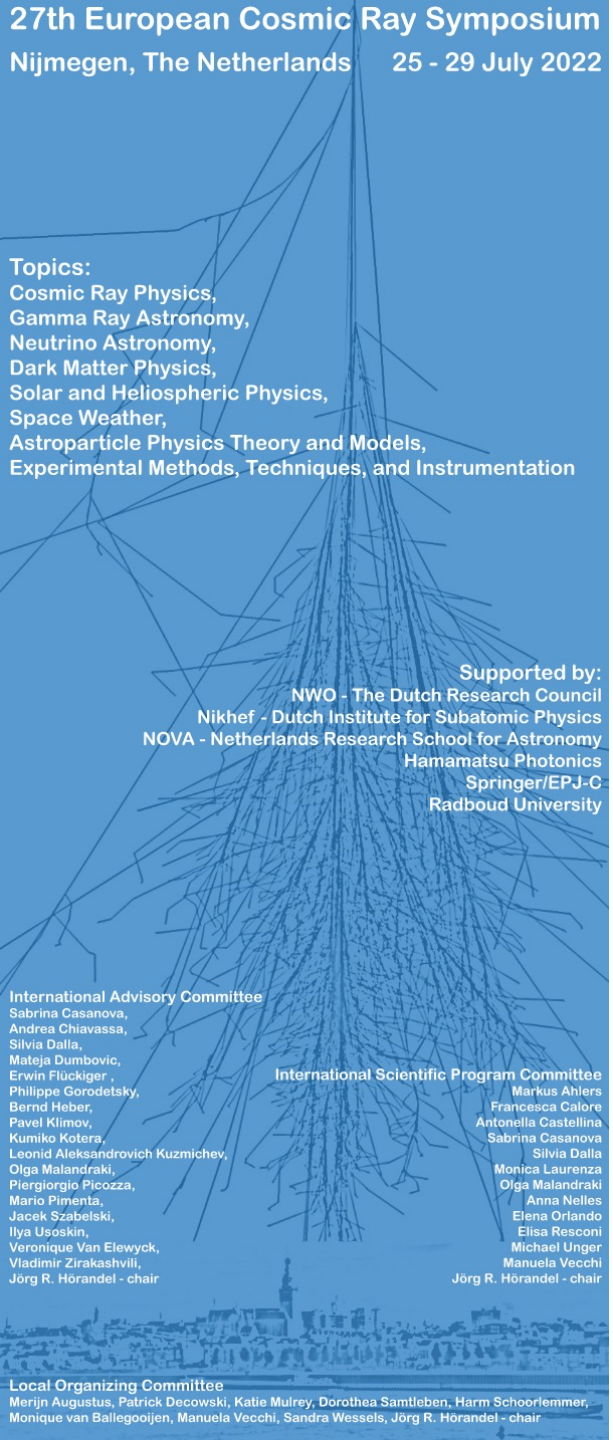


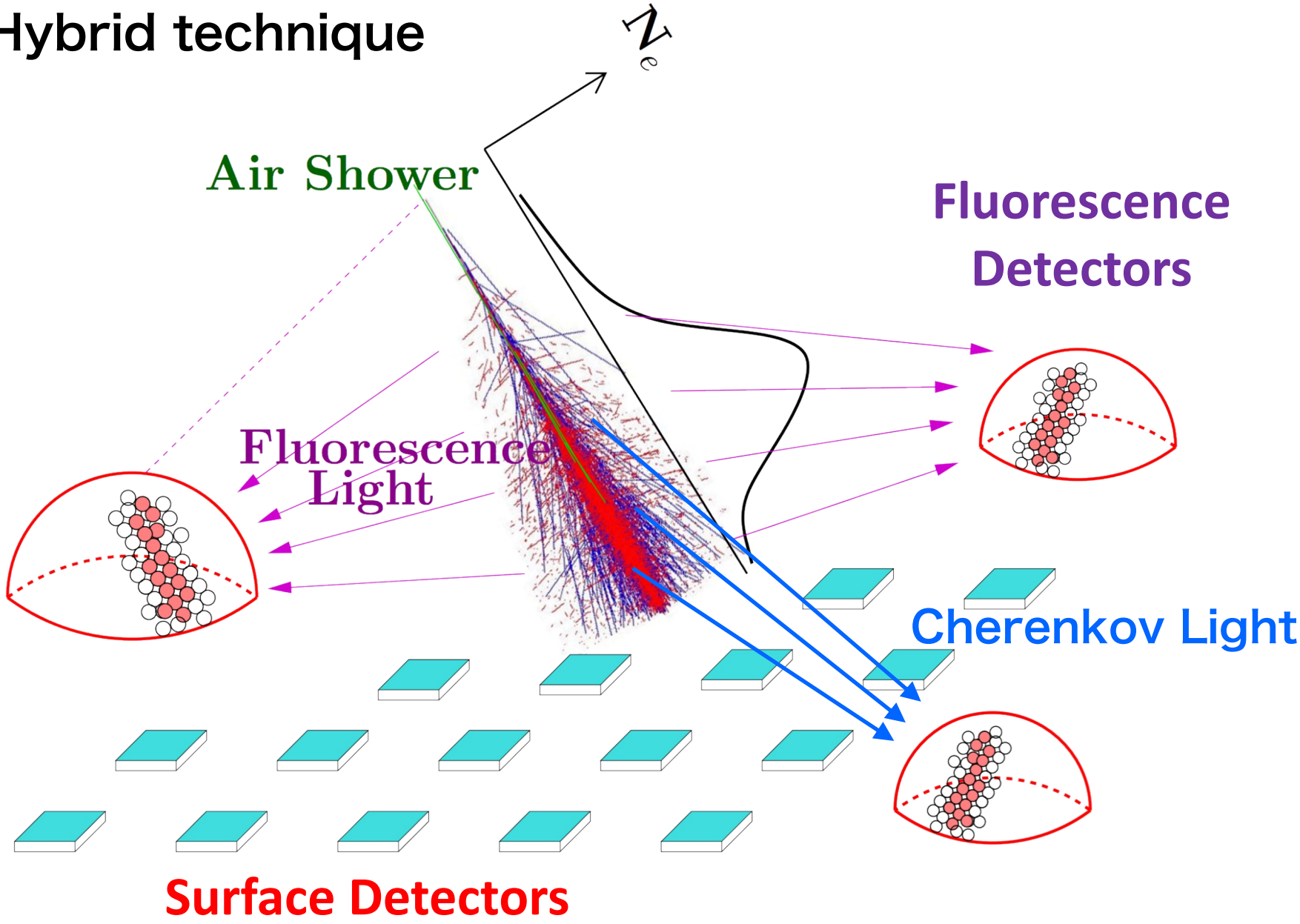
Cosmic ray energy spectrum measurements by Pierre Auger Observatory and Telescope Array

Keitaro Fujita
ICRR, University of Tokyo

Contents:

UHECR detection, Auger/TA

-> Hybrid technique



Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

Auger highlight talk in ICRC2021

Radio antenna array
(153 antennas, 17 km²)

LIDARs and laser facilities

(UMD)

Underground muon
detectors (24+)

Sub-array of 750 m
(63 stations, 23.4 km²)

High elevation telescopes (3)

4 fluorescence detectors
(24 telescopes up to 30°)

1665 surface detectors:
water-Cherenkov tanks
(grid of 1.5 km, 3000 km²)

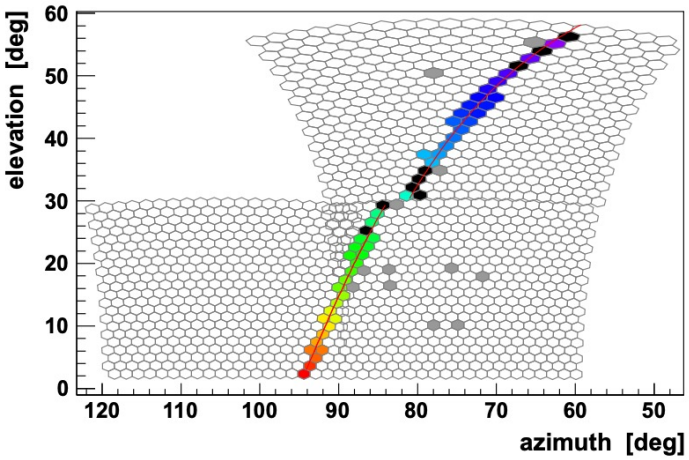
Water-Cherenkov detectors and

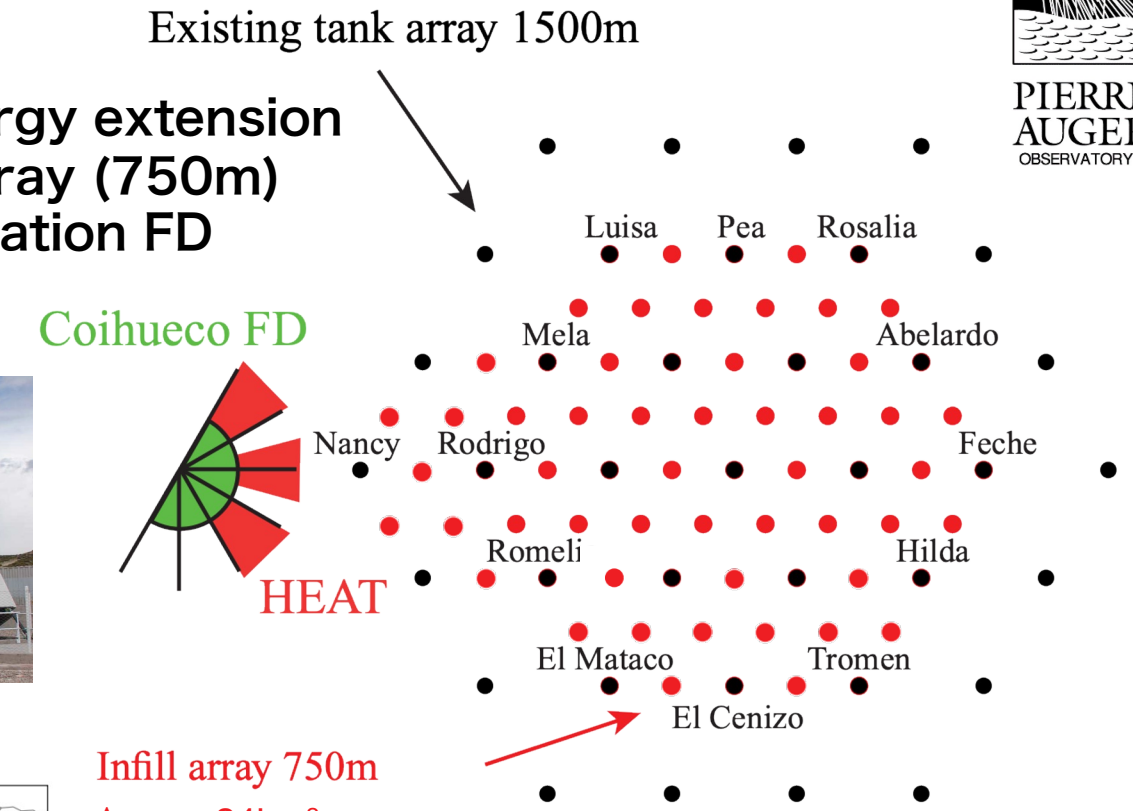
Fluorescence telescopes

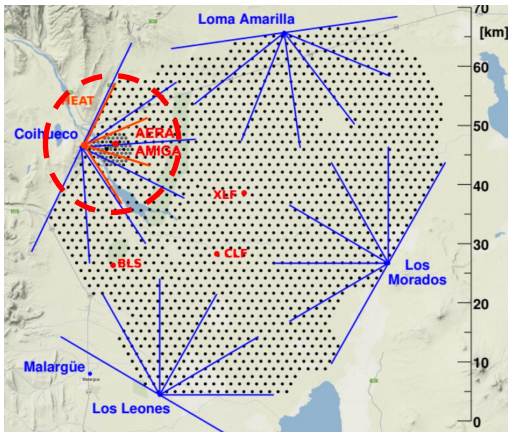
Pierre Auger Observatory

for low energy extension
- Dense array (750m)
- High elevation FD

high elevation telescopes



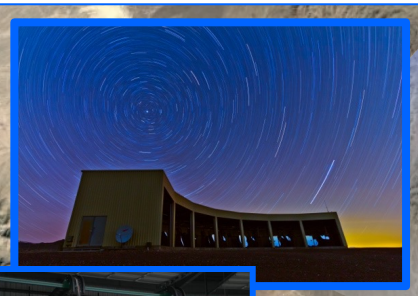




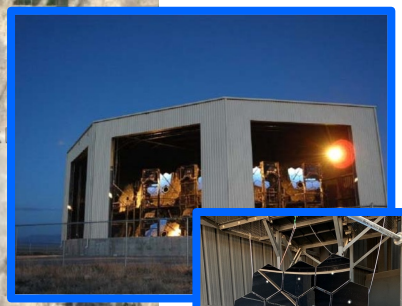
Telescope Array Detectors

Fluorescence Detectors(FDs)
Middle Drum(MD) station
14 telescopes
+ TA Low energy Extension (TALE) 10 telescopes

Surface Detector(SD) array
507 scintillation detectors
each 3m^2 , 1.2 km spacing
total coverage ~ 700km^2



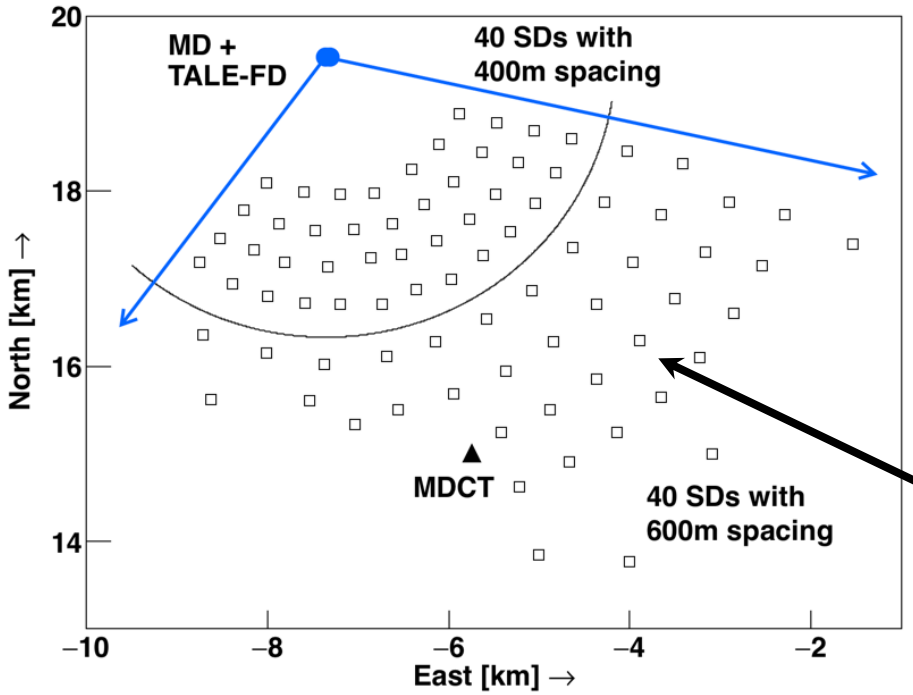
FDs
Black Rock Mesa(BRM) station
12 telescopes

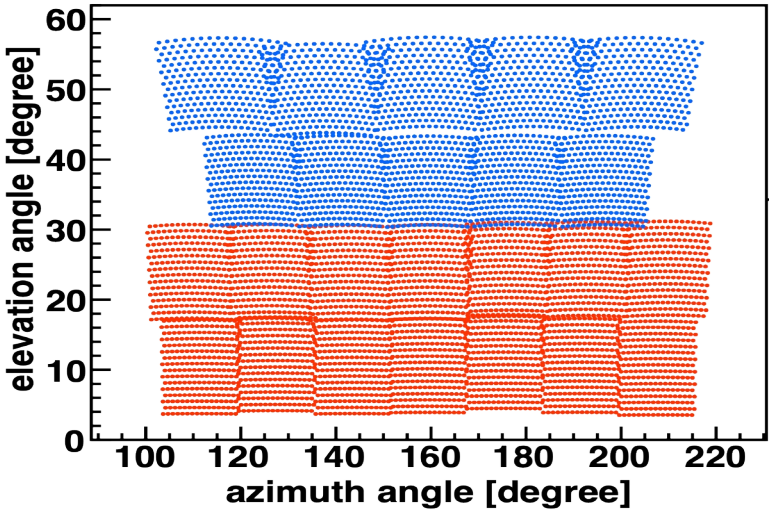


FDs
Long Ridge(LR) station
12 telescopes

TA Low energy Extension(TALE)

