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Measurement of the 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 (GCRs)

⬍

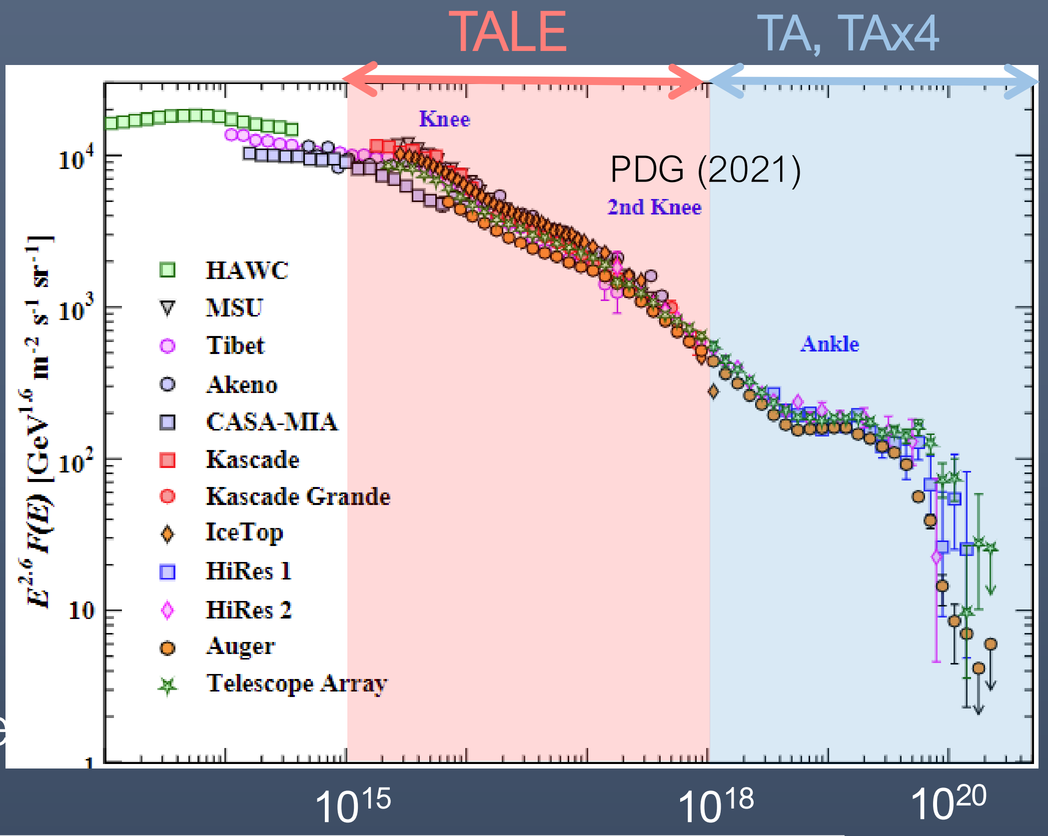
Shielding and confinement of GCRs

⬍

Structure of the GMF and EGMF

⬍

Origins of the extra galactic cosmic rays



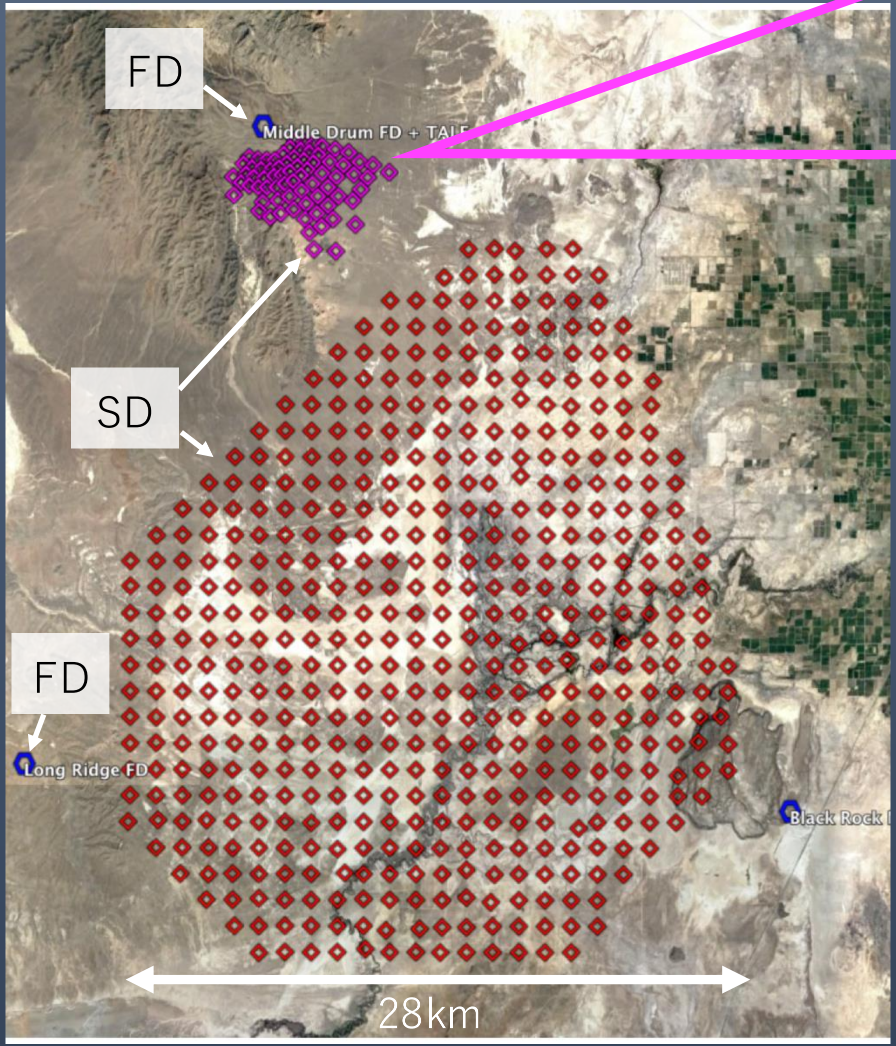
The energy spectrum reflects these physical phenome in complex.

