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

(GCRs)

↕

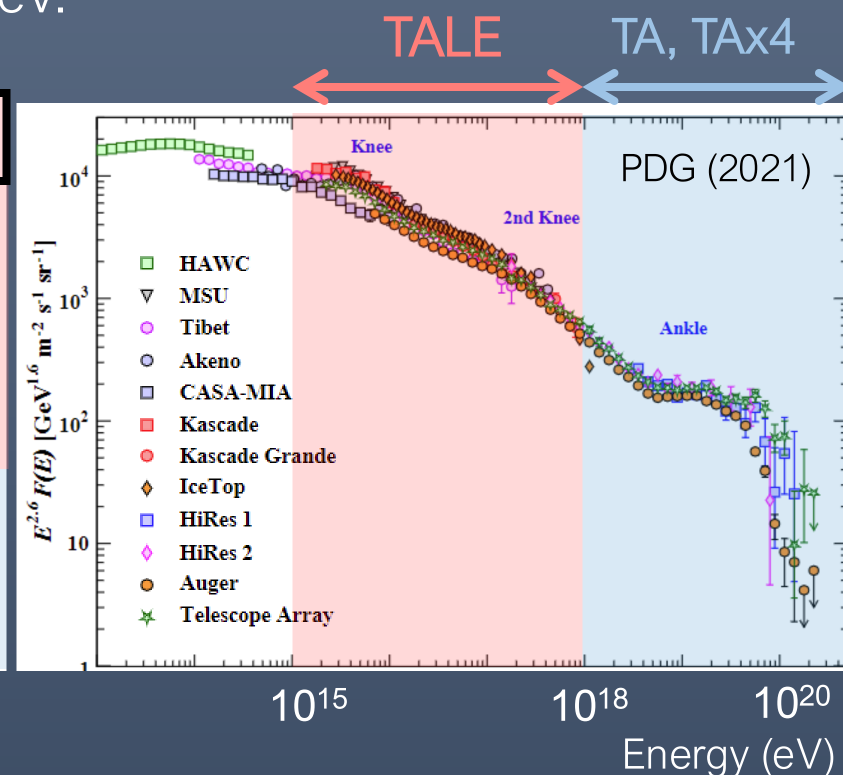
Shielding and confinement of GCRs

↕

Structure of the GMF and EGMF

↕

Origins of the extra galactic cosmic rays



The energy spectrum reflects these physical phenomena in complex.

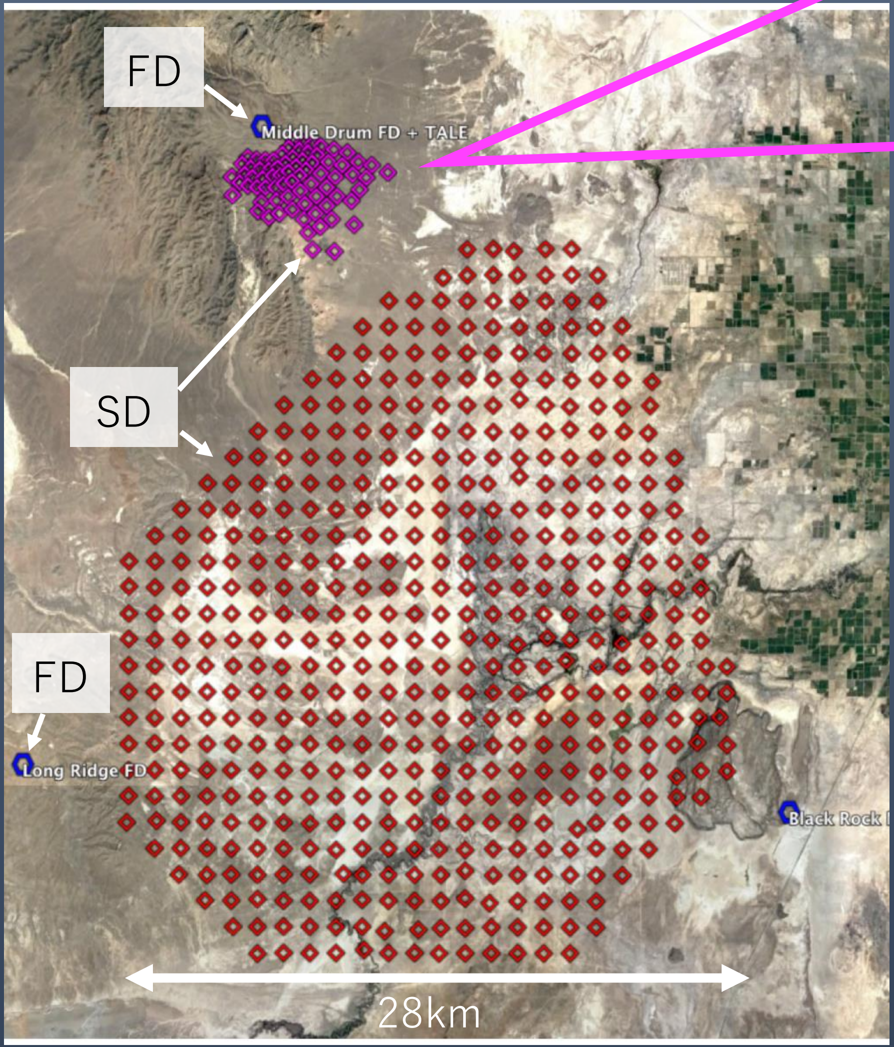
As the first physical goal, through the measurements of

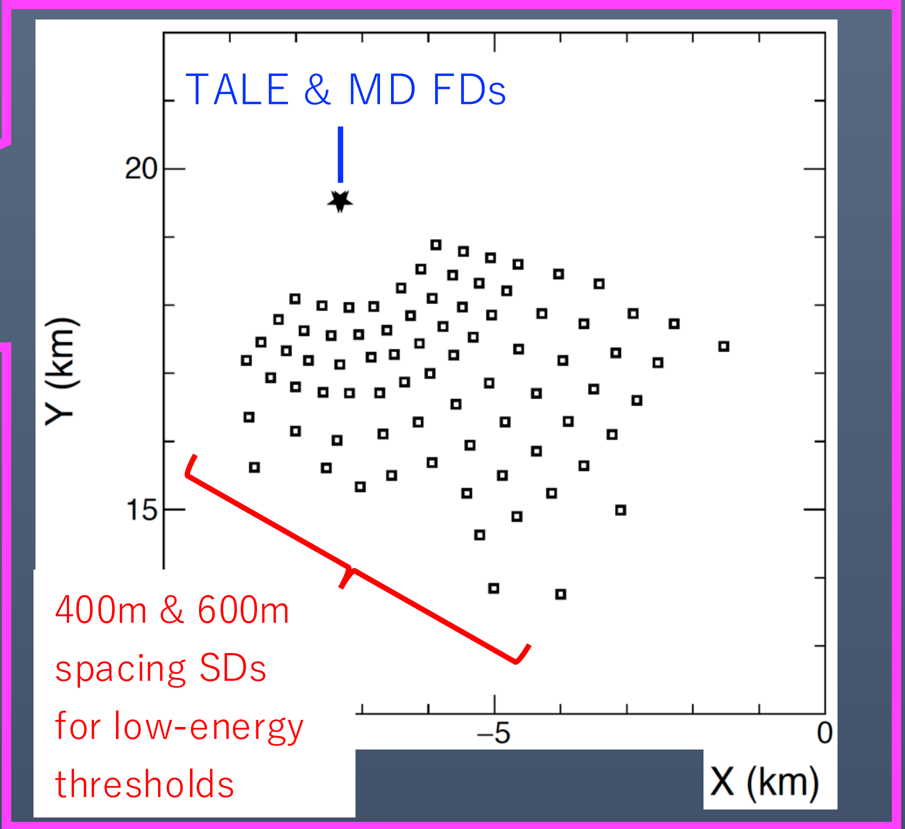
- Composition and energy spectrum, and
- Transition from galactic to extragalactic cosmic rays,

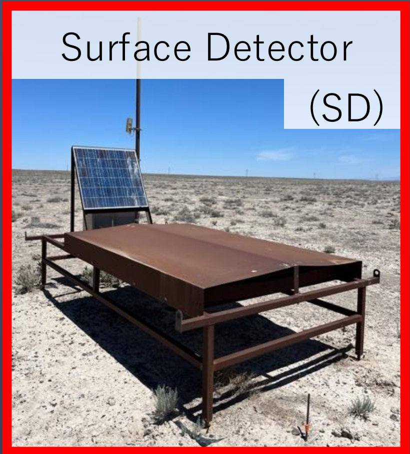
we aim to measure the acceleration limit of galactic cosmic rays.