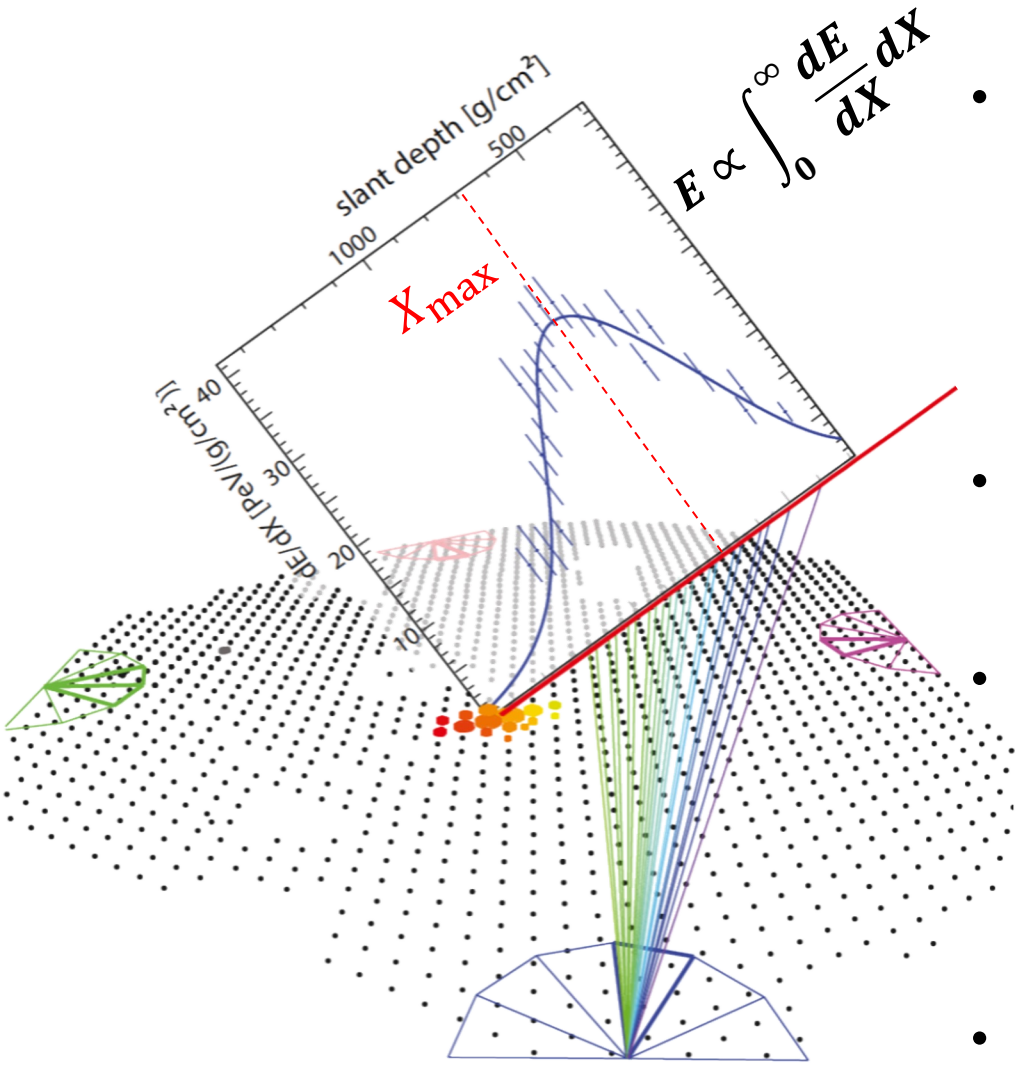
- Low energy target: E > 10^{16} eV
- Same concept as TA detector
  - 10 Fluorescence Telescopes
  - 80 Surface Detectors, 20 km^2
- Operation: FD since Sep. 2013
  SD since Nov. 2017





Event Reconstruction

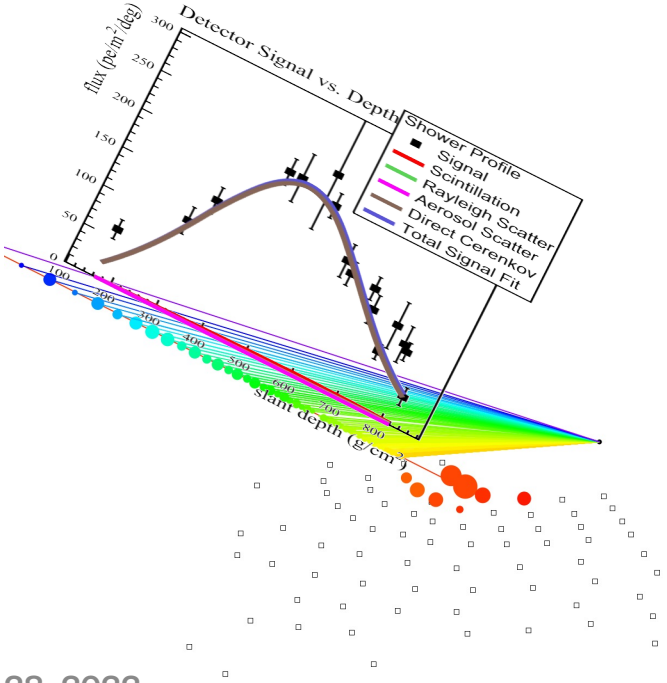
Event Reconstruction, Hybrid



- time vs. angle fit to obtain shower geometry
  - in hybrid: add SD info.
    → most precise shower geometry
- shower profile reconstruction using signal intensities
- Integral of dE/dX to obtain energy
  - $E \propto \int_0^\infty \frac{dE}{dX} dX$
- Archive ~8% E resolution
  - Both Auger/TA

Event Reconstruction, FD
Low energy event

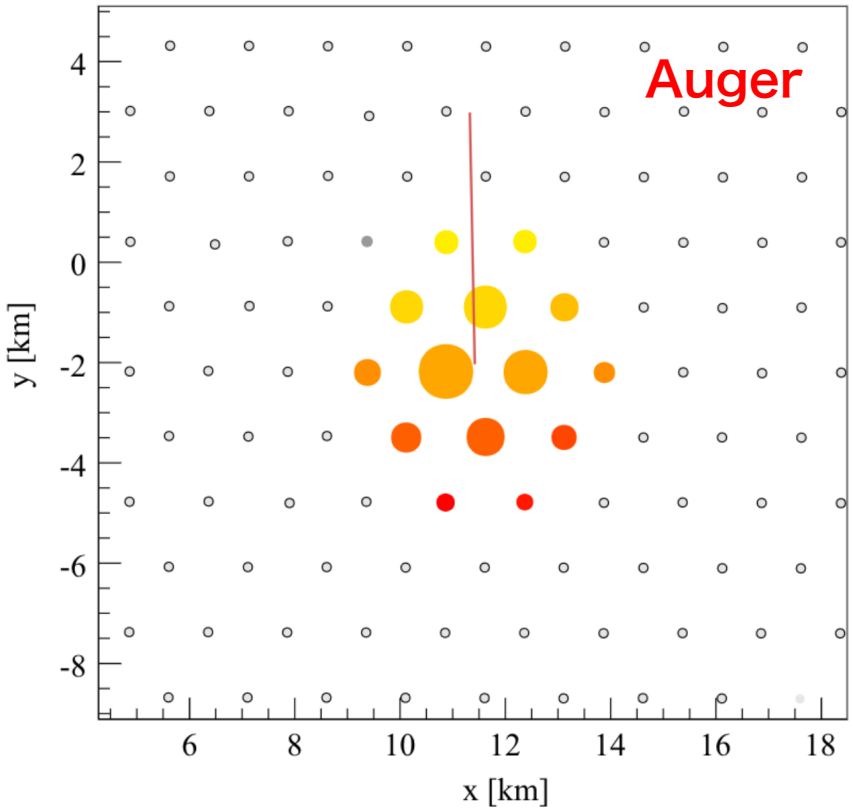
- detect Cherenkov light like IACT
  → archive low energy threshold
- simultaneous reconstruction for shower geometry and shower profile
  - constrained shower geometry by shower profile because of Cherenkov light directivity

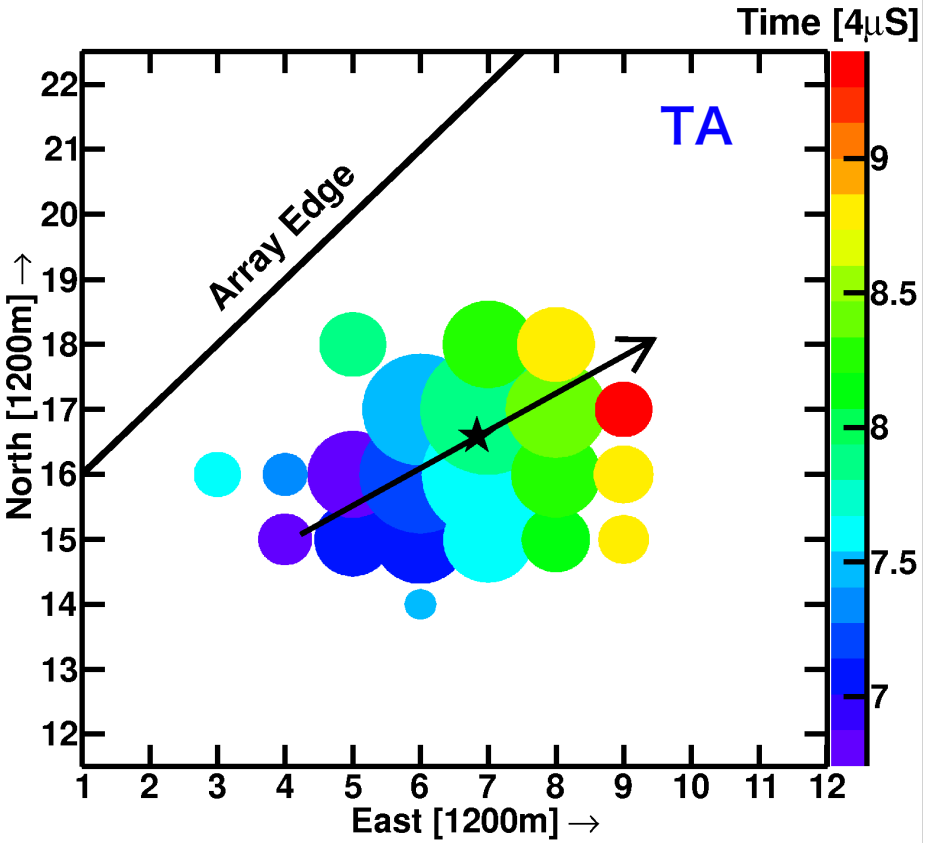


- Integral of dE/dX to obtain energy
  - $E \propto \int_0^\infty \frac{dE}{dX} dX$
  - same way as high energies
- Archive ~1° angular resolution
  ~10% E resolution @10PeV
  - Both Auger/TA

Event Reconstruction, SD

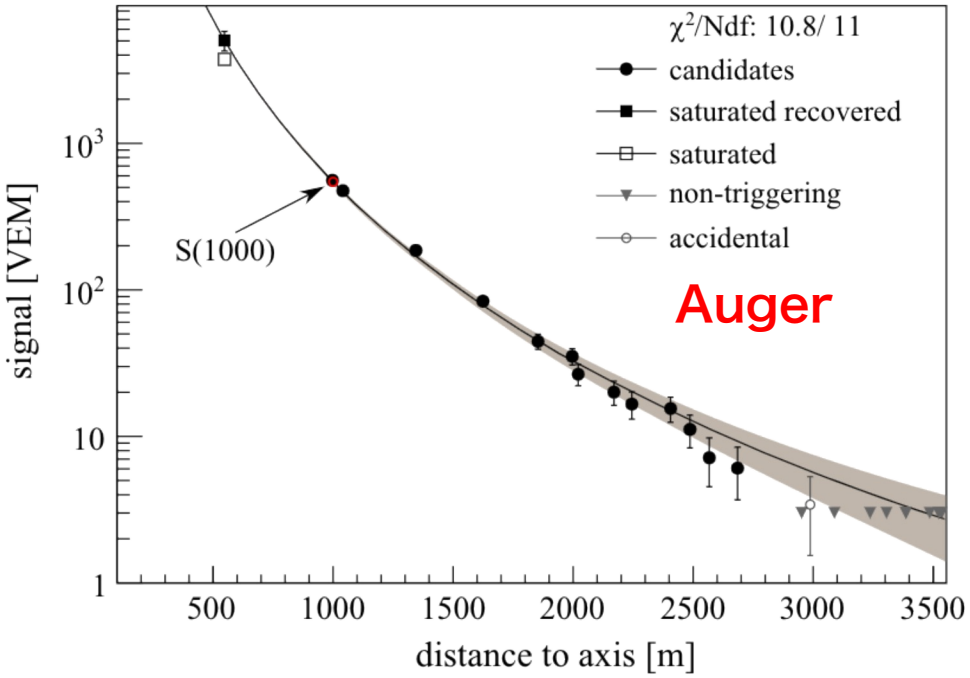
- Measured footprint
- Arrival direction reconstructed using relative timing differences

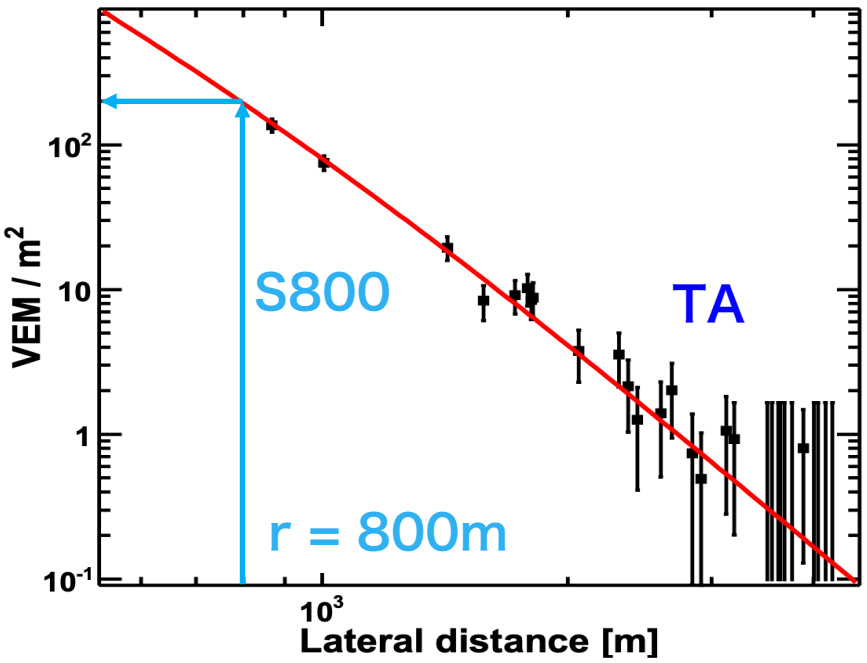




Event Map:
Size: # of particles
Color: relative timing

Event Reconstruction, SD

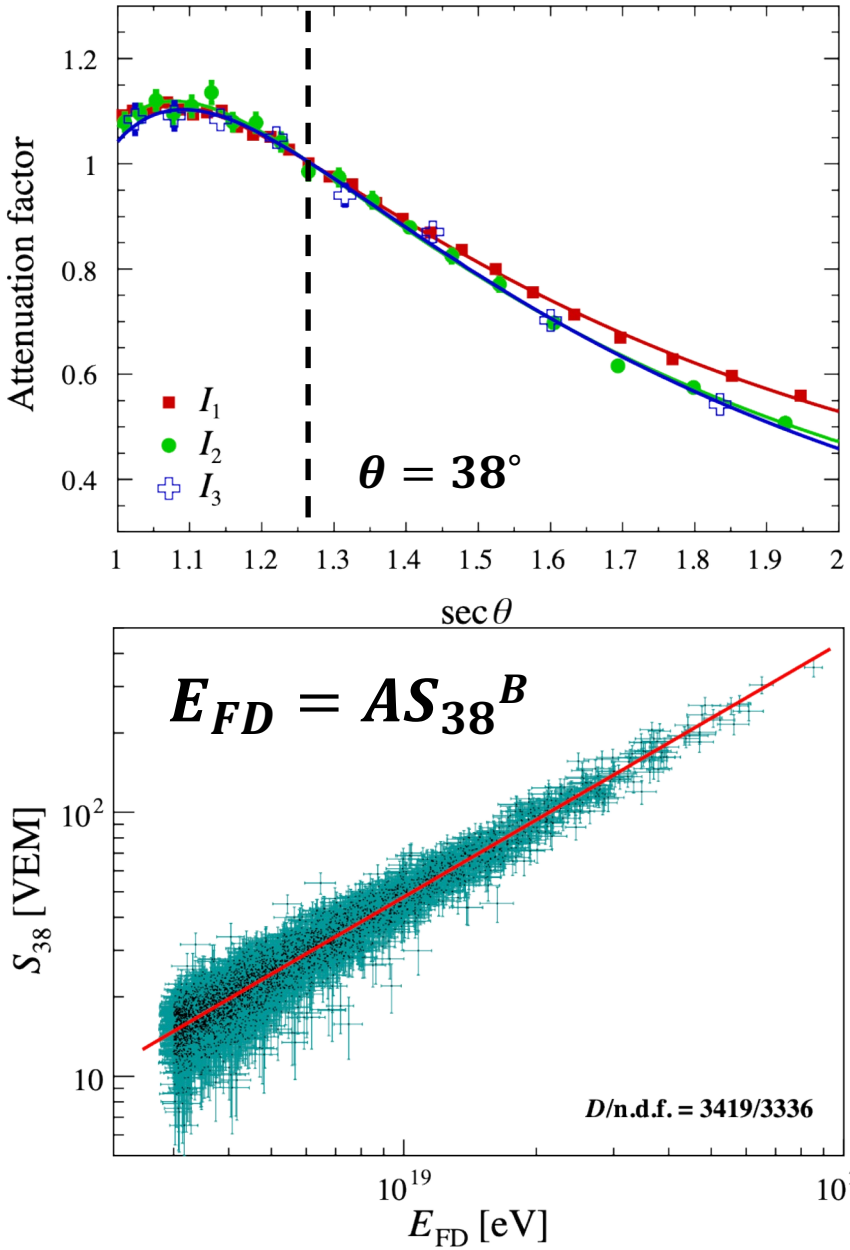




LDF in Auger: $S(r) = S(1000\mathrm{m})\left(\frac{r}{1000\mathrm{m}}\right)^{\beta}\left(\frac{r+700\mathrm{m}}{1000\mathrm{m}+700\mathrm{m}}\right)^{\gamma}$

