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Latest results of ultra-high-energy cosmic ray measurements with prototypes of the Fluorescence detector Array of Single-pixel Telescopes (FAST)

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The origin and nature of ultra-high-energy cosmic rays (UHECRs) remain an open question in astroparticle physics. Motivated by the need for an unprecedented aperture for further advancements, the Fluorescence detector Array of Single-pixel Telescopes (FAST) is a prospective next-generation, ground-based UHECR observatory that aims to cover a huge area by deploying a large array of low-cost fluorescence detectors. The full-scale FAST prototype consists of four 20 cm photomultiplier tubes at the focus of a segmented mirror 1.6 m in diameter. Over the last five years, three prototypes have been installed at the Telescope Array Experiment in Utah, USA, and one prototype at the Pierre Auger Observatory in Mendoza, Argentina, commencing remote observation of UHECRs in both hemispheres. We report on the latest results of these FAST prototypes, including telescope calibrations, atmospheric monitoring, ongoing electronics upgrades, development of sophisticated reconstruction methods, and UHECR detections.

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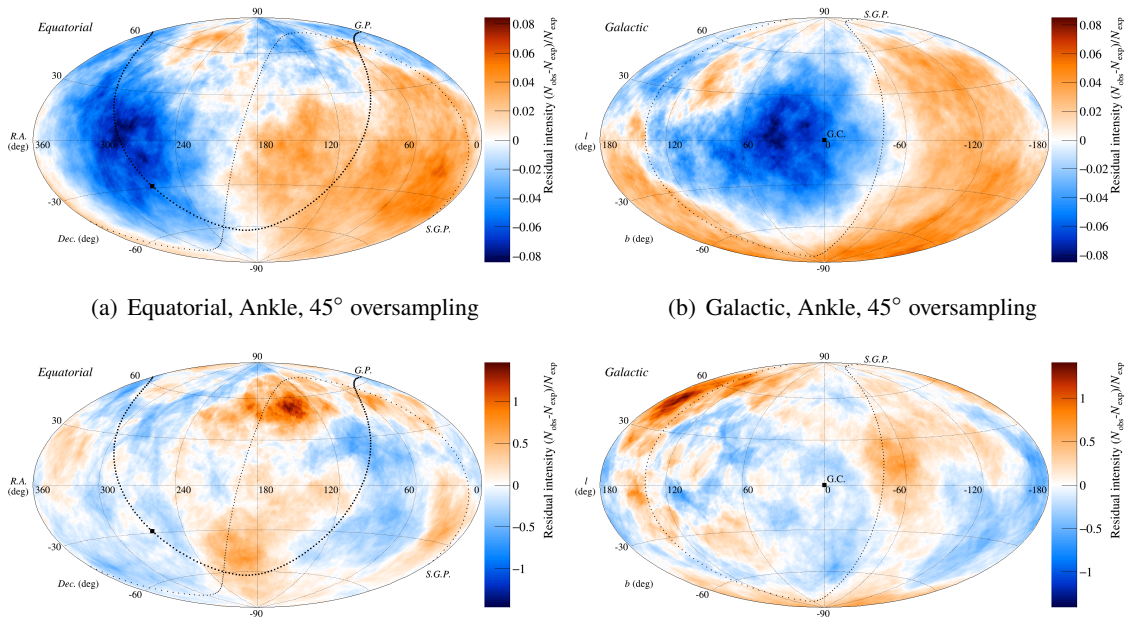
1. Detection of ultra-high-energy cosmic rays

Since the discovery of cosmic rays above 100 EeV ($\equiv 10^{20}$ eV) in 1963 [1], scientists have constructed increasingly-large observatories to detect ultra-high-energy cosmic rays (UHECRs). UHECR sources and acceleration mechanisms at the highest energies are still largely unknown [2], making them one of the most intriguing mysteries in particle astrophysics. Since they are deflected less strongly by magnetic fields (due to their enormous kinetic energies), their arrival directions are more significantly correlated with their sources. Charged-particle astronomy with UHECRs is hence a potentially viable probe of extremely energetic phenomena in the nearby universe.