Physical location of the TALE detector

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





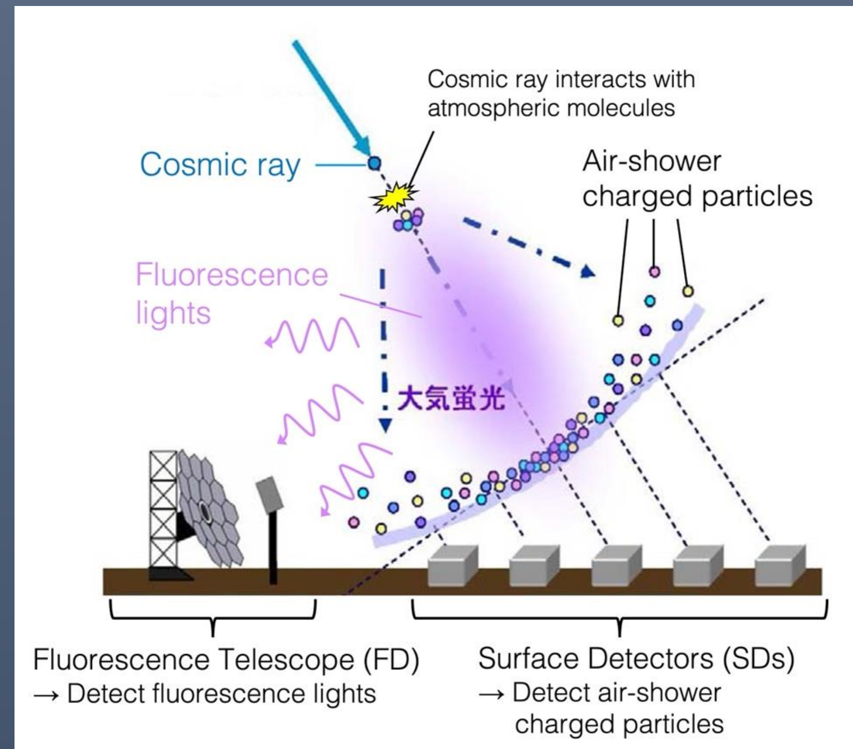


Analysis strategy: Hybrid analysis

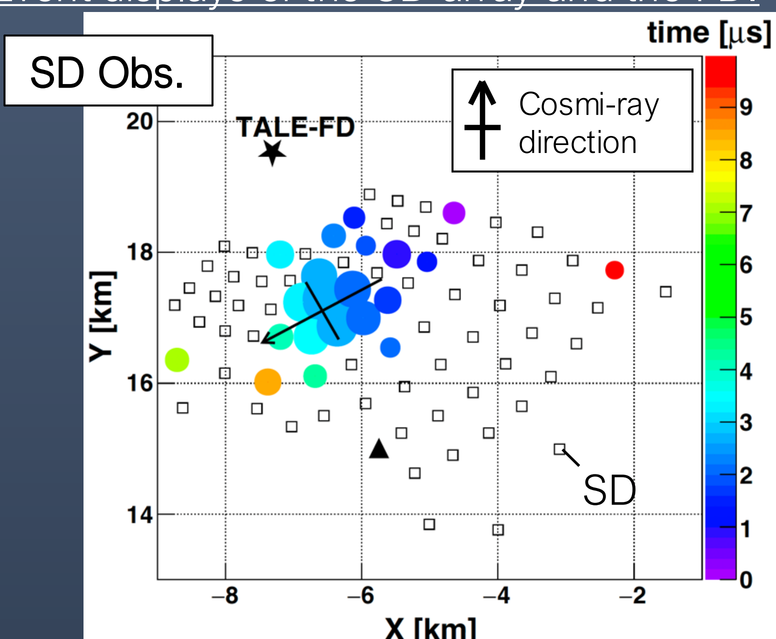
Hybrid analysis using FD and SD array

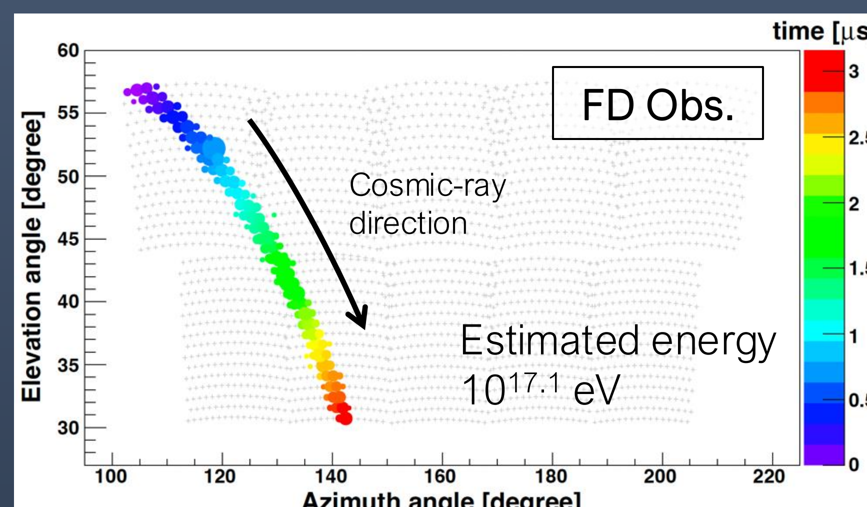
- X_{max} measurement
  → Composition sensitive

- 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: **16.2 ≦ log E ≦ 18.5**
- Zenith angle: **0° ≦ θ ≦ 70°**

"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

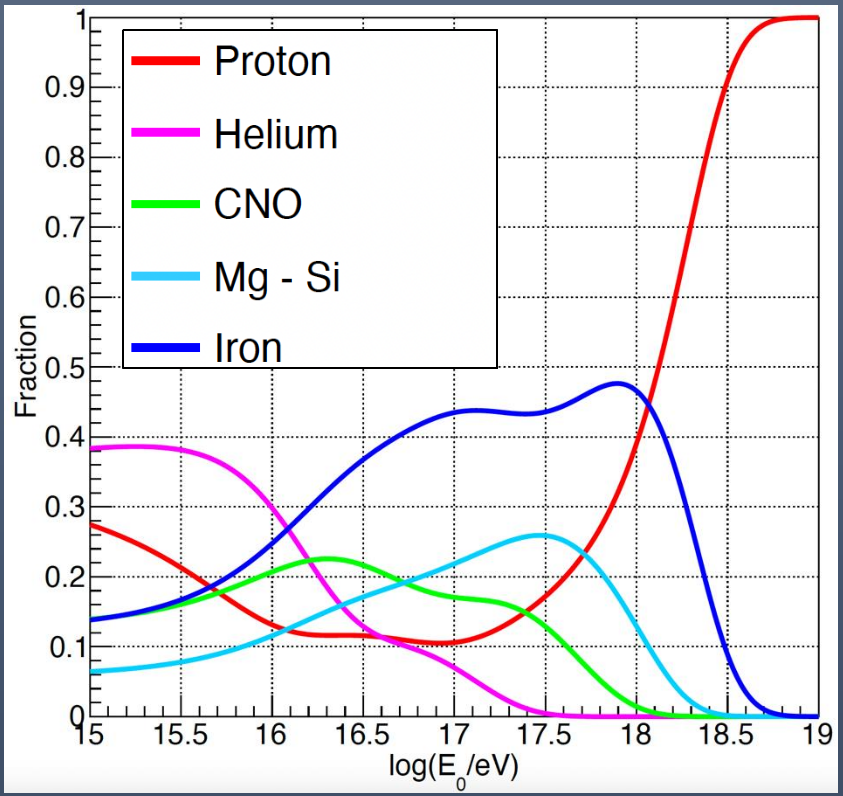
Hybrid trigger events: FD + any1 SD w/ 1 MIP

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	No saturated PMTs in TALE-FD	
Selection 2	Sel.1 + X_{max} is inside the geometrical field of view of the FDs + 210 g/cm^2 < X_{max} + χ^2_{long} /ndf < 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 + 16.5 < log(Erec / eV) < 18.3 + θ_{zenith} < 60° + Good Weather	

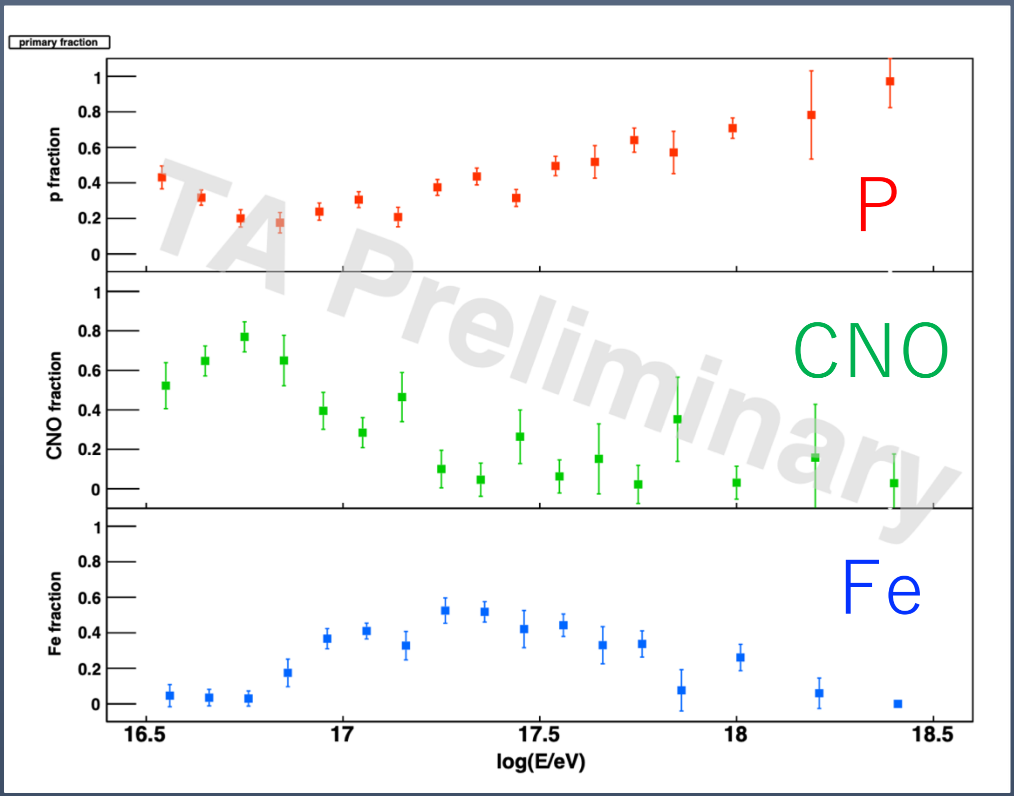
Composition models used for this analysis

H4a model



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

TALE Hybrid X_{max} Fitting (THXF)