LDF in TA : $S(r) = A\left(\frac{r}{91.6\mathrm{m}}\right)^{-1.2}\left(1+\frac{r}{91.6\mathrm{m}}\right)^{-\{\eta(\theta)-1.2\}}\left(1+\left[\frac{r}{1000\mathrm{m}}\right]^{2}\right)^{-0.6}$

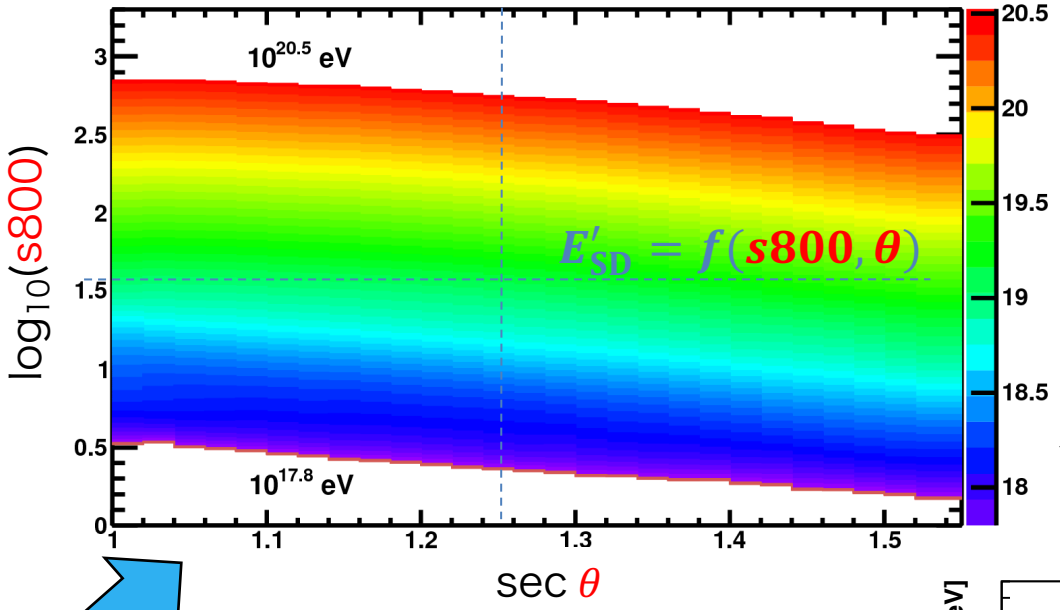
Energy determination, Auger



- Take account of shower attenuation
  - smaller S(1000) for inclined
- Attenuation curve obtained by constant-intensity cut (CIC) method
  - Data driven, free from MC
- Convert S(1000) to S_{38}
- S_{38} has good liner correlation between E_{FD}
  - $E_{FD} = AS_{38}{}^{B}$
  - applied to ALL SD events

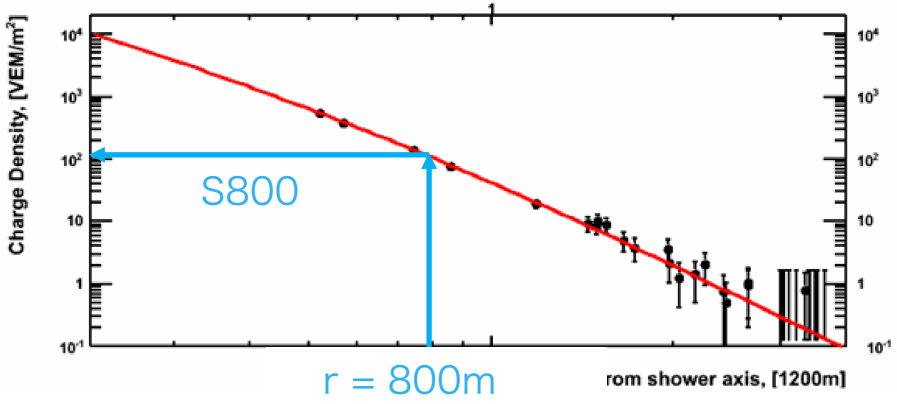
Energy determination, TA

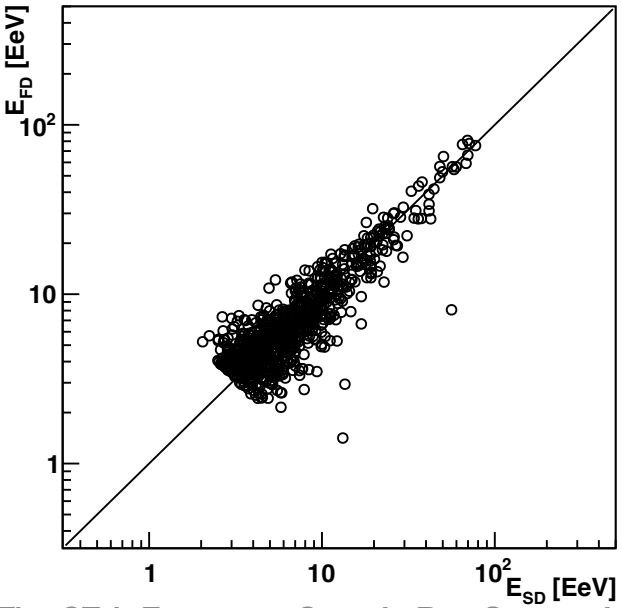
→ Energy look-up table (S800, θ)



Scale to FD(Hybrid) energy

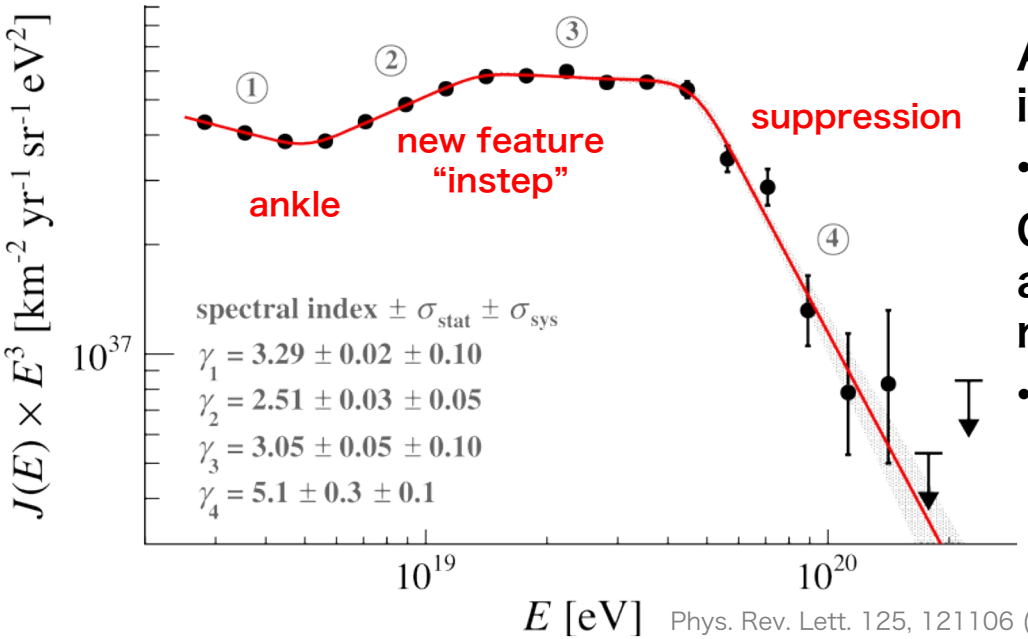
$E_{SD} = E'_{SD}$ /1.27





Energy Spectrum

New feature in energy spectrum



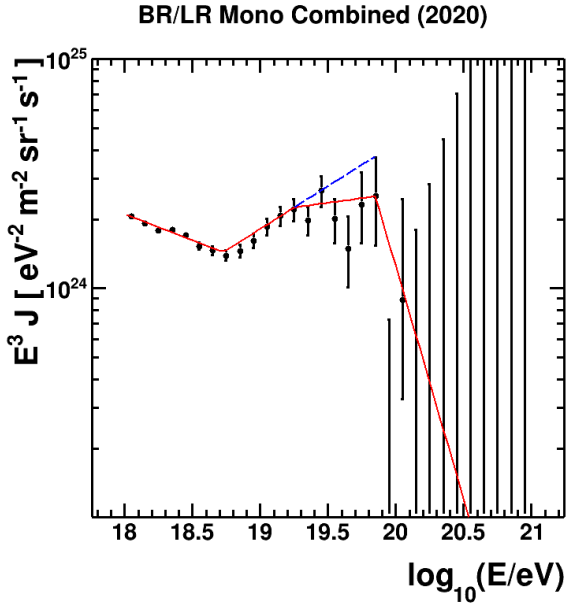
Phys. Rev. Lett. 125, 121106 (2020)

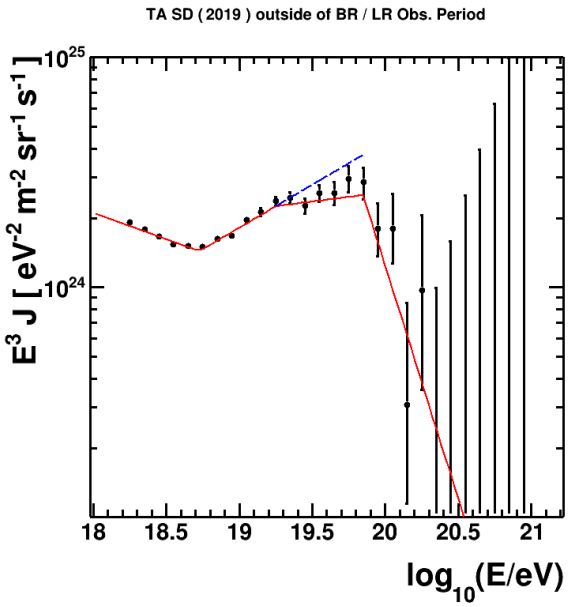
Auger found a new feature in 10^{19} – $10^{19.5}$ eV range

- 2-step softening after the ankle

Combining HiRes, TA SD, and TA FD, a two-step softening exists in the northern hemisphere data.

- 5.3σ deficit above $10^{19.25}$ eV from an assumption of no breaks before the high-energy steepening



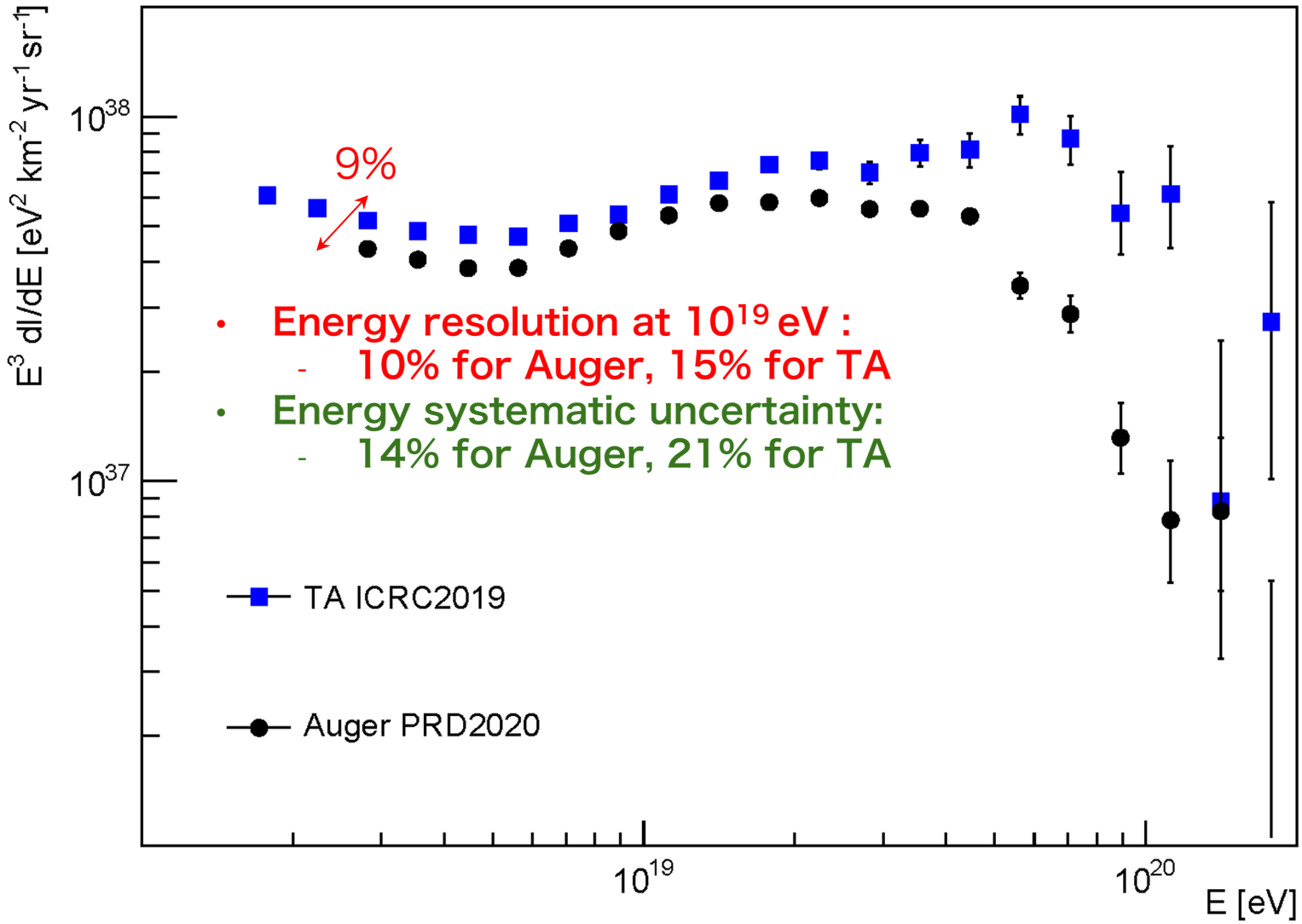


Parameter	Auger	TA
γ_1	3.29 ± 0.02	3.23 ± 0.01
γ_2	2.51 ± 0.03	2.63 ± 0.02
γ_3	3.05 ± 0.05	2.92 ± 0.06
γ_4	5.1 ± 0.3	5.0 ± 0.4
$E_{\rm ankle}$/EeV	5.0 ± 0.1	5.4 ± 0.1
$E_{\rm instep}$/EeV	13 ± 1	18 ± 1
$E_{\rm cut}$/EeV	46 ± 3	71 ± 3

