2022/9/29

計画研究C02レビュー
高精度観測で探究する
最高エネルギー銀河系外
宇宙線起源

木戸英治

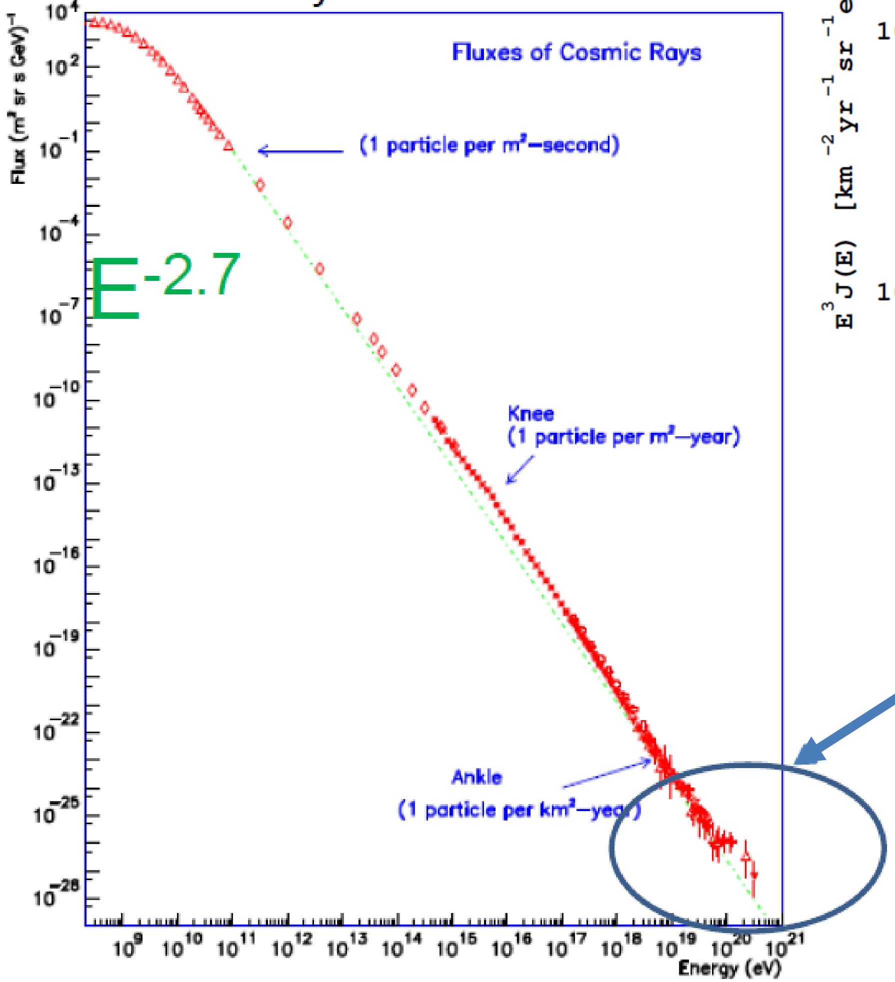
理研 開拓研究本部

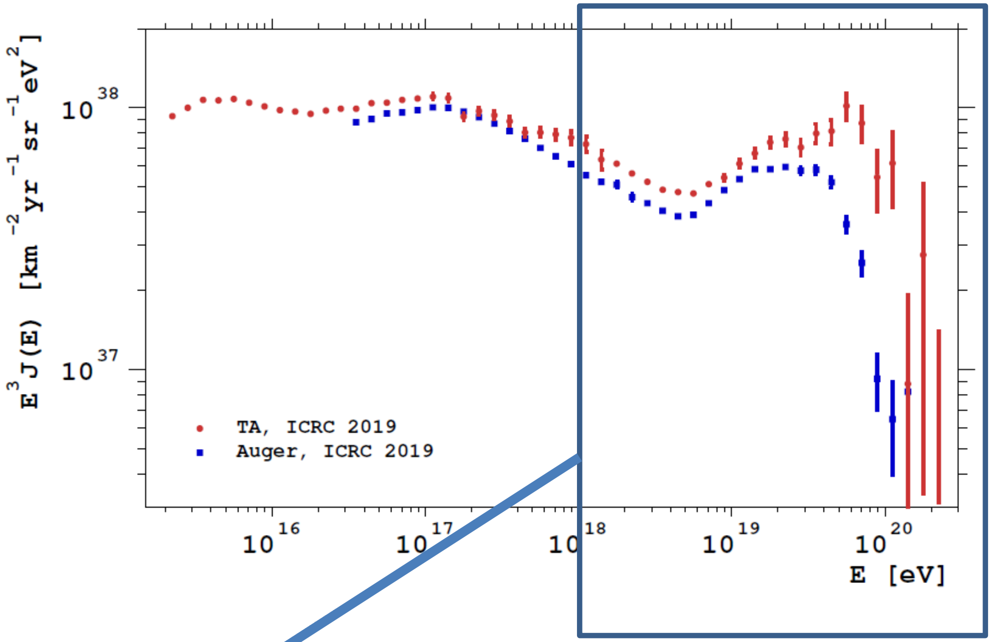
Outline

- Introduction to Ultra-High-Energy Cosmic Rays (UHECRs)
- Observation of UHECRs
  - Telescope Array (TA)
  - Pierre Auger (Auger)
- Recent Results
  - Energy Spectrum
  - Composition
  - Anisotropy
- Current status and future developments of the TAx4 experiment
- Summary

Ultra-High-Energy Cosmic Rays

Differential energy spectrum of cosmic rays





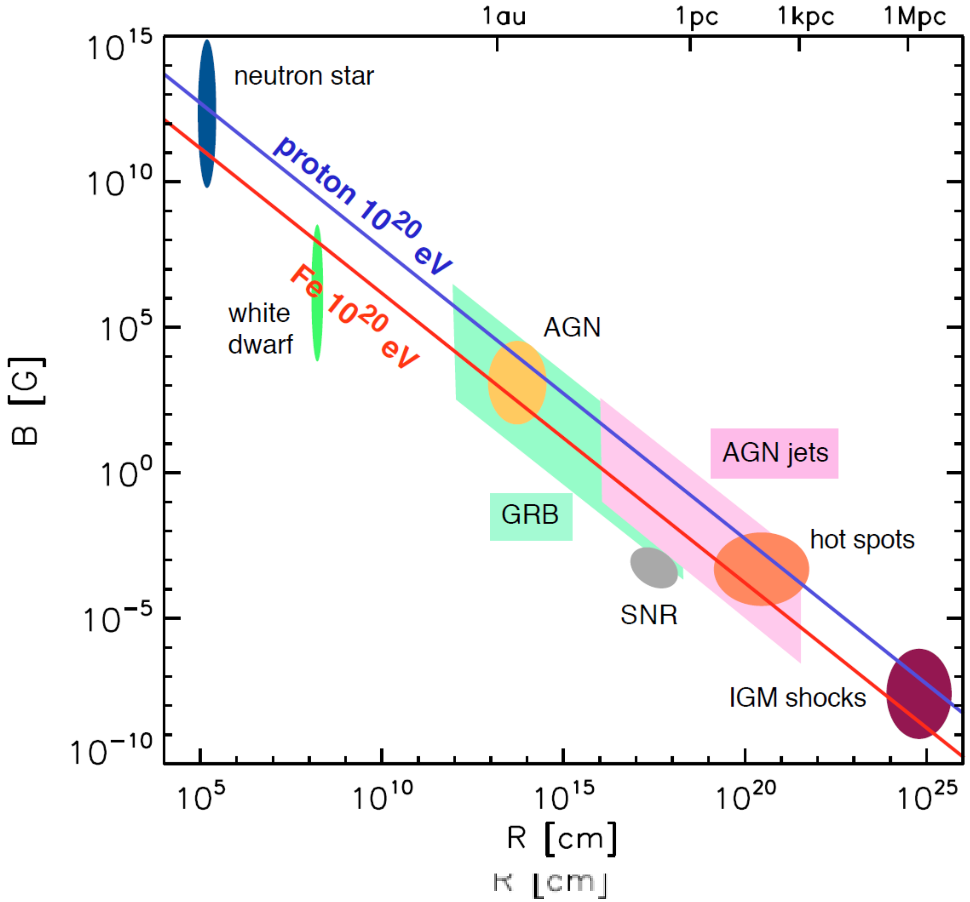
Energy > 1 EeV (1 EeV = 10^{18}eV)

Small number of events:

$\sim 10^{-3}$ km^{-2} yr^{-1} (E > 10^{20} eV)

Cosmic ray sources are uncertain.

Hillas Diagram



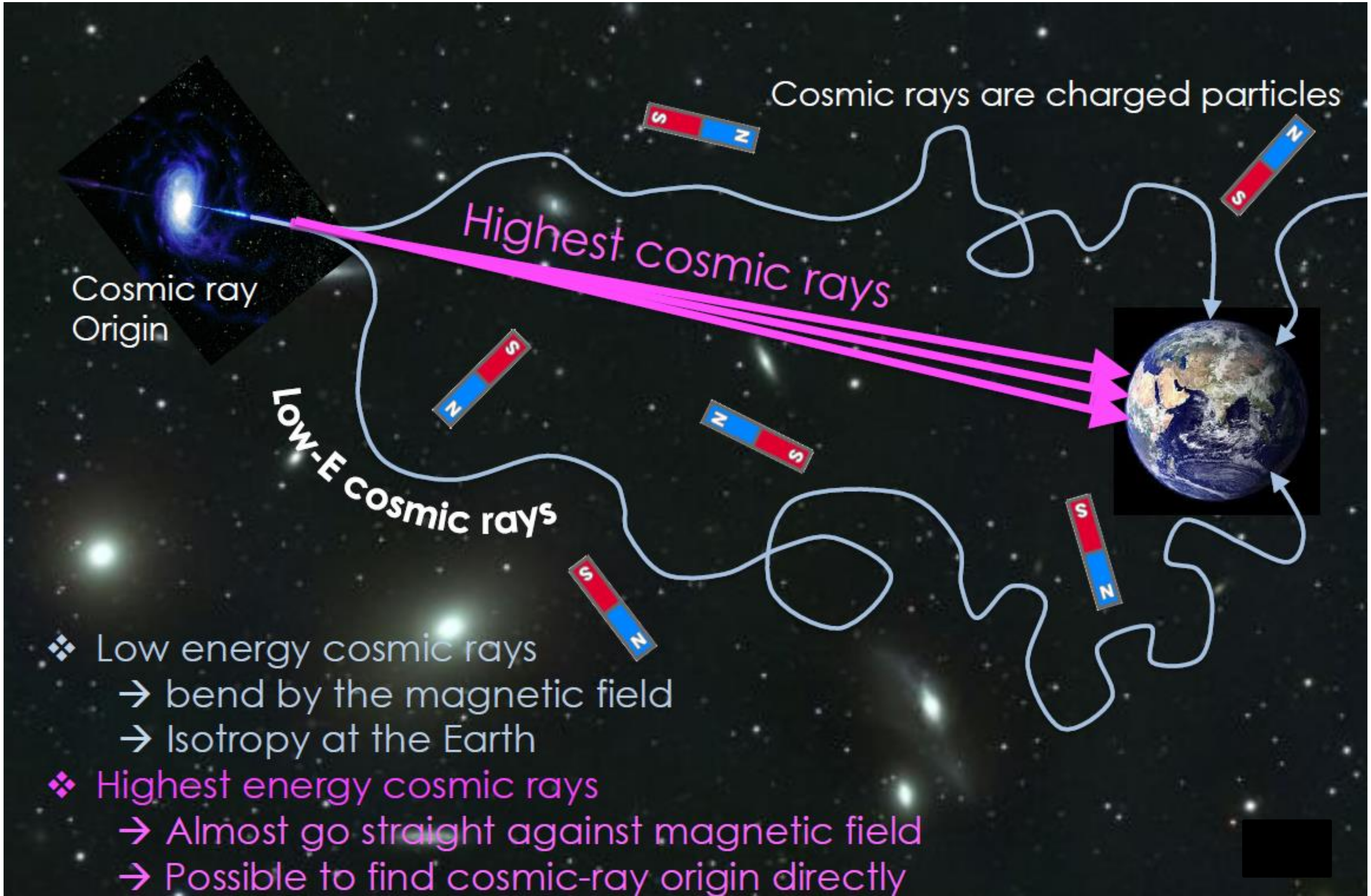
Kotera & Olinto, Annu. Rev. Astron. Astrophys (2010)

- Larmor radius

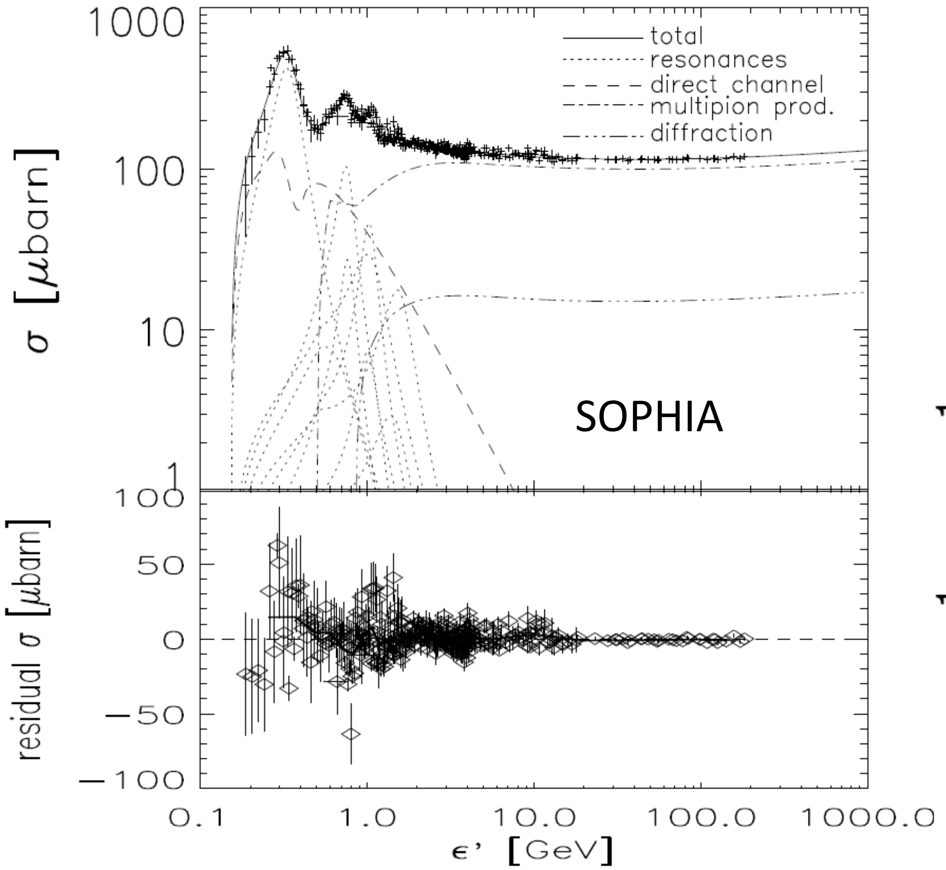
R_L ~
100 kpc (1/Z) (uG/B)(E/100 EeV)

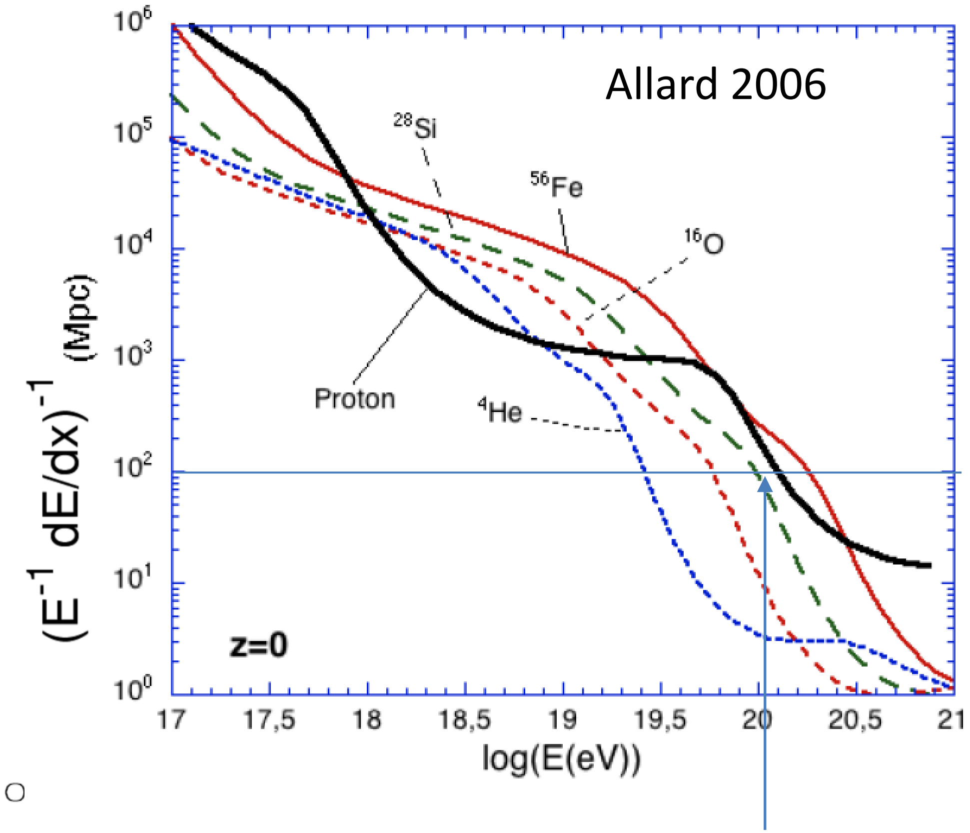
- Magnetic fields of the sources confine cosmic ray particles up to the energies
  (Blue: Emax = 10^{20} eV, Z=1)
  (Red: Emax = 10^{20} eV, Z=26)
  → candidates of sources

Arrival Directions



超高エネルギー宇宙線陽子の相互作用





$p + \gamma \rightarrow p(n) + \pi^0(\pi^+)$

最高エネルギーで
エネルギー損失距離 < 100 Mpc
→ 宇宙線源は近傍に限られる

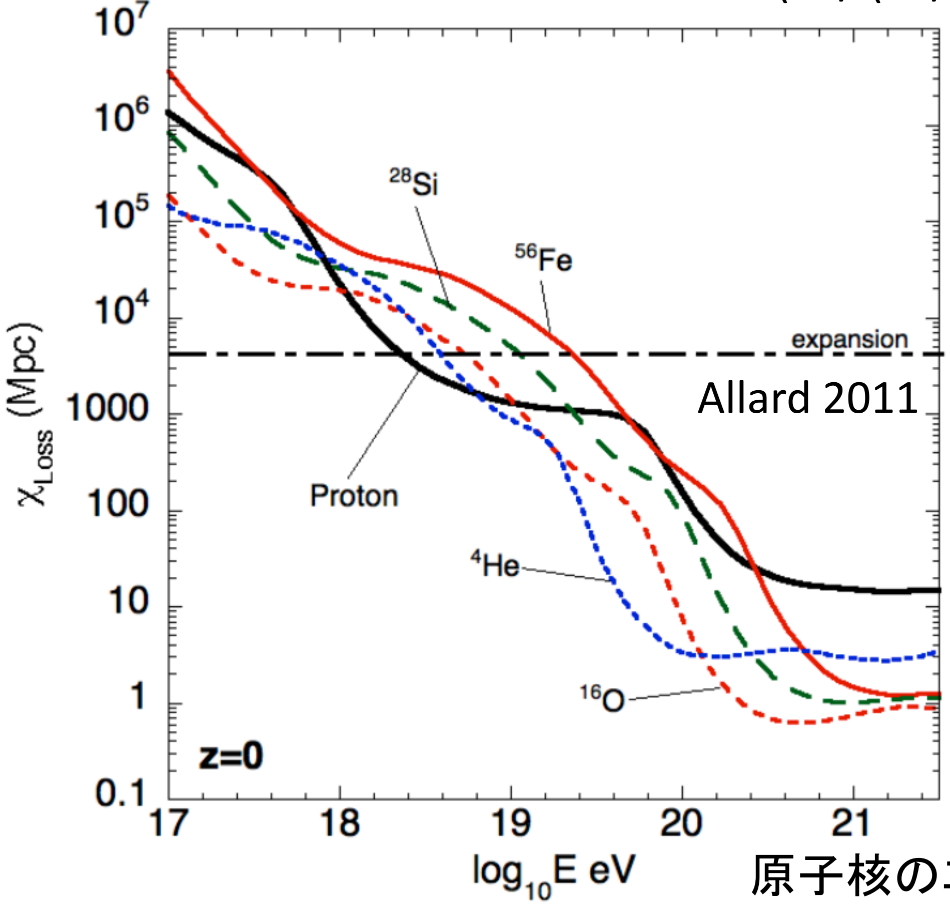
超高エネルギー宇宙線原子核の相互作用

宇宙線原子核のエネルギー:
ローレンツ因子Γ×質量数A に比例

1回の光崩壊によるエネルギー損失:
A → A-1　の時
E → E - E/A
軽い原子核で比較的影響が大きい

CMB(z=0)とのGDRによる
エネルギー損失距離の減少:
～A×4･10^{18} eV

宇宙線原子核のエネルギー損失距離 (- E/ (dE/dx))



