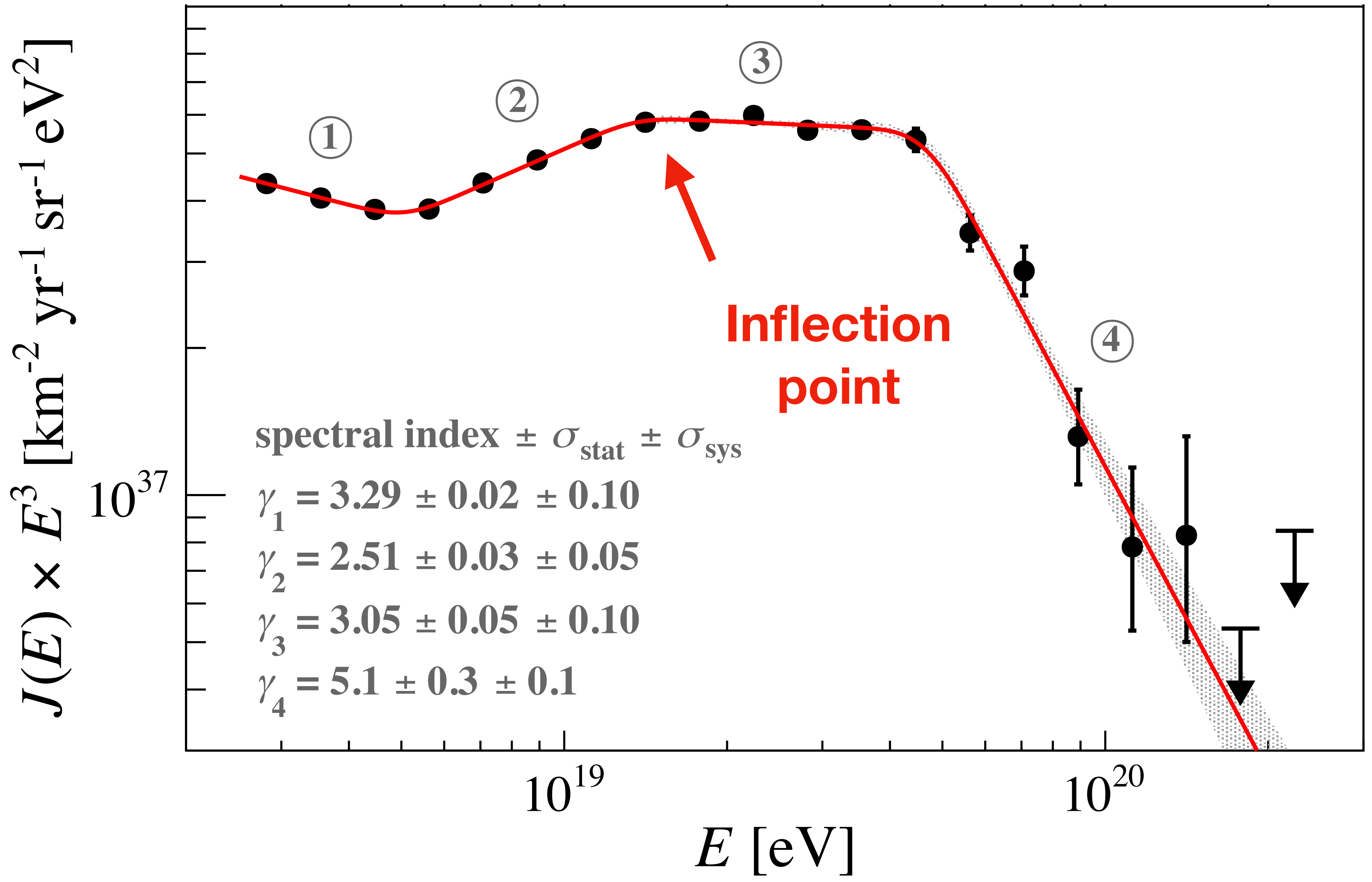
$$E_{\text{cal}} = \int_0^\infty \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\text{obs}} \mathrm{d}X$$

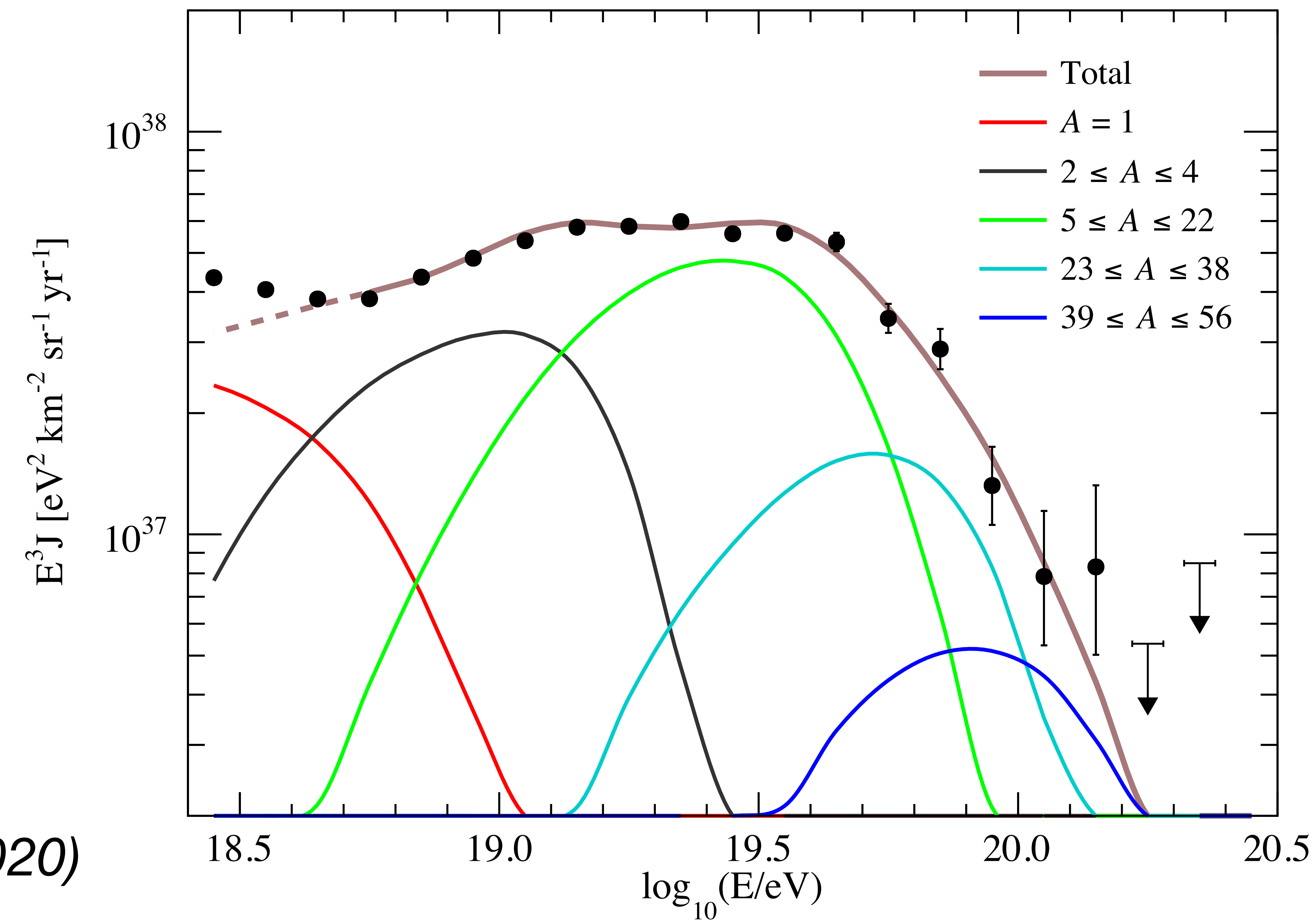
Example: event observed with Auger Observatory

Highlights of flux measurements

(Auger & TA, Deligny et al, ICRC 2019)





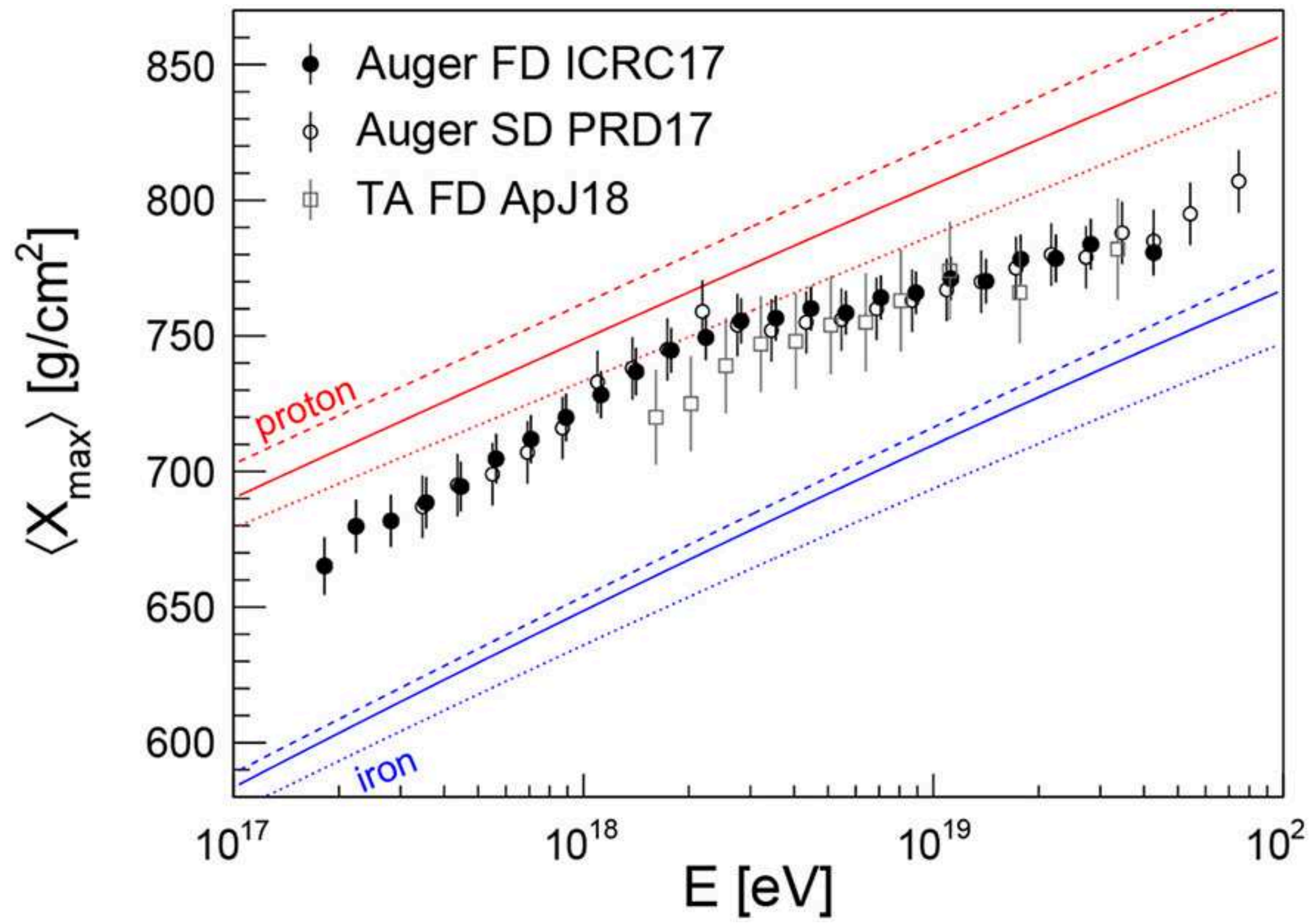


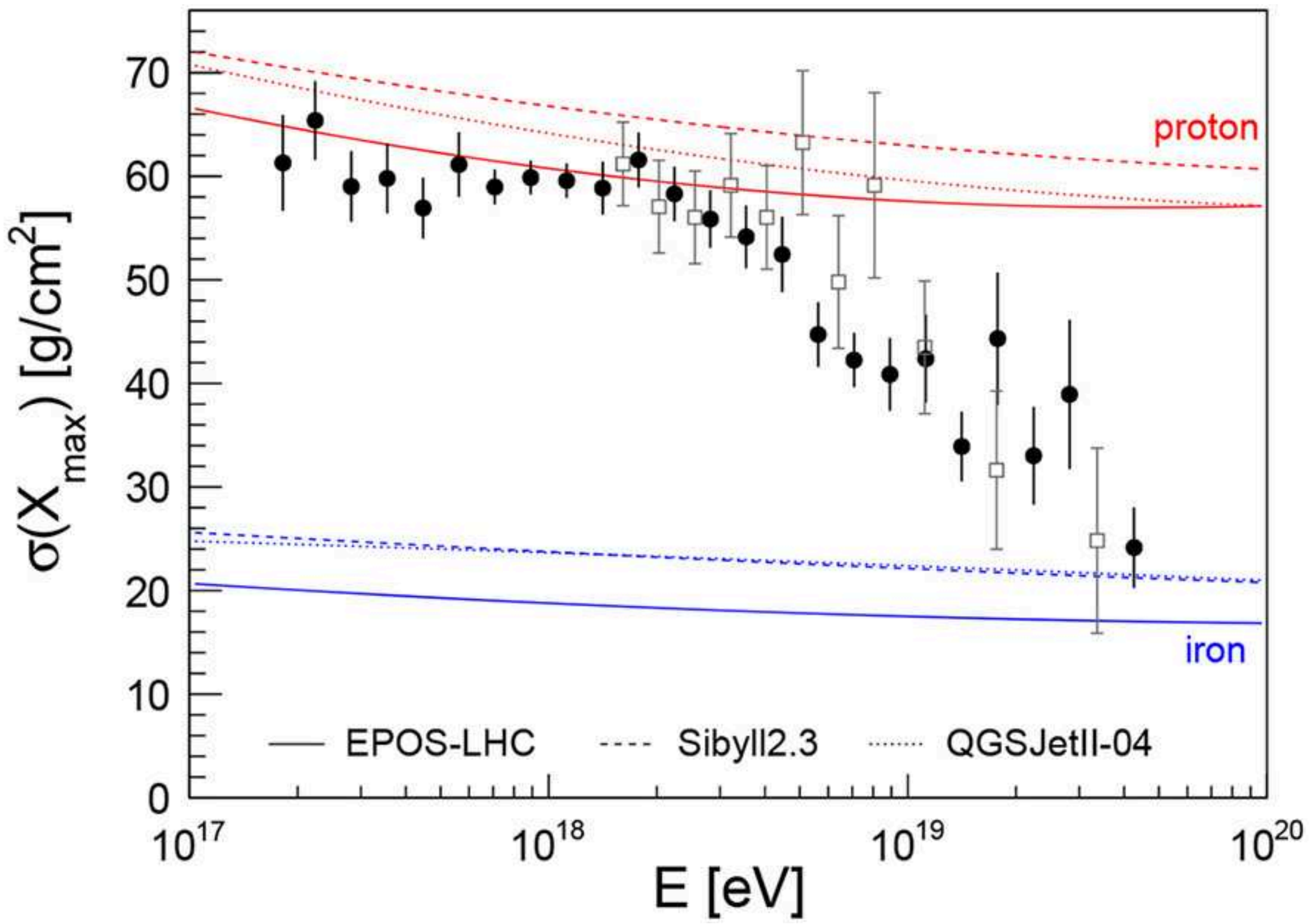
Auger and TA data are compatible with each other, highest energies under investigation

New feature at 1.3 x 10^{19} eV

(Auger, Phys. Rev. Lett. & Phys. Rev. D 2020)

