The Telescope Array

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Abstract

The Telescope Array is the largest cosmic ray observatory in the northern hemoisphere. It consists of three telescope stations observing the sky over an array of 507 scintillator surface detectors spread over more than 700 square km in area. The observatory has been in operation since 2008 and measures the nature and origin of ultra high energy cosmic rays. The most recent results on the spectrum, composition, and anisotropy are reported. In addition, we have begun TALE, the Telescope Array Low Energy Extension. Status and preliminary data are presented.

1 Introduction

The Telescope Array is the largest ultra High energy cosmic ray observatory in the northern hemiphere. The observatory is sited in the west desert of Utah about 2.5 hours south of Salt Lake City. The apparatus consists of an array of 507 scintillator surface detectors spread over more than 700 square km. These sample the desnsity of particles in the footprint of cosmic ray induced extensive air showers. In addition, there are three telescope stations on the periphery of the array which view the sky over the scintillator array. The telescopes measure the longitudinal development of the air shower via the UV excitation light generated by the air shower as the shower traverses the atmosphere.

The surface detectors are composed of two layers of half inch thick scintillator extruded with grooves in it. Wavelength shifting optical fibers run through the grooves. They gather the light and direct it to two PMTs, one per layer. The area of an individual detector is 3 m^2 and they are deployed on a 1.2 km square grid. The scintillators are powered by solar panels and batteries and they communicate with towers near the telescope stations via 2.4 GHz radio. Industrial PCs at the towers form triggers and record data.

Every 10 minutes, each SD calibrates itself using the pulse distribution from minimum-ionizing cosmic muons. The signal from each PMT is digitized at 50 MSPS. Data is stored for pulses that exceed 0.3 vertical equivalent muons (VEM). An array trigger is formed when 3 adjacent counters report ≥ 3 VEM in time coincidence. Once a trigger has formed, the tower polls all counters and all stored pulses in the trigger window are recorded. Twice per day, the data is transfered ny radio from the tower back to the nearby town of Delta for storage on a PC at the Cosmic Ray Center. The scintillator array runs 24/7 with near 100% on time.

The telescope stations are on a $\sim$30 km triangle and view the sky over the scintillator array. The northern station reutilizes 14 $\sim$2 m diameter telescopes from the High Resolution Fly's Eye (HiRes) observatory. Each of the two stations in the south is instrumented with 12 newer telescopes with $\sim$3 m telescopes. In all cases, the telescopes have 256 hexagonal PMTs in a hexagonal close pack geometry and the PMTs view 1° of sky. The stations each view 3-31° in elevation. The telescopes operate on clear moon-less nights with $\sim$10% duty-cycle.

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2 Energy Spectrum

The sintillator array has the greatest number of events. The energy spectrum of ultra high energy cosmic rays from this data set is shown in figure 1. The Telescope Array measurements are in excellent agreement with the previous measurements by the HiRes experiment. Using the 6 year data set, break point for the GZK cut-off is found to be $10^{19.74\pm0.04}$ eV. Integrating an unbroken line from $10^{19.8}$ - 10^{21} eV, one would expect to find ∼86 events in this range, while we actually observe 32 events. Hence, the significance of the cut-off is $\sim 6.6\sigma$.

The spectrum is also in agreement with the Auger spectral measuerments below $\sim 10^{19.3}$ eV when the Auger energies are scaled up by 10%, which is well within the undertainty of both experiments. However, for $E > 10^{19.3}$ eV, the two spectra appear to diverge. Understanding this discrepancy is one area of joint study between the two groups.

3 Composition

The main means by which the Telescope Array measures chemical composition of the primary cosmic rays is via the Xmax technique.

The longitudinal development of the shower depends upon the chemical composition of the primary particle. In general, an iron primary will begin its shower earlier and reach shower maximum (Xmax) higher in the atmosphere. The protons will reach the point of maximum development 100gm/cm^2 deeper into the atmosphere. There is much overlap between the two distributions, so one can not determine the composition on an event-by-event basis, however, statements can be made about sets of events.