原子核のエネルギー:
$E_N = m_N c^2 \Gamma$
$= A m_p c^2 \Gamma$

Motivation to observe highest energy cosmic rays

- Cosmic ray sources are uncertain
- Smaller deflection angles ($\propto 1/E$)
- Sources are limited in the local universe

  (～a few tens of Mpcs)

  → anisotropy in arrival directions

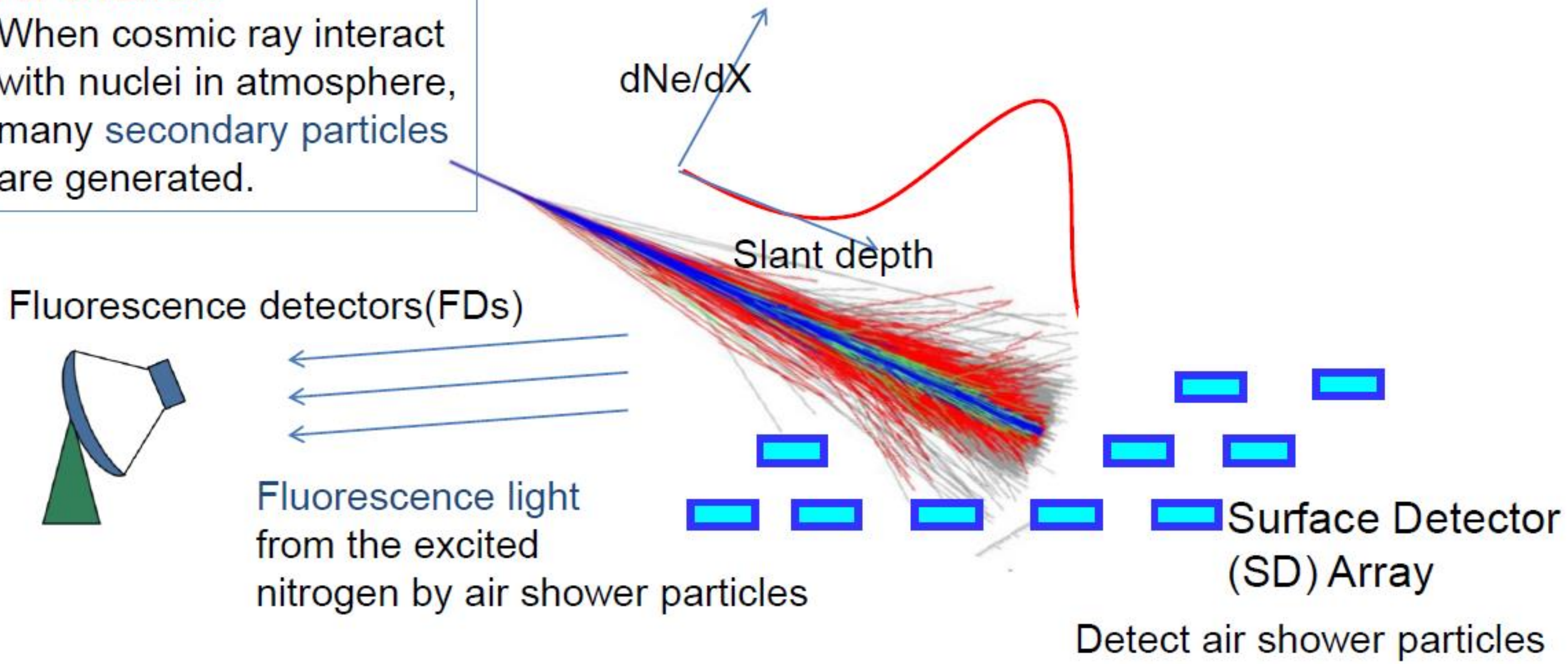
  → origin of cosmic rays
- Difficulty: To obtain

  high statistics (～E_{th}^{-2} above E_{th})

Observation of UHECRs

UHECR Detectors

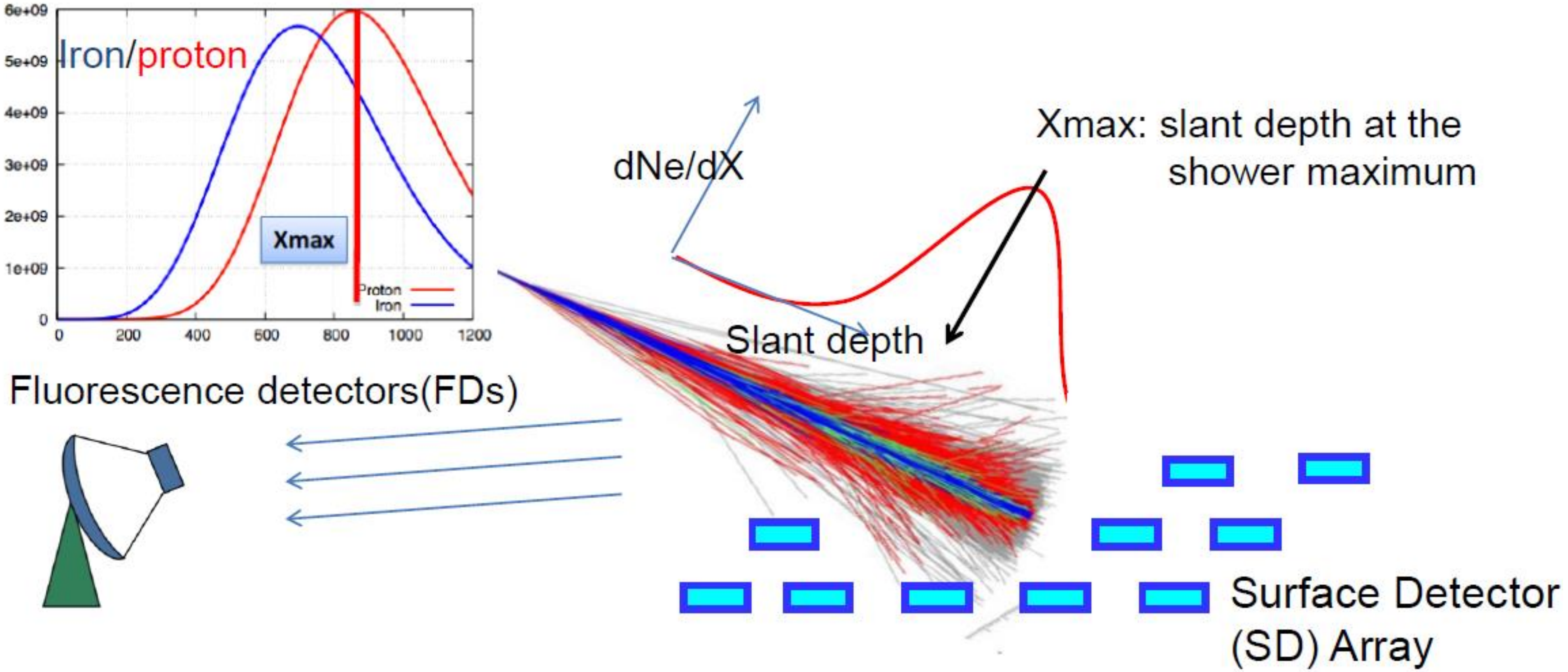
Air shower:
When cosmic ray interact with nuclei in atmosphere, many secondary particles are generated.



Surface Detector (SD) and Fluorescence Detector (FD) cover large area and detect the air shower.

→ Large detection area (~1000 km^2) is realized.

UHECR Detectors

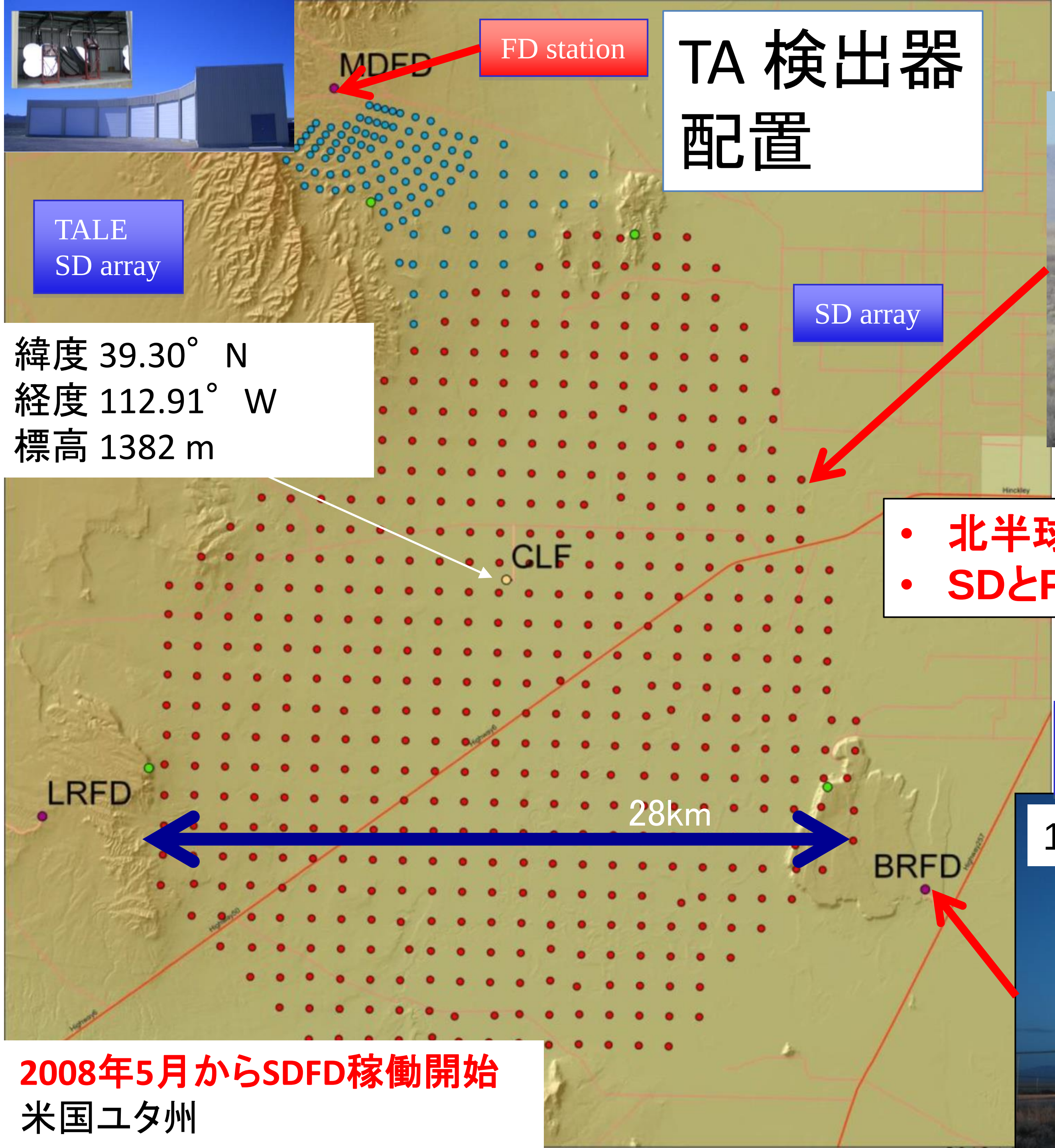


- SD: Regardless of weather condition, high duty circle and wide FoV → high statistics (～FDx10) → Anisotropy & Spectral shape
- FD: limited to clear moonless night.

  Longitudinal development of air shower→Mass composition (Xmax)

  Measure the energy deposit calorimetrically → absolute energy scale

TA 検出器配置



緯度 39.30° N
経度 112.91° W
標高 1382 m

Surface Detector (SD)

1.2 km 間隔
～700 km^2
507 SDs
2 層 3 m^2 面積 1.2 cm 厚
プラスチックシンチレータ

- 北半球最大の検出面積
- SDとFDのハイブリッド観測

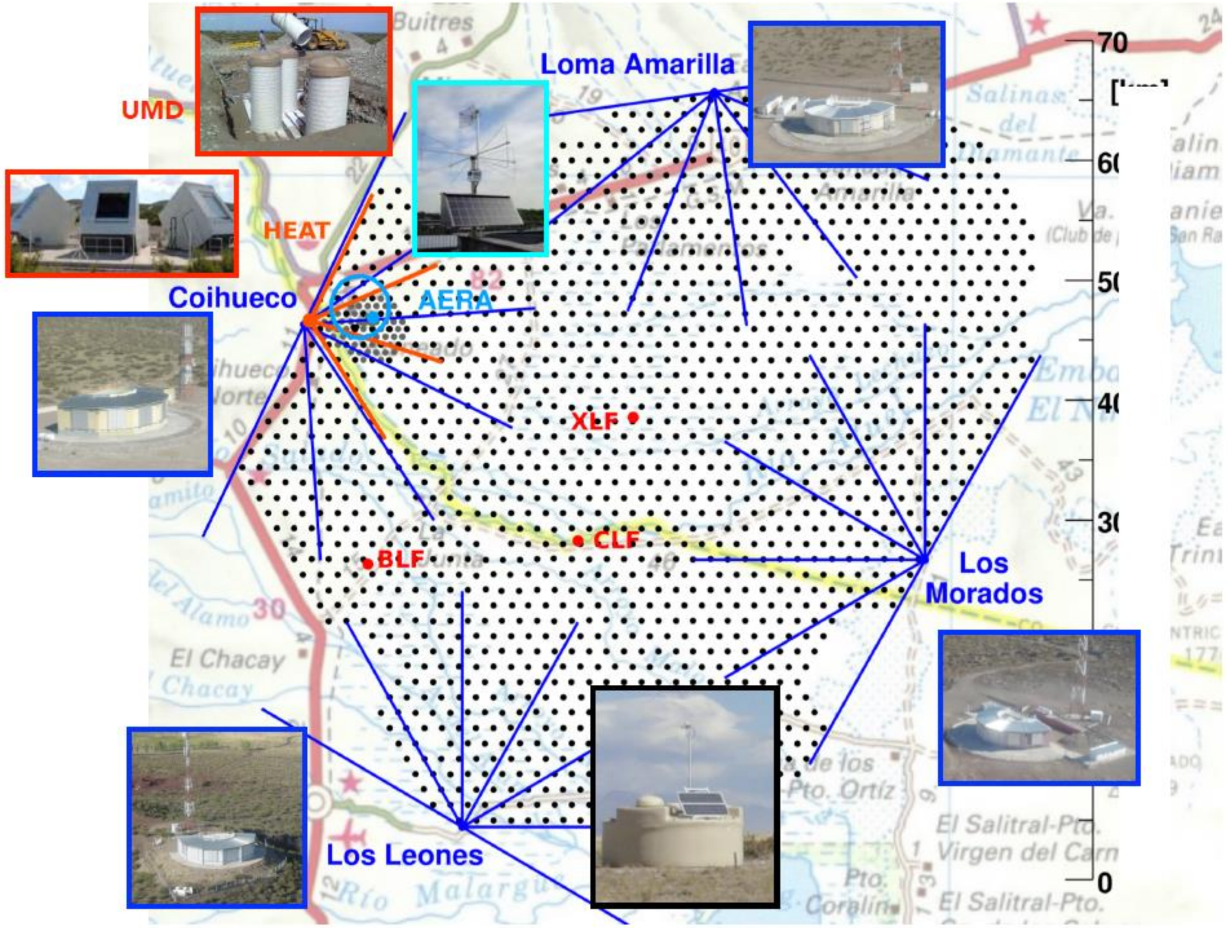
Fluorescence Detector (FD) station

12 telescopes

2008年5月からSDFD稼働開始
米国ユタ州

The Pierre Auger Observatory

TeVPA2019 Dawson



- Water-Cherenkov stations
  - ➡SD1500 : 1600, 1.5 km grid, 3000 km²
  - ➡SD750 : 61, 0.75 km grid, 25 km²
- 4 Fluorescence Sites
  - ➡24 telescopes, 1-30⁰ FoV
- Underground Muon Detectors
  - ➡7 in engineering array phase - 61 aside the Infill stations
- HEAT
  - ➡3 high elevation FD, 30-60⁰ FoV
- AERA radio antennas
  - ➡153 graded 17 km²

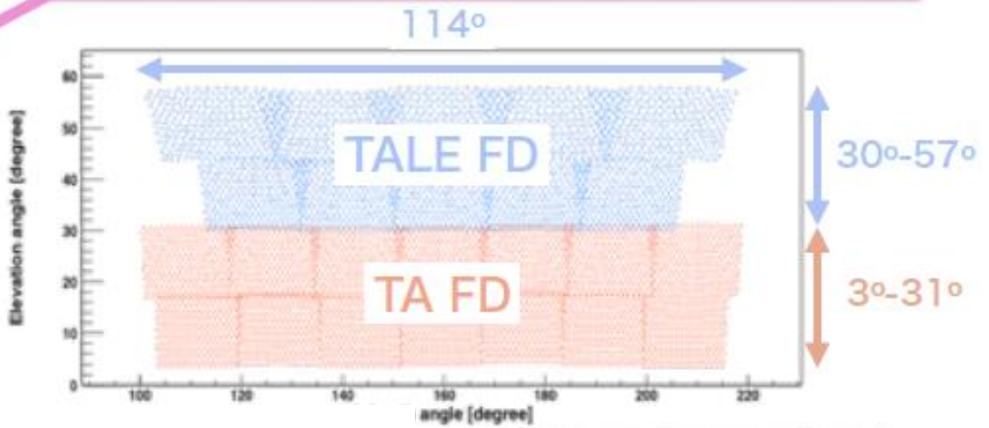
+Atmospheric monitoring devices
CLF, XLF, Lidars, …

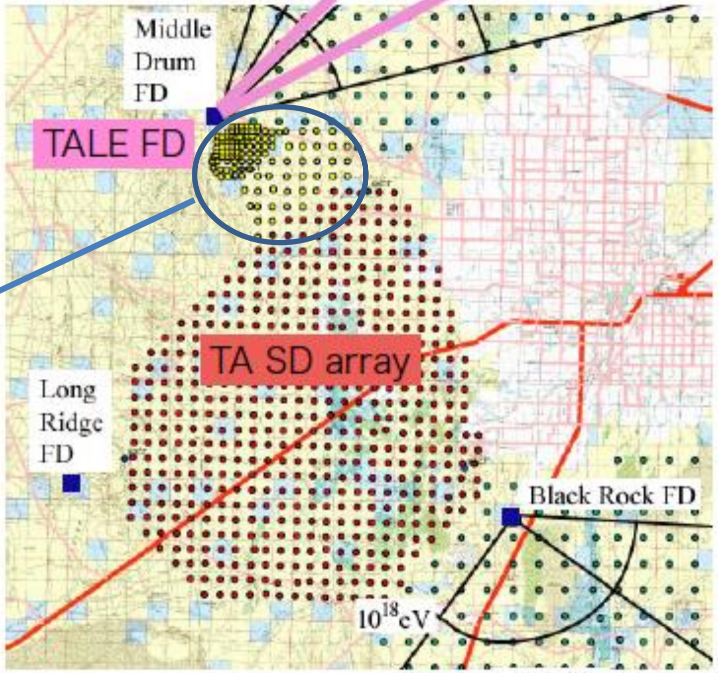
1.5 km spacing 1600 SDs: cover **～3000 km^2**
4 FD sites
Operation in a stable mode from 2004

TALE (Telescope Array Low energy Extension)

Located in TA MD site
10 FDs in the TALE station
Elevation: 30°-57° (higher elevation than MD)
Azimuthal: 114°

Refurbished HiRes telescopes & electronics
Mirror: same as TA FD (MD)
Elec.: 10 MHz 8bit FADC