Highlights of composition measurements

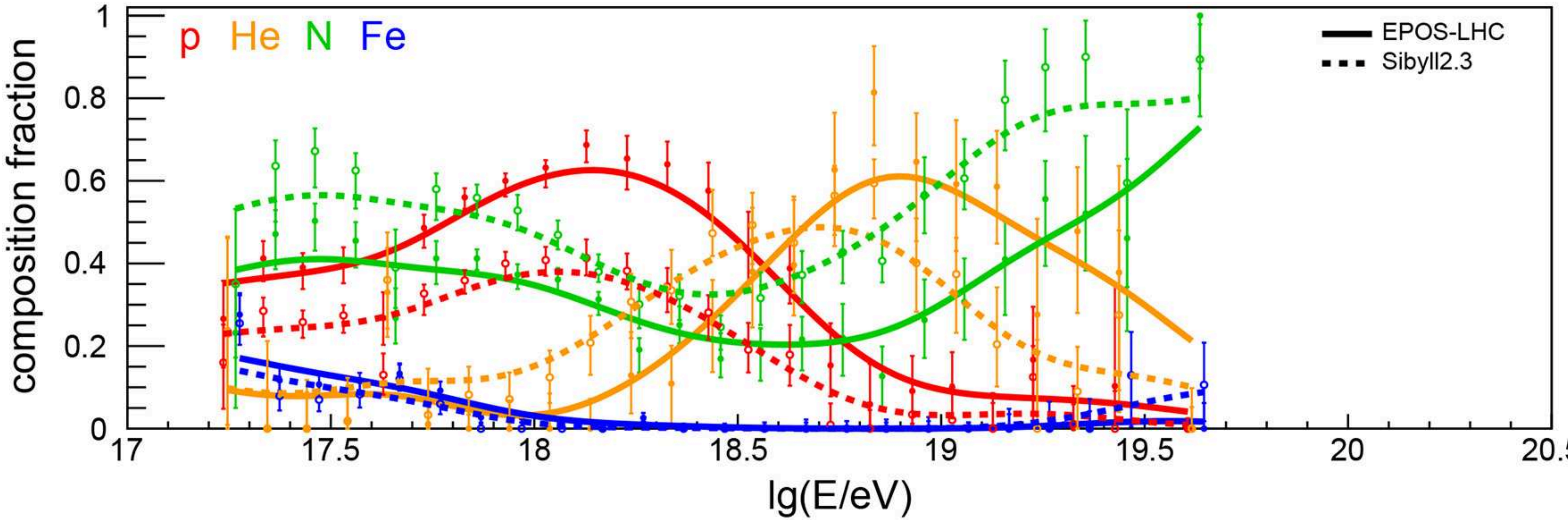




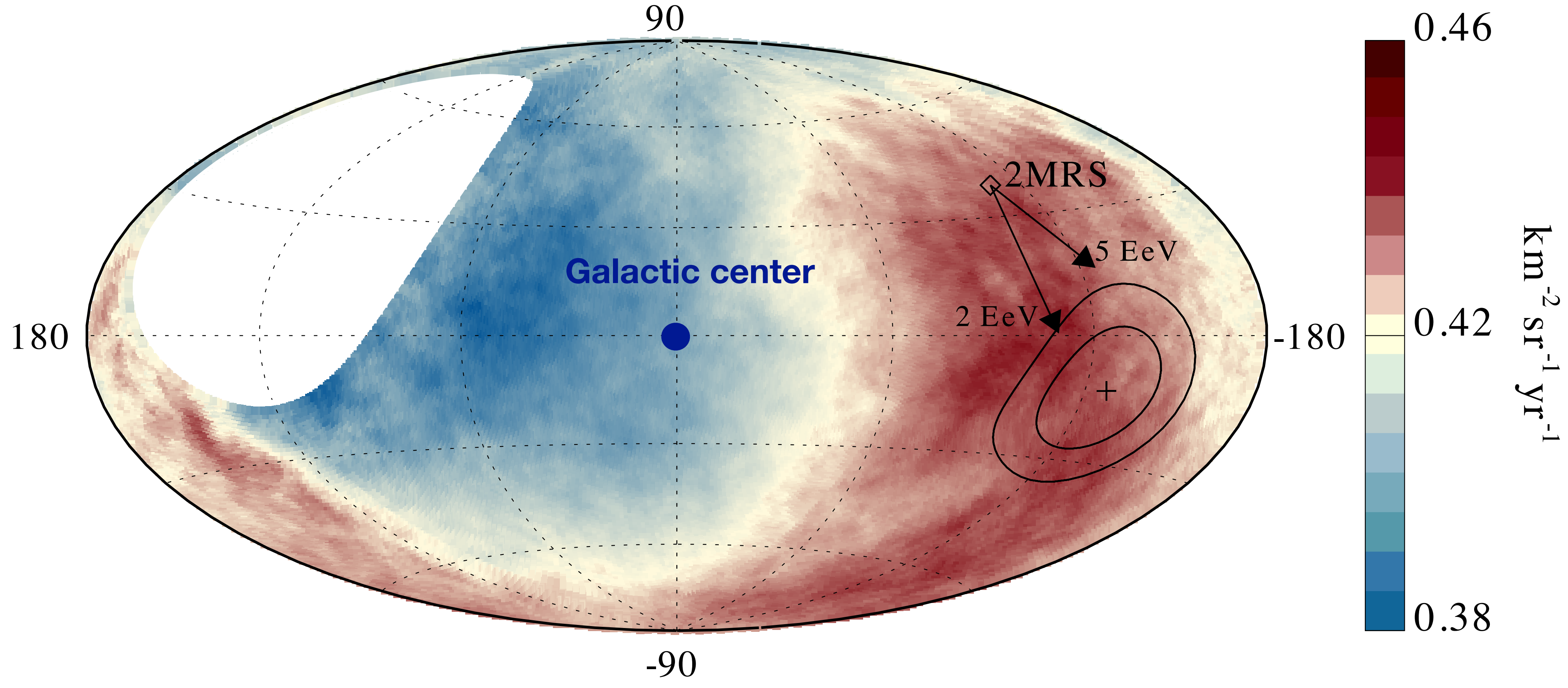
(MIAPP, Front. Astron. Space Sci. 2019
Auger, ICRC 2017 & 2019
Auger, Phys. Rev. D 2014
TA, ApJ 858, 2018, 2)

Auger and TA data are compatible with each other

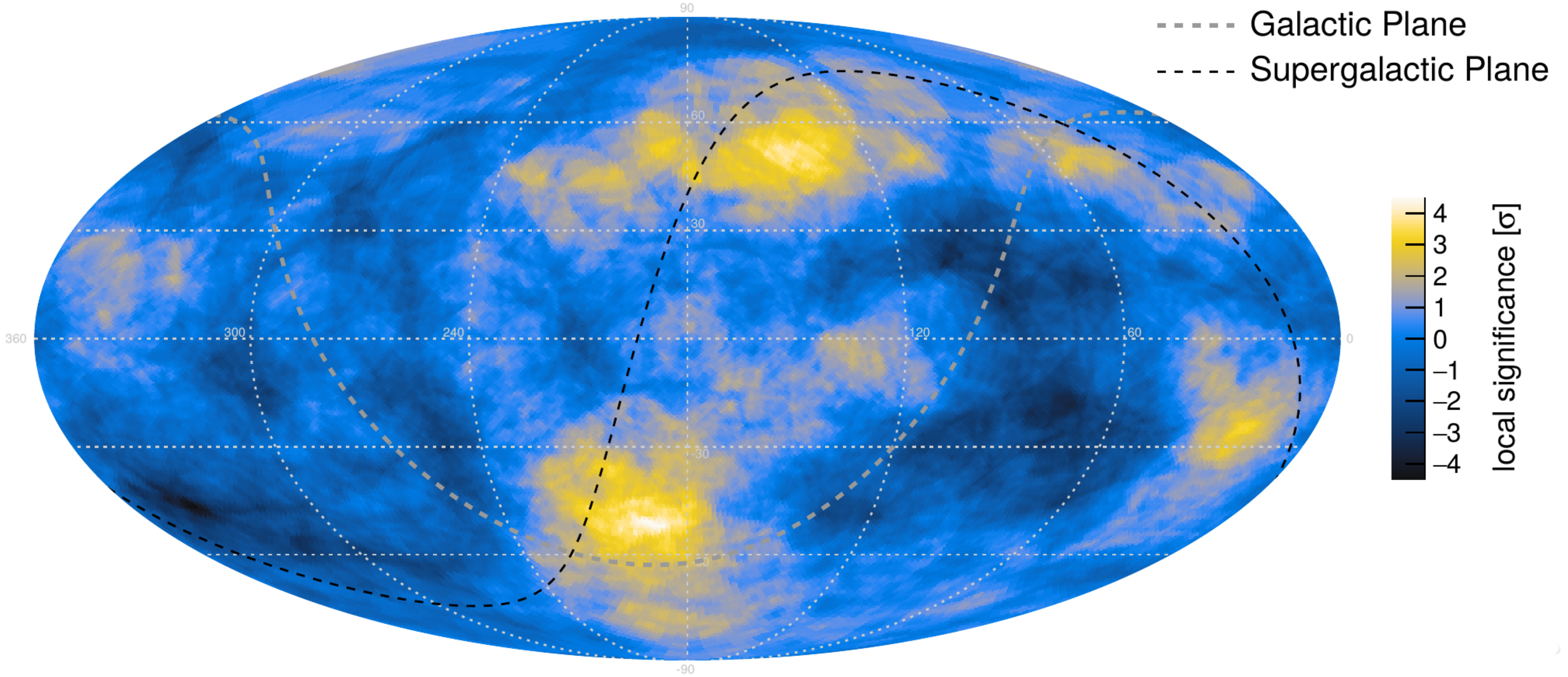
Interpretation depends on models



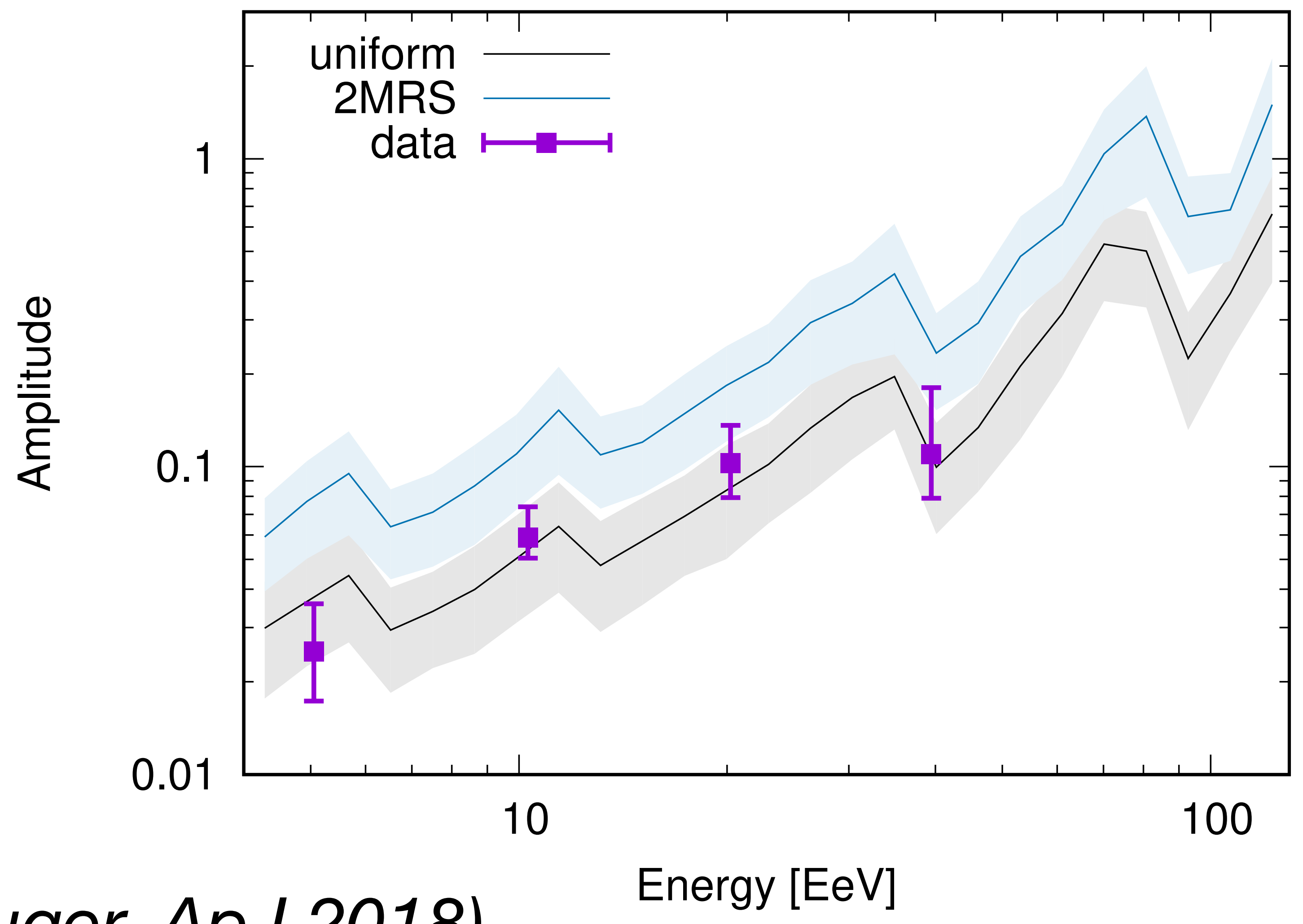
Highlights of anisotropy measurements



6.5% dipole at 5.2 sigma
Science 357 (2017) 1266

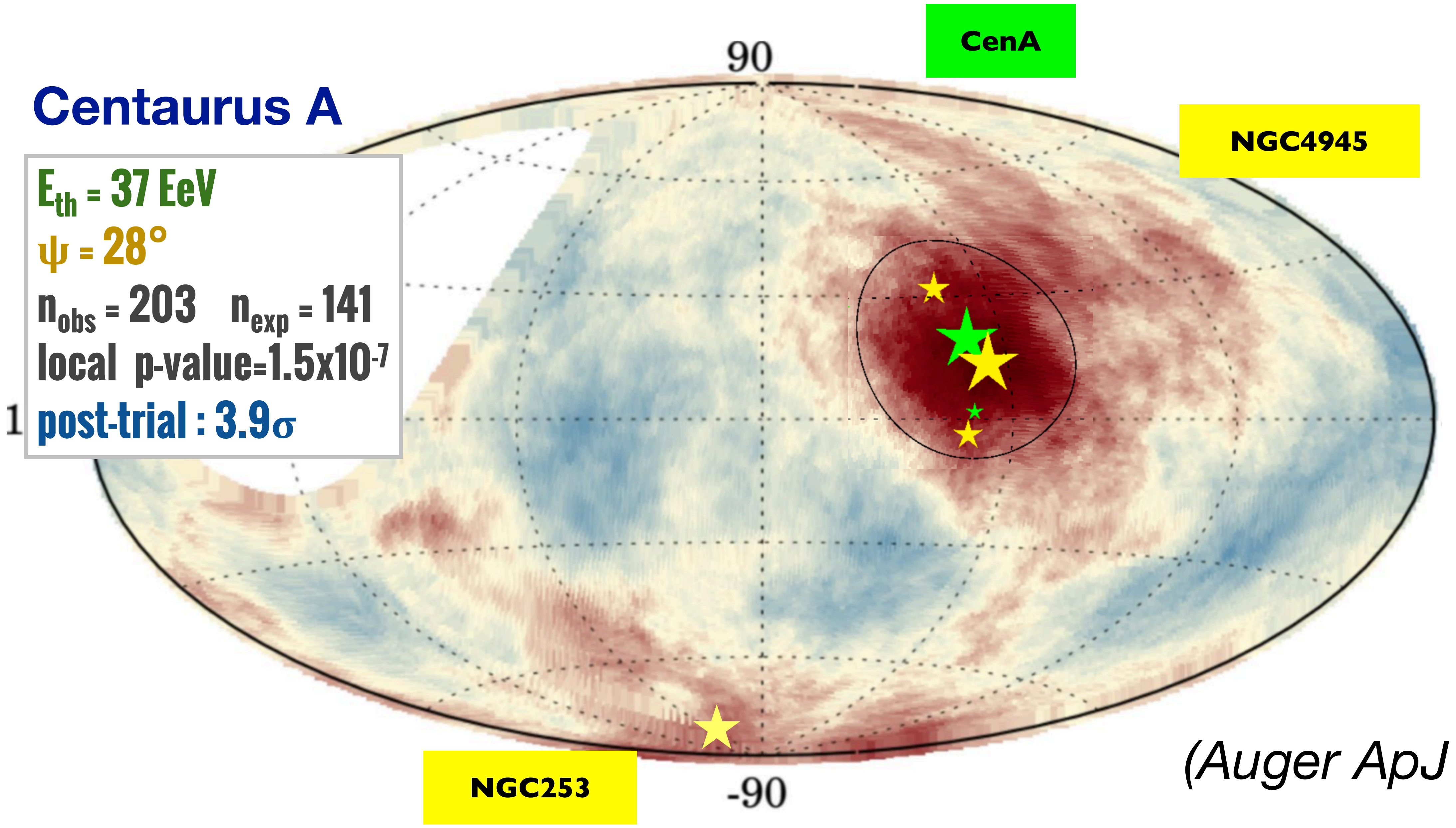


UHECR Auger-TA working group 2018



(Auger, ApJ 2018)

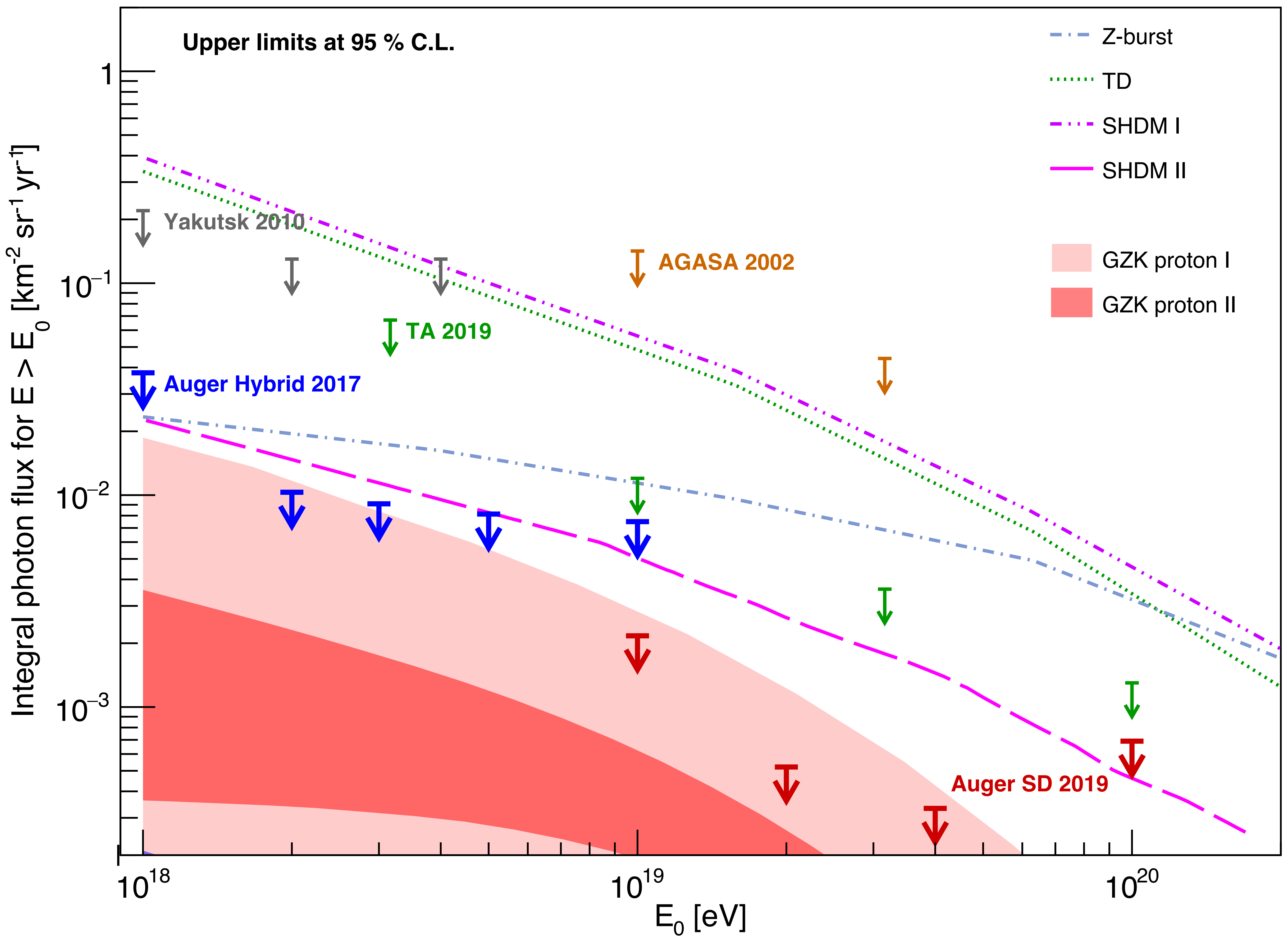
Centaurus A



(Auger ApJ 2018, ICRC 2019)

