

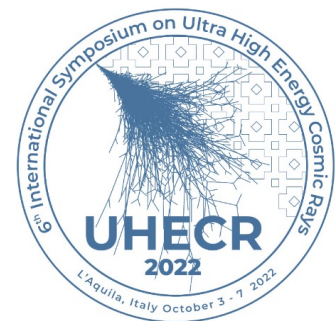
Measurement of cosmic-ray energy spectrum with the TALE detector in hybrid mode

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Introduction

TALE ($10^{15} - 10^{18}$ eV) & TA, TAx4 ($> 10^{18}$ eV) can cover a wide-energy range of 5 orders of magnitude from 10^{15} eV to 10^{20} eV.

Acceleration limit of galactic cosmic rays



Shielding and confinement of GCRs (GCRs)

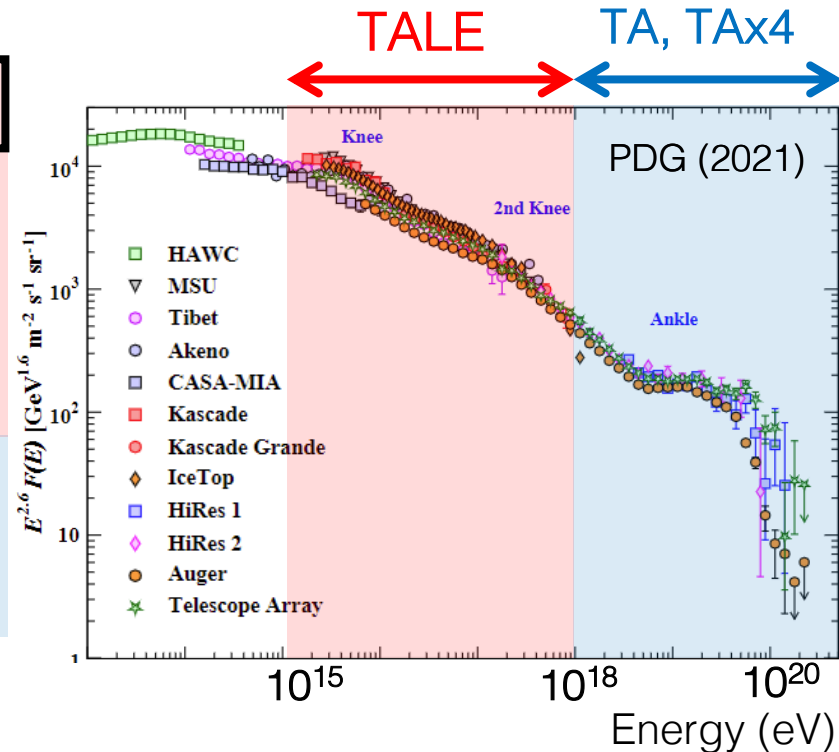


Structure of the GMF and EGMF



Origins of the extra galactic cosmic rays

The energy spectrum reflects these physical phenomena in complex.



