最高エネルギー宇宙線でみる宇宙

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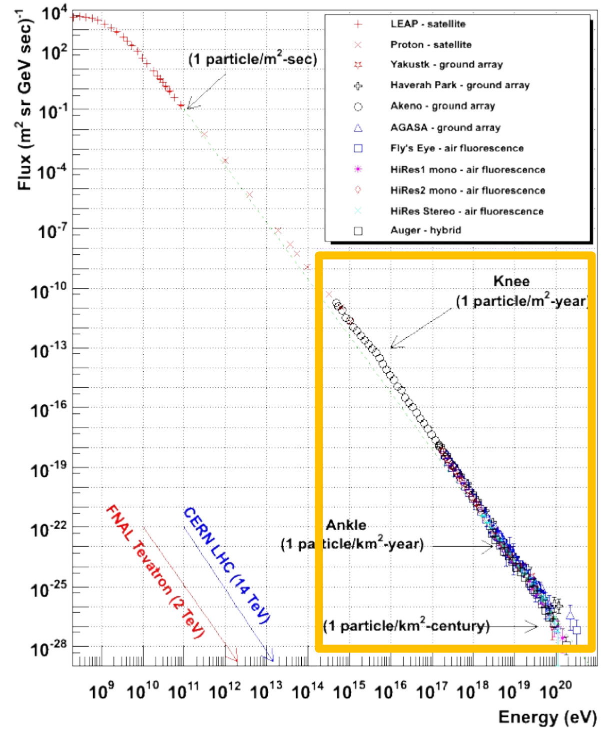
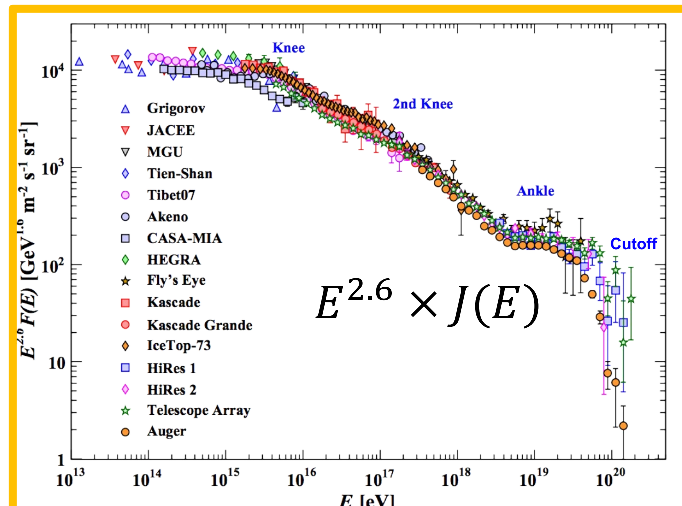
Indirect Cosmic Ray Measurement

- Cosmic ray flux
  - Power law feature
    - Flux(E) $\propto E^{-\gamma}$
  - Spectral features
    - “Knee” @ E ~ $10^{15.6}$ eV
    - “2nd Knee” @ E ~ 10^{17} eV
    - “Ankle” @ E ~ $10^{18.7}$ eV
    - “Cutoff” @ E ~ $10^{19.8}$ eV



- UHECRs
  - $E > 10^{18}$ eV
  - Event rate: 1 particle/km²/year
  - extra-galactic origin



Indirect Cosmic Ray Measurement

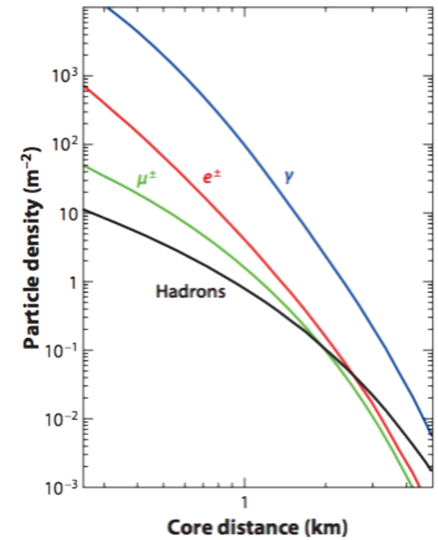
- We can investigate the cosmic ray properties by detecting the EAS particles or photons instead of direct measurements
- Particle detection
  - Scintillation detector
  - Water Cherenkov detector
  - Muon detector
- Photon detection
  - Imaging atmospheric Cherenkov telescopes (IACTs)
  - Non-Imaging Cherenkov detector array
  - Fluorescence Detector
- Radio detection

- $\boldsymbol{E \sim 10^{12}}$ **eV**: Air shower array, IACT
- $\boldsymbol{E \sim 10^{15}}$ **eV**: Air shower array, Cherenkov, Radio
- $\boldsymbol{E \sim 10^{18}}$ **eV**: Air shower array, FD, or both

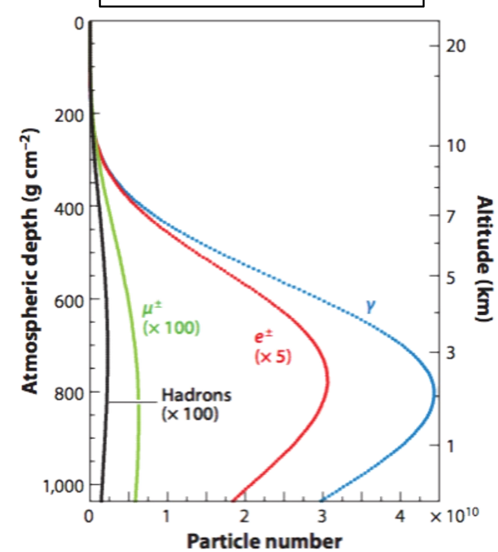
How to measure CR energy

- Air shower phenomena
  - Lateral spread:
    - Perpendicular to an arrival direction
    - Particle density ∝ CR energy
      → sampling by Air Shower Array
  - Shower profile:
    - Cascade continues up to
      limitation of particle production
    - Atmosphere act as calorimeter
    - Light flux ∝ energy deposition
      by EAS charged particles
      → detection by Fluorescence Detector

Lateral distribution

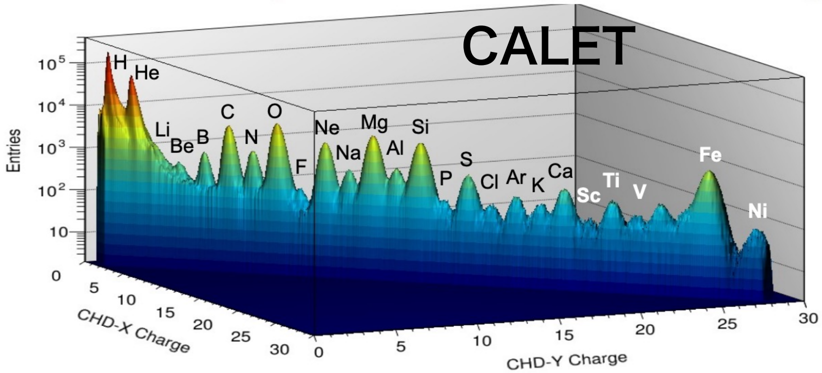


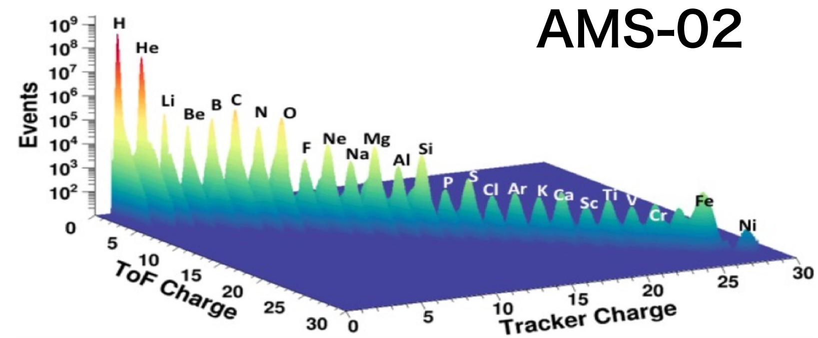
Shower profile



How to measure CR charge

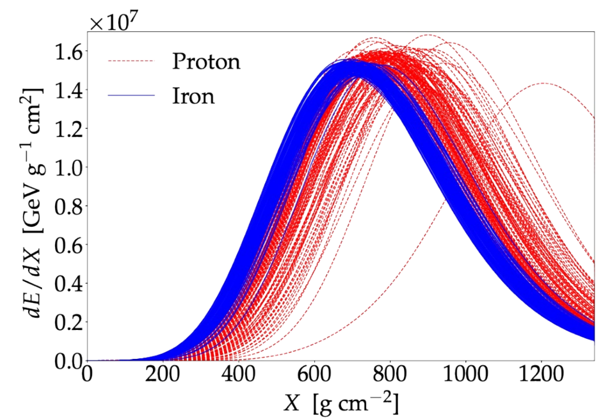
- Direct measurement

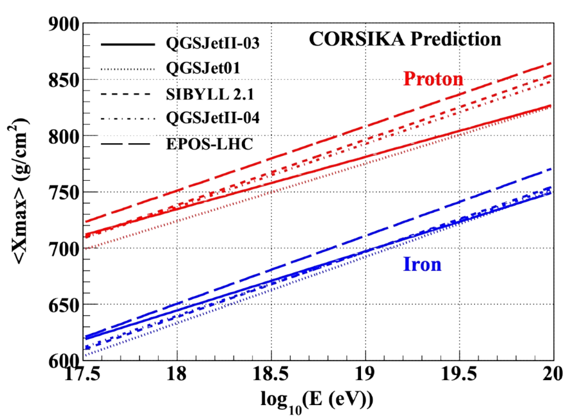


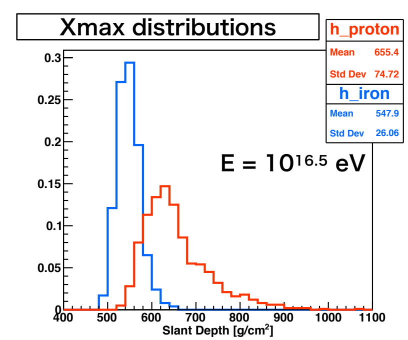


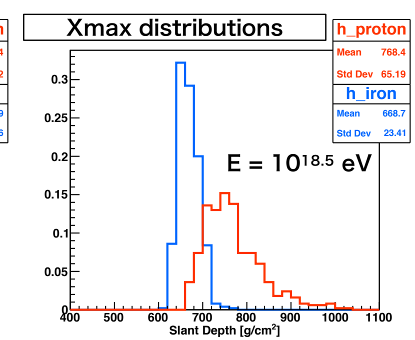
https://calet.jp/wp-content/uploads/2022/07/COSPAR22_akaike_pub.pdf https://ams02.space/advances-data-analysis/improvements-charge-resolution

- Indirect measurement
  - mass sensitive parameter
    - depth of shower maximum, $X_{\max}$
    - μ component



