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Highlights from the Telescope Array Experiment

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Abstract

The Telescope Array (TA) is the largest hybrid cosmic ray detector in the Northern Hemisphere, which observes primary particles in the energy range from 2 PeV to 100 EeV. The main TA detector consists of 507 plastic scintillation counters on a 1.2-km spacing square grid and fluorescence detectors at three stations overlooking the sky above the surface detector array. The TA Low energy Extension (TALE) detector, which consists of ten fluorescence telescopes, and 80 infill surface detectors with 400m and 600 m spacing, has continued to provide stable observations since its construction completion in 2018. The TAx4, a plan to quadruple the detection area of TA is also ongoing. About half of the planned surface detectors have been deployed, and the current TAx4 continues to operate stably as a hybrid detector. I review the present status of the TA experiment and the recent results on the cosmic-ray anisotropy, mass composition and energy spectrum.

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Contents

1 Introduction

The Telescope Array (TA) is the largest ultra-high-energy cosmic-ray (UHECR) observatory in the northern hemisphere. The main goal is to explore the origin and nature of UHECRs by measuring the energy spectrum, arrival direction distribution and mass composition.

The TA detector is located in Utah in the U.S.A. and consists of a surface array of 507 plastic scintillator detectors (SD) [1], which is overlooked by three stations of fluorescence detectors (FD). The SDs are deployed on a square grid with 1.2-km spacing, and the SD array covers an area of approximately 700 km^2. Each individual SD has two layers each of a 1.2-cm-thick scintillator with an area of 3 m^2. The full operation of the SDs started in March 2008, and the duty cycle is greater than 95%. Two FD stations are located at the Black Rock Mesa (BR) and Long Ridge (LR) sites [2], respectively. At each station, 12 fluorescence telescopes, each with 256 photomultipliers (PMTs), cover a total field of view of 3—31° in elevation angle and 108° in azimuthal angle. The northern FD station situated at the Middle Drum (MD) site consists of 14 telescopes refurbished from the HiRes-1 telescopes [3], which were arranged to view $\sim$120° in azimuthal angle. All three FD stations started the observation in November 2007, and they have duty cycles of approximately 10%. Hybrid cosmic-ray events, which are detected simultaneously by FD and SD, are used to cross-check the SD energy by using the FD energy measurements and to improve mass composition identification from longitudinal shower profiles measured with the FD by the inclusion of SD information that better determines the directions of air-shower axes.

The TALE enables detailed studies of the energy spectrum and composition at energies over $\sim 10^{16}$ eV. The main goal of the TALE is to clarify the expected transition from galactic to extragalactic cosmic rays. The TALE FD station is located at the MD site and consists of 10 telescopes refurbished from HiRes-2 [4] and has a field of view of 31—59° in elevation angle. A total of 80 TALE SDs are operating. The data acquisition is ongoing with the hybrid trigger from FD. Additionally, information on timing around the cores of cosmic-ray air showers measured by SDs is expected to improve the event reconstruction accuracy of the FD measurement. Consequently, mass composition measurements from the longitudinal shower profile with FD are expected to be improved. Further low energy extension with hybrid mode is planned with 45 SDs with 100-m spacing and 9 SDs with 200-m spacing. The target energy range is $E > 10^{15}$ eV. The counters were assembled in October 2021.They will be deployed in 2022.

With enhanced statistics, we expect to verify the hotspot [5] along with other anisotropy results. We intended to quadruple the TA aperture (TAx4), including the TA SD array by installing 500 SDs at 2.08-km spacing [6]. The construction started in 2015 by reviewing the TA scintillator detector components. A total of 257 SDs were deployed in February and March 2019 [7]. The array is 2.5 times larger than the TA SD array. The additional array started stable data acquisition in November 2019. The new array requires two FD stations overlooking the SD array to increase the number of detected hybrid events and to calibrate the energy measured by SD. These FDs are formed using refurbished HiRes telescopes. The first light was observed by the FDs at the northern site and southern site in February 2018 and October 2019, respectively. The layout of the TAx4 SD and FD including TA and TALE is shown in Fig. 1.

In this report, the TA results on spectrum, composition and anisotropy are described in Section 2, Section 3 and Section 4, respectively. Section 5 concludes this report [8].