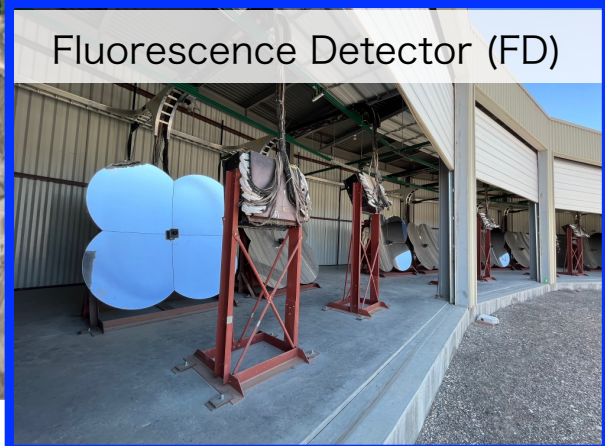
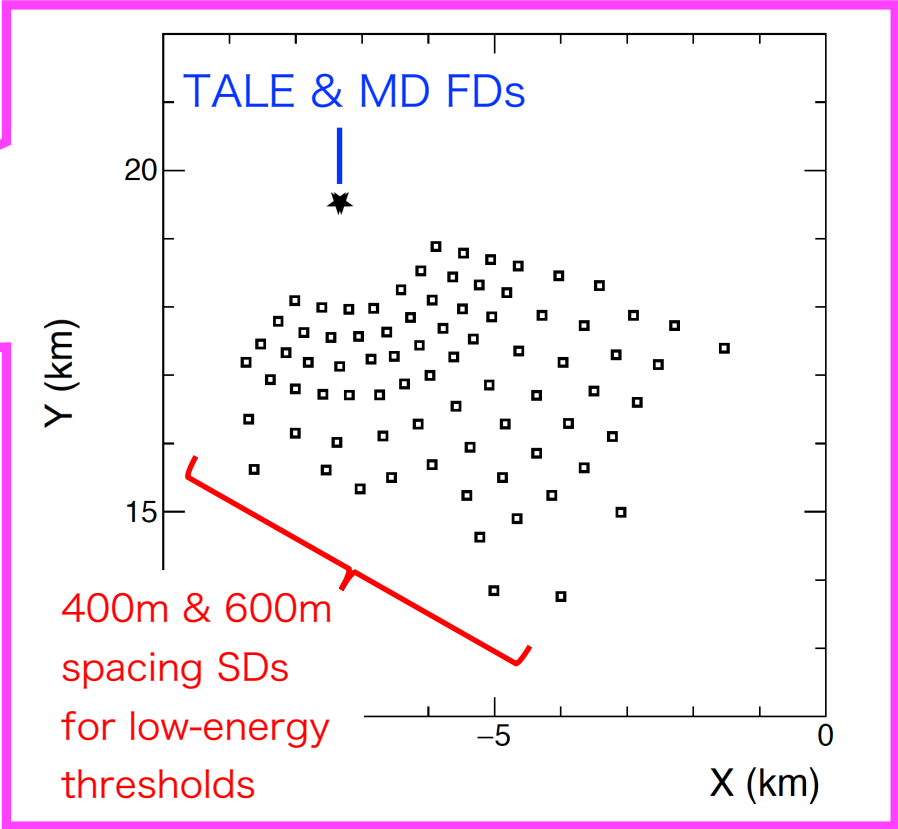
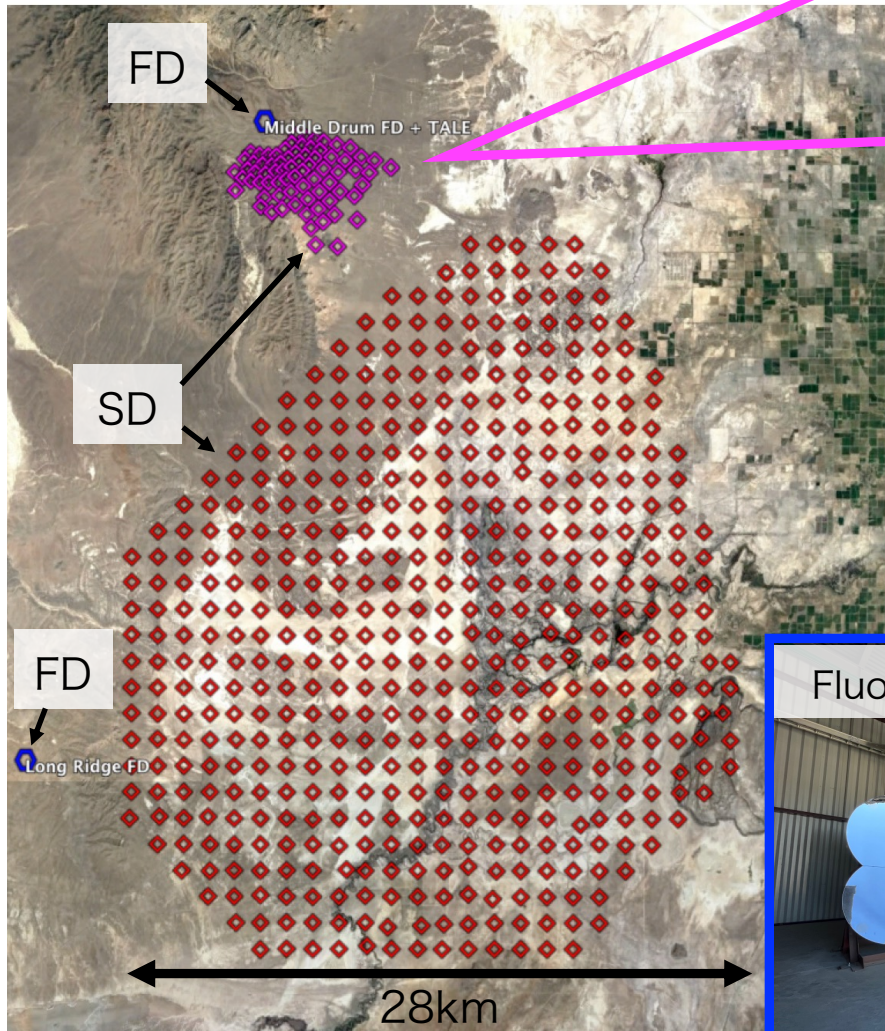
As the first physical goal, through the measurements of

- Composition and energy spectrum, and
- Transition from galactic to extragalactic cosmic rays,

we aim to measure the acceleration limit of galactic cosmic rays.

Physical location of the TALE detector

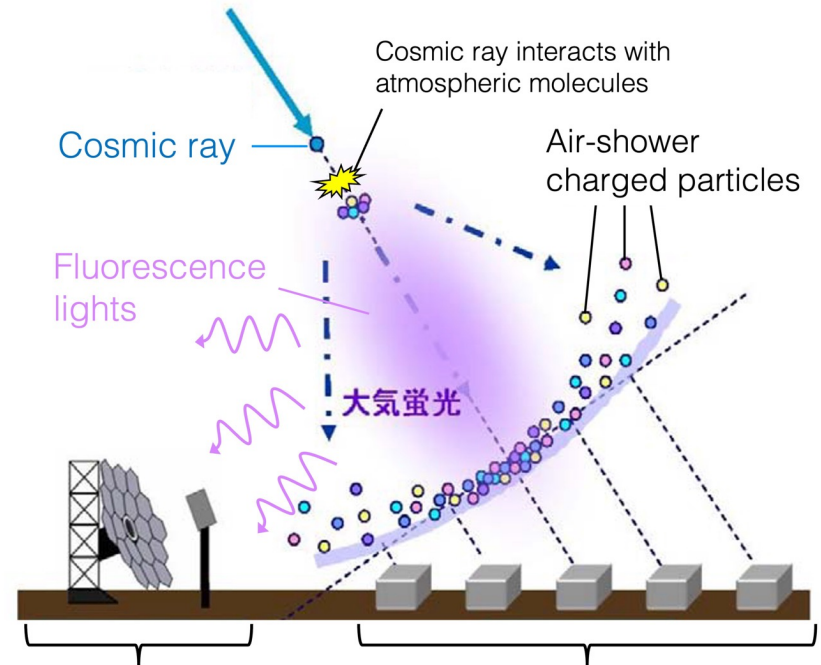
The TA & TALE detectors are located located in Millard County, Utah, USA.