Particle physics (new particles and phenomena)

Photon limits

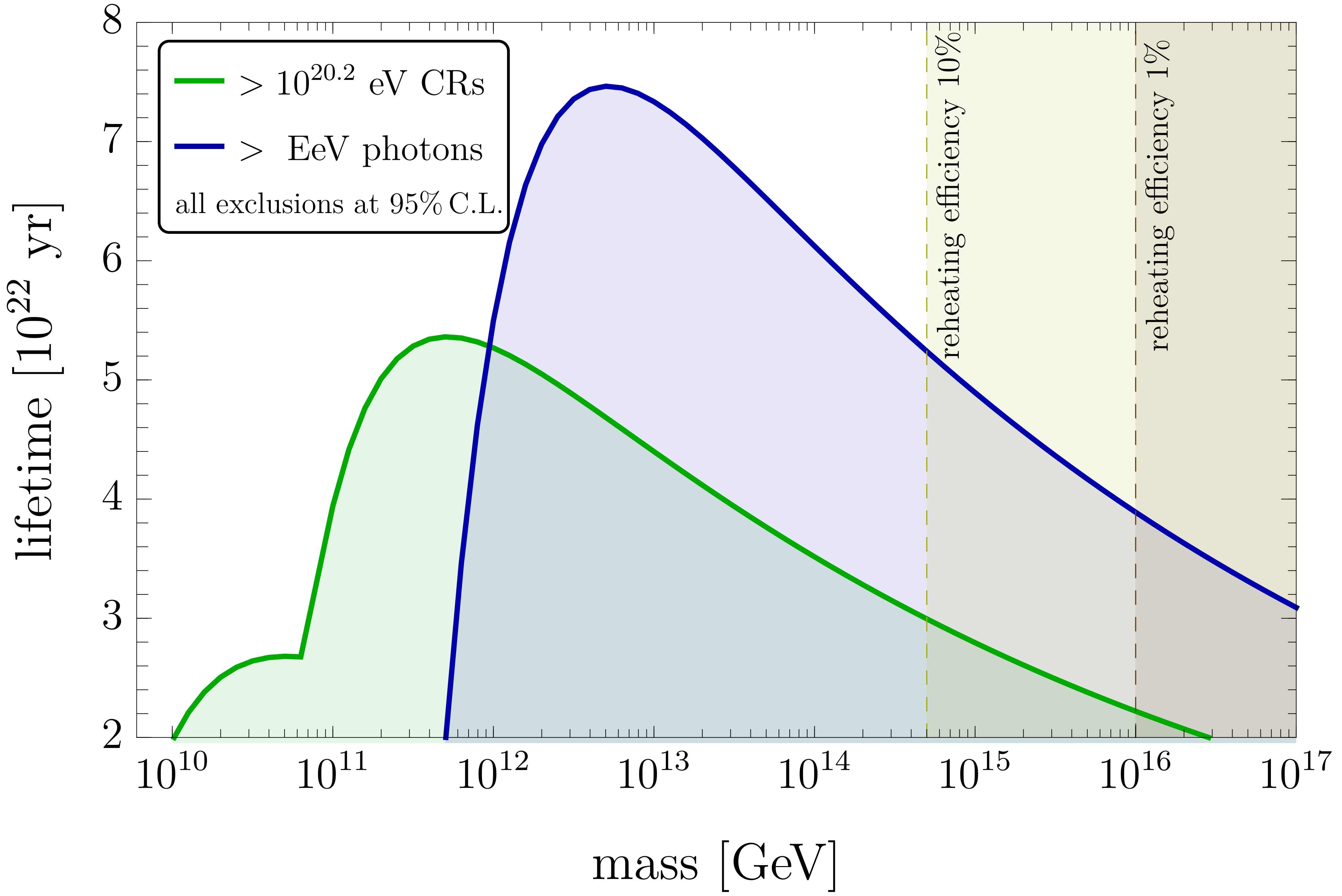


Auger Letters of Interest related to UHE photons:

SNOWMASS21-CF7_CF3-NF4_NF0_Jaime_Alvarez-Muniz-140

SNOWMASS21-CF1_CF7-203

Super-heavy particles



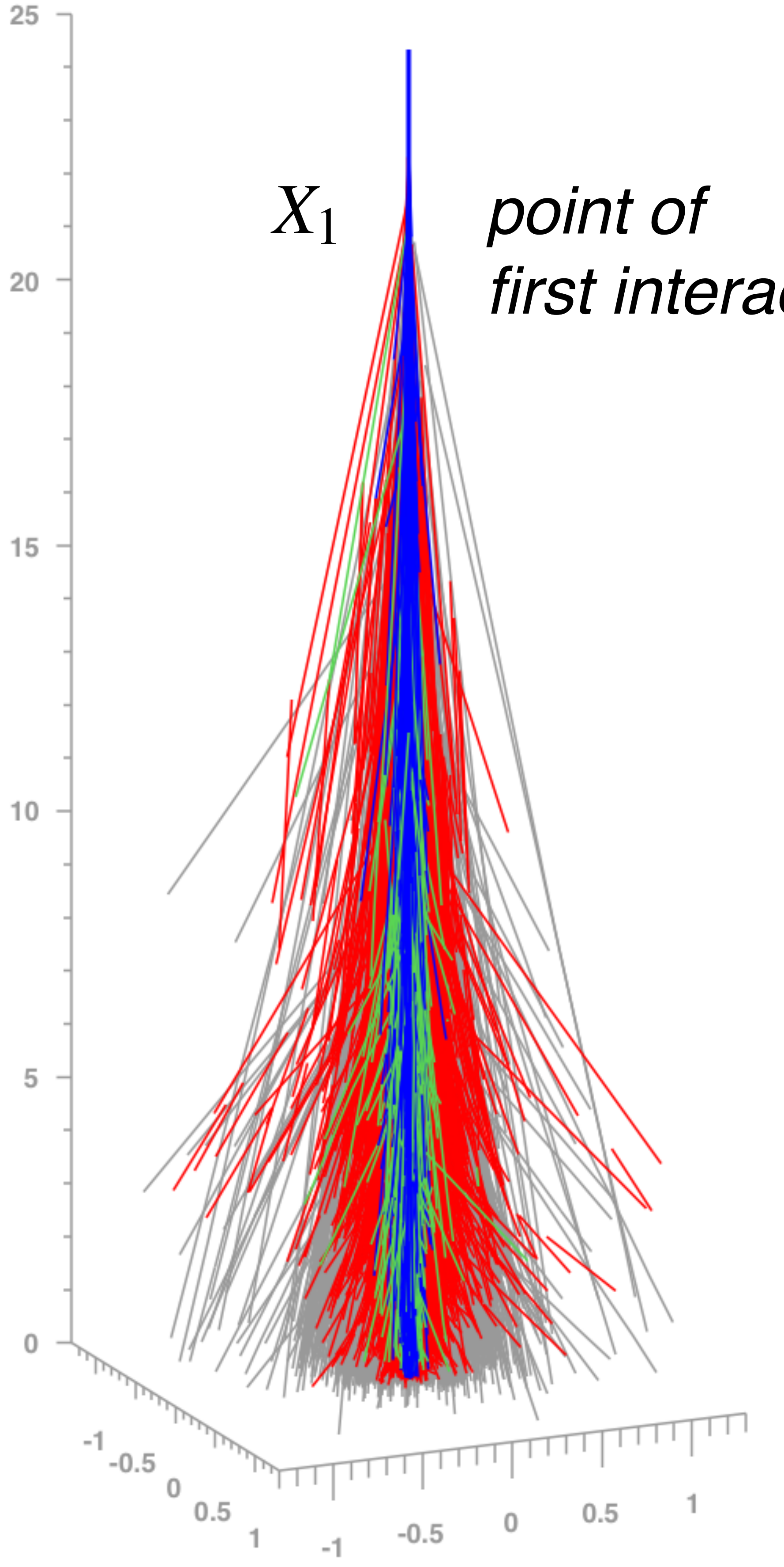
SNOWMASS21-CF1_CF7-203.pdf

Violation of Lorentz invariance (propagation of UHECR, shower development)

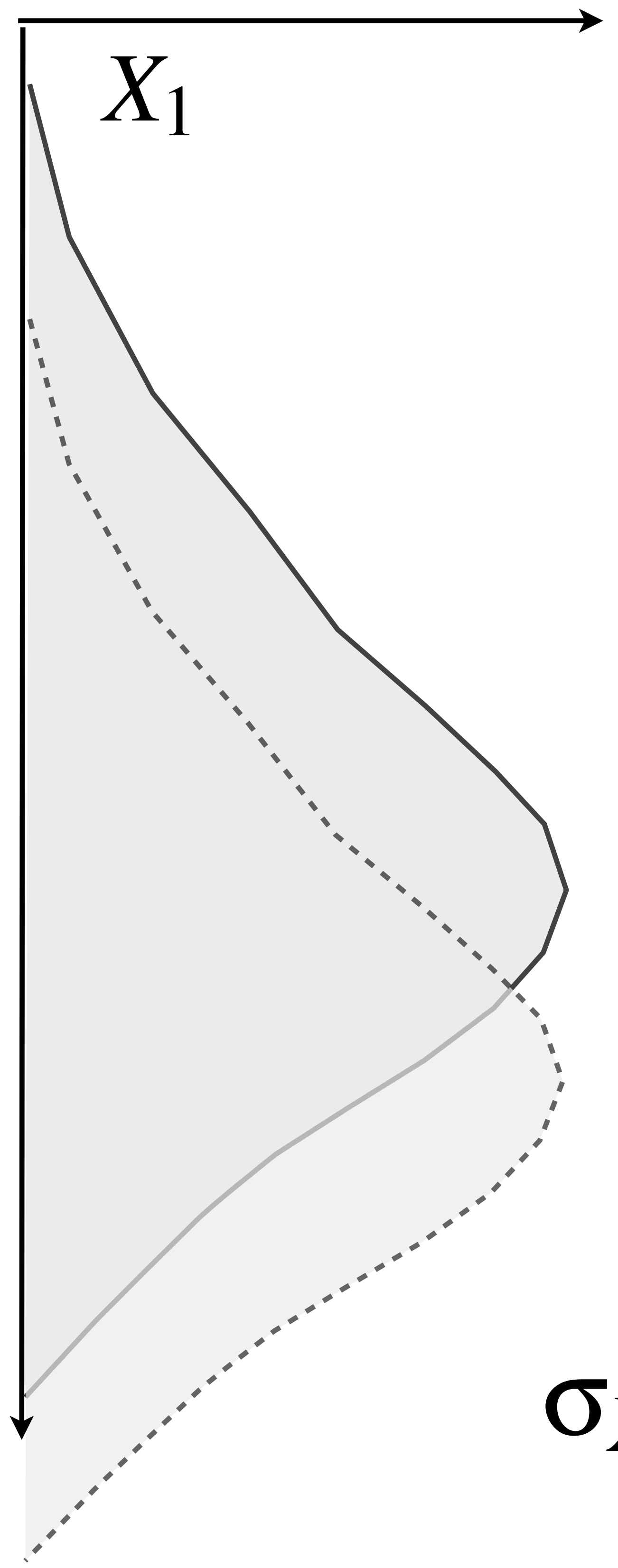
CF7 CF0 Yoshiki Tsunesada-265

Particle physics (hadronic interactions)