The fluorescence telescopes measure the longitudinal development of the extensive air shower and after taking into account the geometrical and light scattering effects, one can find the number of charged particles as a function of depth into the atmosphere. The HiRes-MIA experiment found that the composition was primarily heavy (iron-like) around 10^{17} eV, but became lighter with energy, becoming protonic by 10^{18} eV. The HiRes-MIA experiment was followed by the HiRes stereo experiment. Stereo measurement has the advantage that one gets a redundant measurement of the shower's development and Xmax. The HiRes Stereo measurements indicated a composition that was light, protonic, from 10^{18} eV to the highest energies.

The Auger experiment also looks at shower development and Xmax to determine composition. However, it uses a hybrid technique where the information from the array of surface detectors is used to constrain the shower geometry. With this constraint, the fluorescence telescope is able to get a more precise geometry which aids in determining energy and Xmax. They find a composition which is light from 10^{18} - 4×10^{18} eV, but then becomes increasingly heavier at higher energies.

At Telescope Array, we wanted to determine if there was any effect in the measurement due to the technique, therefore, we performed a hybrid analysis of Xmax. To improve the quality of the events, we fit each shower profile with two triangles. The first triangle includes the flux and depth of first observation as well as the flux, depth of the fit shower maximum. The second triangle also includes the flux,depth of shower maximum in addition to the flux,depth at the last point of observation. Cuts are made on these two triangles for area included as well as obliquesnes. In this way, we ensure that we are not including showers which are very flat or showers which we have a poor determination of shower maximum, Xmax.

The exact same analysis is performed on both the real data and the Monte Carlo generated (simulated) data. After this analysis, we compare the event distributions for the real data with Monte Carlo simulated proton data and Monte Carlo simulated iron data. In figure 2, we show these distributions in event energy bins. At all energies where there are sufficient statistics to tell, the real data always looks much more like the protons than the iron. We also performed a KS test to determine consistancy of the data with the proton and iron simulations. At all energies $>10^{18}$ eV, the data is consistant with the proton model. For energies 10^{18} - $10^{19.9}$ eV, the data is not consistant with the iron model. The KS test provides a P-Value $<10^{-10}$. While this analysis has less resolving power (in part due to the tighter cuts made to ensure very clean events) than the HiRes stereo measurement, it does show that the resulting compostion measurement is not a function of the technique. Both HiRes and Telescope Array find a very light composition from 10^{18} eV to the highest energies.

We are also looking at the Xmax measurements in the stereo data in Telescope array. The same type of plots showing Xmax distributions for energy slices are made. Again, the data always looks much more like protons. In figure 3 we plot elongation rate, the mean Xmax as a function of energy, for the data collected in stereo between the Black Rock and Long Ridge telescope stations. Again the data looks much more like protons than iron.

4 Anisotropy

We looked at the Telescope Array events which passed the Auger AGN correlation search cuts ($E>5.7\times10^{18}$ eV) as our very high energy events that should be bent very little in the galactic/extragalactic magnetic fields. Very early, we bagan to notice what looked like a grouping of events in the sky. As we watched, the grouping became more pronounced. It was just south of the super-galactic plane. In our first 5 years of scintillator array data, there were 72 events in this data set. We followed the AGASA (Akeno Giant Air Shower Array) prescription and plotted the events, oversampling in 20 degree circles. The result is shown in figure 4.

We found that 19 of the 72 events fell in a "Hot Spot" which was located at (RA,Dec) = (146.7, 43.2), where a background of 4.5 events was expected. This means that 26% of the events are in 6% of the area. The LiMa significance for this is 5.2σ. We attempted to determine prejudice of our eyeballing the grouping and of the possibility of the grouping anywhere in the sky. We estimated a 3.4σ chance probability of this happening.

The angular distance between the hotspot and the supergalactic plane is $\sim19^\circ$ and the near-by Ursa Major supercluster is extended by more than 10° from the plane. Mrk421 is on the periphery of the Hot Spot and Virgo is even further away. There is also a filament connecting us to the local cluster, so perhaps one of these is the origin of the Hot Spot.