Analysis strategy: Hybrid analysis

Hybrid analysis using FD and SD array

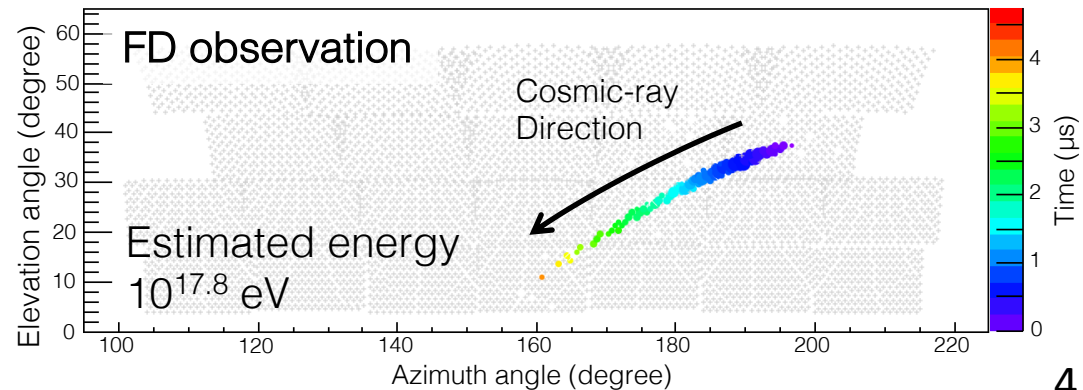
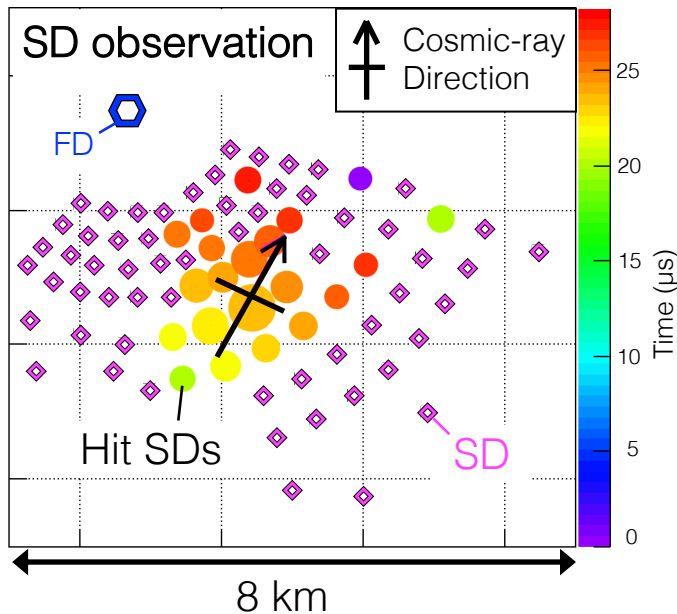
- X_{\max} measurement
→ Composition sensitive
- Energy resolution is improved using SD array for shower-axis detection.



Fluorescence Telescope (FD)
→ Detect fluorescence lights

Surface Detectors (SDs)
→ Detect air-shower charged particles

Event displays of SD array (left) and FD (right bottom).



Monte Carlo Simulation

Monte Carlo (MC) simulation is performed following processes:

(1) Air-Shower simulation (CORSIKA)

- Hadronic interaction model: EPOS-LHC, Iron
- Energy range: $16.0 \leq \log E < 19.1$

“Reuse” events with random distributions in core position and azimuth angle.

(2) SD simulation

- The energy deposit in each SD with Geant4
- Detector calibration using the monitor data
- Response of the SD electronics

(3) FD simulation

- Fluorescence and Cherenkov photons are generated.
- Telescope optics and detector calibration are taken into account.

(4) Hybrid analysis simulation

- Same processes for the data analysis are performed.

