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Recent Progress of the Telescope Array Experiment

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The Telescope Array (TA) experiment has been observing ultra-high-energy cosmic rays (UHECRs) using a surface detector (SD) array and fluorescence detector (FD) stations since 2008. TA is the largest UHECR observatory in the Northern Hemisphere. It has been expanded by constructing additional SDs and FDs to extend its energy coverage toward both lower and higher energies. These extensions are called the TA Low Energy Extension (TALE) and the TAx4 experiment, respectively. Together, they allow us to observe cosmic rays over more than five orders of magnitude in energy above $10^{15.3}$ eV. An overview of the experimental setup and the latest measurement results is presented in this paper.

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1. Introduction

Cosmic rays with energies exceeding 10^{18} eV are called "ultra-high-energy cosmic rays" (UHECRs), and their origins remain unresolved. UHECRs with higher energies are considered crucial for understanding the origins of UHECRs due to the short propagation distances. As UHECRs travel through intergalactic space, they lose energy rapidly, primarily through interactions with the cosmic microwave background photons. Consequently, if a cosmic ray proton with an energy of 10^{20} eV is observed, its origin is within the propagation distance $\sim$ 50 Mpc. Also, since cosmic rays are charged particles, they are deflected by Lorentz forces in the magnetic fields. This deflection angle is approximately inversely proportional to their rigidity $\sim E/Z$ if the angle is small. Therefore, as the rigidity increases, the deflection angle decreases, allowing the arrival direction to more closely indicate the direction of the cosmic ray source.

While the observation of UHECRs offers potential clues about the origins of UHECRs, it is very challenging due to the small number of events. Therefore, indirect observation of UHECRs through air showers allows for realizing the vast detection areas necessary to observe more UHECRs with higher energies. The Telescope Array (TA) experiment [1] was constructed mainly for detecting UHECRs. Currently, the TAx4 experiment [2], the largest experiment in the Northern Hemisphere, covers approximately 1700 km^2. In the Southern Hemisphere, the Pierre Auger Observatory [3], the world's largest experiment, covers about 3000 km^2. Both experiments conduct long-term steady observations using a combination of surface detectors (SDs) and fluorescence detectors (FDs). In Section 2, we overview the detectors of the TA experiment. We review the latest results with these detectors in Section 3, and describe the recent software and hardware developments in Section 4. Finally, we summarize the results and future prospects in Section 5.

2. Overview of the TA Experiment

TA uses both SDs and FDs to detect air showers. SDs detect air shower particles, and FDs detect fluorescence lights from molecules in the atmosphere excited by air shower particles. SDs and FDs have complementary detection characteristics.

Fluorescence lights are faint, so FDs can operate only on moonless, clear nights, whereas SDs can observe continuously. Consequently, SDs have a much higher duty cycle, and their data are mainly used for studies on energy spectra and arrival direction distributions of cosmic rays. On the other hand, FD data can measure the primary energy of cosmic rays calorimetrically by integrating fluorescence lights. Therefore, primary energies measured by FDs are used to calibrate energies measured by SDs using "hybrid" events, which mean the same events measured both by SDs and FDs. FD data also provide the slant atmospheric depth at the air shower maximum, X_{max}, which is well known as a sensitive parameter to the mass composition of primary cosmic rays.

Section 2.1 shows the TA SDs and FDs' status. Telescope Array Low Energy Extension (TALE) [4] and TAx4 were designed for the lower and higher energy extension of the TA, respectively. Both experiments have SDs and FDs that use the same measurement techniques as the TA. In Section 2.2 and Section 2.3, status of the TALE detectors and TAx4 detectors is shown, respectively.

In this section, we explicitly write *"main TA"* when referring to the main TA experiment alone.

2.1 Main TA Detectors

The observation site is located in Utah, USA. The central laser facility (CLF), constructed at the center of the SD array for the calibration of the FDs, is located at Latitude 39°.30 N, Longitude 112°.91 W, and altitude 1382 m. A total of 507 SDs of the main TA are placed with 1.2 km spacing in a square grid (see red circles in Fig. 1), and the SD array covers approximately 700 km^2. Each SD consists of two layers of 3 m^2 area and 1.2 cm thick plastic scintillators. The three FD stations surround the SD array, providing wide-area hybrid observations. The full operation of the SDs and FDs started in May 2008. An overview of the detector layout of the main TA experiment is illustrated in Fig. 1. The SD array, the FD stations, and the TALE SD sites in the northern area are shown for reference.

