Measurements of the Energy Spectrum of Ultra-High Energy Cosmic Rays by the Pierre Auger Observatory and the Telescope Array

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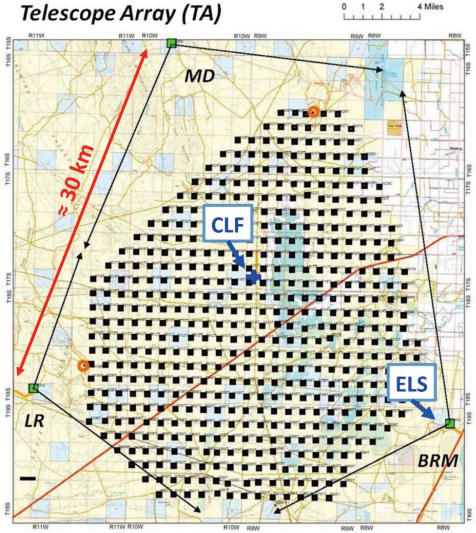
The Auger-TA Joint Working Group

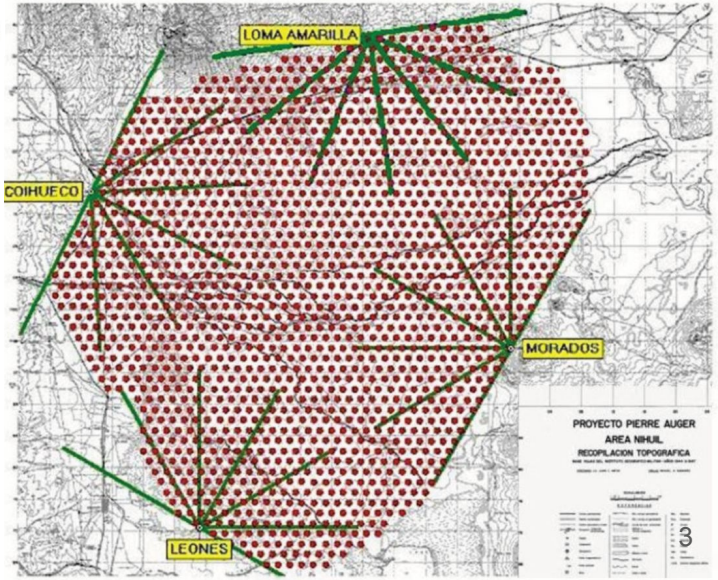
Auger-TA Joint Working Group Activities

0. UHECR2010 (Nagoya): Proposed the idea of joint working groups
1. UHECR2012 (CERN): First WG joint talk - Y. Tsunesada
2. UHECR2014 (Springdale) - I. Maris
3. UHECR2016 (Kyoto) - V. Verzi
4. ICRC2017 (Busan) - D. Ivanov
5. UHECR2018 (Paris) - D. Ivanov
6. ICRC2019 (Madison) - O. Deligny
    - UHECR2020 (Moscow) - Postponed
7. ICRC2021 (Berlin/Online) - This talk

Auger and TA



TA
39°N
700km^2

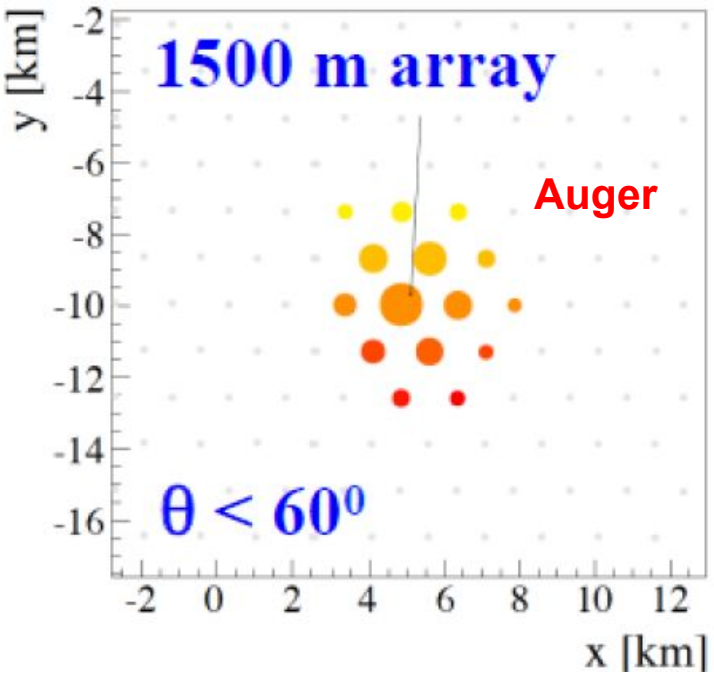


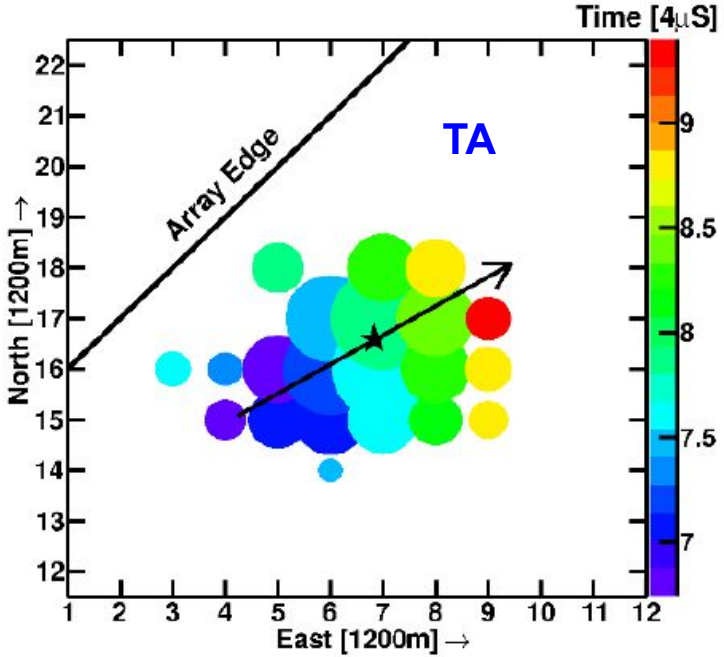
Auger
35°S
3000km^2

Auger and TA

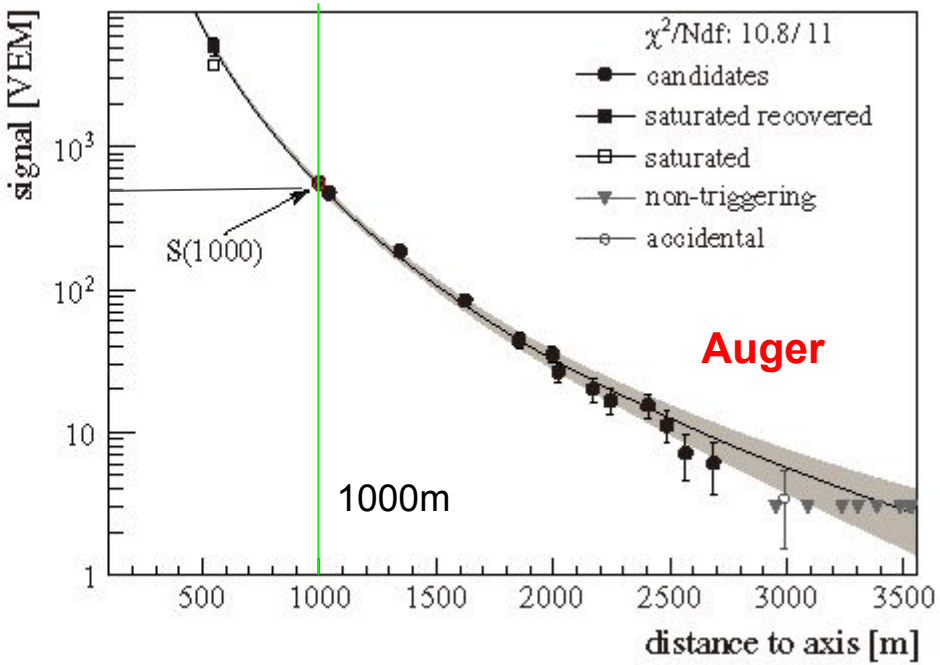
- Hybrid detectors: Fluorescence detectors (FD) and Surface Detectors (SD)
- FD: the longitudinal development, calorimetric measurement, 10% duty cycle
- SD: ~100% duty cycle -> Use SD data for spectrum study
- Energy calibration
  - Pick up hybrid events triggered by both FD and SD
  - Compare the FD energy E_{FD} and an SD energy estimator S
  - Use the formula $E(S, \theta)$ for all the SD events