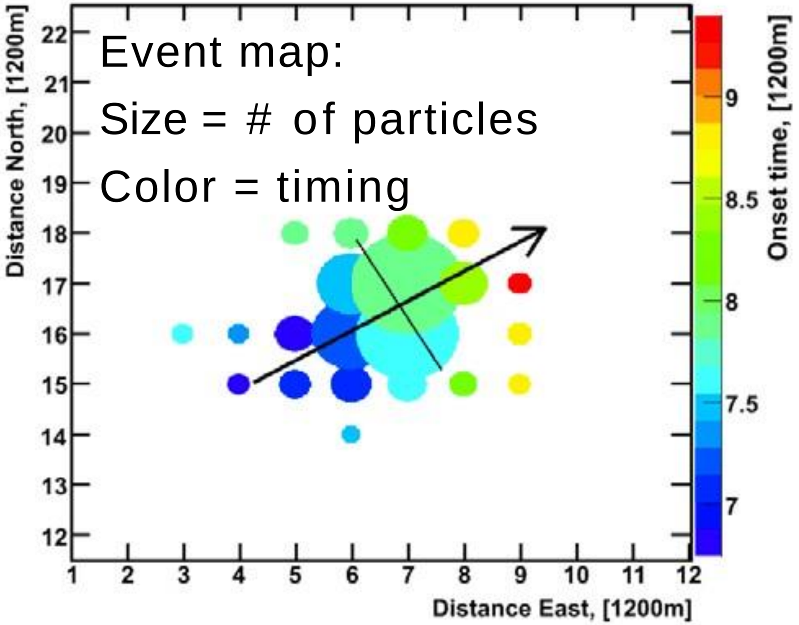
TALE
80 SDs

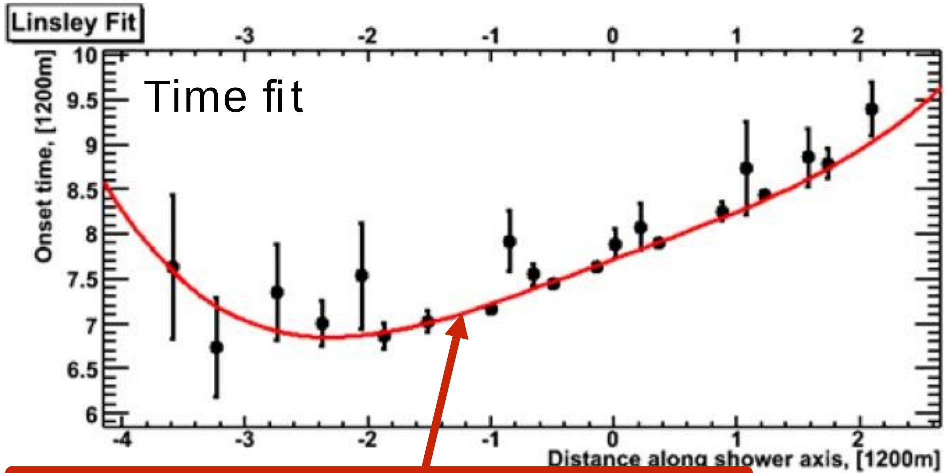
TALE FD was
installed in Nov. 2012

Operation since Sep. 2013
Hybrid trigger: Sep. 2018

5

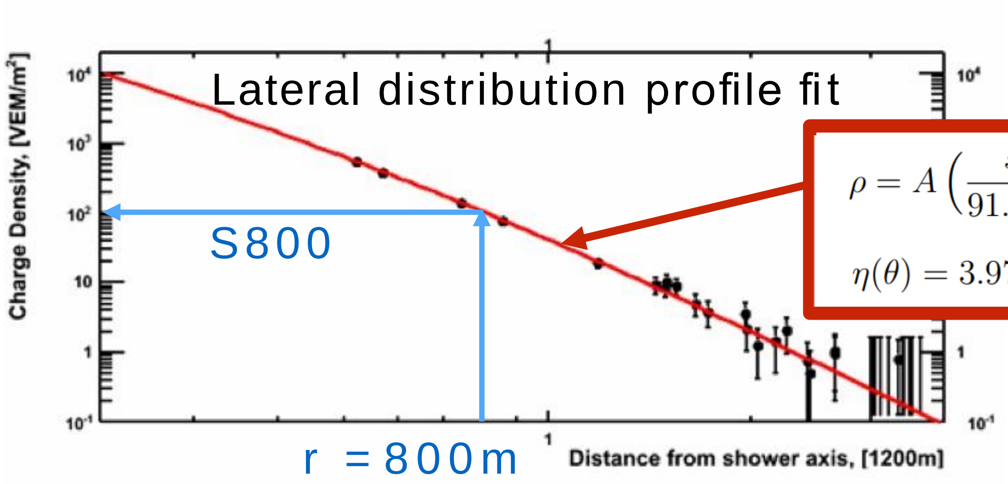
Event reconstructions with SDs





$$\tau = a\left(1 - \frac{l}{12\times 10^3\mathrm{m}}\right)^{1.05}\left(1.0 + \frac{s}{30\mathrm{m}}\right)^{1.35}\rho^{-0.5}$$

Modified empirical formula in AGASA



Timing -> shower geometry

$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1 + \frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1 + \left[\frac{s}{1000\mathrm{m}}\right]^2\right)^{-0.6}$$

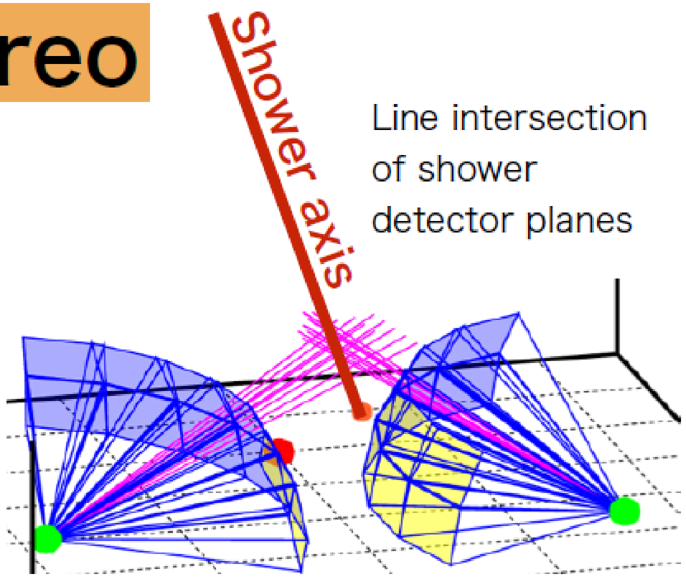
$$\eta(\theta) = 3.97 - 1.79\,[\sec(\theta) - 1]$$

Empirical formula used by AGASA

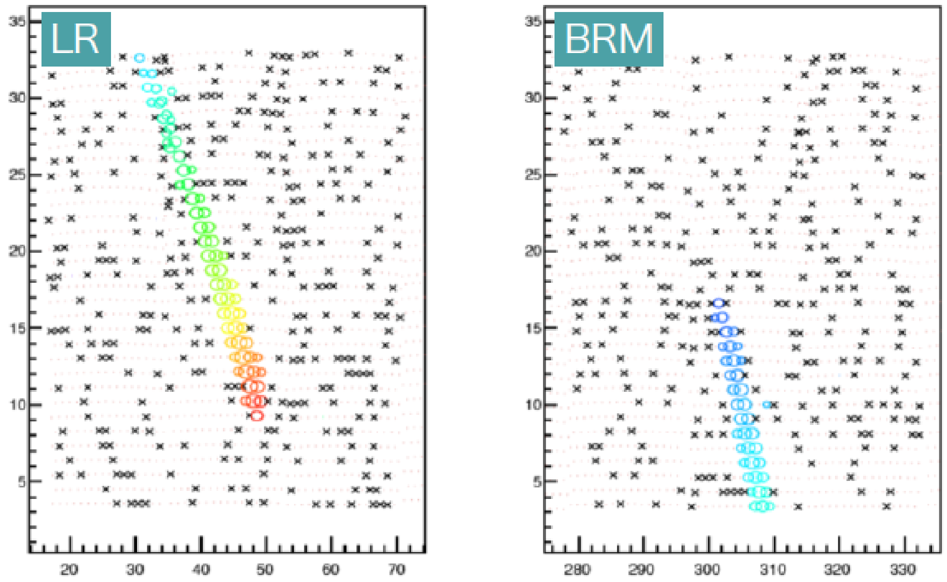
S800 -> primary energy

Event reconstructions with FDs

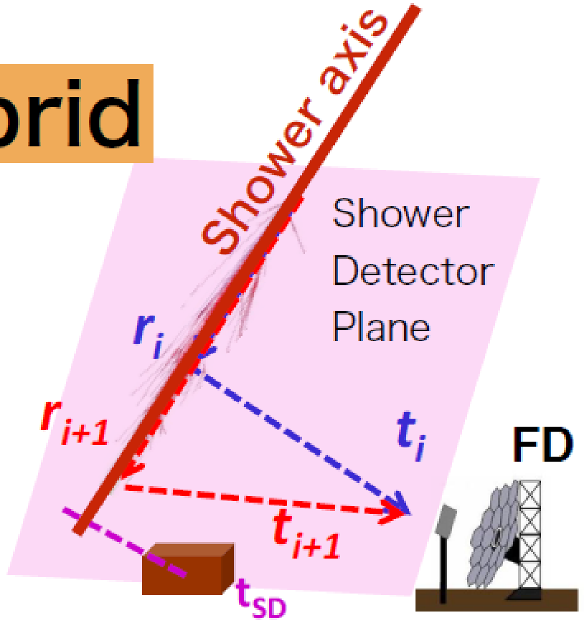
Stereo



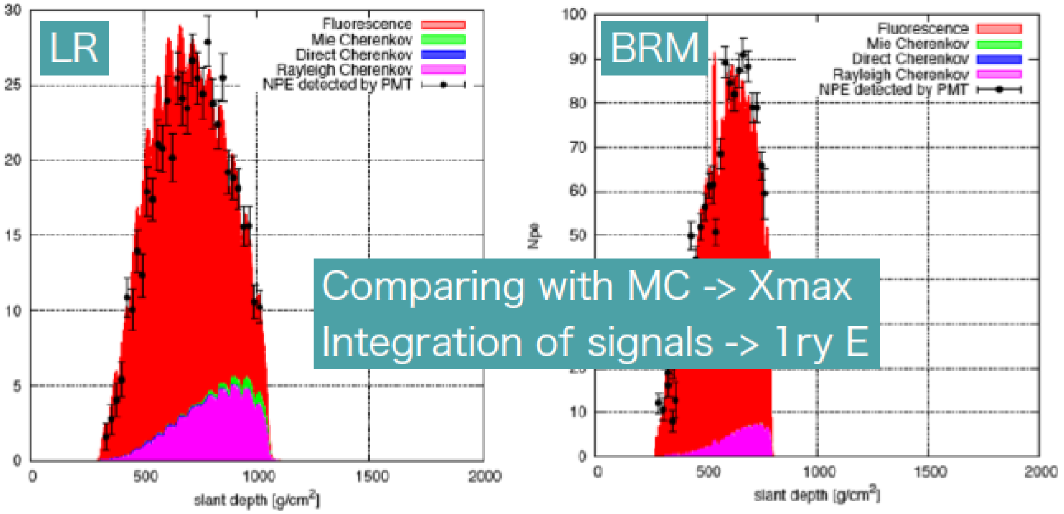
observed images



Hybrid

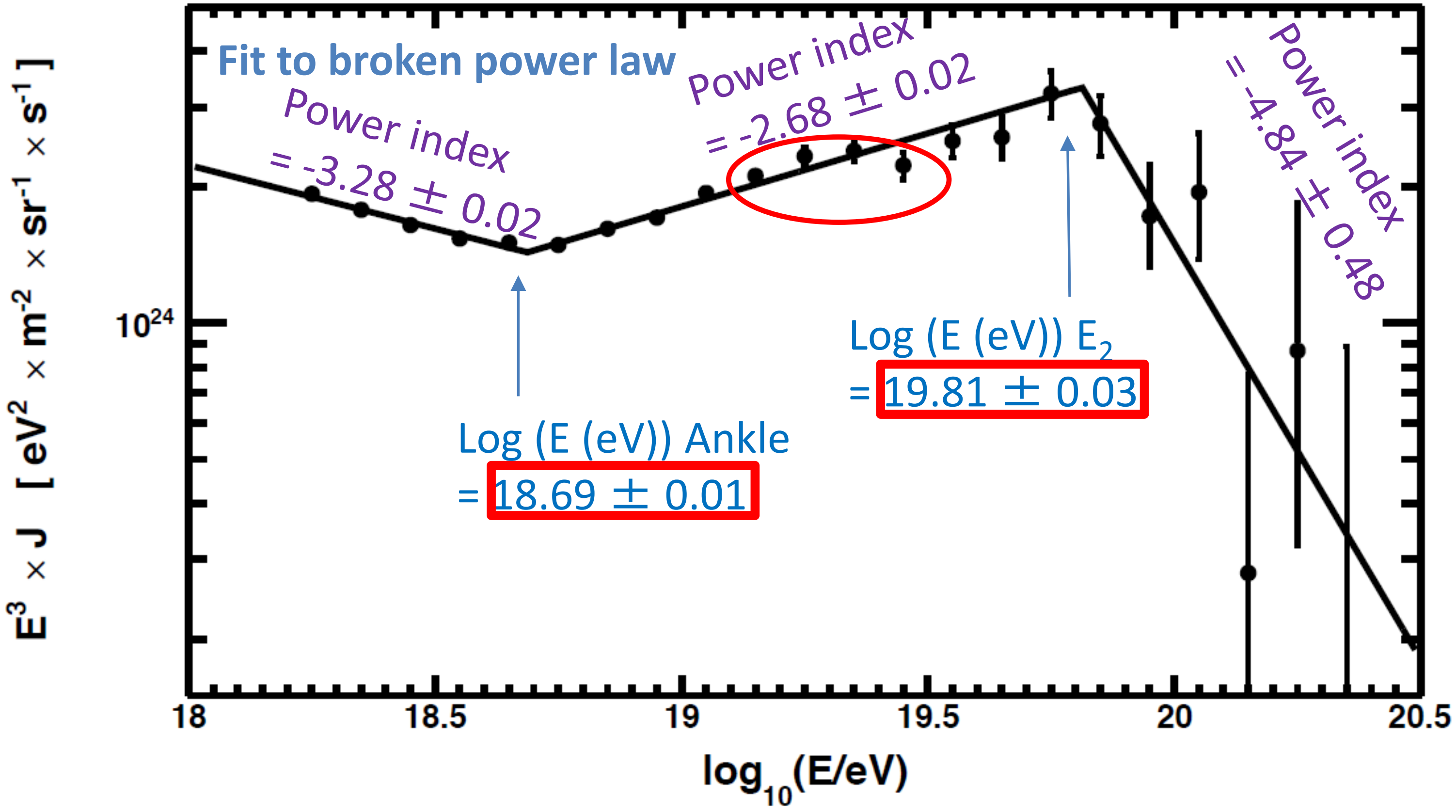


reconstructed shower profiles

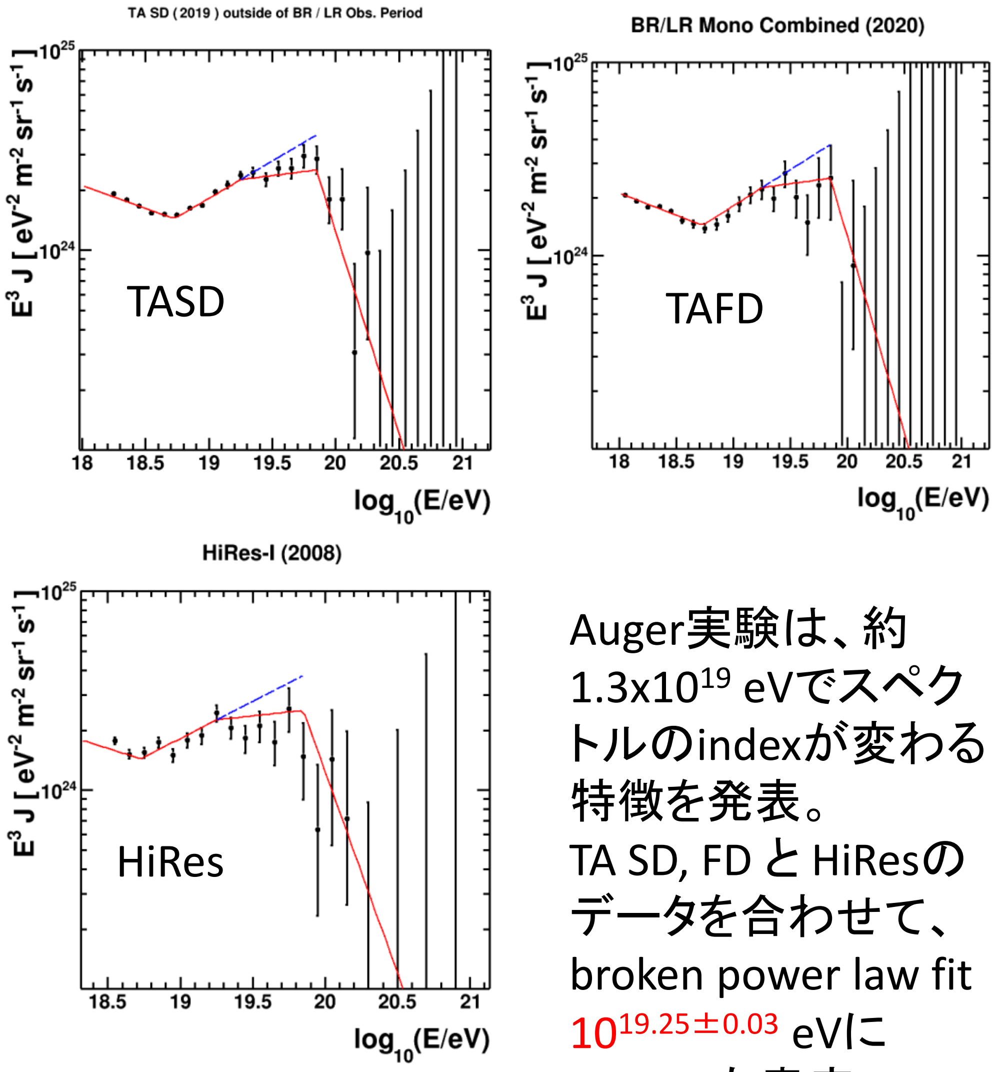


エネルギースペクトル

TA SD 11 years data



D. Ivanov, ICRC2021

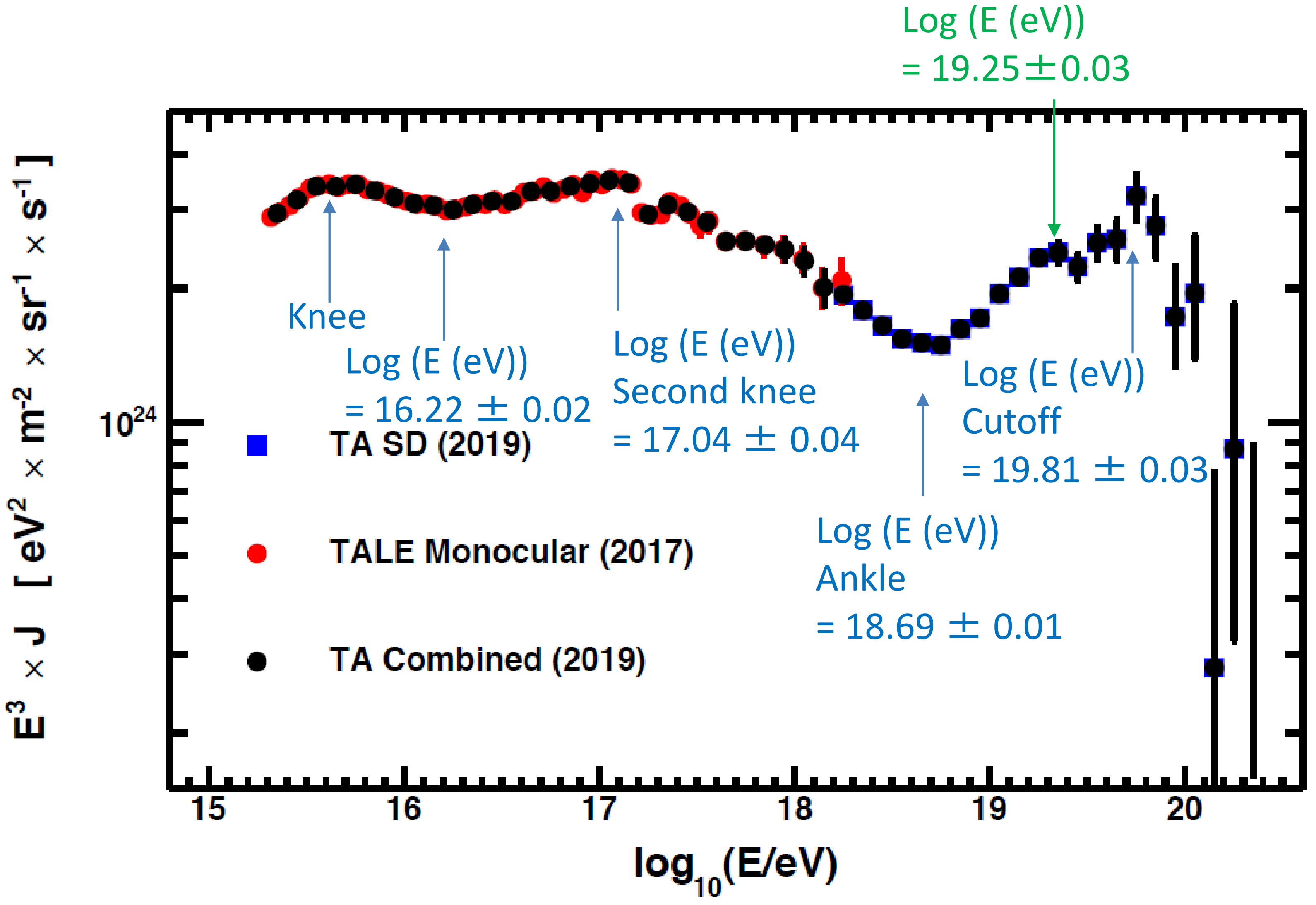


Auger実験は、約 1.3×10^{19} eVでスペクトルのindexが変わる特徴を発表。

TA SD, FD と HiResのデータを合わせて、broken power law fit $10^{19.25\pm0.03}$ eVにbreak，有意度5.3σ

Combined energy spectrum of TA SD with TALE FD Mono.