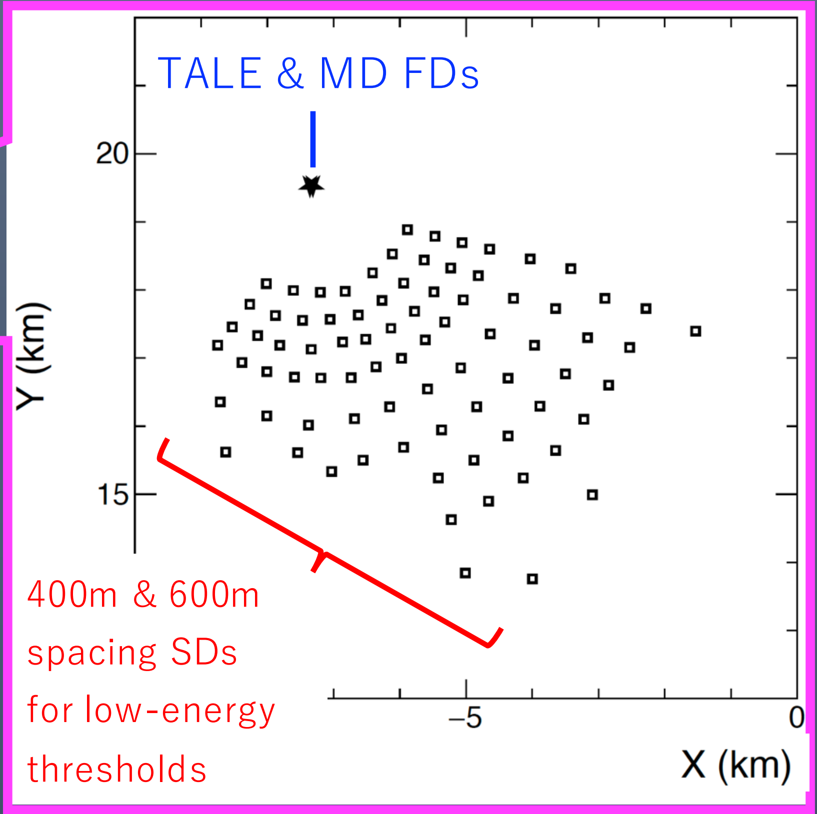
As the first physical goal, through the measurements of
- Composition and energy spectrum, and
- Transition from galactic to extragalactic cosmic rays,

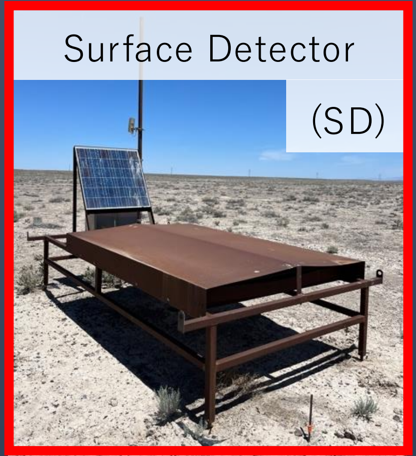
we aim to measure the acceleration limit of galactic cosmic rays.

Physical location of the TALE detector

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







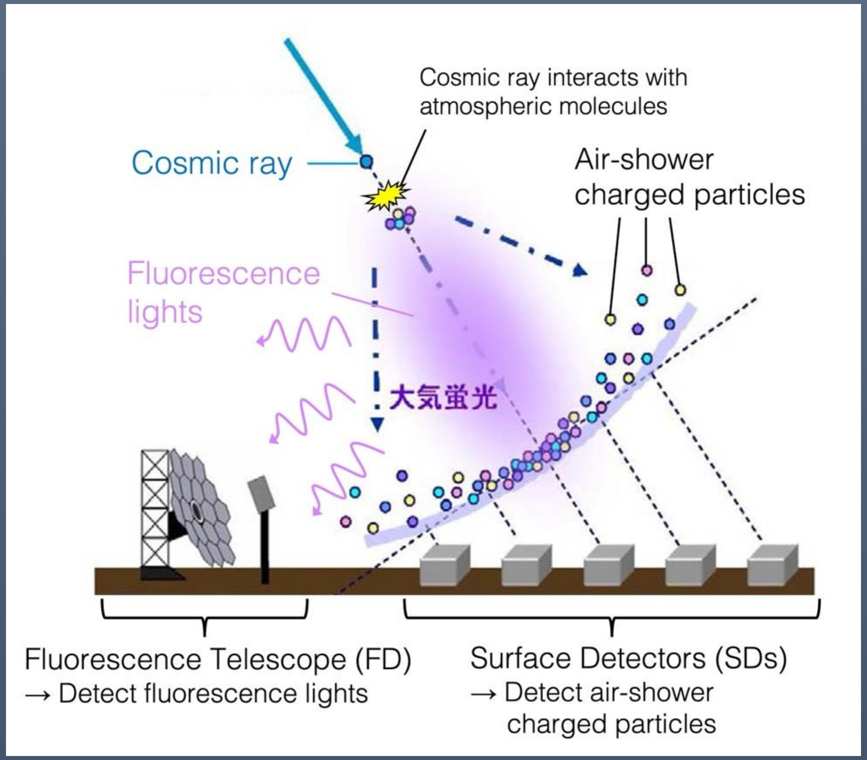
Analysis strategy: Hybrid analysis

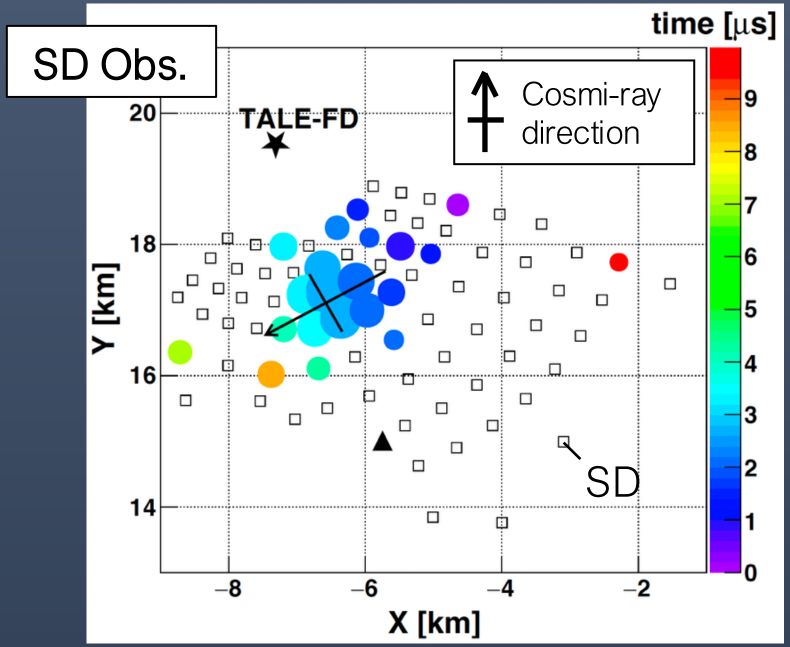
Hybrid analysis using FD and SD array

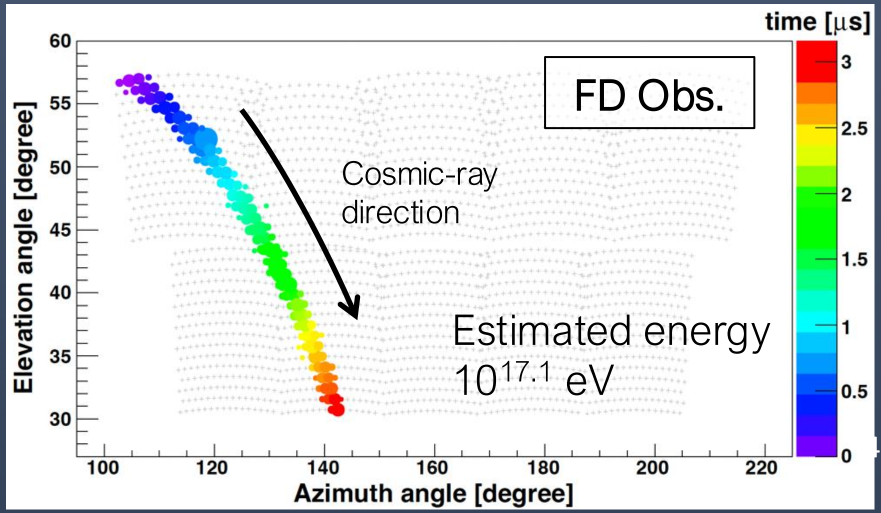
- X_{max} measurement
  → Composition sensitive

- Energy resolution is improved using SD array for shower-axis detection.