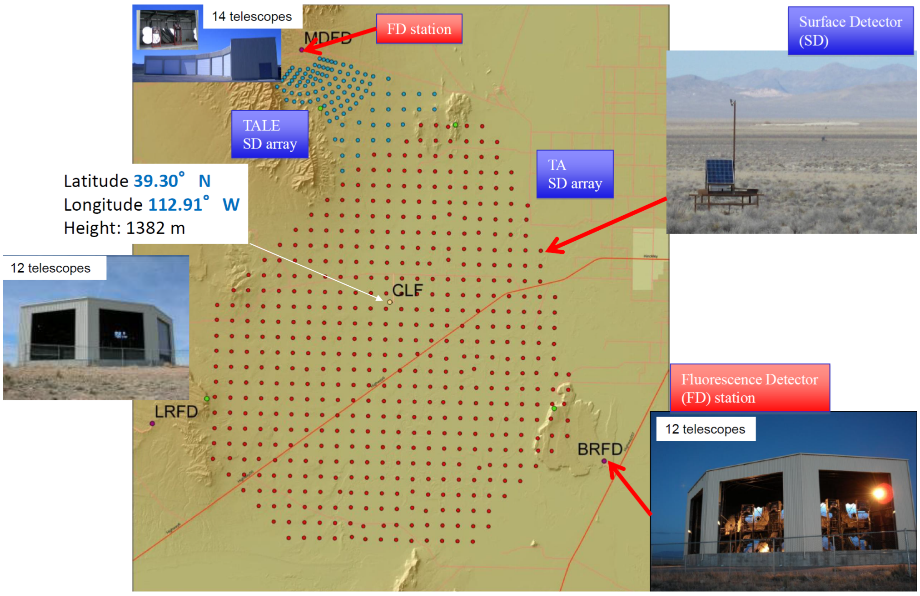

Figure 1: A map of the constructed detectors of the main TA. Red circles indicate the locations of SDs, magenta circles indicate the locations of fluorescence detectors FDs, and blue circles represent the TALE SD sites located in the northern area of the main TA array.

2.2 Extension to the Lower Energies (TALE)

We constructed an additional SD array and FD station for the extension to observe cosmic rays with lower energies than the main TA. This project was named as the TALE. Fig. 2 shows the locations of the SD array and FDs for the TALE in the northern area of the main TA. To detect cosmic rays with lower energies, an FD station was constructed with higher elevation angles than those of the main TA. This FD station has been in stable operation since September 2013. Two SD arrays with 400 m and 600 m spacing were constructed and have been in operation since 2018, and the SD array named "TA-infill," with 100 m spacing, was added [5] in 2023.

2.3 Extension to the Higher Energies (TAx4)

For the extension for cosmic rays with higher energies than the main TA, we also constructed a new SD array and FDs. This project was named the TAx4 due to the total detection area of the

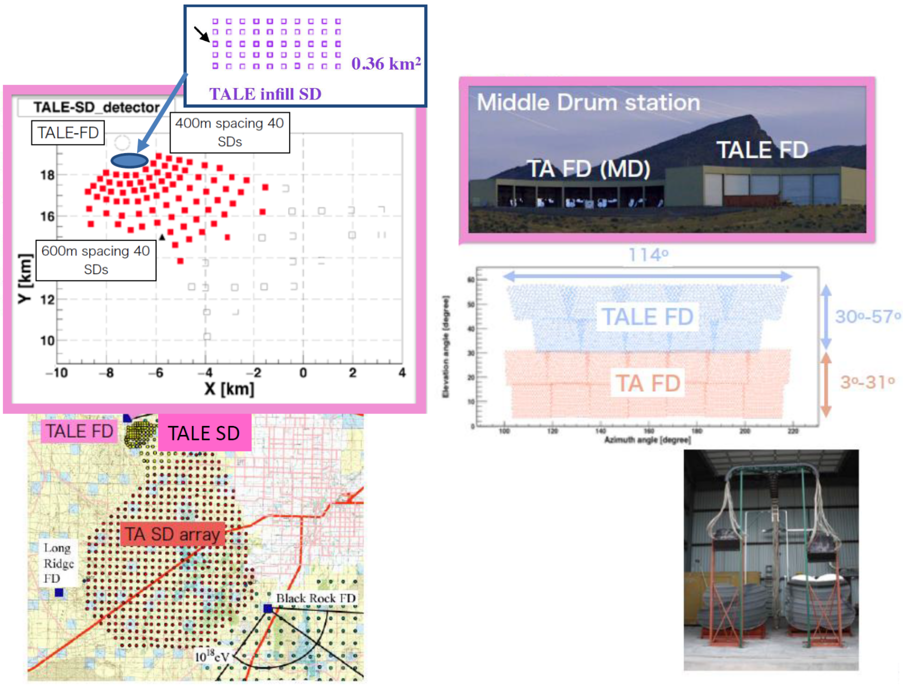

Figure 2: Maps of newly constructed detectors for the TALE experiment. The top left figure in a magenta square shows the relative positions of SDs and FDs from the CLF site. The locations of 50 new SDs with 100 m spacing are shown at the top. The TALE sites are located in the northern area of the main TA, as shown in the bottom left figure.

SD array. The 500 new SDs with 2.08 km spacing, together with the main TA SD array, will cover a total area four times that of the main TA SD array (~2800 km^2). A total of 257 new SDs, about half of the planned, were deployed in 2019. These SDs have been running stably since October 2019. The current detection area of the new SD array combined with the main TA SD array is approximately 1700 km^2. We finished constructing two new FD stations. The north FD station has been in stable operation since June 2018, and the south FD station since September 2020. Fig. 3 shows the locations of sites of the new SD array and FD stations. Four (eight) telescopes were installed in the north (south) FD station.