Two well-established methods are used for UHECR detection: arrays of detectors (e.g. plastic scintillators or water-Cherenkov stations) that sample extensive air shower (EAS) particles at the ground level and large-field-of-view telescopes that directly measure atmospheric shower development by observing ultra-violet nitrogen fluorescence. The two largest UHECR observatories are hybrid detectors that combine both techniques, employing arrays of ground detectors overlooked by fluorescence detectors (FDs). These are the Pierre Auger Observatory (Auger) in Mendoza, Argentina [3], and the Telescope Array Experiment (TA) in Utah, USA [4, 5].

Recent results have shown novel structures at higher energies. Figure 1 shows full-sky maps of residual intensities measured by both Auger and TA observatories above the "ankle" energy of ∼10 EeV and the "cutoff" energy of ∼50 EeV, calibrated by an energy scale from the common declination band's flux [6, 7]. Auger reported a large-scale dipole anisotropy above 8 EeV of 6.5% amplitude with a 5.2σ significance [8], which supports an extragalactic origin for these particles.



(a) Equatorial, Ankle, 45° oversampling

(b) Galactic, Ankle, 45° oversampling

(c) Equatorial, Cutoff, 20° oversampling

(d) Galactic, Cutoff, 20° oversampling

Figure 1: Residual intensity sky-maps in Equatorial and Galactic coordinates: (a, b) above the ankle energy, with a 45° top-hat oversampling; and (c, d) above the cutoff energy with a 20° top-hat oversampling. The event data are taken from [6, 7].

Auger also has reported a 4.0σ correlation between the positions of nearby starburst galaxies and the arrival directions of 9.7% of their measured UHECR events above 39 EeV [9]. TA has measured an excess of cosmic rays above 57 EeV as a "hotspot" centered at a right ascension of 147° and a declination of 43° with a 3.4σ significance [10] and has also reported results consistent with Auger for the dipole search [11] and the flux pattern analysis [12].

Further results at the highest energies are limited by statistics due to sharp attenuation of the spectrum. Future ground arrays will require an unprecedented aperture (exceeding current experiments by an order of magnitude) and mass composition sensitivity above 100 EeV. Future detectors should hence be low-cost and easy to deploy, operate and maintain. A worldwide collaboration is necessary to construct such an array.

2. Fluorescence detector Array of Single-pixel Telescopes (FAST)

One way to achieve this unprecedented aperture is a ground-based fluorescence detector array. The Fluorescence detector Array of Single-pixel Telescopes (FAST)[1] features compact FD telescopes with a smaller light-collecting area and far fewer pixels than current-generation FD designs, leading to a significant reduction in cost that allows for the production of more FD units.

In the FAST design, a 30° × 30° field-of-view is covered by four 20 cm photomultiplier-tubes (PMTs) at the focal plane of a compact segmented mirror of 1.6 m diameter [14]. Its smaller light-collecting optics, smaller telescope housing, and fewer number of PMTs significantly reduces its cost to be ~35 kUSD per telescope. Each FAST station would consist of 12 such telescopes, covering 360° in azimuth and 30° in elevation. These stations would be deployed in a triangular array with a 20 km spacing, suggested by simulations. Figure 2 shows the simulated waveforms from