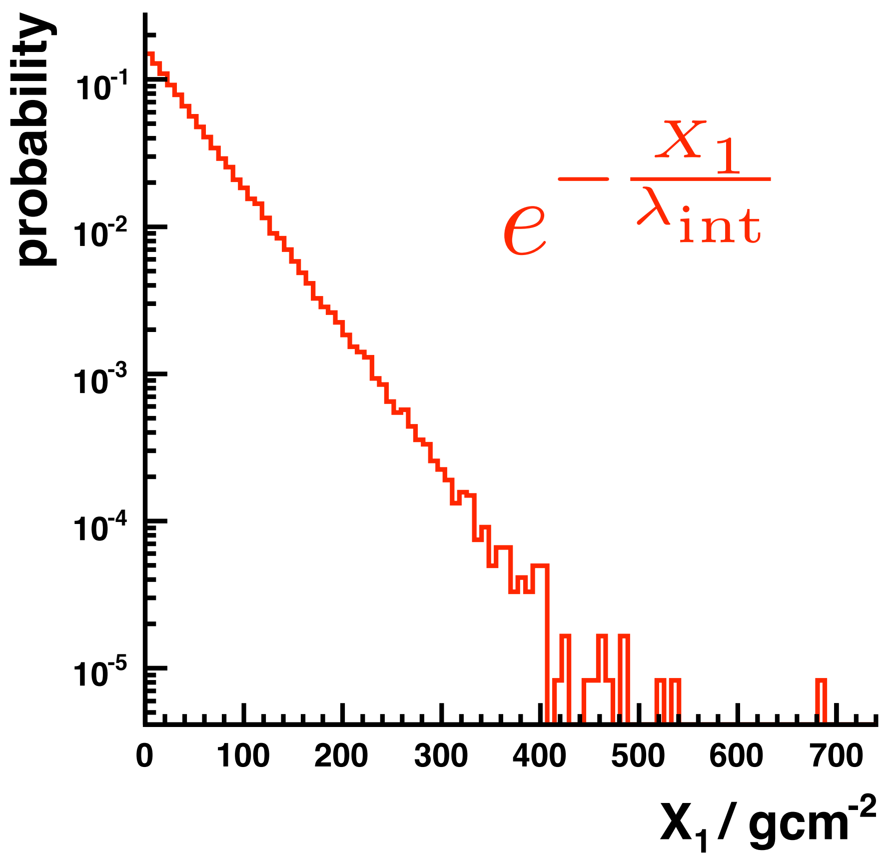
X_1 *point of first interaction*



Number of charged particles



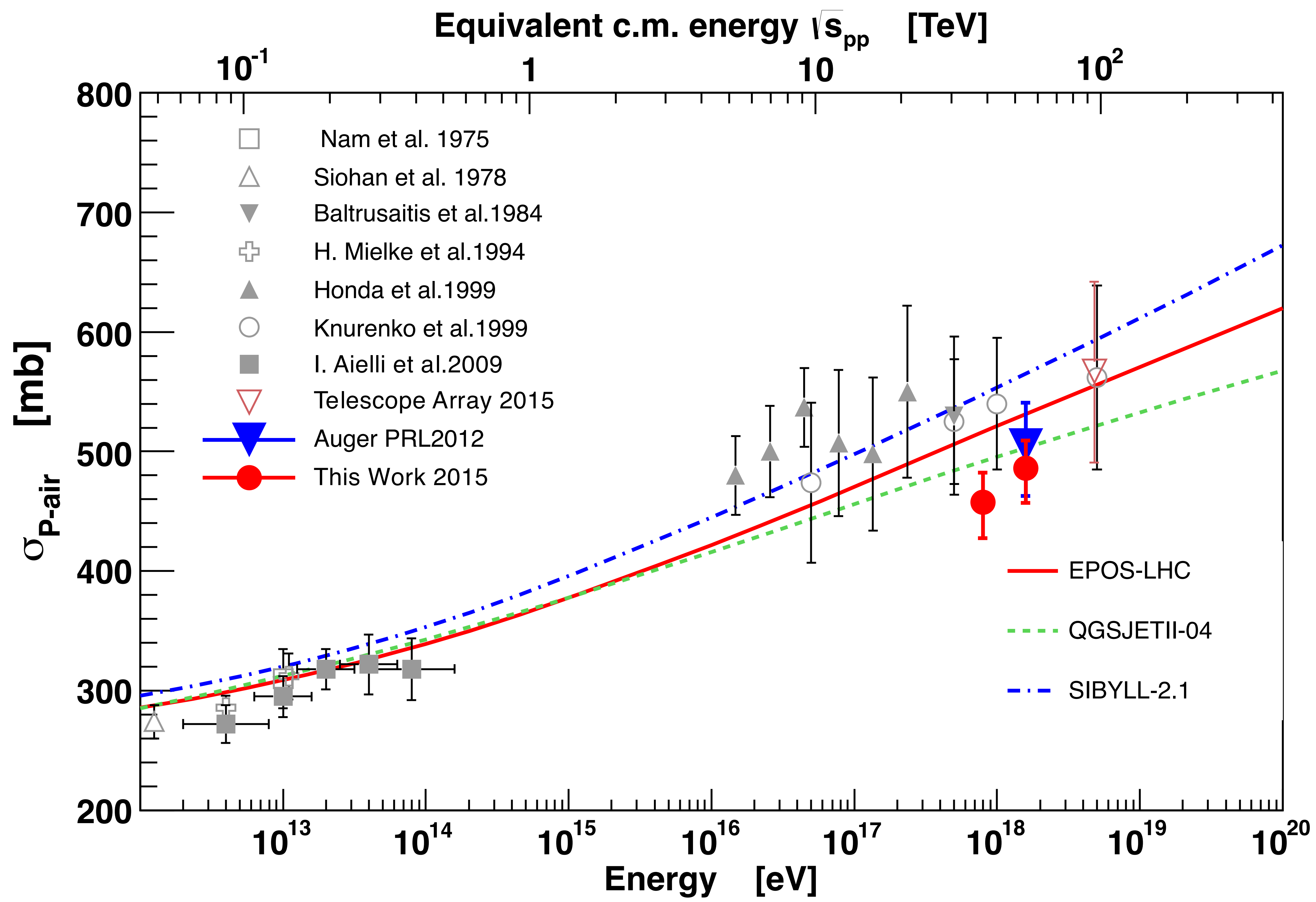
X_{max}



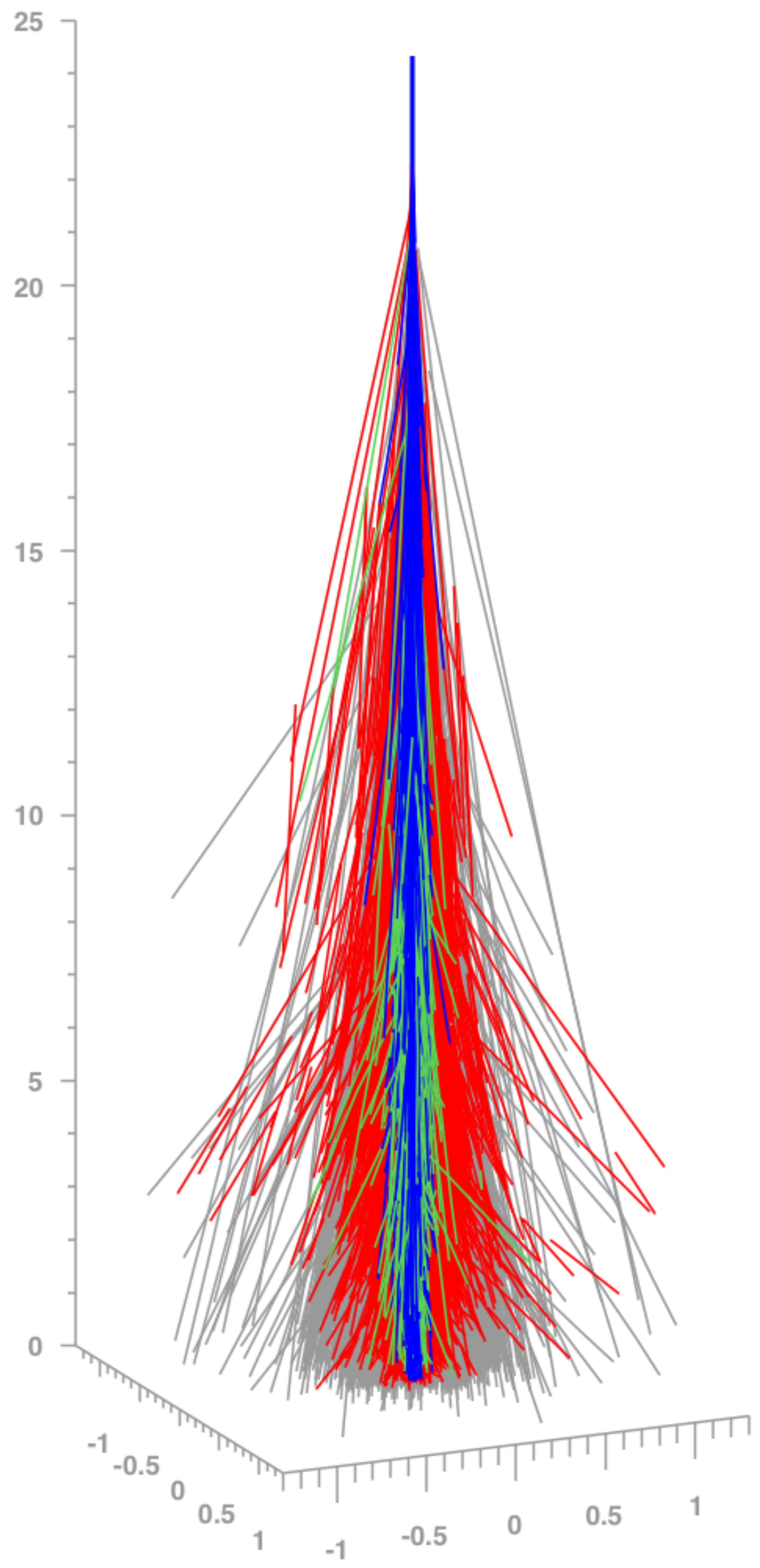
(Auger, Phys. Rev. Lett. 2012, ICRC 2017, TA, Phys. Rev.D 2015, 2019)

$$\sigma_{X_1} = \lambda_{int}$$

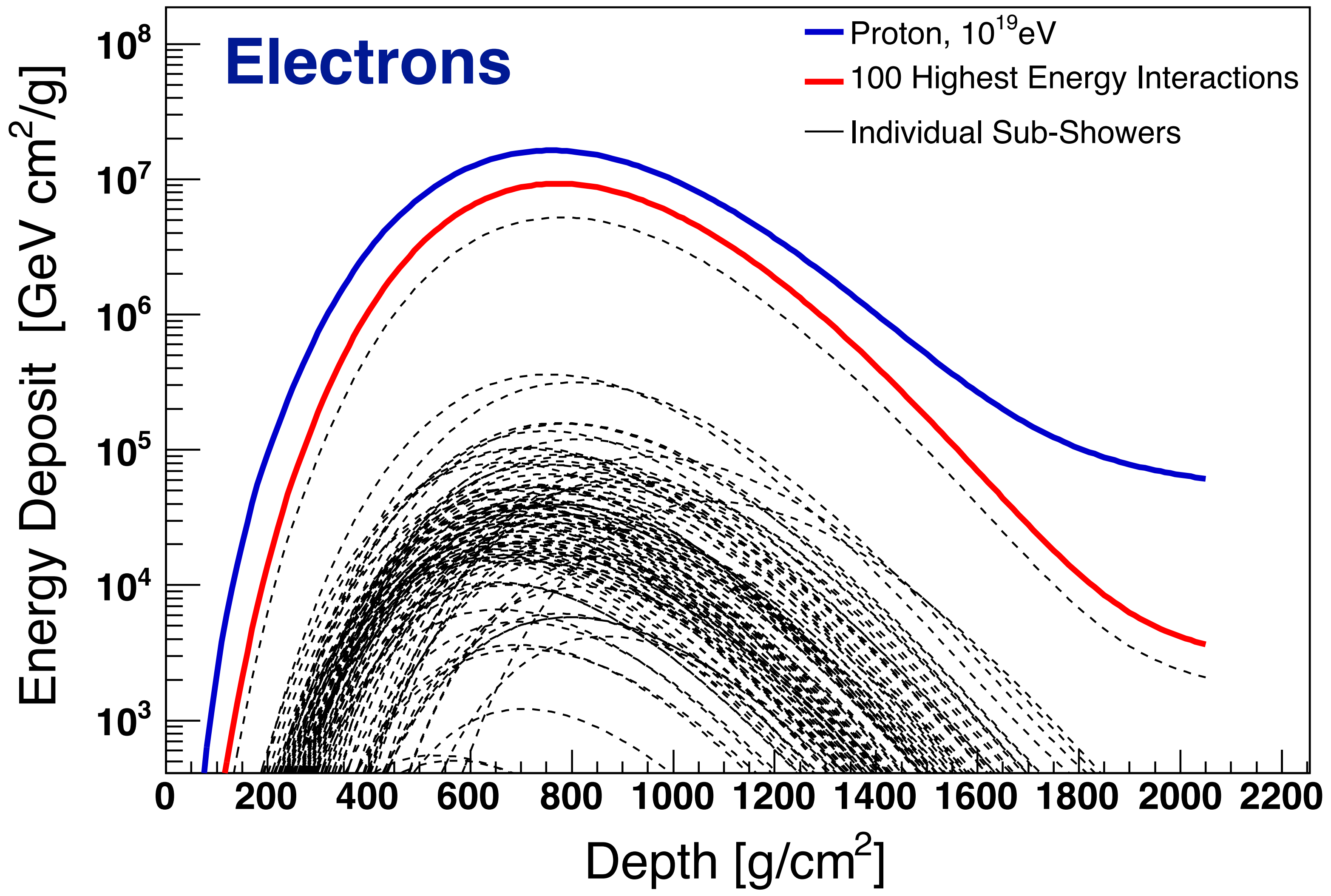
$$\lambda_{int} = \frac{\langle m_{air} \rangle}{\sigma_{p-air}}$$

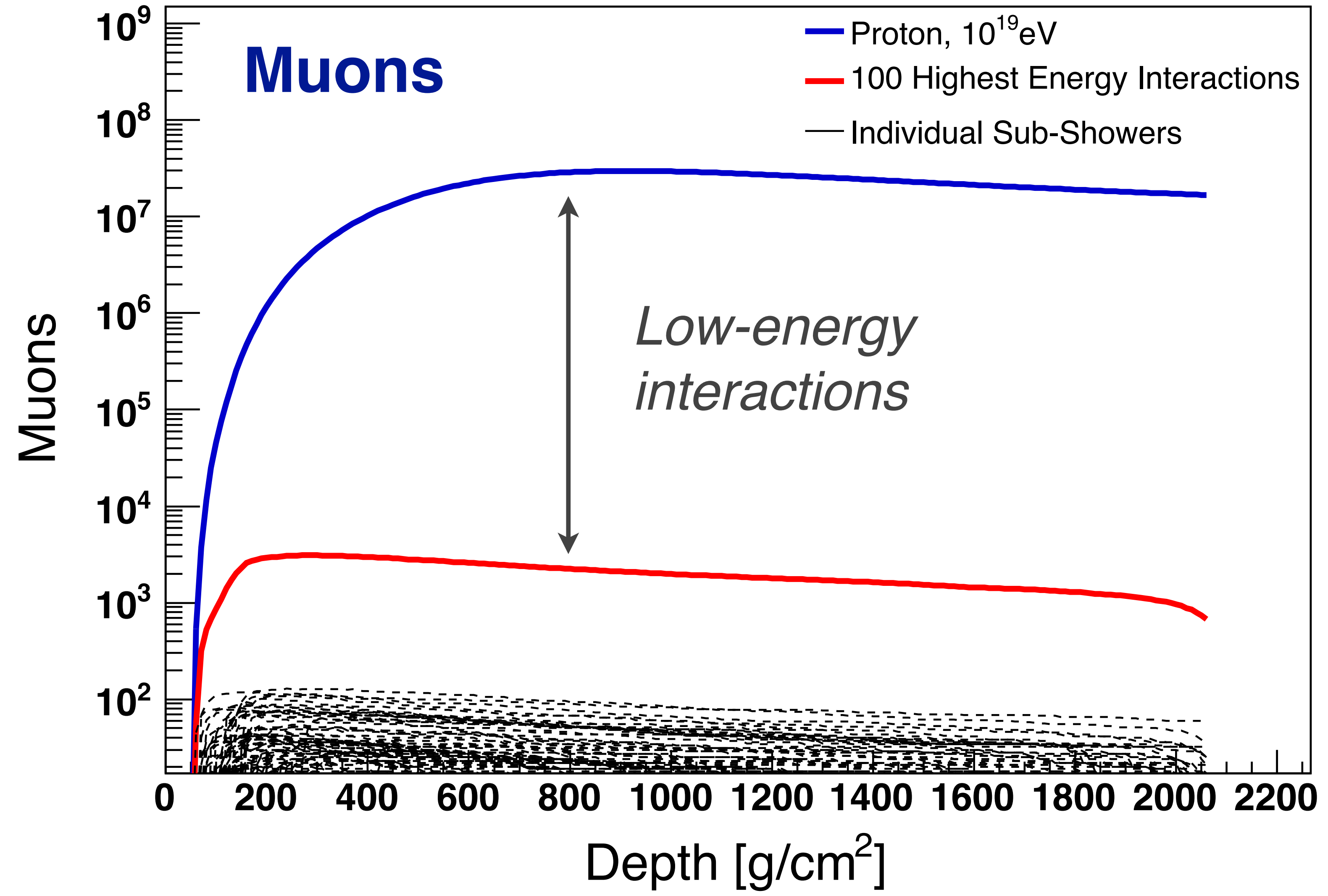


Importance of hadronic interactions at different energies



(Ulrich APS 2010)





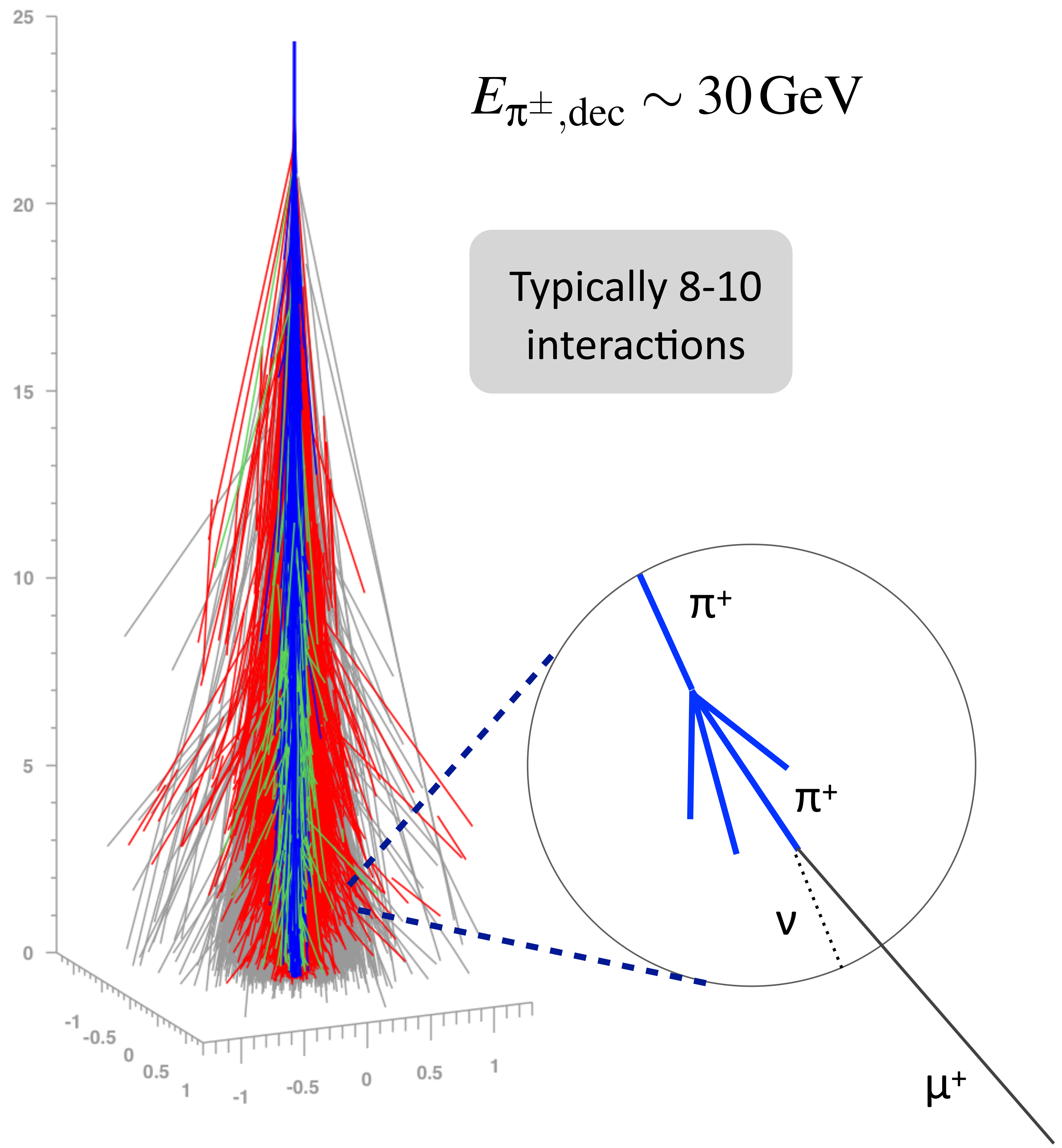
Shower particles produced in 100 interactions of highest energy