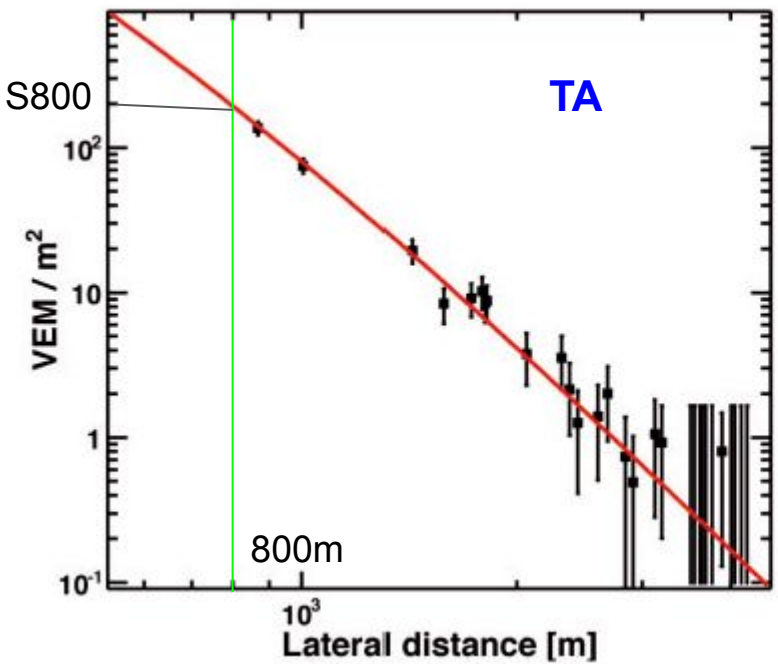
Air shower footprints by Auger and TA SD arrays





