Pierre Auger Observatory: new results on the spectrum of high-energy cosmic rays

PIERRE AUGER OBSERVATORY

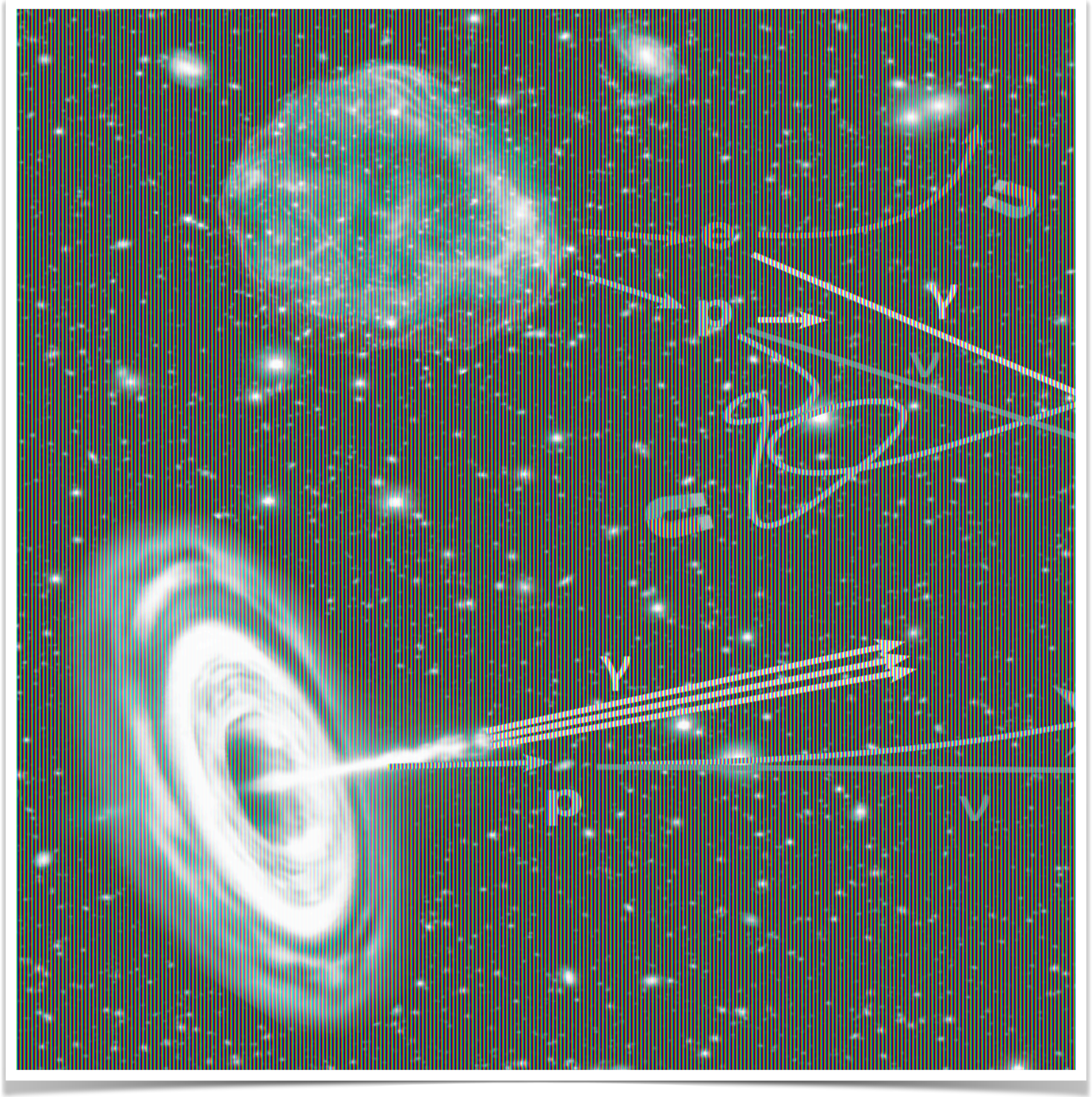
Karlsruhe Institute of Technology

Markus Roth for the Auger collaboration
Karlsruhe Institute of Technology (KIT)

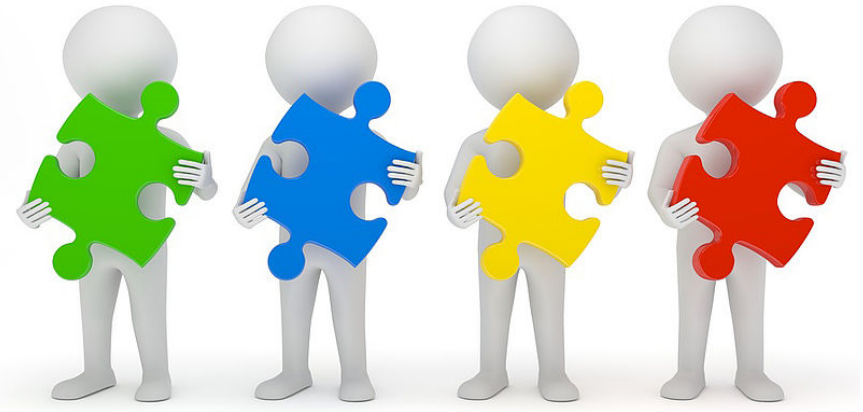
Photo by S. Saffi

Pierre Auger Observatory: new results on the spectrum of high-energy cosmic rays

Ultra-high energy cosmic rays above 10^{18} eV



Physics questions



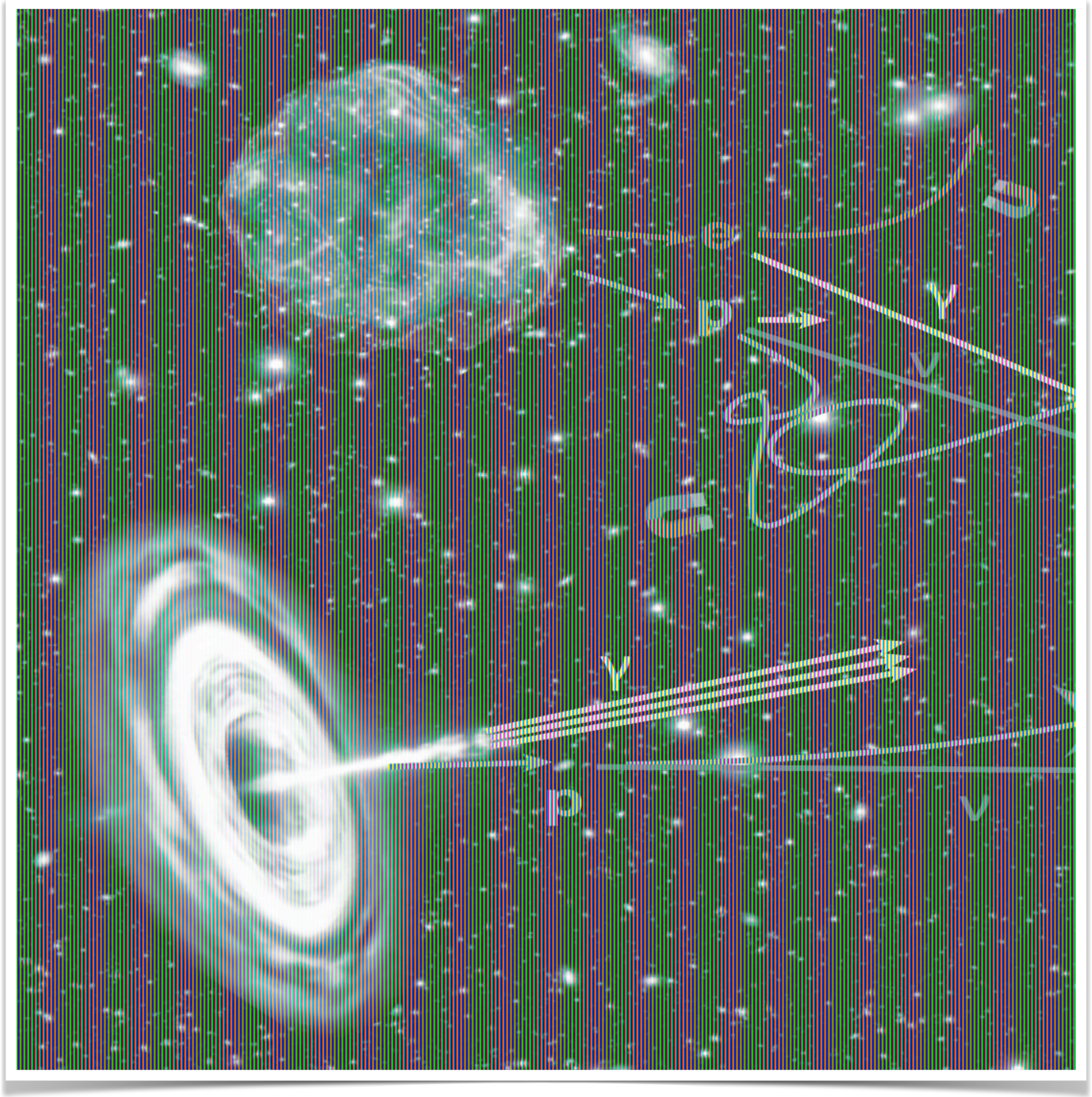
- What are the sources?
- How are they accelerated?
- How do they propagate?
- How do they interact in the atmosphere?

Measured quantities and inference

- Energy spectrum
- Mass composition
- Arrival direction

Theoretical interpretation

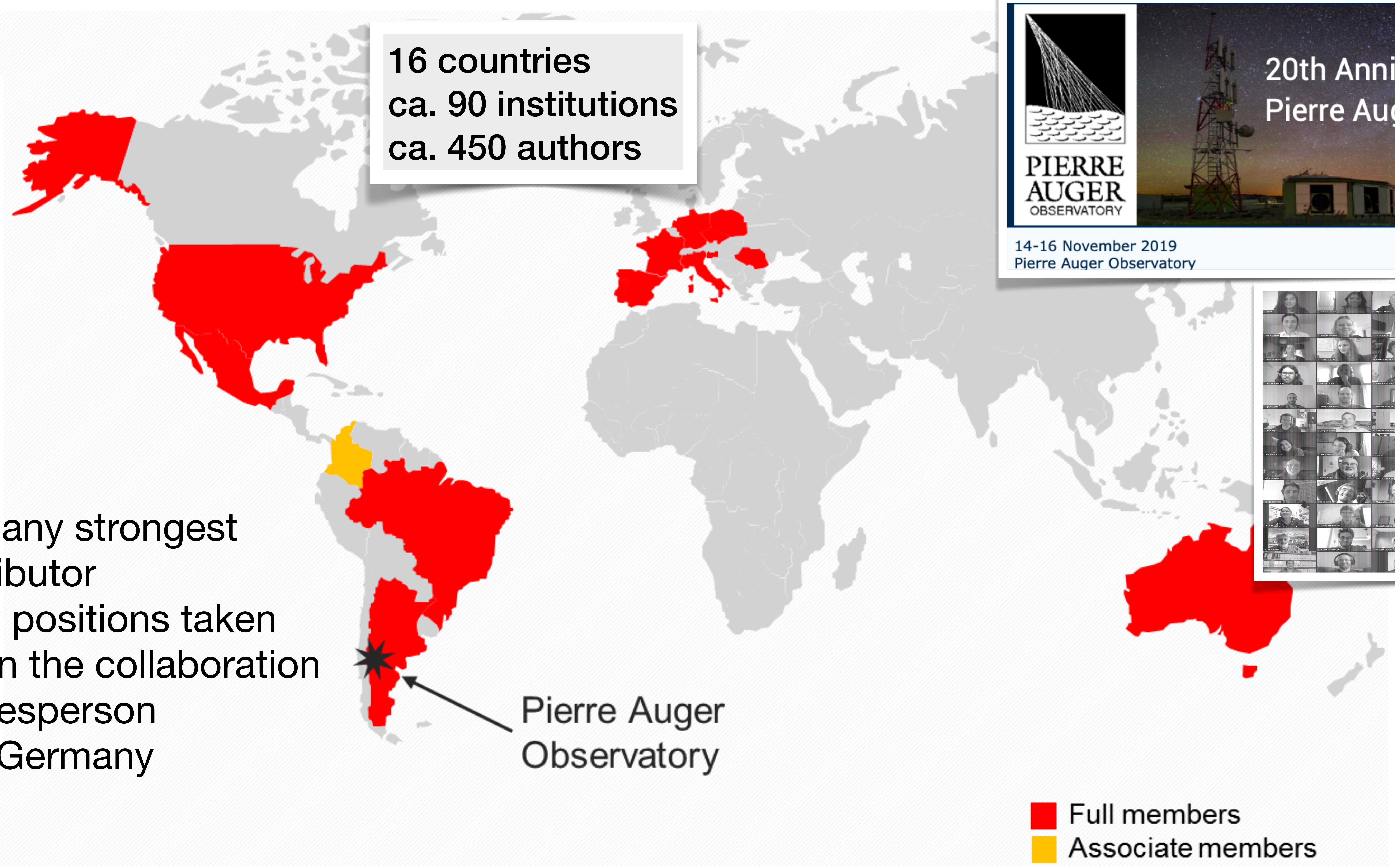
Ultra-high energy cosmic rays above 10^{18} eV



Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

Auger collaboration

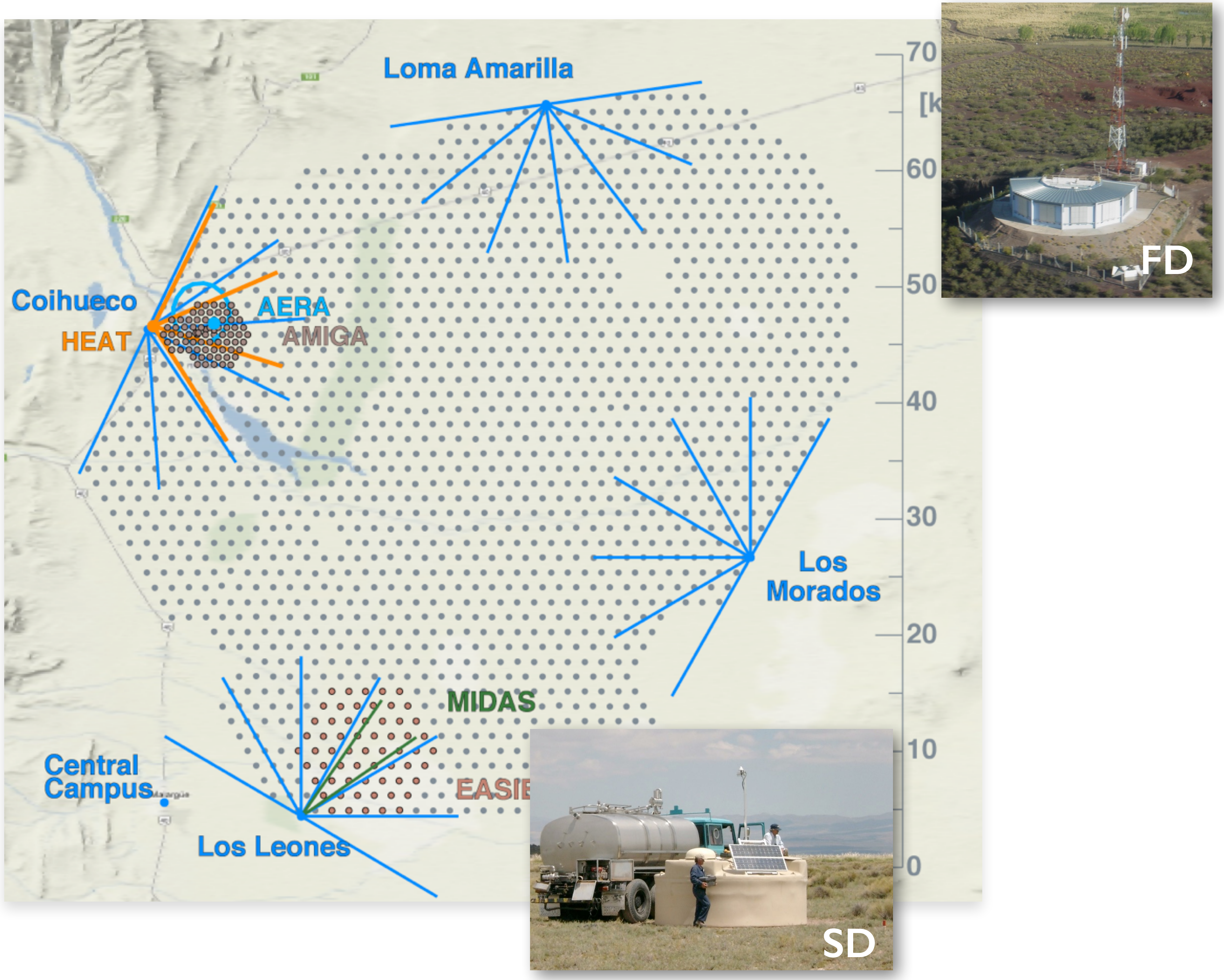


- Germany strongest contributor
- Many positions taken within the collaboration
- Spokesperson from Germany

The Pierre Auger Observatory

Fluorescence detector (FD)
- 4 sites
  - 0-30°
  - E>10^{18} eV
- HEAT
  - 30°-60°
  - E>10^{17} eV

Surface detector array (SD)
- Grid of 1500 m
  - 3000 km^2
  - 1660 stations
  - E>$10^{18.5}$ eV
- Grid of 750 m
  - 24 km^2
  - 61 stations
  - E>$10^{17.5}$ eV



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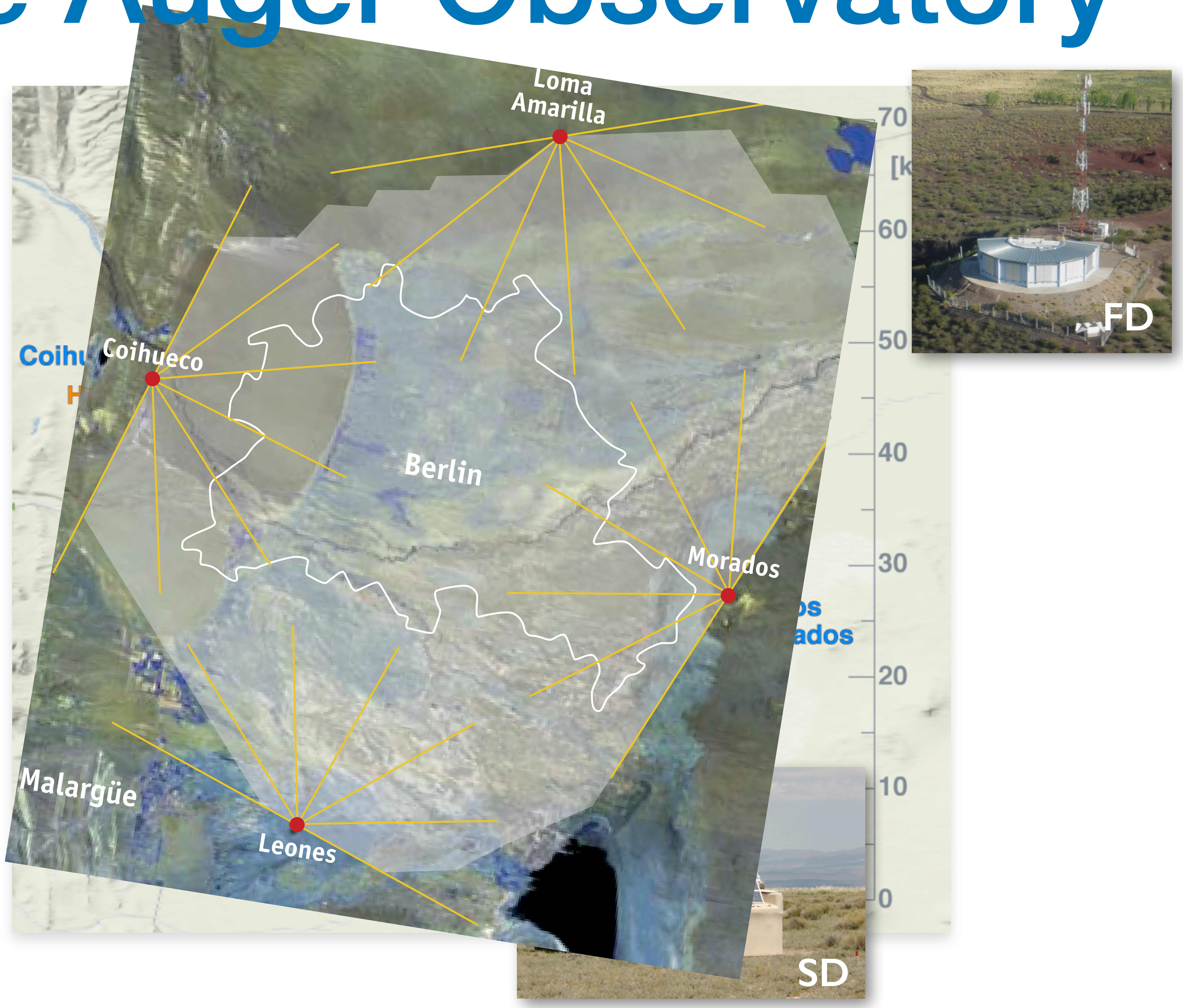

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Hybrid detection

Fluorescence Detector (FD):

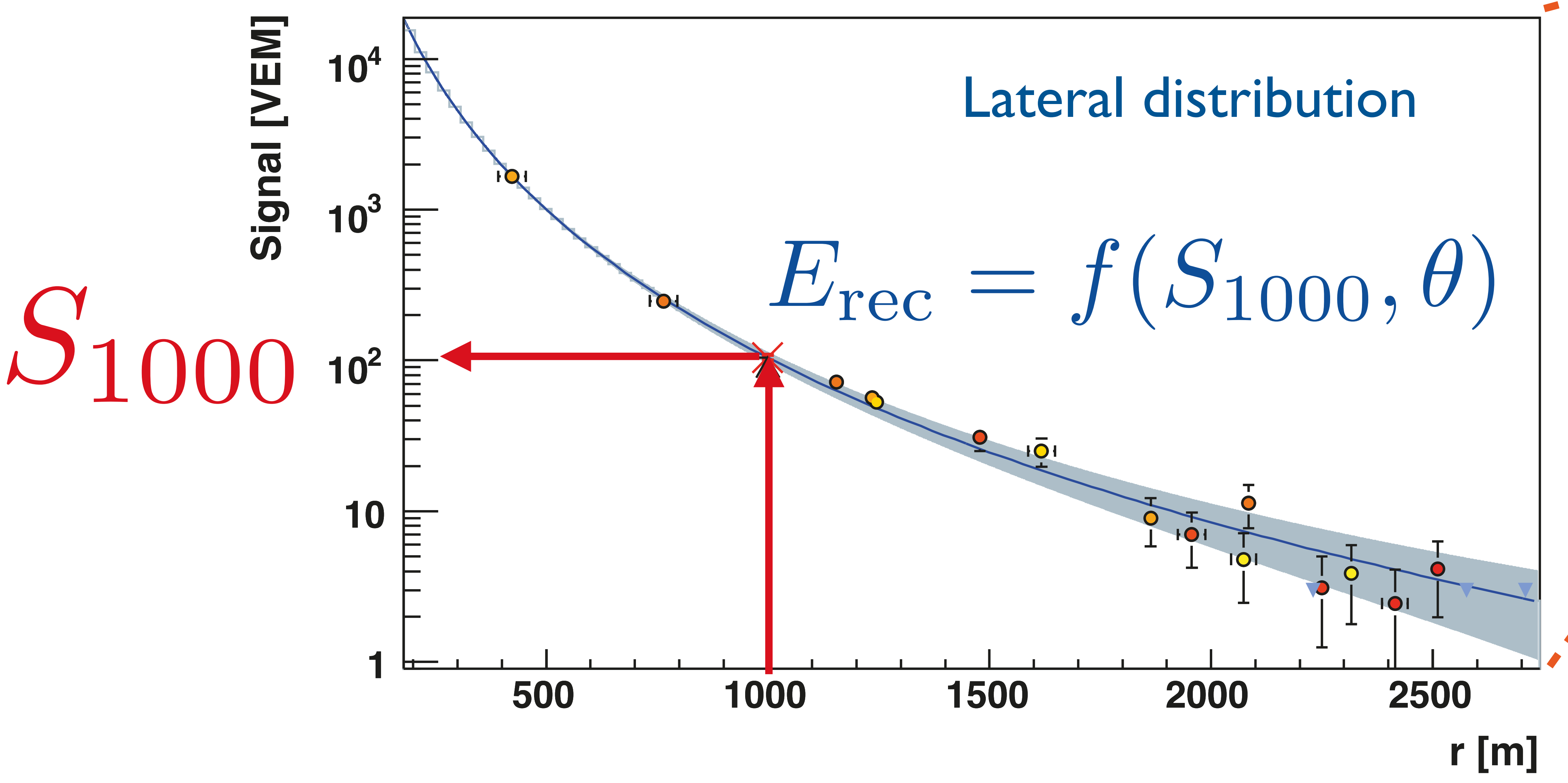
- calorimetric measurement of energy
- ca.15% duty cycle