Electrons/photons:
high-energy interactions

Muons/hadrons:
low-energy interactions

Muons: majority produced in ~30 GeV interactions

Muon production at large lateral distance

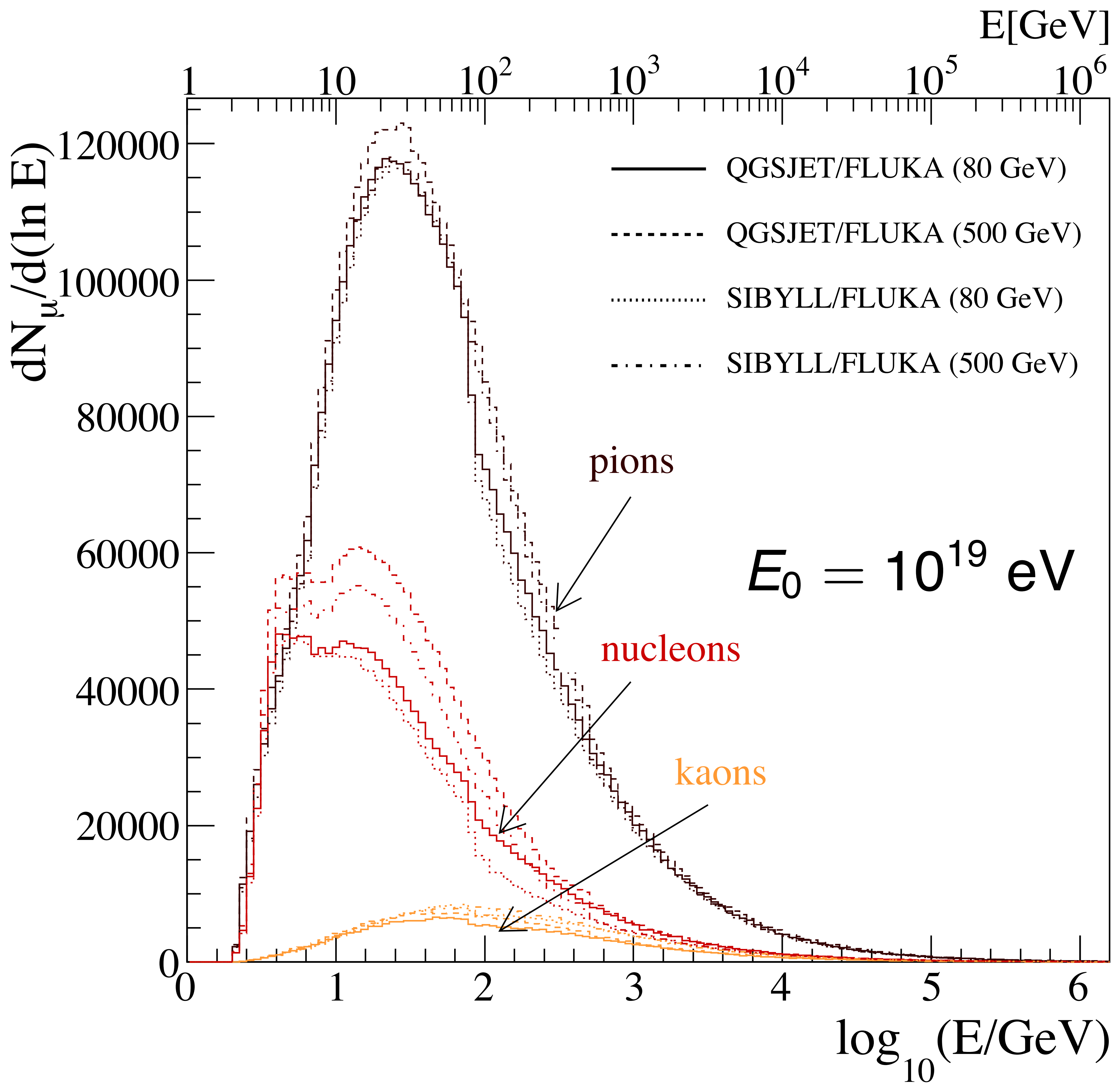


$E_{\pi^{\pm},\mathrm{dec}} \sim 30\,\mathrm{GeV}$

Typically 8-10 interactions

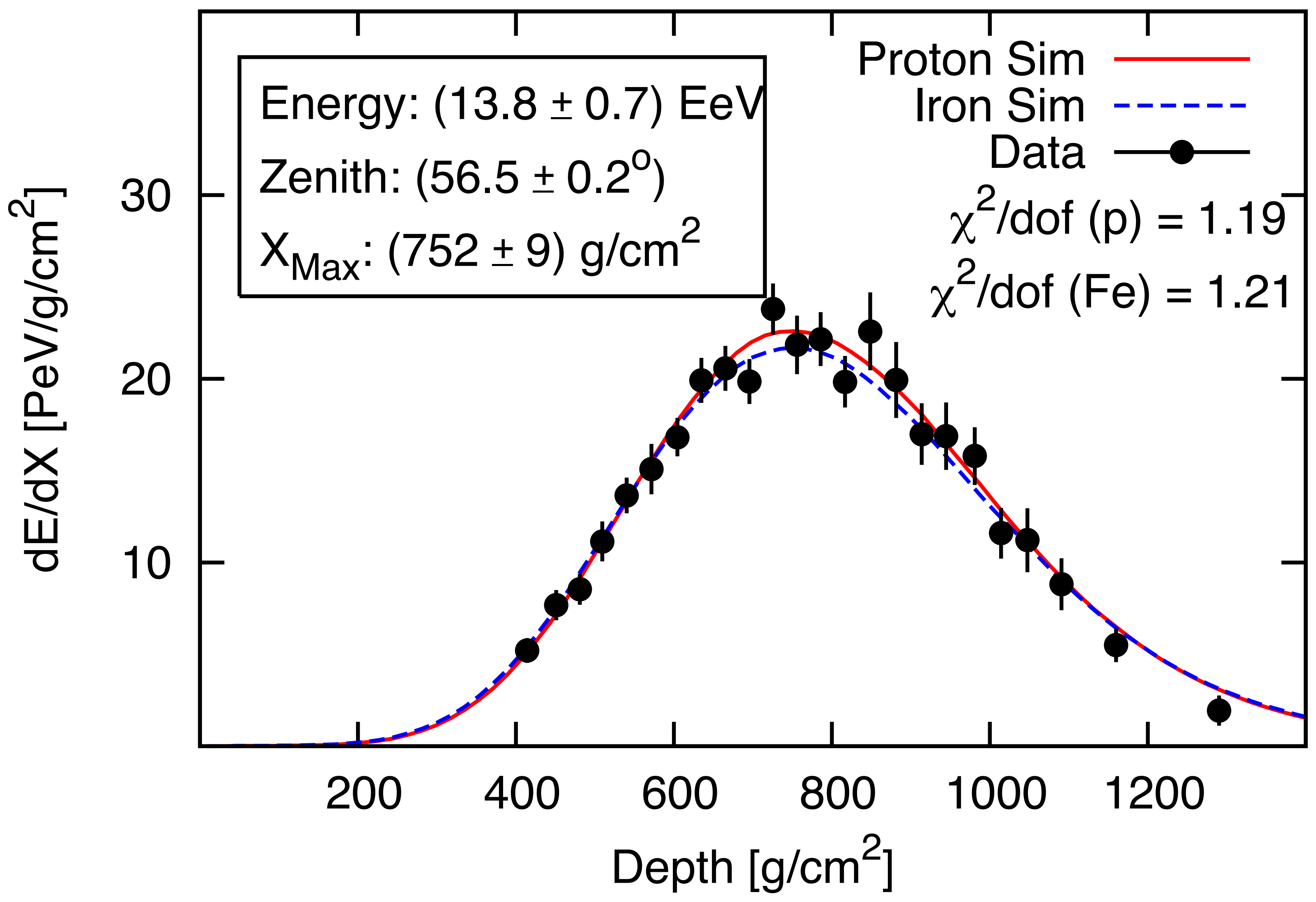
Muon observed at 1000 m from core

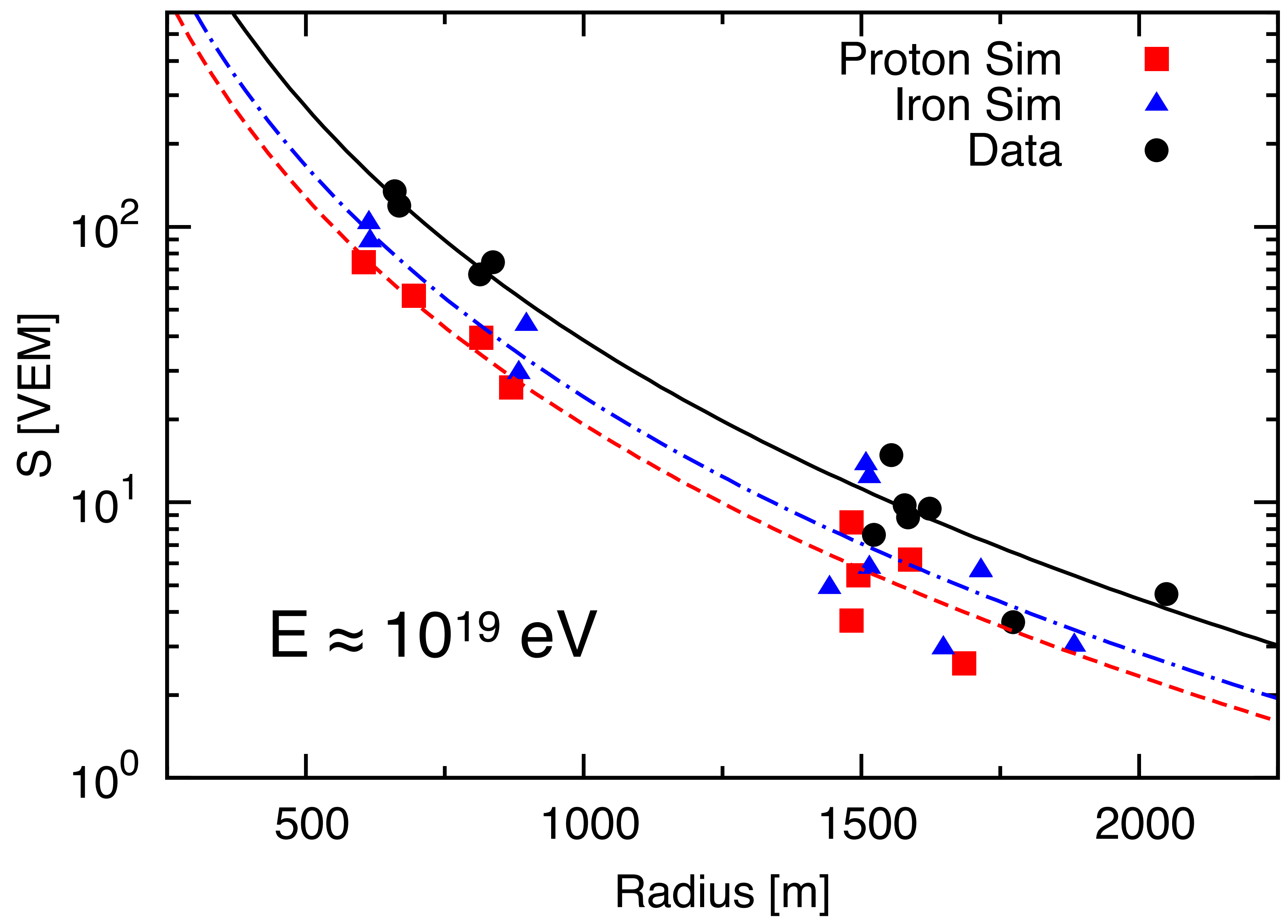
Energy distribution of last interaction that produced a detected muon



(Maris et al. ICRC 2009)

Ultimative test: simulation of individual events





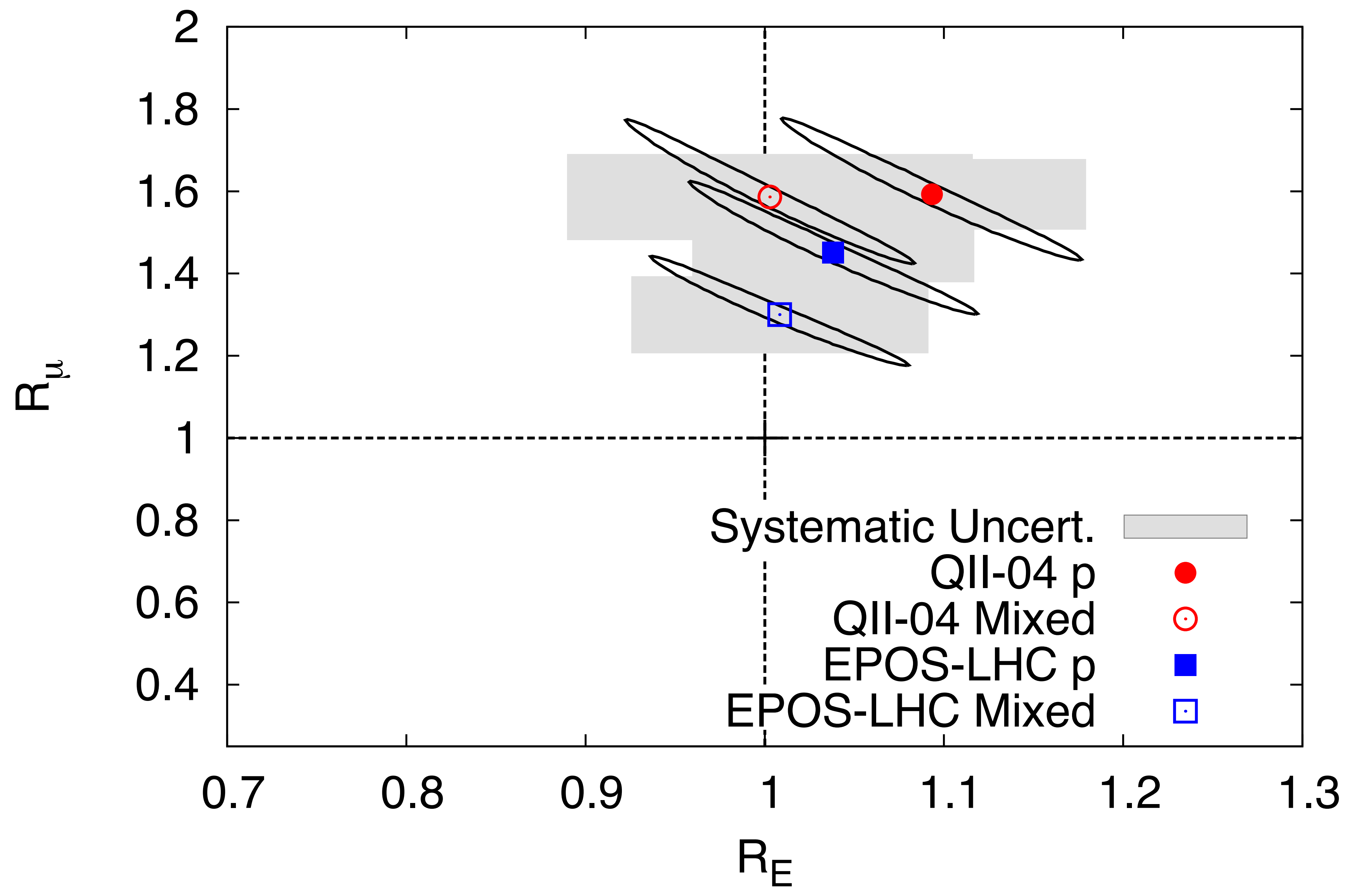
(Auger, PRL 117, 2016)

Phenomenological model ansatz

Energy scaling: em. particles and muons

Muon scaling: hadronically produced muons and muon interaction/decay products

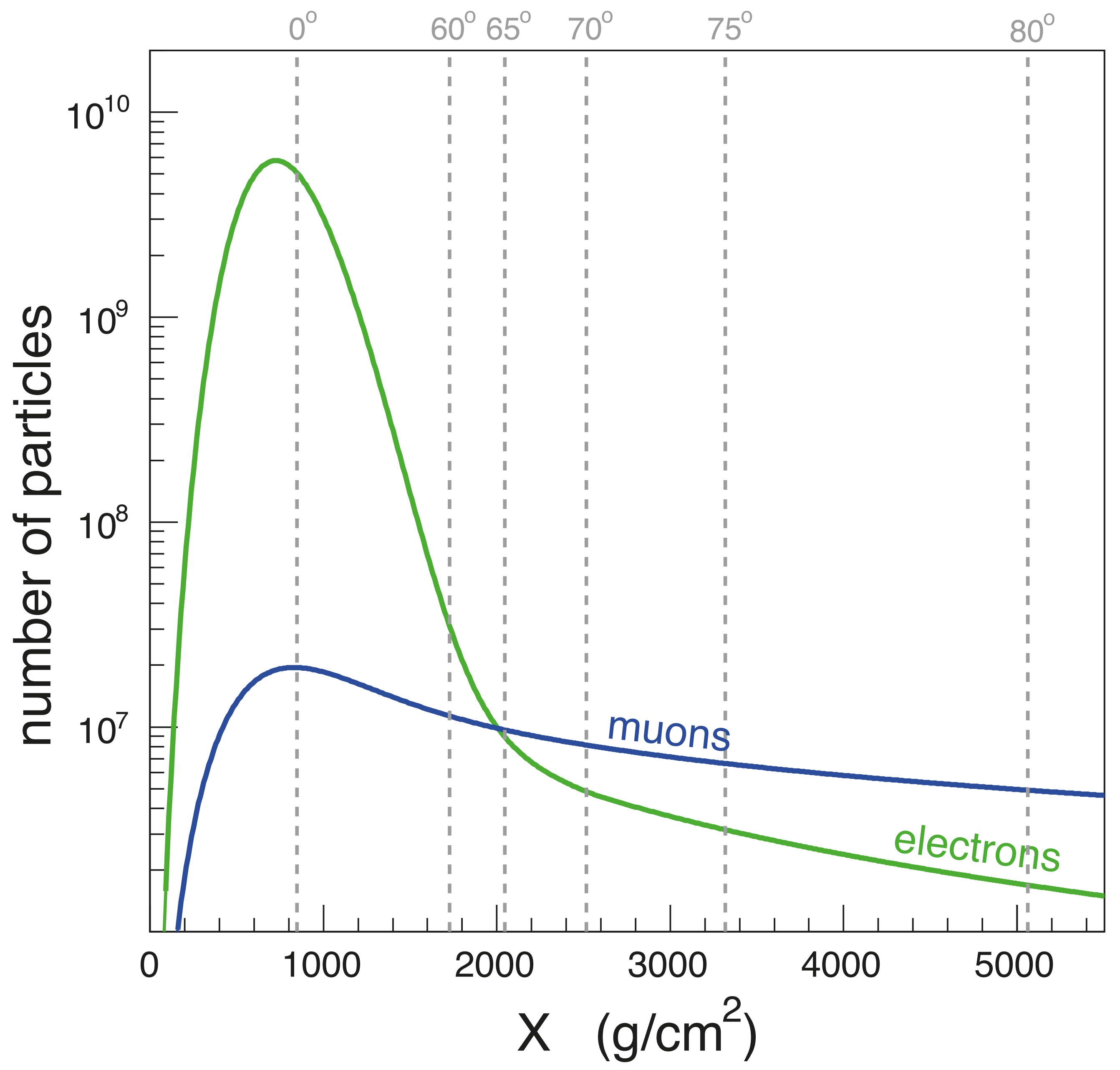
Full detector simulation after re-scaling