Y. Tsunesada et al. (Auger+TA Spectrum WG) PoS ICRC2021 (2021) 337

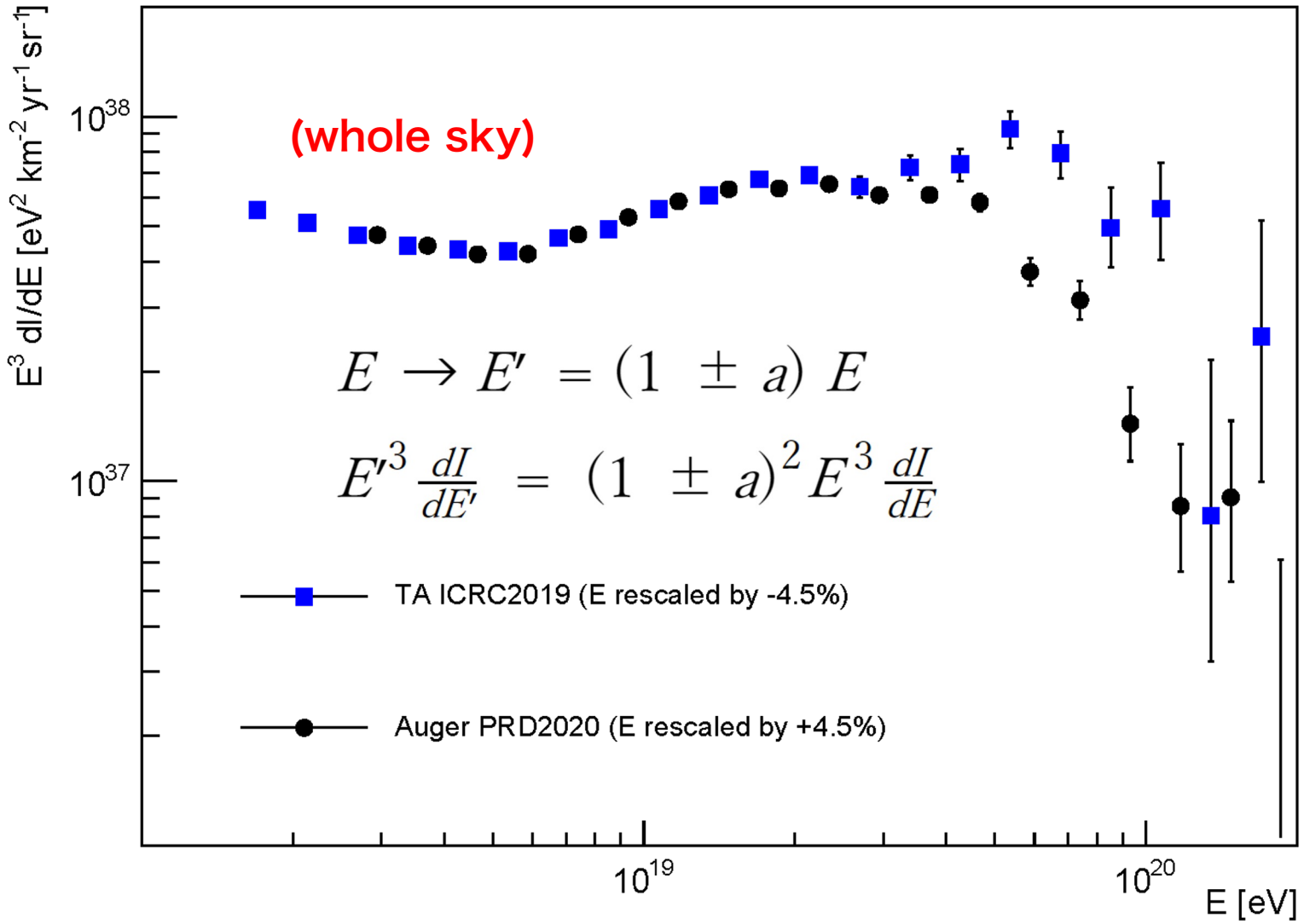
PoS ICRC2021 (2021) 341

Auger + TA energy spectrum



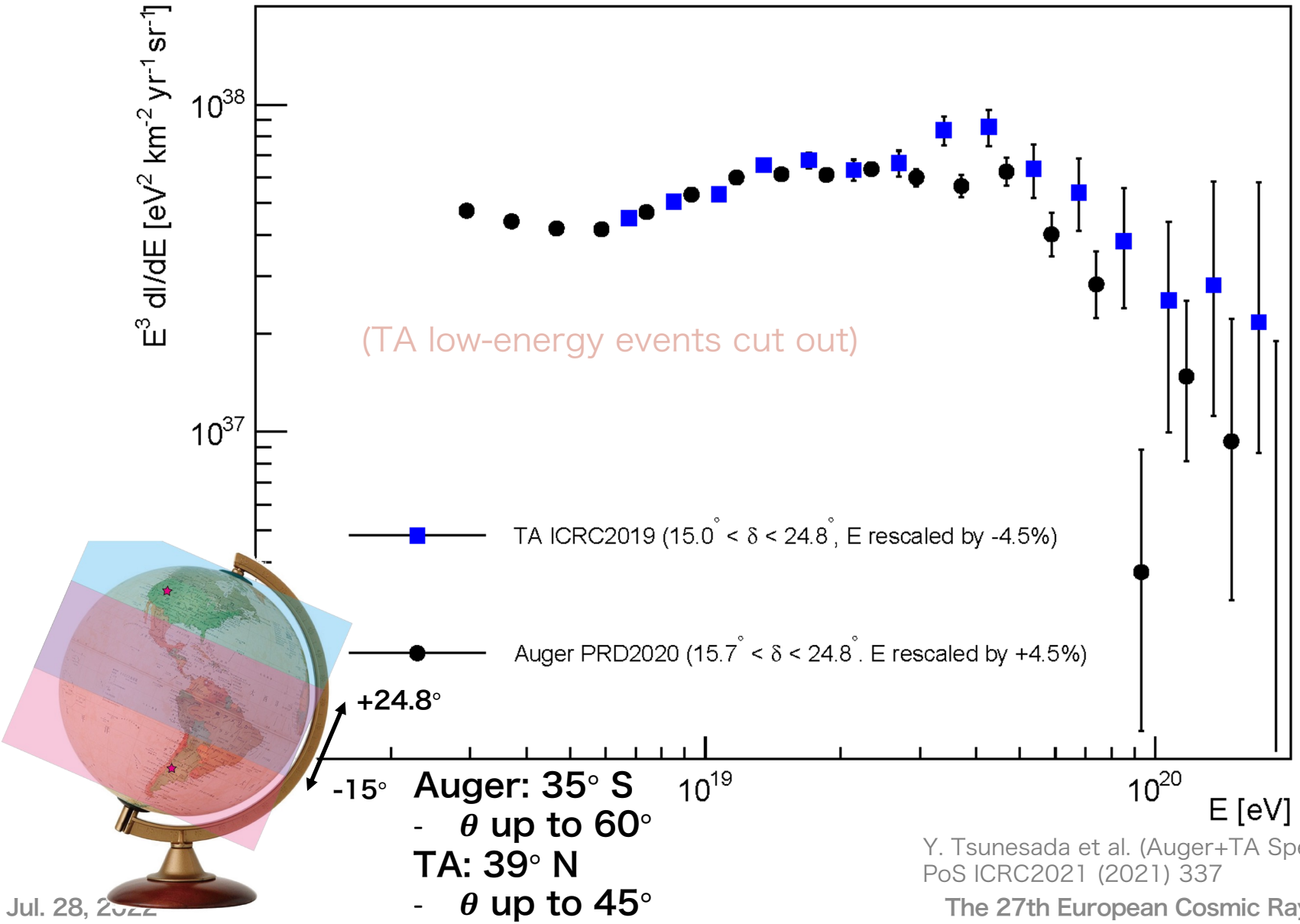
Y. Tsunesada et al. (Auger+TA Spectrum WG)
PoS ICRC2021 (2021) 337

Auger + TA energy spectrum
Energy ±4.5% rescaled



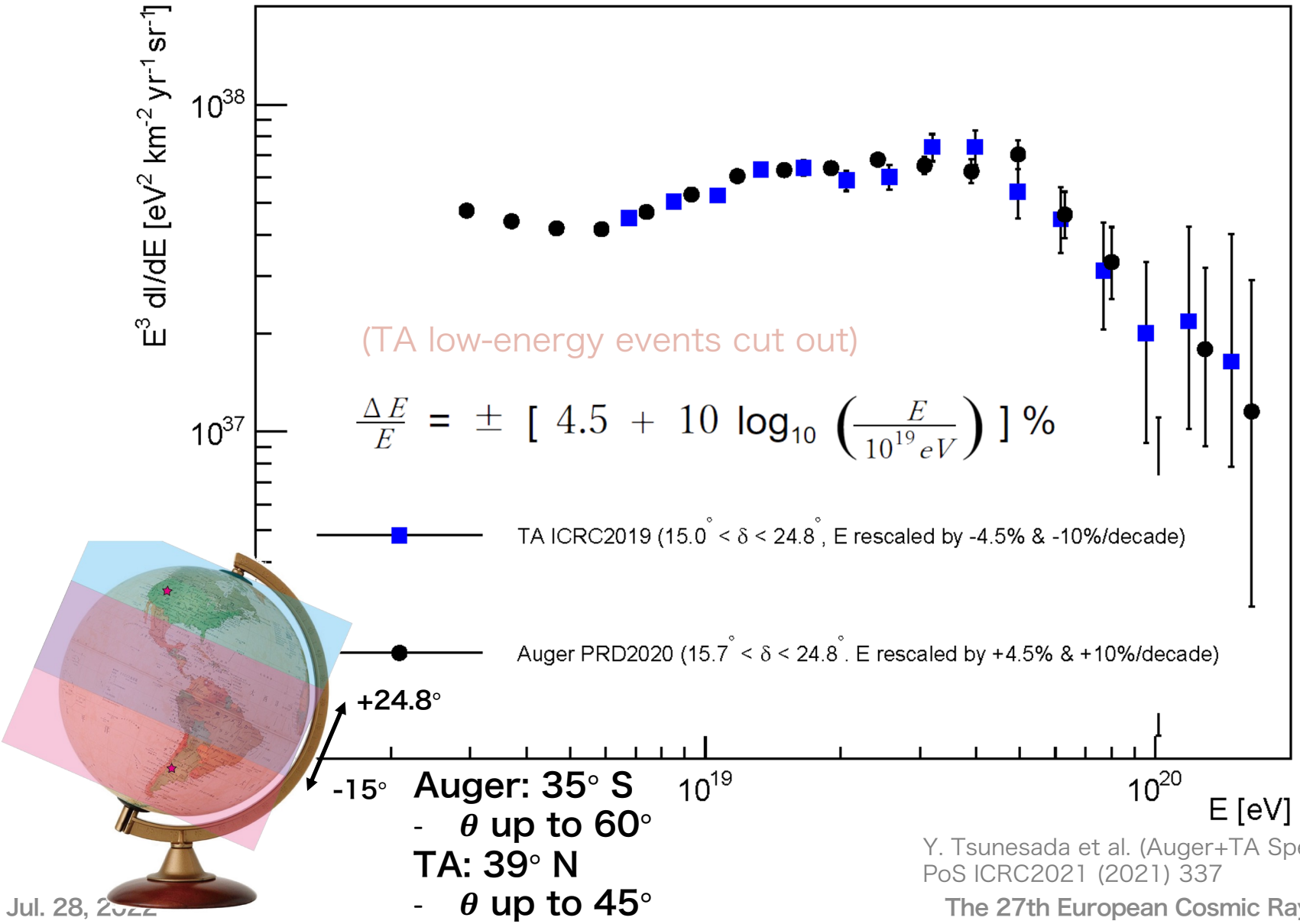
Y. Tsunesada et al. (Auger+TA Spectrum WG)
PoS ICRC2021 (2021) 337

Common declination band spectrum Energy ±4.5% rescaled



Y. Tsunesada et al. (Auger+TA Spectrum WG)
PoS ICRC2021 (2021) 337

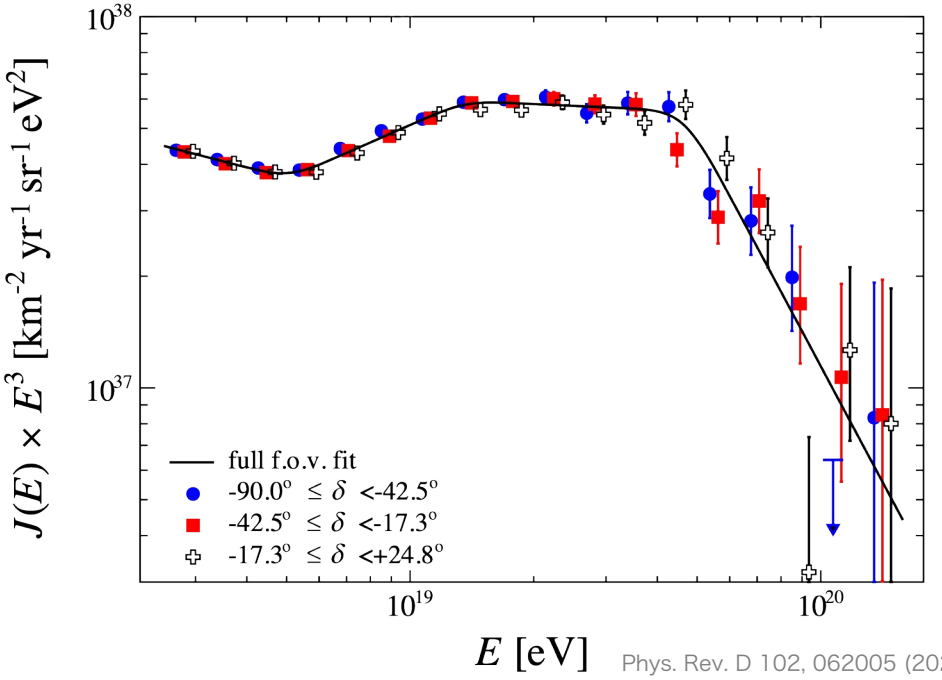
Common declination band spectrum Rescale + E-dependent shift



Y. Tsunesada et al. (Auger+TA Spectrum WG)
PoS ICRC2021 (2021) 337

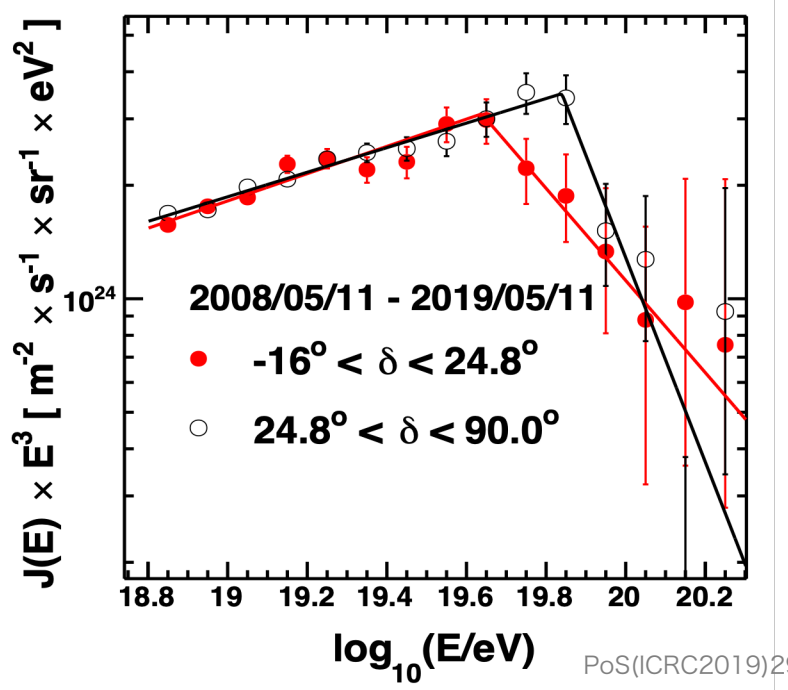
Declination dependence

Auger spectrum

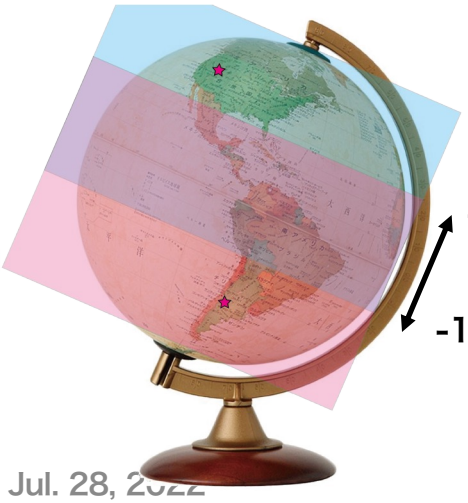


Phys. Rev. D 102, 062005 (2020)