3. Latest Results of the TA Experiment

In this section, we present the latest results based on the detectors described in Section 2, focusing on the energy spectrum (Section 3.1), anisotropy (Section 3.2), mass composition (Section 3.3), search for neutral particles (Section 3.4), and lightning events (Section 3.5).

3.1 Energy Spectrum

The energy spectra measured by the TALE FD and TA SD cover more than five orders of magnitude, from $10^{15.3}$ eV to the highest energies [6]. Several spectral features are observed in the spectrum, with characteristic break energies at ~ $10^{16.2}$ eV (intermediate break), ~ $10^{17.2}$ eV (second knee), ~ $10^{18.7}$ eV (ankle), ~ $10^{19.2}$ eV (spectral shoulder), and ~ $10^{19.7}$ eV (suppression).

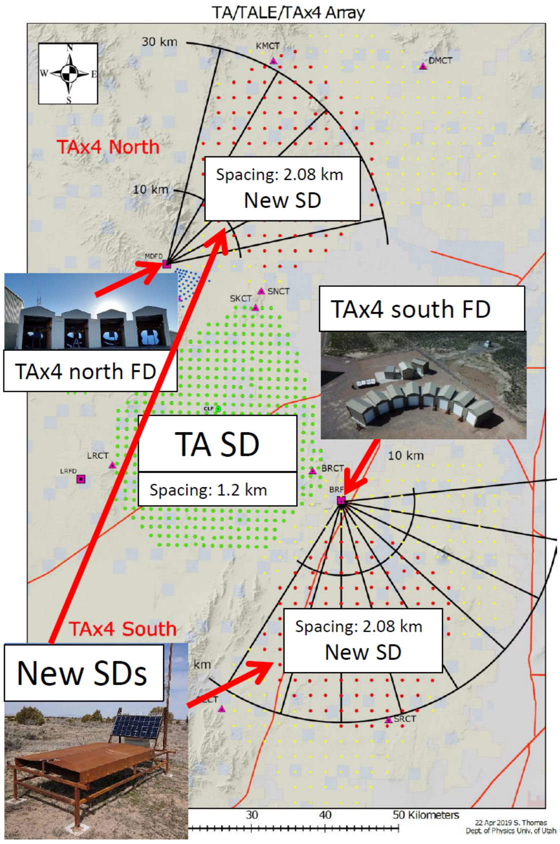

Figure 3: A map of newly constructed detectors for the TAx4 experiment. Each red point shows the site of each deployed new SD. A total of 257 new SDs have been deployed, and another 243 will be deployed at the yellow points in the future, bringing the total to 500 SDs. Each black fan shape shows the field of view of each telescope in the FD station.

The TALE FD and SD hybrid energy spectrum is newly measured at the second-knee region, and the break point is estimated as $\log_{10}(E/\mathrm{eV}) = 17.11 \pm 0.09$ that shows consistency with previous measurements [7]. Fig. 4 compares the updated TALE FD monocular spectrum with the 2018 result [8], illustrating the improvement in statistical precision and the consistency of the fitted spectral shape [9]. A new study of the TALE SD energy spectrum is also ongoing [10]. Based on 16 years of observations with the TA SD, the break energies of the ankle, spectral shoulder, and suppression have been updated to $\log_{10}(E/\mathrm{eV}) = 18.70 \pm 0.01$, 19.15 ± 0.08, and 19.83 ± 0.03 [11], respectively. The statistical significances of the spectral shoulder and the suppression are estimated to be 5.2σ and 6.3σ, respectively. Figure 5 shows the TA SD energy spectrum [11], demonstrating the stability and reproducibility of the spectral features such as the ankle, spectral shoulder, and suppression. In addition to the results obtained with the TA SD, the new TA×4 SD array with a 2.08 km spacing has also been analyzed. The reconstructed events show reasonable agreement in geometry between data and Monte Carlo (MC) simulations. Inclined showers with zenith angles of 55°–65° have been newly incorporated into the event reconstruction. The TA×4 SD energy spectrum is consistent with that measured by the TA SD [12]. These results demonstrate the consistency and precision of the TA energy spectrum measurements across multiple detector systems, providing a solid foundation for exploring directional or anisotropic features in the arrival directions of UHECRs.

The discussion on the declination dependence of the energy spectrum originated from the joint analyses by the Auger and TA Spectrum Working Group, where a discrepancy still exists at the highest energies [13]. The reported evidence of the declination dependence in the energy spectrum measured with the TA SD [14, 15] has been updated. The discrepancy between TA SD energy spectrum and a simultaneous fit function to both TA and Auger energy spectra on the full exposure is estimated to be $8.0^{+2.0}_{-2.4}\sigma$ [11], while the discrepancy decreases to 1.8σ if a specific sky region at lower declination angles is selected. Energy-independent bias is calibrated using FD–SD hybrid events, while an energy-dependent bias has been studied using an extreme case of pure-iron MC simulations over the entire energy range [16]. The discrepancy in the energy spectrum was not explained by this study. A new Bayesian framework is being developed to incorporate energy-dependent systematic uncertainties into the spectrum comparison. The observed declination dependence has motivated several theorists to consider local-source scenarios for interpretation [e.g. 17, 18].