Event selection

Hybrid trigger events: FD + any1 SD w/ 3 MIPs

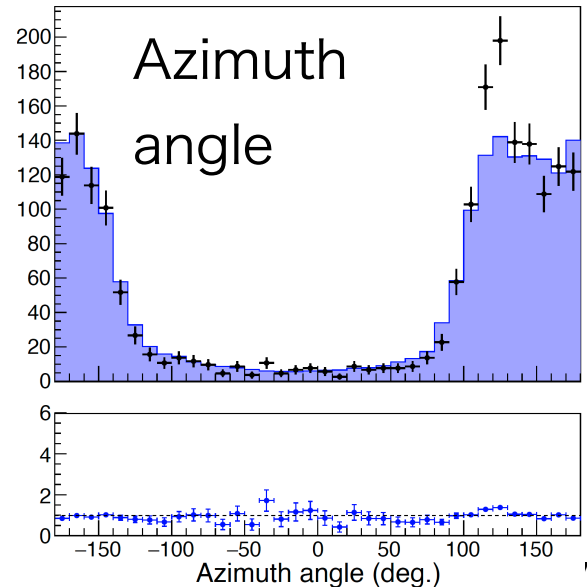
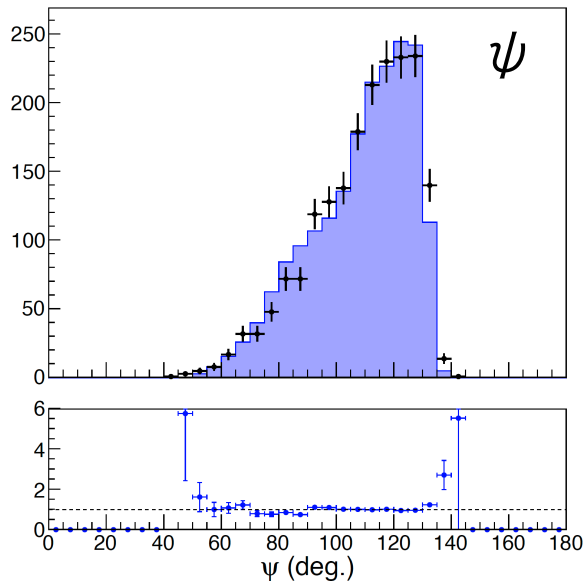
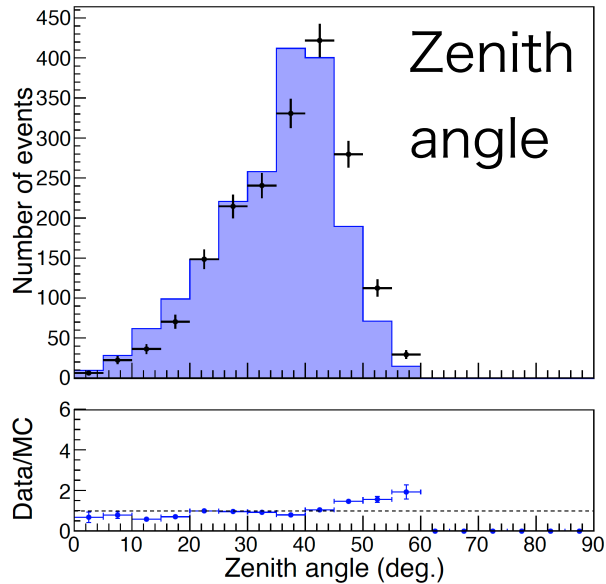
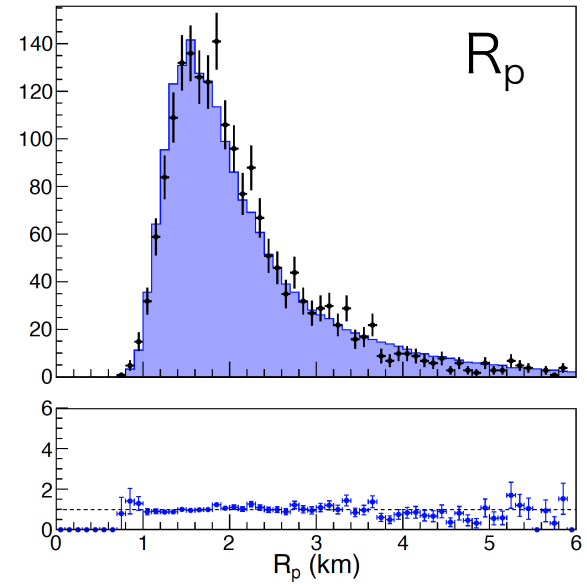
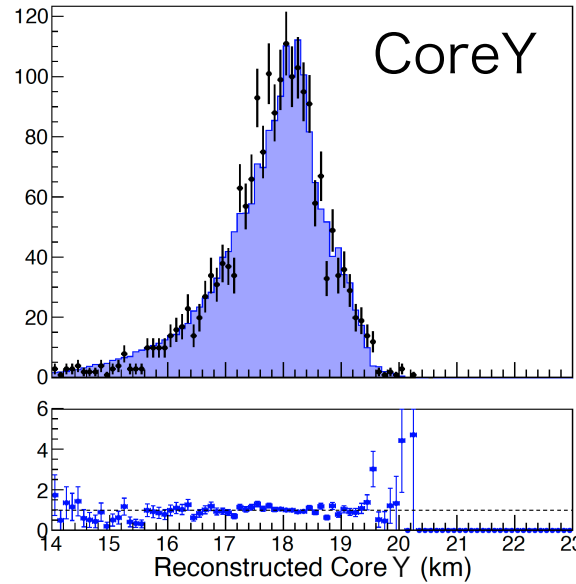
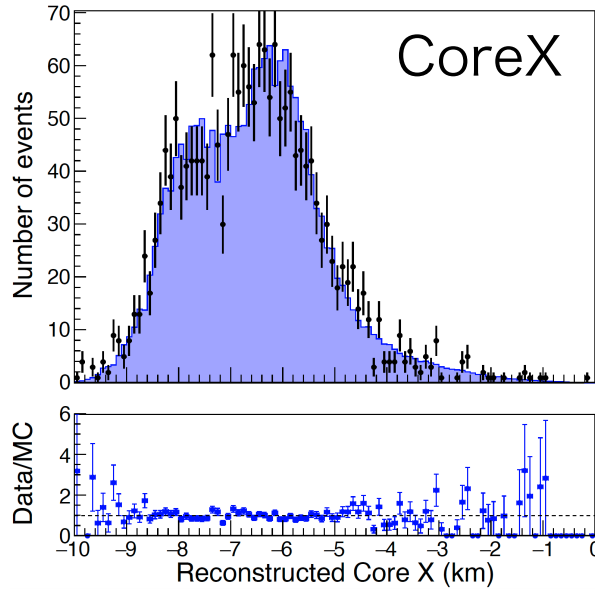
Events with a fractional contribution to the total signal of fluorescence light less than 75% are defined as CL events, while the others are defined as FL events.