D. Ivanov

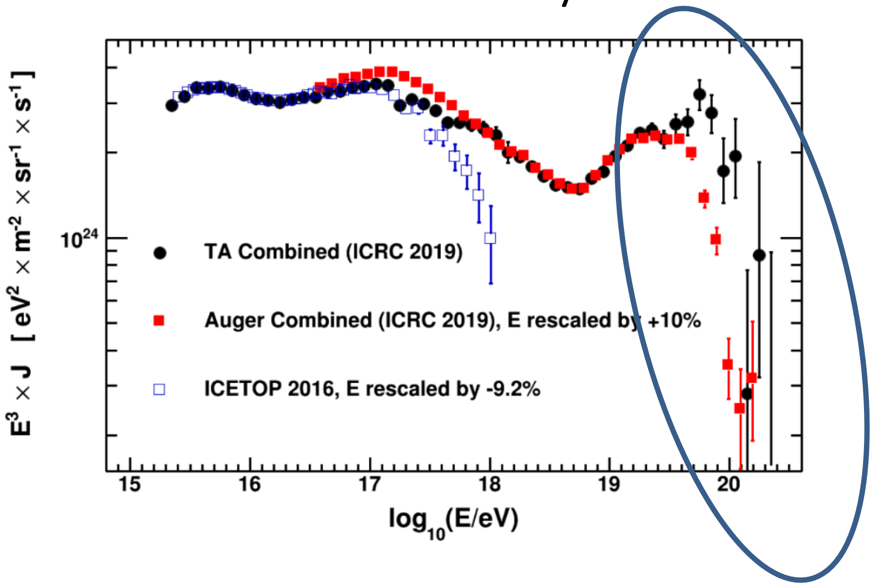


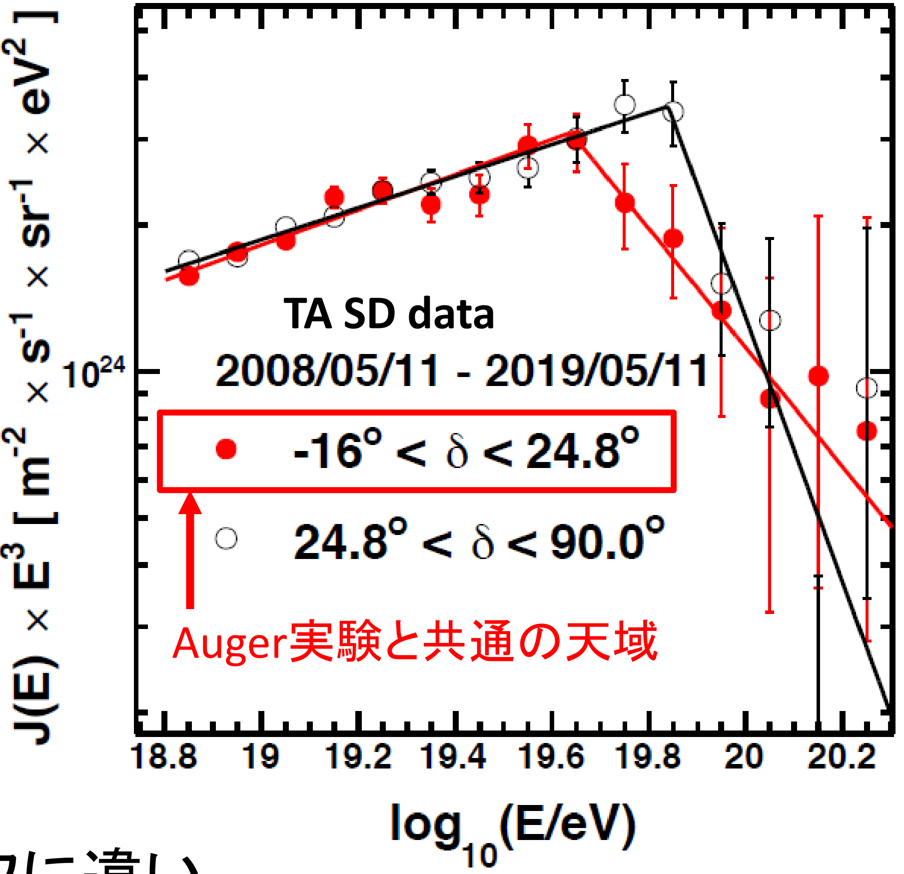
Combined TA spectrum using
22 months TALE FD monocular data +
11 years TA SD data

エネルギースペクトルの赤緯依存性

D. Ivanov

22 months TALE FD monocular data + 11 years TA SD data

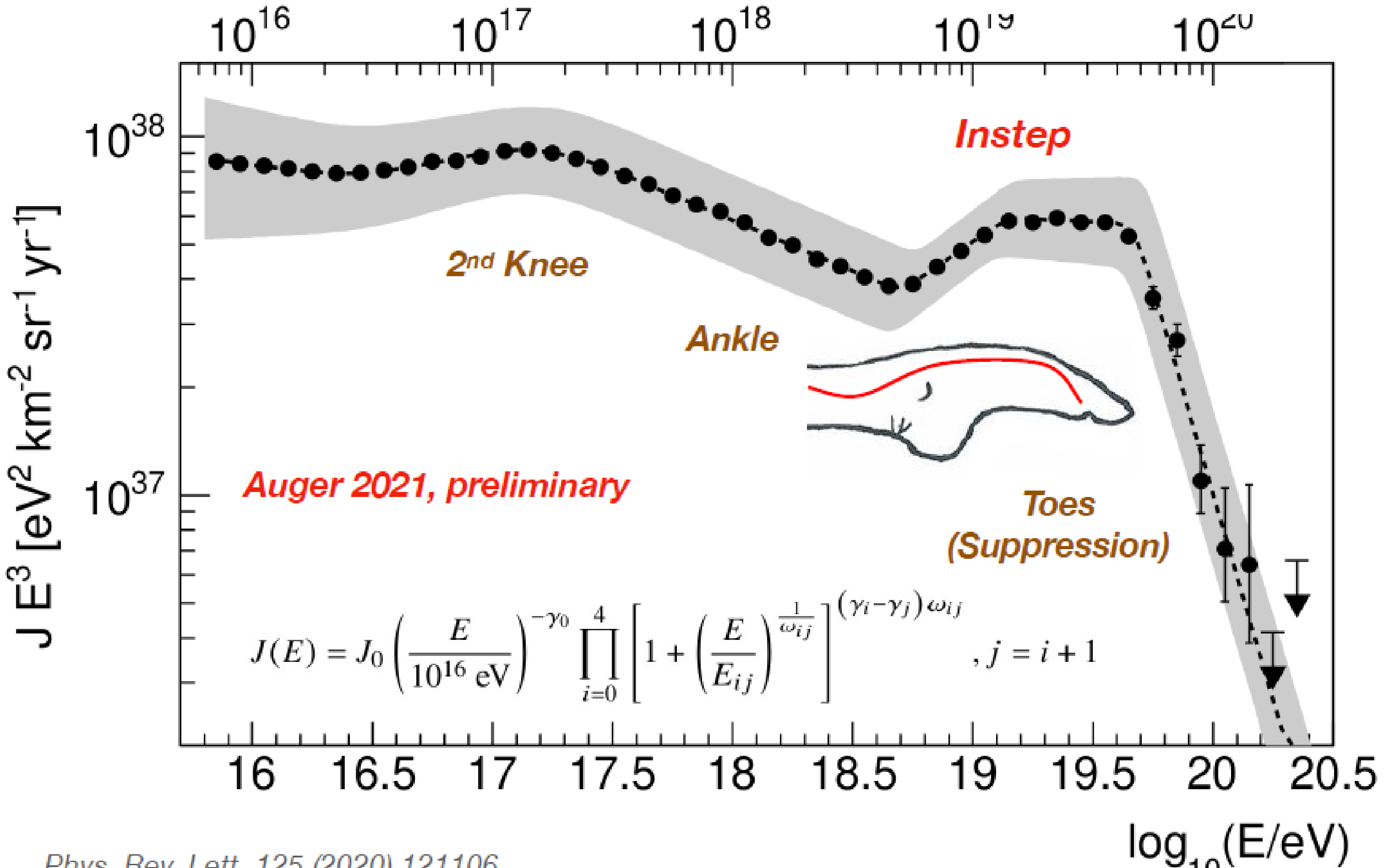


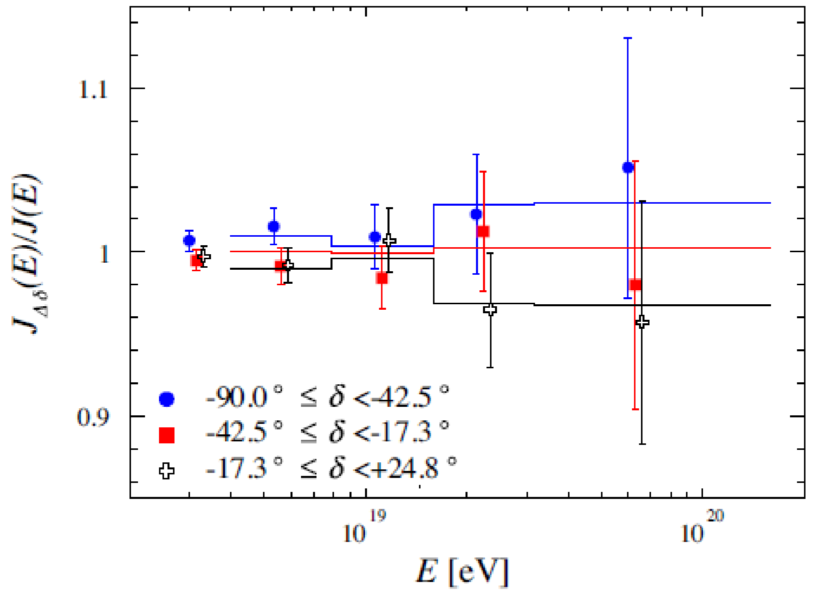


- エネルギースペクトルのカットオフに違い
  - log(E/eV) = 19.64 ± 0.04 低赤緯帯 (-16° - 24.8°)
  - log(E/eV) = 19.84 ± 0.02 高赤緯帯 (24.8° - 90°)
- カットオフの違いの有意度～ **4.3σ**

Auger Energy Spectrum

ICRC2021





Lines: Expectation from observed dipole

Uncertainty dominated by 14% sys. energy scale

$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$
$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV
$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$
$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV
$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$
$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV

$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$
$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV
$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$
$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV
$\gamma_5 = 5.3$
$J_0 = (8.3$ 0) x 10^{-11} km^{-2} sr^{-1} yr^{-1} eV^{-1}

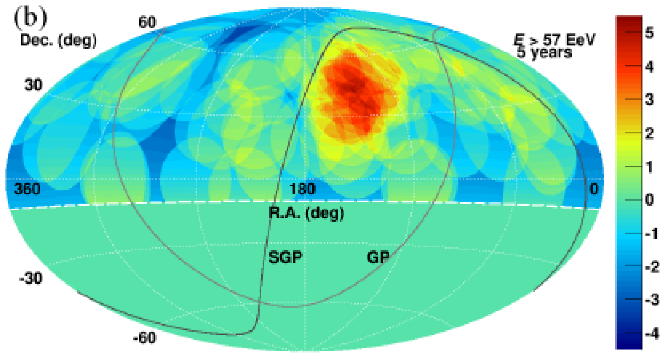
Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
submitted to Eur. Phys. J. C (2021)

(Vladimir Novotny)

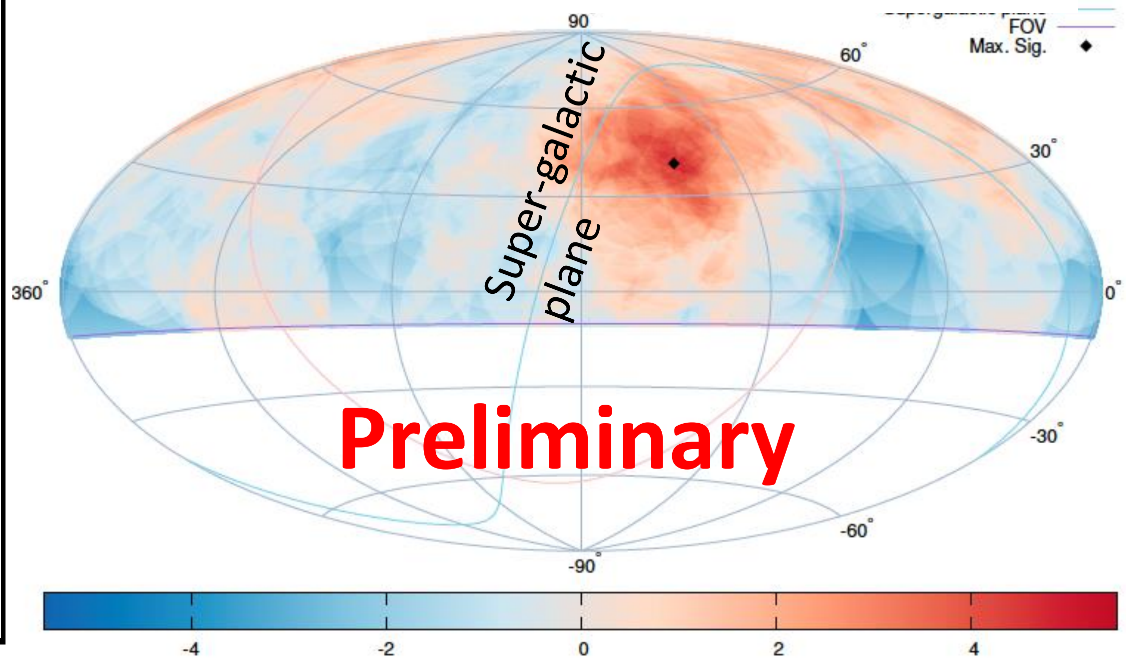
E > 57 EeV の宇宙線の到来方向の異方性 (TA hotspot)

Original hotspot reported in 2014, from 5 years of data

Ap. J., 790, L21(2014)
E > 57 EeV (Observed 72 events)
20º over-sampling circle
19 events fall in “Hotspot” centered at (146.7º, 43.2º)
(Expected = 4.5 events)
local significance 5.1σ, post trial significance 3.4σ



J.H. Kim,
TA SD 12 years data
Significance map from isotropy expectation

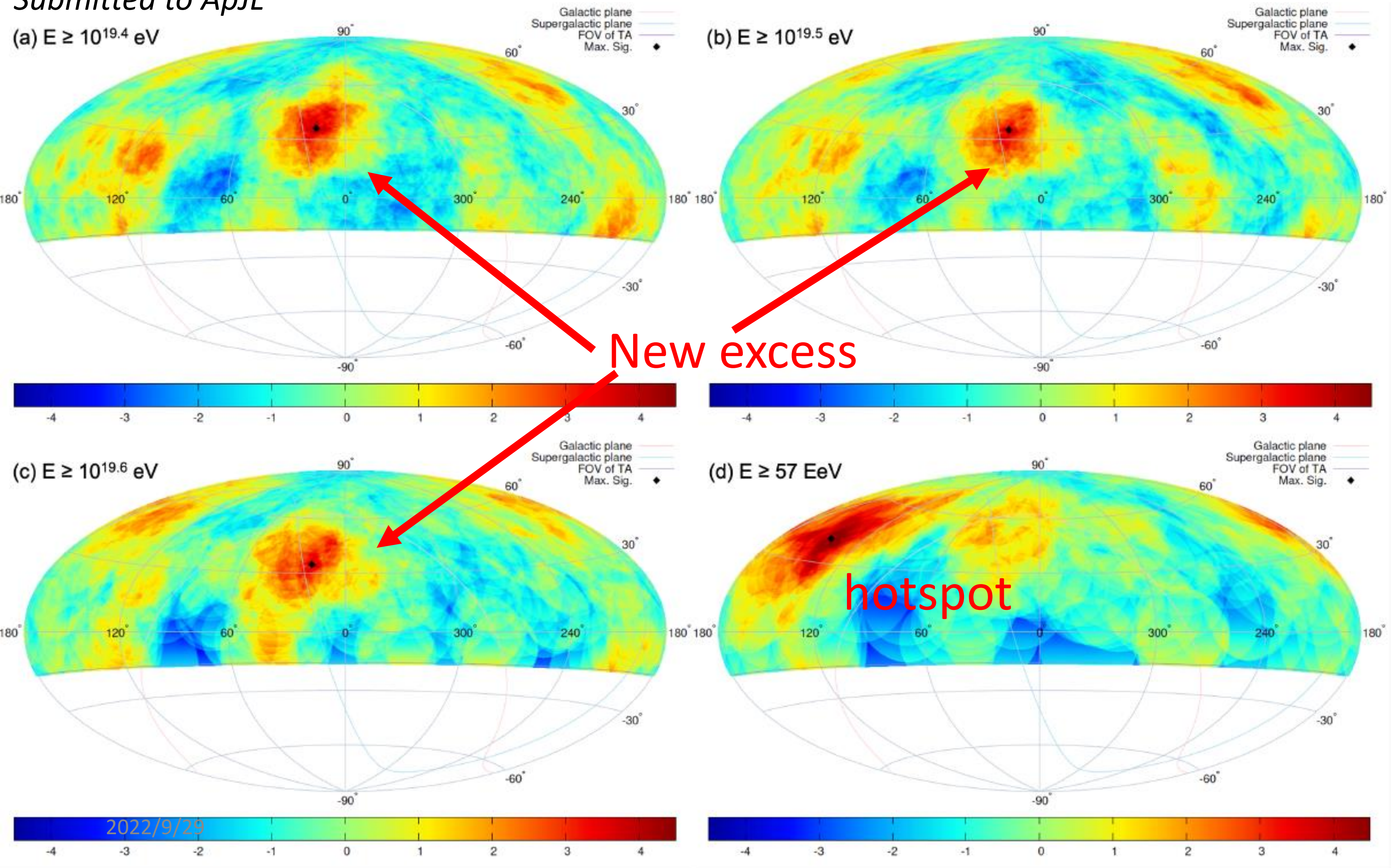


赤道座標

- 179 イベント E > 5.7×10^{19} eV (12年 TA SD データ)
- Maximum local significance: 5.1σ (144.0°, 40.5°)
  - 観測: 40 イベント
  - 等方分布の期待値: 14.6 イベント
- **Post−trial probability:** $P(S_{MC} > 5.1\sigma) = 6.8 \times 10^{-4}$ → 3.2σ

E > $10^{19.4}$ eVの宇宙線の到来方向

arXiv: 2110.14827
Submitted to ApJL



イベントの超過 がホットスポットよりも少し低いエネルギーでも観測された。

イベント超過の有意度

For E ≥ $10^{19.4}$, **3.6σ**

For E ≥ $10^{19.5}$ eV, **3.6σ**

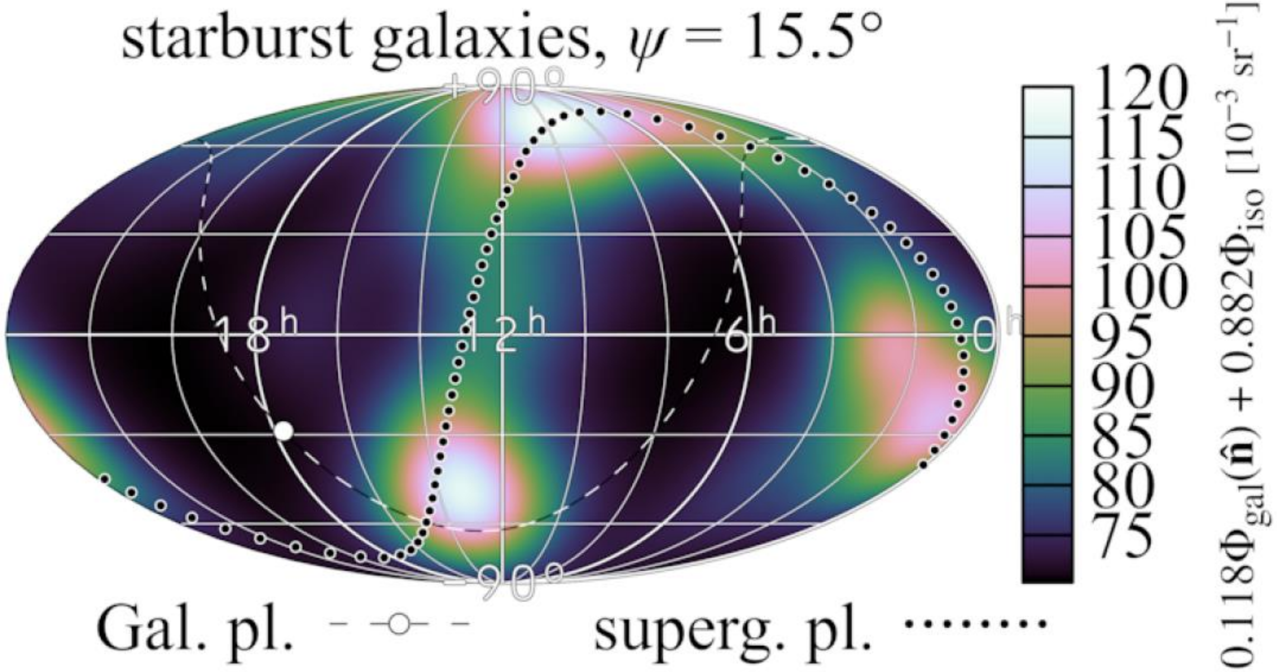
For E ≥ $10^{19.6}$ eV, **3.4σ**

(20 度のoversampling半径)