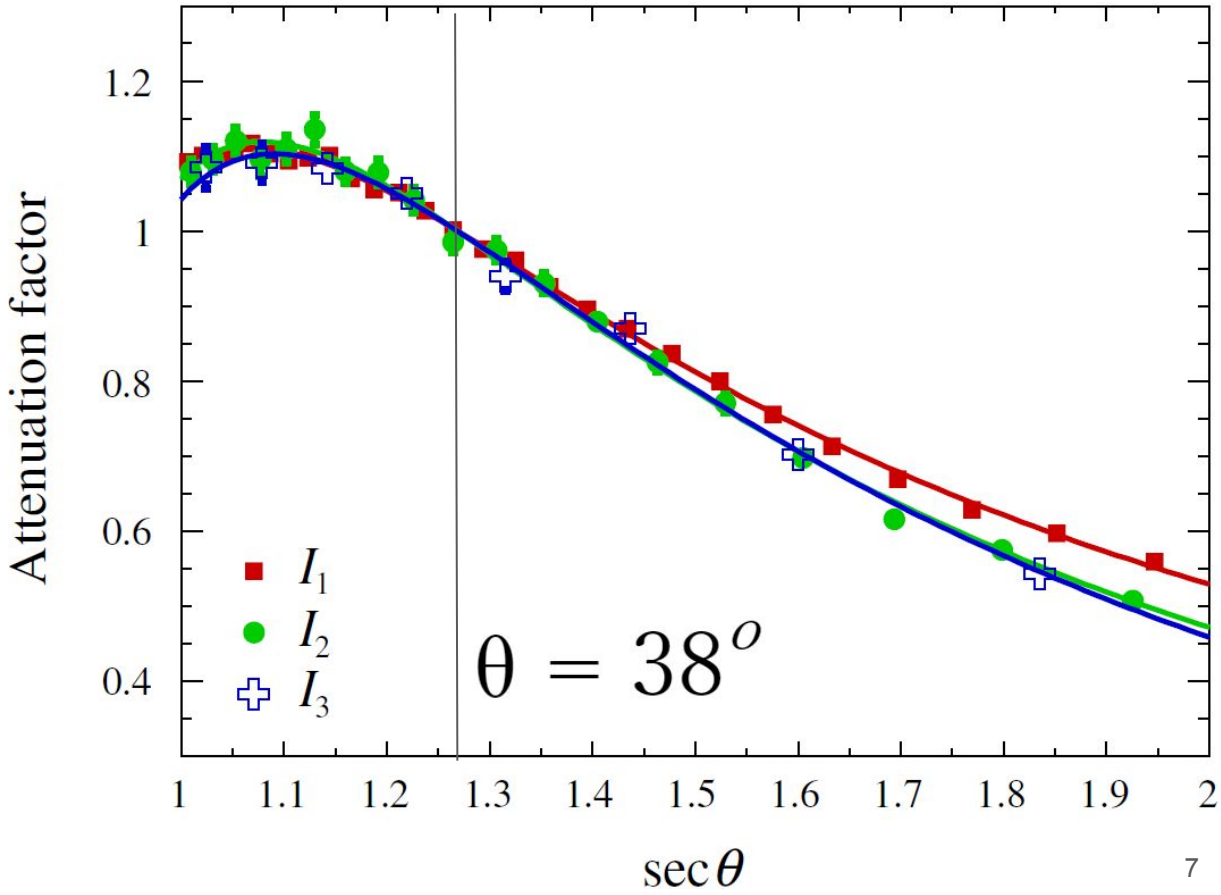
SD Energy Estimators: S1000 and S800



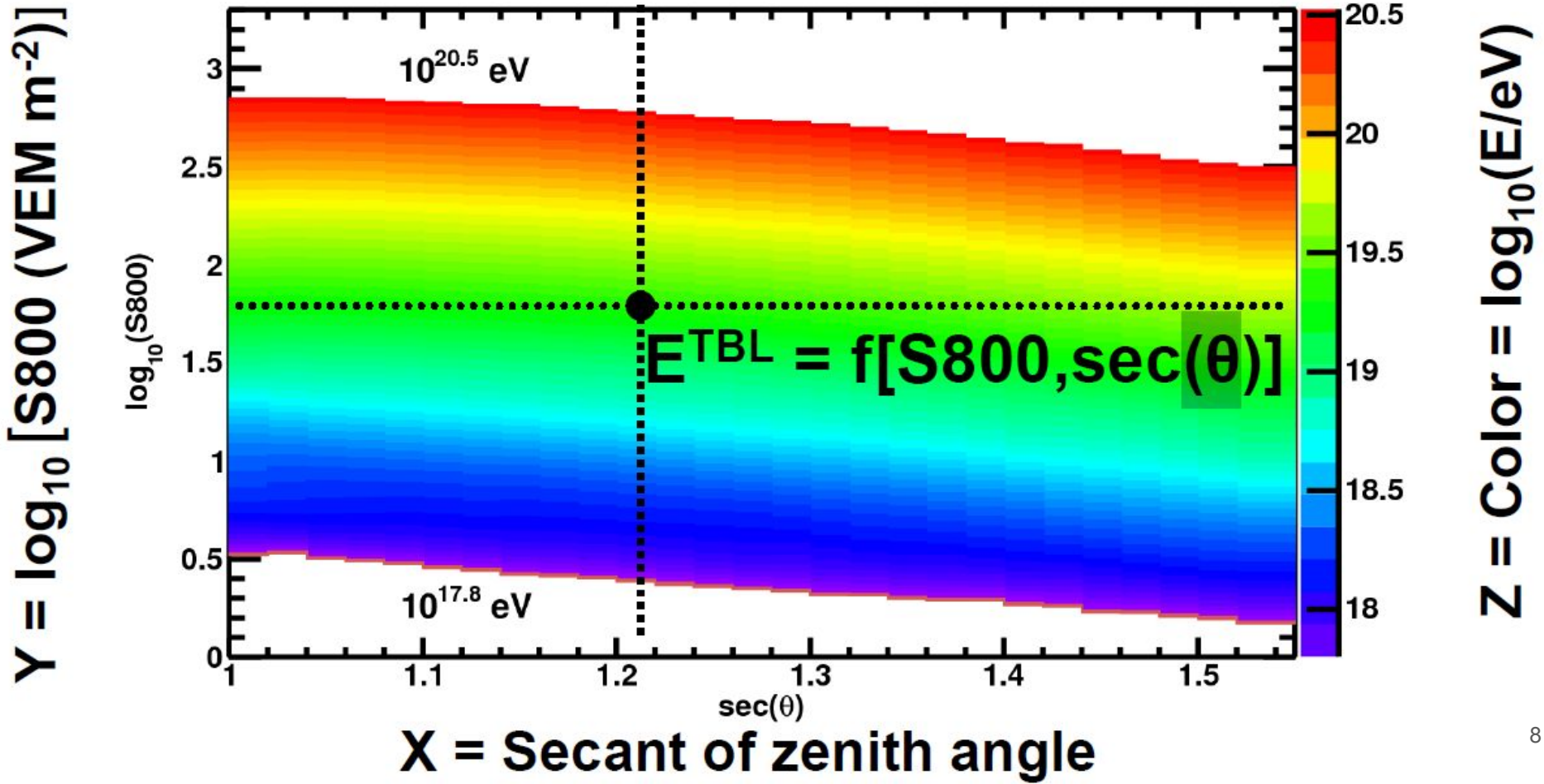


Auger: shower attenuation: S1000 -> S_{38}

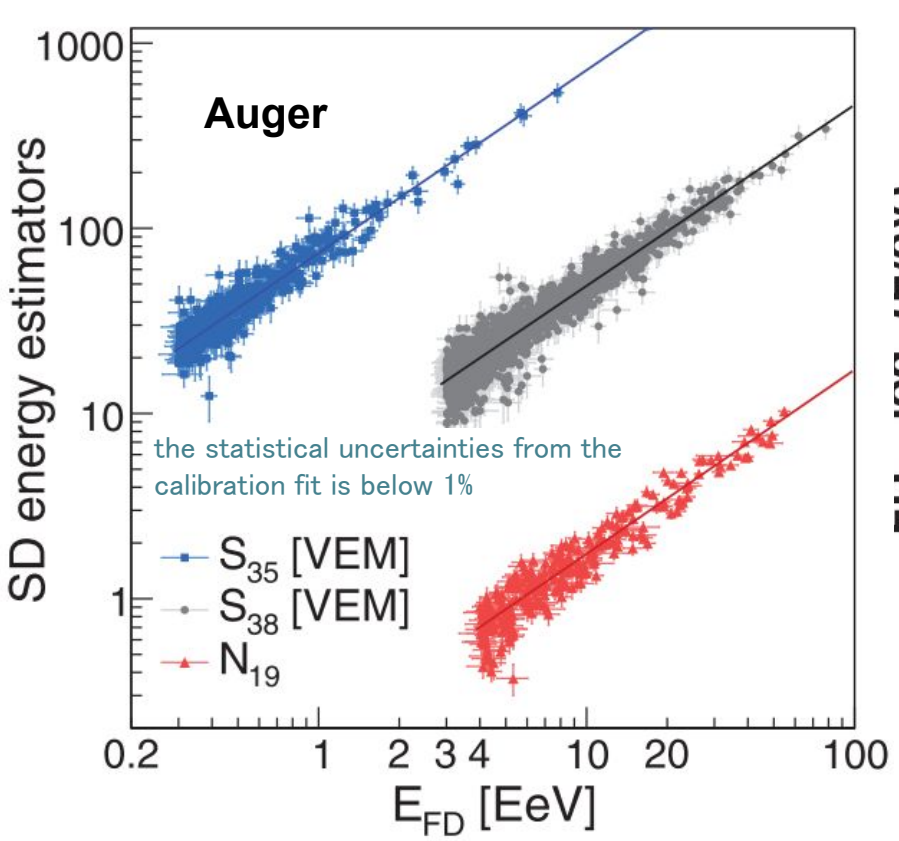
- Attenuation curve obtained by the constant-intensity cut (CIC) method - free from shower Monte-Carlo
- S_{38} has a good linear correlation between E_{FD}
- Formula $E(S_{38})$ is applied to all the SD events