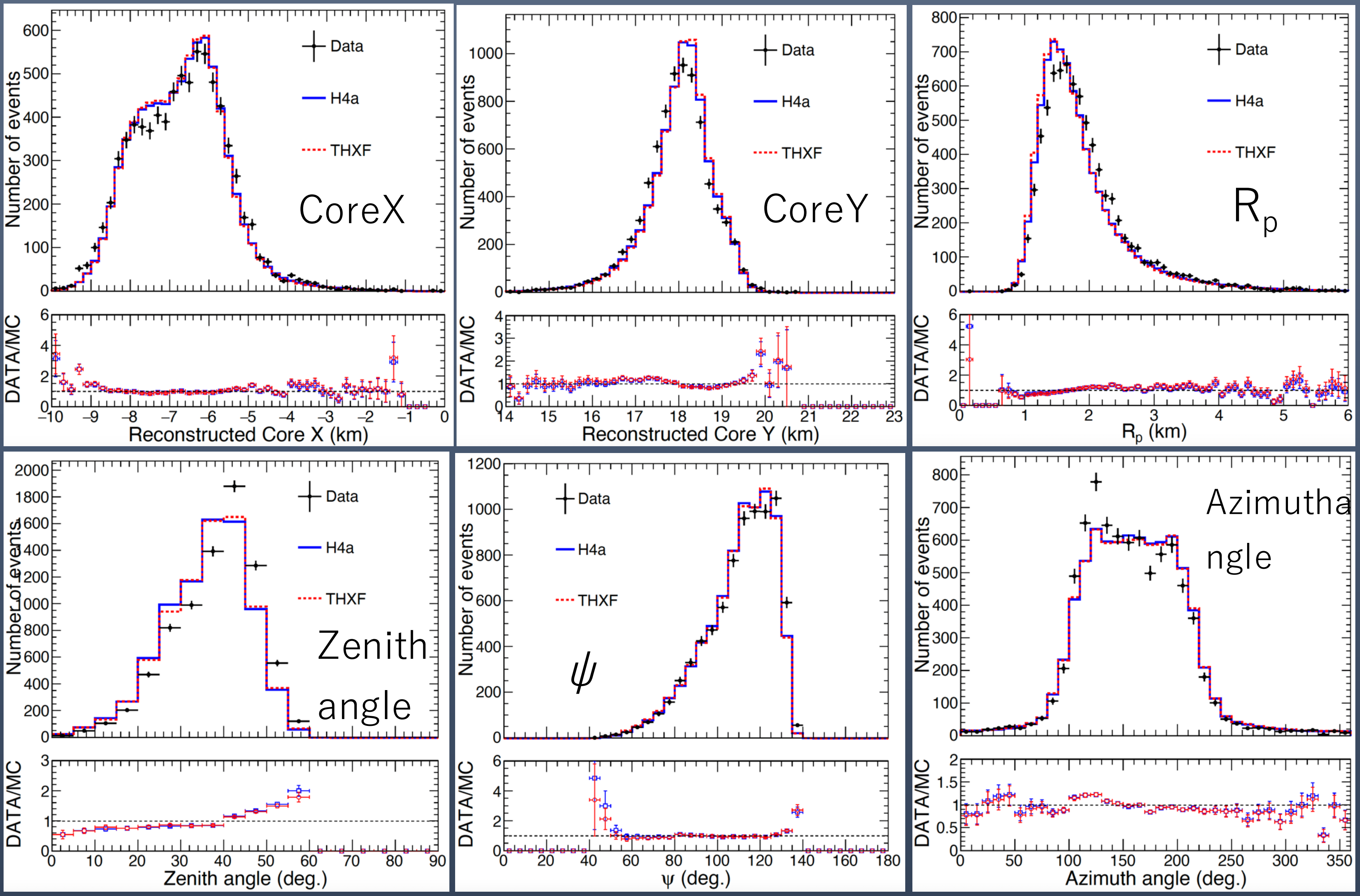
K. Fujita, PoS(ICRC2023)401

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

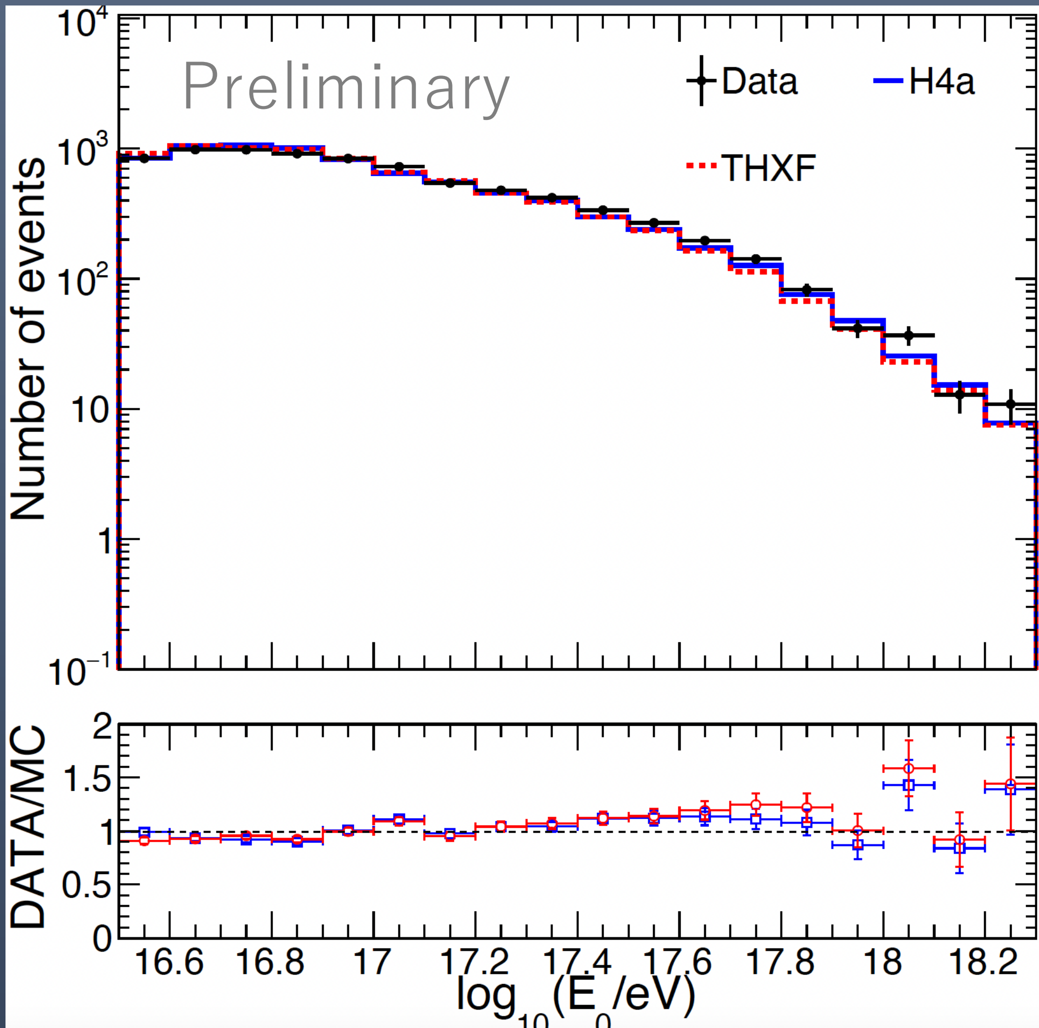
Preliminary

Points: Data, Histograms: MC (Area normalized)



Energy measurements

Points: Data, Histogram: MC (Area normalized)

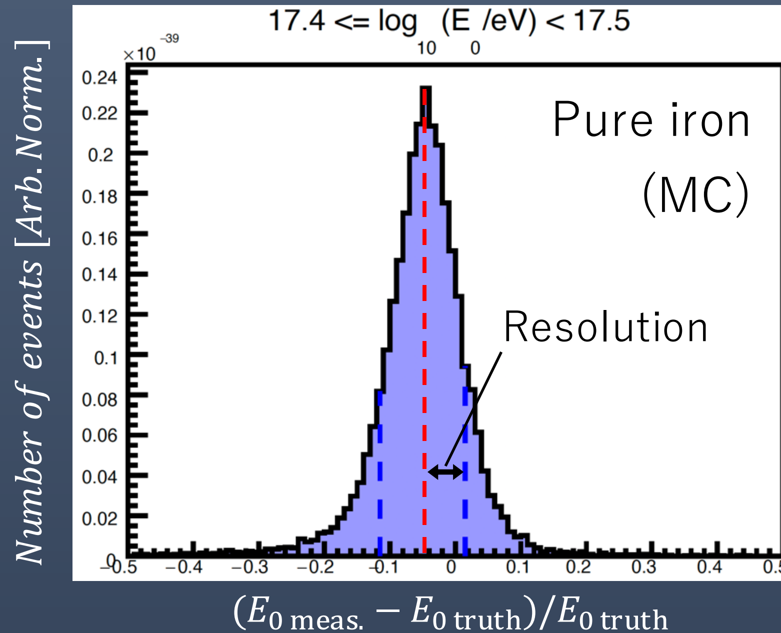


Energy Resolution (MC)

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

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.