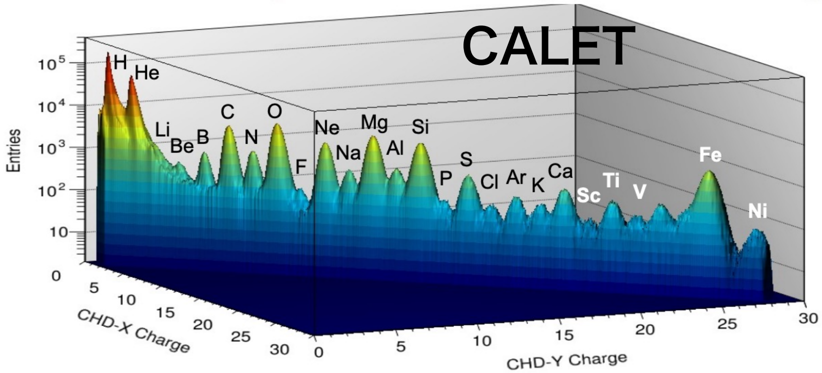


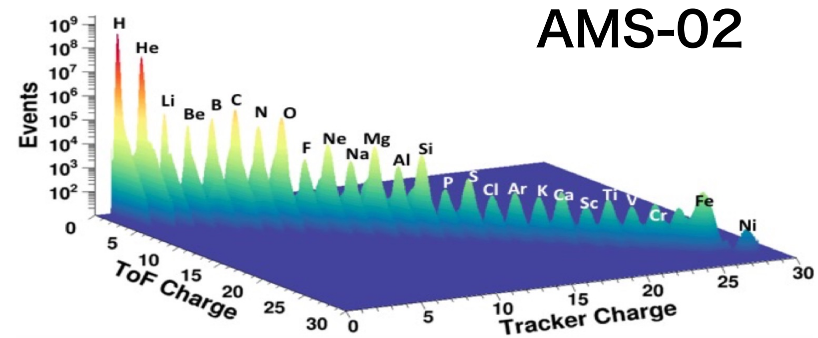




How to measure CR charge

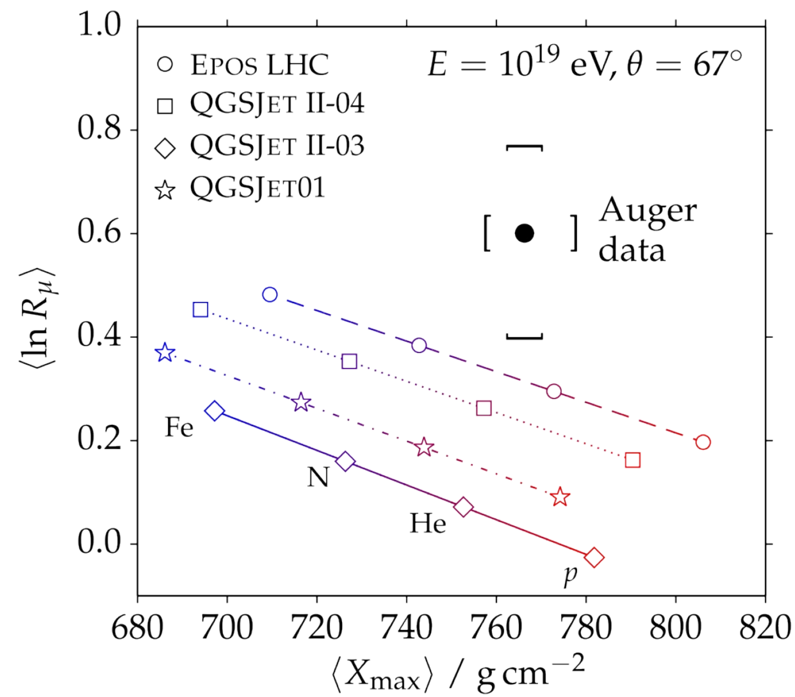
- Direct measurement



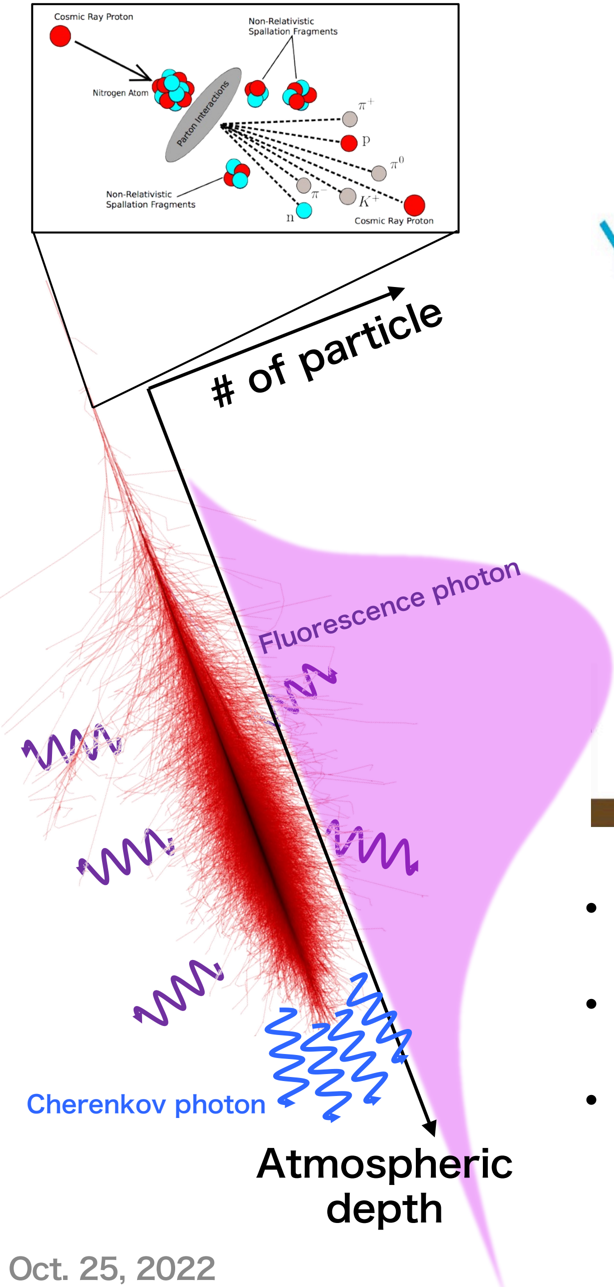


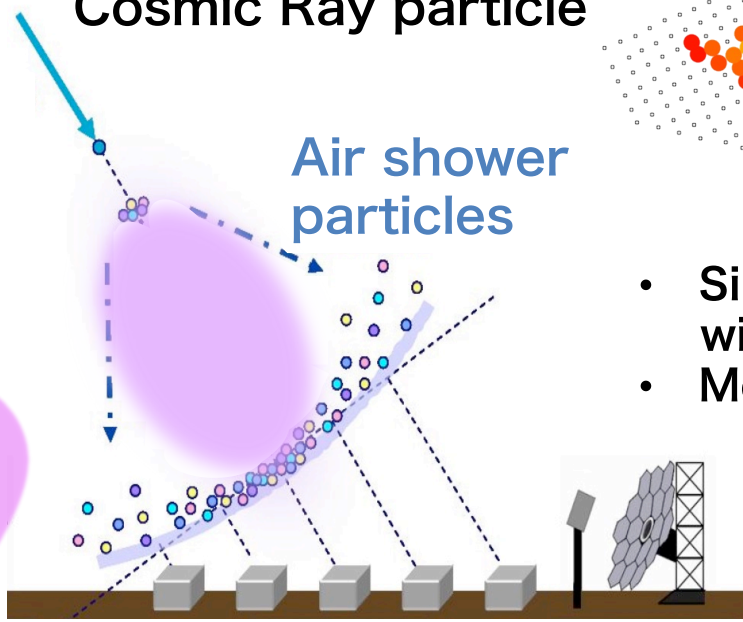
https://calet.jp/wp-content/uploads/2022/07/COSPAR22_akaike_pub.pdf https://ams02.space/advances-data-analysis/improvements-charge-resolution

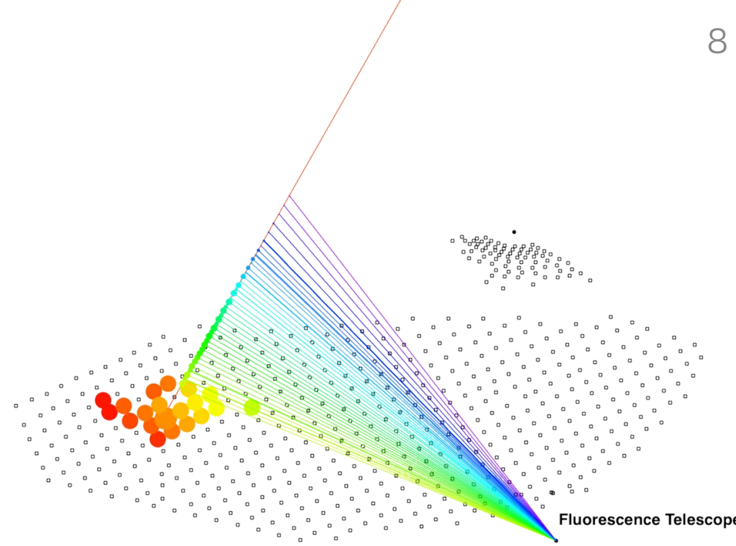
- Indirect measurement
  - mass sensitive parameter
    - depth of shower maximum, $X_{\mathbf{max}}$
    - μ component (large uncertainty…)



UHECR detection







Hybrid Detector

- Simultaneous detection with FD + SD
- Most precise measurement

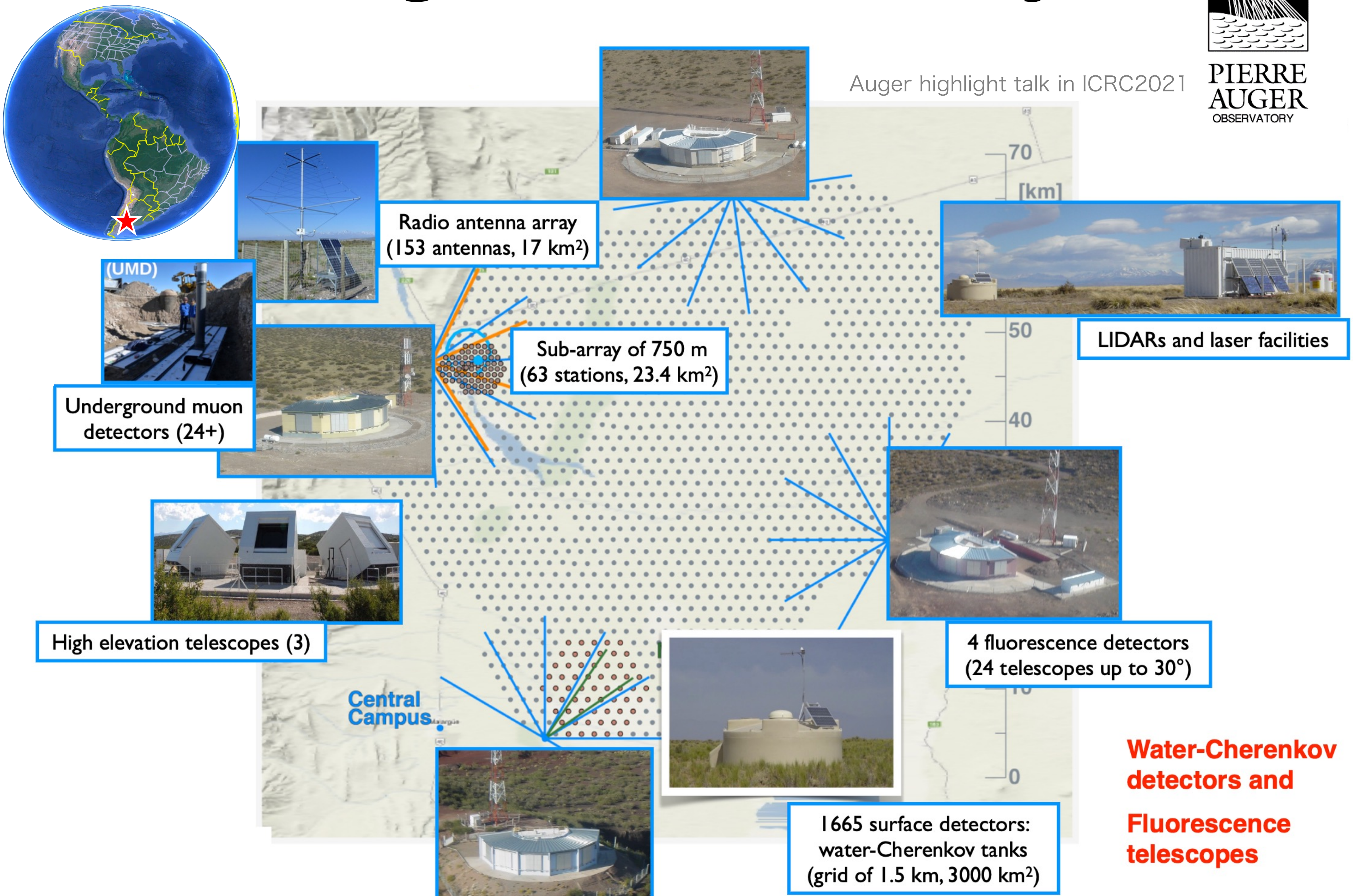
Surface Detector Array

- Detect particle densities and timing information at ground
- Duty cycle: ~100%
  - High statistics
- Measure shower lateral spread

Fluorescence Detector

- Detect air shower photons
- Duty cycle: ~10%
  - moonless night
- Measure shower profile → sensitive to mass composition