3.2 Anisotropy

Recently, several interesting results have been reported from UHECR events above 100 EeV. Among them, an extremely energetic cosmic ray event with an energy of 244 $\pm$29(stat.)$^{+51}_{-76}$(syst.) EeV— nicknamed the "Amaterasu particle" — was detected in 2021 in the direction of the Local Void, a region of space that is notably sparse in galaxies [19]. The arrival direction of this event, shown in Fig. 6, is compared with potential nearby source candidates and with back-tracked paths calculated under different Galactic magnetic field models. The fact that such a high–energy event arrived from this galaxy–poor region is particularly intriguing. There was no apparent clustering with other $E > 100$ EeV events, and the source of the event has not yet been identified.

To investigate the overall distribution of arrival directions, a comparison was made between the observed events and expectations from a large-scale-structure (LSS) model, as illustrated in Fig. 7. In this model, the source distribution is based on the 2MASS Redshift Survey catalog (limited to distances within 250 Mpc), and the propagation of UHECRs is simulated taking into account different Galactic magnetic field models. The smearing angle, representing the effect of extragalactic magnetic fields, is treated as a free parameter [20, 21]. In particular, the arrival directions of 19 events with $E > 100$ EeV, observed over 14 years with the TA SD, were compared with the predictions of the LSS model. The data are compatible with isotropy. To achieve compatibility between the LSS model and the observations within the 2σ level, the model would require either a very heavy mass composition (heavier than iron), or, in the case of proton or helium primaries, strong extragalactic magnetic fields of > 20 nG (for a coherence length of $\lambda = 1$ Mpc) [21].

In 2014, based on the first five years of observations, the TA Collaboration reported an indication of an excess in the arrival directions of UHECRs in the vicinity of Ursa Major [22]. A total of 19 out of 72 TA events above 57 EeV were found within a 20°-radius circle, corresponding to a 5.1σ excess. The chance probability of observing such a hotspot was estimated to be 3.7×10^{-4}, or 3.4σ. In this analysis, the oversampling method was applied, where the number of UHECR events within a fixed-radius circle around each arrival direction was counted, and the Li–Ma significance [23] was evaluated relative to an isotropy expectation. Using the updated dataset corresponding to 16

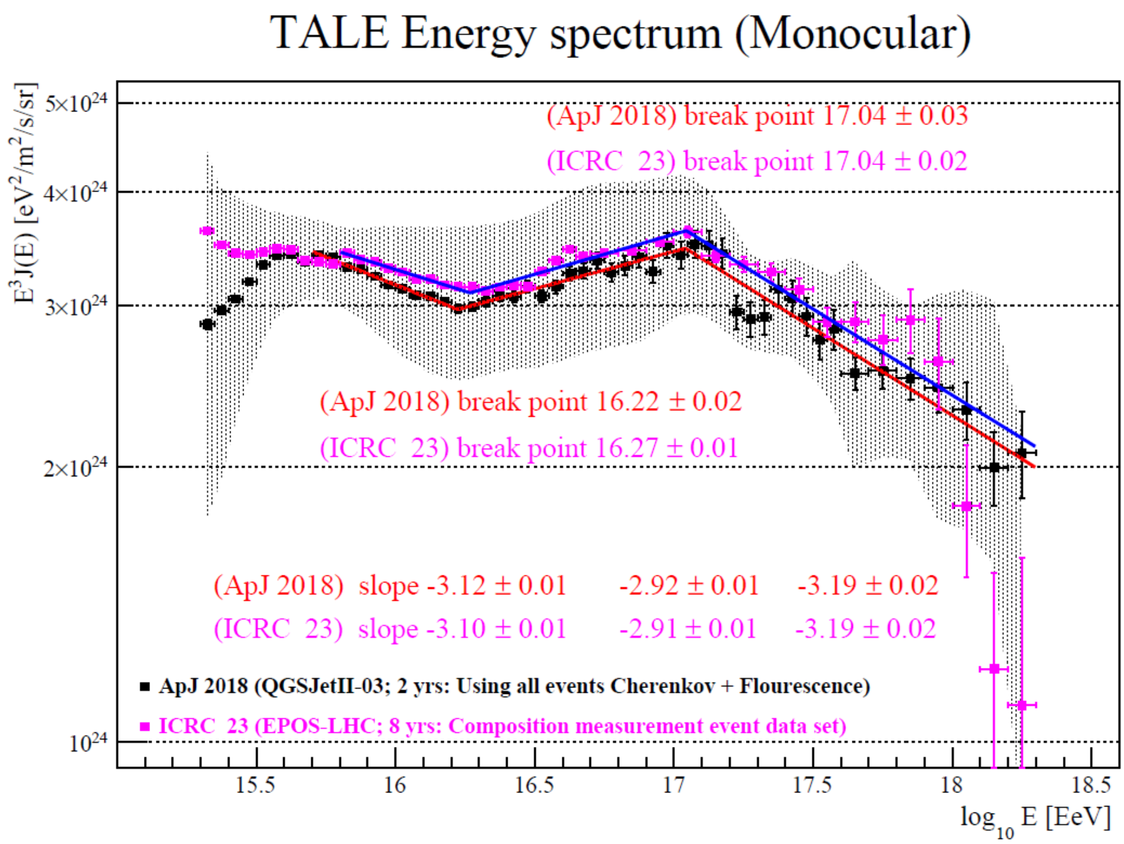

Figure 4: The TALE FD monocular energy spectrum is compared with the previous measurement published in 2018 [8]. The fit results for both the updated and the original spectra are shown [9]. The fitting is performed using a broken power-law function, and the red and magenta numerical values in the figure indicate the two break energies (the intermediate break and the second knee) and the three power-law indices before, between, and after the breaks.