Event displays of the SD array and the FD.







Monte Carlo Simulation

Monte Carlo (MC) simulation is performed in the following processes:

(1) Air-Shower simulation (CORSIKA)

- Hadronic interaction model: **QGSJETII-04 P, He, N, Si, and Fe**
- Energy range: **16.3 ≦ log E ≦ 18.5**
- Zenith angle: **0° ≦ $\boldsymbol{\theta}$ ≦ 65°**

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

(2) SD simulation

- The energy deposit in each SD with Geant4 detector simulation
- 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

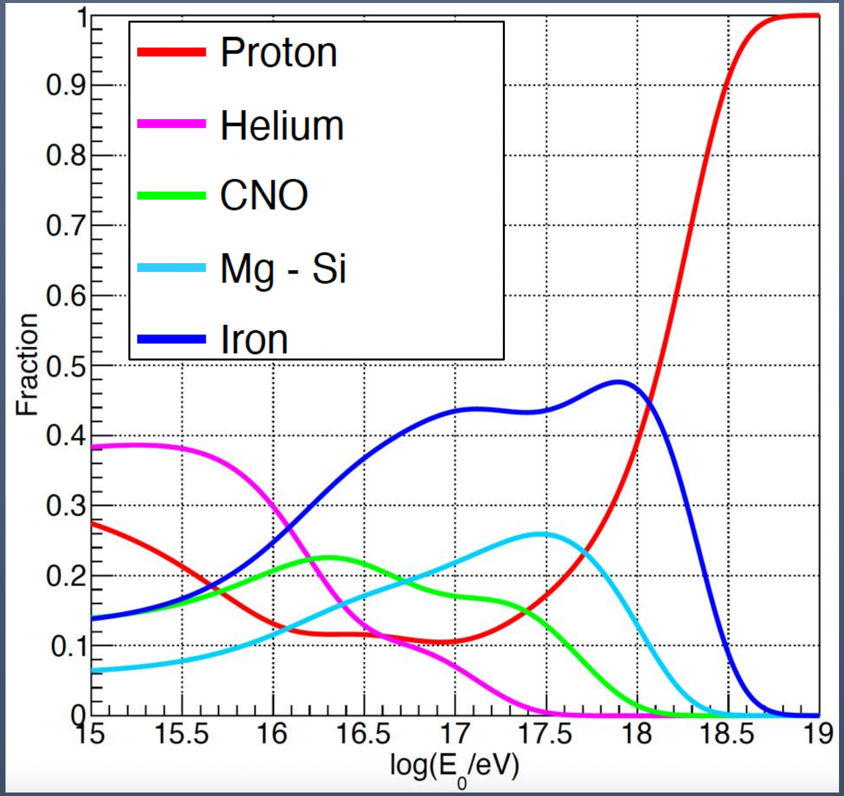
Hybrid trigger events: FD + any1 SD w/ 1 MIP

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	Sel.1 + X_{max} is inside the geometrical field of view of the FDs + 210 g/cm^2 < X_{max} + χ^2_{long}/ndf < 3	
Selection 2	-	Sel.2 + # of photo-electrons > 2000
Selection 3	Sel.3 + Event duration > 100 ns	-
Selection 4	Sel.4 + # of PMTs > 10	-
Selection 5	Sel.5 + # of photo-electrons/# of PMTs > 50	-
Selection 6	Sel.6 + Angular track length > 6.5 deg	-
Selection 7	Sel.7 + 16.5 < log(E_{rec} / eV) < 18.3 + θ_{zenith} < 60° + Good Weather	

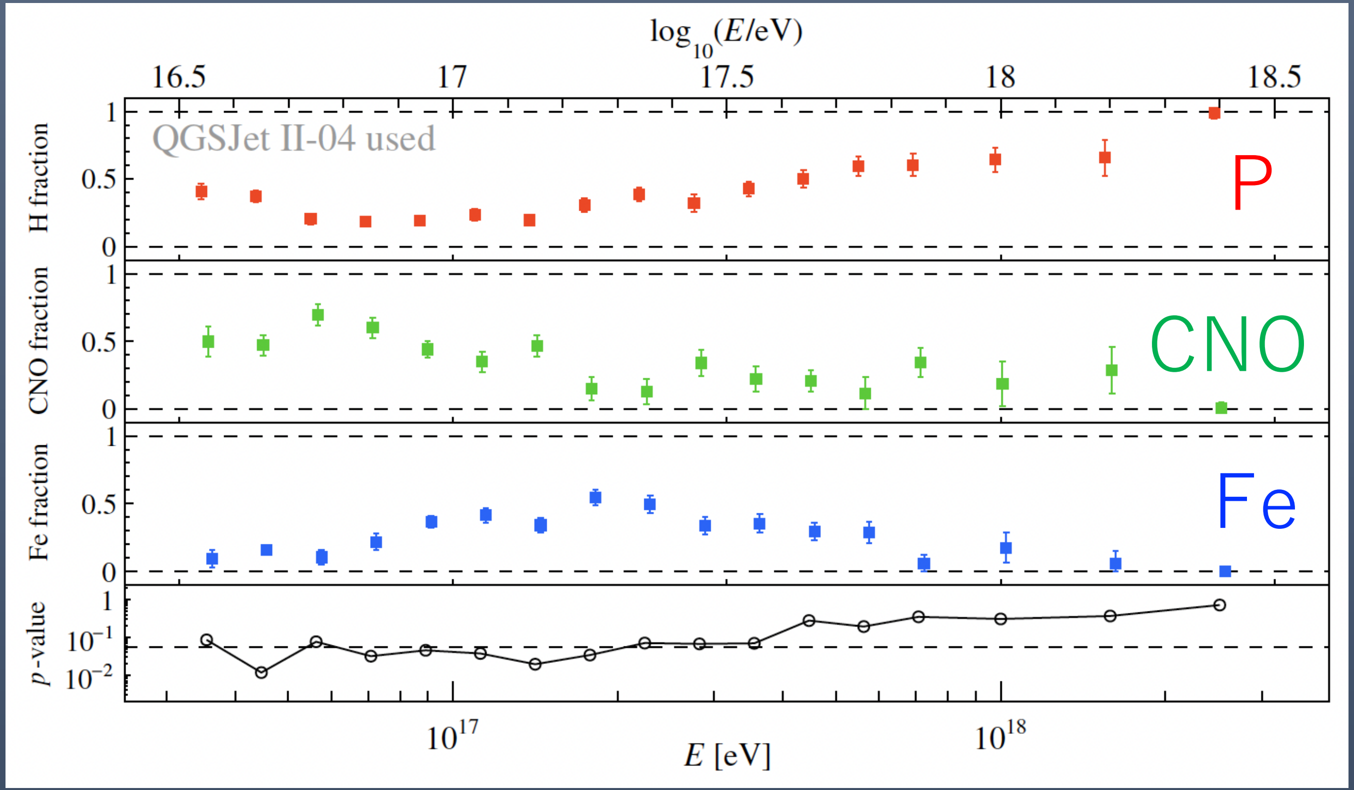
Composition models used for this analysis