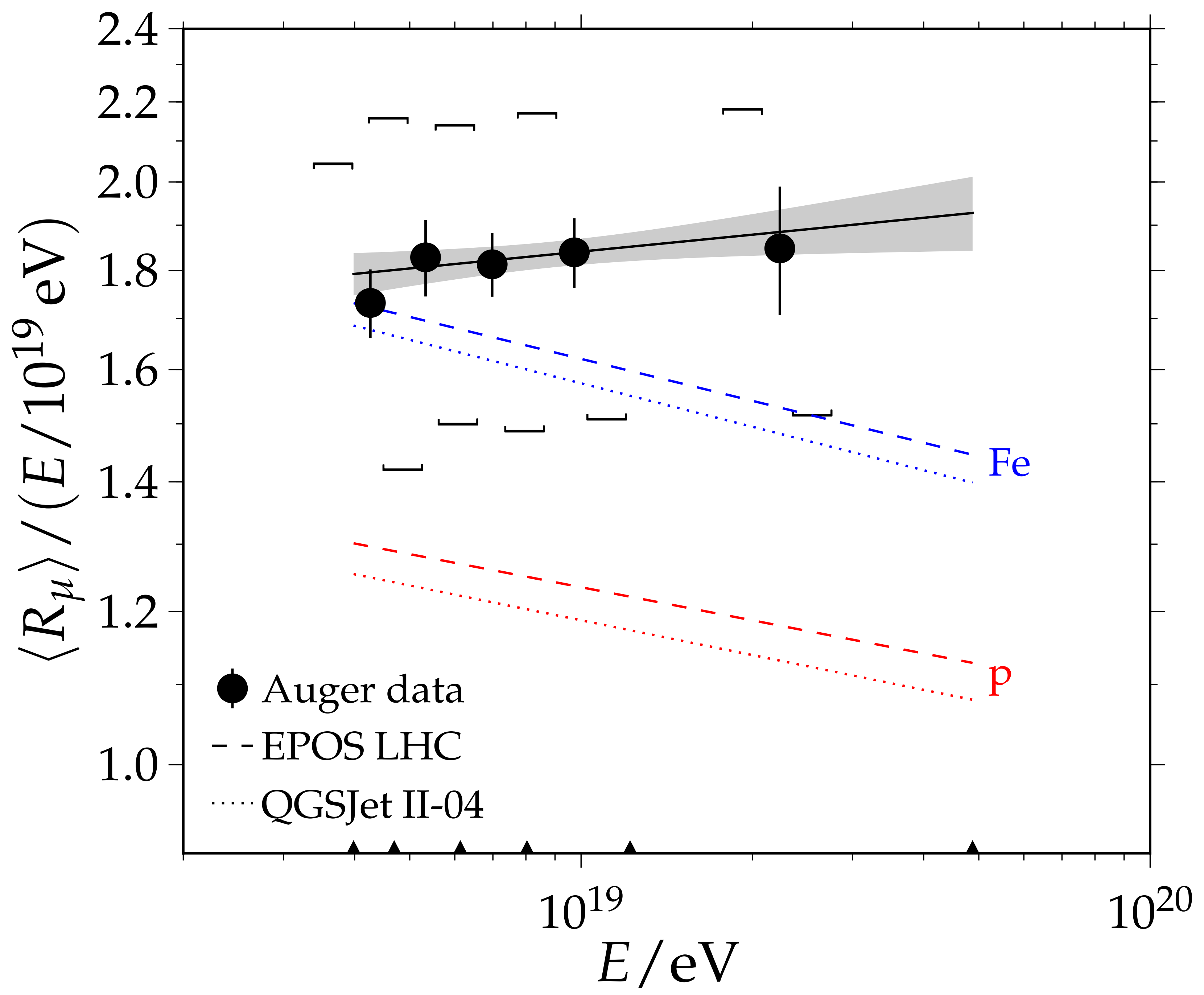
None of the models gives a really good description

Muon number in inclined showers

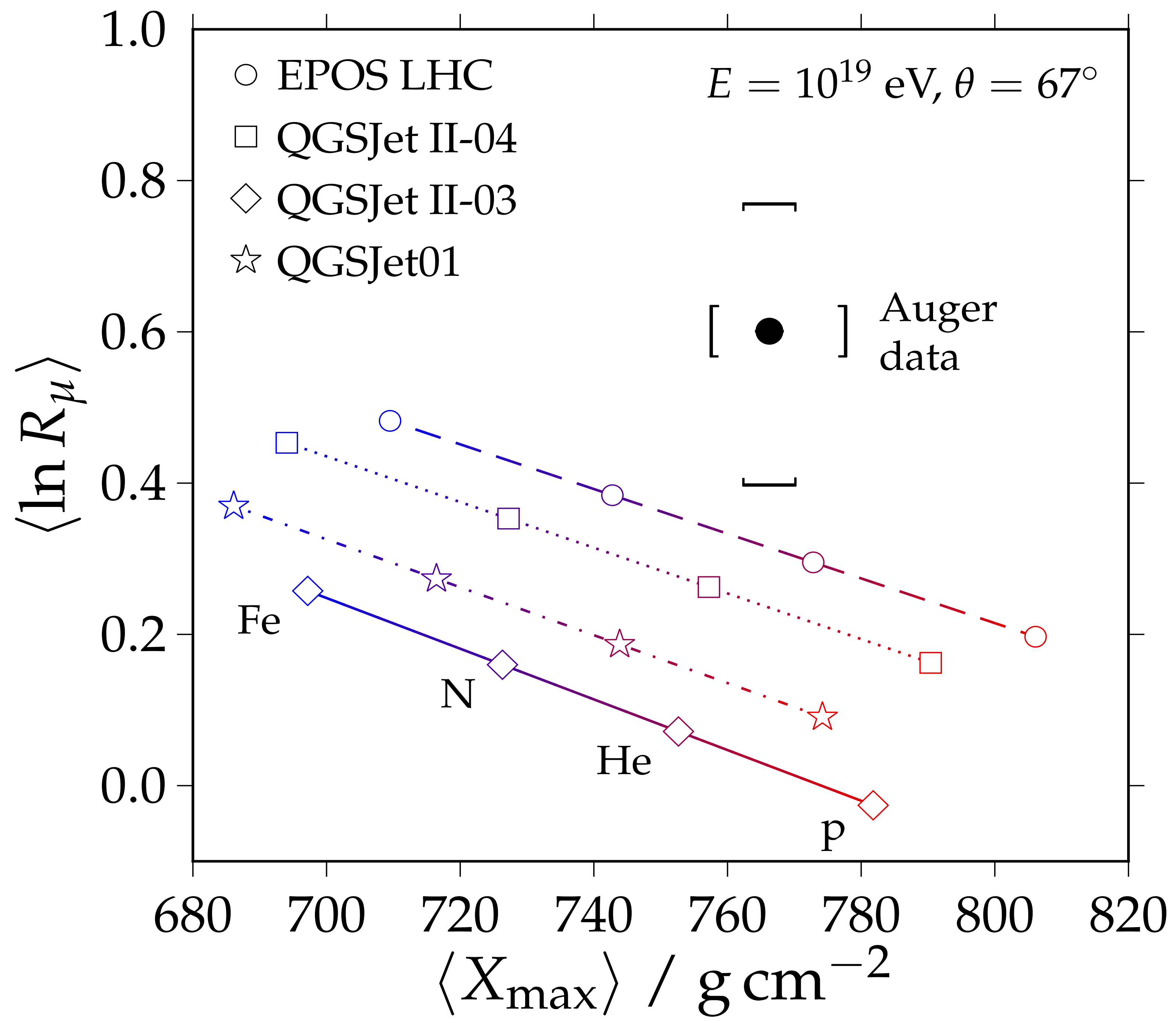
Shower size attenuation



Number of muons in showers with θ>65°



Combination of information on mean depth of shower maximum and muon number at ground



Several measurements: strong indications (evidence?) for muon discrepancy

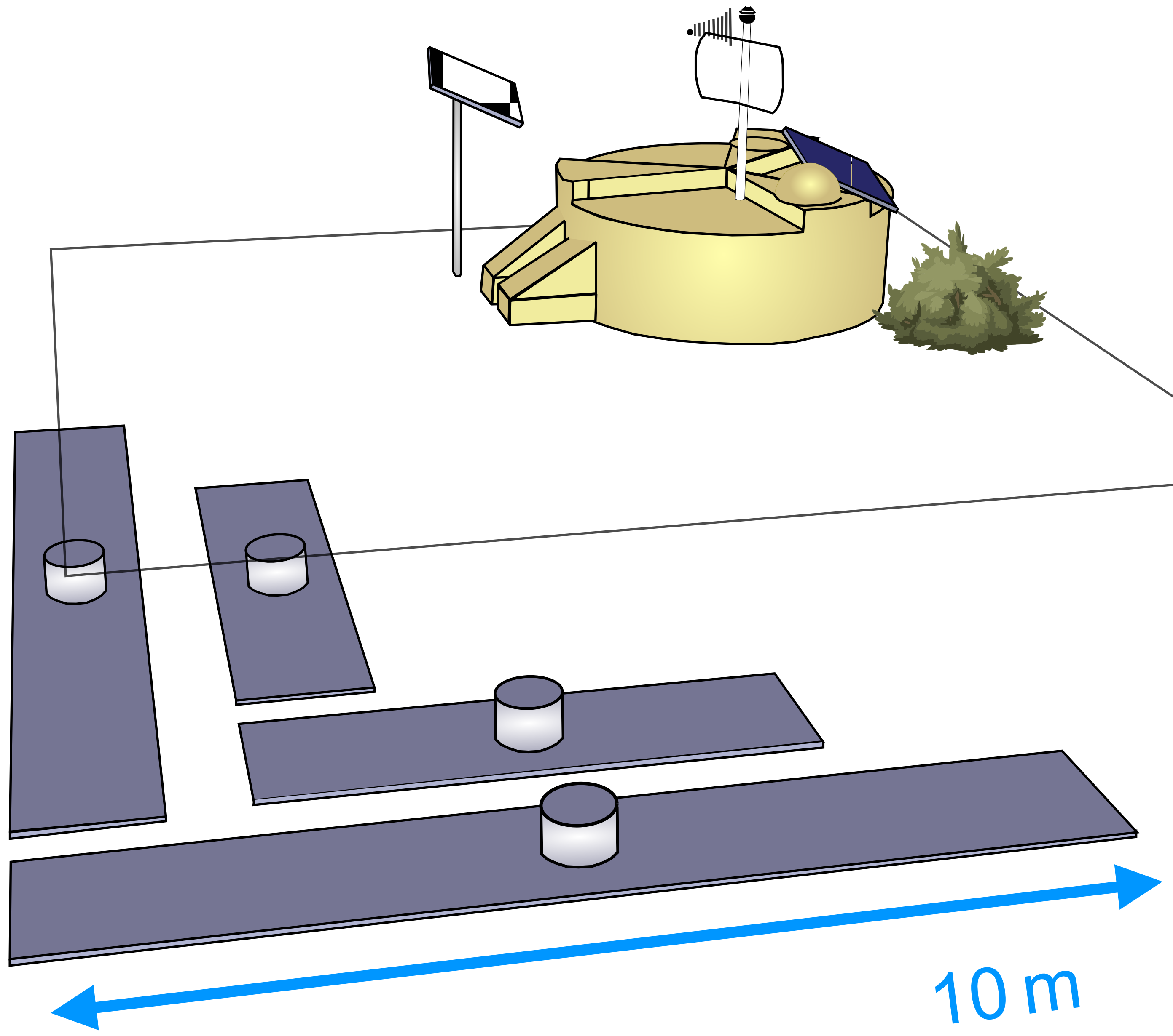
(Auger, PRD91, 2015)

AMIGA – buried muon detectors

- Direct counting of muons
- **Energy range overlapping with LHC c.m. energy**
- Composition and hadronic interactions

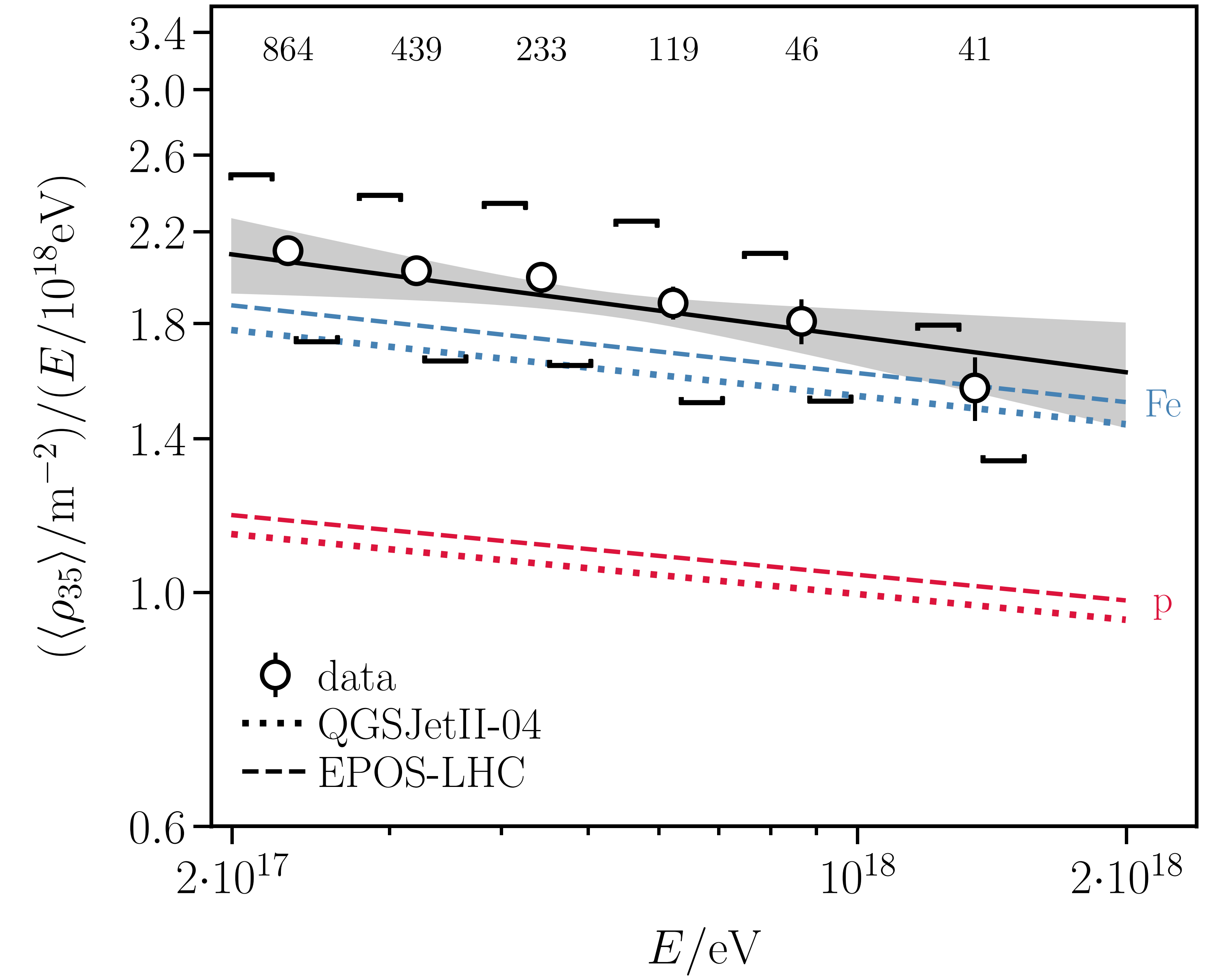
Scintillation counters:

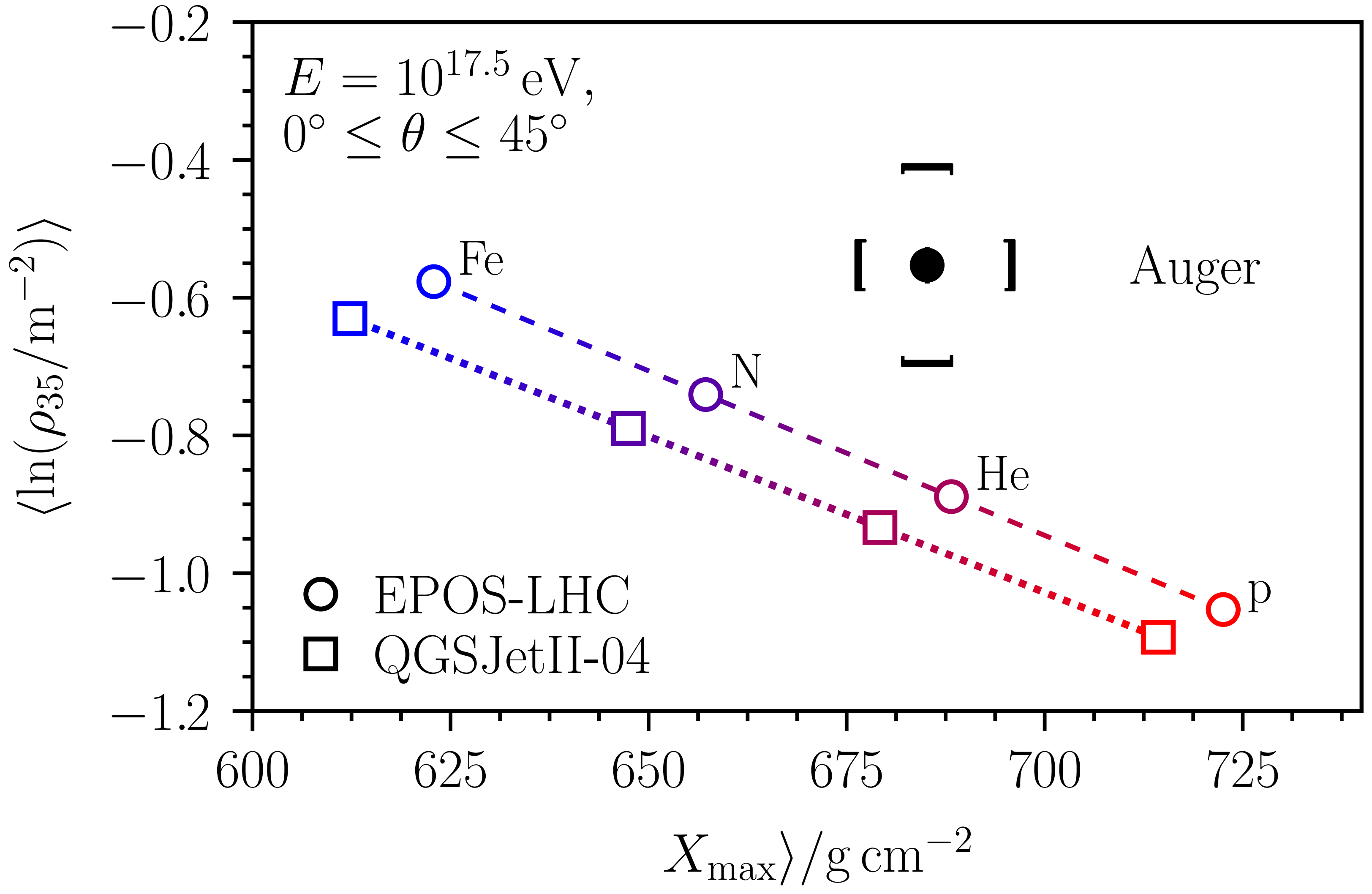
- 61 positions
- 30 m^2 each
- 750 m spacing
- 2.5 m of soil