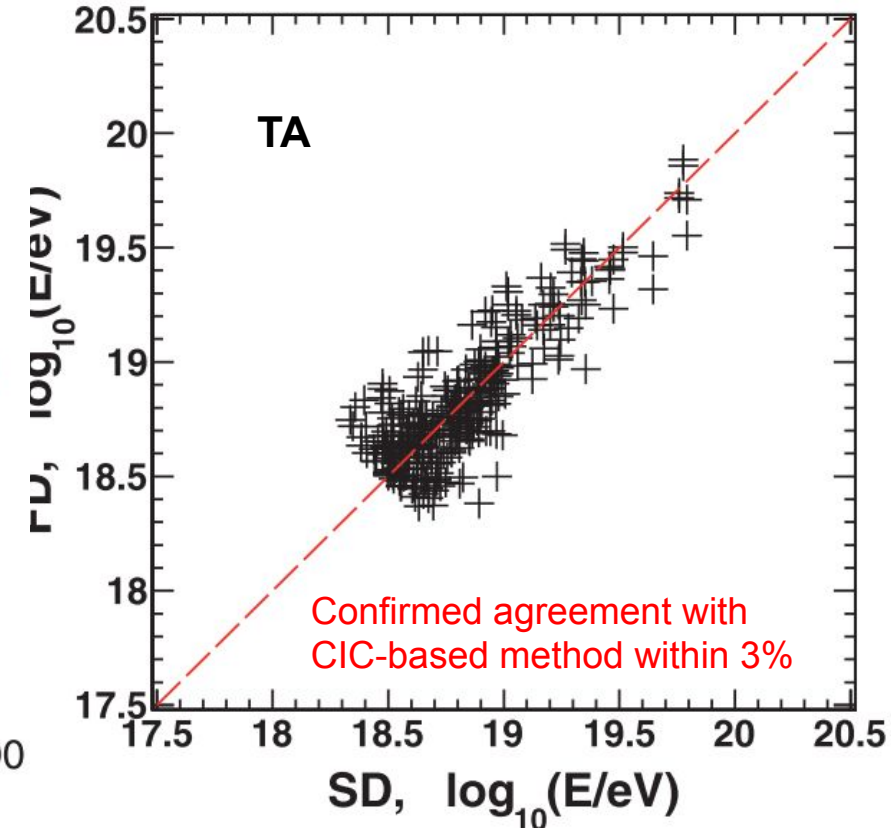


TA: Energy look-up table (S800, θ) -> E

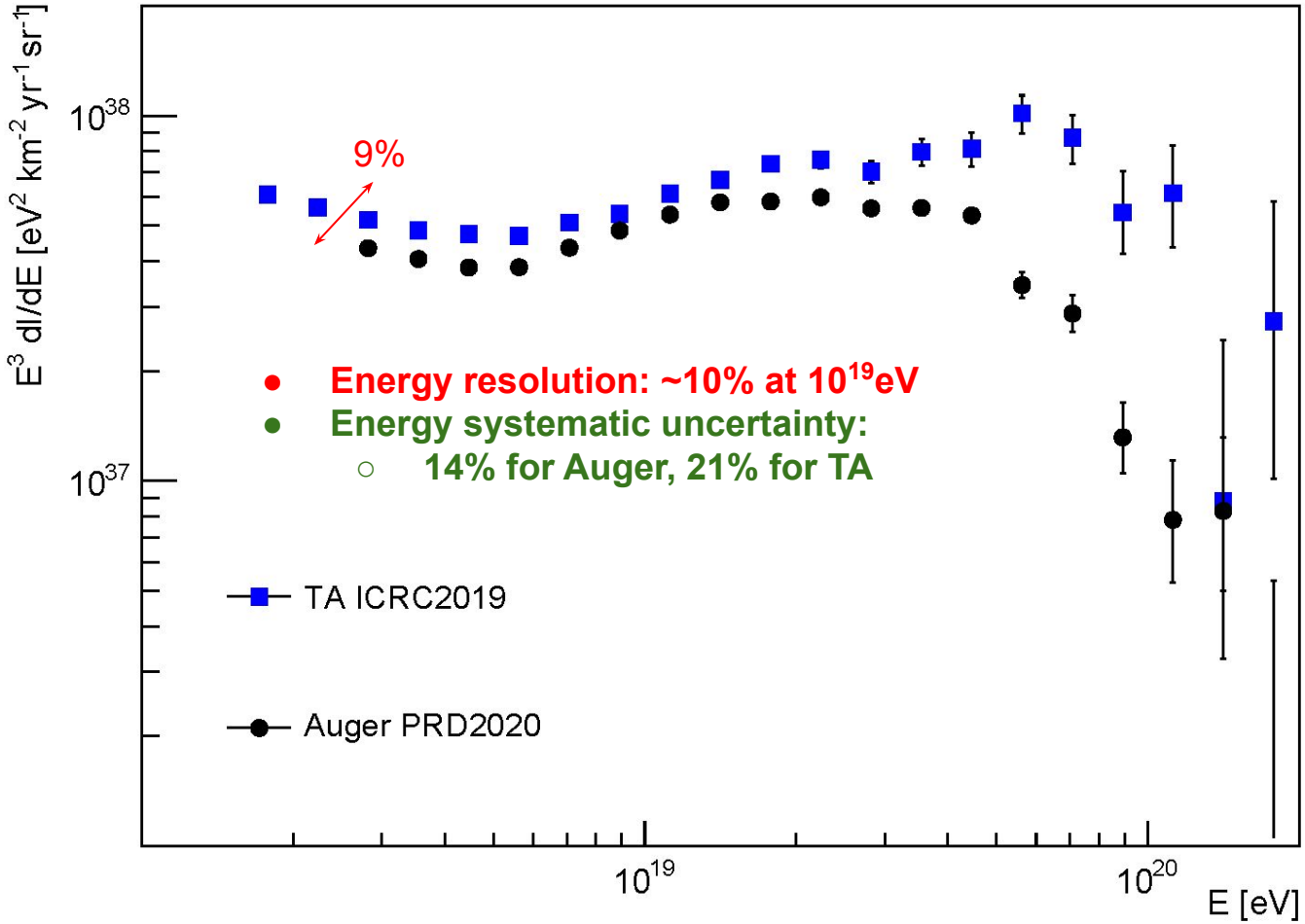


E_{SD}-E_{FD} Correlation

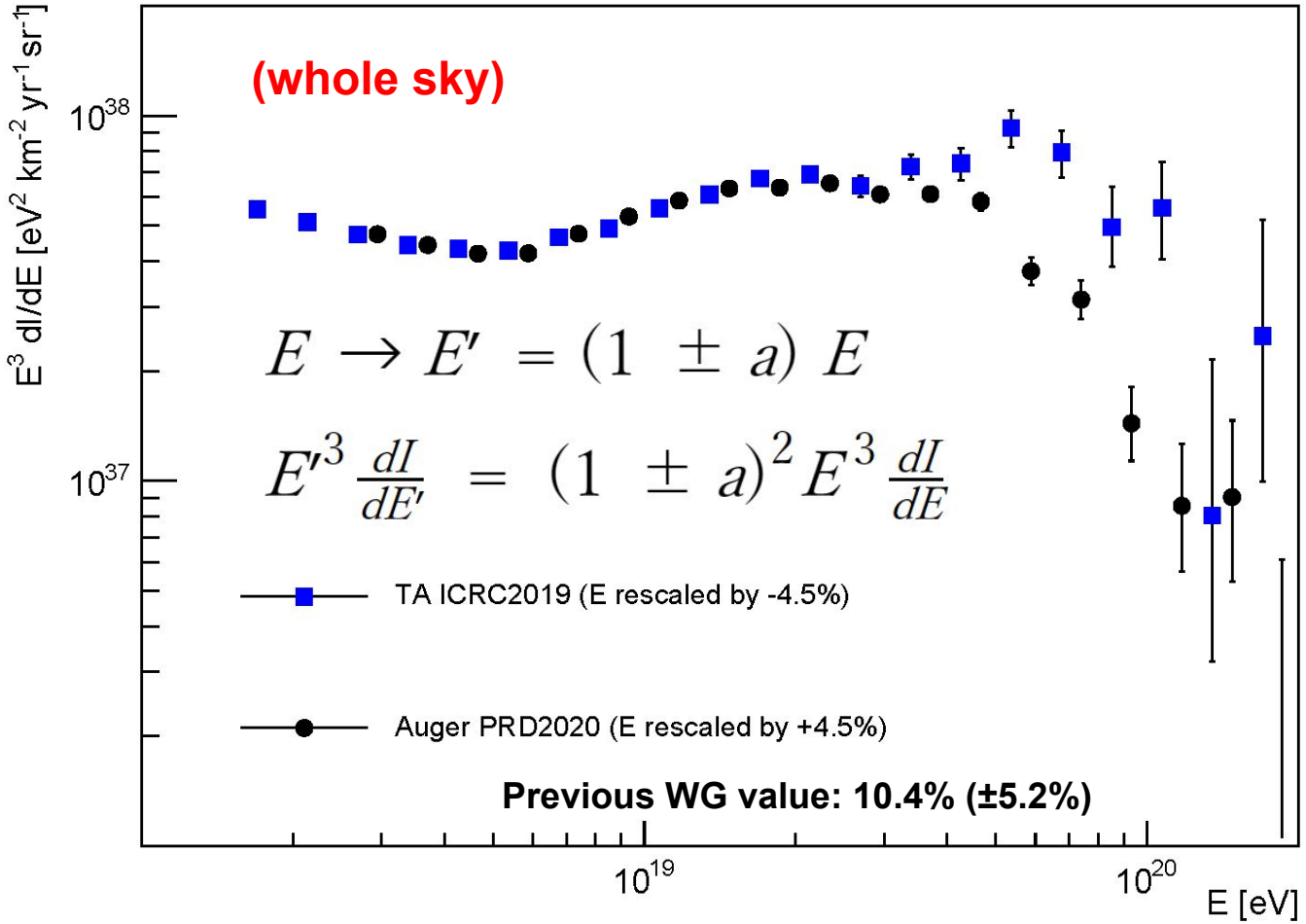




Auger & TA Energy Spectrum

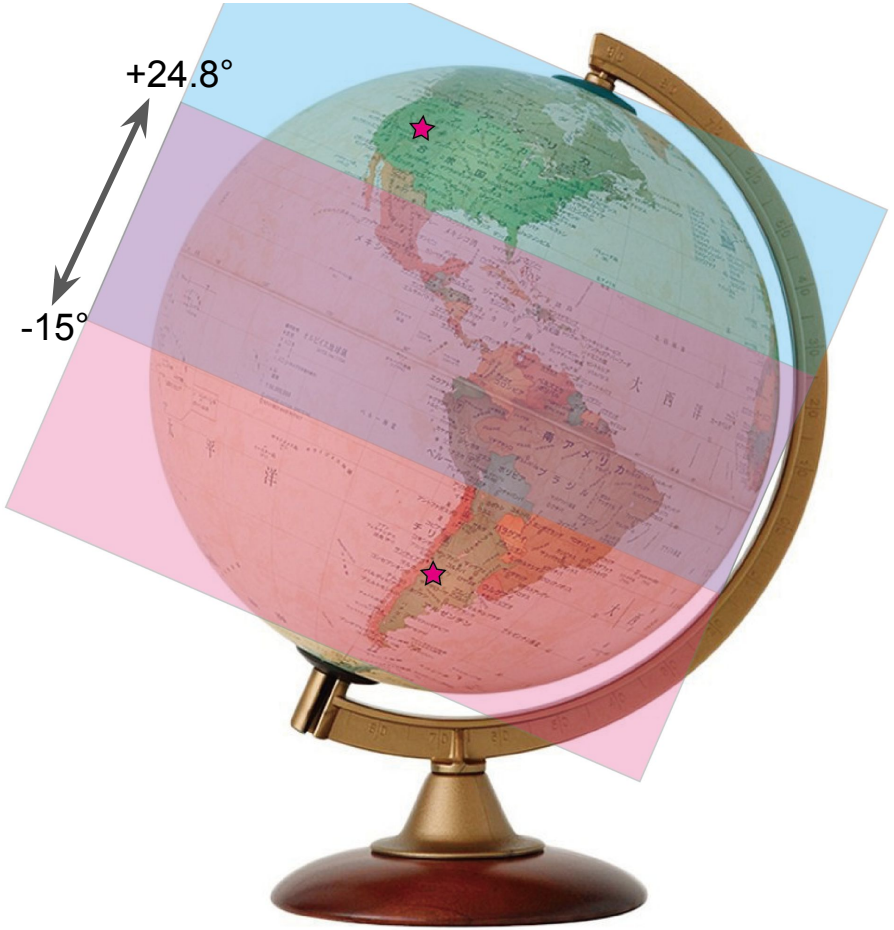