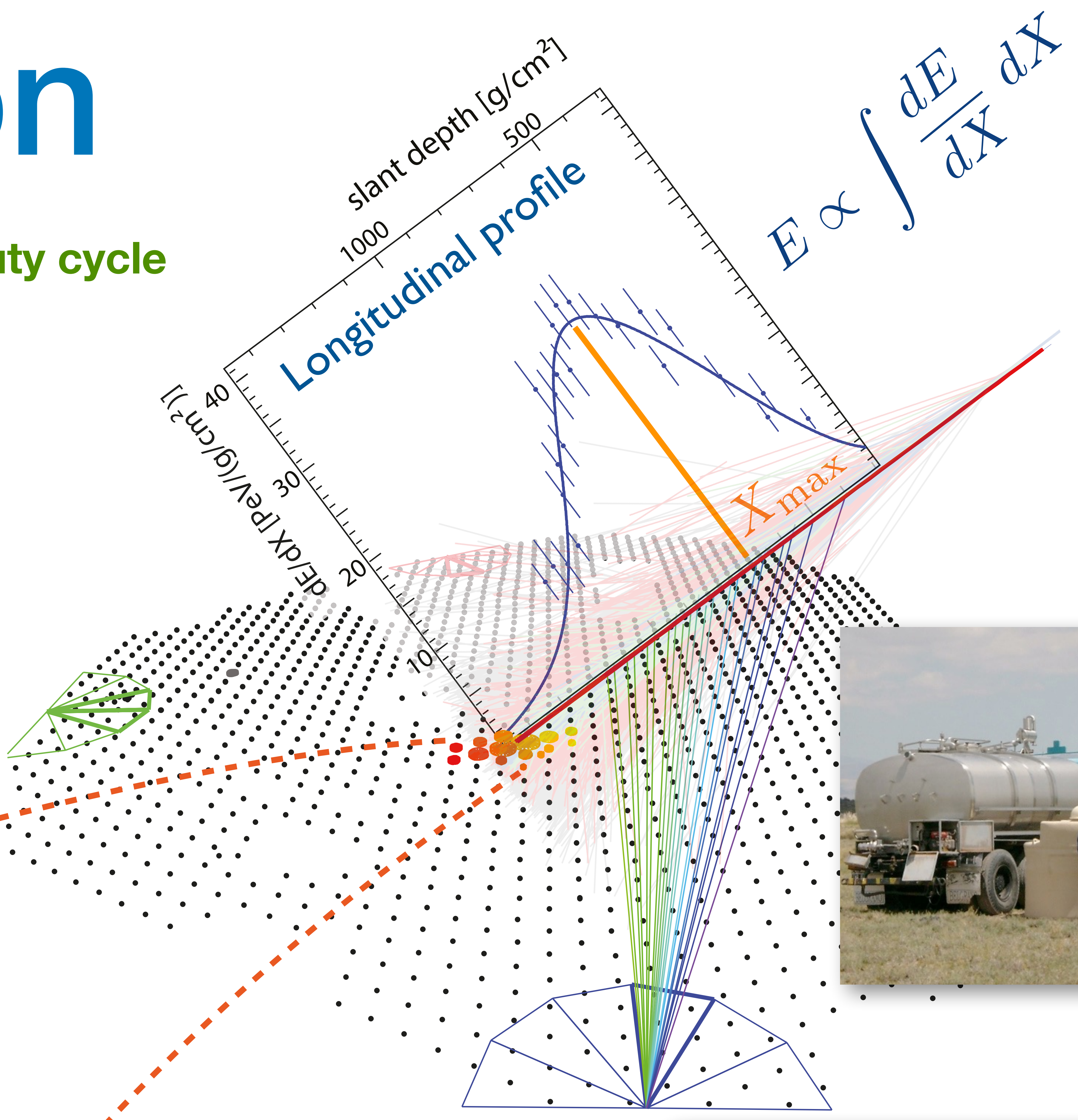
Surface Detector (SD):

- data driven shape of Lateral Distribution function (LDF)
- optimal distance at 1000 m
- ca. 100% duty cycle

15% duty cycle

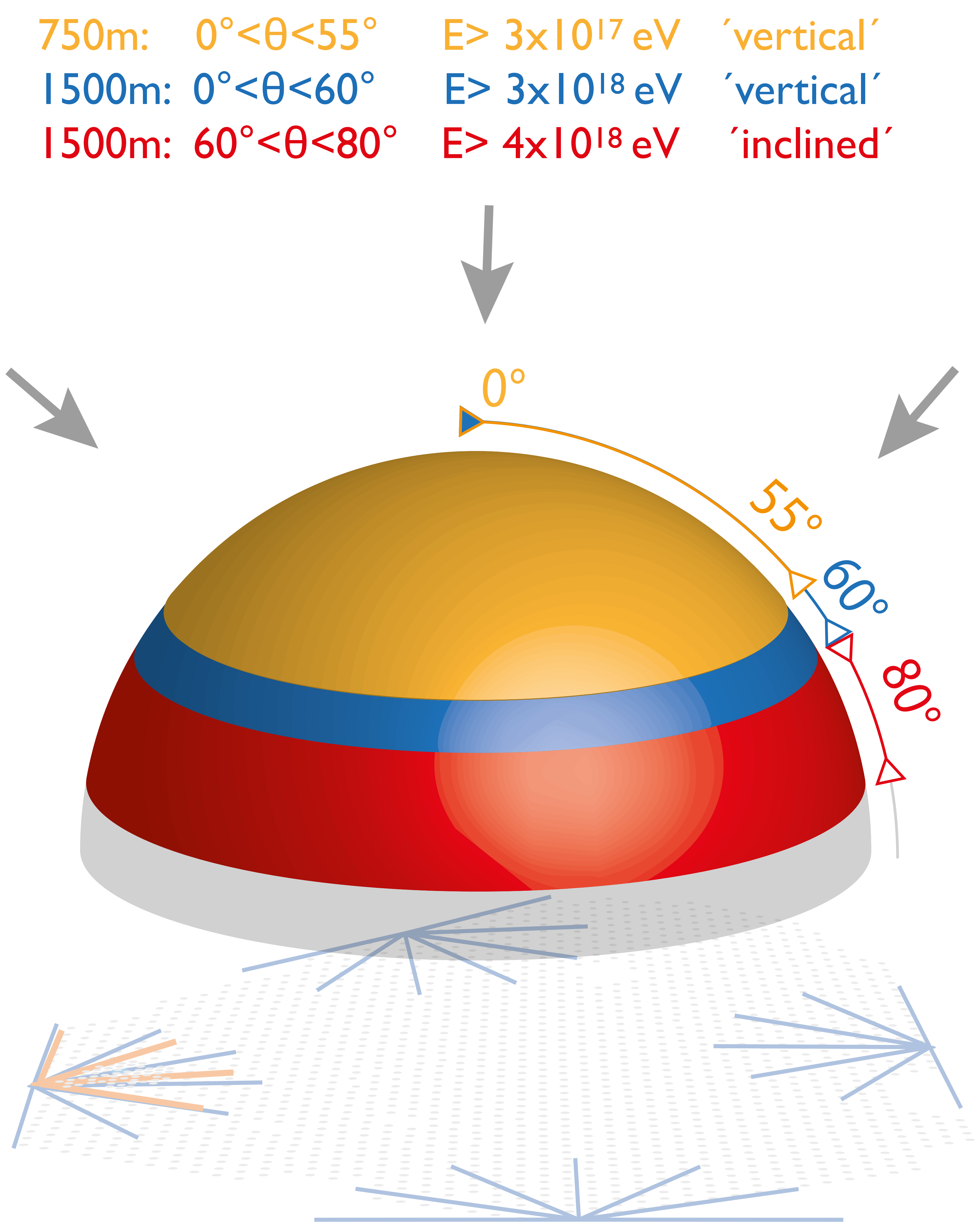
100% duty cycle

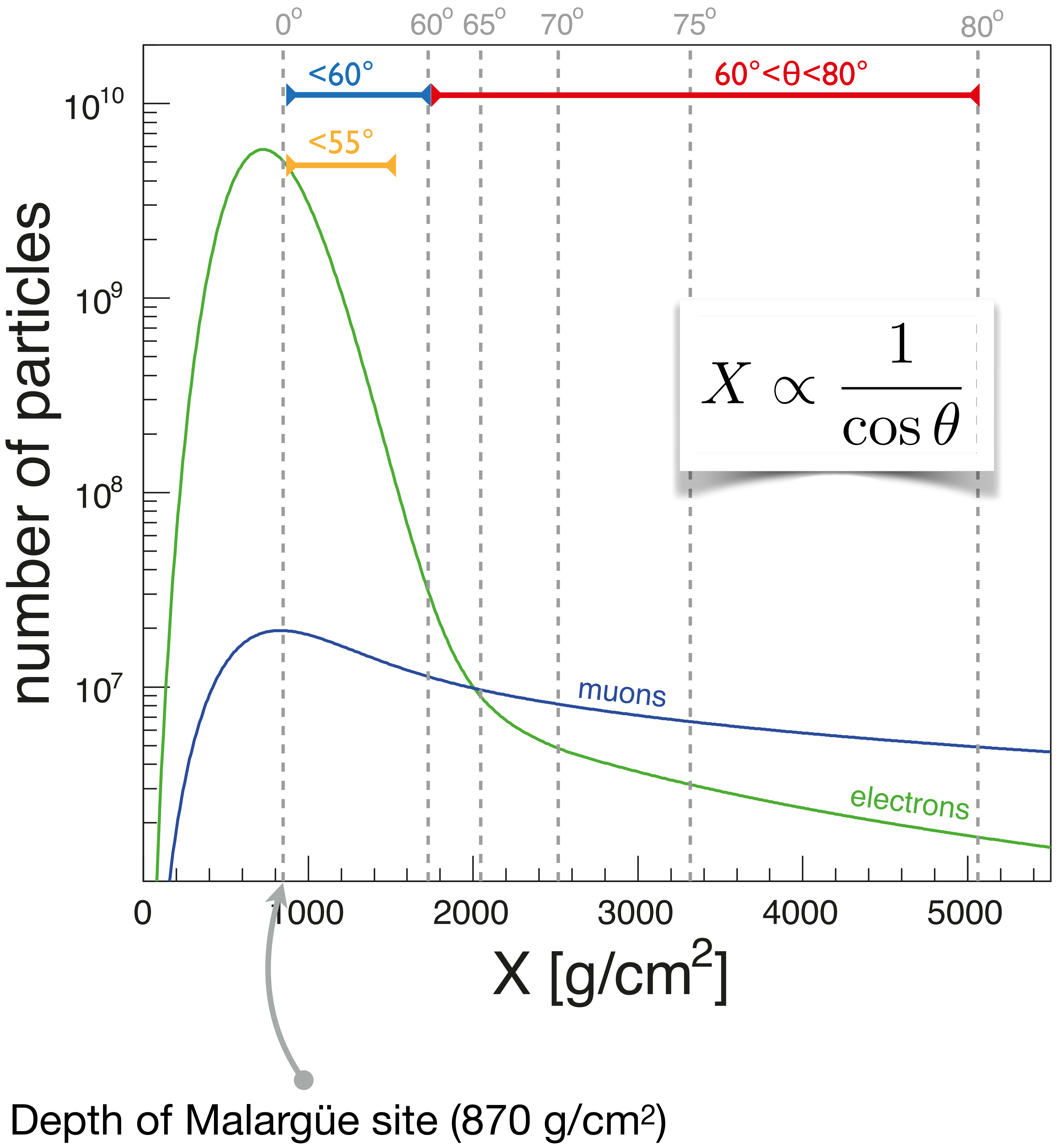




Event observed with Auger Observatory

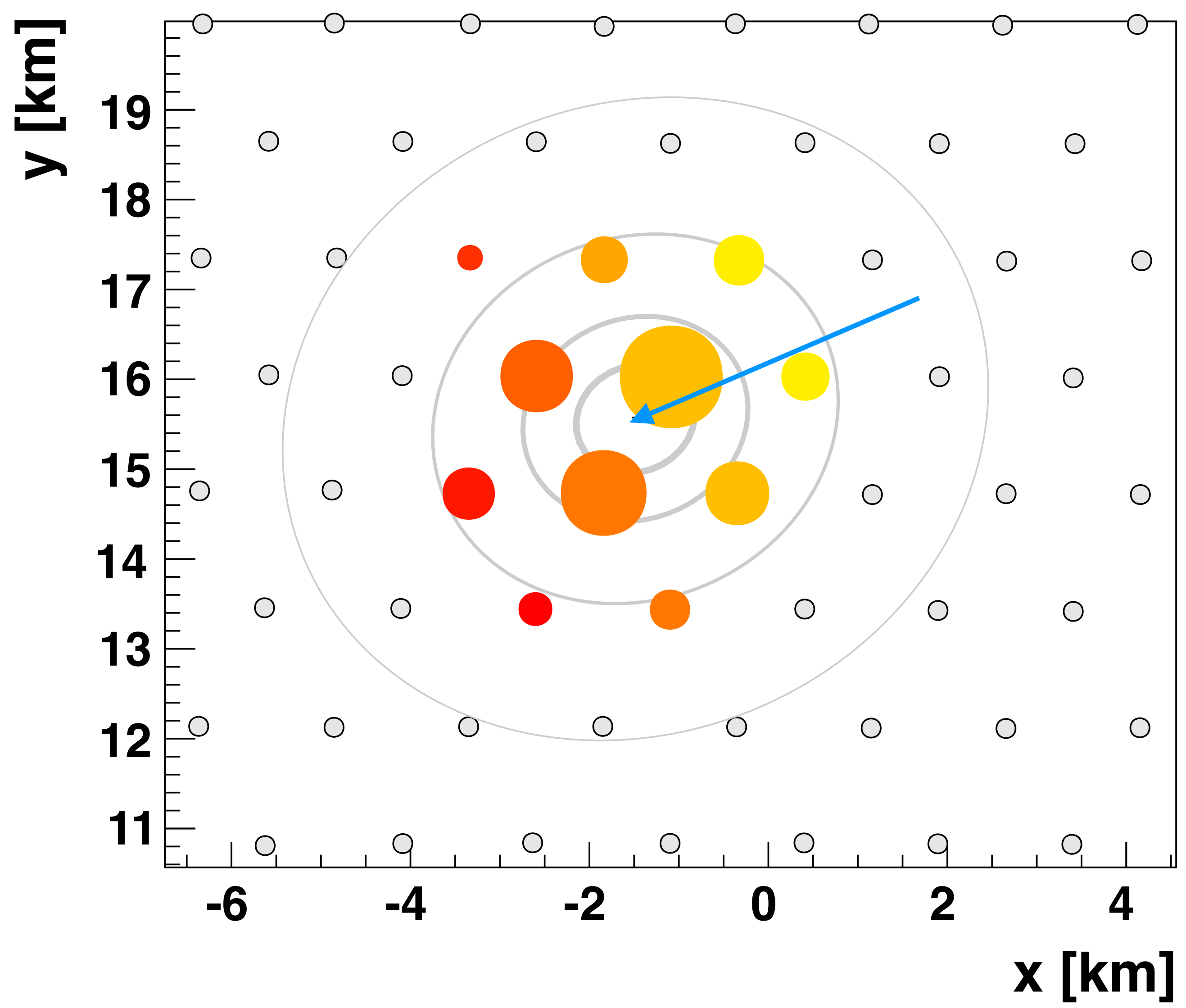
Zenith angle ranges of SD derived spectra

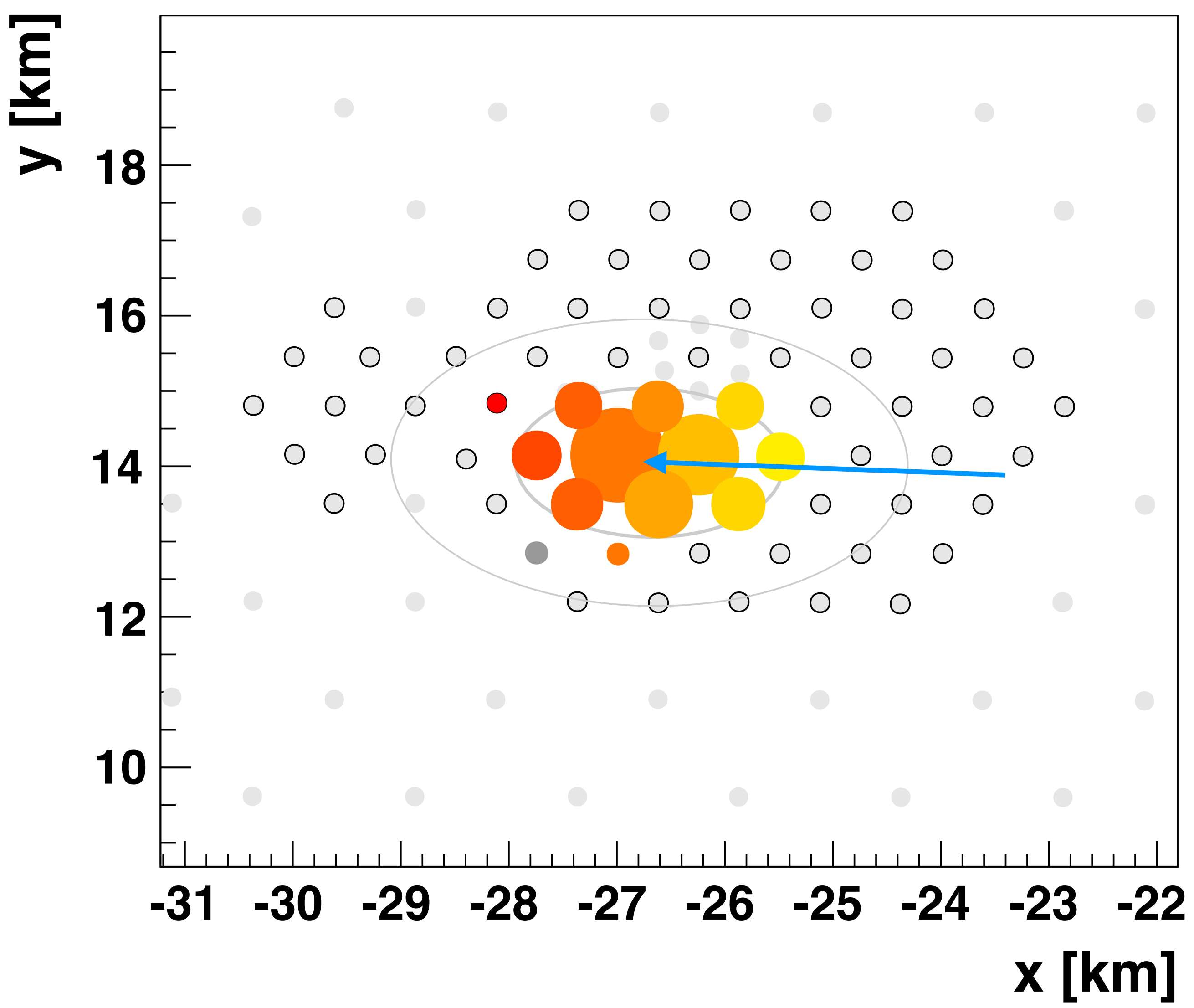




Footprint on ground depends on geometry and energy

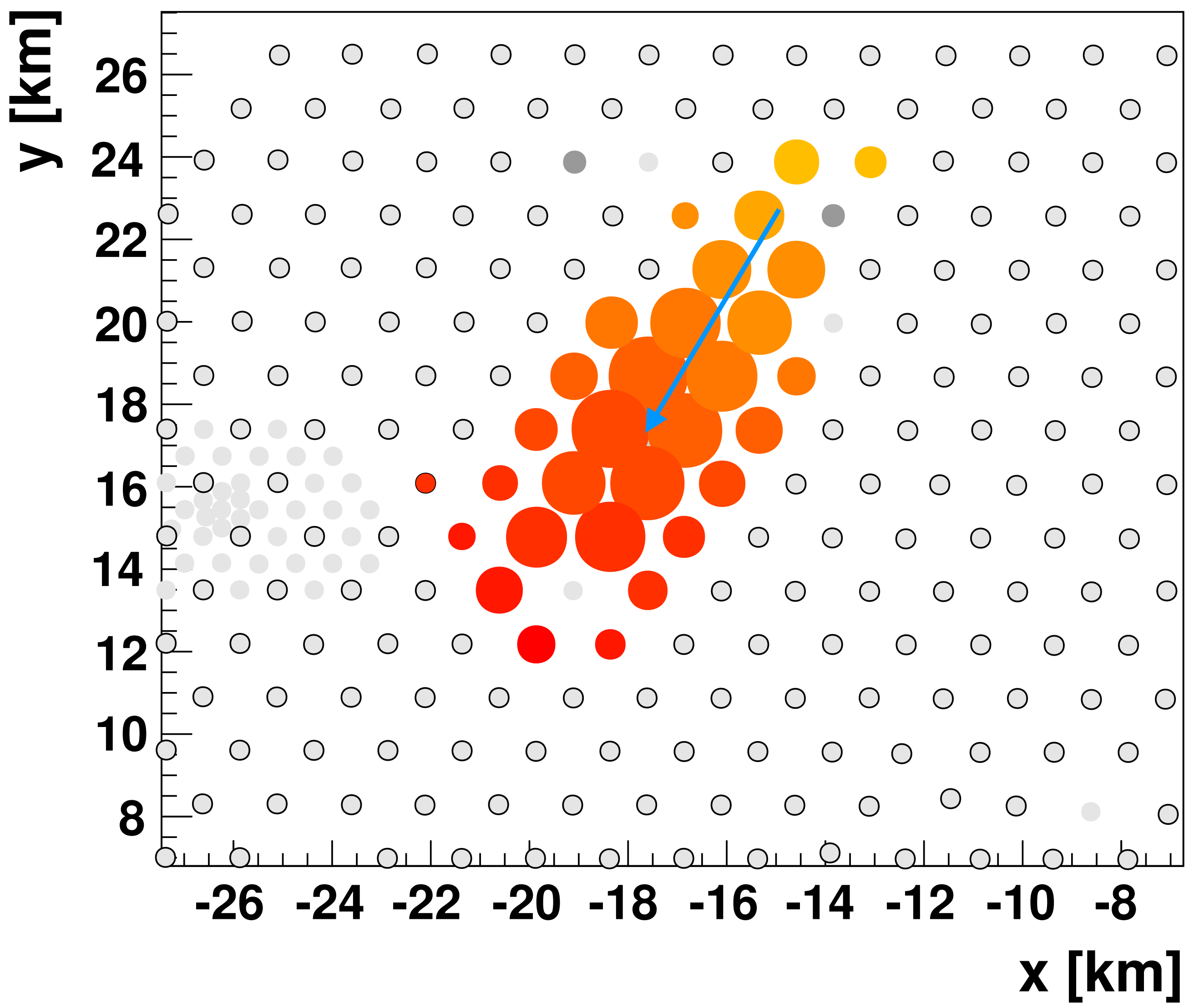
- 1500 m
- θ < 60°
- 100% eff. @ 3 EeV
- $E = A\ S_{38}^{B}$