	CL	FL
No Cut	Hybrid triggered events	
Selection 1	No saturated PMTs in TALE-FD	
Selection 2	Sel.1 + X_{\max} is inside the geometrical field of view of the FDs + $\chi^2_{\text{long}} < 100$	
Selection 3	-	Sel.2 + # of photo-electrons > 2000
Selection 4	Sel.3 + Event duration > 100 ns	-
Selection 5	Sel.4 + # of PMTs > 10	-
Selection 6	Sel.5 + # of photo-electrons/# of PMTs > 50	-
Selection 7	Sel.6 + Angular track length > 6.5 deg	-
Selection 8	Sel.7 + $\log(E_{\text{rec}} / \text{eV}) > 16.6 + \theta_{\text{zenith}} < 60^\circ$	

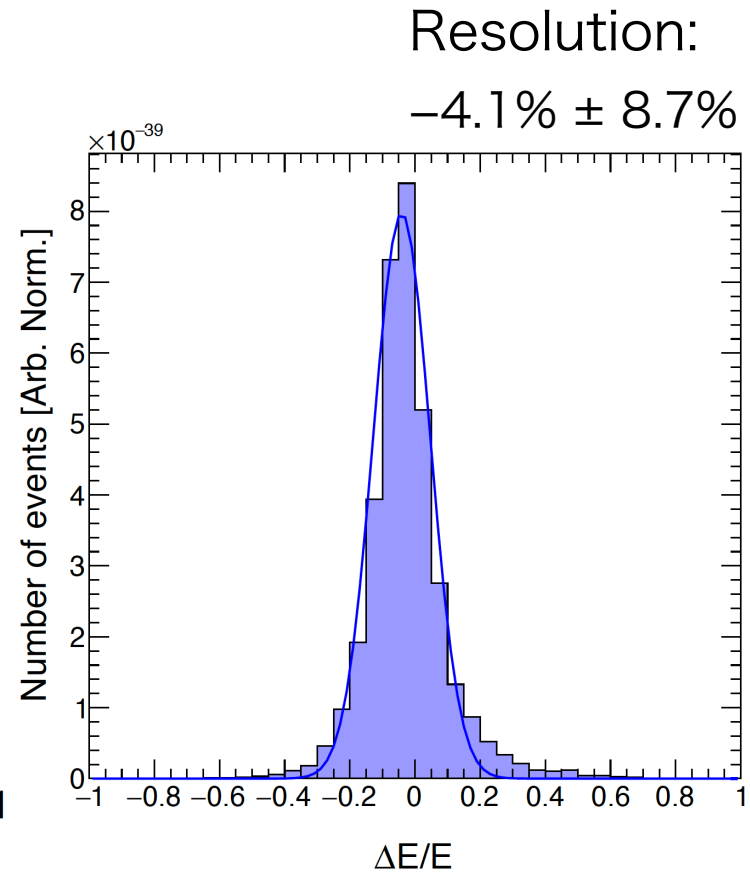
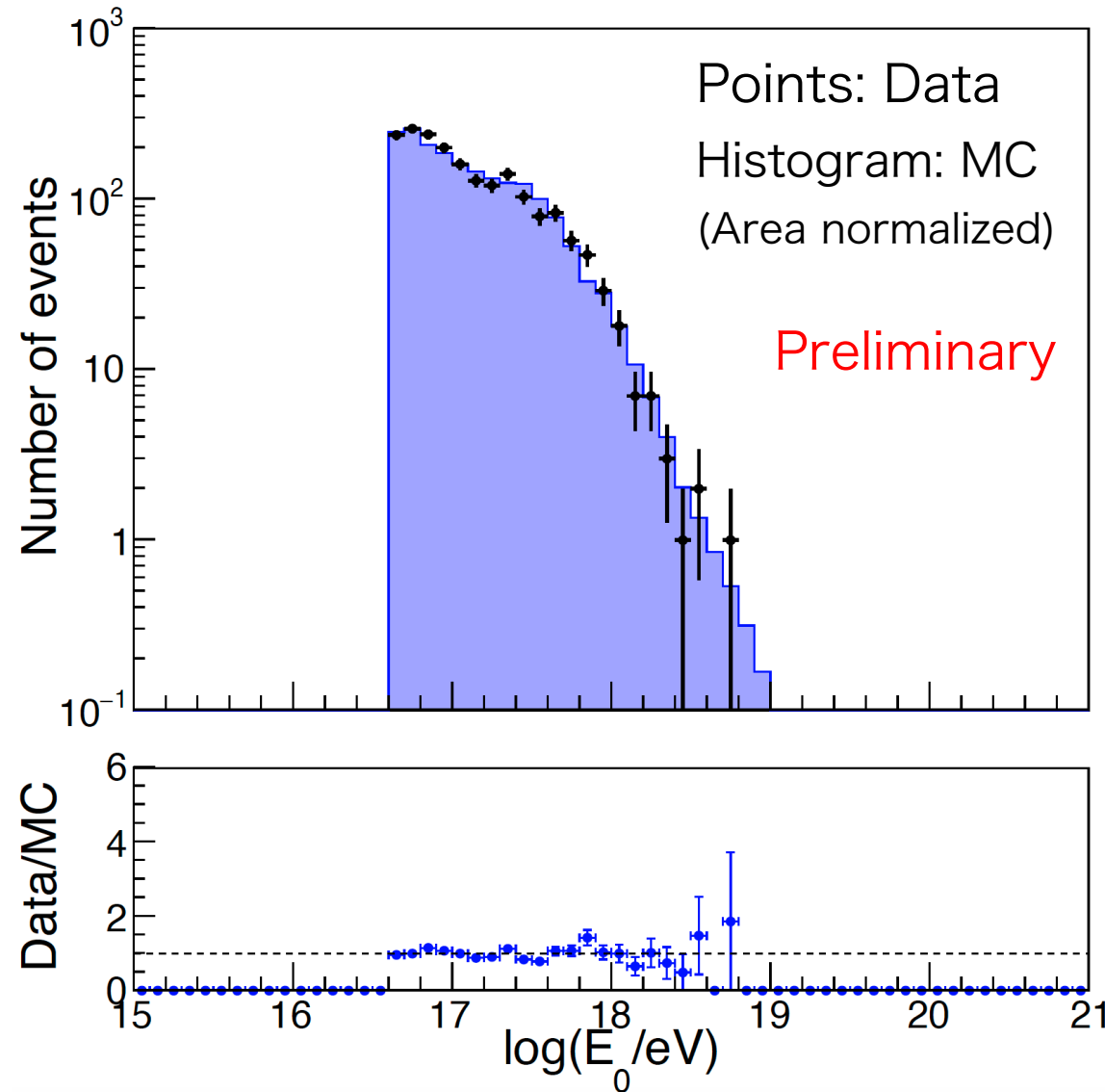
Comparison between the data & MC prediction