Pierre Auger Observatory



Auger highlight talk in ICRC2021

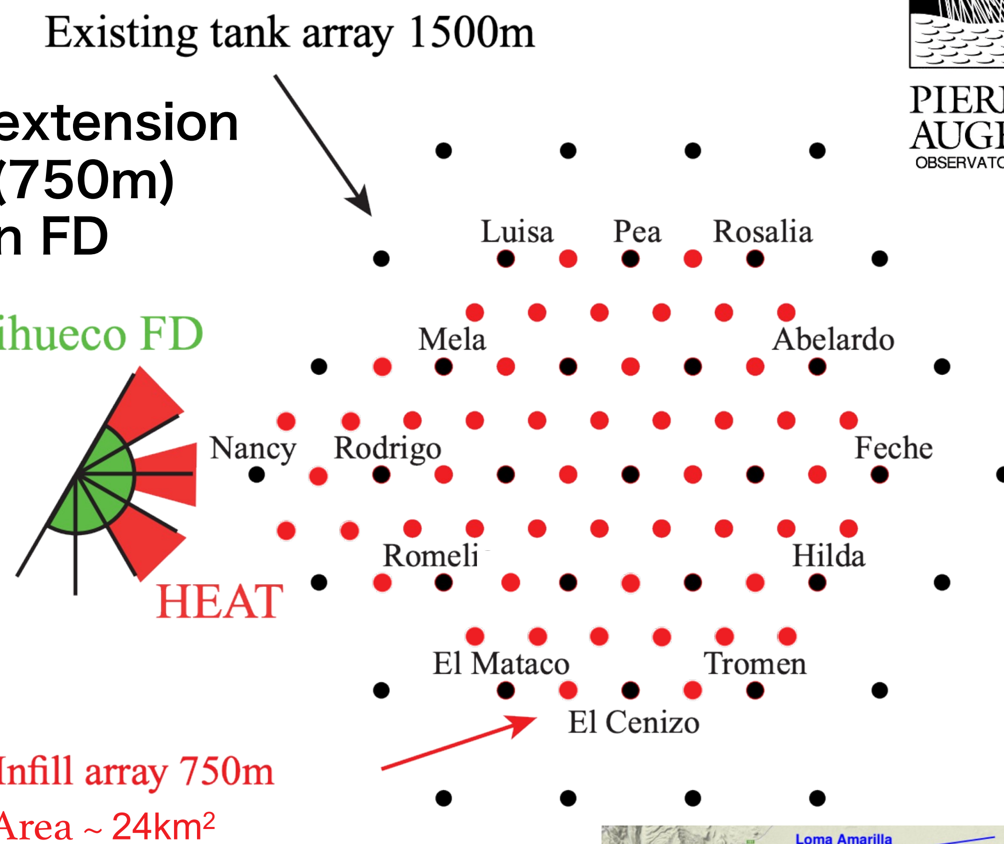
Water-Cherenkov detectors and

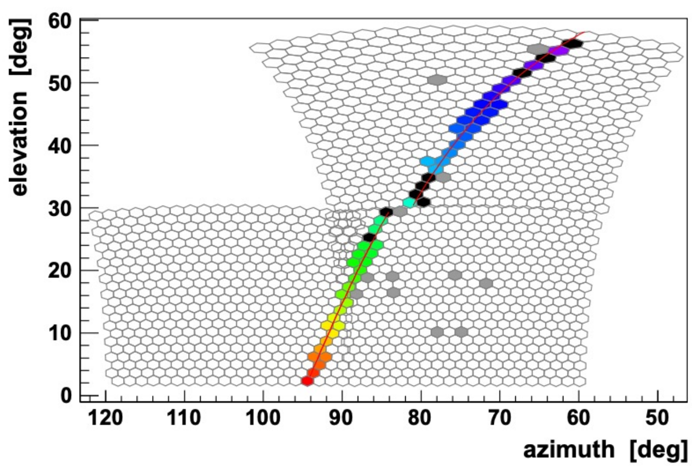
Fluorescence telescopes

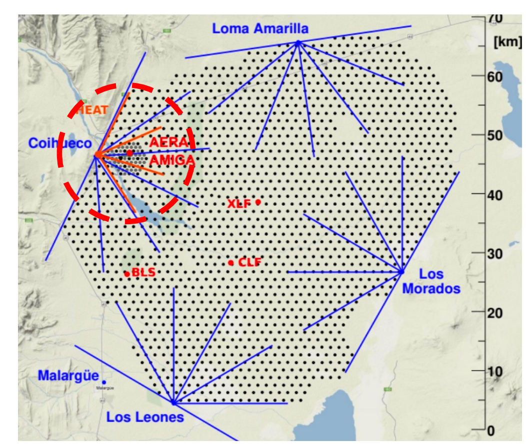
Pierre Auger Observatory

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

high elevation telescopes



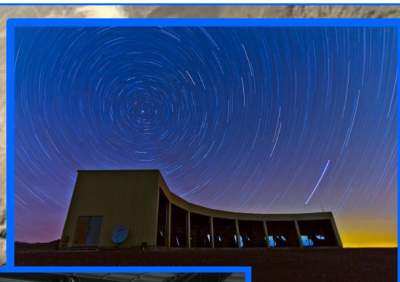


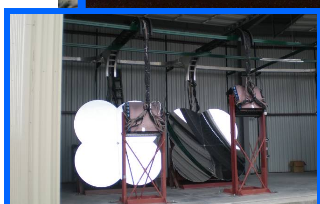


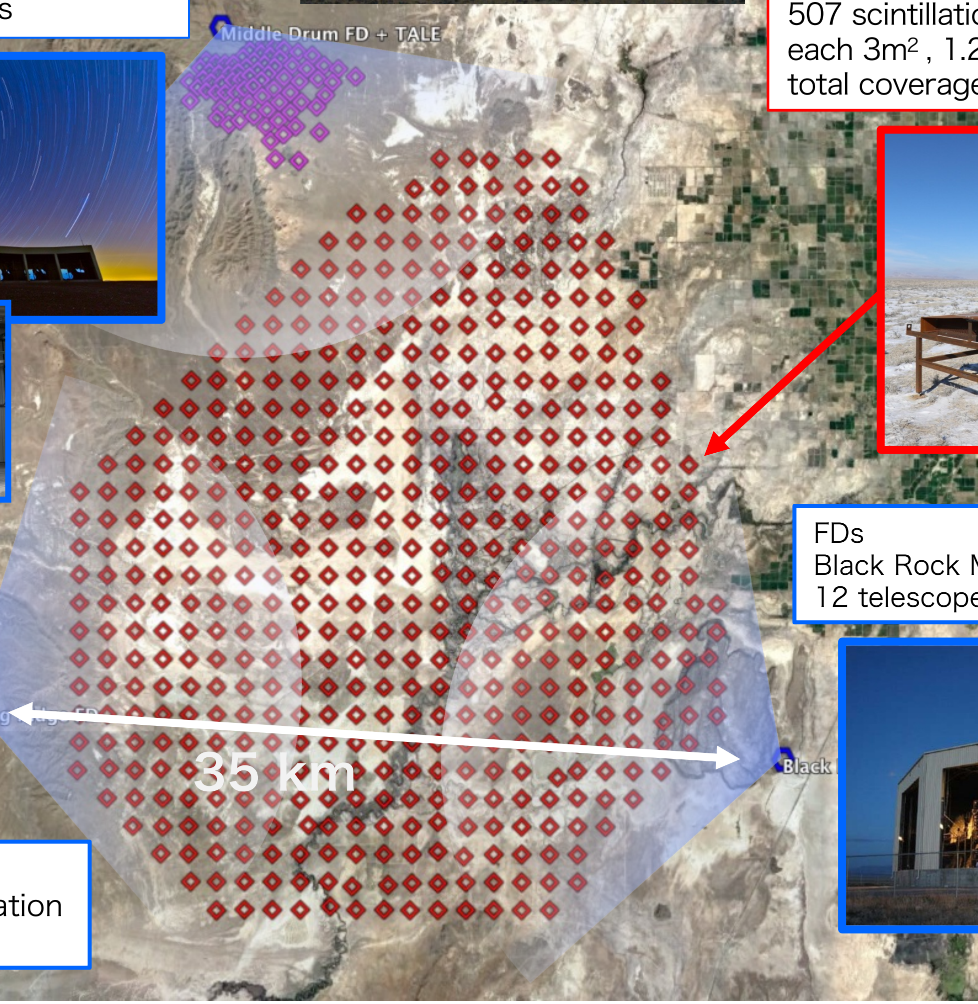
Telescope Array Detectors

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

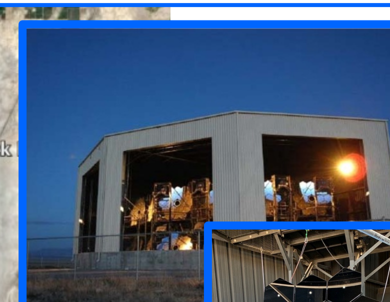
Surface Detector(SD) array
507 scintillation detectors
each $3m^2$, 1.2 km spacing
total coverage ~ $700km^2$

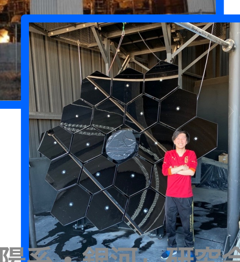






FDs
Black Rock Mesa(BRM) station
12 telescopes



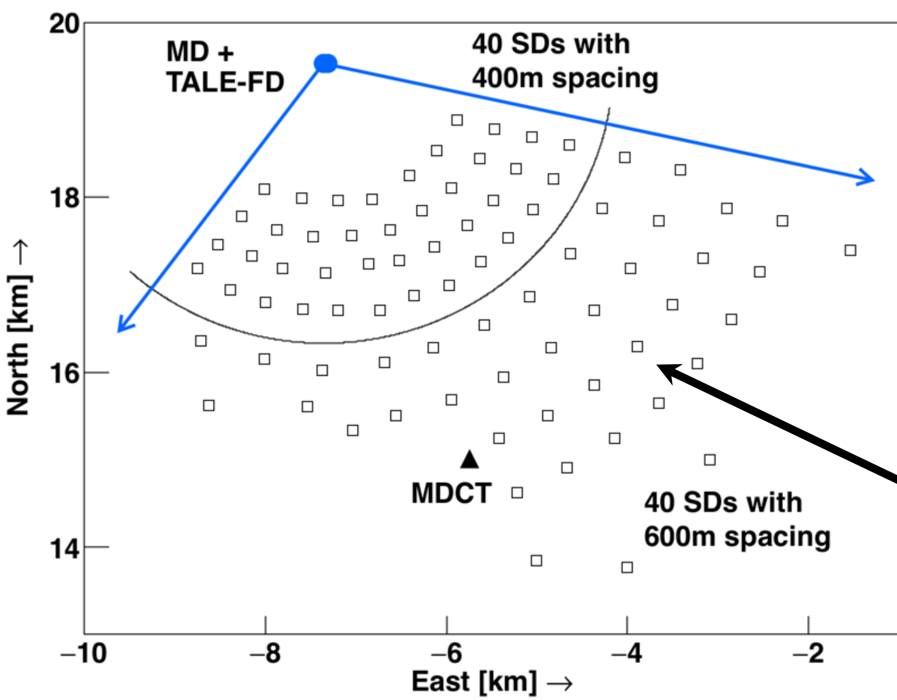


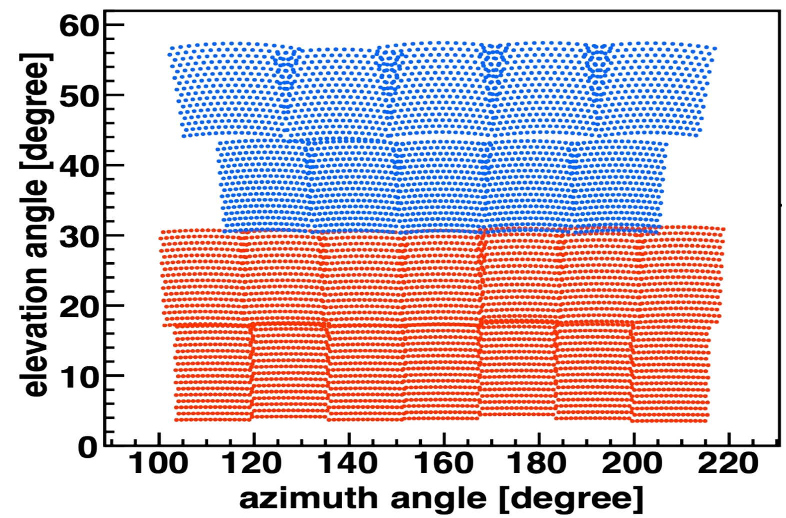
FDs
Long Ridge(LR) station
12 telescopes