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

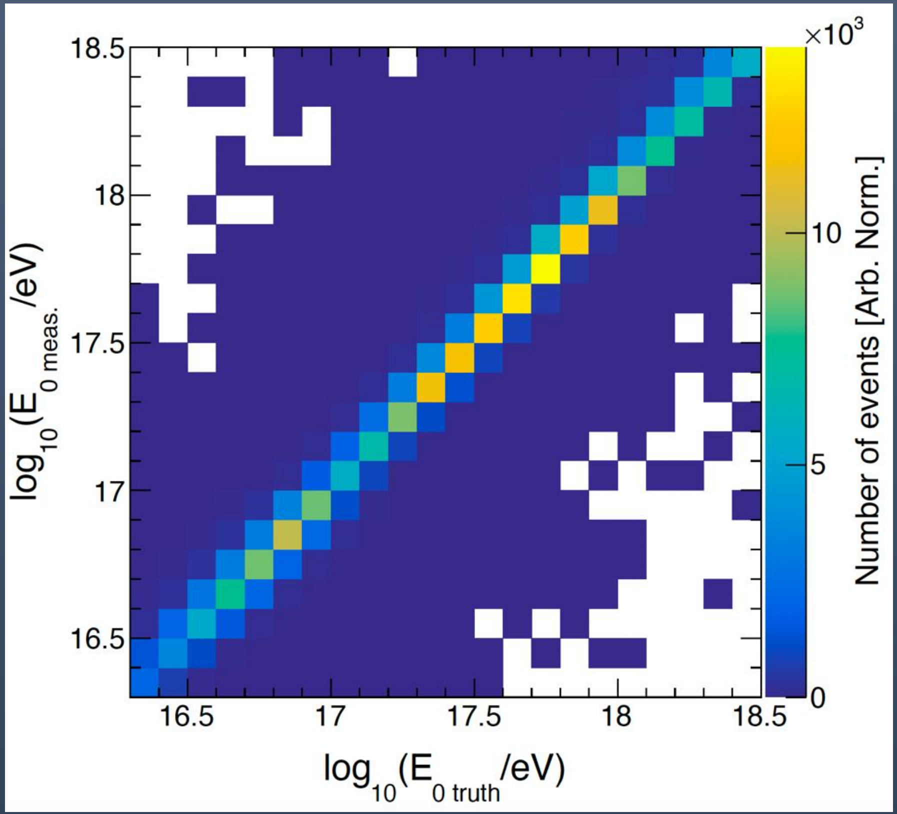
Smearing matrix: U_{ij}

Number of events in measured bin j: N_j^{data}

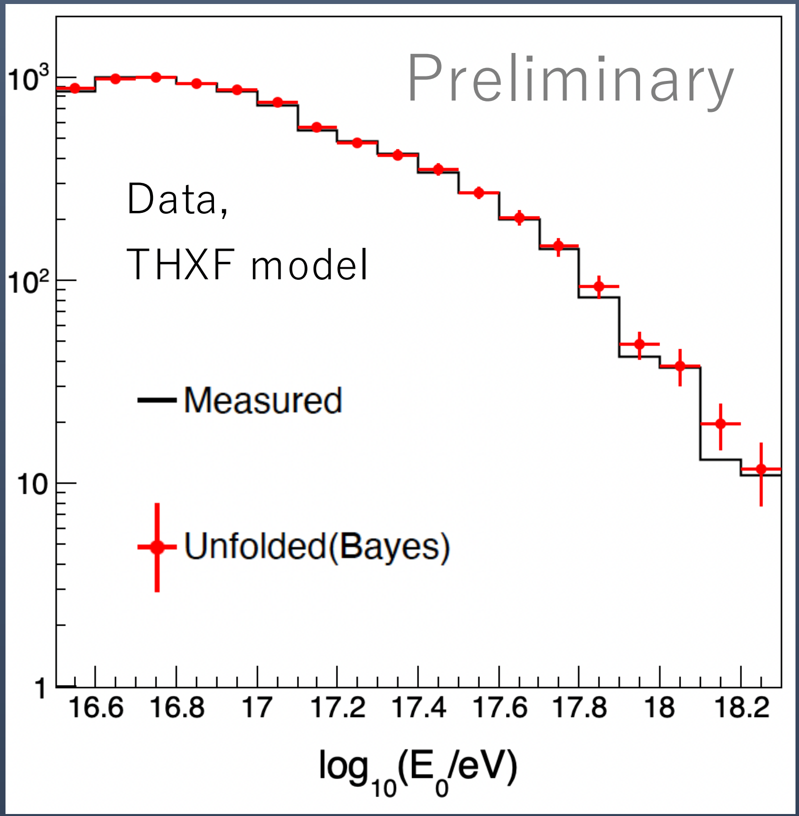
G. D'Agostini, arXiv:1010.0632.

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

Resolution map of energy measurement



Energy distribution



Equation of energy spectrum

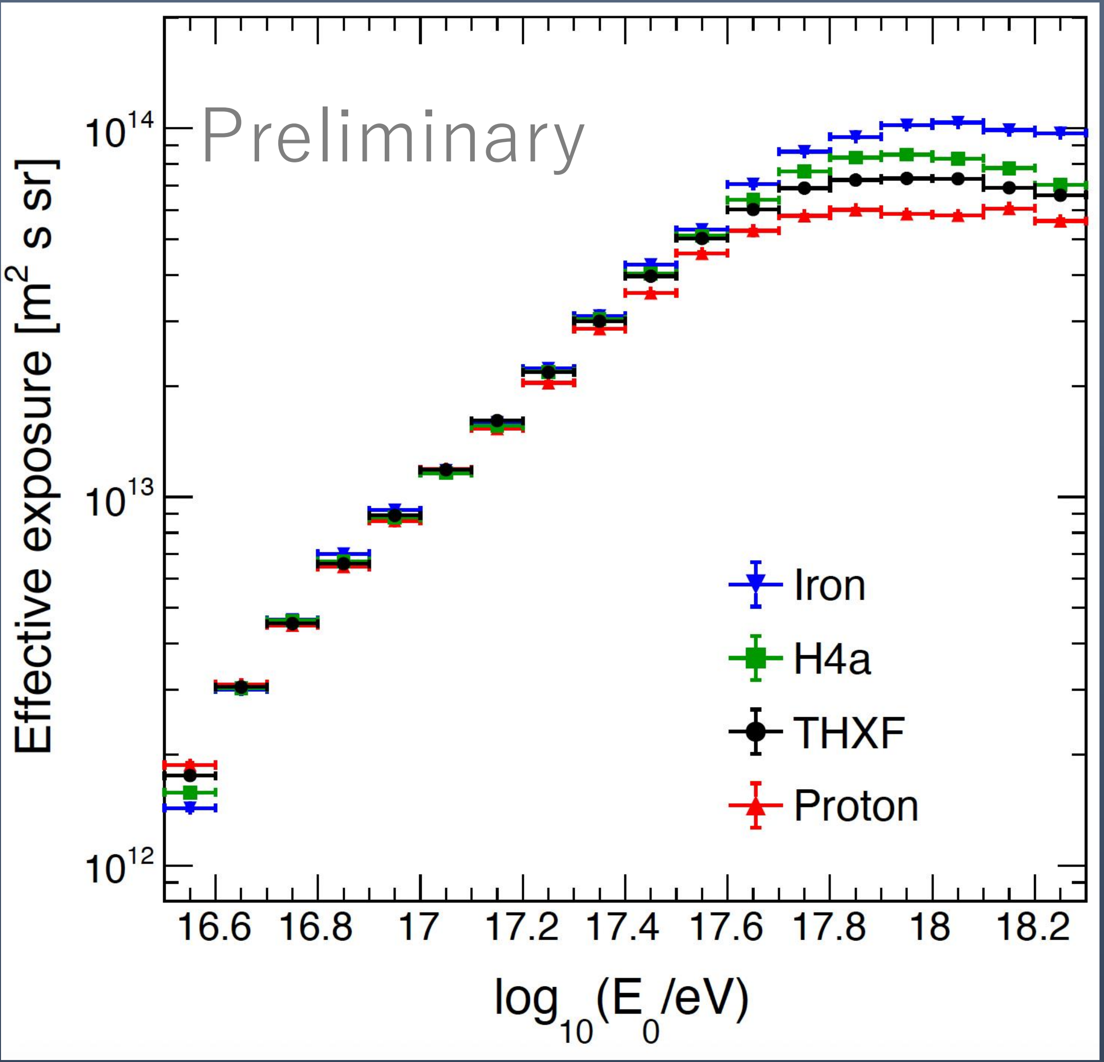
Number of events with unfolding

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

Effective exposure for the true energy spectrum

$J(E_i)$	:	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

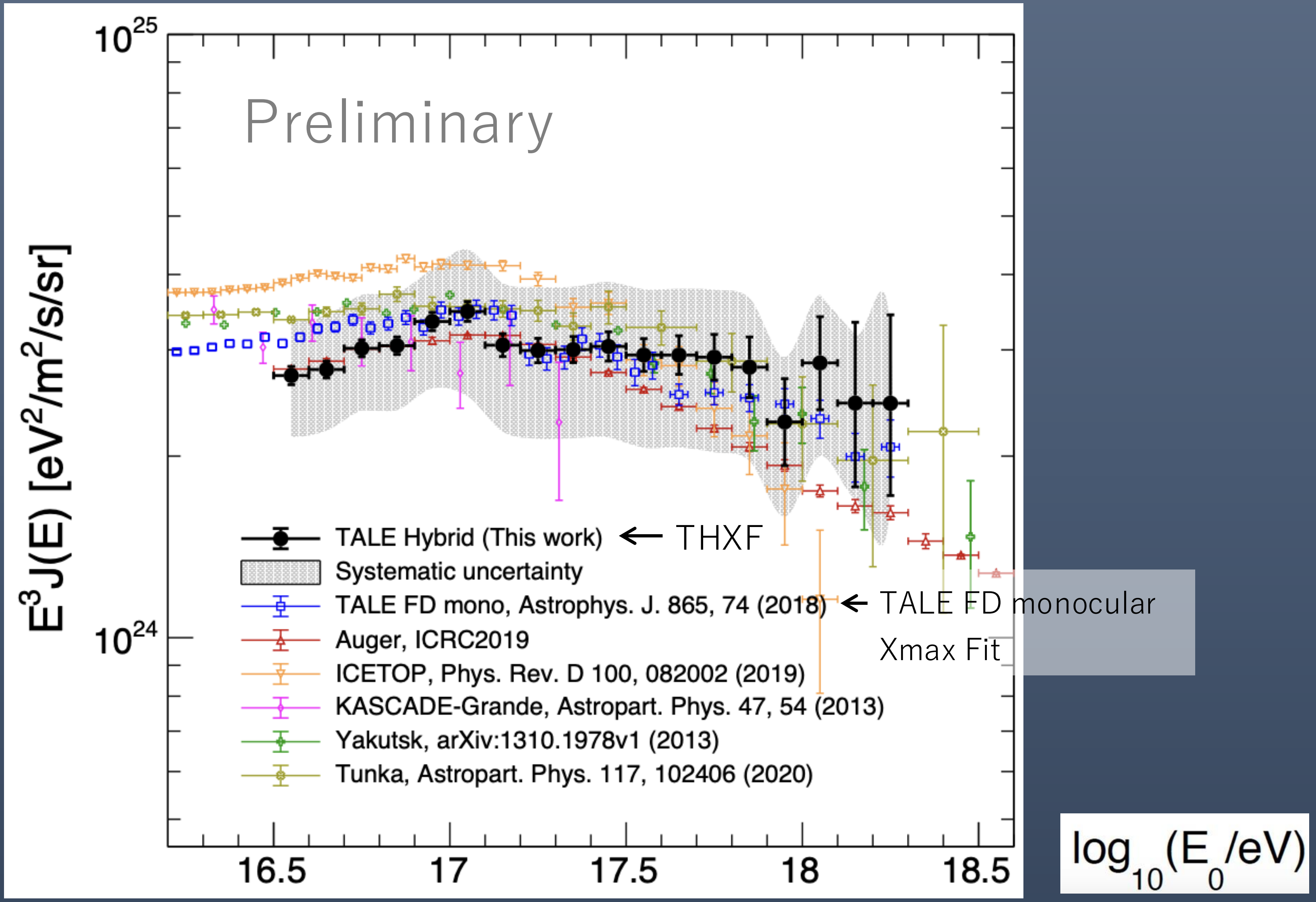
- Zenith angle： $\theta_{zenith} < 60°$

Observation time：

1,247 hours

(Nov. 14, 2018 – May 22, 2023)