[1] https://www.fast-project.org

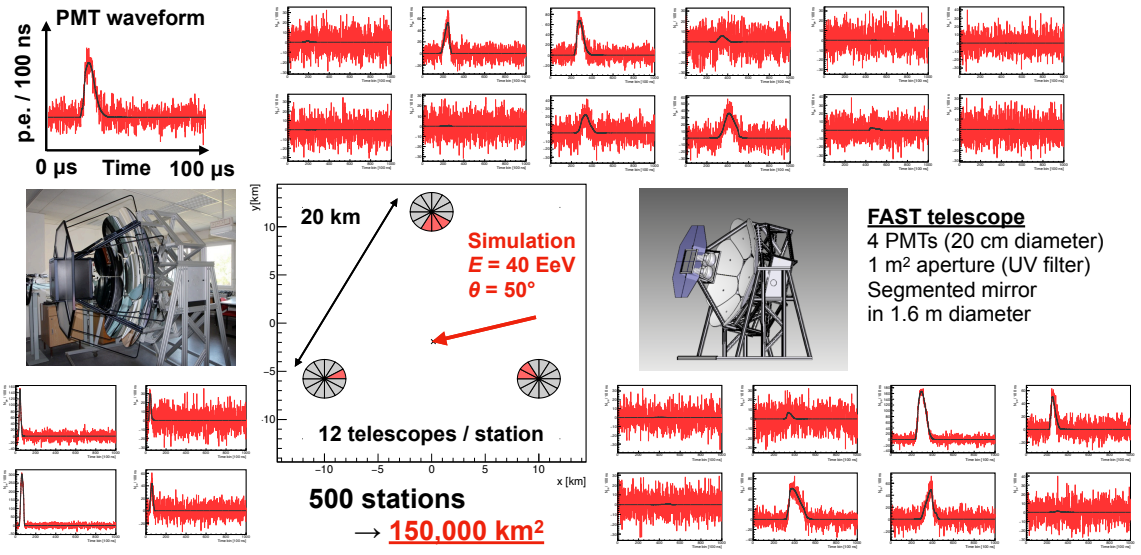


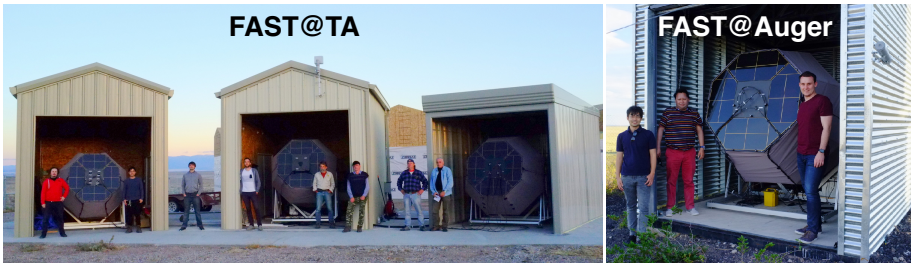
Figure 2: The Fluorescence detector Array of Single-pixel Telescopes: a possible solution for a future giant ground array [13]. The traces show simulated signals emitted from a UHECR with an energy of 40 EeV and a zenith of 50°.

a UHECR shower detected in 3-fold coincidence by such an array. To achieve our aperture goals, 500 stations covering 150,000 km^2 are required, after accounting for the standard FD duty-cycle and additional moon-night operation.

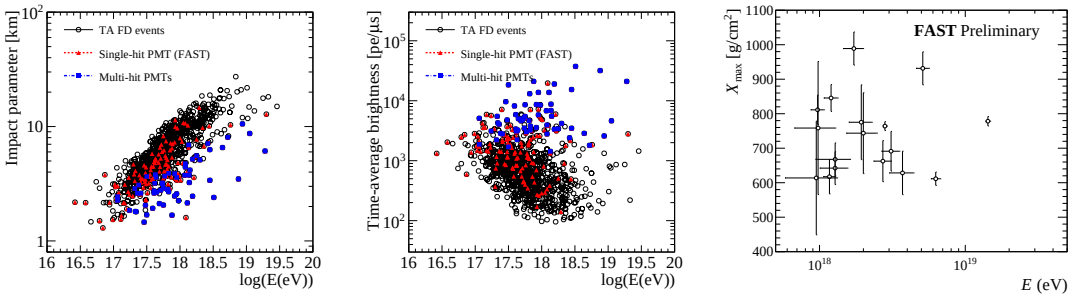
3. Progress of developments on the FAST prototypes