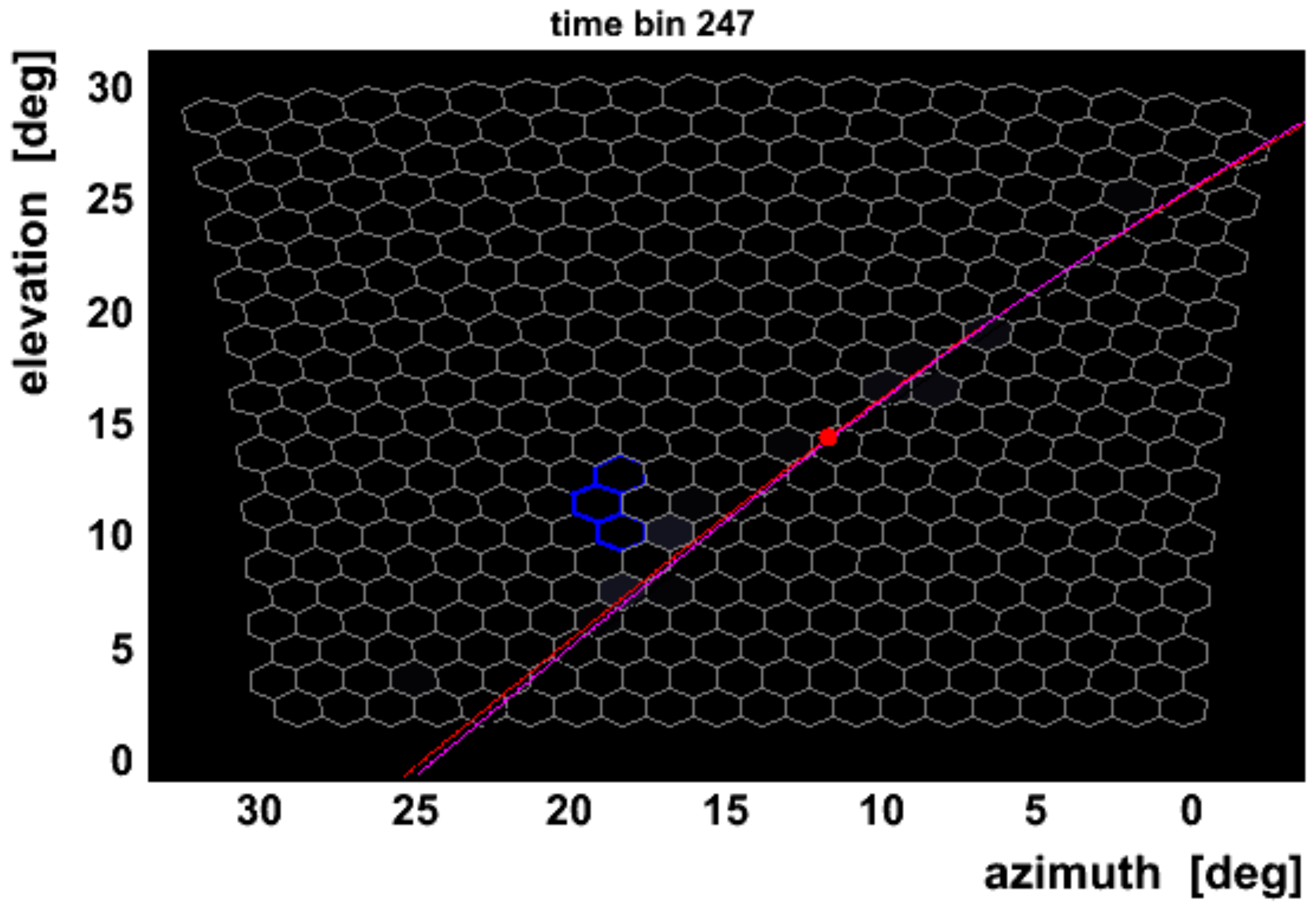


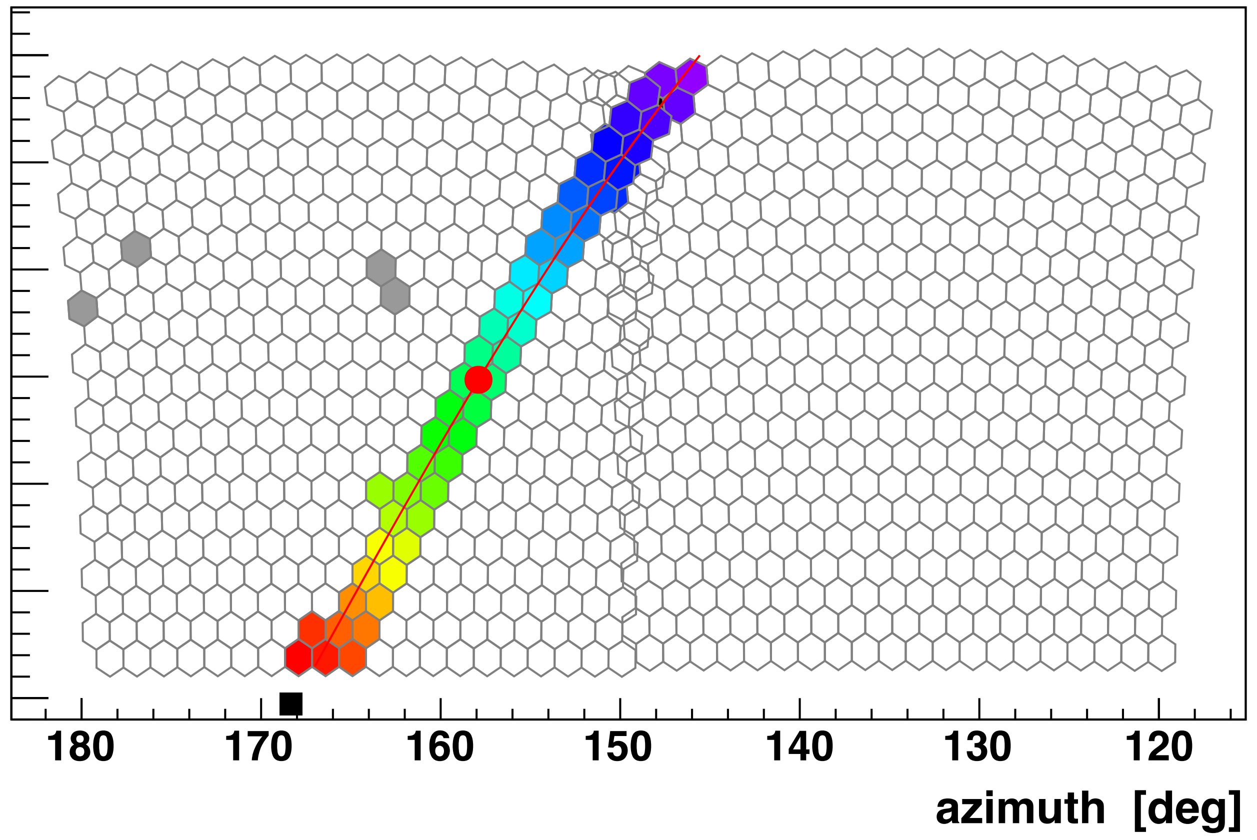
- 750 m
- θ < 55°
- 100% eff. @ 0.3 EeV
- $E = A\ S_{35}^{B}$

- 1500 m
- 60°<θ < 80°
- 100% eff. @ 4 EeV
- $E = A\ N_{19}^{B}$
- N_{19} by definition independent of θ



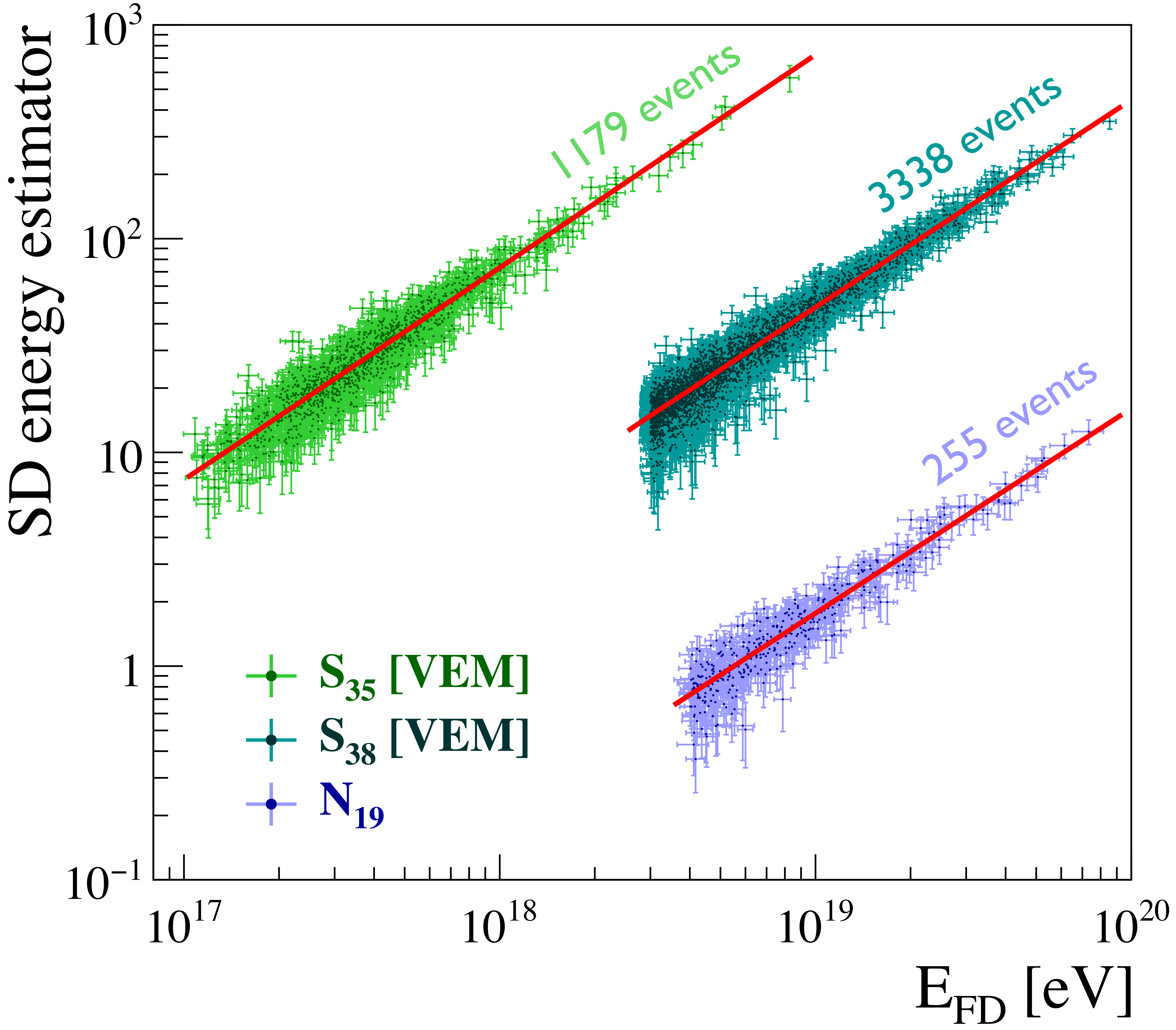
- FD + 1 SD station
- 100% eff. @ 1 EeV
- $E = E_{\mathrm{FD}}$





SD data: energy calibration

$$E_{\mathrm{FD}} = A\ S^{B}$$



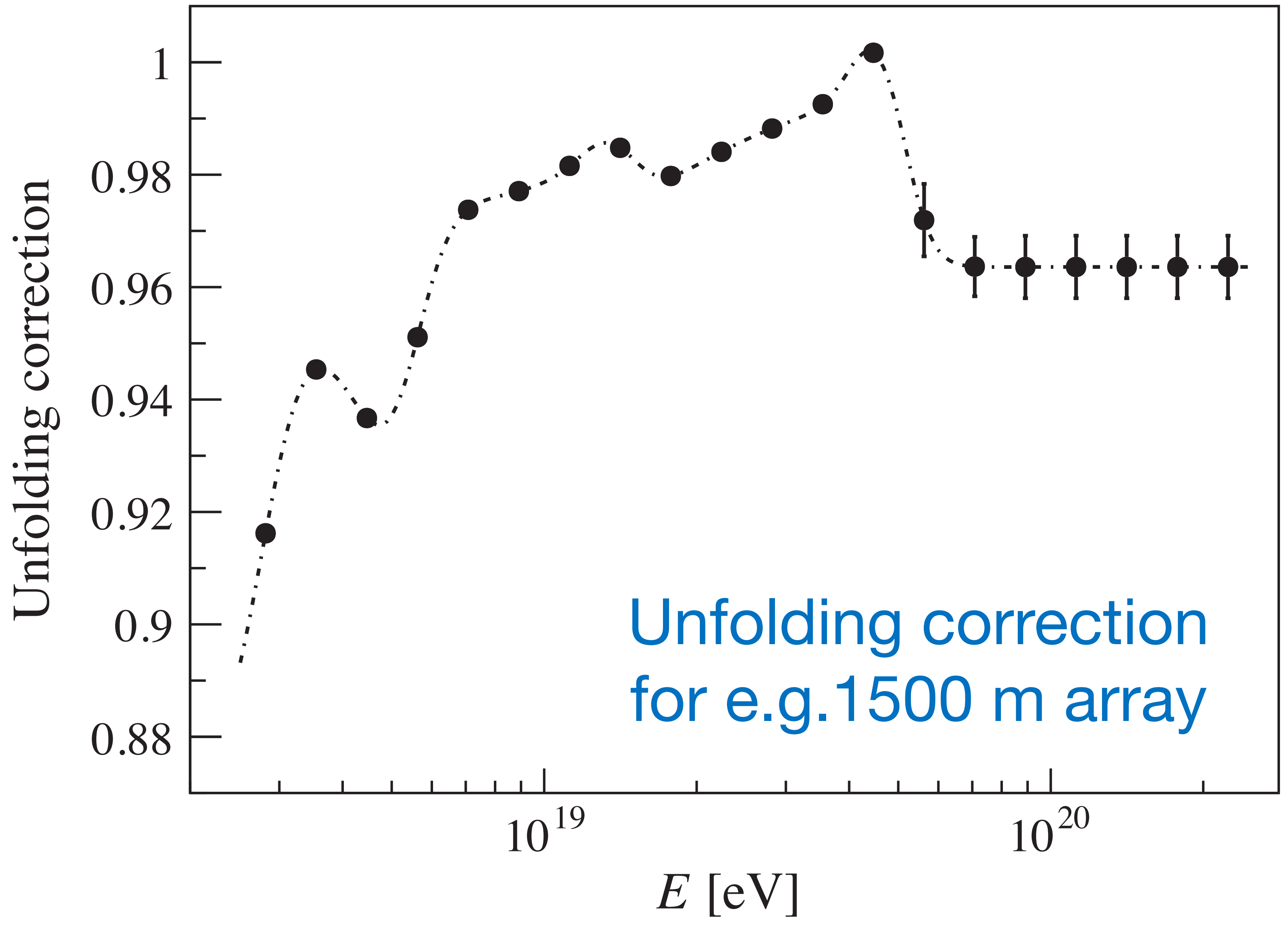
Energy resolution

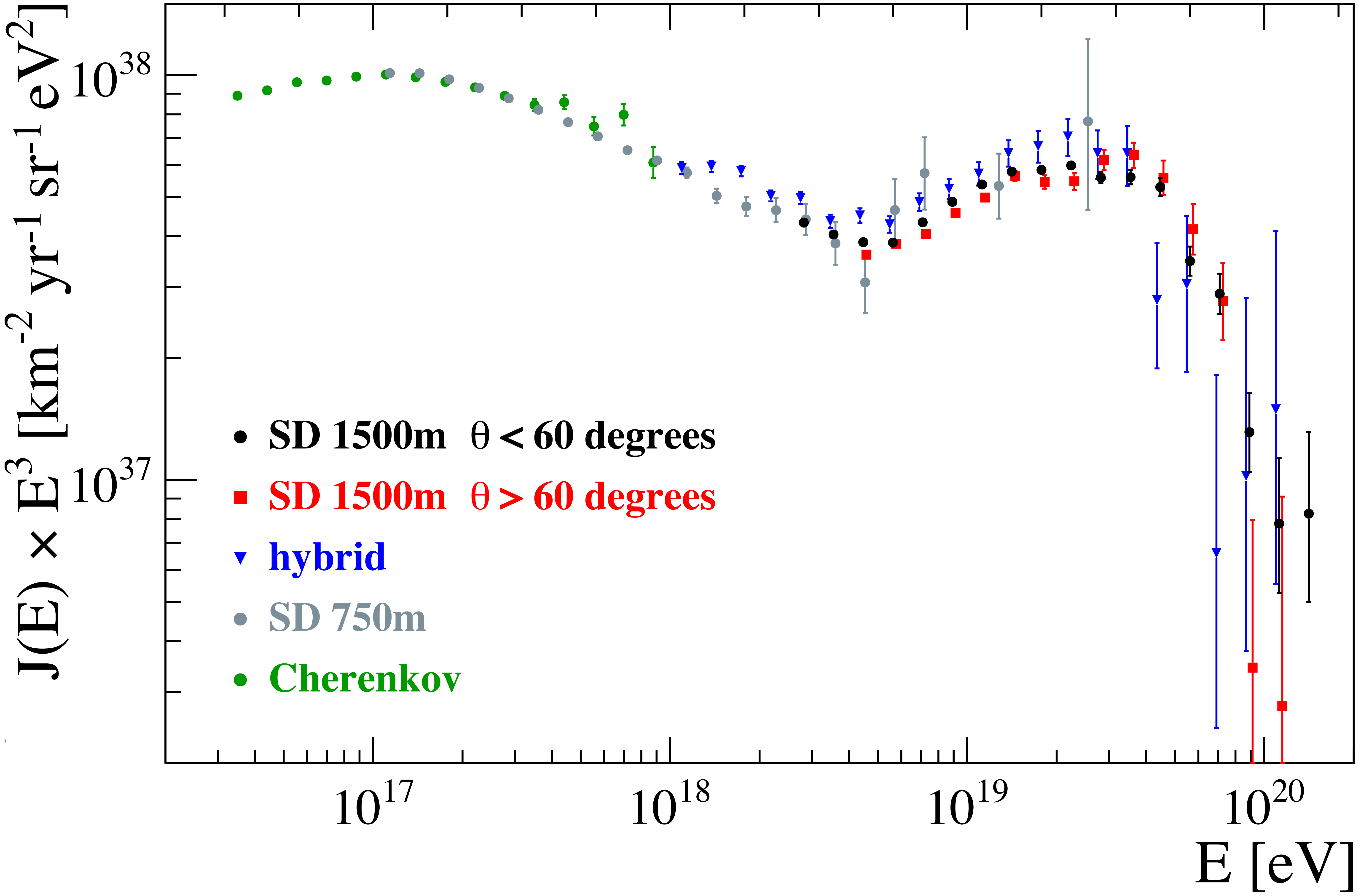
- 750m θ<55°: 15% @ 0.3 EeV (13% @ 1 EeV)
- 1500m θ<60°: 16% @ 3 EeV (12% @ 10 EeV)
- 1500m 60°θ<80°: 19% @ 4 EeV

Data driven calibration
⇒ Air shower simulations are avoided

Five measurements of the cosmic-ray flux

Deconvolution of spectra done to account for finite energy resolution (i.e. forward folding; <10% SD, <3% Hybrid)