H4a model



T. K. Gaisser, Astropart. Phys. **35**, 801 (2012).

TALE Hybrid X_{max} Fitting (THXF)



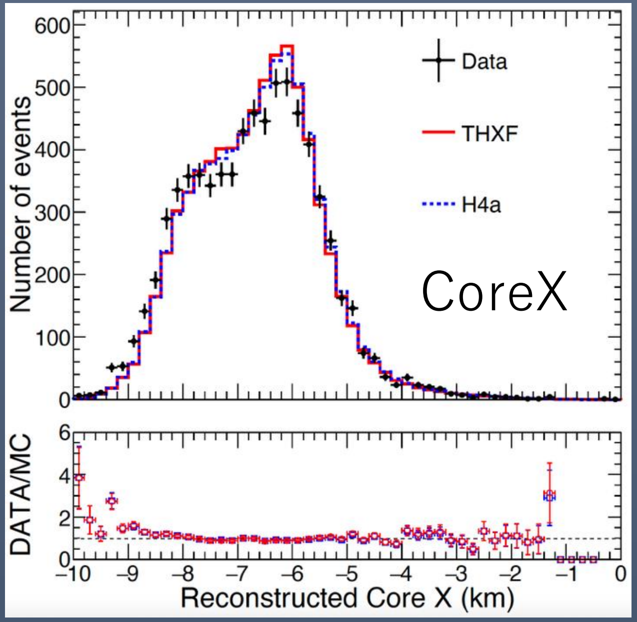
R. U. Abbasi et al., Phys. Rev. D 113, 062003 (2026).

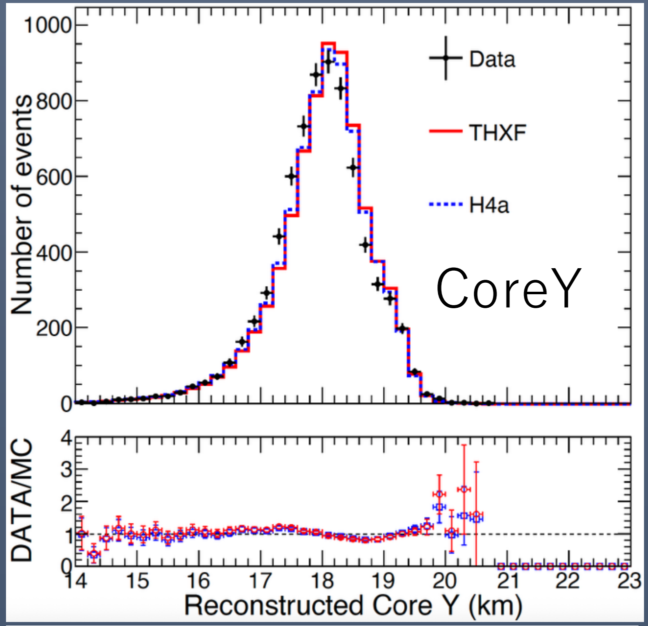
H4a model and TALE Hybrid X_{max} Fit (THXF) result were used as the theoretical and the data-driven models, respectively.

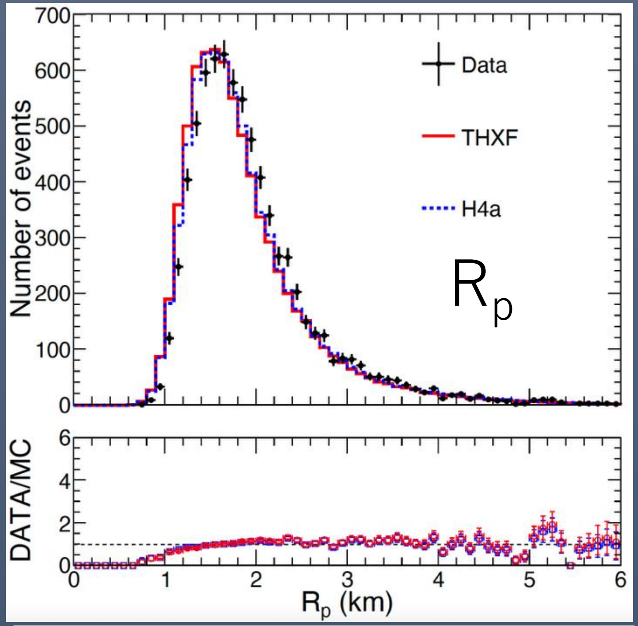
Comparison between the data & MC prediction

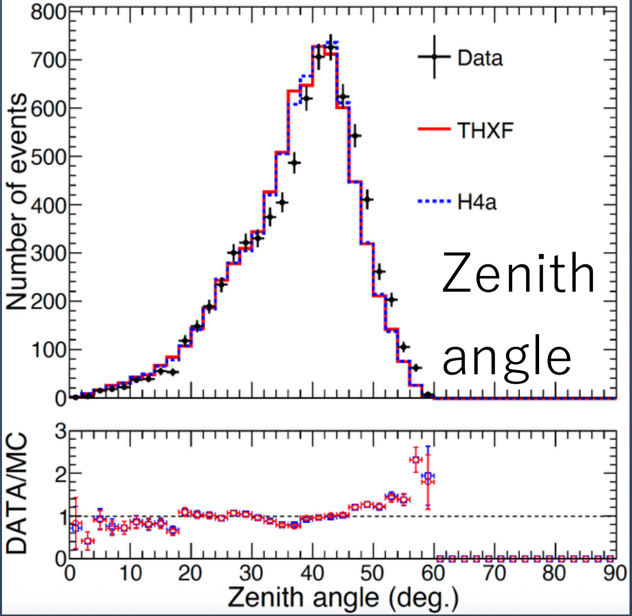
Preliminary

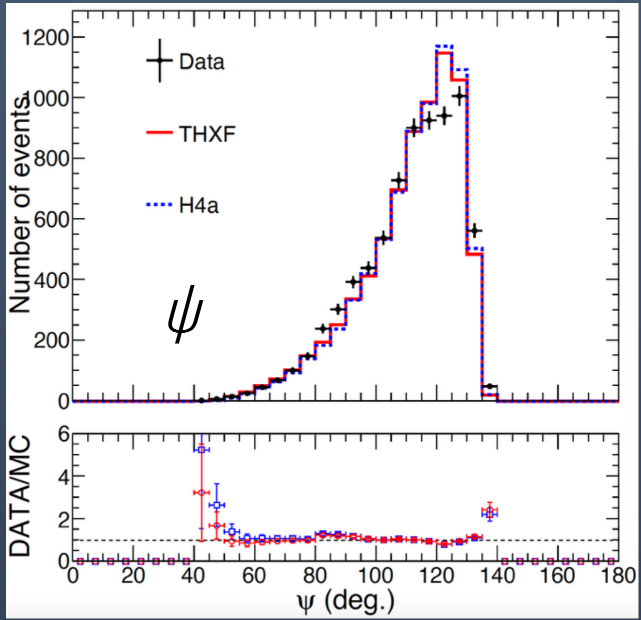
Points: Data, Histograms: MC (Area normalized)