TA spectrum



PoS(ICRC2019)298



Auger: 35° S
- θ up to 60°

TA: 39° N
- θ up to 45°

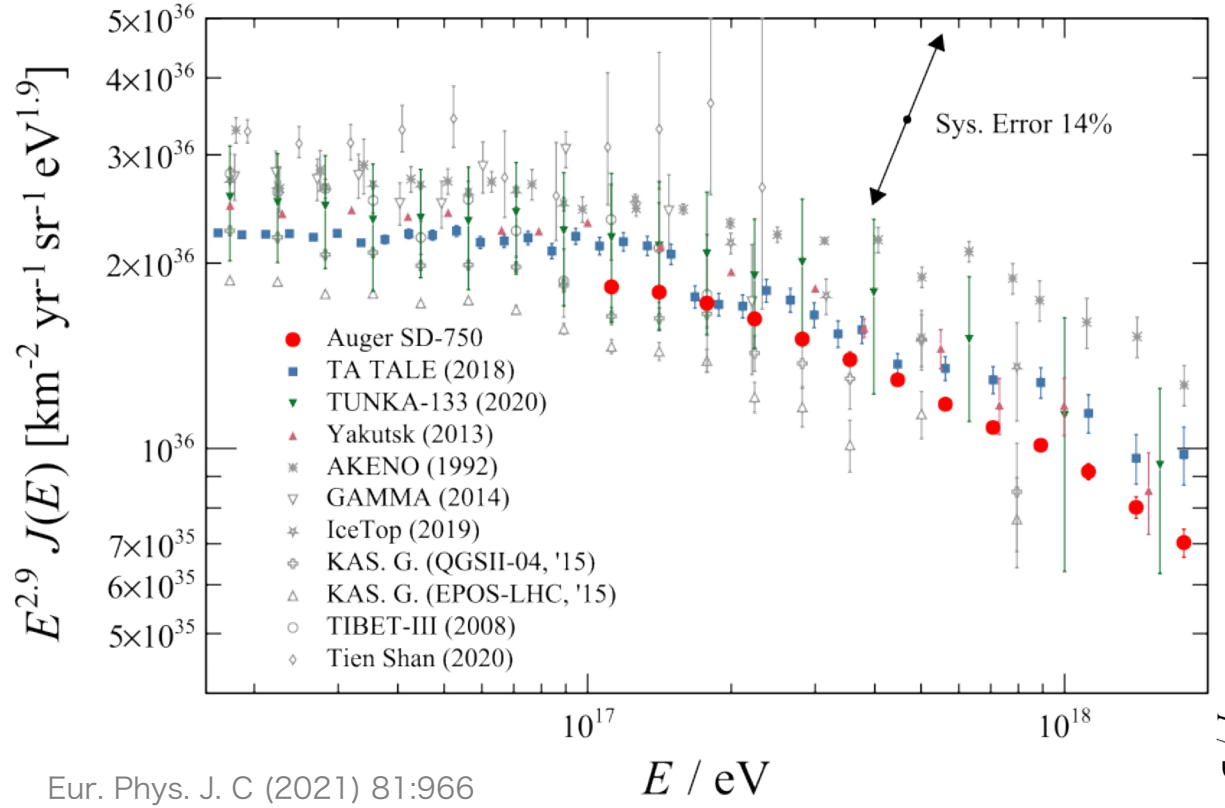
Auger: no significant declination dependence

TA : Difference of the cutoff energies

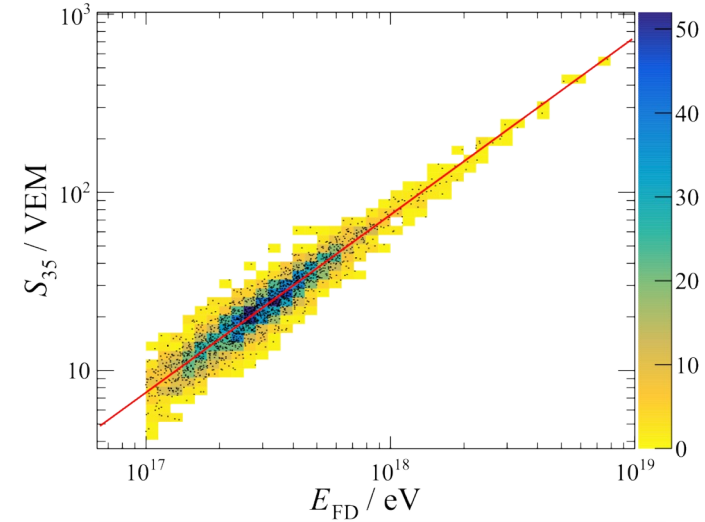
- log(E/eV) = 19.64 ± 0.04 for low dec. band
- log(E/eV) = 19.84 ± 0.02 for high dec. band
  - global significance: **4.3σ** (local: 4.7σ)

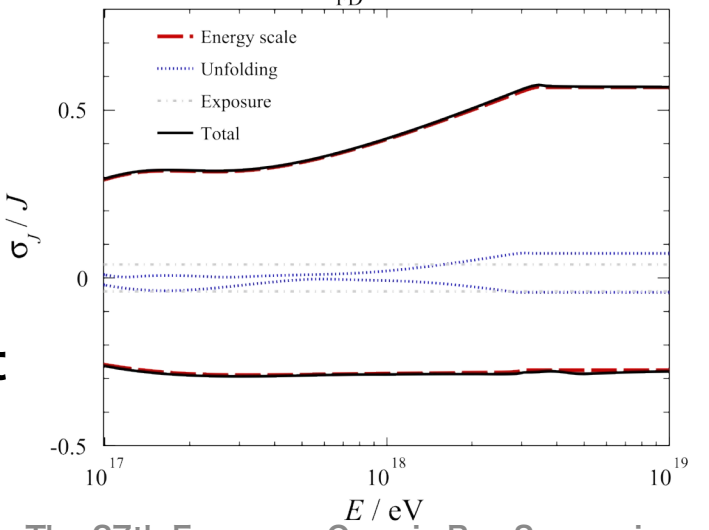
Low energy spectrum: Auger

- Auger 750m measurement
  - Energy estimator: S450, (main Auger: S1000)



Eur. Phys. J. C (2021) 81:966

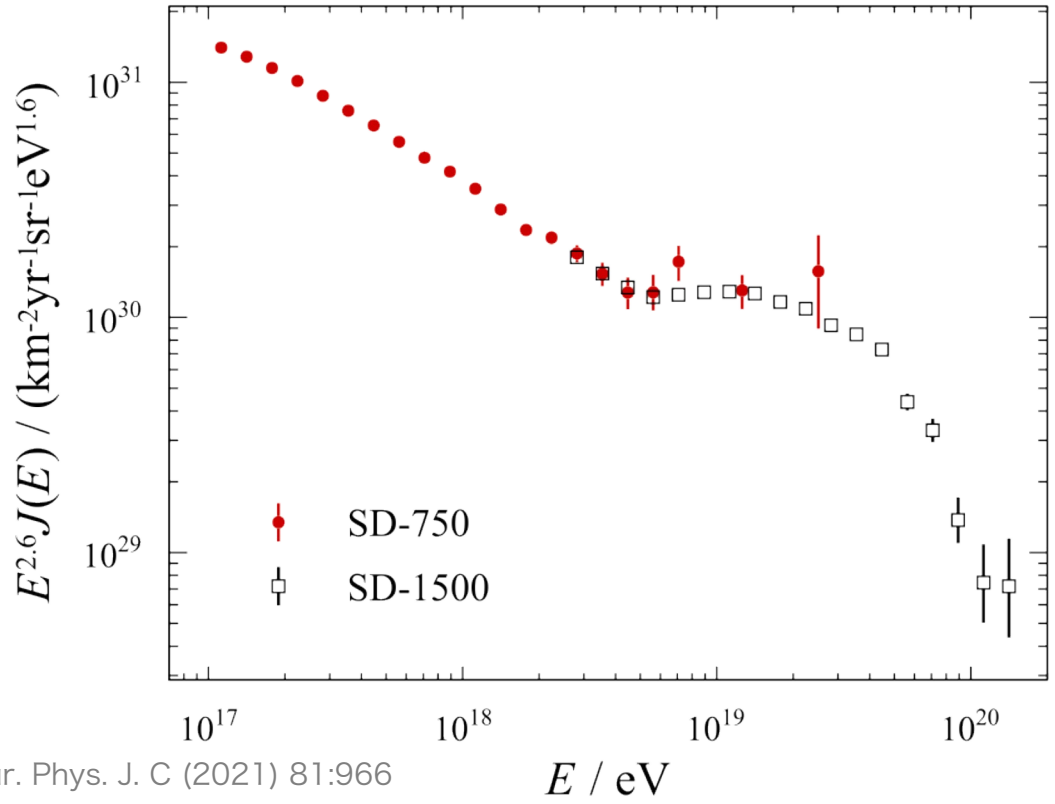




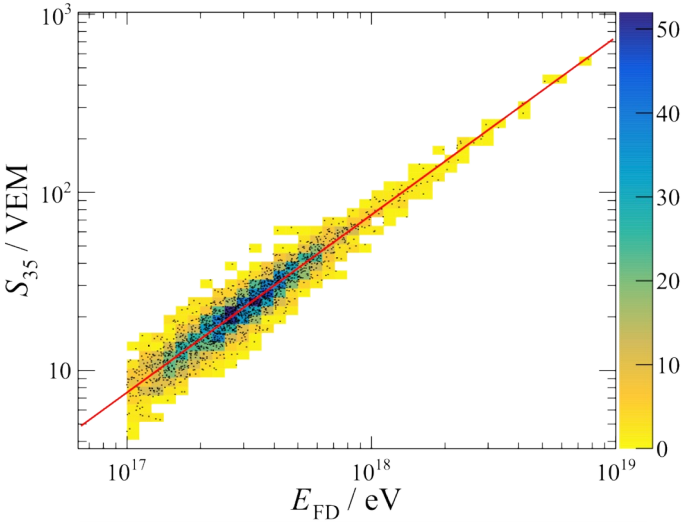
Down to 100 PeV with SD measurement
Energy resolution at 100 PeV: 20%

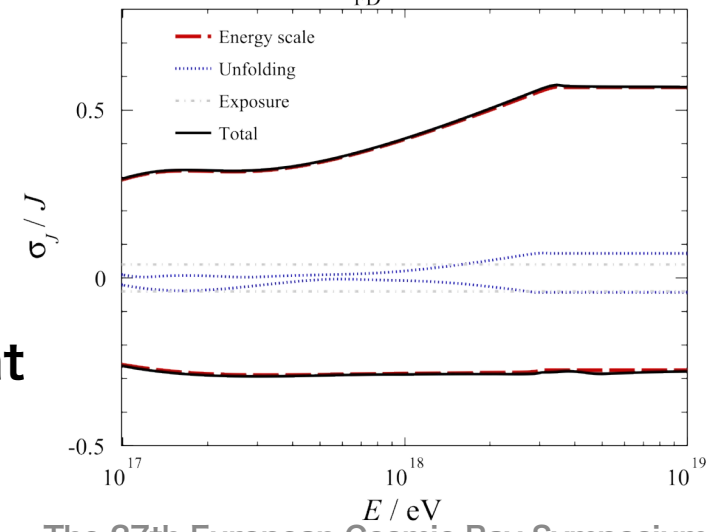
Low energy spectrum: Auger

- Auger 750m measurement
  - Energy estimator: S450, (main Auger: S1000)



Eur. Phys. J. C (2021) 81:966

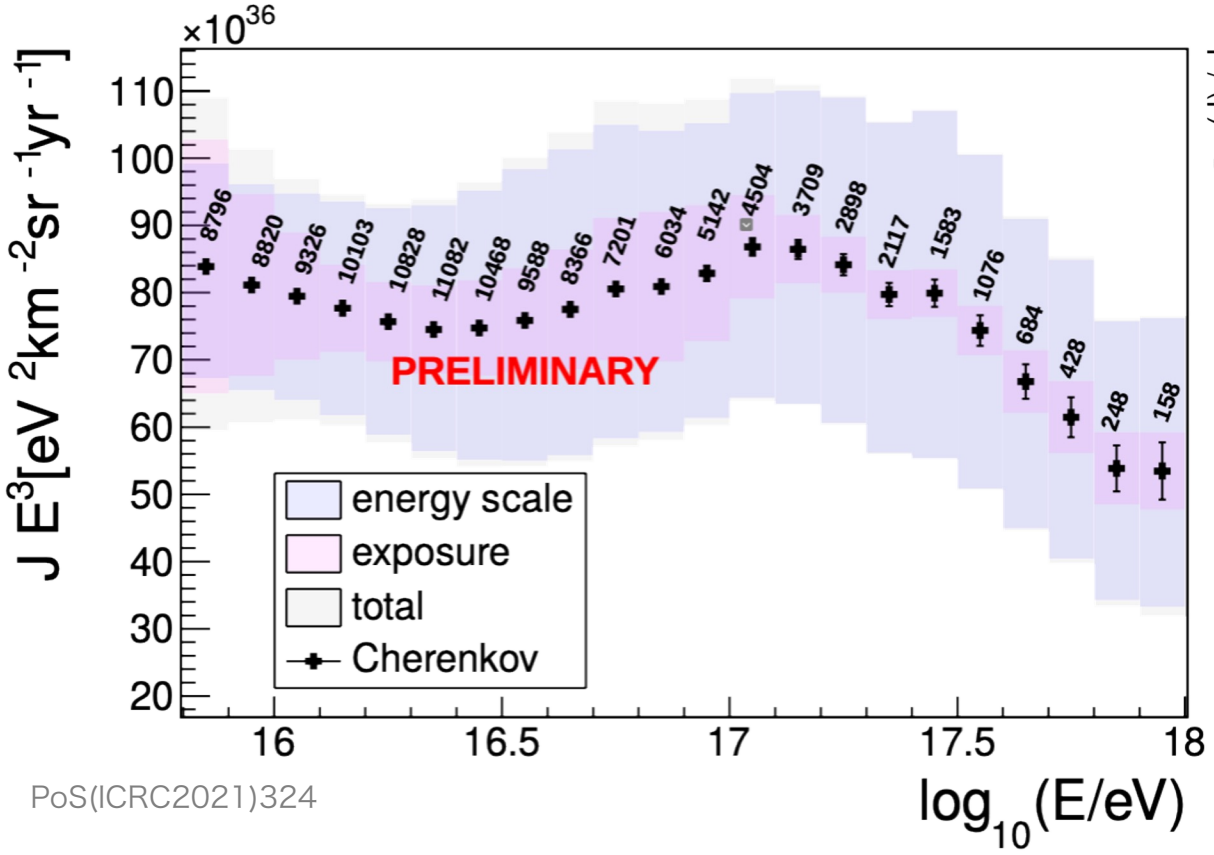




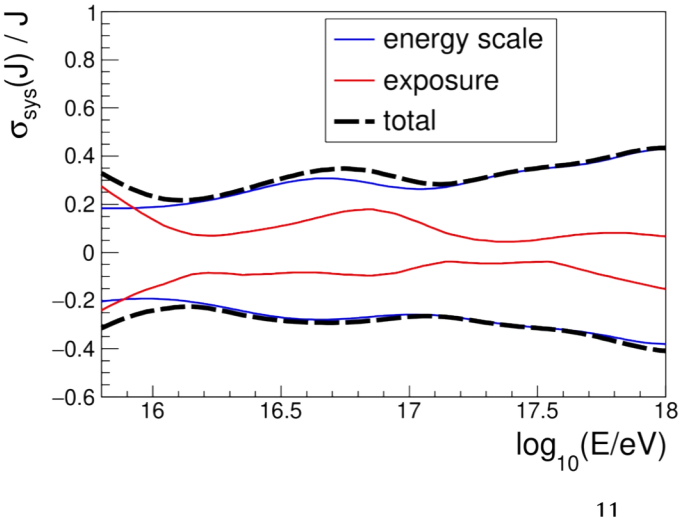
Down to 100 PeV with SD measurement
Energy resolution at 100 PeV: 20%