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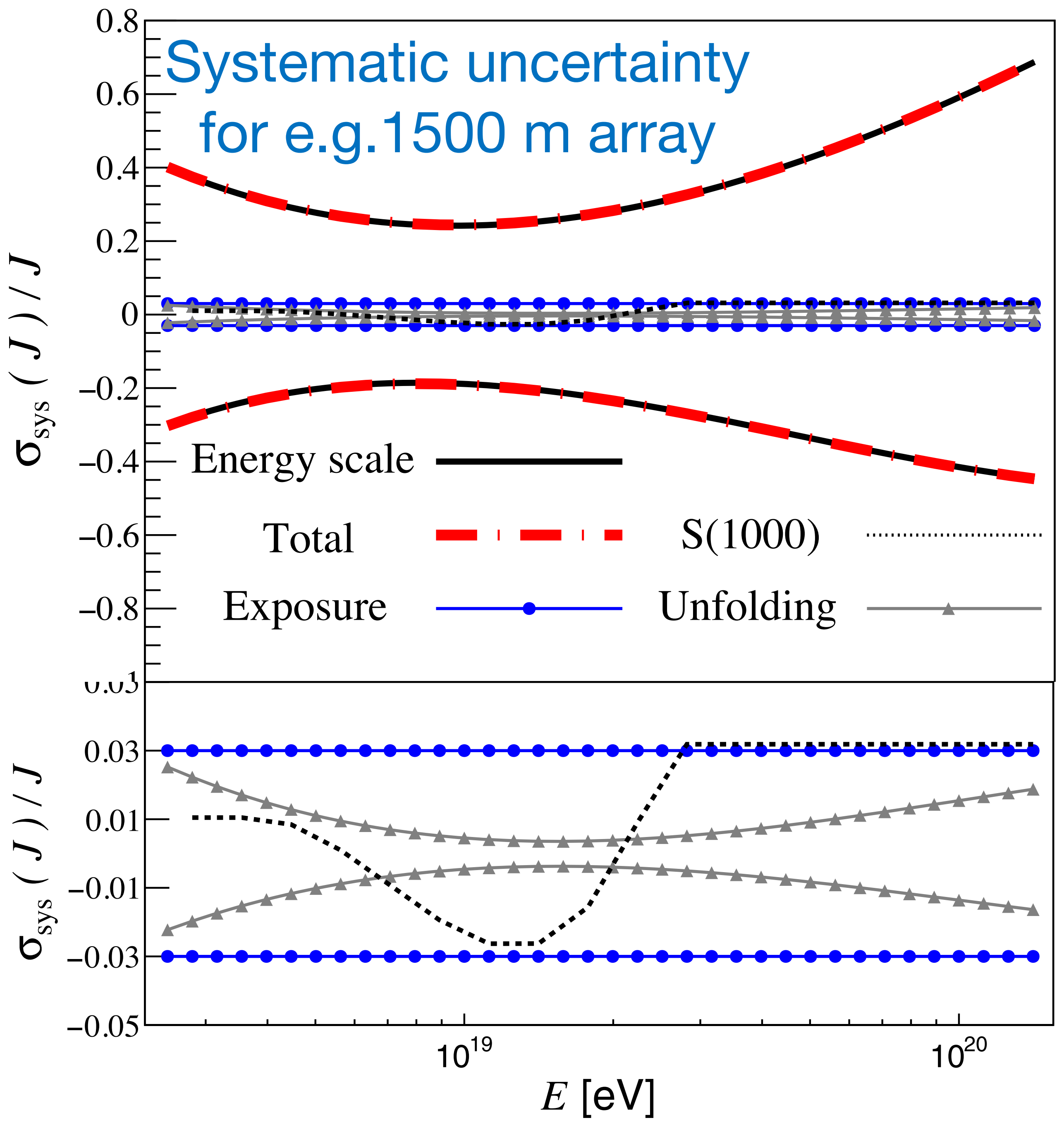
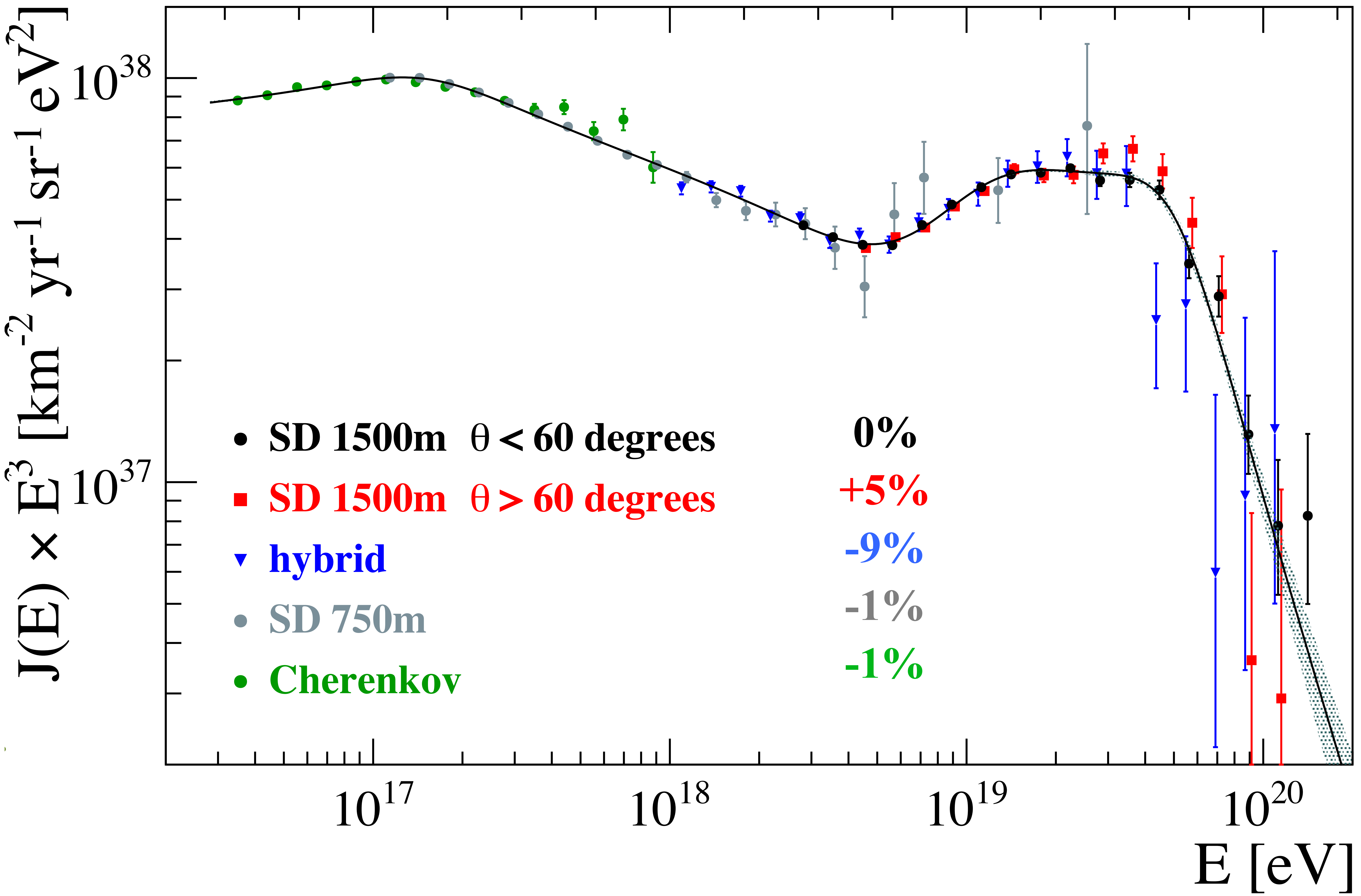
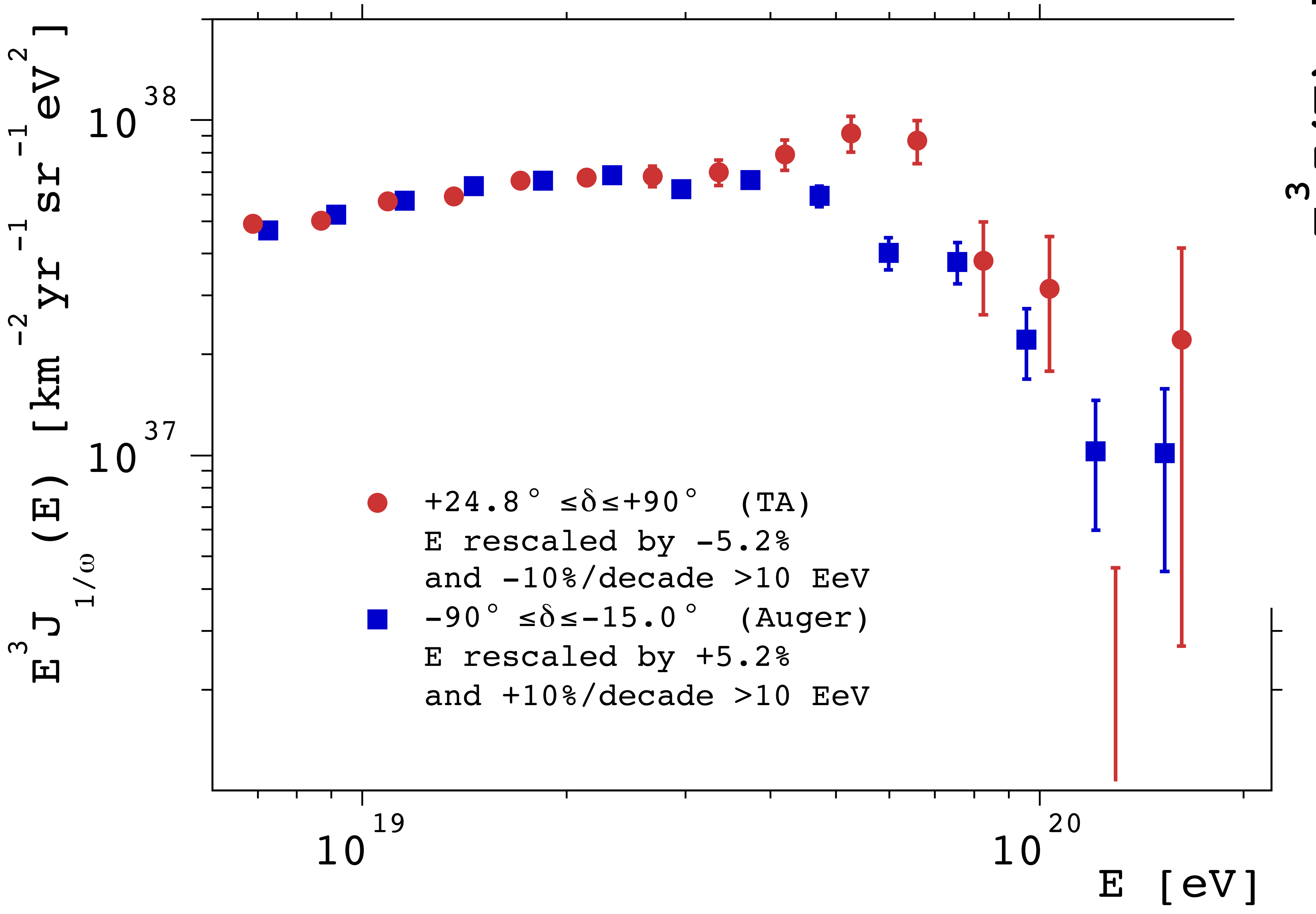


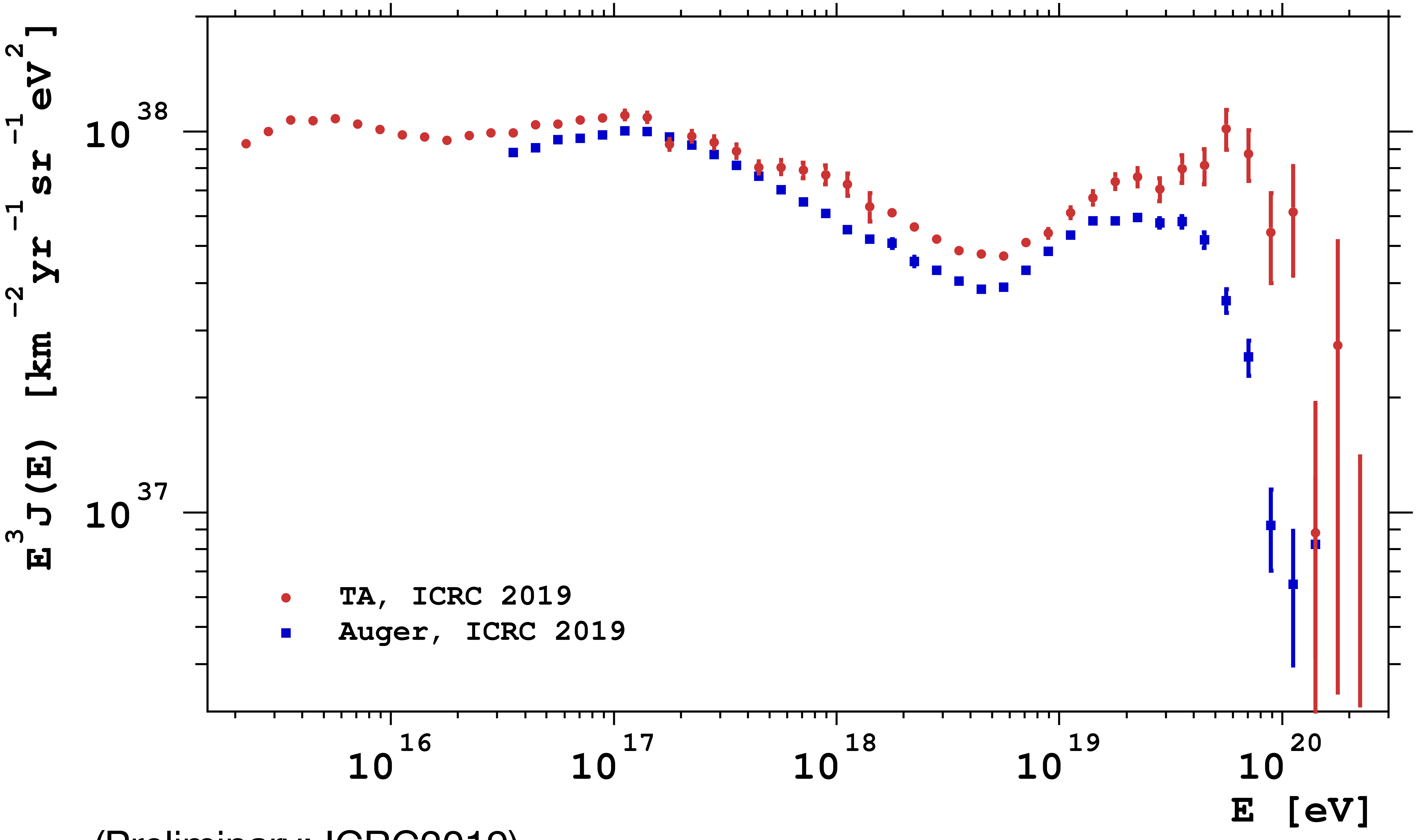


Combined energy spectra of Auger and TA

Overall difference covered by systematic uncertainties of the energy scale except at highest energies

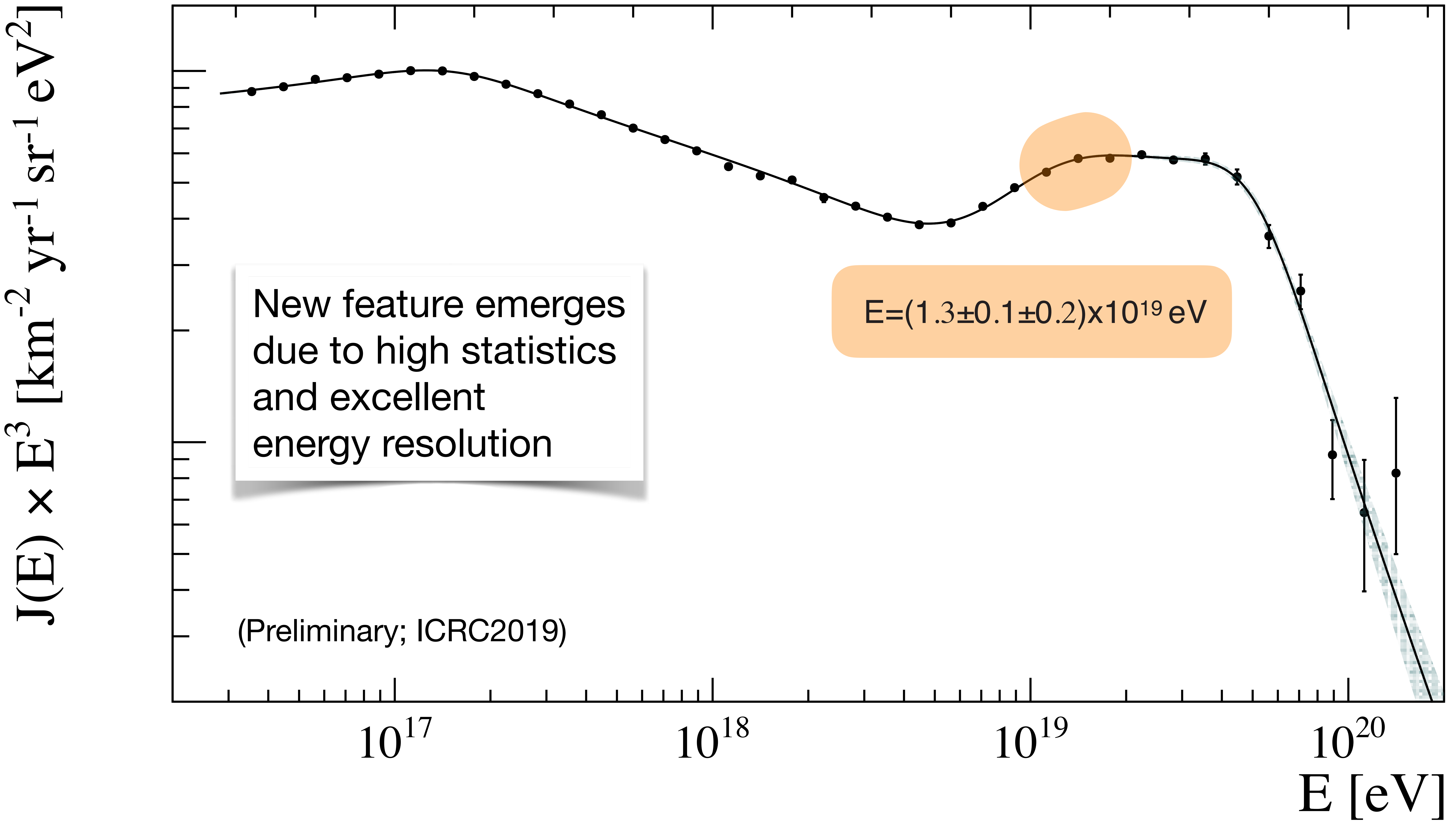
Auger: σ_E=14%
TA: σ_E=21%





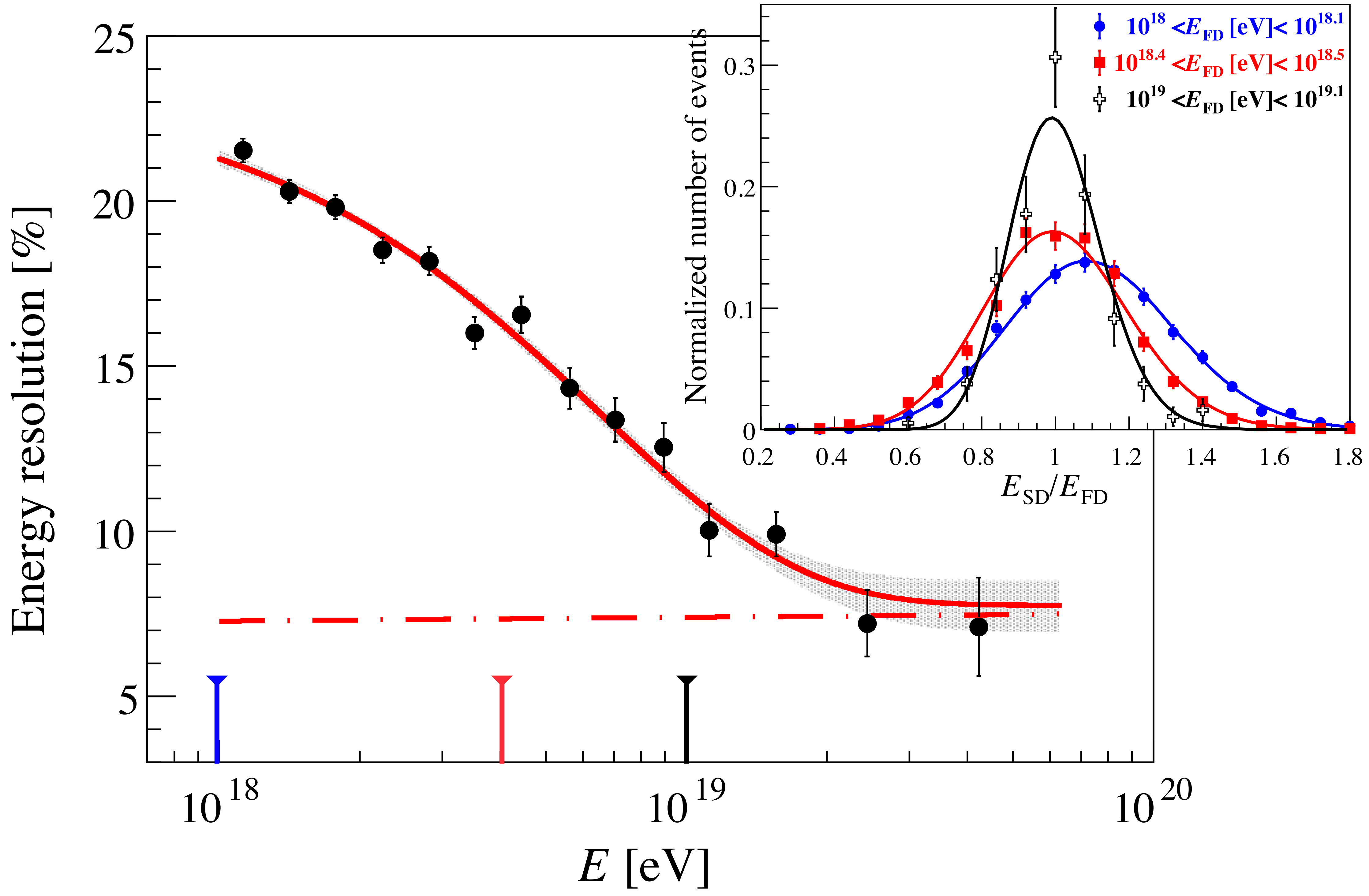
(Preliminary; ICRC2019)

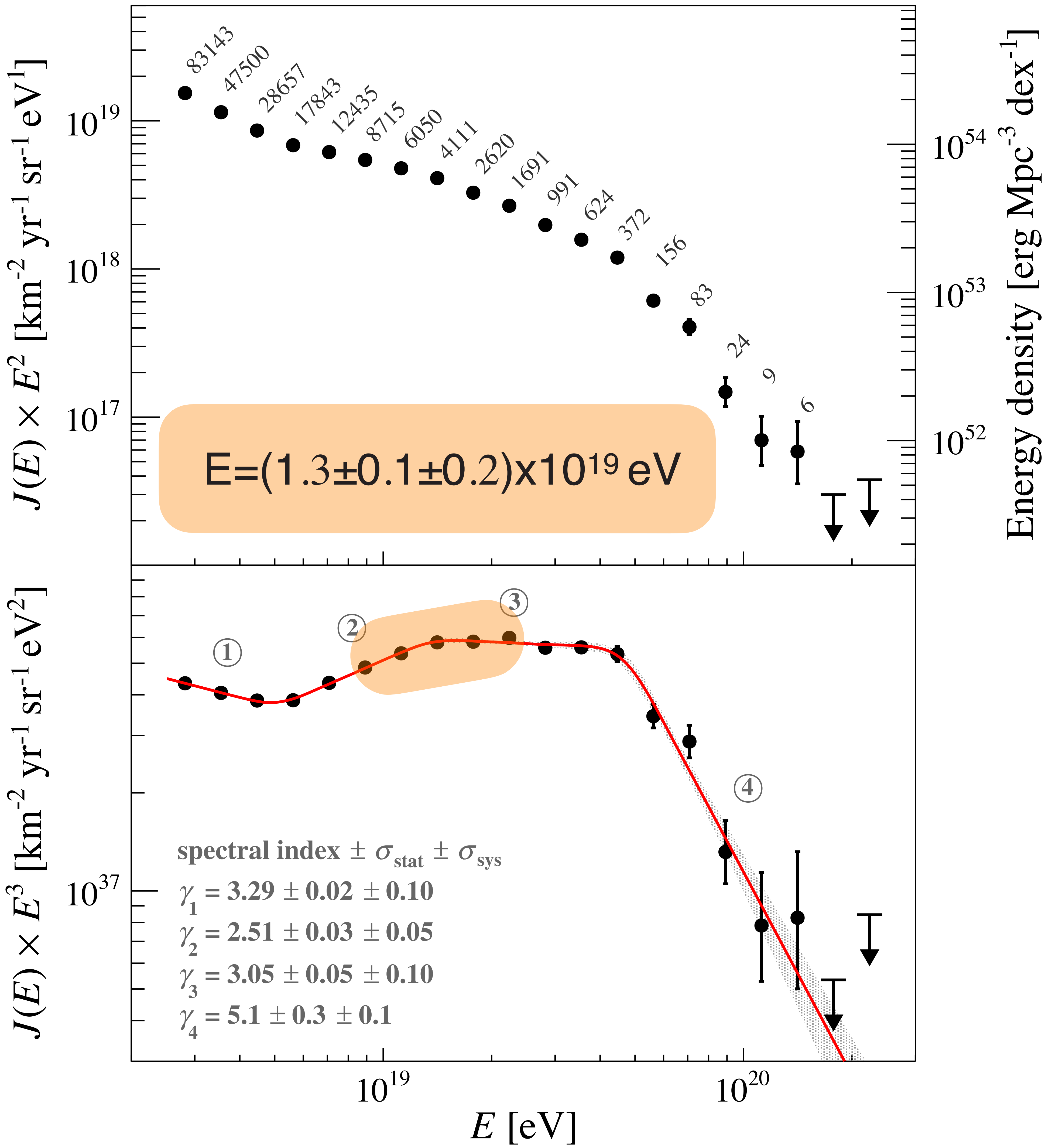
Combined energy spectrum



New feature at high statistics

(i.e. data of the 1500m array)