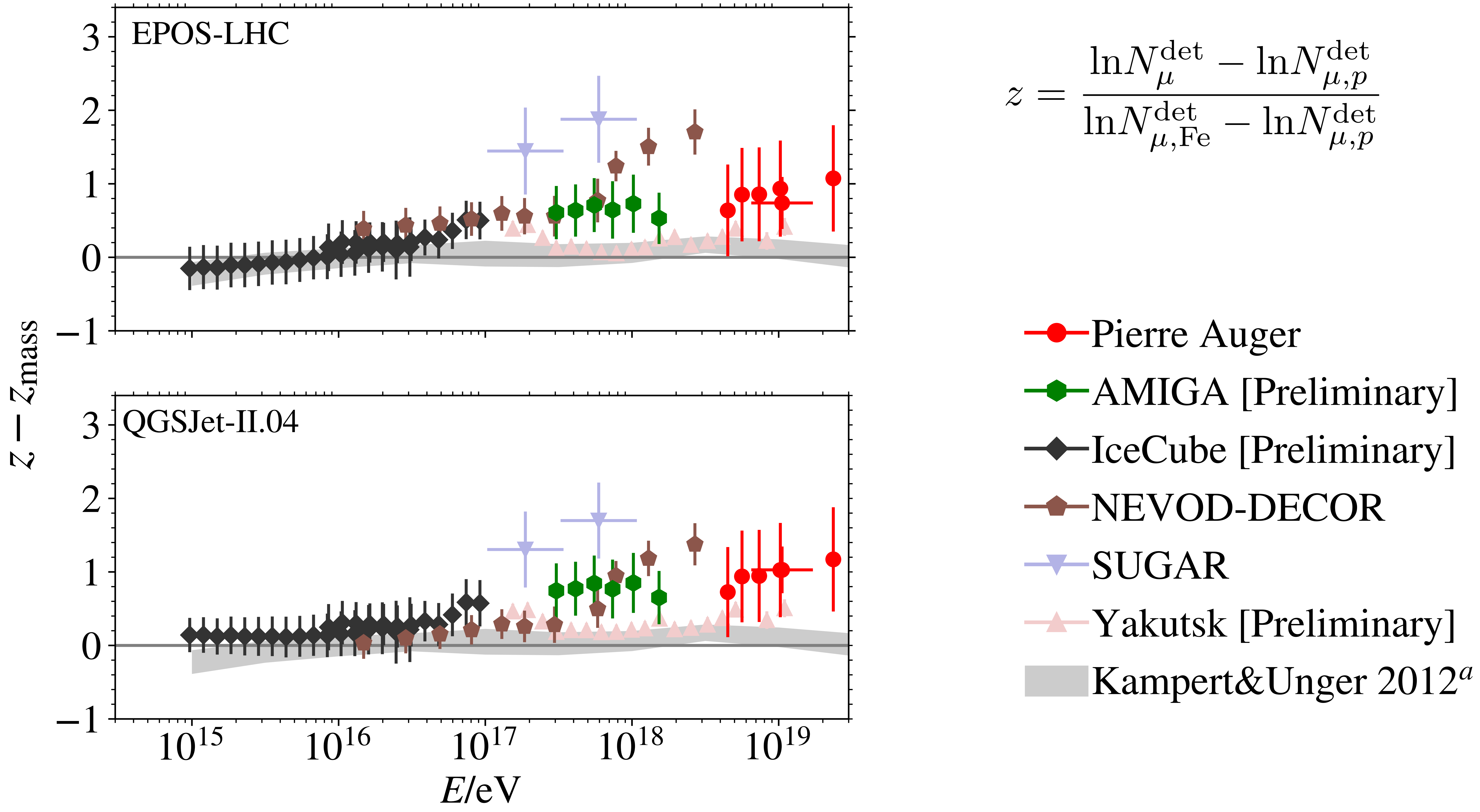
(*Auger, EPJ 2020*)

Muon density





Muon excess seen by many experiments



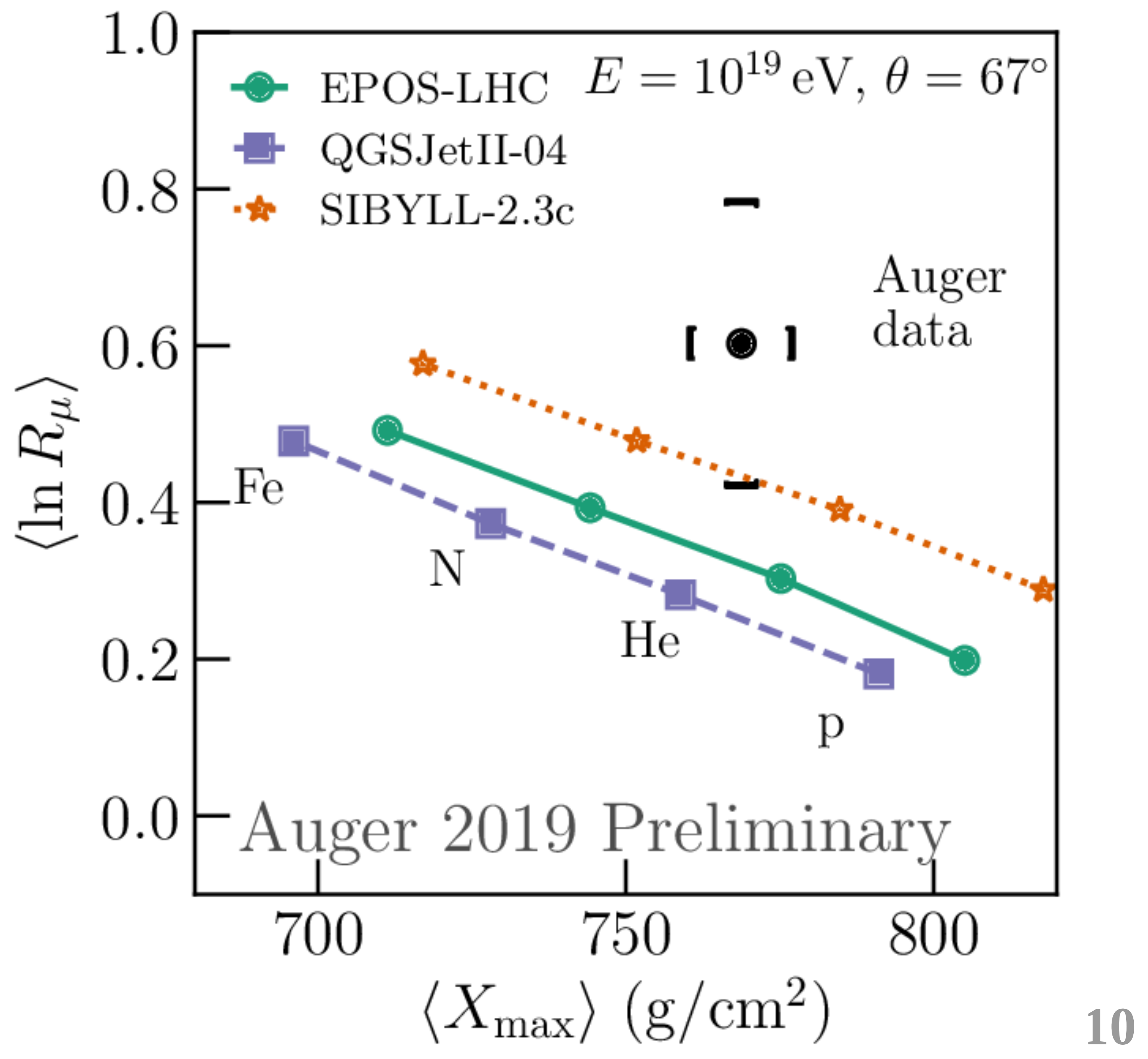
$$z = \frac{\ln N_{\mu}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$

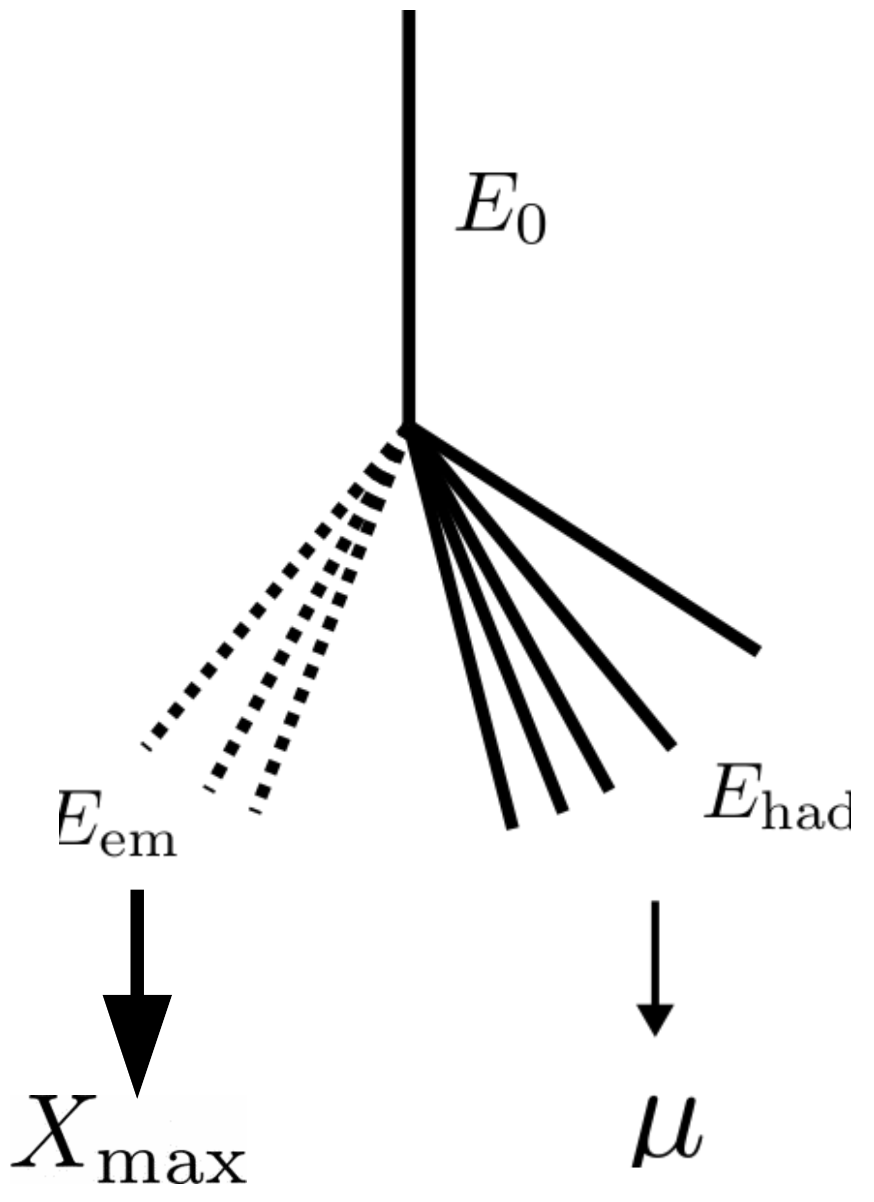
CF7 CF0-EF6 EF7-AF4 AF0 Dennis Soldin-083

(WHISP working group, Cazon et al., ICRC 2019)

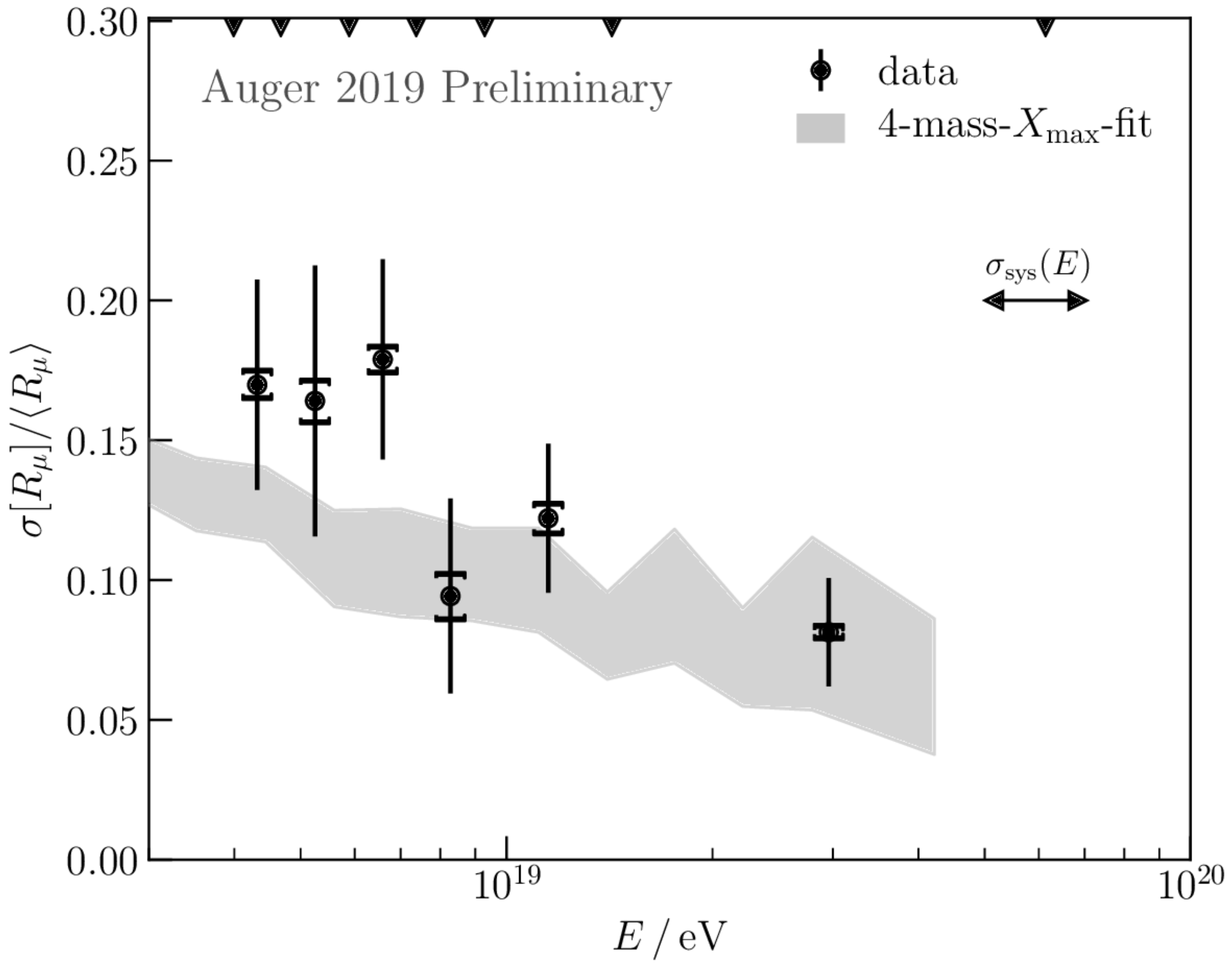
Shower-to-shower fluctuation of number of muons

Average





Fluctuations

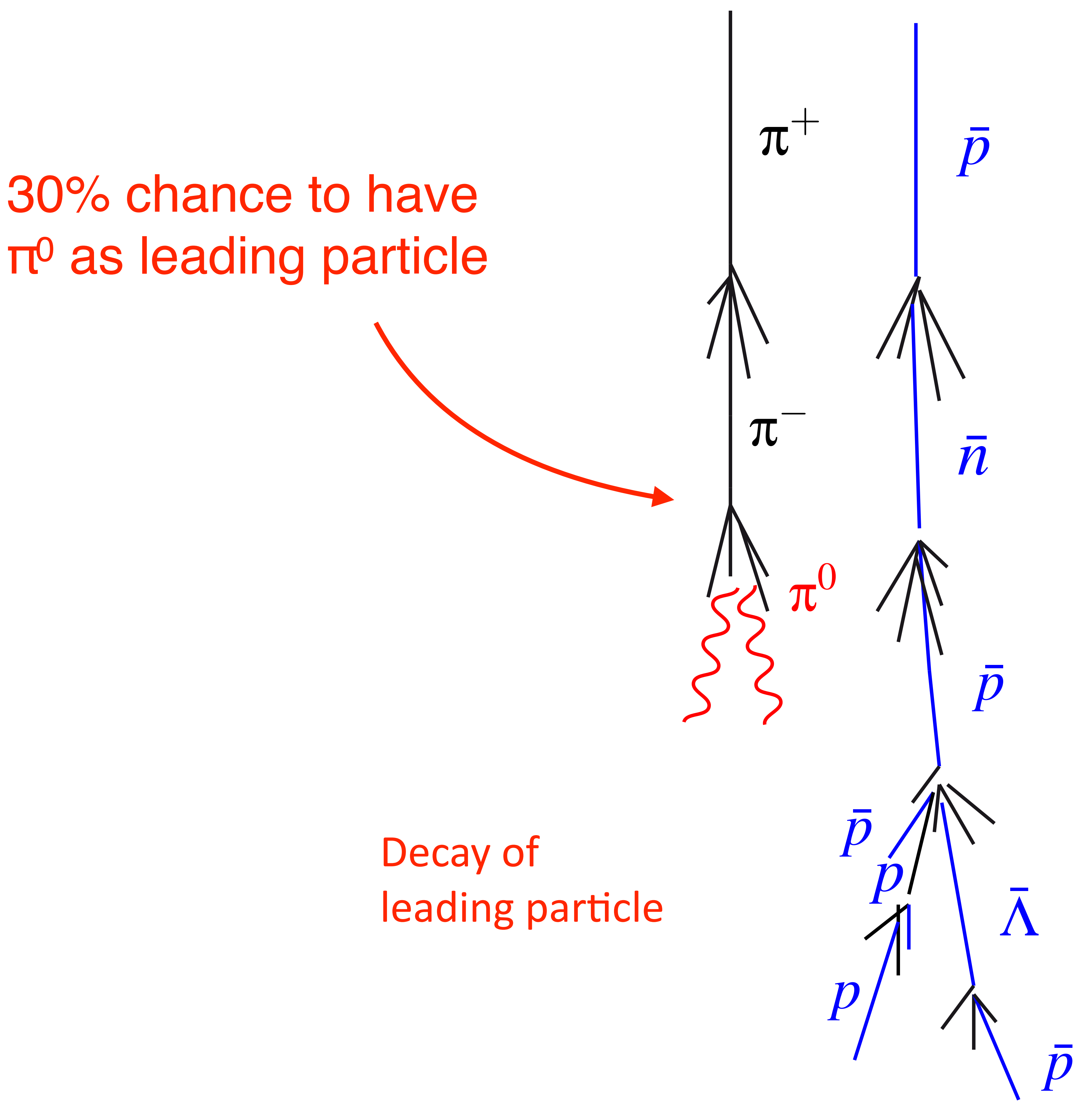


Mean number of muons depend on whole chain of hadronic interactions

Fluctuations are driven by multiplicity & energy distribution fluctuations of first interaction

(Auger ICRC 2019, Cazon et al. Phys. Lett. B 784 (2018) 68, 2006.11303)

Model scenarios for increasing number of muons



1 Baryon-Antibaryon pair production *(Pierog, Werner 2008)*

- Baryon number conservation
- Low-energy particles: large angle to shower axis
- Transverse momentum of baryons higher
- Enhancement of mainly **low-energy** muons

(Grieder ICRC 1973; Pierog, Werner PRL 101, 2008)

2 Leading particle effect for pions *(Drescher 2007, Ostapchenko 2016)*

- Leading particle for a π could be ρ^0 and not π^0
- Decay of ρ^0 to 100% into two charged pions
- Unknown leading particle effects?