Low energy spectrum: Auger

- Auger HEAT measurement
  - Cherenkov dominated spectrum



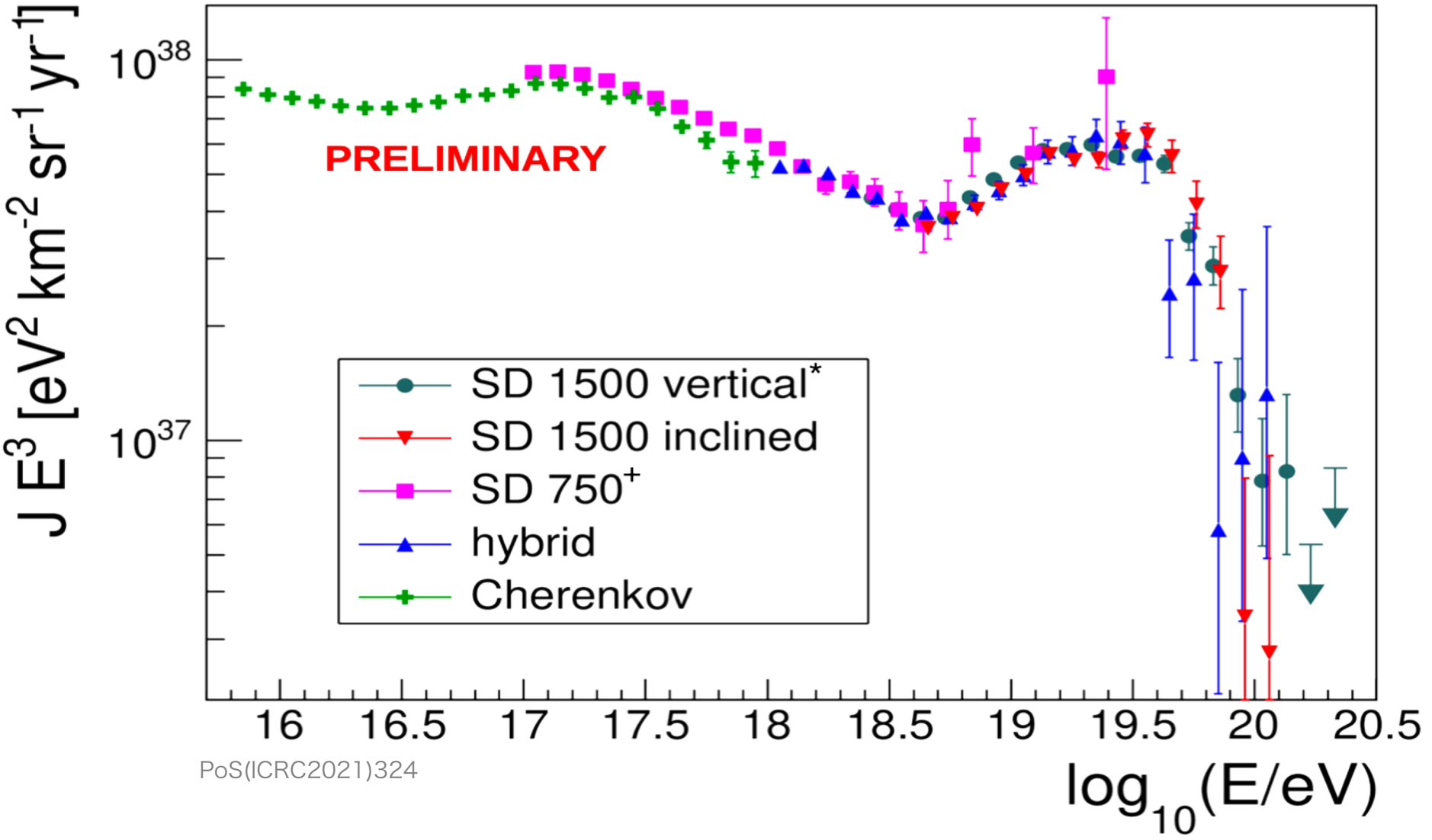
PoS(ICRC2021)324



11

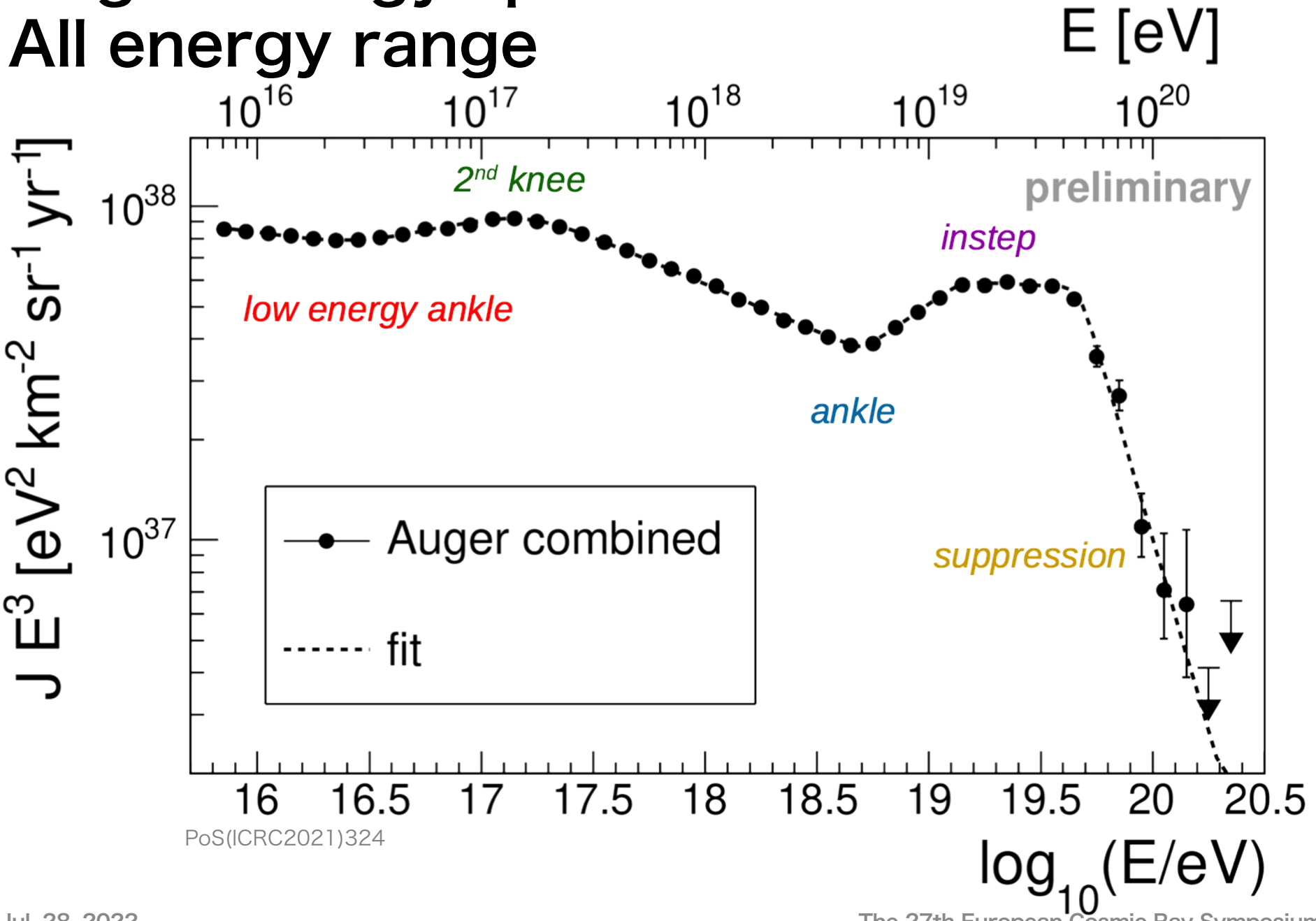
Down to 6 PeV with FD measurement
Energy resolution at 6 PeV: 12%

Auger energy spectrum
All energy range



PoS(ICRC2021)324

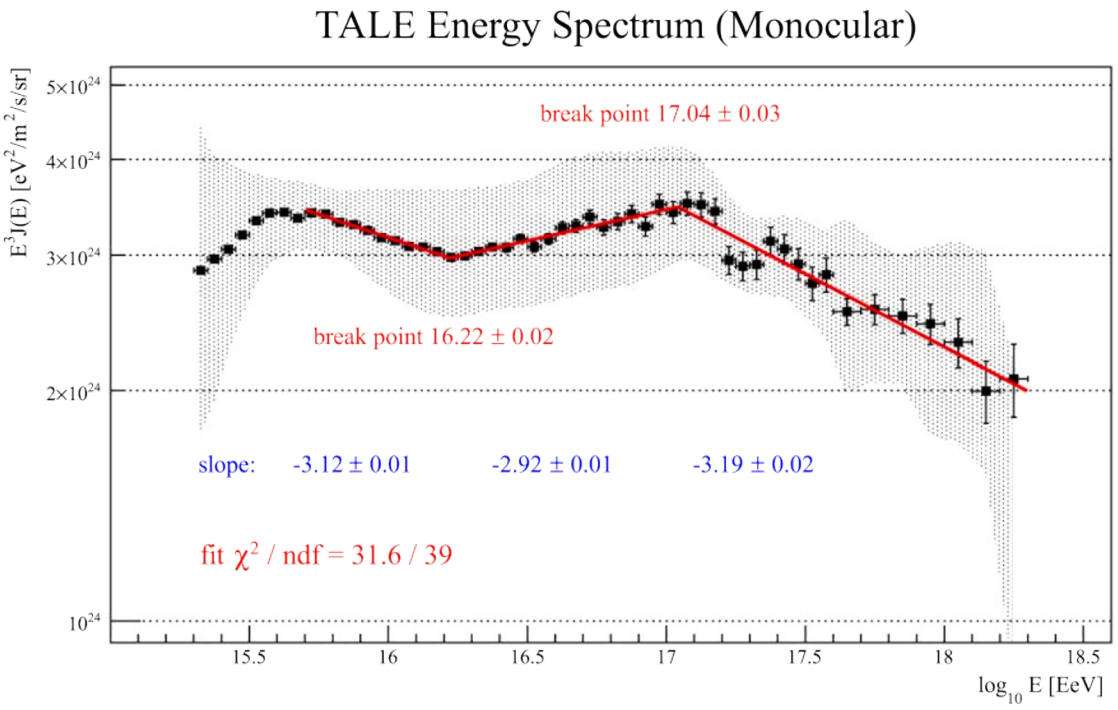
Auger energy spectrum
All energy range



PoS(ICRC2021)324

Low energy spectrum: TA

- TALE FD monocular mode measurement
  - Cherenkov dominated spectrum



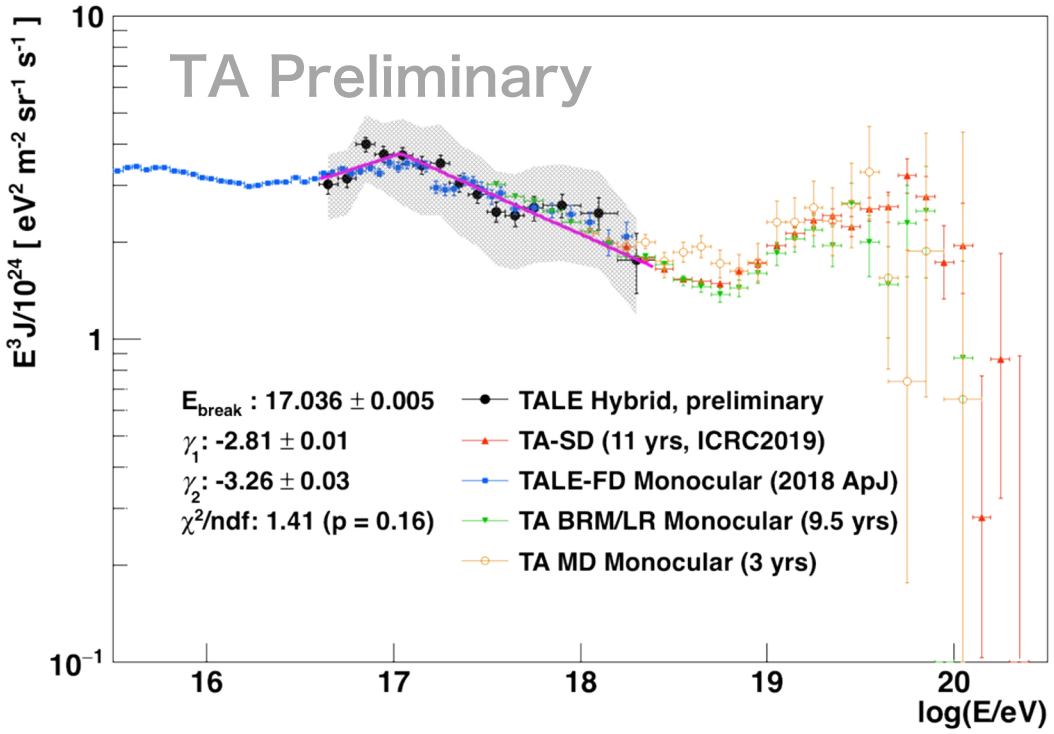
Energy	Source	Value	Contribution to Flux
$<10^{17}$ eV	photonic scale	10%	20%
$<10^{17}$ eV	missing energy	10%	20%
$<10^{17}$ eV	atmosphere	0	0
$<10^{17}$ eV	Cherenkov model	5%	10%
$<10^{17}$ eV	fluorescence yield	0	0
$<10^{17}$ eV	composition (X_{max})	3%	6%
10^{18} eV	photonic scale	10%	20%
10^{18} eV	missing energy	5%	10%
10^{18} eV	atmosphere	2%	4%
10^{18} eV	Cherenkov model	0	0
10^{18} eV	fluorescence yield	10%	20%
10^{18} eV	composition (X_{max})	3%	6%
$<10^{17}$ eV	total	15%	31%
10^{18} eV	total	15%	31%

Down to 2 PeV with FD measurement
Energy resolution at 2 PeV : 20%
at 6 PeV : 15%
at 100 PeV: 10%