11年間のTA実験のSDデータを使用

Correlation of arrival directions with astrophysical sources searched by the Auger and TA anisotropy working group

A. di Matteo



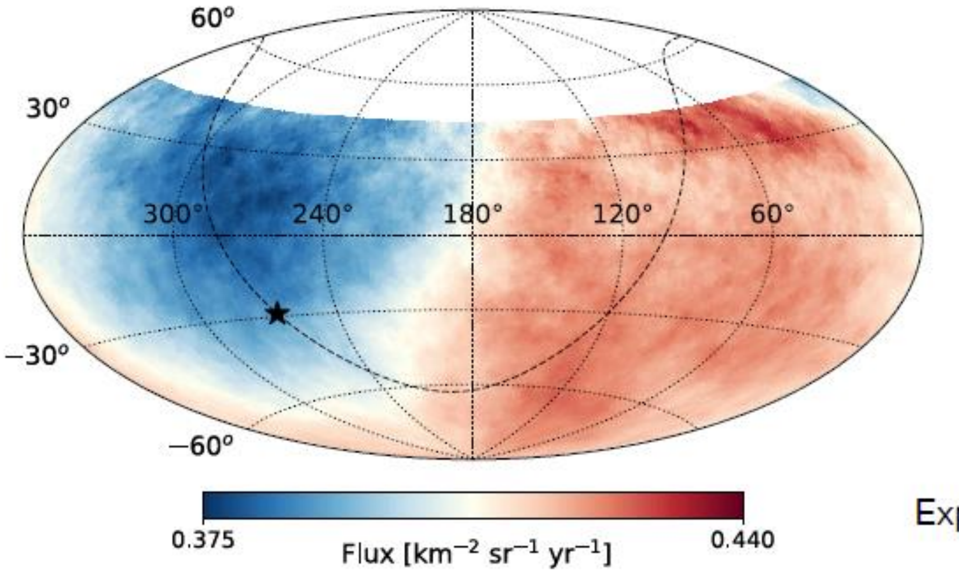
Equatorial coordinate

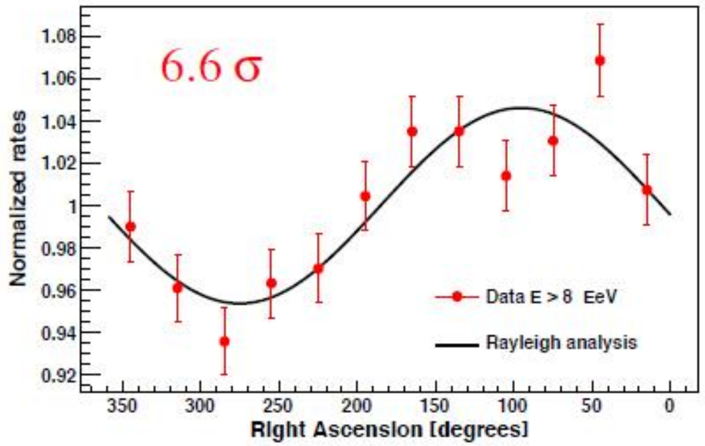
- Auger: E > 38 EeV
- TA: E > 49 EeV
- Correlations with a sample of nearby starburst galaxies and 2MRS catalog galaxies.
- Angular scales and energy thresholds were scanned.
- Post-trial significance of the correlation with **starburst galaxies** is estimated to be **4.2σ**.

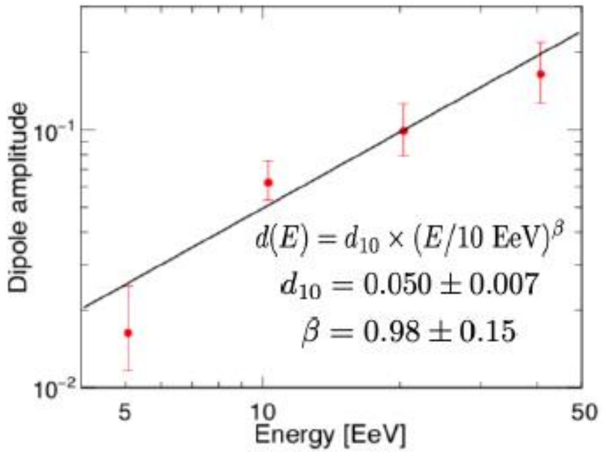
Rescale of energies

$$E_{TA} \mapsto E_{Auger} = 8.57\,(E_{TA}/10\ \text{EeV})^{0.937}\ \text{EeV}$$

Auger intermediate-scale anisotropy



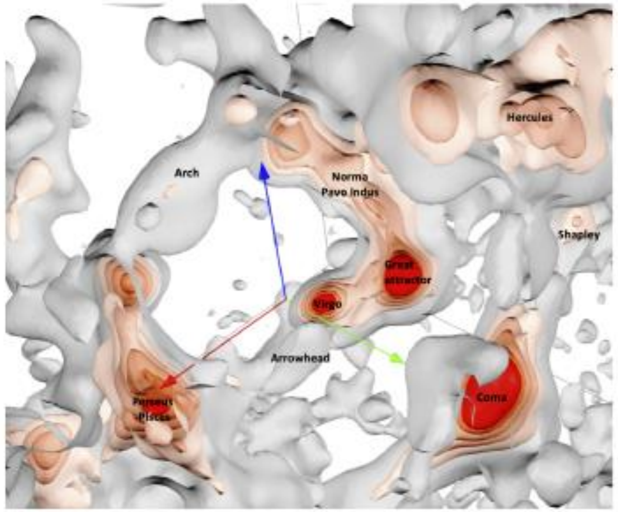




Exposure until end of 2020 (θ < 80°): 110,000 km² sr yr

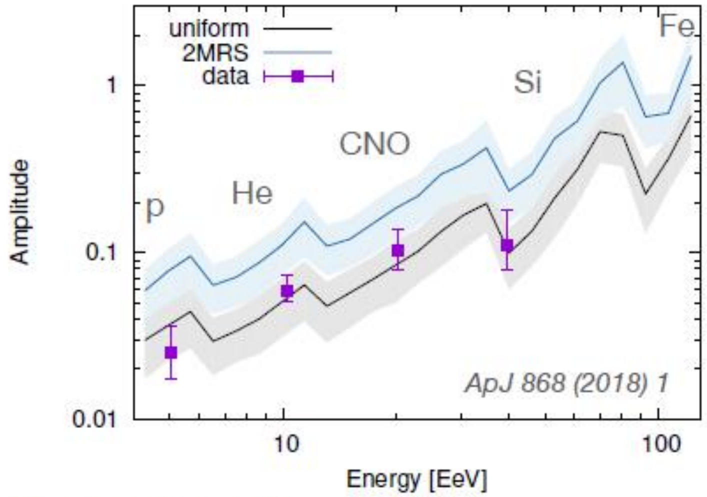
$p \sim 5 \times 10^{-11}$

(Rogerio Menezes)



Fundamental observation:
non-trivial interplay of

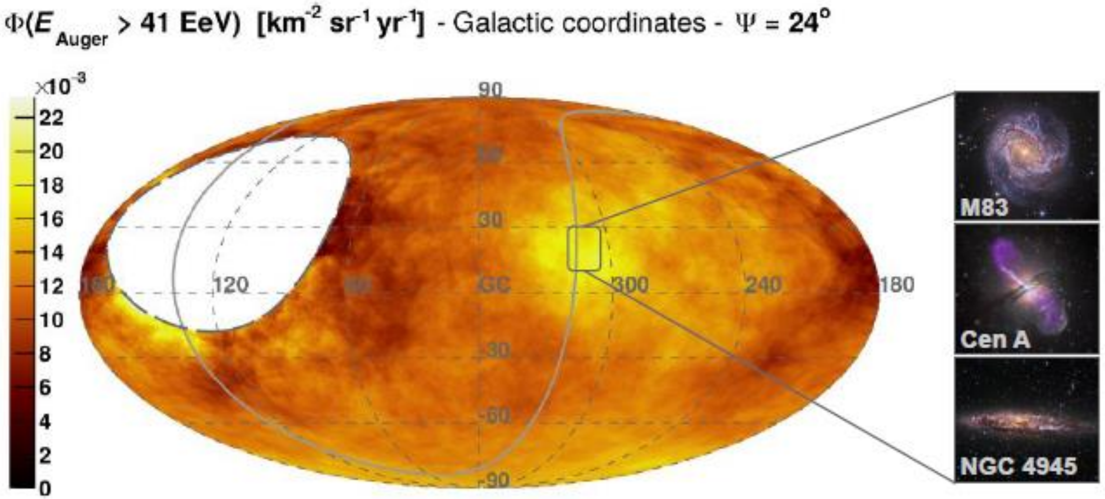
- **mass composition,**
- **magnetic horizon and**
- **local source distribution**



(Ding, Globus & Farrar 2101.04564)

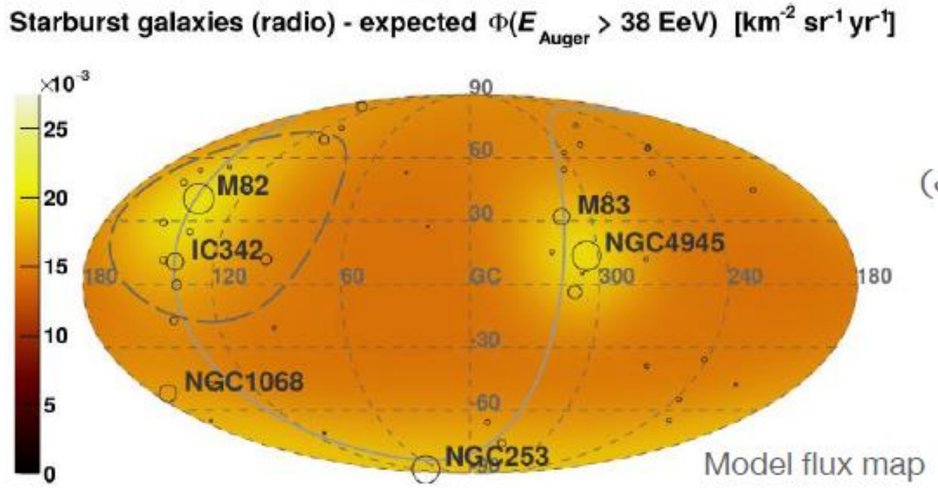
(Harari, Mollerach, Roulet PRD92 (2015) 06314)

Auger correlation study with catalogs



Direction fixed to that of Cen A, free E_{th} and Ψ

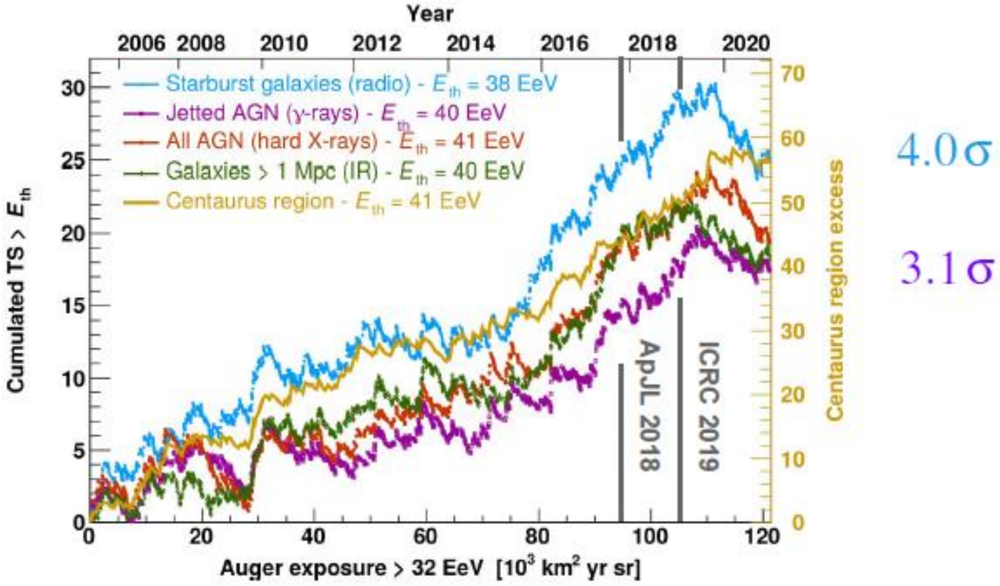
E_{th} > 41 EeV, Ψ = 27°: **3.9σ post-trial** deviation from isotropy (5% excess)



(Jonathan Biteau)

All data until end of 2020, optimized quality cuts: 120,000 km² sr yr

Catalog	E_{th} [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}
Jetted AGNs (γ-rays)	40	23^{+9}_{-8}	6^{+4}_{-3}	17.3	1.0×10^{-3}



Growth of test statistic (TS) compatible with linear increase

Discovery threshold of 5σ expected in 2025 – 2030 (Phase II)

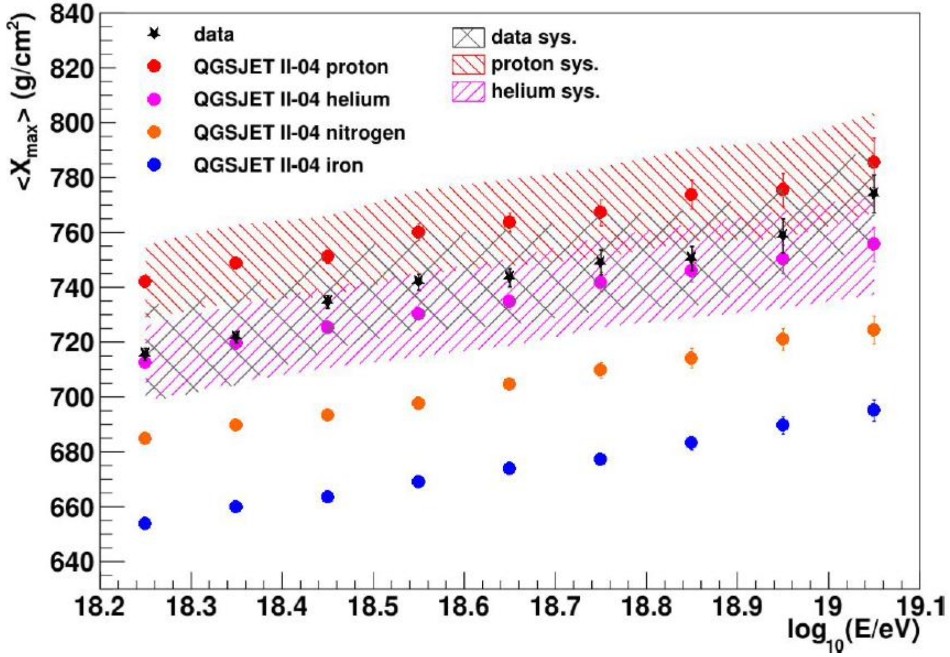
Other means to increase sensitivity (Auger 85% sky coverage)

Measurement of mass composition with TA SD and FD in hybrid mode

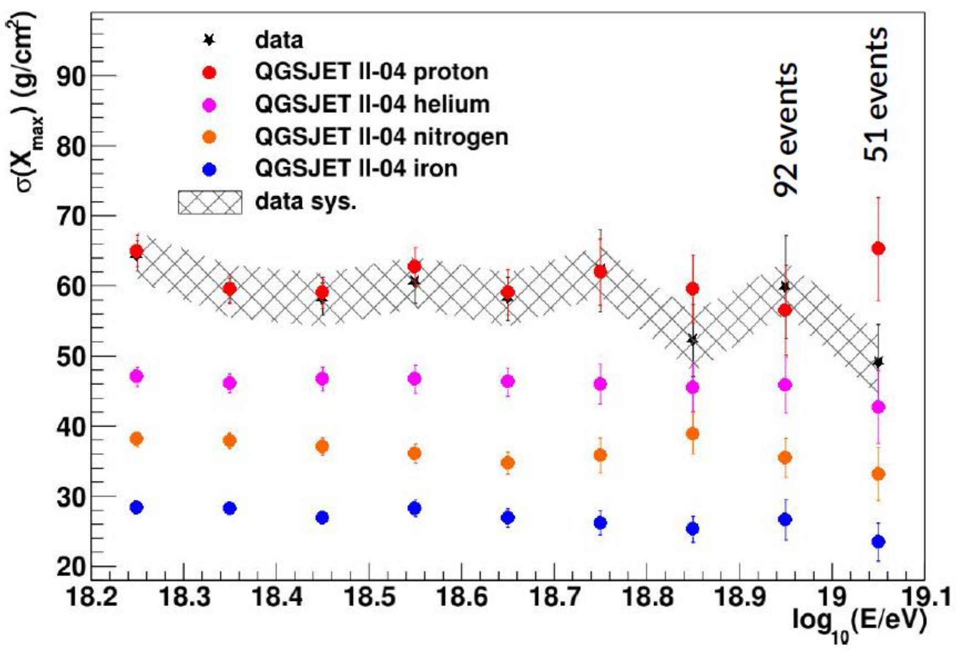
W. Hanlon

10 years TA SD and FD hybrid data

Mean Xmax



σ (Xmax)