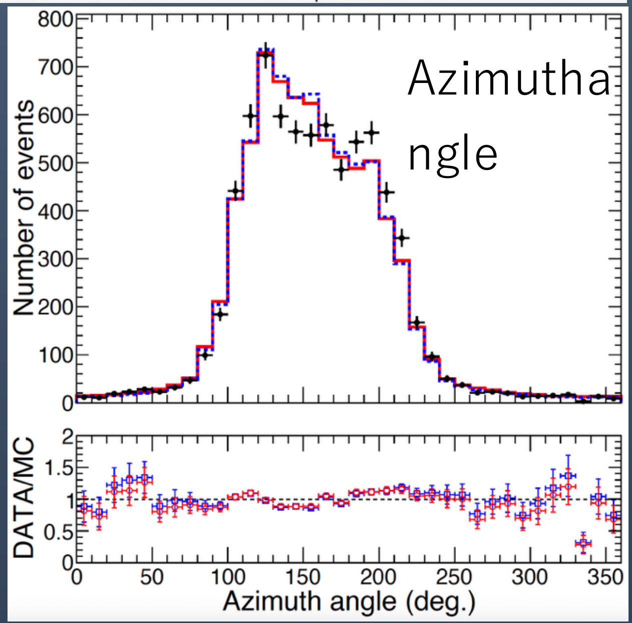






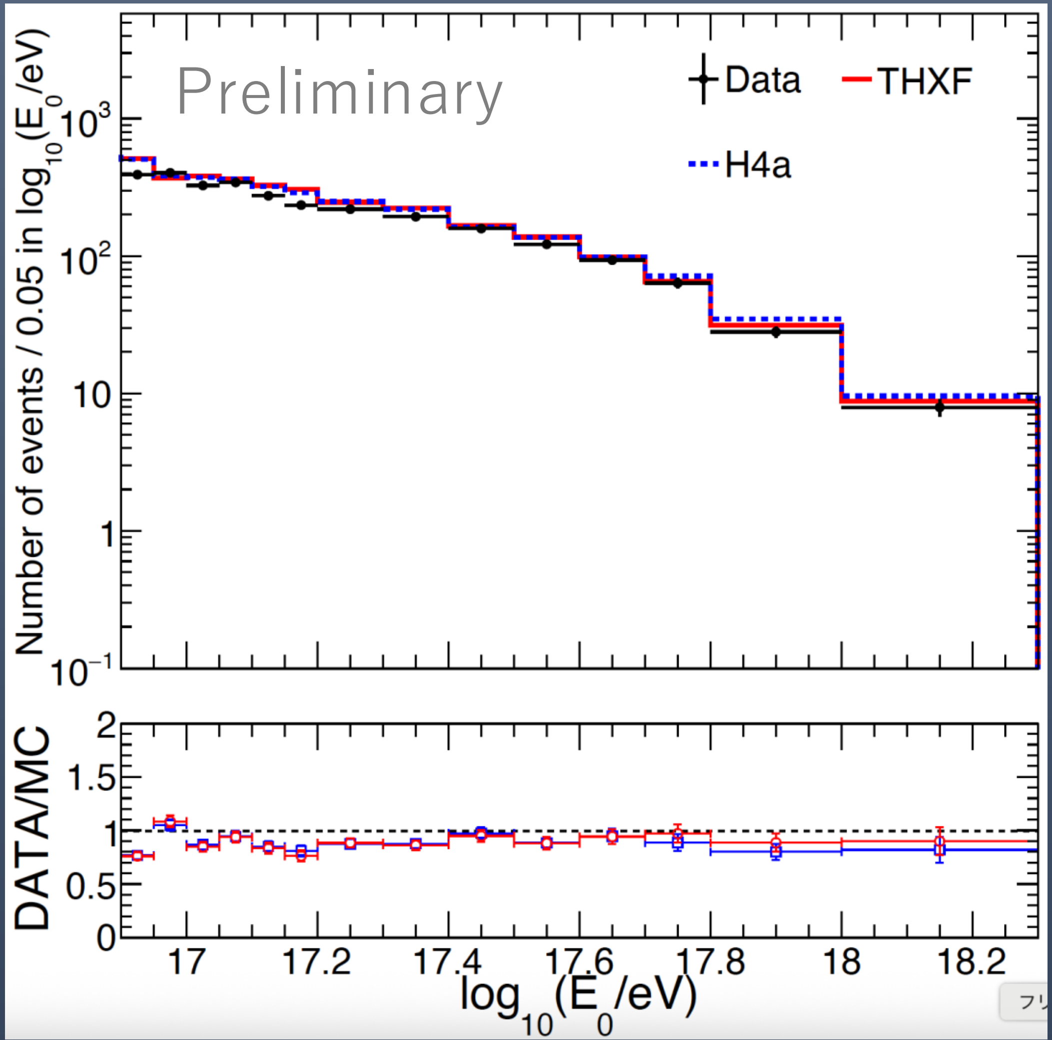






Energy measurements

Points: Data, Histogram: MC (Area normalized)

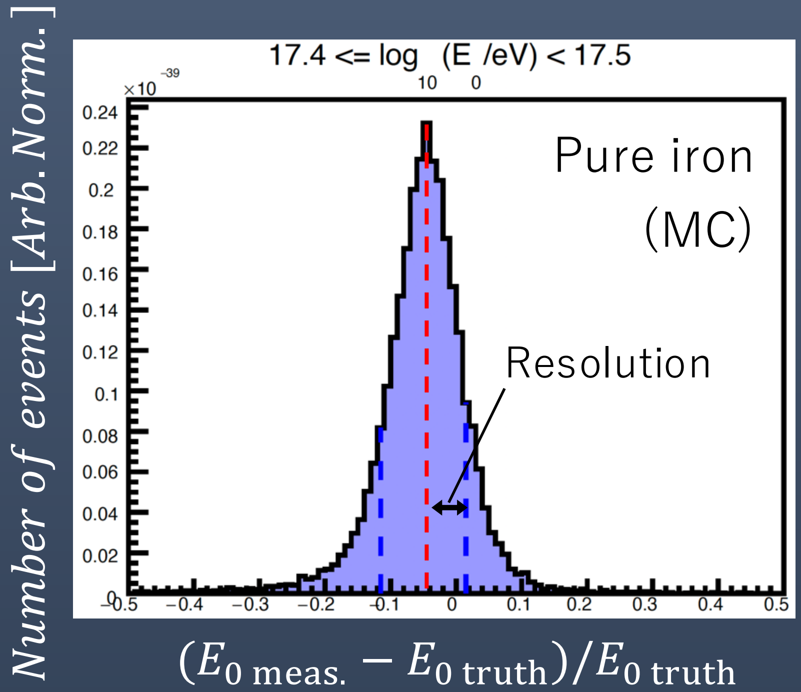


Energy Resolution (MC)