Auger & TA Energy Spectrum (energy ±4.5% rescaled)

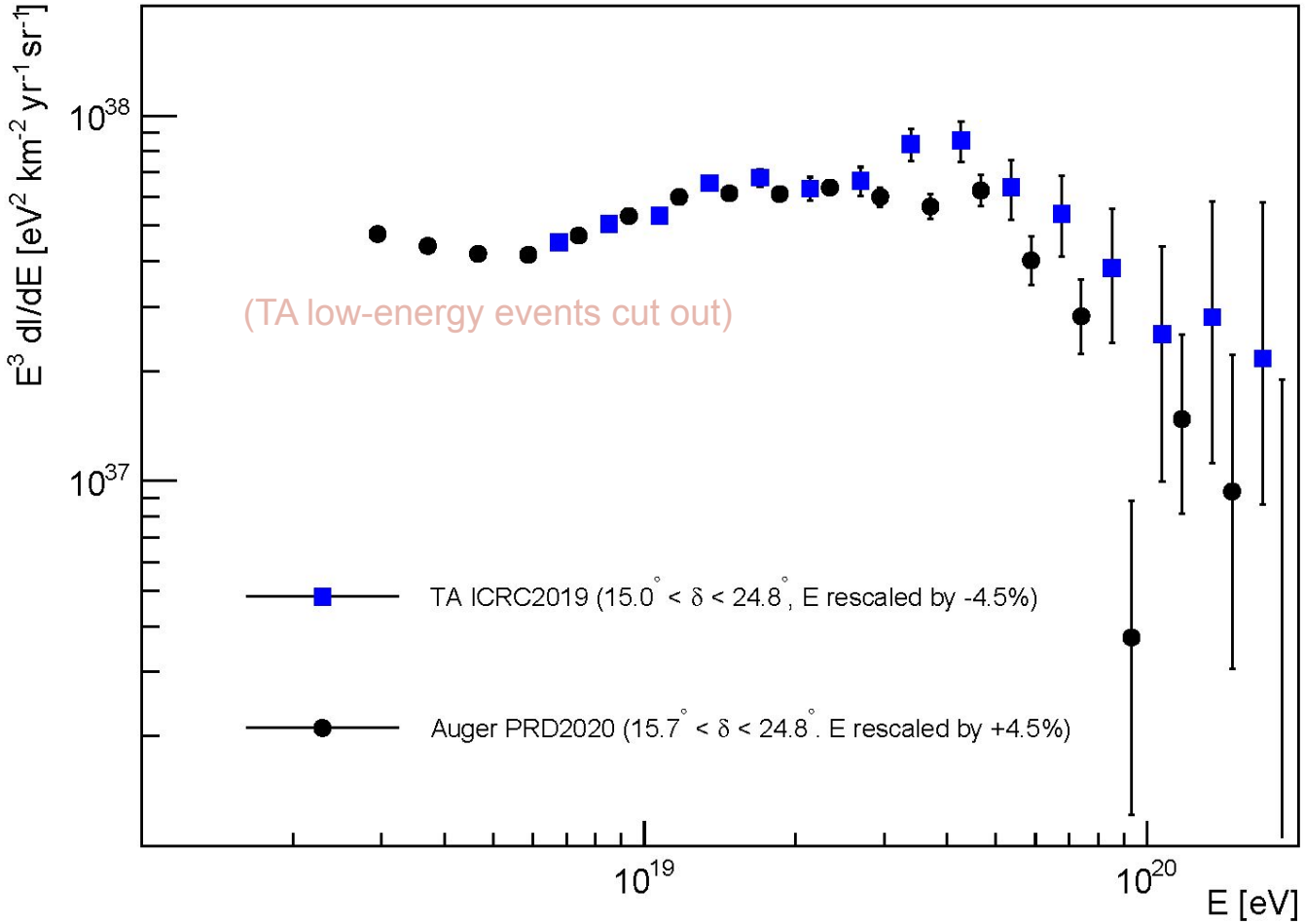


The Common Declination Band

- Auger: 35°S
  - θ up to 60°
- TA: 39°N
  - θ up to 55°
- Common declination band
  - -15° < δ < 24.8°