Preliminary

Points: Data, Histograms: MC (Area normalized)



Energy measurements



The measured energy is consistent with the MC prediction and its resolution is consistent with previous studies.

Iterative D'Agostini unfolding

The Iterative unfolding uses Bays' theorem to obtain an unsmearing matrix from the smearing matrix.

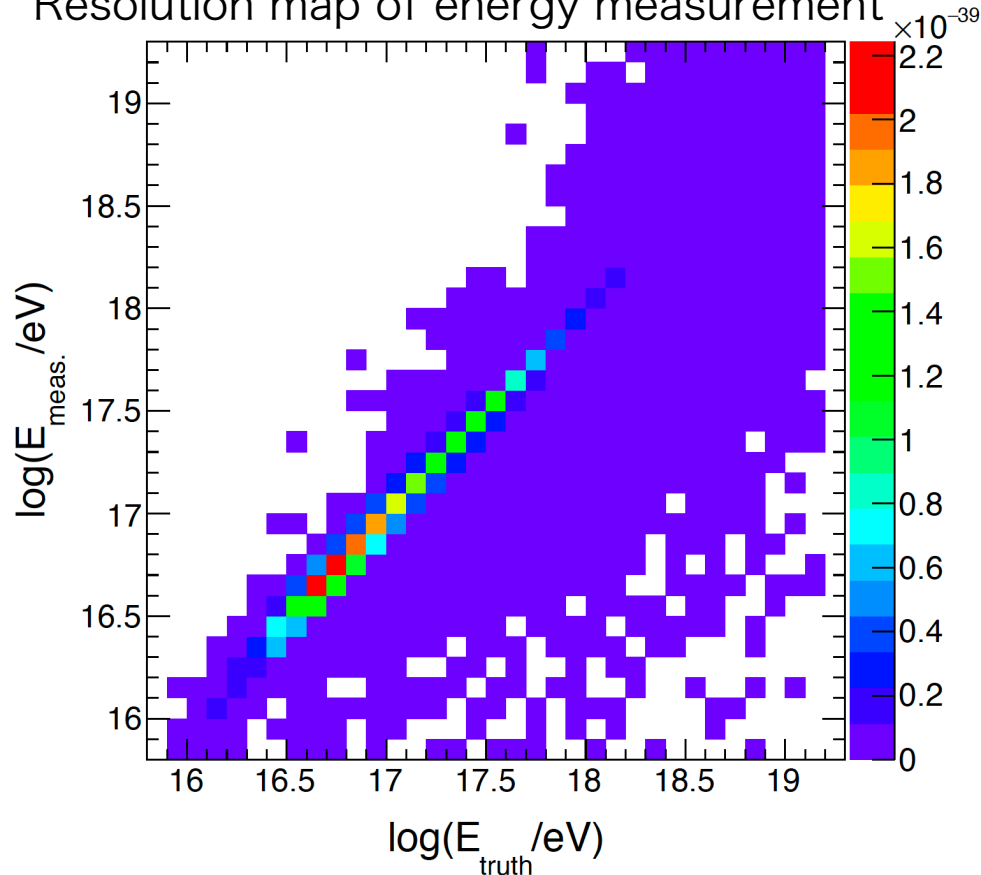
$$\text{Unfolded spectrum} \rightarrow C'_i = \sum_{j=1}^{N_m} U_{ij} E_j^{\text{data}}$$