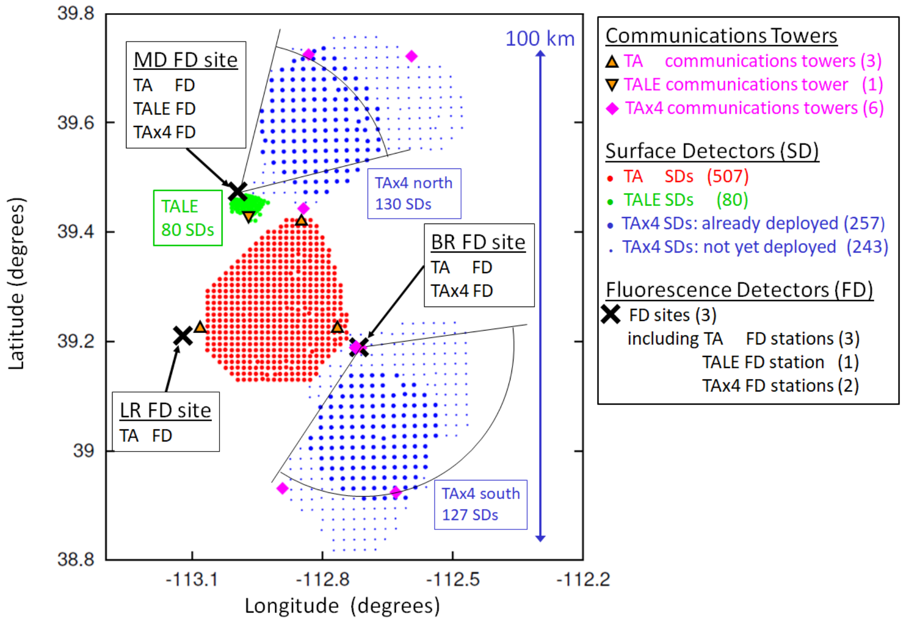

Figure 1: The layout of TA, TALE and TAx4. The symbols for the layout are explained on the right side of the plot. Numbers in parentheses indicate the number of detectors.

2 Energy spectrum

A preliminary result of the cosmic-ray spectrum for 11 years of TA SD data is shown above $10^{18.2}$ eV in Fig. 2 (left) [9]. The TA confirmed the ankle at $10^{18.69\pm0.01}$ eV and the flux suppression above $10^{19.81\pm0.03}$ eV, which is consistent with the Greisen-Zatsepin-Kuzmin cutoff prediction [10,11]. The statistical significance of the difference between the observed cosmic-ray flux above the cutoff and the expected one from the extrapolation of the flux with the spectral index between the ankle and the cutoff (no suppression) is $\sim 8.4\sigma$.

Fig. 2 (right) [12] shows the preliminary result of TAx4 SD spectrum, which is consistent with the TA SD spectrum. Hereafter, when referring to TAx4 results, it means results using only data from 257 SDs deployed for TAx4 in 2019. The monocular energy spectrum using the additional TAx4 FD [13] and the energy spectrum using the hybrid analysis with TAx4 [14] are also consistent with the TA SD spectrum.

The energy spectra measured by the Pierre Auger Observatory (hereafter Auger) [15] in the southern hemisphere and by the TA [9] in the northern hemisphere agree well for energies $(0.1\text{–}2.5) \times 10^{19}$ eV after rescaling the energies by +4.5% for Auger and −4.5% for TA, whereas there is a significant discrepancy between the two results at the suppression [9]. When we compare the energy spectra in the common declination band $(-15^\circ < \delta < +24.8^\circ)$ after the ±4.5% rescalings, the differences are smaller, but the persistent differences require an additional energy rescaling in an energy-dependent way (±10%/decade for $E > 10^{19}$ eV) to get an agreement [16].

As shown in Fig 3, the TA SD data over 11 years yield the cutoffs at $10^{19.64\pm0.04}$ eV and $10^{19.84\pm0.02}$ eV for declinations of $-16^\circ < \delta < 24.8^\circ$ and $24.8^\circ < \delta < 90^\circ$, respectively. The pretrial significance of the difference of these two cutoffs is 4.7σ. The chance probability of exceeding the pretrial significance for an isotropic distribution is 8.5×10^{-6} or 4.3σ [9]