$17.4 < \log_{10}(E_0/\mathrm{eV}) < 17.5$

Pure proton : $+7.2\% / -8.8\%$

Pure iron : $+6.6\% / -6.4\%$



Iterative D'Agostini unfolding

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

Smearing matrix

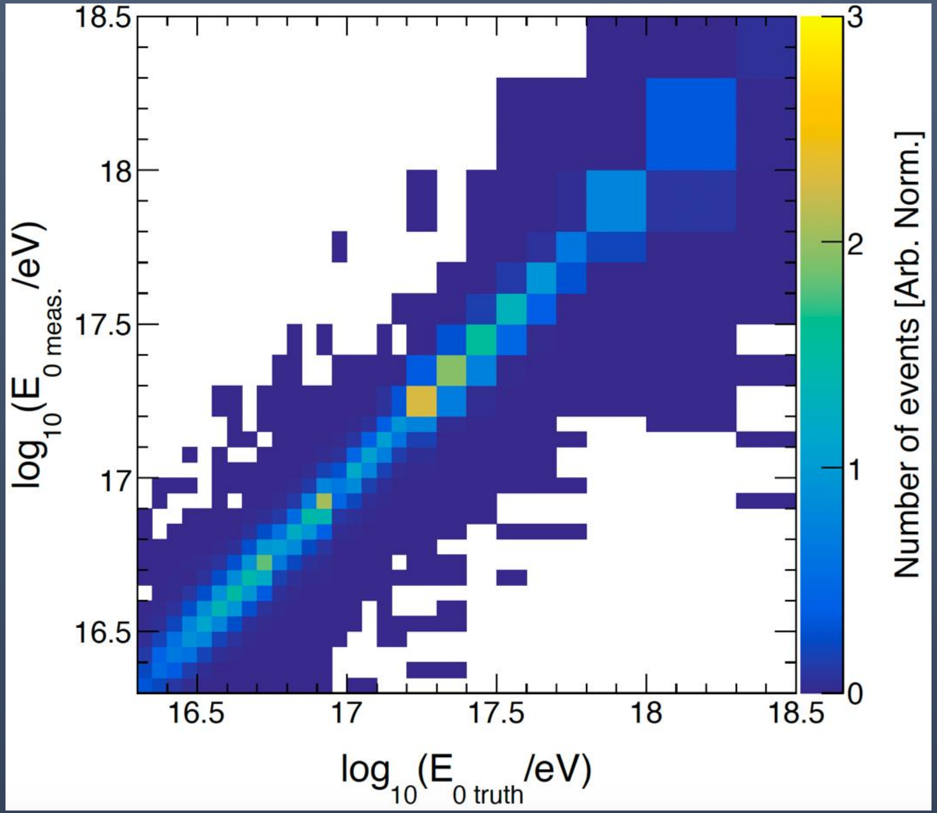
Unfolded spectrum → $C_i' = \sum_{j=1}^{N_m} U_{ij} N_j^{\mathbf{data}}$

Number of events in measured bin j

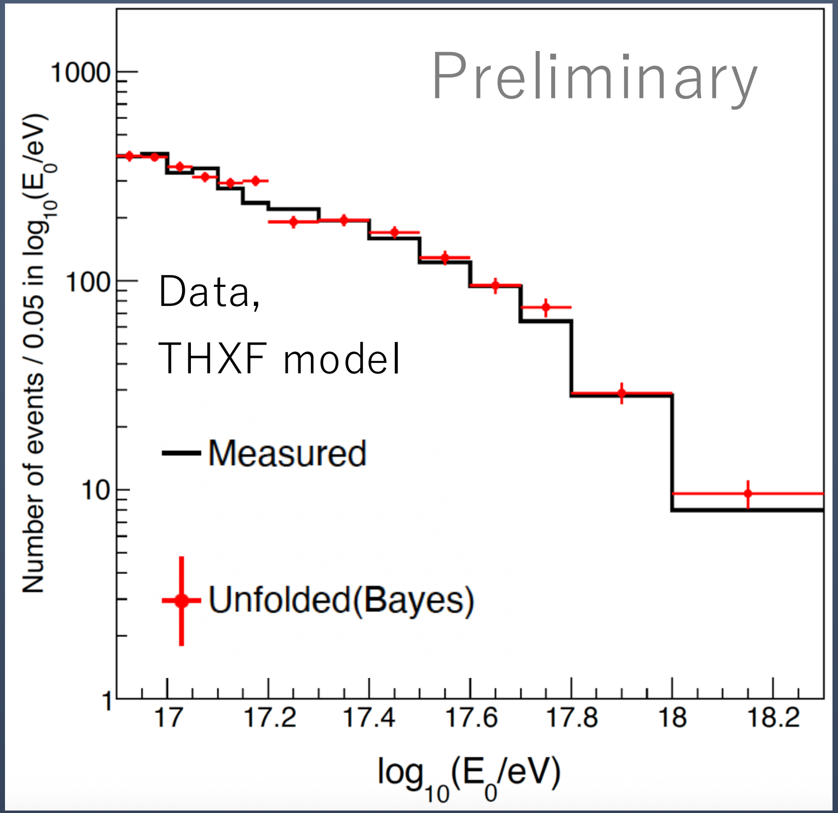
G. D'Agostini, arXiv:1010.0632.