Result: Energy Spectrum

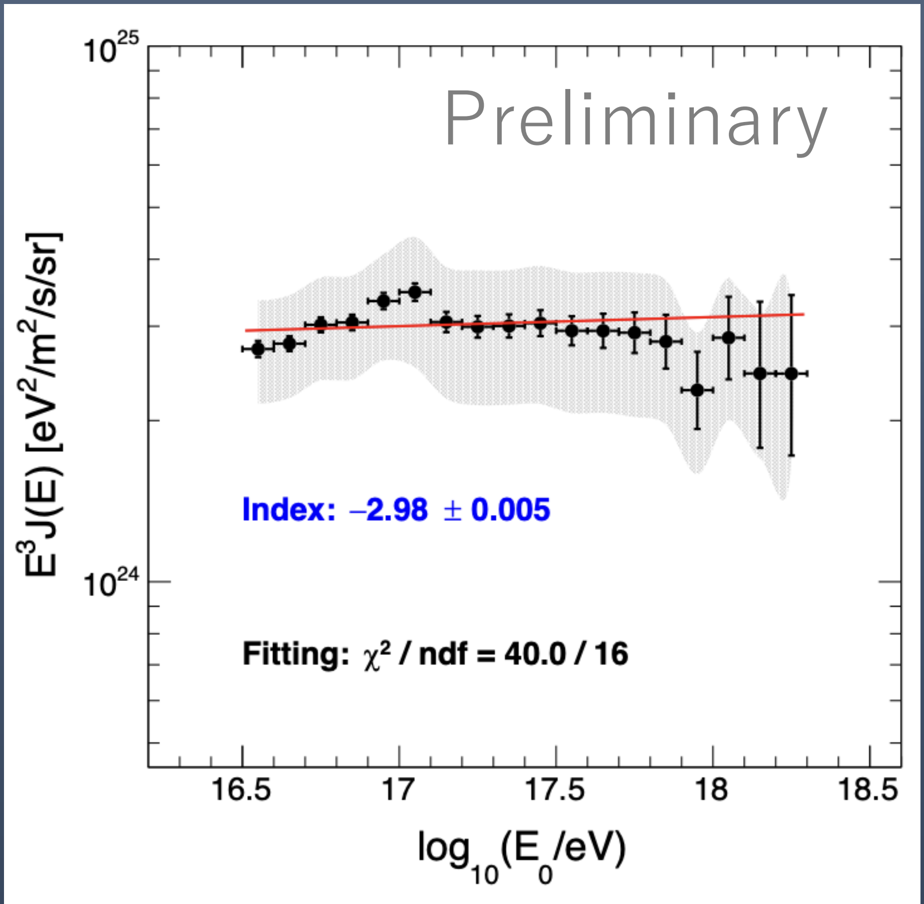


MC studies with EPOS-LHC in progress.

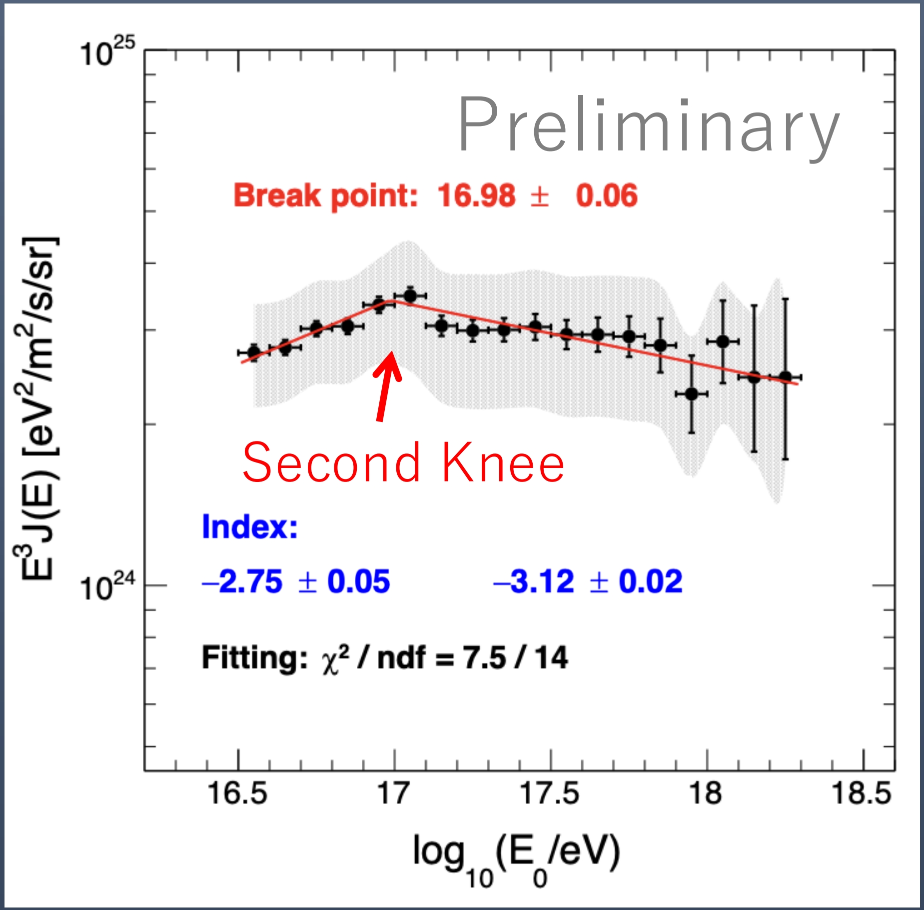
Result: Power-Law fitting

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, $\log(E_{break}/\mathrm{eV}) = 16.98 \pm 0.06$

Thank you for your attention!

Auger site visit, Nov. 17, 2024

Backup

Resolution of energy measurement

TALE FD mono obs.

	Energy Resolution
Cherenkov dominant (All energy)	15.9%
Cherenkov dominant ($E > 10^{16.7}$ eV)	8.7%
Fluorescence dominant	10.3%

TALE Hybrid Obs.

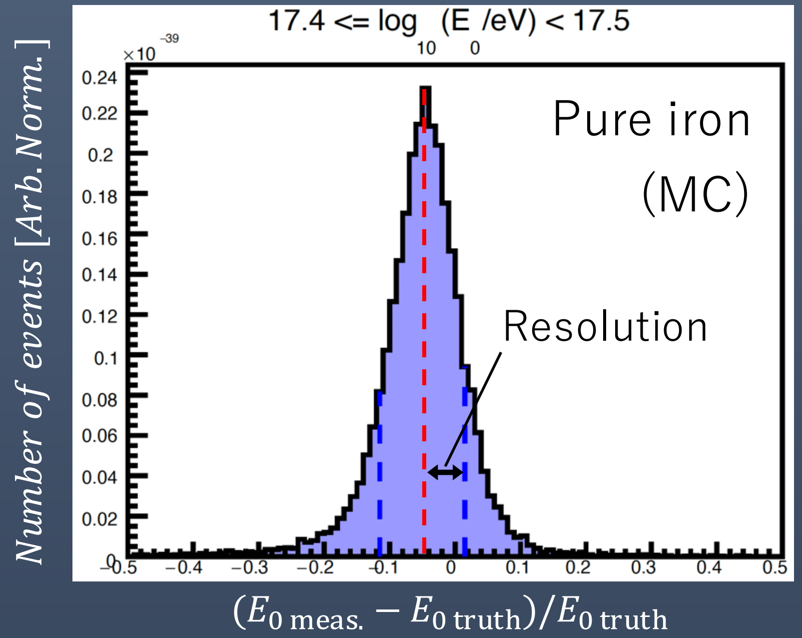
$17.4 < \log_{10}(E_0/\mathrm{eV}) < 17.5$

	Energy Resolution
Pure proton	+7.2%/−8.8%
Pure iron	+6.6%/−6.4%

Preliminary

TALE Hybrid Obs.

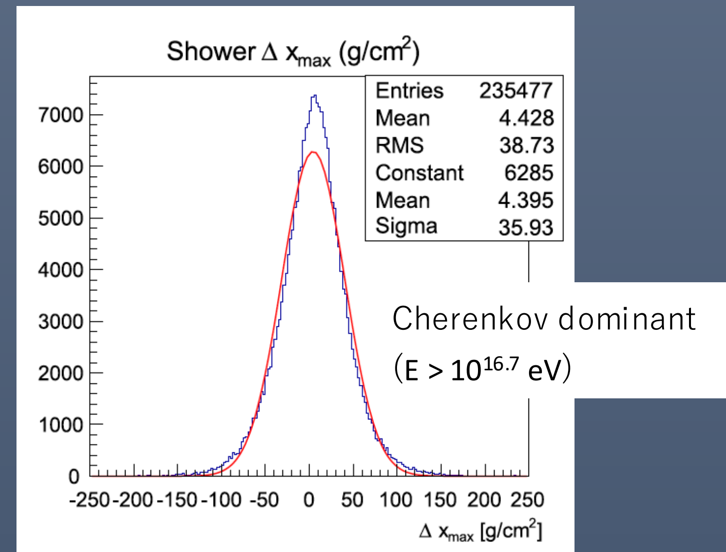
Energy Resolution (MC)



Resolution of Xmax measurement

TALE FD mono obs.

	Xmax Resolution
Cherenkov dominant (All energy)	46.43 g/cm^2
Cherenkov dominant ($E > 10^{16.7}$ eV)	35.93 g/cm^2
Fluorescence dominant	58.87 g/cm^2



R. U. Abbashi et al., Astrophys. J. **865**, 74 (2018).

TALE Hybrid obs.