Functional shape

$$J(E) = J_0\left(\frac{E}{10^{18.5}\ \mathrm{eV}}\right)^{-\gamma_1}\prod_{i=1}^{3}\left[1+\left(\frac{E}{E_{ij}}\right)^{1/\omega_{ij}}\right]^{(\gamma_i-\gamma_j)\omega_{ij}}$$

$$\omega_{ij} = 0.05$$

Phys. Rev. D 102, *062005 (2020*

Phys. Rev. Lett. 125, 121106 (2020)

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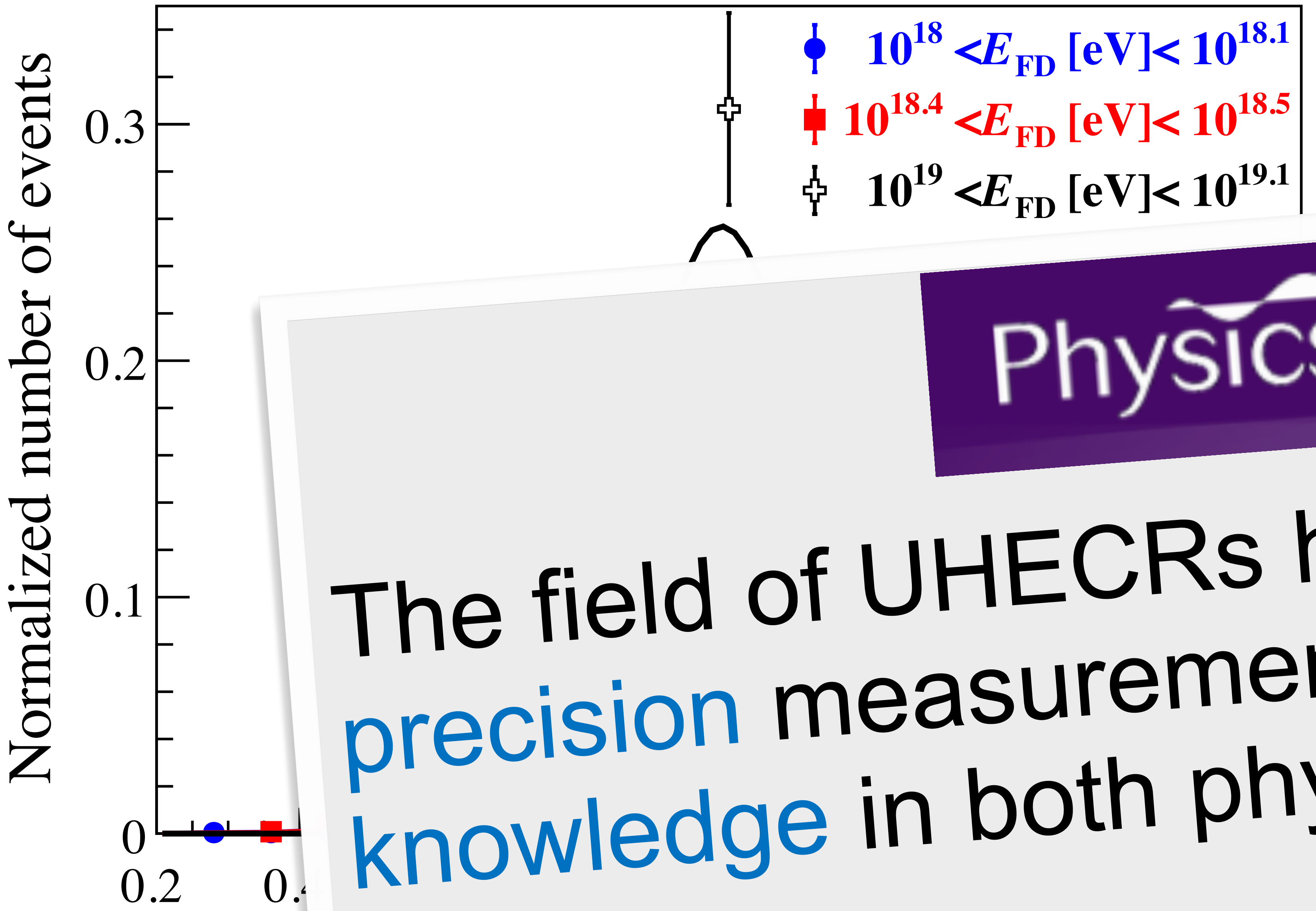


Physics VIEWPOINT

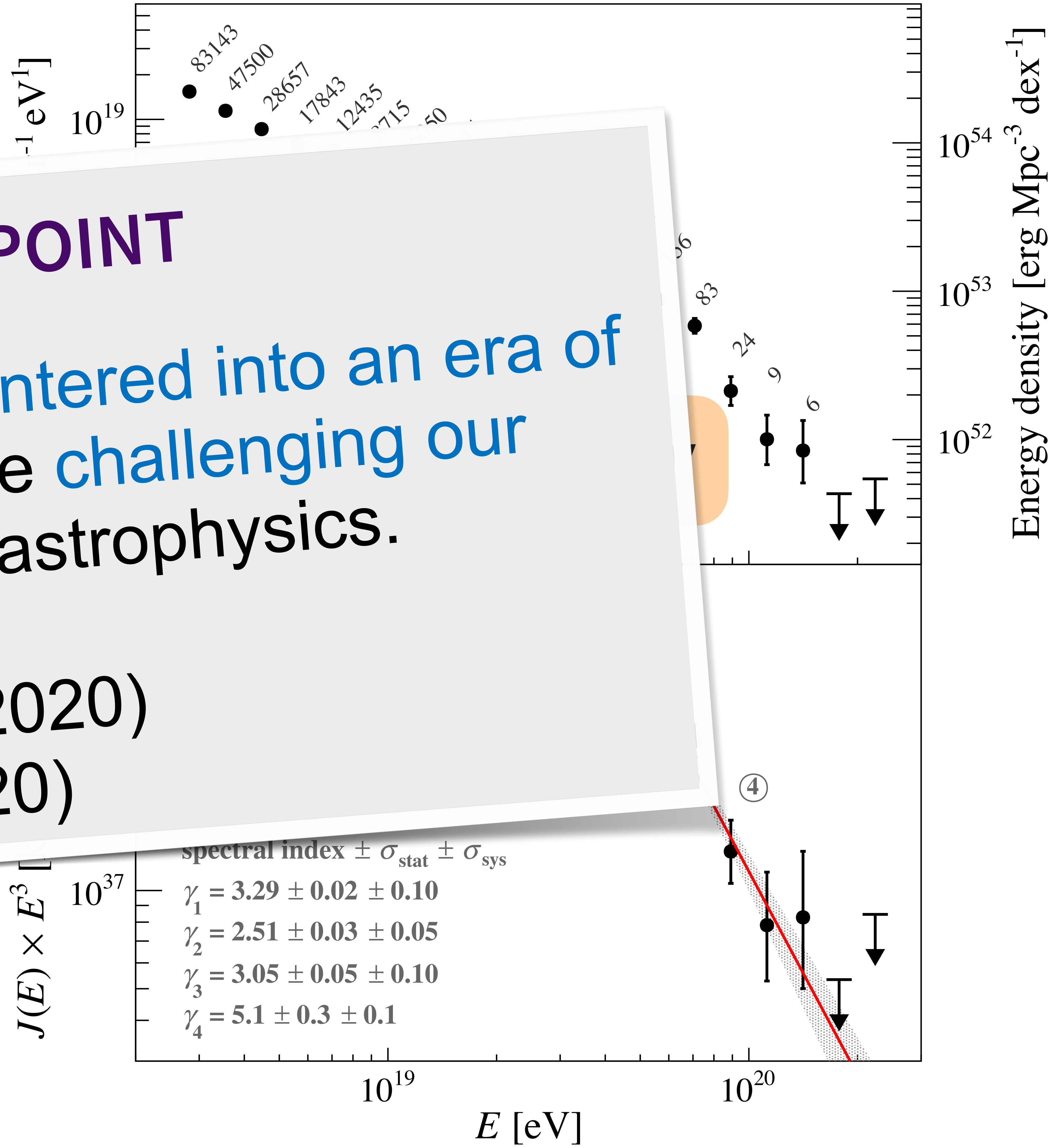
The field of UHECRs has now entered into an era of precision measurements that are challenging our knowledge in both physics and astrophysics.

Phys. Rev. Lett. 125, 121106 (2020)
Phys. Rev. D 102, 062005 (2020)

Functional shap

$$J(E) = J_0 \left(\frac{E}{10^{18.5}\ \mathrm{eV}} \right) \prod_{i=1} \left[1 + \left(\frac{E}{E_{ij}} \right) \right]$$

$$\omega_{ij} = 0.05$$



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New feature at high statistics

(i.e. data of the 1500m array)

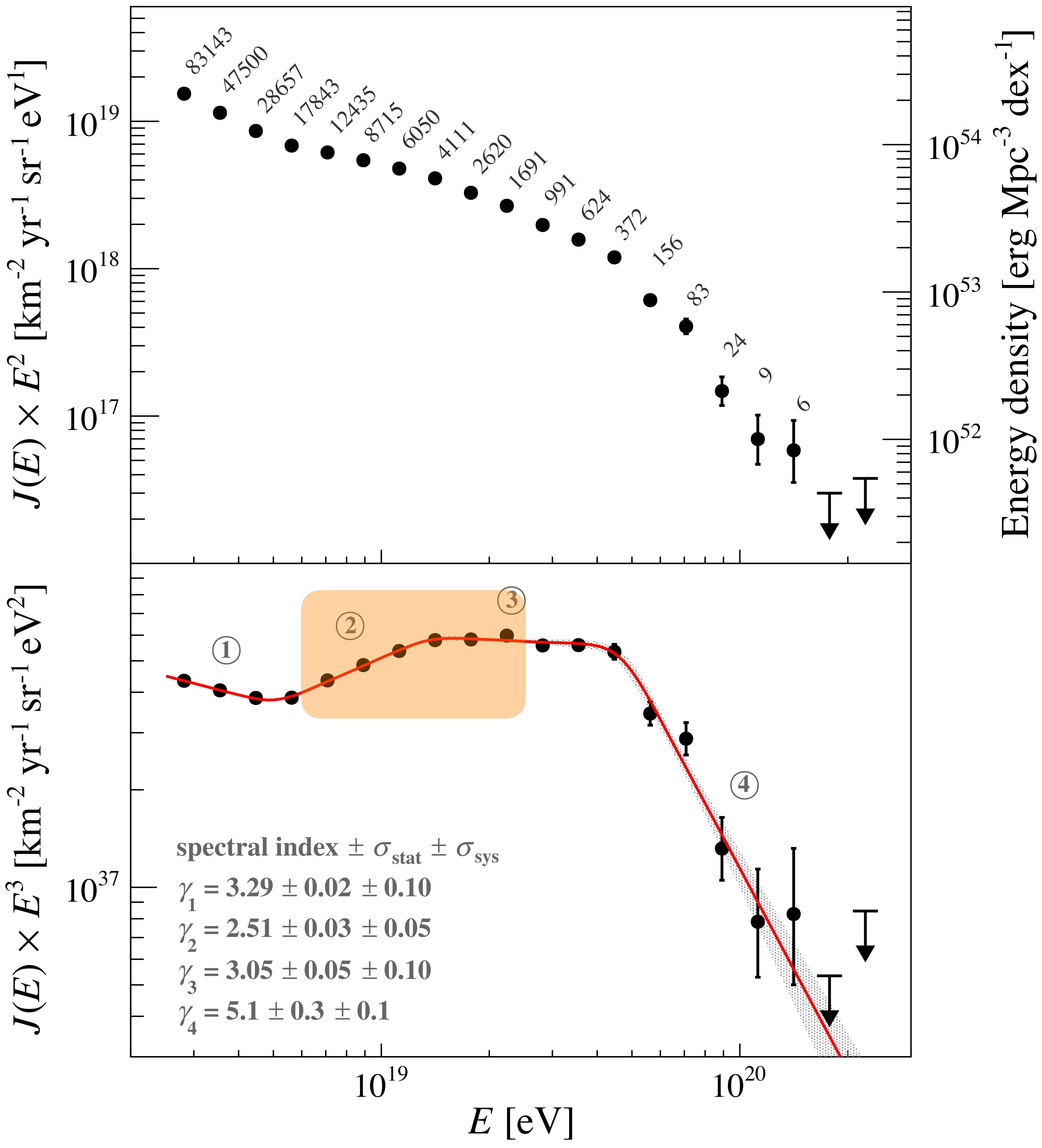
parameter	value $\pm\sigma_{\text{stat}} \pm \sigma_{\text{sys.}}$
J_0 [km^{-2} sr^{-1} yr^{-1} eV^{-1}]	$(1.315 \pm 0.004 \pm 0.400) \times 10^{-18}$
γ_1	$3.29 \pm 0.02 \pm 0.10$
γ_2	$2.51 \pm 0.03 \pm 0.05$
γ_3	$3.05 \pm 0.05 \pm 0.10$
γ_4	$5.1 \pm 0.3 \pm 0.1$
E_{12} [eV] (ankle)	$(5.0 \pm 0.1 \pm 0.8) \times 10^{18}$
E_{23} [eV]	$(13 \pm 1 \pm 2) \times 10^{18}$
E_{34} [eV] (suppression)	$(46 \pm 3 \pm 6) \times 10^{18}$
D/n_{dof}	17.0/12

Previous parametrization disfavored by 3.9 σ

Functional shape

$$J(E) = J_0 \left(\frac{E}{10^{18.5}\ \text{eV}}\right)^{-\gamma_1} \prod_{i=1}^{3} \left[1 + \left(\frac{E}{E_{ij}}\right)^{1/\omega_{ij}}\right]^{(\gamma_i - \gamma_j)\omega_{ij}}$$

$$\omega_{ij} = 0.05$$



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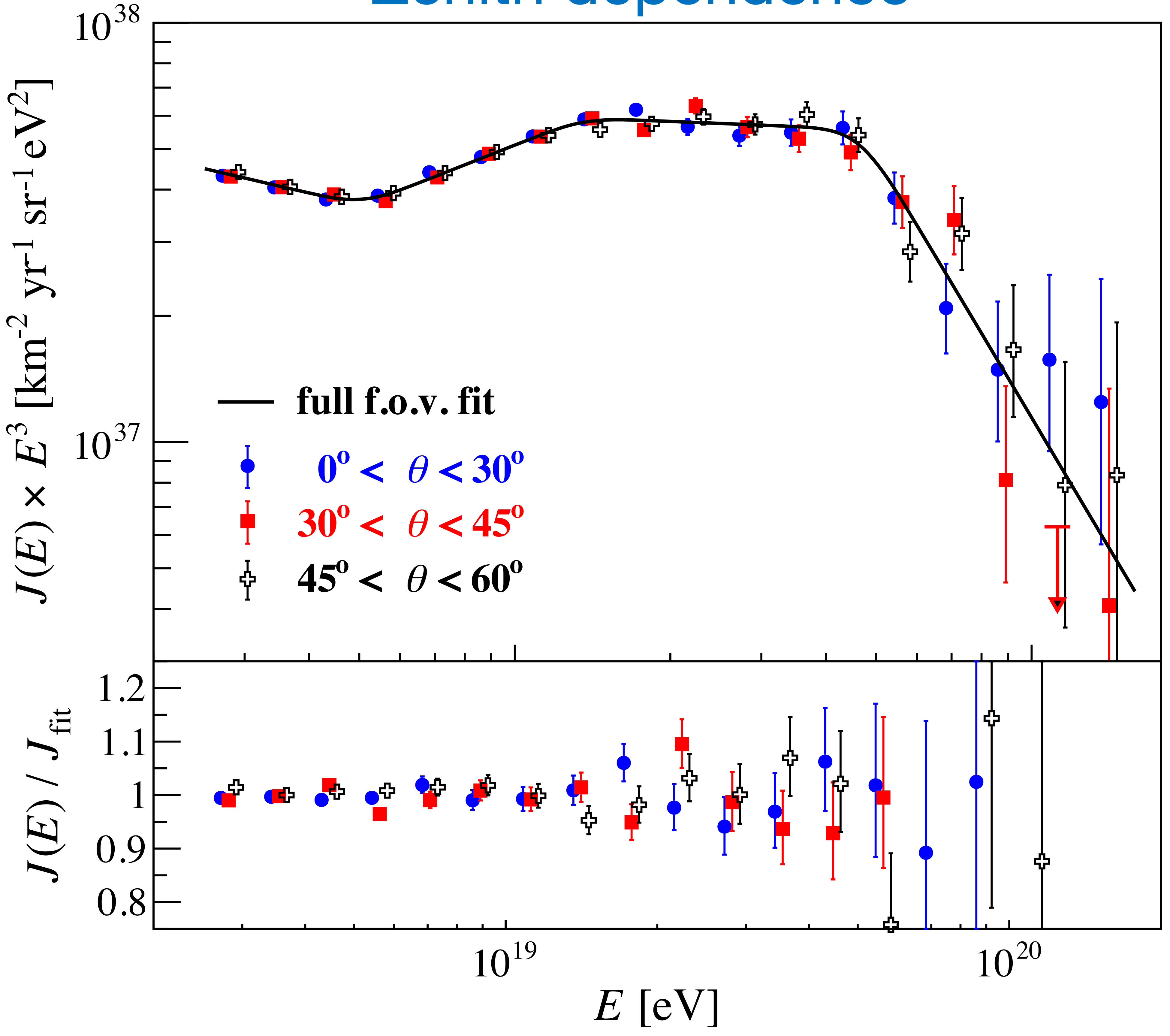
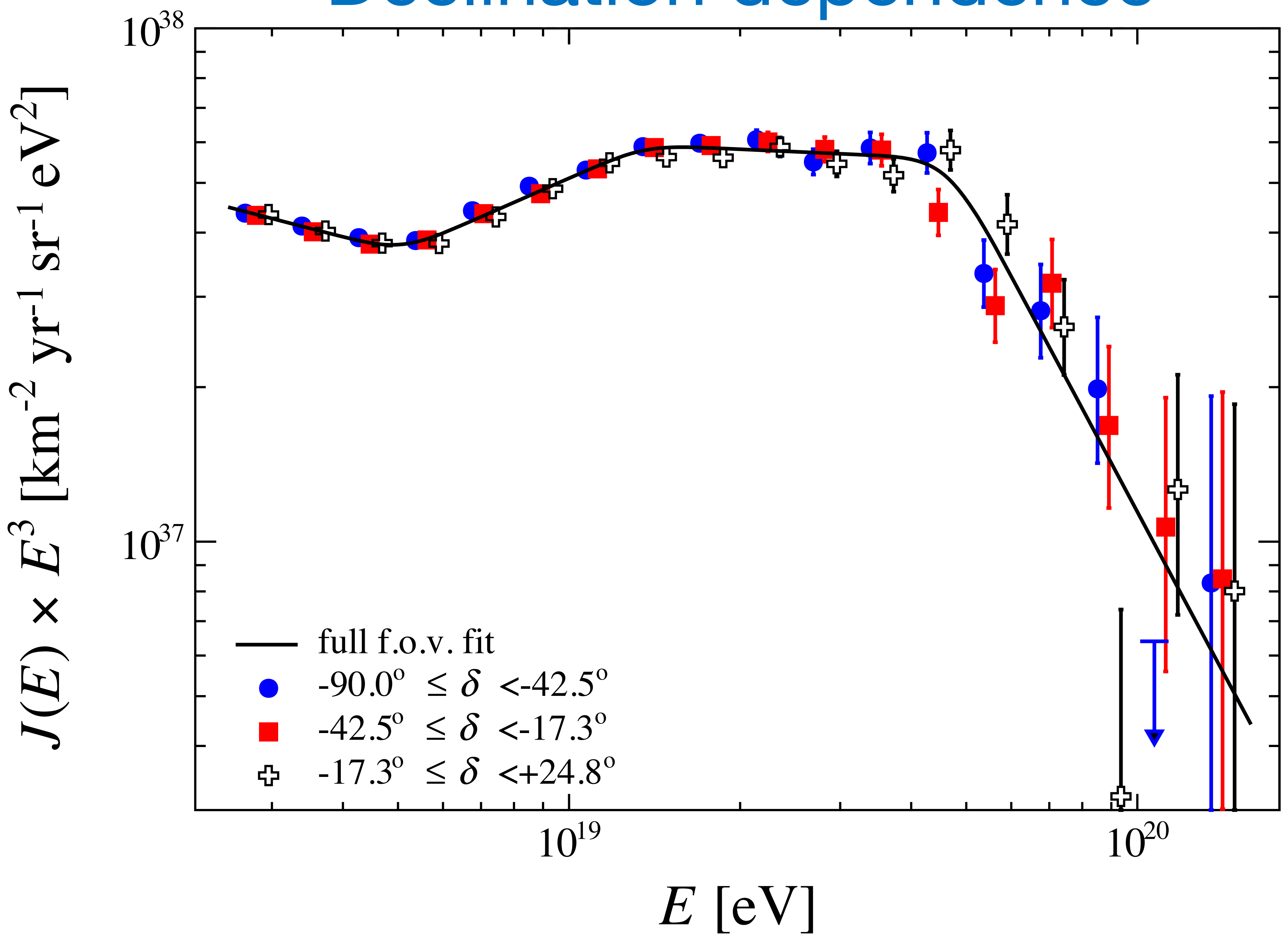
Zenith and declination dependence