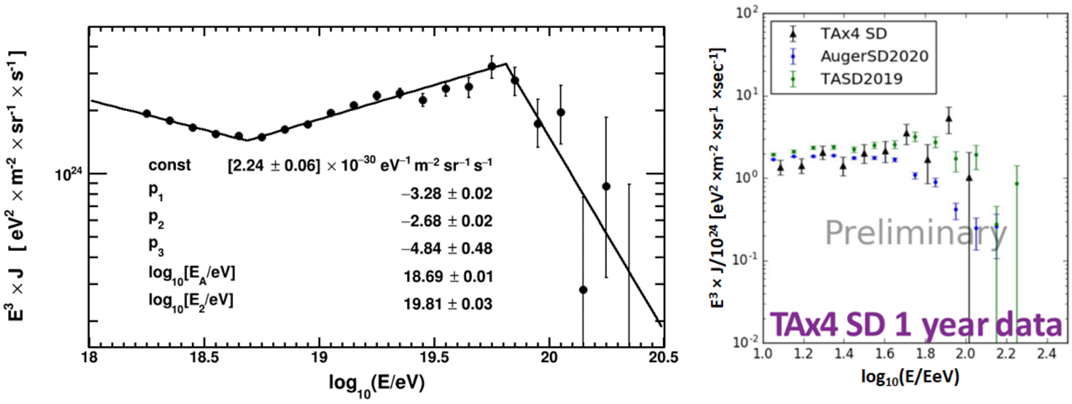

Figure 2: (Left) The TA cosmic-ray flux multiplied by E^3 measured using 11 years of data from the TA SD [9]. The solid line shows the fit of the TA data to a broken power law. (Right) The preliminary spectrum using the first one year of the TAx4 SD data [12] in black together with the Auger spectrum [15] in blue and the TA SD spectrum [9] in green.

The TALE FD measures a spectrum with mixed Cherenkov and fluorescence signals. The energy spectrum collected by the TALE FD monocular measurement over 22 months was published in [18]. Fig. 4 (left) [17] shows the TA combined spectrum, which is made by combining the TA SD and TALE FD spectra. The range of energies below $10^{18.2}$ eV is covered by the TALE FD, while the energy range above $10^{18.2}$ eV is covered by the TA SD. We see three features in the energy spectrum: the knee at approximately $10^{15.5}$ eV, the low-energy ankle at $10^{16.22\pm0.02}$ eV and the second knee at $10^{17.04\pm0.04}$ eV. Fig. 4 (right) shows the preliminary spectrum using 2.5 years of TALE hybrid data, which is consistent with other TA/TALE spectra within systematic uncertainties [19].

A new feature above 10^{19} eV, called the shoulder or instep, was first reported by Auger, of which field of view is concentrated in the southern sky [20]. We performed a joint fit of TA SD, TA Black Rock (BR) - Long Ridge (LR) monocular FD and HiRes I monocular spectra in the northern hemisphere into a thrice broken power law. To ensure statistical independence, the TA monocular FD observation period was removed from the TA SD spectrum measurement. The shoulder feature as shown in Fig. 5 was found at $10^{19.25\pm0.03}$ eV with a statistical significance of 5.3σ [17].

3 Composition

The depth of shower maximum, X_{max}, of extensive air-shower profiles is the key estimate of the mass composition of UHECRs. The results of X_{max} measurements in the energy range between $10^{18.2}$ eV and $10^{19.1}$ eV based on the TA hybrid events observed over 10 years are shown in Fig. 6 together with MC predictions of QGSJET II-04 [21] for proton, helium, nitrogen, and iron primaries [22]. We need more statistics to clarify the feature of X_{max} above 10^{19} eV, for example, to more accurately measure the values of the mean X_{max} and the width of X_{max}. The model predictions for proton and helium primaries appear to agree with the data within systematic uncertainties.

The X_{max} above $10^{15.3} - 10^{18.3}$ eV was measured using the TALE FD data and a change in the elongation rate was observed at an energy of $\sim 10^{17.3}$ eV [23]. The X_{max} was measured using the TALE hybrid data collected over a period of 2.5 years in the energy range $10^{16.6}$ –

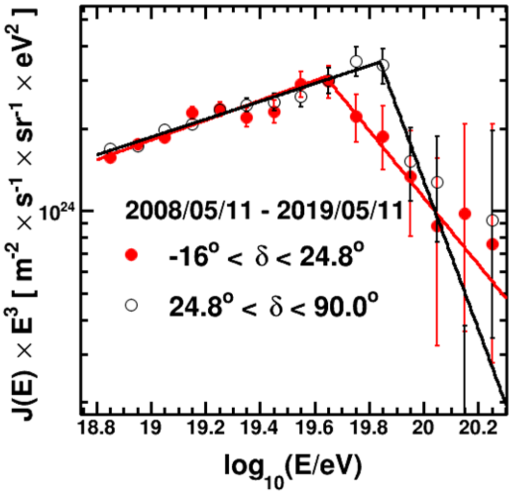

Figure 3: The TA cosmic-ray flux multiplied by E^3 measured using 11 years of data obtained by the TA SD for the upper ($24.8° < \delta < 90°$) and lower ($-16° < \delta < 24.8°$) declination bands with black open circles and red closed circles, respectively [9]. Superimposed lines correspond to the fits of the data to broken power-law functions.