	Xmax Resolution
Pure proton	29.1 g/cm^2
Pure iron	26.6 g/cm^2

K. Fujita, Ph.D. thesis (2022).

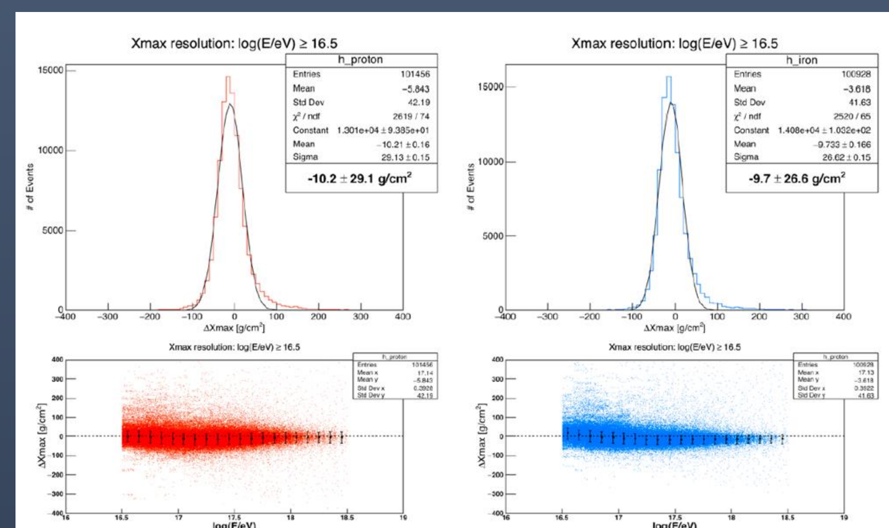


FIGURE 4.23: TALE Hybrid X_{max} angle reconstruction resolution histograms by evaluating ($X_{max\ recon} - X_{max\ thrown}$).

Spectrum index for MC weights

Table 6
Fit Parameters to a Broken Power-law Fit to the TALE Spectrum

$\log_{10}(E_1)$	$16.22 \pm 0.017 \pm 0.10$
$\log_{10}(E_2)$	$17.04 \pm 0.035 \pm 0.09$
γ_1: $15.70 < \log_{10}(E) < 16.22$	$3.12 \pm 0.007 \pm 0.043$
γ_2: $16.22 < \log_{10}(E) < 17.04$	$2.92 \pm 0.008 \pm 0.012$
γ_3: $17.04 < \log_{10}(E) < 18.30$	$3.19 \pm 0.017 \pm 0.026$

R. U. Abbashi et al., Astrophys. J., **865**, 74 (2018).

	γ_3	$\log_{10}(E/eV)$	γ_4
HiRes	-3.25 ± 0.01	18.65 ± 0.05	-2.81 ± 0.03

	γ_4	$\log_{10}(E/eV)$	γ_5
HiRes	-2.81 ± 0.03	19.75 ± 0.05	-5.1 ± 0.7

R. U. Abbashi et al., Phys. Rev. Lett. **100**, 101101 (2008).

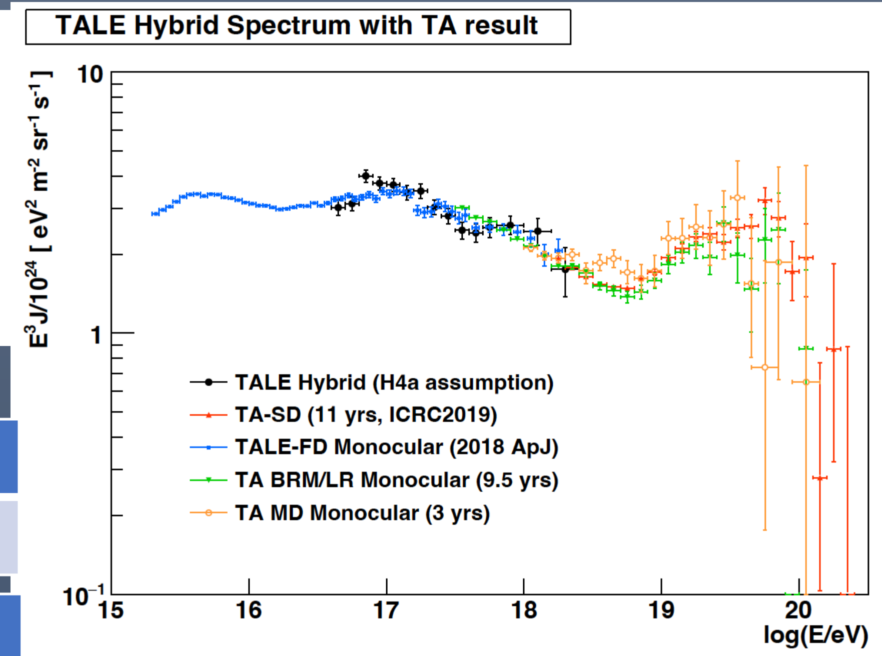


FIGURE 5.33: TALE hybrid cosmic ray energy spectrum comparison with measurements by the TALE FD monocular mode [26], by the TA using the FDs at Black Rock Mesa, Long Ridge [96] and Middle Drum [97] sites, and by the TA SD [25].

K. Fujita, Ph. D. thesis (2022).

Energy region	γ
$\log_{10}(E/eV) < 16.22$	-3.12 ± 0.044
$16.22 \leq \log_{10}(E/eV) < 17.04$	-2.92 ± 0.014
$17.04 \leq \log_{10}(E/eV) < 18.65$	-3.19 ± 0.031
$18.65 \leq \log_{10}(E/eV) < 19.75$	-2.81 ± 0.03
$19.75 \leq \log_{10}(E/eV)$	-5.1 ± 0.7

These spectrum indexes are used for a weighting factor of the MC predictions.

Iterative D'Agostini unfolding (1)

The relation between true and measured spectrum is written by

$$E_j = \sum_{i=1}^{N_t} S_{ji} C_i,$$

where C_i is a number of events in true bin i, E_i is a number of events in measured bin j, S_{ji} is a smearing matrix, and N_t is the number true bins.

An unsmearing matrix can be obtained from the smearing matrix as

$$U_{ij} = \frac{P_{eff}\left(E_j \middle| C_i\right) P_0(C_i)}{\sum_{i=1}^{N_t} P\left(E_j \middle| C_i\right) P_0(C_i)},$$

where $\mathrm{P}(\mathrm{E_j}|C_i)$ is a probability of the true events in bin i measured in bin j written as

$$P\left(E_j \middle| C_i\right) = \frac{N_{ji}}{C_i},$$

where $\mathrm{N_{ji}}$ is the number of true events in bin i measured in bin j.

Iterative D'Agostini unfolding (2)

$P_{eff}(E_j|C_i)$ is defined as:

$$P_{eff}(E_j|C_i) = \frac{\frac{N_{ji}}{C_i}}{\sum_{i=1}^{N_m} \frac{N_{ji}}{C_i}},$$

where N_m is number of measured bins.

$P_0(C_i)$ is a prior probability representing the number of events in bin i, written as

$$P_0(C_i) = \frac{C_i}{\sum_{i=1}^{N_t} C_i}.$$

Therefore, the unfolded spectrum is

$$C_i' = \sum_{j=1}^{N_m} U_{ij} \, E_j^{\mathrm{data}},$$

where $\mathrm{N_m}$ is the number of bins of measured spectrum.

Particle spectrum of the H3a and H4a models

$$\phi_i(E) = \sum_{j=1}^{3} a_{i,j} E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$$