years of observations, the statistical significance of the TA hotspot is now estimated to be 2.9σ [24]. In addition, a doublet above 100 EeV has been detected to the north of the TA hotspot on an angular scale of 1.2°. Because of its high energy and clustered arrival directions, this doublet could have a notable impact on the magnetic–deflection multiplet search. We have also searched for a magnetic–deflection multiplet that could be induced by a single source, using TA SD events above 57 EeV collected over 15 years. The search employs a likelihood analysis developed in our previous works [25, 26], and the statistical significance of the likelihood function is estimated to be approximately 3.0σ [27].

The statistical significance of an excess around the Perseus-Pisces Supercluster (PPSC) reported above $10^{19.4}$ eV, $10^{19.5}$ eV, and $10^{19.6}$ eV [28] is estimated to be 3.1σ, 3.2σ, and 3.0σ, respectively [24]. The analysis uses TA SD data collected over 16 years. The Auger and TA Anisotropy Working Group studies the correlation of the arrival directions of UHECRs with nearby starburst galaxies, and the statistical significance is found to be 4.2σ above 38 EeV in the Auger's energy scale [29].

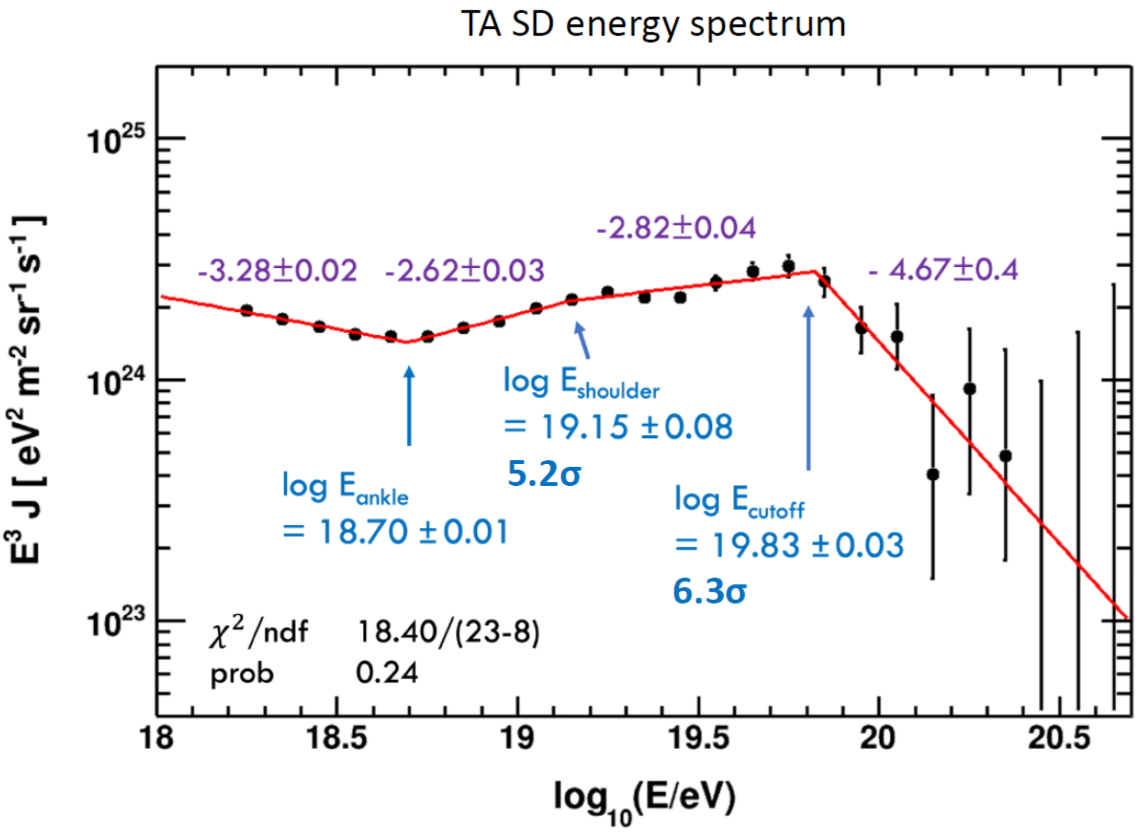

Figure 5: The energy spectrum measured with the TA SDs using data collected over 16 years [11]. The fitted function and its parameters are also shown.