Low energy spectrum: TA

- TALE Hybrid measurement

TALE Hybrid Spectrum



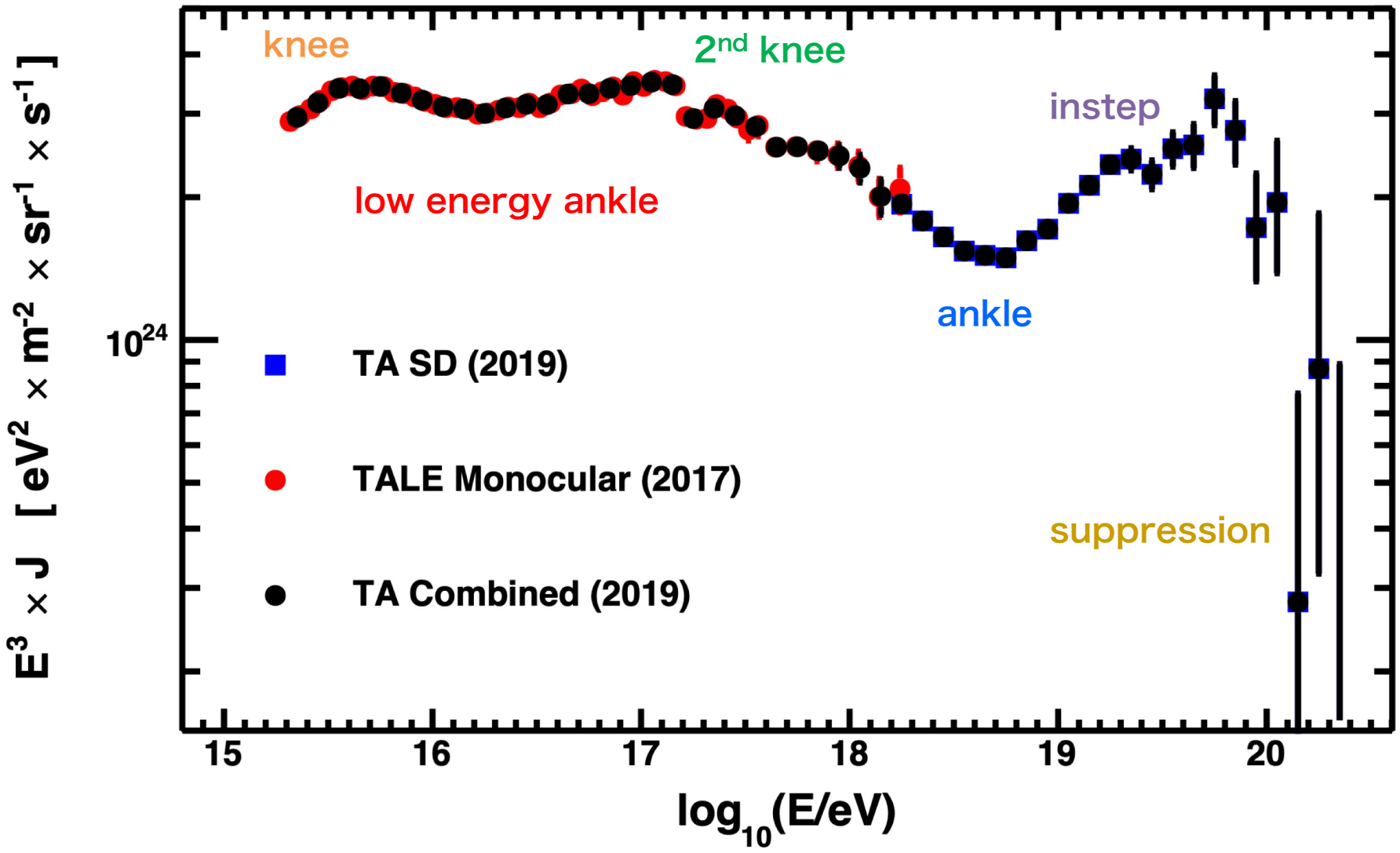
	γ_1	$\log_{10}(E_{break}/eV)$	γ_2
TALE Hybrid	-2.81 ± 0.01	17.04 ± 0.01	-3.26 ± 0.03
TALE Monocular [26]	-2.92 ± 0.01	17.04 ± 0.04	-3.19 ± 0.02
TA SD [25]	-	-	-3.28 ± 0.02
TA BRM / LR FDs [96]	-	-	-3.29 ± 0.01

Summary of systematic uncertainties in energy, X_{max}

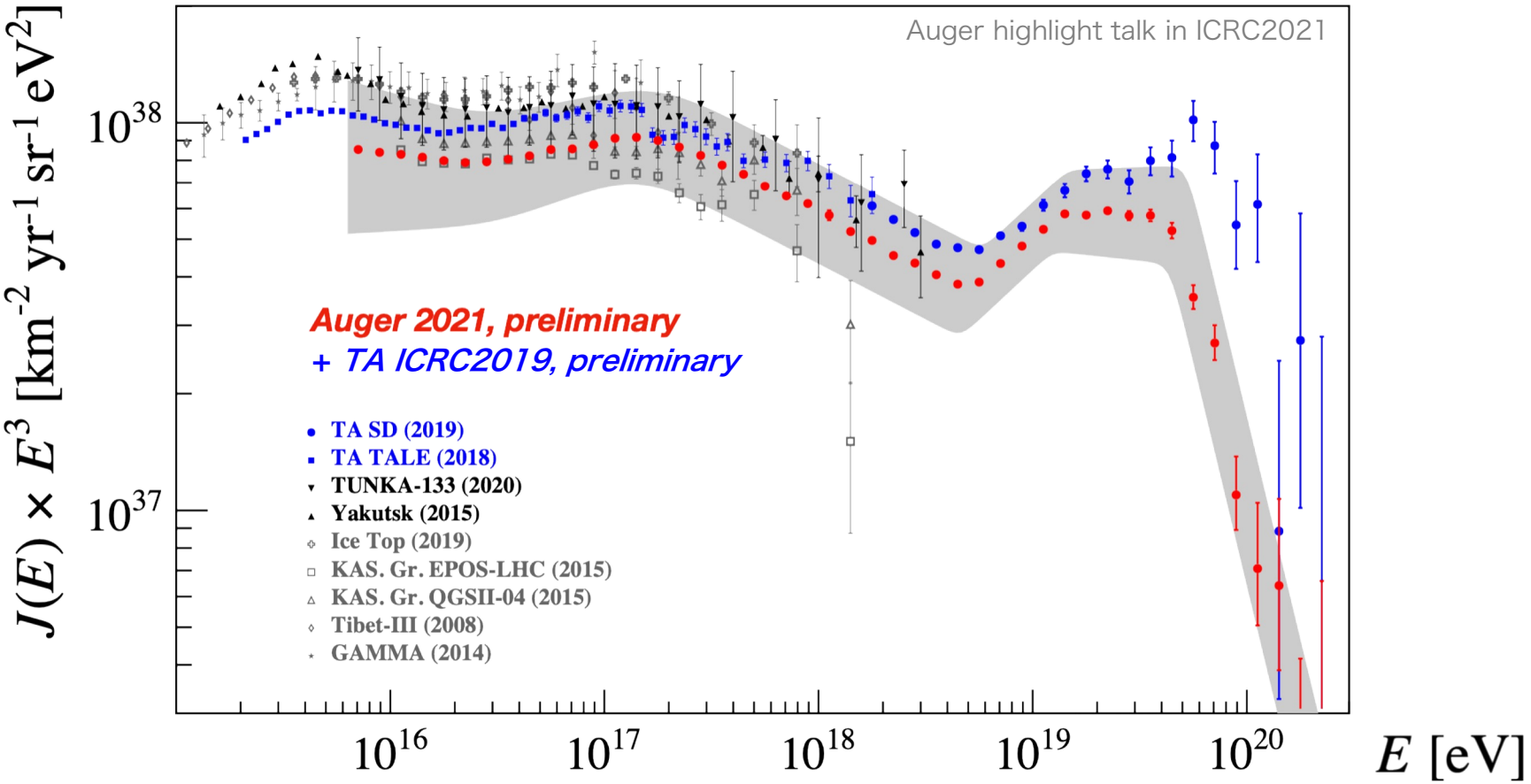
Sources	Energy
Photonic Scale	10 %
Relative Time of FD and SD	0
Fluorescence yield	3 to 10%
Cherenkov model	5 to 1 %
Atmosphere	$^{+2.7}_{-1.8}$ %
Missing energy	6 %
Total	12.6 to 15.7 %

Down to $10^{16.5}$ eV with Hybrid measurement
Energy resolution at $10^{16.5}$ eV: <10%

TA energy spectrum
All energy range



Auger + TA energy spectrum
All energy range



Auger

low energy ankle @ logE = 16.45 ± 0.05
2nd knee @ logE = 17.20 ± 0.01
ankle @ logE = 18.70 ± 0.01
instep @ logE = 19.15 ± 0.03
suppression @ logE = 19.67 ± 0.03

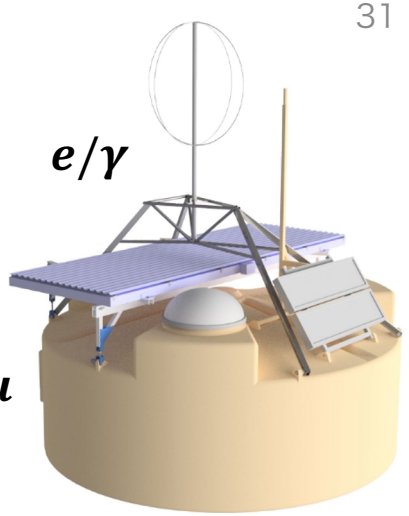
Telescope Array

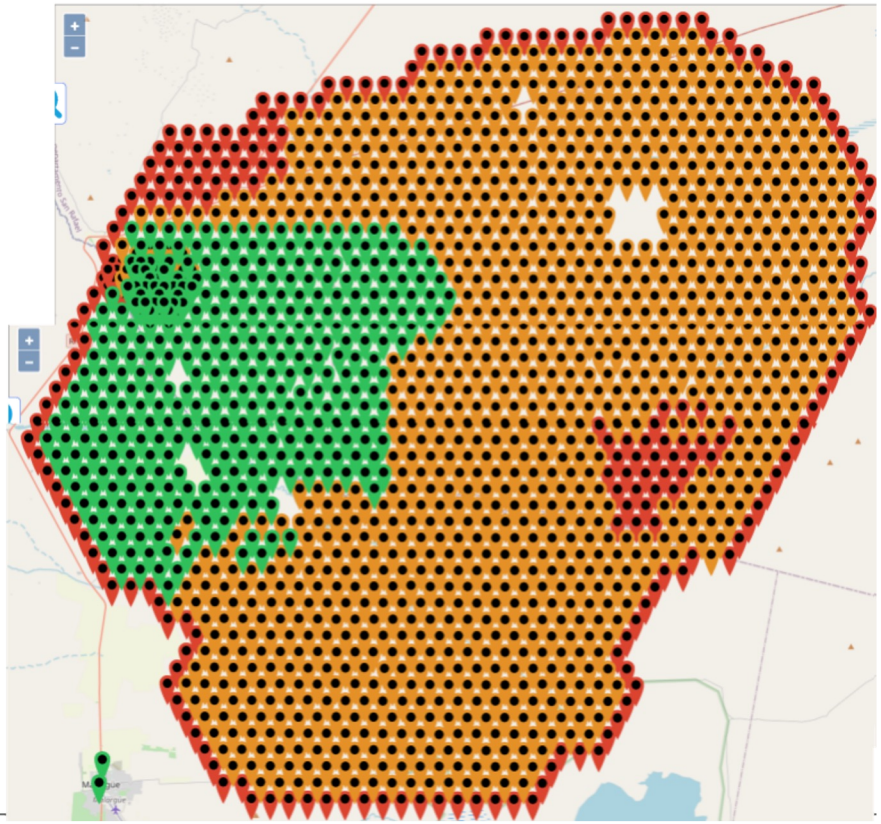
knee @ logE ~ 15.5
low energy ankle @ logE = 16.22 ± 0.02
2nd knee @ logE = 17.04 ± 0.04
ankle @ logE = 18.73 ± 0.01
instep @ logE = 19.25 ± 0.03
cutoff @ logE = 19.85 ± 0.03

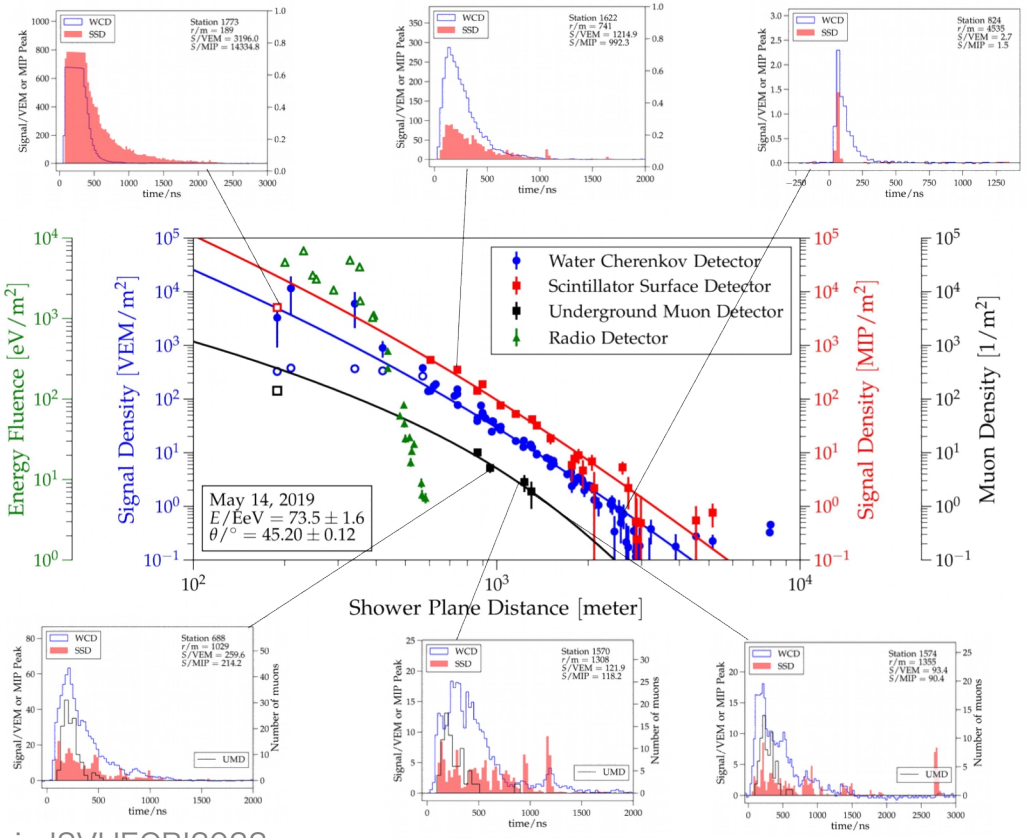
Future prospect for Auger / TA

AugerPrime

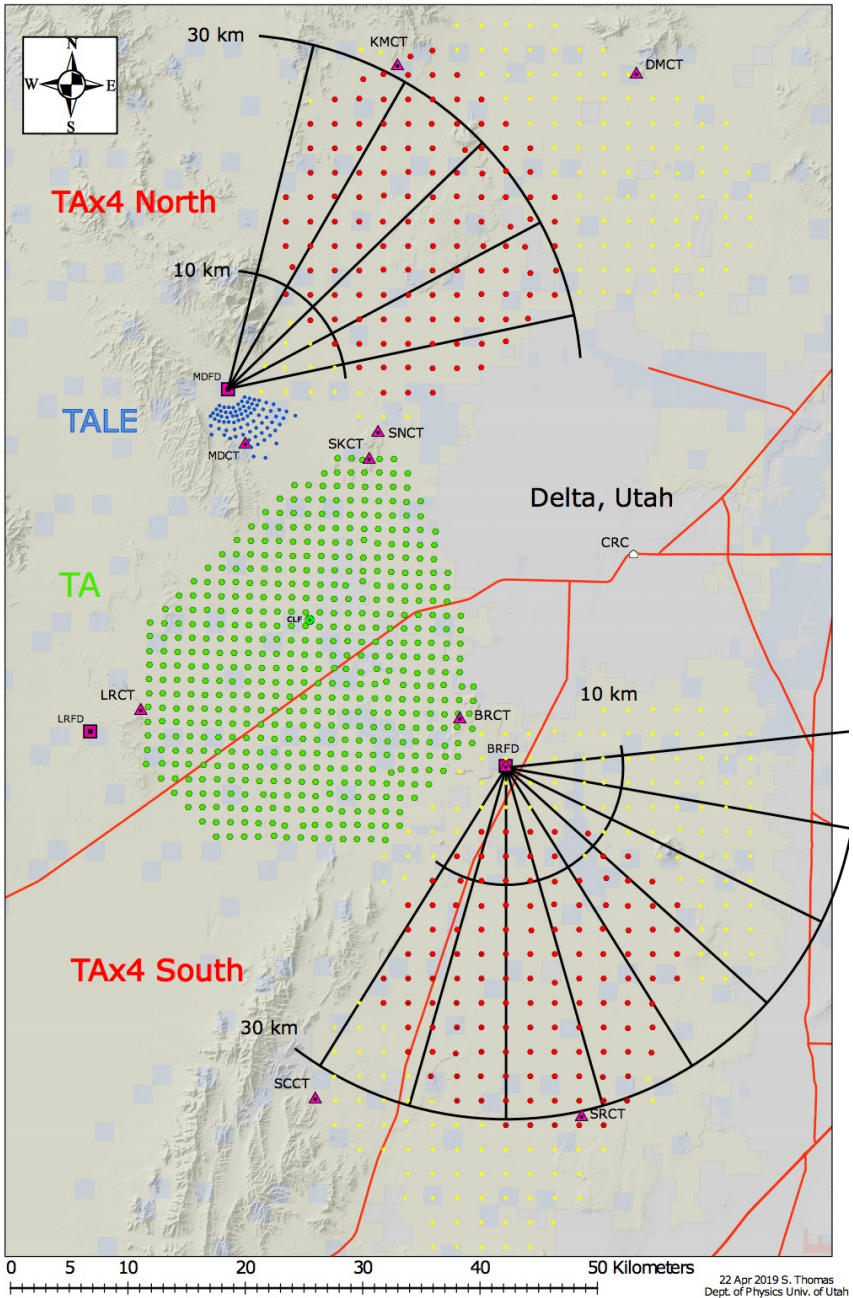
- Large exposure with **composition sensitivity**
  - **Surface Scintillator Detector** to measure e/γ for vertical
  - **Radio Detector** to measure radio for inclined shower
  - **small PMT** for wider dynamic range
  - **Underground Muon Detector** for muon measurement