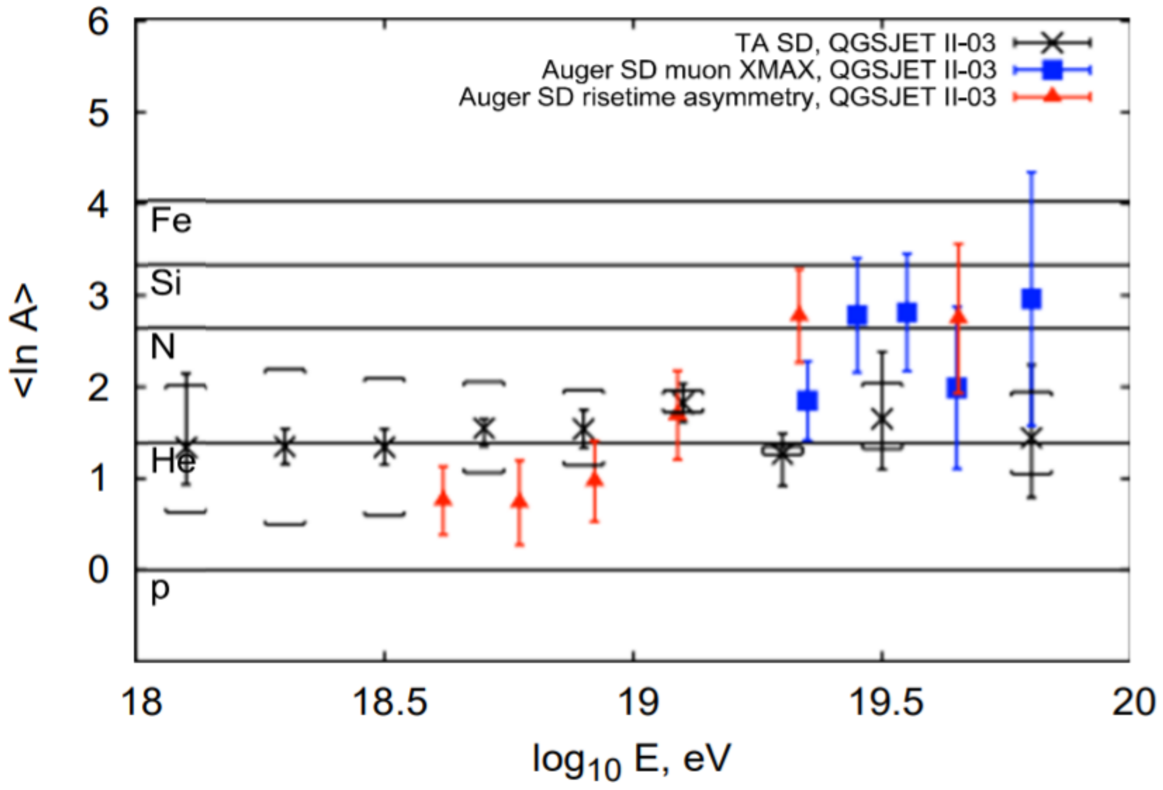


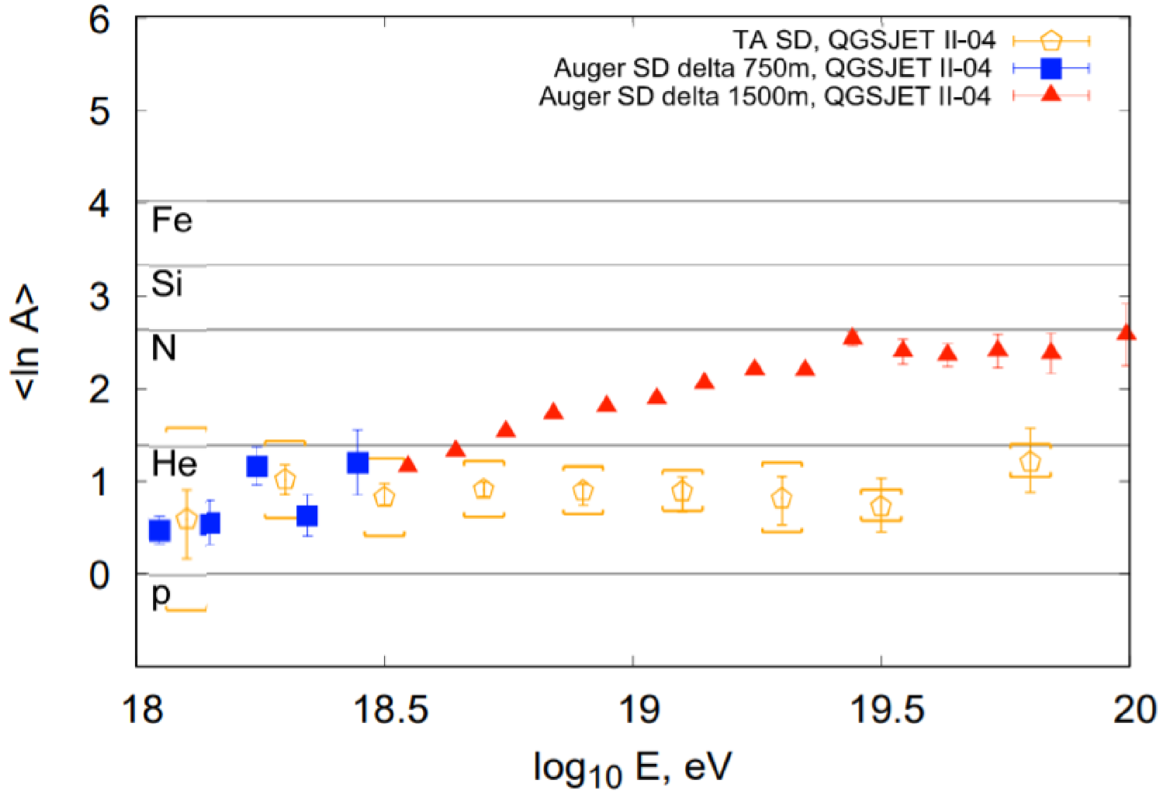
- Energy Range: $10^{18.2}$ eV – $10^{19.1}$ eV
- 3560 events after the quality cuts
- Systematic uncertainty of <Xmax>: ± 17 g/cm^2
- QGSjetII-04 interaction model was compared with the data
  → agreement with light composition
- More events are needed to study highest energies

Measurement of mass composition with TA SDs

Machine learning technique based on BDT and 16 composition-sensitive observables with 12 years of TA SD data.

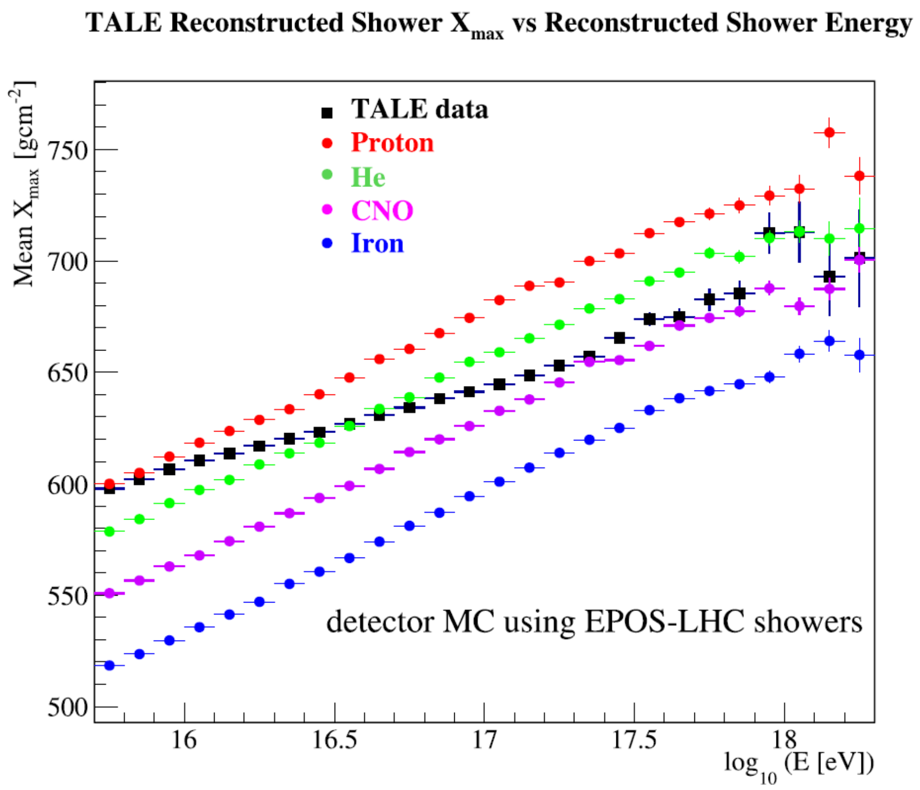
Y. Zhezher

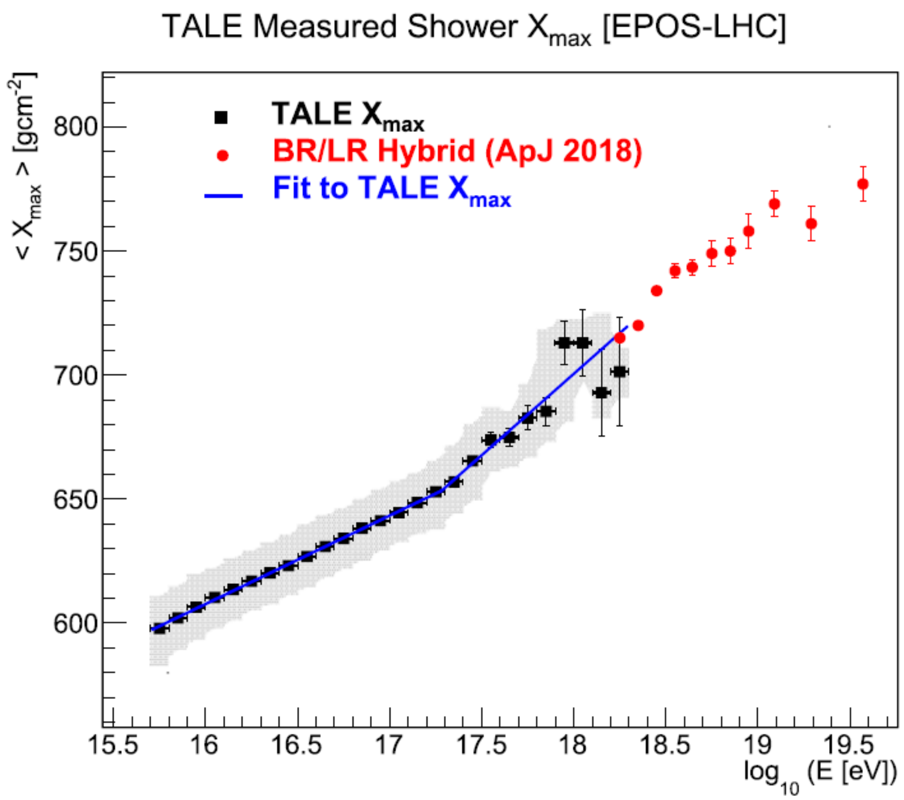




Measurement of mass composition with TALE FD in monocular mode

ApJ 909 178 (2021)

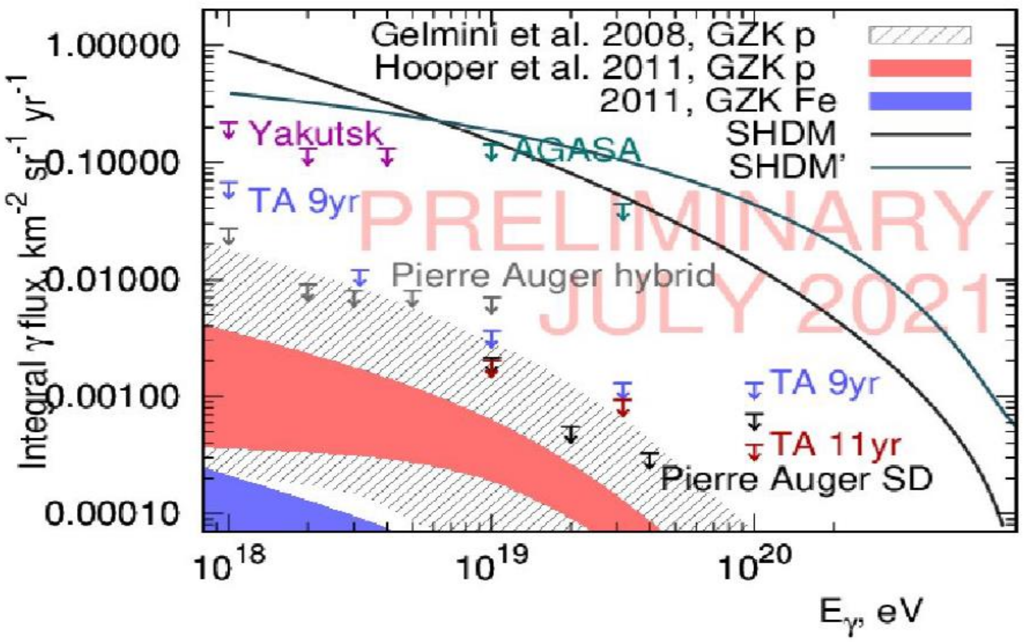




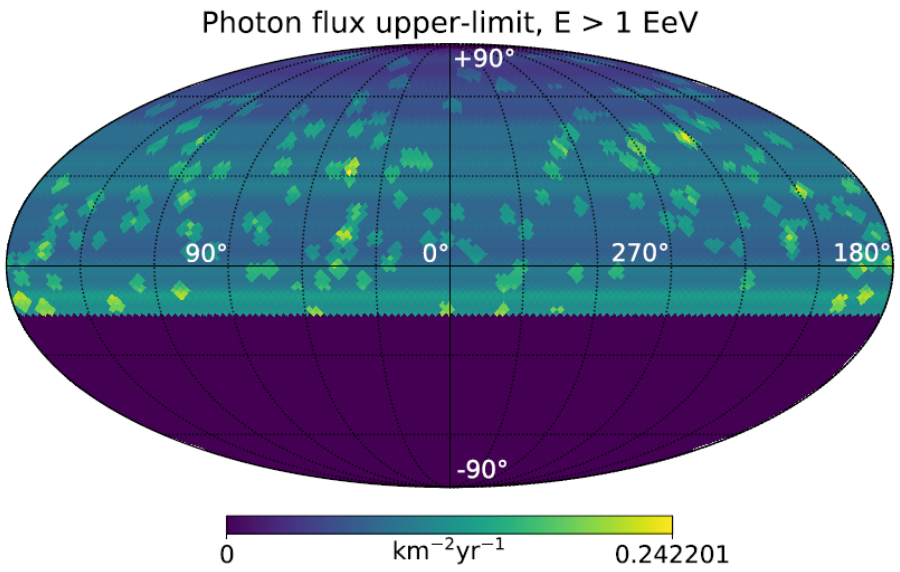
- Jun. 2014 – Nov. 2018 TALE FD mono data
- Energy Range: $10^{15.8}$ eV – $10^{18.3}$ eV
- Break point log (E/eV) = 17.291 ± 0.060 + 0.077 − 0.084 (EPOS LHC)

Upper limits of UHE photons

*Astropart. Phys. **110**, 8 (2019)*
updated in 2021.

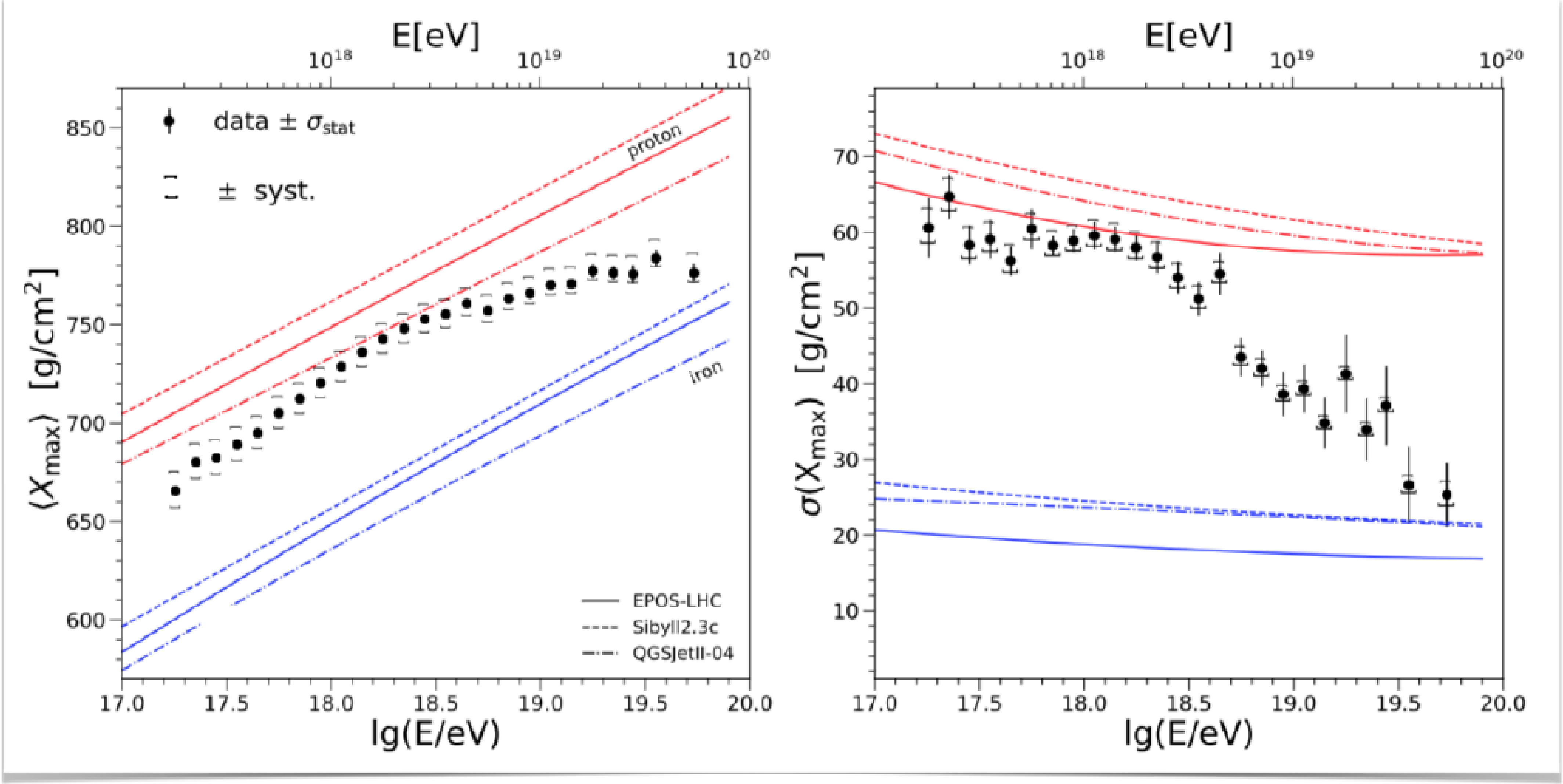


*MNRAS, **492**, 3984 (2020)*



- UHE photons were not detected.
- Left: the updated upper limit on GZK photons with 11-years TA SD data
- Right: upper limit for directions in the field of view with 9-years TA SD data

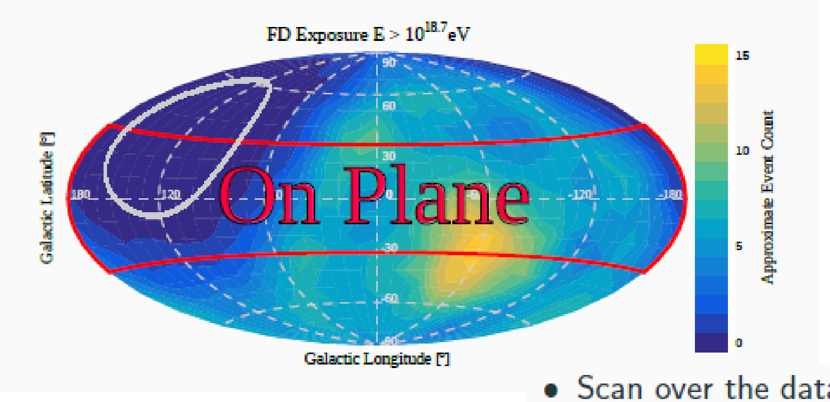
Measurement of mass composition by Auger



Composition becoming lighter up to $\sim 2 \times 10^{18}$ eV, heavier above this energy

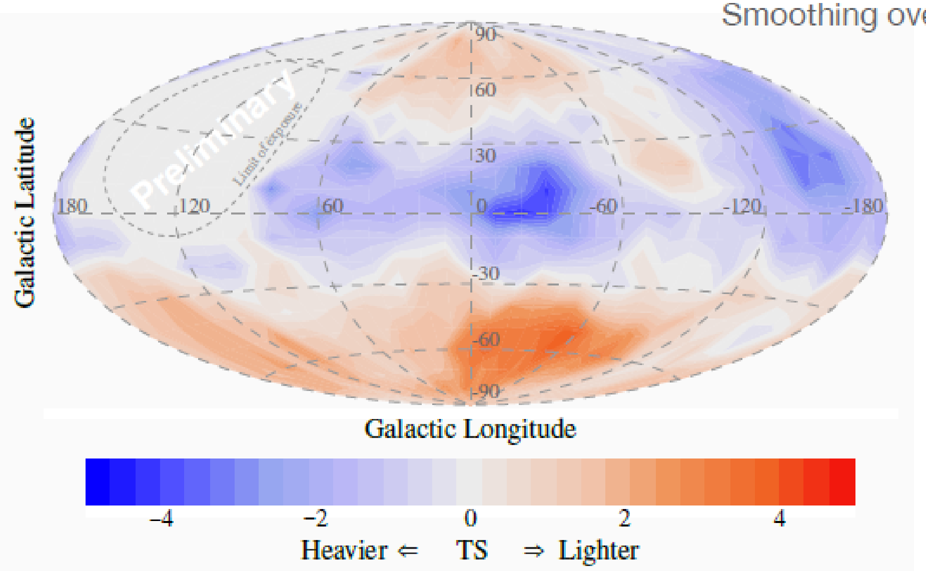
A. Yushkov [Auger Collaboration], ICRC 2019 arXiv:1909.09073

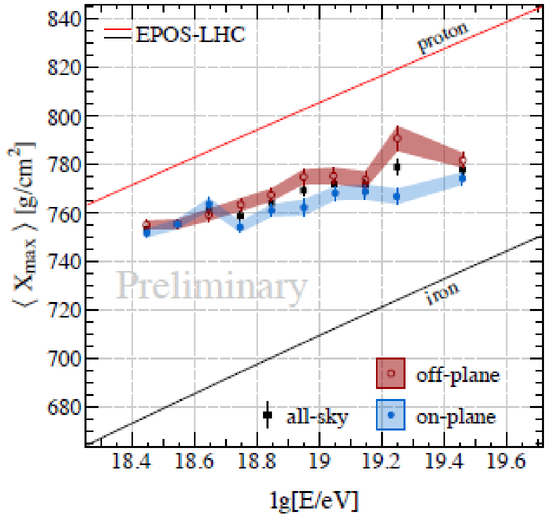
Xmax anisotropy by Auger

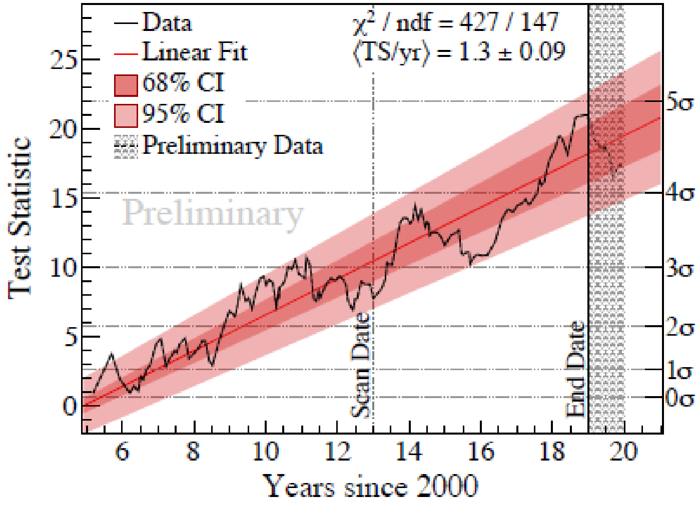


- Scan over the data recorded before 01.01.2013 (54 %)
- 5° steps in b and 0.1 $\lg(E/\mathrm{eV})$ steps in energy
- Highest TS of 8.35 for: $\rightarrow E_{\min} = 10^{18.7}$ eV
  $\rightarrow b_{\mathrm{split}} = 30°$

Smoothing over 30° bins







Not necessarily related to Galaxy

Local source distribution and mass-dependent horizon effect?