While we were preparing the publication about the Hot Spot, we continued to collect data. Shortly after the publication was accepted, we opened the box on the 6th year of data. This data contains 15 new events with $E>5.7\times10^{18}$ eV. The new data contains 3 new events inside the Hot Spot with an expected background of less than 1 event. The combined 6 years of data then has a chance probablity of occuring of $>4\sigma$. If this continues, perhaps in a year or two, we can declare an observation. We will continue to watch this.

5 Telescope Array Expansion

The original layout of telescopes and scintillator array for the Telescope Array were designed to concentrate on events with $E>10^{19}$ eV. Below that energy there is no overlap in the aperture of the fluorescence telescopes and below $\sim10^{18.2}$ eV there is a bias introduced in the Xmax measurement due to events being dimmer and developing higher in the atmosphere. In addition, the efficiency of the scintillator array falls off repidly between 10^{19} and 10^{18} eV due to the lower energy showers having a smaller footprint when they reach the Earth's surface.

There are several reasons for going lower in energy. One of these is that various experiments, including Fly's Eye, HiRes-MIA, Akeno, Yakutsk, and Kascade Grande, have found what is often called the "second knee" between 10^{17} and 10^{18} eV. Unfortunately, these experiments all have different energy scales. The all see a flat region and then a break with the flux falling with energy. When one normalizes the energy scale so that they all have the same energy in the flat region, then the effect is quite clear. However, in doing this, the actual energy of the break is lost.

In addition, as previously mentioned, the HiRes-MIA measurement shows a composition which is heavy, iron-like, around 10^{17} eV. The composition becomes lighter with energy, becoming light/protonic by 10^{18} eV. A separate measurement by the HiRes-stereo determined that the composition was light/protonic from 10^{18} to $\sim 10^{20}$ eV. These were different measurements, done with somewhat different apparatus, at different times. It would be good to remeasure this with a consistant set of equipment all cross calibrated. Finally, measureing the details of the spectral shape in the 10^{17} - 10^{18} eV region is sensitive to the evolution parameter of the source distribution.

We are pushing the Telescope Array energy threshold lower by adding 10 new telescopes to the Middle Drum site. These telescopes are from the HiRes-II site at Camel's Back, Dugway Proving Ground. The new telescopes view the sky above the original telscopes at Middle Drum. Hence, the original telescopes viewed 3-17° in elevation and the new telescopes view 17-59° in elevation. This construction has been completed and the new set of telescopes are in a commissioning phase as of August 2014.

In addition, we are adding a graded scintillator array to the existing scintillator array. The original array is on a 1.2 km square grid, as we expand the array towards the Middle Drum telescope station, the array will first go to 600 m spacing and then 400 m spacing. The arrangement of this The first 36 scintillators of this array have been deployed with 400 m spacing close to the telescope station and they are being commissioned. We are seeking funding for the rest of the array which will eventually add about 100 new scintillator detectors to the array. Sample events which include the TALE extension are shown in figure 5. With the extension, we are able to push the threshold of the experiment below $10^{16.5}$ eV.

Telescopes looking higher in the sky enable us to lower our energy threshold, but that is only part of the solution. We have now begun to utilize events with a large amount of Cerenkov light as a part of our measurement. Below $10^{17.5}$ eV, most of the events reconstructed have at least 60% of the light due Cerenkov. A preliminary spectrum showing the full spectrum Telescope Array plus TALE is shown in figure 6. For the first time we have a measurement of the ultra high energy cosmic ray spectrum covering more than four orders of magnitude in energy with one set of cross calibrated detectors. More work remains to refine this measurement, but correlating the spectrum with the composition measurement will provide information about the galatic to extragalactic transition.