Zenith dependence



Declination dependence



No significant zenith nor declination dependence beyond expected dipole effect

Phys. Rev. D **102**, *062005 (2020*

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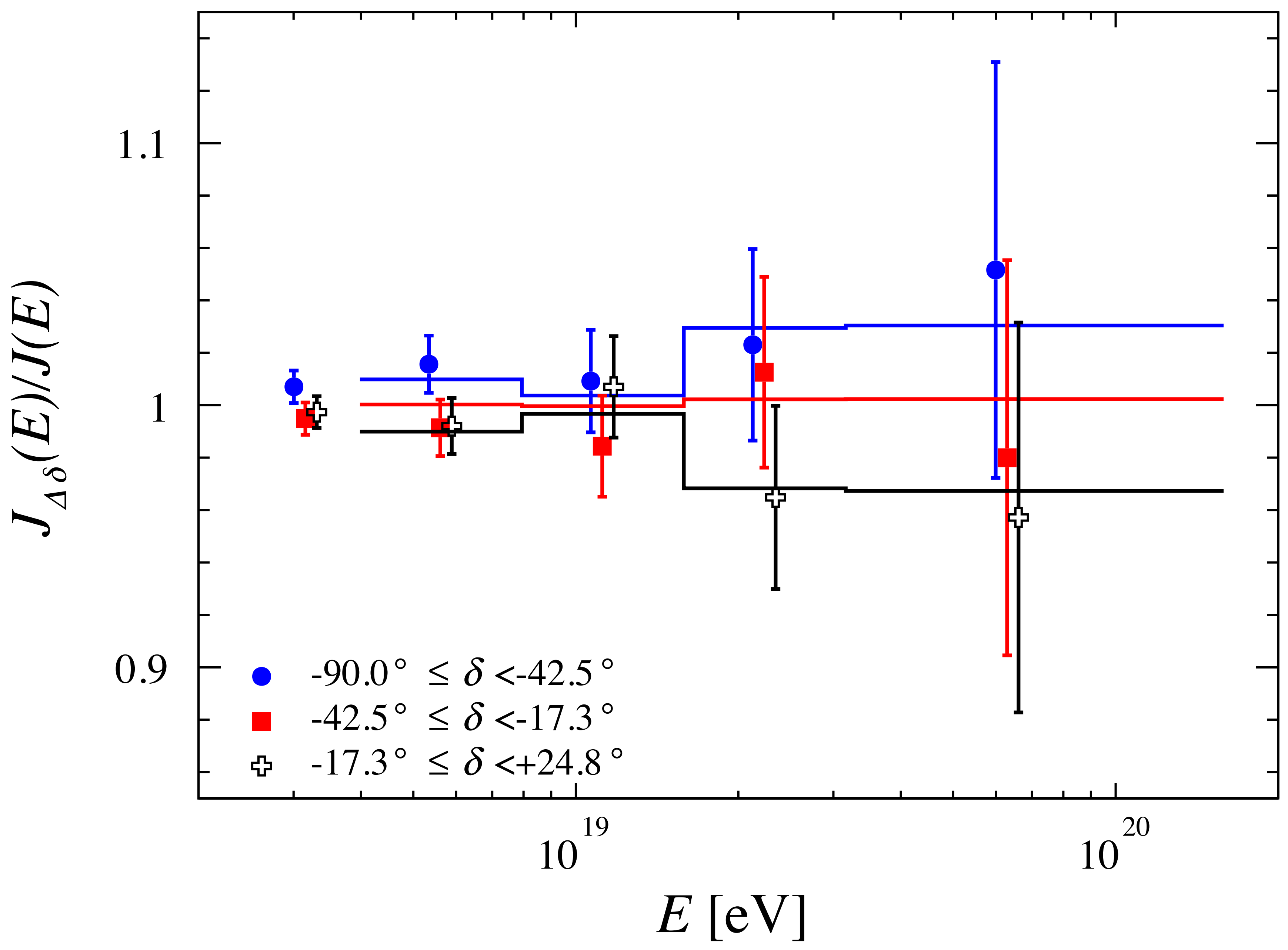
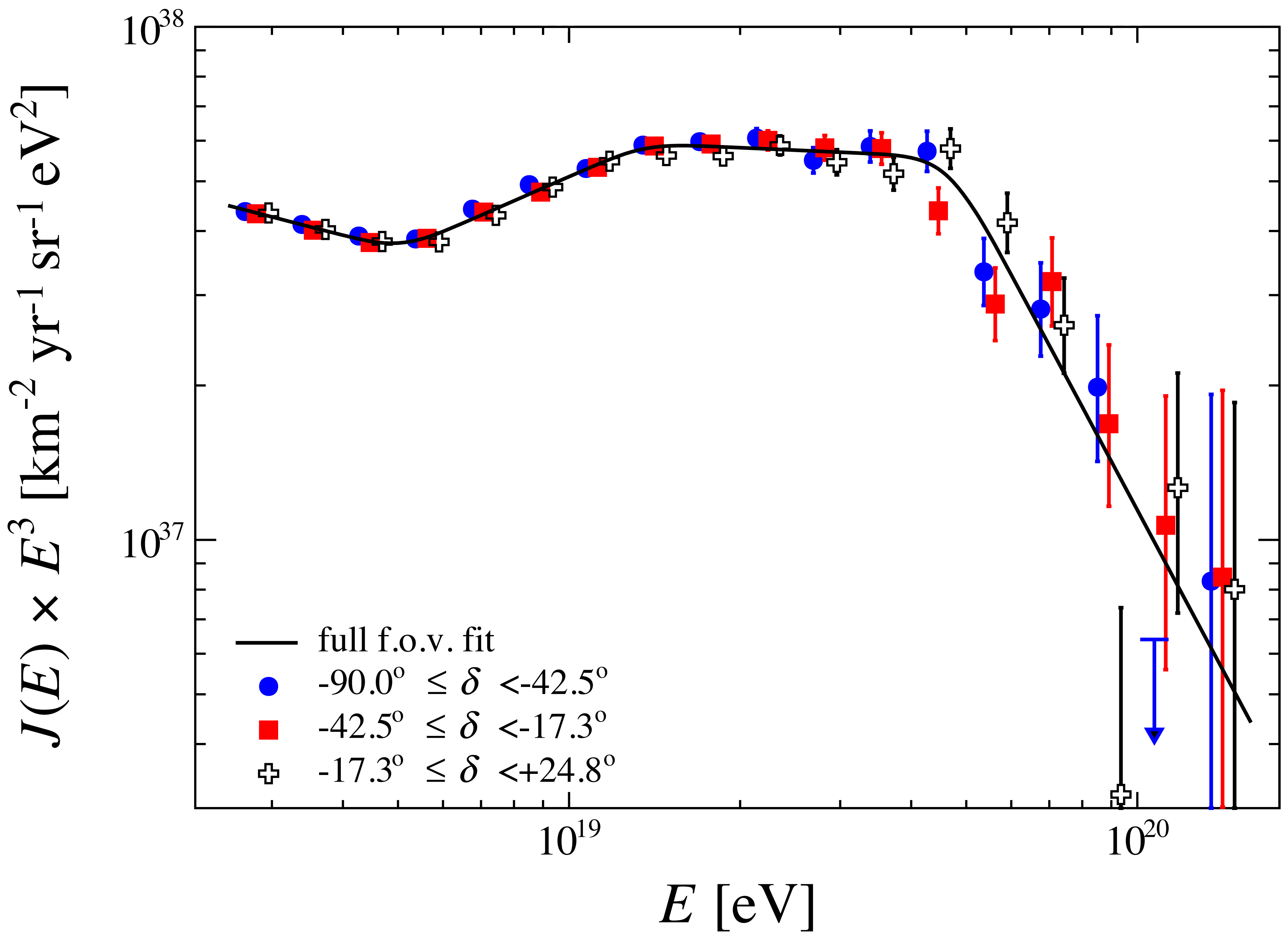
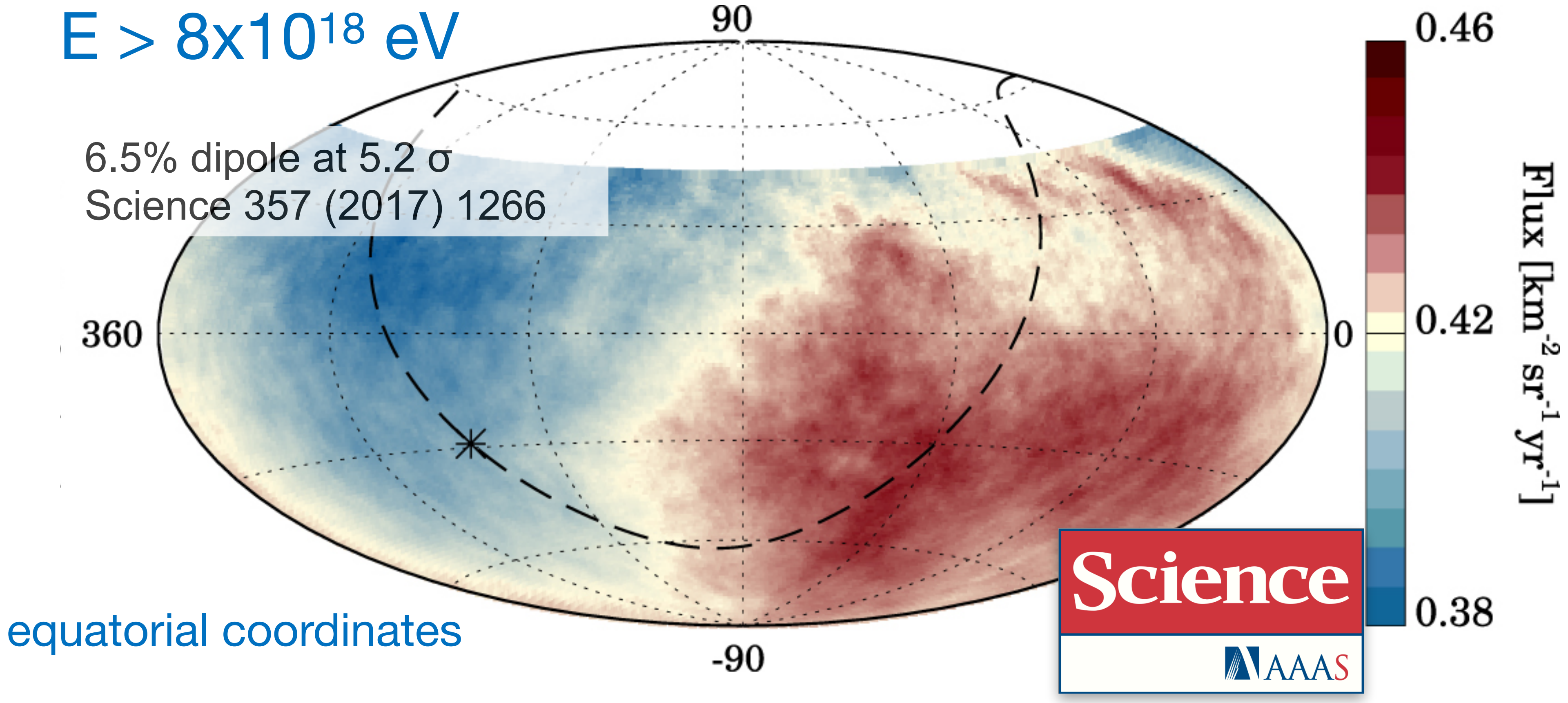
Declination dependence





E > 8×10^{18} eV

Declination band	Integral intensity [km^{-2} yr^{-1} sr^{-1}]
$-90.0° \leq \delta < -42.5°$	$(4.17 \pm 0.04) \times 10^{-1}$
$-42.5° \leq \delta < -17.3°$	$(4.11 \pm 0.04) \times 10^{-1}$
$-17.3° \leq \delta < +24.8°$	$(4.11 \pm 0.04) \times 10^{-1}$



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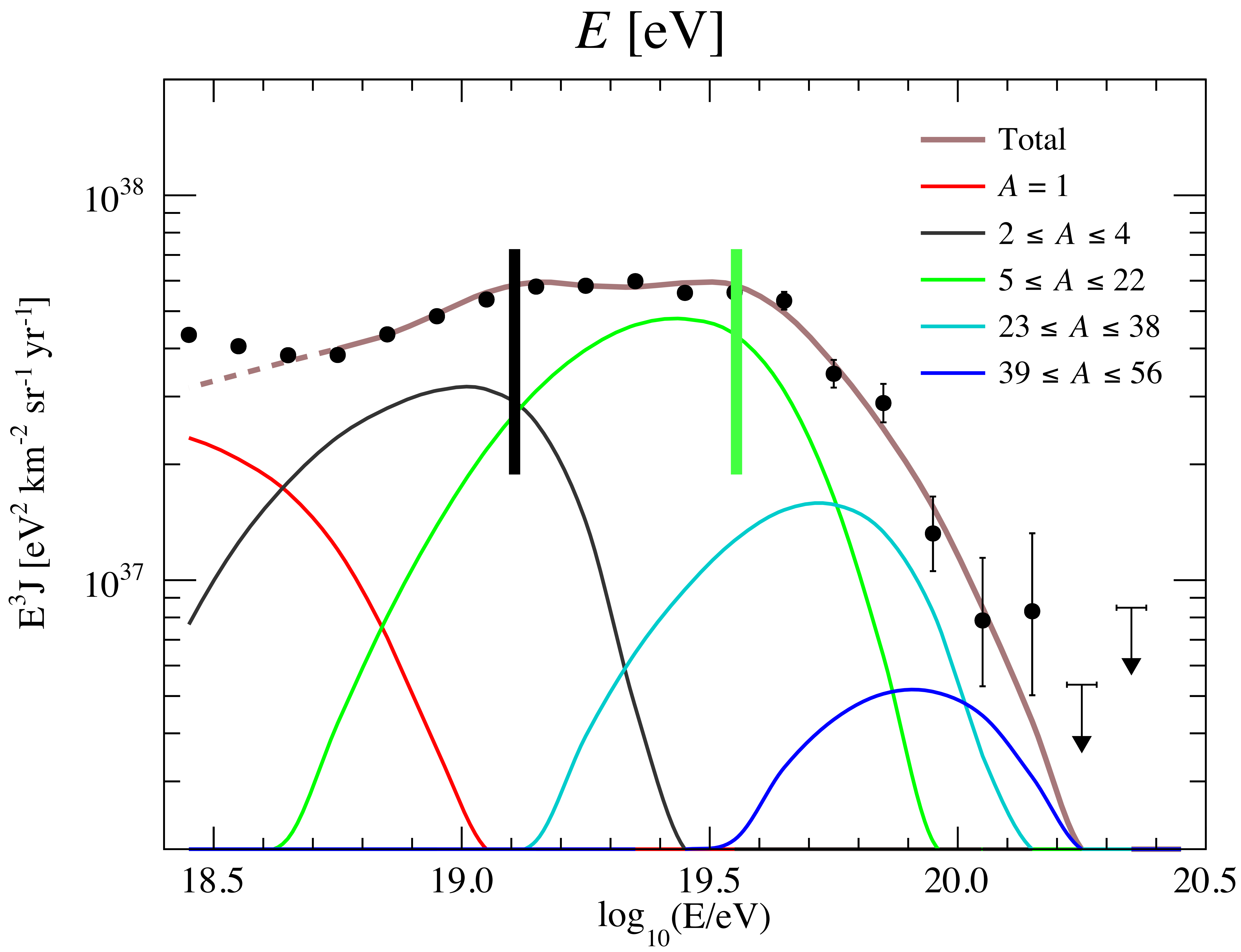
Benchmark scenario

- GZK model at odds with new feature
- Absence of declination dependenc

  ⇒ Disfavors local source emitting protons

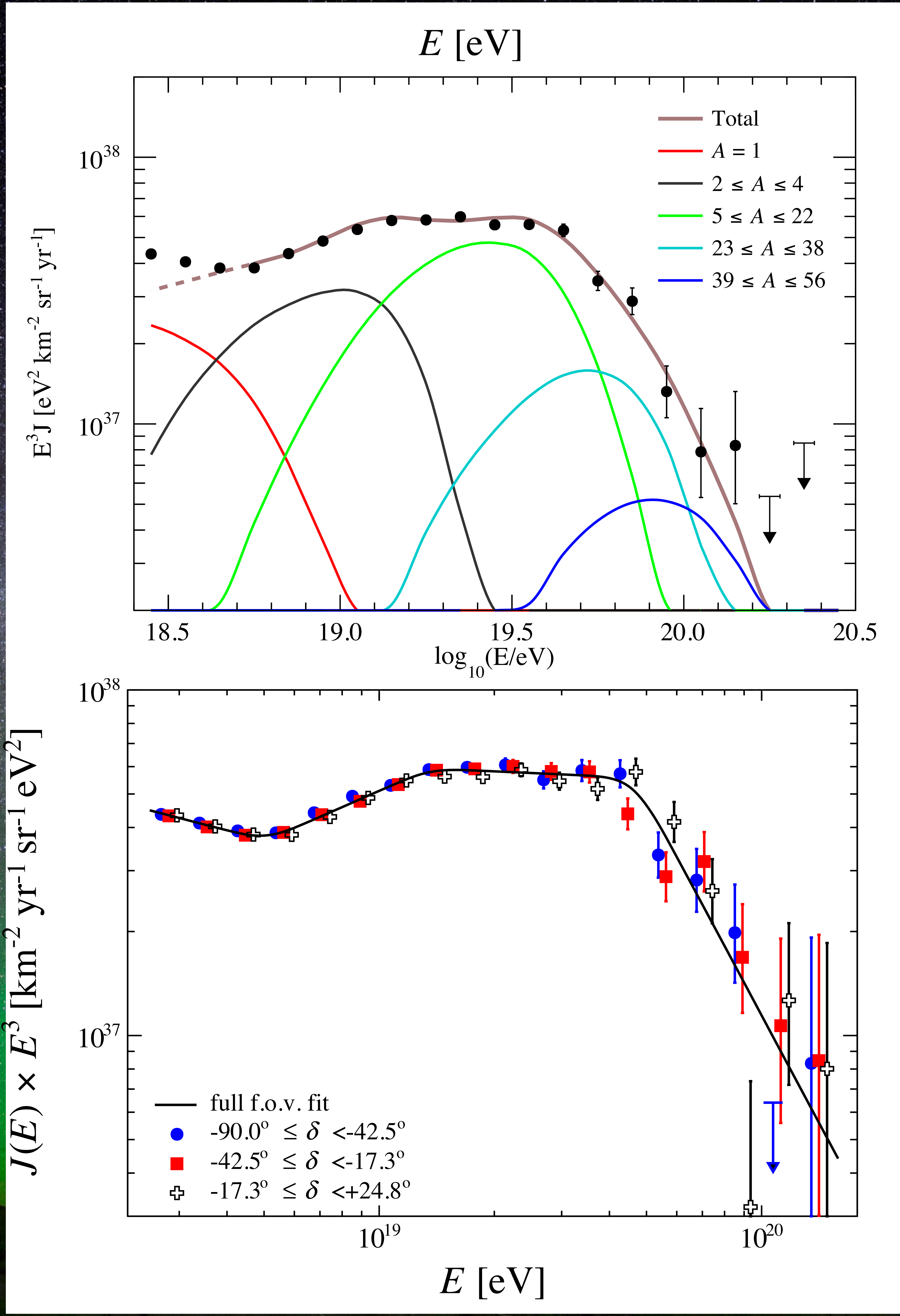
- Ilustrative model:
  - At source $E_{max} \sim Z$
    i.e. heavier elements at high energies
    (in concordance with recent Auger results)
  - Combined fit with X_{max} data (EPOS LHC)
  - Sources stationary and uniform
    in coming volume

    - Hard injection spectra
    - E_{He}/E_{CNO}=3.4±0.3
    - Subdominant light contribution
      not excluded



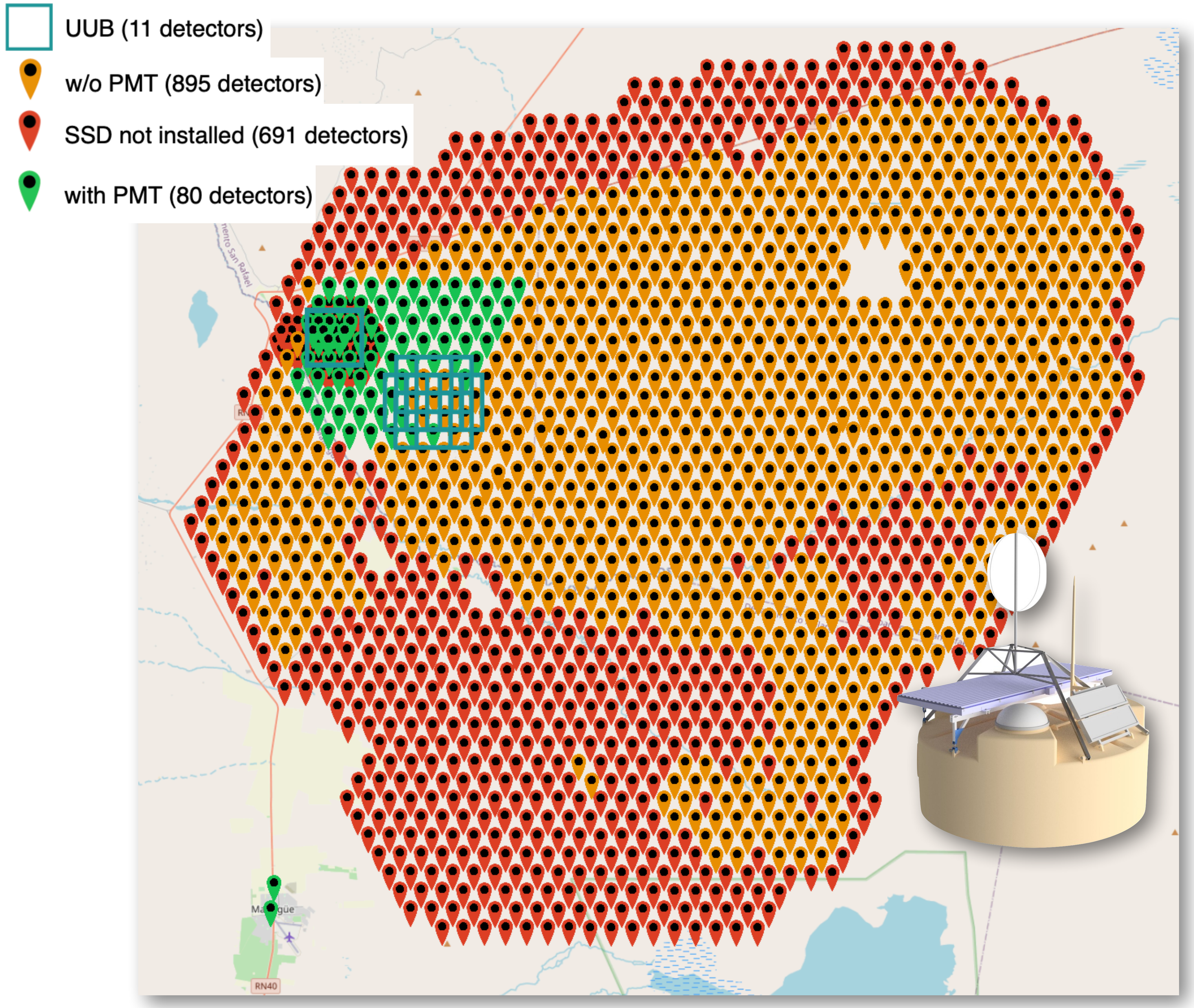
Summary

- Five independent measurements using either SD and FD
- Using same energy scale derived from FD: Syst. uncertainty of 14%
- Combined spectrum covering range from $10^{16.5}$ eV to 10^{20} eV using data collected over almost 15 years
- New feature identified due to high statistics and precision of measurement
- New AugerPrime data will allow for composition selected analyses