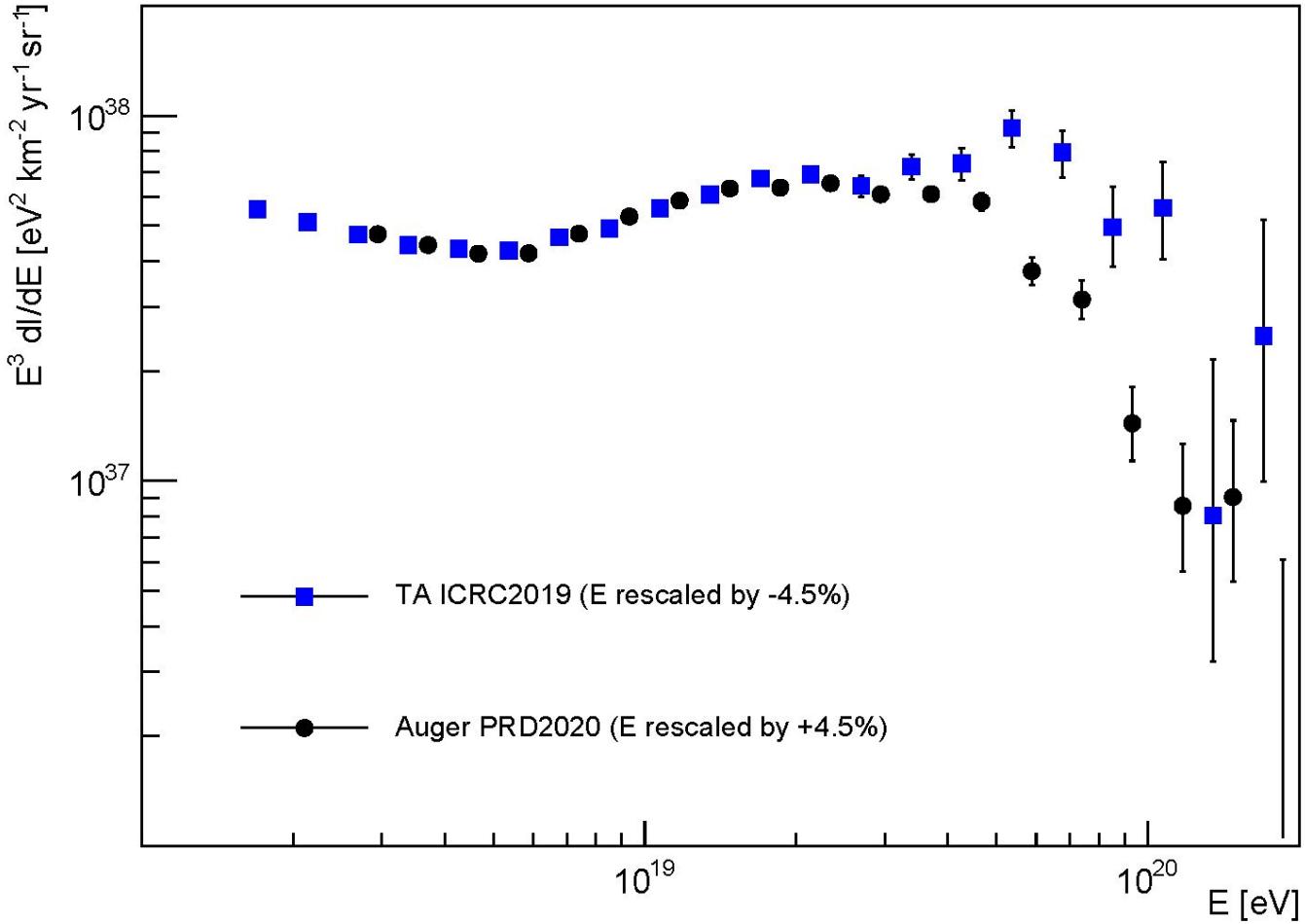


Common declination band spectrum

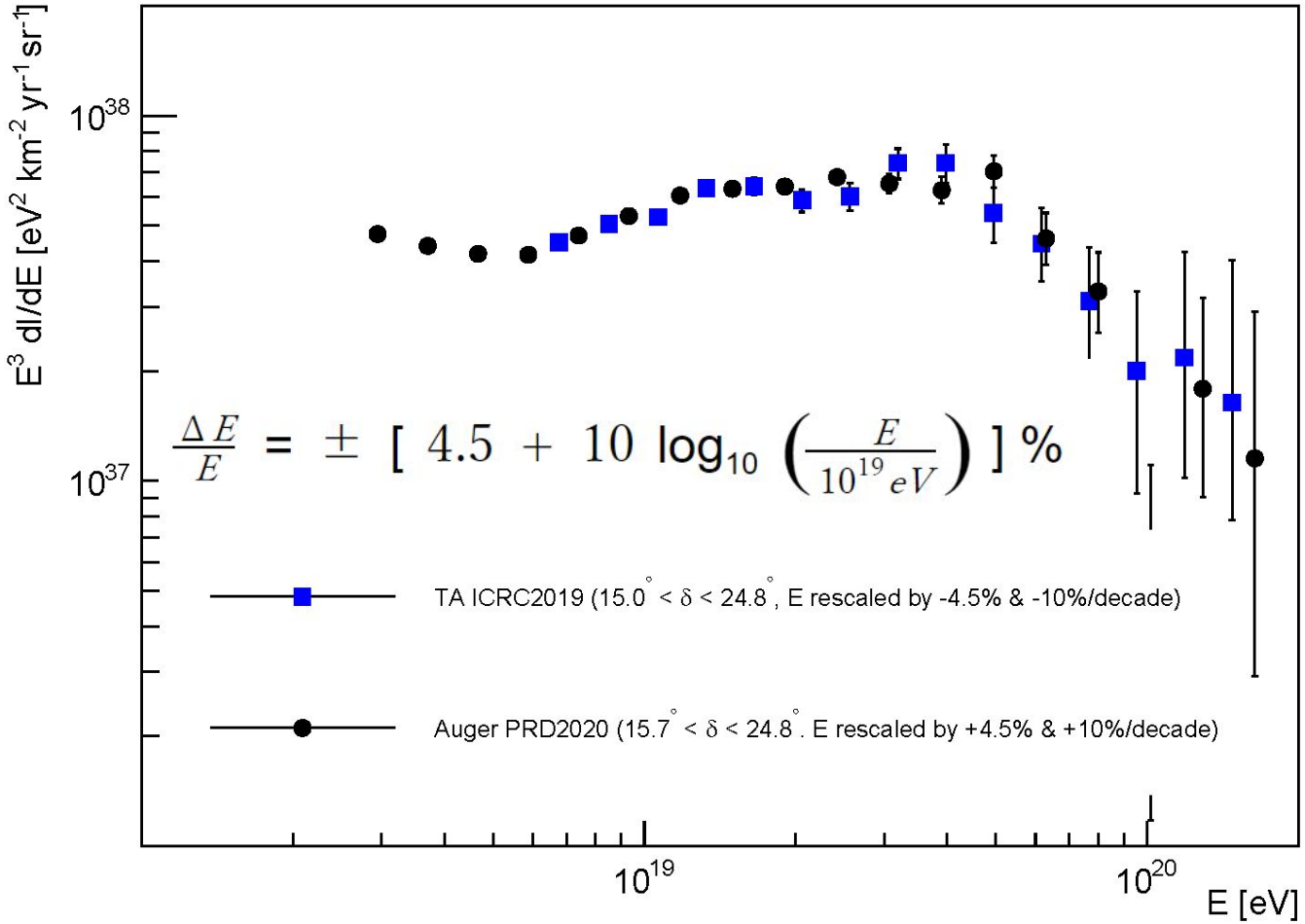


Auger & TA Energy Spectrum (whole sky)

(same as page 11)

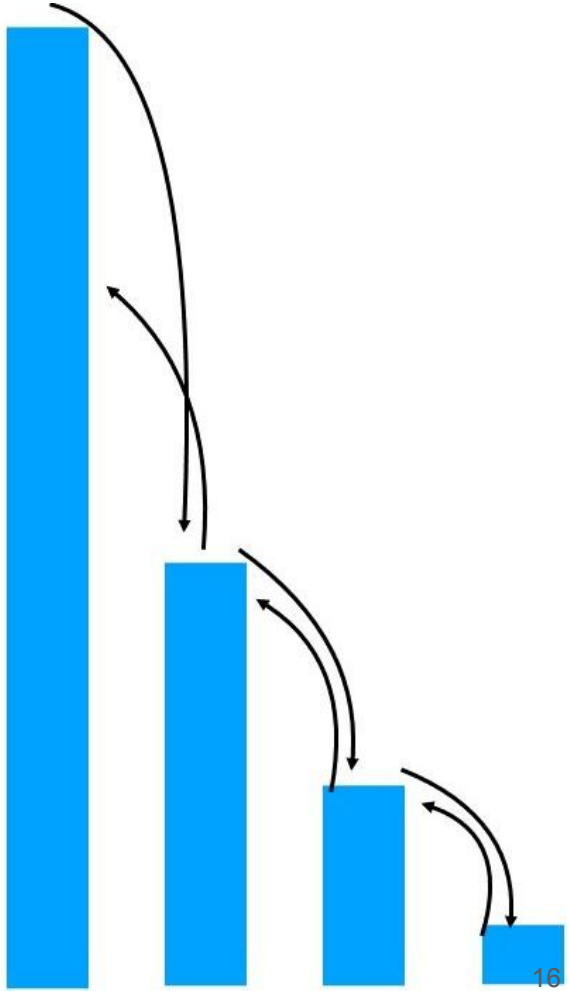


Common band spectrum (shift + E-dependent shift)