The association between UHECR arrival directions and BL Lac objects is also studied. A likelihood analysis is conducted to test the correlation reported by the HiRes Collaboration [30], which suggested the presence of a small fraction of neutral primaries at $E > 10$ EeV. The analysis uses 6,712 TA SD events, and the post-trial p-value obtained with the pair-counting method is 3.0×10^{-2} for events with $E > 10$ EeV. The p-value obtained with the maximum-likelihood method is 3.0×10^{-3} for $E > 10$ EeV, and 2.4×10^{-3} for $E > 1$ EeV [31].

3.3 Mass Composition

The hybrid observation of the TALE SDs and FDs improves composition studies with a higher resolution of $X_{\max}$ than the monocular analysis of the TALE FDs. A newly constructed dense TALE-infill SD array with 100 m spacing enables hybrid observation of cosmic rays with energies lower than 10^{16} eV. New results are obtained using a hybrid analysis of the TALE and TALE-infill detectors [32]. As shown in Fig. 8, the evolution of the mean $X_{\max}$ with energy clearly exhibits two distinct breaks in the elongation rate at $\log_{10}(E/\text{eV}) = 15.71 \pm 0.13$ and $\log_{10}(E/\text{eV}) = 17.13 \pm 0.04$. The breaks coincide with the knee and second knee observed in the energy spectrum. The distribution fits show a transition from light to heavy composition, peaking near $10^{17.2}$ eV. Further studies with helium nuclei and updated hadronic interaction models, such

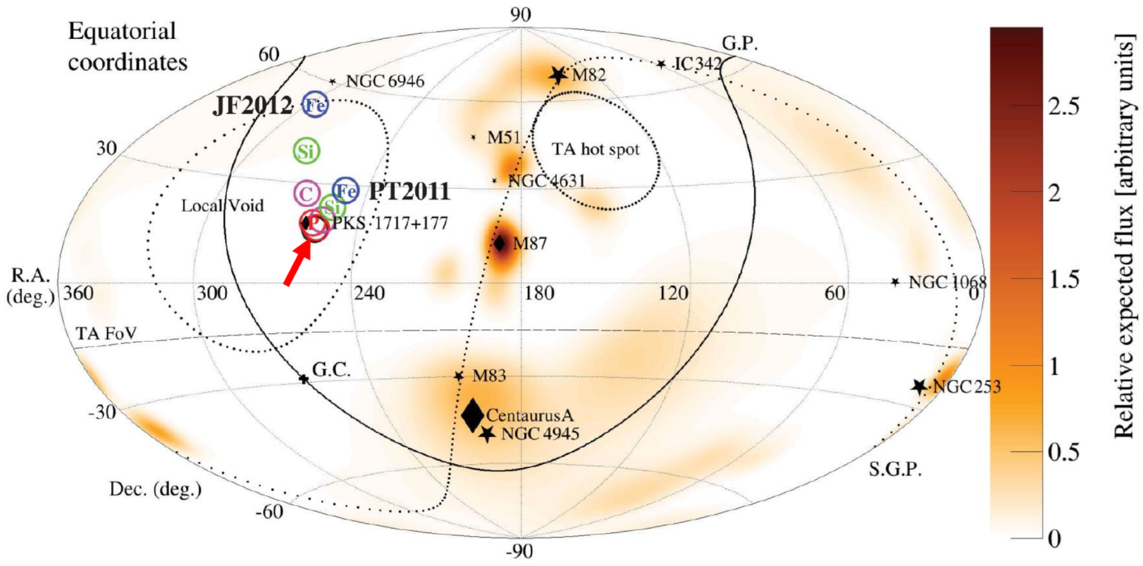

Figure 6: Arrival direction of the Amaterasu particle (black circle with a red arrow) compared with potential source candidates. Colored circles indicate the back-tracked directions calculated under two models of the Galactic regular magnetic field. For each magnetic-field model, different symbols represent the directions calculated for four possible primary particle species [19]. The color bar indicates the relative expected flux from a source-density distribution following the local LSS, weighted by the expected attenuation for a 244 EeV iron primary and smoothed to reflect the smearing resulting from turbulent Galactic magnetic fields.

as EPOS-LHC-R and QGSJET-III, are ongoing.

The TAx4 hybrid observation, combining the TAx4 FDs (new stations) and the TAx4 SD, provides $X_{\max}$ results consistent with the main TA experiment. The hybrid data over four years show a reasonable agreement between data and MC simulations, and two events above 100 EeV are detected [33].

3.4 Search for Neutral Particles

A neural network classifier is developed and trained on photon-induced and proton-induced MC event sets to search for ultra-high-energy (UHE) photons. The classifier is fine-trained using data events that are identified as non-photon events with high confidence. The upper limits on the UHE photon flux are established based on 14 years of TA SD data [34].

The upper limits on UHE neutrinos are newly obtained using 16 years of TA SD data [35]. No neutrino candidate event is observed, with an expected number of events of $N_{\rm exp} = 2.44$. The analysis targets inclined shower events with zenith angles in the range of the zenith angle, $65° < \theta < 85°$. Two observables are used for event classification: the shower curvature parameter and the area-over-peak (AoP) ratio.