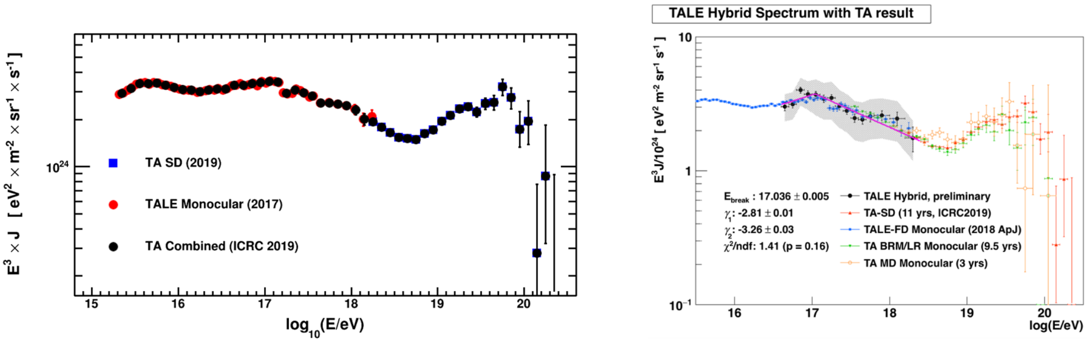

Figure 4: (Left) The TA combined spectrum in black, which is made by combining the TALE FD monocular data in red and the TA SD data in blue [17]. (Right) The preliminary TALE hybrid spectrum in black together with other measurements from TA and TALE [19].

$10^{18.4}$ eV [19]. Figure 7 shows the mean X_{max} as a function of the cosmic-ray energy. The systematic uncertainty on X_{max} is less than 16 g/cm^2. The result is not corrected for a bias of about −10 g/cm^2. We can see a break point at $\sim 10^{17}$ eV, which is likely correlated with the observed softening ($\sim 10^{17}$ eV) in the TALE energy spectrum [18]. The values of the mean X_{max} and the slope of the X_{max} elongation ratio for the TALE hybrid analysis are consistent with those for the TA hybrid analysis at around $10^{18.2}$ eV.

The composition information was also derived by the Boosted Decision Trees (BDT) method using 16 composition sensitive signals from 12 years of TA SD data [25]. The measured mean logarithmic cosmic-ray atomic number $< lnA >$ shows no significant energy dependence above 1 EeV and $< lnA > = 0.90 \pm 0.05(\text{stat.}) \pm 0.30(\text{syst.})$ with the QGSJET II-04 model.

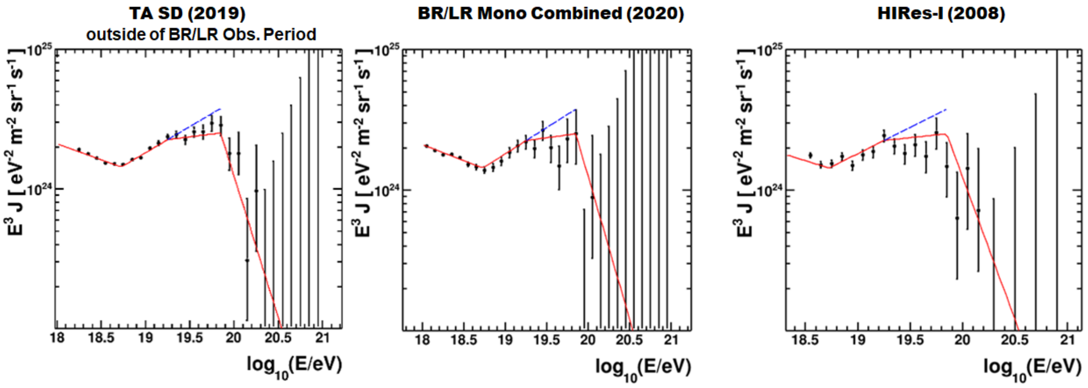

Figure 5: A joint fit [17] to the TA SD (left), TA BR - LR monocular FD (center), and HiRes I monocular energy spectra (right) together with a red fit line with three break points. The significance of the shoulder is obtained by comparing the number of events expected in the absence of the feature (blue line) and the number of events observed by the experiments.