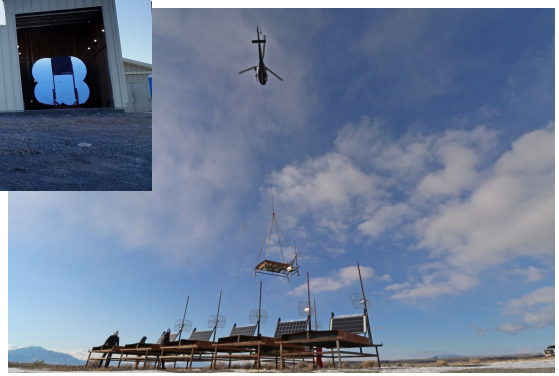




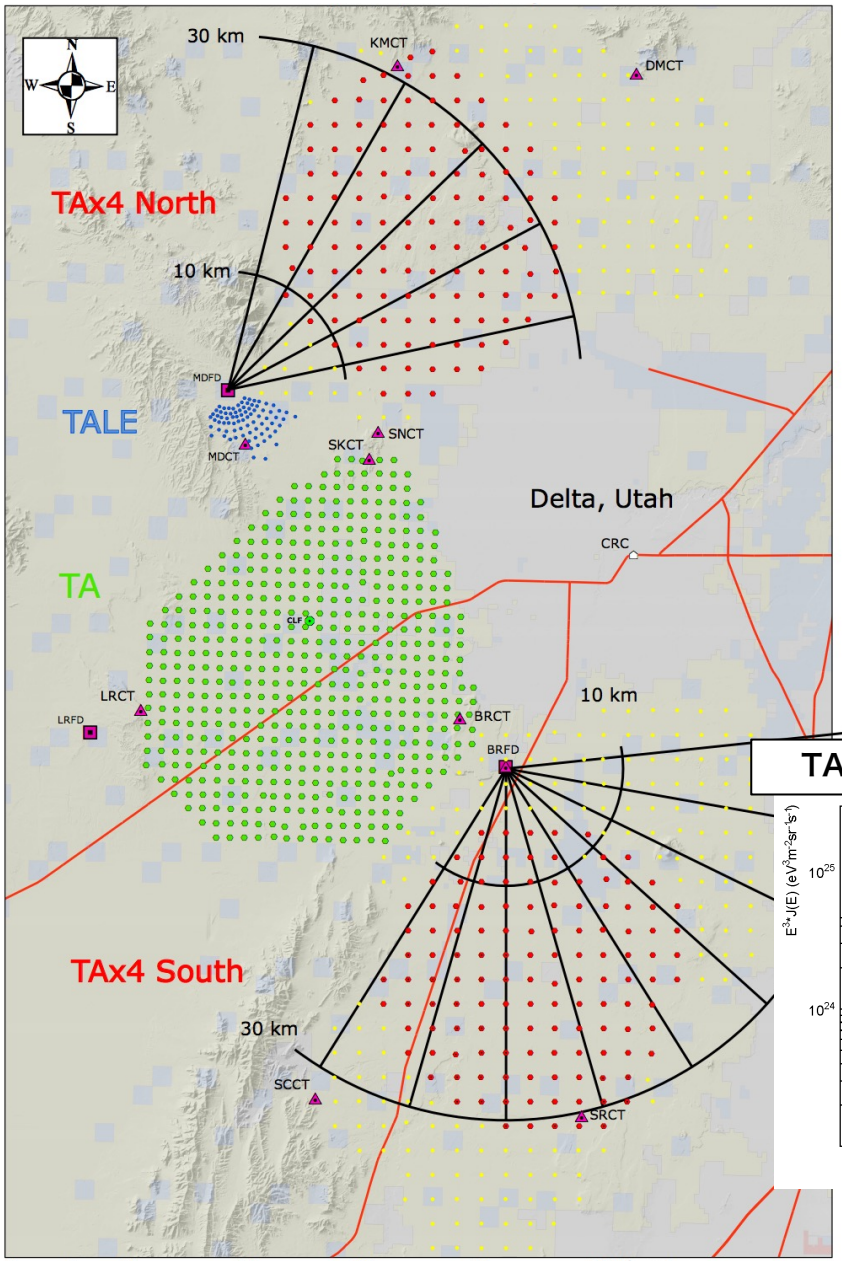
TAx4



- Focus on highest energies
  - $E > 10^{19.5}$ eV
- New 4 + 8 FDs
- New Northern and Southern SD array
  - expand TA SD area by factor 4 ~3000 km^2
  - 2.08 km spacing (TA: 1.2km)
- In operation both detectors
  - over 2.5 yrs data taking

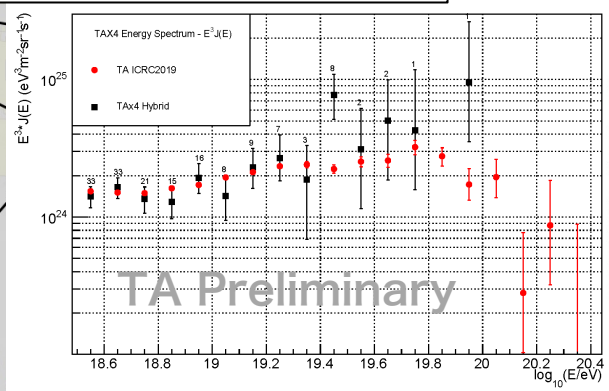


TAx4

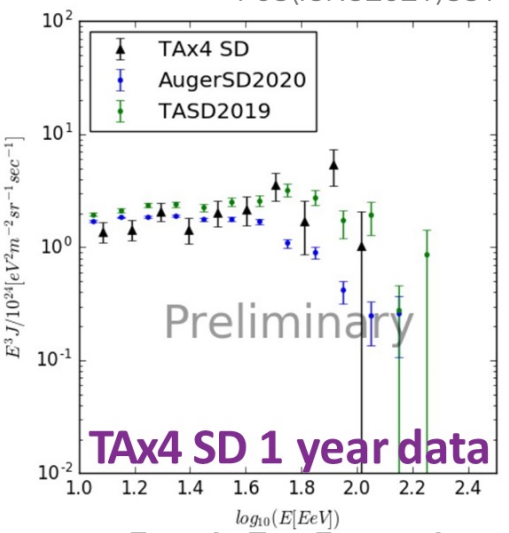


- Focus on highest energies
  - E >$10^{19.5}$ eV
- New 4 + 8 FDs
- New Northern and Southern SD array
  - expand TA SD area by factor 4 ~3000 km^2
  - 2.08 km spacing (TA: 1.2km)
- In operation both detectors
  - over 2.5 yrs data taking

TAx4 Hybrid Spectrum

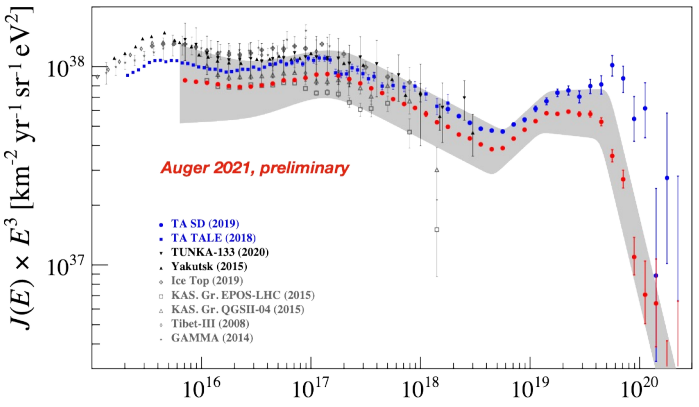


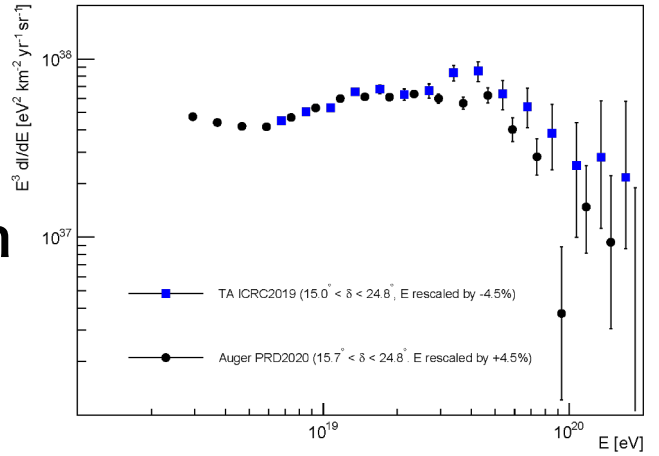
PoS(ICRC2021)331



Summary

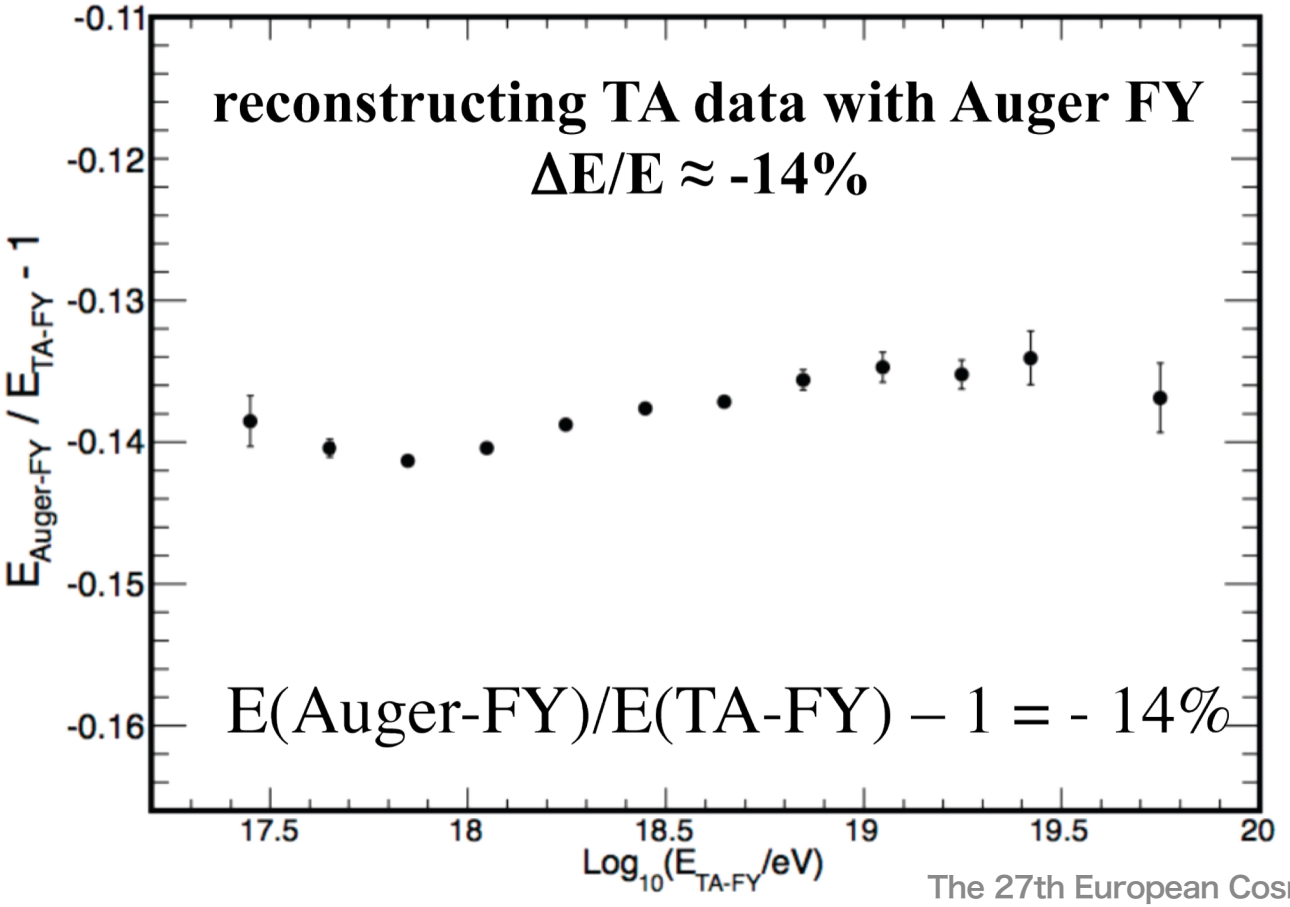
- 5 orders of spectrum are observed by Auger / TA
- New spectral feature “instep”
  - 2 step softening above ankle (Auger *PRL,PRD 2020*)
  - Confirmed in northern hemisphere data
- Absolute energy scale difference is 9% in higher energy region
- Better agreement in common declination band $-15^\circ < \delta < +24.8^\circ$
  - Even better agreement if an energy-dependence shift of 10%/decade allowed
- Future prospect
  - Highest energy difference
    - Statistics? or Astrophysical sources only in northern hemisphere?
  - AugerPrime, TAx4 data
  - Low energy comparison (HEAT, Auger-750m, TALE FD, TALE SD)





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



Energy Scale Uncertainties

Auger

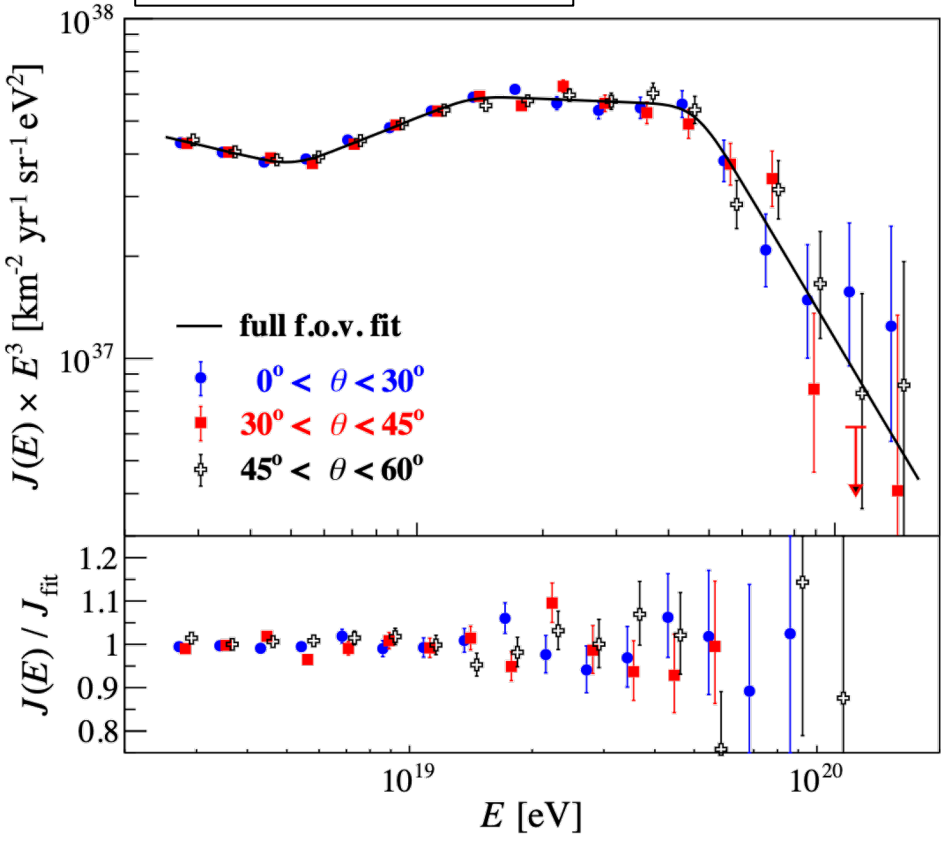
Systematic uncert. in energy scale	
Fluorescence yield	3.6%
Atmosphere	3.4% – 6.2%
FD calibration	9.9%
FD profile recon.	6.5% – 5.6%
Invisible energy	3% – 1.5%
Energy scale stability	5%
TOTAL	14%

TA

Item	Error	Contributions
Detector sensitivity	10%	PMT (8%), mirror (4%), aging (3%), filter (1%)
Atmospheric collection	11%	aerosol (10%), Rayleigh (5%)
Fluorescence yield	11%	model (10%), humidity (4%), atmosphere (3%)
reconstruction	10%	model (9%) missing energy (5%)
Sum in quadrature	21%	

Auger + TA energy spectrum Zenith angle dependence

Auger spectra



TA spectra