3.5 Search for Lightning Events

Terrestrial gamma-ray flashes (TGFs) are observed at the TA site. The first observations are recorded using the *Photometric Array* at the TA detector. For the first time, time-resolved leader spectra are associated with a downward TGF observation [36]. These results demonstrate that

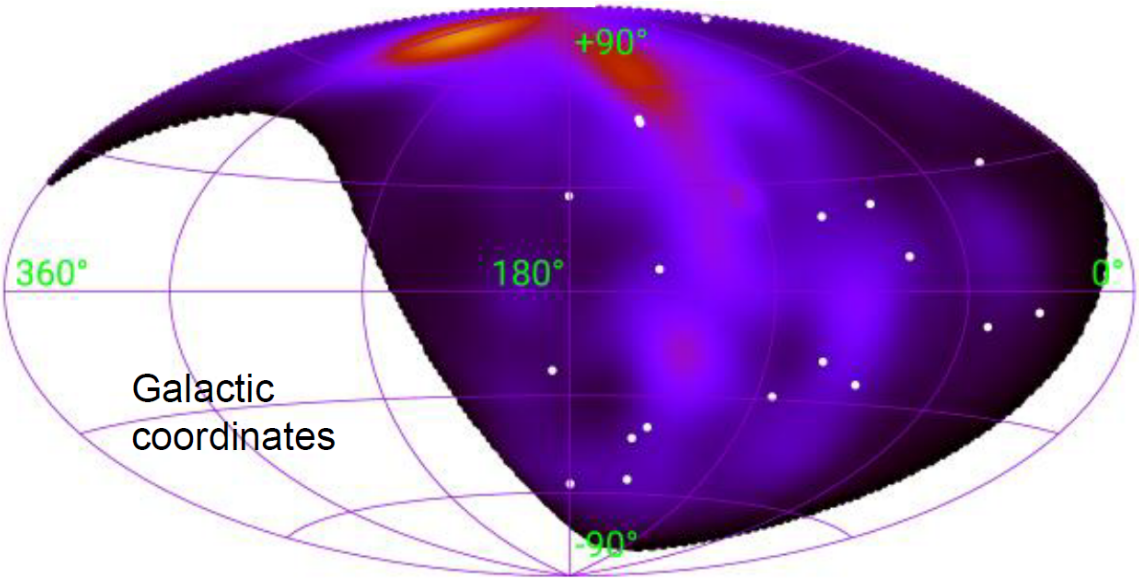

Figure 7: Flux map of UHECRs with $E > 100$ EeV, calculated using the LSS model assuming pure protons as primary particles. The color scale represents the expected flux intensity (red: higher flux). A smearing angle of 10° is applied at 100 EeV. White points indicate the 19 observed events with $E > 100$ EeV [21].

the TA detector systems are capable of observing transient luminous events in the atmosphere in coincidence with lightning activity, providing new opportunities to study the connection between thunderstorm electric fields and high-energy particle emissions.

4. Software and Hardware Developments

Several software developments are in progress to improve the accuracy and efficiency of SD event reconstructions. A systematic study of energy-dependent systematics is ongoing to better understand the reconstruction bias at different energy ranges [16]. A deep neural network (DNN) approach is introduced to enhance the reconstruction performance [37]. The DNN model can improve the resolution compared to the standard SD reconstruction, which allows for more relaxed quality cuts and consequently increases the event statistics.

The characteristics of the lateral distribution of UHECR air showers observed by the TA are also under detailed investigation. A study of air shower reconstruction using an asymmetric lateral distribution function for the TAx4 SD array is conducted [38], and the characteristics of the lateral distribution observed in UHECR events are analyzed [39]. These studies aim to improve the understanding of the shower front asymmetry and to refine the reconstruction accuracy.

Calibration and monitoring studies for the FDs are also being conducted to improve the accuracy of energy and composition measurements. Atmospheric monitoring by star signal analysis using a CMOS camera system is performed [40]. In addition, the optical properties of the FDs are investigated using the *Opt-copter* system [41]. These efforts contribute to a better understanding of the atmospheric transparency and optical throughput, which are essential for precise FD calibration.

The Non-Imaging CHErenkov Array (NICHE) is an associate experiment of the TA. It measures the cosmic-ray air showers by detecting the Cherenkov light produced in the atmosphere, using a