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

Resolution map of energy measurement



Energy distribution

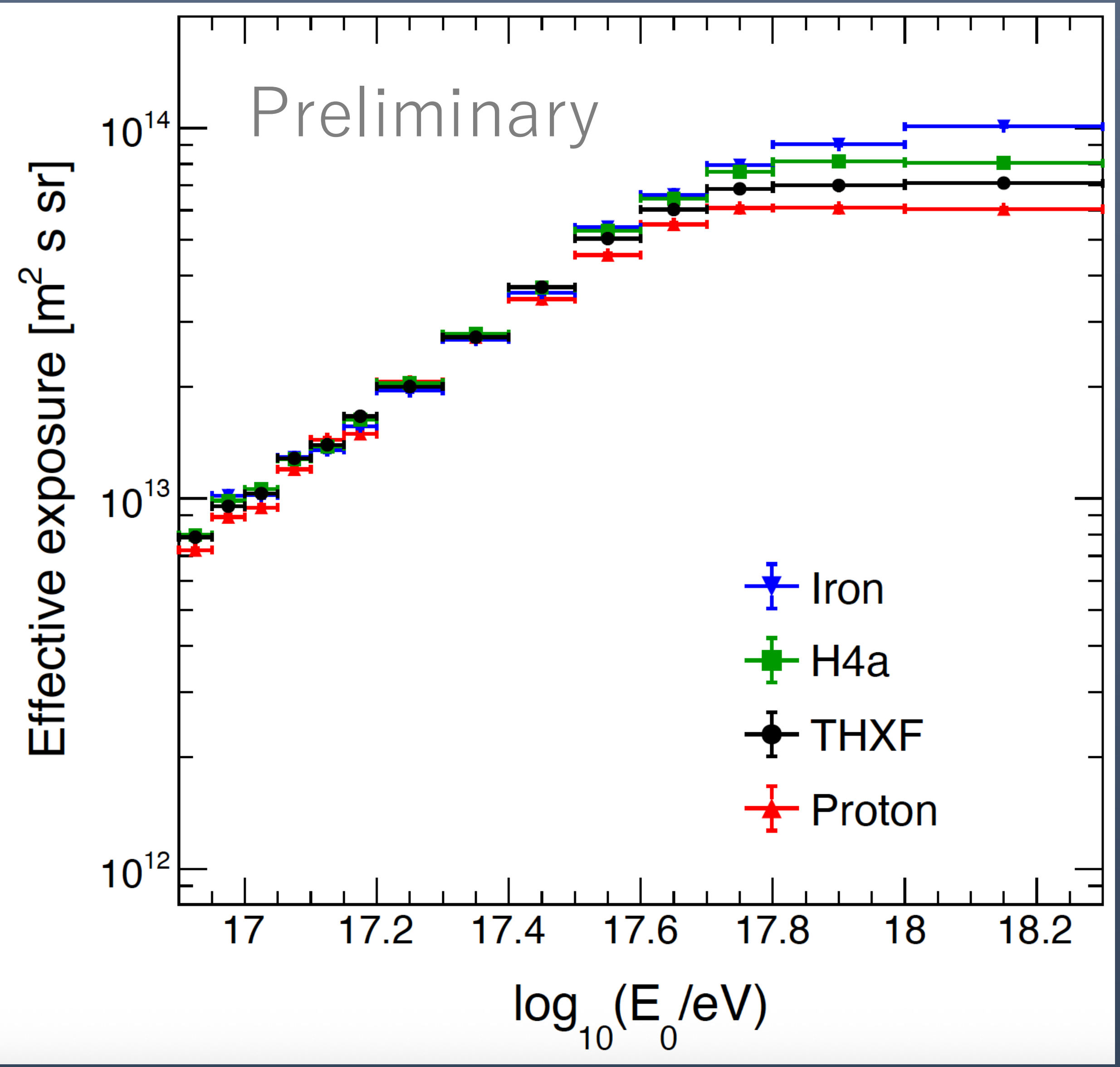


Equation of energy spectrum

$$J(E_i) = \frac{\overbrace{\sum_{j=1}^{N_m} U_{ij}\, N_j^{\mathrm{sel}}}^{\text{Number of events with unfolding}}}{\underbrace{A\Omega(E_i)}_{\text{Effective exposure for the true energy spectrum}} \cdot T \cdot \Delta E_i}$$

$J(E_i)$	:	Differential Flux $[\mathrm{m}^2 \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1} \cdot \mathrm{eV}^{-1}]$
$\mathrm{U_{ij}}$	:	Unsmearing matrix
$\mathrm{N_j^{sel}}$	:	Number of selected events
$A\Omega\ (E_i)$	:	Effective aperture $[\mathrm{m}^2 \cdot \mathrm{sr}]$
T	:	Observation time [s]
$\Delta\mathrm{E_i}$	:	Width of i-th bin

Effective Exposure



Effective exposure is evaluated using the MC simulation.

Geometrical aperture :

299.8 km^2・sr

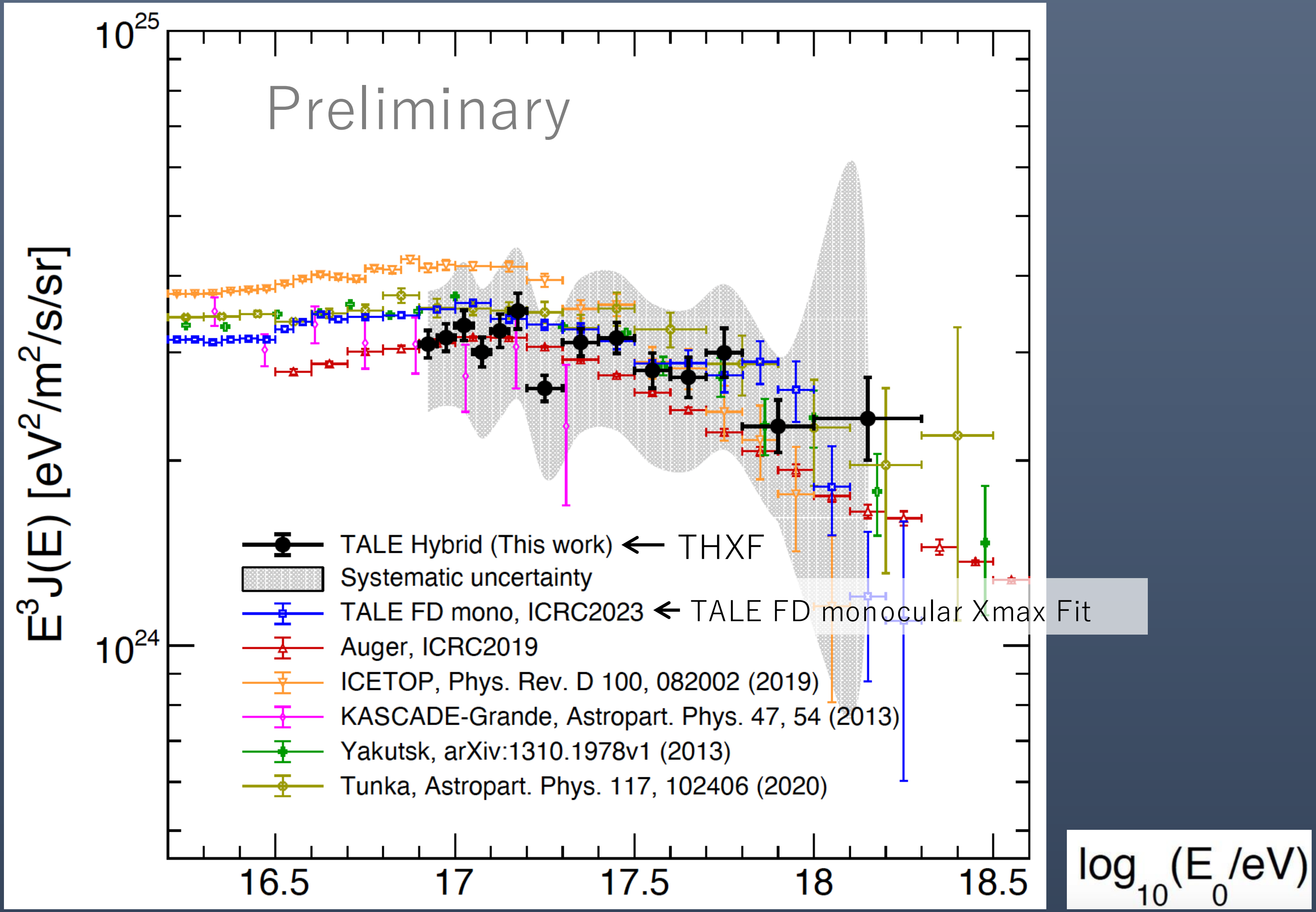
- Zenith angle : $\theta_{zenith} < 60°$

Observation time :

1,247 hours

(Nov. 14, 2018 – May 22, 2023)