Motivated by UHECR detections with a single 20 cm PMT at the focus of a 1 m^2 Fresnel lens in 2014 [13], we installed three full-scale FAST prototypes at the TA site from 2016 to 2019, as shown in Figure 3(a)-left [15]. We assembled the telescope frames on-site, mounted the PMTs in their camera boxes, and installed ultra-violet band-pass filters at their apertures. We then astrometrically aligned the telescopes using a camera mounted to their frames' exteriors [14]. Following this, we began observation via remote connection, using external triggers from the adjacent TA fluorescence detector. We used an automated all-sky monitoring camera to record cloud coverage and atmospheric transparency [16]. As shown in Figure 3(a)-right, an identical FAST prototype was also installed at the Auger site for a cross-calibration of energy and $X_{\rm max}$ scales.

Analyzing 224 hours of data measured by the FAST prototypes at the TA site from March 2018 to October 2019, we found 964 showers with corresponding monocular reconstructions from the TA FD [17]. We searched for significant signals (defined as a $\geq 6\sigma$ signal-to-noise ratio over ≥ 500



(a) FAST prototypes installed at TA and Auger observatories

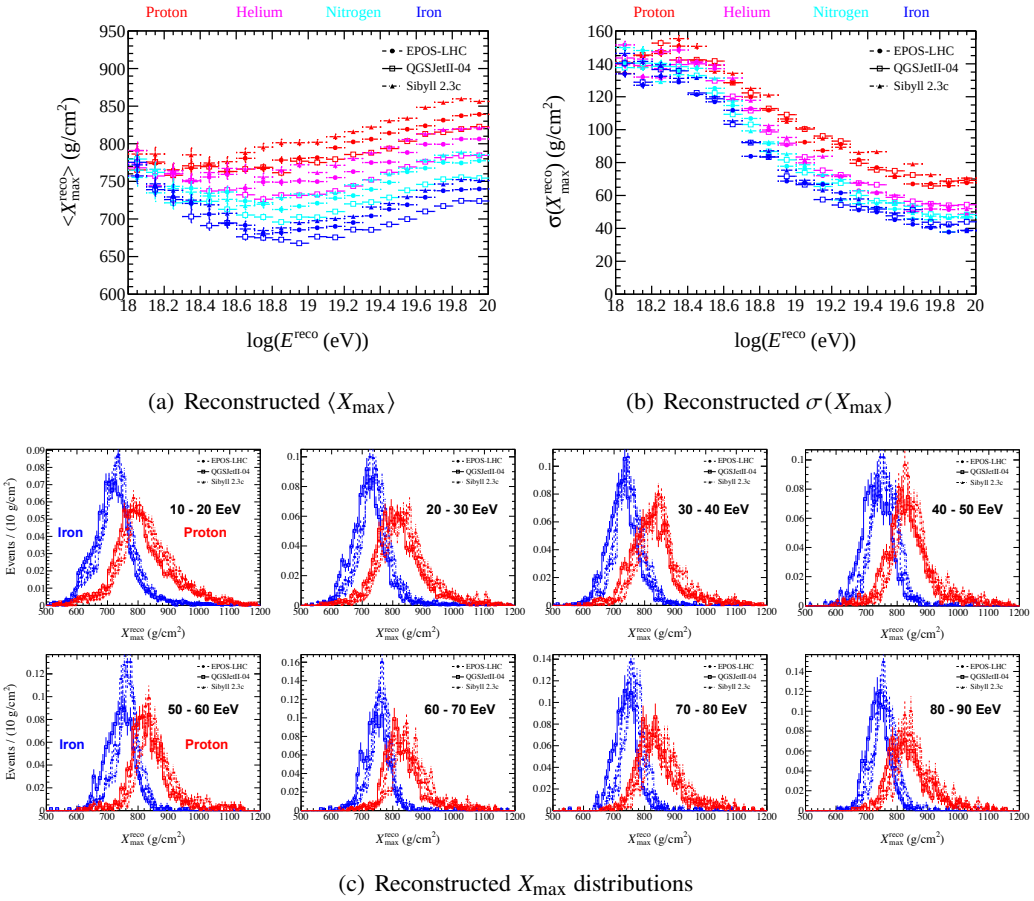


(b) Impact parameter for coincidences between TA FD and FAST

(c) Time-average brightness for coincidences between TA FD and FAST

(d) Energy and $X_{\rm max}$ reconstructed by FAST top-down reconstruction

Figure 3: (a) The three FAST prototypes installed at the Black Rock Mesa site of the Telescope Array Experiment and the one prototype installed at Los Leones site of the Pierre Auger Observatory. (b) Impact parameter and (c) time-average brightness for the coincidence search between TA FD and FAST. (d) Preliminary result of top-down Energy and $X_{\rm max}$ reconstructions for multi-hit events above 1 EeV.



(a) Reconstructed $\langle X_{\max} \rangle$

(b) Reconstructed $\sigma(X_{\max})$

(c) Reconstructed $X_{\max}$ distributions