Upgrade of Auger Observatory: AugerPrime

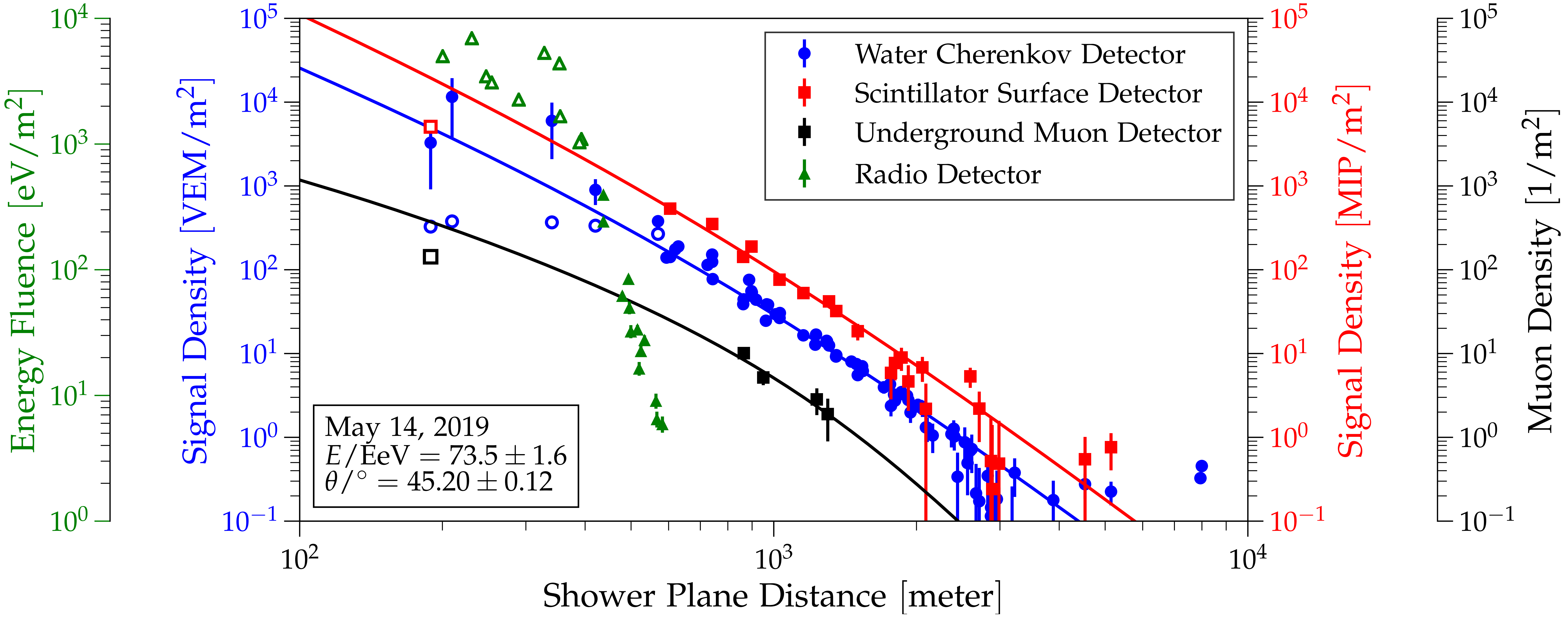
- Scintillators ($3.8\ m^2$) and radio antenna on top of each array detector
- Composition measurement up to 10^{20} eV
- Composition selected anisotropy
- Particle physics with air showers

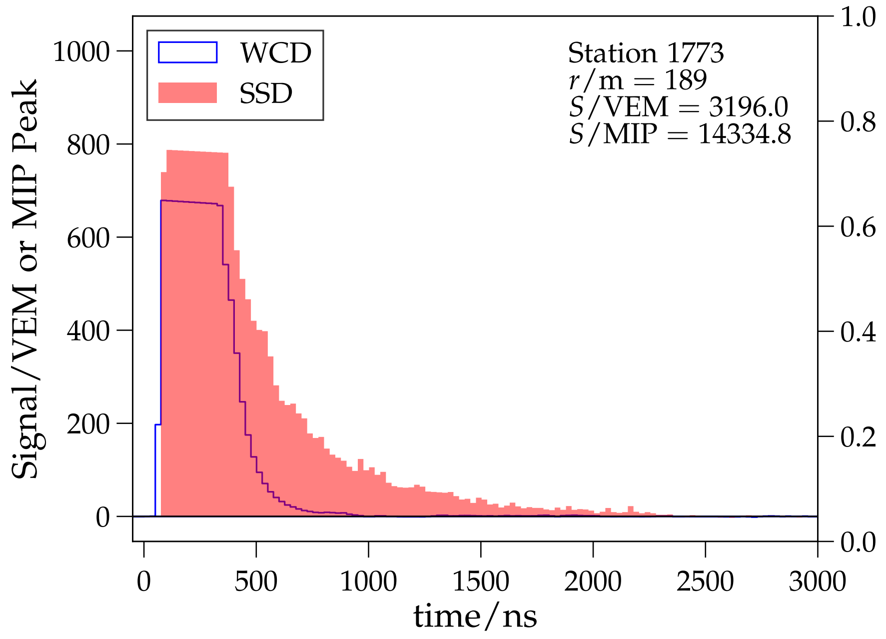


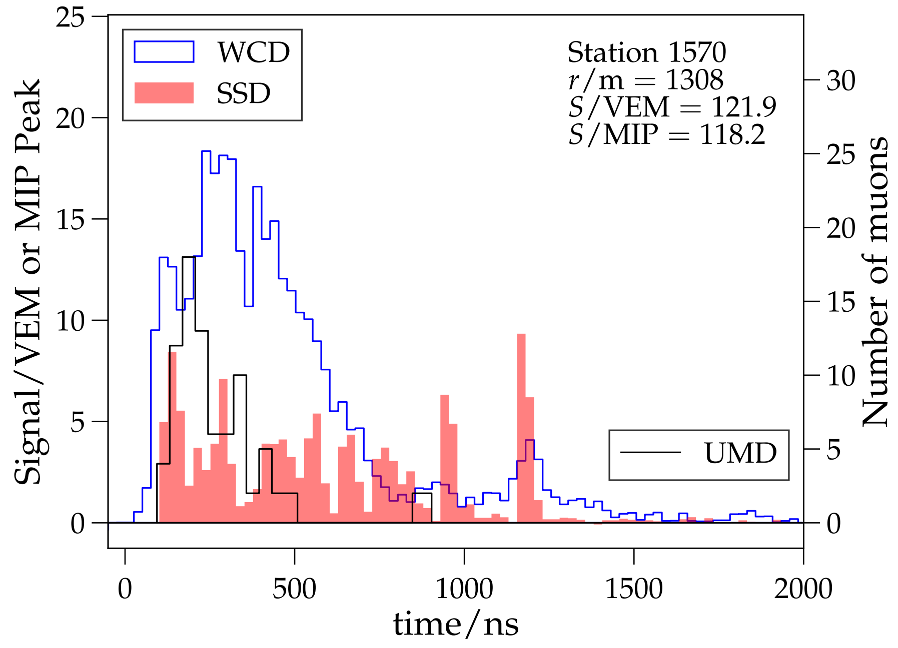
Ongoing upgrade AugerPrime (scintillators and radio antennas)

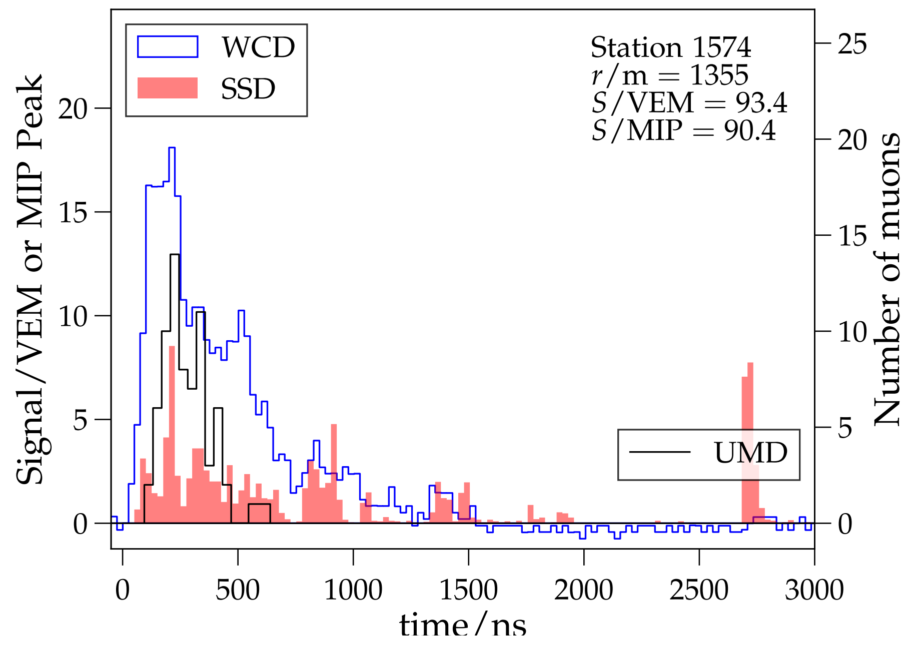
(AugerPrime design report 1604.03637)

AugerPrime — Advent of multi-hybrid data

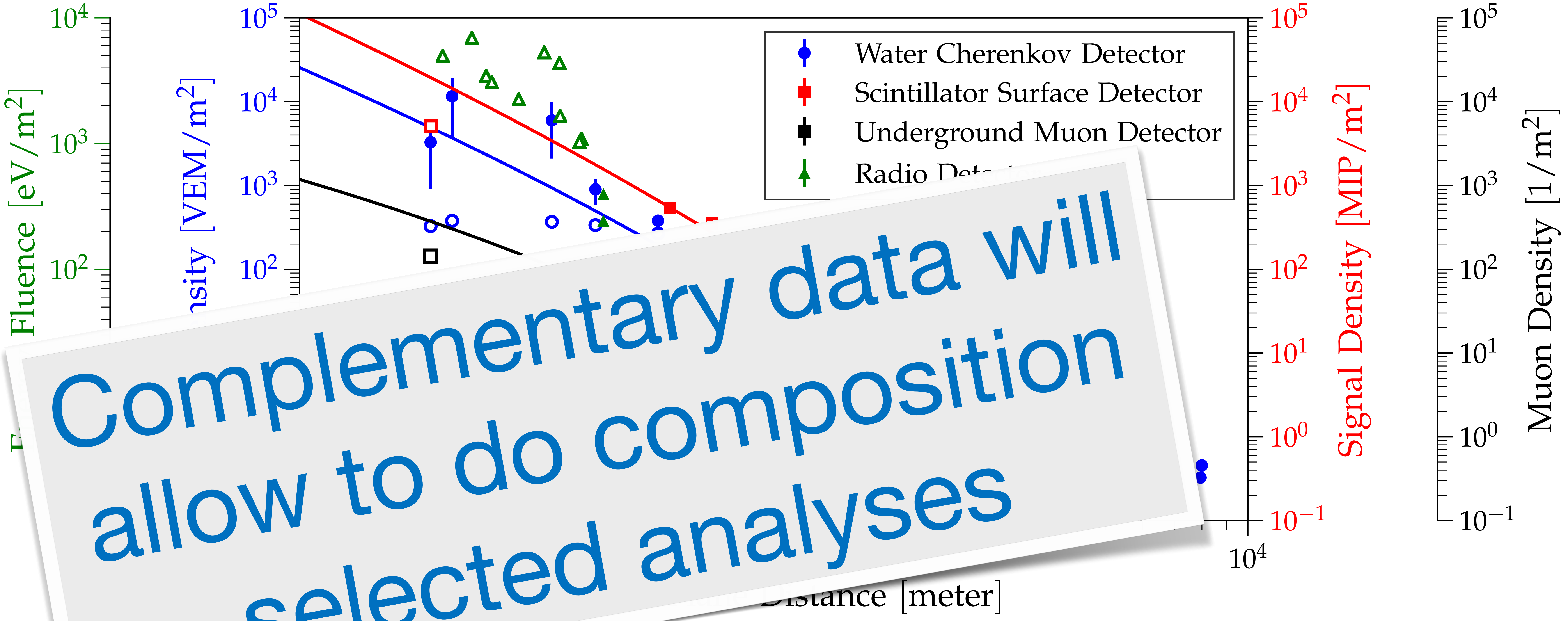




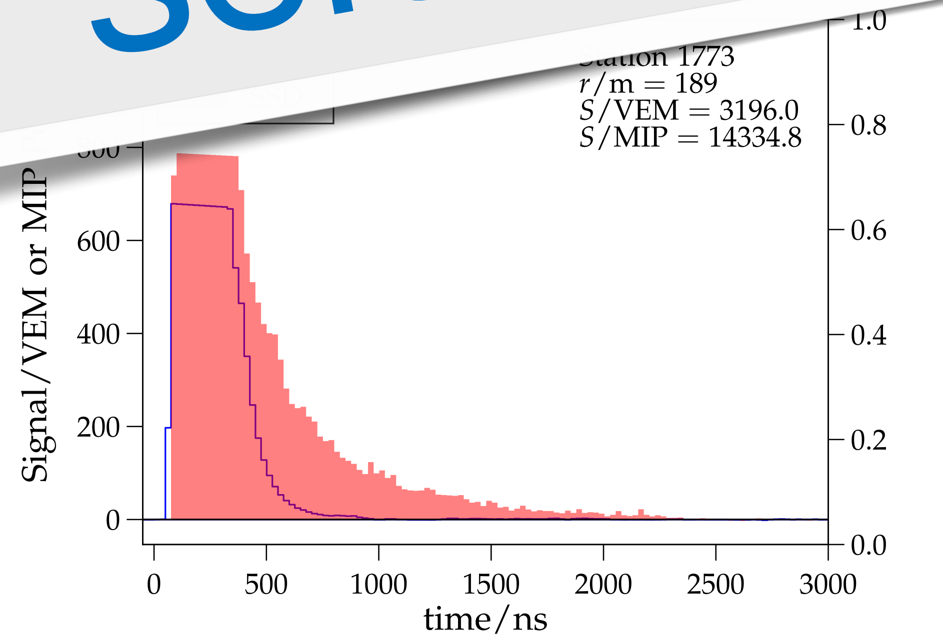


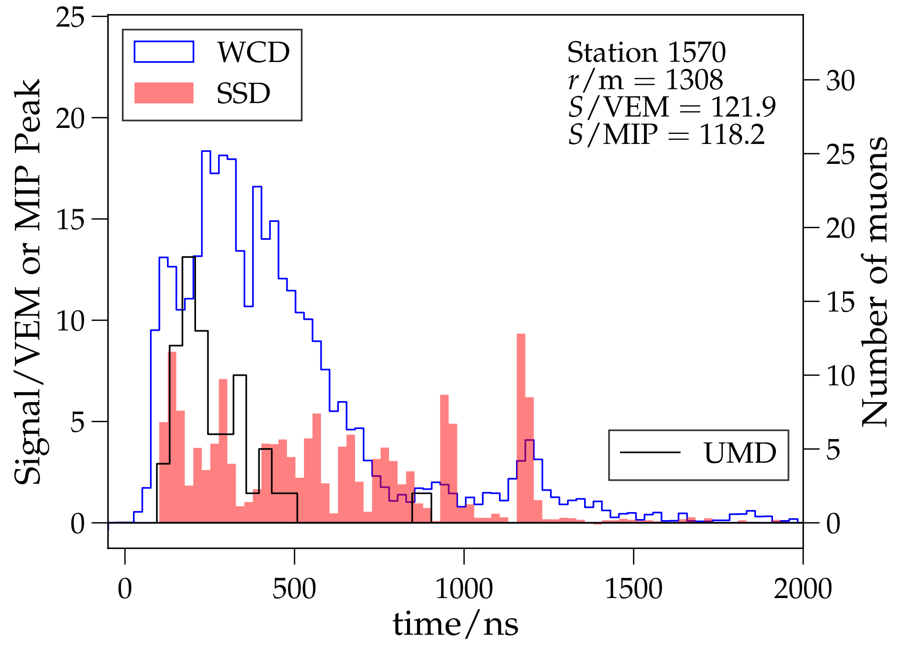


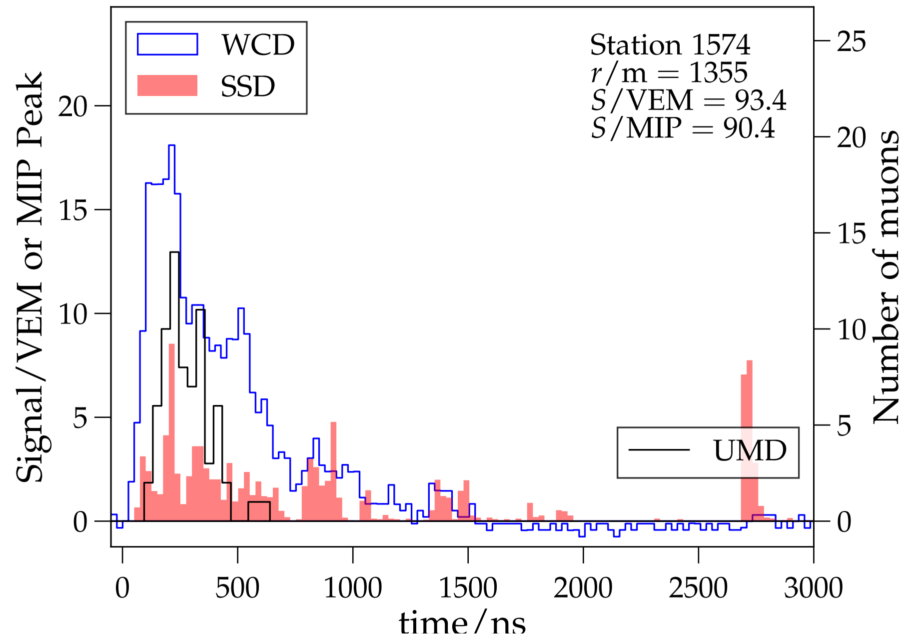
AugerPrime — Advent of multihybrid data



Complementary data will allow to do composition selected analyses








THANK YOU
MAAKE
TERMA KASIH
RAIBH MAITH AGAT
JUSPAXAR
OBRIGADO
MATONDO
SALAMAT
KIITOS
MOCHCHAKKERAM
KIA ORA
MULTUMESC
GRAZIE
MULTUMESC
MERCI
CHOKRANE
SALAMAT
CAM ON BAN
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MERCI
MOCHCHAKKERAM
RAIBH MAITH AGAT
OBRIGADO
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MATUR NUWUN
UA TSAUG RAU KOJ
MOCHCHAKKERAM
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RAIBH MAITH AGAT
SPASIBO
SPASIBO
WELALIN
OBRIGADO
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MAAKE
ARIGATO
KIITOS
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NIRRINGRAZZJAK
MOCHCHAKKERAM
MOCHCHAKKERAM
OBRIGADO
SPASIBO
MULTUMESC
VINAKA
NIRRINGRAZZJAK
MAMANA

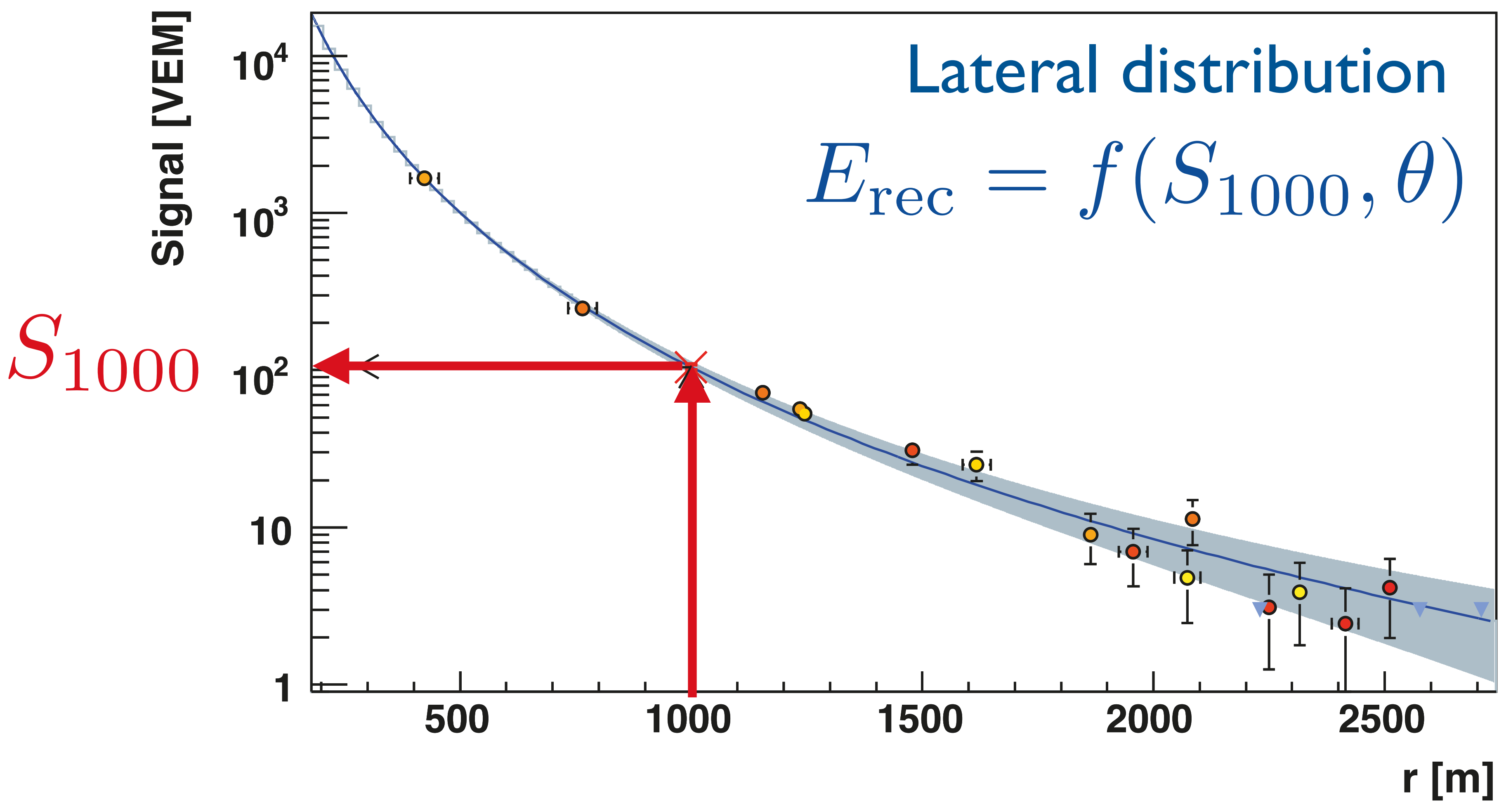
SD energy estimator for vertical events

$$S(r) = S(r_{\mathrm{opt}})f(r)$$

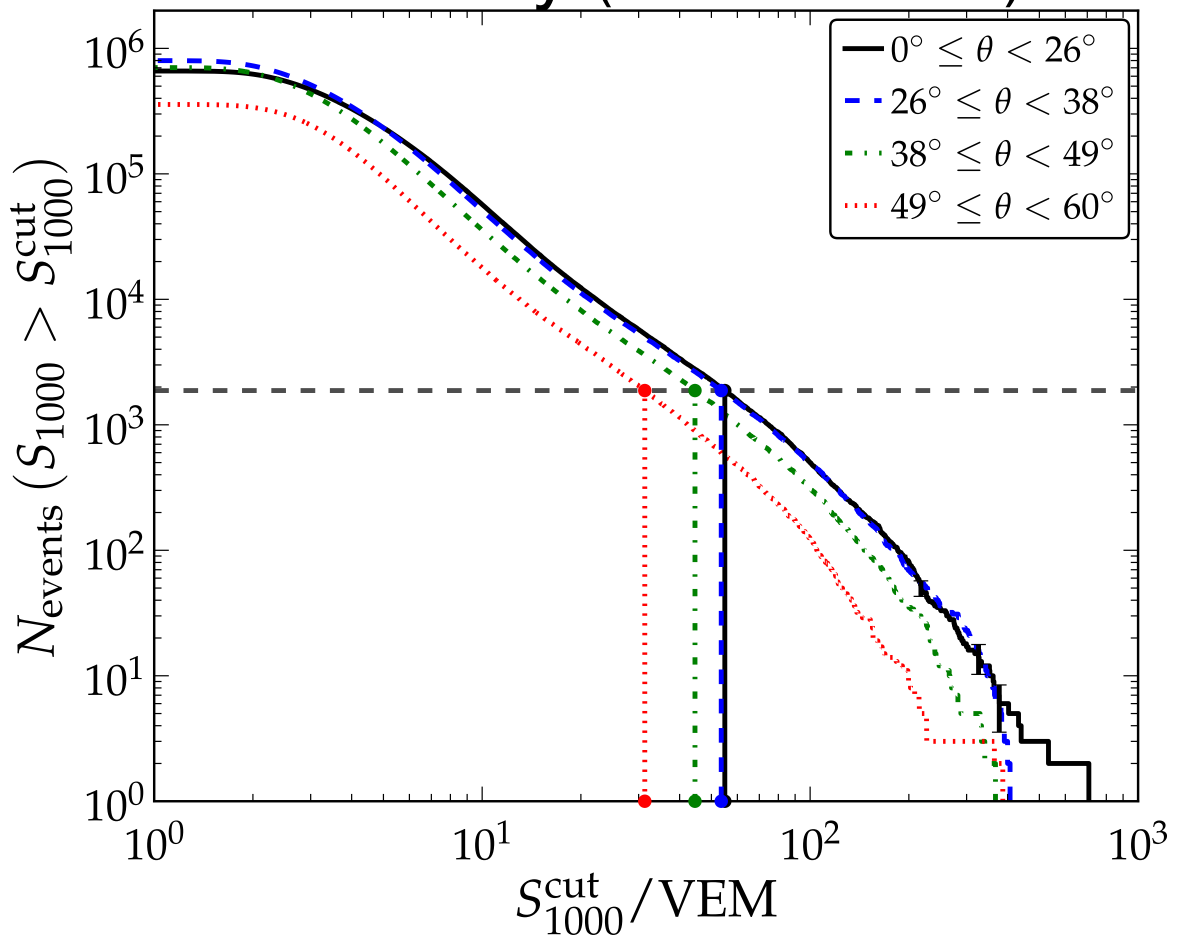
1500 m array: $S(r_{\mathrm{opt}}) = S1000$