Driven, in part, by the Hot Spot, we are also seeking to extend the aperture of the Telescope Array. We have proposed TAx4 which will expand the aperture of Telescope Array by a factor of four to about 3000 square km. We will add 500 new scintillator stations on a 2.08 km square grid and two new telscope stations overlooking these detectors. The telescope stations will provide cross calibration of the new array spacing and hybrid coverage for composition measurements. Assuming funding, we plan to begin this construction in the fall of 2015. Such an array would increase the significance of the Hot Spot measurement much more quickly and also might be able to observe sub-structure within the Hot Spot to narrow down the source(s).

6 Summary

The Telescope Array has observed and confirmed the Ankle and the GZK suppression of cosmic rays. The composition of cosmic rays $E>10^{18.2}$ eV is in good agreement with light/protonic MC models. We have also compared Xmax meaurement via hybrid technique with that via stereo technique and found them to be in good agreement with eachother. We have, thus, ruled out a potential discrepancy here as the reason for the differences between HiRes/Telescope Array measurements and the Auger Measurements.

The Telescope Array has observed its first evidence that there may be some anisotropy - a

3σ discrepany with isotropy near Ursa Major, just off of the supergalactic plane. Adding a 6th year of data to the set has increased the significance to more than 4σ, which is an encouraging sign.

The Telescope Array Low Energy Extension (TALE) is extending the reach of the Telescope Array down to 3×10^{16} eV and perhaps beyond. This will enable us to study the cosmic ray transition from galactic to extra-galactic sources. Finally, we have proposed TAx4 which will expand the Telescope Array to 3000 sq km.

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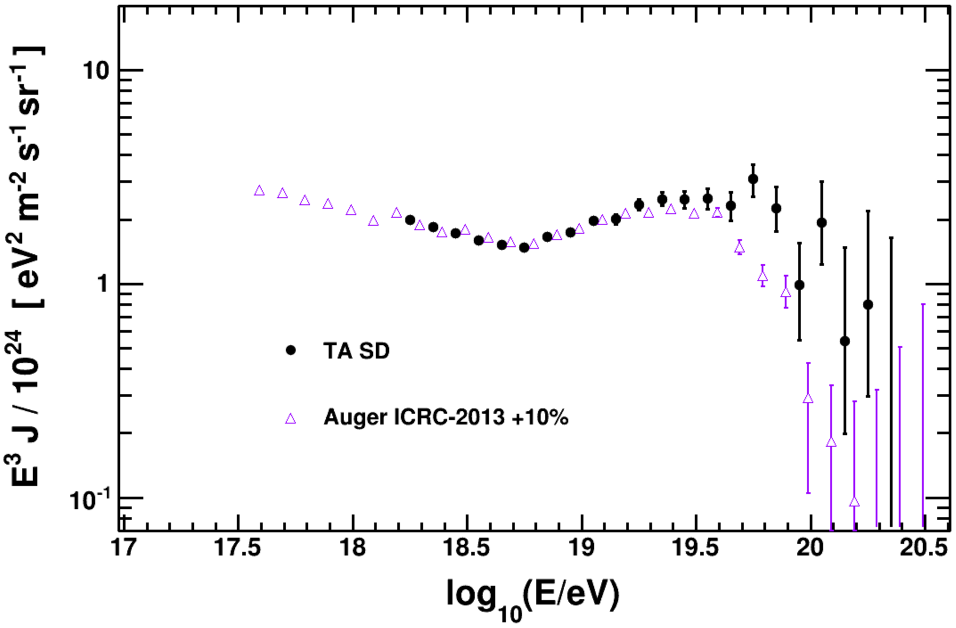
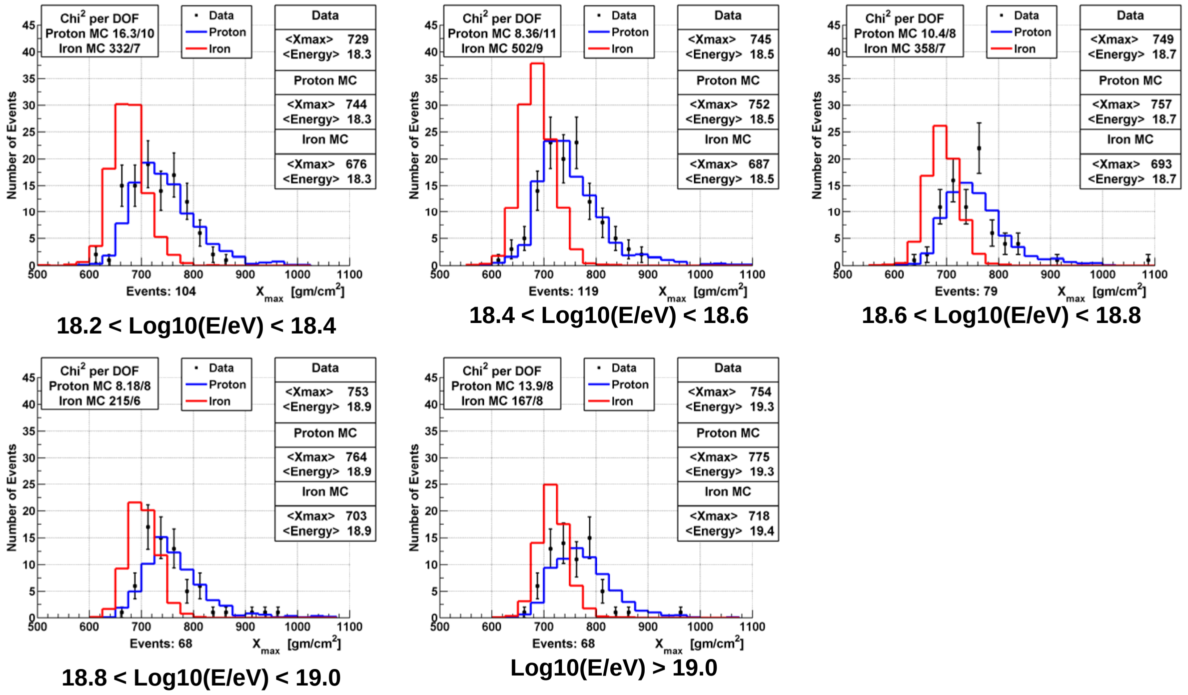