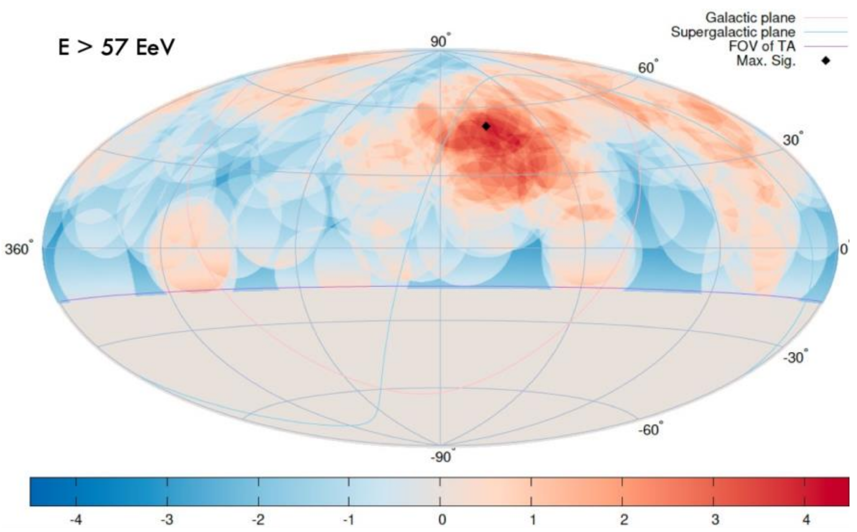
No independent confirmation from other data

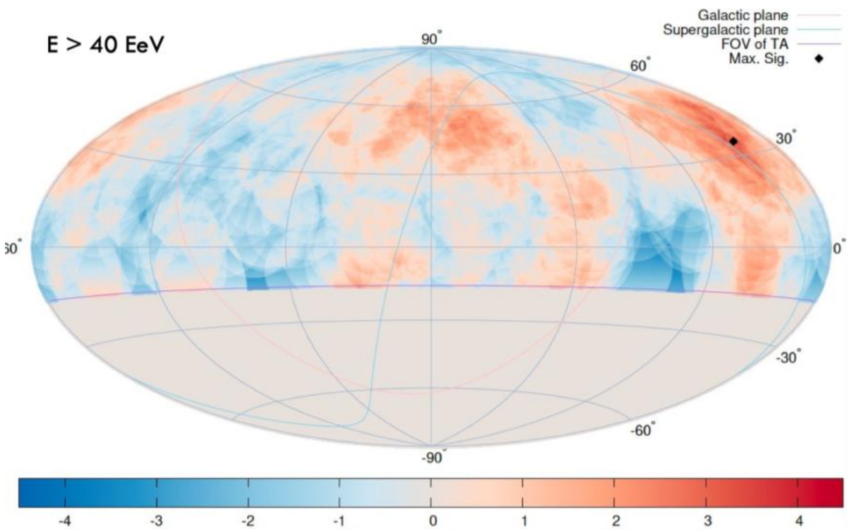
Phase II data and more statistics really important to make progress

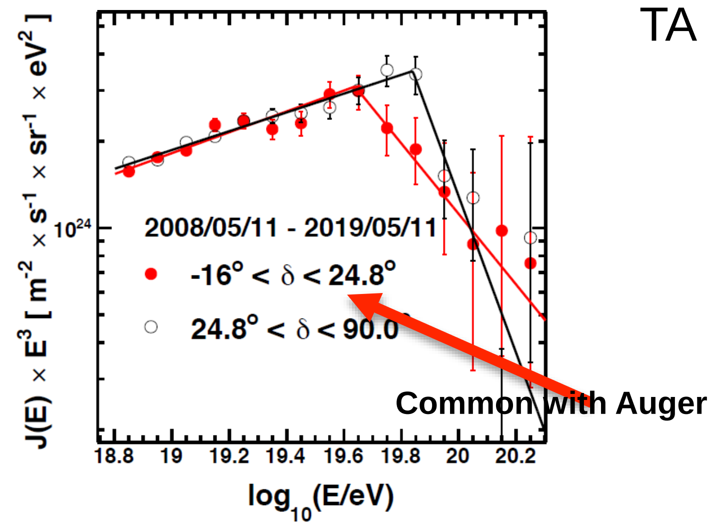
(Eric Mayotte)

Implications of anisotropies from the ICRC2021

TA



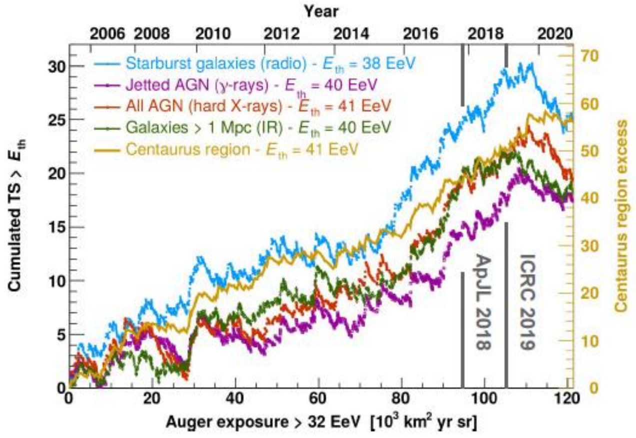




Auger

All data until end of 2020, optimized quality cuts: 120,000 km² sr yr

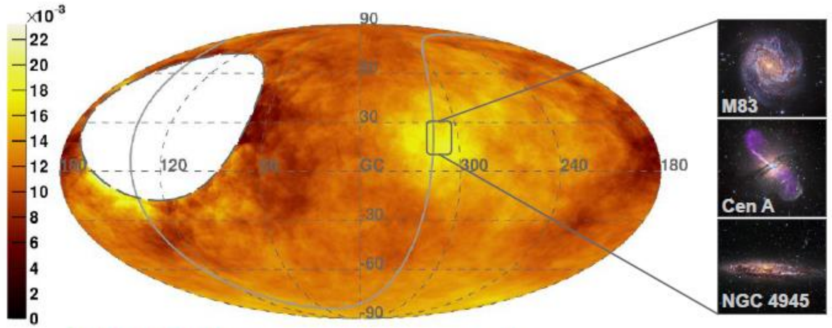
Catalog	E_{th} [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}
Jetted AGNs (γ-rays)	40	23^{+9}_{-8}	6^{+4}_{-3}	17.3	1.0×10^{-3}



4.0σ

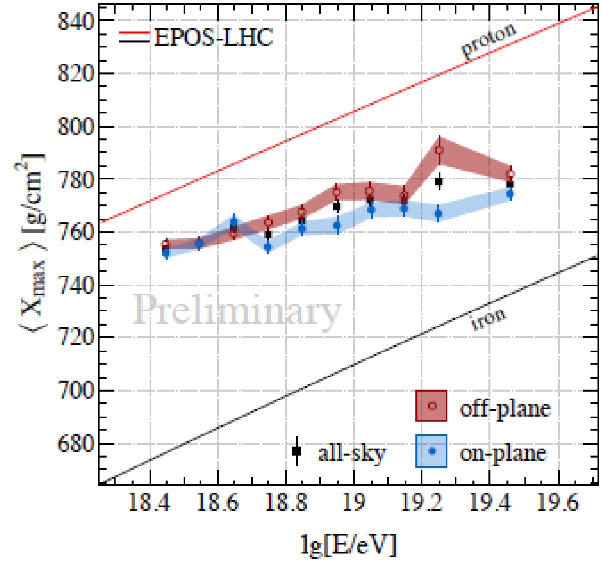
3.1σ

$\Phi(E_{Auger} > 41$ EeV) [km^{-2} sr^{-1} yr^{-1}] - Galactic coordinates - Ψ = 24°

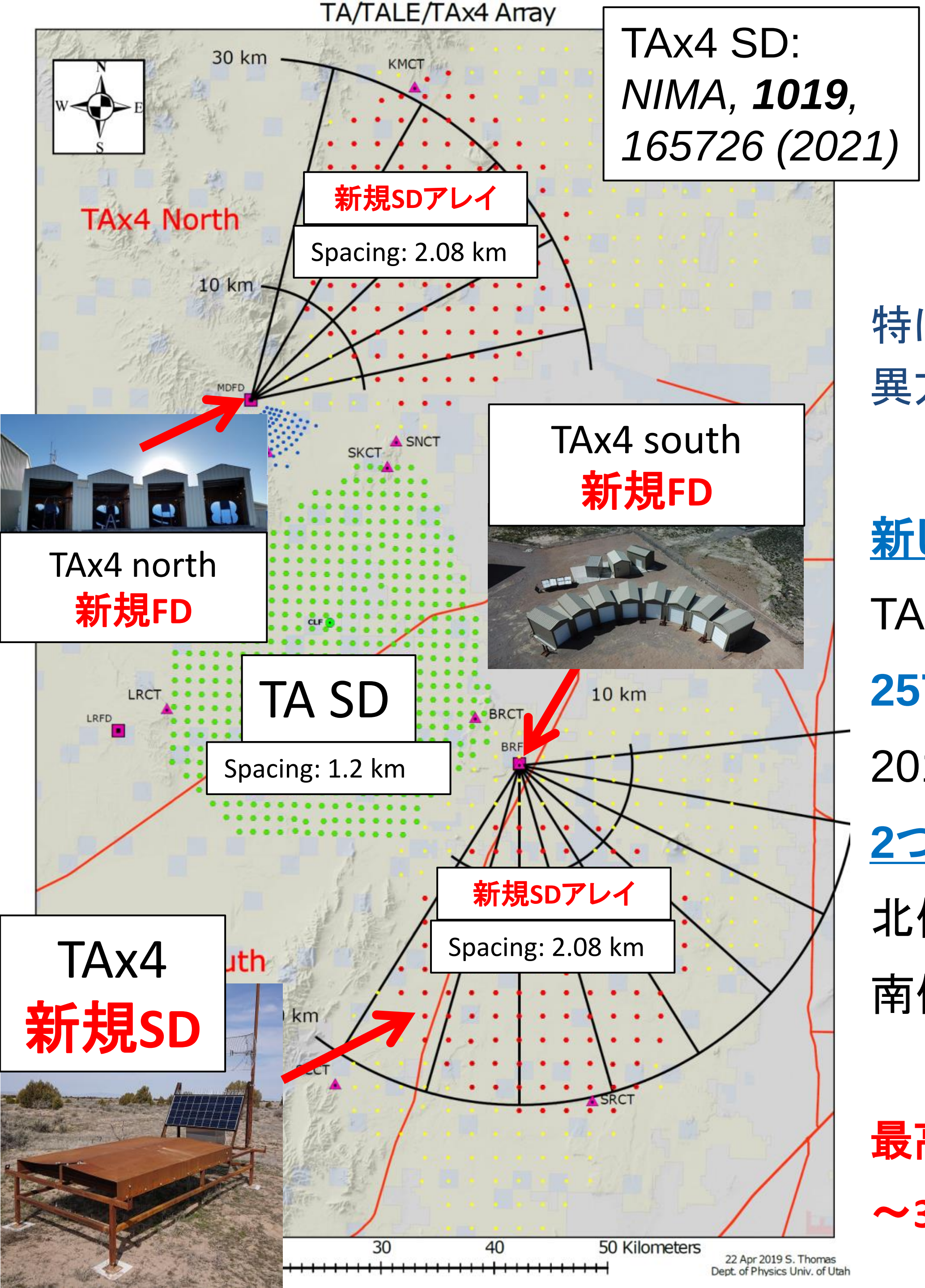


Direction fixed to that of Cen A, free E_{th} and Ψ

$E_{th} > 41$ EeV, Ψ = 27°: **3.9σ post-trial** deviation from isotropy (5% excess)



TAx4実験



特に最高エネルギーの宇宙線イベントの取得を加速させ、TA実験で得られた異方性の兆候を確かめる

新しく2.08 km 間隔のSDを**500台**建設 (TASD: 1.2 km spacing)

TA SDs とあわせて **4×TA SD** の検出面積 (~2800 km^2)