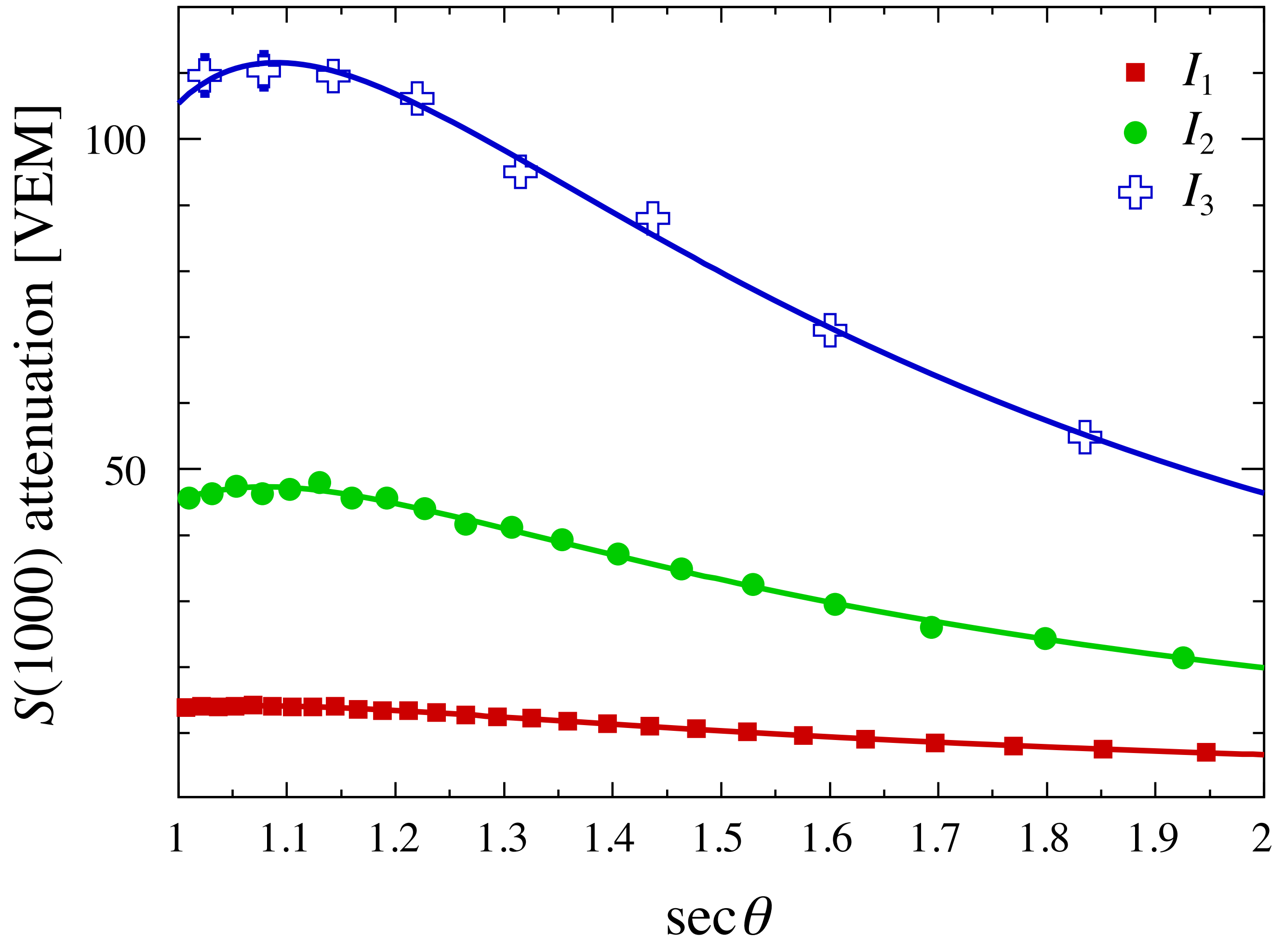
750 m array: $S(r_{\mathrm{opt}}) = S450$

θ-dependence (attenuation in atmosphere) corrected for using CIC

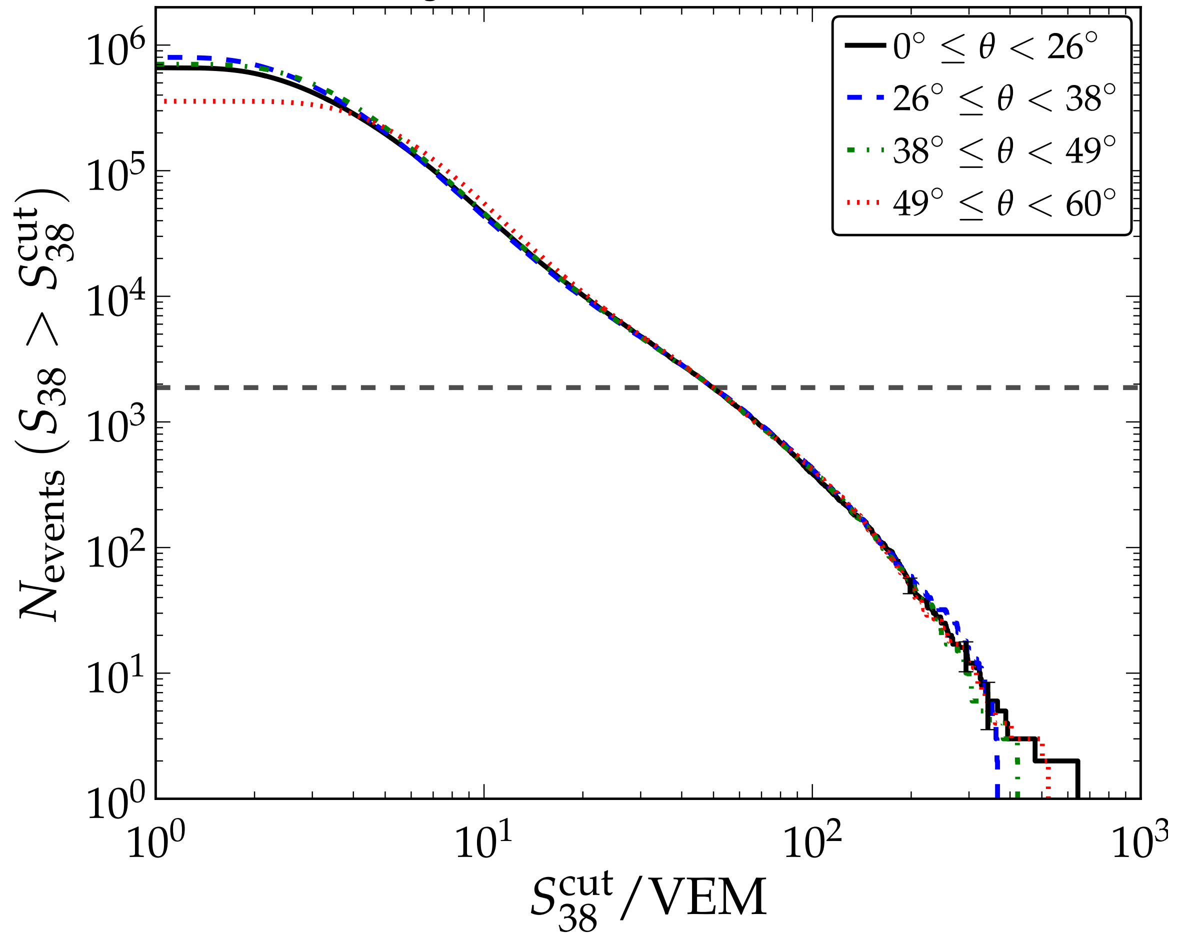


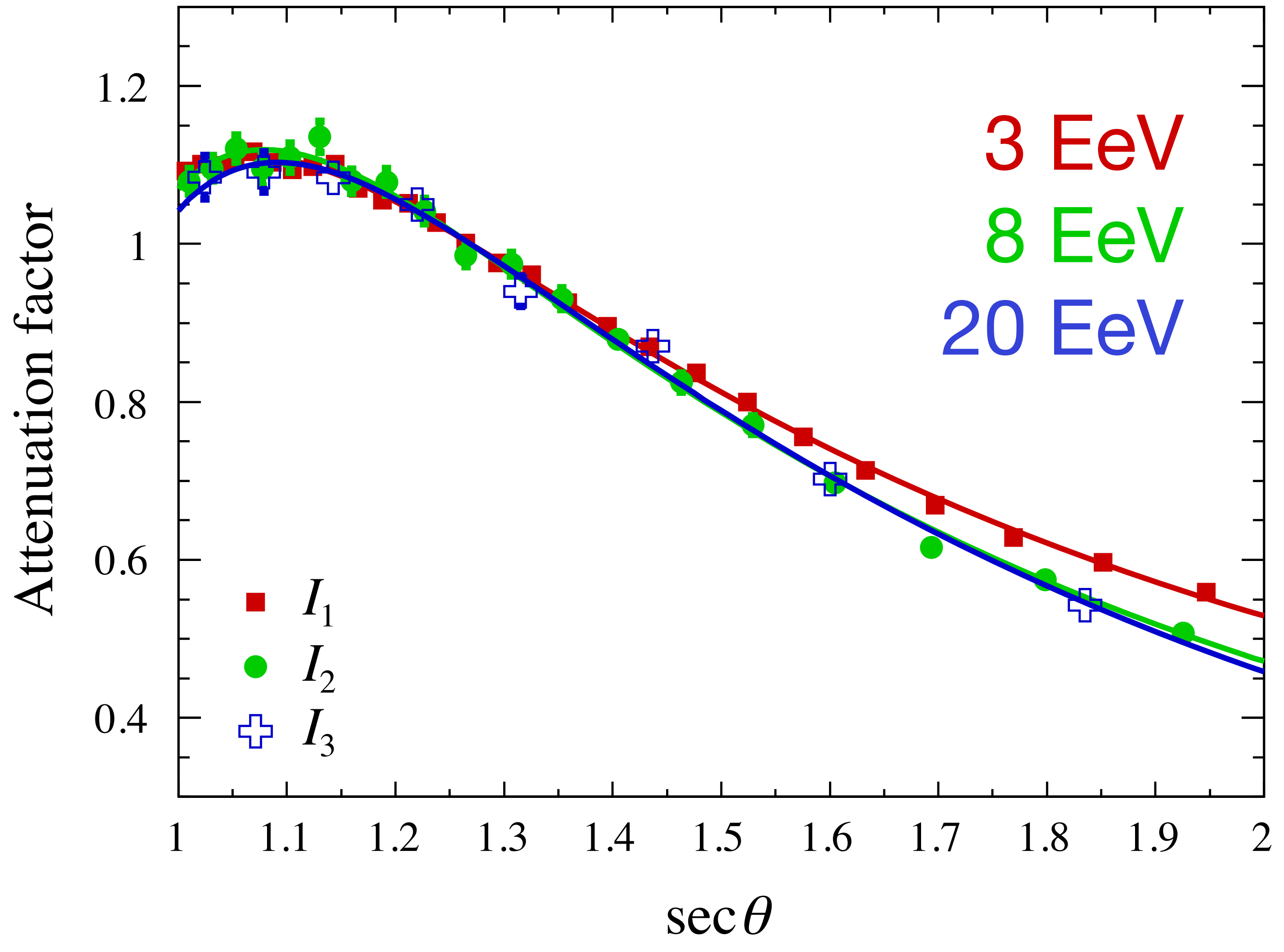
Intensity (sin²θ intervals)



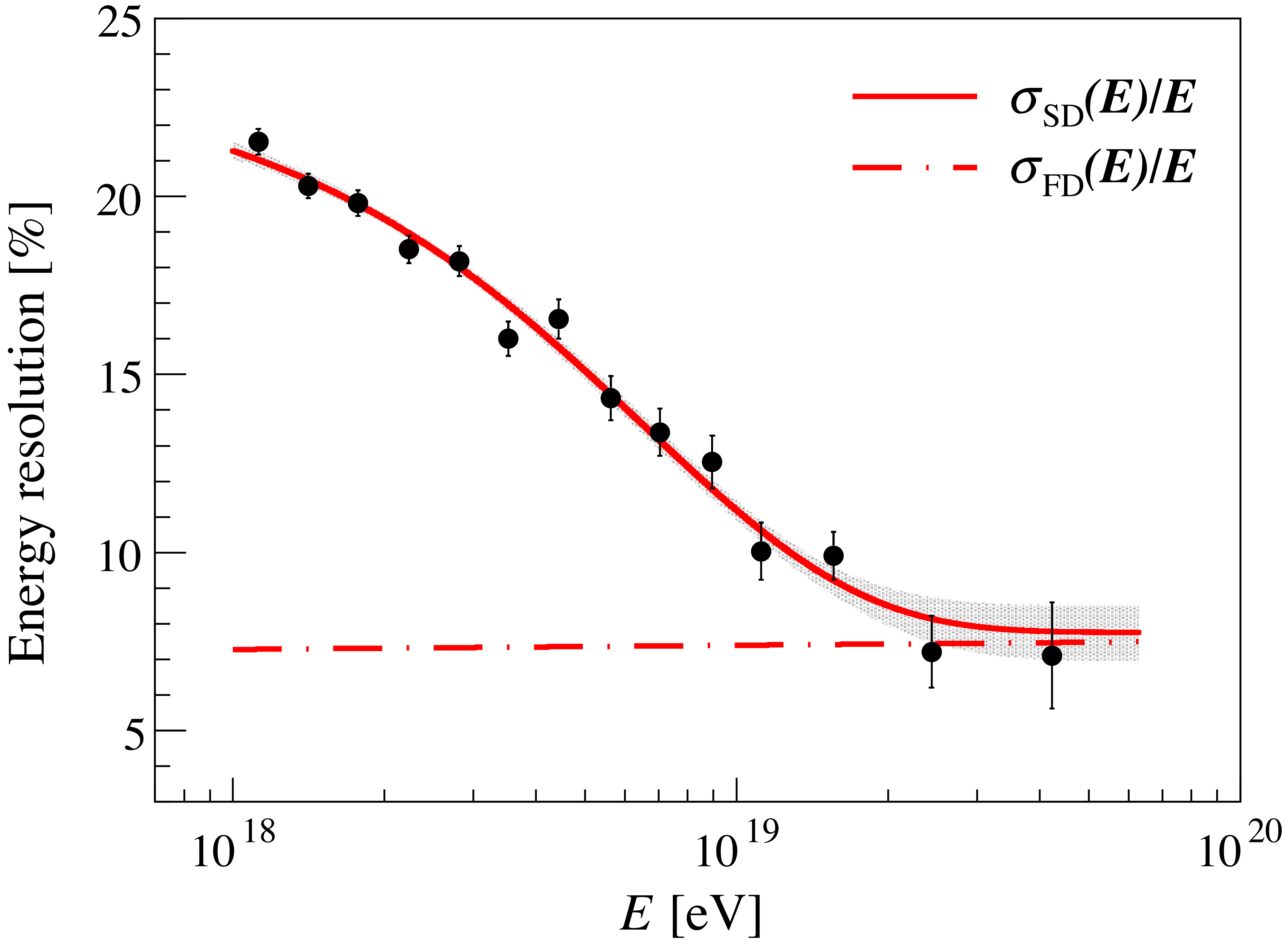


Intensity (attenuation corrected)

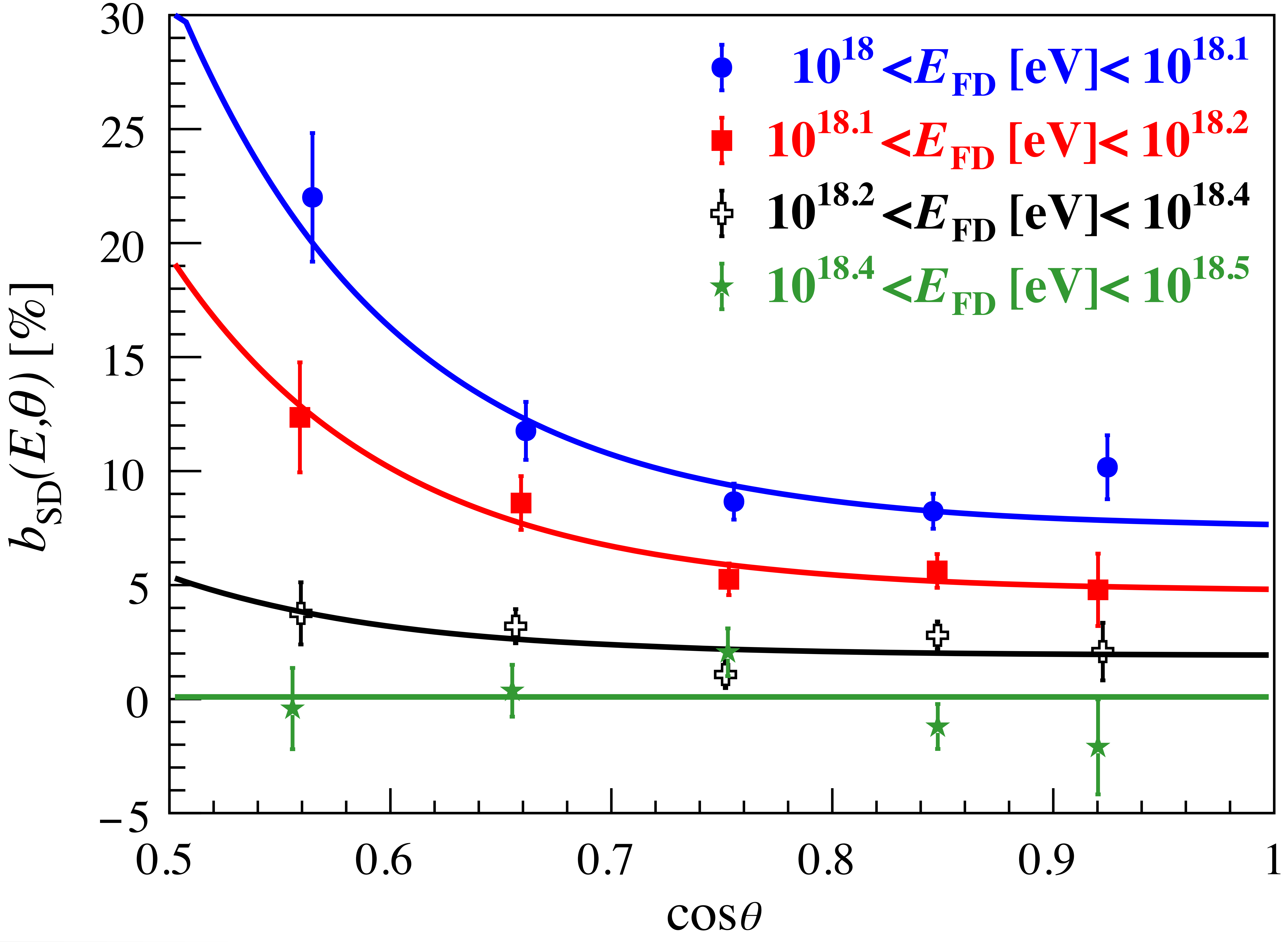




Energy resolution



Zenith dependent bias



FD correlated uncertainties

Total uncertainty: 14%
≈ energy independent

Largest contribution from FD calibration

1500 m array θ < 60°

Absolute fluorescence yield	3,4 %
Fluores. spectrum and quenching param.	1,1 %
Sub total (Fluorescence Yield)	**3,6 %**
Aerosol optical depth	3 % — 6 %
Aerosol phase function	1 %
Wavelength dependence of aerosol scattering	0,5 %
Atmospheric density profile	1 %
Sub total (Atmosphere)	**3,4 % — 6,2 %**
Absolute FD calibration	9 %
Nightly relative calibration	2 %
Optical efficiency	3,5 %
Sub total (FD calibration)	**9,9 %**
Folding with point spread function	5 %
Multiple scattering model	1 %
Simulation bias	2 %
Constraints in the Gaisser-Hillas fit	**1 % — 3,5 %**
Sub total (FD profile rec.)	**5,6 % — 6,5 %**
Invisible energy	**1,5 % — 3 %**
Statistical error of the SD calib. fit	**0,7 % — 1,8%**
Stability of the energy scale	**5 %**
TOTAL	**14 %**