Smearing matrix
Number of events in measured bin j

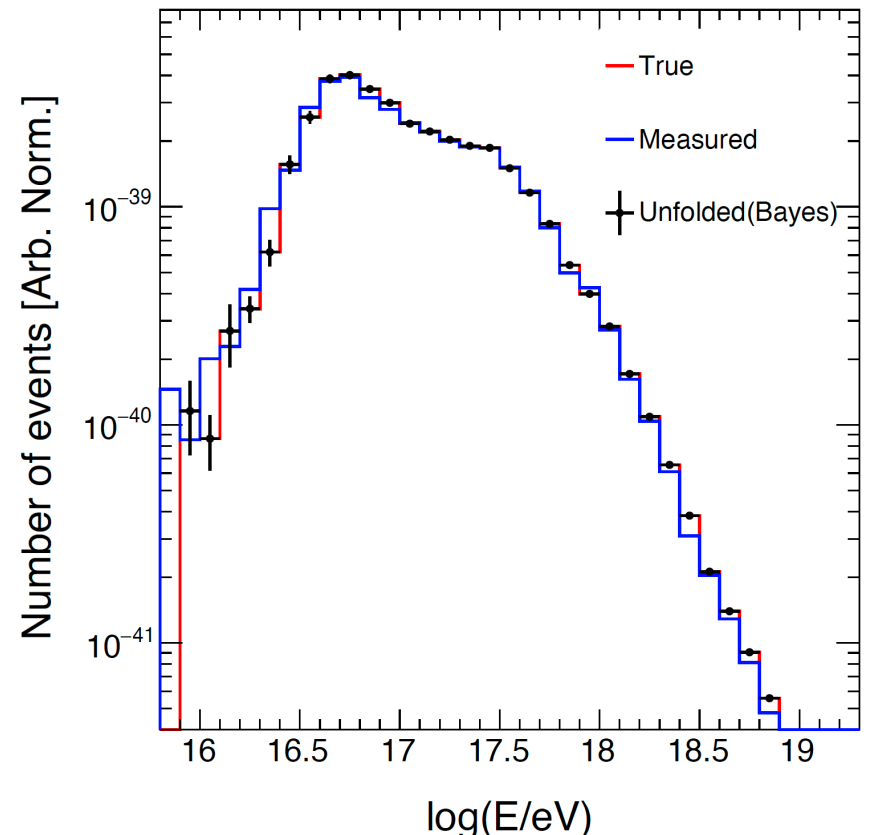
G. D'Agostini, arXiv:1010.0632.

G. D'Agostini, Nucl. Instrum. Methods Phys. Res., Sect A **362**, 487 (1995).

Resolution map of energy measurement



Unfolding of energy spectrum (MC)



Energy Spectrum

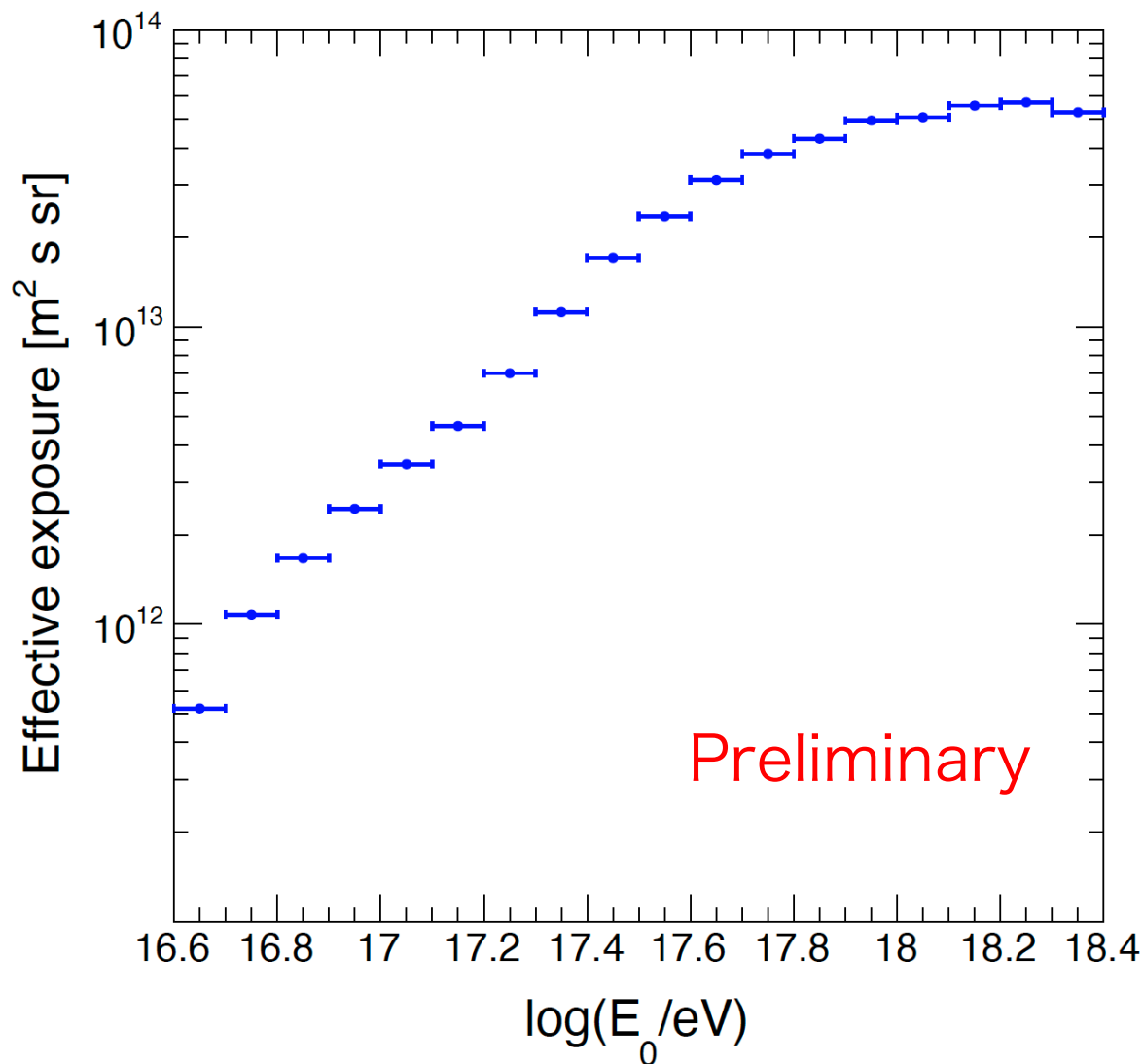
$$J(E_i) = \frac{\sum_{j=1}^{N_m} U_{ij} N_j^{\text{sel}}}{A\Omega(E_i) \cdot T \cdot \Delta E_i}$$