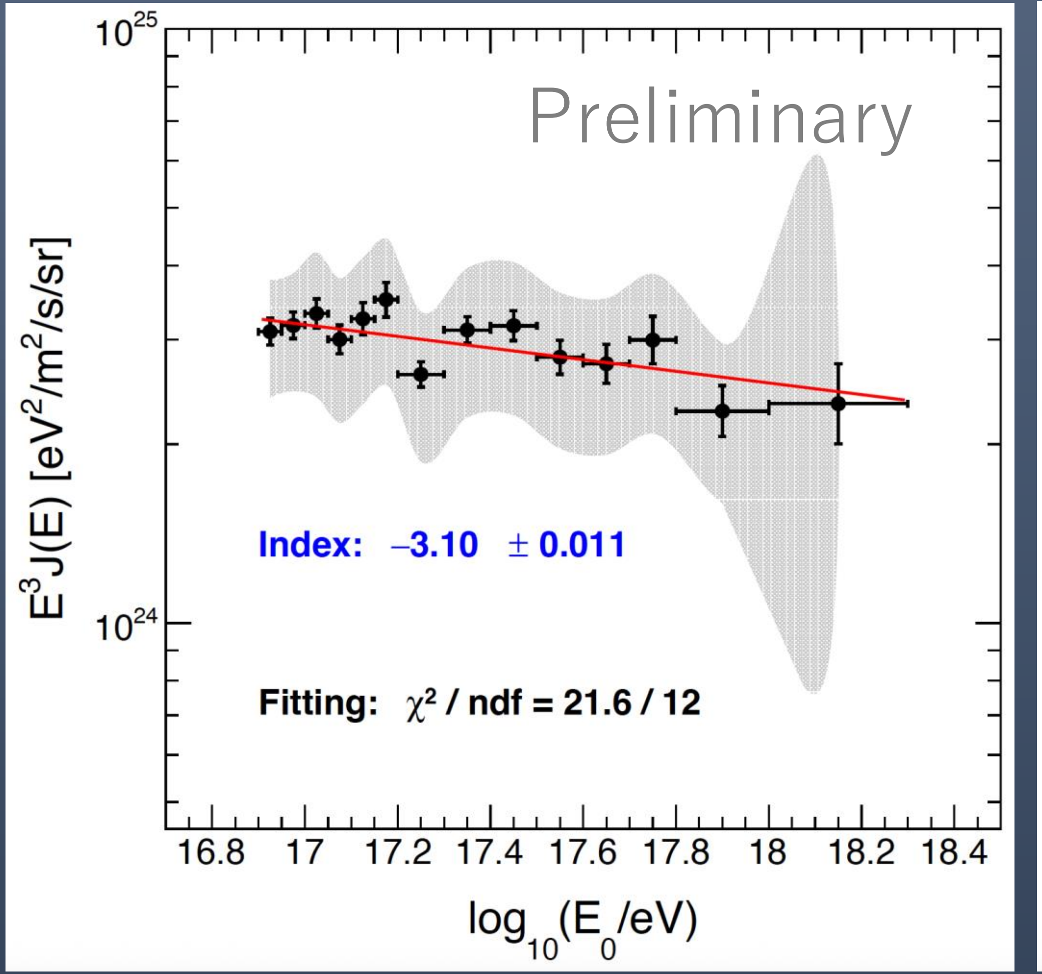
Result: Energy Spectrum



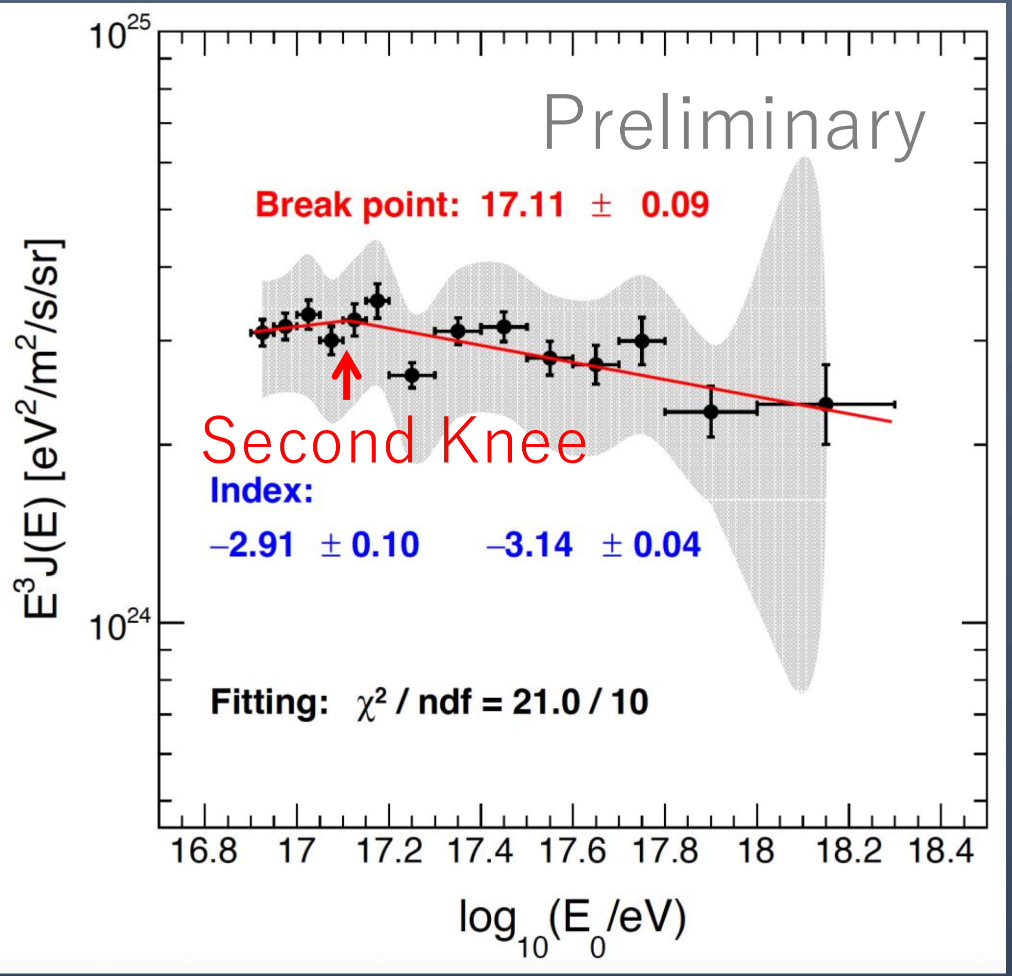
Result: Power-Law fitting

Data: TALE Hybrid Observation with THXF model

Single Power-Law fitting



Broken Power-Law fitting



Summary

- Aim of the TALE hybrid analysis:

  Using spectrum and composition measurements in 10^{16} eV – 10^{18} eV

  ➡ Measure the acceleration limit of galactic cosmic rays

  ➡ Separate galactic and extragalactic components

- Using the 1,247 hours observation data of the TALE hybrid detector
  - Data/MC comparison of the shower geometrical parameters
  - Measurement of the energy distribution

  ➡ The data are generally reproduced by the MC simulation

- We measured the energy spectrum with TALE Hybrid observation

  ➡ We show the preliminary result of energy spectrum measurement

  ➡ Second Knee position, $\log(E_{\mathrm{break}}/\mathrm{eV}) = 17.11 \pm 0.09$