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

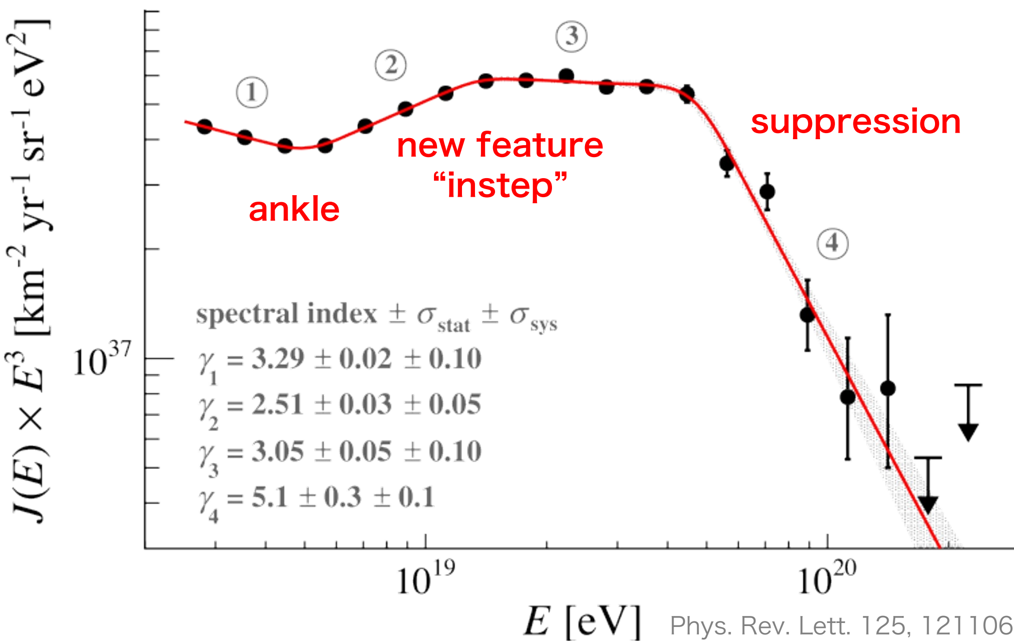
  SD since Nov. 2017





Energy Spectrum

New feature in energy spectrum



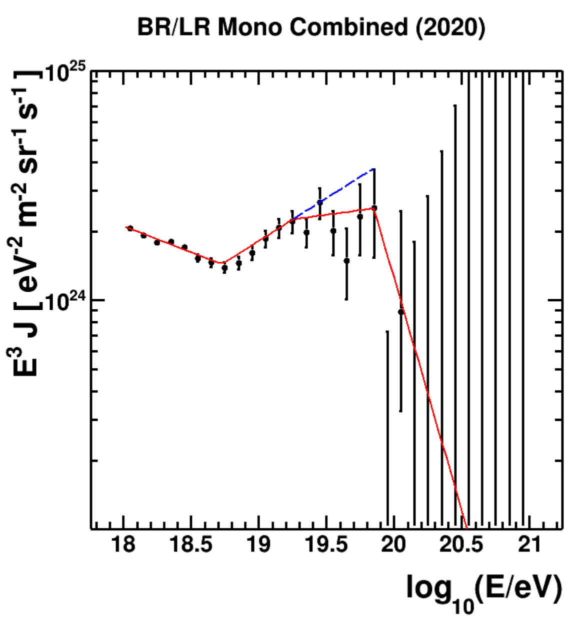
Phys. Rev. Lett. 125, 121106 (2020)

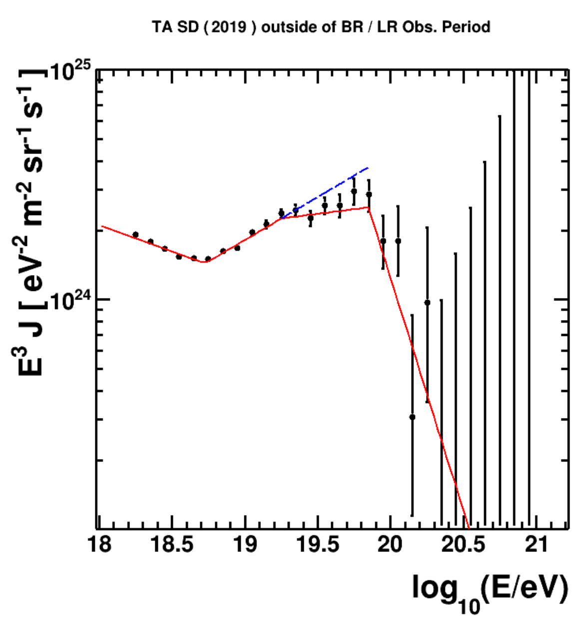
Auger found a new feature in 10^{19} – $10^{19.5}$ eV range

- 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



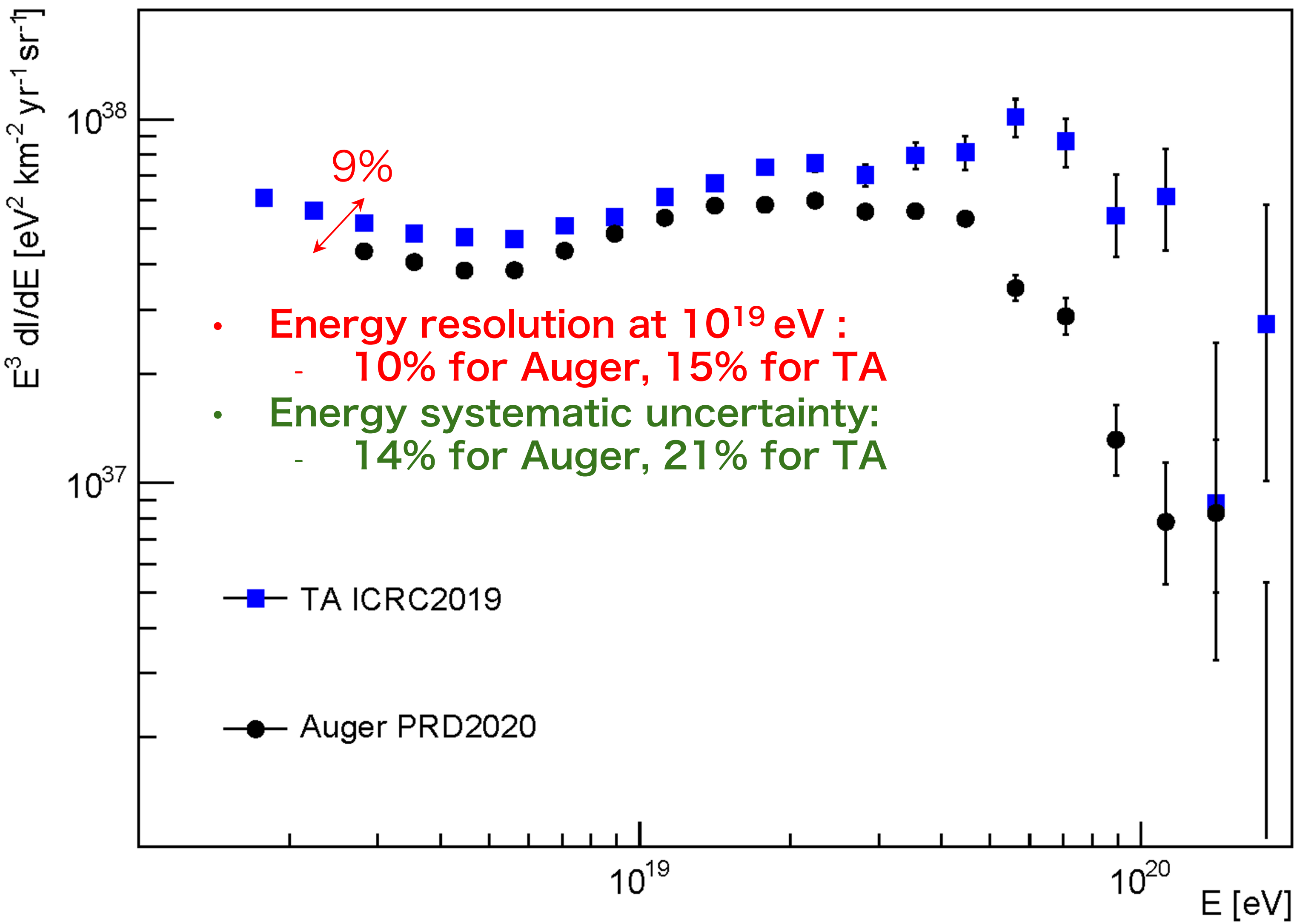


PoS ICRC2021 (2021) 341

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_{ankle}/EeV	5.0 ± 0.1	5.4 ± 0.1
E_{instep}/EeV	13 ± 1	18 ± 1
E_{cut}/EeV	46 ± 3	71 ± 3

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

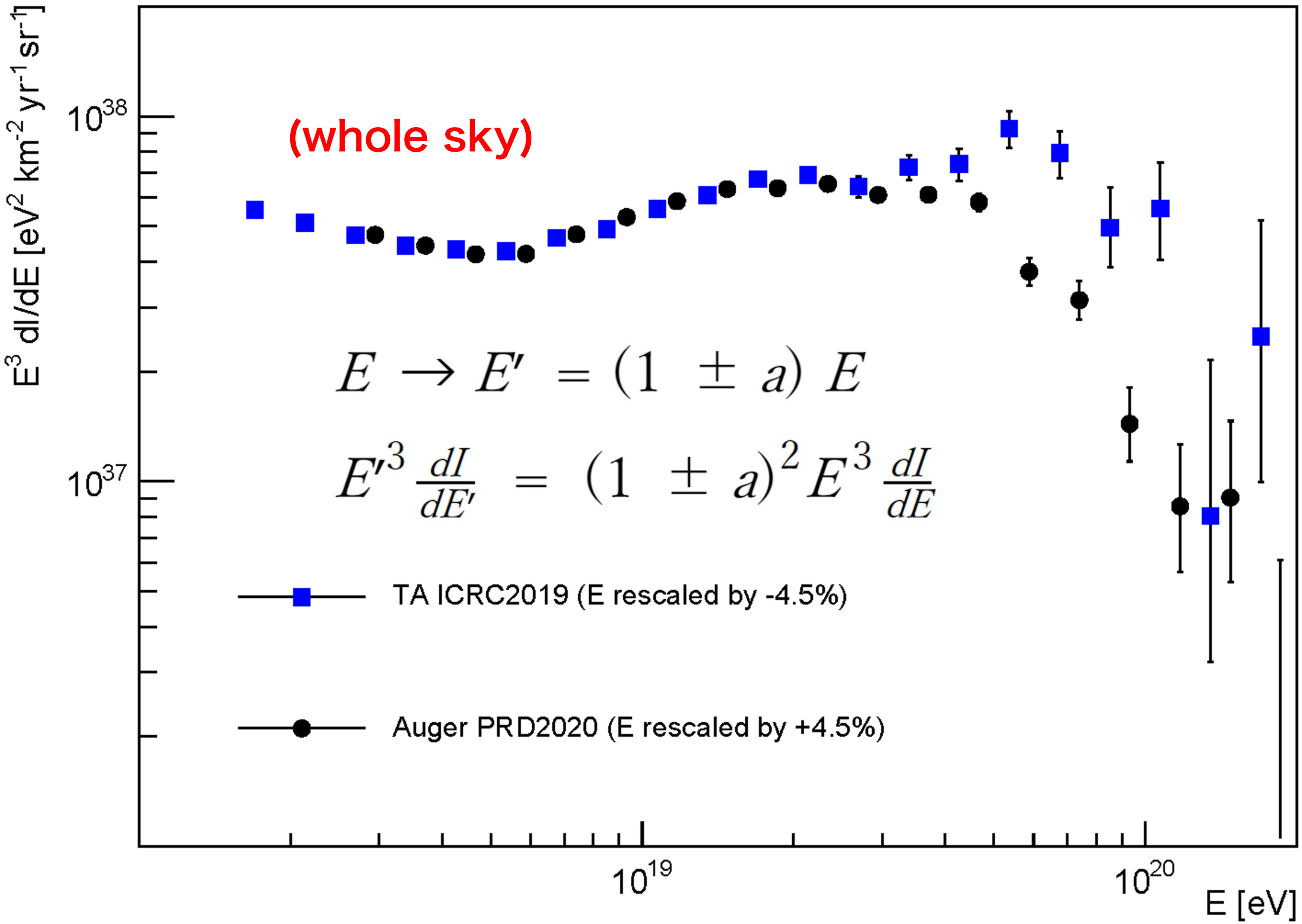
Auger + TA energy spectrum



- Energy resolution at 10^{19} eV :
  - 10% for Auger, 15% for TA
- Energy systematic uncertainty:
  - 14% for Auger, 21% for TA