Figure 1: The ultra high energy cosmic ray spectrum as measured by 6 years of data from the Telescope Array scintillator array (black points) is shown in here in comparison with the measurement of the Auger Observatory in Argentina (purple). In this plot, the Auger energies have been scaled up by 10%. The measurements are in good agreement below $\sim 10^{19.3}$ eV. The two experiments appear to have different cut-off energies.



18.2 < Log10(E/eV) < 18.4

18.4 < Log10(E/eV) < 18.6

18.6 < Log10(E/eV) < 18.8

18.8 < Log10(E/eV) < 19.0

Log10(E/eV) > 19.0

Figure 2: The Xmax distribution from the Middle Drum hybrid data in energy slices. The data is shown as black points with error bars. The proton and iron simlated data is cut and analyzed with the same programs as the real data. The analyzed proton/iron MC is shown as a blue/red histogram. In all energy bins, the data looks much more like the protons than the iron.

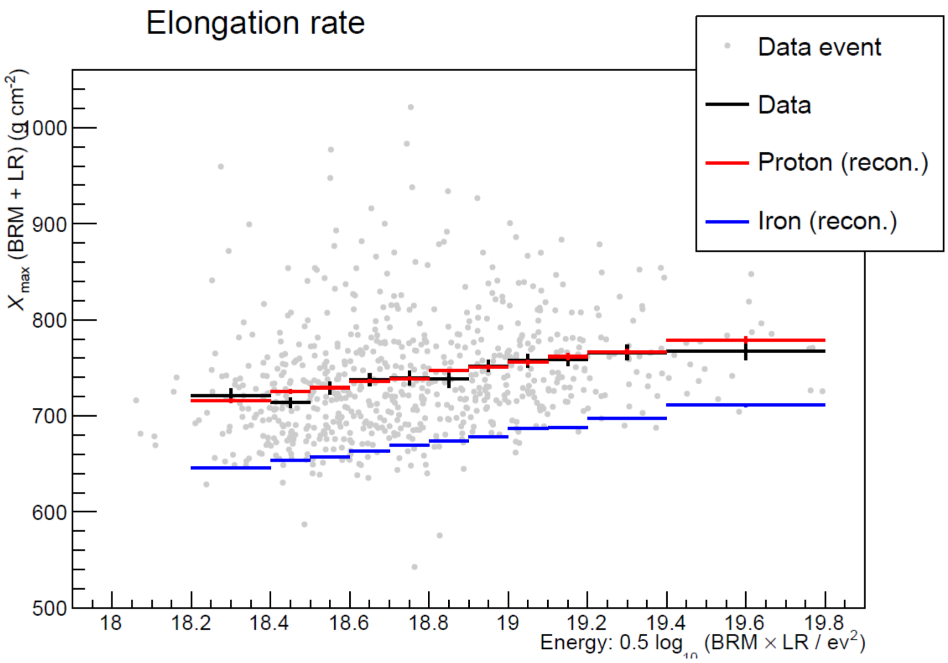
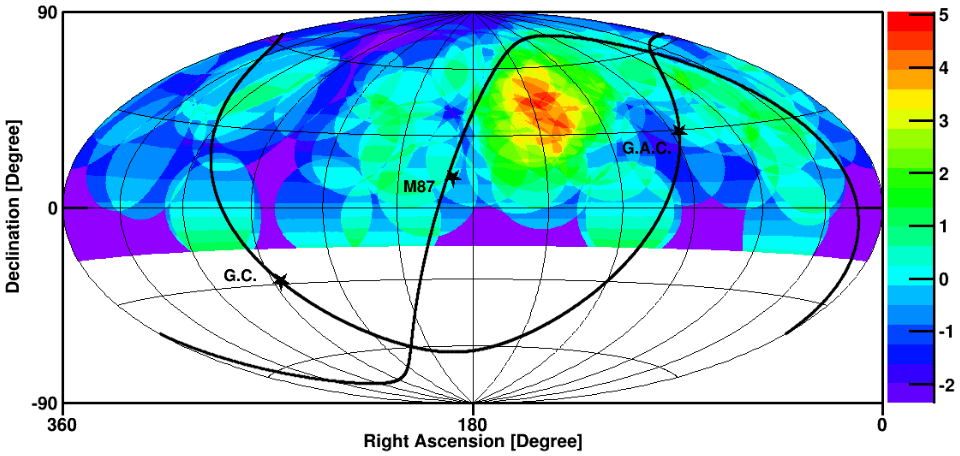


Figure 3: The stereo Xmax elongation rate. The gray points show the (Xmax/energy) measurements of individual data events to give an idea of the spread of the data. The mean Xmax for the data is shown as a function of energy as the black points with error bars. The red/blue bars show the analyzed MC for protons/iron. The data looks very light/protonic in this measurement.