257台を2019年3月に設置

2019年11月から全6通信塔を稼働 →定常観測

2つの新しいFDステーション (4+8 HiRes Telescopes) を建設

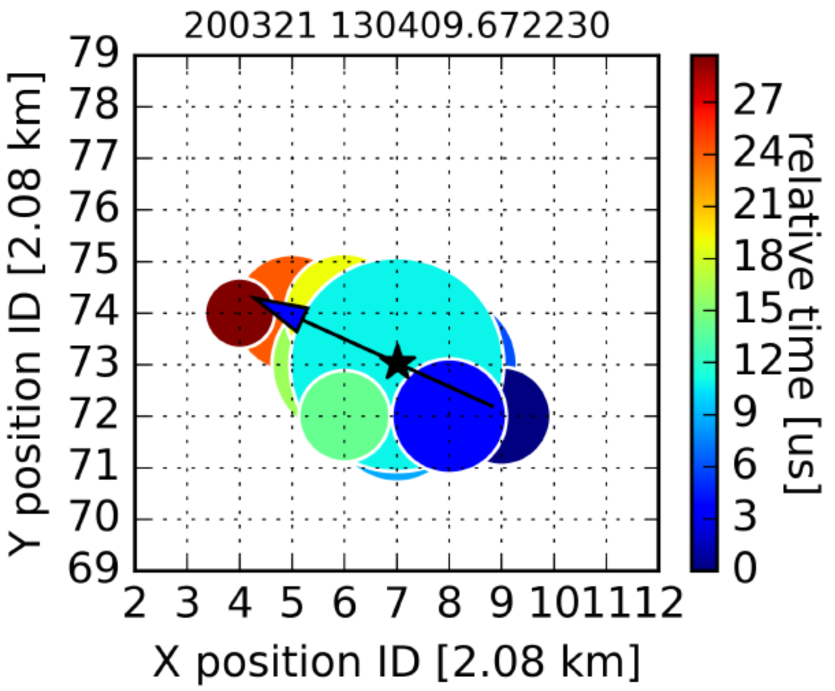
北側: 2018年6月から定常観測

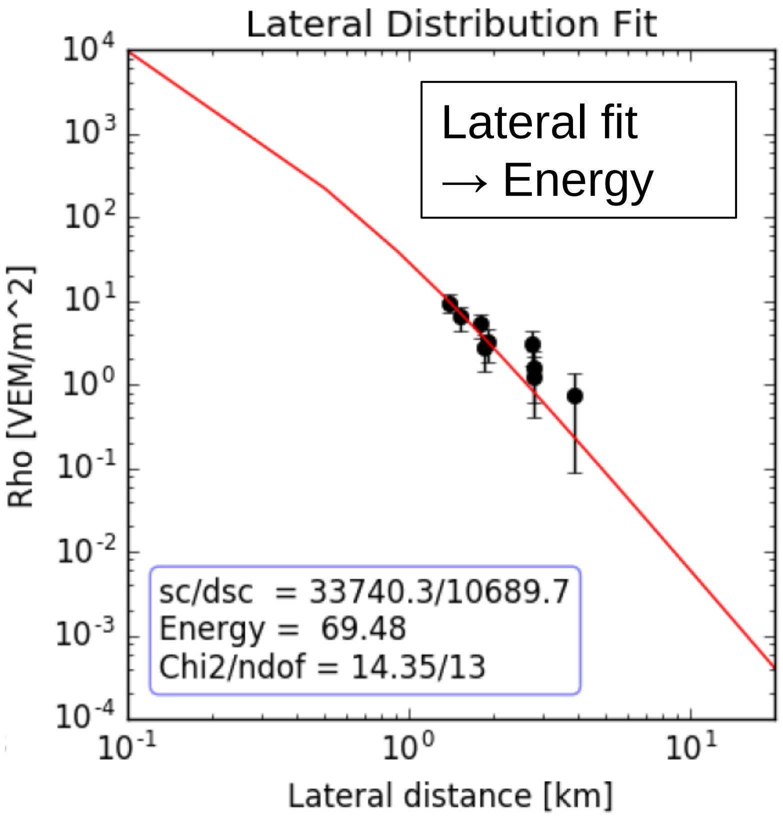
南側: 2020年9月から定常観測

最高エネルギーで、~4×TA SD 相当のSDイベント数

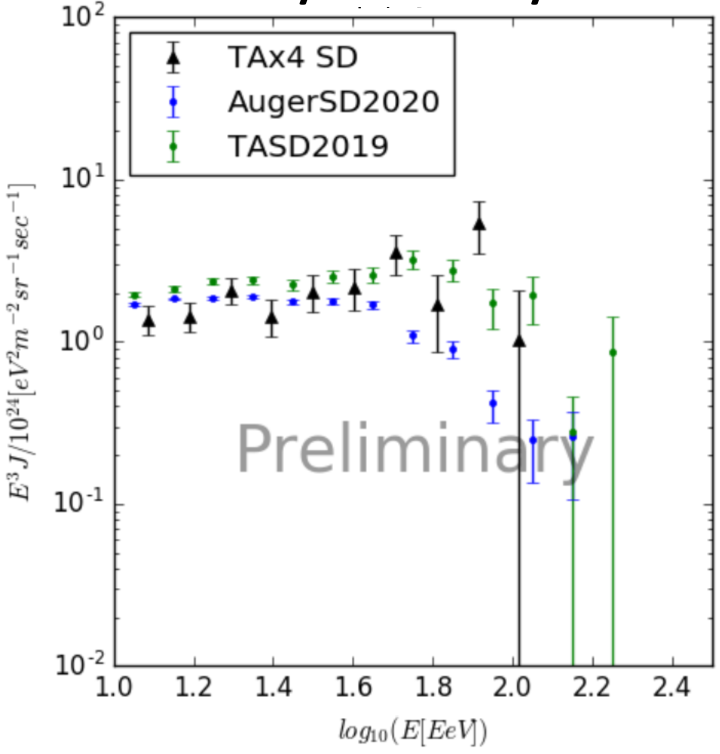
~3×TA SDFD 相当のSDFD ハイブリッドイベント数

新規SDアレイ(2.08km間隔、257台)のデータ解析

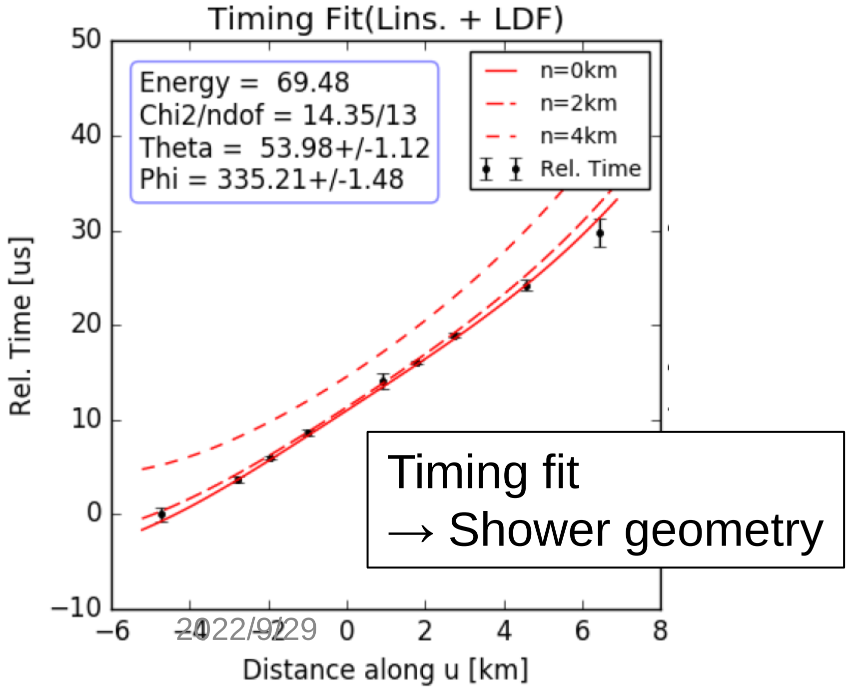




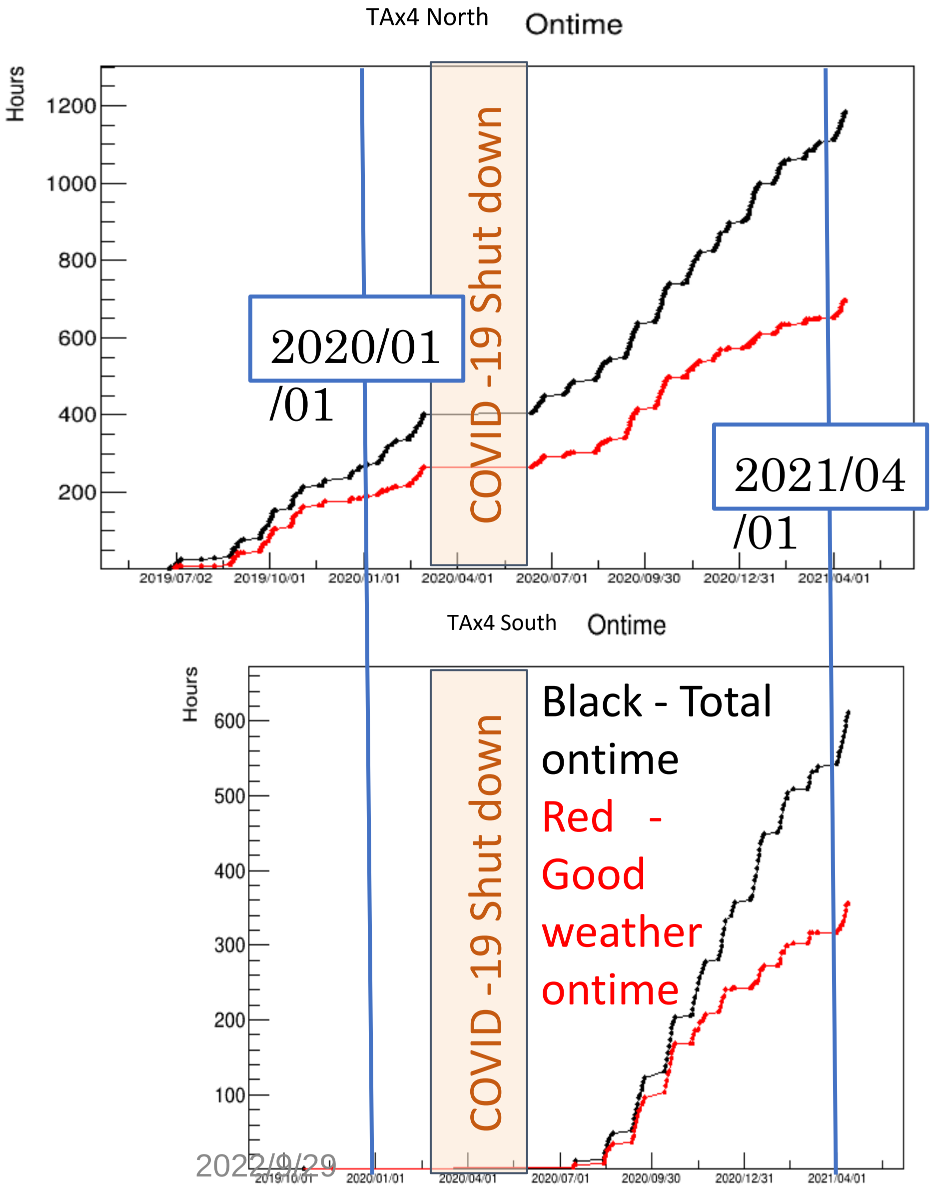
TAx4 SD 1 year data
2019/11 – 2020/11



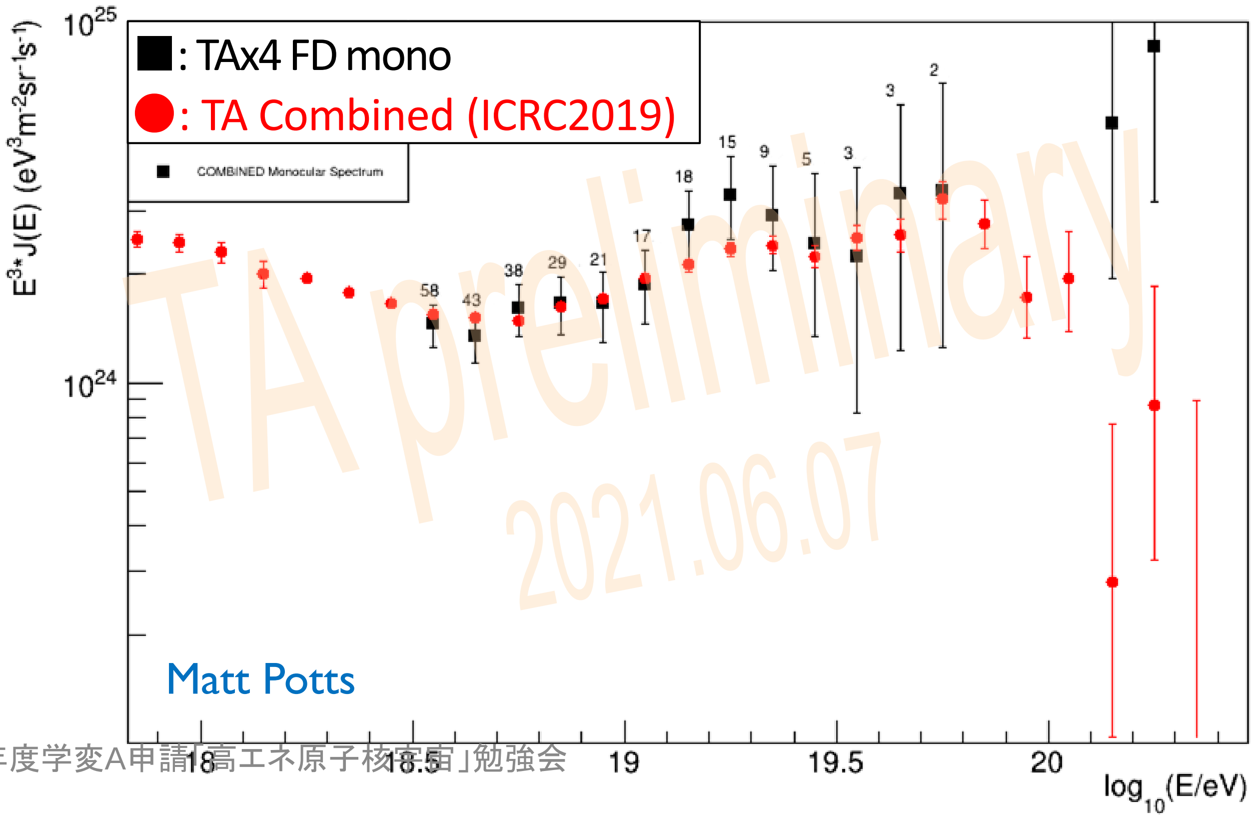
H. Jeong



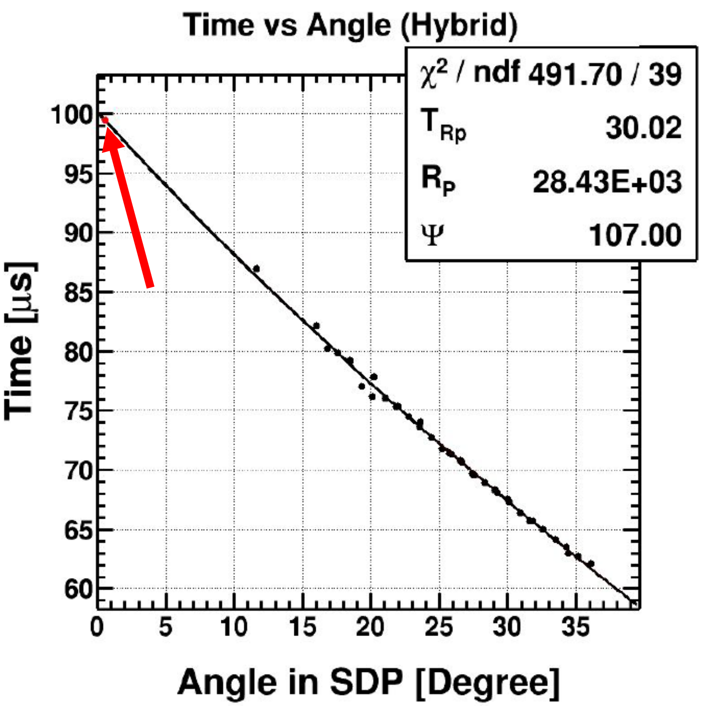
新規FD単眼解析

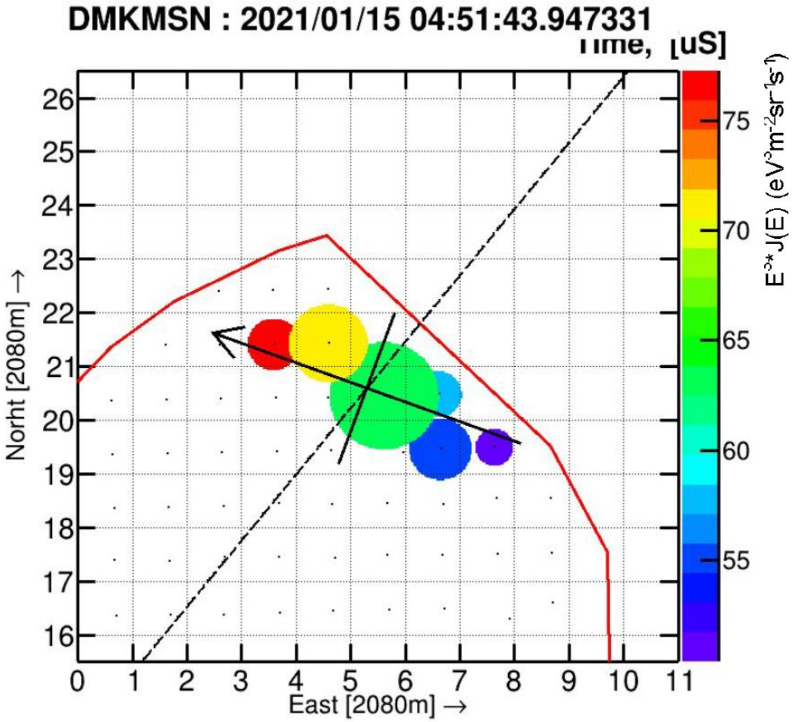


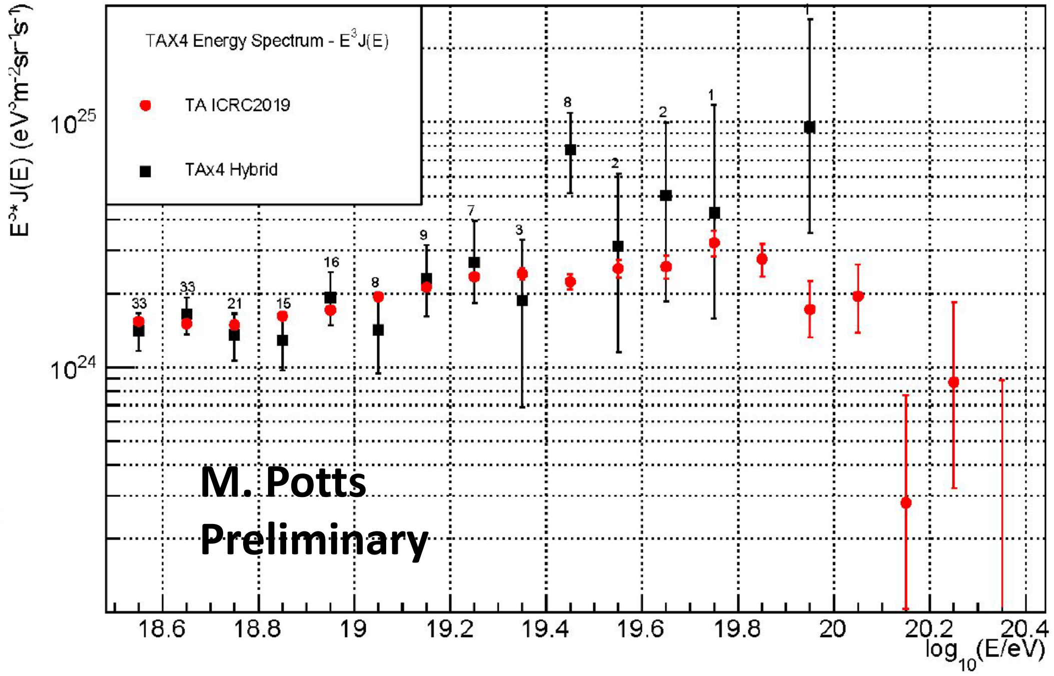
- 2019/06/26 – 2021/04/14
- エネルギー分解能: ~20%
- 天頂角分解能: ~3°
- Ψ 分解能: ~7°
- Impact Parameter 分解能: ~11%
- 全ての幾何学的なパラメタは、十分MCと一致していることを確認。



新規FDSD ハイブリッド解析







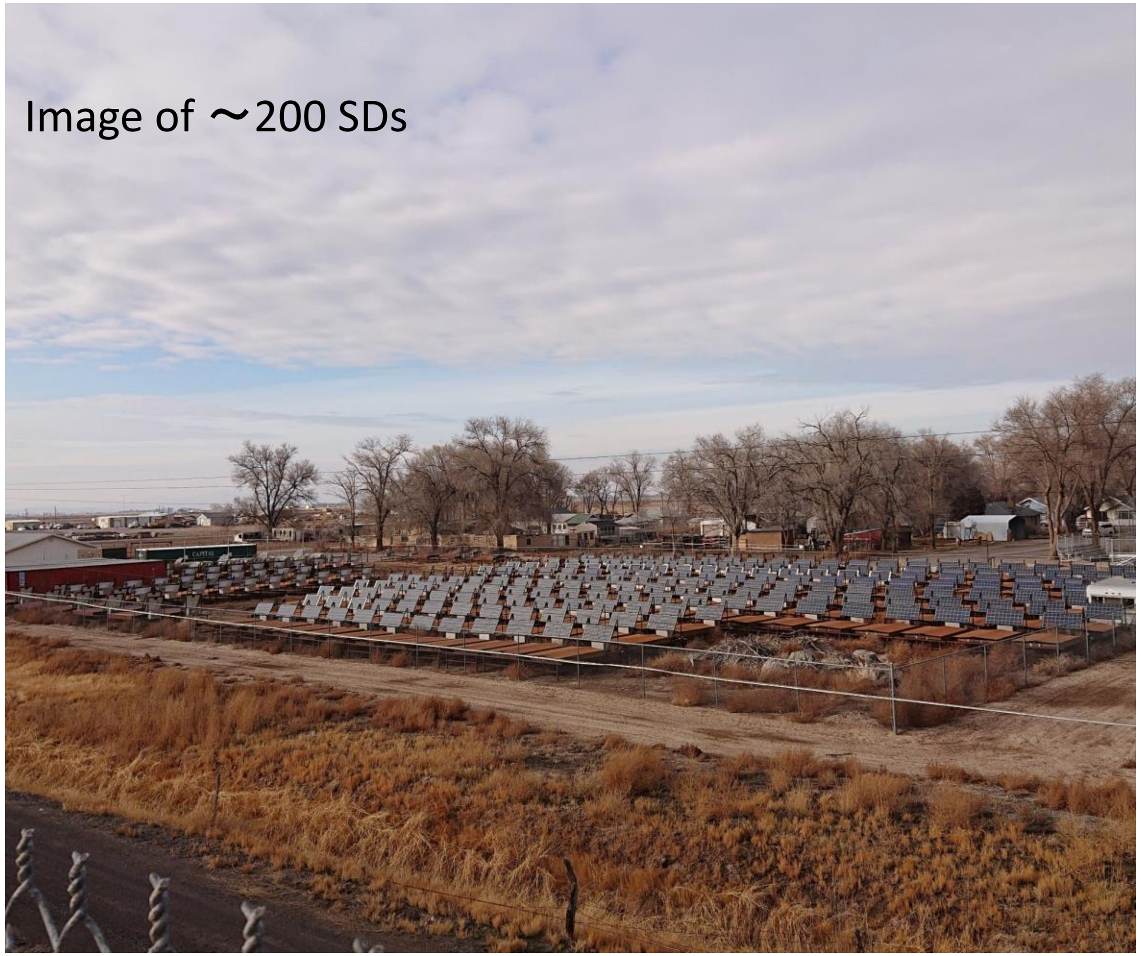
TAx4 SD のトリガー条件: 10 EeV 付近で～30%

→ **ハイブリッドトリガー** の安定運用は**2020年6月** に開始。

FDs がトリガーした時間をSDの通信塔に送り、その付近(+/- 128 usec)の時間の信号を取得する。

→ **～3×TA SDFD 相当のイベント数** (E > 10 EeV) を見込んでいる。

Future prospects: the TAx4 experiment



- We plan to deploy the remaining 250 SDs to realize the full TAx4 coverage in 2023-2024.
- We are investigating the analyses of anisotropies and compositions with new detectors.

Upgrade of the Observatory – AugerPrime

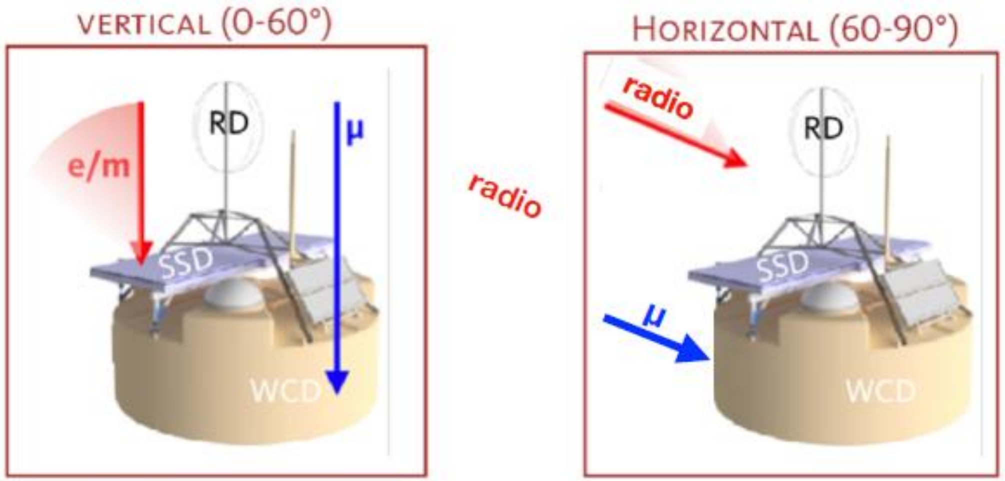
Physics motivation

- Composition measurement up to 10^{20} eV
- Composition selected anisotropy
- Particle physics with air showers
- Much better understanding of **new and old** data

Components of AugerPrime

- 3.8 m^2 scintillator panels (SSD)
- New electronics (40 MHz -> 120 MHz)
- Small PMT (dynamic range WCD)
- Radio antennas for inclined showers
- Underground muon counters (750 m array, 433 m array)
- Enhanced duty cycle of fluorescence tel.

Composition sensitivity with 100% duty cycle



(AugerPrime design report 1604.03637)

(Gabriella Cataldi) (Giovanni Marsella) (Ana Botti)
(Tomas Fodran) (Felix Schlüter) (Gaia Silli)

Summary

- The TA experiment continue to observe UHECRs from 2008 with the largest detection area in the northern hemisphere.
- Arrival directions
  - **3.2σ** hotspot with E > **57** EeV was obtained using TASD 12 years data
  - **3.5σ** excess with E > **$10^{19.4}$**eV was obtained using TASD 11 years data
  - Correlation with a sample of **Starburst Galaxies** at **4.2σ** confidence level obtained by the Auger and TA working group.
- Energy Spectrum
  - Declination dependence was claimed at **4.3σ** in the energy spectrum using TASD 11 years data
- Mass composition
  - TA SD and FD hybrid: consistent with light composition with 18.2 < log (E/eV) < 19.1. More events at the highest energies are needed.
  - TA SD: Analysis was conducted for 18.0 < log (E/eV). More events at the highest energies are also needed.
  - TALE FD mono.: Xmax results were obtained with log (E/eV) > 15.3.
  - Upper limits of photons are being updated.
- **Implications of anisotropy are being updated by the TA experiment.**
- Plan of the detectors of the TAx4 experiment:
  - **500 new** SDs with **2.08 km** spacing + TA SDs (1.2 km spacing) → Coverage of **4 × TA SDs ～2800 km^2**
  - **2 new** Fluorescence Detector (FD) stations (4+8 Telescopes)
- **257 new SDs** were deployed in 2019. The SDs are running stably since Nov. 2019.
- **New FDs were completed.** New north FD is running stably since Jun. 2018. New south FD is running stably since Sep. 2020.
- The extension of the SDs to the full coverage of TAx4 is scheduled for 2023 and 2024.
- Preliminary energy spectra were measured with new SDs, FDs, and SD FD hybrid.