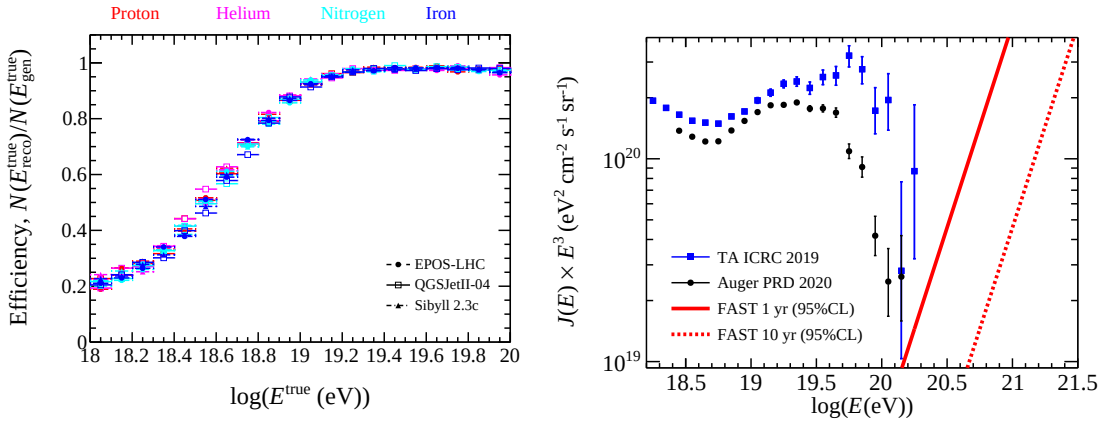
Figure 4: Reconstruction bias on (a) $\langle X_{\max} \rangle$ and (b) $\sigma(X_{\max})$ evaluated by only the neural network first-guess estimation. (c) Reconstructed $X_{\max}$ distributions in each energy bin.

nanoseconds) in time coincidence with these FD events and found 179 significant FAST events out of the 964 TA EASs, with 59 events producing significant signals in more than one PMT. Figure 3(b) and (c) show the impact parameter and time-average brightness of the detected EASs as a function of energy, split by single-PMT and multi-PMT events. These parameters are reconstructed by the TA FD.

A "top-down" reconstruction algorithm has been implemented that determines the best-fit shower parameters by comparing our measured traces to the simulated ones [15]. Because FAST features only four pixels, rather than use the entry and exit times for each pixel as traditional reconstruction methods do, we extract timing information from each individual bin of the traces. Figure 3(d) shows preliminary $X_{\max}$ and energy values reconstructed by this method for multi-hit events above 1 EeV using only FAST prototypes.

4. Neural network first-guess estimation

The top-down reconstruction requires a reasonable first-guess geometry to reduce computational time. This is provided by a neural network first-guess estimation [20]. The total signal,



(a) 3-fold Trigger efficiency

(b) Expected sensitivity of full FAST array

Figure 5: (a) Trigger efficiency for 3-fold detections with a hypothetical FAST array. (b) Expected 95% C.L. detectable sensitivities of the energy spectrum with the full FAST array of 500 stations compared to the spectra reported from TA [18] and Auger [19].

centroid time, and pulse height of each PMT with a significant signal are used as inputs. The outputs are six parameters: $X_{\rm max}$, energy, zenith, azimuth, and west-east/south-north core positions. The model uses the Keras/Tensorflow library with two hidden fully-connected layers.