i: composition

j: population

$\phi_i(E)$: $dN/d\ln E$

$a_{i,j}$: Normalization constant

$\gamma_{i,j}$: Integral spectral index

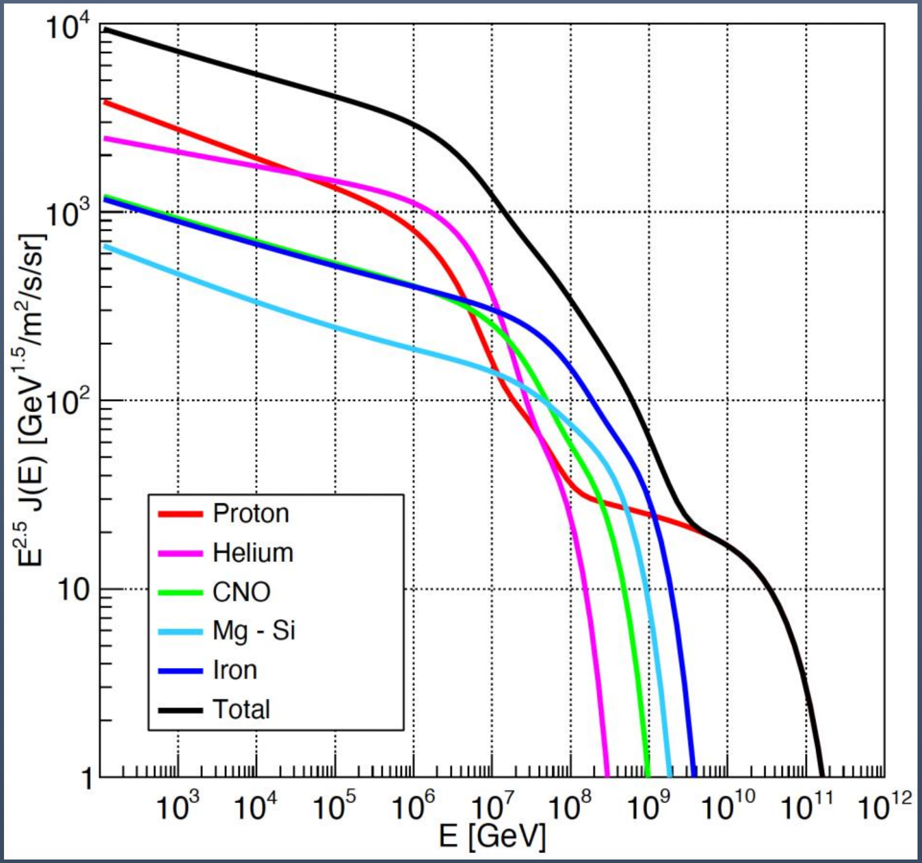
Z_i: Atomic number

$R_{c,i}$: Characteristic rigidity

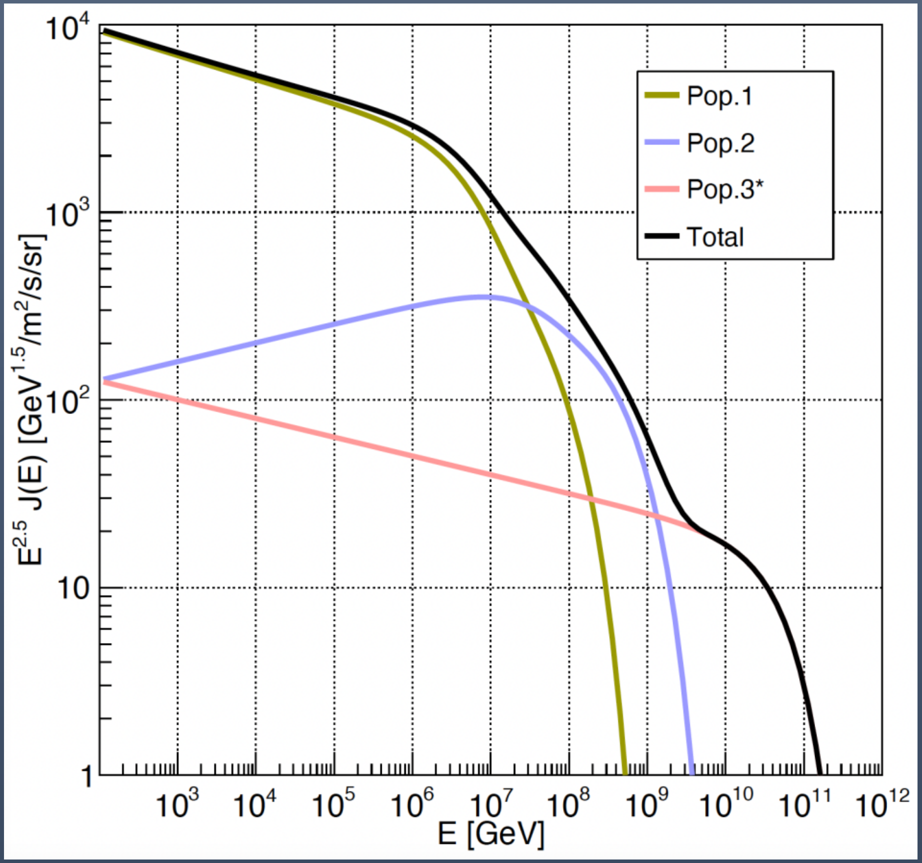
	R_c	γ	p	He	CNO	Mg-Si	Fe
	γ for Pop. 1	–	1.66	1.58	1.63	1.67	1.63
	Population 1: 4 PV	See line 1	7860	3550	2200	1430	2120
	Pop. 2: 30 PV	1.4	20	20	13.4	13.4	13.4
H3a→	Pop. 3 (mixed): 2 EV	1.4	1.7	1.7	1.14	1.14	1.14
H4a→	Pop. 3 (Proton only): 60 EV	1.6	200	0	0	0	0