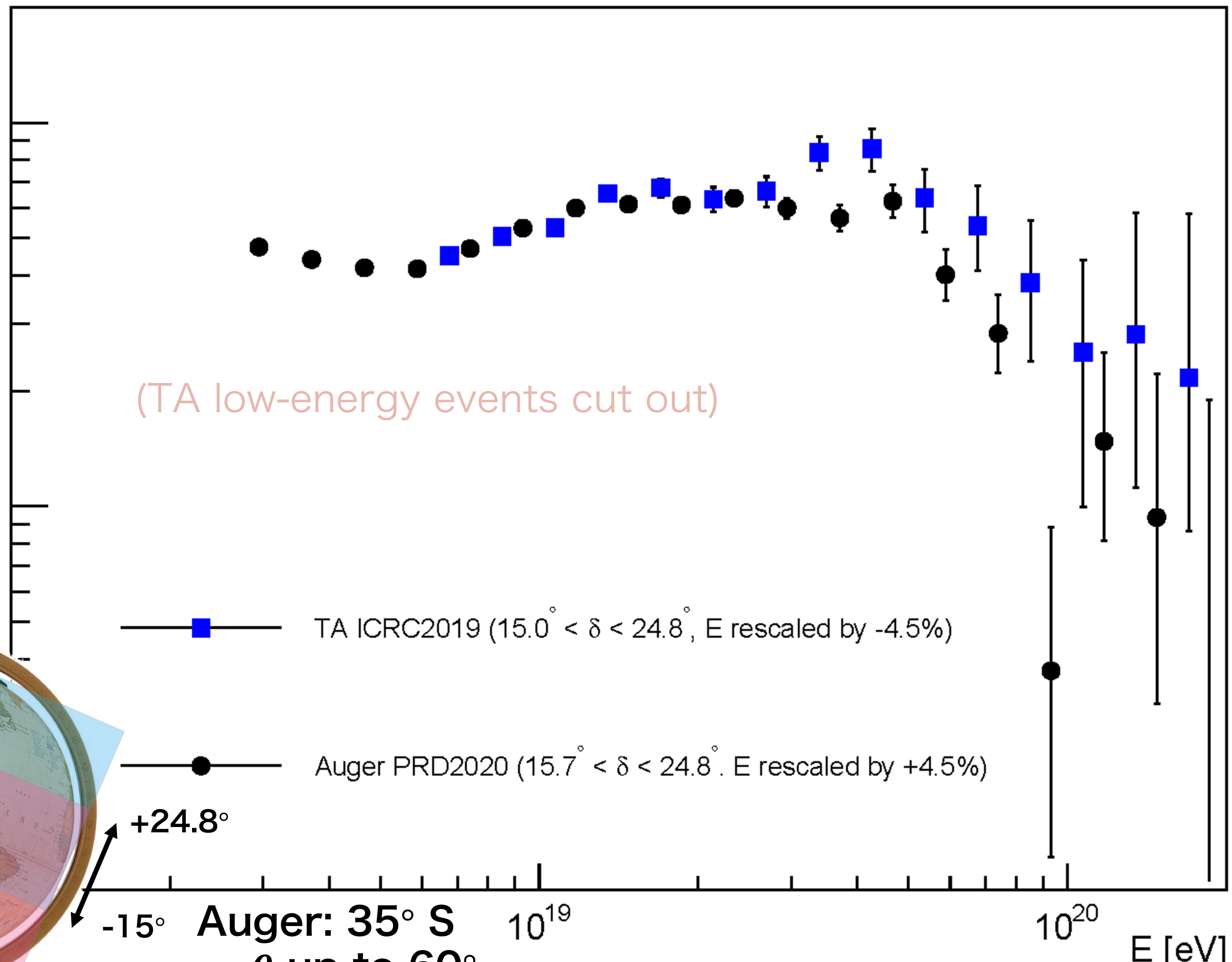
Y. Tsunesada et al. (Auger+TA Spectrum WG)
PoS ICRC2021 (2021) 337

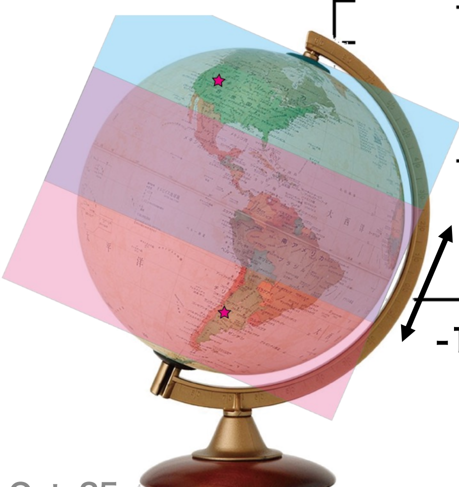
Auger + TA energy spectrum
Energy ±4.5% rescaled



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

Common declination band spectrum Energy ±4.5% rescaled





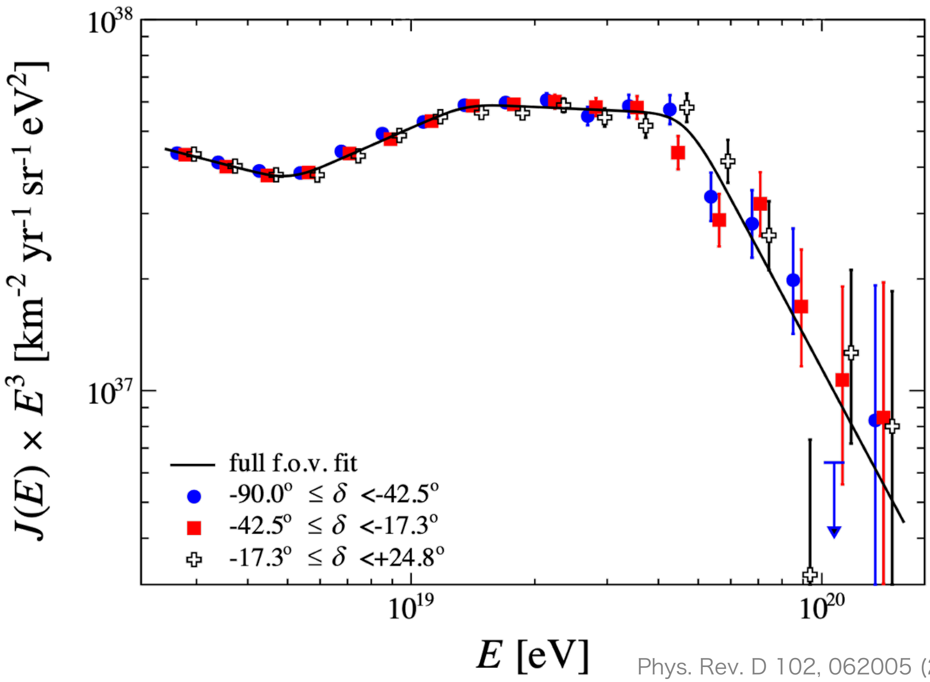
Auger: 35° S
- ***θ* up to 60°**

TA: 39° N
- ***θ* up to 45°**

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

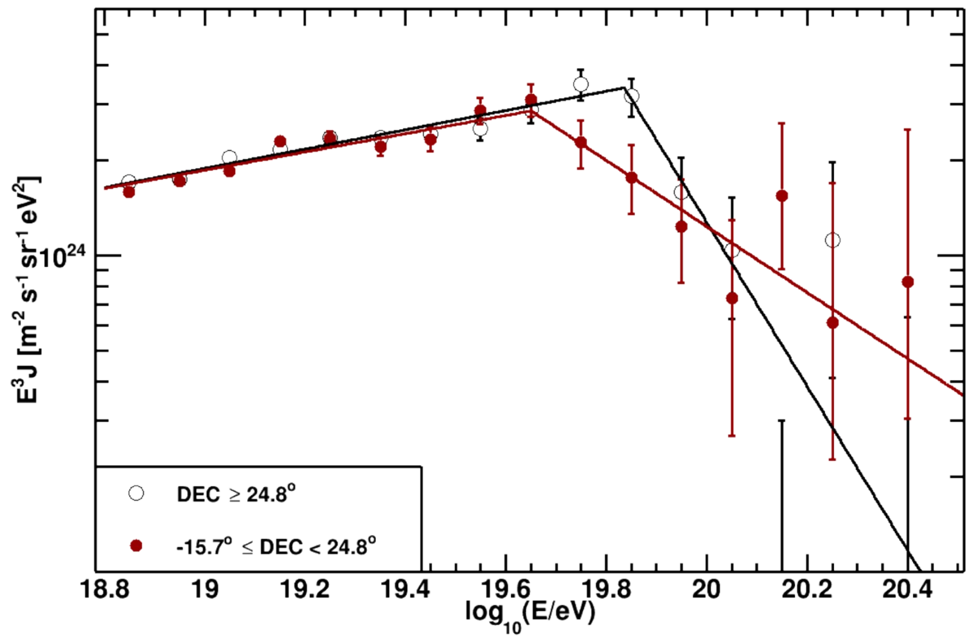
Declination dependence

Auger spectra

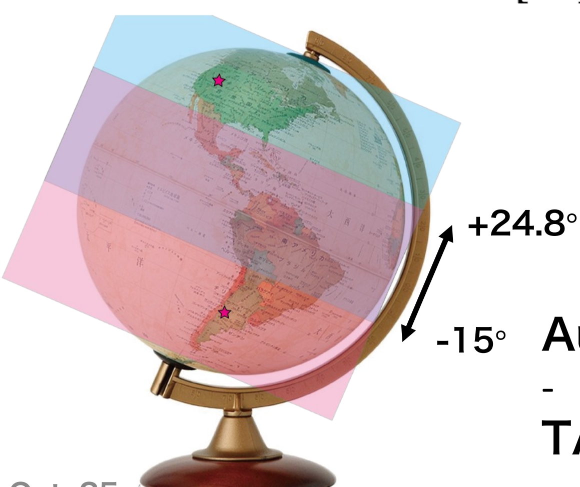


Phys. Rev. D 102, 062005 (2020)