The resolution and detection bias on $X_{\rm max}$ are evaluated by only applying this first-guess estimation for EASs of four primaries (proton, helium, nitrogen, and iron) with three hadronic interaction models (EPOS-LHC, QGSJetII-04 and Sibyll 2.3c) [21]. The EASs are generated with uniformly-distributed arrival directions and core positions randomly generated in the triangular array's inner circle. The resolutions are 4.2 degrees in arrival direction, 465 m in core position, 8% in energy, and 30 g/cm^2 on $X_{\rm max}$ at 40 EeV for 3-fold coincidences without any quality cuts. Figure 4 shows a preliminary detection bias on $\langle X_{\rm max}\rangle$ and $\sigma(X_{\rm max})$, and also reconstructed $X_{\rm max}$ distributions in each energy bin. Note that this performance is evaluated by only the neural network first-guess estimation. The full-chain performance of both top-down reconstruction and neural network first-guess estimation is being investigated.

The trigger efficiency for 3-fold detections is shown in Figure 5(a). The FAST array has a 100% efficiency above 20 EeV. The energy threshold is related to the bias on the average $\langle X_{\rm max}\rangle$ and $\sigma(X_{\rm max})$ as shown in Figure 4. Figure 5(b) is the expected sensitivity on the energy spectrum with a full-size FAST array. We use an effective exposure of 90,000 km^2 sr per year to estimate our detectable flux at the 95% confidence level. A full-sized FAST array will extend UHECR measurements beyond 300 EeV.

5. Developments for stand-alone observation of FAST array

Since these tests, several advances have been made: improvements in our telescope design, development of electronics with low-power consumption, and improvements in PMT calibration systems, as shown in Figure 6. The improved electronics is particularly important as previous tests have capitalized on the infrastructure of existing FD detectors. These new electronics will allow for

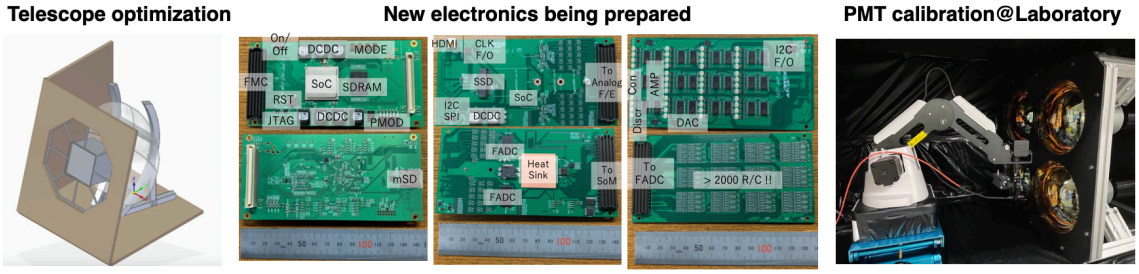


Figure 6: Developments for future stand-alone operations: the lighter telescope frame and mirror design with fewer pieces, the new electronics under development, and the PMT calibration system using a robotic arm.

the first deployment of an independent, solar-powered FAST station, as well as permit stand-alone observation with the FAST array, an important step in validating our design and testing our expected resolution. The potential infield calibration could be performed using an extended uniform light source such as the integrating sphere [22].

6. Summary

We have developed a low-cost, easily-deployed fluorescence detector optimized for detection of the highest energy cosmic rays in anticipation of a future array with 30,000 km^2 of effective coverage. Three FAST prototypes have been installed at the Telescope Array Experiment, and one prototype has been installed at the Pierre Auger Observatory. We have begun observations in both hemispheres and have demonstrated the viability of sophisticated, novel reconstruction methods. We will continue the steady operation of all four FAST prototypes and developments stand-alone observations with the FAST array.

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