- $J(E_i)$: Differential Flux [$\text{m}^2 \cdot \text{s} \cdot \text{sr}$]
- U_{ij} : Unsmearing matrix
- N_j^{sel} : Selected events
- $A\Omega(E_i)$: Effective aperture [$\text{m}^2 \cdot \text{sr}$]
- T : Observation time [s]
- ΔE_i : Width of i-th bin

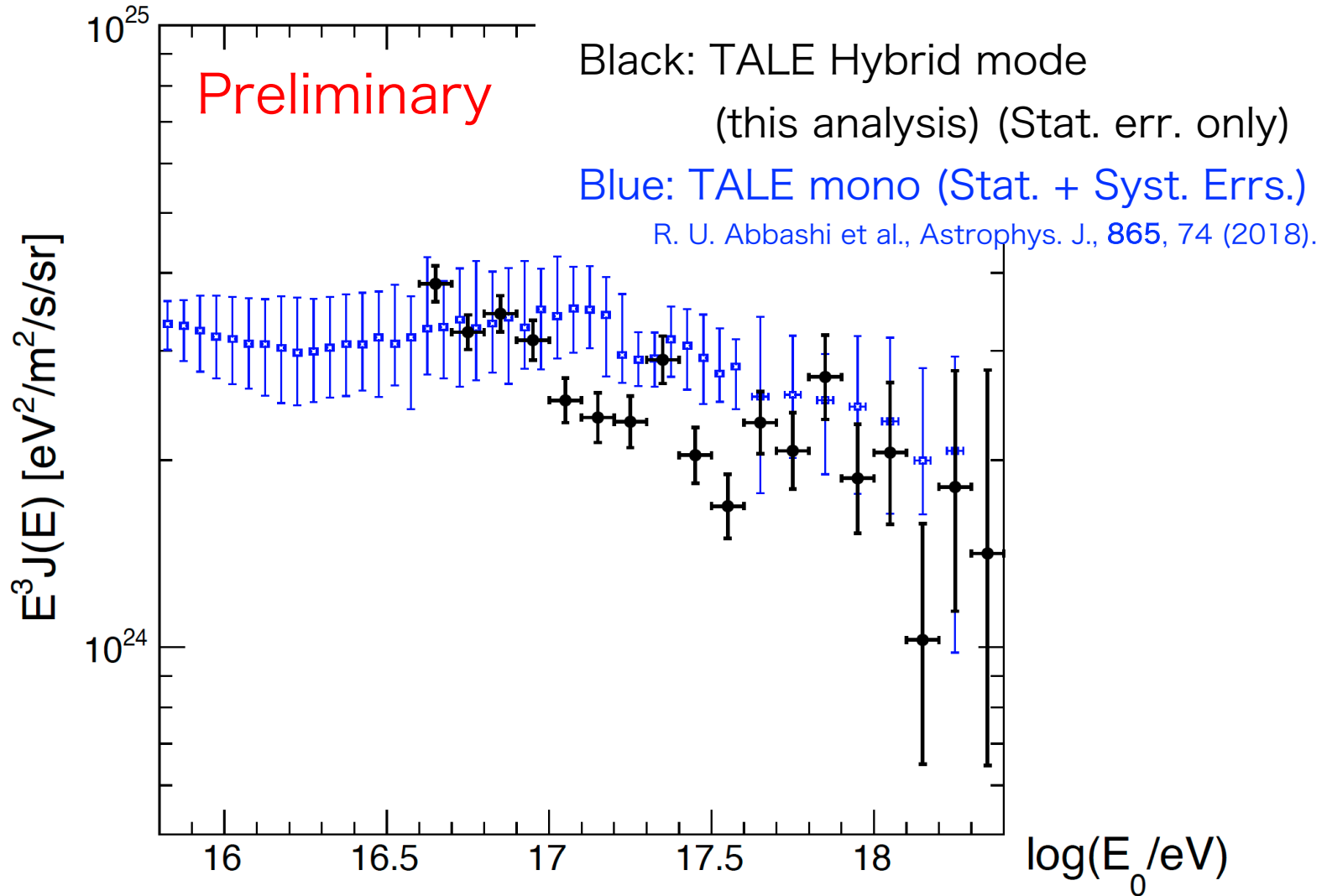
Effective exposure

$A\Omega = 299.8 \text{ km}^2 \cdot \text{sr}$ (Area = 127.2 km^2 , $0^\circ < \theta \text{ zenith} < 60^\circ$)

$T = 1411877 \text{ sec.}$ (Nov. 14, 2018 – Feb. 2, 2020)



Result



Analysis with more statistics is on-going and the expected statistics will increase around 4 times. The MC studies with other hadronic interaction model and compositions are also work in progress.

Summary & Prospects

- We aim to measure the acceleration limit of galactic cosmic rays.
- We check the fundamental information, such as core positions, and measure the energy spectrum with the TALE hybrid mode. Analysis with more statistics is on-going and the expected statistics will increase around 4 times.
- Combining the TA and TAx4 as well as TALE observation data, the energy spectrum will be measured over 5 orders of magnitude from 10^{15} eV to 10^{20} eV.
- We will separate the galactic and extragalactic components using the result of composition measurements to measure the acceleration limit of the galactic cosmic rays.



Thank you for your attention!

Mirror washing at MD station.
Jun 14, 2022.

Backup