3 New hadronic physics at high energy *(Farrar, Allen 2012, Anchrodoqui et al., Pierog et al. 2019)*

- Quark-gluon plasma formation (collective effects)
- Inhibition of π^0 decay (Lorentz invariance violation etc.)
- Chiral symmetry restauration

CF7 CF0-EF6 EF7-NF5 NF6-AF4 AF0 LAA-074 ,
CF7 CF0-EF6 EF7-NF5 NF6 Jorge Soriano-058

TAx4 Project

TA SD (~3000 km²): Quadruple area

Approved in Japan 2015

500 scintillator SDs

2.08 km spacing

3 yrs construction, first 173 SDs have arrived in Utah for final assembly, next 77 SD to be prepared at Akeno Obs. (U.Tokyo) 2017-08 and shipped to Utah

2 FD stations (12 HiRes Telescopes)

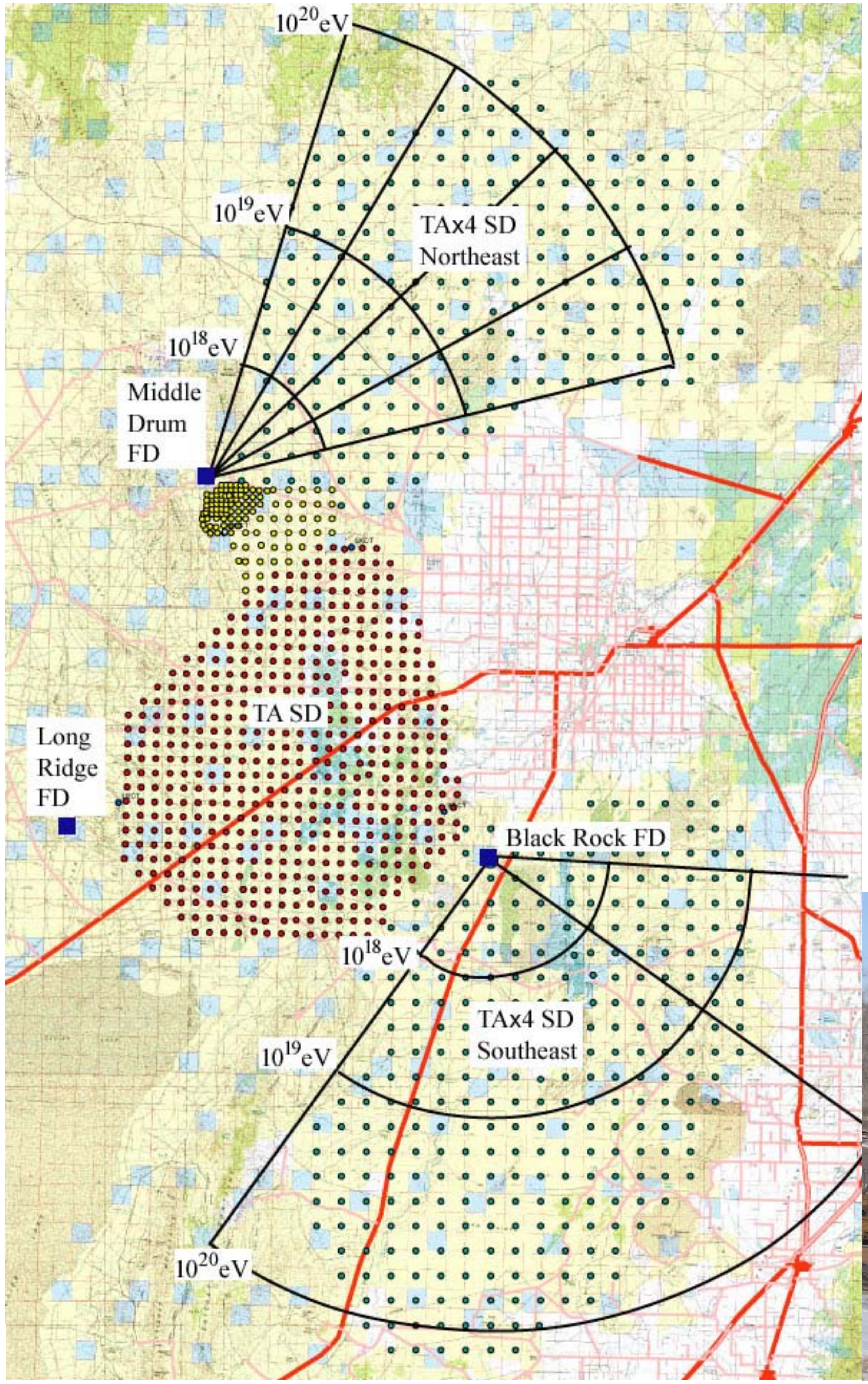
Approved US NSF 2016

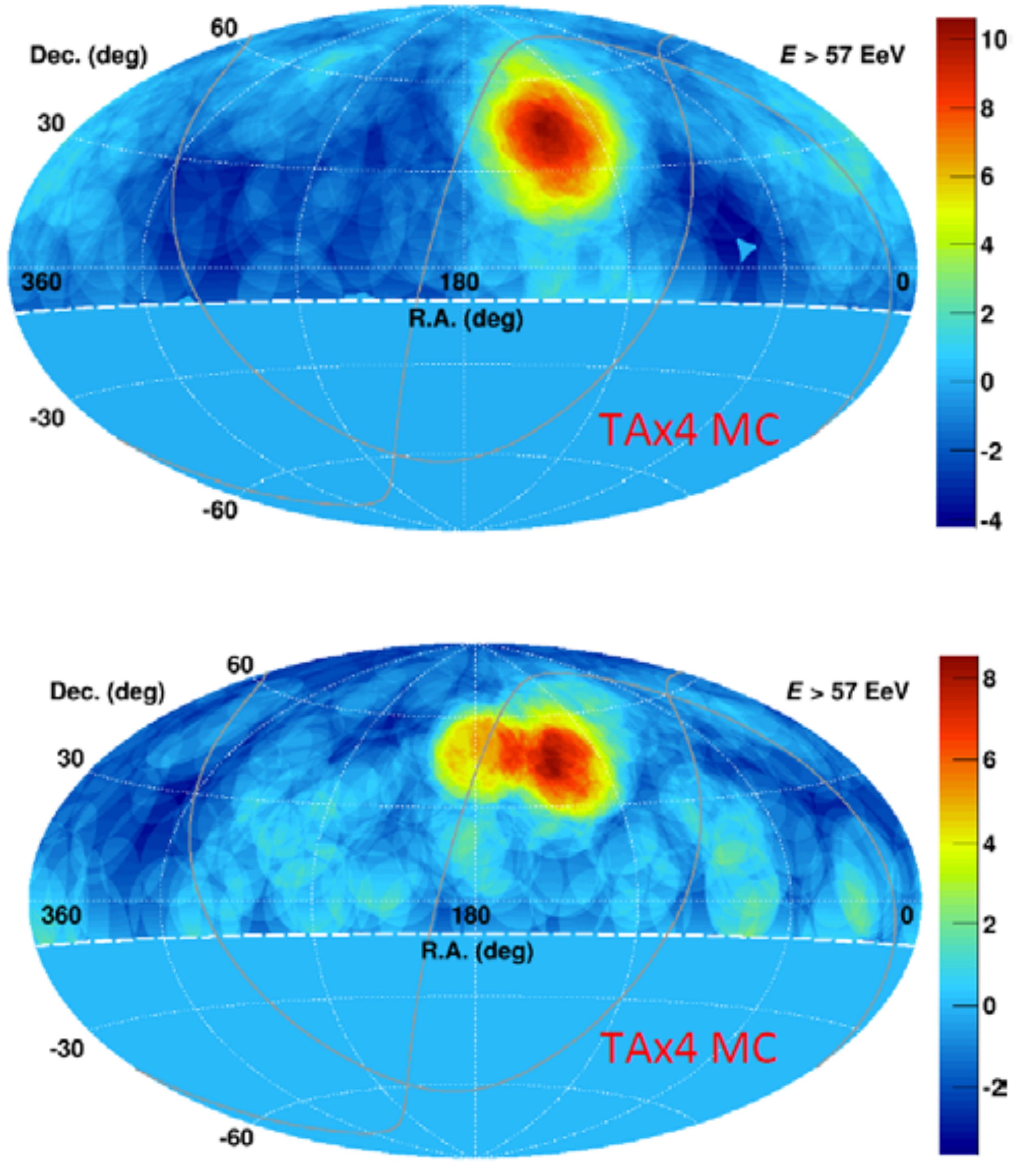
Telescopes/electronics being prepared at Univ. Utah

Site construction underway at the northern station.

Get 19 TA-equiv years of SD data by 2020

Get 16.3 (current) TA years of hybrid data



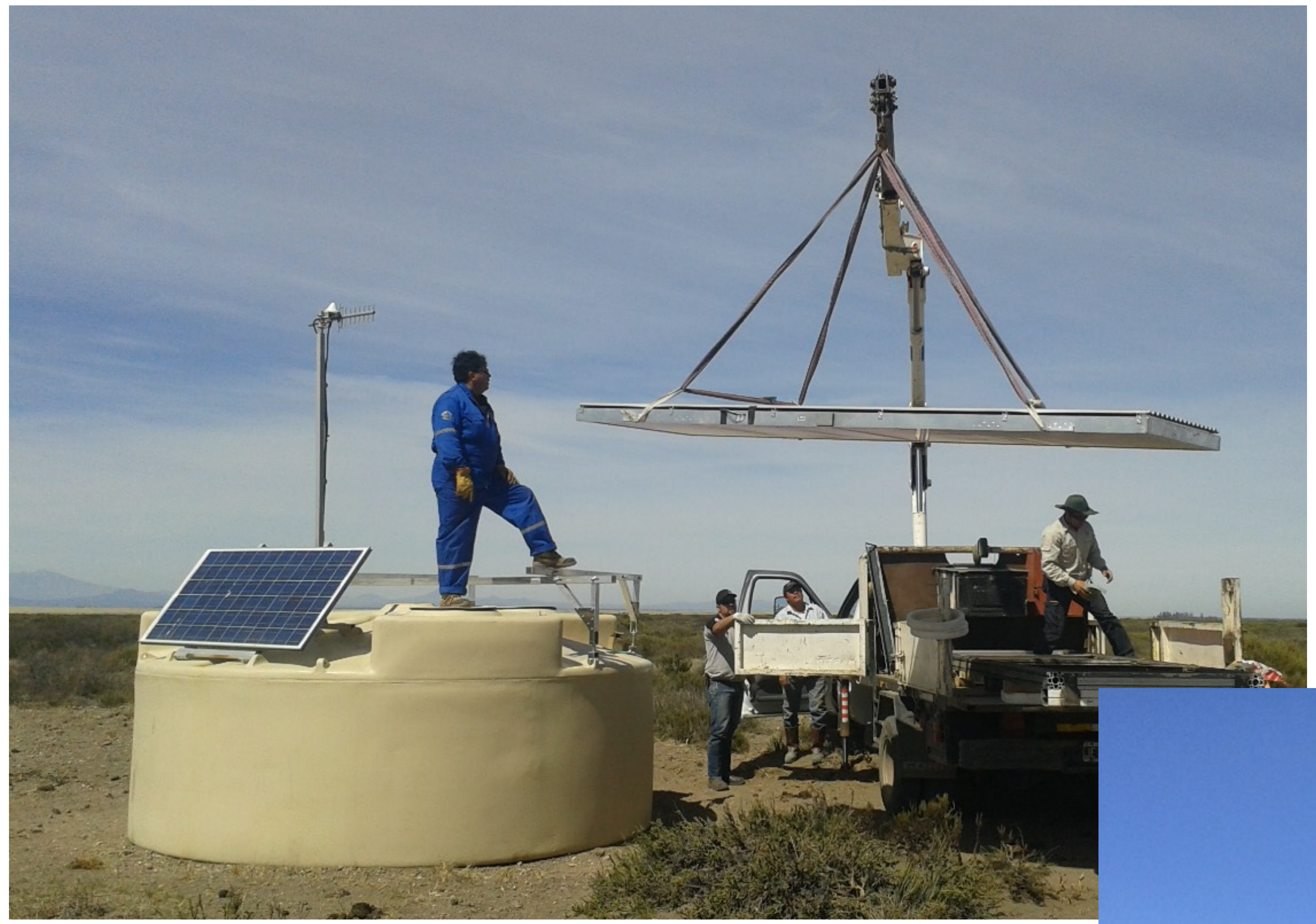


(Kido, Matthews ICRC 2017)

Upgrade of Auger Observatory: AugerPrime

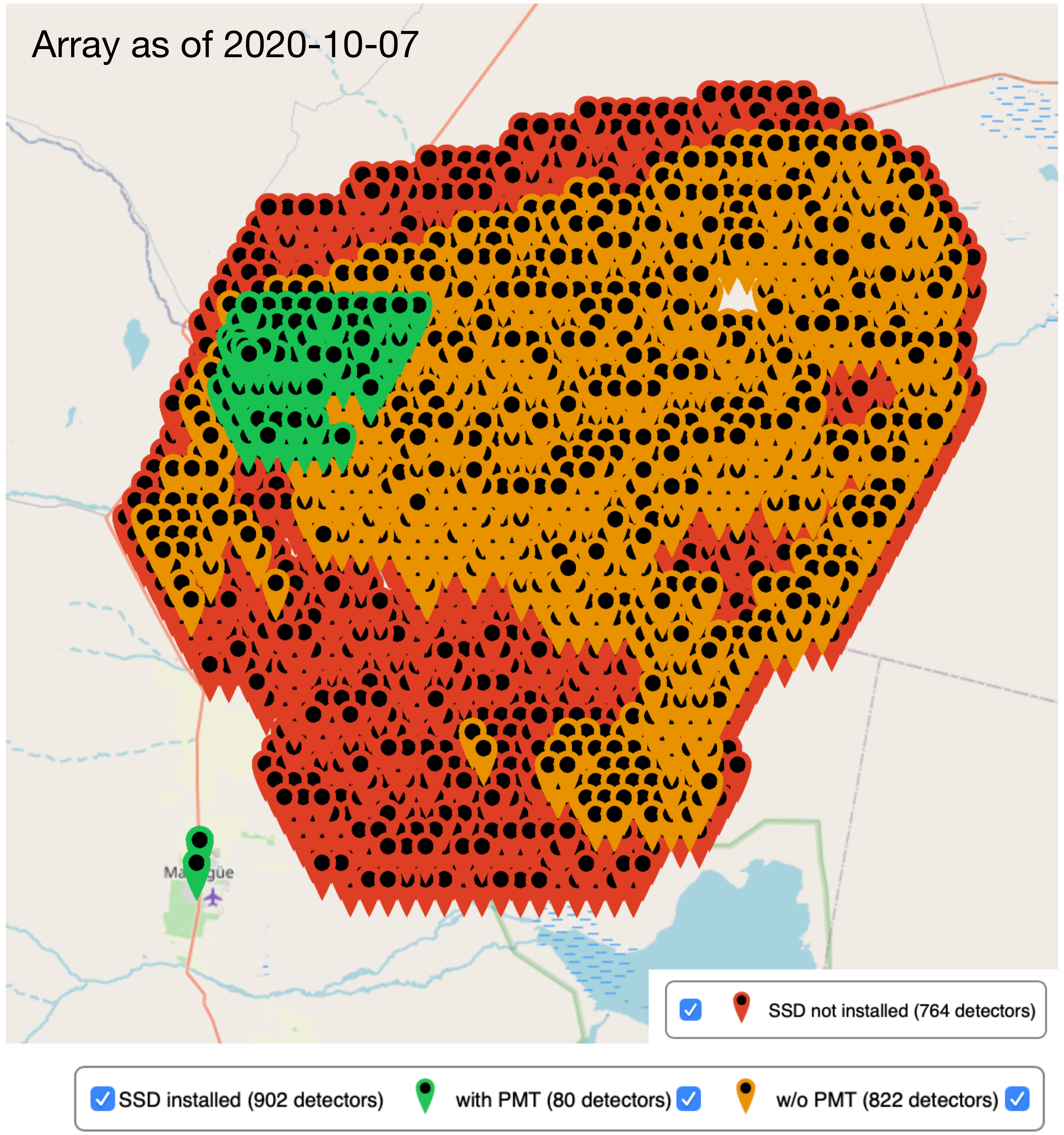
15% duty cycle

100% duty cycle



Vertical showers:
scintillators and water-Cherenkov detectors:
em. particles vs. muons

Inclined showers:
radio antennas: energy of showers
water-Cherenkov detectors: muons



Ongoing upgrade AugerPrime (scintillators and radio antennas)

- **Scintillators (3.8 m^2) and radio antenna on top of each array detector**
- **Composition measurement up to 10^{20} eV**
- **Composition selected anisotropy**
- **Particle physics with air showers**

(AugerPrime design report 1604.03637)

AugerPrime – first data