Spectra of the H4a model

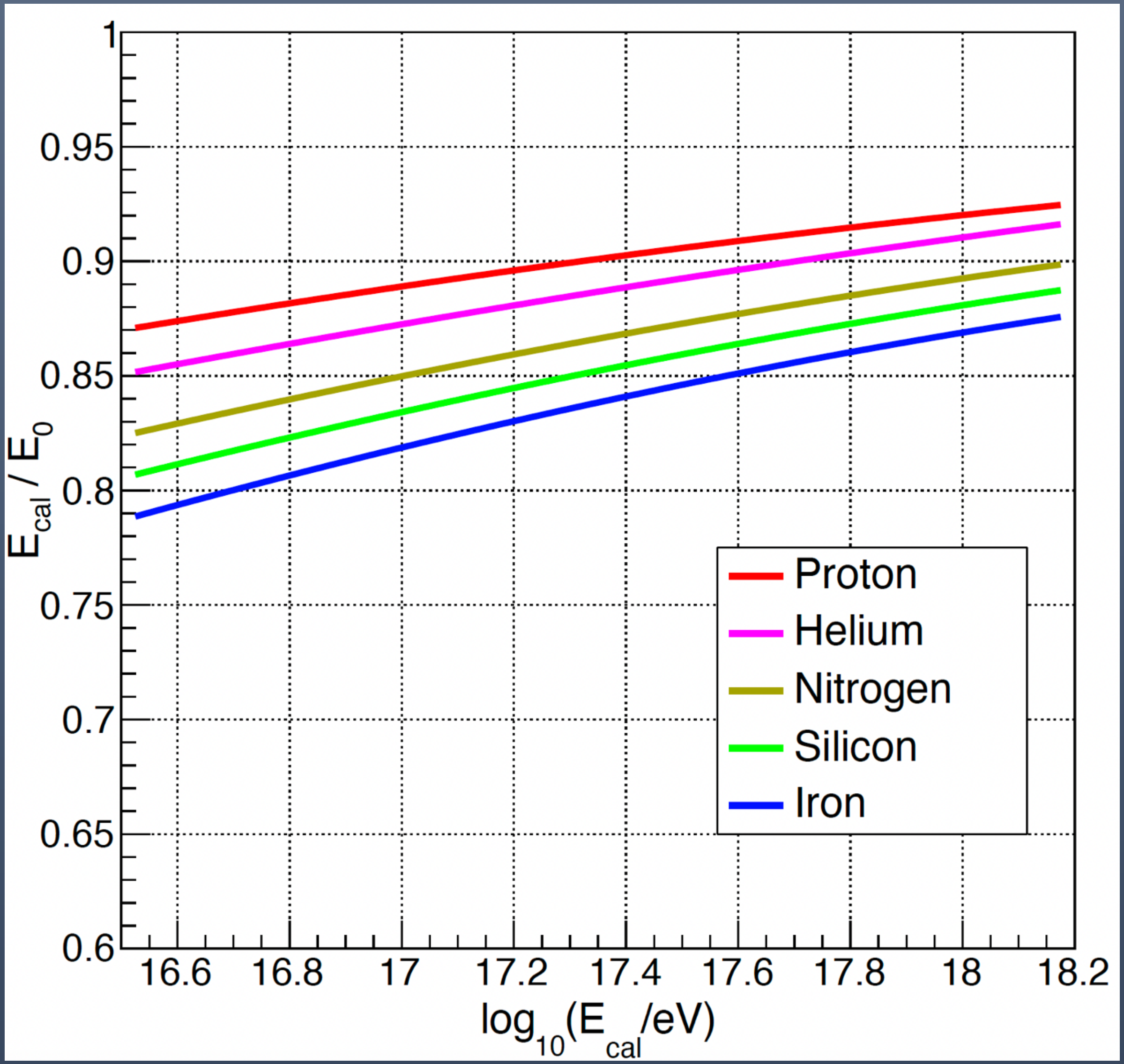
Particle spectra



Population spectra



Calorimetric energy fraction

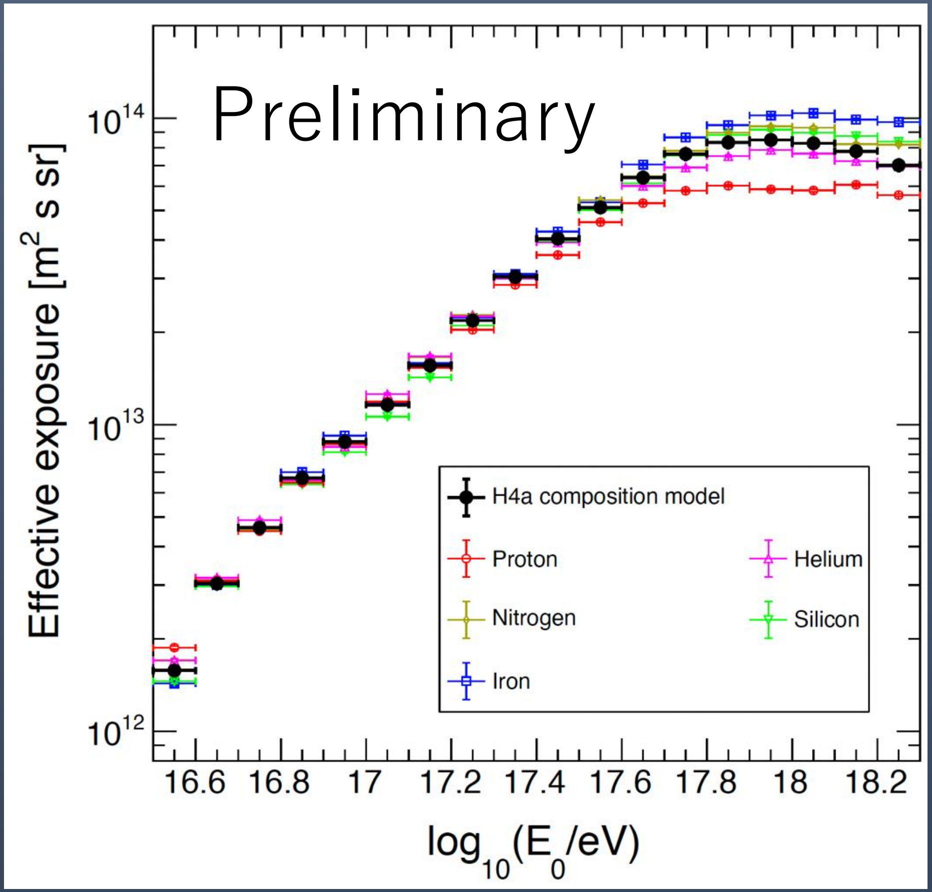


→ use for the missing energy correction

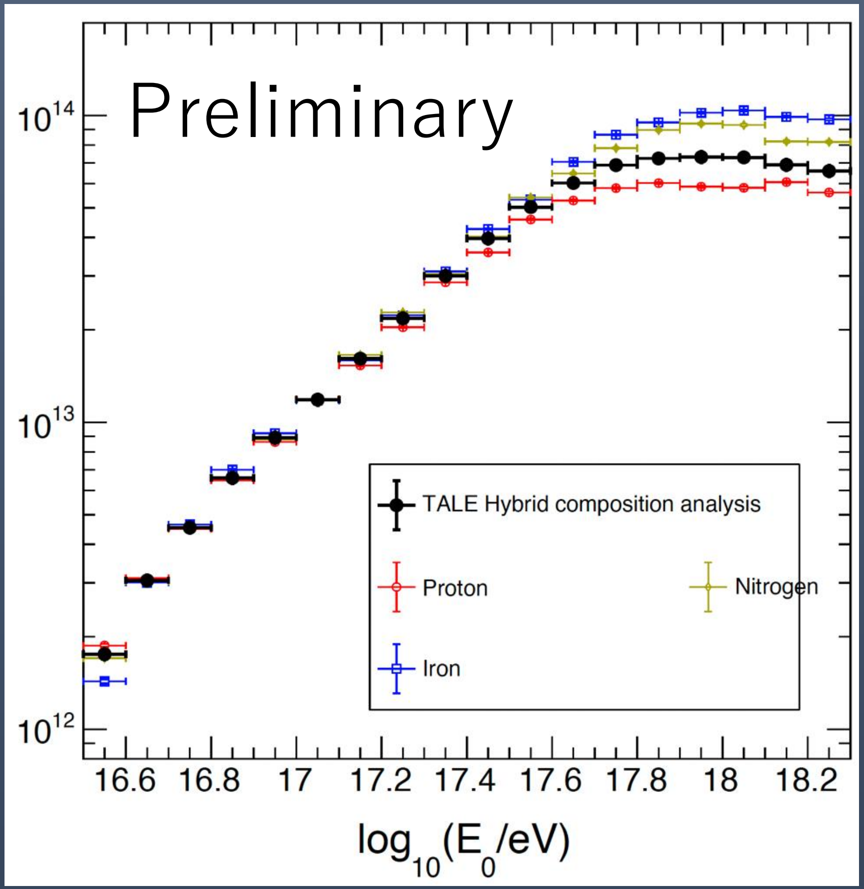
Effective Exposure

Mixed composition model:

H4a model

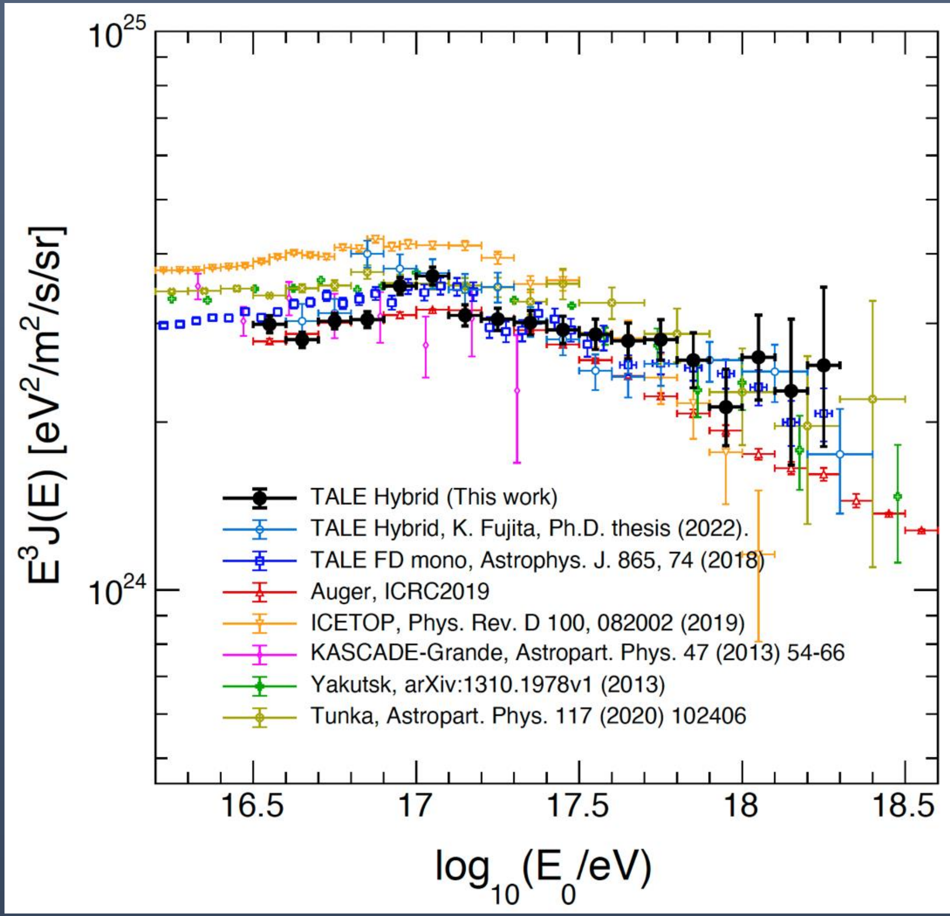


TALE data driven

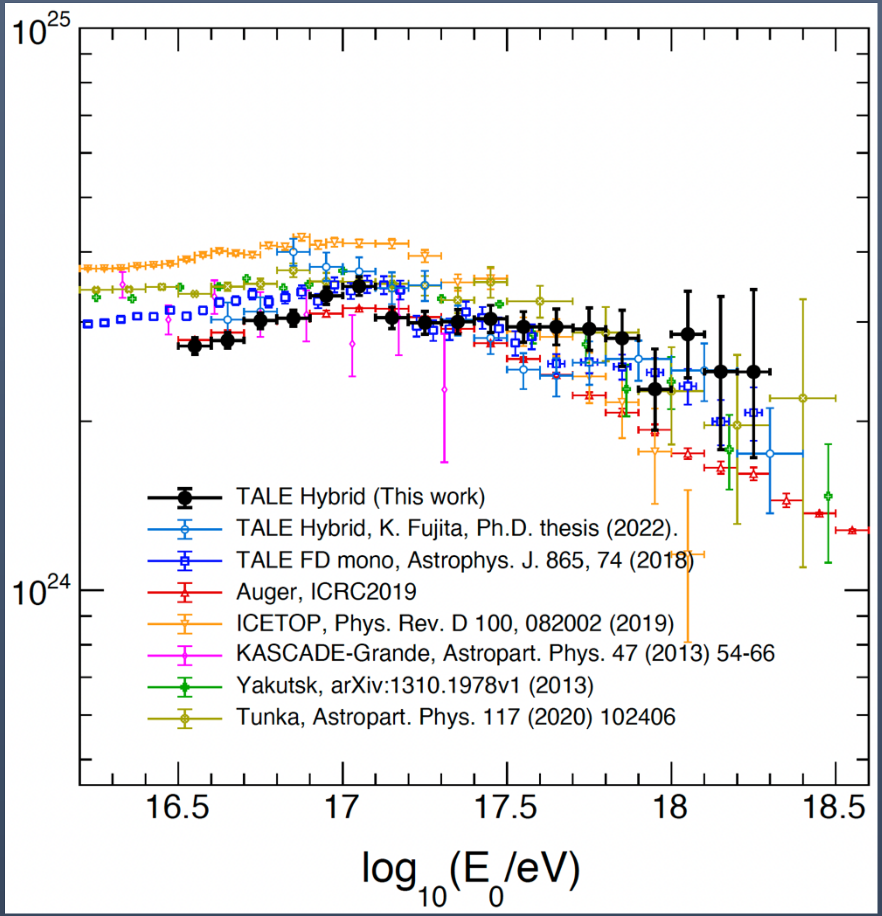


Result: Energy spectrum

H4a model: P, He, N, Si, and Fe



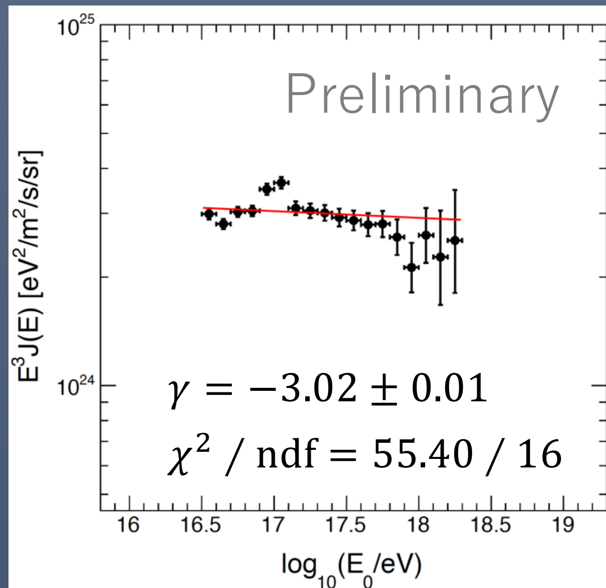
THXF: P, N, and Fe

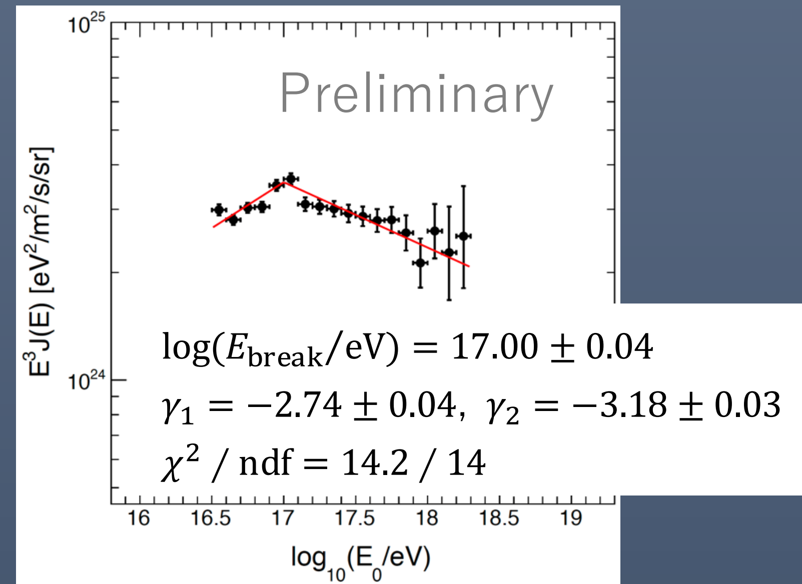


Result: Power-Law fiiting

Single Power-Law fitting | Broken Power-Law fitting

H4a model





TALE Hybrid

X_{max} Fit

(THXF)