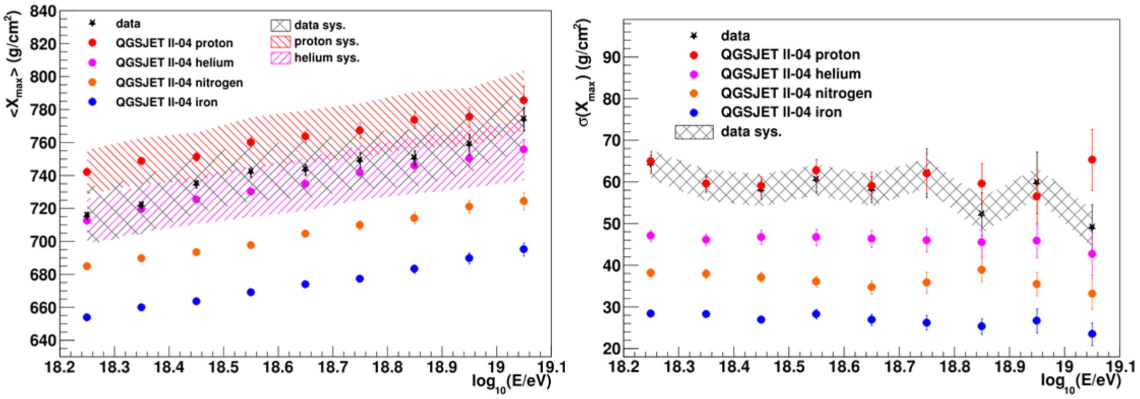

Figure 6: The results of the mean $X_{\max}$ ($< X_{\max} >$) (left) and the width of $X_{\max}$ ($\sigma(X_{\max})$) (right) as a function of the cosmic-ray energy measured from TA hybrid events [22].

4 Anisotropy

The TA has previously reported an indication of an intermediate-scale cluster of cosmic rays with energies over 5.7×10^{19} eV for five years of observation with the TA SD [5]. This TA hotspot result has since been updated using 12 years of data from the TA SD [26]. Figure 8 shows the significance maps of 179 UHECR events with $E > 5.7\times10^{19}$ eV. We found the maximum significance of 5.1σ at R.A.=144.0° and Dec.=40.5° for the oversampling circle with a radius of 25° after searching for the maximum significance in circles with all grid directions and five different oversampling radii (40 events were observed where 14.6 would be expected). The chance probability of the 12-year hotspot in an isotropic sky is estimated to be 6.8×10^{-4} or 3.2σ.

Now we lower the energy threshold slightly. The significances of the TA 11-year data at energies $\log_{10}(\mathrm{E/eV}) > 19.4$, 19.5, and 19.6 by the oversampling analysis with 20°-radius circle are 4.4σ, 4.2σ, and 4σ, respectively (see Fig. 9). A new excess was found in the direction of the Perseus-Pisces Supercluster. For $\mathrm{E} > 10^{19.6}$ eV, the chance probability of the excess within 6.8° from the supercluster center is 3.5σ.

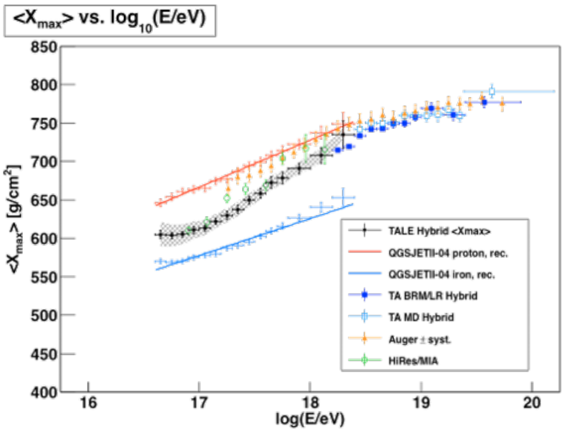

Figure 7: The preliminary result of $< X_{\max} >$ of the reconstructed TALE hybrid events as a function of energy [19]. The $< X_{\max} >$ values for proton and iron MC primary elements, using QGSJET II-04, are also shown.