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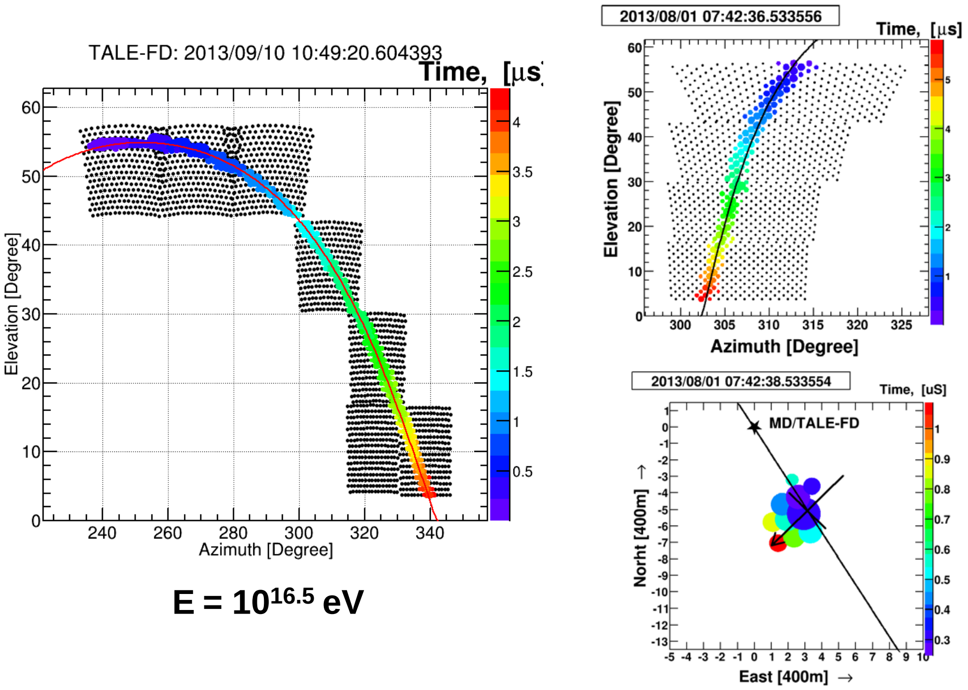

Figure 5: Sample events from Telescope Array + the TALE low energy extension. On the left is a telescope event pdflatex involving all four layers of telescopes - the set of telescopes view from 3-59° in elevation. This event reconstructed with an energy of $10^{16.5}$ eV. On the right is another event that was observed in hybrid. Right-top is the telescope view of the event, below-right is the TALE infill array view of the event as it reached the Earth's surface.

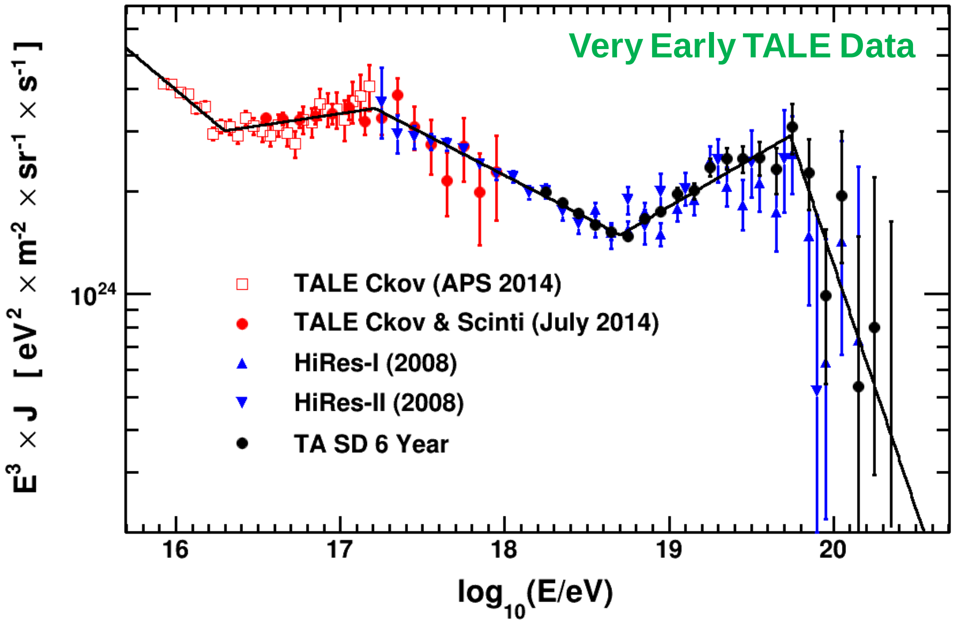

Figure 6: The Telescope Array spectrum from the first 6 years of scintillator array data, now extended by using the TALE telescopes. The black points are the Telescope Array scintillator measurements. The blue triangles are the HiRes-I and HiRes-II measurements. The filled red circles are TALE measurements using showers that contain predominantly scintillation light, while the open circles use events dominated by Cerenkov light.