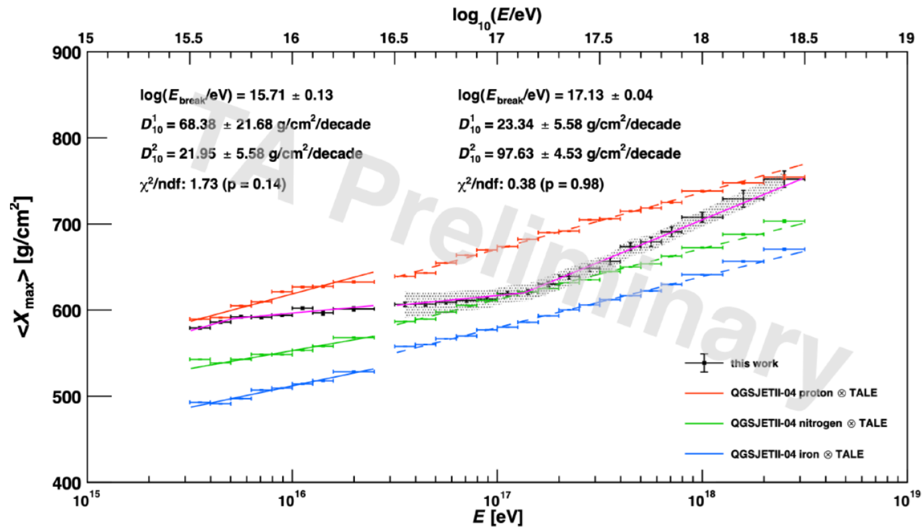

Figure 8: The mean $X_{\max}$ as a function of energy measured with the TALE hybrid detector. Black points represent the observational data, and the magenta line indicates the best-fit result obtained with a single-break fit. For comparison, the expected $\langle X_{\max} \rangle$ values for proton, nitrogen, and iron primaries from MC simulations are also shown [32].

ground-based array that does not employ imaging optics. The energy spectrum of cosmic rays in the knee region is measured by the NICHE array at the TA site [42]. This complementary approach provides an independent cross-check of the energy calibration and composition measurements in the transition region between the knee and the second knee.

In addition to the NICHE array, several research and development activities are ongoing at the TA site to explore next-generation detection techniques. The *Auger@TA* project is a collaborative effort between the TA and Auger, aiming to perform cross-calibration of detector responses and energy scales under common observation conditions. This project is being developed and tested at the TA site. The IceCube-Gen2 prototype detectors are installed at the TALE infill site to evaluate surface scintillator and radio detector performance under the same environmental conditions as the TA. This activity strengthens the synergy between cosmic-ray and neutrino observatories. The Fluorescence detector Array of Single-pixel Telescopes (FAST) project is also operated at the TA site, developing a low-cost, wide field-of-view fluorescence detection technique suitable for future large-scale UHECR observatories [43]. The Cosmic Ray Air Fluorescence Fresnel-lens Telescope (CRAFFT) project tests a compact Fresnel-lens optical system for the detection of air-shower fluorescence light [44]. Finally, the Global Cosmic Ray Observation System (GCOS) project aims to establish a worldwide network of air-shower observatories to achieve full-sky coverage and long-term monitoring of UHECRs [45]. This project is envisioned as a future extension building upon the infrastructure and experience of the TA. These ongoing developments highlight the TA site as an active hub for experimental innovation and international collaboration in cosmic-ray research.

5. Summary and Future Prospects

Status of the TA detectors. The TA experiment operates a hybrid detection system consisting of SDs and FDs, which have been fully operational since May 2008. The low-energy extension, TALE, has operated its FDs since September 2013, and the hybrid triggers between TALE FDs and SDs have been running since September 2018. A new dense array with 100 m spacing, the TALE infill SD array, has been in operation since October 2023. The high-energy extension, TAx4, expands the aperture by a factor of four with 257 new SDs (out of 500 planned) and two new FD stations, covering an area of approximately 1700 km^2. The north FD station has been running stably since June 2018, the south FD since September 2020, and the SD array since November 2019.

Energy spectrum. The combined energy spectrum measured with the TA and TALE detectors covers more than five orders of magnitude between $10^{15.3}$ and $10^{20.4}$ eV. A declination dependence is reported, showing a discrepancy between the full-aperture TA spectrum and the simultaneous fit with Auger data. The energy spectrum obtained with the new TAx4 SD array is found to be consistent with that measured by the main TA SD array.

Anisotropy. The TA hotspot above $E > 57$ EeV [22] is updated with the latest data, and its statistical significance is estimated to be 2.9σ. An excess around the PPSC is observed at $E > 10^{19.4}$ eV with a significance of 3.0–3.2σ. An extremely energetic cosmic-ray event with $E = 244 \pm 29\,(\text{stat.})^{+51}_{-76}\,(\text{syst.})$ EeV was detected in the direction of the Local Void. The arrival directions of events above 100 EeV suggest that either a heavy composition or strong extragalactic magnetic fields are required for consistency with the LSS model. A correlation with nearby starburst galaxies is studied jointly by the Auger and TA collaborations, and a significance of 4.2σ is reported.

Mass composition and neutral particle searches. The TALE FD results show a light–to–heavy–to–light transition in the energy range from 10^{15} eV to 10^{18} eV, and a distinct break in the mean $X_{\max}$ at around $10^{17.2}$ eV. Upper limits on the fluxes of UHE photons are updated, and new upper limits on UHE neutrino fluxes are obtained from 16 years of TA SD data.

Future prospects. Analyses with the TAx4 SD and FD data are ongoing to study the properties of the highest-energy cosmic rays. Software developments for SD event reconstruction are actively progressing, including studies on energy-dependent systematics and deep-learning–based reconstruction techniques. Hardware developments for the current and next-generation detectors, such as calibration systems, dense arrays, and new optical devices, are also under continuous development at the TA site. These efforts will further improve the energy scale, exposure, and composition measurements, leading to a deeper understanding of the origin and nature of UHECRs.

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