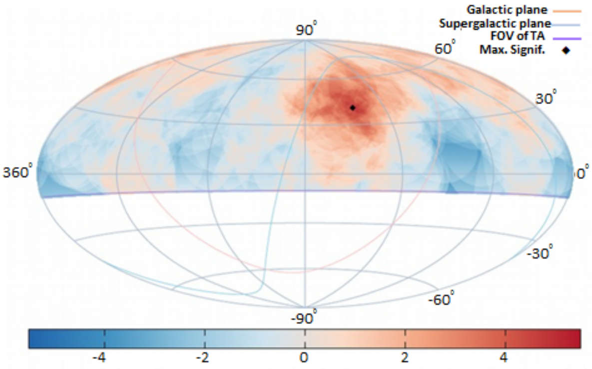

Figure 8: The statistical significance of UHECR events with $E > 5.7 \times 10^{19}$ eV in equatorial coordinates [26]. The TA events observed over 12 years are smoothed by the 25° oversampling radius circle. The solid red and blue curves indicate the galactic (GP) and supergalactic (SGP) planes, respectively.

5 Conclusion

TA confirmed the ankle at $10^{18.69}$ eV and the flux suppression above $10^{19.81}$ eV in the energy spectrum of UHECRs. The shoulder feature in the energy spectrum in the northern sky was found at $10^{19.25}$ eV. We confirmed the breaks at $10^{16.22}$ eV and $10^{17.04}$ eV in the energy spectrum measured using the data observed with the TALE FD.

The TA hybrid $X_{\max}$ measurements for the energy band $10^{18.2}$–$10^{19.1}$ eV are consistent with a light composition, in particular, with predictions of QGSJET II-04 proton and helium. We need more statistics to clarify the feature of $X_{\max}$ above 10^{19} eV. For the TALE FD $X_{\max}$ results in the energy range $10^{15.3} - 10^{18.3}$ eV, a change in the elongation rate was observed at an energy of $\sim 10^{17.3}$ eV, which is likely correlated with the observed break at $10^{17.04}$ eV in the TALE FD energy spectrum.

We obtained 179 events above 5.7×10^{19} eV in 12 years of observation with the TA SD. We found a maximum pretrial significance of 5.1σ when using a circle with a 25° oversampling radius. The post-trial significance of detecting such clustered events by chance in the isotropic arrival distribution is estimated to be 3.2σ. Evidences for some features of anisotropy are found, for example, as a declination dependence of spectrum cutoff in the energy spectrum,

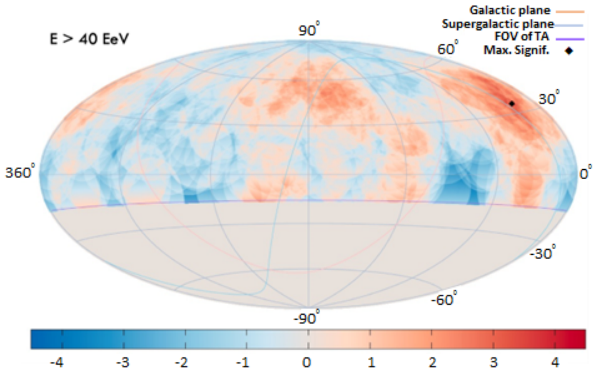

Figure 9: The statistical significance of UHECR events with $E > 4\times10^{19}$ eV in equatorial coordinates [26]. The TA events observed over 11 years are smoothed by the 20° oversampling radius circle. The solid red and blue curves indicate the galactic (GP) and supergalactic (SGP) planes, respectively.

and a new excess in the direction of Perseus-Pisces Supercluster using a slightly lower energy threshold.

To confirm the TA hotspot and understand its features, we proposed a plan, which we call the TAx4, to quadruple the TA SD aperture and add two FD stations. The 257 TAx4 SDs were deployed in 2019, and currently the total area is 2.5 times the TA SD. Two TAx4 FD stations are operating.

The 80 TALE SDs were deployed at the TALE site. The preliminary result of the spectrum and X_{max} using the TALE hybrid data was presented in this conference. The TALE infill SD array is planned to further lower the energy threshold for the TALE hybrid analysis.

The TA, TAx4, and TALE will provide important measurements of the energy spectrum, composition, and arrival directions of UHECRs from the knee region up to the highest-energy region spanning five to six decades in energy.

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