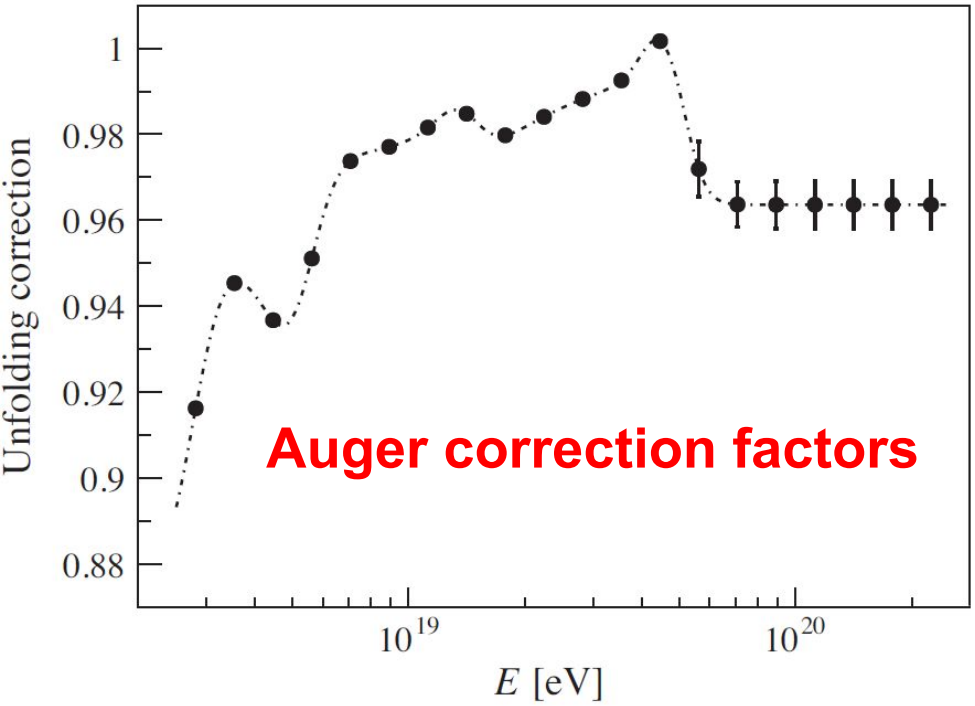


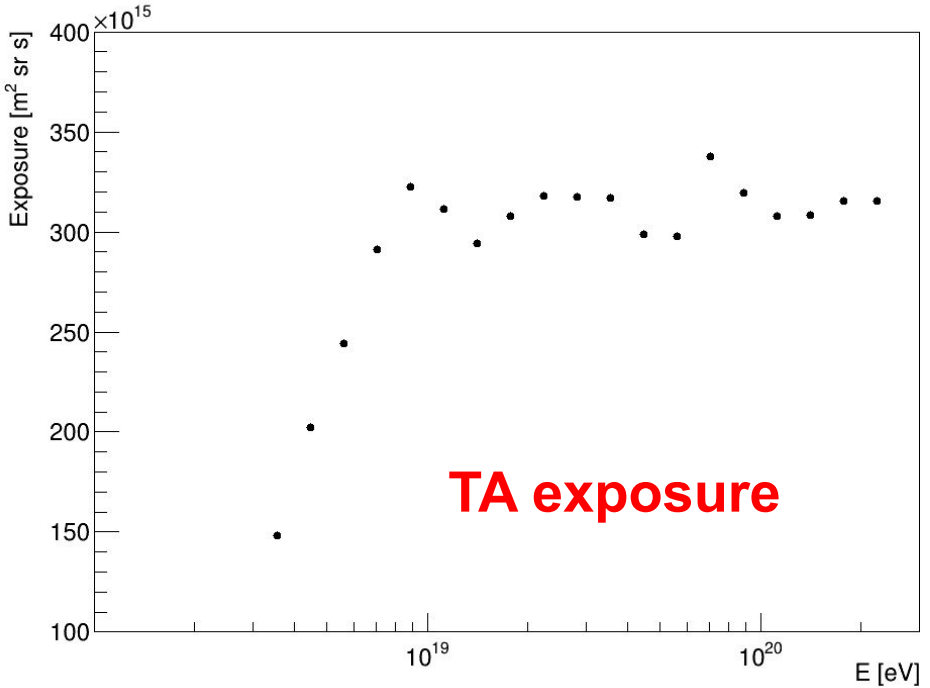
Bin migrations/Spectrum unfolding

- Finite energy resolution / Finite bin width
- Asymmetric net effects even in symmetric migration in E^3 spectrum
- Energy distribution dN/dE must be somehow "unfolded" to calculate dI/dE = (1/ω) dN/dE
- Auger: A *forward folding method* using the geometrical exposure, shower physics and detector response, and an energy spectrum fitting function (*JCAP* **04** 038 (2017), *PRD* **102** 062005 (2020))
- TA: Evaluate the exposure $\omega(E)$ as a function of energy by shower MC + detector response, assuming a previously measured spectrum



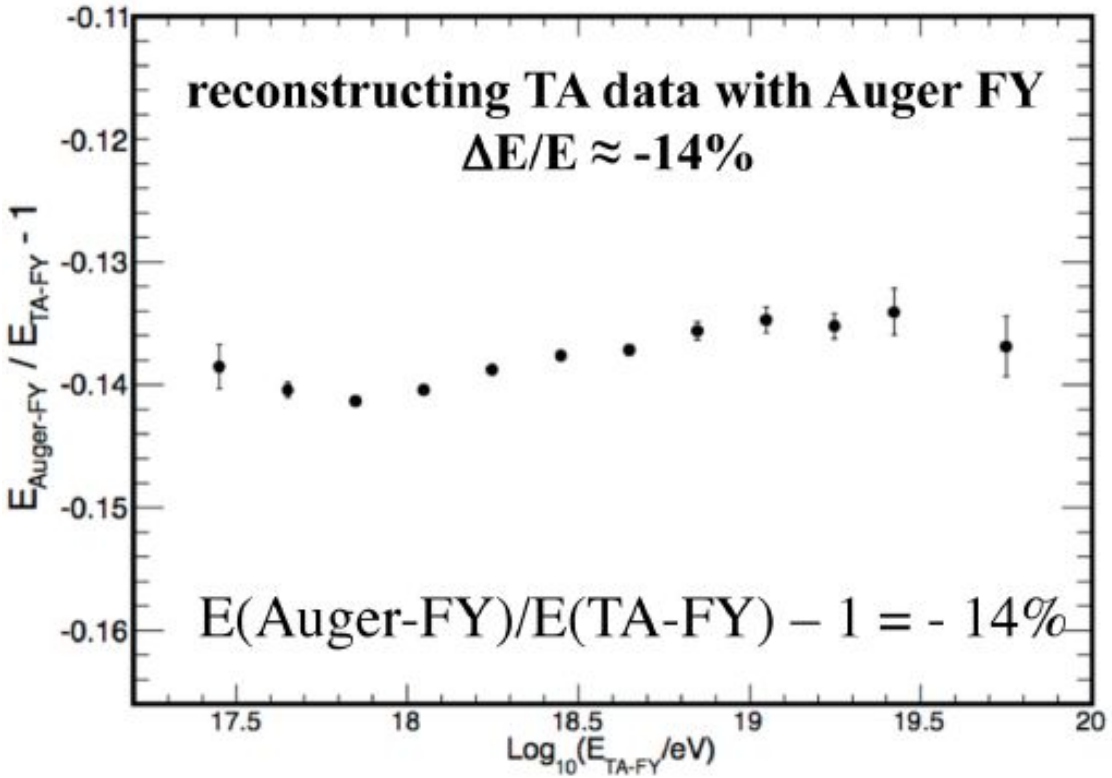
Spectrum unfolding





Impact of the Fluorescence Yield Model

- Auger: AirFly result (*Astropart. Phys.* **42** 90 2013, 3.6% uncertainty)
- TA: Kakimoto et al. (*NIM-A*, **372** 527 1996, 11% uncertainty) + FLASH spectrum
- 14% difference