TA spectra



PoS(ICRC2019)298



Auger: 35° S
- θ up to 60°

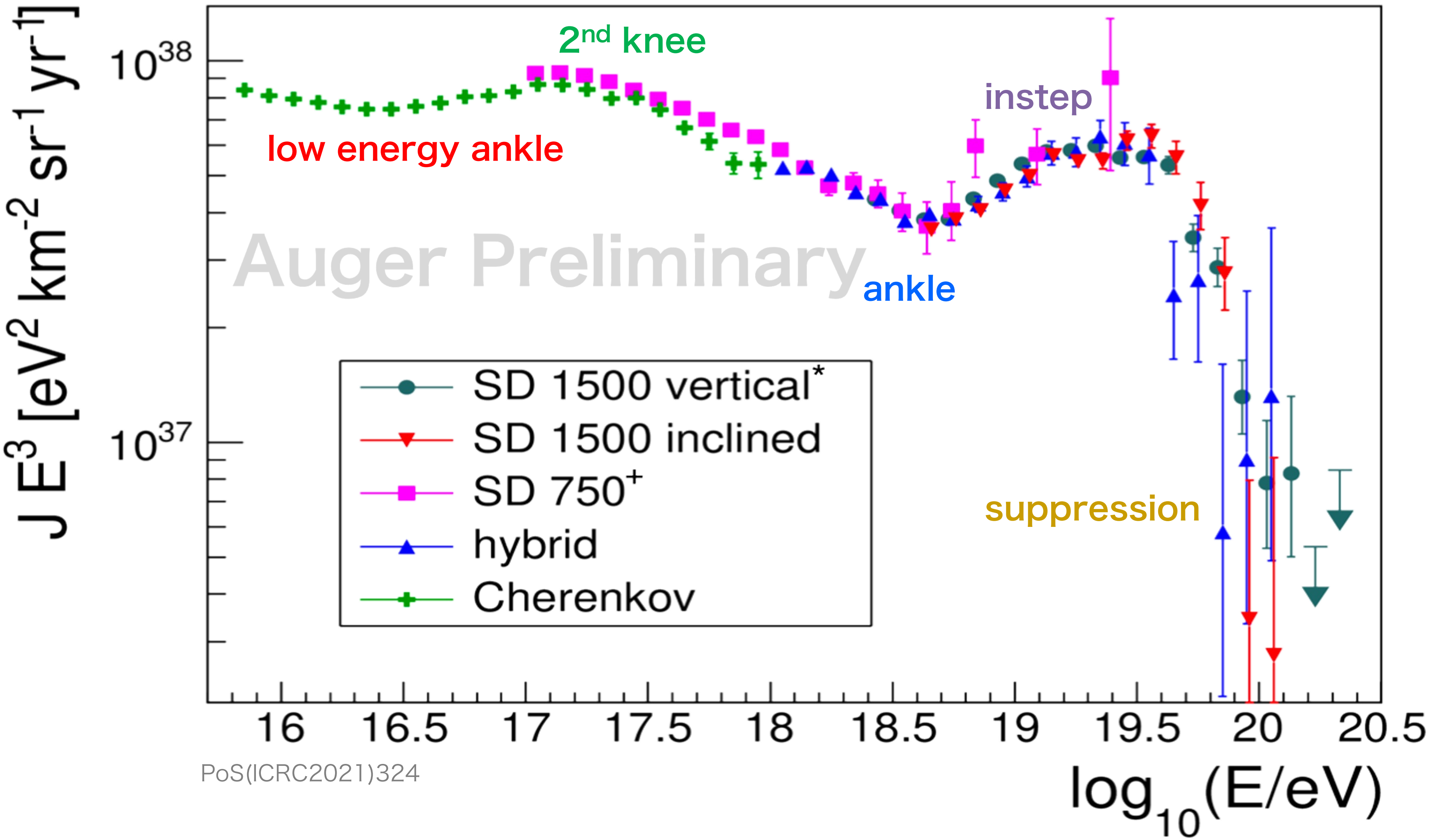
TA: 39° N
- θ up to 45°

Auger: no significant declination dependence

TA : Difference of the cutoff energies

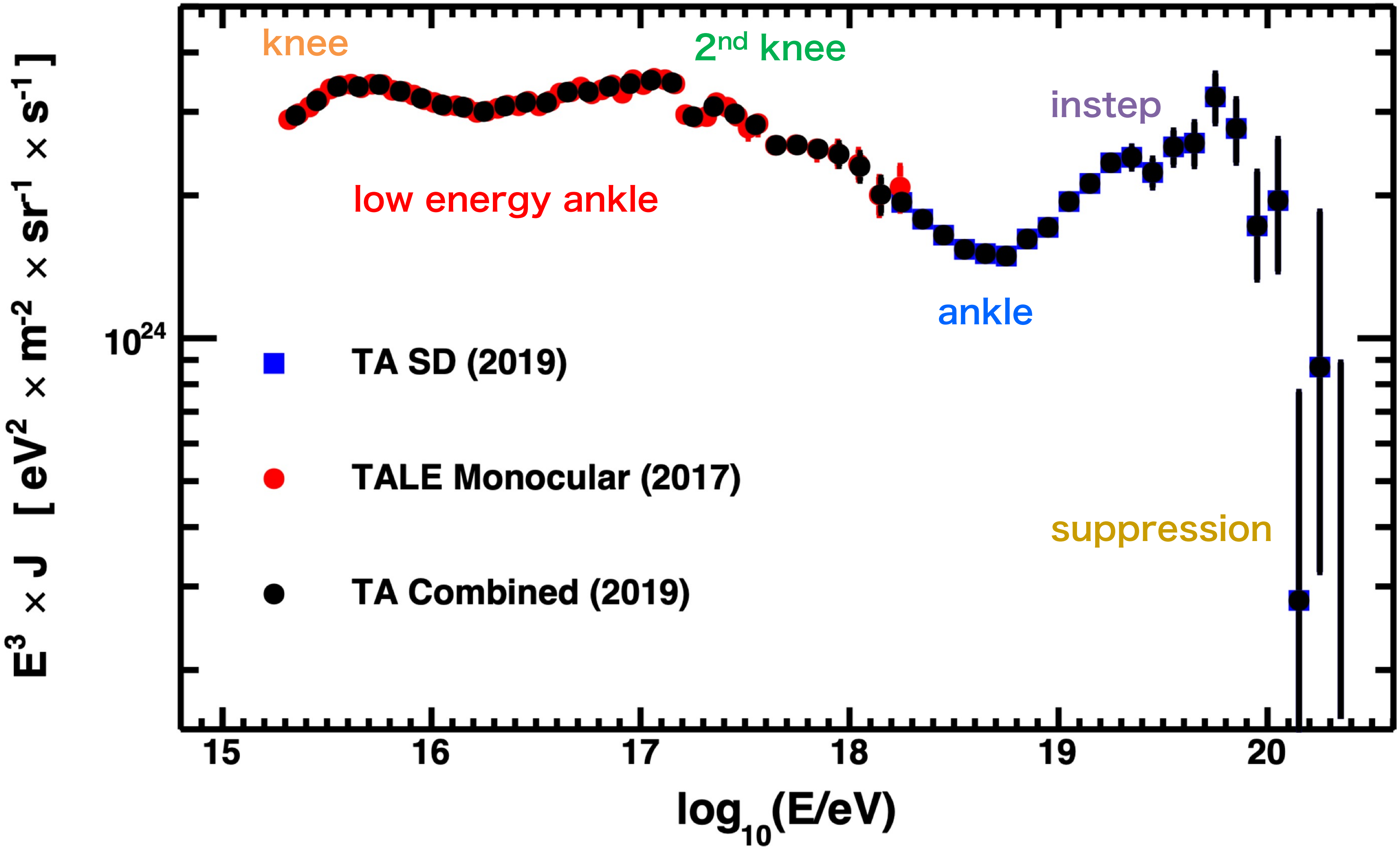
- log(E/eV) = 19.65 ± 0.02 for low dec. band
- log(E/eV) = 19.84 ± 0.02 for high dec. band
  - global significance: 4.3σ (local: 4.7σ)

Auger energy spectrum
All energy range

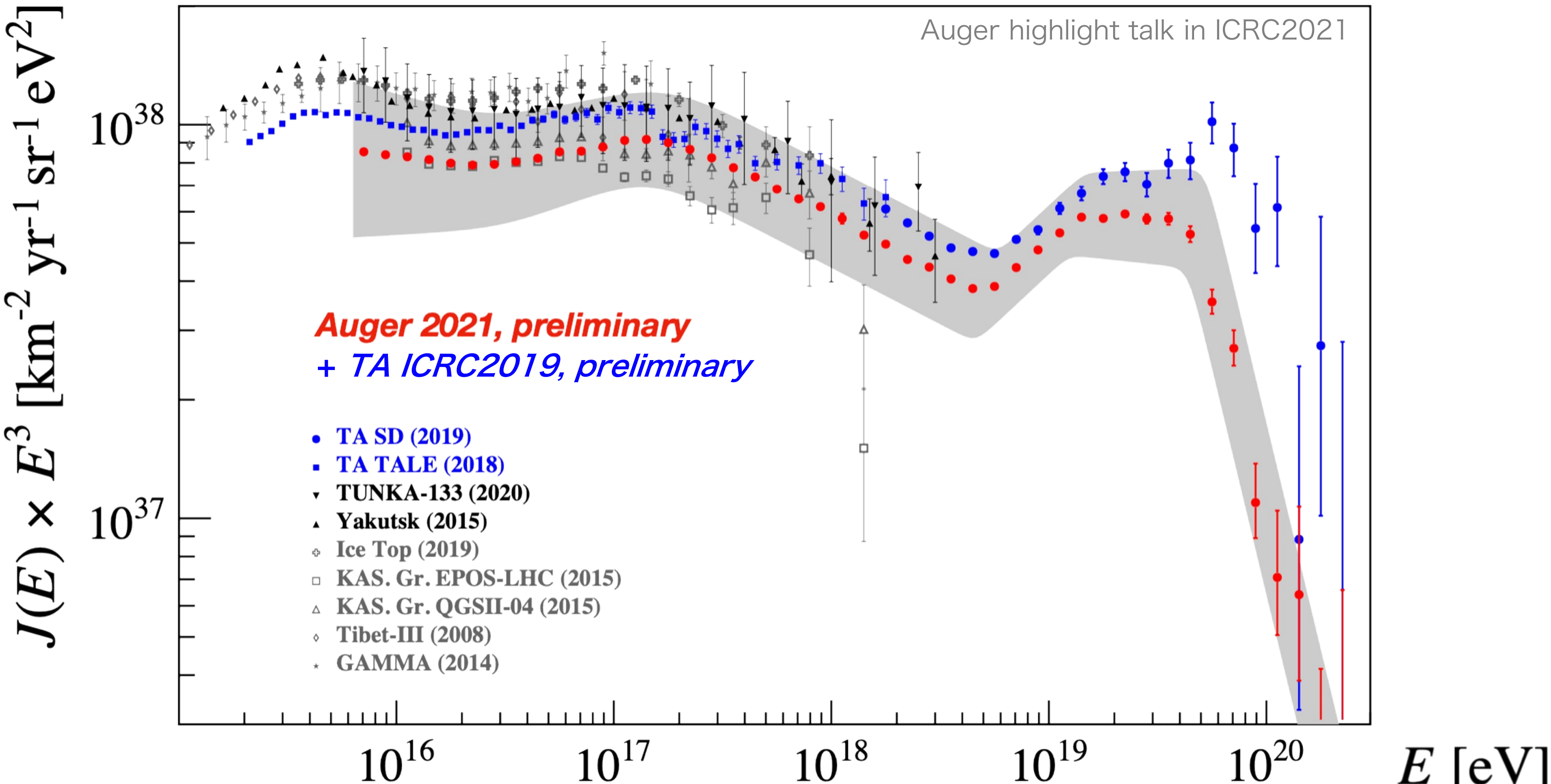


PoS(ICRC2021)324

TA energy spectrum
All energy range



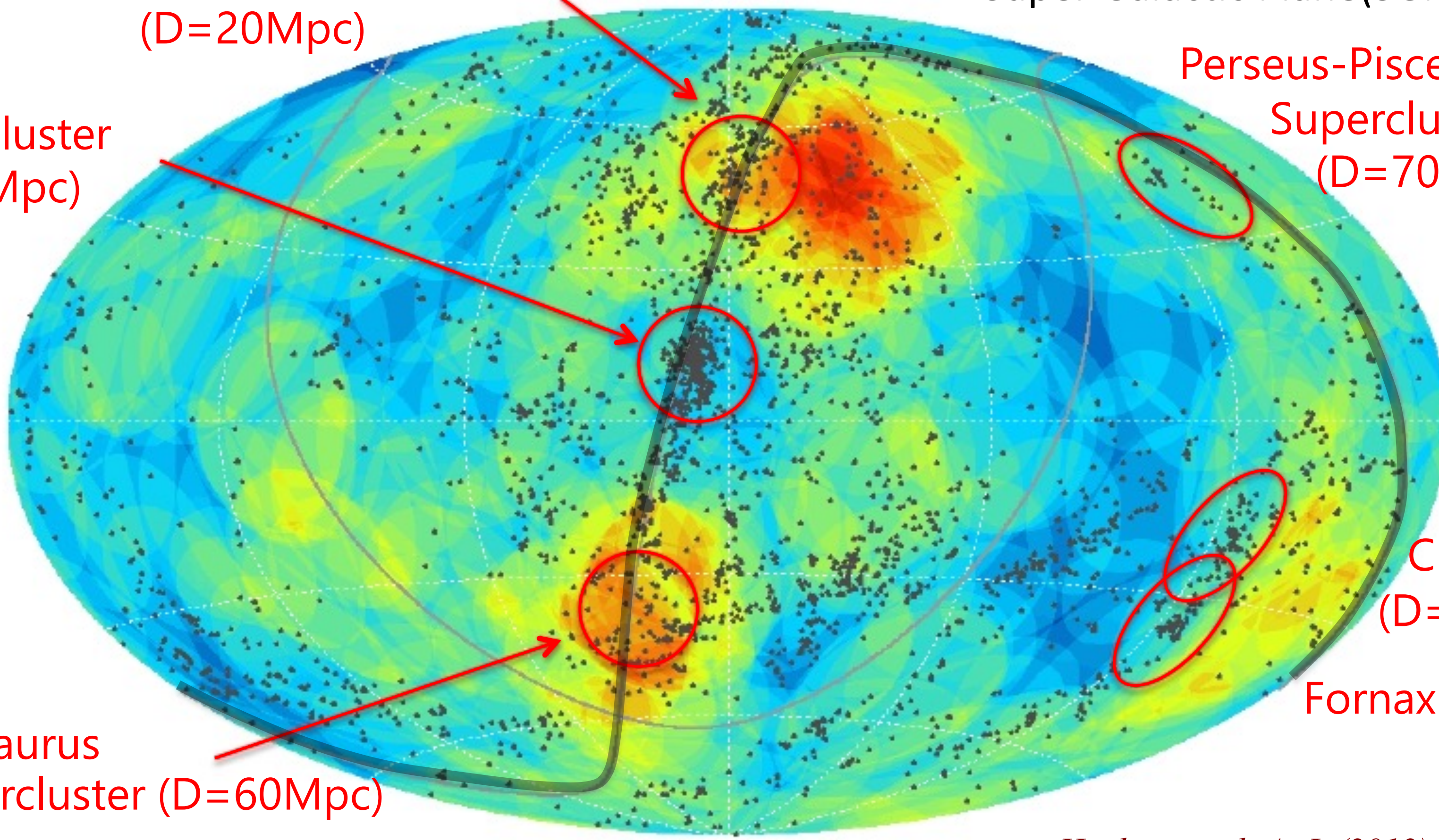
Auger + TA energy spectrum
All energy range



Auger		Telescope Array	
		knee	@ logE ~ 15.5
low energy ankle	@ logE = 16.45 ± 0.05	low energy ankle	@ logE = 16.22 ± 0.02
2nd knee	@ logE = 17.20 ± 0.01	2nd knee	@ logE = 17.04 ± 0.04
ankle	@ logE = 18.70 ± 0.01	ankle	@ logE = 18.73 ± 0.01
instep	@ logE = 19.15 ± 0.03	instep	@ logE = 19.25 ± 0.03
suppression	@ logE = 19.67 ± 0.03	cutoff	@ logE = 19.85 ± 0.03

Anisotropy

Anisotropy, in highest energy ($E>10^{19.75}$ eV)

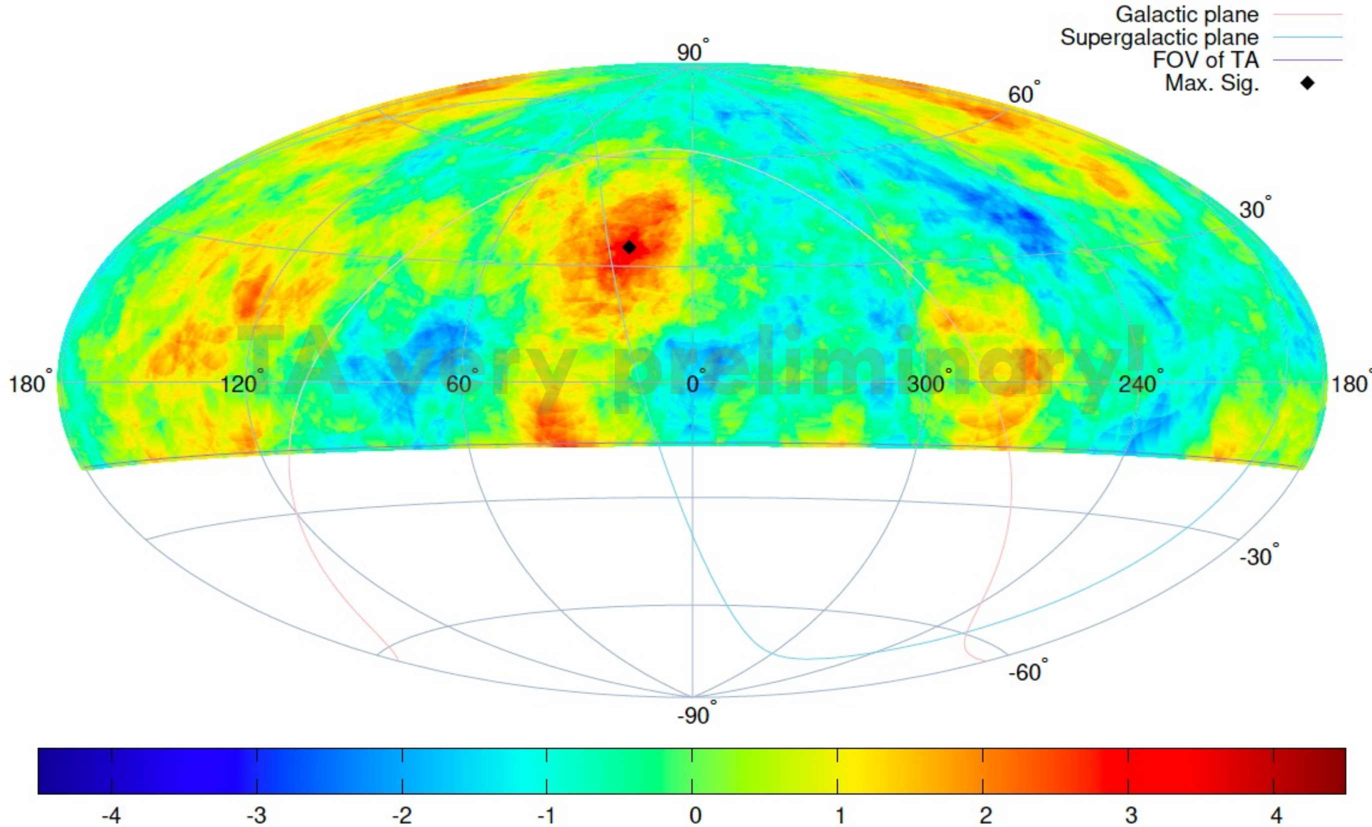


Huchra, et al, ApJ, (2012)

Dots : 2MASS catalog Heliocentric velocity <3000 km/s (D<~45MpC)

TA hotspot is found near the Ursa Major Cluster
TA & PAO see no excess in the direction of Virgo.

New excess of events with E ≥$10^{19.5}$ eV

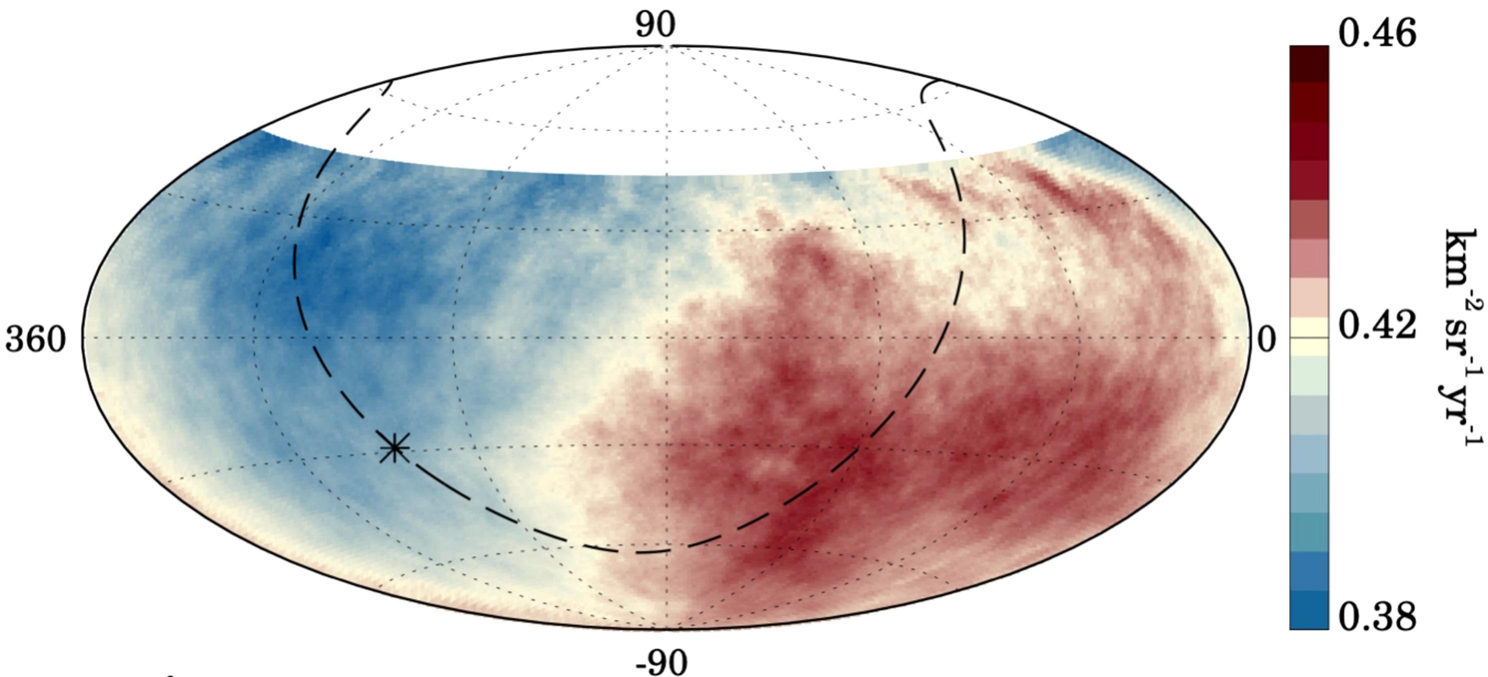


Skymaps in the equatorial coordinates

Deficit Li-Ma significance Excess

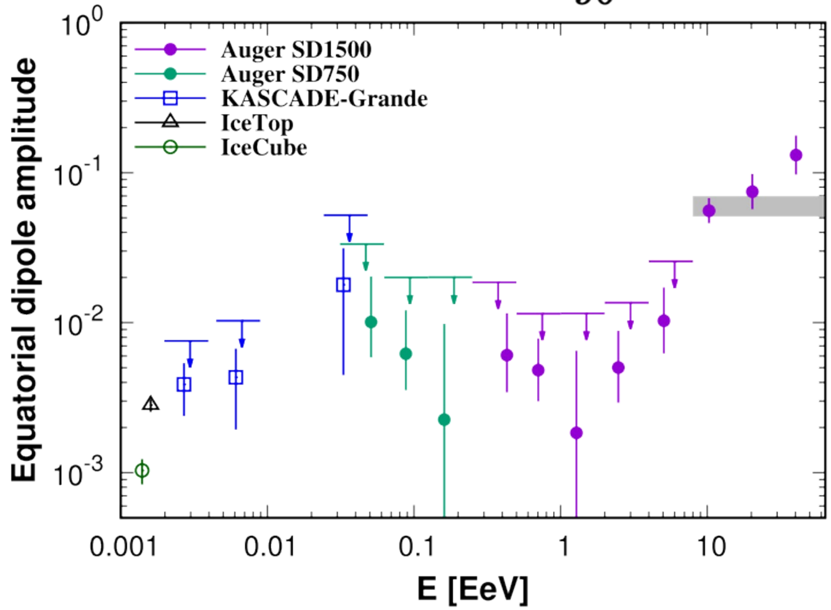
- 685 events with E ≥ $10^{19.5}$ eV (14yrs TA SD data)
- Maximum local significance: 3.8σ at (19.0°, 35.1°)
  - Observed: 66 events
  - Expected from isotropy: 39 events
- post trial : 3.2σ