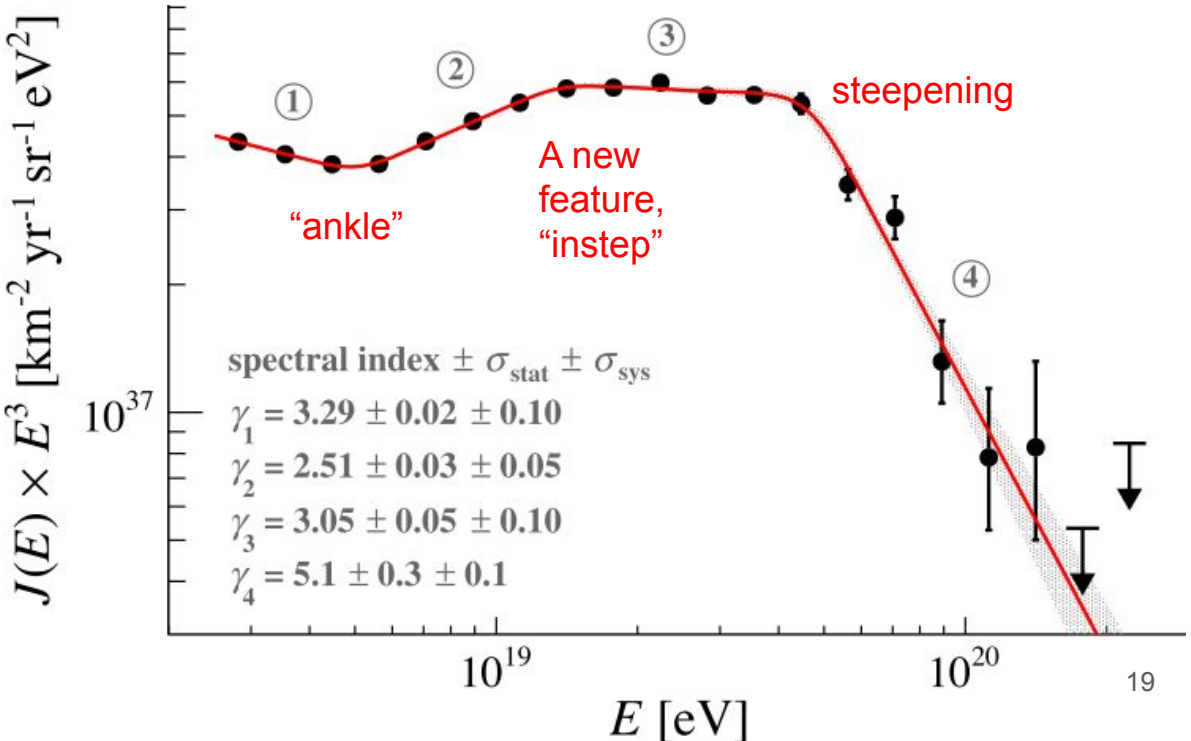


New Feature in the Energy Spectrum

Auger *PRL* **125** 121106 (2020), *PRD* **102** 062005 (2020)

$$\frac{dI}{dE} = I_0 \left(\frac{E}{10^{18.5}\ eV}\right)^{-\gamma_1} \prod_{i=1}^{3} \left[1 + \left(\frac{E}{E_{ij}}\right)^{1/\omega_{ij}}\right]^{(\gamma_i - \gamma_j)\omega_{ij}}$$

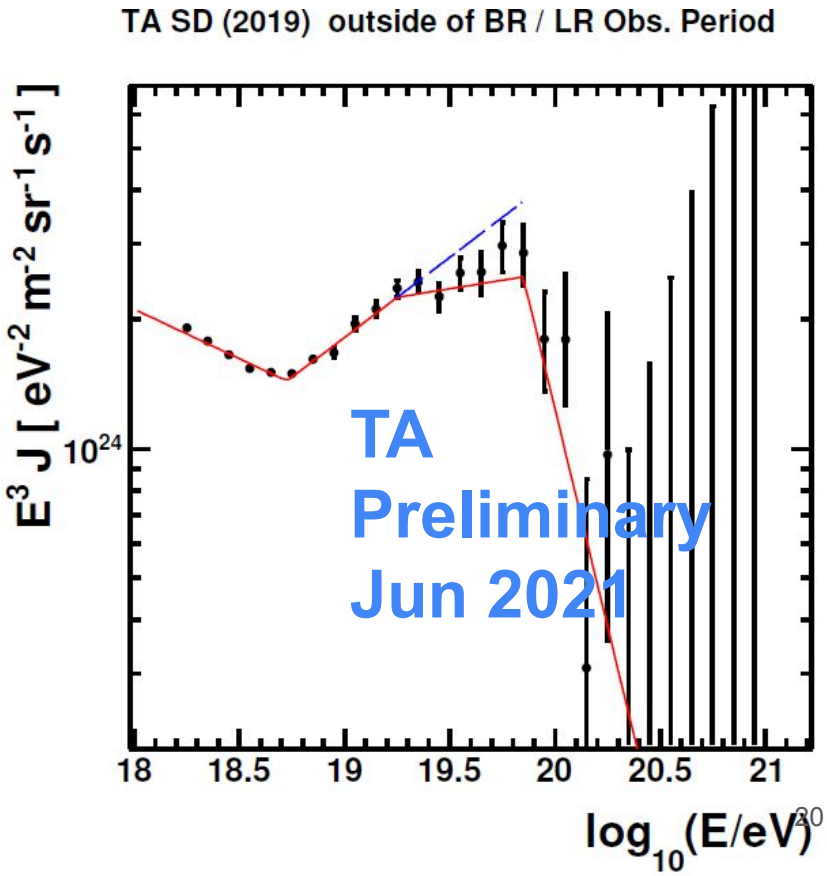
- 2-step softening after the *ankle*
- No dependence on θ and δ



New Feature in the Energy Spectrum - TA Case

- Combining HiRes-1, TA SD, and TA FD, a two-step softening exists in the northern heisphere data.
  - 5.3σ deficit above $10^{19.25}$eV from an assumption of no breaks before the high-energy steepening

Parameter	Auger	TA
γ_1	3.29 ± 0.02	3.23 ± 0.01
γ_2	2.51 ± 0.03	2.63 ± 0.02
γ_3	3.05 ± 0.05	2.92 ± 0.06
γ_4	5.1 ± 0.3	5.0 ± 0.4
$E_{\rm ankle}$/EeV	5.0 ± 0.1	5.4 ± 0.1
$E_{\rm instep}$/EeV	13 ± 1	18 ± 1
$E_{\rm cut}$/EeV	46 ± 3	71 ± 3



Summary

- Update the Auger and TA spectrum comparisons
- Absolute energy scale difference 9%
- Better agreement in the common declination band $-15° < \delta < 24.8°$
  - Even better if an energy-dependent shift of 10%/decade added
- The new spectral feature: “instep”
  - 2-step softening after ankle (Auger *PRL*, *PRD* 2020)
  - Confirmed in the northern hemisphere data (TA SD, FD and HiRes-1)
- Future prospects
  - Highest energy difference, Statistics? Energy-dependent shift?
  - Astrophysical interpretation of the spectral feature
  - TAx4 spectrum, AugerPrime data
  - Extension to lower energies (TALE FD, TALE SD, HEAT, etc.)