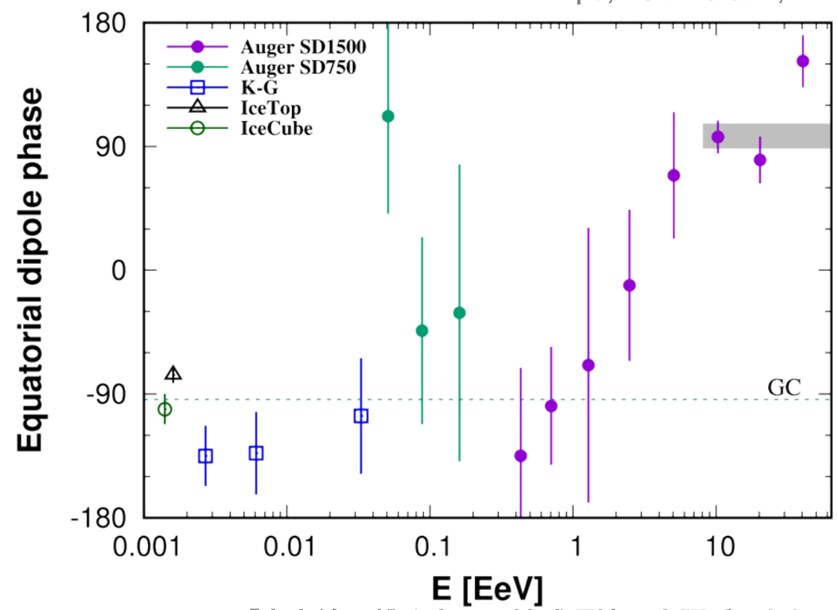
Large Scale Anisotropy (E>8EeV)



6σ level E>8EeV

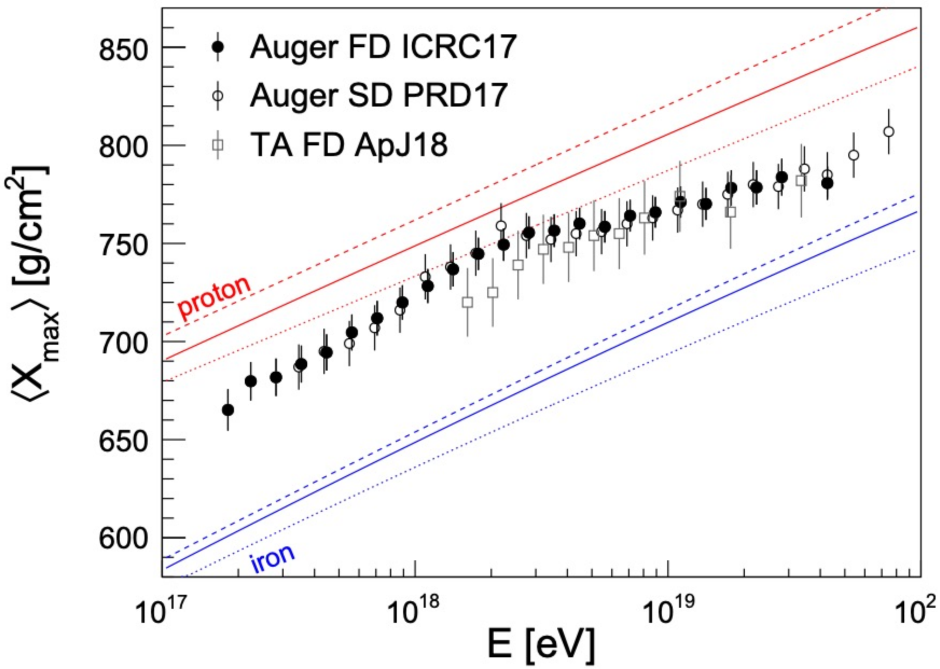
Science 357 (2017)
ApJ, Volume 891, 142 (2020)

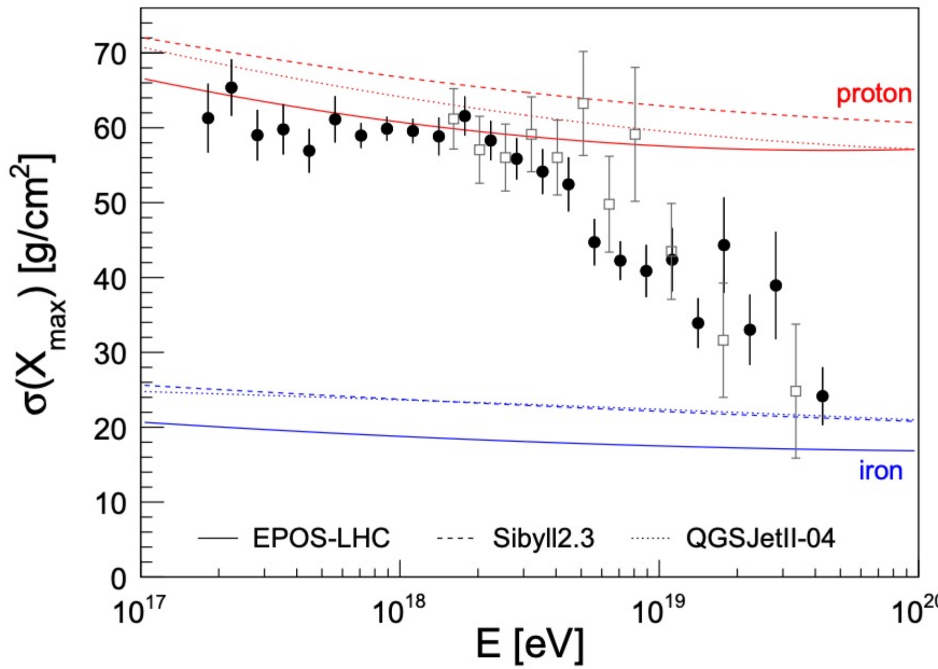


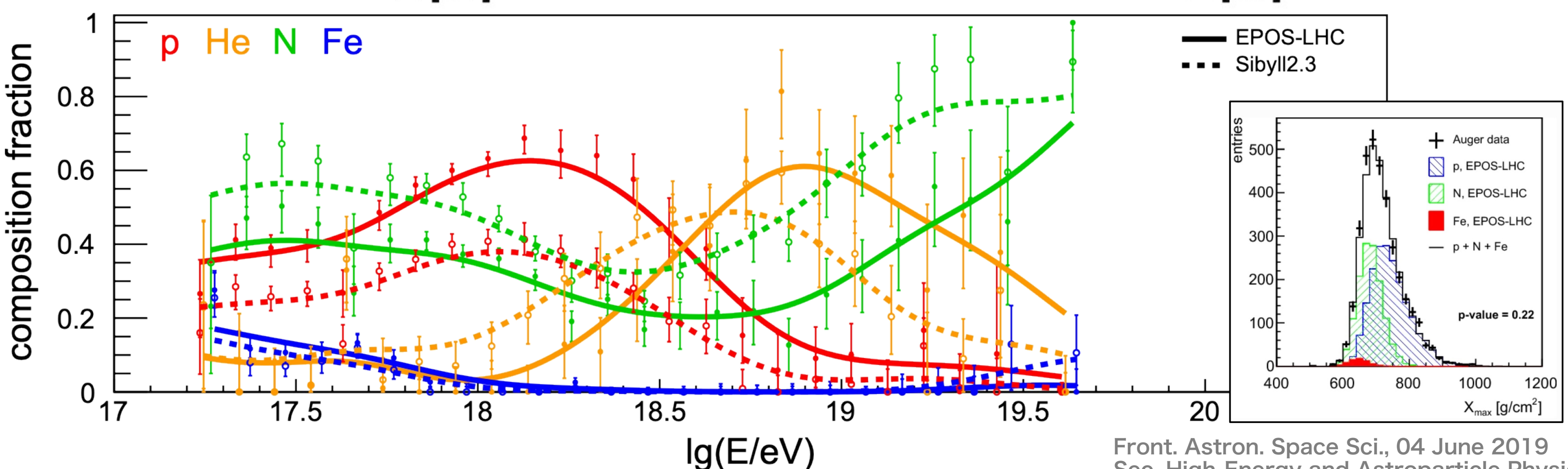


Mass Composition

Auger/TA X_{max} measurement



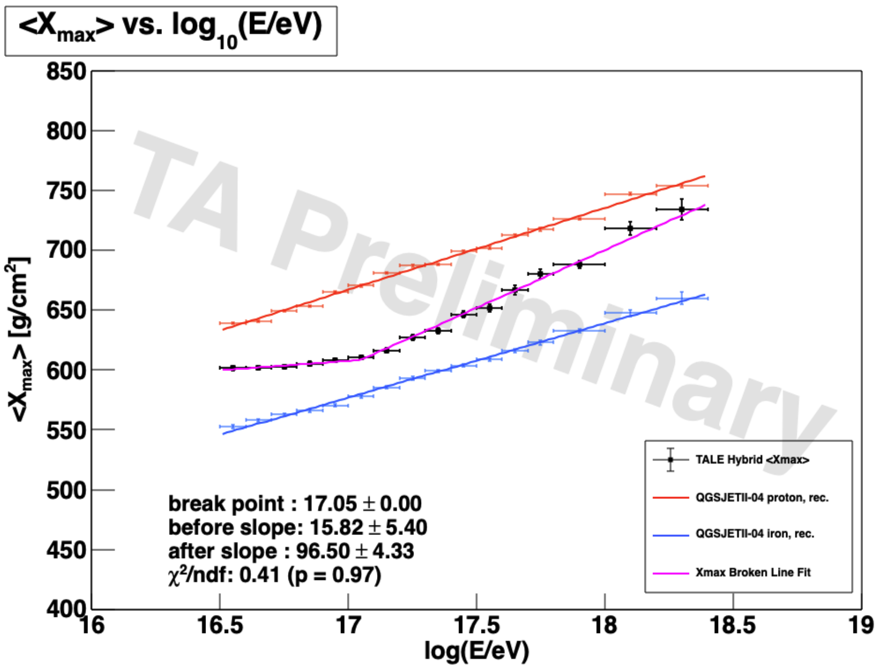


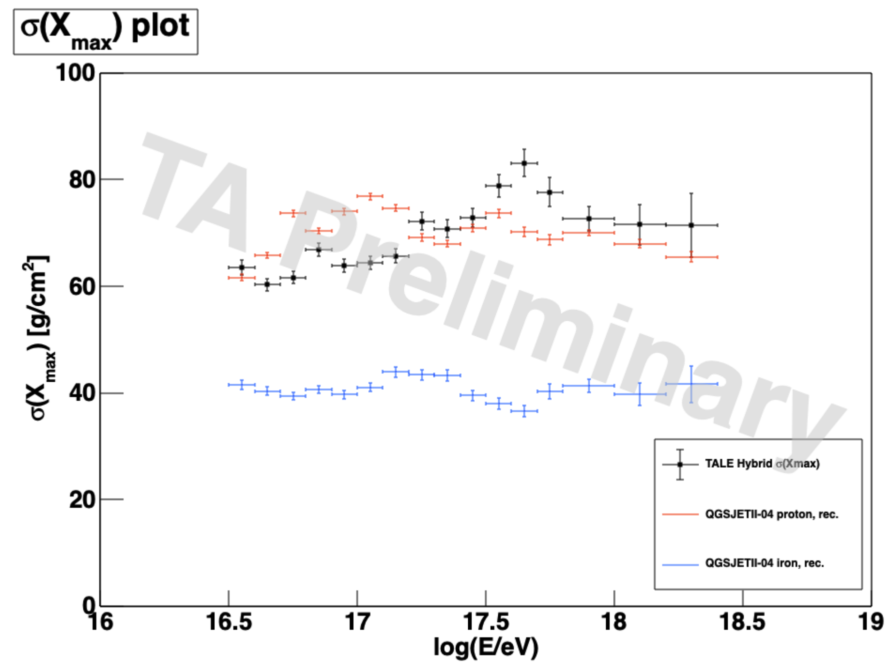


Front. Astron. Space Sci., 04 June 2019
Sec. High-Energy and Astroparticle Physics

TALE X_{max} measurement

- Measured reconstructed $\langle X_{max}\rangle/\sigma(X_{max})$ vs. shower energy
  - Nov. 2017 - May. 2022 (4 yrs, 1880 hours)





D_{10}^{before} = 16 ± 5 g/cm²/decade
D_{10}^{after} = 97 ± 4 g/cm²/decade
$\log_{10}(E_{\text{break}}/\text{eV})$ = 17.1

MC elongation rate [g/cm²/decade]

	proton	iron
D_{10}^{MC}	68 ± 2	62 ± 2

Suggest light to heavy below 10^{17} eV, then getting lighter above

Mass Composition